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Major Features and Forcing of High-atitude Northern Hemisphere Atmospheric Circulation using a 110,000-year-long Glaciochemical Series

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Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series

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Abstract. The Greenland Ice Sheet Project 2 glaciochemical series (sodium, potassium, ammonium, calcium, magnesium, sulfate, nitrate, and chloride) provides a unique view of the chemistry of the atmosphere and the history of atmospheric circulation over both the high latitudes and mid-low latitudes of the northern hemisphere. Interpretation of this record reveals a diverse array of environmental signatures that include the documentation of anthropogenically derived pollutants, volcanic and biomass burning events, storminess over marine surfaces, continental aridity and biogenic source strength plus information related to the controls on both high- and low-frequency climate events of the last 110,000 years. Climate forcings investigated include changes in insolation of the order of the major orbital cycles that control the long-term behavior of atmospheric circulation patterns through changes in ice volume (sea level), events such as the Heinrich events (massive discharges of icebergs first identified in the marine record) that are found to operate on a 6100-year cycle due largely to the lagged response of ice sheets to changes in insolation and consequent glacier dynamics, and rapid climate change events (massive reorganizations of atmospheric circulation) that are demonstrated to operate on 1450-year cycles. Changes in insolation and associated positive feedbacks related to ice sheets may assist in explaining favorable time periods and controls on the amplitude of massive rapid climate change events. Explanation for the exact timing and global synchroneity of these events is, however, more complicated. Preliminary evidence points to possible solar variability-climate associations for these events and perhaps others that are embedded in our ice-core-derived atmospheric circulation records.

Introduction

Understanding the Earth system and, in particular, its climate, remains one of the major intellectual challenges faced by science. The processes influencing climate, the mechanisms through which they act, and the responses they generate are, in general, as complex and poorly understood as they are important. Because observational records of climate processes span only the most recent years of Earth's history and, in many instances, are known to be markedly affected by anthropogenic influences, paleorecords of past climates are exceedingly important to the development of scientific understanding of local, regional, and global climate systems. Of the various paleorecords available to science, ice cores from polar ice sheets provide the most direct and highest-resolution view of the paleoatmosphere.

On July 1, 1993, the Greenland Ice Sheet Project 2 (GISP2) successfully completed drilling to the base of the Greenland Ice Sheet in central Greenland (Summit site, 72.6°N; 38.5°W; 3200 m above sea level). In so doing, GISP2 recovered a 3053.44-m-deep ice core that penetrated 1.5 m into the underlying bedrock and, along with its European companion project, the Greenland Ice Core Project (GRIP), developed the longest paleoenvironmental record, >250,000 years, available from the northern hemisphere. On the basis of the comparison of electrical conductivity and oxygen isotope series between the two cores [*Grootes et al.*, 1993; *Taylor et al.*, 1993a], at least the upper 90% (~2800 m) displays extremely similar, if not absolutely equiv-

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alent records. The current best estimate of age at this depth is believed to be ~110,000 years. This dating is based on multiparameter annual layer counting down to ~50,000 years [*Alley et al.*, 1993; *Meese et al.*, 1994a, this issue; *Ram and Koenig*, this issue]. Below ~50,000 years, measurements of the $\delta^{18}O$ of atmospheric O_2 calibrated with similar measurements from the Vostok ice core in Antarctica provide a relative chronology back to ~110,000 years [*Bender et al.*, 1994]. Error estimates in the dating used in this paper are 2% for 0-11,640 years ago, 5% for 11,640-17,380 years ago, <10% for 17,380-40,500 years ago, and up to 10% for the remainder of the record [*Alley et al.*, 1993; *Sowers et al.*, 1993; *Meese et al.*, 1994a, b]. Agreement between the GISP2 and GRIP ice cores (separated by 30 km or ~10 ice thicknesses) provides strong support for the climatic origin of even the minor features of the records and implies that investigations of subtle environmental signals (e.g., rapid climate change events with 1- to 2-year onset and termination) can be rigorously pursued.

One of the primary sets of measurements developed from the GISP2 ice core is the glaciochemical record. It has set a new standard for ice-core research by providing a robust measure of change for both the chemistry of the atmosphere and climate [*Mayewski et al.*, 1993a, b, 1994]. The GISP2 glaciochemical record is a highly resolved, continuously sampled time series of the major chemical species found in glacial ice and snow (sodium, potassium, ammonium, calcium, magnesium, sulfate, nitrate, and chloride) that represents over 95% of the soluble ionic species comprising the atmosphere.

The core was sampled at a resolution of 0.6-2.5 years through the Holocene, a mean of 3.48 years through the deglaciation, ~3-116 years throughout the remainder of the 110,000-year-long portion of the record, and at lower resolution over the rest of the core, for a total of 16,395 samples. Concentrations of the eight major ionic species were then determined from each core sample. An additional 4500 blanks and/or replicate samples were also analyzed. Analytical and sample processing techniques have been described in detail elsewhere [e.g., *Mayewski et al.*, 1986, 1987; *Buck et al.*, 1992].

Records of change in atmospheric chemistry developed from ice cores are important for paleoclimatology because the atmosphere responds more quickly than other components of the Earth system and holds within it measures of both the cause(s) of and response(s) to climate change on all timescales. For example, in modern times the polar vortex, a major feature of atmospheric circulation, has been linked through changes in size and shape to variations in northern hemisphere tropospheric temperature and wind [*Nastrom and Belmont*, 1980; *Venne and Dartt*, 1990; *Burnett*, 1993], North Atlantic storm tracks [*Brown and John*, 1979; *Tinsley*, 1988], and solar sunspot cycles [*Labitzke and van Loon*, 1989]. At longer timescales, modeling studies reveal the influence continental ice sheets have had on tropospheric circulation during the last glaciation [*Broccoli and Manabe*, 1987a, b; *Budd and Rayner*, 1990; *Leroux*, 1993]. Thus atmospheric circulation is influenced by factors ranging from the millennial-scale advance and retreat of continental ice sheets to decadal-scale sunspot activity and even shorter-scale (annual and seasonal) climate patterns.

Chemical Species Sources, Input Timing, Accumulation Rate Controls, and Spatial Distribution

The sources of the chemical species deposited in polar snow and ice have been summarized in numerous papers [e.g., *Herron*, 1982; *Lyons and Mayewski*, 1984; *Delmas and Legrand*, 1989; *Shaw*, 1989; *Davidson et al.*, 1992; *Mayewski et al.*, 1992; *Whitlow et al.*, 1992; *Legrand and Mayewski*, 1997]. On the basis of our present knowledge of the chemistry of the atmosphere, polar precipitation is expected to be composed of various soluble and insoluble impurities which are either introduced directly into the atmosphere as primary aerosols, such as sea salt (mainly sodium and chloride and some magnesium, calcium, sulfate, and potassium) and continental dust (magnesium, calcium, carbonate, sulfate, and aluminosilicates), or are produced within the atmosphere along various oxidation pathways involving numerous trace gases primarily derived from the sulfur, nitrogen, halogen, and carbon cycles [e.g., *Crutzen and Bruhl*, 1989]. In the latter case, the secondary aerosols and gases (H^+, ammonium, chloride, nitrate, sulfate, fluoride, $CH_3SO_3^-$, $HCOO^-$, and other organic compounds [*Legrand et al.*, 1993]) are derived from a variety of biogenic and anthropogenic emissions or volcanic activity. Some chemical species have multiple sources. For example, sulfate present in snow can be linked to primary marine sea salt (as Na_2SO_4) or continental dust (as $CaSO_4$). It can also arise due to volcanic eruptions, anthropogenic activity, or atmospheric oxidation of various other S compounds emitted from the biosphere.

Seasonal chronologies developed from a series of snow pits collected in the Summit region and other parts of Greenland [*Mayewski et al.*, 1990a; *Whitlow et al.*, 1992; *Yang et al.*, 1996] were defined by comparing oxygen isotope and chemical species data series. The total beta activity peaks corresponding to inputs from the Chernobyl nuclear accident and earlier nuclear testing served as both an absolute time stratigraphic marker and a check on the oxygen isotope chronology [*Dibb*, 1989]. On the basis of this analysis, chemical species peak concentrations have the following pattern: (1) in midwinter to spring, there are maximum peaks in total chloride (where total equals sea salt plus other sources), sea-salt chloride (derived by comparison with observed sea-salt associations), sodium, sea-salt potassium, calcium, magnesium, total sulfate, sea-salt sulfate, and excess sulfate (greater than the ratio in seawater); (2) in spring to summer, there are maximum peaks in excess chloride and nitrate; and (3) in summer, there is a maximum peak in ammonium. Since maxima for total and excess potassium occur with no apparent regularity during both midwinter and summer, a unique input timing could not be determined. This input timing is similar to that identified by *Langway et al.* [1975] for sodium, magnesium, and calcium in southern and central Greenland; by *Busenberg and Langway* [1979] for ammonium, sulfate, chloride, calcium, and sodium in southern Greenland; and by *Mayewski et al.* [1987] for excess sulfate, nitrate, chloride, and sodium in southern Greenland. Therefore it is assumed that the input timing for chemical species is probably uniform over the entire inland portion of the Greenland Ice Sheet.

The relationship between concentration and flux (concentration times accumulation rate) of chemical species versus snow accumulation rate was investigated at Summit and compared to several other sites throughout Greenland as well as to ice cores in the Yukon Territory and the Indian Himalayas to determine which is a more appropriate measure for investigating glaciochemical time series [*Yang et al.*, 1995; 1996]. At all sites, only nitrate flux and snow accumulation rate had a significant linear relationship. Further, only nitrate concentration data are normally distributed. This suggests that nitrate is affected by postdepositional exchange with the atmosphere over a broad range of environmental conditions [*Yang et al.*, 1995]. In addition, examination of concentration-accumulation rate relationships for the major ions demonstrates that previously studied samples of mixed age and geographic setting were related to geographic setting (as a consequence of air mass trajectories) rather than accumulation rate, further verifying the use of concentration versus flux in the interpretation of glaciochemical series [*Yang et al.*, 1996].

Detailed examination of the last 17,000 years of high-resolution accumulation rate and chemical species concentration series demonstrates that, while major changes in accumulation rate do coincide with major changes in species concentration, the relationship is poorly correlated at sample resolution level. This suggests that accumulation rate and species concentration may be linked in the former case through climate change rather than through accumulation rate controls on concentration [*Meeker et al.*, this issue].

Variations in atmospheric concentration of GISP2 major ions over the period of the last deglaciation have been reconstructed based on simple models that estimate the influence of the two primary types of species deposition (wet and dry). Results of these calculations were validated by comparison with ^{10}Be fluxes (based on established accumulation rate dependence and near constant production rate), demonstrating that chemical concentrations in the GISP2 ice core follow atmospheric fluxes more closely than do chemical fluxes in the ice [*Alley et al.*, 1995]. Previous studies have demonstrated that anthropogenically derived sulfate and nitrate concentrations mirror closely the pattern of source region emission levels [*Mayewski et al.*, 1990b], further verifying the close association between species concentration in ice and that of the atmosphere. Major chemical species sampled from 25 snow pits (maximum time span 1987-1993) covering north, central, and south Greenland suggest that the mean annual concentrations of these species are very similar [*Yang et al.*, 1996].

In summary, glaciochemical series derived from Summit appear to provide a reasonable proxy of the atmospheric concentration history over much of the Greenland Ice Sheet. As will be demonstrated in a later section ("Atmospheric Circulation Derived From Glaciochemical Series"), these glaciochemical series also provide a general history of atmospheric circulation for at least the high latitudes of the northern hemisphere.

Unique Chemical Events

Anthropogenic influences on climate and atmospheric chemistry have been investigated in the GISP2 record. Previously identified increases in sulfate and nitrate seen in south Greenland ice cores attributed to anthropogenic activity [*Neftel et al.*, 1985; *Mayewski et al.*, 1986] have also been identified at GISP2 and contrasted to the pre-anthropogenic atmosphere [*Mayewski et al.*, 1990b]. In addition, increases in excess chloride associated with anthropogenically increased sulfate and nitrate have also been demonstrated [*Mayewski et al.*, 1993a]. Confirmation of the role that anthropogenic sulfate may have on the depression of North Atlantic temperatures has been provided by a comparison of GISP2, south Greenland, and Yukon Territory ice cores with temperature change records [*Mayewski et al.*, 1993c].

Volcanic event signatures have been identified in the GISP2 core by the measurement of electrical conductivity, chemistry, and insoluble particles, providing evidence of local eruptions (e.g., the A.D. 1783 Laki (Iceland) eruption [*Fiacco et al.*, 1996] and the A.D. 1362 Oraefajokull (Iceland) eruption [*Palais et al.*, 1991]), intrahemispheric eruptions (e.g., the A.D. 1479 Mount St. Helen's (Washington) eruption [*Fiacco et al.*, 1993]), and interhemispherically distributed eruptions (e.g., Tambora (A.D. 1815)). The last 300 years of the GISP2 volcanic record has also been compared to volcanic records developed from cores in south Greenland and the Yukon Territory in order to investigate transport of volcanic aerosols [*Mayewski et al.*, 1993c].

A record of volcanism (determined from the GISP2 sulfate series) since 7000 B.C. and its relationship to climate is presented by *Zielinski et al.* [1994]. Recent work has extended this record to the last 110,000 years [*Zielinski et al.*, this issue]. Three times as many volcanic events occur from 5000 to 7000 B.C. as over the last 2000 years. As reported in this study, this increased volcanism may have contributed to volcanic cooling in the early Holocene. The impact of volcanism on climate has also been investigated by *Zielinski et al.* [1995] for the A.D. 1783 Asama (Japan) eruption and the A.D.

934±4 Eldgjá (Iceland) eruption, and by *Chesner et al.* [1991] and *Zielinski et al.* [1996] for the Toba megavolcanic eruption (~73,000±4000 years ago.

Ammonium increases and accompanying enrichment in nitrate and potassium in three ice cores (GISP2, south Greenland, and Yukon Territory) covering the period A.D. 1750 to the 1980s are believed to reflect biomass-burning events [*Whitlow et al.*, 1994]. Independent verification of the ammonium outlier to biomass-burning relationship is provided by *Legrand et al.* [1992] based on fingerprinting using organic acids. Most of the recent era ammonium spikes at GISP2 and south Greenland occur between A.D. 1820 and A.D. 1920 when large, intense fires burned in North America [*Whitlow et al.*, 1994; *Holdsworth et al.*, 1996]. An ~6000-year-long forest fire chronology developed from a combination of electrical conductivity and ammonium measurements from the GISP2 ice core reveals variability in biomass burning originating from eastern Canada that is correlated with drier conditions [*Taylor et al.*, 1996].

Glaciochemical and EOF Analysis Used to Interpret Atmospheric Circulation

The general chemical composition of the atmosphere is a reflection of overall species' source type(s) and source strength(s). The chemical composition of an individual air mass provides a fingerprint that documents the history of the source area over which the transporting air mass passed. Therefore atmospheric circulation systems can be labeled by the identification of the source areas that contribute to their chemistry. In the simplest case, marine versus continental air masses can be differentiated based on the identification of sea salts (e.g., NaCl) versus continental dusts (e.g., $CaSO_4$), respectively, in the chemistry of these air masses. More complex atmospheric circulation patterns can be differentiated by the addition of other tracers such as the presence of specific chemical species indicators that record, for example, continental biogenic inputs (e.g., ammonium) as noted by *Mayewski et al.* [1983] in the Ladakh Himalayas. Since, as noted earlier, the chemical concentrations in GISP2 snow and ice follow atmospheric fluxes [*Mayewski et al.*, 1990b; *Alley et al.*, 1995], the former provide a history of atmospheric circulation.

Examination of the bulk chemistry of the Holocene (11,640 years ago to present) versus pre-Holocene stadials and interstadials reveals that the Holocene atmosphere is generally acidic (H^+ required to balance the excess of anions versus cations measured), while the remainder of the record is alkaline (Plate 1). Further, variability during different climate regimes is primarily accounted for by increases in sodium, magnesium, calcium, chloride, and sulfate (Plate 1). Increases in these species indicate that the atmosphere was more highly charged with a variety of sea salts and terrestrial dusts such as NaCl, Na_2SO_4, $CaSO_4$, $CaCO_3$, and $Ca(Mg,Fe)(CO_3)_2$ plus, undoubtedly, minerals such as silicates which were not examined as part of this study.

Variability is significantly subdued in the Holocene portion of the record relative to the pre-Holocene (Figure 1) for all species except ammonium and nitrate. However, detailed examination of this portion of the series has revealed species signal structure related to a variety of factors, such as changes in source region for some species, biogenic source strength, and atmospheric circulation [*Mayewski et al.*, 1993a; *O'Brien et al.*, 1995]. An example of the latter follows.

Approximately 95% of the Holocene sodium is derived from sea salt, and almost all of the calcium is of continental origin. General intensification of atmospheric circulation occurs in the Arctic during midwinter to spring [*Eriksson*, 1959] when the highest concentrations of sea salt and calcium reach Greenland [*Mayewski et al.*, 1990a]. Moreover, the late winter cyclonic storms traveling over continental North America incorporate crustal dusts and then sea salt as they cross the North Atlantic. Provided that similar conditions generated elevated species concentrations in the past, the terrestrial dust and sea-salt record reveals extended periods of winter-like circulation patterns and storm conditions that recurred with some regularity throughout the Holocene. Increases occur from ~A.D. 1420-1900 and 2400-3100, 5000-6100, 7800-8800, and 11,300-12,900 years ago. *O'Brien et al.* [1995] have correlated these events with previously identified worldwide or Arctic glacier expansions and cool intervals [*Andrews and Ives*, 1972; *Denton and Karlen*, 1973; *Harvey*, 1980]. The most recent increase (A.D. 1410-1420) coincides with the onset of the Little Ice Age. Notably, this event is the most abrupt of any in the GISP2 Holocene chemistry series [*O'Brien et al.*, 1995]. A detailed glaciochemical reconstruction of the environmental conditions during this period is given by *Mayewski et al.* [1993a].

In general, increased levels of terrestrial dusts require one, or a combination of, such factors as increased or new source areas due to enhanced aridity or changes in atmospheric circulation patterns [*Mayewski et al.*, 1994; *O'Brien et al.*, 1995] or enhanced incorporation due to increases in wind strength. Detailed differentiation of these influences is currently being undertaken by investigating species associations versus modern atmospheric circulation patterns (P. Krusic, personal communication, 1996; J. Kahl, personal communication, 1996), ratios of species over time [*O'Brien et al.*, 1995], and paleo-atmospheric circulation patterns using general circulation models (further discussion under "Ice Volume (Sea Level)-Atmospheric Circulation Association" in this paper; M. Prentice et al., manuscript in preparation, 1997).

There appears to be a clear explanation for the increased levels of NaCl observed during pre-Holocene cold periods. First, the ratio of sodium to chloride in the pre-Holocene is extremely close to that of sea

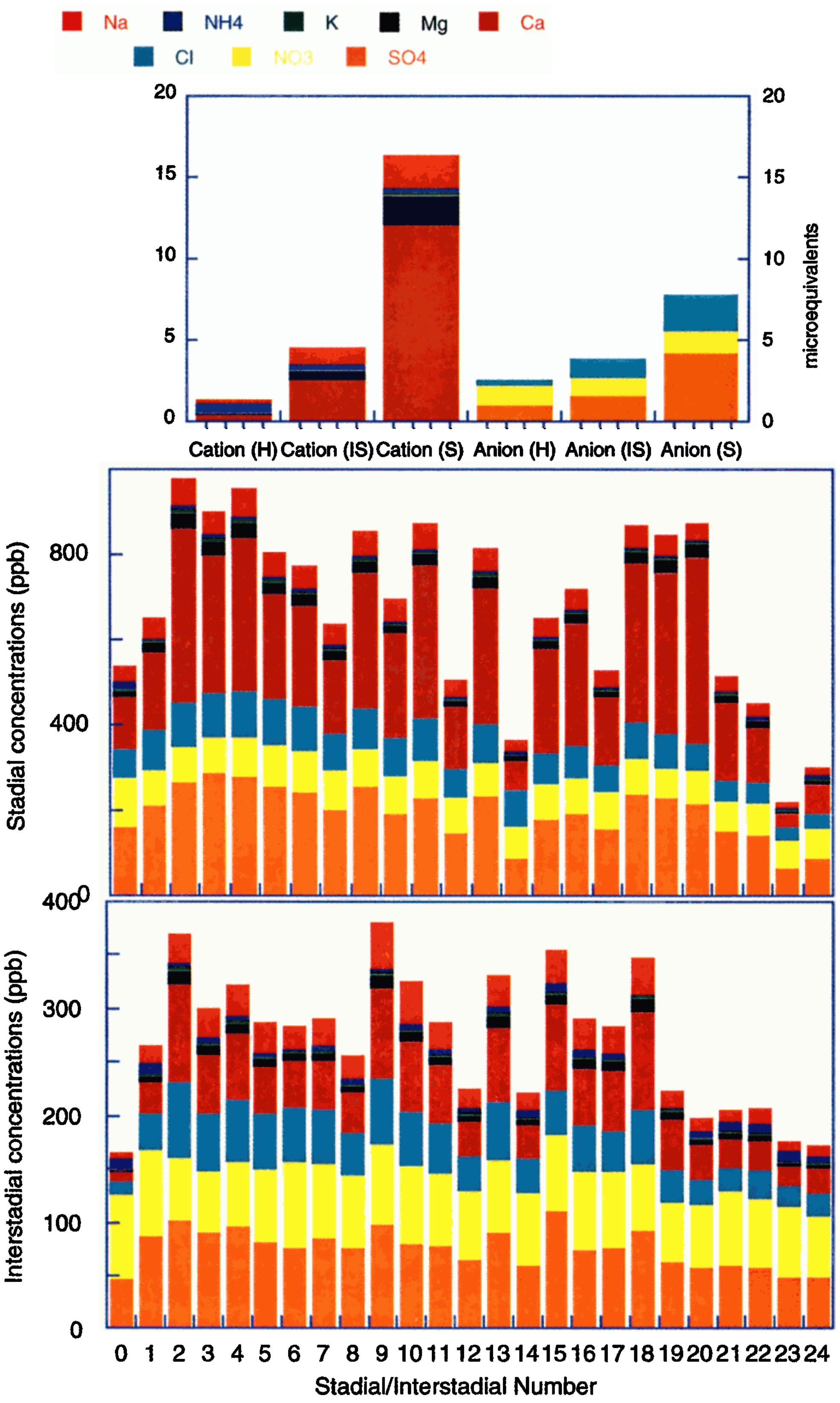

Plate 1. Cation versus anion distribution for major climate intervals (Holocene (H), interstadials (IS), and stadials (s)) (top panel) and for individual interstadials and stadials (bottom two panels).

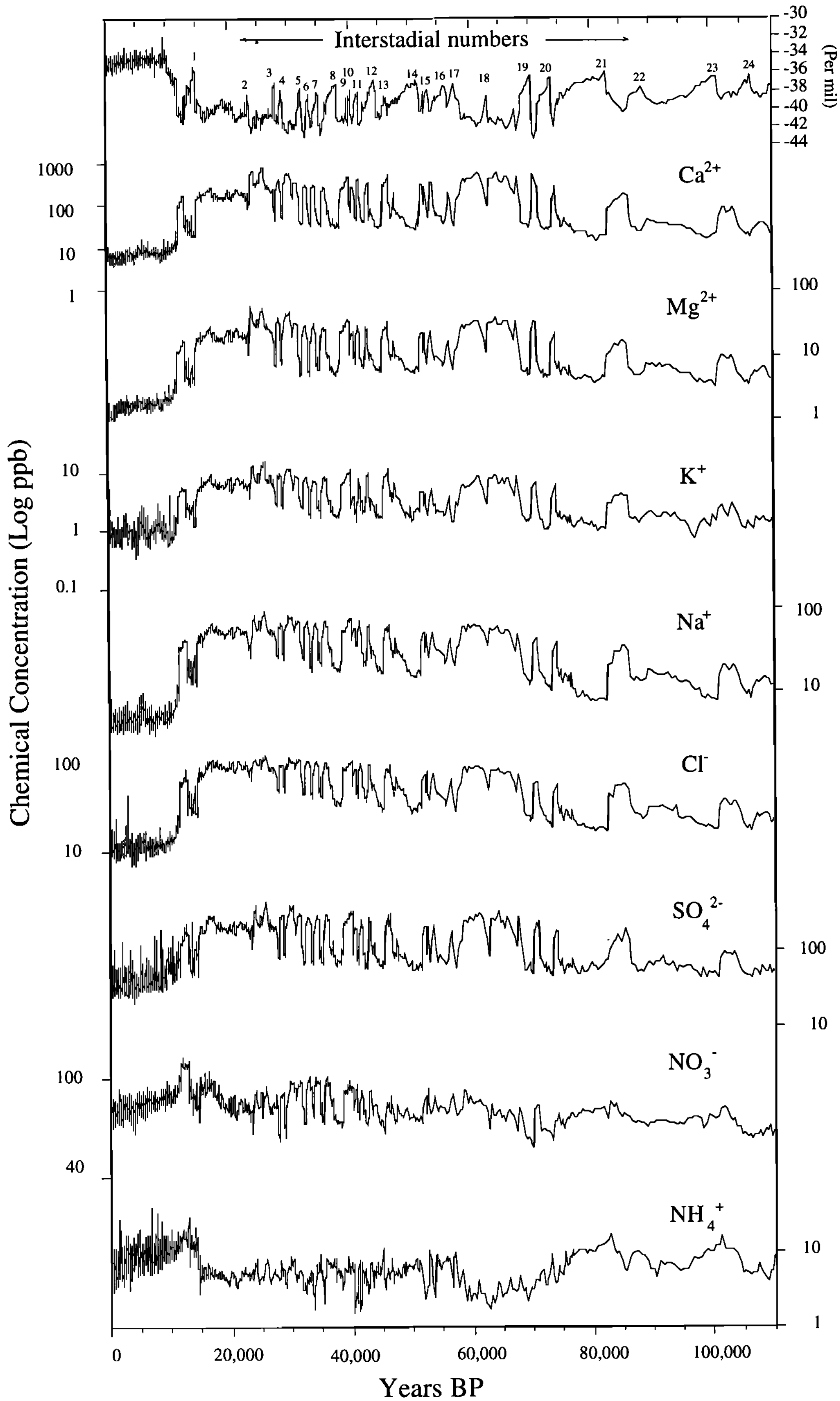

Figure 1. The $\delta^{18}O$ series [from *Grootes et al.*, 1993] and major ion series covering the last 110,000 years.

salt, demonstrating that nearly all of the sodium and chloride is of marine source. Second, pre-Holocene levels of sea salt increase despite an associated decrease in temperature which would have increased land and sea ice cover and thus transport distances from ice-free seas. Thus an increase in wind speed is required if sea-salt concentration is to increase as transport distances increase. Sea-salt concentration, which varies dramatically throughout the record (Figure 1), provides a proxy for relative wind speed.

Examination of the pre-Holocene portion of the major ion series reveals significantly more common behavior between species than in the Holocene (Figure 1). Thus, while the Holocene chemical record is more subdued in magnitude than the pre-Holocene, it appears to represent a more complex record of changes in source strength and atmospheric circulation. Further, unlike the Holocene, the pre-Holocene portion of the terrestrial and sea-salt species record is strongly anticorrelated with $\delta^{18}O$ (levels of these species increase during cold periods [*Mayewski et al.*, 1994]). Notably, nitrate and ammonium correlate neither with $\delta^{18}O$ nor with terrestrial and sea-salt species. The significance of these two groupings of chemical species (terrestrial and sea salt versus nitrate and ammonium) is discussed below.

The statistical methods which we utilize to investigate our glaciochemical series are similar to standard procedures used in oceanography, meteorology, and tree ring studies [e.g., *Imbrie et al.*, 1989; *Peixoto and Oort*, 1992; *Cook et al.*, 1996], although their use in the analysis of ice-core series is relatively recent [*Mayewski et al.*, 1993a, 1994]. Previously, we [*Mayewski et al.*, 1993a, 1994] developed a measure of the joint behavior of the 110,000-year-long GISP2 chemical series based on empirical orthogonal function (EOF) decomposition [*Peixoto and Oort*, 1992]. Briefly described, the EOF decomposition provides objective representations of multivariate data by analyzing the covariance structure of its variates [*Peixoto and Oort*, 1992]. As in previous studies [*Mayewski et al.*, 1993b, 1994], the dominant EOF of the suite of eight series resampled at 50 years combines chemical species with different sources (e.g., continental dust and marine aerosols) and various transport histories and explains such a high degree of variance (76%) that it must describe a large-scale feature of northern hemisphere climate. As noted in our earlier work [*Mayewski et al.*, 1993b, 1994], it represents a well-mixed atmosphere in which the concentrations of all species, except ammonium, increase or decrease together in fixed proportions. This model well-mixed atmosphere is significantly less sensitive to changes in individual species source regions than could be expected of univariate ice-core series [*Charles et al.*, 1994].

We have chosen to call the time series describing the

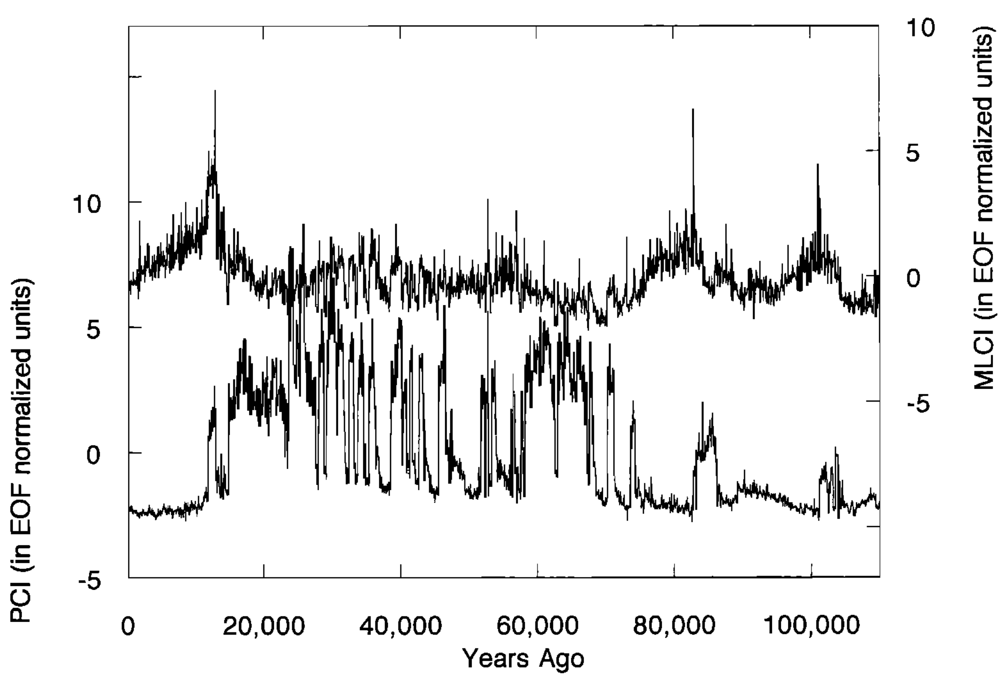

Figure 2. The PCI (Polar Circulation Index) and MLCI (Mid- to Low-Latitude Circulation Index, both in normalized units, are presented here as uniformly spaced 50-year sampling (this sample interval exceeds all but 2.5% of those of the original series). The PCI represents 76% of total variance in the eight series and 88, 94, 95, 96, 92, 95, 34, and 14% of the variance in the ion species calcium, potassium, magnesium, sodium, chloride, sulfate, nitrate, and ammonium, respectively. Ammonium is inversely associated with the other species of this assemblage. PCI values increase during cold periods (more continental dusts and marine aerosols) and decrease during warm periods, inversely to stable isotope series [*Mayewski et al.*, 1994]. The MLCI represents 15% of total variance and describes common behavior of the ammonium (76% of the variance) and nitrate (46% of the variance) series.

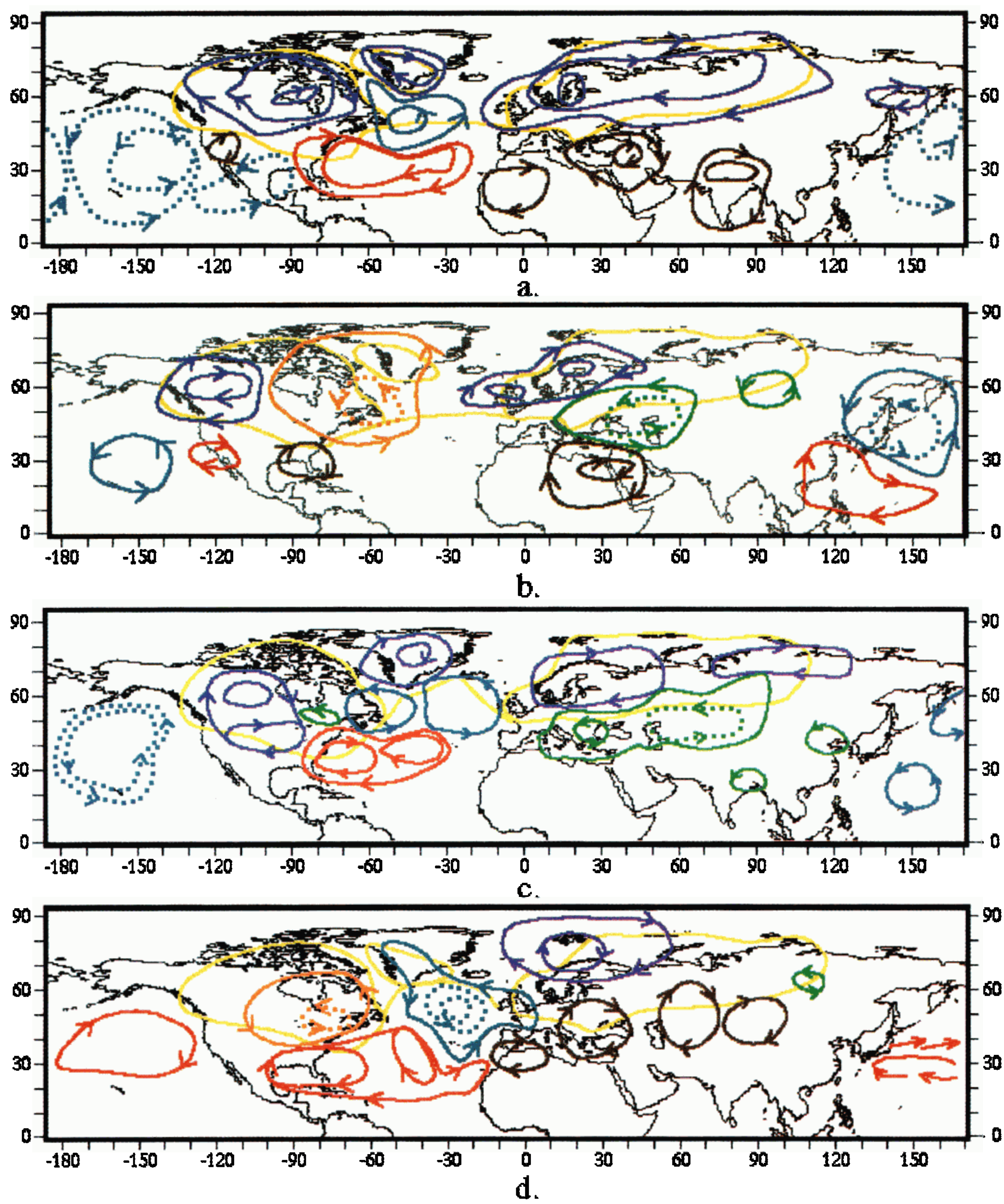

Plate 2. Conceptual view of changes in northern hemisphere atmospheric circulation between the present and the last glacial maximum (LGM) as simulated by the NASA GISS GCM derived from Rind [1987]. All results are for the LGM minus present. Anticyclonic circulation reflects relative high pressure in the change pattern (purple, ice sheet; brown, continental; red, oceanic). Cyclonic circulation reflects relative low pressure in the pressure change (orange, ice sheet; green, continental; blue, oceanic). Solid (dashed) lines represent LGM increases (decreases) in pressure relative to today. Outer (inner) lines show the areal extent (core) of the circulation systems in the change pattern. Arrows indicate the change in wind direction between the LGM and present (add change to present circulation systems to get LGM circulation systems). Southern sea ice limit and ice sheet outlines (yellow) were among the prescribed boundary conditions derived from Climate; Long-Range Investigation, Mapping, and Prediction (CLIMAP). (a) Surface pressure and wind changes for winter (December, January, February (DJF)). (b) Changes in jet winds and 500-mbar pressure for winter. (c) Surface pressure and wind changes for summer (June, July, August (JJA)). (d) Changes in jet winds and 500-mbar pressure for summer.

dynamics (i.e., increase and decrease from mean values) of the well-mixed atmosphere represented by the dominant EOF the "Polar Circulation Index" (PCI) (Figure 2) [*Mayewski et al.*, 1994]. In effect, the PCI provides a relative measure of the average size and intensity of polar atmospheric circulation. In general terms, PCI values increase (e.g., more continental dusts and marine contributions) during colder portions of the record (stadials) and decrease during warmer periods (interstadials and interglacials) [*Mayewski et al.*, 1994].

Another 15% of the total variance in the record is contributed by the second EOF component which is dominated by ammonium and nitrate, much of which may travel in the atmosphere as NH_4NO_3 [*Meeker et al.*, this issue]. The dynamics of this ion grouping are statistically uncorrelated with the PCI series (Figure 2) reflecting differences between the source regions contributing ammonium and nitrate versus the assemblage contributing to the PCI. Ammonium is largely derived from continental biogenic sources [*Logan*, 1983], while nitrate originates from a variety of sources of which lightning may be the major contributor [*Legrand and Kirchner*, 1990]. Continental biogenic source regions and regions of extensive lightning would have been located in the mid-low latitudes throughout the majority of the record since the high latitudes were ice covered. Thus the second EOF time series describing the dynamics of the ammonium and nitrate assemblage provides a measure of source strength and air mass circulation emanating from mid-low latitudes which we name the "Mid- to Low-Latitude Circulation Index" (MLCI) (Figure 2).

Time Series Analysis Used to Interpret Atmospheric Circulation

Following *Imbrie et al.* [1993], our strategy is to divide the atmospheric circulation records into their periodic components to allow us to investigate the system response to the individual forcing potentially associated with each component. However, these time series, which record the atmosphere's nonlinear response to the growth and decay of the great ice sheets over a full glacial cycle, cannot be assumed to be stationary. As this fundamental assumption underlying both "red" and "white" noise comparisons is violated, the assessment of significance of prominent peaks in an estimated spectrum is nonroutine. Nevertheless, the proportion of total series variance represented by the output of a narrow passband filter centered on the estimated peak frequency provides an unambiguous measure of the significance of the peak. The nonstationary character of the processes associated with the, in general, quasi-periodic amplitude-modulated filtered components can be assessed by comparison to the constant amplitude and phase Fourier component at the peak frequency. Accordingly, periodicities exhibiting strong spectral power were investigated by band-pass filtering and used to construct the independent almost periodic band pass components (bpc) of the series. Digital filters of elliptic type [*Krauss et al.*, 1993] were used to estimate the variable amplitude periodic structure in the series. The passbands of the filters were determined by estimating (using extensive simulation) the possible error in period estimation due to a maximum 10% error in dating. For the larger periods this resulted in an increment of approximately 5% of the central period. Simulation was used to test filter designs for their ability to detect nonstationary variable amplitude signals at the central periodicity and to eliminate serious overlaps in the passbands.

This approach to spectral analysis (Figure 3) [*Meeker et al.*, this issue; *Yiou et al.*, this issue] of the PCI and MLCI reveals periodicities commonly found in other paleoclimate records [e.g., *Emiliani*, 1955; *Shackleton and Opdyke*, 1973; *Hays et al.*, 1976; *Ruddiman and McIntyre*, 1976; *Imbrie*, 1985; *Shackleton and Pisias*, 1985; *Imbrie et al.*, 1992, 1993]. The GISP2 glaciochemical series is, however, unique because it contains such a robust assemblage of these periodicities. Because of the length of our record (~110,000 years) and its 50-year resampling, the discussion below is limited to periodicities between 500 years (10 samples) and 70,000 years. Periodicities <500 years will be considered elsewhere using higher-resolution resampled series. Periodicities >70,000 years, which are undetectable in this record, are represented by the output from a low-pass filter with cutoff at a period of 70,000 years.

Major Orbital Cycles

Both the PCI and the MLCI have periodicities in the general range of the Earth's orbital cycles of obliquity (e.g., ~41,000 years) and precession (e.g., 23,000 years) that affect climate through changes in the distribution of solar insolation. The presence of a strong obliquity influence in the PCI record is consistent with previous findings in marine records from the North Atlantic [*Ruddiman and McIntyre*, 1984] and stable isotope series from the Vostok (Antarctica) ice core [*Yiou et al.*, 1994, this issue]. However, records from lower-latitude regions are often dominated by precession induced insolation variability [*Prell and Kutzbach*, 1987; *Crowley and North*, 1991] as is the MLCI series. Notably, the GRIP ice-core stable isotope series displays important periodicities related to the precessional cycles suggesting a mid-low latitude source [*Yiou et al.*, 1995, this issue]. Thus, while originating from the same set of cores, the PCI versus the MLCI plus GRIP stable isotope series characterize atmospheric circulation from distinctly different regions and record latitudinally controlled responses to insolation forcing. This aspect is further emphasized by the phase relationship among the orbitally related components in the two series. The obliquity component of the PCI is almost 180° out of phase with that of the MLCI. Comparison with the obliquity com-

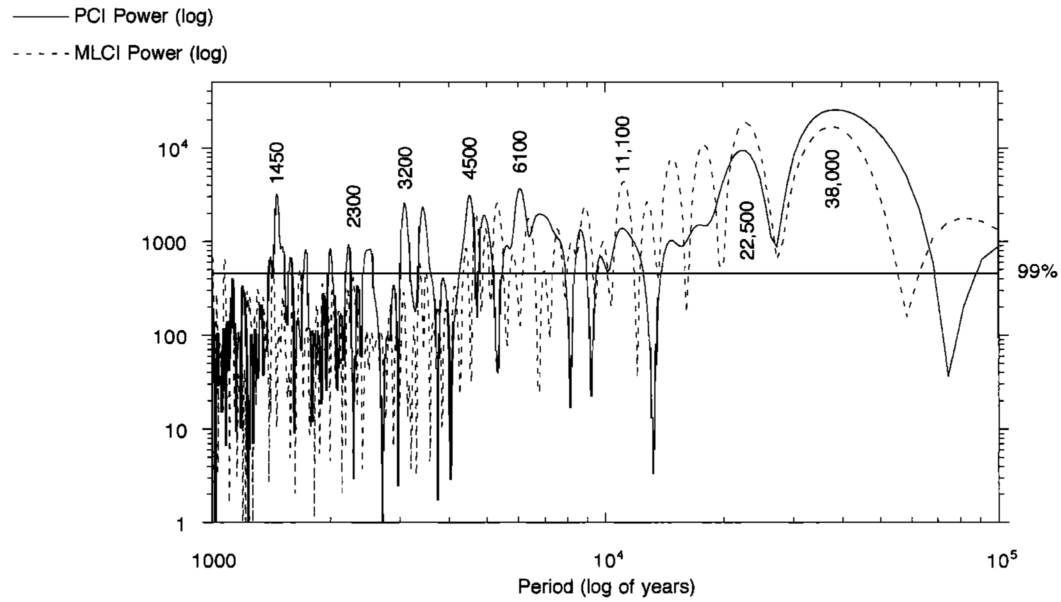

Figure 3. Power spectra for the PCI and MLCI series from Figure 2: (top) 10,000- to 100,000-year periodicities and (bottom) 500- to 10,000-year periodicities. Periodicities in excess of 70,000 years were removed by low-pass filtering and estimates of spectral power were developed using a sinusoidal taper [*Reidel and Sidorenko*, 1995] which, given the length of the series, provides minimum bias estimation of spectral peaks. Significance levels were estimated by extensive simulation using a Gaussian white noise null model. Spectral peaks above the horizontal line are significant at the >99% significance level. The 38,000-year periodicity represents 26% of the variance and the 22,500-year periodicity represents 9% of the variance in the PCI series. The 38,000-year periodicity represents 15% of the variance and the 22,500-year periodicity represents 27% of the variance in the MLCI series. Our estimate of the obliquity cycle is 38,000 years rather than the 41,000 years of theory. This is most likely a result of the relatively short length of our 110,000-year record and the influence of the growing and, later, receding ice sheets on atmospheric circulation and the PCI.

ponent of insolation at 60°N demonstrates that the PCI increases during periods of low insolation. The behavior of the MLCI is closely correlated with the obliquity and precessional components of insolation, demonstrating an association between continental biogenic source strength and insolation [*Meeker et al.*, this issue].

Lag correlation functions of the obliquity and longer bpc's in the PCI and the insolation series for mid-December and mid-July for various latitude bands [*Berger*, 1978] appear in Table 1. As expected, the correlation between the PCI and northern latitude December insolation is positive and that with mid-July insolation at northern latitudes is negative.

Although not shown here, the absolute magnitudes of the correlations increase with increasing lag (low latitude in December and high latitude in July, which change sign at small lag values, being the exceptions). The positive association with December insolation and the negative association with July insolation for 0 and small lags indicate an immediate response to changes

Table 1. Maximum and Minimum Correlations and Corresponding Time Lags From Correlation Functions of the PCI Series and Estimated Insolation per Latitude Over the Last 110,000 Years

Month	Latitude Band, °N	Max. Correlation	Lag, years
July	90	−0.56	5350
	60	−0.50	5500
	30	−0.39	5650
	0	−0.24	5750
December	60	0.55	5650
	30	0.52	6650
	0	0.35	7100

From *Berger* [1978]. The mean lag for July is 5563 years, and the mean lag for December is 6763 years.

in insolation forcing, probably due to the PCI response to changes in ocean ice (sea ice and icebergs) cover proposed in our previous work [*Mayewski et al.*, 1994]. The correlations increase (decrease) with increasing (decreasing) lag as shown in Table 1. The mean lag for the strongest correlations of July and December versus the PCI is ~6200 years. Comparison between these components and the obliquity and longer components for 60°N insolation demonstrates variability in lag over time (Table 1). As previously demonstrated, the orbitally related bpc's of the PCI series closely approximate ice volume (sea level) changes. The longest lag (~7500 years) occurs at times of ice buildup (~60,000-70,000 years ago) and the shortest (~6000 years) close to the late glacial maximum, both of which are consistent with estimated response times for large polar ice sheets [*Paterson*, 1972].

Ice Volume (Sea Level)-Atmospheric Circulation Association

Documentation of the PCI's sensitivity to large-scale changes in northern hemisphere atmospheric circulation is provided by the strong correspondence between the filtered PCI record (orbitally related bpc's summed from the PCI series) and fluctuations in the size of the northern hemisphere ice sheets as revealed by the glacioeustatic record (M. Prentice et al., manuscript in preparation, 1997) (Figure 4). As discussed below, the ice sheets had a strong impact on northern hemisphere atmospheric dynamics, and it is therefore expected that low-frequency components of the PCI tracked changes in northern hemisphere ice volume. We take the coral reef record of sea level fluctuations to be the best single indicator of this ice volume change during the last glacial cycle. The bulk of the coral reef record comes from the Huon Peninsula of New Guinea, with supplementary reef records covering the last deglaciation and the last interglaciation coming from Barbados and Australia.

Correspondence between the filtered PCI and the sea level record is quite good throughout the last 110,000 but is particularly strong between 30,000 and 70,000 years ago. The sea level record for this interval has recently been revised by *Chappell et al.* [1994] and exhibits a distinctive sea level high stand at 35,000 years ago and a broad multipeaked high stand between 46,000 and 55,000 years ago. The filtered PCI record exhibits

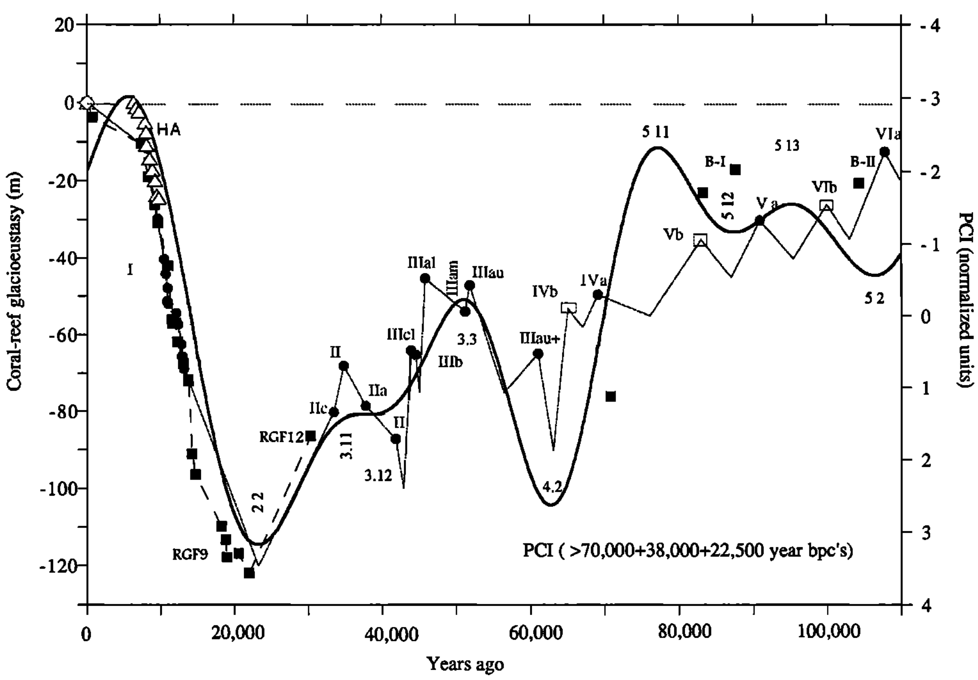

Figure 4. Comparison between our hypothesis for global sea level based on globally distributed coral reef records and the filtered GISP2 PCI record (>70,000-year + 38,000-year + 22,500-year band-pass components). Sea level turning points from New Guinea (red) are based on either dated coral samples (circles) [*Edwards et al.*, 1993; *Stein et al.*, 1993; *Chappell et al.*, 1994] or undated reef crests (boxes) and undated disconformities (no symbol) between adjacent reef tracts [*Chappell*, 1974; *Chappell and Shackleton*, 1986]. The placement of the crests of undated New Guinea reefs VIb, Vb, and IVb is arbitrary as is placement of the low stands inferred from reef stratigraphy. Barbados turning points are from dated coral samples (blue boxes) [*Edwards et al.*, 1987; *Bard et al.*, 1993; *Gallup et al.*, 1994] and also from borehole data [*Fairbanks and Matthews*, 1978]. Australian coral data (triangles) are from *Collins et al.* [1993] and *Eisenhauer et al.* [1993]. For each sea level point, there is generally more uncertainty in sea level estimate than in the age estimate.

negative peaks at nearly the same times with nearly the same durations and with the same relative magnitudes. The PCI increases significantly from the end of the last interglacial, about 75,000 years ago, until about 63,000 years ago. This step is coeval with an increase in ice volume represented by the stratigraphic breaks between New Guinea reefs V, IV, and III.

During the last interglacial between 80,000 and 100,000 years ago, the PCI record exhibits two major interglacial peaks which are consistent with the high stands of New Guinea reefs V and VI as well as Barbados reefs I and II. However, the date for Va carries a large uncertainty and the Vb high stand is undated. The Barbados I reef, named Worthing, is well dated relative to these New Guinea reefs and is roughly coeval with the PCI interglacial peaks. Prior to 100,000 years ago, the lesser interglacial peaks in the PCI record are consistent with New Guinea reefs VIa and VIb.

Not only is there strong correspondence between filtered PCI and sea level events, but also there is a strong linear relationship between these variables over the last 110,000 years. Due to lack of low stand data prior to 30,000 years ago, the linear relationship pertains primarily to negative PCI and high stands. Only since 30,000 years ago is it possible to document the linear relationship from the last glacial maximum (LGM) low stand to the Holocene high stand.

Atmospheric general circulation model (GCM) simulations of the LGM help to reveal the changes in atmospheric circulation that can account for the observed close relationship between the PCI and size of northern hemisphere ice sheets. Plate 2 depicts conceptual views of selected differences in surface and upper air circulation patterns between the LGM and the present, as calculated by the Goddard Institute for Space Studies (GISS) GCM [*Hansen et al.*, 1983, 1984; *Rind*, 1987]. The differences that we note between the present and LGM atmospheres were also achieved by *Kutzbach et al.* [1993] using the National Center for Atmospheric Research (NCAR) Community Climate Model and so can be considered robust. The approach in the following discussion is to point out simulated atmospheric changes consistent first with increased marine components in the PCI and, second, with increased terrestrial components.

Simulated LGM winter conditions appear highly favorable for much increased transport of marine constituents from the North Atlantic to the Summit site (Plates 2a and 2b). It is probably that the Icelandic low-pressure system that was centered on the sea ice edge in the western North Atlantic was much intensified relative to today and played the key role. However, the intensification was not due to a decrease in surface pressure of the Icelandic Low since that pressure is likely to have increased, due to colder LGM temperatures, making the low more stable at the LGM than at present [*Rind*, 1987]. Rather, the intensification reflects the size of the ice sheets around the North Atlantic that intensely cooled their overlying atmospheres, producing centers of such high pressure around the North Atlantic that the pressure gradients to the Icelandic Low were much increased relative to today. In other words, the core pressure of the Icelandic Low increased, but the ice sheet surface anticyclones increased so much more that the Icelandic Low was greatly intensified. A secondary supportive influence in the eastern North Atlantic was the western perimeter of the sprawling anticyclone over the Eurasian Ice Sheet.

According to the GCM, the ice sheets also strongly altered atmospheric transport aloft (500 mbar) over the subpolar North Atlantic into a configuration that was very different from that of today and that should have steered subpolar cyclones toward Summit. The key ice sheet-controlled changes were lower than present pressure aloft over eastern Canada and the western North Atlantic as well as higher than present pressure aloft over the European Ice Sheet and eastern North Atlantic (Plate 2b). The resulting increase in the east-to-west pressure-gradient force in the upper atmosphere over the subpolar North Atlantic intensified the LGM jet winds relative to today and imparted a more southerly component.

Simulated LGM circulation changes over northern hemisphere continents south of the ice sheets are also consistent with the much increased flux of continental chemical species to Summit at the LGM. Wintertime cooling of Asia, south-central Russia, and the Middle East, reflecting cold air advection off the tremendous Eurasian Ice Sheet anticyclone, increased surface high pressure as far south as the Arabian Peninsula (Plate 2a). This LGM ridge of increased surface pressure created an east-to-west pressure gradient that intensified southeasterly winds over deserts east and south of the Mediterranean. Such winds could have delivered considerably more dust from Africa and the Middle East to the North Atlantic atmosphere than currently occurs. This LGM transport direction received more support aloft than would have been the case today. LGM jet winds over North Africa were weakened and veered northward relative to today because of the pressure increase aloft over the Arabian Peninsula. The stronger than present southerly winds over the subpolar North Atlantic in LGM winter should have increased dust delivery to Greenland. Intensified westerly flow over the Tibetan Plateau and China during the LGM winter indicates that this region probably also contributed to the GISP2 record despite the travel distance across the Pacific and either north or south of the Laurentide Ice Sheet.

Conditions in LGM summer might have been equally conducive to increased North African-Middle East dust transport to Greenland. The GISS GCM simulation indicates a broad belt of significantly decreased surface pressure across south western and central Siberia (Plate 2c). The strong pressure-gradient force directed from the Eurasian Ice Sheet anticyclone south to the belt of lowered surface pressure would have increased easterly air flow over deserts in southern Russia and central Asia and westerly flow over the Tibetan Plateau. Even in LGM summer, there was probably much more southerly air flow over the North Atlantic than occurs today that could have transported this dust toward Greenland (Plates 2c and 2d).

Our earlier suggestion that the North American southwest may have been the dominant source for Summit dust-derived species when the Laurentide Ice Sheet was present [*Mayewski et al.*, 1993b] seems much less likely in view of our more recent analysis [*O'Brien et al.*, 1995] of the Holocene portion of the GISP2 chemistry series sources in the eastern hemisphere, which showed that both winter and summer LGM jet winds over the desert southwest were weaker than at present. Further, the winter high and summer low at surface had more of an easterly component than at present.

The selected GISS GCM results that we have sketched indicate that the substantial differences between present and LGM atmospheric circulation in the northern hemisphere strongly reflect the size of the ice sheets. The development of the strong ice sheet surface anticyclones affected zonal pressure gradients on east and west sides of the anticyclones differently. Eastern sides at surface cooled because of northerly advection, whereas western sides warmed with southerly advection. Such changes caused LGM jet winds to increase in velocity relative to today over eastern cold sectors and slow over warm western sectors. Subtropical pressure systems were strengthened in some regions and weakened in others in partial response to the subpolar anticyclones. The resulting differential changes in zonal pressure gradients had opposing effects on jet wind velocities [*Rind*, 1987]. Overall, it appears that the LGM atmosphere exhibited more meridional flow both at surface and aloft than occurs without high ice sheets. Correspondingly, LGM jet winds were in some regions located to the north of their present locations and, in other regions, located to the south.

In conclusion, the close association between the orbital-scale bpc's (~60% of the total variance in the PCI series) and the sea level reconstruction plus the GCM results demonstrate that long-term atmospheric circulation is dominated by ice sheet dimensions.

Heinrich and Rapid Climate Change Events

Previous paleoclimate records have identified and modeled periodicities that operate faster than the primary insolation forcing cycles. These periodicities may reveal evidence of interactions in the ocean-atmosphere-cryosphere system [*LeTreut and Ghil*, 1983; *Ghil and Childress*, 1987]. Both the PCI and MLCI series display 6100- and 11,100-year periodicities (Figure 3) within the range of the 5000- to 7000-year and 10,000- to 12,000-year periods, respectively, identified in marine and ice-core records [*Pisias et al.*, 1973; *Pestiaux et al.*, 1988; *Hagelberg et al.*, 1994; *Yiou et al.*, 1994]. The more precise timing of the GISP2 periodicities is a result of the higher resolution and more highly constrained dating of this record. The 6100-year periodicity is stronger in the PCI series, while the 11,100-year periodicity is stronger in the MLCI series.

Most of the long-term behavior of the PCI and 68% of its total variance is explained by the combination of orbital cycles of obliquity and greater plus the 6100-year bpc (Figure 5). Further, the 6100-year bpc reveals a very strong association with the timing of Heinrich events (Figure 5). These events are represented by marine layers rich in ice-rafted debris and poor in foraminifera [*Heinrich*, 1988] that result from massive iceberg discharge and attendant cooling of surface waters [*Bond et al.*, 1992]. They have been correlated to Summit ice-core stable isotope and chemical series [*Bond et al.*, 1992; *Mayewski et al.*, 1994]. These discharges have also been linked to reductions in North Atlantic thermohaline circulation [*Bond et al.*, 1993] and deepwater circulation [*Oppo and Lehman*, 1993]. However, previous studies did not recognize the relatively precise timing demonstrated in Figure 5. We suggest that the 6100-year bpc is a result of the ~6200-year mean lag between the PCI series and insolation, described above (Table 1). It is produced primarily as a function of insolation-induced ice sheet volume changes (translated to the ice sheet through changes in temperature and precipitation) in accord with the near 6000-year cyclic behavior predicted by simple ice sheet oscillation models [*Ghil and LeTreut*, 1981; *MacAyeal*, 1993] and the 5000- to 10,000-year modeled phase lag between ice sheet dynamics and insolation suggested by *Budd and Rayner* [1995]. The positive feedbacks created by the presence of ice sheets have been demonstrated in previous studies [*Birchfield and Weertman*, 1983; *LeTreut and Ghil*, 1983; *Budd and Smith*, 1987; *Damon and Jirikowic*, 1996]. Notably, the 6100-year bpc is significantly enhanced in amplitude during periods when ice sheets expand as expected if related to ice sheet dynamics.

However, an ~6100-year cooling cycle, although markedly subdued during periods of low ice sheet volume, is maintained during the Holocene. It coincides with the timing of the mid-Holocene cool period and the Little Ice Age [*O'Brien et al.*, 1995]. Therefore the 6100-year cooling cycle appears not to be related solely to ice sheet dynamics but must also be related to other mechanisms that allow suborbital-scale changes in insolation to be translated through the ocean-atmosphere-cryosphere system into changes in climate.

Following the primary insolation cycles in the PCI and MLCI spectra, the 6100- and 11,100-year periodicities appear to gradually decay in power into 4500- and 3200-year periodicities (Figure 3). However, this pattern of decreasing power as a function of decreasing period ends at the increased energy band represented by the 1450-year spectral peak in the PCI series.

Comparison of the PCI with its extracted 1450-year bpc (Figure 6) reveals that the rapid climate change

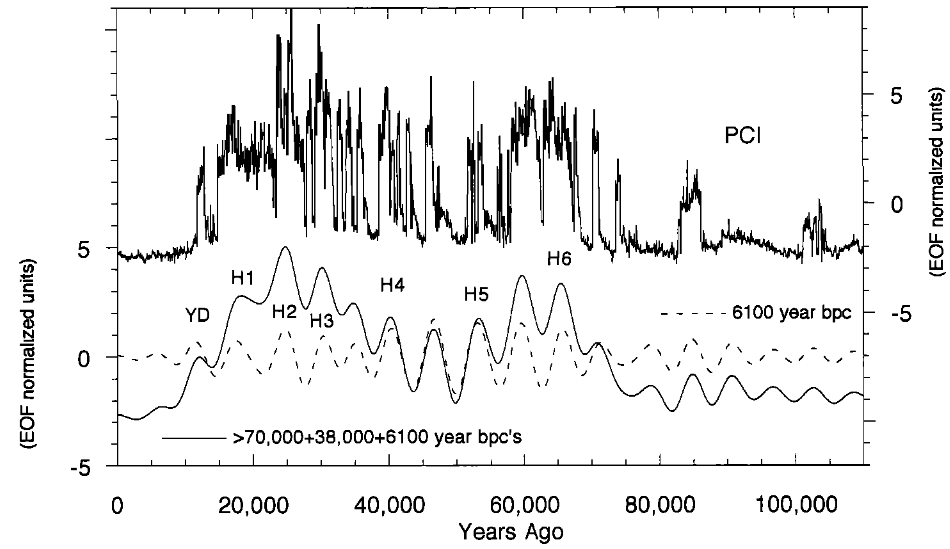

Figure 5. The 6100-year PCI band-pass component (bpc) compared to the PCI series and the timing of Heinrich events (H1-H6 [after *Bond et al.*, 1993]) and the Younger Dryas (YD).

events in the PCI record occur at or near a 1450-year periodicity. When added to the longer periodicities already described, the 1450-year bpc approximates much of the fast behavior of the PCI (Figure 6). These rapid climate change events are important because they are the most dramatic and rapid changes in climate (occurring over periods of years to decades) noted in the ice-core record [*Alley et al.*, 1993; *Mayewski et al.*, 1993b, 1994; *Taylor et al.*, 1993b], and they are known to affect both surface and deepwater circulation, potentially through changes in thermohaline circulation [*Keigwin et al.*, 1991; *Oppo and Lehman*, 1993]. Previous studies have attributed these rapid climate change events to massive reorganizations in atmospheric circulation [*Mayewski et al.*, 1994; *Kapsner et al.*, 1995] that are, perhaps, stimulated and sustained by changes in ocean ice cover (sea ice and icebergs) [*Mayewski et al.*, 1994]. A near-periodic 1500-year component is found in North Atlantic marine records covering the last glacial cycle [*Cortijo et al.*, 1995]. Internal oscillations in the ocean-ice-climate system [*Ghil et al.*, 1987; *Maasch and Saltzman*, 1990] have been suggested as causes for such rapid climate change events, or the processes by which they might occur, because these events operate on timescales

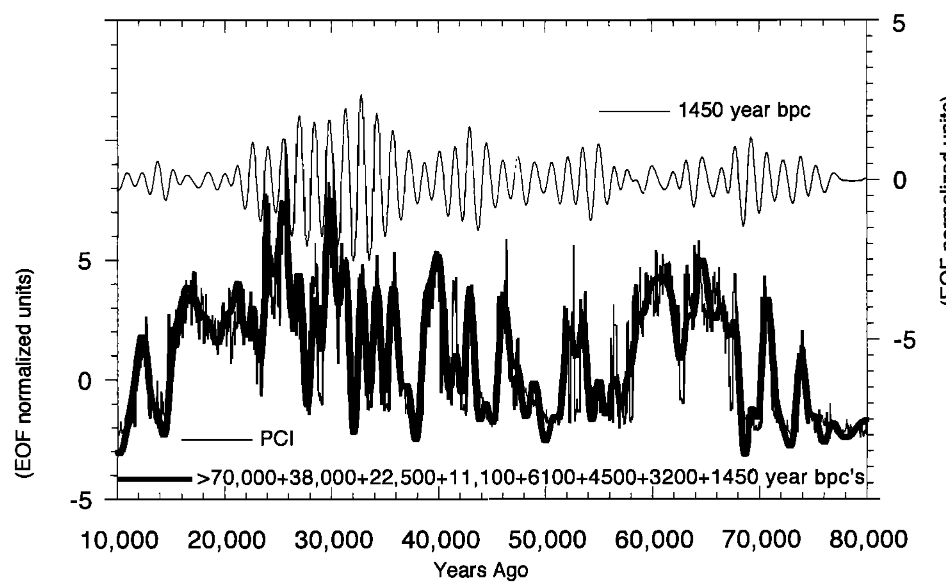

Figure 6. Timing of the 1450-year band-pass component relative to the rapid climate change events identified in the PCI series and modification of the 1450-year band-pass component by cancellation and addition of other band-pass components. The sum of the >70,000 low-pass filter plus band-pass components at 38,000 + 22,500 + 11,100 + 6100 + 4500 + 3200 + 1450 years accounts for 86% of the variance in the PCI series.

that are close to ocean turnover times. However, increasing evidence documenting the global synchroneity of some of the rapid climate change events [*Chappellaz et al.*, 1993; *Roberts et al.*, 1993; *Denton and Hendy*, 1994; *Kotilainen and Shackleton*, 1995] reduces the likelihood that such internal oscillations are their sole or even primary control.

The 1450-year bpc represents 9% of the total variance in the PCI series and stands out prominently in the spectra for this series. It is also part of the approximate harmonic sequence described by the 1450-, 3200-, 4500-, and 6100-year periodicities and thus may be a combination tone or low-order harmonic of these longer cycles. However, the increase in power at the 1450-year periodicity (Figure 3) is not consistent with this concept.

The 1450-year periodicity is amplified when ice sheets are relatively more extensive (~20,000-75,000 years ago, Figure 7), no doubt due to positive feedbacks. During this period, however, the correspondence between ice volume change and magnitude of the 1450- year events appears to be phase lagged (Figure 7). Further, 1450-year events operate too rapidly to be produced solely by changes in ice sheet dimensions.

During the period ~20,000-75,000 years ago the amplitude of the 1450-year periodicity is closely associated with periods of low insolation. Notably, periods of large-magnitude 1450-year events are significantly better correlated to insolation decreases than to ice volume change during the periods ~56,000-39,000 and 76,500-64,000 years ago (Figure 7). These insolation changes may set the scene for changes in ocean ice cover and related changes in thermohaline circulation in the ocean plus other changes (e.g., terrestrial snow cover) that could dramatically alter atmospheric circulation patterns. Even under modern conditions the mid-high latitudes of the northern hemisphere are characterized by a relatively large range in albedo due to changes in the distribution of sea ice and snow cover [*Kukla and Robinson*, 1980; *Parkinson et al.*, 1987].

In summary, changes in insolation and associated positive feedbacks related to ice sheets may assist in explaining favorable time periods and controls on the amplitude of massive rapid climate change events. However, the 1450-year timing of these events remains to be explained.

Solar Variability

Emerging evidence, noted previously, for the global synchroneity of at least some rapid climate change events may indicate that there is some significant forcing through changes in solar output. The $\delta^{14}C$ residual series (produced after subtracting the influence of the geomagnetic dipole moment or changing carbon-reservoir effects [*Stuiver and Braziunas*, 1993]) has known associations with cosmogenic production of $\delta^{14}C$ (high $\delta^{14}C$ coincides with low solar activity [*Damon and Jirikowic*, 1992]) and is therefore a valuable proxy for testing potential solar-climate links. An ~2300-year periodicity in the $\delta^{14}C$ residual series may demonstrate such a link because this periodicity strongly modulates the ~200- and 11-year known solar-related periodicites in this series [*Damon et al.*, 1989; *Hood and*

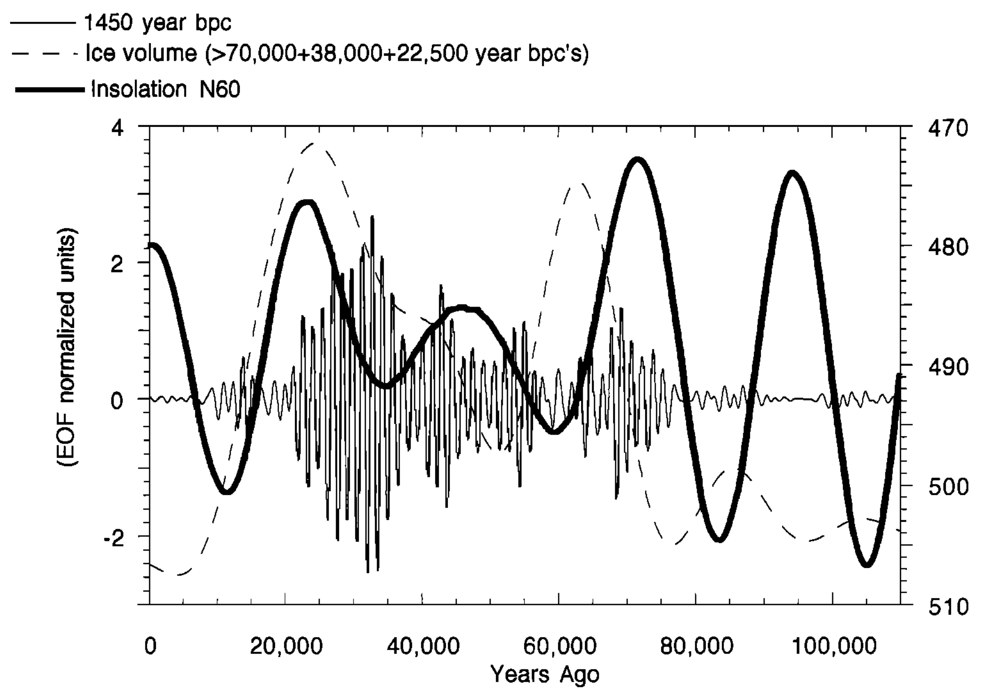

Figure 7. The 1450-year band-pass component compared to change in ice volume (represented by PCI band-pass components as in Plate 2) and change in northern hemisphere insolation developed from *Berger* [1978].

Jirikowic, 1990]. However, variability in the $\delta^{14}C$ residual series may also be a consequence of other production processes. A 512-year periodicity in the early Holocene has been attributed to instabilities in North Atlantic thermohaline circulation which affect the carbon cycle [*Stuiver and Braziunas*, 1993].

To investigate the possible role of solar variability in forcing changes in the PCI, we compare the spectrum of the ~11,500-year $\delta^{14}C$ residual series derived from tree rings and coral reefs [*Stuiver and Braziunas*, 1993] with the most recent 11,500 years of the 110,000-year-long PCI series. Higher-resolution sampling available over this more recent portion of the PCI allowed bidecadal sampling comparable to the $\delta^{14}C$ series. Spectra for the two series show that both have several strong periodic components in common (Figure 8). For purposes of this study we chose only to investigate those periodicities which are common to both series and which we have thus far dealt with in this paper, namely those at 2300, 1450, and 512 years. They are all at the >99% significance level except for the 512-year periodicity for the PCI, which is >95% significant. Summation of the three bpc's extracted for each series explains ~40% of the variance in each series. Comparison of the summed bpc's (Figure 9) demonstrates that much of the similarity in the PCI and $\delta^{14}C$ residual series is a consequence of these periodicities. While this similarity does not demonstrate a solar-climate link between the two series, it is interesting to note the strong association between our record of atmospheric circulation and the $\delta^{14}C$ residual series. It is also noteworthy that both series contain a 1450-year periodicity. However, the relative importance of this periodicity over the last 11,500 years of the PCI record is markedly less than it is over the full record, perhaps, as noted earlier, because of the lack of a large Holocene ice sheet and consequent loss of associated positive feedbacks.

While we cannot demonstrate a clear solar-climate link for the 1450-year periodicity, we suggest that the presence of such a periodicity in the $\delta^{14}C$ residual series warrants future investigation. While not as strong as other periodicities in the $\delta^{14}C$ residual series, the 1450-year periodicity may resonate with internal oscillations in the ocean-climate system, producing larger magnitude events when the latter are more pronounced (during periods of low insolation and increased ice volume as described above). Most importantly, a 1450-year solar cycle that resonates in this fashion offers an explanation for both the regular timing of the rapid climate change events and their global synchroneity.

Finally, the presence of a possible solar-linked 2300-year periodicity, close to the global scale 2500-year cooling cycle suggested from Holocene glacier fluctuation records [*Denton and Karlen*, 1973] demonstrates that atmospheric circulation records may contain embedded evidence of solar-climate relationships.

Conclusions and Remarks

The GISP2 chemical series (sodium, potassium, ammonium, calcium, magnesium, sulfate, nitrate, and chloride) contain a diverse array of environmental signatures that include the documentation of anthropogenically derived pollutants, volcanic and biomass-burning events, storminess over marine surfaces, continental aridity, and biogenic source strength.

Analysis of the spatial distribution of the major chemical species over the Greenland Ice Sheet indicates that

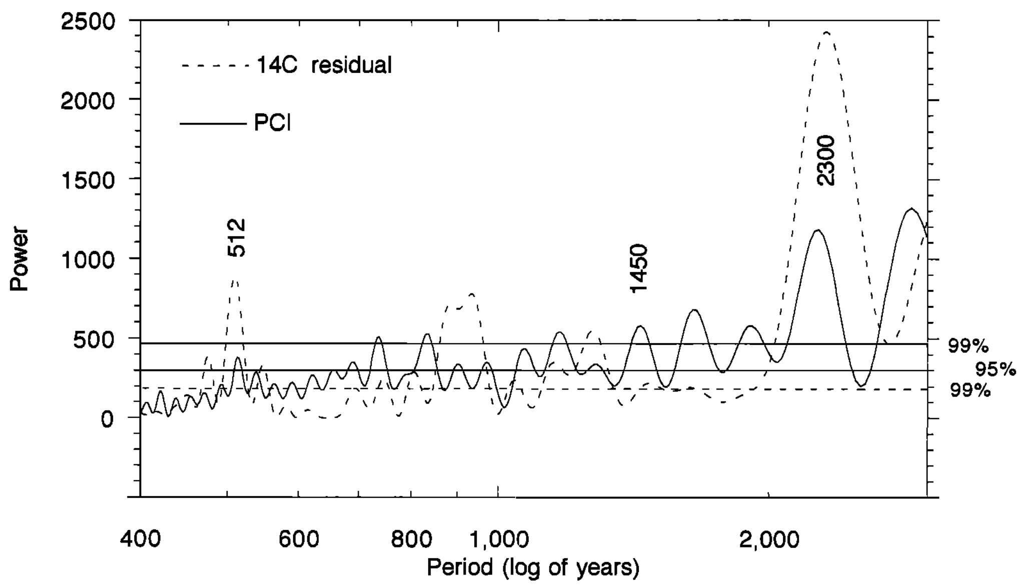

Figure 8. Power spectra for $\delta^{14}C$ residual series covering the last 11,500 years and the 20-year sampled PCI restricted to the same time interval. Spectral peaks above the upper horizontal line (upper solid PCI, dashed $\delta^{14}C$ residual series) are significant at the >99% significance level, while the lower horizontal line (lower solid PCI) denotes 95% significance.

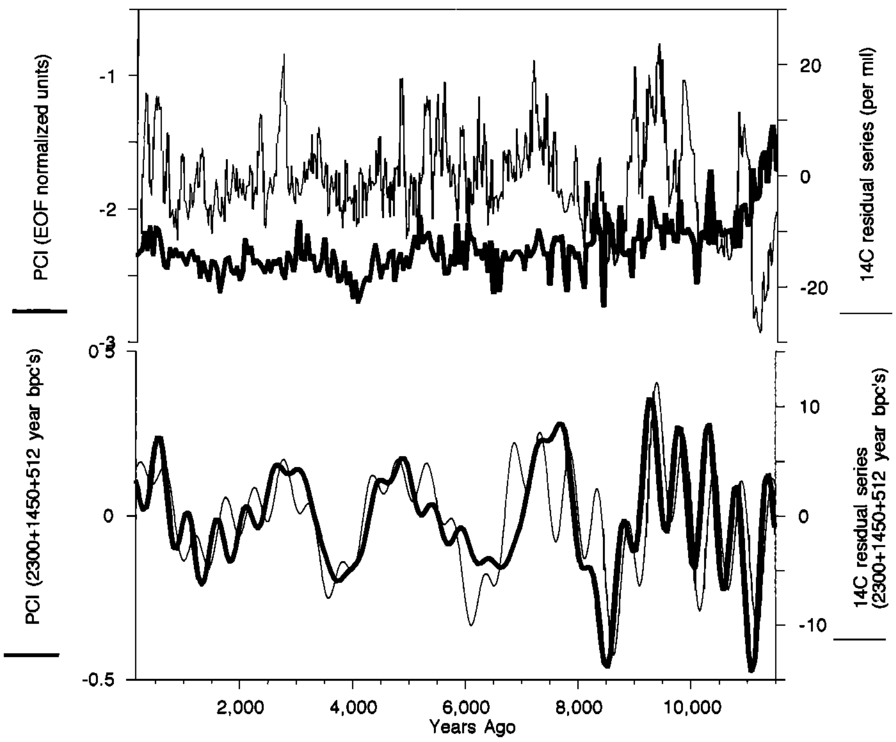

Figure 9. Sum of the energy in the band-pass components covering 2300 + 1450 + 512 years for both the $\delta^{14}C$ residual series [from *Stuiver and Braziunas*, 1993] versus the PCI series demonstrating their close association.

the GISP2 site is representative of this entire region [*Yang et al.*, 1996]. Further, the chemical species contained in this ice core are similar in relative concentration to those of the atmosphere over Greenland [*Mayewski et al.*, 1990b; *Alley et al.*, 1995]. Since the source area for these species is from throughout much of the northern hemisphere and, in some cases, more distant regions, the GISP2 ionic series potentially contain a robust record of environmental change. GCM simulations suggest that during the LGM the dominant source for marine species entering Greenland was the North Atlantic Ocean, while continental dusts appear to have been derived from regions immediately south of the Eurasian Ice Sheets.

Because the GISP2 chemical series records >95% of the soluble ionic components in the atmosphere, it can be used to reconstruct atmospheric circulation systems. The dominant behavior (90% of the total variance) of these chemical series is translated into a history of response and forcing of two general atmospheric circulation systems described here in terms of a Polar Circulation Index (PCI) and a Mid- to Low-Latitude Circulation Index (MLCI).

High-latitude ice sheet growth and consequent atmospheric circulation patterns (PCI) appear to be controlled mostly by obliquity and longer orbital cycles as suggested previously from marine sediment cores [*Ruddiman and McIntyre*, 1984]. Mid-low latitude atmospheric circulation patterns (MLCI) are controlled mostly by precessional-scale orbital cycles as suggested previously from marine sediment cores [*Prell and Kutzbach*, 1987]. Comparison between the orbitally related band-pass components of the PCI and a reconstruction of sea level demonstrates that the dominant long-term structure of the PCI is related to ice volume change, hence linking changes in ice sheet dimensions with changes in atmospheric circulation.

Periodicities at 11,100 and 6100 years, close to similarly ascribed periodicities in marine and Antarctic ice cores [*Hagelberg et al.*, 1994; *Yiou et al.*, 1994], are prominent in the behavior of the PCI. The 6100-year periodicity is stronger in the PCI series, and the 11,100-year periodicity is stronger in the MLCI series. Further, the 6100-year periodicity mirrors the timing of ice-rafted marine debris events (Heinrich events) which have been ascribed to ice sheet dynamics [*Bond et al.*, 1993]. The lag time between insolation-driven ice volume changes and insolation is close to 6100 years, supporting the concept of ice dynamics involvement in the production of Heinrich events [*Bond et al.*, 1993].

The 1450-year periodicity in the PCI record matches closely the timing of the pre-Holocene rapid climate change events which are now known to represent massive reorganizations in atmospheric circulation [*Mayewski et al.*, 1994, *Kapsner et al.*, 1995]. In addition, the 1450-year periodicity is close to the turnover time of the ocean, suggesting some association with internal oscillations in the ocean-climate system, although such a process does not explicitly describe why these events are globally synchronous. Further, these events appear to be amplified largely by thermal differences that are developed as a consequence of changes in insolation plus the positive feedback effect of ice sheets. The insolation changes may lead to variations in sea ice extent and ocean surface cooling that could affect atmospheric circulation through changes in albedo and thermohaline circulation.

If the 1450-year rapid climate change events are related to internal oscillations in the ocean-climate system, the forcing for such events may be multiple, complex, and nonlinear in operation. We suggest at least two potential causes that could contribute to the forcing of these rapid climate change events. First, as demonstrated in our time-series analysis, the 1450-year periodicity may be, in part, a combination tone of orbitally driven insolation cycles. Second, the presence of a 1450-year bandpass component in both the PCI and $\delta^{14}C$ residual series may suggest a link to climate-solar variability. Alternately, this association may occur in both series in response to changes in the ocean-atmosphere exchange of carbon, linked through changes in thermohaline circulation.

Finally, while the PCI-$\delta^{14}C$ residual series association at the 2300- and 512-year periodicities can only be validated for the Holocene, due to lack of longer $\delta^{14}C$ series, it provides intriguing potential for future investigation into solar-climate links.

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