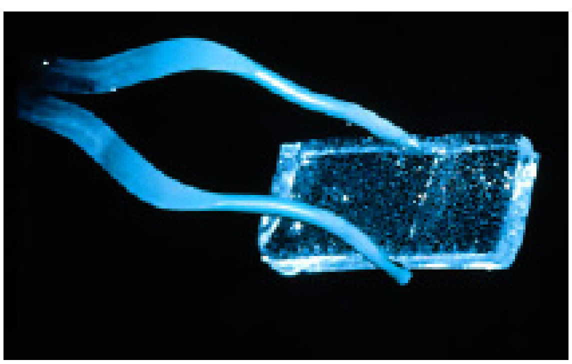


Ice Core Contributions To Global Change Research:

Past Successes and Future Directions

Ice Core Working Group

May 1998

Ice Core Contributions to Global Change Research:

Past Successes and Future Directions

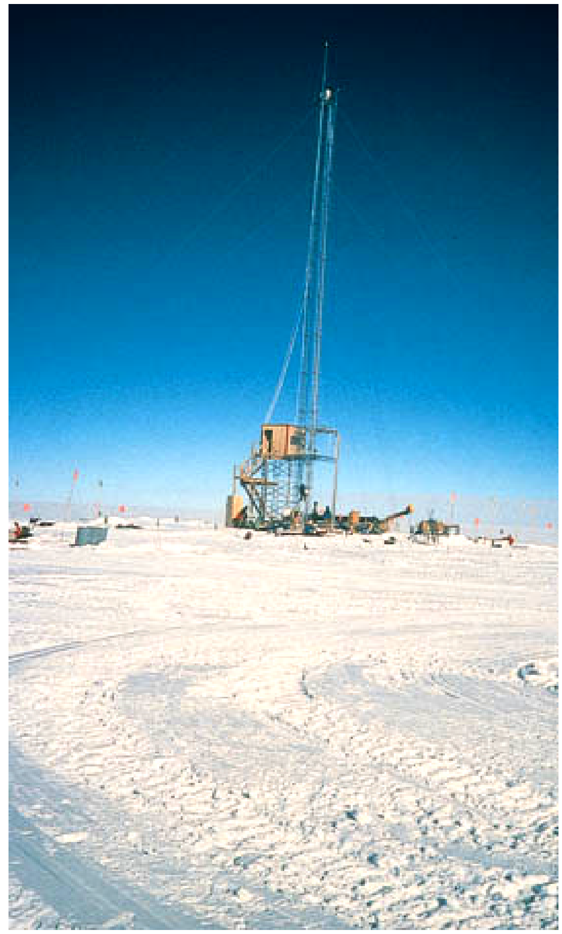
By: Ice Core Working Group, May, 1998.

Table of Contents

This material is based upon work supported by the National Science Foundation under Cooperative Agreement Number OPP-9617009 to the Climate Change Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

A copy of this document can also be accessed on the World Wide Web at: http://www.nicl-smo.sr.unh.edu/icwg/icwg.html

Drill at North Side, Mt. Everest, C. Wake



Drill Rig at Taylor Dome, J. Fitzpatrick

Inside GISP2 Drill Dome, M. Twickler

Intermediate Drilling at Newall Glacier, Antarctica, M. Twickler

Published by
The National Ice Core Laboratory -- Science Management Office
At the University of New Hampshire

For more information please contact
The National Ice Core Laboratory -- Science Management Office
Telephone: 603-862-1991, fax: 603-862-2124, email: nicl.smo@unh.edu

Photography credits:
Front Cover: Top -- Snowpit Sampling, M. Twickler;
GISP2 Drill Dome, M. Twickler;
Taylor Dome, Antarctica, J. Fitzpatric;
Ice Core Section, M. Morrison.

Preface

In 1986 an ad hoc committee of the Polar Research Board issued a series of recommendations intended to stimulate U.S. ice coring activities (National Research Council, 1986) in response to the growing need for high quality paleoclimate records that could be used to understand climate change. Their report reviewed the then current status of ice core research in the U.S. and the elements necessary to implement a strong program of ice core collection and analysis. Now, in 1998, the vision set forth for a strong U.S. ice coring program has been achieved. The U.S. ice coring community has, in concert with its international partners, made remarkable strides to advance in our understanding of global change. This new document, assembled by the Ice Core Working Group (ICWG), provides a synthesis of the global change lessons learned thus far, and the requirements and plans for solving new global change questions utilizing future ice coring activities.

The Ice Core Working Group (ICWG)

The ICWG is sponsored by the Office of Polar Programs, National Science Foundation, in response to a recommendation made by the Polar Research Board (National Research Council, 1986). It provides a forum for the discussion of issues related to, and future directions for, the U.S. ice coring community. Previous planning documents developed by this group (e.g., ICWG 1987, 1988, 1989) have led to the initiation of major deep drilling efforts (GISP2, Siple Dome) for the U.S. community. The current members of the ICWG* and authors of this document are:

- Paul A. Mayewski* (University of New Hampshire), Chair
- Roger Bales* (University of Arizona)
- John Bolzan (Ohio State University)
- Gordon Hamilton* (Ohio State University)
- Debra Meese* (Cold Regions Research and Engineering Laboratory)
- David Morse* (University of Texas at Austin)
- Michael Ram* (State University of New York at Buffalo)
- Todd Sowers* (Pennsylvania State University)
- Eric Steig* (University of Colorado)
- Mark Twickler (University of New Hampshire)
- Cameron Wake* (University of New Hampshire)
- Gregory Zielinski* (University of New Hampshire)

The Challenge

Since ancient times humans have modified their environment, but only since the beginning of the Industrial Revolution has human activity had a dramatic effect at global scales. Without question, human activities have affected the composition of the global atmosphere, and the magnitude of human disturbance to biogeochemical cycles may now be approaching a critical level. Over the past decades concentrations of atmospheric carbon dioxide (CO_2) and methane (CH_4) have moved into a range unprecedented during the last few million years. This increase has produced serious concern regarding the heat balance of the entire planet. Greenhouse gases are, however, only part of the human-induced problem. Sulfur aerosols, ozone and dusts, to mention only a few, can either reinforce or counteract greenhouse gas effects on local to regional scales.

While intense efforts are underway to determine the history and significance of human influences on climate, including atmospheric chemistry, and on resource depletion, our understanding of climate change is still hampered by lack of knowledge of the natural controls on climate. Mounting evidence points to the significance of a variety of natural climate forcing agents such as solar variability, planetary orbital cycles, volcanic activity, changes in size and flow of large ice sheets, and changes in thermohaline circulation of the ocean. From records of climate variability in the past we know that these controls have produced significant changes in climate that have, at times, occurred very rapidly (over a few years).

Our ability to understand climate change, to decipher the influence of human activity, and to predict future climate depends on a coupled investigation of both modern and past climate. The modern era of climate is probably the most difficult to understand because of the combined influences of natural and human-induced activities; hence climate understanding and prediction now poses an immense challenge to science.

Investigating Past Climate and the Environment Through Ice Cores

Records from a variety of sources (e.g., instrumental records, historical documents, deep-sea and continental sediments, tree rings, and ice cores) provide the basic boundary conditions (e.g., sea surface temperature, precipitation and atmospheric circulation patterns) necessary for robust environmental reconstructions. However, ice core records provide the most direct, detailed, and complete measure of past climate change; as a consequence, considerable national and international attention has been paid to the unique perspective they provide. Much of this attention has been focused on the deep ice cores recovered from Summit, Greenland and from Vostok in East Antarctica (Figure 1).

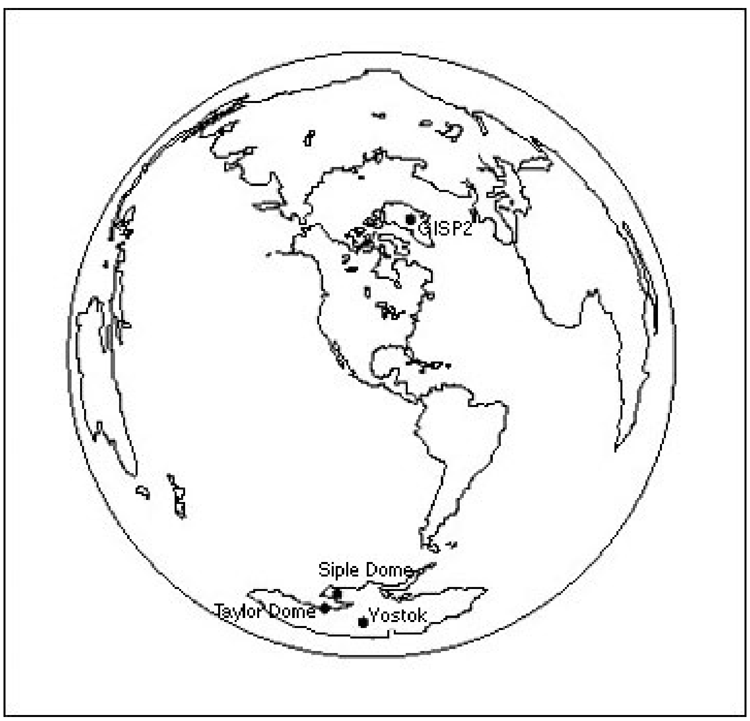


Figure 1 – Location map for deep drilling sites discussed in this document: GISP2 (central Greenland), Vostok and Taylor Dome (East Antarctica) and Siple Dome (West Antarctica).

Ice core records provide detailed descriptions of climate change that are extremely valuable for comparison with modern observations. Further, they document not only a wide range of environmental parameters that are both measures of and responses to climate change (e.g., atmospheric chemistry and circulation, temperature, precipitation) but also many of the causes of climate change (e.g., solar variability, volcanic activity, greenhouse gases). Because of their high resolution (sub-annual), long time span (several glacial cycles) and precise dating (annual), they also provide a framework for interpreting other records of past climate.

Lessons Learned From Ice Core Research Over the Last Decade

While the following overview is by no means an exhaustive compilation of the lessons learned from ice core research over the last decade, it is intended to highlight many of the major scientific accomplishments of this period.

The Greenhouse Gas/Temperature Relationship

The climate records from the Vostok ice core are the longest continuous record of Antarctic climate available to date. Geochemical measurements have been conducted to a depth of 3350 meters, and the results indicate that the age of the ice at this level is approximately 420,000 years, covering more than three full glacial/interglacial cycles (Petit et al., 1997). Data from the upper 2100 meters (corresponding to ~160,000 years) are included in Figure 2.

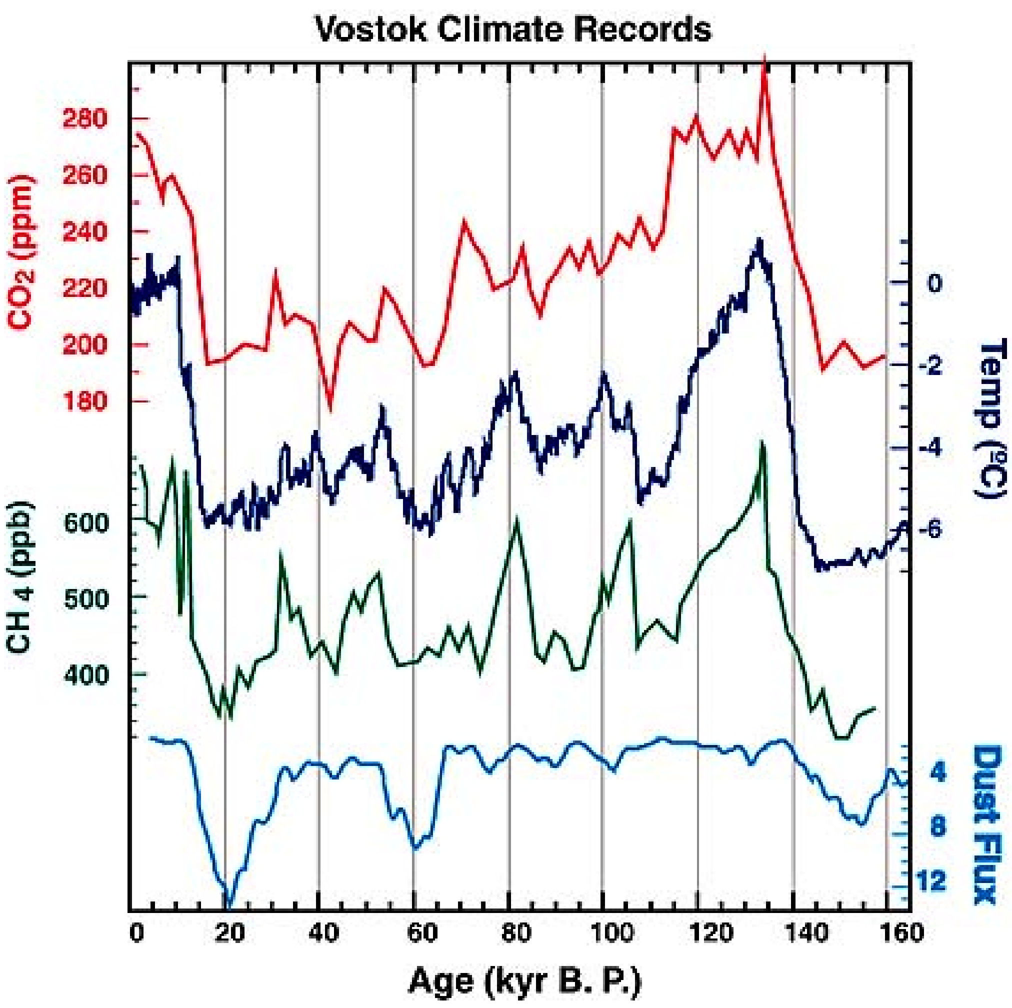


Figure 2 – Various climate records from the Vostok ice core (East Antarctica) covering the last 160,000 years. Included are the CO_2 and CH_4 greenhouse gas records, which are closely tied to Antarctic temperature variations over the last full glacial/interglacial climate cycle (Lorius et al., 1985; Barnola et al., 1987; Jouzel et al., 1987; Chappellaz et al., 1990). Temperature data are plotted as deviations from the present day mean annual temperature of -56ºC. Comparisons like these are important for deducing the impact of changing greenhouse gases on climate. Also included is the record of the flux of dust to the area (shown on an inverted scale for comparison purposes) (Petit et al., 1990). Higher dust fluxes during glacial periods are related to increased transport efficiency (stronger winds) and increased aridity in source regions.

Of prime importance is the temperature record, which has been reconstructed from data on the isotopic composition of paleoprecipitation (Lorius et al., 1985; Jouzel et al., 1987). The last interglacial period (centered at 130,000 years ago) had characteristic temperatures that were slightly higher than today. Beginning about 130,000 years ago, Antarctic temperatures dropped in a step-wise fashion until they reached full glacial values of at least -6^{o}C, relative to today, between 25,000 and 18,000 years ago. The last glacial/interglacial transition began around 18,000 years ago and ended around 10,000 years ago with a slight cooling trend apparent throughout the last 10,000 years.

The most oft-cited finding from the Vostok ice core is the close correspondence between temperature and concentrations of two radiatively active gases, viz., CO_2 and CH_4. During glacial periods, atmospheric CO_2 and CH_4 levels were 30% and 50% lower respectively than interglacial levels, (Barnola et al., 1987; Chappellaz et al., 1990). Because CO_2 and CH_4 absorb a portion of the outgoing long wavelength radiation and re-emit it back to the Earth's surface (a process better known as the greenhouse effect), higher concentrations of these gases in the atmosphere will tend to raise global surface temperatures (with all other factors being equal). The fact that atmospheric CO_2 and CH_4 levels were lower during the glacial period helps explain the lower temperatures and increased continental ice volume during these periods. In a study employing a general circulation model to test the sensitivity of global climate to CO_2 and CH_4 variations, Lorius et al. (1990) estimated that as much as 50% of the temperature variations over the last full climate cycle could be related to observed CO_2 and CH_4 variations. The strong degree of covariation between the concentration of greenhouse gases and climate throughout the last 160,000 years has been used to predict future climate changes related to the buildup of CO_2 and CH_4 in the atmosphere as a result of anthropogenic activities.

Rapid Climate Change Events

One of the most dramatic recent contributions to our understanding of paleoclimate during the last glacial cycle has come in the millennial scale range of climate variability. Unprecedented swings in the Earth's climate over sub-decadal to millenial time scales have now been recorded in two ice cores from central Greenland, instigating new, higher resolution investigations of land and marine paleoclimate records.

In 1993 the Greenland Ice Sheet Project Two (GISP2) successfully completed drilling to the base of the Greenland Ice Sheet in central Greenland. In so doing, GISP2, along with its European companion project GRIP (Greenland Ice Core Program), developed the longest (110,000 years) high resolution paleoenvironmental record available from the northern hemisphere. Based on the comparison of electrical conductivity and oxygen isotope series between the two cores (Grootes et al., 1993; Taylor et al., 1993), at least the upper 90% of these cores display extremely similar, if not absolutely equivalent records. The current best estimate of the age at this depth (~2800 meters) is ~110,000 years, based on a combination of multi-parameter annual layer counting (Alley et al., 1993; Meese et al., 1994a, 1997) and measurements of the oxygen isotope ratios ($\delta^{18}O$) of atmospheric O_2 calibrated with the Vostok ice core (Bender et al., 1994). Maximum error estimates in the dating are quite remarkable: 1% for the last 3,500 years, 2% to 40,000 years , 10% to 57,000 years and 20% at 110,000 years (Alley et al., 1993; Sowers, et al, 1993; Meese et al., 1994a, 1994b, 1997). Agreement between the GISP2 and GRIP ice cores (separated by 30 km or ~10 ice thicknesses) over the record period of the last ~110,000 years provides strong support for the climatic origin of even the minor features of these records and implies that investigations of subtle environmental signals can be rigorously pursued.

The millennial scale events recorded in the upper 110,000 years of the two central Greenland ice cores are unequivocally climate events. They represent large climate deviations (massive reorganizations of the ocean-atmosphere system) that occur over decades or less, during which ice-age temperatures in central Greenland may have been slightly more than 20^{o}C colder than today (Cuffey et al., 1995; Figure 3).

These climate deviations seem to have been largest during the cooling to the glacial maximum and the warming from the glacial maximum, with smaller amplitudes during the glacial maximum as well as during the interglacial maximum.

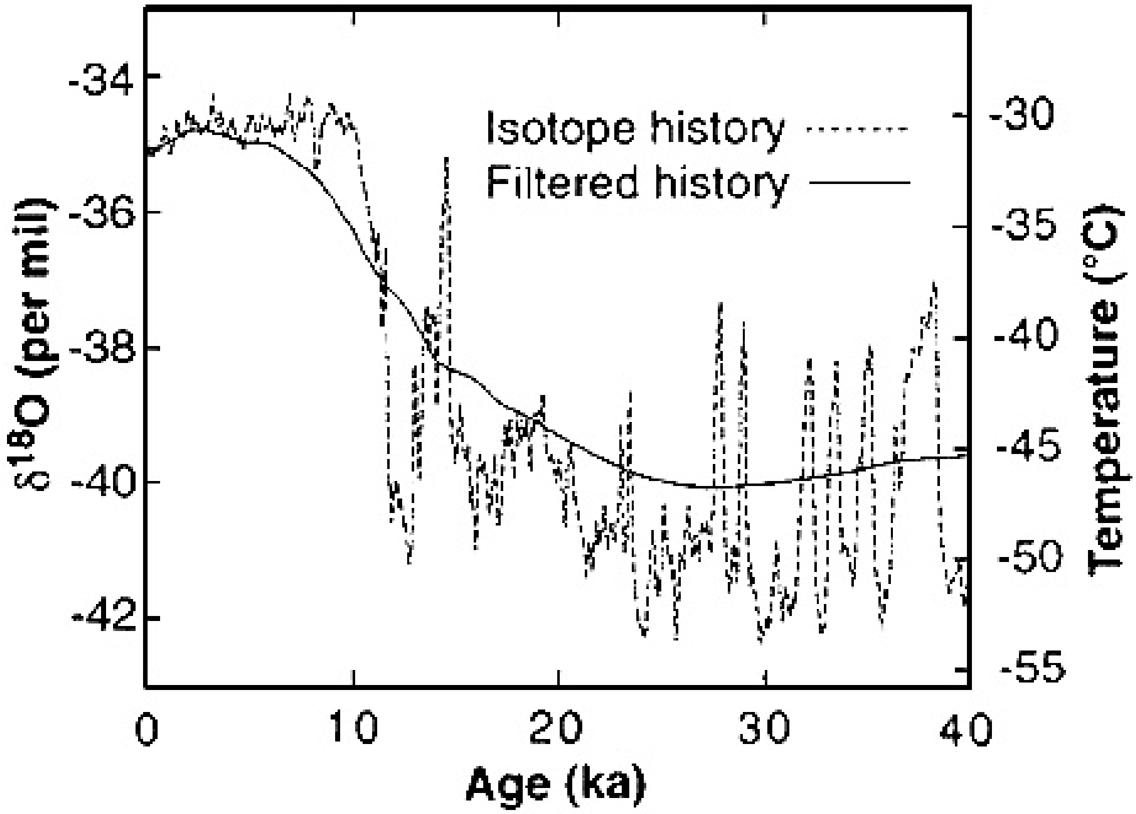


Figure 3 – The central Greenland $\delta^{18}O$ history for the most recent 40,000 years. The smooth curve results when this history is filtered to mimic the thermal averaging in the ice sheet. All temperature histories that give this same curve when filtered are indistinguishable to borehole thermometry. The right axis shows the calibrated temperature scale. Reprinted figure with permission from Cuffey et al., *Science,* 270, 455-458. ©1995, American Association for the Advancement of Science.

The GISP2 record of insoluble dust, which complements the dissolved calcium record, provides another insight into the abruptly variable global atmosphere and climate. It has long been known that the atmosphere was much dustier during cold periods than warm periods but the exact cause is not certain. Recent results from GISP2 using mineralogical and isotopic tracer characteristics (Biscaye et al., 1997) and continuous dust content by laser-light scattering (Ram and Koenig, 1997) have provided new insights into how source area conditions and dust production affects atmospheric turbidity. Using mineralogical and isotopic tracer characteristics, it was determined that dust from just prior to the last glacial maximum originated from the deserts of eastern Asia. Since these tracer characteristics were virtually constant throughout this period, the source areas could not have changed substantially in location or size, and the observed dust variations must have been due to changes in the intensity of atmospheric circulation (Biscaye et al., 1997). Examination of the GISP2 dust profile measured by laser-light scattering has revealed that the dust concentration in the core is modulated by an 11-year period back to 100,000 years before present. These modulations are believed to be a result of solar energy flux changes associated with the 11-year solar cycle which affects the aridity of dust source regions. The effect is very strong, particularly during the Wisconsinan, where fivefold changes in dust concentration occur over a single 11-year cycle (Ram et al., 1997; Figure 4).

Examination of a subsequent abrupt event, the Younger Dryas (a return to near-glacial conditions during the last deglaciation, previously identified in a variety of paleoclimate records), demonstrates the importance of conducting multi-parameter, high resolution paleoclimate investigations on well-dated records. During this event, lowered temperatures ($15^{o}C$ +/- $3^{o}C$ relative to today; Severinghaus et al., 1998) were accompanied by a 50% drop in snow accumulation (Alley et al., 1993), order-of-magnitude increases in the amount of wind-blown dust and sea-salt in the atmosphere (Mayewski et al., 1993a; Zielinski and Mershon, 1997) and large changes in methane concentration (Brook et al., 1996), synonymous with cold, dry, and dusty conditions (Figure 5).

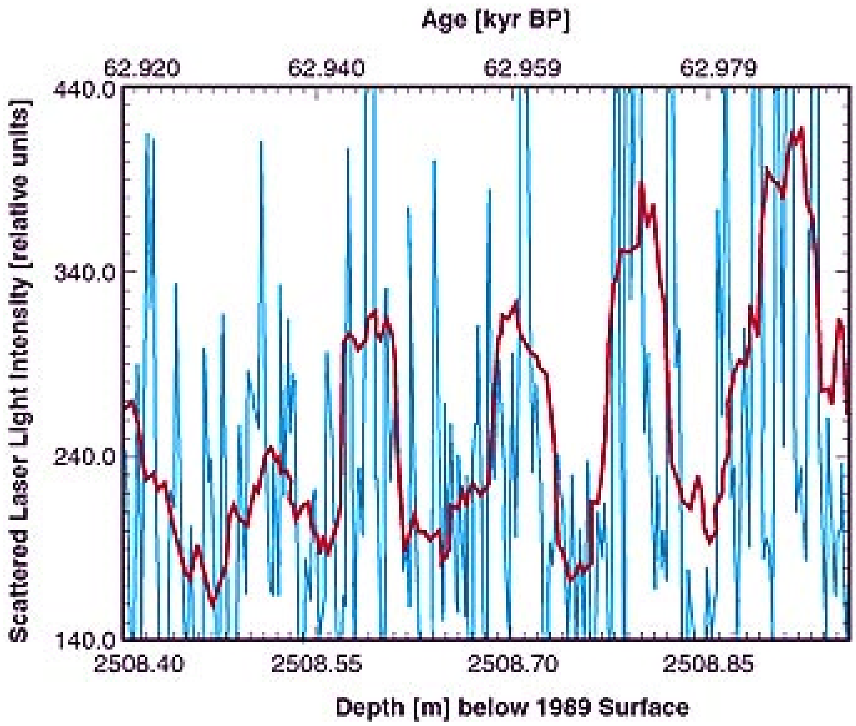


Fig. 4 – Expanded plot of a short section of the GISP2 ice core laser-light scattering data (light line). The dark line, which corresponds to a four-year running average of the data, shows five complete dust modulation cycles that have an average period of ~11 years. Similar modulations are present throughout the GISP2 ice core dust record. These modulations are attributed to the solar cycle. Taken from Ram et al. (1997).

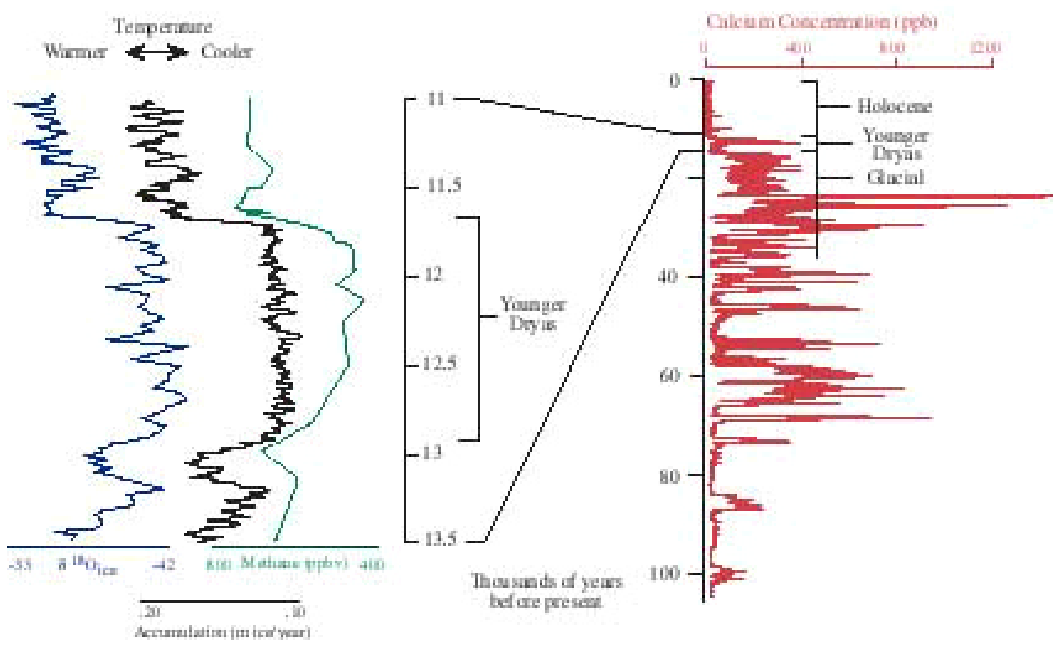


Figure 5 – Composite figure. Left: The Younger Dryas was an abrupt return to near glacial conditions (15 +/- 3oC cooling relative to today), decreased accumulation rate, decreased CH4, and increased atmospheric dust that lasted approximately 1300 years and punctuated the transition from glacial to interglacial climates. Figure modified from Alley et al., (1993), Grootes et al., (1993), Brook et al., (1996), Severinghaus et al., (1998). Right: This high resolution calcium record from the GISP2 ice core indicates the relative amount of dust in the atmosphere over Greenland and thus documents other abrupt, frequent and massive changes in climate that characterize the glacial portion of the ice core record. Figure modified from Mayewski et al. (1994, 1997).

Annually resolved sampling over early and late stages of the Younger Dryas indicates that this ~1300-year-duration event had an onset and termination each accomplished in 5-20 years (Alley et al., 1993, Mayewski et al., 1993a, Taylor et al., 1993, 1997; Figure 6). The identification of rapid climate change events in the GRIP CH_4 record (Chappellaz et al., 1993; Brook et al., 1996; Figure 7) prompted considerable interest in the identification of such events in other regions since the source areas for CH_4 during the last glaciation may have been in the middle to lower latitudes.

Recent work in correlating ice cores from Greenland and Antarctica has shown that the millennial scale "Dansgaard/Oeschger" events, which are so prominent in the North Atlantic, are also found in Antarctica when the event lasts more than 2,000 years (Bender et al., 1994; Figure 8).

Bipolar similarities in climate events are now known to extend to events less than 2000 years in duration (Mayewski et al., 1996) based on comparison between GISP2 and Taylor Dome ice cores (Figure 1). Unfortunately, it has not yet been possible to unambiguously establish the precise temporal relationship between the Greenland and Antarctic climate variations. The ambiguity arises partly from the uncertainty in the age difference between the solid ice and the gas trapped within it.

While the temporal relationship between the Antarctic and Greenland ice core climate records has yet to be established for rapid climate change events, timing of events leading to the last deglaciation has been suggested. The initial phase of the deglaciation in Antarctica is believed to begin with a warming at around 18,000 years ago (Sowers and Bender, 1995) that is coincident with a decrease in the flux of dust to Antarctica (Jouzel et al., 1992), increases in atmospheric CO_2 and CH_4 concentrations, and the initial rise in sea level as deduced from the U/Th-dated Barbados coral record (Bard et al., 1990). In the North Atlantic, deglaciation has been linked to the northward migration of the polar front and the consequent "turn-on" of deep water formation by 14,700 years ago. These results suggest that the North Atlantic warming may not have responded to the initial forcing that caused the southern hemisphere to warm, ice sheets to begin melting, and accumulation of CO_2 and CH_4 to increase in the atmosphere.

Ice core records provide a framework for the interpretations of records recovered from other natural archives. Paleoclimate records from North Atlantic marine sediment cores also contain notable millennial scale variability (e.g., Heinrich, 1988; Broecker et al., 1992; Bond et al., 1992; Andrews and Tedesco, 1992; Lehman and Keigwin, 1992), although the exact timing of these events is known less precisely than for the Greenland ice cores. Several of the marine cores reveal evidence that the formation of NADW (North Atlantic Deep Water-warm, saline, nutrient-depleted deep return flow water), and thus the oceanic thermohaline circulation, fluctuated dramatically in the past (e.g., Ruddiman and McIntyre, 1981; Boyle and Keigwin, 1987). NADW diminished greatly during the last glaciation and was relatively strong during the interglacials. Recent studies confirm that NADW fluctuates on millennial time scales and correlates with sea surface and atmospheric temperature (e.g., Oppo and Lehman, 1995).

Changes in the flux of ice-rafted detritus, $\delta^{18}O$ of foraminifera shells, and the abundance of climate-sensitive foraminifera, as recorded in deep sea sediments, indicate that during the last glaciation the North Atlantic was punctuated by iceberg discharge events, termed "Heinrich events" (Heinrich, 1988), potentially produced in response to changes in ice sheet dynamics (MacAyeal, 1993). The larger of these Heinrich events has a characteristic recurrence in the marine record of 5000-10,000 years. The Dansgaard/Oeschger rapid climate change events, which were first idenified in ice cores, are also observed in marine record (Bond et al., 1993; Bond and Lotti, 1995; Cortijo et al., 1995).

Evidence for the presence of millennial scale climate fluctuations has been extended beyond the North Atlantic and polar regions. Marine cores from the Santa Barbara Basin reveal that perturbations in the ocean circulation patterns of the East Pacific region (Kennett and Ingram, 1995; Kotilainen and Shackleton, 1995; Behl and Kennett, 1996;) correlate with ice-rafted debris events in the North Pacific and with the Greenland ice core records. Abrupt changes in atmospheric circulation patterns and precipitation regime are recorded over eastern Asia in a thick sequence of wind-deposited loess from central China (Porter and An, 1995). Records of alpine glacier fluctuations, mountain snowlines and paleo-vegetation in the Andes reveal climate fluctuations that are similar to events in the Greenland ice cores (Lowell et al., 1995).

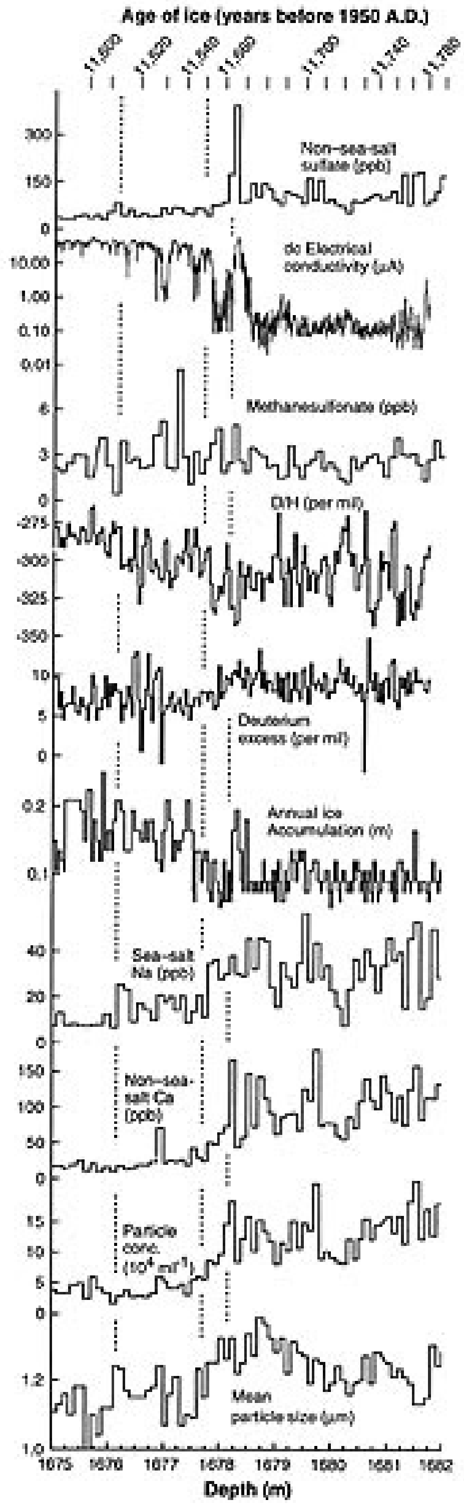


Figure 6 – Left: The Younger Dryas-Holocene transition as recorded in the GISP2 core. All data are plotted with depth as a linear scale on the bottom of the plots. The corresponding ages are on the top scale. The dashed vertical lines are time horizons to facilitate between plots. Reprinted by permission from Taylor et al., *Science*, 278, 825-827. ©1997, American Association for the Advancement of Science.

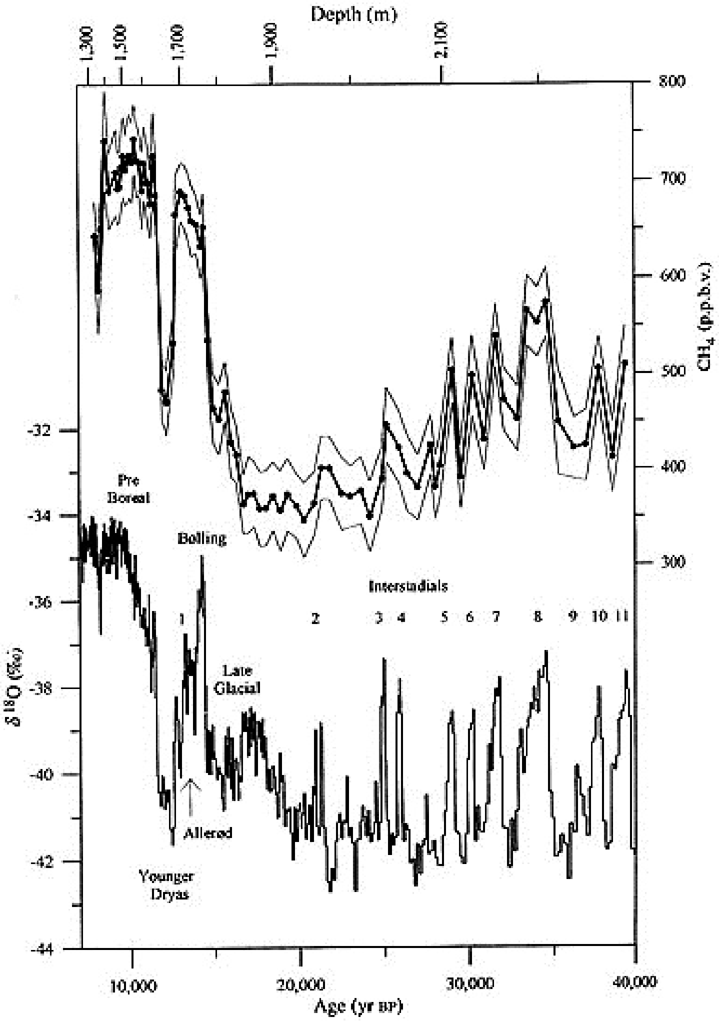


Figure 7 – Above: GRIP CH_4. The thick line runs through the mean concentration (black dots) and the two accompanying thin lines correspond to the experimental uncertainty. Bottom: $\delta^{18}O$ record along 2.2m sections of the core (Johnsen et al., 1992; Dansgaard et al., 1993;). The significant climatic events are noted by name or by suggested numbering (Dansgaard et al., 1993). The time scale applies to both records. The depth scale applies only to CH_4 curve (top) because of the difference in age between trapped air and ice at a given depth. Reprinted by permission from Chappallaz et al., *Nature* 345, 127-131. © 1993 Macmillan Magazines Ltd.

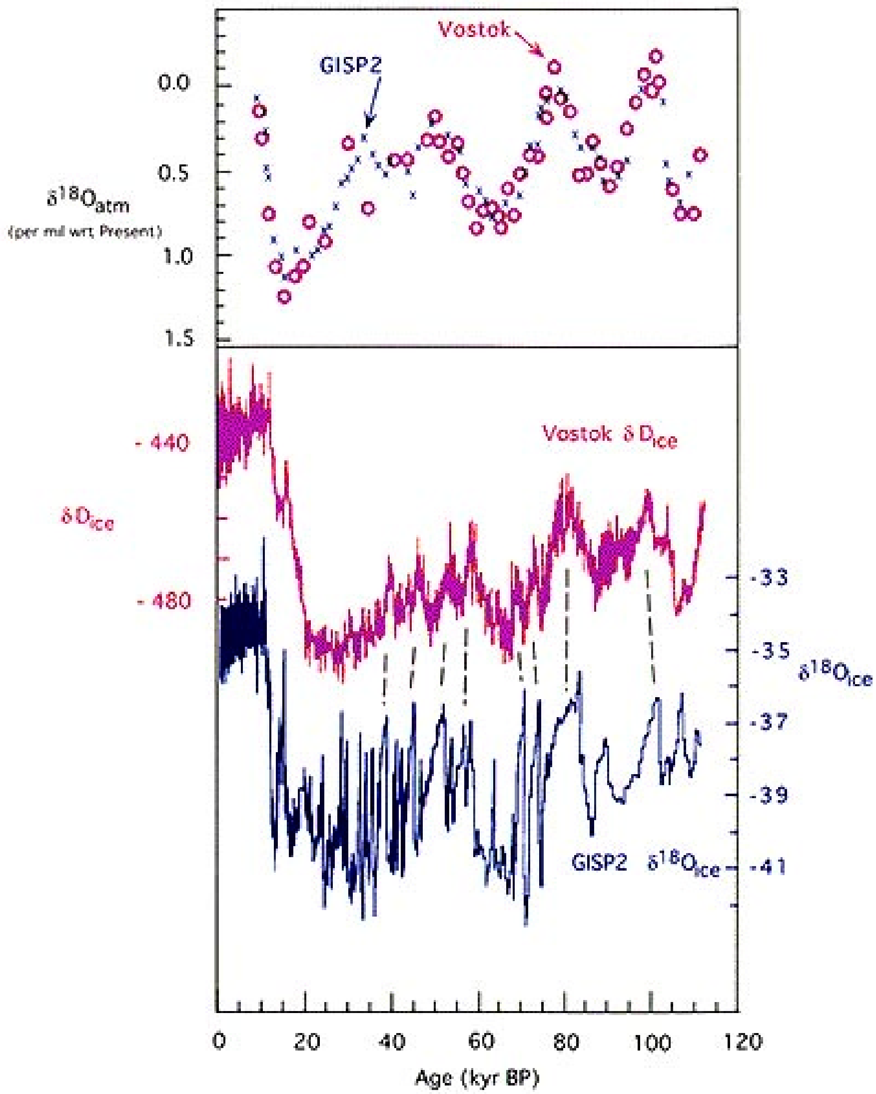


Figure 8 – Greenland (GISP2) and Antarctic (Vostok) climate records covering the last glacial-interglacial cycle. Upper part shows close correlation between GISP2 and Vostok $\delta^{18}O$ of O_2 in air in these ice cores. Lower part shows close correlation between δD and $\delta^{18}O$ (proxies for temperature) of the ice. Modified from Bender et al. (1994).

New advances in paleoclimate reconstruction also come from the tropics. For example, a 30,000-year-long paleotemperature record from lowland Brazil suggests a cooling of as much as 5°C (Stute et al., 1995), which contrast with earlier estimates from marine cores which limit cooling to < 3°C (CLIMAP Members, 1981). Further, an ice core from the Andes suggests reduced water vapor content during the Younger Dryas (Thompson et al., 1995). These new findings have stimulated examination of other tropical paleoclimate records and renewed investigations into climate forcing related to the hydrological cycle that is tied to changes in the tropics.

While the exact timing and causal mechanisms for glacial age climate fluctuations are not fully understood, important and new guidance is provided by high resolution, well-dated, continuous records like GISP2. For example, evidence of regularity in the timing of some climate events is building. Studies ranging from the North Atlantic (GISP2) to the subtropics demonstrate 1450-to 1800-year periodicities for rapid climate change events (Cortijo et al., 1995; Sirocko et al., 1996; Mayewski et al., 1997). In addition, the cumulative effect of multiple climate forcings can now be demonstrated. As an example, ~90% of the variance in the GISP2 paleoatmospheric circulation series is produced from a combination of the following: insolation changes induced by earth's orbital cycles, ice sheet dynamics, thermohaline ocean circulation and solar variability (Mayewski et al., 1997; Figure 9).

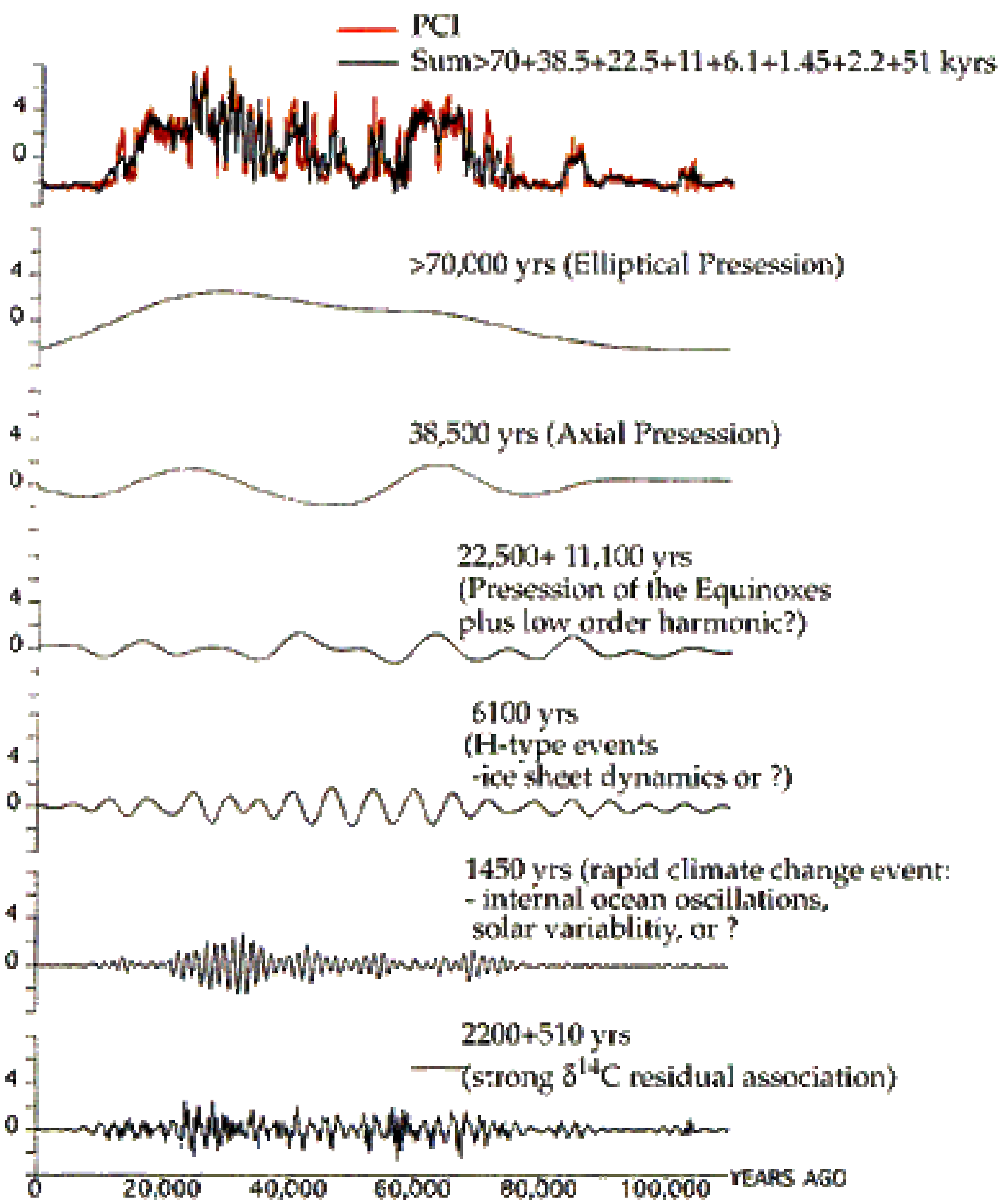


Figure 9 – Upper plate: The PCI (Polar Circulation Index) is a time series describing the dynamics (i.e., increase and decrease from mean values) of the well-mixed atmosphere represented by the dominant EOF of the major ions in the GISP2 ice core (Mayewski et al., 1994). The PCI provides a relative measure 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). The PCI is contrasted with the sum of the bandpass components (>99% significance) estimated from this series. The sum represents ~90% of the variance in the original PCI series. Lower plates: Major bandpass components derived from the PCI series include those with periodicities close to elliptical precession, axial precession, precession of the equinoxes, lower order harmonics of the foregoing, and periodicities potentially related to ice sheet dynamics, internal ocean oscillations and solar variability. The 6100-year bandpass component aproximates the timing of H (Heinrich events) and the 1450-year bandpass component the timing of the rapid climate change events (Dansgaard/Oeschger) in the GISP2 record. Figure modified from Mayewski et al. (1997).

Natural Climate Variability During the Holocene

Annually resolved, continuous paleoclimate records from the GISP2 ice core demonstrate that Holocene climate is characterized by annual to millennial scale variability and that Holocene climate is significantly more complex than glacial age climate (e.g., Meese et al., 1994b; O'Brien et al., 1995). Time series of major ion concentrations in the ice, used as tracers for major atmospheric circulation systems (Mayewski et al., 1994, 1997) reveal a strong association between expansions of northern hemisphere polar atmospheric circulation systems and a variety of discontinuous paleoclimate records (Denton and Karlen, 1973; Harvey, 1980) that record worldwide coolings (O'Brien et al., 1995; Figure 10).

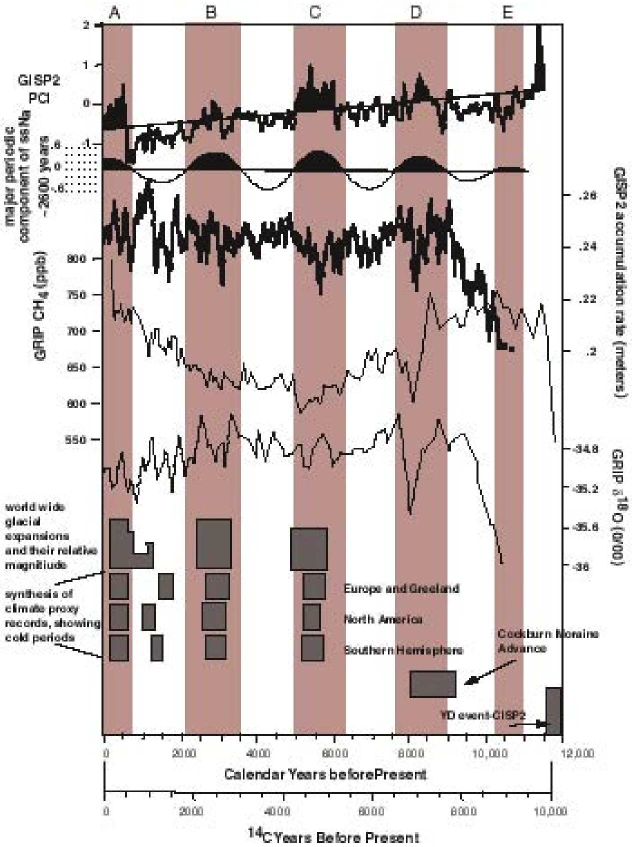


Figure 10 – GISP2 annually dated Holocene EOF1 (a proxy for northern hemisphere polar cell intensity (also referred to as the PCI–Polar Circulation Index–and described in Figure 9 caption) smoothed with a robust spline (equivalent to a 100-year smooth) with a quasi-2600-year periodicity (O'Brien et al., 1995); GISP2 accumulation rate (Meese et al., 1994b); GRIP methane (Blunier et al., 1995); GRIP _18O record (Dansgaard et al., 1993); worldwide glacial expansions and their relative magnitude (Denton and Karlen, 1973); synthesis of various climate proxy records from Europe, Greenland, North America, and the Southern Hemisphere showing cold periods (Harvey, 1980); the Cockburn Stade (Andrews and Ives, 1972; Alley et al., 1997; Stager and Mayewski, 1997) and the Younger Dryas event (Alley et al., 1993; Mayewski et al., 1993a). Letters specify major cold periods with A equal to the Little Ice Age.

Complexities in Holocene climate are noted in a comparison of several environmental parameters. For example, a major reorganization in the climate system ~7800-8400 years ago has recently been documented using a variety of northern hemisphere paleoclimate records plus the GISP2 ice core (Alley et al., 1997) and in a comparison of lake sediment records from tropical Africa with ice core records from Greenland and Antarctica (Stager and Mayewski, 1997). Based on the GISP2 record the climate system response during this major event operated similarly to pre-Holocene cooling events (Figure 4). Namely, cooler temperatures (more negative $\delta^{18}O$), reduced CH_4, reduced accumulation rate and intensification of polar atmospheric circulation (expanded PCI (polar circulation index)) vary together. However, the coherence between these variables weakens as the events get younger, and is particularly poor during periods between these events, suggesting increased regionalization of climate from early to late Holocene. This progressive regionalization of climate may be the manifestation of the varying influences of a variety of climate forcings such as changes in total and season-to-season insolation, ice sheet and sea ice extent, solar variability and volcanism (O'Brien et al., 1995).

Major reorganizations in Holocene climate as well as finer scale climate fluctuations may be explained by a combination of climate forcings. A variety of paleorecords are available from ice core studies for testing the impact of these forcing mechanisms, including, for example, ^{10}Be time-series (Beer, 1990; Steig et al., 1996; Finkel and Nishiizumi, 1997); CO_2 time-series (Barnola et al., 1987; Wahlen et al., 1991; Etheridge et al., 1996); CH_4 time-series (Chappellaz et al., 1993; Blunier et al., 1995; Brook et al., 1996) and volcanic sulfate time-series (Zielinski et al., 1994, 1996a). Particularly exciting results from high-resolution ice cores include the observation that many geochemical parameters show strong spectral power at frequencies close to or identical to those observed in the sun. Worldwide coolings during the Holocene have a quasi-periodicity of 2600 years in phase with previously defined ~2500 year variations in $d^{14}C$ (e.g., Denton and Karlen, 1973; Stuiver and Braziunas, 1989, 1993; O'Brien et al., 1995). Also, $\delta^{18}O$ in the GISP2 core is coherent with both the ice-core ^{10}Be time-series and with the tree-ring record of atmospheric ^{14}C (Stuiver et al, 1995; Figure 11). Remarkably, the series are coherent not only in phase but also in amplitude, providing what is probably the best evidence to date for the elusive sun-climate relationship, a subject of debate for more than a century.

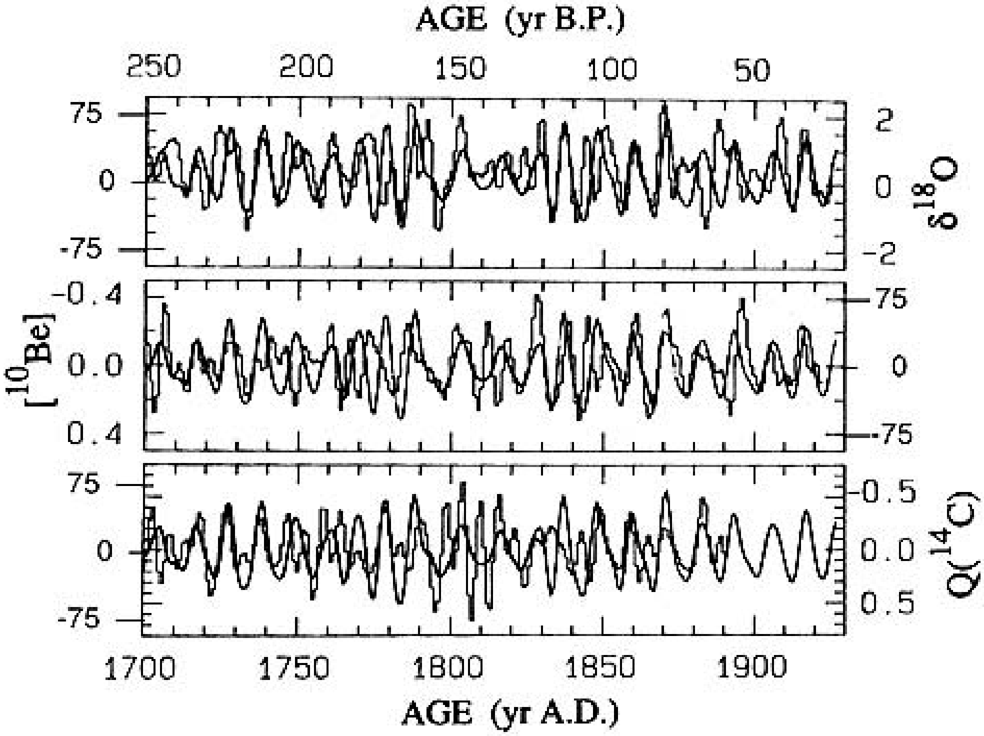


Figure 11 – Comparison of stable isotope ($\delta^{18}O$) ratios in the GISP2 core, ^{10}Be in the Dye 3 core, and ^{14}C residual in tree rings with sunspot number (bold lines). All time-series were filtered using an identical 10-12 year bandpass filter. Taken from Stuiver et al. (1995).

The detection of the solar cycle in dust concentrations and geochemical data may not only provide information about the sun-climate relationship, but can be used to improve ice core chronologies. It is possible to detect the 11-year cycle in ^{10}Be at some low-accumulation-rate sites where annual stratigraphy is not preserved (Steig et al., 1998). Measurement of the "11-year" layer thickness can be used as an independent check on flow-model estimates of layer thickness and to estimate past accumulation rates, or to provide a direct, layer-counted chronology.

Extreme Events-Volcanic Events and Biomass Burning

Perhaps no single naturally occurring phenomenon better illustrates the dynamic nature of the Earth and its individual systems than does an explosive volcanic eruption. Ice core records provide the best means available to the scientific community for determining the potential atmospheric impact of explosive volcanic activity with several key findings of global significance stemming from these studies. For example, volcanic events recorded in Greenland ice core sulfate series correlate with annual changes in atmospheric temperature, providing evidence for sulfate aerosol shielding (Lyons et al., 1990; Stuiver et al., 1995; White et al., 1997; Figure 12) and providing the most reliable means for evaluating past variability within the volcanism-climate system.

Estimates of the stratospheric mass loading of an eruption with the subsequent calculation of the stratospheric optical depth (Zielinski, 1995), as derived from volcanic sulfate flux values, are the important parameters needed to hindcast and forecast the climatic impact of an eruption. These parameters are particularly useful to climate modelers.

Ice core records from both polar regions have clearly shown that the number of eruptions capable of perturbing climate over the last 110,000 years is far higher than previously thought as based on geological and historical records (e.g., Langway et al., 1995; Zielinski et al., 1996a; Figure 13).

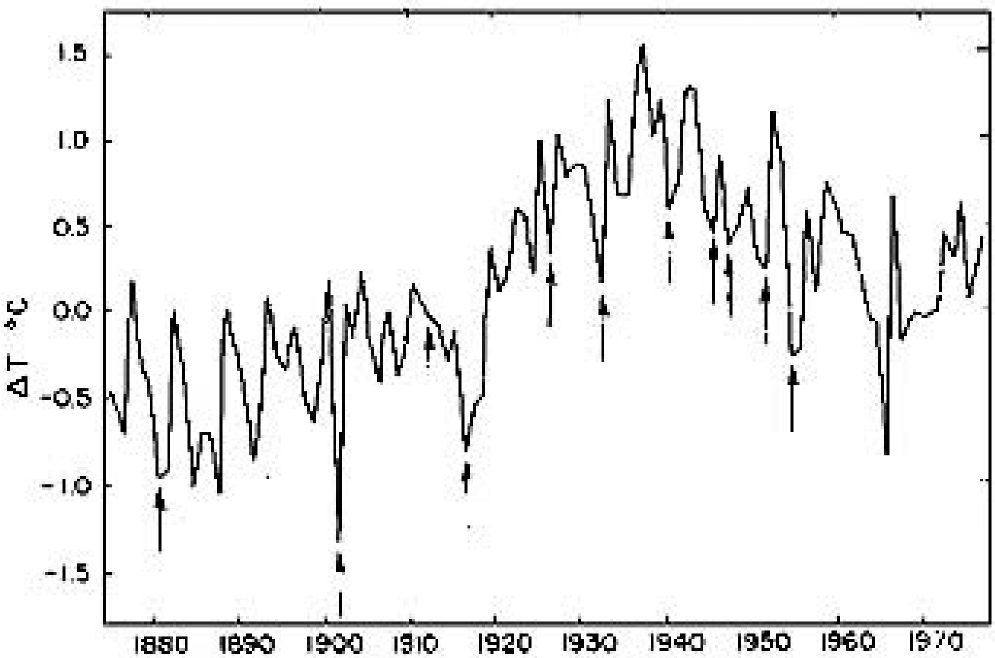


Figure 12 – Average yearly temperature change between 60-90°N from AD 1875-1977 (Self et al., 1981). Arrows represent volcanic events observed in the 20D ice core (Mayewski et al., 1990) from southern Greenland. Taken from Lyons et al. (1990).

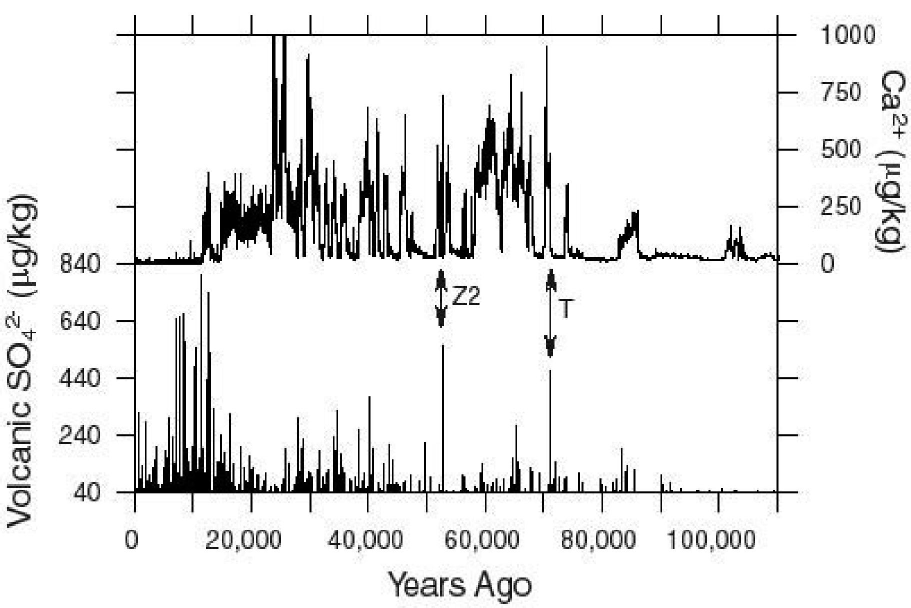


Figure 13 – The 110,000-year GISP2 record of volcanic SO_4^{2-}, compared to the GISP2 Ca^{2+} record (higher calcium reflects colder climatic conditions, lower calcium reflects warmer climatic conditions). All of the eruptions represented by the signals shown here probably were of sufficient magnitude to have perturbed climate. The number of eruptions recorded in the GISP2 core is fewer than the number of northern hemisphere or equatorial eruptions that actually occured over the last 110,000 years because of the decreased temporal resolution of individual samples with depth and age. Also shown are glaciochemical signals believed to be from the equatorial Toba eruption (T) and the high-latitude Icelandic eruptions that produced the Z2 tephra layer in North Atlantic marine sediment cores. Tephra found in the the Z2 layer of the GISP2 core matches that found in marine sediments (Zielinski et al., 1997), thereby providing an example of one absolute means of establishing a distinct time line for correlation among ice core, marine, and terrestrial records. Modified from Zielinski et al., 1996a.

Ice core records have shown that in some cases large historical eruptions have been poorly studied and that these eruptions undoubtedly had a major impact on the atmosphere (e.g., Dai et al., 1991; Delmas et al., 1992; Zielinski, 1995). Consequently, future activity from these same volcanoes should be monitored closely. Findings from the GISP2 ice core suggest that the Toba eruption (largest eruption of the last 500,000 years, occurring about 71,000 years ago) may have been a driving force leading to several centuries of cold climatic conditions. Should such an eruption occur today it would have a tremendous impact on human populations (Zielinski et al., 1996b). Interestingly, the results from the GISP2 ice core also yielded information that supports a converse hypothesis, namely, that deglaciation can actually lead to increased volcanic activity, particularly in the northern hemisphere (Zielinski et al., 1997).

An additional phenomenon that has an impact on the chemistry of the atmosphere and biogeochemical cycles as a whole is widespread biomass burning. As for the volcanic records in ice cores, it has recently been determined that changes in chemical species such as ammonium, potassium and nitrate (NO3) recorded in ice cores characterize the deposition of chemical compounds associated with plumes from biomass burning events (e.g., Legrand et al., 1992; Dibb et al., 1996). As of now, the available records reflect variability in biomass burning events in the northern hemisphere and particularly in subarctic regions of Canada and possibly into Alaska (Whitlow et al., 1994; Taylor et al., 1996). Establishing the past record of these burn events enables the scientific community to evaluate the relationship between hot and dry climatic conditions and the frequency of large fires (such as the Yellowstone fires of 1988). Burn records from several northern hemisphere ice cores have shown the impact of fire management in North America over the last few decades (Whitlow et al., 1994).

Recent Climate Change (last 2000 years) as a Precursor to Modern Climate

Although the exact timing and geographic distribution of Holocene climate change events is complex, the last 1000-2000 years offer important opportunities for unraveling the climate variability, on centennial scales and finer, that influences modern climate. There is general agreement that glaciers around the world and, notably, Arctic sea ice expanded during at least parts of the 13th to 19th centuries (Grove, 1988), a period called the Little Ice Age (LIA), and that warming occurred for several centuries prior to this period, at least in some regions, during what is controversially called the Medieval Warm Period (MWP). Previous research summarized by Lamb (1995) demonstrates changes in climate such as increased severity of winter storms and sea ice extent plus accompanying changes in food harvests during the LIA and contrasting milder conditions during the MWP.

The LIA event appears to play an important role in our understanding of modern climate. Based on the GISP2 paleo-atmospheric circulation record (Figure 10) the LIA had the most abrupt onset (AD 1400-1430) of any of the Holocene rapid climate change events (O'Brien et al., 1995). This extends previous findings from a 1500-year-long ice core record in the Andes (Thompson and Mosley-Thompson, 1987) and a 1300-year-long ice core from central Greenland (Mayewski et al., 1993b) both of which suggested that entrance into and out of the LIA was abrupt.

A bipolar comparison of annually resolved ice cores from Greenland (GISP2) and West Antarctica (Siple Dome, Figure 1) demonstrates the near synchronous onset of increased intensity of marine storminess in the North Atlantic and South Pacific, that characterized the onset of the LIA (AD 1400-1420) (Figure 14).

Interestingly, marine storminess in these regions has yet to return to MWP levels, and some combination of changes in earth orbit-induced insolation, solar output, greenhouse gases, and perhaps volcanism and other factors must be invoked to explain the timing and duration of the LIA (Kreutz et al., 1997).

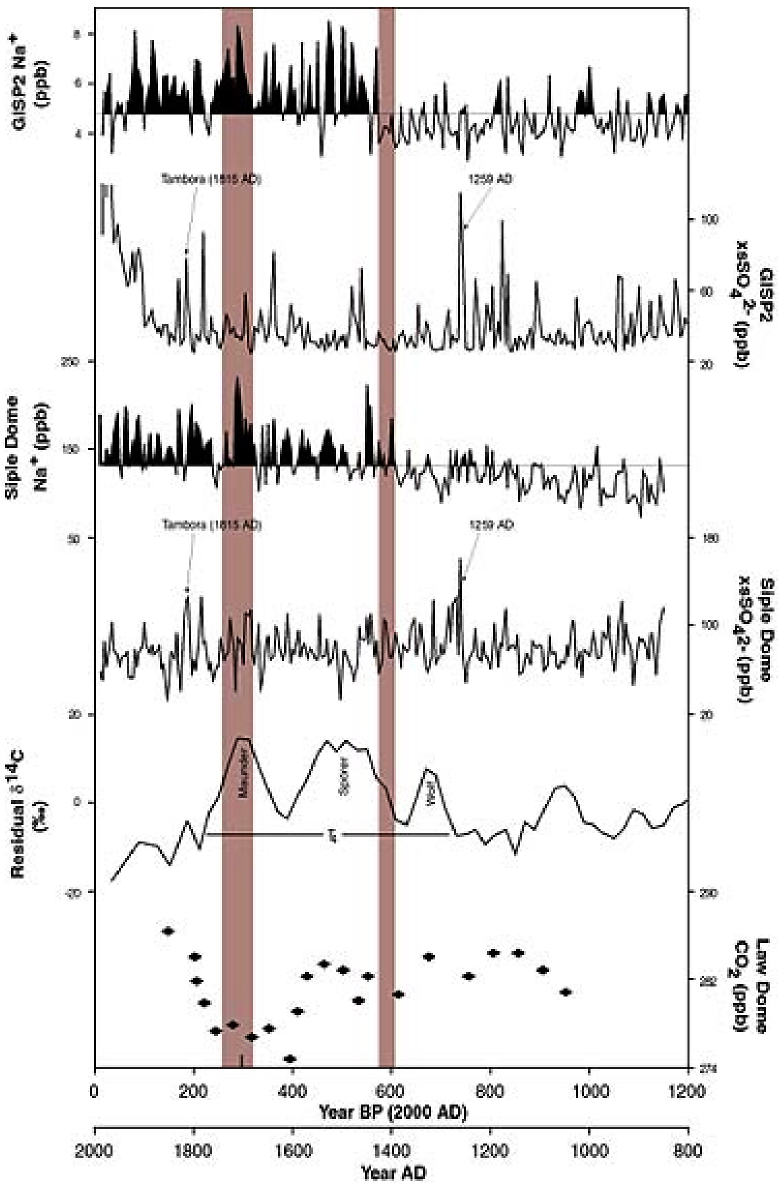


Figure 14 – Comparison of GISP2 and Siple Dome ice core records with potential climate forcing factors. The GISP2 and Siple Dome Na and excess (xs) SO_4^{2-} records (in ppb) were resampled to 5-year intervals (the lowest common resolution in both records is ~3 years). Two time periods discussed in the text are highlighted: 1680-1730 AD (period of coeval Na increase in Siple Dome and GISP2 records) and 1399-1427 AD (onset of LIA conditions). Two prominent volcanic events at 1815 AD (Tambora) and 1259 AD (possibly El Chichon) were used to confirm the Siple Dome annual layer counting and to correlate with the GISP2 record. The obvious $xsSO_4^{2-}$ increase during the last century in the GISP2 record, attributed to anthropogenic emissions (Mayewski et al., 1986), is notably absent from the Siple Dome and other Antarctic $xsSO_4^{2-}$ records . Other potential climate forcing factors include solar activity $\delta^{14}C$ residual series (Stuiver and Braziunas, 1989) and CO_2 (the scale has been expanded to highlight LIA changes and does not include 20th century values) (Etheridge et al., 1996). Reprinted by permission from Kreutz et al., Science, 277, 1294-1296. © 1997, American Association for the Advancement of Science.

Hindcasting Instrumental Records

The ice core record offers great potential as a tool for deciphering regional climate variability. Where relationships can be developed between instrumental and paleoclimate records, the latter can be used to hindcast the former. Several examples follow.

GISP2/GRIP $\delta^{18}O$ and δD (deuterium) series have significant correlations with the North Atlantic Oscillation (NAO, pressure contrast between Icelandic Low and Azores High) instrumental series, demonstrating that the former can be used in hindcasting this series (Barlow et al., 1993; White et al., 1997; Figure 15).

Proxy ENSO(El Nino Southern Oscillation) series are available from polar ice cores (Legrand and Feniet-Saigne, 1991) and tropical ice cores (Thompson et al., 1992). For example, over the past 60 years in south polar snow and firn, high methylsulfonic acid (MSA) concentrations are correlated with the occurrence of El Nino years, possibly reflecting more efficient air-sea exchange of dimethyl sulfide (DMS) due to higher winds (Legrand and Feniet-Saigne, 1991). Proxies for Antarctic sea ice extent are also available (Welch et al., 1993; Steig et al., in press).

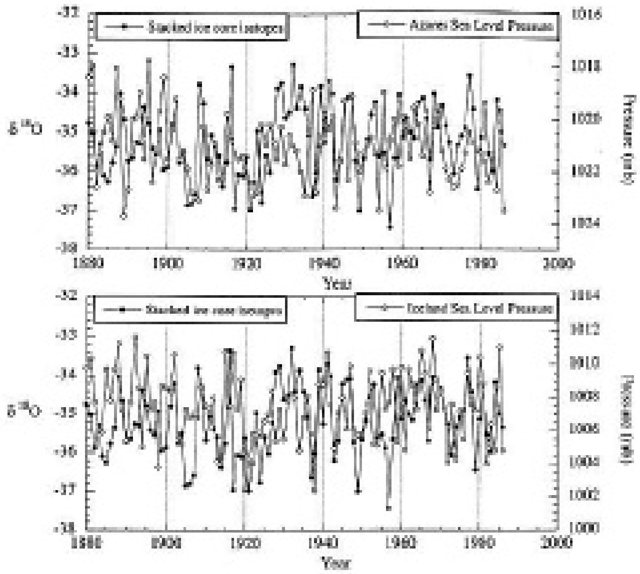


Figure 15 – Comparison of stacked isotope record from the Summit Greenland ice cores with sea level pressure measured in Iceland and the Azores. These sites are used in calculating the North Atlantic Oscillation (NAO) index. Note that the pressure in the Azores is inverted. Correlation coefficients is 0.256 (with Iceland) and 0.248 (with Azores). Taken from White et al. (1997).

Anthropogenic Impact on Atmospheric Chemistry

Over the last 200 years, world population has increased by more than 500% (McEvedy and Jones, 1978). One consequence of the population explosion and industrialization is increased CO_2, CH_4 and nitrous oxide (N_2O) emissions over a very short time period. Because the removal of these species from the atmosphere cannot keep pace with the elevated emissions, the concentration of these trace species has been increasing. However, the first direct measurements of these trace gases were not made until after 1957 AD which constitute the best archive of atmosphere prior to 1957. The record of the concentration of CO_2, N_2O, and CH_4 in the atmosphere over the last 200 years has been reconstructed from measurements of the trapped gases in ice (Figure 16).

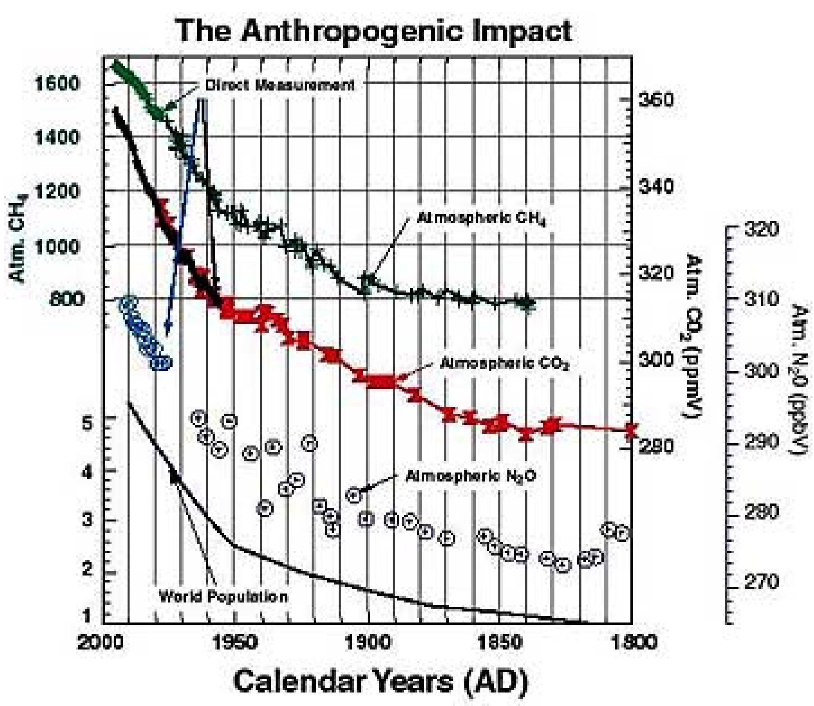


Figure 16 – Atmospheric compositional variations throughout the last 200 years as deduced from analyses of trapped gases in Antarctic ice. The records show the rapid accumulation of three trace gas species in the atmosphere, largely the result of increased emissions of these gases, which relate to increased world population (McEvedy and Jones, 1978). Also included are records of direct measurements, which started in 1957 (Keeling et al., 1976). Data taken from Etheridge et al. (1992, 1996) for CO_2 and CH_4, and Machida et al. (1995) for N_2O.

The results show a doubling of CH_4, a 25% increase in CO_2, and a 10% increase in atmospheric N_2O concentrations. While there is still some doubt as to the exact portion of the increase which can be related to human activities, there is no doubt that the majority of the increase in all three species is related to the world population increase and accompanying industrial and land use stresses over the last two centuries.

High resolution time series for sulfate and nitrate from a south Greenland ice core covering the last two centuries show dramatic increases in the concentration of these anions over the past one hundred years and clearly demonstrate the difference between natural, pre-1900 levels of these two acidic species versus post-1900 values (Mayewski et al., 1990; Figure 17).

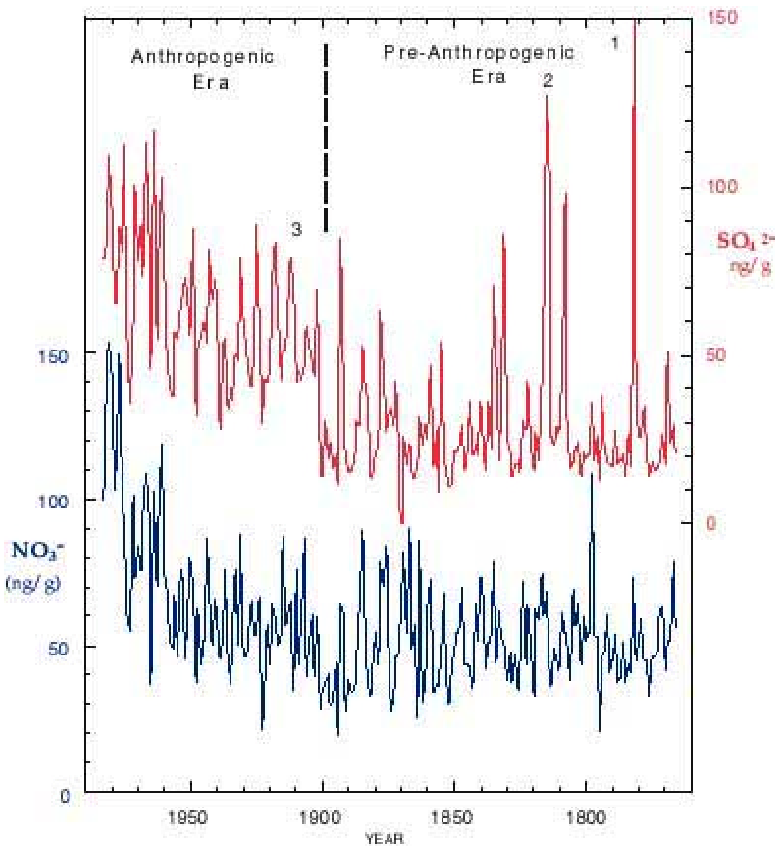


Figure 17 – Time series of the non-seasalt sulfate (SO_4^{2-}, red line) and nitrate (NO^{3-}, blue line) concentrations at ice core site 20D, southern Greenland. To remove seasonal signals, data have been smoothed to 1 year from the original ~5.8 samples per year. Examples of volcanic events recorded in nss sulfate spikes are: (1) Laki (1783); (2) Tambora (1815); (3) Katmai (1912). Modified from Mayewski et al. (1990).

In the pre-anthropogenic atmosphere over Greenland, nitrate levels were approximately twice the sulfate levels. Increased levels of sulfate during the anthropogenic era mask volcanic sulfate levels, indicating the large rise over natural background during this period. An observed increase in excess chloride (portion of chloride not at seasalt ratio) at GISP2 (Mayewski et al., 1993b) as of the 1940s is believed to be a byproduct of the increased levels of anthropogenically derived nitric (HNO_3) and sulfuric (H_2SO_4) acids, which are believed to aid in the volatilization of hydrochloric acid (HCl) from seasalt aerosol (Eriksson, 1959). Confirmation of the role that anthropogenic pollutants may have on perturbing the chemistry of the atmosphere comes from the coincidence of increased sulfate levels and depression of North Atlantic temperatures between ~1940-1970 (Wigley, 1990; Charlson et al., 1992), which has been demonstrated by a comparison of GISP2, south Greenland and Yukon Territory ice cores with temperature change records (Mayewski et al., 1993c).

Documentation of the distribution of the radioactive fallout related to the Chernobyl nuclear accident has been aided by analysis of ice cores throughout the polar regions. Remarkably, this event is even detected at the South Pole (Dibb et al., 1990).

Human Response to Climate Change As Deduced From the Paleorecord

Although the issue of human response to climate change is controversial, several recent studies find close correlations in timing between climate change and changes in civilization. These studies have focused on changes in temperature in relation to high latitude societies and changes in moisture availability for mid to low latitude societies.

In ice marginal regions, events such as the disappearance of the Norse colonies in Greenland during the mid to late 14th century appear to be chronologically correlated at some sites with the occurrence of a few extremely cold winters at the onset of the LIA and recorded in Greenland ice cores (Stuiver et al., 1995; Buckland et al., 1996).

Ice cores recovered from the Peruvian Andes have provided evidence connecting the rise and fall of coastal and highland human activity to regional climatic changes. Annual accumulation records reconstructed from the Quelccaya ice cores (Thompson et al., 1985) indicate that an extended period of relatively high accumulation from about 750 to 1050 AD roughly corresponds to when southern highland cultures flourished (Thompson et al., 1994). Low accumulation intervals before and after this period in the ice core are synchronous with the flourishing of Peruvian coastal cultures, which declined during highland wet periods. Similarly, the highland cultures declined during the low accumulation intervals seen in the ice core. An explanation may be related to ENSO events, during which precipitation today in coastal Peru and Ecuador is out of phase with that in the southern Peruvian highlands. The Quelccaya records suggest that this seesaw relation may have been a persistent feature of the regional climate, extending over at least a millennium.

Pronounced dust peaks from the Quelccaya record lasting about 130 years and centered at about 600 and 900 AD seem to reflect local agricultural activity, rather than climatic or volcanic events (Thompson et al., 1987). Analysis of the dust indicates that it is primarily of local origin with few volcanic shards, while the periods of enhanced dust concentration do not correspond to pronounced isotopic variations. These ice core records document an intimate connection between climate and human activity in this region and enhance our understanding of the evolution of human society.

Key Scientific Questions for Future Ice Core Research

The key scientific questions facing paleoclimate researchers have been articulated in a series of international projects including: PAGES (Past Global Changes), IGBP; CLIVAR (Climate Variability), WCRP; and GLOCHANT (Global Changes in the Antarctic), SCAR. Through the integration of ice, ocean and terrestrial paleorecords, these international efforts seek to develop a basis for understanding the characteristics of natural global environmental change, notably climate change. These paleodata are essential for assessing human influence on the global environment and for the evaluation of predictive climate models.

Several questions and issues have evolved as foci for the paleo community. These consensus views have been expressed in several documents, notably PAGES PANASH (1995) and the PAGES/CLIVAR Intersection (1994). These documents and the lessons learned from previous ice core studies form the basis for the following key scientific aims developed by the Ice Core Working Group.

- Understand and predict regional to global scale climate variability, e.g., frequency and magnitude of extreme events such as rapid climate change events, ENSO, NAO, monsoon, volcanism.

- Extend our understanding of anthropogenic perturbations on the composition of the atmosphere, e.g., radiative forcing, acid deposition, ozone, trace metals, distribution of radioactive fallout.

- Understand and predict regional to global scale variability in Earth's biogeochemical cycles (i.e., Carbon, Sulfur, Nitrogen, Oxygen), e.g., climate forcing, biosphere productivity.

- Provide critical information necessary to understand the influence of climate change on human habitability, e.g., socio-economic impacts, water resources, sea level changes, storm frequency.

Requirements for the Continuation of U.S. Ice Core Research

In order for U.S. ice core research to maintain its cutting edge in the field of paleoclimate, the Ice Core Working Group suggests that the following requirements be vigorously addressed:

1. Recovery and analysis of a global array of well-dated, high-resolution, continuous, multivariate ice core records.
2. Production of lightweight, inexpensive, intermediate depth (300-500m) ice core drilling capability.
3. Archiving of long-term meteorological records and maintenance of existing stations.
4. Year-round surface and air monitoring coupled to selected major drill sites.
5. Standard site surveys for deep drilling sites to include: radar, surface geophysics, stake nets, shallow coring and snowpits.
6. Continual development of high resolution analytical capabilities.
7. Development of additional regional to global scale stratigraphic markers.
8. Expansion of modeling efforts to enhance interpretation of ice cores.
9. Continuation of efficient data and sample management and an archival repository site.
10. Timely dissemination of results to the scientific community and the public.
11. Maintenance of established centers of excellence and opportunities for the inclusion of new investigators.

Future Directions for U.S. Ice Core Research

The Ice Core Working Group has developed a plan for future U.S. ice core research that outlines ice coring activities in three broad geographic regions (Antarctica, mid-low latitudes and the Arctic).

Antarctica

The vast continent of Antarctica has been a major focus of scientific exploration for relatively few decades when compared to most areas on Earth. Yet what is already known about Antarctica conclusively demonstrates that despite its remote location it plays a significant role in the global system. Encircled by the world's most biologically productive oceanic regions, Antarctica is the largest storehouse of fresh water on the planet, a major site for the production of the cold deep water that drives ocean circulation, a major player in Earth's albedo dynamics, and an important driving component for atmospheric circulation. Thus, Antarctica plays a critical role in the dynamic linkages that couple the spatially and temporally complex components of the Earth's system (atmosphere, biosphere, anthrosphere, hydrosphere, cryosphere and lithosphere).

While several ice cores have been recovered from Antarctica (Figure 18), surprisingly few of them are well dated or provide continuous, multivariate records.

As a consequence, understanding of even the modern spatial distribution of some primary ice core parameters is quite limited. Based on modern understanding of the regional differences in climate, the sparse distribution of well-documented records does not provide sufficient temporal or spatial coverage. As a consequence, the U.S. and several other nations have embarked on a series of new ice coring activities. Over the next few years U.S. ice coring activities will primarily focus on two community projects in West Antarctica, WAISCORES and U.S. ITASE.

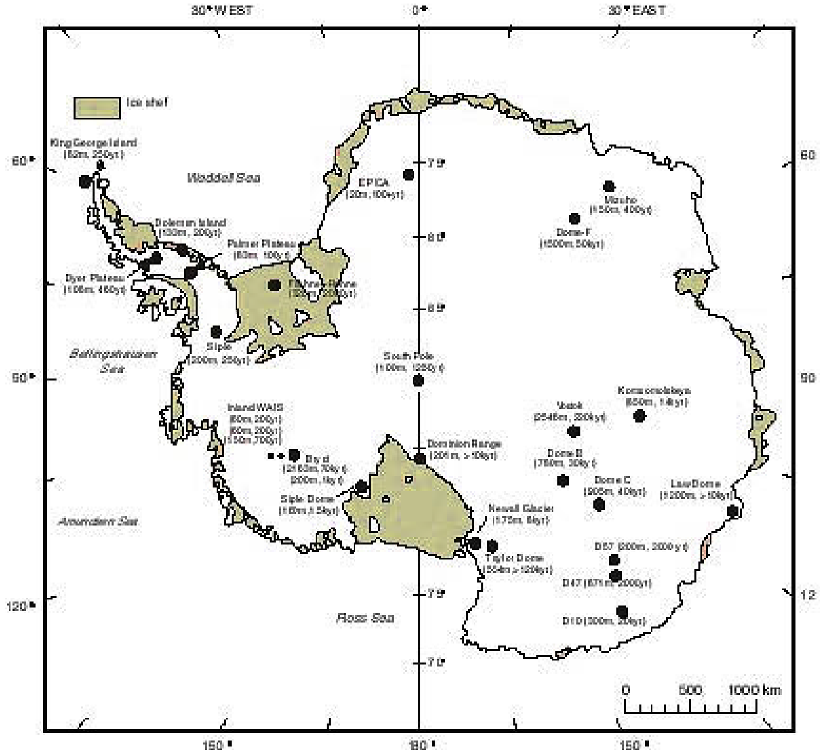


Figure 18 – Distribution of ice cores collected and analysed in Antarctica as of 1996 (depth, approximate time period). Taken from U.S. ITASE (1996).

WAISCORES (Siple and Western Divide)

The main goals of the WAISCORES program are to investigate the stability of the West Antarctic Ice Sheet and to investigate the cause of rapid changes in climate. The program is part of the larger West Antarctic Ice Sheet (WAIS) Program already underway. The program will analyze two ice cores, one from Siple Dome, and one from an inland site near the ice flow divide in West Antarctica. The two sites have different characteristics.

Siple Dome, at a lower elevation (680 m) near the edge of the ice sheet, is surrounded by ice streams. The Western Divide (or Inland) site will be at a higher elevation (~2000m) that is more representative of the center of the WAIS. Both sites are expected to provide records of the last 80,000+ years, with annually resolved records to ~11,000 years ago at Siple Dome and ~30,000 years ago at the Western Divide site (Nereson ET al., 1996). Site selection activities are underway for the Western Divide site, where drilling is expected to begin around 2002. Drilling started at Siple Dome in 1996/97, and a 1000 m core is expected to be recovered by January 1999.

There are now 14 science groups funded by NSF to work on the Siple Dome core. More projects may be added. In conjunction with other ongoing programs, the Siple Dome Project will address many aspects of climate change and ice sheet stability, including:

1. What is the elevation history of Siple Dome, and what does this say about the existence and size of the WAIS in the past?
2. What is the age of deep ice and the history of its site of origin, and what do these reveal about the existence and size of the ice sheet in the past?
3. What is the phase relationship between northern and southern hemisphere climate?
4. What is variability of climate on time scales of decades to millennia and subcontinental spatial scales?
5. What are the causes of previous climate changes?
6. What is the origin of the deep ice at Siple Dome, and has it always been a dome?

For further information about WAISCORES, refer to the Ice Core Working Group document "Science plan for WAISCORES deep ice coring in West Antarctica" or the WAISCORES web site at http://www.maxey.dri.edu/WRC/waiscores, where the science plan and other information is available.

ITASE and U.S. ITASE

The broad aim of the multi-national ITASE (International Trans Antarctic Scientific Expedition) effort is to establish how the recent atmospheric environment (climate and atmospheric composition) is represented in the upper layers of the Antarctic ice sheet. This activity has been formally accepted at the international level by both PAGES (IGBP) and GLOCHANT (SCAR). Primary emphasis is placed on the last ~200 years of the record. This time period was chosen since observational records for the Antarctic are sparse in time and space and because it covers the onset of major anthropogenic involvement in the atmosphere. Four U.S. ITASE traverses are planned as a complement to WAISCORES (Figure 19).

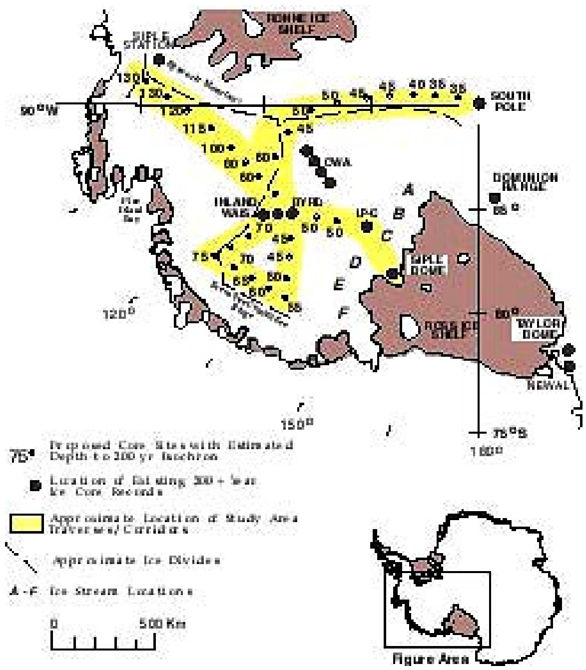


Figure 19 – U.S. ITASE traverse plans in West Antarctica. Taken from U.S. ITASE (1996).

The following six major U.S. ITASE scientific objectives have been formulated in order to understand environmental change in West Antarctica:

1. What is the current rate of change in mass balance over West Antarctica?
2. What is the influence of major atmospheric circulation systems (e.g., ENSO) and oceanic circulation on the moisture flux over West Antarctica?
3. How does climate (e.g., temperature, accumulation rate, atmospheric circulation) vary over West Antarctica on seasonal, interannual, decadal and centennial scales, and what are the controls on this variability?
4. What is the frequency, magnitude and effect (local to global) of any extreme climate events recorded in West Antarctica?
5. What is the impact of anthropogenic activity (e.g., ozone depletion, pollutants) on the climate and atmospheric chemistry of West Antarctica?
6. How much has biogeochemical cycling of S, N and C, as recorded in West Antarctica, varied over the last 200+ years?

In fulfilling these objectives, U.S. ITASE in conjunction with ITASE will produce continental-scale "environmental maps," elucidate transfer functions between components of the atmosphere and snow/ice, validate atmospheric models, and interpolate spatial time-series by satellite remote sensing.

For further information concerning U.S. ITASE, refer to the "Science and Implementation Plan for a U.S. Contribution to the International Trans Antarctic Scientific Expedition: 200 Years of Past Antarctic Climate and Environmental Change" (1996).

Proposed Schedule (Antarctic)

1998	**June**
	Science proposals for ITASE (first attempt)
	98/99 field season
	Deep drilling at Siple Dome Rock coring at Siple Dome Install 1-3 AWS (Automatic Weather Stations) units around proposed Inland site
1999	**June**
	Science proposals for ITASE (second attempt)
	99/00 field season
	Clean up Siple Dome ITASE traverse: Surface evaluation of proposed Inland sites includingsnowpits, shallow cores, shallow radar Install several more AWS units for Inland WAISCORES
2000	**June**
	Propose preliminary hot water coring at Inland WAISCORES site
	August
	Complete maps and models of Inland WAISCORES site and identify proposed sites
	00/01 field season
	ITASE traverse
2001	**June**
	Submit science proposals for Inland WAISCORES site (first attempt) Submit Inland WAISCORES science coordination/lead proposal
	01/ O2 field season
	ITASE traverse Preliminary hot water coring at Inland WAISCORES site
2002	**June**
	Submit Inland WASICORES science proposals (second attempt) Submit proposals for preliminary work (site selection, geophysical reconaissance) for future intermediate to deep drilling sites (e.g., South Pole, Titan Dome, Hercules Dome, Transantarctic Mountains, Antarctic Peninsula, Siple Station)
	August
	Select Inland WAISCORE site
	O2/03 field season
	ITASE traverse Move drilling equipment to Inland WAISCORES site, shallow drilling, set casing for deep drilling

2003	**03/04 field season**
	Deep drilling at Inland WAISCORE site
2004	**04/05 field season**
	Deep drilling at Inland WAISCORE site
2005	**05/06 field season**
	Deep drilling at Inland WAISCORE site
2006	**06/07 field season**
	Clean-up Inland WAISCORE site

Mid to Low Latitude Sites

While the longest and most detailed ice core records of global change have been recovered from the polar regions, the vast majority of the Earth's population lives in the mid to low latitudes. It is in these regions where future climate change will have the greatest impact on people's lives. In order to extend the findings from the poles, and to document the regional scale variability associated with global change in the tropical and temperate regions, it is imperative that we continue to develop multi-parameter, high-resolution ice core records from mid to low latitude glaciers that can be compared directly with those available from the Greenland and Antarctic ice sheets. In addition, the most direct paleorecords of mid to low latitude circulation systems (e.g., Asian monsoon and ENSO) are likely to come from ice cores recovered from the Himalaya/Tibetan Plateau and the Andes.

The widespread occurrence of high elevation glaciers in the mountains of central Asia provides a variety of sites from which ice core records can be recovered (Figure 20).

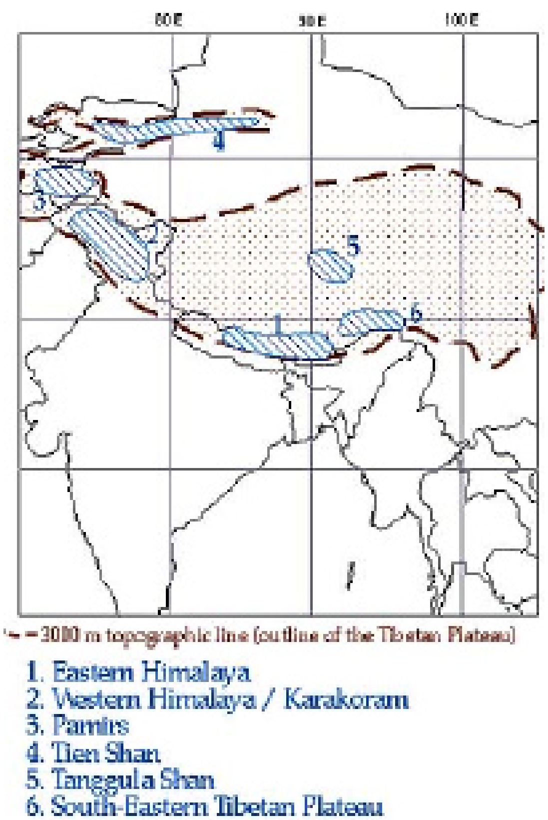


Fig. 20 – Focus locations for the recovery of ice cores in the future from the highlands of central Asia: 1. Eastern Himalaya; 2. Western Himalaya / Karakoram; 3. Pamirs; 4. Tien Shan; 5. Tanggula Shan; 6. Southeastern Tibetan Plateau. Taken from Wake and Mayewski (1996).

Well-dated, high-resolution (i.e., annual to decadal) ice core records offer a means of extending the climate record back in time in this region where the Asian monsoon impacts almost half of the world's human population. In addition, the Tibetan Plateau exerts a strong influence on global climate, making the study of climatic change in this region globally significant. In this way, we hope to better understand the natural variability of the Asian monsoon climate system and identify processes and forcing factors that contribute to this variability. Ultimately, this improved understanding should lead to the development of models that can explicitly forecast future variability of climate in monsoon Asia. The collection and analysis of ice core records from central Asian glaciers, and comparison with instrumental and other paleorecords available from the highlands of central Asia (e.g., tree rings, lake sediments, loess, glacier variations, peat deposits), are the central objectives of the Himalayan Interdisciplinary Paleoclimate Program (HIPP) (Wake and Mayewski, 1996).

The current extent of surface-to-bedrock ice cores from central Asian glaciers that have already been recovered (i.e., Dunde (Thompson et al., 1989) and Guliya (Thompson et al., 1997) ice caps) provide very valuable but limited spatial coverage. Given the spatially variable influence of circulation patterns, there is clearly a need to develop detailed ice core records throughout central Asia if we are to document and determine the causes of climate variability over this broad region. U.S. programs are currently recovering and analyzing ice cores from the Mt. Everest and Mt. Xixabangma regions of the eastern Himalaya, which should provide high resolution records that can be directly tied to monsoon circulation. Future ice coring programs should focus on the recovery of surface-to-bedrock cores from suitable high elevation glaciers in the other mountain ranges that are spread throughout central Asia, including the western Himalaya, Karakoram, the Pamirs, the Tien Shan, the Tanggula Shan and southeastern Tibet (Figure 20).

Ice core records from Huascaran in the Peruvian Andes (Figure 21) have provided a record of low latitude climate change extending back through the past glacial-interglacial transition (Thompson et al., 1995).

A good correlation is found between the Huascaran isotopic record and a marine isotopic record recovered off the coast of Portugal, indicating a close climatic connection between the North Atlantic and the Amazon Basin.

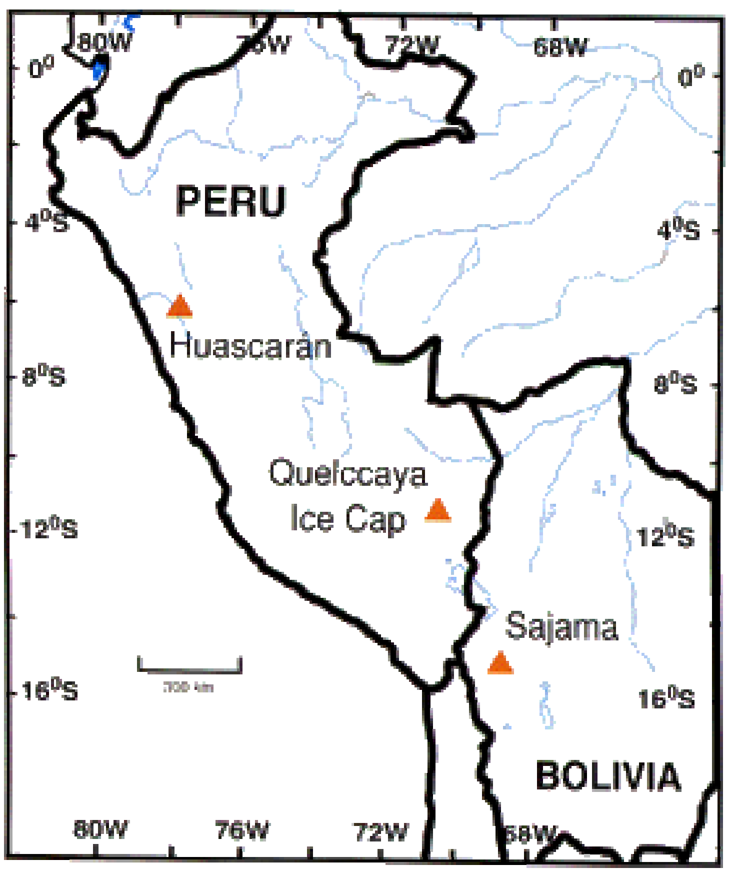


Figure 21 – South American coring sites.

Unfortunately, many of the low latitude, high elevation glaciers, such as those in the Andes and Central Asia, are currently retreating. While complete wastage may not occur for some time, increased melting is destroying their structure and compromising the valuable information these unique archives contain. Thus there is an urgent need to obtain a spatial network of high-quality ice cores from these glaciers and ice caps as soon as possible.

The Arctic

Models of future climatic change from anthropogenic emissions and the records produced from the GISP2 and GRIP ice cores have played major roles in placing the importance of the Arctic region into global perspective. The greatest warming from increased greenhouse gases, as would occur with a doubling of CO_2, often is predicted to occur in the Arctic (ARCSS, 1993). Future warming could also result in melting of many permafrost regions in northern polar regions, with the subsequent release of additional greenhouse gases (i.e., CH_4). Such a scenario would have a major impact on biogeochemical cycles initially in the Arctic and sub-Arctic and, eventually, globally. The rapid climatic shifts observed in the Greenland cores particularly emphasize the sensitive nature of the Arctic atmosphere. Changes in the global climate system are undoubtedly amplified in the Arctic. The ideal example is the much higher cooling observed in the high latitudes of the northern hemisphere compared to mid latitudes and equatorial regions following an explosive volcanic eruption in the tropics (Self et al., 1981). Once changes in the climate system occur in the Arctic, different hemispheric circulation patterns may develop as an adjustment to new pole-equator pressure gradients. Moreover, feedbacks and linkages among various components in the Arctic climate system (e.g., sea ice, meltwater, iceberg discharge, ocean circulation, variability in albedo) may then lead to further modification of global climate (e.g., Alley, 1995). Thus, understanding the natural variability in Arctic climate is of utmost importance, not only to the U.S. Global Change Program, but to the major population centers of the entire northern hemisphere.

As the U.S. ice core community attempts to decipher the natural variability in climate across the circum-Arctic, the complexity of the task is becoming evident. Complicating the undertaking is the existence of many modern climatic boundaries, both north-south and east-west, especially in the Canadian Arctic archipelago (Maxwell, 1980, 1982), the region with the greatest number of ice caps in the Arctic. As a result, any single ice core from the Arctic is unable to provide a complete picture of variability in past climate. This regionalization of Arctic climate is most pronounced under warmer climatic conditions (O'Brien et al., 1995).

To evaluate the regional nature of Arctic climate, it is necessary for the U.S. ice core community to obtain an array of ice cores across the circum-Arctic (Figure 22), including the Greenland Ice Sheet , smaller ice caps and mountain glaciers.Recent work in Greenland is being coordinated through the Program for Arctic Regional Climate Assessment (PARCA, 1997), an initiative directed to measuring and understanding the mass balance of the ice sheet. Special emphasis is placed on establishing long term histories of climate and accumulation rate into which results of short term observations, such as those from remote sensing platforms, can be placed. Four cores covering the last 300-900 years and eight cores covering the last 50-70 years have been obtained from sites well distributed over the ice sheet (Figure 22). The records are used to study interannual and decadal scale changes in accumulation rates, climate and atmospheric chemistry. Automatic weather stations installed at many of the core sites are being used to study the processes of snow accumulation and surface ablation. One of the expected products of the core analyses is an improved map of surface accumulation rates for the Greenland Ice Sheet. Work in future field seasons is expected to concentrate on recovering additional 50 to 70 year core records.

Work outside of Greenland has included the collection of several cores from the Canadian Arctic, primarily by the Geological Survey of Canada, although more extensive collaboration with U.S. investigators has begun.Several cores from the Russian Arctic have been collected by the international ice coring community, including U.S. investigators (e.g., Kupol Ventrenxy), thus providing a perspective on past change from the eastern Arctic (Figure 22).However, parameters measured in many of these cores have been limited to $\delta^{18}O$, and occasionally electrical conductivity and melt layers (a proxy for summer temperature; e.g., Koerner and Fisher, 1990). Consequently, the multiparameter approach to ice core analysis developed for the GISP2 core is necessary to obtain the most complete paleoclimate record available. We encourage individuals intending to obtain future cores from the Arctic to take this approach.

Guidance for the collection of future cores by U.S. researchers is available from the Ice-Core Circum-Arctic Paleoclimate Program (ICAPP-PAGES). This recently developed international program will assist in synthesizing existing ice core records, especially for use with other proxy data (such as those used in CAPE, the Circum-Arctic Paleoenvironments program of PAGES), as well as in developing multinational programs to more thoroughly evaluate ice core records from the smaller ice caps of the Arctic.

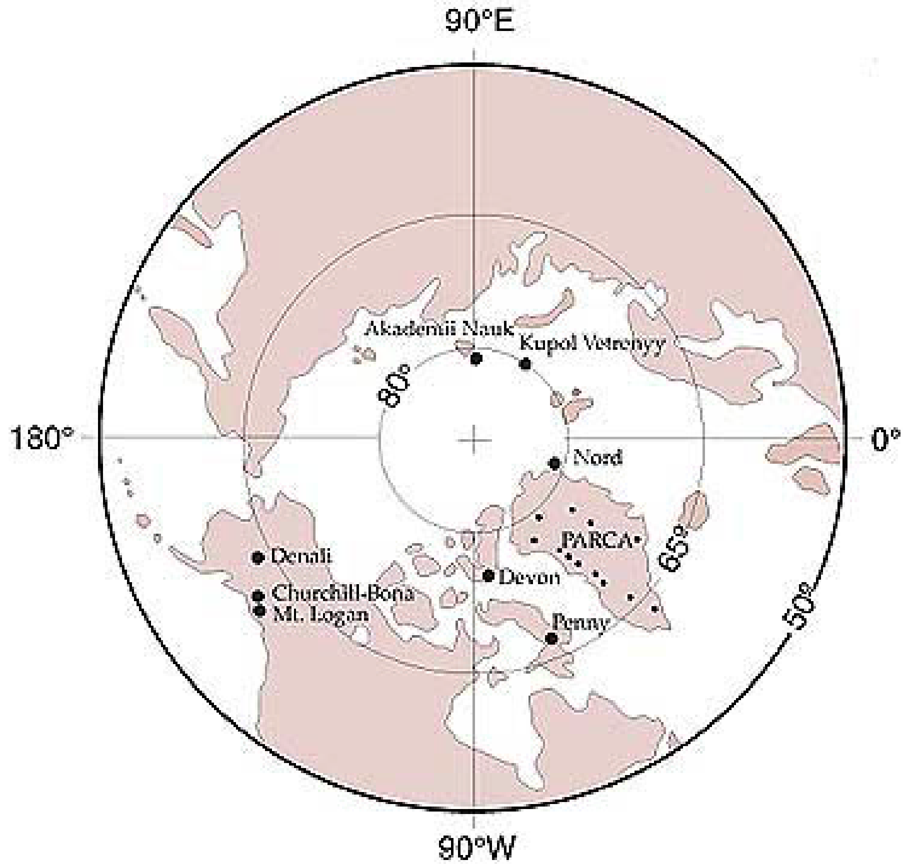


Figure 22 – Location of circum-Arctic ice core sites mentioned in this document.

The 1995 Penny ice core was the first core collected under the auspices of ICAPP. Presently, ICAPP is directly involved with plans to collect a surface-to-bedrock cores from Akademii Nauk and Severnaya Zemlya. This will be an international effort with the intention of producing the first high-resolution, multi-parameter record through the Holocene, and probably a discernible record to the last glacial maximum, from the Russian Arctic. Because ice coring on the smaller ice caps of the Arctic and the collection of shallow-depth cores from Greenland does not require the extensive planning needed for deep coring operations to bedrock on the Greenland and Antarctic ice sheets, a detailed schedule of upcoming projects is not presented in this document. Nevertheless, plans for work in the near future on the smaller ice caps of the Arctic continue to be developed (e.g., Devon Ice Cap, near Nord Station). Plans for the collection of high elevation ice cores from Alaska (e.g., Churchill-Bona, Denali) are also under development.We anticipate a continued effort in the Arctic by the U.S. ice core community in the more distant future.

Acknowledgements

We are grateful for the support and guidance of the Office of Polar Programs at the National Science Foundation; the helpful comments from the community, especially from R. Alley and E. Waddington; editorial comments from I. Pittallwala and F. Smith helped blend the writing styles of the various authors;the graphic and layout design of J. Fithian. Portions of this document were taken from Mayewski and Bender (1995). Much of the data presented in the figures accompanying this document are available to the public on the NGDC server ftp://ftp.ngdc.noaa.gov/paleo/ , the NOAA web site http://www.cmdl.noaa.gov/ftpdata.html and the NSIDC web site http://arcss.colorado.edu.

References

Alley, R.B., 1995, Resolved: The Arctic controls global climate change, Marginal ice zones and continental shelves coastal and estuarine studies, Arctic Oceanography, 49, 263-283.

Alley, R.B., D. Meese, C.A. Shuman, A.J. Gow, K. Taylor, M. Ram, E.D. Waddington and P.A. Mayewski, 1993, Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event, Nature, 362, 527-529.

Alley, R.B., P.A. Mayewski, T. Sowers, M. Stuiver, K.C. Taylor and P.U. Clark, 1997, Holocene climatic instability: A large event 8000-8400 years ago, Geology, 25(6), 482-486.

Andrews, J.T. and J.D. Ives, 1972, Late and post-glacial events (<10,000 BP) in eastern Canadian Arctic with particular reference to the Cockburn moraines and the breakup of the Laurentide Ice Sheet, in: Climate Changes During the Last 10,000 Years, edited by Y. Vasari, H. Hyvarinen and S. Hicks, pp. 149-176, Univ. of Oulu, Oulu, Finland.

Andrews, J.T. and K. Tedesco, 1992, Detrital carbonate-rich sediments, northwestern Labrador Sea: implications for ice sheet dynamics and ice-berg rafting (Heinrich) events in the North Atlantic, Geology, 20, 1087-1090.

ARCSS, 1993, Arctic System Science: A plan for integration, Arctic Research Consortium of the United States, Fairbanks.

Bard, E., B. Hamelin, R. Fairbanks and A. Zindler, 1990, Calibration of the 14C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals, Nature, 345, 405-410.

Barlow, L.K., J.W.C. White, R.G. Barry, J.C. Rogers and P.M. Grootes, 1993, The North Atlantic Oscillation signature in deuterium and deuterium excess signals in the Greenland Ice Sheet Project 2 ice core, 1840-1970, Geophys. Res. Lett., 20(24), 2901-2904.

Barnola, J. M., D. Raynaud, Y.S. Korotkevich and C. Lorius, 1987, Vostok ice core provides 160,000-year record of atmospheric CO2, Nature, 329, 408-414.

Beer, J., A. Blinov, G. Bonani, R.C. Finkel, H.J. Hofmann, B. Lehmann, H. Oeschger, A. Sigg, J. Schwander, T. Staffelback, B. Stauffer, M. Suter and W. Wölfli, 1990, Use of 10Be in polar ice to trace the 11-year cycle of solar activity. Nature, 347, 164-166.

Behl, R.J. and J.P. Kennett, 1996, Brief interstadial events in the Santa Barbara basin, NE Pacific, during the past 60 kyr, Nature, 379, 243-246.

Bender, M., T. Sowers, M.-L. Dickson, J. Orchardo, P. Grootes, P.A. Mayewski and D. Meese, 1994, Climate connections between Greenland and Antarctica during the last 100,000 years, Nature, 372, 663-666.

Bergthorsson, P., 1969, An estimate of drift ice and temperature in Iceland in 1000 years. in: Climate: Past, Present and Future, Vol. 2, edited by H.H. Lamb, pp. 94-101, Methuen, London.

Biscaye, P.E., F.E. Grousset, S. Revel, S. Van der Gaast, G.A. Zielinski, A. Vaars and G. Kukla, 1997, Asian Provenance of glacial dust (stage 2) in the Greenland Ice Sheet Project 2 Ice Core, Summit, Greenland, J. Geophys Res., 102, 26,765-26,781.

Blunier, T., J.A. Chappellaz, J. Schwander, B. Stauffer and D. Raynaud, 1995, Variations in atmospheric methane concentration during the Holocene epoch, Nature, 374, 46-49.

Bond, G., H. Heinrich, W. Broecker, L. Labeyrie, J. McManus, J. Andrews, S. Huon, R. Jantschik, S. Clasen, C. Simet, K. Tedesco, M. Klas, G. Bonani and S. Ivy, 1992, Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period, Nature, 360, 245-250.

Bond, G., W.S. Broecker, S.J. Johnsen, J. McManus, L.D. Labeyrie, J. Jouzel and G. Bonani, 1993, Correlations between climate records from North Atlantic sediments and Greenland ice, Nature, 365, 143-147.

Bond, G. and R. Lotti, 1995, Iceberg discharge into the North Atlantic during the last glacial period, Science, 267, 1005-1010.

Boyle, E.A. and L.D. Keigwin, 1987, North Atlantic thermohaline circulation during the past 20,000 years linked to high latitude surface temperature, Nature, 330, 35-40.

Broecker, W., G. Bond, M. Klas, E. Clark and J. McManus, 1992, Origin of the North Atlantic's Heinrich events, Climate Dynamics, 6, 265-273.

Brook, E.J., T. Sowers and J. Orchado, 1996, Rapid variations in atmospheric methane concentration during the past 110,000 years, Science, 273, 1087-1091.

Buckland, P.C., T. Amorosi, L.K. Barlow, A.J. Dugmore, P.A. Mayewski, T.H. McGovern, A.E.J. Ogilvie, J.P. Sadler and P. Skidmore, 1996, Bioarchaeological evidence and climatological evidence for the fate of Norse farmers in medieval Greenland, Antiquity, 70, 267, 88-96.

Chappellaz, J., J.M. Barnola, D. Raynaud, Y.S. Korotkevich, and C. Lorius, 1990, Atmospheric CH4 record over the last climatic cycle revealed by the Vostok ice core, Nature, 345, 127-131.

Chappellaz, J., T. Blunier, D. Ratnaud, J.M. Barnola, J. Schwander and B. Stauffer, 1993, Synchronous changes in atmospheric CH4 and Greenland climate between 40 and 8 kyr B.P., Nature, 366, 443-445.

Charlson, R.J., S.E. Schwartz, J.M. Hales, R.D. Cress, J.A. Coakley, J.E. Hansen and D.J. Hofmann, 1992, Climate forcing by anthropogenic aerosols, Science, 255, 423-430.

CLIMAP Project Members, 1981, Seasonal reconstruction of the earth's surface at the last glacial maximum, Map and Chart Series 36, Geol. Soc. of Am. Bull., Boulder, Co.

Cortijo, D.G., P. Yiou, L.D. Labeyrie and M. Cremer, 1995, Sedimentary record of climatic variability in the North Atlantic ocean during the last glacial cycle, Paleoceanography, 10(5), 911-926.

Cuffey, K.M., G.D. Clow, R.B. Alley, M. Stuiver, E.D. Waddington and R.W. Saltus, 1995, Large Arctic-temperature change at the Wisconsin-Holocene transition, Science, 270, 455-458.

Dai, J., E. Mosley-Thompson and L.G. Thompson, 1991, Ice core evidence for explosive tropical volcanic eruption 6 years preceding Tambora, J. Geophys. Res., D9, 17,361-17,366.

Dansgaard, W., S. Johnsen, H. Clausen, D. Dahl-Jensen, N. Gundestrup, C. Hammer, C. Hvidbeg, J. Steffensen, A. Sveinbjornsdottir, J. Jouzel and G. Bond, 1993, Evidence for a general instability of the past climate from a 250 kyr ice core record, Nature, 364, 218-220.

Delmas, R., J.S. Kirchner, J.M. Palais and J.R. Petit, 1992, 1000 years of explosive volcanism recorded at the South Pole, Tellus, Ser. B, 44, 335-350. Denton, G.H. and W. Karlen, 1973, Holocene climatic variations - Their pattern and possible cause, Quater. Res. 3, 155-205.

Dibb, J., P.A. Mayewski, C.F. Buck and S.M. Drummey, 1990, Beta radiation from snow, Nature, 344 , 6270, 25. Dibb, J.E., R.W. Talbot, S.I. Whitlow, M.C. Shipham, J. Winterle, J. McConnell and R. Bales, 1996, Biomass burning signatures in the atmosphere and snow at Summit, Greenland: An event on 5 August 1994, Atmos. Environ., 30(4), 553-561.

Erickson, D.J., J.T. Merrill and R.A. Duce, 1986, Seasonal estimates of global atmospheric seasalt distribution, J. Geophys. Res. 9, 1067-1072.

Etheridge, D.M., G.I. Pearman and P.J. Fraser, 1992, Changes in tropospheric methane between 1841 and 1978 from a high accumulation rate Antarctic ice core, Tellus, Ser. B, 44, 282-294.

Etheridge, D.M., L.P. Steele, R.P. Langenfields, R.J. Francey, J.-M. Barnola and V.I. Morgan, 1996, Natural and anthropogenic changes in atmospheric CO2 over the last 1,000 years from air in Antarctic ice and firn, J. Geophys. Res., 101, 4115-4128.

Finkel, R. and K. Nishiizumi, 1997, 10Be Concentrations in the GISP2 ice core from 3-40 kabp, J. Geophys. Res., 102, 26,699-26,706.

Grootes, P.M., M. Stuiver, J.W.C. White, S. Johnsen and J. Jouzel, 1993, Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores, Nature, 336, 552-554.

Grove, J.M., 1988, The Little Ice Age, Methuen and Company, London.

Harvey, L.D.D., 1980, Solar variability as a contributing factor to Holocene climatic change, Prog. Phys. Geogr., 4, 487-530.

Heinrich, H., 1988, Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years, Quat. Res. 29, 142-152.

Ice Core Working Group, 1987, U.S. Ice Core Research Capabilities, University of New Hampshire, Durham, New Hampshire, 62 p.

Ice Core Working Group, 1988, Compiled Reports of a Workshop on U.S. Ice Core Research, University of New Hampshire, Durham, New Hampshire, 74 p.

Ice Core Working Group, 1989, U.S. Global Ice Core Reseach Program West Antarctica and Beyond, University of Washington.

Johnsen, S., H. Clausen, W. Dansgaard, K. Fuhrer, N. Gundestrup, C. Hammer, P. Iversen, J. Jouzel, B. Stauffer, and J. Steffensen, 1992, Irregular glacial interstadials recorded in a new Greenland ice core, Nature, 359, 311-313.

Jouzel, J., C. Lorius, J.R. Petit, C. Genthon, N.I. Barkov, V.M. Kotlyakov and V.M. Petrov, 1987, Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years), Nature, 329, 403-407.

Jouzel, J., E. Bard and W.S. Broecker, 1992, The last deglaciation in Antarctica: Further evidence of a "Younger Dryas" type climatic event, Springer-Verlag, 229-266.

Keeling, C.K., J.A. Adams, C.A. Ekdahl and P.R. Guenther, 1976, Atmospheric carbon dioxide variations at the South Pole, Tellus, 28, 552-564.

Kennett, J.P. and B.L. Ingram, 1995, A 20,000 year record of ocean circulation and climate change from the Santa Barabara Basin, Nature, 377, 510-513.

Koerner, R.M., 1977, Devon Ice Cap: Core stratigraphy and climate, Science, 196, 15-18.

Koerner, R.M., and D.A. Fisher, 1990, A record of Holocene summer climate from a Canadian high-Arctic ice core, Nature, 343, 630-631.

Kotilainen, A.T. and N.J. Shackleton, 1995, Rapid climate variability in the North Pacific Ocean during the past 95,000 years, Nature, 377, 323-326.

Kreutz, K.J., P.A. Mayewski, L.D. Meeker, M.S. Twickler, S.I. Whitlow and I.I. Pittalwala, 1997, Bipolar changes in atmospheric circulation during the Little Ice Age, Science, 277, 1294-1296.

Lamb, H.H., 1995, Climate History and the Modern World, second edition, Routledge, 433p.

Langway, C.C., Jr., K. Osada, H.B. Clausen, C.U. Hammer, and H. Shoji, 1995, A 10- century comparison of prominent bipolar volcanic events in ice cores, J. Geophys. Res., 100(D8), 16,241-16,247.

Legrand, M. and C. Feniet-Saigne, 1991, Methanesulfonic acid in south polar snow layers: A record of strong El Nino?, Geophys. Res. Lett., 18, 187-190.

Legrand, M., M. DeAngelis, T. Staffelbach, A. Neftel and B. Stauffer, 1992, Large perturbations of ammonium and organic acids content in the Summit Greenland ice core, fingerprint from forest fires?, Geophys. Res. Lett., 19, 473-475.

Lehman, S.J. and L.D. Keigwin, 1992, Sudden changes in North Atlantic circulation during the last deglaciation, Nature, 356, 757-762.

Lorius, C., J. Jouzel, C. Ritz, L. Merlivat, N.E. Barkov and Y.S. Korotkevich, 1985, 150,000-year climatic record from Antarctic ice, Nature, 316, 591-595.

Lorius, C., J. Jouzel, D. Raynaud, J. Hansen and H. Le Treut, 1990, The ice-core record: climate sensitivity and future greenhouse warming, Nature, 347, 139-145.

Lowell, T., C. Heusser, B. Andersen, P. Moreno, A. Hauser, L. Heusser, C. Schluchter, D. Marchant and G. Denton, 1995, Interhemispheric correlation of late Pleistocene glacial events, Science, 269, 1541-1549.

Lyons, W.B., P.A. Mayewski, M.J. Spencer, M.S. Twickler and T.E. Graedel, 1990, A Northern Hemispheric volcanic chemistry (1869-1984) record and climatic implications using a south Greenland ice core, Annals of Glaciol., 14, 176-182.

MacAyeal, D.R., 1993, A low-order model of the Heinrich event cycle, Paleoceanography, 8, 767-773.

Machida, T., T. Nakazawa, Y. Fujii, S. Aoke and O. Watanabe, 1995, Increase in atmospheric nitrous oxide concentrations during the last 250 years, Geophys. Res. Lett., 22, 2921-2924.

McEvedy, C. and R. Jones, 1978, Atlas of world population history, Penguin.

Maxwell, J.B., 1980, The Climate of the Canadian Arctic Islands and Adjacent Waters, Vol. 1, 531 pp., Minister of Supply and Services, Hull, Quebec.

Maxwell, J.B., 1982, The Climate of the Canadian Arctic Islands and Adjacent Waters, Vol. 2, 589 pp., Minister of Supply and Services, Hull, Quebec.

Mayewski, P.A., W.B. Lyons, M.J. Spencer, M.S. Twickler, B. Koci, W. Dansgaard, C. Davidson and R. Honrath, 1986, Sulfate and nitrate concentrations from a South Greenland ice core, Science, 232, 975-977.

Mayewski, P.A., W.B. Lyons, M.J. Spencer, M.S. Twickler, C.F. Buck and S.I. Whitlow, 1990, An ice core record of atmospheric response to anthropogenic sulphate and nitrate, Nature, 346, 554-556.

Mayewski, P.A., L.D. Meeker, S.I. Whitlow, M.S. Twickler, M.C. Morrison, R.B. Alley, P. Bloomfield and K. C. Taylor, 1993a, The atmosphere during the Younger Dryas, Science, 261, 195-197.

Mayewski, P.A., L.D. Meeker, M.C. Morrison, M.S. Twickler, S.I. Whitlow, K.K. Ferland, D.A. Meese, M.R. Legrand and J.P. Steffenson, 1993b, Greenland ice core "signal" characteristics: An expanded view of climate change, J. Geophys. Res. 98(D7), 12,839-12,847.

Mayewski, P.A., G. Holdsworth, M.J. Spencer, S.I. Whitlow, M.S. Twickler, M.C. Morrison, K.F. Ferland and L.D. Meeker, 1993c, Ice core sulfate from three northern hemisphere sites: Source and temperature forcing implications, Atmosph. Environ., 27A(17/18) 2915-2919.

Mayewski, P.A., L.D. Meeker, S.I. Whitlow, M.S.Twickler, M.C. Morrison, P. M. Grootes, G.C. Bond, R.B. Alley, D.A. Meese, A.J. Gow, K.C. Taylor, M. Ram and M. Wumkes, 1994, Changes in atmospheric circulation and ocean ice cover over the North Atlantic during the last 41,000 years, Science, 263, 1747- 1751.

Mayewski, P.A. and M. Bender, 1995, The GISP2 ice core record - Paleoclimate highlights, Rev. of Geophys. Supp, U.S. National Report to International Union of Geodesy and Geophysics 1991-1994, 1287-1296.

Mayewski, P.A., M.S. Twickler, S.I. Whitlow, L.D. Meeker, Q. Yang, J. Thomas, K. Kreutz, P. Grootes, D. Morse, E. Steig and E.D. Waddington, 1996, Climate change during the last deglaciation in Antarctica, Science, 272, 1636-1638.

Mayewski, P.A., L.D.Meeker, M.S. Twickler, S.I. Whitlow, Q. Yang and M. Prentice, 1997, Major features and forcing of high latitude northern hemisphere atmospheric circulation over the last 110,000 years, Jour. Geophys. Res., 102, 26,345-26,366.

Meese, D., R. Alley, J. Fiacco, M. Germani, T. Gow, P. Grootes, Illing, P. Mayewski, M. Morrison, M. Ram, K. Taylor, Q. Yang and G. Zielinski, 1994a, Holocene time scale and accumulation profile of the GISP2 core, U.S. Army Cold Regions Res. Lab. Pub. SR94-01.

Meese, D.A., R.B. Alley, A.J. Gow, P. Grootes, P.A. Mayewski, M. Ram, K.C. Taylor, E.D. Waddington and G. Zielinski, 1994b, The accumulation record from the GISP2 core as an indicator of climate change throughout the Holocene, Science, 266, 1680-1682.

Meese, D.A., A.J. Gow, R.B. Alley, G.A. Zielinski, P.M. Grootes, M. Ram, K.C. Taylor, P.A. Mayewski and J.F. Bolzan, 1997, The Greenland Ice Sheet Project 2 depth-age scale: Methods and results, J. Geophys. Res., 102, 26,411-26,423.

National Research Council, 1986, Recommendations for a U.S. Ice Coring Program, ad hoc Panel on Polar Ice Coring, Committee on Glaciology, Polar Research Board, Commission on Physical Sciences, Mathematics and Resources, National Academy Press, Washington, D.C., 67 p.

Nereson, N.A., E.D. Waddington, C.F. Raymond and H.P. Jacobson, 1996, Predicted age-depth scales for Siple Dome and Inland WAIS ice cores in West Antarctica. Geophys. Res. Lett., 23, 3163-3166.

O'Brien, S.R., P.A. Mayewski, L.D. Meeker, D.A. Meese, M.S. Twickler and S.I. Whitlow, 1995, Complexity of Holocene climate as reconstructed from a Greenland ice core, Science, 270, 1962-1964.

Oppo, D.W. and S.J. Lehman, 1995, Suborbital timescale variability of North Atlantic deep water during the past 200,000 years, Paleoceanography, 10(5), 901-910.

PAGES/CLIVAR, 1994, The PAGES/CLIVAR Intersection: Providing the paleoclimate perspective needed to understand climate variability and predictability, IGBP/WCRP.

PANASH Project, 1995, Paleoclimates of the Northern and Southern Hemispheres, The PANASH Project, The Pole-Equator-Pole Transects, PAGES, IGBP, PAGES Series 95-1.

Program for Arctic Regional Climate Assessment (PARCA), 1997, Contributed Reports, Greenland Science and Planning Meeting, Tucson, Arizona. 116 pages.

Petit, J. R., L. Mounier, J. Jouel, Y.S. Korotkevich, V.I. Kotlyakov and C. Lorius, 1990, Paleoclimatological and chronological implications of the Vostok core dust record, Nature, 343, 56-58.

Petit, J.R., I. Basile, A. Leruyuet, D. Raynaud, C. Lorius, J. Jouzel, M. Stievenard, V.Y. Lipenkov, N.I. Barkov, B.B. Kudryashov, M. Davis, E. Saltzman and V. Kotlyakov, 1997, Four climate cycles in Vostok ice core, Nature, 387, 359-360.

Porter, S.C. and Z. An, 1995, Correlation between climate events in the North Atlantic and China during the last glaciation, Nature, 375, 305-308.

Ram, M., M. Stolz and G. Koenig, 1997, Eleven year cycle of dust concentration variability observed in the dust profile of the GISP2 ice core from central Greenland: Possible solar cycle connection, Geophys. Res. Lett., 24, 2359-2362.

Ram, M. and G. Koenig, 1997, Continuous dust concentration profile of pre-Holocene ice from the Greenland Ice Sheet Project 2 ice core: Dust stadials, and the Eemian, J. Geophys. Res., 102, 26,641-26,648.

Ruddiman, W.F. and A. McIntyre, 1981, The North Atlantic Ocean during the last glaciation, Palaeogeogr. Palaeoclim. and Palaeoecol., 35, 145-214.

Self, S., M. Rampino and J.J. Barbera, 1981, The possible effects of large 19th and 20th century volcanic eruptions on zonal and hemispheric surface temperatures, J. Volcan. and Geotherm. Res., 11, 41-60.

Severinghaus, J.P., T. Sowers, E.J. Brook, R.B. Alley and M.L. Bender, 1998, Timing of abupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice, Nature, 391, 141-146.

Sirocko, F., D. Garbe-Schonberg, A. McIntyre and B. Molfino, 1996, Teleconnections between the subtropical monsoons and high latitude climates during the last deglaciation, Science, 272, 526-529.

Sowers, T., M. Bender, L. Labeyrie, D. Martinson, J. Jouzel, D. Raynaud, J.J. Pichon and Y.S. Korotkevich, 1993, A 135,000-year Vostok-SPECMAP common temporal framework, Paleoceanography, 8(6), 737-766.

Sowers, T. A. and M. Bender, 1995, Climate records during the last deglaciation, Science, 269, 210-214.

Stager, J.C. and P.A. Mayewski, 1997, Abrupt mid-Holocene climatic transitions registered at the equator and the poles, Science, 276, 1834-1836.

Steig, E. J., P.J. Polissar, M. Stuiver, R.C. Finkel and P.M. Grootes, 1996, Large amplitude solar modulation cycles of 10Be in Antarctica:implications for atmospheric mixing processes and interpretation of the ice core record, Geophys. Res. Lett., 25, 523-526.

Steig, E.J., D.L. Morse, E.D. Waddington and P.J. Polissar, 1998, Using the sunspot cycle to date ice cores. Geophys. Res. Lett., 25 , 163-166. Steig, E.J., C.P. Hart, J.W.C. White, W.L. Cunningham, M.D. Davis and E.S. Saltzman, in press, Changes in climate, ocean and ice sheet conditions in the Ross Embayment at 6 ka., Annal. Glaciol, 27.

Stuiver, M. and T.F. Braziunas, 1989, Atmospheric 14C and century scale solar oscillations, Nature, 338, 405-408. Stuiver, M. and T.F. Braziunas, 1993, Sun, ocean, climate and atmospheric 14CO2: an evaluation of causal and spectral relationships, The Holocene 3(4), 289-305.

Stuiver, M., T. Braziunas and P.M. Grootes, 1995, The GISP2 d18O climate record of the past 16,500 years and the role of the sun, ocean, and volcanoes, Quat. Res. 44, 341-354.

Stute, M., M. Forster, H. Frischkorn, A. Serejo, J.F. Clark, P. Schlosser, W.S. Broecker and G. Bonani, 1995, Cooling of tropical Brazil (5oC) during the last glacial maximum, Science, 269, 379-383.

Taylor, K.C., C.U. Hammer, R.B. Alley, H.B. Clausen, D. Dahl-Jensen, A.J. Gow, N.S. Gundestrup, J. Kipfstuhl, J.C. Moore and E.D. Waddington, 1993, Electrical conductivity measurements from the GISP2 and GRIP Greenland ice cores, Nature, 366, 549-552.

Taylor, K.C., P.A. Mayewski, M.S. Twickler and S.I. Whitlow, 1996, Biomass burning recorded in the GISP2 ice core: A record from eastern Canada?, The Holocene, 6(1), 1-6.

Taylor, K.C., P.A. Mayewski, R.B. Alley, E.J. Brook, A.J. Gow, P.M. Grootes, D.A. Meese, E.S. Saltzman, J.P. Severinghaus, M.S. Twickler, J.W.C. White, S.I. Whitlow and G.A. Zielinski, 1997, A close look at the Holocene/Younger Dryas transition recorded at Summit, Greenland, Science, 278, 825-827.

Thompson, L.G., E. Mosley-Thompson, J.F. Bolzan and B.R. Koci, 1985, A 1500-year record of tropical precipitation in ice cores from the Quelccaya ice cap, Peru. Science, 226, 50-53.

Thompson, L.G. and E. Mosley-Thompson, 1987, Evidence of abrupt climate change during the last 1500 years recorded in ice cores from the tropical Quelccaya ice cap, Peru, in: Abrupt Climate Change, edited by, W.H. Berger and L.D. Labeyrie, pp. 99-110, D. Reidel, Dordrecht.

Thompson, L.G., E. Mosley-Thompson, M.E. Davis, J.F. Bolzan, J. Dai, T. Yao, N. Gundestrup, X. Wu, L. Klein and Z. Xie, 1989, Holocene-Late Pleistocene Climatic Ice Core Records from Qinghai-Tibetan Plateau, Science, 246, 474-477.

Thompson, L.G., E. Mosley-Thompson and P.A. Thomson, 1992, Reconstruction of interannual climate variability from tropical and subtropical ice-core records, in: Paleoclimatic Aspects of El Nino/Southern Oscillation, edited by, H. Diaz and V. Markgraf. pp. 295-322, Cambridge University Press.

Thompson, L.G., M.E. Davis and E. Mosley-Thompson, 1994, Glacial records of global climate: A 1500-year tropical ice core record of climate, Human Ecology, 22(1), 83-95.

Thompson, L.G., E. Mosley-Thompson, M.E. Davis, P.N. Lin, K.A. Henderson, J. Cole-Dai, J.F. Bolzan and K.B. Liu, 1995, Late glacial stage and Holocene tropical ice core records from Huscaran, Peru, Science, 269, 46-50.

Thompson, L.G., T. Yao, M.E. Davis, K.A. Henderson, E. Mosley-Thompson, P.-N. Lin, J. Beer, H.-A. Synal, J. Cole-Dai and J.F. Bolzan, 1997, Tropical climate instability: The last glacial cycle from a Qinghai-Tibetan ice core, Science, 276, 1821-1825.

US ITASE, 1996, U.S. ITASE: Science and Implementation Plan for a U.S. Contribution to the International Trans Antarctic Scientific Expedition: 200 Years of Past Antarctic Climate and Environmental Change, University of New Hampshire, Durham, New Hampshire, 62p.

Wahlen, M., D. Allen, B. Deck and A. Herchenroder, 1991, Initial measurements of CO2 concentrations (1530-1940 AD) in air occluded in the GISP2 ice core from central Greenland, Geophys. Res. Lett. 18, 1457-1460.

Wake C.P. and P.A. Mayewski, 1996, Himalayan Interdisciplinary Paleoclimate Program (HIPP) - Science and Implementation Plan, IGBP-PAGES Workshop Report 96-1.

Welch, K.A., P.A. Mayewski and S.I. Whitlow, 1993, Methanesulfonic acid in coastal antarctic snow related to sea-ice extent, Geophys. Res. Lett., 20(6) 443- 446.

Whitlow, S., P. Mayewski, J. Dibb, G. Holdsworth and M. Twickler, 1994, An ice- core-based record of biomass burning in the Arctic and Subarctic, 1750-1980, Tellus, Ser. B, 46, 234-242. White, D.E., J.W.C.

White, E.J. Steig and L.K. Barlow, 1997, Reconstructing annual and seasonal climatic responses from volcanic events since A.D. 1270 as recorded in the deuterium signal from the GISP2 ice core, J. Geophys. Res., 102, 19,683-19,694.

White, J.W.C., L.K. Barlow, D. Fisher, P. Grootes, J. Jouzel, S.J. Johnsen, M. Stuiver and H. Clausen, 1997, The climate signal in stable isotopes of snow from Summit, Greenland: Results of comparisons with modern climate observations, J. Geophys. Res., 102, 26,425-26,439.

Wigley, T.M.L., 1990, Could reducing fossil-fuel emissions cause global warming, Nature, 349, 503-506. Zielinski, G.A., P.A. Mayewski, L.D. Meeker, S.I. Whitlow, M.S. Twickler, M.C. Morrison, D. Meese, R. Alley and A.J. Gow, 1994, Record of volcanism since 7000 BC from the GISP2 Greenland ice core and implications for the volcano-climate system, Science, 264, 948-952.

Zielinski, G.A., 1995, Stratospheric loading and optical depth estimates of explosive volcanism over the last 2100 years derived from the GISP2 Greenland ice core, J. Geophys. Res., 100 (D10), 20,937-20,955. Zielinski, G.A., P.A. Mayewski, L.D. Meeker, S.I. Whitlow and M.S. Twickler, 1996a, A 110,000-year record of explosive volcanism from the GISP2 (Greenland) ice core, Quat. Res., 45, 109-118.

Zielinski, G.A., P.A. Mayewski, L.D. Meeker, S.I. Whitlow, M.S. Twickler and K.C. Taylor, 1996b, Potential atmospheric impact of the Toba mega-eruption ~71,000 years ago, Geophys. Res. Lett., 23(8), 837-840.

Zielinski, G.A., P.A. Mayewski, L.D. Meeker, K. Grönvold, M.S. Germani, S.I. Whitlow, M.S. Twickler and K.C. Taylor, 1997, Volcanic aerosol records and tephrochronology of the Summit, Greenland, ice cores, J. Geophys. Res., 102, 26,625-26,640.

Zielinski, G.A. and G.R. Mershon, 1997, Paleoenvironmental implications of the insoluble microparticle record in the GISP2 (Greenland) ice core during the rapidly changing climate of the Holocene-Pleistocene transition, Geol. Soc. of Am. Bull., 109, 547-559.