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Parallel climate and vegetation responses to the early Holocene collapse of the Laurentide Ice Sheet

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Abstract

Parallel changes in lake-level and pollen data show that the rapid decline of the Laurentide Ice Sheet (LIS) between 10,000 and 8000 cal yr BP triggered a step-like change in North American climates: from an ice-sheet-and-insolation-dominated climate to a climate primarily controlled by insolation. Maps of the lake-level data from across eastern North America show a reorganization of climate patterns that the pollen data independently match. Raised lake-levels and expanded populations of moist-tolerant southern pines (*Pinus*) document that summer monsoons intensified in the southeastern United States between 9000 and 8000 cal yr BP. Simultaneously, low lake-levels and an eastward expansion of the prairie illustrate an increase in mid-continental aridity. After the Hudson Bay ice dome collapsed around 8200 cal yr BP, lake-levels rose in New England, as populations of mesic plant taxa, such as beech (*Fagus*) and hemlock (*Tsuga*), replaced those of dry-tolerant northern pines (*Pinus*). Available moisture increased there after a related century-scale period of colder-than-previous conditions around 8200 cal yr BP, which is also recorded in the pollen data. The comparison between pollen and lake-level data confirms that vegetations dynamics reflect climatic patterns on the millennial-scale.

1. Introduction

During deglaciation, the retreating ice sheets and the changing seasonal contrast in insolation caused progressive changes in North American climates (COHMAP, 1988; Bartlein et al., 1998; Webb et al., 1993). Abrupt changes, however, punctuated the otherwise gradual shift from glacial to interglacial conditions (Broecker et al., 1985; Alley et al., 1997; Yu and Eicher, 1998; Clark et al., 1999; Hu et al., 1999; Peteet, 2000). These abrupt changes can be generalized into two types: (1) rapid, monotonic shifts or transitions and (2) climatic 'events' or oscillations (Bartlein, 1997). Rapid transitions may result from abrupt changes in regional or global climatic controls that do not rapidly reverse (e.g. ice sheet collapses, rapid increases in atmospheric CO_2 concentration, ocean circulation changes, or vegetation-atmosphere feedbacks), whereas climatic oscillations appear to be the product of temporary forcing, such as meltwater pulses or glacial surges. However, because regional climate controls differ, the spatial mosaic of responses to a particular climate forcing could include both types of abrupt change simultaneously in different regions. The local responses differ depending on location, due to the combination of direct effects and the indirect influences of the other intermediating systems (e.g. proximate ocean currents, ice sheets, air masses).

Here, we investigate the spatial patterns of climate change triggered by the rapid collapse of the Hudson Bay dome of the Laurentide Ice Sheet (LIS) between 8400 and 7900 cal yr BP (Barber et al., 1999), which likely had a dramatic influence on the climate system (Hughen et al., 1996; Alley et al., 1997; Stager and Mayewski, 1997; Hu et al., 1999). One product of the collapse was the '8.2 ka event', evident as an oscillation from warm to cool to warm climates in the North Atlantic region, due to a massive release of meltwater into the North Atlantic and the consequent influence on

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thermohaline circulation (THC) (Stuiver et al., 1995; Hughen et al., 1996; Alley et al., 1997; Barber et al., 1999). The strength of the THC strongly influenced the North Atlantic region, causing the oscillations in temperatures there, but synoptic-climatological reasoning suggests that responses should have differed in other regions.

We propose that the broad-scale consequence of the collapse was a rapid transition in circulation patterns caused primarily by the disappearance of the ice sheet, rather than by the short-lived changes in North Atlantic circulation. The large change in the elevation and extent of the ice sheet should have created a step-like change in boundary conditions that resulted in a substantial shift in regional circulation patterns (Felzer et al., 1996; Hostetler et al., 1999). Therefore, many paleoclimate data globally record a roughly synchronous transition around 8200 cal yr BP (Stager and Mayewski, 1997). In North America, the transition may be more pronounced than the '8.2 ka climatic oscillation', because the LIS, rather than THC, is a major climate control there (COHMAP, 1988; Bartlein et al., 1998). However, regional responses in North America may have differed, because different portions of North America are controlled by different factors.

The well-documented eastward shift in the prairie-forest boundary in the central United States began about 9000 cal yr BP (Cushing, 1967; Webb et al., 1983; Bartlein et al., 1984; Winkler et al., 1986), and may be one of the phenomena related to the ice sheet collapse. Similarly, Shuman et al. (2001) noted that a well-documented increase in moisture availability around 8000 cal yr BP in New England and Quebec (Webb et al., 1993; Lavoie and Richard, 2000; Newby et al., 2000) may have resulted from the diminishing influence of the LIS. Likewise, Carcaillet and Richard (2000) reported a conspicuous decline in fire incidence in Quebec around 8000 cal yr BP. In the southeastern United States, Webb III et al. (1993) map an early Holocene increase in precipitation, inferred from changes in pollen assemblages, which may also be related. Here, we synthesize fossil pollen and lake-level data from across eastern North America to show coordinated, but differing, regional climate changes indicative of a rapid reorganization of atmospheric circulation after the collapse of the ice sheet. Because lake-level and pollen data are two independent records of paleoclimates, they are used together to confirm the inferred regional moisture-balance patterns. The comparison between the pollen and lake-level data will also test the hypothesis that vegetation patterns closely track climatic conditions on the millennial-scale. The vegetation responses illustrate broad-regional patterns controlled by climate, as well as site-specific variations due to soils and other ecosystem-scale controls.

2. Dataset and methods

2.1. Lake-level data

To illustrate Holocene moisture-balance changes, we compiled and mapped three types of lake-level data from eastern North America (Table 1). Multi-core, multi-proxy studies provide millennial-scale lake-level records from New England (Newby et al., 2000; Almquist et al., 2001; Shuman, 2001; Shuman et al., 2001), Quebec (Lavoie and Richard, 2000), Ontario (Yu et al., 1997), Wisconsin (Winkler et al., 1986), and Minnesota (Digerfeldt et al., 1992). Our conclusions rely most heavily on the results of such studies. However, we have also included qualitative lake-level data for the north-central United States (Harrison, 1989), and for Virginia (Kneller and Peteet, 1993), and following from Webb and Webb III (1988), we also identified sedimentary hiatuses in published pollen records as an indicator of lake desiccation.

In synthesizing this wide array of data, we systematically assessed the records in order to ensure consistent and comparable lake-level interpretations. As a consequence, we have adopted alternative estimates of the past lake levels at some sites, although most are consistent with the published interpretations (see Shuman, 2001 for details). We focused on data that do not merely have the potential to reflect past lake-level change but carry a definitive moisture-balance signal. Relatively large lakes, complicated by processes such as isostatic adjustment (e.g. Yu and Andrews, 1994; Balco et al., 1998) were not included, nor were complex sites where ecological or local hydrological processes may explain the record (e.g. Delcourt et al., 1983; Thorson and Webb, 1991).

Depositional hiatuses in pollen cores, however, were widely accepted under the assumption that significant numbers of simultaneous hiatuses within a region may be a good indicator of dry conditions. Even if local controls influenced individual sites, the regional pattern should reflect the regional climate. Many other stratigraphic data from these pollen cores are ambiguous (e.g. loss-on-ignition changes and changes in the abundance of aquatic pollen types). They may be indicative of limnological changes, but are not definitive in terms of direction of water-level change. Single cores also do not provide the data needed to differentiate between a climatologically driven lake-level lowering and shallowing due to sediment infilling. Therefore, only the hiatuses were accepted as robust indicators of lake-status change in most pollen cores. Some sites outside of the glaciated portion of North America were also accepted as recording hiatuses because the basal age of lacustrine sedimentation dated within the Holocene, even though the basin presumably existed for much longer.

Table 1
Lake levels sites

Site name	Latitude	Longitude	Lake status				References
	Deg. N	Deg. W	10 ka	9 ka	8 ka	7 ka	
Mulitple core sites							
Crooked Pond	41.89	−70.65	3	3	2	2	Shuman et al. (2001)
Makepeace Cedar Swamp	41.93	−70.77	3	3	2	2	Newby et al. (2000)
Lake Mendota	43.10	−89.42	2	2	3	3	Winkler et al. (1986)
Crawford Lake	43.46	−79.95	2	2	2	2	Yu et al. (1997)
Echo Lake	44.06	−71.14	3	3	1	1	Shuman (2001)
Mansell Pond	45.04	−68.73	3	3	2	2	Almquist et al. (2001)
Albion Lake	45.85	−71.40	3	3	3	2	Lavoie and Richard (2000)
Adley Lake	46.13	−95.34	2	3	3	3	Digerfeldt et al. (1992)
Almora Lake	46.21	−95.30	2	3	3	3	Digerfeldt et al. (1992)
Qualitative studies							
Browns Pond	38.14	−79.62	3	3	1	1	Kneller and Peteet (1993)
Kettle Hole Lake	43.00	−95.00	1	1	2	2	see Harrison (1989)
Pickerel Lake	43.30	−97.20	3	3	3	3	see Harrison (1989)
Kirchner Marsh	44.50	−92.46	3	3	3	3	see Harrison (1989)
Rutz Lake	44.52	−93.52	2	2	3	3	see Harrison (1989)
Medicine Lake	44.82	−97.35	1	2	2	2	see Harrison (1989)
Elk Lake	47.13	−95.13			3	3	see Harrison (1989)
Weber Lake	47.47	−91.65	2	2	2	3	see Harrison (1989)
Hiatus sites							
Buck Lake	27.14	−81.19	0	1	1	1	Watts (1971)
Lake Annie	27.30	−81.40	1	1	1	1	see Harrison (1989); Webb and Webb III (1988)
Scott Lake	27.95	−81.97	0	0	0	0	Watts (1971)
Mud Lake	29.30	−81.87	0	1	1	1	see Harrison (1989); Webb and Webb III (1988)
Sheelar Lake	29.52	−82.00	1	1	1	1	see Webb and Webb III (1988)
Camel Lake	30.27	−85.02	0	0	1	1	Watts et al. (1992)
Barchamp Lake	30.37	−83.15	0	0	1	1	E. Grimm, unpublished
Langdale Lake	30.38	−83.11	0	1	1	1	E. Grimm, unpublished
Lake Louise	30.73	−83.26	0	1	1	1	see Webb and Webb III (1988)
Goshen Springs	31.72	−86.13	0	1	1	1	see Harrison (1989); Webb and Webb III (1988)
Cahaba Pond	33.50	−86.53	1	0	0	0	see Harrison (1989); Webb and Webb III (1988)
Quicksand Pond	34.33	−84.87	0	1	1	1	see Webb and Webb III (1988)
Anderson Pond	36.03	−85.50	1	1	1	1	see Webb and Webb III (1988)
Hack Pond	37.98	−79.07	0	0	1	1	see Webb and Webb III (1988)
Cranberry Glades	38.20	−80.23	0	1	1	1	see Webb and Webb III (1988)
Prison Pond	39.34	−75.61	0	0	0	0	Webb (1990)
Longhauser Pond	39.38	−75.68	0	0	0	1	Webb (1990)
Walters Puddle	39.38	−75.68	0	0	0	0	Webb (1990)
Nowakowski Pond	39.39	−75.68	0	0	0	1	Webb (1990)
Muscotah Marsh	39.53	−95.51	1	1	1	1	see Webb and Webb III (1988)
Governor's Branch Pond	39.70	−75.38	0	0	0	0	Watts (1979); see also Webb (1990)
Mitchell Farm Site	39.80	−75.67	0	0	1	1	Wright (1983); see also Webb (1990)
Helmetta Bog	40.23	−74.43	1	1	1	1	Watts (1979)
Szabo Pond	40.40	−74.48	0	1	1	1	see Harrison (1989); Webb and Webb III (1988)
Longswamp	40.48	−75.67	0	0	0	0	Watts (1979)
Panther Run Pond	40.80	−77.42	0	0	0	1	Watts (1979); see also Webb (1990)
Lawyers Bog	40.85	−75.03	0	0	0	0	Cotter (1983); see also Webb (1990)
Francis Lake	40.97	−74.83	0	0	0	0	Cotter (1983); see also Webb (1990)
Red Maple Swamp	41.36	−72.12	1	0	0	0	Beetham and Niering (1961); see Webb (1990)
Belmont Bog	42.25	−77.92	0	0	0	0	Spear and Miller (1976); see Webb (1990)
Houghton's Bog	42.32	−78.40	0	0	1	1	Miller (1973)
Hook Lake Bog	42.95	−89.33	1	1	1	1	see Webb and Webb III (1988)
Lake George	43.52	−73.65	0	0	0	1	see Harrison (1989)
Washburn Bog	43.53	−89.65	1	1	1	1	see Webb and Webb III (1988)
Mirror Lake	43.95	−71.70	0	0	1	1	Davis and Ford (1982); see also Webb (1990)
Paynter Site	44.10	−78.33	1	1	1	1	Yu et al. (1996)
Lac Dufresne	45.85	−70.35	1	1	1	1	see Webb and Webb III (1988)

Lake status is shown for 1000 calendar year intervals from 10,000 to 7000 cal yr BP, where 3 is low and 1 is high. Zero represents periods with a hiatus. References to Harrison (1989) and Webb and Webb III (1988) indicate sites included in these previous lake syntheses; other sites from these previous syntheses were not included here (see Methods). Unpublished data were obtained from the NAPD.

For comparison and mapping, the estimated lake-levels were categorized into lake-status classes—high, intermediate, or low (Table 1)—following a scheme similar to that used by Harrison (1989), Tarasov et al. (1994), and Yu and Harrison (1995). The total inferred range of water-level change was estimated by taking the difference between the highest level recorded and the lowest level recorded. Then, this range was divided so that the upper 30% was considered high, and the lowest 10% was considered low, with the middle 60% as intermediate. For qualitative estimates, the lake levels were assigned relative rankings and then categorized according to the same system, with the highest 30% of the relative rankings considered high and so forth. Sites with hiatuses were considered to reflect either dry or relatively moist conditions only, and provide no data regarding intermediate conditions. The regional pattern, or tally, of hiatuses does, however, reflect the broader moisture-balance trend.

To illustrate the regional moisture-balance trends, rather than site-to-site differences, the lake-level data were interpolated to a $50\,\text{km} \times 50\,\text{km}$ grid, using a locally weighted mean. Similar to the technique used by Guiot et al. (1993) to apply the lake-status data across a broad region, this technique weights the status of sites within a moving window ($\sim$300 km diameter) to produce a mean for each grid point. Sites within the moving window were weighted according to their normalized Euclidean distance from the center point (d, normalized by the size of the window), so that the weight is equal to $(1-d^3)^3$. The maps of interpolated lake-status should be considered to represent the general regional-scale moisture-balance, without much accuracy at the scale of individual grid points. Caution is required when interpreting the interpolated mapped patterns in regions where the density of lake-status data is low, such as in portions of the Great Lakes region and the southeastern United States. Furthermore, because nearly all sites within this study have relatively high water-levels in the modern, the mapped patterns generally represent the degree to which past conditions were drier than modern.

2.2. Fossil pollen data

For comparison with the lake-level data, pollen data from the North American Pollen Database (NAPD) (http://www.ngdc.noaa.gov/paleo/pollen.html) were also mapped. The relative percentages of pine (*Pinus*), beech (*Fagus*), hemlock (*Tsuga*), elm (*Ulmus*), ragweed (*Ambrosia*), and total prairie forb pollen were calculated based on the sum of all tree, shrub, and herb pollen. Modern data indicate that these taxa differ in their moisture requirements, even though some of their temperature tolerances are similar (Fig. 1; Webb et al., 1993; Webb III et al., 1993). Thompson et al. (1999) show, for example, that the minimum moisture requirements, based on the ratio of actual evapotranspiration to potential evapotranspiration (Thornwaite and Mather, 1955), vary significantly among beech (0.85), hemlock (0.87), and northern pines (0.37), even though their temperature tolerances are similar (July temperatures $\sim$14–26°C for all three taxa). Southern and northern species of pine tolerate different temperature ranges, and also have significantly different minimum moisture requirements. Southern pines require more moisture than northern pines, and grow only where the ratio of actual evapotranspiration to potential evapotranspiration exceeds 0.81 (Thompson et al., 1999). Given these modern climate preferences, the taxa may have tracked specific conditions over time as climate changed during the late-Quaternary (Prentice et al., 1991).

The pollen percentage data, like the lake-level data, were interpolated to a network of grid points spaced at 50-km intervals using a locally weighted tri-cubic function (Bartlein et al., 1998; Williams et al., 2001). Therefore, the maps illustrate regional-scale variations in the abundance of the taxa, which are controlled by climate. Individual sites may record somewhat higher or lower values than the regional mean due to other landscape-scale controls (i.e. soils) (Graumlich and Davis, 1993). The fossil pollen data were weighted according to both lateral and elevational distance from each grid point (so that topography is taken into account). The maps rely most heavily on well-dated, high-resolution pollen stratigraphies by also weighting the data according to the temporal-resolution of the pollen stratigraphy and the quality of the stratigraphic age control (Shuman, 2001; Williams et al., 2001). The radiocarbon dates underlying the NAPD age models were calibrated into calendar years (Stuiver et al., 1998; Shuman, 2001), and pollen sample ages were obtained by linear interpolation between the calibrated ages. Due to dating uncertainties, each map is best considered as an envelope of $\approx$500-years about the calendar-year interval assigned to it. Paleogeography is based on digitized versions of the Dyke and Prest (1987) maps shifted into calendar years, following the IntCal98 relationship between radiocarbon and calendar years (Stuiver et al., 1998). However, the Dyke and Prest (1987) 8400 ^{14}C yr BP map was specifically reassigned to 9000 cal yr BP in accordance with Barber et al. (1999).

3. Map patterns

The maps of the lake-status data illustrate a transition in climatic patterns by ca 8000 cal yr BP. Maps depicting 10,000 and 9000 cal yr BP contrast with those for 8000 and 7000 cal yr BP, indicating a relatively rapid change in moisture-balance patterns as the ice sheet collapsed (Fig. 2). Distinct and differing regional trends exist,

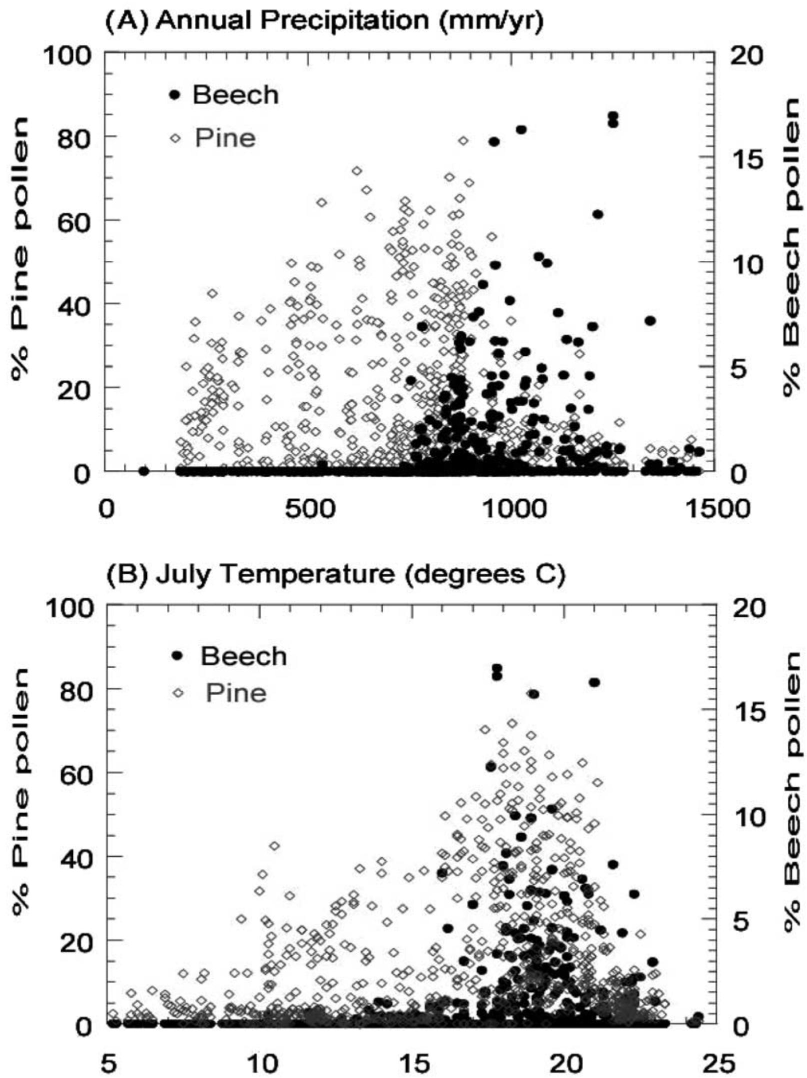

Fig. 1. Modern pollen percentages for northern pines (*Pinus*) and beech (*Fagus*) from modern sediment samples collected in eastern North America (north of 39° Lat., and east of 110° Long.). The maximum abundances of the two taxa occur within the same temperature range, but occur within different precipitation ranges.

however, in the northeast United States and adjacent Canada ('the Northeast'), the northcentral United States ('the Midwest'), and the southeastern United States ('the Southeast'). At 10,000 cal yr BP, most sites in the Midwest record relatively high or intermediate water-levels, but by 9000 cal yr BP, most sites record intermediate water-levels and, by 8000 cal yr BP, many record low water-levels. Sites in the Southeast record a simultaneous transition, in the opposite direction, between 10,000 and 8000 cal yr BP. Most sites there initially record hiatuses, and low water-levels. Only about half of these sites continue to record a hiatus at 9000 cal yr BP, and by 8000 cal yr BP, all but two sites record lacustrine sedimentation. Data from the Southeast, therefore, indicate a shift from dry to relatively moist conditions between 10,000 and 8000 cal yr BP when Midwestern sites record a change from moist to dry conditions. In both regions, the amount of change decreased significantly after 8000 cal yr BP.

In the Northeast, the data also indicate a shift from dry to moist conditions. However, the sites in the Northeast record low lake-levels persisting from before 10,000 until 9000 cal yr BP. Significant change occurs only by 8000 cal yr BP, when most of the multi-core sites record intermediate water-levels and the number of hiatuses significantly decreased. Some remaining hiatuses correspond with the intermediate water-levels recorded in the multi-core records and indicate that conditions, while wetter than earlier, remain drier than modern. In Virginia, the period of low-water levels recorded at Browns Pond (Kneller and Peteet, 1993) corresponds well with hiatuses at two nearby sites and also indicates that moisture-levels increased around 8000 cal yr BP.

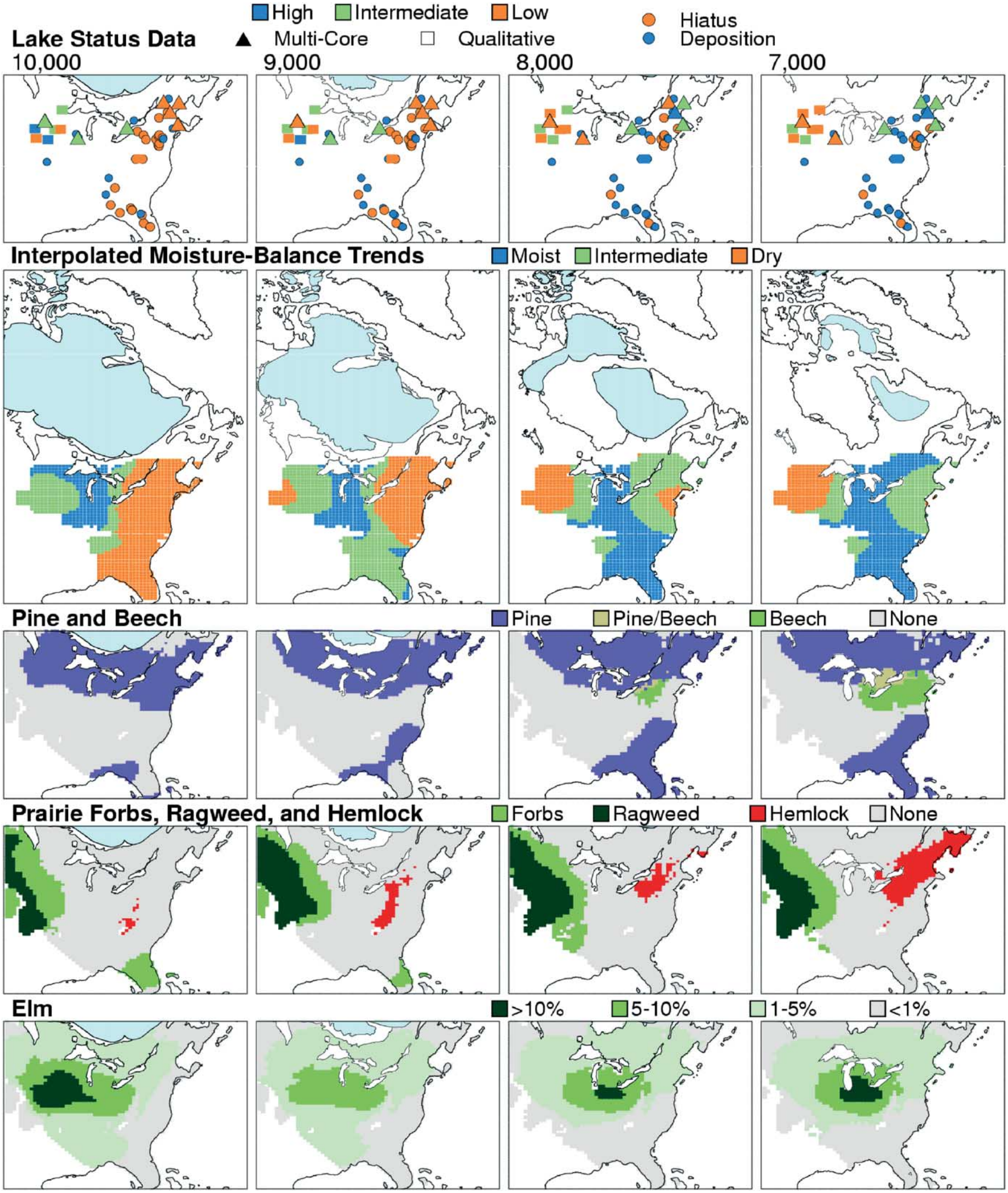

Fig. 2. Maps contrasting 10,000 and 9000 cal yr BP against 8000 and 7000 cal yr BP illustrate changing moisture-balance patterns and vegetation distributions as the LIS collapsed. The uppermost panel shows three types of lake-level data: multi-core, multi-proxy studies like Digerfeldt et al. (1992), qualitative assessments of lake-level indicators following Harrison (1989), and hiatuses in published pollen stratigraphies. The second panel shows the general trends in moisture-balance according to a locally weighted interpolation of the lake-level data. Two lower panels show parallel changes in the extent of regions with >25% pine (*Pinus*), 5% beech (*Fagus*), 15% prairie forb (Asteraceae, Chenopodiaceae/Amaranthanceae, and *Artemisa*), 10% ragweed (*Ambrosia*), and 10% hemlock (*Tsuga*) pollen. Four levels of elm (*Ulmus*) pollen percentages are mapped in the lowest panel.

4. Comparison with isopol maps

During the early Holocene, vegetation also appears to have undergone a significant reorganization coinciding with the collapse of the LIS by 8000 cal yr BP. The mapped patterns of the pollen data from 10,000 to 9000 cal yr BP differ sharply from those for 8000–7000 cal yr BP (Fig. 2). Progressive changes did, however, influence the patterns between 10,000 and 9000 cal yr BP, as the ice sheet decreased in size. The changes differ between the Midwest and Southeast, but changes begin in both regions by 9000 cal yr BP and become intensified by 8000 cal yr BP (Fig. 2). Immediately downstream of the ice sheet, in the Northeast, however, the most dramatic changes occur between 9000 and 8000 cal yr BP, when the Hudson Bay dome collapsed (Fig. 2).

In the Midwest, lake-levels decreased ca 9000 cal yr BP (Winkler et al., 1986; Digerfeldt et al., 1992), when pollen data indicate that the prairie/forest ecotone shifted to the east (Fig. 2). The increase in the abundance and areal extent of drought-tolerant ragweed pollen and that of the other prairie forbs fit with the interpretation of drier conditions from the lake-levels. Elm pollen percentages, which had been high from 11,000 to 10,000 cal yr BP, decreased until the prairie expanded further to the east ca 8000 cal yr BP (Webb et al., 1983). Elm pollen then became more abundant again, although to the east of where it had previously been abundant (Fig. 2). Ragweed pollen percentages also increased by 8000 cal yr BP and remained abundant across the Midwest until after ca 7000 cal yr BP, when lake-level data indicate a renewed increase in moisture (Digerfeldt et al., 1992).

Around 9000 cal yr BP, pollen and lake-level data also record parallel changes in the Southeast. At this time, pollen from the southern species of pine increased to $>25\%$. The increase in pine populations corresponds with the onset of lacustrine sedimentation at a large number of hiatus sites, indicating raised lake-levels across the region (Fig. 2). By the time drying intensified in the Midwest, ca 8000 cal yr BP, nearly all southern hiatus sites began to record lacustrine sedimentation and pine pollen percentages had increased to $>25\%$ across Florida and the Carolinas.

Low lake-levels prevailed in the Northeast from ca 11,000–8200 cal yr BP, and the drier-than-modern conditions favored high abundances of northern pine pollen (Webb et al., 1993; Newby et al., 2000; Shuman, 2001; Shuman et al., 2001). However, by 8000 cal yr BP, pine pollen percentages decreased and lake-levels became higher (Webb et al., 1993; Asnong and Richard, 1998; Newby et al., 2000; Shuman et al., 2001). The shift to moist conditions is supported by an increase in the abundance of pollen from beech and hemlock, which require more moisture and are much less fire tolerant than pine (Fig. 2). Beech occurred at low abundances in the Southeast until the southern pines increased around 9000 cal yr BP (see maps in Webb III et al., 1993), and did not expand significantly to the north until moisture levels increased there around 8000 cal yr BP (Fig. 2). Similarly, hemlock remained most abundant in the relatively moist, upper elevations of the Appalachians until ca 8000 cal yr BP (Fig. 2). Although hemlock populations expanded into the Northeast before beech populations, both underwent a significant expansion and increase in frequency after 8000 cal yr BP.

5. Pollen evidence for the century-scale '8.2 ka event'

A number of pollen records show that the changes around 8200 cal yr BP are associated with brief, century-scale changes in vegetation. In Minnesota, a century-scale peak in ragweed pollen at Kirchner Marsh, just prior to a calibrated radiocarbon date of 7920 (7980–7800) cal yr BP, marks the transition from oak savanna to prairie vegetation (Webb et al., 1983) and a transition to lower water-levels (Harrison, 1989). However, a century-scale event, potentially correlative with the '8.2 ka event' recorded in Greenland ice core records (Alley et al., 1997), is more widely recorded in pollen records from the Northeast. At North Pond, Massachusetts, the pollen stratigraphy from a relatively high-sedimentation-rate core (Whitehead and Crisman, 1978) shows that beech populations became more abundant in New England following an event that significantly reduced hemlock pollen percentages for approximately a century (Fig. 3). A calibrated radiocarbon date places this event just after 8380 (8660–8070) cal yr BP (Whitehead and Crisman, 1978; Stuiver et al., 1998).

Radiocarbon dates and pollen stratigraphies from two lake-level study sites, Makepeace Cedar Swamp (Newby et al., 2000) and Crooked Pond (Shuman et al., 2001) in southeastern Massachusetts, show that the century-scale change in vegetation coincides with (1) the increase in water-levels and (2) a shift to more mesic vegetation at $\sim$8200 cal yr BP (Fig. 4). Newby et al. (2000) interpreted the sharp change from abundant pine to abundant oak pollen at Makepeace Cedar Swamp (Fig. 4b) as indicating a hiatus during extremely dry conditions, but the bracketing radiocarbon dates do not record a gap in sedimentation. The dates indicate that both the regional vegetation and the sediment type changed abruptly at $\sim$8200 cal yr BP. The change coincides with the final peak in pine pollen percentages that lasted from $\sim$8400 to 8000 cal yr BP, which probably correlates with the North Atlantic climatic oscillation. The century-scale change in the pollen record from the Makepeace swamp reflects the expansion of cold-tolerant pine populations (*Pinus banksiana*/*P. resinosa*) on relatively clay-rich soils (Newby et al.,

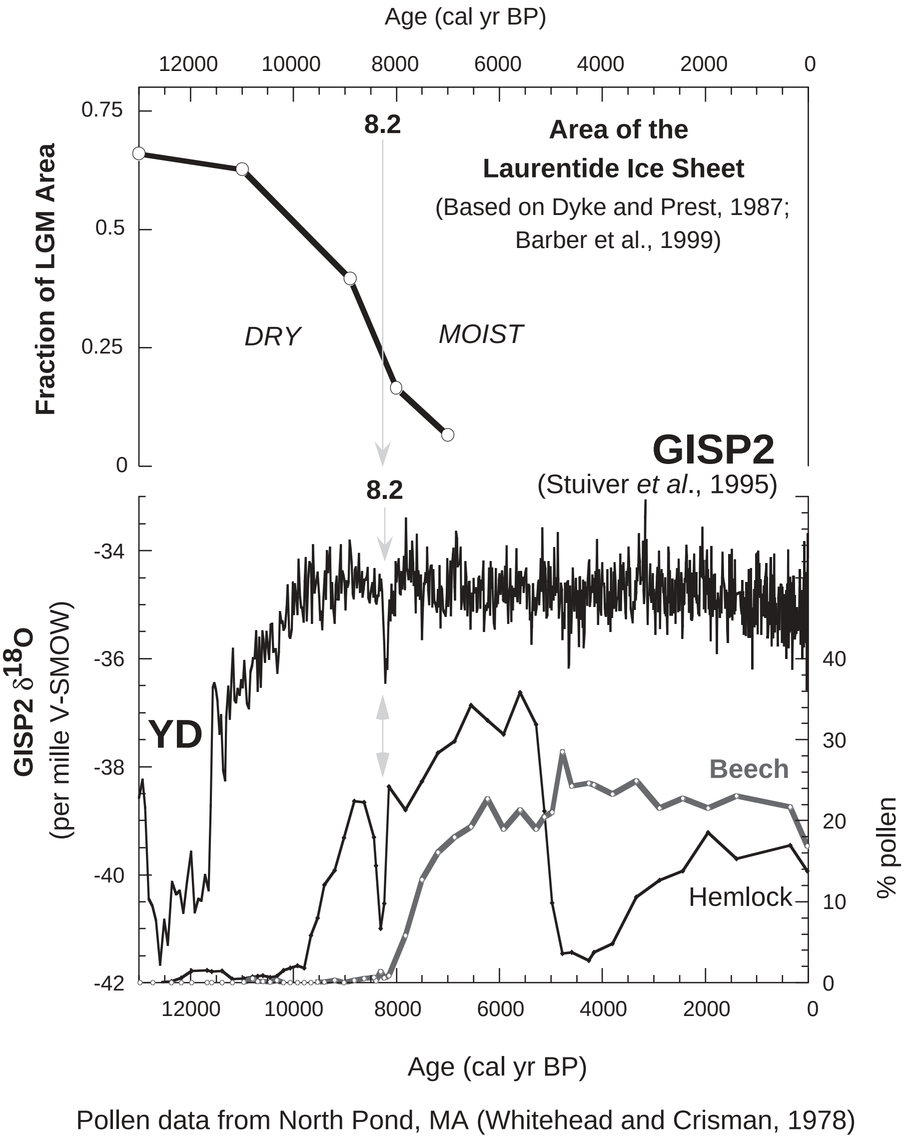

Fig. 3. Fossil pollen percentages of hemlock (*Tsuga*) and beech (*Fagus*) at North Pond, Massachusetts (Whitehead and Crisman, 1978), plotted versus calendar years along with the oxygen isotope record from GISP2 (Stuiver et al., 1995) and the area of the LIS over time, estimated from Dyke and Prest (1987) and Barber et al. (1999).

2000). By contrast, on sandy, well-drained soils at Crooked Pond (Fig. 4a), a century-scale decline in relatively warm-tolerant white pine (*Pinus strobus*) populations correlates with the climatic oscillation (Shuman et al., 2001). A short-lived increase in alder (*Alnus*) pollen percentages follows immediately after the event at both sites, but the coinciding transition led to oak-dominated forests on clay-rich soils (Fig. 4b) and a mixture of pine and oak on sandy soils (Fig. 4a). Limited beech populations then also appeared near both sites.

Pollen data from additional sites also corroborate the widespread expansion of mesic taxa after a short-lived, century-scale vegetation phase around 8200 cal yr BP. A zone of abundant spruce (*Picea*) and fir (*Abies*), before the expansion of birch (*Betula*) at Observation Peatland in Quebec, dates from ca 8240-7960 cal yr BP (Lavoie and Filion, 2001). In Maine, short-lived increases in pine populations at Unknown Pond (Mott, 1977) and birch populations at Mansell Pond (Almquist-Jacobson and Sanger, 1995) both occur just before the regional expansion of hemlock populations around 8200 cal yr BP. Further south, at Tannersville Bog in Pennsylvania (Watts, 1979), a small birch peak coincides with the expansion of beech and alder populations there. Many other sites presumably lack the temporal-resolution to capture the century-scale change in vegetation.

6. Discussion

6.1. Vegetation response to moisture-balance change

As illustrated by Webb et al. (1993), Webb III et al. (1993), and Thompson et al. (1999), plant taxa differ in their moisture tolerances. Beech and hemlock populations are abundant in relatively moist areas, and prairie forbs are abundant under extremely dry conditions. Ragweed is particularly representative of droughty conditions. High ragweed pollen percentages correspond with low levels of soil moisture that cannot sustain tree populations; ragweed populations depend upon summer precipitation that may not significantly recharge dry soils because summer evaporation and transpiration rates are high (Grimm and Clark, 1999; Grimm, 2002). Pine populations are frequent in cool, dry climates in the north, and warm, moist climates to the south (Webb III et al., 1993; Thompson et al., 1999). Given these modern climatic preferences among taxa, the parallel patterns in the pollen and lake-level data indicate that the vegetation has responded to changes in moisture-balance over time, in ways that would be expected.

Pollen and lake-level data show that after 9000–8000 cal yr BP, when the drier-than-previous conditions triggered the eastward expansion of the prairie forbs (Bartlein et al., 1984; Winkler et al., 1986), simultaneous changes also occurred in the Southeast and Northeast. In the Southeast, the increase in southern pine populations around 9000 cal yr BP has been interpreted to represent increased moisture availability (Webb III et al., 1993). Here, the end of numerous hiatuses by around 9000 cal yr BP supports this interpretation. Rising sea level may have played a role in raising water tables in Florida (Watts and Stuiver, 1980; Watts et al., 1992), but across the wider region, the simultaneous increases in lake levels and southern pine populations indicate that an increase in available moisture after 9000 cal yr BP was the major control. In the northeast United States, when lake-levels increased about 8000 cal yr BP, mesic beech and hemlock populations replaced dry-tolerant northern pine populations there, also indicating greater moisture availability.

Moisture-balance trends inferred from the pollen data match those exhibited by the lake-level data. Therefore, the parallel between the two datasets confirms the robustness of the inferred climatic trends, and lends support for the idea that both sense moisture-balance well. In terms of the processes involved, the parallel between the two datasets then confirms the strong climatic control of vegetation history. Vegetation appears to be in dynamic equilibrium with moisture-balance on at least the millennial-scale (Webb, 1986). Changes in temperature probably parallel the inferred moisture-balance changes, but clearly the association shown here indicates that changing moisture-balance regimes can have a significant impact of regional vegetation.

6.2. Climatic impact of the collapse of the Hudson Bay ice dome

Long-term progressive trends recorded by lake-level data and fossil pollen data are consistent with the overall reduction of the LIS since the last glacial maximum (Harrison, 1989; Prentice et al., 1991; Webb III et al., 1993). Here, we confirm that the data also reflect changes driven by millennial-scale ice-sheet dynamics. The data show relatively rapid changes that are simultaneous across eastern North America. The final collapse of the Hudson Bay dome of the LIS by 8000 cal yr BP (Barber et al., 1999) decreased the albedo of a large portion of boreal North America, and intensified the influence of excess summer insolation (Berger, 1978). Additionally, as the ice sheet and its associated anticyclone waned, the influence of the Bermuda subtropical high increased (COHMAP, 1988; Bartlein et al., 1998). Together these phenomena resulted in coordinated regional climate changes across the different portions of eastern North America.

The intensified influences of insolation and the Bermuda subtropical high triggered the onset of the summer monsoon in the Southeast by increasing the ocean-continent temperature contrast and by drawing more subtropical air into the eastern United States. As a result, lake levels increased and southern pine populations expanded (Fig. 2). In the Midwest, climate changed in the opposite direction. Increased aridity lowered lake levels and expanded the prairie (Fig. 2), indicating that the newly developed conditions prevented the monsoonal circulation from increasing moisture availability in the mid-continent. Potentially, changes in the position of the subtropical high were important, because as noted by Forman et al. (1995), drought conditions exist in the mid-continent today when the subtropical high is located further to the north and east, with a strong ridge developed over the central United States. However, expanded ragweed populations (precipitation- rather than soil-moisture dependent) may indicate that subtropical moisture reached the Midwest during the summers after 9000 cal yr BP; reduced winter precipitation may have decreased soil moisture, causing the prairie-forest boundary to shift eastward (Grimm, 2002).

The onset of these changes in the Southeast and Midwest by 9000 cal yr BP may reflect an initial change in the ice sheet at that time. The hydrogen isotope stratigraphy of Austin Lake in southern Michigan (Kristamurthy et al., 1995) records a related, positive shift around 8900 cal yr BP. The positive shift may represent a change in atmospheric circulation after

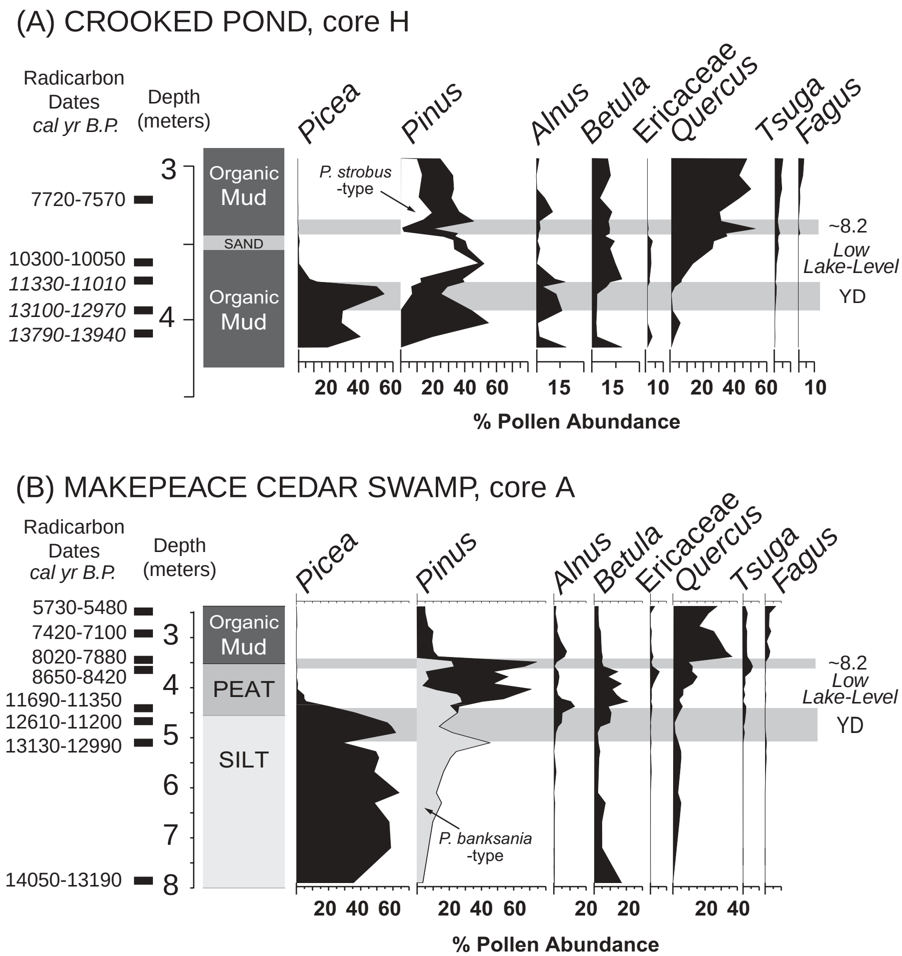

Fig. 4. Fossil pollen percentages of spruce (*Picea*), pine (*Pinus*), alder (*Alnus*), birch (*Betula*), heaths (Ericaceae), oak (*Quercus*), hemlock (*Tsuga*), and beech (*Fagus*) at Crooked Pond (Shuman et al., in press) and Makepeace Cedar Swamp, Massachusetts (Newby et al., 2000), with lithostratigraphy and calibrated radiocarbon ages (Stuiver et al., 1998) for each core. Ages given for Crooked Pond, core H, are based on dates from cores D and K (italics; Shuman et al., 2001). Grey bands mark the Younger Dryas chronozone (YD, 12,900–11,600 cal yr BP) and the century-scale event around 8200 cal yr BP ($\sim$8.2). The estimated low lake-levels at both sites between these two periods are based on data from transects of cores (Newby et al., 2000; Shuman et al., 2001), including shallow-water lithostratigraphic facies (sand and peat) shown here.

8900 cal yr BP, which allowed a greater fraction of moisture derived from the Gulf of Mexico to reach southern Michigan. Potentially, the elevation of the ice sheet decreased significantly around 8900 cal yr BP, weakening its influence even before the final collapse ca 8200 cal yr BP. Climate model experiments suggest that such a change in the elevation of the ice sheet would also cool the northern mid-continent (Felzer et al., 1996; Hostetler et al., 1999). The reduction in the regional frequency of warm-tolerant elm populations around 9000 cal yr BP (Fig. 2e) fits with this possibility. A negative shift in oxygen isotope data from Deep Lake, Minnesota, similarly indicates cooling around 8900 cal yr BP, and that cool conditions prevailed until 8200 cal yr BP (Hu et al., 1999). These examples reflect different local expressions of broad-scale climate changes as the ice sheet waned. Together, however, they may be indicative of abrupt changes in atmospheric circulation driven by an initial decline in ice elevation ca 8900 cal yr BP.

In the northeastern United States and adjacent Canada, nearer to the ice sheet, moisture levels increased more abruptly around 8200 cal yr BP when the influence of the glacial-anticyclone diminished. Prior to the collapse, the glacial anticyclone strongly controlled circulation patterns over the Northeast, preventing meridional flow of moisture (COHMAP, 1988; Webb III et al., 1993, 1998; Bartlein et al., 1998). When the ice dome collapsed, the glacial anticyclone waned, and the change allowed increased moisture availability by increasing northward advection of subtropical moisture. The subtropical high may have been both more intense than earlier and shifted further to the north and east than before. Possibly then, the increased influence of the subtropical high brought more moisture to the region, causing lake-levels to rise and pine populations to be replaced by those of beech and hemlock (Fig. 2; Shuman et al., 2001). Additionally, maximum aridity in the Northeast prior to 8000 cal yr BP corresponded with the maximum August and September insolation anomaly, with seasonal dry conditions in late summer amplified by the excess radiation. The insolation anomaly progressively declined when the ice sheet collapsed, and both factors contributed to wetter conditions in the Northeast.

The records from North Pond, (Fig. 3; Whitehead and Crisman, 1978), Crooked Pond (Fig. 4a; Shuman et al., 2001), and Makepeace Cedar Swamp (Fig. 4b; Newby et al., 2000) indicate that the increase in moisture-availability in the Northeast followed the century-scale climatic event recorded in the Greenland ice cores around 8,200 cal yr BP (Alley et al., 1997). The collapse of the ice sheet caused the release of meltwater into the North Atlantic, decreasing THC, and causing regional cooling from about 8400 to 8000 cal yr BP (Alley et al., 1997; Barber et al., 1999). Because the sites in southeastern Massachusetts record vegetation responses to THC changes during the Younger Dryas chronozone (Fig. 4), they were most likely also sensitive to similar changes in North Atlantic sea-surface temperatures around 8200 cal yr BP.

After this short-lived event, a new climatic regime developed (Figs. 2–4), allowing beech populations to expand into New England, where lake levels rose. As noted by Felzer et al. (1996), global circulation patterns depend on the area of the ice sheet more than on the elevation. The collapse of the Hudson Bay ice dome around 8200 cal yr BP would then have had a more pronounced impact on the climate system than previous changes. For that reason, 8200 cal yr BP may represent a time of transition in many paleoclimate records worldwide (Alley et al., 1997; Stager and Mayewski, 1997).

7. Conclusions

The collapse of the LIS by 8200 cal yr BP (Barber et al., 1999) coincided with a major reorganization of North American climates, consistent with the step-like switch from an ice-sheet-and-insolation-dominated climate to a climate influenced primarily by insolation. The dramatic change in climatic boundary conditions impacted the strength and position of the subtropical high, and as a result, the intensity of mid-continent aridity and the Southeastern monsoon. Because of the atmospheric circulation changes, different regions responded to the collapse of the LIS in different ways. The related period of cooler-than-previous conditions in the North Atlantic region ('The 8.2 ka Event'; Stuiver et al., 1995; Hughen et al., 1996; Barber et al., 1999) was an indirect effect of the LIS collapse. Although synchronous with the broader climatic shift, it was probably an independent regional consequence of the release of meltwater into the North Atlantic, which caused a shift in THC and, consequently, a regional temperature oscillation. In the North Atlantic region, which is sensitive to THC changes, the '8.2 ka event' was pronounced, whereas in other regions, the step-like transition in atmospheric circulation patterns was more prominent.

Parallels between lake-level and pollen data during the early Holocene show (1) that vegetation closely tracks climate on the millennial-scale, and (2) that vegetation responds to moisture-balance, as well as temperature change. Additionally, the pollen records of the '8.2 ka event' show that vegetation can potentially respond to both factors on the scale of centuries or less. By using lake-level and pollen data together as two independent records of climate, climatic patterns can be well documented and understood.

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