THREE AMPHI-ATLANTIC CENTURY-SCALE COLD EVENTS DURING THE BØLLING-ALLERØD WARM PERIOD

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ABSTRACT Oxygen isotope composition of carbonates in the sediments of Crawford Lake, southern Canada, reveals multiple climatic events during the last deglaciation, including the Bølling warming, intra-Allerød cold period, Younger Dryas, Preboreal Oscillation, and early-Holocene 8.2-ka cooling. Here we present a high-resolution record (~50-yr sampling interval) of oxygen isotopes from this site during the Bølling-Allerød warm period and discuss its significance by comparing it with other records around the North Atlantic. These new data show three century-scale cold events, including the intra-Bølling cold period, Older Dryas, and intra-Allerød cold period. These climatic events correlate well in sequence and relative magnitude with those found in Greenland ice cores, European lacustrine sediments, and Atlantic Ocean sediments. Three similar oscillations in glaciochemical records from GISP2 ice core imply shift in atmospheric circulation patterns. The amphi-Atlantic distribution of these climate events suggests that these events likely originated from the North Atlantic Ocean and that climatic signals were transmitted through the atmosphere.

INTRODUCTION

In the North Atlantic region, large and abrupt climatic oscillations during the last glaciation continued into the last deglacial period, including quasi-periodic millennial-scale Dansgaard-Oeschger (D-O) events (~1500 year spacing) from ice and marine records (Dansgaard *et al.,* 1993; Hughen *et al*., 1996; Bond *et al*., 1997; Grootes and Stuiver, 1997; Alley, 1998; Alley and Clark, 1999). During the last glacial - interglacial transition, the most recent manifestation of these millennial-scale climatic events was broadly experienced in terrestrial records from both Europe (*e.g.,* Lotter *et al*., 1992; Björck *et al.,* 1996) and North America (*e.g.*, Levesque *et al*., 1993; Yu and Eicher, 1998). These climatic events include the Bølling warming at 14600 cal BP (12700 ^{14}C BP) and the gradual cooling trend toward the Younger Dryas climate reversal. Recent paleoclimatic studies in Europe have documented three century-scale oscillations during the general cooling trend of the Bølling-Allerød warm period (BOA) (Von Grafenstein *et al*., 1999; Brauer *et al.,* 2000; Zolitschka *et al*., 2000). However, limited data comparable with

European records exist in North American terrestrial records. Establishing the geographical extent of these cold events in a warm climate would provide useful insights into understanding the mechanisms of present climate variability.

Here we present a high-resolution (~50-yr sampling interval) oxygen-isotope record during the BOA warm period from a small lake in southern Canada. The coarse-resolution data (~100-yr sampling interval) from this site presented earlier (Yu and Eicher, 1998) documented the intra-Allerød cold period (IACP), Younger Dryas (YD), and Preboreal Oscillation (PB). The new data provide evidence for other cold-climate events of century scale that closely resemble records from the North Atlantic region, indicating an amphi-Atlantic distribution of these century-scale climate variations. The triple cold events during the BOA warm period warrant the recognition in Björck *et al.* (1998) late-glacial event stratigraphy, as also suggested by Brauer *et al*. (2000).

MATERIALS AND METHODS

Crawford Lake (43° 28' N, 79° 57' W; 278 m asl altitude) is located about 60 km southwest of Toronto atop Ontario's Niagara Escarpment (Fig. 1). The study region was deglaciated about 13000 ^{14}C BP, and the surface around the lake is dominated by bedrock outcrops and coarse materials (gravel, stony or sandy tills) (Karrow, 1987). The lake is small (2.4 ha surface area) and deep (24 m maximum depth) within a bedrock basin in a small watershed (about 80 ha). The data presented in this paper were obtained from a shallow core (core SC), taken with a Wright-Livingstone piston sampler on 7 March 1993 at water depth of 7.6 m (Yu *et al*., 1997; Yu and Eicher, 1998).

The subsamples for stable-isotope analysis were taken mostly at 1-cm intervals, with higher resolution (at 0.25 cm) during the BOA warm period. Sediment mixing caused by bioturbation activity was likely minimal at 376-360 cm (the BOA period) because of the banded or laminated nature of the sediments (Yu and Wright, 2001), justifying the fine-interval sampling. Bulk carbonate samples were dried at 50 °C overnight, and macroscopic plant remains and mollusc shell fragments were picked out under a microscope and discarded. Each sample of 40-50 mg of bulk carbonate was reacted with 95 % phosphoric acid (H_3PO_4) at a constant temperature of 50 °C for 1 hour to produce CO_2. The CO_2 was then analyzed for its $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios with a mass spectrometer (Finnigan MAT 250) at the University of Bern, Switzerland (Siegenthaler and Eicher, 1986). The results were presented as conventional delta (δ) notation, which is defined as $[(R_{sample} - R_{standard})/R_{standard}] \times 1000$ (where R is the absolute ratio of $^{18}O/^{16}O$ or $^{13}C/^{12}C$, and Vienna-PDB [Peedee belemnite] is standard for carbonates). The analytical precision is ± 0.02 ‰ for both $\delta^{18}O$ and $\delta^{13}C$.

RESULTS

The sediments show an upward sequence from clay through transitional clayey marl to marl (Fig. 2; Yu and Eicher, 1998). The basal 5-cm silty clay has a very low content of organic matter and carbonates. The transition from clay to marl at 380-373 cm is laminated, with gradually rising carbonate contents. From 373 to 362 cm, the sediments are banded marl with up to 82 % carbonate.

The $\delta^{18}O$ values above 378.5 cm upcore register the isotopic composition of authigenic calcite. Initially, the $\delta^{18}O$ values show a positive shift of > 1 ‰ from –10 to –8.7 ‰ from 378.5 to 375 cm. From 375 to 362 cm, the $\delta^{18}O$ values are relatively high and show a downward trend, with several minor negative excursions at 369.5, 367 and 364 cm. A major negative excursion at 361–351 cm reaches a minimum of –11.1 ‰ at 358 cm. The abrupt positive shift of 1.4 ‰ in $\delta^{18}O$ from –10.8 to –9.4 ‰ occurs within 2-cm sediment around 351 cm. After another minor negative excursion of 0.4 ‰ from 346 to 342 cm, the $\delta^{18}O$ values reach a high of –8.6 ‰.

$\delta^{13}C$ values show a step-wise decrease from –0.6 ‰ to –5.8 ‰ from 378.5 to 350 cm, with several oscillations. After a positive shift in the early Holocene, $\delta^{13}C$ stabilize around –5 ‰. In general no significant correlation between $\delta^{18}O$ and $\delta^{13}C$ values is apparent (Fig. 3).

DISCUSSION

RADIOCARBON DATES, CHRONOLOGY AND TERMINOLOGY

The chronology is based on AMS ^{14}C dates on terrestrial plant macrofossils from core DC at Crawford Lake (9670 ± 70 and 9620 ± 60 ^{14}C BP) and from nearby Twiss Marl Pond (10920 ± 80 ^{14}C BP; Fig. 2; Yu and Eicher, 1998). The ages were transferred to core SC on the basis of pollen correlation and major isotopic shifts. The other ages used for chronology were based on the local deglaciation history and from nearby dated pollen sequences by pollen correlation (Fig. 2; see Yu and Eicher, 1998; Yu, 2000 for detail).

The multiple proxy data from three cores at this site unequivocally place this interval in the late glacial and early Holocene. However, the equivalent calendar time scale cannot be established closer than 400 years, because of the lack of straightforward conversion between radiocarbon and calendar ages for this time period (Stuiver *et al*., 1998). For example, the calibration of two AMS ages generates wide ranges (440 and 320 years, respectively for 9650 and 10920 ^{14}C BP) of calendar ages (Fig. 4). As a result, the time scale for Crawford Lake as presented in Fig. 4 is tuned to GISP2 ice-core time scale based on major isotopic shifts; thus the correlation does not imply synchrony within ± 400 years. On the other hand, there is still an age discrepancy between two Greenland Summit ice cores (GISP2, and GRIP), ~30 km apart (Figs. 4B and 4C). In any case, the remarkable similarity of records as shown in Fig. 4 justifies the assumption of synchrony for the major climate shifts, unless future independent chronology from lake sediments indicates otherwise.

In this paper, we chose to use the terms of the Bølling, Old Dryas, Allerød, and Younger Dryas in a climatostratigraphic sense (“climatic events”; Wohlfarth, 1996), but not necessarily the chronostratigraphy of Mangerud *et al.* (1974). As many authors have pointed out (*e.g.*, Broecker, 1992; Lowe, 1994; Wohlfarth, 1996; Björck *et al.*, 1998; Walker *et al*., 1999), there are several problems with the Mangerud *et al*. (1974) chronostratigraphy, which was originally proposed for northwest Europe and was based on bulk radiocarbon dates. For example, the Bølling was originally defined as starting from 13000 ^{14}C BP (calibrated to ~15650 cal BP; Stuiver *et al*., 1998). However, most recent records based on AMS dates or independent annual chronology indicate a much later onset of the Bølling (*e.g*., 14600 cal BP as in most records in Fig. 4). Broecker (1992) suggested the use of a single warm interval (the Bølling-Allerød: BOA) because there were limited number of records at that time showing evidence for the Older Dryas. As summarized in this paper, more recent high-resolution records show not only the Older Dryas but also other minor oscillations during the BOA warm period. As a result, the placement of these minor cold events may not be consistent among records and may not correspond with the chronostratography of Mangerud *et al*. (1974). We take the advice of Wohlfarth (1996) to use these historical terms in a climatic sense, because these terms have already been widely used in the literature and the sequence of these events is not in dispute. Perhaps it is more appropriate now to properly define these “climatic events” as represented in these existing terms, especially when more well-dated records are available from terrestrial, oceanic and ice-core sources. A new set of terminology for this event stratigraphy as proposed by Björck *et al.* (1998) is probably premature and may be even further confusing the matter (Broecker, 1992; Brauer *et al*., 2000), for the ages used in the scheme are still preliminary (see Table 2 in Björck *et al*., 1998) and the GRIP ice core and its oxygen-isotopic proxy may not be representative of the amphi-Atlantic region (Hughen *et al*., 1996; Bond *et al.,* 1997; Von Grafenstein *et al.,* 1999; Figs. 4D, E).

OXYGEN AND CARBON ISOTOPES IN LACUSTRINE CARBONATES

The isotopic fractionation between carbonate and water has a negative temperature coefficient of -0.24 ‰ per °C (Friedman and O'Neil, 1977), whereas $\delta^{18}O$ in precipitation is positively correlated with air temperature at 0.6 ‰ per °C for the global average (Rozanski *et al.,* 1992). The combination of these two temperature-dependent factors suggests a coefficient of 0.36 ‰ per °C, assuming that water temperature closely tracks air temperature (Yu and Eicher, 1998). In high- and mid-latitude regions, the isotopic signal of the water in general prevails over the temperature effect (Dansgaard, 1964; Siegenthaler and Eicher, 1986; Rozanski *et al.,* 1992). The $^{13}C/^{12}C$ ratio of authigenic marl depends mainly on local factors, particularly through the change in $\delta^{13}C$ of dissolved inorganic carbon (DIC) of lake water. These factors include exchange rates between water and atmospheric CO_2, residence time of the lake water and the associated evaporation effect, decomposition of organic matter, and biological productivity (Siegenthaler and Eicher, 1986; Yu *et al.,* 1997). The general lack of correlation between $\delta^{18}O$ and $\delta^{13}C$ suggests that the effect of local hydrology is unimportant in determining overall isotopic pattern of lacustrine carbonate and lake water (Fig. 3; Talbot, 1990).

The oxygen-isotope records from Crawford Lake document the classic Bølling - Allerød -Younger Dryas - Preboreal climate sequence (Yu and Eicher, 1998). During the BOA warm period, three cold events with negative excursions of 0.5 to 0.8 ‰ in $\delta^{18}O$ occurred (Fig. 4A), including the intra-Bølling cold period (IBCP; Koç Karpuz and Jansen, 1992; Hughen *et al.,* 1996), the Older Dryas (OD; Dansgaard *et al*., 1993), and the intra-Allerød cold period (IACP; Lehman and Keigwin, 1992). If we use a simple carbonate $\delta^{18}O$ – air temperature relation of 0.36 ‰ per °C and attribute the isotopic shifts to temperature changes, then these climate events as a first approximation represent 1-2 °C cooling.

The $\delta^{13}C$ results show a step-wise decrease of 5 ‰ from the Oldest Dryas before the BOA warming to the beginning of the Holocene (Fig. 2). Yu *et al*. (1997) attributed this general depletion trend to an increased input of organic matter from the watershed into the lake, when upland vegetation changed from treeless tundra through spruce woodland to closed pine forest. Subsequently the ^{13}C-depleted particulate organic carbon was oxidized and recycled back into the water to affect the $\delta^{13}C$ of DIC. The lack of covariance between $\delta^{18}O$ and $\delta^{13}C$ during the late glacial and early Holocene suggests that the local hydrology did not play a significant role in driving the $\delta^{18}O$ shifts in carbonates (Talbot, 1990), rather that the $\delta^{18}O$ shifts most likely reflected climatic changes, specifically temperature changes. Close examination of $\delta^{18}O$ and $\delta^{13}C$ covariance during these century-scale cold events may help to determine the nature of these oscillations (Fig. 3). During the IBCP and perhaps also IACP, $\delta^{18}O$ values inversely correlate with $\delta^{13}C$, but during the OD $\delta^{18}O$ shows positive correlation with $\delta^{13}C$, suggesting dry conditions with high evaporation, as well as cold.

TELECONNECTION OF CENTURY-SCALE COLD EVENTS

Three century-scale cold events during the Bølling-Allerød warm period were clearly documented at several high-resolution paleoclimatic records around the North Atlantic Ocean (Fig. 1). The $\delta^{18}O$ record from GRIP ice core shows all three cold events (Fig. 4B; Dansgaard *et al.*, 1993), as do other earlier Greenland ice cores (*e.g*., Dye 3, Renland; Johnsen *et al*., 1992; see their Fig. 2). The GISP2 $\delta^{18}O$ record only clearly shows two of them (Grootes *et al*., 1993; but see 3-yr resolution $\delta^{18}O$ in Fig. 4 of Stuiver and Grootes, 2000), but snow-accumulation record indicates three events (Fig. 4C; Alley *et al*., 1993; Cuffey and Clow, 1997). Both $\delta^{18}O$ and snow accumulation represent changes in local climate over Greenland (Alley, 2000). Similar oscillations in chemistry of GISP2 ice core (*e.g*., Ca, Cl, K, Mg, Na) and derived Polar Circulation Index suggest shifts in large-scale atmospheric-circulation pattern (Mayewski *et al.,* 1994, 1997; Alley, 2000), which indicates a broad geographic signature. These multiple cold events have also been documented in terrestrial $\delta^{18}O$ records at Ammersee, southern Germany (Fig. 4D; Von Grafenstein *et al*., 1999), and at other European sites, including Gerzensee, Switzerland (Eicher and Siegenthaler, 1976; Lotter *et al*., 1992; Birks and Ammann, 2000; Schwander *et al.*, 2000). These continental isotopic records represent changes in mid-European air temperatures. These short-term climatic oscillations have also been documented in marine records. In Cariaco basin (offshore Venezuela) in tropical Atlantic Ocean, grey-scale measurements of varved marine sediments, which are thought to be related to upwelling and trade-wind strength, also show three oscillations during the BOA warm period (Fig. 4E; Hughen *et al*., 1996). The BOA period of these records is expanded in Figure 5, which also shows difference in trend and details after detrending of these records. The Bølling-Allerød Interstadial Complex was recorded in diatom-inferred sea-surface temperature record from high-resolution sediment record from the Norwegian Sea (Koç Karpuz and Jansen, 1992). The petrologic tracers from VM23-81 in the North Atlantic show 3-4 oscillations during the BOA period, though Bond *et al*. (1999) only labeled two of them in their numbering systems of 1000-2000-year cycles (their numbers 10 and 11; see their Fig. 7).

The trans-Atlantic similarity and difference in patterns of these cold events may reveal the nature of these climatic changes. Von Grafenstein *et al.* (1999) identified a climatic asymmetry between Greenland and Europe on the basis of their derived oxygen isotopes in precipitation from ostracode shells. During the OD, Europe has cooling similar to that in Greenland, whereas during the IBCP and IACP Greenland was much colder than Europe. This suggests shifts in the climate gradient across the Atlantic, probably caused by shifts in atmospheric circulation pattern (Von Grafenstein *et al*., 1999). This asymmetry may relate to differences in covariance of $\delta^{18}O$ (a proxy of air temperatures and evaporative strength) and $\delta^{13}C$ (a proxy of lake productivity and evaporation) at Crawford Lake. Clearly this aspect of BOA century-scale climatic events deserves further investigations with multiple-proxy paleorecords.

Another contrasting pattern is the general trend during the BOA warm period. At Crawford Lake, the $\delta^{18}O$ values declined more than 2 ‰ during the BOA warm period. The ice-cores from Greenland show declining trend in $\delta^{18}O$ values (Johnsen *et al.,* 1992; Dansgaard *et al*., 1993; Grootes *et al*., 1993); a similar declining trend was documented in European fossil beetle (Atkinson *et al*., 1987) and isotopic records (Eicher and Siegenthaler, 1976; Lotter *et al*., 1992). However, the Ammersee and Cariaco records show a plateau-like Bølling-Allerød warm period (Figs. 4D and 4E). A similar plateau-like BOA was documented in marine records from Norwegian Sea (Koç Karpuz and Jansen, 1992; Lehman and Keigwin, 1992; Haflidason *et al*., 1995). The atmospheric CH_4 records from GRIP and GISP2 also show a plateau-like or even increasing trend during the BOA; however, the coarse temporal resolution from GRIP prevents detection of century-scale oscillations (Chappellaz *et al*., 1993), while the high-resolution CH_4 record from GISP2 shows evidence for the IACP (Brook *et al*., 2000). This difference may relate either to different regional responses to change in oceanic and atmospheric circulations or to differential responses of individual sites and proxies.

Similarity of climatic variations as summarized above indicates that the three events are real features during the BOA warm period. The teleconnection of these century-scale minor climatic oscillations from North America to central Europe suggests that they originated in the North Atlantic Ocean, likely caused by switching of different modes in thermohaline circulation (Broecker *et al*., 1985), which would affect sea-surface temperatures and atmospheric circulation over large geographic regions.

CONCLUSIONS

During the Bølling-Allerød warm period, three century-scale climatic oscillations existed, as inferred from high-resolution (~50-yr sampling interval) oxygen isotopes of carbonates at Crawford Lake, southern Canada. These events correspond to the intra-Bølling cold period, Older Dryas, and intra-Allerød cold period, which have been documented in proxy records from Greenland ice cores, Ammersee, and Cariaco Basin. The broad geographic distribution of these climate events suggests that they were probably caused by changes in thermohaline circulation in the North Atlantic and subsequent change in sea-surface temperatures. Change in atmospheric-circulation patterns is implied by similar patterns in glaciochemical records from the GISP2 ice core. The results indicate that climatic signals were transmitted by the atmosphere.

Alternatively, the nature and response of climate change at Crawford Lake in particular and in North America in general may be different from Greenland and Europe, but assessing this possible difference requires high-resolution independent chronology from this site and other sites. New multiple proxy data together with lake water isotopic calibration data collected from this site in the future can also be used to address possible change in the climatic gradient across the North Atlantic during this period of abrupt climatic oscillations (*e.g.,* Von Grafenstein *et al.*, 1999). Similarly, the North Atlantic region might have responded to an even broader forcing, if records with sufficiently detailed analyses from other parts of the world show similar patterns. In any case, there is a great need to obtain high quality paleo-records from different regions in resolving century-scale climate oscillations during the most recent warm period before the Holocene. Understanding spatial patterns and regional links of past climate changes are critical in testing and improving climate models and projecting future climate.

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Figure Captions:

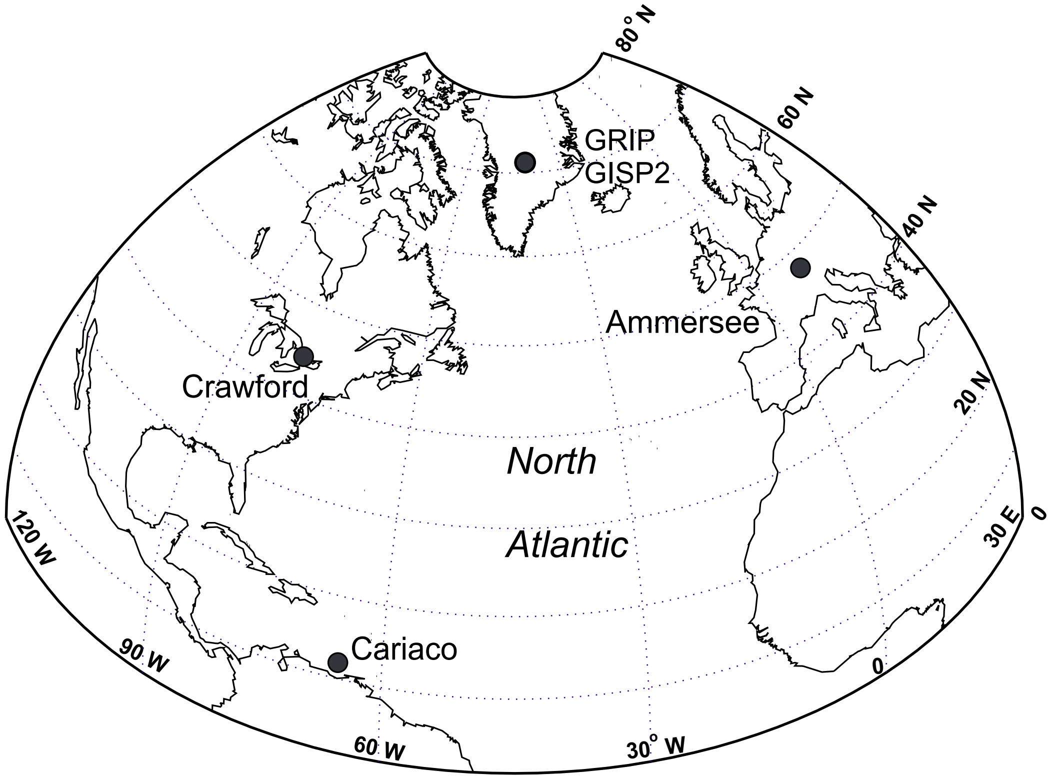
FIGURE 1. Location map of paleoclimate sites around the North Atlantic Ocean. Crawford Lake in North America (Yu and Eicher, 1998), GRIP/GISP2 ice cores from Summit Greenland (Dansgaard *et al*., 1993; Grootes *et al*., 1993; Mayewski *et al*., 1994, 1997), Ammersee in central Europe (Von Grafenstein *et al*., 1999), and marine core PL07-56PC from Cariaco basin in tropical Atlantic (Hughen *et al*., 1996).

FIGURE 2. Photograph of late-glacial and early-Holocene sediment section and oxygen and carbon isotopes of carbonates from core SC at Crawford Lake, Canada. PB, Preboreal Oscillation; IACP, intra-Allerød cold period; OD, Older Dryas; IBCP, intra-Bølling cold period. The ^{14}C dates and ages on the right side were transferred from other cores at same and nearby sites on the basis of major isotopic shifts and regional pollen correlation (see Yu and Eicher, 1998 and Yu, 2000 for detail). The dashed horizontal lines show the correlation of δ^{18}O and δ^{13}C during the century-scale climate oscillations.

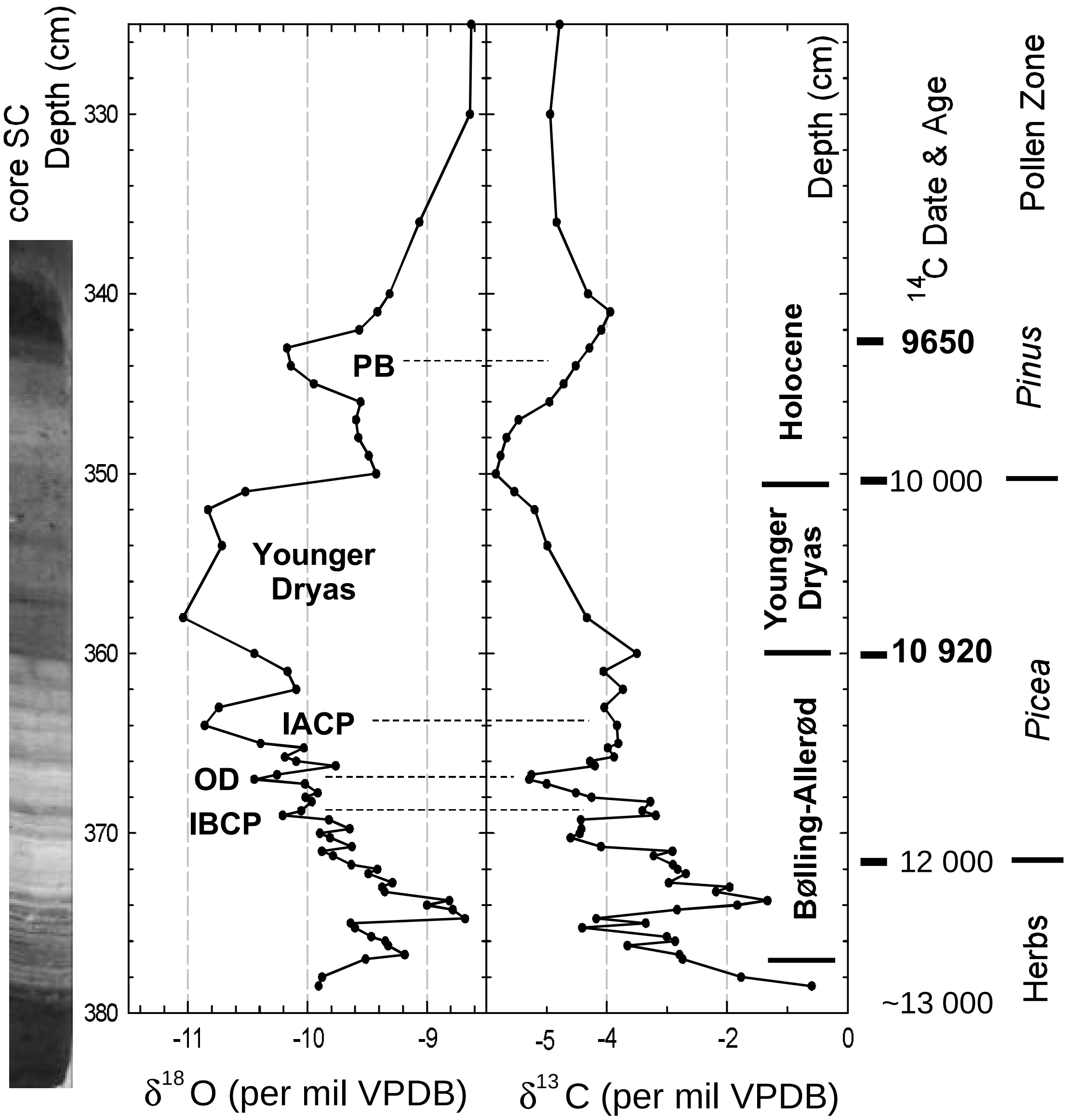
FIGURE 3. Covariance of δ^{18}O and δ^{13}C for the period of 14600-10000 cal year BP at core SC of Crawford Lake. The general lack of correlation (r^2 = 0.056; dashed regression line) suggests minimal role of local hydrology in causing major isotopic shifts. Three century-scale cold events during the Bølling-Allerød warm period show different pattern of δ^{18}O and δ^{13}C variations (trends indicated by double-arrowed lines): IBCP, inverse relation; OD, positive relation; and IACP, constant δ^{13}C.

FIGURE 4. Correlation of paleorecords during the last deglaciation (15000-10000 cal BP) around the North Atlantic. **A:** δ^{18}O of lacustrine carbonates at Crawford Lake; **B:** δ^{18}O of ice-core GRIP (Dansgaard *et al*., 1993); **C:** Snow accumulation rates of ice-core GISP2 (Cuffey and Clow, 1997); **D:** δ^{18}O of lacustrine carbonates at Ammersee, south Germany (Von Grafenstein *et al.,* 1999); **E:** Grey scale of core PL07-56PC at Cariaco basin off Venezuela (Hughen *et al*., 1996; revised age scale). Solid correlation lines indicate major climatic shifts, whereas dashed lines indicate minor cold climatic events. Ages for Crawford Lake based on AMS ^{14}C dates from nearby cores are tuned to GISP2 ice-core time scales on the basis of similar climatic oscillations, so the similarity in timing does not mean synchrony of events at centennial scales. The hatched bars along the time scale on the left side show the ranges of calibrated ages of two AMS ^{14}C ages in Fig. 2 on the basis of calibration program Calib 4.2 (Stuiver *et al.,* 1998): (a), 10750-11190 cal BP for 9650 ^{14}C BP; and (b), 13140-12820 cal BP for 10920 ^{14}C BP at 2 σ significance level (95 % probability). Three century-scale cold events during the Bølling-Allerød warm period are the IBCP (intra-Bølling cold period), OD (Older Dryas), and IACP (intra-Allerød cold period). PB, Preboreal Oscillation. Most of these data sets are available from the World Data Center – A Paleoclimatology at the National Geophysical Data Center, Boulder, CO, USA (www.ngdc.noaa.gov/paleo).

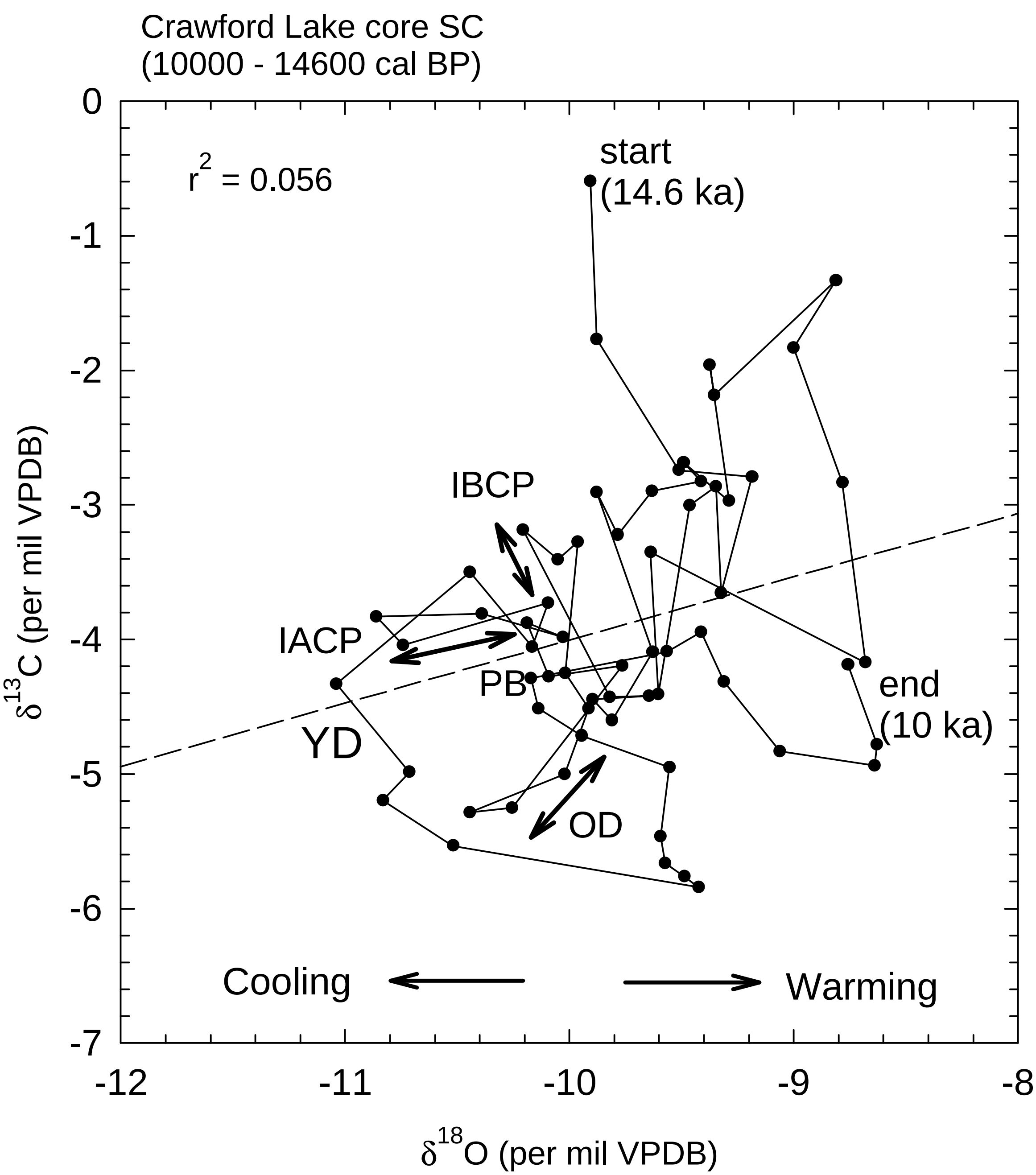
FIGURE 5. Details of climatic fluctuations during the BOA period in paleoclimatic records as shown in Fig. 4. The top panels show the trend lines based on linear fits, whereas the bottom panels show the detrended records after subtracting the fits and means.



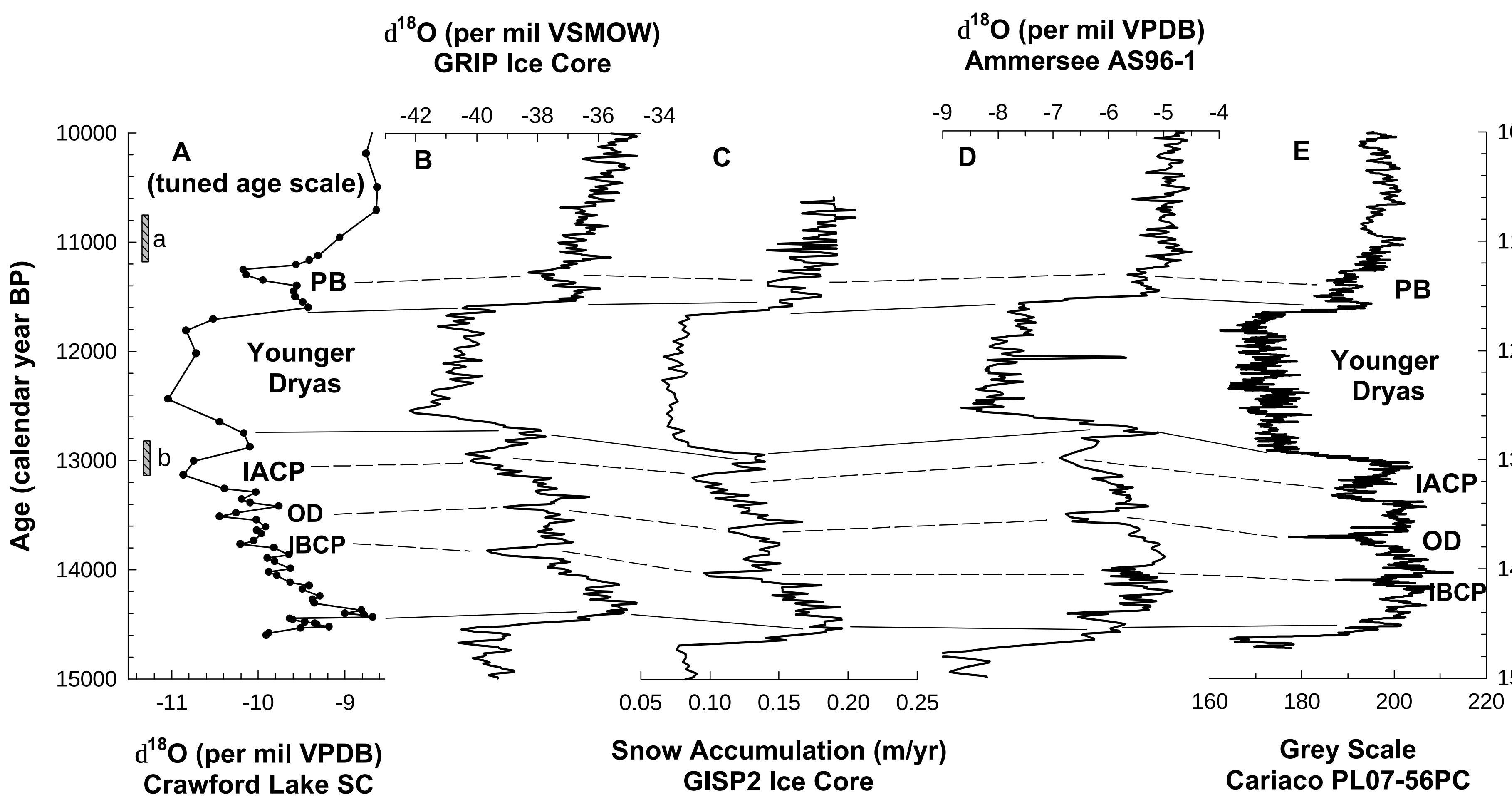
Yu & Eicher Fig. 1



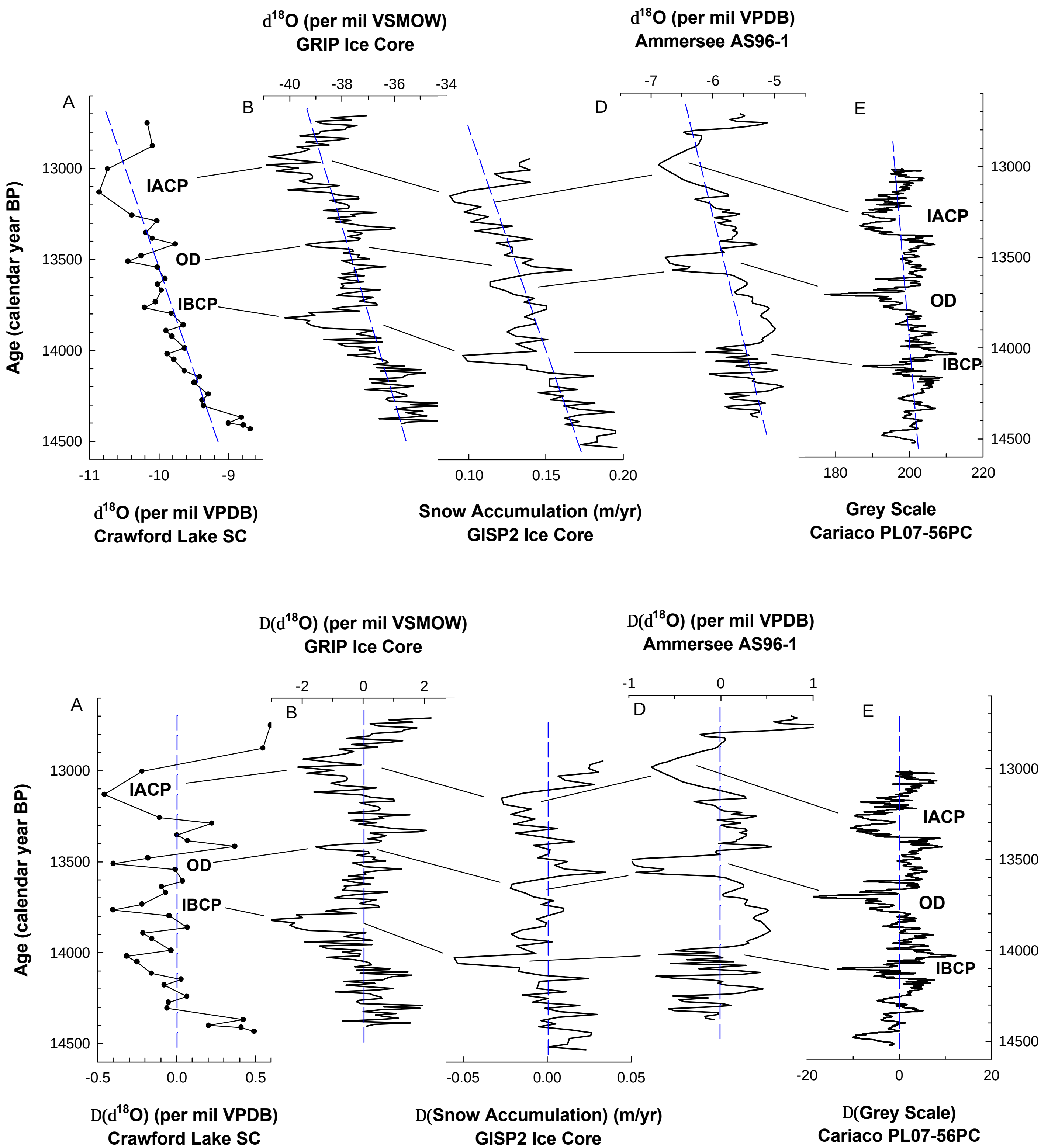
Yu & Eicher Fig. 2



Yu & Eicher Fig. 3



Yu & Eicher Fig. 4



Yu & Eicher Fig. 5