the cooling and the heating cycle. Figure 3 shows the tilt angle as a function of temperature. If the transition from homeotropic to tilted orientation is second order, then according to Landau theory the tilt angle should scale as $(T_c - T)^{1/2}$. This argument is based on using the tilt angle Θ as the order parameter and expanding the free energy in terms of its even powers[10]. The insert in Fig. 3 suggests that this is the case if one chooses T_c to correspond to the onset of the homeotropic transition temperature.

Several other liquid crystals show this behaviour. Although most of the detailed studies reported here have been done with the polar liquid crystal E7, we have also observed similar behaviour with M24 (Merck), S3 MBBA and a nematic liquid crystal composed of centre-symmetric molecules. The mechanism of this anchoring transition is not yet clear, but we suspect that two competing temperature-dependent forces are involved, one that prefers the homogeneous orientation and the other that prefers homeotropic. □

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Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event

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THE warming at the end of the last glaciation was characterized by a series of abrupt returns to glacial climate, the best-known of which is the Younger Dryas event[1]. Despite much study of the causes of this event and the mechanisms by which it ended, many questions remain unresolved[1]. Oxygen isotope data from Greenland ice cores[2–4] suggest that the Younger Dryas ended abruptly, over a period of about 50 years; dust concentrations[2,4] in these cores show an even more rapid transition ($\lesssim$20 years). This extremely short timescale places severe constraints on the mechanisms underlying the transition. But dust concentrations can reflect subtle changes in atmospheric circulation, which need not be associated with a large change in climate. Here we present results from a new Greenland ice core (GISP2) showing that snow accumulation doubled rapidly from the Younger Dryas event to the subsequent Preboreal interval, possibly in one to three years. We also find that the accumulation-rate change from the Oldest Dryas to the Bølling/Allerød warm period was large and abrupt. The extreme rapidity of these changes in a variable that directly represents regional climate implies that the events at the end of the last glaciation may have been responses to some kind of threshold or trigger in the North Atlantic climate system.

We report accumulation-rate data from the Greenland Ice Sheet Project II (GISP2) ice core, which is being drilled at 72.6° N, 38.5° W, at an elevation of 3,200 m. The core has reached a depth of 2,250 m, about 75% of the ice-sheet thickness. The parallel Greenland Icecore Project (GRIP) core was completed close to bedrock in the summer of 1992 (ref. 3), about 30 km east of the GISP2 drill site. Multi-parameter analyses of both of these cores are yielding high-resolution records of North Atlantic climate changes[3,4].

We reconstruct snow accumulation by identifying annual layers in the ice core. Primary indicators (Table 1) include visible strata produced by summer insolation[5,6], direct-current electrical conductivity controlled by annually varying strong acids and dust[7,8], laser-light scattering from dust[9], and isotopic composition responding to temperature[2,3,8]. These indicators are compared with annually varying chemistry over selected intervals of a few metres (ref. 8; dating and Holocene accumulation will be discussed elsewhere (D. Meese *et al.*, manuscript in preparation)).

The accuracy of counting annual layers is sometimes operator-dependent. In common with all other layer-counting techniques, we lack a completely objective, unequivocal way to check our accuracy for the entire record. We use three approaches to estimate our accuracy (Table 1): internal consistency, comparison to volcanic records, and comparison to other published dates for the end of the Younger Dryas (YD). We find good consistency among annual indicators[8]. Cumulative differences over centuries are typically 1% or less, although there are locally larger percentage differences over shorter times, suggesting randomly distributed errors. Use of electrical conductivity measurements (ECM) and dust data to adjust a visible-only timescale required a cumulative change of <1% over 1,800 years between 335 m and 679 m depth.

We find that visible-only or multi-parameter dating matches various volcanoes dated historically, dendrochronologically or by counting of layers in other ice cores to within 1% or better

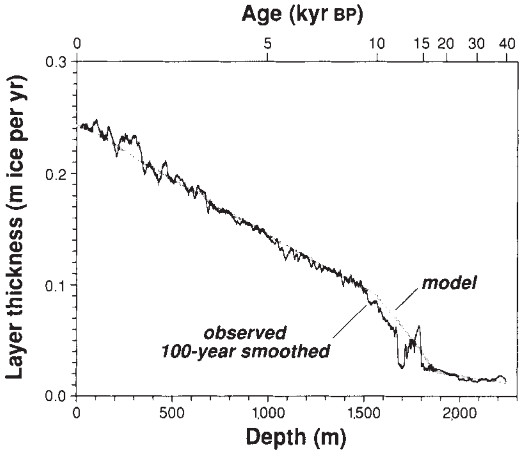

FIG. 1 Measured annual layer thickness in the GISP2 core smoothed with a 100-year running mean, and thicknesses predicted by the model of Schøtt *et al.*[16].

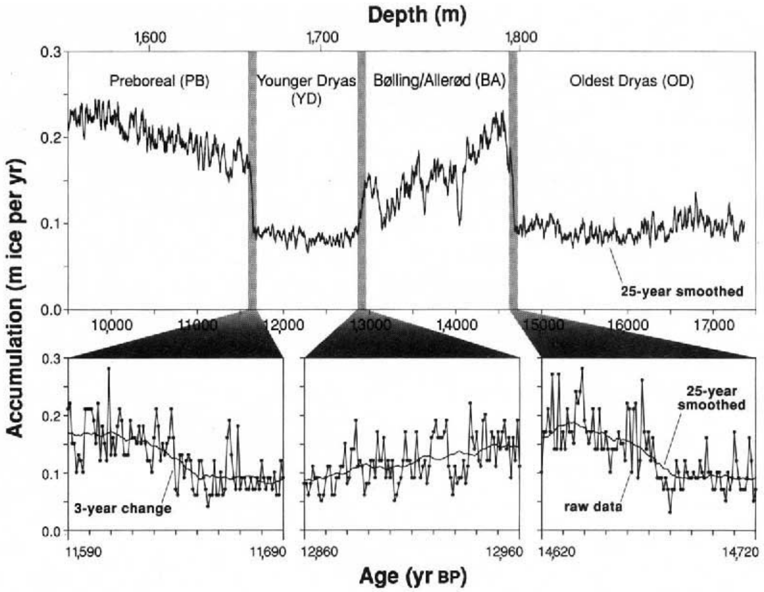

Fig. 2 Late-glacial accumulation-rate history at GISP2, estimated from data and model in Fig. 1. Ages are in years before 1950. The 25-yr running mean is shown in all panels. Yearly data are shown for the rapid changes at the onsets of the Preboreal (*b*) and the Bølling/Allerød (*d*), and the slower change at the onset of the Younger Dryas (*c*). The arrow in *b* indicates the possible one- to three-year termination of the Younger Dryas. The resolution in *b*, *c* and *d* is controlled by the 5-mm precision used in recording the layer-thickness data.

over century-length timescales, for the most recent 2,000 years. We used ECM and sulphate to identify volcanic fallout (compare with ref. 7). Some iteration is required; one must know the approximate age of an ECM peak to match it to a historically dated volcano. Several of our peaks over the last 700 years have been verified by comparing major-element chemistry of volcanic glass recovered from the ice core to glass from the suspected volcano (see also refs 10, 11).

We identify the sharp change in layer thickness at 1,678 m depth, corresponding to 11,640 ± 250 yr BP (years before 1950) in Figs 1 and 2 with the end of the YD: this depth also is marked by rapid changes in stable-isotopic composition and in dust concentration[4], with the YD having 'colder' isotopes, more dust and thinner layers than in the younger Preboreal (PB). The YD termination in Europe is dated ~10,000–10,200 ^{14}C yr BP (refs 12, 13), which has been calibrated to within about two centuries of 11,500 calendar years BP (Table 2). The duration of the YD (1,300 ± 70 years between the midpoints of the onset and termination in the accumulation-rate record) and the timing of the transition from the Oldest Dryas (OD) to the Bølling/Allerød (BA) at 14,680 ± 400 yr BP in our record also match U–Th data from corals[14,15] and new data from the GRIP ice core[3] within likely error limits. We believe that these calibration checks confirm our ability to recognize annual layers in the GISP2 core.

Measured annual-layer thickness, λ, allows us to calculate accumulation rate, $\dot{b}$, by correcting for ice flow. Layer thicknesses and a depth–age scale were modelled[16] for the GISP2 core using an assumed climate history consistent with earlier ice-core data ($\dot{b}_{\text{model}} = 1/3$ of the modern value in the ice age, increasing linearly from 15 to 10 kyr BP to constant modern value of 24 cm ice per year). Modelled layer thicknesses, λ_{model}, are close to observed values except for rapid steps such as the YD (Fig. 1). This allows a first approximation from $\dot{b} = (\lambda/\lambda_{\text{model}})\dot{b}_{\text{model}}$ for each depth (Fig. 2).

The steps in layer thickness were not caused by ice flow. Examination of the core showed no evidence of thrust-faulting or other discontinuities. If anomalous gradients in layer thickness had been caused by enhanced shear strain in soft YD or OD ice[17], there should be rapid or step changes at the climatic termination in the tightness of ice *c*-axis fabrics about the vertical, because that tightness increases with cumulative strain in cold inland ice sheets[18]. We measured this tightness by optical and sonic techniques, and found no significant steps in cumulative strain across these boundaries, although the rate of increase of tightness with depth may increase slightly at the YD/PB boundary.

Ice accumulation is low in cold periods (YD and OD) and high in warm periods (PB and BA). The accumulation decrease from BA to YD (Fig. 2*c*) was gradual, but the increases from YD to PB (Fig. 2*b*) and OD to BA (Fig. 2*d*) were abrupt; Broecker[19] has proposed an explanation for this shape in terms of gradual slowdown but abrupt resumption of North Atlantic

TABLE 1 Data used in dating

Depth (m)	Age (yr BP)	Data used	Estimated age error in interval	Estimated age error at bottom (yr)
0–719	0–3,300	visible + ECM, + isotopes 0–300, + laser dust 372–719m; limited chemistry	2%	±70
719–1,371	3,300–8,020	visible, occas. intercompar. with ECM + laser dust	2%	±160
1,371–1,510	8,020–9,380	visible + ECM + laser dust	2%	±190
1,510–1,678	9,380–11,640	visible, occas. intercompar. with ECM + laser dust	2%	±250
1,678–1,867	11,640–17,380	visible, occas. intercompar. with ECM + laser dust	5%	±520
1,867–2,250	17,380–40,500	visible occas. intercompar. with ECM + laser dust; 1/10 or 1/20 of metres counted	10%?	±3,000?

Recovery of intact core exceeded 97%, and visible logging of this intact core was essentially continuous. 'Occasional intercomparison' refers to checks of about 1 m in 50, usually made in the field. Estimated counting uncertainty on the century to millenial scale (fourth column) is believed to be smallest in Holocene ice where physcial properties control the visible signal, acids control the ECM signal and dust controls the laser signal, larger in deeper ice where all three methods respond primarily to dust, and larger still where only 1 m in 10 or 1 m in 20 was counted in the field and interpolations were used; planned counting of the metres skipped in this deepest ice should reduce the uncertainties significantly. We have tried to be slightly conservative in our error estimates.

TABLE 2 Recent dates for end of Younger Dryas

YD end (yr BP)	Method	Ref.	Comment
11,640 ± 250*	GISP2 ice core, Greenland layer count	this work	also Meese *et al.* manuscript in preparation
11,550 ± 70*	GRIP ice core, Greenland layer count	3	isotopic, other data; preliminary
11,700*	U-Th calibration of ^{14}C	14	
11,200–11,500*	U-Th calibration of ^{14}C	15	
11,000–11,700*	Lake Gosciaz varve calibration of ^{14}C	23	also sharp change in oxygen isotopes
>11,300†	tree-ring calibration of ^{14}C	24, 25	
>10,720 ± 150†	Dye 3 ice core, Greenland	22	our interpretation of published data
10,500–10,800‡	Swedish varve calibration of ^{14}C	26	preliminary
10,630‡	Lake Holzmaar varve date for pollen changes	27	any error from misidentification of turbidites or indistinct layers in some regions not quantified
11,500 ± 200	Average of entries marked with asterisk(*); agrees with †, not ‡	this work	likely age of YD termination

The European radiocarbon age of 10,000–10,200 ^{14}C yr BP[12,13] has been calibrated by U-Th, tree rings and lake varves. The ice-core records and some of the lake-varve records directly date climate events associated with the YD termination. We treat U–Th years, tree-ring years, varve years and ice-core years as equivalent to calendar years, although recognizing that errors are different for different techniques. The 10,720 yr BP date for the YD/PB transition from the Dye 3, Greenland ice core[22] is an undercount, as shown by high-resolution laser-dust calibration of the ECM data used (Fig. 2 of ref 22), probably because current-spreading between the ECM electrodes reduced the resolution below the thickness of some annual layers in the deeper part of the Dye 3 core dated by ECM; our ECM[4,8] experiences a similar problem for slightly thinner layers, but these occur at more than $\sim$2,000 m depth and 25,000 yr BP at GISP2.

Deep Water formation. Doubling of accumulation from YD to PB seems to have followed a precursor event and to have occurred in three years with most of the change in one year (arrow in Fig. 2*b*); accumulation increased more than twofold from OD to BA almost as rapidly. From YD to PB, the 25-year running mean increased by 80% in 25 years and doubled in 41 years; thus, even a conservative interpretation shows a transition in accumulation of similar rapidity to that in dust at Dye 3 (ref. 2), and an oscillatory, faster transition similar to ones in the GISP2 ECM record[4] seems more likely.

Average accumulation on an ice sheet should vary with the temperature-derivative of the saturation vapour pressure at cloud level if dynamical processes in the atmosphere do not change[20]. If so, the twofold YD/PB accumulation increase requires a warming of $\sim$7 °C for assumed PB precipitation temperature equal to the modern mean annual surface temperature of −31 °C; this estimate would change only ±1 °C for ±17 °C change in assumed precipitation temperature.

Dansgaard *et al.*[2] report an isotopic change in the Dye 3 core from YD to PB equivalent to 7 °C warming; similar or slightly smaller isotopic changes occur in the GRIP[3] and GISP2 cores[4]. Dansgaard *et al.*[2] also interpret a rapid change in deuterium excess from YD to PB as indicating a significant cooling of the oceanic vapour source, as sea-ice retreat exposed a large region of cold ocean water. Isotopic composition of snow depends among other factors on the temperature difference between the vapour source and the site of snow formation[21], so some of the isotopic change in Greenland ice may reflect this oceanic cooling, leaving 7 °C as an upper limit for ice-sheet warming from YD to PB. But because the full 7 °C warming is required to explain the observed accumulation-rate change thermodynamically, it is likely that accumulation was affected by changes in atmospheric dynamics, such as an increase in the number or duration of precipitating weather systems from YD to PB. Such an increase might have occurred as the storm track followed the sea-ice edge northward towards Greenland from YD to PB[2].

It has been proposed that late-glacial climate oscillations including the YD are linked to the thermohaline circulation of the oceans through changes in deep-water formation in the north Atlantic and associated changes in advection of warm surface water (see for example ref. 19). The rapidity of the YD/PB and OD/BA transitions in accumulation rate, an important climate variable, together with the possibly oscillatory nature of the accumulation-rate changes and the clearly oscillatory nature of the ECM and dust record[4], place severe constraints on models of these events. In particular, such climate variables as whole-ocean salt budgets, insolation, atmospheric CO_2 concentration and ice-sheet size are unlikely to have changed as rapidly as this. Causes must be sought in threshold levels in the climate system or in especially fast-acting components of the climate system including restricted, sensitive 'trigger' regions of deep oceanic convection, and atmospheric circulation patterns. □

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