nature geoscience

REVIEW ARTICLE
PUBLISHED ONLINE: 26 AUGUST 2012 | DOI: 10.1038/NGEO1528

Northern Hemisphere ice-sheet responses to past climate warming

Anders E. Carlson[1,2]* and Kelsey Winsor[1]

During ice-age glacial maxima of the last ~2.6 million years, ice sheets covered large portions of the Northern Hemisphere. Records from the retreat of these ice sheets during deglaciations provide important insights into how ice sheets behave under a warming climate. During the last two deglaciations, the southernmost margins of land-based Northern Hemisphere ice sheets responded nearly instantaneously to warming caused by increased summertime solar energy reaching the Earth. Land-based ice sheets subsequently retreated at a rate commensurate with deglacial climate warming. By contrast, marine-based ice sheets experienced a delayed onset of retreat relative to warming from increased summertime solar energy, with retreat characterized by periods of rapid collapse. Both observations raise concern over the response of Earth's remaining ice sheets to carbon-dioxide-induced global warming. The almost immediate reaction of land-based ice margins to past small increases in summertime energy implies that the Greenland Ice Sheet could be poised to respond to continuing climate change. Furthermore, the prehistoric precedent of marine-based ice sheets undergoing abrupt collapses raises the potential for a less predictable response of the marine-based West Antarctic Ice Sheet to future climate change.

One of the most profound responses to Quaternary period deglacial climate change is the retreat and disappearance of Northern Hemisphere ice sheets[1–4]. During glacial periods, ice sheets covered large portions of North America and Eurasia, extending southwards to between 50° and 40° N at glacial maxima. On North America, the Laurentide Ice Sheet expanded east of the Canadian Rockies, covering most of Canada and the northern third of the United States[5]. At its western edge, the Laurentide Ice Sheet abutted the Cordilleran Ice Sheet, which grew over the Canadian Rockies[5] (Fig. 1). The Scandinavian Ice Sheet advanced over northern Europe and, during glacial maxima, was connected to the Barents-Kara Ice Sheet to the north as well as the British-Isles Ice Sheet to the southwest[6] (Fig. 1). The Greenland Ice Sheet also advanced onto the continental shelf during glacial periods[5]. Most of these ice sheets were predominately land-based; the exceptions are the mainly marine-based Barents-Kara Ice Sheet[6], which expanded into the Barents and Kara Seas, and the portions of the Greenland Ice Sheet on the continental shelf[5].

Changes in the Earth's orbit around the Sun, and its resultant effect on incoming boreal summer energy (insolation), ultimately caused deglaciations by warming the high northern latitudes during the peak ablation season of Northern Hemisphere ice sheets (May to July; Fig. 2a), which was reinforced by rising atmospheric carbon dioxide and other greenhouse gases[1–4,7–15] (Fig. 2b). Northern Hemisphere ice sheets were originally viewed as slow-responding parts of the climate system[2,7,8], but there is growing evidence that ice sheets may have responded faster than previously thought to changes in radiative forcing from increased boreal summer insolation and greenhouse gases. Sufficient data now exist to assess the manner in which individual Northern Hemisphere ice sheets retreated during the last two deglaciations, or terminations (TI and TII, ~23–6 kyr ago and ~139–126 kyr ago, respectively), which were forced by different increases in boreal summer insolation[1,9] (Fig. 2). For TI, direct terrestrial records of ice-margin positions and records of meltwater runoff to the ocean document ice-sheet retreat. Ice cover during the glacial period following TII removed much of the TII terrestrial deglacial record, requiring ice retreat patterns to be inferred from marine runoff records. Ice-sheet retreat records can be compared with relative sea-level data that provide an integrated record of global ice-volume, or eustatic sea level, once the effects of land-surface loading and rebound from glacial isostasy are taken into account[16].

We use these data to assess the manner in which different Northern Hemisphere ice sheets retreated during TI and TII. Did ice sheets respond to increasing radiative forcing from rising boreal summer insolation and greenhouse gas concentration in a rapid-linear fashion, or were they prone to more abrupt collapses in a lagged-nonlinear response? We define a rapid-linear response as one where the ice sheet responds essentially immediately to initial warming, followed by increases in retreat rate that are in step with rising radiative forcing (Fig. 3a). This is contrasted to our definition of a lagged-nonlinear response, where the ice sheet does not initially respond to rising radiative forcing, but then experiences a large response, or abrupt collapse, once a climate threshold is crossed (Fig. 3b). With this comparison, we attempt to characterize the retreat behaviour of predominately land-based and marine-based ice sheets.

The penultimate deglaciation

Eustatic sea-level rise probably lasted 11–13 kyr during TII. The onset of TII eustatic sea-level rise is, at present, not directly dated, but corals from Tahiti show that relative sea level had risen to ~85 m below present levels by ~137 kyr ago[17] (Fig. 4d), suggesting that ice sheets began to retreat within 2 kyr of the initial increase in boreal summer insolation around 139 kyr ago (Fig. 4a). Eustatic sea level was near present-day levels approximately 126 kyr ago[18]. This duration of TII agrees with inferences of global ice volume based on the $\delta^{18}O$ ($^{18}O/^{16}O$ relative to a standard) of calcite shells of bottom-dwelling foraminifera[14] that record the preferential removal of ^{16}O relative to ^{18}O from Earth's oceans and its accumulation in global ice sheets. After ~126 kyr ago, eustatic sea level continued to rise to an interglacial sea-level highstand of at least 4 m above present due to continued retreat of the Greenland and Antarctic Ice Sheets[18–20].

[1]Department of Geoscience, University of Wisconsin, Madison, Wisconsin 53706, USA, [2]Center for Climatic Research, University of Wisconsin, Madison, Wisconsin 53706, USA. *e-mail: acarlson@geology.wisc.edu

NATURE GEOSCIENCE DOI: 10.1038/NGEO1528

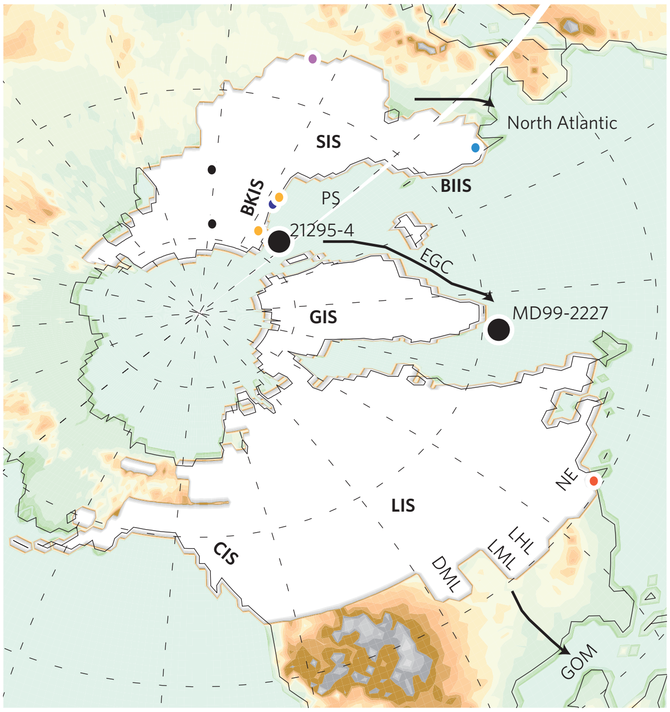

Figure 1 | Northern Hemisphere ice sheets at the last glacial maximum[15,38] with the Cordilleran (CIS), Laurentide (LIS), Greenland (GIS), British-Isles (BIIS), Scandinavian (SIS) and Barents-Kara (BKIS) ice sheets labelled. Also shown are the Lake Michigan (LML), Lake Huron (LHL) and Des Moines (DML) ice lobes, and the New England margin (NE). Coloured dots correspond to dates on Fig. 5b (cosmogenic dates) and Fig. 5c (radiocarbon dates). Large black circles show locations of ocean core records. The black line illustrates the direction that would be taken by meltwater discharged from the BKIS into the East Greenland Current (EGC). Other arrows denote SIS and BIIS runoff routing to the North Atlantic[60] and LIS runoff routing to the Gulf of Mexico[51] (GOM).

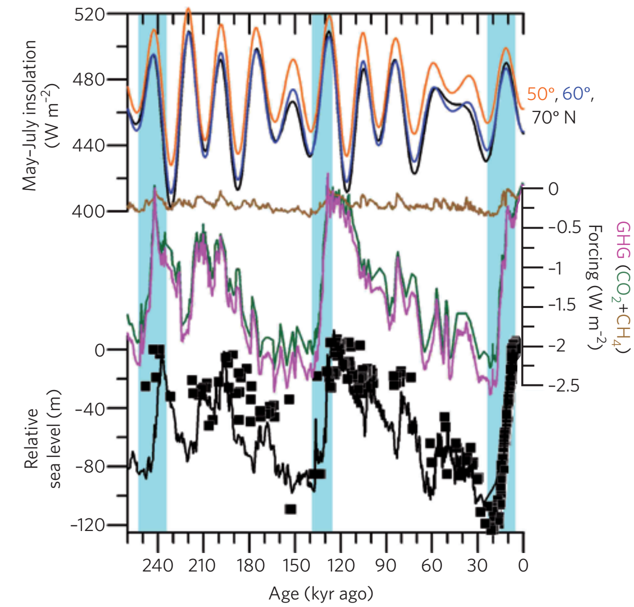

Figure 2 | The last three terminations (light blue). (**a**) Boreal summer insolation for 50°, 60° and 70° N (ref. 9) during May, June and July. (**b**) Combined radiative forcing (pink) of atmospheric CO_2 (green) and CH_4 (brown)[12] radiative forcing. (**c**) Relative sea-level data[15,17,20,42] (symbols) and Red Sea relative sea-level record[84] (black line). Note that peak TIII corals at ~240 kyr ago are assumed to be at 0 m (ref. 20), which may not be the case[83].

During TII, relative sea level may have risen locally to between −50 and −20 m by ~136 kyr ago, before potentially falling 20–40 m by ~133 kyr ago[17,20,21] (Fig. 4e). Whether eustatic sea level fell by a similar magnitude at this time has yet to be confirmed[18]. A fall in eustatic sea level during a deglaciation is somewhat perplexing, as it would imply growth of one or more ice sheets during an interval of global warming. A TII eustatic sea-level oscillation could suggest that millennial-timescale sea-level variability of glacial periods (Fig. 2c) persisted into TII (ref. 21). Alternatively, this oscillation may only reflect a local relative sea-level change at several locations rather than a true eustatic sea-level fluctuation[18]. Further research is needed to verify if eustatic sea level fell for several thousand years during TII (refs 18,21).

Retreat of the Laurentide and Scandinavian ice sheets probably contributed to the initial TII eustatic sea-level rise in response to increasing boreal summer insolation (Fig. 4a). During the penultimate glacial maximum, the Laurentide and Scandinavian Ice Sheets advanced slightly further south than their last glacial maximum positions, allowing direct dating of sediments deposited by these ice sheets as they began their retreat. The Lake Huron Lobe of the Laurentide Ice Sheet (Fig. 1) started to retreat from its penultimate glacial maximum extent before 138±3 kyr ago[22] (Fig. 5d), whereas the southernmost Scandinavian Ice Sheet may have begun retreat shortly after ~140 kyr ago[23].

The onset of Barents-Kara and Greenland ice-sheet retreat during TII may have been more abrupt than that of the Laurentide and Scandinavian Ice Sheets. Several marine records constrain the behaviour of the Barents-Kara and Greenland ice sheets during TII, although direct lead-lag comparisons are not possible as this interval is beyond the range of radiocarbon age control. The onset of the Barents-Kara Ice Sheet TII retreat is documented by Labrador Sea (Fig. 1) $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$; temperature-corrected $\delta^{18}O$ of surface-dwelling foraminifera calcite shells), which shows an abrupt decrease approximately 134 kyr ago in response to the discharge of ^{16}O-enriched meltwater from retreat of this ice sheet (Fig. 4b; refs 24,25 and K. Winsor, A. E. Carlson, G. P. Klinkhammer, J. S. Stoner and R. G. Hatfield, manuscript in preparation). The following increase in $\delta^{18}O_{sw}$ by ~132 kyr ago implies a cessation of Barents-Kara Ice Sheet retreat, with later fluctuations probably reflecting runoff from the Laurentide Ice Sheet once its southern margin had retreated northwards enough to discharge meltwater into the Labrador Sea (Fig. 4b; refs 5,26,27 and K. Winsor, A. E. Carlson, G. P. Klinkhammer, J. S. Stoner and R. G. Hatfield, manuscript in preparation). The beginning of Greenland Ice Sheet retreat back from the shelf break, and off the continental shelf, is suggested by pulses of sediment from this ice sheet ~134–132 kyr ago[28–30] (Fig. 4c). After TII, the Greenland Ice Sheet continued to retreat within its present terrestrial margins in response to elevated boreal summer insolation relative to peak insolation during TI (refs 19,30–35; Fig. 2a)

The last deglaciation

Significantly more data exist for TI to constrain relative sea-level rise and the retreat of Northern Hemisphere ice sheets. Most Northern Hemisphere ice sheets had advanced to near their last glacial maximum extents by ~26 kyr ago[15]. Although the Laurentide Ice Sheet discharged icebergs through Hudson Strait ~24 kyr ago in what is called Heinrich event 2 (ref. 36), this event seems to have had little impact on other parts of the Laurentide Ice Sheet, other Northern Hemisphere ice-sheet margins, and eustatic sea level[15]. Following the last glacial maximum, relative sea-level records suggest the onset of eustatic sea-level rise was 20–19 kyr ago, with present-day eustatic sea level achieved by ~6 kyr ago[4,15,37–40] (Fig. 5f). Although

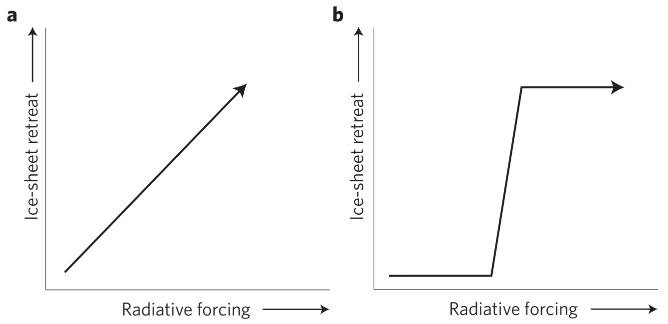

Figure 3 | Conceptual models of ice-sheet retreat in response to increasing radiative forcing from boreal summer insolation and greenhouse gas concentrations. (**a**) The rapid-linear model predicts an ice sheet responding quickly, with retreat increasing in step with rising radiative forcing. (**b**) The lagged-nonlinear model predicts a delayed response of the ice sheet to rising radiative forcing, followed by an abrupt response that then abates.

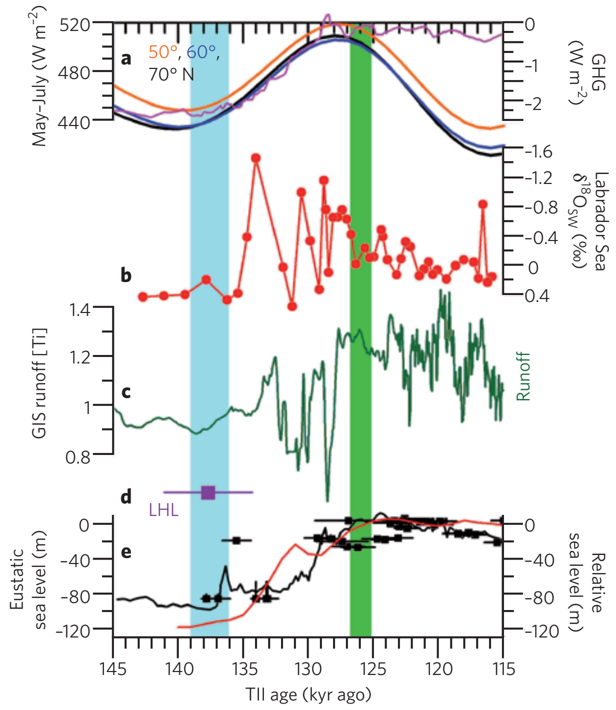

Figure 4 | TII ice-sheet retreat. (**a**) Boreal summer insolation[9] and greenhouse gas forcings[12] (GHG). (**b**) Labrador Sea $\delta^{18}O_{sw}$ record (MD99-2227 ocean core record; see Fig. 1 for position; ig. 1; K. Winsor, A. E. Carlson, G. P. Klinkhammer, J. S. Stoner and R. G. Hatfield, manuscript in preparation). (**c**) Greenland Ice Sheet (GIS) runoff reconstruction based on titanium concentration[30] (MD99-2227; Fig. 1). (**d**) Optically stimulated luminescence dates on the Lake Huron ice lobe (LHL; ref. 22). (**e**) Relative sea-level data[17,20] (symbols), Red Sea relative sea-level record[85] (black line) and eustatic sea level[18] (red line). Light blue bar indicates Northern Hemisphere retreat onset; green bar indicates when eustatic sea level reached ~0 m.

no eustatic or relative sea-level reversals are evident during TI, greater-than-average rates of eustatic sea-level rise occurred 20–19, 14.5–13.5 and 11.5–10.5 kyr ago (Fig. 5f) due to increases in the retreat rate of one or more ice sheets[41,42].

Most Northern Hemisphere ice sheets were retreating by 20–19 kyr ago[15], lagging behind the initial rise in boreal summer insolation ~23 kyr ago by 3–4 kyr (Fig. 5a). However, the southernmost margins of the Northern Hemisphere ice sheets may have begun deglacial retreat several thousand years earlier than other Northern Hemisphere ice-sheet margins due to their warmer setting. The Lake Michigan and Lake Huron Lobes of the Laurentide Ice Sheet (Fig. 1) retreated from their TI maximum positions before 21.7±0.2 kyr ago and 23.6±1.0 kyr ago[43–47], respectively (Fig. 5b), with the Des Moines Lobe (Fig. 1) beginning retreat before 20.1±0.2 kyr ago[48]. Similarly, the Laurentide Ice Sheet margin in southern New England (Fig. 1) retreated 21.2±0.4 kyr ago[49,50] (Fig. 5b). Much of the meltwater from early Laurentide Ice Sheet retreat was directed down the Mississippi River to the Gulf of Mexico[26] (Fig. 1), where the $\delta^{18}O$ of surface-dwelling foraminifera calcite shells decreased due to increased discharge of ^{16}O-enriched meltwater after ~23 kyr ago[51]. On the other side of the North Atlantic, the southeast Scandinavian Ice Sheet began retreating 22.1±1.9 kyr ago[52,53], whereas the southern margin of the British Isles Ice Sheet in Ireland started to retreat before 21.8±0.2 kyr ago[54] and 21.2±0.5 kyr ago[55–57] (Fig. 5b), and potentially as early as ~23 kyr ago[58,59]. The enhanced ablation of the southern Scandinavian and British Isles Ice Sheets may be recorded in the increased discharge of organic material to the North Atlantic[60] (Fig. 1).

Comparison of the timing of Laurentide, Scandinavian and British Isles ice-sheet retreat with boreal summer insolation suggests an essentially instantaneous southernmost-margin response to the initial increase in insolation after 23 kyr ago (Fig. 5a). Initial retreat of these ice sheets also led to the first significant rise in eustatic sea level 20–19 kyr ago[4,37–41], suggesting that the amount of retreat was probably small and within the uncertainty of relative sea-level records (Fig. 5f), or that increased precipitation on the ice sheets partially offset ice-margin ablation. However, the Cordilleran Ice Sheet may have begun retreat before 20±0.1 kyr ago[5,15], possibly later than the southernmost Laurentide, Scandinavian and British Isles ice sheets. This lag seems at odds with a rapid response of southernmost ice-sheet margins, but one explanation could be the location of the Cordilleran Ice Sheet just to the west of the Laurentide Ice Sheet (Fig. 1), where both cold katabatic winds off the Laurentide and increased precipitation from orographic uplift of the westerlies would help to sustain the Cordilleran Ice Sheet[61,62].

The initial retreat of the Barents-Kara and Greenland ice sheets began slightly later than land-based Northern Hemisphere ice sheets, lagging the rise in boreal summer insolation by more than 3 kyr. The marine-based Barents-Kara Ice Sheet was still at its maximum extent 20.6±0.2 kyr ago but began retreat before 19.5±0.1 kyr ago[63–66], with an accompanying discharge of meltwater to the Nordic and Labrador Seas approximately 18.5 kyr ago[24–26,67,68] (Fig. 5c). The Barents-Kara Ice Sheet may have subsequently lost almost half of its last glacial maximum area before 15.7±0.3 kyr ago[63] (Fig. 5c). Southern Greenland Ice Sheet runoff records show a large pulse of terrestrial sediment discharged into the ocean between ~20 and 18 kyr ago (Fig. 5d), suggesting retreat of the marine-terminating Greenland Ice Sheet margins[28–30,69,70], which may be recorded at two terrestrial sites[71,72]. Subsurface North Atlantic Ocean temperatures began to warm around the time of the onset of Barents-Kara and Greenland ice-sheet retreat, potentially identifying the deglacial trigger for this lagged onset of marine-based ice-sheet retreat[73].

Following the onset of TI, Northern Hemisphere ice sheets may have responded to oscillations in deglacial climate. Northern Hemisphere atmospheric and surface ocean climate initially warmed but then fluctuated on millennial timescales, with cooling during the Oldest Dryas (~18.5–14.6 kyr ago), warming during the Bølling-Allerød (~14.6–12.9 kyr ago), cooling again during the Younger Dryas (~12.9–11.7 kyr ago), and finally warming again into the Holocene (<11.7 kyr ago)[3,4]. The areas of ice covering North America (Laurentide and Cordilleran)[5] and Eurasia[6] (Scandinavian, British Isles and Barents-Kara; R. Gyllencreutz, J. Mangerud,

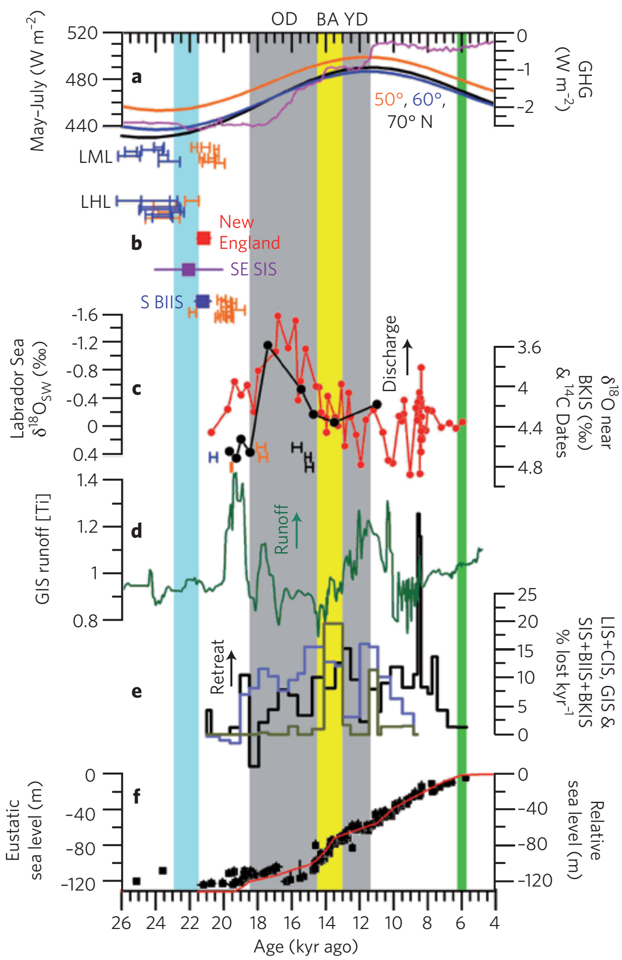

Figure 5 | TI ice-sheet retreat. (**a**) Boreal summer insolation[9] and greenhouse gas forcings[12] (GHG). (**b**) Radiocarbon dates for the retreat onset of the southern British Isles Ice Sheet[54] (BIIS) and of the Lake Michigan (LML) and Lake Huron (LHL) ice lobes of the Laurentide Ice Sheet[43–48] (LIS). Bars: blue, maximum-limiting; orange, minimum-limiting. Cosmogenic dates (squares) for the LIS in New England[49,50] (red), southeast Scandinavian Ice Sheet[52,53] (SE SIS; purple) and south British Isles Ice Sheet[55–57] (S BIIS; blue). (**c**) δ¹⁸O record of Barents-Kara Ice Sheet (BKIS) discharge[67] (black time series, PS-21295-4; see Fig. 1 for position) and radiocarbon dates[63] (bars: blue, maximum extent; orange, onset; black, significantly retreated. See Fig. 1). Labrador Sea $\delta^{18}O_{sw}$ record (red time series, MD99-2227; Fig. 1; K. Winsor, A. E. Carlson, G. P. Klinkhammer, J. S. Stoner and R. G. Hatfield, manuscript in preparation). (**d**) Greenland Ice Sheet (GIS) runoff reconstruction based on titanium concentration[28] (MD99-2227; Fig. 1). (**e**) Rate of area loss for: LIS and CIS (ref. 5; black); GIS (ref. 5; olive); and SIS, BIIS and BKIS (blue; R. Gyllencreutz, J. Mangerud, J.-I. Svendsen and Ø. Lohne, personal communication). (**f**) Relative sea-level data[15,42] (black squares) and eustatic sea level[4] (red line). Light blue bar indicates Northern Hemisphere retreat onset; green bar indicates when eustatic sea level reached ~0 m. Yellow bar indicates North Atlantic warm period during the Bølling-Allerød (BA). Grey bars indicate North Atlantic cold periods during the Oldest Dryas (OD) and Younger Dryas (YD).

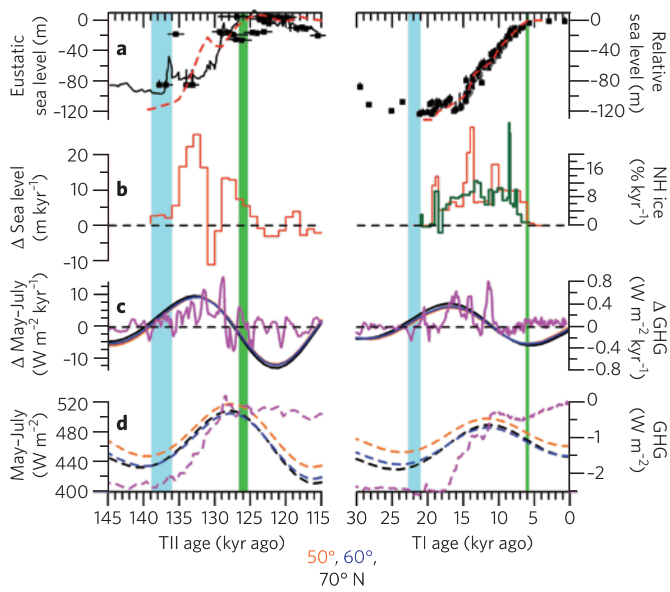

Figure 6 | TII (left) and TI (right) comparison. (**a**) Relative sea-level records[15,17,20,42,84] (black) and eustatic sea level[4,18] (red). (**b**) Rate of eustatic sea-level rise[4,18] (red line) and rate of Northern Hemisphere (NH) ice-sheet retreat (green line; see Fig. 5e). (**c**) Rates of boreal summer insolation change[9] and greenhouse gas radiative forcing change[12] (GHG). (**d**) Boreal summer insolation[9] and greenhouse gas radiative forcing[12]. Light blue bars indicate the onset of Northern Hemisphere ice-sheet retreat; green bars indicate when eustatic sea level reached ~0 m.

J.-I. Svendsen and Ø. Lohne, personal communication) are relatively well mapped and dated for TI, allowing for comparison with these North Atlantic climate fluctuations. North American ice sheets readvanced during the early part of the Oldest Dryas (Fig. 5e). Icebergs were discharged through Hudson Strait ~17.5 kyr ago in Heinrich event 1 (ref. 36), which was concurrent with, and potentially triggered by, the subsurface warming of the North Atlantic during the otherwise cold Oldest Dryas[73]. North American ice-sheet retreat rate then increased during the Bølling-Allerød, decreased during the Younger Dryas and increased again with warming into the Holocene (Fig. 5e). The one divergence from this gradual response of North American ice sheets to deglacial climate occurs approximately 8.2 kyr ago, when a large portion of the Laurentide Ice Sheet residing in the Hudson Bay marine basin collapsed[74,75]. Eurasian ice sheets behaved similarly to North American ice sheets, with retreat slowing during cold periods and accelerating during warm periods (Fig. 5e). The exception to this gradual retreat is during the early part of the Oldest Dryas, when rapid retreat of the Barents-Kara Ice Sheet caused a large reduction in Eurasian ice-sheet area. Greenland Ice Sheet records also suggest reduced retreat during the latter part of the Oldest Dryas, and increased retreat during the Bølling-Allerød and early Holocene[5,28–30,67,68,72,76–81], but with a more step-like recession compared with other Northern Hemisphere ice sheets (Fig. 5d,e). Comparing these retreat chronologies with eustatic sea level suggests that acceleration of Northern Hemisphere ice-sheet retreat during deglacial warm intervals preceding the Oldest Dryas, during the Bølling-Allerød and after the Younger Dryas[3,4] can at least in part explain the increases in the rate of TI eustatic sea-level rise 20–19, 14.5–13.5 and 11.5–10.5 kyr ago[4,15,37–42] (Fig. 5f).

Deglacial ice-sheet behaviour

Eustatic sea-level rise during TII was faster than during TI[19,27,82] (Fig. 6a). As greenhouse gas radiative forcing during both terminations was approximately the same (Fig. 6d) and the increases in greenhouses gas concentration occurred at similar rates (Fig. 6c), the most likely cause of faster TII ice retreat is the greater increase in boreal summer insolation (Fig. 6d) during TII relative to TI[19,27,82]. Indeed, the sum of boreal summer insolation increase at 50°, 60°, and 70° N (the latitudinal range for the majority of Northern Hemisphere ice sheets; Fig. 1) during TI between 23 and 6 kyr ago is ~1690 W m⁻². This is quite similar to the sum of boreal summer insolation increase for TII between 139 and 126 kyr ago (~1700 W m⁻²), suggesting that approximately the same amount of energy was required to deglaciate the Northern Hemisphere for the last two terminations. During TI, Northern Hemisphere ice-sheet retreat roughly tracked the rate of eustatic sea-level rise (Fig. 6b). Assuming a similar relationship, the more rapid eustatic sea-level rise during TII due to a more rapid rise in insolation would suggest that the aggregate retreat of Northern Hemisphere ice sheets roughly agrees with the rapid-linear ice-sheet response model (Fig. 3a), where a greater rate of radiative forcing (Fig. 6c) drives more rapid ice-sheet retreat (Fig. 6b).

In terms of individual ice sheets, it seems that the mainly land-based ice sheets behaved differently from the marine-based ice sheets of the Northern Hemisphere during the last two deglaciations. The near-instantaneous — given dating uncertainties — response of southernmost terrestrial ice margins to the initial rise in deglacial boreal summer insolation[22,23,43–60] agrees more with a rapid-linear response (Fig. 5b), as does their gradual retreat (Fig. 5e) in step with increasing boreal summer insolation and greenhouse gas forcing (Fig. 3a). However, once the Laurentide Ice Sheet became predominately marine-based over Hudson Bay during TI, it underwent a relatively rapid reduction in area[5,74,75] (Fig. 5e), analogous to a lagged-nonlinear response. The retreat onset of the marine-based Barents-Kara Ice Sheet[24,25,63–67] (and K. Winsor, A. E. Carlson, G. P. Klinkhammer, J. S. Stoner and R. G. Hatfield, manuscript in preparation) that lagged other Northern Hemisphere ice sheets, and its subsequent rapid deglaciation over several thousand years during TI and potentially TII, fits the lagged-nonlinear response model to deglacial warming (Fig. 3b). The Greenland Ice Sheet may have initially responded in a lagged-nonlinear fashion[27–29,69–72], with the ensuing staggered retreat of its marine margins also akin to a nonlinear response[5,77] (Fig. 5d,e). However, continued Greenland Ice Sheet retreat after TII through the last interglaciation (Fig. 4c) suggests a transition to a rapid-linear response model once this ice sheet was mainly land-based. The fact that most Northern Hemisphere ice sheets were mainly land-based[5,6] (Fig. 1) explains why their aggregated retreat (as recorded by eustatic sea-level rise) is more in accord with a rapid-linear response model.

Future directions in understanding ice-sheet behaviour

The possibility that different rates of Northern Hemisphere ice-sheet retreat during TI and TII can be explained by the different rates of boreal summer insolation increase poses an interesting question. Were the duration and magnitude of earlier deglaciations determined by the rate of boreal summer insolation increase, as would be suggested by a rapid-linear response model? A comparison of the last four terminations suggests that the progression of deglacial climate change is relatable to the magnitude of boreal summer insolation increase[14,27]. Did ice sheets respond in a similar manner, reaching current global ice volume only when ~1700 W m^{-2} of boreal summer insolation had accumulated, such as during TI and TII? The few relative sea-level records for Termination III (~254–235 kyr ago) suggest that eustatic sea level did not reach current levels[20,83,84] (Fig. 2c). The sum of the boreal summer insolation increase across this termination (Fig. 2a) is ~1180 W m^{-2}, which may be insufficient to drive a full deglaciation, in agreement with a rapid-linear response model for Northern Hemisphere terminations.

Relative sea-level records are insufficient at present, however, to assess the relationship between relative sea-level rise and boreal summer insolation for earlier deglaciations, necessitating the construction of precisely dated relative sea-level records further back in time from regions far removed from ice sheets[16,20,83–85]. These records should be produced in conjunction with glacio-isostatic modelling efforts to extract changes in eustatic sea level from the relative sea-level data[16,18,86]. The behaviour of individual Northern Hemisphere ice sheets beyond TII is also poorly, or not at all, known. Marine records of ice-sheet proxies that are strategically located near a given ice sheet may hold the key to assessing the responses of individual ice sheets to boreal summer insolation across multiple deglaciations[28–30,87–89]. These records have the potential to be extended back to the onset of the Quaternary[87] and can be correlated to each other using global paleomagnetic records[90]. Such new relative sea-level and ice-sheet records will test if a rapid-linear retreat relationship between Northern Hemisphere ice sheets and boreal summer insolation is applicable to earlier deglaciations, as well as document if the deglacial response of individual Northern Hemisphere ice sheets holds true for a wider range of increases in boreal summer insolation. Furthermore, these records would allow for the development of data-driven semi-empirical models of the relationship between the cryosphere, or individual ice sheets, and changes in radiative forcing from boreal summer insolation and greenhouse gases[84,91,92], complimenting thermodynamic ice-sheet models[31–35,80,93,94].

The deglaciation of Northern Hemisphere ice sheets may also provide information on how the basic geographic setting of an ice sheet might predispose it to a particular style of retreat. Land-based ice sheets have, during the last two terminations, probably retreated in a more rapid-linear fashion, whereas the marine-based Barents-Kara Ice Sheet and the marine-based portions of the Greenland and Laurentide Ice Sheets may have retreated in a more lagged-nonlinear manner. How applicable are these interpretations of palaeo ice-sheet behaviour to the response of Earth's remaining ice sheets — the Greenland and Antarctic Ice Sheets — to future climate change from anthropogenic greenhouse gas emissions[95]? Does the more rapid-linear response of land-based palaeo ice sheets suggest that the now mainly land-based Greenland Ice Sheet will respond to climate change in a similar rapid-linear fashion, with a near instantaneous onset of margin recession followed by more predictable retreat[96]? Likewise, is the marine-based West Antarctic Ice Sheet more likely to respond nonlinearly to climate change, with an abrupt (but less predictable) onset of retreat[73,93,96,97]?

Timescales become important when attempting such analogies. In the case of the rapid-linear model, the TI onset of southernmost Laurentide, Scandinavian and British Isles ice-margin retreat can only be dated to within centuries relative to the initial rise in boreal summer insolation (Fig. 5), which is a longer timescale than currently being considered for adaptation to eustatic sea-level rise in the coming century[98]. However, the retreat of these southernmost terrestrial ice margins within centuries of an increase in boreal summer insolation of only 1–2 W m^{-2} (Fig. 5a) suggests that terrestrial ice margins near their climatic limit are responsive to small changes in radiative forcing. For the lagged-nonlinear model, the Barents-Kara Ice Sheet may have taken several millennia to fully collapse[63–66], a significantly longer period than present concerns over future eustatic sea-level rise[98]. However, the final collapse of the marine portion of the Laurentide Ice Sheet at ~8.2 kyr ago occurred in less than 130 years and raised eustatic sea level 0.8–2.2 m[75], which is a timescale of more importance to global society[98].

The rate of radiative forcing also needs to be considered with these palaeo ice-sheet analogues. The increase in boreal summer insolation and rise of 90–100 ppm in atmospheric CO_2 during terminations occurred over ~11,000 years (Fig. 2). In contrast, human carbon emissions have increased atmospheric CO_2 by over 100 ppm in less than 200 years, with even greater increases predicted to occur in the coming century[98]. Given this more rapid rise in greenhouse gas radiative forcing, Earth's remaining ice sheets could respond in a manner not previously observed in the late Quaternary.

Received 18 July 2011; accepted 25 June 2012;
published online 26 August 2012

References

1. Broecker, W. S. & van Donk, J. Insolation changes, ice volumes, and the O[18] record in deep-sea cores. *Rev. Geophys. Space Phys.* **8,** 169–198 (1970).
2. Imbrie, J. *et al.* On the structure and origin of major glaciation cycles 2: The 100,000-year cycle. *Paleoceanography* **8,** 699–735 (1993).

3. Shakun, J. D. & Carlson, A. E. A global perspective on Last Glacial Maximum to Holocene climate change. *Quat. Sci. Rev.* **29,** 1801–1816 (2010).
4. Clark, P. U. *et al.* Global climate evolution during the last deglaciation. *Proc. Natl Acad. Sci. USA* **109,** E1134–E1142 (2012).
5. Dyke, A. S. in *Quaternary Glaciations: Extent and Chronology* Vol. 2 (eds Ehlers, J. & Gibbard, P. L.) 373–424 (Elsevier, 2004).
6. Svendsen, J.-I. *et al.* Late Quaternary ice sheet history of northern Eurasia. *Quat. Sci. Rev.* **23,** 1229–1271 (2004).
7. Hays, J. D., Imbrie, J. & Shackleton, N. J. Variations in the Earth's Orbit: Pacemaker of the Ice Ages. *Science* **194,** 1121–1132 (1976).
8. Weertman, J. Milankovitch solar radiation variations and ice age ice sheet sizes. *Nature* **261,** 17–20 (1976).
9. Berger, A. & Loutre, M. F. Insolation values for the climate of the last 10 million years. *Quat. Sci. Rev.* **10,** 297–317 (1991).
10. CAPE-Last Interglacial Project Members. Last Interglacial Arctic warmth confirms polar amplification of climate change. *Quat. Sci. Rev.* **25,** 1383–1400 (2006).
11. Roe, G. In defense of Milankovitch. *Geophys. Res. Lett.* **33,** L24703 (2006).
12. Jouzel, J. *et al.* Orbital and millennial antarctic climate variability over the past 800,000 years. *Science* **317,** 793–796 (2007).
13. Huybers, P. & Denton, G. Antarctic temperature at orbital timescales controlled by local summer duration. *Nature Geosci.* **1,** 787–792 (2008).
14. Cheng, H. *et al.* Ice age terminations. *Science* **326,** 248–252 (2009).
15. Clark, P. U. *et al.* The Last Glacial Maximum. *Science* **325,** 710–714 (2009).
16. Milne, G. A., Mitrovica, J. X. Searching for eustasy in deglacial sea-level histories. *Quat. Sci. Rev.* **27,** 2292–2302 (2008).
17. Thomas, A. L. *et al.* Penultimate deglacial sea-Level timing from uranium/thorium dating of Tahitian corals. *Science* **324,** 1186–1189 (2009).
18. Kopp, R. E. *et al.* Probabilistic assessment of sea level during the last interglacial stage. *Nature* **462,** 863–867 (2009).
19. Overpeck, J. T. *et al.* Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. *Science* **311,** 1747–1750 (2006).
20. Thompson, W. G. & Goldstein, S. L. Open-system coral ages reveal persistent suborbital sea-level cycles. *Science* **308,** 401–404 (2005).
21. Siddall, M., Bard, E., Rohling, E. J. & Hemleben, C. Sea-level reversal during Termination II. *Geology* **34,** 817–820 (2006).
22. Wood, J. R., Forman, S. L., Pierson, J. & Gomez, J. New insights on Illinoian deglaciation from deposits of Glacial Lake Quincy, central Indiana. *Quat. Res.* **73,** 374–384 (2010).
23. Larsen, N. K. *et al.*, Late Quaternary ice sheet, lake and sea history of southwest Scandinavia — a synthesis. *Boreas* **38,** 732–761 (2009).
24. Green, C. L., Bigg, G. R. & Green, J. A. M. Deep draft icebergs from the Barents Ice Sheet during MIS 6 are consistent with erosional evidence from the Lomonosov Ridge, central Arctic. *Geophys. Res. Lett.* **37,** L23606 (2010).
25. Stanford, J. D. *et al.* A new concept for the paleoceanographic evolution of Heinrich event 1 in the North Atlantic. *Quat. Sci. Rev.* **30,** 1047–1066 (2011).
26. Licciardi, J. M., Teller, J. T. & Clark, P. U. in *Mechanisms of Global Climate Change at Millennial Time Scales* (eds Clark, P. U., Webb, R. S. & Keigwin, L. D.) 177–201 (AGU, 1999).
27. Carlson, A. E. Why there was not a Younger Dryas-like event during the Penultimate Deglaciation. *Quat. Sci. Rev.* **27,** 882–887 (2008).
28. Stoner, J. S., Channell, J. E. T. & Hillaire-Marcel, C. Magnetic properties of deep-sea sediments off southwest Greenland: Evidence for major differences between the last two deglaciations. *Geology* **23,** 241–244 (1995).
29. Carlson, A. E., Stoner, J. S., Donnelly, J. P. & Hillaire-Marcel, C. Response of the southern Greenland Ice Sheet during the last two deglaciations. *Geology* **36,** 359–362 (2008).
30. Colville, E. J. *et al.* Sr-Nd-Pb isotope evidence for ice-sheet presence on southern Greenland during the last interglacial. *Science* **333,** 620–623 (2011).
31. Tarasov, L. & Peltier, W. R. Greenland glacial history, borehole constraints, and Eemian extent. *J. Geophys. Res.* **108,** 2143 (2003).
32. Cuffey, K. M. & Marshall, S. J. Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet. *Nature* **404,** 591–594 (2000).
33. Lhomme, N., Clarke, G. K. C. & Marshall, S. J. Tracer transport in the Greenland Ice Sheet: constraints on ice cores and glacial history. *Quat. Sci. Rev.* **24,** 173–194 (2005).
34. Otto-Bliesner, B. L. *et al.* Simulating Arctic climate warmth and icefield retreat in the last interglaciation. *Science* **311,** 1751–1753 (2006).
35. Robinson, A., Calov, R. & Ganopolski, A. Greenland ice sheet model parameters constrained using simulations of the Eemian Interglacial. *Clim. Past* **7,** 381–396 (2011).
36. Hemming, S. R. Heinrich events: massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint. *Rev. Geophys.* **42,** RG1005 (2004).
37. Yokoyama, Y., Lambeck, K., De Deckker, P., Johnston, P. & Fifield, L. K. Timing of the Last Glacial Maximum from observed sea-level minima. *Nature* **406,** 713–716 (2000).
38. Peltier, W. R. Global glacial isostacy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE. *Annu. Rev. Earth Planet. Sci.* **32,** 111–149 (2004).
39. Hanebuth, T. J. J., Stattegger, K. & Bojanowski, A. Termination of the Last Glacial Maximum sea-level lowstand: The Sunda-Shelf data revisited. *Global Planet. Change* **66,** 76–84 (2009).
40. Clark, P. U., McCabe, A. M., Mix, A. C. & Weaver, A. J. Rapid rise of sea level 19,000 years ago and its global implications. *Science* **304,** 1141–1144 (2004).
41. PALSEA Members. The sea-level conundrum: case studies from palaeo-archives. *J. Quat. Sci.* **25,** 19–25 (2009).
42. Deschamps, P. *et al.* Ice-sheet collapse and sea-level rise at the Bølling warming 14,600 years ago. *Nature* **483,** 559–564 (2012).
43. Hansel, A. K. & Johnson, W. H. Fluctuations of the Lake Michigan lobe during the late Wisconsin subepisode. *Geolog. Surv. Sweden* **81,** 133–144 (1992).
44. Curry, B. B. *et al.* The DeKalb mounds of northeastern Illinois as archives of deglacial history and postglacial environments. *Quat. Res.* **74,** 82–90 (2010).
45. Curry, B. & Petras, J. Chronological framework for the deglaciation of the Lake Michigan lobe of the Laurentide Ice Sheet from ice-walled lake deposits. *J. Quat. Sci.* **26,** 402–410 (2011).
46. Mickelson, D. M., Clayton, L., Fullerton, D. S. & Borns, H. W. in *Late-Quaternary Environments of the United States* Vol. 1 (ed. Wright, H. E.) 3–37 (1983).
47. Glover, K. C. *et al.* Deglaciation, basin formation and post-glacial climate change from a regional network of sediment core sites in Ohio and eastern Indiana. *Quat. Res.* **76,** 401–410 (2011).
48. Bettis, E. A., Jr., Quade, D. J. & Kemmis, T. J. Hogs, bogs, and logs: Quaternary deposits and environmental geology of the Des Moines Lobe. *Geol. Surv. Bureau Guidebook* **18,** 1–170 (1996).
49. Balco, G., Stone, J. O. H., Porter, S. C. & Caffee, M. W. Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA. *Quat. Sci. Rev.* **21,** 2127–2135 (2002).
50. Balco, G. *et al.* Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quat. Geochronol.* **4,** 93–107 (2009).
51. Leventer, A., Williams, D. F. & Kennett, J. P. Dynamics of the Laurentide ice sheet during the last deglaciation: evidence from the Gulf of Mexico. *Earth Planet. Sci. Lett.* **59,** 11–17 (1982).
52. Rinterknecht, V. R. *et al.* The last deglaciation of the southeastern sector of the Scandinavian Ice Sheet. *Science* **311,** 1449–1452 (2006).
53. Goehring, B. M. *et al.* Late Glacial and Holocene ^{10}Be production rates for western Norway. *J. Quat. Sci.* **27,** 89–96 (2012).
54. McCabe, A. M., Clark, P. U. & Clark, J. AMS ^{14}C dating of deglacial events in the Irish Sea Basin and other sectors of the British-Irish ice sheet. *Quat. Sci. Rev.* **24,** 1673–1690 (2005).
55. Clark, J. *et al.* ^{10}Be chronology of the last deglaciation of County Donegal, northwestern Ireland. *Boreas* **38,** 111–118 (2009).
56. Ballantyne, C. K. Extent and deglacial chronology of the last British-Irish Ice Sheet: implications of exposure dating using cosmogenic isotopes. *J. Quat. Sci.* **25,** 515–534 (2010).
57. Ballantyne, C. K. & Stone, J. O. Did large ice caps persist on low ground in north-west Scotland during the Lateglacial Interstade? *J. Quat. Sci.* **27,** 297–306 (2012).
58. Clark, J. *et al.* Response of the Irish Ice Sheet to abrupt climate change during the last deglaciation. *Quat. Sci. Rev.* **35,** 100–115 (2012).
59. Clark, C. D., Hughes, A. L. C., Greenwood, S. L., Jordan, C. & Sejrup, H. P. Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quat. Sci. Rev.* **44,** 112–146 (2012).
60. Menot, G. *et al.* Early reactivation of European rivers during the last deglaciation. *Science* **313,** 1623–1625 (2006).
61. Dyke, A. S. & Prest, V. K. Late Wisconsinan and Holocene history of the Laurentide Ice Sheet. *Geogr. Phys. Quatern.* **41,** 237–263 (1987).
62. Pollard, D. & Thompson, S. L. Climate and ice-sheet mass balance at the Last Glacial Maximum from the GENESIS Version 2 global climate model. *Quat. Sci Rev.* **16,** 841–863 (1997).
63. Landvik, J. Y. *et al.* The Last Glacial Maximum of Svalbard and the Barents Sea area: ice sheet extent and configuration. *Quat. Sci. Rev.* **17,** 43–75 (1998).
64. Vogt, C., Knies, J., Spielhagen, R. F. & Stein, R. Detailed mineralogical evidence for two nearly identical glacial/deglacial cycles and Atlantic water advection to the Arctic Ocean during the last 90,000 years. *Glob. Planet. Change* **31,** 23–44 (2001).
65. Rasmussen, T. L. *et al.* Paleoceanographic evolution of the SW Svalbard margin (76 °N) since 20,000 ^{14}C yr BP. *Quat. Res.* **67,** 100–114 (2007).
66. Jessen, S. P., Rasmussen, T. L., Nielsen, T. & Solheim, A. A new late Weichselian and Holocene marine chronology for the western Svalbard slope **30**, 000–0 cal years BP. *Quat. Sci. Rev.* **29,** 1301–1312 (2010).
67. Jones, G. A. & Keigwin, L. D. Evidence from Fram Strait (78° N) for early deglaciation. *Nature* **336,** 56–59 (1988).
68. Koç, N. & Jansen, E. Response of the high-latitude Northern Hemisphere to orbital climate forcing: Evidence from the Nordic Seas. *Geology* **22,** 523–526 (1994).

69. Nam, S. I., Stein, R., Grobe, H. & Hubberten, H. Late Quaternary glacial-interglacial changes in sediment composition at the East Greenland continental margin and their paleoceanographic implications. *Mar. Geol.* **122,** 243–262 (1995).
70. Andrews, J. T., Smith, L. M., Preston, R., Cooper, T. & Jennings, A. E. Spatial and temporal patterns of iceberg rafting (IRD) along the East Greenland margin, ca. 68° N, over the last 14 cal.ka. *J. Quat. Sci.* **12,** 1–13 (1997).
71. Håkansson, L., Briner, J., Alexanderson, H., Aldahan, A. & Possnert, G. ^{10}Be ages from central east Greenland constrain the extent of the Greenland ice sheet during the Last Glacial Maximum. *Quat. Sci. Rev*. **26,** 2316–2321, (2007).
72. Rinterknecht, V., Gorokhovich, Y., Schaefer, J. & Caffee, M. Preliminary ^{10}Be chronology for the last deglaciation of the western margin of the Greenland Ice Sheet. *J. Quat. Sci.* **24,** 270–278 (2008).
73. Marcott, S. A. *et al.* Ice-shelf collapse from subsurface warming as a trigger for Heinrich events. *Proc. Natl Acad. Sci. USA* **108,** 13415–13419 (2011).
74. Barber, D. C. *et al.* Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature* **400,** 344–348 (1999).
75. Li, Y.-X., Törnqvist, T. E., Nevitt, J. A. & Kohl, B. Synchronizing a sea-level jump, final Lake Agassiz drainage, and abrupt cooling 8200 years ago. *Earth Planet. Sci. Lett.* **315–316,** 41–50 (2012).
76. Jennings, A. E., Hald, M., Smith, M. & Andrews, J. T. Freshwater forcing from the Greenland Ice Sheet during the Younger Dryas: evidence from southeastern Greenland shelf cores. *Quat. Sci. Rev.* **25,** 282–298 (2006).
77. Bennike, O. & Björck, S. Chronology of the last recession of the Greenland Ice Sheet. *J. Quat. Sci.* **17,** 211–219 (2002).
78. Roberts, D. H., Long, A. J., Schnabel, C., Freeman, S. & Simpson, M. J. R. The deglacial history of southeast sector of the Greenland Ice Sheet during the Last Glacial Maximum. *Quat. Sci. Rev.* **27,** 1505–1516 (2008).
79. Roberts, D. H. *et al.* Ice sheet extent and early deglacial history of the southwestern sector of the Greenland Ice Sheet. *Quat. Sci. Rev.* **28,** 2760–2773 (2009).
80. Simpson, M. J. R., Milne, G. A., Huybrechts, P. & Long, A. J. Calibrating a glaciological model of the Greenland ice sheet from the Last Glacial Maximum to present-day using field observations of relative sea level and ice extent. *Quat. Sci. Rev.* **28,** 1631–1657 (2009).
81. Young, N. E. *et al.* Response of Jakobshavn Isbræ, Greenland, to Holocene climate change. *Geology* **39,** 131–134 (2011).
82. Ruddiman, W. F., Molfino, B., Esmay, A. & Pokras, E. Evidence bearing on the mechanism of rapid deglaciation. *Climatic Change* **3,** 65–87 (1980).
83. Dutton, A. *et al.* Phasing and amplitude of sea-level and climate change during the penultimate interglacial. *Nature Geosci.* **2,** 355–359 (2009).
84. Rohling, E. J. *et al.* Antarctic temperature and global sea level closely coupled over the past five glacial cycles. *Nature Geosci.* **2,** 500–504 (2009).
85. Andersen, M. B. *et al.* High-precisions U-series measurements of more than 500,000 year old fossil corals. *Earth Planet. Sci. Lett.* **265,** 229–245 (2008).
86. Raymo, M. E., Mitrovica, J. X. Collapse of polar ice sheets during the stage 11 interglacial. *Nature* **483,** 453–456 (2012).
87. Joyce, J. E., Tjalsma, L. R. C. & Prutzman, J. M. North American glacial meltwater history for the past 2.3 m.y.: Oxygen isotope evidence from the Gulf of Mexico. *Geology* **21,** 483–486 (1993).
88. Hodell, D. A., Channell, J. E. T., Curtis, J. H., Romero, O. E. & Röhl, U. Onset of "Hudson Strait" Heinrich events in the eastern North Atlantic at the end of the middle Pleistocene transition (~640 ka)? *Paleoceanography* **23,** PA4218 (2008).
89. de Vernal, A. & Hillaire-Marcel, C. Natural variability of Greenland climate, vegetation, and ice volume during the past million years. *Science* **320,** 1622–1625 (2008).
90. Channell, J. E. T., Xuan, C. & Hodell, D. A. Stacking paleointensity and oxygen isotope data for the last 1.5 Myr (PISO-1500). *Earth Planet. Sci. Lett.* **283,** 14–23 (2009).
91. Rahmstorf, S. A semi-empirical approach to projecting future sea-level rise. *Science* **315,** 368–370 (2007).
92. Siddall, M. *et al.* Changing influence of Antarctic and Greenlandic temperature records on sea-level over the last glacial cycle. *Quat. Sci. Rev.* **29,** 410–423 (2010).
93. Pollard, D. & DeConto, R. M. Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature* **458,** 329–332 (2009).
94. Tarasov, L., Dyke, A. S., Neal, R. M. & Peltier, W. R. A data-calibrated distribution of deglacial chronologies for the North American ice complex from glaciological modeling. *Earth Planet. Sci. Lett.* **315–316,** 30–40 (2012).
95. Siddall, M. & Kaplan, M. R. A tale of two ice sheets. *Nature Geosci.* **1,** 570–571 (2008).
96. Alley, R. B., Clark, P. U., Huybrechts, P. & Joughin, I. Ice-sheet and sea-level changes. *Science* **310,** 456–460 (2005).
97. Mercer, J. H. West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster. *Nature* **271,** 321–325 (1978).
98. Meehl, G. A. et al. in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC* (eds Solomon, S. *et al.*) (Cambridge Univ. Press, 2007).

Acknowledgements

The authors wish to thank F. Anslow, S. Marcott, S. Peters, and J. Shakun for their insightful comments on this manuscript, R. Kopp for providing his sea-level record, and R. Gyllencreutz, J. Mangerud, J.-I. Svendsen and Ø Lohne for sharing their compilation of Eurasian ice-sheet margin chronologies. PALSEA, a PAGES/WUN working group, was instrumental in forming the ideas presented here. A.E.C. and K.W. are supported by the National Science Foundation Paleoclimate and Graduate Research Fellowship Programs, respectively.

Additional information

The authors declare no competing financial interests.