Widespread evidence of 1500 yr climate variability in North America during the past 14 000 yr

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ABSTRACT

There is debate concerning the spatial extent and magnitude of the recently identified 1500 yr climate oscillation. Existing evidence is largely restricted to the North Atlantic and adjacent landmasses. The spatial extent, magnitude, and effects of these climate variations within the terrestrial environment during the Holocene have not been established. We show that millennial-scale climate variability caused changes in vegetation communities across all of North America with a periodicity of 1650 ± 500 yr during the past 14 000 calendar years (cal yr). Times of major transitions identified in pollen records occurred at 600, 1650, 2850, 4030, 6700, 8100, 10 190, 12 900, and 13 800 cal yr B.P., consistent with ice and marine records. We suggest that North Atlantic millennial-scale climate variability is associated with rearrangements of the atmospheric circulation with far-reaching influences on the climate.

Keywords: paleoclimatology, Holocene, Quaternary, pollen diagrams, radiocarbon dating.

INTRODUCTION

Evidence from marine and ice-core records suggests a persistent North Atlantic millennial-scale climate oscillation operating for the past 1 m.y. with a 1500 ± 500 yr quasiperiodic cycle, independent of the glacial-interglacial cycles (McManus et al., 1999; Raymo et al., 1998; Oppo et al., 1998). Rapid environmental changes occurred during the Wisconsinan, most likely associated with changes in ocean-circulation patterns and large outflows of icebergs in the North Atlantic region (Dansgaard et al., 1993; Bond et al., 1992; Bond and Lotti, 1995; Grimm et al., 1993; Guiot et al., 1993). Evidence for millennial-scale Holocene climate variability was first observed in the 1800s, when alternating climate periods were interpreted from peat bogs of northern Europe. This variability became established as the Blytt-Sernander zonation (Flint, 1971). Synchronous advances of North American and European alpine glaciers during the Holocene also suggested millennial-scale climate variations (Denton and Karlén, 1973), although this interpretation was questioned (Grove, 1979). More recent measurements from soluble impurities in Greenland ice (O'Brien et al., 1995), and marine sediments (Bianchi and McCave, 1999; Bond et al., 1997, 2001), show similar Holocene millennial-scale climate shifts in the North Atlantic region that are also most likely due to reorganizations of the atmosphere-ocean system (Bianchi and McCave, 1999; Bond et al., 1997, 2001). We here show that Holocene millennial-scale events are found in the terrestrial pollen record and are widespread throughout North America.

Pollen diagrams, depicting percentages as a function of time, record times of environmental change. One approach to identify times of change was proposed by Wendland and Bryson (1974), who analyzed terrestrial records of botanical and archaeological change to search for climate transitions in the Holocene. They assumed that climate changes are abrupt step functions causing discontinuities within sedimentary pollen and archaeological sequences and further that paleoecologists preferentially date these biostratigraphic changes. They used the frequency distribution of 855 ^{14}C dates and the method of partial collectives to identify relative peaks in the multimodal distribution of these records (Johnson, 1966; Bryson, 1966), finding these modes consistent with the Blytt-Sernander framework.

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METHODS

We analyzed a set of 3076 ^{14}C dates obtained from the North American Pollen Database (Grimm, 2000) used to date sequences in more than 700 pollen diagrams from across North America. We analyzed only ^{14}C dates from pollen diagrams because these are transitions in a proxy with similar lag times to climate changes.

A sedimentary sequence undergoing palynological analysis typically has radiocarbon dates obtained at the base and at significant discontinuities. Spatially widespread synchronous discontinuities should therefore correspond to major climate changes. These would be identified as modes within the multimodal frequency distribution of all radiocarbon dates with normally distributed variation.

Clustering of ^{14}C dates around specific events from the sequences was solved using a nonlinear mixture modeling approach (Titterington et al., 1985). Normal curves were fitted to the multimodal distribution of all ^{14}C dates using statistical analysis software. Basal, cultural impact (<150 yr B.P.) and dates older than 12 000 ^{14}C yr B.P. were excluded, leaving 2372 ^{14}C dates. The model was based on the expectation-maximization algorithms (Newton-Raphson algorithm). For n distributions the model contains $3n$ parameters: the expected value μ_i, the standard deviation σ_i, and the posterior probability of the distribution p_i, for $i = 1...n$, where p_i must sum to unity. At optimal solution, the log-likelihood ratio curve flattens out, yielding the optimal number of components or modes (Fig. 1B). A standard deviation constraint was implemented to avoid extremely spread distributions but was optimized to ensure that upper bounds were not too tight, which would lead to nonoptimal solutions. We ran several versions of the algorithm, in which the upper bound of the standard deviations varied between 500 and 1500 yr (Fig. 1C).

RESULTS

Statistical Analysis

The optimal solution found nine modes representing times when many pollen diagrams across North America recorded synchronous vegetation changes (Fig. 1A). The dates chosen by the model exhibit, when converted to calendar years, a periodicity of roughly 1650 yr (Table 1).

We needed to ascertain that these events were really associated with transitions in pollen sequences. First, we scoured the literature and examined the pollen diagrams associated with the identified modes and confirmed that typically dates corresponded to changes in the pollen assemblages. Another issue was that each ^{14}C date has an associated standard deviation, and we required robust results in the presence

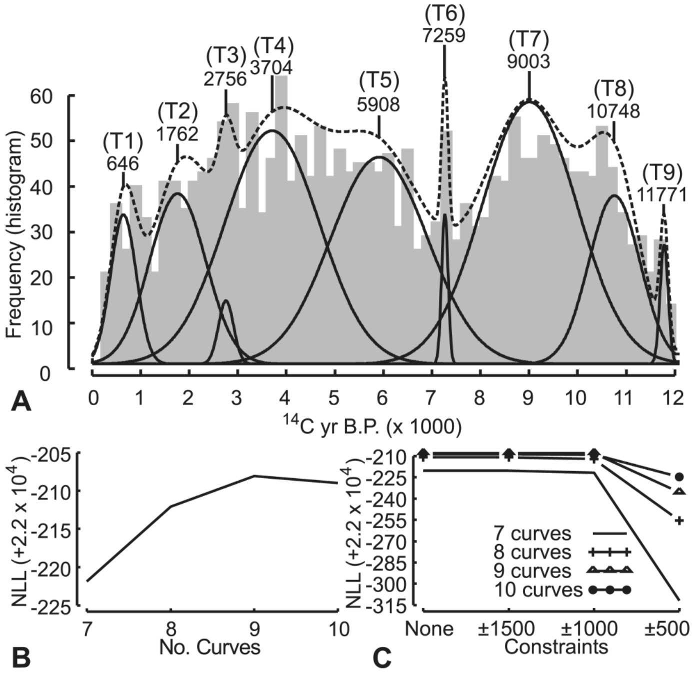

Figure 1. Model output results and sensitivity analysis.

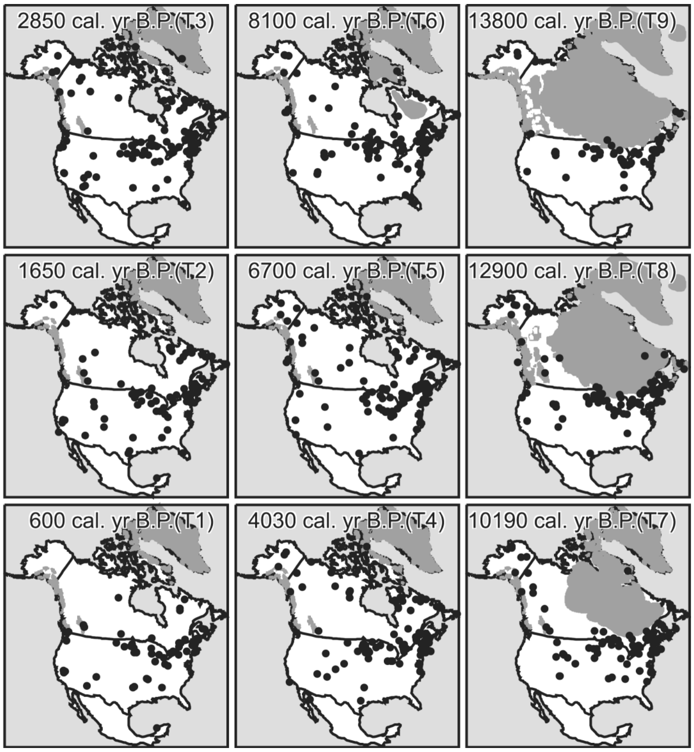

Figure 2. Site distributions for synchronous times of environmental change identified in this study. Site locations containing dated transitions (±200 yr) identified in this study were extracted from North American Pollen Database (Grimm, 2000). Ice-sheet contours were obtained from Dyke and Prest (1987).

of this imprecision. Reanalysis with each date randomly perturbed by plus or minus one standard deviation (uniformly distributed in that interval) led to discrepancies caused only by extremely high standard deviations on a few dates. This approach, along with a variable bandwidth classification scheme, was enough to ensure consistency with the original analyses (Table 1).

Our null hypothesis is that randomly distributed dates throughout the study interval can account for the original distribution of dates. This was tested using a Monte Carlo approach to determine if the distribution of dates could be reproduced by chance alone. Results under randomization (100 times) show that the original distribution of dates cannot be reproduced by chance alone (99%). In addition, the original distribution of dates showed 7 significant modes but a mean of 3.8 under randomization (98%).

To depict the spatial distribution of each mode, all associated sites ±200 yr were mapped (Fig. 2) and the difference in K functions (Rowlingson and Diggle, 1993) tested to determine whether each mode was a spatially random subset of the heterogeneous population of ^{14}C sites in North America. Results show that only modes T8 and T9 departed (at distances >100 km) and T1 and T4 marginally departed from spatially random subsamples.

We conclude that the original dates are not randomly distributed through the study interval, but are representative samples of transitions in North American pollen diagrams. Although many of these pollen transitions have been noted in regional summaries (see Bryant and Holloway, 1985), a continental-scale synthesis has not been previously attempted. The transitions identified here are synchronous with events found in ice cores and marine records, further suggesting a large-scale climate cause (Table 2).

Late Glacial

The pollen stratigraphic transition identified at 13 800 cal yr B.P. (T9) correlates with the Older Dryas–Ållerød transition centered ca. 13 500 cal yr B.P. (Anderson, 1997). This abrupt interstadial is associated with vegetation changes in most of Europe and North America (Anderson, 1997) and is clearly evident in marine (Bond et al., 1997) and Greenland ice cores (Dansgaard et al., 1993). The 12 900 cal yr B.P. mode (T8) coincides with the transition between the Ållerød and Younger Dryas (Alley et al., 1993; Johnsen et al., 1992) when there is considerable evidence of a temperature decline in western Europe (Anderson, 1997) and northeastern North America (Cwynar et al., 1994). Previous syntheses and model simulations suggested that the Ållerød and Younger Dryas events were restricted to the North Atlantic (Manabe and Stouffer, 1995). Although the site distribution associated with

TABLE 1. MODEL OUTPUT RESULTS

Components	Original	STD	Class	STD	Perturb	STD	Difference
T1	647	264	647	263	649	275	2
T2	1763	578	1688	506	1840	604	152
T3	2757	156	2679	302	2757	158	77
T4	3705	971	3764	853	3741	734	59
T5	5908	1000	5845	1000	5731	1000	178
T6	7259	66	7260	72	7278	105	19
T7	9003	978	9019	994	8973	974	47
T8	10 749	527	10 775	525	10 643	482	132
T9	11 771	83	11 778	87	11 596	243	182

Note: Dates are presented in radiocarbon years. STD is standard deviation.

TABLE 2. MILLENNIAL-SCALE CLIMATE TRANSITIONS FOR THE HOLOCENE AND LATE GLACIAL IDENTIFIED IN SEVERAL STUDIES

Period*	Terrestrial							Marine**	GISP2††	Significant discontinuities	
	Botanical This study		Alpine glaciers†		Botanical§		Regional syntheses#			Date	Diff.
					Major	Minor					
LIA maximum			330				300	300			
Pacific	(T1)	600			730		700		600	650	
neo-Atlantic				Exp				1400			
Scandic	(T2)	1650		Con	1550		1600		1500	1550	900
sub-Atlantic	(T3)	2850	2800	Exp	2780		2600	2800	2750	2800	1250
sub-Boreal 1	(T4)	4030		Con		4000	4000	4200		4050	1250
sub-Boreal			5300	Exp	5900	5000	5500	5900	5550	5500	1450
Atlantic 2	(T5)	6700		Con		6850			6300	6600	1100
Atlantic 1	(T6)	8100	7800	Exp		8100	7500	8100	8100	8100	1500
Atlantic					9500			9400	9300	9400	1300
Boreal	(T7)	10 190	10 300		10 450		10 000	10 300	10 600	10 300	900
pre-Boreal				Con	11 500		11 500	11 100	11 300	11 300	1000
Younger-Dryas	(T8)	12 900	12 800	Exp	12 800		12 800	12 600		12 800	1500
Ållerød	(T9)	13 800		Con						13 800	1000
Late Glacial				Exp							

Note: Radiocarbon dates were calibrated to calendar years using INTCAL98 Calib 4.2 software (Stuiver and Reimer, 1993).
*Blytt-Sernander names assigned to these periods following Wendland and Bryson (1974). GISP2—Greenland Ice Sheet Project 2; LIA—Little Ice Age.
†From Denton and Karlén (1973).
§From Wendland and Bryson (1974).
#From Bryant and Holloway (1985).
**From Bond et al. (1997, 2001).
††From O'Brien et al. (1995).

these two modes shows vegetation transitions from all parts of North America (Fig. 2), our spatial analysis shows a tendency toward an eastern North American bias. Although our analysis does not provide an interpretation of the direction of the changes associated with each of these climate transitions (e.g., cooling, warming), it indicates that the vegetation changed at these times across all of North America, and this is true of the other transitions presented here.

Holocene

Transition 7 is dated as 10 190 cal yr B.P., and marks the beginning of the Holocene. One transition of particular interest is centered at 8100 cal yr B.P. (T6) and correlates with the 8200 yr B.P. cold event evident in the marine record (Bond et al., 1997, 2001) and Greenland Ice Sheet Project 2 (GISP2) ice core (Alley et al., 1997). In our analysis, this transition shows up as a distinct mode with little variation around the estimated mean (Table 1). Although data from the ice core suggest a time span of only 400 yr with only half the magnitude of the Younger Dryas to Holocene transition (Alley et al., 1997), our results suggest that this climate event induced changes in vegetation across North America (Fig. 2), supporting the hypothesis that this 8200 yr B.P. event was sufficient in magnitude to have had at least a hemispheric if not global impact (Alley et al., 1997).

The middle Holocene mode (T5) is particularly broad, even though constrained by the analysis. This climate transition has been identified globally (Steig, 1999) and in midwestern North America is a transition toward a warm and dry climate (Winkler et al., 1986). One reason for the large standard deviation is that analysts have historically tried to fit postglacial pollen diagrams into a three-part climate scheme and therefore dated the beginning and end of the Hypsithermal Period, ignoring the variability within this period. In addition, the scale interaction of the millennial-scale events with the lower frequency Milankovitch forcing may mean that climate changes were more subdued during this time (Fisher, 1982; Gajewski, 1987). In general, the intervals between modal means in the middle Holocene are longer and less consistent between different proxies, some lasting more than 2000 yr (Table 2). During glacial times, some Dansgaard-Oeschger events (D/O) lasted from centuries to millennia (Dansgaard et al., 1993), and the marine record also shows fewer ice-rafting debris events in the middle Holocene (Bond et al., 1997).

T4 is centered at 4030 cal yr B.P., consistent with the beginning of neoglaciation in the Northern Hemisphere (Denton and Karlén, 1973; Wendland and Bryson, 1974). This widespread transition is identified in pollen data from most parts of the world (Bryant and Holloway, 1985; Denton and Karlén, 1973; Wendland and Bryson, 1974; Harvey, 1979). It is associated with an ice-rafting debris event in the North Atlantic (Table 2) and represents a cooling following decreasing insolation in the Northern Hemisphere (Kutzbach, 1981). The next two modes at 2850 (T3) and 1650 cal yr B.P. (T2) are geographically widespread in North America (Fig. 2) and are found in different proxies (Table 2). These represent transitions toward cooler climatic conditions (Denton and Karlén, 1973; Bryant and Holloway, 1985; Harvey, 1979) ca. 2800 yr B.P., followed by a climate amelioration ca. 1600 yr B.P. Evidence of vegetation change during these times has been recorded across North America (Bryant and Holloway, 1985; Harvey, 1979). T2 represents the beginning of a climate amelioration culminating in the maximum warming of the Medieval Warm Period 1000 yr ago (Bryant and Holloway, 1985).

T1, centered at 600 cal yr B.P., is interpreted as yet another reorganization of the atmospheric circulation culminating in the Little Ice Age, with maximum cooling 300 yr ago. The site distribution associated with this event suggests that this transition may have been widespread in North America, although the record becomes somewhat disturbed by human impact at this time (Fig. 2). However, there is clear evidence of vegetation change in North America for this period (Gajewski, 1987; Nichols, 1967).

DISCUSSION AND CONCLUSIONS

This study presents a robust analysis demonstrating continental-scale synchronicity of the 1500 yr cycle with marine and ice-core records. Furthermore, this result is based on hundreds of sites and thousands of radiocarbon dates, thus ensuring better dating of these events than previously possible. Because these climate changes are more extensive than previously identified, our results will be essential to climate modelers in determining the appropriate forcing.

Our findings also bring new insight into discussions of climate-vegetation interactions. During the Holocene, millennial-scale variations were sufficient to cause rapid changes in vegetation composition synchronously throughout North America. These vegetation changes are synchronous with transitions in marine and ice-core records, a discovery with significant implications for the long-running debate regarding whether vegetation was in equilibrium with climate changes of the late Quaternary. As such, our results clarify the issue of vegetation response to the rapid global warming predicted for the 21st century. This large-scale synchronicity has implications for interpretation of past vegetation and archaeological records. Our results illustrate large-scale synchronicity of rapid changes between climate regimes in the Holocene and the late glacial, suggesting impacts on societies through the past 10 000 yr.

In summary, the large-scale nature of these transitions and the fact that they are found in different proxies confirms the hypothesis that Holocene and late glacial climate variations of millennial-scale were abrupt transitions between climatic regimes as the atmosphere-ocean system reorganized in response to some forcing. Although several mechanisms for such natural forcing have been advanced, recent evidence points to a potential solar forcing (Bond et al., 2001) associated with ocean-atmosphere feedbacks acting as global teleconnections agents. Because these transitions are identifiable across North America and presumably the world, the spatial-temporal evolution of the climate changes at this scale can be quantified. This exercise can lead to a better understanding of scale interactions within the climate system with implications for global warming scenarios due to human-induced CO_2 greenhouse gas forcing.

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