Millennial-scale climate variations in the Holocene – the terrestrial record

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Introduction

In this paper, we will discuss our recent work in the Laboratory for Paleoclimatology and Climatology (LPC) at the University of Ottawa (UO) on the question of Holocene climate variability and relate it to work done at University of Wisconsin (UW) Center for Climatic Research (CCR) from the 1960-1980s. This paper is not a comprehensive review of the subject; rather we will discuss our own work and place it in the context of previous studies at CCR and elsewhere.

The impact of the training received at CCR will be apparent throughout this paper, as will be the connection between our present work and the approach used at Wisconsin since the 1960s. We will refer at times to mimeographed notes for the class Meteor/GEG/IES 528 given in the spring of 1977 by J Kutzbach and taken by the first author during his first semester at the University of Wisconsin (Kutzbach, 1977; Figure 1). In the 1970s, paleoclimatology was an obscure field on the fringes of meteorology, archaeology, botany and geology; today climate change is recognized as one of the major environmental issues of our times. Many of the questions raised in Meteor/GEG/IES 528 are still unresolved 25 years later. However, the overall approach to paleoclimatology learned at CCR has served us well, and the success of our research program at the University of Ottawa is a tribute to the interdisciplinary and global approach taught by J Kutzbach to a whole generation of paleoclimatologists.

The nature of Holocene climate variations has been under discussion for well over a century (Sears 1942). Studies of the present-day and fossil distribution of plant remains indicated large-scale changes in their distribution (Gray 1878; Gleason 1922); climate changes were invoked as possible explanations although the complexity of climate change was little understood at that time and concepts of scale were not explicitly considered. Analysis of tree remains in peat deposits (e.g. Vaupell 1857; Geikie 1874), as well as the nature of the peat itself provided evidence of more recent, postglacial climate variations. By the early 20th century, enough data had accumulated that there were debates about alternate interpretations of the fossil data, including the well-known Blytt-Sernander hypothesis, Anderson’s view emphasizing more gradual temperature changes and von Post’s three-part division of the postglacial (Sears 1935). Sears summarized this state of knowledge in several papers (Sears 1935, 1942). The relation of vegetation changes to climate variations was discussed during this period; apparently, Blytt considered climate variations proposed by Croll as a possible cause of these vegetation changes (Sears 1942). Pollen diagrams prepared during this time were undated, and one interpretation was of a concordance between the postglacial climates of North America and Europe (Sears 1932). By the 1950s, when Deevey and Flint (1957) defined the Hypsithermal, the idea of a mid-postglacial optimum had taken hold, however, it was realized that the optimum may have occurred at different times in different regions (Wright 1976). A late Holocene cooling was identified in glacial records (neoglaciation); Porter and Denton (1967) discussed the development of this idea. Similar results were identified in pollen diagrams (Sears 1933). Meanwhile the Blytt-Sernander scheme was being routinely used in Europe (Berglund et al. 1996).

By the 1970s, as the COHMAP project got underway at the UW, two alternate views of postglacial climate change and vegetation response were being discussed, a reflection of the debate that had been ongoing for a century. One view was that climate variations in the Holocene were of minor importance, they occurred slowly and gradually, and that the vegetation responded even more slowly, if at all (e.g., Wright 1976; Davis 1986). The major interpretation of pollen diagrams was of a migration to lands made available as the ice sheets disappeared. As recently as
In the early 1990’s, the 1st IPCC volume adopted this general view (Houghton et al. 1990), although today it is no longer held.

The alternate view, expressed, for example, in Bryson & Wendland (1967) was that climate changes were step functions when the climate system switched from one regime to another. An important part of this model and overall thinking was that climate changes should be global in extent as, for example, the long waves respond to a change in some forcing factor (Kutzbach 1976; Kutzbach notes, Figure 2). When viewed in the context of the general circulation, it is reasonable to have synchronous climate changes that vary in sign in different regions. This had caused considerable confusion in the literature. The more explicit climate model behind this view was one difference with earlier thinking expressed by those attempting, for example, to apply the Blytt-Sernader scheme in areas outside of northern Europe (op cit.). Applying knowledge of the general circulation and climate dynamics to paleoclimatology enabled the transition of the field from a descriptive and historical to a quantitative and experimental science, where model “experiments” could be tested by data, and new field data generated further hypotheses for testing with model experiments.

From UW CCR to UO LPC
Interpreting past climates from pollen records requires an understanding of both the climate system as well as the vegetation system that produced the pollen record. A long discussion of how to interpret pollen records took place during the 1970s and 1980s. A summary of Holocene climates in the mid 1970s (Kutzbach notes, Figure 3) lists one important issue at that time; both time-transgressive and time-stratigraphic changes could be identified. This is a recurring theme in Quaternary paleoecology. An example, from the latitudinal treeline, will illustrate why this discussion occurred.

Treeline is associated with the mean July position of the Arctic Front and is thus a major climatic, as well as biogeographic transition (Bryson 1966). In the 1950s and 1960s a long-term project on the bioclimatology of treeline (e.g. Larsen 1965) included a palynological component (e.g. Nichols 1975). The reconstruction of treeline variations developed during this project is still referred to today. Since the 1980s, however, several major projects have presented treeline reconstructions from different regions of North America (MacDonald and Gajewski 1992; Gajewski and Atkinson 2003), including Alaska (Anderson and Brubaker 1993), the Mackenzie Delta region (Ritchie 1987), central Canada (Moser and MacDonald 1990), northwestern Quebec (Gajewski et al. 1993) and Labrador (Short and Nichols, 1977; Lamb 1985). The spruce (Picea) curves of three pollen diagrams from the tundra, just to the north of treeline, from the Mackenzie Delta, central Canada, and northwestern Quebec show that tree migration north of the present-day position occurred at different times in the different regions (Figure 4; after MacDonald and Gajewski 1992). In northwestern Canada, treeline was farther north than it is today in the early Holocene, in central Canada the northward movement occurred in the mid–Holocene but in northwestern Quebec, treeline was never farther north than today. The movements of treeline were not large – several 10s of km in the northwest and several 100 km in central Canada. This would appear to be a time-transgressive movement of treeline in response to climate change. However, inspection of the spruce curves illustrates that at all three sites, spruce pollen input to these tundra lakes has been decreasing in the past 3000 years and that the movement northward in central Canada occurred at the same time as the southward movement in the Mackenzie Delta. While treeline was further north in central Canada, there were no changes in the pollen diagram from the Mackenzie Delta region northwest, and an increasing trend in northwest Quebec. That
is, when small changes in the relative abundance of spruce pollen are analyzed, they seem to be occurring at the same time at all sites. Although large-scale vegetation (i.e. biome transitions, that is, ecotones) changes appear to be non-synchronous, more subtle changes (i.e. relative abundance of species) are synchronous. Biome-level changes, indicated by the presence or near absence of spruce pollen (actually, it is the presence above a threshold that indicates local presence; in the case of *Picea* this threshold is 20% spruce pollen; Anderson *et al.* 1991) may appear time-transgressive, but the variations in the relative abundance of spruce within its range appears to be synchronous, although not necessarily in the same direction at all sites (increasing or decreasing). Bernabo and Webb (1977) illustrated this way of thinking using data from eastern North America and Gajewski (1983, 1987, 1993) discussed it in more detail.

One interesting aspect of this study is that these sites are all in the tundra, yet it is variations in spruce pollen that are being studied. Thus, the variations illustrated in Figure 4 are in some cases caused by changes in the transport of spruce pollen northward from the forest to lakes in the tundra. This suggests that not only do changes in the abundance of plants cause affect the pollen assemblages deposited in lake sediments, but changes in pollen production or transport in the atmosphere may as well. The implications are that pollen diagrams may record rapid climate changes, as an increase or decrease in pollen productivity could presumably occur more quickly than a replacement of the vegetation. Evidence of such a rapid response is shown in Figure 5, where a high-resolution analysis of several pollen diagrams from treeline in northwestern Québec is presented (Gajewski 2000). In the graphs from the forest-tundra and tundra, a decrease in spruce pollen transport northward is seen during the Little Ice Age. This is all the more remarkable when it is realized that these diagrams are rather poorly dated by only 3-4 radiocarbon dates lower in the sediment core, yet even so the spruce pollen curves from these sites are similar.

There is another example of this phenomenon, in a study accomplished as part of the COHMAP project. The COHMAP projects had several components. The most extensive involved the mapping and analysis of global climates in response to the Milankovitch variations that seem to have caused the overall climate sequence during the Holocene (Wright *et al.* 1993). A second project, directed by Al Swain and involving several people to varying degrees (Gajewski, M. Winkler, G. Peterson, M. Pollack, D. Clark), focused on the past 2000 years (Kutzbach notes, Figure 6). The purpose of this project was to study the late Holocene climate variations in eastern North America, where there was no previous record of climate variations such as the Little Ice Age. This project was based on the analysis of pollen sequences from lakes with varved sediments, permitting a high temporal resolution. Swain discovered a series of lakes with these sediments (Figure 7) through extensive fieldwork over several years, and the pollen were analysed, typically at 40-year intervals. The major conclusions are summarized in Figure 7 (see also Gajewski 1983).

Inspection of the pollen diagram from Basin Pond (Figure 7) shows little variation in the pollen curves, apart from a decrease in beech (*Fagus*) and hemlock (*Tsuga*), and increase in spruce (*Picea*) and pine (*Pinus*) in the past 400 years. This seems to be a response of the vegetation to the Little Ice Age. However, inspection of all of the 6 other pollen diagrams indicated more significant changes. A principal components analysis was used to summarize the variability of all of these sites and showed coherent changes that are in phase and can be interpreted in climatic terms in each region (Figure 7). That is, the relative abundance of several taxa in all pollen diagrams from across this region oscillated in phase, although the individual populations of the different species may have responded differently (i.e. increased in one region but decreased in
another). Several aspects of his study are notable. First, small subtle changes, such as the decease in hemlock and beech and increase in spruce between 1250 and 800 years ago in the Basin Pond pollen diagram are recording climate variations, although if viewed in isolation (and considering all of the errors involved in pollen analysis) this small change would be considered insignificant. Second, the principal component analysis shows that the Little Ice Age was not an isolated climate variation (c.f. Houghton et al. 1990), but that similar magnitude and frequency variability occurred during the past 1500 years and presumably the Holocene. However, the scale interaction with the Holocene Milankovitch climate variations may cause the impact of these centennial and millennial changes to be more or less expressed in any region (Gajewski 1987). Third, this analysis shows that pollen diagrams do record small and relatively rapid climate variations, in spite of modeling studies that suggest that there is a long time lag of the vegetation (Davis and Botkin 1985, Campbell and McAndrews 1993). In the 1970’s, we demonstrated that high-resolution pollen diagrams record rapid climate variations and more recently we, and others, have shown that they can be interpreted from non-varved sediments when these are sampled at high enough intervals (cf Gajewski 1993, Weart 2003).

CSHD: mapping transitions

In the early 1990s, we became involved in the Climate System History and Dynamics Project, headed by R Peltier (U Toronto). This project involved around 10 groups from across Canada, including climate modelers, oceanographers, and terrestrial paleoclimatologists. There were a number of subprojects and themes to this program, and these have evolved through time. One project we were involved in was a PMIP (Paleoclimate Model Inter-comparison Project) contribution comparing the 6ka climate reconstructed using pollen (Gajewski et al. 2000; Sawada et al. 2004) and lake levels (Viau and Gajewski 2001) to climate model output (Gajewski et al. 2000; Sawada et al. 2004). We used data from the Canadian (CPD) and North American (NAPD) Pollen Databases with the modern analogue technique (MAT) to produce maps of July temperatures for North America at 6ka. By the third major iteration (each one using better data and with improvements to the methodology), we realized our maps were looking realistic (Figure 8). We then felt that we could map the climate patterns associated with millennial climate variability in North America.

In the late 1980s and early 1990s, rapid and large climate changes had been identified in Full Glacial sediments from the North Atlantic (Figure 9; Heinrich 1988; Bond et al. 1992). The Greenland ice core also showed evidence of similar variability (Dansgaard et al. 1993). These results convinced many people of the importance of abrupt climate changes (Weart 2003); that is, the climate may change as a step function. Efforts were made to relate these results to climate “episodes” that had been known for many years, such as the Younger Dryas Period (e.g. Wright 1989; Broecker et al. 1988). However, much of this work was done in the North Atlantic region, where large outbreaks of icebergs and pack ice could amplify the actual climate changes. Subsequently, climate variability of this timescale was also identified in postglacial sediments from some ocean cores in the North Atlantic, and it was suggested that Holocene climates varied significantly at a periodicity of roughly 1500 years during both interglacial and glacial times, as well as during the transition between them (Figure 9; Bond et al., 1997, 2001). This has important consequences for the identification of possible causes. The spatial distribution of the changes must be known, and this has occupied many people for the past decade.

In the late 1990s, we decided to tackle the problem of synthesizing the terrestrial pollen record to better understand millennial to century-scale climate variations. One of the first questions was to
understand times of change. When did the climate “flip” from one “state” to another? Note that we assumed from the start that the climate changes were step-wise transitions. Also, we assumed that the lag of vegetation change to these transitions was very short, as discussed above.

The first step was to identify transitions in the pollen diagrams of North America. We recalled the study of Wendland and Bryson (1974), which seemed to offer a relatively simple way to identify transitions, to start to project going. We also investigated this question using more detailed multivariate methods (Viau, 2003), not discussed here.

The methodology is based on three suppositions:
1. Climate changes are step functions (i.e., rapid and abrupt).
2. Vegetation response is rapid at this scale.
3. Palynologists preferentially date transitions (i.e., obvious changes) in pollen diagrams.

Figure 10 illustrates the procedure. Experience suggests that a pollen diagram consists of transitions separating periods of time with lower variability, where the vegetation changes from one community to another. Since only a few radiocarbon dates can be submitted for each diagram (due to cost), palynologists tend to date transitions, to obtain as accurate an estimate of the timing of the change in the pollen assemblages without the problems of interpolation. Therefore, studying populations of radiocarbon dates was a method for studying transitions (Wendland and Bryson 1974).

The procedure was implemented as follows. Although the general approach was from Wendland and Bryson (1974), we developed a new implementation (Viau et al. 2002; Atkinson et al. in prep.):
1. Radiocarbon dates were obtained from the NAPD (Contributors to the North American Pollen Database 2000). A series of queries removed basal and top dates.
2. A series of normal curves are fitted to the data in a two-step procedure, where the means of these normal curves are considered estimates of the transition times. The first step is a cluster analysis that establishes “seeds” for a second step, which fits n distributions to the data using the Newton-Raphson algorithm.
3. The optimal number of curves is identified when the log-likelihood ratio no longer significantly increases.

A similar analysis was performed on two sets of data from Europe (Gajewski et al., subm). Radiocarbon dates obtained from the European Pollen Database (EPD; Contributors to the European Pollen Database, 2000) were analysed in the same way as the North American data. In another analysis, pollen assemblage zone (PAZ) boundaries from Berglund et al (1996) were similarly analysed. In a synthesis of pollen diagrams from the temperate zone of Europe, experts from many countries identified “type” pollen diagrams for many regions of northern Europe, and on each diagram identified zone boundaries based solely on the pollen diagram (pollen assemblage zones; paz). These were not compared nor synthesized between regions in the original publication, however.

The optimal solution shows 9 transitions in North America and 10 or 13 in Europe (Figure 11). These are synchronous across the 2 continents, and also with IRD events in the North Atlantic and with transitions in the Greenland Ice core (Table 1). Indeed, Wendland and Bryson (1974) had earlier found similar transitions.
Secondly, we wanted to know the spatial pattern of temperature (or precipitation) associated with these transitions. If we could identify the spatial patterns of temperature, for example, before and after each transition, we could generate hypotheses about possible causes for these climate transitions (Kutzbach notes, Figure 12). So we used the Modern Analogue Method and produced values of the mean July temperature for every sample in the data file. These were interpolated every 100 years, and maps created at 100-year intervals (several examples are shown in Figure 13; Viau 2003). The idea was that there were several realizations of the climate between each of the transitions, and we could compute the mean climate of the different regimes. However, these have yet not been analyzed, as we got sidetracked, and these new results were interesting enough to demand our attention.

**Terrestrial evidence of millennial-scale climate variations**

The nature of the Little Ice Age is still in question, as it has been for many years (Kutzbach notes, Figure 14). In the late 1990s, several groups computed the mean temperature of the northern hemisphere or globe using proxy records (Mann et al. 1999, Mann and Jones 2003; Jones et al. 2001; Esper et al. 2002; Crowley 2000), to determine how unusual the 20th century was in relation to natural climate variations. We wondered if it would be possible to extend this curve back in time through the Holocene. To quantitatively reconstruct climate through 10,000 years using pollen assemblages for the globe may not be possible at this time, but we wanted to begin the process of assembling the regional curves by at least computing the mean July temperature for North America, that is, a continental-scale response to climate change. So we used the interpolated pollen-based reconstructions described above and computed the mean July temperature of North America of each 100-year period. Results are shown in Figure 15 (Viau et al. subm).

Let’s first zoom in on the past 10,000 years (Figure 16). The mean July temperature of North America in the Holocene can be divided into 4 major periods. The first, from 10000 to 8000 cal yr BP showed rising temperatures. At 8000 yr BP, there was an abrupt change, as the Laurentide Ice Sheet collapsed and its impact on the climate decreased (ie. 8,200 yr BP event). There was a cooling for the next 2000 years, which was followed by an abrupt warming. From 6000 to 3200 yr BP, temperatures increased. Note that the warmest temperatures reconstructed here are just before 3000 cal yr BP and not 6000 cal yr BP. The mean July temperature of North America then abruptly decreased associated with increased temperature variability (Neoglacial). Thus, these results reveal a four-part division of the Holocene: a rapid warming of the early Holocene (10,000-8000 cal. yr. BP), a cooling between 8,000 cal. yr. BP and 6000 cal yr BP, a warmest and least variable middle Holocene, and a late Holocene cooling after 3000 cal yr BP. This four-part division of the Holocene suggests millennial-scale climate variations occurred on average every 2,500 years, comparable to those observed from alpine glacier advances and retreats (Denton and Karlén 1973), dust and sea salt content in the GISP2 record (O’Brien et al. 1995) and the four part division proposed by the Blytt-Sernander climate scheme. Note that in the middle Holocene, the temperature fluctuations were damped, in accordance with previous studies (Overpeck 1987; Grimm and Jacobson 1991, Viau et al., 2002).

Superimposed on these long-term trends is millennial-scale climate variability, which is shown in Figure 17, where the long-term trend has been removed. Here alternating peaks and troughs occur irregularly around every 1100 years. At least 10 transitions can be visually identified during the past 12000 years, although there is some ambiguity in interpretation, as there always is when analyzing real geophysical series. The form of many of these is an abrupt warming followed by a
gradual cooling - a saw-tooth curve. This saw-tooth structure of abrupt climate change appears to be a feature of the climate system response observed in paleoclimate records on orbital to millennial-scales during both glacial and interglacial regimes. Rial (2004) suggests that this is a nonlinear response of the climate system to external forcing and internal instabilities.

We can compare this curve to several others recently derived that purport to show millennial scale climate variations (Figure 18). These include records from ocean (Bond et al. 1997, 2001) and ice cores (O’Brien et al. 1995), as well as an index of the carbon cycle (ie. $^{14}$C; Bond et al., 2001) and cosmogetic nuclide record ($^{10}$Be; Bond et al. 2001). When attempting to “wiggle match” these curves, some coherence is seen, but also differences. The timing of individual millennial-scale cool/warm events between the different records appears to be synchronous for some events (ie. the Little Ice Age), leading or lagging at other times.

A good example of this divergence between the different records occurs during the mid-Holocene (i.e. 8,000 – 5,000 year BP). Although the records virtually all show a distinct set of cooling periods, there appear to be leads and lags between the different records. For example, the IRD record shows an initial cooling lasting 1000 years followed by a second lasting 2000 years. Note the saw tooth structure of the record during this time period. For the Santa Barbara ocean core, the first cooling is more intense and the second less so. In Greenland, the $^{18}$O record doesn’t show much except the 8,200-year BP event, but the $\text{Na}^+$ concentration curve shows only the second cooling, synchronous with the IRD record. In North America, pollen records show a major cool period between around 7000 and 6000 yr BP.

Indeed, this is a characteristic of paleoclimate data. Any individual data series may lack a particular event, lead or lag one another during the mid-Holocene and this may be a function of several factors, including insufficient dating control, some particularity of the sedimentation in that region, or that the climate change was too weak to be recorded in that particular proxy record. It may be that the scale interaction between the Milankovitch-scale variations play a more active role and may reduce/amplify the importance of millennial-scale climate variability during the mid-Holocene when the highest rates of decrease in Northern Hemisphere insolation occurred. In any event, visual inspection of these data series suggests the average pacing of these cooling events is 1500 years.

An alternative approach is to test the coherence between these records in the frequency domain. When spectral analysis (Kutzbach and Bryson 1974) is performed on these series, a different picture emerges. Our North American pollen-derived curve has significant power at a period of around 1150 years. Evidence of a ca 550 and 1,000-year periodicities have been detected in North Atlantic Ocean circulation patterns (NADW) during the Holocene correlated with the $^{14}$C record (Chapman and Shackleton, 2000). A significant ca 1100 and 950 year periodic signal was also found in pollen records from the Midwest of the United States (Overpeck, 1987). Moreover, a ca 900 to 1100-year periodicity was identified in the GRIP $^{18}$O record during the present interglacial (Shulz and Paul, 2002) and last glacial period (Rial, 2004) although not the dominant spectral peak during the glacial. We therefore suggest that the dominant millennial-scale climate frequency in the Holocene is not 1500 years, but rather circa 1,000 ± 100 years.

This circa 1,000 ±100-year periodicity actually matches better with the record of $^{14}$C variations in the atmosphere and $^{10}$Be. Cross-spectral analysis of the North Atlantic IRD marine record and cosmogetic nuclide records ($^{14}$C and $^{10}$Be; proxies for solar variability and ocean ventilation
changes) shows power at 300-500 and 900 to 1100-year frequency bands during the past 12,000 years (Bond et al., 2001). Hughen et al. (2000) suggest that climate variations such as the Younger Dryas are synchronous with atmospheric $^{14}$C changes, interpreted by the authors as ocean circulation changes. This suggests that these climate transitions are associated with major changes in the carbon cycle (Kutzbach notes Figure 19; Stuiver et al. 1995). Therefore it is possible that a weak periodic solar and/or ocean forcing in frequency bands of 300-500 and 900-1100 years may be the dominant forcing during the Holocene when ice-sheets are less significant components of the climate system. The dominant ca 1500-year periodic signal during glacial regimes could have an internal origin and could explain why this periodicity does not show up in the $^{14}$C nor the GISP2 $^{18}$O record of the past 12000 years (Stuiver et al. 1995; Schulz and Paul 2002). Although a ca 1500-year periodic signal has been observed in some marine and terrestrial records (Bianchi and McCave 1999, Hu et al. 2003), we have argued above that individual records may simply be lacking some particular warming or cooling event.

It is critical to understand the leads and lags in the climate system, as well as the spatial patterns of past climates in order to disentangle these potential factors. We are now pursuing this question, by investigating in detail the phasing, timing and spatial patterns of the circa 1,000-yr millennial-scale variability in the Holocene.

Summary and Conclusions
In our work, we are attempting to better understand both the temporal changes in the climate system over the Holocene as well as the spatial expression of these changes within the northern hemisphere. We are now expanding our spatial extent to more global analyses, and our temporal scale to century and decadal. All of these themes were introduced to the primary author during his tenure at Wisconsin. We have shown that pollen data has sufficient temporal resolution to elucidate century to millennial scale climate responses while at the same time allowing us to better understand the spatial extent of these in North American and Europe. We have thus made progress toward understanding rapid climate changes, begun as part of the COHMAP project.

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Figure 1. J.E. Kutzbach class notes for Meteor/GEG/IES 528, spring 1977.
A. Climatic Variations of the Past 100 Years

4. Instrumental records

5. Hemisphere climatic variations

Large-scale mid-latitude wave patterns undergo changes that are often hemispheric in extent. As a result, climatic changes in one region often occur simultaneously with climatic changes in other regions, although the sign of the change may differ from region to region.

Ref: Dickson and Namias, 1976, MWR 104: 1256-1261

(changes in hemispheric patterns 1846-57, 18-69, 20-75)

Ref: Kutzbach, 1970, MWR 98(9): 708-716

(Eigenvectors or modes of winter and summer variability patterns of 1900-1920's; 1920's-1950's; 1950's-1970's; importance of wave number 1, hemispheric asymmetry, especially in winter. Variations of Iceland and Atlantic sector.)

Ref: Van Loon and Williams, 1976, MWR 104(6): 365-376

(Relationship between circulation changes and temperature changes. Most of N.H. change has been in the North Atlantic sector. Warming from before 1900 to 1940's, followed by cooling. Regional changes are far greater than hemispheric average changes.)


(Climate of the 1960's)

Namias, 1968 and Bjerknes, 1968, both in MWR.

(Conflicting ideas about role of oceans in climatic fluctuations.)
6.3 Summary of Holocene climates
- Note that record seems to contain both time-transgressive and time-stratigraphic elements
  Note:
  a) estimates of times of change
  b) advantages of terminology chosen
  c) method of analysis
  d) study Table 3 and 7, prepare “time” diagram and enter major “episodes” along with other evidence of major changes (for example, events described in 6.4 of this outline).
- Additional references:

Figure 3. Kutzbach class notes for Meteor/GEG/IES 528, spring 1977.
Figure 4. *Picea* (spruce) pollen percentage curves from three sites in northern Canada. The sites are all presently in tundra, north of treeline. Dotted line shows 20% spruce pollen, which today indicates regional presence of spruce at regional and continental scales. After MacDonald and Gajewski (1992).
Figure 5. High-resolution analysis of *Picea* (spruce) pollen from four sites in northwestern Québec. Site GB2 is in the boreal forest, Site EC2 is in the forest-tundra, and sites BI2 and LR3 are in the tundra. Location of sites is shown in Figure 7. After Gajewski (2000).
5.5 Annual Laminated Lake Sediment Records


Methodology: Pollen Lab techniques; sampling strategy - COREMAP - transect across N. America established to detect any shifts in long-wave pattern of climate.

Calibration techniques (Level I + Level II)
Ref: Webb and Bryson, 1972, QR 2: 70-115.

Climatic Reconstructions
Swain (in preparation)
Pollack, J. A. (1976), Climatic reconstruction from pollen in annually - laminated lake sediments - an application to a 2040 yr. pollen chronology from N. Wisconsin (UW-Madison M.S. thesis)

Figure 6. Kutzbach class notes for Meteor/GEG/IES 528, spring 1977.
Figure 7. (a) Pollen diagram of Basin Pond, Maine (Gajewski et al. 1987). (b) Location of sites discussed in text. (c) Principal components analysis of 7 pollen diagrams from eastern and Midwestern North America after Gajewski (1983, 1987); pollen data from Swain (1973, 1978) and Gajewski et al. (1985, 1987).
Figure 8. (a) Modern July temperatures based on data at 545 pollen sites. (b) 6 ka July temperatures reconstructed at fossil pollen sites. (c) July temperature anomalies derived from pollen-based estimates. (d) Modeled July temperature anomalies from CCCma AGCM2. After Sawada et al. (2004).
Figure 9. Two records of climate variability from the North Atlantic. (a) Oxygen isotope record from the GISP2 ice core (Grootes and Stuiver, 1997). Data from http://www.ngdc.noaa.gov/paleo/. (b) Ice rafted debris in a core from the North Atlantic (Bond et al., 2001). Data courtesy of Bond.
Figure 10. (a) Pollen diagram from Kirshner March (Wright et al., 1963; data and image from http://www.ngdc.noaa.gov/paleo/) illustrating radiocarbon dates (horizontal lines) located at major transitions. (b) Histogram of the number of radiocarbon dates from the North Atlantic Pollen Database (NAPD: http://www.ngdc.noaa.gov/paleo/) as a function of time.
Figure 11. Frequency histogram or radiocarbon dates and results of mixture model fitting optimal number of normal curves North American and European pollen diagrams (a) Radiocarbon dates from the NAPD (Viau et al. 2002; Contriburors of the North American Pollen Database 2000) and fitted normal curves. (b) Radiocarbon dates from the European Pollen Database (EPD; Contriburors of the European Pollen Database 2000) and fitted normal curves. (b) Pollen assemblage zones boundaries (from Berglund et al. 1996) and fitted normal curves. Radiocarbon dates from http://www.ngdc.noaa.gov/paleo/.
- Vegetation changes as inferred from pollen
  - Note new information being provided by maps of pollen changes rather than individual diagrams for single points.
  - Discussion of northward movement of spruce associated with retreat of ice sheet
  - Discussion of prairie advance (until 7 KYBP) followed by westward retreat
  - Note time-transgressive character, Wright’s article


Figure 13. Maps of July temperature anomaly for North America at 100 year intervals for the time period 3100-4000 cal yr BP (Viau 2003).
ref: LAMB, 1961, On the nature --

An experiment in the systematic treatment of documentary weather records since AD 1100. (Lamb)

1) Summer wetness index (W. & E. Europe)
2) Winter mildness index (W. & E. Europe)

Wet summers = AD 1550-1850
Cold winters = AD 1350-1850 (E. Europe)
               = AD 1550-1850 (W. Europe)

Lamb "defines" Little Ice Age as AD 1430-1850

Many questions remain:

What was the **global** character of this period?
Should it be divided into sub-intervals?
What was the cause?

Lamb also identifies a prior warm period AD 1000-1200.
Needs much more study in other regions, longer records, etc.

Study Fig. 11 and Table 1 of Lamb (1961)
Figure 15. Mean July temperature anomaly for North America based on pollen records (Viau et al. subm). See text for explanation.
Figure 16. Mean July temperature anomaly for North America (Holocene only). After Viau et al. (subm). Four-part division of the Holocene is indicated.
Figure 17. Detrended curve, mean July temperature of North America based on pollen data. After Viau et al. (subm). Four part division of the Holocene is indicated, as well as major warmings (arrows).
Figure 18. Synthesis of several high-resolution proxy-climate records of the Holocene. IRD North Atlantic from Bond et al. (2001), Santa Barbara $^{18}$O from Fridell et al. (2003), GISP2 ionic record after O’Brien et al. (1995), N.A July temperature from Viau et al. (subm). Two records of solar activity and/or changes in the global carbon cycle: tree-ring $^{14}$C record and $^{10}$Be (Bond et al. 2001). Cooling events in the mid-Holocene indicated by arrows. All data except the North Atlantic IRD from the NOAA NGDC (http://www.ngdc.noaa.gov/paleo/); IRD data courtesy of Bond.
Possible causes of climatic fluctuations of past 10-20,000 years
- Actual causes are unknown

Various possibilities:

a) Orbital parameter variations? May have played a role in overall timing of interglacial

b) Volcanic eruptions? Little evidence for or against

c) Solar variability? Denton and Karlén have noted that timing of mountain glacier expansions seem to be related to δC-13 chronology. See also Eddy, 1976, The Haunder Minimum, Science 192: 1189-1202.

d) Internal system adjustments? Adjustments in ice sheet topography and ocean temperature patterns might have led to either gradual or abrupt circulation changes at various times.
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Table 1. Climate transitions identified in several paleoclimate records from the North Atlantic and North American regions. See text for explanation.