

# Eemian interglacial reconstructed from a Greenland folded ice core

NEEM community members\*

Efforts to extract a Greenland ice core with a complete record of the Eemian interglacial (130,000 to 115,000 years ago) have until now been unsuccessful. The response of the Greenland ice sheet to the warmer-than-present climate of the Eemian has thus remained unclear. Here we present the new North Greenland Eemian Ice Drilling ('NEEM') ice core and show only a modest ice-sheet response to the strong warming in the early Eemian. We reconstructed the Eemian record from folded ice using globally homogeneous parameters known from dated Greenland and Antarctic ice-core records. On the basis of water stable isotopes, NEEM surface temperatures after the onset of the Eemian (126,000 years ago) peaked at  $8 \pm 4$  degrees Celsius above the mean of the past millennium, followed by a gradual cooling that was probably driven by the decreasing summer insolation. Between 128,000 and 122,000 years ago, the thickness of the northwest Greenland ice sheet decreased by  $400 \pm 250$  metres, reaching surface elevations 122,000 years ago of  $130 \pm 300$  metres lower than the present. Extensive surface melt occurred at the NEEM site during the Eemian, a phenomenon witnessed when melt layers formed again at NEEM during the exceptional heat of July 2012. With additional warming, surface melt might become more common in the future.

A 2,540-m-long ice core was drilled during 2008–12 through the ice at the NEEM site, Greenland (77.45° N, 51.06° W, surface elevation 2,450 m, mean annual temperature  $-29$  °C, accumulation 0.22 m ice equivalent per year). The top 1,419 m is from the current interglacial, the Holocene, and together with the glacial ice below it can be matched to the NGRIP GICC05 extended timescale<sup>1,2</sup> down to 2,206.7 m (108 thousand years before present, referred to as kyr BP, where 'present' is defined as AD 1950). Below this, the ice is disturbed and folded, but it contains zones with relatively high stable isotope values of H<sub>2</sub>O ( $\delta^{18}\text{O}_{\text{ice}}$ , a proxy for condensation temperature), indicating that it stems from the last interglacial, the Eemian (130–115 kyr BP; Fig. 1). Near bedrock, low  $\delta^{18}\text{O}_{\text{ice}}$  values suggest that the ice layers are most probably from the glacial period before the Eemian. The lowest 5 m of the ice core contain accreted ice, with dark layers 1–20 cm thick that contain high concentrations of basal material. In this study, information from the Eemian period of the NEEM ice core will be used to constrain the surface elevation of the ice sheet and the temperature of this warm climate period. Measurements of  $\delta^{18}\text{O}_{\text{ice}}$  have been made, and air bubbles trapped within the ice have yielded concentrations of CH<sub>4</sub> and N<sub>2</sub>O, stable isotope values  $\delta^{15}\text{N}$  of N<sub>2</sub> and  $\delta^{18}\text{O}$  of O<sub>2</sub> ( $\delta^{18}\text{O}_{\text{atm}}$ ), and total air content (see details in Supplementary Information). In addition, the rheology of the ice, radio echo sounding (RES) images and surface temperatures and ice temperatures are used in the interpretation.

## Reconstruction of the climate record

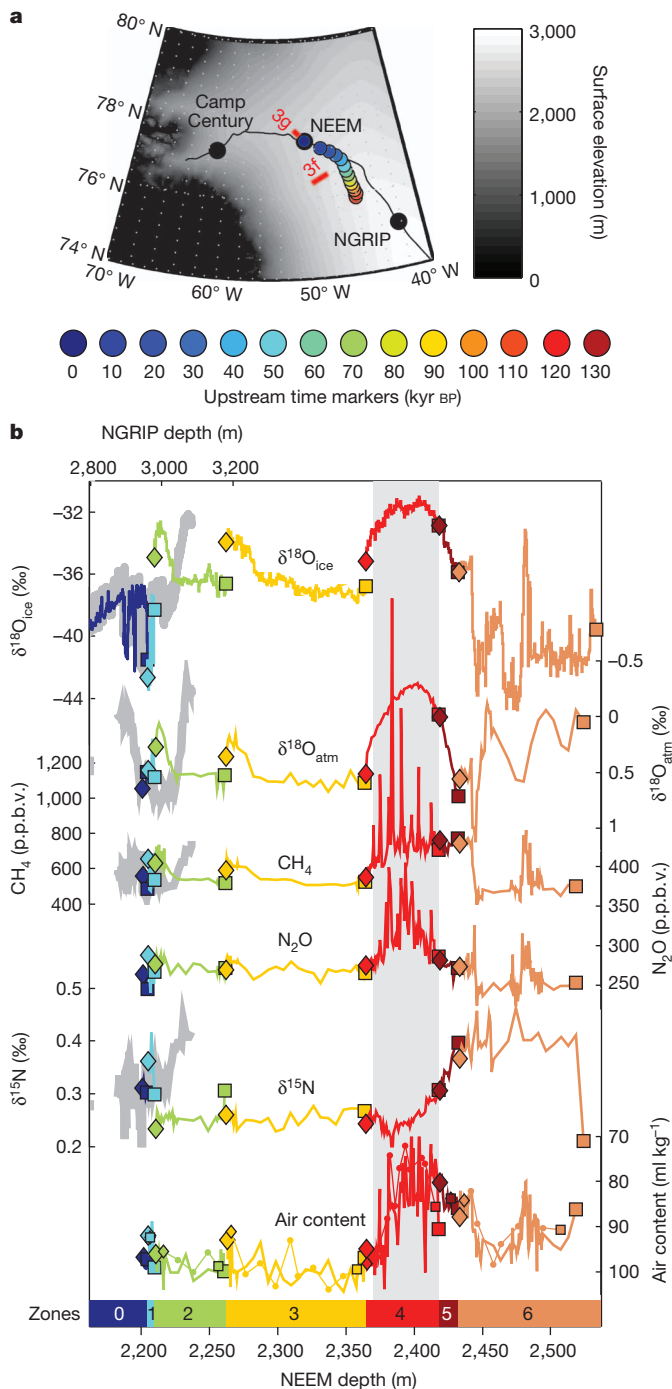
Stratigraphic disruptions are identified from discontinuities of  $\delta^{18}\text{O}_{\text{ice}}$  at depths of 2,209.60 m, 2,262.15 m, 2,364.45 m and 2,432.19 m. Corresponding shifts in gas concentrations are found at these depths, so the bubble enclosure process has not caused the expected depth offset for stratigraphic undisturbed ice (Fig. 1). Possible discontinuities below 2,432.19 m have not been investigated. The records of CH<sub>4</sub> concentrations and  $\delta^{18}\text{O}_{\text{atm}}$  are also disturbed and are not identical with the globally-homogeneous signals documented at the nearby NGRIP ice core (which contains undisturbed stratigraphy

back to 123 kyr BP) or with the EDML Antarctic ice core (which reaches back more than 135 kyr BP)<sup>3–6</sup>. Measurements of N<sub>2</sub>O,  $\delta^{15}\text{N}$  and air content in the NEEM ice below 2,200 m further confirm these discontinuities.

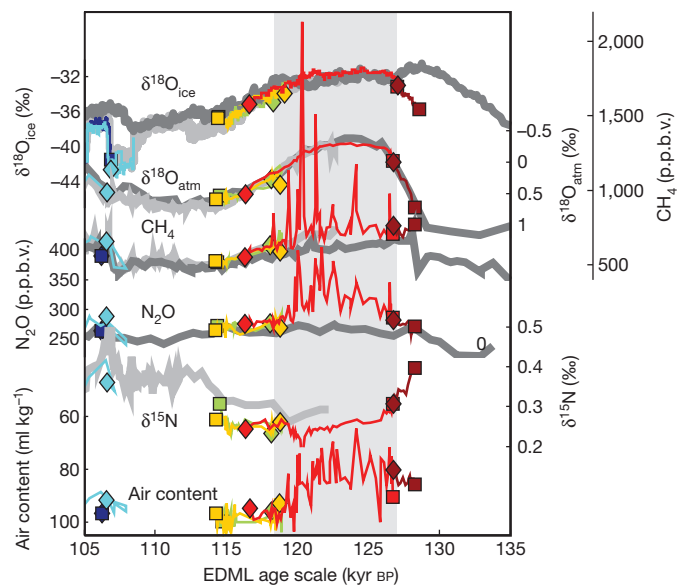
NEEM data reveal spikes in CH<sub>4</sub> and N<sub>2</sub>O records between depths of 2,370 m and 2,418 m, which are too rapid to be explained by climatic variability and coincide with lower air content in the ice (Figs 1b, 2, 4, shaded areas, and Supplementary Fig. 6). These characteristics point to surface melting or wet surface conditions. Indeed, surface melting or percolating rain reduces the firn air content and allows *in situ* production of CH<sub>4</sub> and N<sub>2</sub>O. This hypothesis is supported by results in the near-surface ice from the warmer south Greenland Dye3 ice core (Supplementary Fig. 9, mean annual temperature  $-21$  °C) and by measurements of noble gases over the NEEM spikes, which also support the hypothesis of melting surface layers (Supplementary Fig. 8). The lack of parallel variability in  $\delta^{18}\text{O}_{\text{ice}}$ ,  $\delta^{15}\text{N}$  or  $\delta^{18}\text{O}_{\text{atm}}$  suggests that these parameters are uninfluenced by surface melting. The spikes occur in the warmest interval at the depositional location indicated by water isotopes ( $\delta^{18}\text{O}_{\text{ice}} > -33\text{‰}$ ). The mean water isotope value over the past millennium is  $-33.6\text{‰}$  at NEEM, and very few melt layers are found in the ice core before 1995<sup>7</sup>. During our NEEM field campaigns (2007–12), the mean surface air temperature in July reached  $-5.4$  °C (with annual mean values of  $\delta^{18}\text{O}_{\text{firn}} > -33\text{‰}$ ; ref. 8), and studies with ice cores and snow pits show that episodic melt events occurred. Over the period 12–15 July 2012, an exceptional heat wave produced significant surface melt over 97% of the Greenland ice sheet, leaving a strong fingerprint at the NEEM site in the form of melt layers 5–6 cm thick at 50–70 cm below the surface.

For depths of 2,201.10–2,432.19 m, the NEEM records of  $\delta^{18}\text{O}_{\text{atm}}$  and the subset of CH<sub>4</sub> values not corrupted by surface melting are matched with globally-homogeneous signals of these values observed from other ice cores<sup>6,9,10</sup> (Supplementary Figs 4 and 5). For younger ice, the nearby NGRIP  $\delta^{18}\text{O}_{\text{ice}}$  record is used as a reference temperature target for synchronization by assuming simultaneous abrupt

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**Figure 1 | Observed NEM records.** **a**, A surface elevation map (scale to the right) of the position of the NEM camp, including coloured upstream depositional positions (upstream time marker scale below) of the ice found in the NEM ice core. The deep ice-core sites NGRIP, NEEM and Camp Century and the tracks of the RES images shown in Fig. 3f and g (red lines) are shown on the map. **b**, The observed records of  $\delta^{18}\text{O}_{\text{ice}}$ ,  $\delta^{18}\text{O}_{\text{atm}}$  (reversed scale)  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ,  $\delta^{15}\text{N}$  and air content (reversed scale) from 2,162 m and deeper are plotted on the NEM depth scale (bottom x axis). The air content measurements from LGGE and from University of Bern (thin curve, small symbols) are both included. Zones 0–6 (blue, 0–2,206.5 m; cyan, 2,206.5–2,209.6 m; green, 2,209.6–2,262.2 m; orange, 2,262.2–2,364.5 m; red, 2,364.5–2,418.0 m; dark red, 2,418.0–2,432.2 m; and brown, 2,432.2–2,537 m) represent the sections of the NEM ice-core records with symbols marking the start (diamond) and end (square) of each zone. There is no discontinuity between zones 4 and 5 but spikes of  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and air content occur in zone 4 (shaded grey). For comparison, the NGRIP data are plotted as light grey curves on the NGRIP depth scale on top of the plot. The NEM and NGRIP depth scale are synchronized between 2,162 and 2,207.6 m NEM depths.

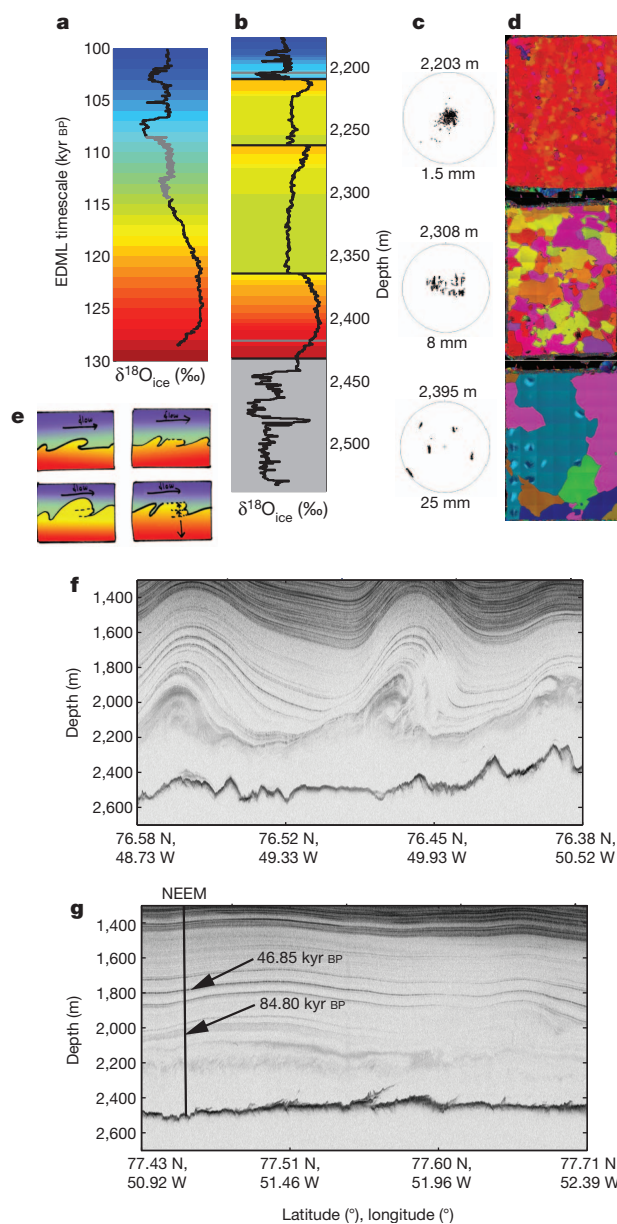


**Figure 2 | Reconstructed records from the NEM ice core.** The reconstructed records of  $\delta^{18}\text{O}_{\text{ice}}$ ,  $\delta^{18}\text{O}_{\text{atm}}$  (reversed scale)  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ,  $\delta^{15}\text{N}$  and air content (reversed scale) on the EDML1 timescale<sup>12</sup>. Zone 1 (cyan) is seen to contain a fold while zone 2 (green) and zone 3 (orange) are reversed and cover identical time periods. NGRIP records (light grey) and EDML records (dark grey) are included where they are available. The  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and air content records contain spikes from 127 to 118.3 kyr BP (shaded grey).

climate changes at the transitions between stadials and interstadials<sup>11</sup> (Supplementary Fig. 3).

In Fig. 2, the reconstructed NEM records are shown on the EDML1 timescale<sup>12</sup> and compared to the NGRIP (light grey) and EDML (dark grey) records. Zones 1 to 5, identified in Fig. 1, map onto the timescale as coherent pieces. Zone 1 is folded such that the records are mirrored and repeated, zone 2 and zone 3 cover identical time periods, both inverted, while zone 4 (with melt-related spikes) and zone 5 are undisturbed and contain the major part of the ice from the Eemian (128.5–115 kyr BP) (Figs 2 and 3a, b). It cannot be ruled out that small disruptions or folds are present within the individual zones. The reconstructed records, however, show no unexpected discontinuities in either zones 1–5 or in all other measured parameters, such as  $\delta^{15}\text{N}$  (Fig. 2), dust or electrical properties. As the timescale is transferred from the EDML ice core by matching it to the globally-homogeneous signals, small undetectable disruptions will not influence the conclusions based on the parameters presented here. The reconstruction is unambiguous and no other solution exists to match the NEM  $\delta^{18}\text{O}_{\text{atm}}$  and the uncorrupted  $\text{CH}_4$  values simultaneously to the undisturbed EDML and NGRIP records. No ice from 114–108 kyr BP can be found in the NEM ice core, while the ice layer from 118–115 kyr BP is found three times (zones 2, 3 and 4), two of which are inverted.

Northern Hemisphere temperatures are known to vary in parallel with the atmospheric  $\text{CH}_4$  concentration<sup>13,14</sup>, which is seen to increase abruptly into the warm Eemian period at 128 kyr BP at EDML. This is evidence that no substantial warm phases of the NEM Eemian record are missing before 128.5 kyr BP. Ice from below 2,450 m (zone 6) appears to be too disturbed to reconstruct an age scale based on the data available at present. The very low (glacial)  $\delta^{18}\text{O}_{\text{ice}}$  values ( $-44.9\text{‰}$  at 2,476 m) are first found again in the record above 2,011 m. The ice layering at the NEM site is undisturbed above 2,200 m (Fig. 3g), so the section below 2,476 m is believed to contain ice older than 128.5 kyr BP from Marine Isotopic Stage (MIS) 6, and we may speculate that the increased levels of  $\delta^{18}\text{O}_{\text{ice}}$ ,  $\text{CH}_4$  and  $\text{N}_2\text{O}$  at 2,480 m might be from MIS-7 interglacial.



**Figure 3 | Disturbances of the deep NEEM ice.** **a**, The reconstructed NEEM water stable isotope record (black curve) including NGRIP data between 114–108 kyr BP (grey) on the EDML1 timescale that has been colour coded according to age. Below 2,432.19 m (grey shading) no dating has been attempted. **b**, The colour-coded data plotted with the original data on the NEEM depth scale visualizing the discontinuities and the reversed sections. **c**, **d**, *c*-Axis orientations on Schmidt diagrams for depths 2,203 m, 2,308 m and 2,395 m (**c**) and polarized light pictures of ice thin sections from the same three depths (**d**) demonstrate the very different ice rheology of the glacial and interglacial ice, leading to different flow properties. **e**, Cartoon of a possible history of the formation of two overturned folds at NEEM inspired by the observed undulations in the RES images (**f** and **g**). **f**, **g**, Center for Remote Sensing of Ice Sheets (CRISIS) ice-penetrating RES images from NASA Operation IceBridge campaign 2011. **f**, A 52-km-long line to the west that illustrates that overturning folds do occur (MCORDS: 20110329\_02\_020); **g**, a 48-km-long line crossing the deep drill site (MCORDS 20110329\_02\_028). The NEEM site is marked on the image, and two dated horizons are marked. More details can be found in Supplementary Information.

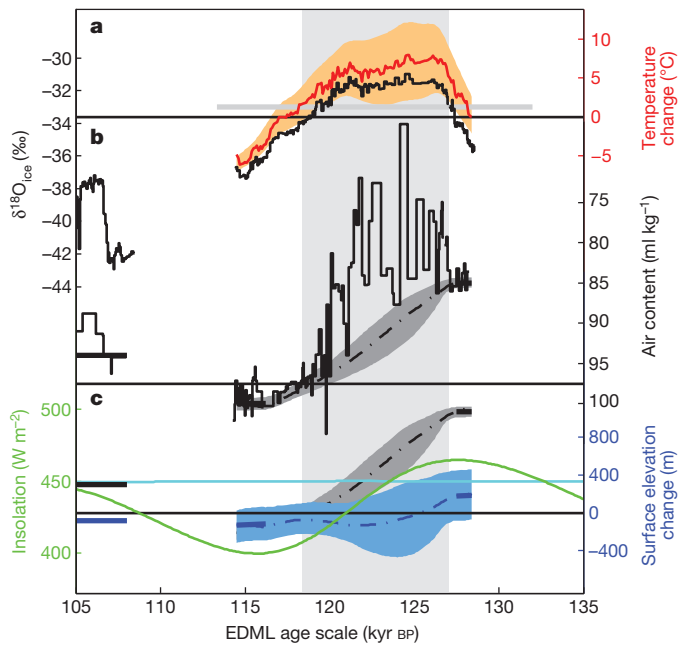
### The disturbed and folded ice

RES data were collected in north Greenland during 2011 and 2012 with a multichannel coherent ice-penetrating radar depth sounder/imager<sup>15,16</sup>. The RES images show continuous and undisturbed internal layers (isochrones) to a depth of about 2,200 m in the NEEM

region, which agrees with the ice-core observations<sup>17</sup>. Below 2,200 m, internal layers become fuzzy and less continuous: undulations and even overturned folds and shearing of basal material are observed (Fig. 3f, g, Supplementary Fig. 2b–e). The transition between clear and fuzzy layers often appears at the interface between ice from the glacial and Eemian periods. Very large differences in ice rheological properties are documented (Fig. 3c, d) between glacial ice (with crystal sizes of 1.5 mm and a strong preferred vertical *c*-axis orientation) and Eemian ice (with crystal sizes of 25 mm and multiple maxima fabrics). The viscosities of these two types of ice differ by a factor of 50–100 (refs 18–21), allowing glacial ice to deform very easily while the interglacial ice remains more rigid. The missing, folded and inverted parts of the ice are from the interface between the relatively rigid Eemian and the early glacial (118–106 kyr BP), supporting the idea that the glacial ice deforms over the harder Eemian ice. The broken record at 128.5 kyr BP can be explained by contrasting the deformation properties of the underlying ice from the previous glacial period and the Eemian ice. It should be noted that the discontinuous and folded structures of the GRIP and GISP2 ice cores also occur for ice older than 105 kyr (refs 9, 10). The consistency of the RES images and deep ice-core results at NEEM is a breakthrough result, and demonstrates that RES imaging can now be used to predict folded ice layering. This creates the potential for a systematic reconstruction of the Eemian Greenland ice-sheet layering from new RES imaging. Assimilation of such data in ice-sheet models may lead to much improved histories of the configuration of the ice sheet in the past, improving our ability to predict its future evolution.

### Climate reconstruction from observed records

The reconstructed Eemian sequence (128.5–114 kyr BP, Fig. 2) allows for initial climate interpretations of this period. As mentioned above, the regular occurrence of melt features at 127–118.3 kyr BP is an indication of warmer temperatures at the depositional surface locations of the ice than the mean of the recent millennium at NEEM. This is independently confirmed by the decrease of  $\delta^{15}\text{N}$  in this zone, which is indicative of  $\sim 5^\circ\text{C}$  warmer mean annual firn temperatures at the depositional site<sup>22,23</sup> (Supplementary Fig. 7). Between 128.5 kyr BP and 126.0 kyr BP,  $\delta^{18}\text{O}_{\text{ice}}$  increases from  $-35\text{‰}$  to  $-31.4\text{‰}$  while EDML  $\delta^{18}\text{O}_{\text{ice}}$  values slowly drop from those of the warm early Antarctic period<sup>24</sup>. This bipolar see-saw behaviour suggests that inter-hemispheric heat redistribution by the Atlantic meridional overturning circulation<sup>25</sup> was taking place within the Eemian interglacial period; this has also been observed during the last Northern Hemisphere deglaciation 19–11 kyr BP<sup>24–27</sup>. Before surface melt began between 128.5 and 126.7 kyr BP, the air content at the depositional site had a stable level of  $85\text{ ml kg}^{-1}$  compared to the present level of  $97.5\text{ ml kg}^{-1}$ . When corrected for changing local summer insolation<sup>28–30</sup> (Supplementary Fig. 10), the air content difference suggests a surface elevation at the depositional site  $540 \pm 300\text{ m}$  higher at the onset of the Eemian (128 kyr BP) than the surface elevation at NEEM today<sup>28,31–33</sup>. The locations of the depositional sites of the Eemian ice found in the NEEM ice core are modelled using a nested three-dimensional flow model<sup>34</sup> (Fig. 1a and Supplementary Fig. 1). A second model used to date the NEEM ice core reaches similar locations<sup>35</sup> within 20 km. At present, the surface elevation at the depositional site of the 128-kyr-BP ice ( $205 \pm 20\text{ km}$  upstream from NEEM) is  $330 \pm 50\text{ m}$  higher than the present at NEEM<sup>33,34</sup>. The surface elevation increase of  $210 \pm 350\text{ m}$  at the 128-kyr-BP depositional site (Fig. 4c, blue) is the difference between the elevation at 128 kyr BP ( $540 \pm 300\text{ m}$ ) and the present elevation ( $330 \pm 50\text{ m}$ ), both related to the present elevation at NEEM. This surface elevation increase is expected at the onset of a warm climatic period due to increased precipitation and mass balance changes that occur before the central part of the ice sheet adjusts to the warmer climate by increasing the ice flow. This is also established at the onset of the present interglacial at 11.7 kyr BP<sup>32</sup>.



**Figure 4 | Reconstruction of the temperature and elevation history.**

Reconstruction of the temperature and elevation history through the Eemian based on the stable water isotopes ( $\delta^{18}\text{O}_{\text{ice}}$ ) and the air content records. The zone with surface melt (127–118.3 kyr BP) is shaded in light grey. **a**, The measured  $\delta^{18}\text{O}_{\text{ice}}$  record (black) on the constructed timescale. The average of the recent millennium ( $-33.60\text{‰}$ ) is marked with a thin black line. It is seen that the  $\delta^{18}\text{O}_{\text{ice}}$  values at the depositional locations in the melt zone are above  $-33.0\text{‰}$  (grey horizontal line). The fixed-elevation change of temperature—constructed from the observed  $\delta^{18}\text{O}_{\text{ice}}$ , the elevation changes determined from the air content and the upstream corrections (curves below)—is shown as a red curve using the red axis. The standard error range (orange shading) is a sum of the error of the  $\delta^{18}\text{O}_{\text{ice}}$  and the elevation change correction (Supplementary Information 1.1, equations (2) and (5) in Supplementary Information, Supplementary Table 2). **b**, Air content (black) is plotted and guided by the two stable levels on each side of the melt zone. A dot-dashed line connecting these levels has been suggested with an error range as the dark grey shaded area. The standard error range is a sum of the error assumed in the zone with surface melt (127–118.3 kyr BP) and the 1% error on the air content measurements (Supplementary Information section 1.4). In addition, the average level 107–105 kyr BP is marked with a horizontal black bar. The changes in the air content are caused by pressure changes due to changing surface elevation at the depositional sites and changes to the air trapping processes in the firm assumed to be controlled by the changing summer insolation<sup>28,32,49,50</sup>. **c**, When corrected for upstream flow (cyan) and summer insolation changes (green), the air content curve can be ‘translated’ to elevation changes (blue, dashed) with the shaded zone indicating the uncertainty range introduced by this translation. Blue bars mark the air content of the ‘translated’ air content black bars. The standard error range is based on the error range of the air content (dark grey shaded area) and the additional standard errors from calculation of the elevation changes (equation (5) in Supplementary Information, and Supplementary Table 2).

In the period 127–118.3 kyr BP, the air content in the ice where surface melt occurred was highly variable and cannot directly be used for ice elevation reconstructions (Fig. 2, shaded zone). We can tentatively estimate elevation changes through the Eemian climate period by connecting the two air content levels before and after the melt zone (Fig. 4b) after correcting for summer insolation, which accounts for 50% of the observed change (Fig. 4c, Supplementary Information). At 126 kyr BP the surface elevation was  $45 \pm 350$  m higher than at present. The  $\delta^{18}\text{O}_{\text{ice}}$  increased to  $-31.4\text{‰}$  at 126 kyr BP, exceeding the current mean value of the recent millennium of  $-33.6\text{‰}$  (at the NEEM site) and the current mean value of  $-35.0\text{‰}$  at the depositional site<sup>32,33</sup> (Supplementary Information, section 2). Using the temperature–isotope relation of  $2.1 \pm 0.5 \text{ K } \text{‰}^{-1}$  (calibrated using data from the present interglacial<sup>32</sup>), the  $3.6\text{‰}$  anomaly at 126 kyr

BP implies that precipitation-weighted surface temperatures were  $7.5 \pm 1.8 \text{ °C}$  warmer at the depositional site compared to the last millennium. Note that the modelled location of the depositional site is the only modelled parameter required to compare the 126-kyr-BP data to the present-day data at the depositional site. When further correcting for the more uncertain elevation change of  $45 \pm 350$  m at the 126-kyr-BP depositional site using a lapse rate of  $7.5 \pm 0.5 \text{ K km}^{-1}$ , the fixed-elevation temperature increase here is  $8 \pm 4 \text{ °C}$  (Fig. 4a, red). Our data depict a gradual cooling until 110 kyr BP (Fig. 4a, red curve).

The reconstructed precipitation-weighted annual temperature changes are remarkably high. In general, warmer summer temperatures are reported from palaeorecords<sup>36,37</sup>, and a few find temperatures at 126 kyr BP on high Arctic latitudes as high as those reported from NEEM<sup>38–40</sup>. Climate models equipped with water stable isotopes point to a limited ( $1 \text{ °C}$ ) seasonality bias caused by a stronger enhancement of temperature and precipitation in summer than in winter<sup>41–43</sup>. A large spread in temperature has been reported among simulations of the last interglacial climate, which appear to systematically underestimate North Atlantic/Arctic warming, possibly due to missing vegetation and ice-sheet feedback<sup>37,42,43</sup>.

Within 6,000 yr, from 128 to 122 kyr BP, the surface elevation is estimated to have decreased from  $210 \pm 350$  m above to  $130 \pm 300$  m below the present surface elevation, which translates to a moderate ice thickness change of  $400 \pm 350$  m after accounting for isostatic rebound. Based on this estimate, the ice thickness at NEEM decreased by an average of  $7 \pm 4$  cm per year between 128 and 122 kyr BP and stayed at this level until 117–114 kyr BP, long after surface melt stopped and temperatures fell below modern levels.

Even with minimum ice thickness of only about 10% less than the present ice thickness at the NEEM site, as reported here, substantial melting can cause significant reduction of ice thickness near the margins; this in turn reduces the volume of the Greenland ice sheet. Although the documentation of ice thickness at one location on the Greenland ice sheet cannot constrain the overall ice-sheet changes during the last interglacial period, the NEEM data can only be reconciled with Greenland ice-sheet simulations<sup>30</sup> that point to a modest contribution (2 m) to the observed 4–8 m Eemian sea level high stand<sup>44,45</sup>. For comparison, no continuing elevation change has so far been detected in areas with elevations above 2,000 m in north Greenland during the past few decades<sup>46</sup>. These findings strongly imply that Antarctica must have contributed significantly to the Eemian sea level rise<sup>47</sup>.

Despite the complex ice flow, the disturbed record of the deep ice in the NEEM ice core can be unambiguously reconstructed. The anatomy of the last interglacial shows that Greenland temperatures peaked after the onset of the Eemian, 126 kyr BP, with temperatures (at fixed elevations)  $8 \pm 4 \text{ °C}$  warmer than the average of the recent millennium and multiple indications of summer melt. Temperatures gradually decreased during the interglacial, very probably owing to the strong local summer insolation decreasing trend. The surface elevation first increased due to increased mass balance to  $210 \pm 350$  m above the present at 128 kyr BP, then decreased to  $130 \pm 300$  m below the present elevation around 122 kyr BP. Our results provide multiple new targets to constrain coupled climate/ice-sheet models. Our record, together with recent observations of rainfall and strong surface melting in July 2012 at NEEM, show that conditions are conducive to the start of melt layer formation at NEEM, with the 2010–12 mean annual surface temperatures  $1\text{--}2 \text{ °C}$  above the 1950–80 average.

Our results have implications for both ice deformation near the bedrock and the response of the Greenland ice sheet to climate change. The combination of high-resolution RES data and NEEM glacial–interglacial ice layers brings new knowledge of the near-bed deformation of ice. We believe that the folding and disturbances we observe near the bed are strongly related to the rigid deformation properties of the interglacial ice. This offers an alternative explanation

for the large anomalies in RES profiles recently observed under both the Antarctic and Greenland ice sheets, which were previously attributed to refrozen basal water<sup>48</sup>.

## METHODS SUMMARY

Measurements of stable water isotopes in the ice ( $\delta^{18}\text{O}_{\text{ice}}$ ) and  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  concentrations and the isotopes  $\delta^{15}\text{N}$  of  $\text{N}_2$  and  $\delta^{18}\text{O}_{\text{atm}}$  of  $\text{O}_2$ , noble gases and the air content have been measured in the air extracted from the air bubbles in the ice, all using well-described methods. These measurements are presented in Supplementary Information section 1. Models calculating temperatures from water isotopes, elevation changes from air content, and temperature changes from  $\delta^{15}\text{N}$  values have been calibrated using observations from the present interglacial.

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