Databases of ecological and cultural records, especially of pollen diagrams, record climate variability of several time scales during the Holocene and late glacial. Results from lake and wetland ecosystems geographically extend the evidence of rapid climate change obtained from ice cores and ocean sediments. Continental and regional climate curves for North America, based on pollen diagrams from the North American Pollen Database, illustrate abrupt changes on the order of every ~1000 years during the past 12 kyr, and major times of change in North American pollen records are coherent with vegetation changes across Europe. Novel analyses of the database show that even taxa that are widespread and with presumably broad climate tolerances were affected by abrupt climate changes such as the Younger Dryas and illustrate the complexity of ecosystem response to these changes. Reconstructions of freshwater as well as terrestrial ecosystems across northern Canada also show how climate variability affects terrestrial and freshwater ecosystem-level properties such as nutrient cycling. These results can be used to reconstruct the spatial patterns of abrupt climate change, as well as the impacts of climate change on ecosystem and cultures.

1. INTRODUCTION

Although most of the “iconic” paleoclimate time series are from ocean [e.g., Imbrie et al., 1989] or ice cores [e.g., Johnsen et al., 2001; EPICA Members, 2006], a considerable amount of information is known about the terrestrial paleoclimates of the past 21 kyr [e.g., Bryant and Holloway, 1985; Wright et al., 1993]. Evidence from marine and ice cores suggests abrupt climate changes superimposed on the “Milankovitch-scale” variability that occurred throughout the last million years [e.g., Bond et al., 1997, 2001; MacManus et al., 1999; O’Brien et al., 1995; Oppo et al., 1998; Raymo et al., 1998; Bianchi and McCave, 1999; Heinrich, 1988; Dansgaard et al., 1993; Rahmstorf, 2003]. However, one major uncertainty that arises in paleoclimate research is the lack of spatial corroborating evidence. For example, the Greenland ice core records offer a temporal record of past climate variations on several time scales; however, they remain a single point in space until results can be compared to records found in other regions. This lack of the spatial dimension has plagued large-scale paleoclimate research for many years. The last few decades have seen assembled large databases of paleoclimate information. The availability of large databases of pollen, tree ring, and other data enables syntheses of the terrestrial paleoclimate at several time and space scales.

Considerable progress has been achieved in the past 30 years in producing paleoclimate estimates for the postglacial using pollen as a climate proxy for all of North America and Europe. This has come about due to the availability of a critical mass of fossil and calibration data and methodological developments suitable for large-scale reconstructions,
for example, the modern analogue technique (MAT) [Overpeck et al., 1985]. This work has been done in the context of an extensive knowledge of the ecology and biogeography of the principal plant species of the region, which lends theoretical justification to the conclusions.

Records of vegetation change preserved in pollen time series have been used to document climate variability on several time and space scales [Wright et al., 1993]. Studies have shown that vegetation responds rapidly to climate change [e.g., Webb, 1986; Gajewski, 1987], and there is evidence of synchronous vegetation response to abrupt climate changes during the late glacial and glacial period [Grimm and Jacobson, 1991; Shuman et al., 2002a, 2002b; Viau et al., 2002; Williams et al., 2002, 2004; Peros et al., 2008] (see also collection of papers in special section “Vegetation Response to Millennial-scale Variability during the Last Glacial” in Quaternary Science Reviews, 29(21–22), 2010) as well as during the Little Ice Age (LIA) and Medieval Warm Period (MWP) of the past 1000 years [Gajewski, 1987]. The pollen-based paleoclimate reconstructions are beginning to be supplemented by results using other proxy-climate records found as fossils in lake sediments.

In this chapter, we will discuss Holocene climate variability in North America using a spatially extensive pollen database [Grimm, 2010] supplemented with other terrestrial proxy-climate data. Quantitative reconstructions of Holocene climates are made possible due to a large publically available modern pollen database [Whitmore et al., 2005] for quantitative calibration of the fossil paleoecological time series. This research effort provides information of how climate variability affects terrestrial ecosystem structure and function. Although radiocarbon dating of these series is currently a limitation to the resolution that can be obtained, this can be overcome, and high-resolution series of past vegetation and ecosystem dynamics can be obtained.

Using these pollen databases and the modern analogue method, maps have been prepared of the climates of North America at 100 year intervals for the past 12 kyr, and when compared to climate model simulations of 6 kyr, both simulated and reconstructed patterns show important similarities [e.g., Wright et al., 1993; Gajewski et al., 2000; Sawada et al., 2004]. Regional averaging of several pollen sequences is one method to enable high-resolution time series to be obtained [Viau et al., 2006] and is a methodology comparable to the development of tree ring chronologies. Time series of the climate of the Holocene have been developed for North America, Europe, and several regions. Although this chapter will focus on North America, studies have shown that the timing of millennial-scale transitions is coherent in North American and European pollen diagrams, as might be expected [Gajewski et al., 2006]. The pollen-based reconstructions also show coherence with marine and ice core records [Viau et al., 2002, 2006].

Increasingly, studies are using several different proxy-climate indicators in the same core to provide more information about past environments. In cases when different fossil organisms from the same core are used for quantitative paleoclimate reconstructions, the time series based on the different indicators can be compared. Other indicators besides pollen are being used, although these are far from being as well studied or understood. For example, chironomids, the larval form of nonbiting midges (insects) are fossilized in lake sediments and can be identified. Initial work suggested that these organisms provide useful paleoclimate estimates [Batarbee, 2000], and although subsequent work has suggested interpretation may be more subtle [Walker and Gwynar, 2006], several local studies have been accomplished. Other fossils, such as diatoms, record changes in aquatic production and factors such as pH. To the extent that the lake chemical environment is affected by climate, diatoms may therefore be an indirect recorder of past climates, although in practice, it has proven difficult to quantify past changes due to the huge diversity of species and large differences even in neighboring lakes [Bouchard et al., 2004]. Many other fossil groups have been studied, but extensive enough data sets and knowledge are not yet available for their use in other than local studies. Chemical and physical components of the sediment are also widely used as indices of past carbon dynamics and temperature [Willemse and Törnqvist, 1999; Kaufman, 2009; Fortin and Gajewski, 2009]. These are especially useful as they are easy to obtain, and thus, high-temporal-resolution records can be developed.

2. DATA AND METHODS

Pollen data are collected from sedimentary deposits and, over the past few decades, mostly from lake sediments. Cores from the sediments are sampled and pollen extracted from a series of levels. The cores are dated using radiocarbon and other methods such as $^{210}$Pb. A pollen diagram from a sediment core describes the vegetation history of the region, and since plant growth is limited in part by climate, changes in climate can be interpreted. However, pollen data are multivariate time series, and to be useful as paleoclimate indicators, they must be transformed, using some kind of transfer function, to climate series in the units of degrees Celsius or millimeters precipitation.

2.1. The North American Pollen Database

Continental-scale maps and time series of Holocene climate are made possible due to the availability of databases of
accumulated pollen data. The North American Pollen Database (NAPD) [Grimm, 2010] has incorporated pollen diagrams from across North America, with a relatively high density of sites in the northeastern region (Figure 1). Available at the National Climate Data Center (www.ncdc.noaa.gov/paleo), the data are stored in a uniform and accessible format, so queries can extract all the data needed for a particular project. The database is taxonomically complex, so usage is not straightforward; some examples are reviewed in the work of Gajewski [2008].

For quantitative paleoclimate reconstructions, a spatial array of modern pollen samples, along with associated climate data are necessary. Recently, a continental database of modern pollen data has been made publically available in easily accessible form [Whitmore et al., 2005]. This database consists of roughly 4600 sites from across North America, and new data are being periodically added (Figure 1). Analysis of these data illustrates the climatic constraints on the major pollen taxa used in paleoclimate reconstructions [Williams et al., 2006].

The large numbers of sites provides opportunities but also challenges. A dense network of sites across an entire continent provides opportunities for regional and continental maps depicting climates at various times in the past [Wright et al., 1993; Viau et al., 2006]. However, when synthesizing the large numbers of pollen diagrams, each slightly different due to local site conditions or disturbance histories, it is easy to get lost in all of the details. Diagrams from different regions of North America can contain dissimilar pollen taxa, so to determine which changes are caused by climate variations and which by some local factor requires knowledge of the local ecological and biogeographic conditions (see below). Many of these diagrams have few radiocarbon dates and low temporal resolution of samples. The spatial replication of the results nevertheless lends confidence to our conclusions, as inspection and multivariate analysis of many pollen diagrams from a region show similarities between sites, suggesting a climate cause to many of the vegetation transitions [Gajewski, 1987, 1993]. Studies of the transitions show preferred times of transition in pollen data across North America [Viau et al., 2002] and that these are coherent with changes in Europe [Gajewski et al., 2006].

2.2. Data Suitability and Biogeography

At a descriptive level, paleoecologists have been able to make general conclusions about past climate changes using pollen and plant macrofossil data. Indeed, many of the terms used in discussing Holocene climate variability, such as Younger Dryas, Bolling, and Ållerød were originally seen in peat and lake sediments from Scandinavia [Birks and Birks, 1980]. The overall Milankovitch-scale climate variability has been successfully reconstructed using pollen data from several regions of the world and compared to climate model output [Wright et al., 1993; Sawada et al., 2004]. Many issues remain, and research is continuing to develop the data needed for this research effort. There are still large areas with few available fossil or modern data, for example, in desert regions, in very cold regions, and in mountain areas.

One reason for the success in using vegetation and pollen records for paleoclimate work is that the ecological tolerances and biogeography of the major tree taxa is well known. Forestry and ecological data and knowledge, accumulated over a century, have resulted in not only an understanding of the site conditions associated with optimal growth for a species but also in maps depicting the distribution in space of most vascular plants. In Europe and eastern North America, the postglacial migration of the major tree taxa has been mapped [Williams et al., 2004; Huntley and Webb, 1989]. This basic biological knowledge means that the reasonableness of resulting climate reconstructions can be assessed.
A question that has for a long time affected paleoclimate work using pollen data is the ability of vegetation to respond rapidly to abrupt climate changes and, therefore, the ability of pollen records to be used for the study of abrupt climate changes. Since many trees are long-lived, it is argued that vegetation responds very slowly to climate changes with a long lag time [Davis, 1986; Wright, 1976]. However, Webb [1986] and Huntley and Webb [1989] have argued that vegetation changes are in equilibrium with climate changes at the Milankovitch scale [Webb, 1986]. Studies have shown that vegetation responds to perturbation at decadal to millennial scales [Wendland and Bryson, 1974; Gajewski, 1987, 1993, 2008; Grimm and Jacobson, 1991; Shuman et al., 2002a, 2002b; Williams et al., 2002; Jackson and Williams, 2004; Peros et al., 2008], and tree ring and ecological analysis has extensively documented the response of trees to climate variations at annual to multidecadal scales [Intergovernmental Panel on Climate Change, 2007]. In part, the response time depends on the type of vegetation; herbaceous or shrubby vegetation responds more rapidly, and indeed, changes in shrub growth at tree line are being observed in Alaska, presumably in response to global warming [Tape et al., 2006]. However, even in forests, structural changes in the vegetation can occur rapidly, after a fire, for example. In an uneven aged forest, subcanopy trees can quickly start to grow faster following a climatic or local perturbation, causing a change in the relative pollen production of the species in the forest. Finally, it is important to note that the fossil indicator used in sediments is pollen and not plants [Webb and Bryson, 1972]. Changes in pollen production of different plant taxa can respond rapidly following rapid climatic transitions (see below) and can be registered in sediment with a high enough sedimentation rate. Thus, abrupt changes can be interpreted from pollen records [Gajewski, 1987, 1993; Shuman et al., 2002b; Gajewski et al., 2007].

Another concern when using pollen records is the potential importance of human impact on the landscape, especially as it may influence paleoclimate reconstructions. If human activities, such as agriculture or urbanization affect the landscape, this may make paleoclimate impacts more difficult to discern. Ruddiman [2003] has recently argued that human activities have had a significant impact on atmospheric composition, suggesting such a large human impact on the global landscape that it should be discernible in pollen records. In Europe, palynologists have identified the impact of human activities on the landscape during the past several millennia, and these impacts are so extensive that much of the subcontinent is considered a “cultural landscape.” However, millennial-scale climate changes still impacted the vegetation, as shown by the coherence of major transitions in pollen diagrams with those occurring in North America [Gajewski et al., 2006]. Although the impact of European settlement on the vegetation of North America is well known, that of Native Americans is under debate. Several local studies have shown indications of Native American agriculture in pollen records from eastern North America, and using pollen and archaeological databases, Munoz and Gajewski [2010, and references therein] showed this at a regional scale. There is ongoing research into these questions, as geographers, archaeologists, and paleobotanists continue to debate questions such as the size of Native American populations and their impact on the vegetation. But it seems that climate change impacts on the vegetation can still be identified in spite of human impacts on the landscape.

Among other aspects of the paleoenvironmental record that are not well understood include the importance of CO₂ fertilization on plant production and biodiversity, where it has been suggested that this may contribute to the so-called “nonanalogue” communities of the full glacial [Cowling and Sykes, 1999; Williams et al., 2000]. Nonanalogue conditions during the late glacial, when CO₂ reached preindustrial levels, are also not entirely explained, although Northern Hemisphere summer insolation changes may be at cause [Webb, 1986; Williams and Jackson, 2007]. In addition, the impact of changes in seasonality on plants and vegetation needs further study, and there appears to be a fundamental difficulty in reconstructing seasonal climates using the MAT [Viau et al., 2008]. At the moment, these effects seem to be secondary and the broad-scale reconstructions are in general agreement with independent proxy records.

3. RECORDS OF ABRUPT CLIMATE CHANGE IN NORTH AMERICA DURING THE HOLOCENE

3.1. Regional Holocene Climate Reconstructions

In North America, the most studied area is the deciduous forest region of eastern North America. Owing in large part to the concentration of data from the region, a long research program has shown conclusively the importance of climate change in affecting the vegetation of the region [e.g., Bernabo and Webb, 1977; Webb, 1986; Williams et al., 2004]. This work has provided key data supporting the importance of Milankovitch-scale climate variations in affecting the climate [COHMAP Members, 1988; Wright et al., 1993]. More recent work has illustrated the importance of abrupt climate changes [Gajewski, 1987; Shuman et al., 2002a, 2002b] on vegetation composition.

In areas with less dense site networks, however, many sites are being studied at high temporal resolution and are showing abrupt climate changes. As an example of a recent multiproxy synthesis from one site in the Canadian Arctic, Lake
KR02 from western Victoria Island, Northwest Territories, Canada, provides a high temporal resolution, multiproxy record of rapid environmental change during the past 10 kyr (Figure 2). Pollen, chironomid, diatom, and sediment parameters were analyzed in the same core [Podrutschke and Gajewski, 2007; Peros and Gajewski, 2008; Fortin and Gajewski, 2010b]. Quantitative estimates of July temperature were developed from the pollen and chironomid records using different methods (transfer function and MAT) for both proxy-climate series, and lake water pH changes through the Holocene could be estimated using biogenic Si and organic matter content of the sediment [Fortin and Gajewski, 2009].

Results show abrupt changes in July temperatures throughout the Holocene, which can be related to independent records of climate variability such as from the Agassiz Ice Cap ice melt record [Fisher et al., 1995]. Interestingly, estimates of both terrestrial primary and aquatic secondary production (pollen and chironomid influx) are also comparable and show a highly productive ecosystem in the early Holocene, with a decrease in aquatic and terrestrial biological production associated with a cooling over the past several thousand years. The general form of these production records from Lake KR02 parallels the ice melt record from the Agassiz Ice Cap, suggesting aquatic and terrestrial production, as well as ice melt on glaciers are related to summer conditions. The millennial-scale climate changes also affected the lake water pH, although interpretation of this curve is complicated by dissolution of the diatoms. Similar results were obtained in another multiproxy record from nearby Melville Island [Peros et al., 2010] and north central Victoria Island [Fortin and Gajewski, 2010a]. Apart from the long-term changes during the Holocene, which clearly indicate a warm early Holocene and cooling in the past millennia [Kaufman et al., 2004; Gajewski and Atkinson, 2003], more rapid changes are coherent across the Canadian Arctic and with records such as Greenland and Ellesmere Island ice cores [Alley, 2004; Fisher et al., 1995] (Figure 2). Thus, a regional picture is emerging from the Canadian Arctic, where abrupt climate changes seen in records from elsewhere also impacted the ecosystems of the region during the Holocene.

![Figure 2](image-url)
Recently, paleoclimate reconstructions using pollen data quantified Holocene climate variability on several timescales across the Canadian Boreal and Alaskan regions [Viau and Gajewski, 2009; Viau et al., 2008]. Regional reconstruction of the past 12,000 years show a time-transgressive pattern of climate change on orbital scales where eastern Canada was relatively cool compared to western Canada and Alaska during the early Holocene due to the remnants of the Laurentide Ice Sheet in the east [Viau and Gajewski, 2009]. A similar time-transgressive pattern is seen at the millennial scale. Results for the past 2 kyr identified multicentennial-scale climate variability (i.e., MWP and LIA) across the boreal region [Viau and Gajewski, 2009], which shows that even relatively brief climate variations cause rapid responses in regional pollen production and vegetation patterns [Gajewski, 1987; Gajewski et al., 2007; Williams et al., 2002].

3.2. Continental Paleoclimate Records of Abrupt Climate Changes

Peros et al. [2008] illustrated the impacts of rapid climate change, especially during the Younger Dryas, on the populations of poplar (Populus) across North America. They found that poplar pollen increased at both the beginning and end of the Younger Dryas. At the beginning of the Younger Dryas, spruce (Picea) pollen decreased in many sites across North America, whereas poplar increased in abundance, probably as the forest opened in many areas, and poplar could tolerate the conditions that were too cold for spruce. Today, poplar is found at or near tree line and forms tree line in a few small areas of North America. Because it is a pioneer species, it could quickly invade the landscape as conditions ameliorated. During the entire period, alder (Alnus) pollen changed little.

Figure 3. Mean July temperature anomaly for North America estimated using the MAT and the pollen data shown in Figure 1. (a) Mean July temperature anomalies for the past 14 kyr. (b) As in Figure 3a, detrended using 10th-order polynomial. (c) Band-pass-filtered curve of Figure 3b. (d) Curve from Figure 3a with x axis expanded. Gray lines are confidence limits, and gray shading shows general subdivisions of the curve for the Holocene. After the work of Viau et al. [2006].
Alder is abundant in the forest-tundra, and thus can probably tolerate more cold conditions than spruce or poplar. However, this example also illustrates another aspect to be considered when interpreting pollen records. Just before 9 ka, poplar populations decreased in abundance and remained low for the remainder of the Holocene, until the European disturbance of the past 400 years. In this case, it was suggested that competition from other trees may have been responsible for the decrease. Analyses such as these indicate the rapid response of tree populations to climate changes. Although the changes may be complex and not always intuitive, they provide good examples of the rapid nature of climate transitions, as well as the response.

Viau et al. [2006] estimated the climate of North America during the past 14 kyr using over 750 pollen records that comprised over 30,000 samples dated by approximately 2500 radiocarbon dates extracted from the NAPD from across North America. After the July temperature was estimated using the MAT for each pollen sample, data were interpolated to uniform time intervals, and a mean temperature curve for North America was computed. This continental-scale reconstruction quantified temperature variations of several timescales during the past 14 kyr (Figure 3). Temperatures increased during the late glacial, and maximum Holocene temperatures occurred between 6000 and 3000 cal years B.P. in North America. Millennial-scale temperature variations, with a range of ±0.2°C and separated by abrupt transitions, are superimposed on the Milankovitch-scale variability. The dominant frequency of the July temperature variability is ~1100 years (as opposed to the ~1500 year cycle found during the last glacial period), with abrupt transitions between climate states. In addition, there was a scale interaction, with the millennial-scale variability being more pronounced during both the late glacial warming and the late Holocene cooling. A comparable study was performed using European pollen data [Davis et al., 2003].

In a related study, Gajewski et al., [2006] showed synchronous abrupt vegetation transitions during the Holocene between both North American and European continents. In this study, two independent data sets from Europe were used to test the robustness of the results. Major vegetation transitions averaging ~1100 years intervals between both continents during the Holocene were also found to be synchronous with North Atlantic ice-rafted detritus (IRD) events [Bond et al., 2001].

### 3.3. Relating Terrestrial to Ice Core and Marine Records

Studies of pollen in marine cores [e.g., Heusser and Morley, 1985; Lezine and Dene, 1997] have been used for large-scale paleoclimate reconstructions. Comparison of pollen records from lakes in Labrador and Quebec with pollen and dinoflagellate records in offshore marine cores showed broad-scale coherence [Sawada et al., 1999]. Pollen have been studied in ice cores [Bourgeois et al., 2000], permitting a direct comparison of the ice core record with vegetation change. Indeed, a high-resolution study of seasonal ice layers in the Agassiz ice core has shown that pollen are transported to the ice cap in the same season as they are liberated and thus faithfully record the phenology of the major plant groups [Bourgeois, 2001; Gajewski, 2006]. Studies such as this can be used to directly relate climate variability reconstructed from terrestrial and marine or ice caps, as the pollen are a common proxy found in all systems.

When well-dated records of abrupt changes in the past are available, they can be compared and lend insight into potential climate forcing mechanisms. A spectral analysis of the reconstruction of Viau et al. [2006] found a major peak around 1100 years (Table 1). A similar peak has been identified in several studies, including the Greenland Ice Core Project $18^O$ record during the Holocene [Schulz and Paul, 2002], North Atlantic IRD records [Bond et al., 2001] and North Atlantic circulation patterns [Chapman and Shackleton, 2000], among others. A similar periodicity was identified in high-resolution records from central United States [Overpeck, 1987], Scotland [Langdon et al., 2003], and Alaska [Hu et al., 2003]. Bond et al. [2001] have shown a cross-spectral coherence of their IRD record with cosmogenic nuclide records ($^{14}C$ and $^{10}Be$, proxies for solar variability), at the 900 to 1100 year frequency bands for the Holocene.

### Table 1. Dominant Peaks in Spectral Analyses of Several Time Series From the North Atlantic Region and North America

<table>
<thead>
<tr>
<th>Reference</th>
<th>Periodicities</th>
<th>$10^2$ Time Scale</th>
<th>$10^3$ Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-spectral ice-rafted detritus $(IRD)^{14}C$ [Bond et al., 2001]</td>
<td>400–500</td>
<td>900–1100</td>
<td></td>
</tr>
<tr>
<td>Cross-spectral IRD/$^{10}Be$ [Bond et al., 2001]</td>
<td>400–500</td>
<td>900–1100</td>
<td></td>
</tr>
<tr>
<td>North Atlantic IRD</td>
<td>~1350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRIP/GISP2 $^{18}O$ [Schulz and Paul, 2002]</td>
<td>550</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>THC/NADW $^{13}C$ [Chapman and Shackleton, 2000]</td>
<td>550</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>North America [Viau et al., 2006]</td>
<td>1150</td>
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<td></td>
</tr>
<tr>
<td>Subarctic Alaska [Hu et al., 2003]</td>
<td>950</td>
<td></td>
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<tr>
<td>Midwest United States [Overpeck, 1987]</td>
<td>1100</td>
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<tr>
<td>Southeast Scotland [Langdon et al., 2003]</td>
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Comparisons in the frequency domain provide a useful strategy for analyzing possible causes of the variability at any time scale; however, there is interest in direct comparison of individual transitions to determine leads and lags in the climate system as well as to describe the nature of the transition (Figure 4). Comparing the various series, there are similarities but also differences among them, and it is difficult to propose an overall spatial model of Holocene climate variability using these data. For example, the North American mean July temperature anomaly, Santa Barbara, and West African marine records all show major changes at around 8, 6, and 3.2 ka, but these transitions are not as clear in the other records. Higher-frequency changes are not always coherent. This is due in part to the low density of sites with high enough temporal resolution and also due to issues with dating the sediments. As noted by Viau et al. [2006] and Gajewski et al. [2007], “wiggle-matching” series from across large distances can lead to difficulties. In any geophysical series, any individual climate transition may be missing, due to local factors such as sedimentation hiatus or simply a lack of local response to the climate forcing. Therefore, oscillations may appear shorter or longer in some records but not even be seen in others, and this may explain, in part, the differences between records. The interactions between slow variations and more abrupt changes further complicates the interpretation of Holocene climate records, especially during the mid-Holocene, when scale interactions between the orbital and suborbital scales seems to have reduced the millennial-scale climate variability [Fisher, 1982; Gajewski, 1983]. An individual paleoclimate series records only the regional climate, but it is the spatial pattern of climate that is the response to forcing [Gajewski, 1987; Viau et al., 2006], and a sufficiently dense series of sites is needed to understand changes in the general circulation.

**Figure 4.** Several high-resolution paleoclimate series from North America and adjacent regions: (a) North Atlantic benthic $\delta^{13}C$ [Oppo et al., 2003]; (b) “stacked” record of hematite-stained glass, an ice-rafted detritus record from Bond et al. [2001]; (c) $\delta^{18}O$ record from the GISP2 ice core, Greenland [Alley et al., 1997]; (d) $\delta^{18}O$ record from the Agassiz Ice Cap, Ellesmere Island [Fisher et al., 1995]; (e) mean July temperature for North America, reconstructed using pollen data [Viau et al., 2006]; (f) $\delta^{18}O$ for the Santa Barbara Basin [Fridell et al., 2003]; and (g) warm season sea surface temperatures off the West African coast [deMenocal et al., 2000]. Shading delimits the four major periods in the North American pollen-based July temperature anomaly reconstruction.
4. DISCUSSION

Results such as those presented by Viau et al. [2006] show that the climate was continually changing during the Holocene, at many timescales. Many of the “events” identified in some records are part of a continuous series of rapid climate changes, including variations such as the Younger Dryas and the latest of which are the MWP and LIA. For example, the Holocene in North America can be divided into four general periods, with abrupt transitions at ~8, 6, and 3 ka (Figure 4). The millennial-scale variability, with a prominent spectral peak at ~1000 ± 100 years (Table 1), varies as a function of these periods of time and shows increased variability during the early Holocene and the past 3 kyr. Transitions between these periods are abrupt in many cases. The LIA, for example, is part of a continual series of events during the Holocene and is especially prominent due to the scale interaction with the slower Milankovitch-forced variability. Rapid events identified in some series, such as the 4.2 or 5.2 “events” are part of this continual variability.

These results suggest that the “relative climate stability” supposedly seen in records such as the Greenland ice cores during the Holocene is overstated, and although the variability during interglacial periods is less than that during glacial regimes, it remains significant and large enough to be of relevance to human activities. The fundamental causes of this variability are not entirely explained; however, the evidence suggests that rapid climate change may be related to the interactions of changes in incoming solar radiation and other forcing and may be amplified through internal feedback mechanisms.

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REFERENCES


Overpeck, J. T. (1987), Pollen time series and Holocene climatic variability of the Midwest United States, in *Abrupt Climate


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