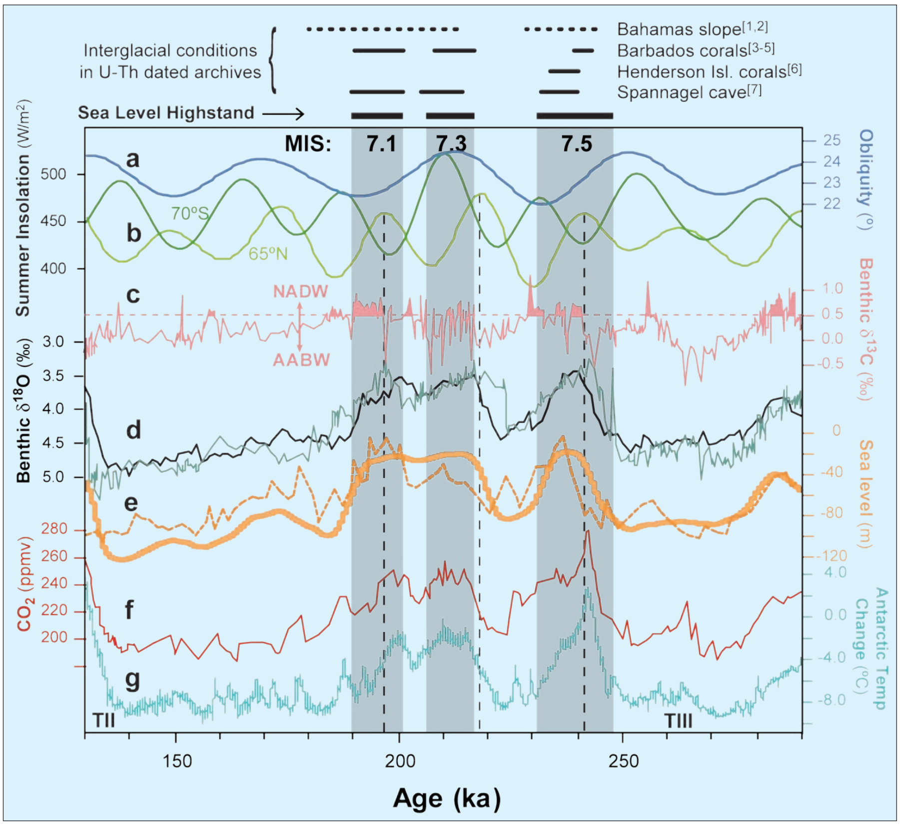

*Figure 3: Sea level and climate reconstructions during MIS 7. Sea level highstands at Argentarola denoted by vertical gray bars. (**a**) Obliquity, and (**b**) summer insolation curves at 65°N (JJA) (maxima shown by dotted lines in MIS 7) and 70°S (DJF) (Laskar, 1990), (**c**) Iberian Margin benthic carbon isotope ($\delta^{13}C$) data (Martrat et al., 2007) highlights the unusual nature of MIS 7.3, (**d**) benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005: black) and benthic $\delta^{18}O$ from the Iberian Margin (Martrat et al., 2007: blue), (**e**) sea level reconstructions (Siddall et al., 2003; Bintanja et al., 2008: dashed and solid orange lines, respectively), (**f**) compiled Antarctic ice core CO$_2$ (Lüthi et al., 2008), (**g**) EPICA Dome C temperature change (Jouzel et al., 2007). TII and TIII = Terminations. Data sources as follows: [1] Henderson et al., 2006; [2] Robinson et al., 2002; [3] Gallup et al., 1994; [4] Edwards et al., 1997; [5] Thompson and Goldstein, 2005; [6] Andersen, 2006; [7] Spötl et al., 2008; [8] Dutton et al., 2009. Figure modified from Dutton et al., 2009.*

termining the sensitivity of sea level response to insolation forcing. While records from submerged speleothems such as this are rare, they are archives that have enormous potential to shed light on the dynamics of climate and sea level in the past, and also to inform us about the interplay of these variables as we head into the future.

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Data Information

Data are available in online supplemental material associated with Dutton et al. (2009) *Nature Geoscience*, at http://dx.doi.org/10.1038/NGEO470

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Tempo of global deglaciation during the early Holocene: A sea level perspective

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High-resolution early Holocene sea level records are essential to aid predictions of future sea level change. However, our current understanding about the nonlinear response of sea level to rapid climate changes during this critical time interval is still in its infancy.

Sea level change is the result of complex interactions among the Earth's lithosphere, hydrosphere, atmosphere and cryosphere as a function of time. Geophysically, this change is defined as the vertical shift of the geoid, an equipotential surface of the Earth's gravitational field that coincides with the ocean surface, due primarily to variations in ocean mass and volume (Farrell and Clark, 1976; Mitrovica and Milne, 2003). This in turn leads to a complex spatio-temporal sea level response (Lambeck and Chappell, 2001). Therefore, studying past sea level changes from different time intervals and geologic settings can not only provide direct information about the dynamics of global ice volume (e.g., Peltier, 2004), but also about the physics of the Earth's interior that cannot be inferred seismologically (e.g., Kaufmann and Lambeck, 2002).

High-resolution sea level records also constitute an important knowledge base for predicting the behavior of future sea level, given the threat that global warming poses to low-lying coastal communities in terms of accelerated sea level rise. However, the predicted magnitude of sea level rise by the end of the 21st century (e.g., 0.26-0.59 m (IPCC, 2007) and 0.5-1.4 m (Rahmstorf, 2007)) remains highly uncertain. This uncertainty lies primarily in our poor understanding of the dynamic response of ice flow to climate change (Alley et al., 2005; Oppenheimer et al., 2007). For example, transient processes that may lead to non-linear sea level responses were not considered in the IPCC Fourth Assessment Report (IPCC, 2007), and the model of Rahmstorf (2007) includes neither ice sheet physics nor makes use of any longer sea level records. Such longer, high-resolution sea level records have the potential to address these issues. Rather than giving answers, here we raise some key questions that may help guide the next wave of investigations.

Conventional wisdom and current knowledge gap

Dating the vertical accretion of coral reefs in tropical oceans deepens our insight into the melting history of continental ice sheets since the Last Glacial Maximum (Fairbanks, 1989; Chappell and Polach, 1991; Bard et al., 1996). A compelling feature revealed by these data sets is not only the progressive rise of global sea level that started about 19 cal ka BP and ceased by about 7 cal ka BP but also the occurrence of episodic sea level jumps at about 19, 14.2, and 11.3 cal ka BP. Unlike the second event, the occurrence of the first and last remains a matter of debate. To further address the rapidity of sea level rise during these time windows, other types of sea level records with smaller vertical errors, notably organic-rich sedimentary records from continental shelves (e.g., Hanebuth et al., 2000), preferably in microtidal settings, are required.

The existing coral records also indicate that the rate of sea level rise slowed from 11-8 cal ka BP, mainly reflecting the reduced contribution from Antarctica (Nakada and Lambeck, 1988), and particularly the Laurentide Ice Sheet (LIS) during the final stage of its life cycle (Carlson et al., 2008). This can provide an analog to the present-day Greenland Ice Sheet (GIS), which might be a significant contributor to ongoing and future sea level rise. Recently, Carlson et al. (2007; 2008) reported evidence for episodically rapid ablation of the LIS around 9 and 7.6 cal ka BP, likely due to summer warming in the Hudson Bay area. This suggests that land-based ice sheets may be more sensitive to rapid climate change than previously thought, thus highlighting the potential threat of accelerated melting of the GIS to sea level rise within the context of global warming. However, the time series of LIS disintegration as documented by Carlson et al. (2008) is partly incompatible with sea level records that contain sufficient detail for (part of) this time interval (e.g., Van de Plassche, 1982; Törnqvist et al., 2006). For example, the Mississippi Delta sea level record shows an acceleration at about 8.2 cal ka BP (Törnqvist et al., 2004), while the data of Carlson et al. (2008) indicate a slow-down.

High-resolution (centennial) sea level records: A key to the future

Given the broadly similar climatic conditions, sea level change during the early Holocene may be regarded as an analog for future sea level rise. Therefore, predictions of sea level rise using either empirical or numerical methods should make full use of these longer records. However, sea level changes during this time span are also dominated by an isostatic component. The late Pleistocene glaciation in high latitudes not only lowered global sea level but also depressed the underlying lithosphere, resulting in a peripheral bulge in large regions surrounding the area of glaciation. As ice sheets melted following glaciation, the deformed crust was restored to its original state. This process is commonly known as glacial isostatic adjustment (GIA), which in turn leads to spatially variable postglacial sea level changes. This spatial variability of sea level is illustrated in Figure 1. The Baltic Sea record (Fig. 1) represents a near-field (i.e., an area within a glaciated region) response of sea level, which is marked by a monotonic fall after about 7 cal ka BP, revealing the slow rebound of the crust well after the demise of the Fennoscandian Ice Sheet. The Mississippi Delta record (Fig. 1) is an expression of sea level history in the intermediate field. Sea level in such regions has experienced a progressive rise throughout the past 7 ka as the result of collapse of the broad peripheral bulge around the LIS. The Malay-Thai Peninsula record (Fig. 1) is an example of far-field sea level response to meltwater addition to the oceans, as characterized by an apparent highstand at about 7 cal ka BP that was then followed by a continuous fall, due primarily to hydro-isostatic effects, the downwarping of ocean basins and associated uplift of continental margins caused by water loading as sea level rises.

A pattern shared by these records is the progressive rise of local sea level prior to 7 cal ka BP (Fleming et al., 1998), at least in part related to the rapid disintegration of the LIS (cf. Carlson et al., 2008). Superimposed upon this pattern, episodic sea level jumps at about 8.2 (Törnqvist et al., 2004) and 7.6 (Blanchon and Shaw, 1995; Yu et al., 2007) cal ka BP (Fig. 1) have been proposed. The former (Fig. 2) may well be associated with the catastrophic drainage of glacial lakes Agassiz and Ojibway (e.g.,

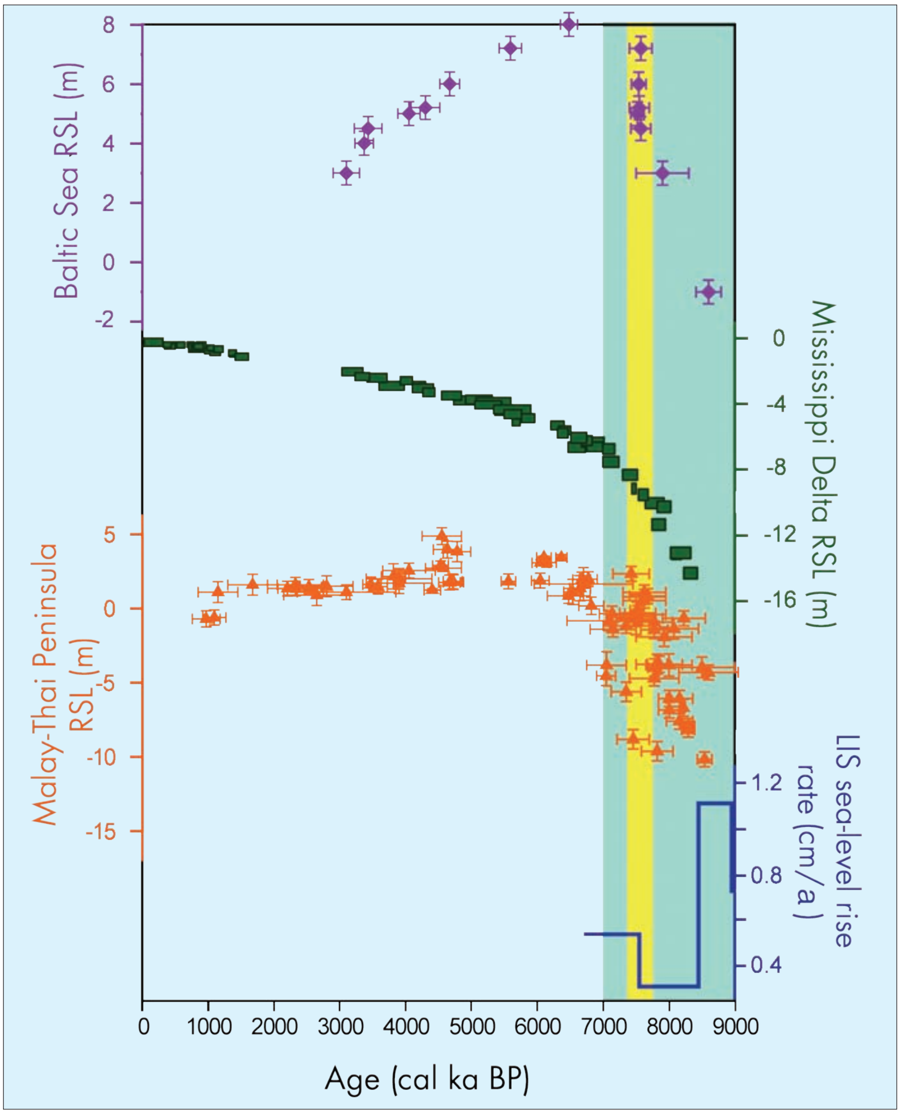

*Figure 1: Comparison of Holocene relative sea level (RSL; height of sea level relative to the present-day datum) records from near-field (**purple**; Yu et al., 2007), intermediate-field (**green**; Törnqvist et al., 2006; plus unpublished data), and far-field (**red**; Horton et al., 2005); **Blue** plot shows rate of sea level rise from the decay of the Laurentide Ice Sheet (LIS; Carlson et al., 2008). Vertical **blue bar** highlights the period of sea level rise dominated by the ice-volume component; **yellow bar** highlights a rapid sea level rise event centered on 7.6 cal ka BP in the Baltic Sea record.*

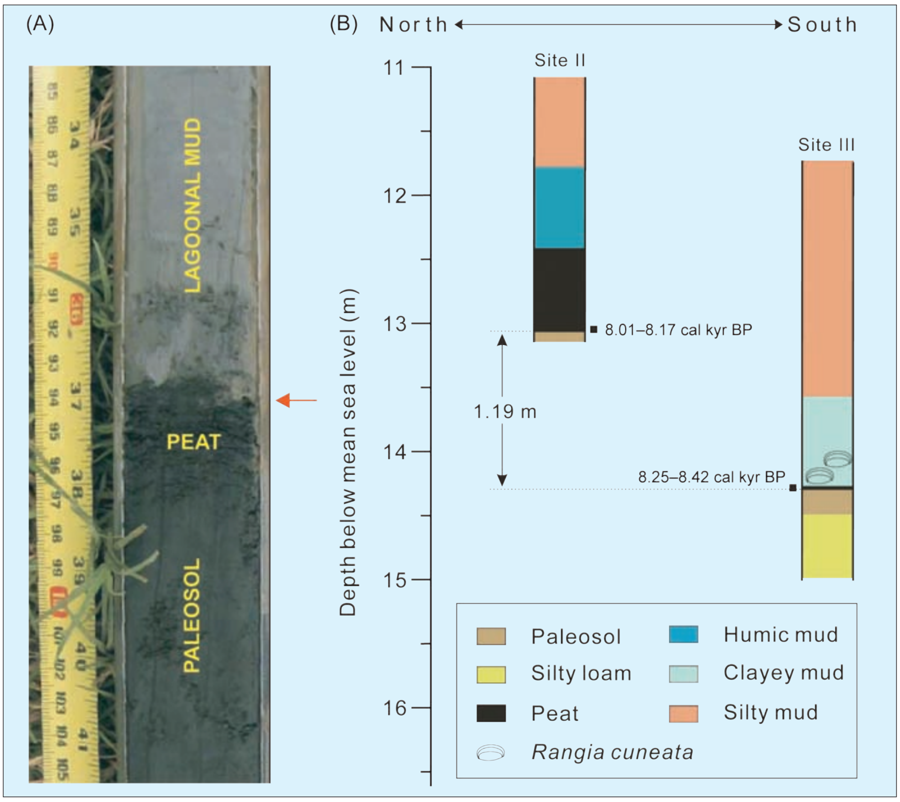

*Figure 2: **A**) A sedimentary sequence including a paleosol (fossil soil) that caps the Pleistocene substrate, basal peat and lagoonal mud from the Mississippi Delta. Note the sharp contact (arrow) between the ~2 cm thick peat layer and the overlying lagoonal mud, which represents an abrupt sea level rise at ca. 8.2 cal ka BP. **B**) Stratigraphic signature of the abrupt sea level rise at ca. 8.2 cal ka BP at Bayou Sale, Mississippi Delta (Törnqvist et al., 2004). The occurrence of* Rangia cuneata*, a brackish water clam characteristic of estuarine and lagoonal environments, is also shown.*

Barber et al., 1999). This rapid sea level rise serves as an example of how the amount and source of meltwater can be inferred from sea level records by the fingerprinting method; a technique that capitalizes on the distinct spatial pattern of the global sea surface due to the gravitational attraction of large ice and/or water masses (Mitrovica et al., 2001; Clark et al., 2002; Kendall et al., 2008). However, more detailed records are required to refine the estimate of the water volume impounded in these glacial lakes. To this end, our ongoing high-resolution sea level work in the Mississippi Delta aims to refine the timing and amplitude of the rapid sea level rise corresponding to the "8.2 ka event" by detailed stratigraphic studies. With regard to the "7.6 ka event", its extent still remains a matter of debate. Some records suggest a ca. 3 m rapid rise that occurred at about 7.5 cal ka BP or slightly later (e.g., Siddall et al., 2003; Liu et al., 2004; Bird et al., 2007), while others indicate a smooth rise of sea level during this time window (e.g., Van de Plassche, 1982; Törnqvist et al., 2006). The causes of such spatial contrasts are at present unknown but may in part be related to the location of the associated meltwater sources and their sea level fingerprints. We therefore conclude that our understanding of rapid sea level rise during the early Holocene is still in its infancy. Many more high-resolution sea level records for this critical time interval are needed. Combined with "fingerprint modeling", they could serve to refine the timing, amplitude and origin of such abrupt events.

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Coastal vegetation evidence for sea level changes associated with Heinrich Events

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A Cariaco Basin pollen record shows the development of tropical salt marshes during marine isotope stage 3 and suggests that millennial sea level changes during the periods encompassing Heinrich Events followed Antarctic climate variability.

The timing of sea level changes during marine isotope stage 3 (MIS 3; 60-25 ka) is a key issue in understanding the role of ice sheets in millennial-scale climate variability. The available reconstructions of sea level changes during this interval greatly rely on oxygen isotope records from deep-sea cores (since coral-based data are sparse and chronologies less precise), and consistently show four cycles of similar amplitude of sea level change in the order of 20-30 m (Siddall et al., 2008 and references therein). However, there is little agreement on the exact timing of these changes or on the relative roles of the Southern and Northern Hemisphere ice sheets in global sea level scenarios.

The ecological response of sensitive terrestrial ecosystems can provide independent information that complements the almost exclusively marine body of evidence of millennial sea level change. For this purpose, intertidal tropical ecosystems can be particularly useful, since they are very sensitive to environmental gradients in the sea-continent interface. In tidal salt marsh plant communities, species composition varies with elevation, usually in a banded pattern parallel to the shore. Its variation often reflects environmental gradients that result from the interaction between tidal regime, local topography, freshwater input, and biota. It has been proposed that the zonation is a spatial expression of successional changes over time and has potential to be reconstructed for the past by pollen analysis. If patterns of pollen deposition follow zonation and succession patterns, these can be