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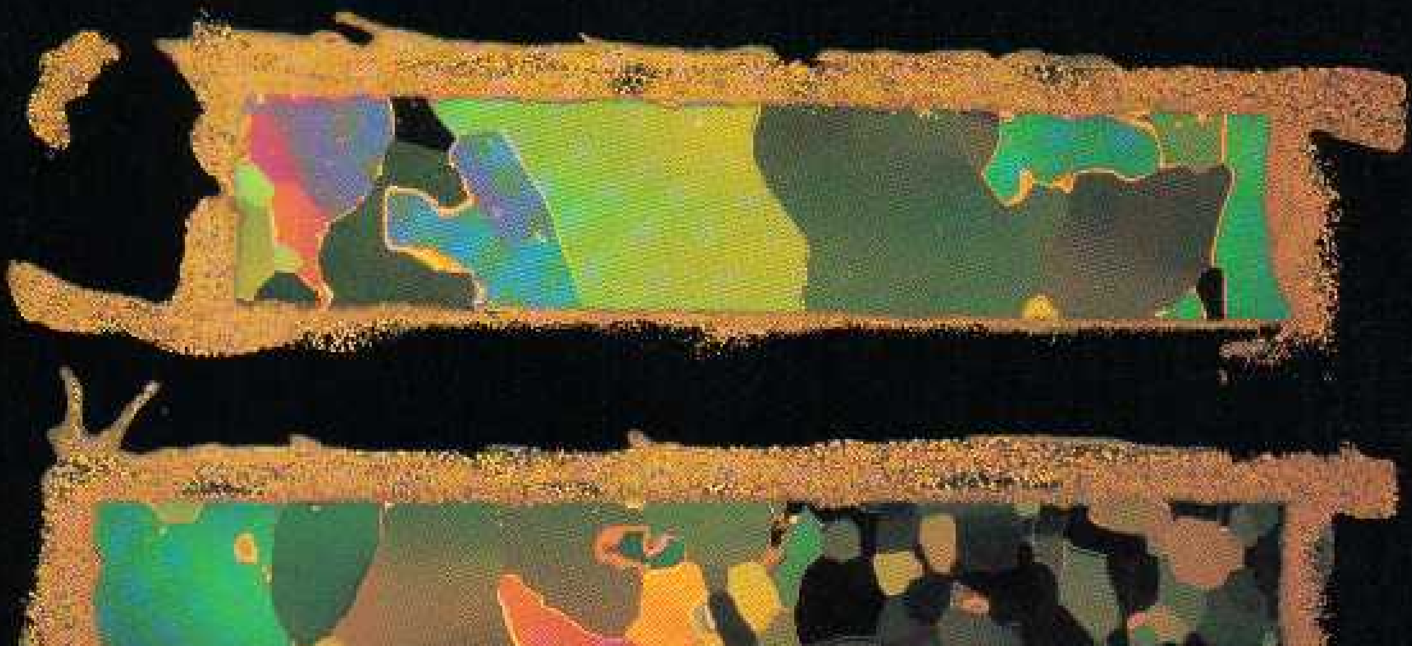

Is our stable climate exceptional?

Global warming and ocean circulation

A *little* insight into the pituitary

Chaotic lives of voles

Climate instability during the last interglacial period recorded in the GRIP ice core

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Isotope and chemical analyses of the GRIP ice core from Summit, central Greenland, reveal that climate in Greenland during the last interglacial period was characterized by a series of severe cold periods, which began extremely rapidly and lasted from decades to centuries. As the last interglacial seems to have been slightly warmer than the present one, its unstable climate raises questions about the effects of future global warming.

THE Eemian interglacial period is a prime target for palaeoclimate reconstruction[1]. A variety of evidence indicates that during isotope stage 5e of the marine oxygen isotope record ($\sim$125 to 115 kyr BP), usually correlated with the Eemian interglacial period in Europe and Sangamon in North America, conditions were at least as warm as today[2,3] and probably fairly stable[4]. Some evidence suggests that there may have been strong regional differences, with cyclical climate changes in areas bordering the north Atlantic[3]. Thus there is some hope of examining the behaviour of the physical and chemical climate of the Earth under conditions rather warmer than present, a possible analogue for future climate evolution.

Polar ice cores drilled in optimum locations allow the reconstruction of highly resolved climate records. The Vostok core[5] from central Antarctica was the first to yield an environmental record spanning the entire last glacial–interglacial cycle. At this site, ice deposited during the Eemian period is still $\sim$300 m thick, and as it lies about halfway through the total ice depth the record can be considered robust against distortion due to flow irregularities close to bedrock. Generally, higher annual snowfall and thinner ice cover in Greenland ensure that the Eemian ice will be found relatively deeper in this ice sheet. The deep Camp Century core from northwest Greenland[6] may have reached the Eemian period, but probably did not penetrate it; in this period, at least the detailed record seems to have been strongly modified by rapid shear in the basal ice.

Here we present data obtained from an ice core drilled close to bedrock at Summit, central Greenland, which penetrates the Eemian period. The data cast doubt on some of our present conceptions of this period. Although the timing and amplitude of low-frequency variations ($>$5 kyr period) in primary indices of climate and atmospheric circulation throughout the last glacial cycle closely mirror those recorded in the Vostok core, there are striking differences at higher frequencies[7]. These are most marked in the Eemian period, for which the record is highly structured. Most constituents examined so far show evidence for a series of shifts from levels typical of warm interglacial conditions to levels more typical of the mid-glacial period. The changes can be transient (lasting only a few decades to centuries), seemingly analogous to the series of climate 'mode-switches' previously identified in the late glacial period[8], or they can remain latched for up to 5 kyr.

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Record of the Eemian at Summit

The GRIP ice core, drilled into silty ice close to bedrock at Summit on the main ice divide (72°34′ N, 37°37′ W) in summer 1992 (refs 7, 9) and the parallel core being drilled about 30 km to the west by the United States Greenland Ice-Sheet Project (GISP2)[10] were positioned to obtain records of the best quality possible through at least the last complete glacial cycle. The stable isotope profile for the complete core is presented in ref. 7. Although detailed analysis of the core is still under way, several constituents were measured continuously at the drill site, or shortly afterwards. These have allowed a partial characterization of the Eemian sequence, which is $\sim$80 m thick and extends from about 163 to 238 m above bedrock. The observed thickness is broadly consistent with model predictions based on the assumption that Greenland was covered by an ice sheet of similar maximum thickness to the present throughout the Eemian interglacial period[11].

A preliminary chronology for the GRIP core going back to 14.5 kyr BP has been proposed[9] based on the stratigraphy. The chronology has been extended through the Eemian section of the core by ice-flow modelling[7], and confirmed by demonstrating a close correlation between low-frequency features ($>$5 kyr period) in the GRIP stable isotope profile with corresponding features in the Vostok profile[5], in the SPECMAP marine sediment standard isotope curve[12] and in the Devil's Hole terrestrial isotope record[13]. The stable isotope composition is a well established climate indicator, depending to first order on air temperature[5,14], but also contains information on conditions in the source regions for atmospheric moisture, and hence is linked also to atmospheric circulation changes[15]. However, the closely paralleled behaviour of stable isotopes in Greenland and Antarctica applies to other constituents such as calcium, as can be seen in Fig. 1. Calcium is mainly derived from terrestrial dusts, correlating closely with aluminium[16], and temporal variations are connected with large-scale changes in the transport and loading of terrestrial dusts[17]. Throughout marine isotope stage 5 (MIS-5) with the exception of a brief period between MIS-5a and -5c, calcium concentrations are uniformly low and roughly equal those in the Holocene. There are, however, striking differences between the appearance of MIS-5e at Summit and that at Vostok, Fig. 1. At Summit, there is a highly structured pattern of variation on both long ($>$1 kyr) and short (sub-century) timescales. By contrast, Vostok[5] shows smooth trends across the whole stage, which can only partially be explained by the coarser resolution of this record.

At Summit, only in the first part of MIS-5e are conditions mainly interglacial in character. Even here there is considerable fine structure with a series of transient returns to apparently cool interstadial conditions. This stage seems to correspond with the warmest stage of the Vostok profile where the temperature

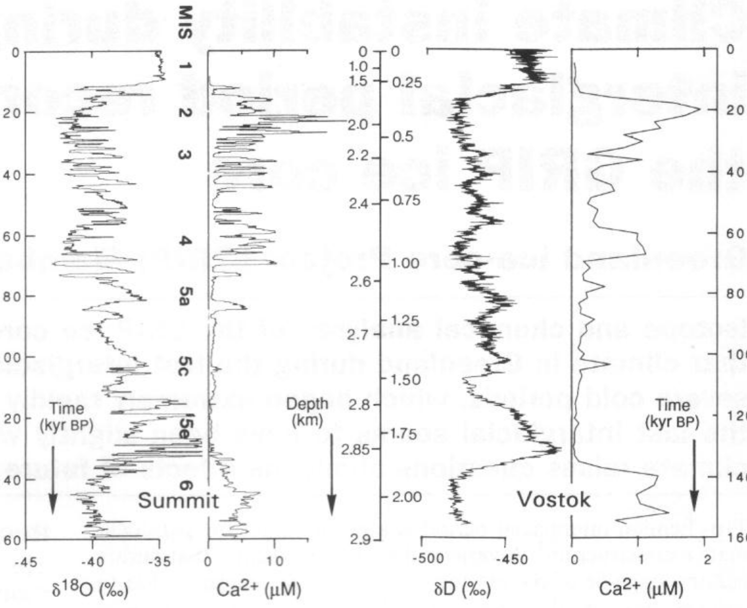

FIG. 1 Comparison of profiles of stable isotopes and calcium ion concentrations through the last glacial cycle in central Greenland and Antarctica. *a*, 200 yr mean $\delta^{18}O$, from Summit[7]; *b*, 200 yr mean Ca, from Summit (based on 3-mm continuous measurements below 1,300 m depth, using continuous-flow analysis[38]); *c*, δD (1 m core-length average) from Vostok[5] with new timescale[39]; *d*, Ca ($\sim$2 kyr average) from Vostok[16].

changes are believed to have preceded sea-level changes[18] by about 4 kyr. This sub-stage may represent less than 10 kyr of MIS-5e, more in accord with the $\sim$11-kyr duration of MIS-5e derived from the SPECMAP curve[12].

The climate over central Greenland seems to be highly sensitive to changes in circulation in the north Atlantic region. The GRIP[7,9] and GISP2[10,19] records, and previous Greenland deep-core records extending into the last glaciation[8], all show evidence for series of 'mode switches' in the isotopic record in the late glacial period which are considered to reflect rapid shifts in the position of the Arctic frontal system, in turn believed to be connected with changes in ocean circulation[20]. Evidence for the most recent event[21], the Younger Dryas (YD), has been traced in many independent media throughout areas under the influence of the north Atlantic, but it is a rather weak feature in Antarctic records[22,23]. There is also evidence for an abrupt transition at the end of the Eemian in pollen records from northeast France[24,25] and in coastal marine sediment sequences from western Norway[26] and off northwest Africa[27]. An isotopic record from an exposure of ancient ice at the margin of the Greenland ice sheet also appears to show structure in ice suggested to be of Eemian age[28]. It seems that the sharp termination of the Eemian and some of the structural features observed at the start of the Eemian may have parallels in other systems and in other regions.

Climatic characteristics of the Eemian

Figure 2 shows the isotopic and dust (Ca) content, and electrical properties of the solid ice during the Eemian period. The low-frequency conductivity of the ice, measured by dielectric profiling (DEP[29]), is controlled by both the neutral salt (probably chloride) and the free acid concentration[30]. This parameter was closely paralleled by the d.c. electrical conductivity (ECM[31]) profile, reflecting only the total acidity along this section of the record. Chloride is mainly derived from sea spray, and concentrations observed in the ice are strongly regulated by atmospheric circulation. The acidic content of the ice is controlled by various sources (marine biogenic, sporadic volcanoes and NO_X), and by transport and neutralization in the atmosphere. On the other hand, calcium levels strongly depend on a source that is known to have varied substantially throughout the course of the last glacial cycle—the extent of loess deposits[32] and of evaporites deposited on the continental shelves. Although we cannot at this stage separate out the various controls on these species, they undoubtedly have very different sensitivity to climate and circulation changes. We suggest that a similar pattern of composition should indicate broadly similar conditions of climate and atmospheric circulation.

In Fig. 2 we have identified three clear, warm substages of (MIS)-5e, which we have named 5el, 5e3 and 5e5, apparent in

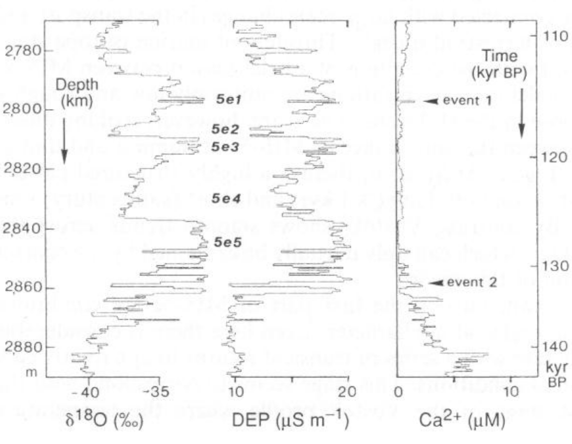

FIG. 2 Detailed profiles of selected isotopic and chemical constituents (averaged along 55 cm segments) through the Eemian (MIS-5e) section of the GRIP Summit core. MIS-5e is divided into three principal warm substages separated by up to 5 kyr of sustained cool periods, which we have named MIS-5e1 to 5e5. The profile for DEP[40] corresponds to the limiting high-frequency conductivity.

TABLE 1 Mean ice-core parameters for stages of the last climatic cycle

	$\delta^{18}O$ (‰)	D excess (‰)	Ca (μM)	DEP (μS m^{-1})	ECM (relative units)
Holocene	−34.8	8	0.203	23.9	1.43
Last Glacial Maximum	−42	6	10.11		
Stade	−41	8	4.72	11.01	0.01
Interstade	−38	4	1.4	12.6	0.25
Warm Eemian	−33.4	8.5	0.28	17.7	1.07
Event 1	−39	7	4.37	11.36	0.0054
Event 2	−38.4	6	2.12	9.66	0.0036
5E4	−36.8	7	0.451	14.75	0.616

Mean isotopic and chemical composition of ice deposited during the Eemian warm and cool stages in comparison with ice drawn from the principle climate stages of the last glacial cycle.

all constituents measured. In each of these, isotopically derived temperatures at least as high as in the Holocene levels were attained. Table 1 gives the comparative ice composition for different stages of the last glacial cycle. The isotopic and chemical signature of the warm stages of the Eemian is consistent with a similar atmospheric circulation to the Holocene. (Similar mean concentrations were obtained for Na, Mg, Cl, SO_4^{2-} and NO_3^-.) The difference in mean oxygen isotope ratios (1.4‰) suggests that temperatures were ~2 °C warmer than now during the warm stages of the Eemian (this is based on an isotope–temperature gradient for Greenland of 1.5 °C per 1‰ change[9]). Deuterium excess ($d = \delta D - 8 \times \delta^{18}O$) is sensitive to conditions in the moisture source region[15] and, in turn, to shifts in atmospheric circulation which could affect the stable isotope–temperature gradient. The similar values for mean deuterium excess in the Holocene and in the warm stages of the Eemian (Table 1) strengthen the idea that circulation changes are unlikely to have perturbed the gradients in the Eemian warm stages. Our dating of the record indicates that the unbroken warm stages characterize only 2 kyr of substage 5e5, <1 kyr of 5e3 and ~3 kyr of 5e1 (except for one major transient event). The isotopic and chemical evidence suggests that conditions overall during the cool stage 5e4 were similar to the mid-glacial warm stages (interstadials), ~5 °C cooler than the Holocene. A marked antiphase variation between Ca concentration and $\delta^{18}O$ during the last glacial cycle has been reported previously in both Greenland and Antarctica[17,33]. This is reflected strongly in Table 1, where the relationship clearly extends through the sub-stages of the Eemian.

Although the isotope and chemical signature of ice laid down during the Eemian warm stages suggests that climate and circulation patterns were similar to those prevailing in the Holocene, at least in the north Atlantic region, the overall pattern of behaviour during MIS-5e is strikingly different. Figure 3 compares the frequency distribution of $\delta^{18}O$ values for MIS-5 in comparison with those obtained for the Holocene and for the glacial sequence MIS-2 to 4. The marked bimodal behaviour of the mid-glacial sequence reflects the now well documented climate switching observed in all Greenland ice cores[8]. It seems that this behaviour was even more pronounced during MIS-5e, with a strongly defined intermediate mode. This contrasts with the single-mode isotope trend for the past 8 kyr of the Holocene, which seems to have a similar distribution to each of the component modes in the other stages, underlining the unusual stability of the present climate[7].

The cool events between the principal substages of the Eemian indicate a marked change in climate in Greenland and adjacent regions, and given the sharp changes in chemical signature, these seem to be connected either with a sudden change in the larger-scale atmospheric circulation or with a sustained shift, for example in the position of the polar front, leading effectively to a systematic change in the average source regions of constituents in the atmosphere over central Greenland. Their persistence suggests that there may have been large-scale changes in oceanic circulation in the north Atlantic region. Measurements on the gas content of the ice should establish the global significance of these findings. Our first measurements of methane trapped in bubbles in the ice show concentrations of 620 p.p.b.v. and 650 p.p.b.v. at points within MIS-5e3 and 5e5 respectively, similar to the values reported for the last interglacial in the Vostok core[34]. A single point so far measured in the MIS-5e4 cool substage gives the significantly lower value of 530 p.p.b.v., at the lower limit of the noise envelope cited for the Vostok core for this period, and a value typical for an interstadial.

Rapid climate change during the Eemian

The most striking feature of MIS-5e is a series of high-amplitude,

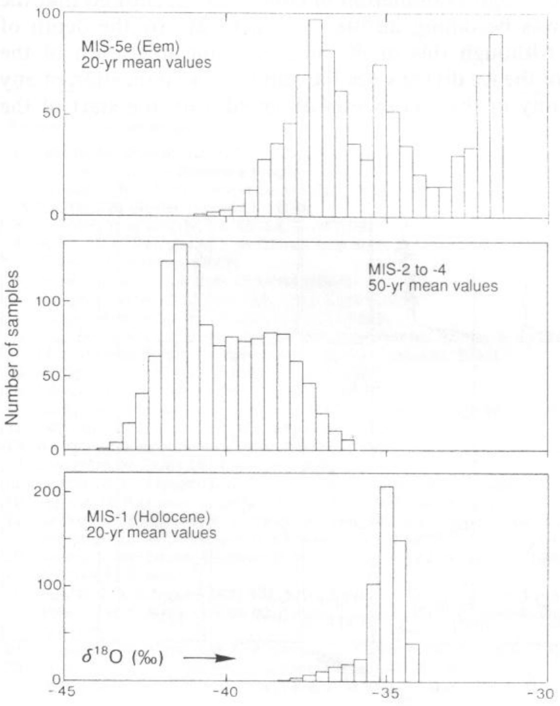

FIG. 3 Frequency distribution of the isotope data measured throughout MIS-5e in comparison with that observed during the last glaciation (MIS-2-4) and during the past 8 kyr of the Holocene. The distinctive single-mode characteristic of the Holocene contrasts with the bi- and trimodal behaviour observed through the last glaciation and during MIS-5e.

high-frequency oscillations seen in all constituents measured continuously along the core (Fig. 2). We have examined two contrasting events in greater detail. Event 1 (Fig. 4) is a catastrophic event within MIS-5e1 at the culmination of the Eemian, where the oxygen isotope values plunge to mid-glacial levels (−41‰). The event is estimated to have lasted ~70 years to judge from an annual layer thickness of 2.5 mm (estimated from the relationship between accumulation-rate[7] and δ, and from flow modelling). Event 2 (Fig. 5) is one of the lengthy series of massive and sustained oscillations that marked the first ~8 kyr of the Eemian and the end of the previous deglaciation sequence. Stable isotope values approach YD levels (~ −40‰) and were sustained for about 750 yr, comparable with the length of the YD itself. Maximum temperature decreases associated with these events are estimated at 14 °C and 10 °C respectively, on the basis of the suggested isotope–temperature relationship[9]. The deuterium excess is significantly reduced during both events, pointing to a lowering of associated moisture source temperatures. This suggests that any correction to the isotope–temperature gradient would only serve to increase the estimated temperature shifts.

The chemical signature of major species is broadly similar in both events. Strong negative correlation between $\delta^{18}O$ and Ca evidently persisted in the more transient events within the Eemian, although peak Ca concentrations, similar to YD levels, are much lower than late glacial concentrations. Calcium concentrations in the warm stages either side of events 1 and 2 are roughly equal to Holocene levels.

Although many features of the Eemian cool events seem to parallel the changes in the YD, there is a striking difference in the signal for deuterium excess which is strongly in phase with $\delta^{18}O$ throughout the Eemian, including events 1 and 2. During the late glacial and including the YD event, these parameters are strongly in antiphase[21]. It seems clear that although a similar mode switching in ocean–atmosphere circulations may be implicated in both the Eemian and late glacial events (including YD), there has been a fundamental difference in the oceanic source regions involved. The vast production of melt water from decaying ice sheets could have been involved in the YD, but was not available at least for event 1, which occurred in the final part of the Eemian.

There is some indication in event 1 of a catastrophic start to the event with a more tapered recovery. This can be seen in the dust profile, a parameter that suffers least from smoothing by diffusion and has been measured at millimetre resolution. Surging of (for example) the west Antarctic ice sheet could have provided the necessary trigger to the system[35], but the rapidity of the start of the event as seen in Greenland would be surprising, especially as it seems to have passed unrecognized in the Vostok core. Alternatively, a sudden weakening of the north Atlantic current could have allowed the Greenland current to carry icebergs much further south. A general cooling of the north Atlantic associated with such events could, in part, account for the observed lower deuterium excess. Whatever the 'trigger' for these events, their duration of up to several hundred years is most probably connected with a re-ordering of the oceanic circulation. Such features have not, however, been observed through the Holocene, despite important climate changes during this period—these include the Climatic Optimum and the Little Ice Age.

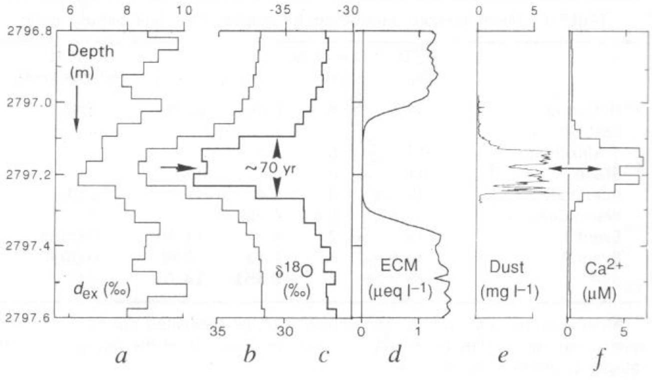

FIG. 4 Profiles of five parameters through 'event 1', a rapid climatic oscillation (~70 yr duration) at the culmination of the Eemian interglacial, ~115 kyr BP. *a*, Deuterium excess[15]; *b*, oxygen isotope ratio[7]; *c*, same as *b*, but deconvoluted to account for diffusion (estimated diffusion length 3 cm); *d*, acidity measured by ECM in microequivalents per litre[31]; *e*, dust concentration measured from scattered laser light and calibrated by Coulter Counter by integrating size distribution[33]; *f*, calcium ion concentration[38].

We have considered the possibility that the events may have been generated or sharpened by processes occurring within the ice sheets, but several factors argue strongly against this. First, the events are located ~200 m above bedrock. Visible examination of the core revealed no evidence for significant disturbance of the layering down to 2,847 m, or ~50 m below the depth of event 1, although examination of cloudy bands showed that the layering was becoming inclined by up to 21° by the depth of event 2. Although this might indicate some migration of the position of the ice divide since the Eemian[7], no indication of any discontinuity in the record was observed after the start of the

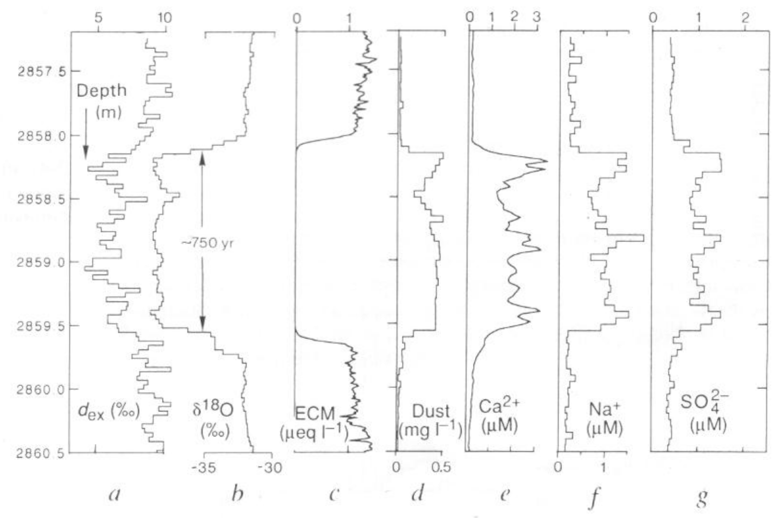

FIG. 5 Profiles of oxygen isotope ratio[7], calcium ion concentration[38], acidity by ECM[31], dust[33], deuterium excess[15], sodium and sulphate[41] through 'event 2', a climate oscillation sustained for ~750 yr in the initial stages of the Eemian interglacial ~131 kyr BP.

Eemian. Observations on the core have revealed a strong anti-correlation between crystal size and dust or Ca content, with sharp changes at the boundaries of both events 1 and 2. Studies on the ice adjacent to and within event 1 show a significant strengthening of the fabric (pattern of preferred orientation) within the smaller crystals inside the event. It is not clear how far this could influence the rate at which the ice thins. Patterson[36] has argued that the effect should not be important near an ice divide where little shearing is expected.

Second, transition times at the start and at the end of the events are similar to those observed for the mid- and late-glacial events, even allowing for peak broadening due to diffusion. Some diffusion is indicated by the symmetry and broader appearance of the ECM (H^+), DEP and $\delta^{18}O$ profiles with respect to the dust profiles. If dust is considered to be immobile, and it is also assumed the shifts were originally simultaneous, then we can estimate a mean diffusion length of ~8 cm for both H^+ and $\delta^{18}O$. This can be compared with a diffusion length for ice molecules of 3–4 cm calculated on the basis of a mean ice temperature of −15 °C, a vertical strain rate of $3 \times 10^{-5}\ yr^{-1}$ estimated for the Eemian ice, and a self-diffusion coefficient for ice of $2.5 \times 10^{-8}\ m^2\ yr^{-1}$. If we therefore assume that the dust signal represents the broad shift in atmospheric circulation pattern at the boundaries of these events, this suggests that the shift was largely completed within ~10 years for event 1 and ~30 years for event 2. These rates of change are comparable with the rates indicated previously for both YD termination[21] and for the late glacial events[7,8].

At this stage, estimates of the rate of change of climate parameters must be tentative, but such processes cannot affect the amplitude of the events themselves. The overall picture of an atmospheric circulation system oscillating between two well defined modes is unaffected.

What the ice cores tell us

Although we knew that abrupt and large climatic oscillations could occur during the cold stages of the glacial–interglacial cycle, the oscillations seen during a warm stage are new. They are prevalent in the early to mid-stages of the warmest part of the Eemian interglacial but occur throughout MIS-5e. The mode switches may be completed in as little as 1–2 decades and can become latched for anything between 70 yr and 5 kyr. The signature of these events revealed in the chemical profiles in the GRIP core is consistent with large changes in atmospheric circulation patterns in the north Atlantic, and important climate changes at least over Greenland and adjacent regions are indicated. The length of these events indicates that shifts in ocean circulation were involved, as is believed to have been the case with the YD event, so the effects are likely to have been much more widespread.

Given the history of the last 150 kyr, the past 8 kyr has been strangely stable; only during the final ~2 kyr of the warmest stage of the Eemian interglacial do our data demonstrate a similar period of stability. The unexpected finding that the remainder of the Eemian period was interrupted by a series of oscillations, apparently reflecting reversals to a 'mid-glacial' climate is extremely difficult to explain. Perhaps the most pressing question is why similar oscillations do not persist today, as the Eemian period is often considered as an analogue for a world slightly warmer than today's. It has been suggested that the north Atlantic Oscillation or related processes may have a bearing on decadal-frequency features[10,37], as they are linked to strong interannual variability at coastal Greenland stations, but clearly this has not left significant evidence in the Holocene ice-core records. If such an oscillation caused the earlier features, it must have been far stronger. Moreover we need to explain how a mode switch can be sustained for 70 yr—5 kyr after being induced by, perhaps, a higher frequency switching in the atmospheric system, or by some catastrophic event such as ice-sheet surging.

As the GISP2 drilling nears bedrock, we can rapidly expect both confirmation of these findings and new clues as the sister cores are subjected to closer scrutiny. The analysis of new parameters should allow us to narrow down the range of possible changes in ocean and atmosphere that favoured instability in the climate. Coordinated analysis of the two cores should allow much firmer dating than has hitherto been possible in any single ice-core, and remove beyond reasonable doubt any question relating to local interferences on the records. Jointly, they may provide the vital clue to answer the question of what it might take to induce Eemian-type instability into the Holocene pattern of climate. Man is already perturbing one of the factors that may be involved, the greenhouse gases, and our first tentative measurements indicate that they may be linked to climatic changes within the Eemian. □

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