Ice-Core Records with Emphasis on the Global Record of the Last 2000 Years

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Introduction

The patterns and sources of interannual, decadal, and century-scale climatic variability are least well known and constitute a gap in our understanding of the climate system. The comparison of climate model results with systematic regional, continental, hemispheric, and global-scale compilations of high-resolution paleoclimatic data is needed to fill this gap in our understanding and to develop more realistic climate models. The earth's ice sheets and ice caps are recognized as the best of only a few libraries of atmospheric history from which the past climatic and environmental conditions may be extrapolated. Much of the climatic activity of significance to humanity may not be strongly expressed at (or may not reach) the polar ice caps. Fortunately, ice-core records can be recovered from polar as well as a select few high-altitude, low- and midlatitude "polar-type" ice caps. In addition, for the last 2000 years the high accumulation on these ice caps and ice sheets makes it possible to recover aerosol records (soluble and insoluble) of high temporal resolution which can serve as a proxy indicator for drought and volcanic activity as well as playing a direct role in determining climate. Ice cores also provide information on net accumulation (from annual layer thicknesses), stable isotope ratios (which can serve as a proxy for temperature), and trapped gas in the air bubbles, which provides a detailed record of the changes of radiatively active gases such as CO_2, CH_4, NO_2, etc. The nonpolar ice-core records, especially, can also serve as an excellent archive of pollen, diatoms, and plant fragments. This archive of organic material also makes it possible to use accelerator mass spectrometer (AMS)–^{14}C dating to establish independent dates for these ice cores, which may prove important on the millennium time scale. Thus, the variety of chemical and physical data extracted from ice caps and ice sheets provides a multifaceted record of both the climatic and environmental history of the earth and may allow assessment of the relative importance of such components as volcanic activity, greenhouse gas concentrations, atmospheric dust, and solar variability. Understanding the climate system with the goal of future predictions must begin with a global synthesis of its history over a period of time for which the most reliable, diverse, and complete data sets exist. The longer records on glacial/interglacial time scales, while lacking in temporal resolution, are important in providing a further perspective against which the variations of the last 2000 years must be viewed.

The last 2000 years are especially important for a number of reasons:

1. It is the period most relevant to human activities, present and future. Any changes in the system due to man's activities will be superimposed on climatic and environmental variability over this period of time.
2. It is a time of extremes within the Holocene (warm period), including the Little Ice Age period from ~A.D. 1450 to 1900.
3. It is the period of maximum proxy data coverage.
4. Multiproxy reconstructions are possible.
5. Annual (or seasonal) resolution is possible.
6. Leads and lags and rates of change within the climate system can be directly studied.
7. Causes of changes in climate remain undetermined.
8. Potential forcing functions can be identified and tested.

Overview

This chapter is written to provide examples of how the ice-core data have been and are being used to address problems that are of concern to a wide sector of the scientific community. Emphasis is on the last 2000 years. The discussions and examples are not intended to be all-inclusive, nor are they intended to provide an exhaustive review of the literature in this field. The reader can find good overviews of ice-core research in *Annals of Glaciology*, volume 10 (Proceedings of the Symposium on Ice-Core Analysis), 1988, and Oeschger and Langway (1989). It is, however, hoped that this summary will succeed in conveying, by way of example, how these multifaceted records can provide an archive of the earth's atmospheric and environmental history on a global scale, long before instrumental observations became available, an archive essential to understanding present and future climate.

Time and Geographical Perspective

One of the important needs in addressing global change issues which the ice core records can provide is a time perspective, that is, a frame of reference against which present and future changes can be compared. The longer-term perspective available from polar cores is discussed in the chapter by Lorius in this volume. Glacial-interglacial records from nonpolar ice cores now appear to be possible (Thompson et al., 1989) and can be used to aid in providing a global perspective of climate (needed to fully understand the earth's climate system), and specifically to determine how well polar ice cores reflect climate variability in the subtropics.

Nonpolar Glacial-Interglacial Records

Three ice cores to bedrock from the Dunde ice cap on the north-central Qinghai-Tibetan Plateau of China provide a detailed record of Holocene and Wisconsin-Würm late glacial stage (LGS) climate changes in the subtropics (Thompson et al., 1988b, 1989a; Thompson et al., in press). The records reveal that LGS conditions were apparently colder, wetter, and dustier than Holocene conditions. The LGS part of the cores in Figure 1 is characterized by more negative $\delta^{18}O$ ratios, greater dust content, and less soluble aerosol concentrations than the Holocene part. The enhanced dust deposition in LGS ice likely resulted from increased wind strength in response to increased baroclinicity (steeper isobaric and isothermal gradients) due to the expanded continental ice sheets in the Northern Hemisphere. The high winds from the deserts of western Asia deposited loess up to 30 m during the LGS across central and eastern China (Porter, this volume), with some material even carried to the Pacific Basin (Braaten and Cahill, 1986) and most likely to the North American continent. Under present-day conditions, large quantities of mineral dust are transported to the North Pacific each spring (Betzer et al., 1988). During the LGS very large and discrete dust events blanketed the Dunde ice cap and most likely much of the extensively snow-covered and glaciated plateau, significantly altering the radiation balance. Growing evidence indicates that under the current climate regime, albedo changes due to variations in Eurasian snow cover affect global climate. These include strong influences on the Asian summer monsoon system and the El Niño–Southern Oscillation (ENSO) phenomenon (Barnett et al., 1988). During the LGS the larger short-term variations in albedo on the Tibetan Plateau due to large multiple, discrete, high-altitude dust events may have increased the

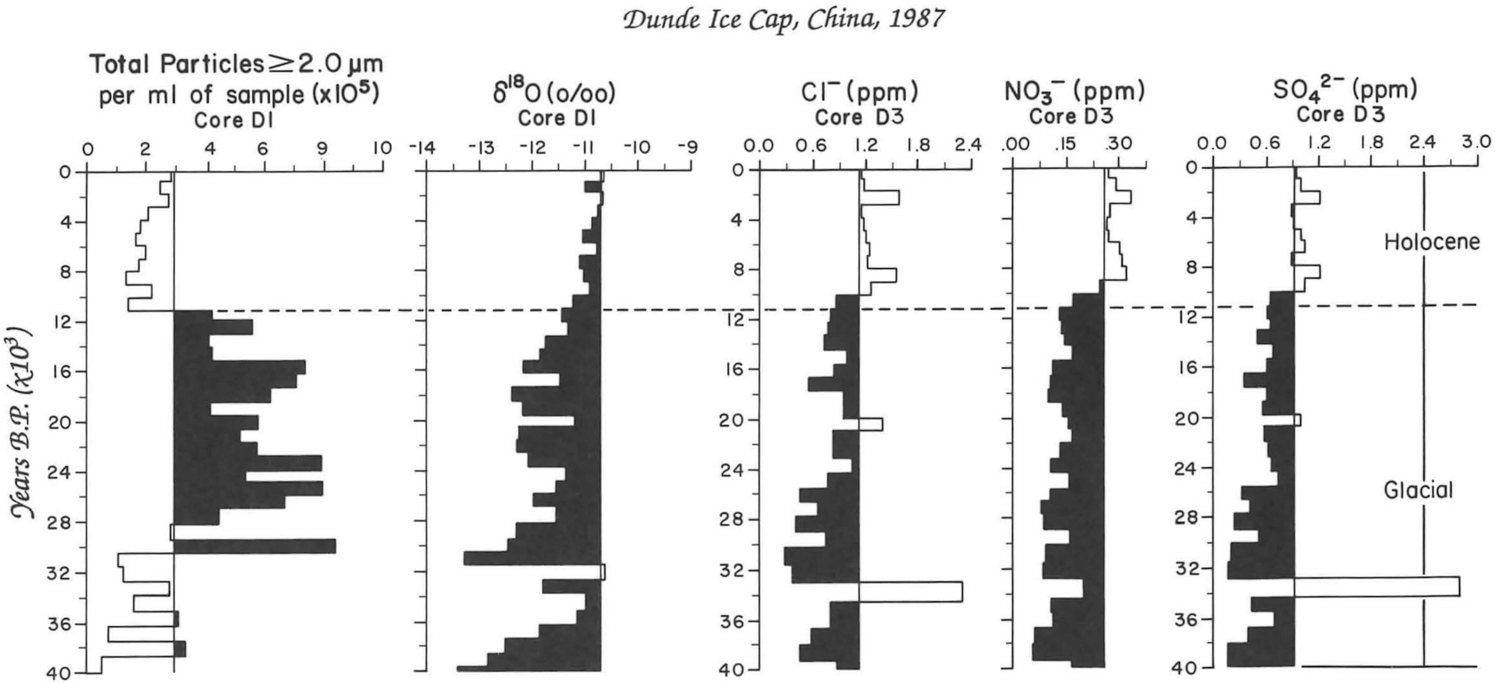

Figure 1. The 1000-year averages of dust concentrations (diameters ≥ 2.0 µm), $\delta^{18}O$, Cl^-, NO_3^-, and SO_4^{--} are illustrated for the last 40,000 years. The late glacial stage–Holocene transition is characterized by an abrupt decrease in insoluble dust, an increase in dissolved species, and a more gradual warming inferred from $\delta^{18}O$. Departures from the mean values of all samples in the 40,000-year record (not the individual 1000-year averages) are shaded. There are 5 meters of ice below the 40,000-year model cutoff shown here (Thompson et al., 1989).

variability in the monsoonal system and, hence, in the global climate system. The decrease in dust deposition at the LGS/Holocene transition was rapid (within ~40 years), reflecting an abrupt and substantial change in the prevailing climatic conditions which severely limited the capability of the atmosphere to transport dust (Thompson et al., 1989).

The $\delta^{18}O$ record (Figure 1) reveals an apparent warming between ~38,000 and ~30,000 yr. B.P., which is associated with less dust deposition. At about 30,000 yr. B.P., full glacial conditions were reestablished and dust deposition increased substantially and abruptly. Between 30,000 and 10,000 yr. B.P., concentrations of Cl- and SO_4^{2-} increased gradually as conditions became drier and the areal extent of salt (playas) and loess deposits increased. About 10,750 yr. B.P., a marked increase in these species occurred as drying of the freshwater lakes was completed. Simultaneously, the insoluble dust decreased sharply (Figure 1). The $\delta^{18}O$ profile suggests a gradual warming, while the aerosol (soluble and insoluble) data indicate rapid environmental changes including reduced wind intensity.

Annually Resolvable Ice-Core Records

Fortunately, the high-altitude regions in the low and midlatitudes, as well as the polar regions, contain ice caps and ice sheets which have continuously recorded climatic and environmental changes over the past several thousand years, often with annual resolution (Dansgaard, 1954; Johnsen et al., 1970, 1972; Thompson, 1977; Thompson et al., 1986; Mulvaney and Peel, 1988; Hammer, 1989). The records can be used to address problems which are of concern to a wide sector of the scientific community. These include: (1) global-scale climatic events such as the Little Ice Age, ENSO, and monsoonal variability; (2) abrupt climatic change and evidence for changes in the amplitude of the annual cycle over the last 2000 years; (3) impact of past low- and high-frequency climatic changes on human activities; and (4) climate changes in the 20th century, but viewed from the long time-perspective provided by ice core records.

The construction of a time scale for an ice core is generally based upon the integrated high-resolution (8 to 12 samples per year) records of $\delta^{18}O$, microparticle concentrations, conductivity, and ionic concentrations, which often exhibit a distinct seasonal variation in flux (Thompson et al., 1986; Hammer, 1989). When possible, as in many high-elevation nonpolar ice caps, the visible dust layers also contribute to dating the sequence of preserved ice (Thompson et al., 1985). The measurement of total beta radioactivity makes it possible to identify the major global chronostratigraphic horizons associated with known atmospheric thermonuclear tests (Picciotto and Wilgain, 1963; Lambert et al., 1977). It is important that two ice cores be drilled at the same site and similarly analyzed to provide an independent verification of the time scale and to ensure an uninterrupted physical and chemical stratigraphic record. For most of the ice-core records presented here, at least two and in some cases three cores are available from each site. The utility of ice-core analyses hinges upon accurate dating of cores; this requires the use of multiple stratigraphic features exhibiting a seasonal variation in concentration or signature which is preserved within the ice. Figure 2 illustrates a 50-year period, 1775–1825, from the tropical Quelccaya ice cap, in southern Peru, which exhibits distinct annual layers preserved in particles, visible stratigraphy, and oxygen isotopes, permitting very accurate dating of the ice cores (Thompson et al., 1986).

Ice-core records provide a unique opportunity to examine the climate on an annual basis and make it possible to determine, for example, the lag time between the injection of a volcanic dust veil (either insoluble ejecta or gases such as sulfur) and the subsequent deposition (as ash or sulfate, respectively) at the different ice-core locations throughout the globe. Figure 3 illustrates the interannual variability in SO_4^{2-} and $\delta^{18}O$ for the time interval from A.D. 1810 to 1827 at Siple Station, Antarctica. Here individual measurements illustrate the distinct seasonality in both the sulfate and oxygen isotope ratios which were used to date the core. Further, the exceptional reproduction of the SO_4^{2-} record in both core A and core B confirms the excellent preservation of the Tambora event in the ice-core record. The sulfate deposited from 1817 to 1819, essentially two years after the eruption, is consistent with the time lag in transport of stratospheric radioactivity to Antarctica (Lambert et al., 1977). Mean acidity of annual layers for the period A.D. 553–1972 in an ice core from Crete, central Greenland, has been successfully used to identify many of the volcanic eruptions north of ~20°S (Hammer, 1980).

Abrupt Climatic Change

The total ecosystem and particularly the future well-being of man is clearly as affected by the rate of climatic change as by the magnitude of the climate change which actually occurs. In general, abrupt change in climate denotes a rupture in the established range of experience and an unexpected and surprisingly fast transition from one state to another (Berger and Labeyrie, 1987). Recent publications (Dansgaard et al., 1989; Jouzel et al., 1987; Oeschger et al., 1984; Thompson and Mosley-Thompson, 1987, 1989b) demonstrate the variety of parameters which can be measured for such periods and how ice-core records can be used to define very precisely the rate of climate change.

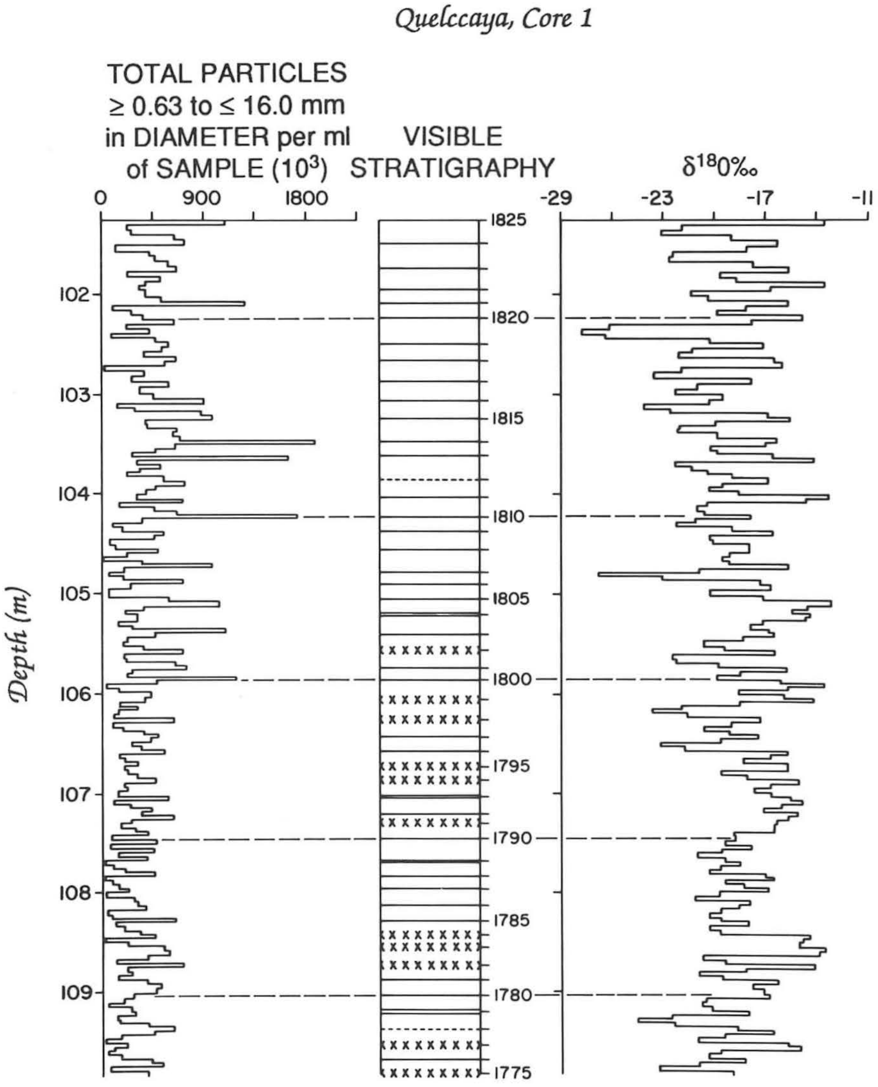

Figure 2. The stratigraphic parameters used to date the Quelccaya cores showing a 50-year period from 1775 to 1825. Annual signals are recorded in microparticle concentrations (particles from ≥ 0.63 to 16.0 μm in diameter per ml) of sample, oxygen isotopes, and visible stratigraphy. For stratigraphy, a single solid line represents a normal dry-season dust layer; a single dashed line and double dashed line represent very light and light dust layers, respectively. Series of X's symbolize diffuse dry-season layers (Thompson et al., 1986).

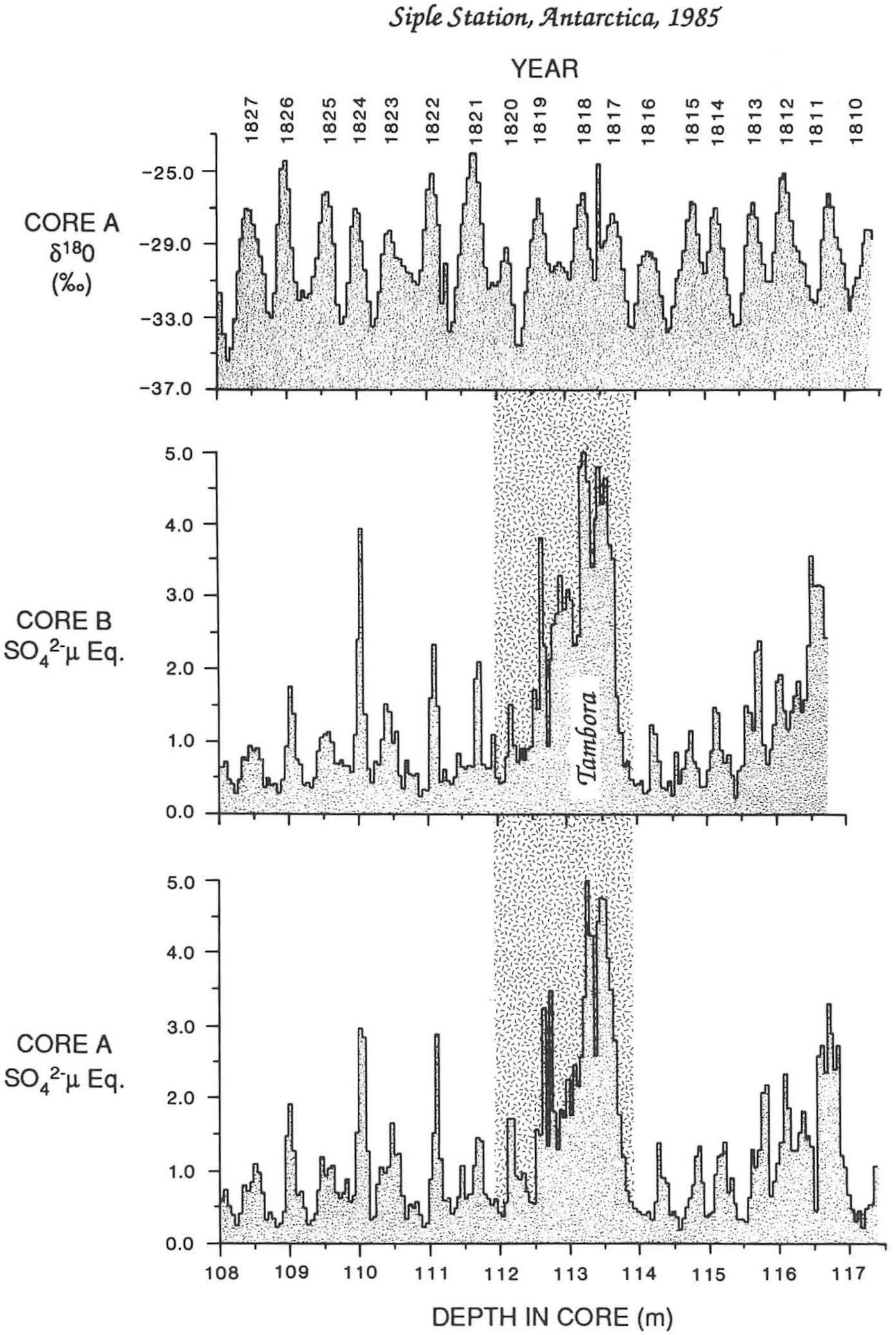

Figure 3. A 10-m section from cores A and B drilled at Siple Station, Antarctica. These show the individual measurements of SO_4^{--} concentration and demonstrate the reproducibility (i.e., the reliability) of the chemistry record. Individual analyses of $\delta^{18}O$ are illustrated for core A. The annual variations in both parameters provide an excellent time scale for this core. The eruption of Tambora in 1816 is preserved as a prominent SO_4^{--} event in both cores (Thompson and Mosley-Thompson, in press).

These abrupt changes seem to occur on a spectrum of time scales in Greenland ice cores; the transition from the last glacial to the present interglacial 10,000 years ago occurred in less than 100 years (Thompson, 1977) and perhaps in less than 30 years (Herron and Langway, 1985), while the termination of the Younger Dryas climate event occurred in perhaps less than 20 years (Dansgaard et al., 1989). In the Dunde ice cores from China the transition in dust concentration is completed within a 30-cm section of ice representative of approximately 40 years (Thompson et al., 1989; Thompson et al., in press).

The annual record of climate variations for the last 500 years from the upper portion of the 1500-year-long Quelccaya, Peru, ice-core record (shown in Figure 4) suggests that the onset and termination of the Little Ice Age were abrupt in tropical South America (Thompson and Mosley-Thompson, 1987), with the transition from the Little Ice Age to the warmth of the current century occurring over a two- to three-year period centered on A.D. 1880. The transition was marked by a sharp reduction in both insoluble and soluble particulates and a sharp reduction in the amplitude of seasonal oxygen isotope variations which averaged 4‰ (per mill) during the Little Ice Age and decreased to an average range of 2‰ during the last 100 years (Thompson and Mosley-Thompson, 1989).

El Niño–Southern Oscillation

As illustrated in Figure 4, ice-core records from the tropical Quelccaya ice cap can be extended with annual resolution well beyond the arrival of the Spanish in A.D. 1531, a period for which there are no written records. Figure 4 also indicates the historical record of El Niño events as established by Quinn et al. (1987). The ice-core record indicates that in southern Peru, major El Niño events vary greatly in both magnitude and impact. Inspection of 19 years of accumulation (1964 through 1983) measured near the summit of Quelccaya reveals a substantial decrease (≤30%) in association with the last five ENSO occurrences in the equatorial Pacific (Thompson et al., 1984).

The Quelccaya ice-core data sets can be viewed as very good records of past climate at one geographical point, as would a record obtained at a single meteorology station. It is essential that other ice-core records be developed in the tropics so that the local events can be separated from those events of regional or global significance.

Archive of Recent Variations in Greenhouse Gases

The CO_2 record is the most detailed of the different ice records of atmospheric gases obtained up to now and joins up nicely (Neftel et al., 1985; Siegenthaler and Oeschger, 1987) with the well-known Mauna Loa record measured since 1958 directly in the atmosphere (Keeling et

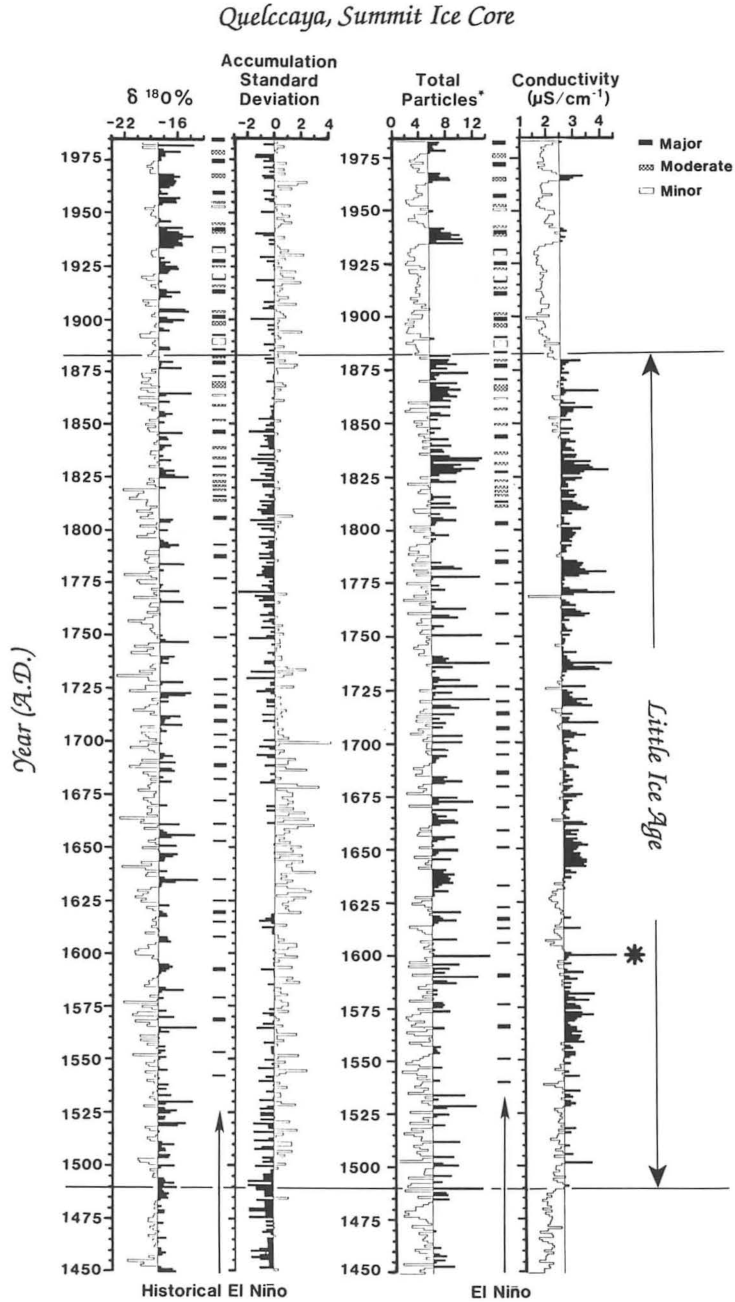

Figure 4. Illustration of annual variations in microparticle concentrations (total particles ≥ 0.63 μm and ≤ 16.0 μm) and large particles (diameter ≥ 1.59 μm) per ml of sample, conductivity, oxygen isotopic ratios, and net accumulation expressed as deviation from the mean for the last 500 years. The Little Ice Age (A.D. 1500 to 1880) stands out clearly and is characterized by increased soluble and insoluble dust and more negative $\delta^{18}O$ values. The Little Ice Age appears to have been a major climatic event in tropical South America. The large dust event, centered on A.D. 1600 (asterisk on figure), was produced by the 19 February to 6 March eruption of Huaynaputina in Peru.

al., 1989). It reveals that the present-day increase began around A.D. 1800, when CO_2 concentrations were about 275 ppmv (Neftel et al., 1985; Raynaud and Barnola, 1985). This CO_2 buildup is attributed mainly to fossil fuel burning and anthropogenic modification of the terrestrial biosphere (agricultural "revolution," deforestation; see Oeschger, this volume). Measurements from ice-core samples also suggest that changes in atmospheric CO_2 of about 10 ppmv could have occurred during the last few centuries of the preindustrial period (Raynaud and Barnola, 1985; Siegenthaler et al., 1988). Such variations could have been induced by the effect of climatic changes like the Little Ice Age on the oceanic and/or terrestrial biospheric reservoirs.

The concentration of present-day atmospheric CH_4 (about 1.7 ppmv) is increasing at a rate of about 1% per year (Blake and Rowland, 1988). The concern about this increase is due to the radiatively and chemically active nature of CH_4. Analyses of air samples trapped in ice show that the present-day increase observed in the atmosphere began a few centuries ago, when atmospheric concentration was between 0.65 and 0.75 ppmv, and seems to parallel human population growth (Rasmussen and Khalil, 1984; Stauffer et al., 1985; Pearman, 1988). This recent enhancement has been attributed mainly to anthropogenic modifications of various sources of methane (cattle, rice production, etc.).

Precipitation/Accumulation Records

In areas where it can be demonstrated that little or no mass loss occurs due to melting or removal by wind, ice cores provide the very best record of the past variations in precipitation available from any proxy source. The annual accumulation rate can be determined by measuring layer thickness changes based on annually varying ice-core parameters such as dust, oxygen isotopes, and other chemistry. Records covering ~1500 years have been produced from the polar Greenland ice sheet (Reeh et al., 1978) and from the tropical Quelccaya ice cores (Thompson et al., 1985). The Quelccaya annual net accumulation record of A.D. 1915–1984 compares well with annual changes in Lake Titicaca water levels and with annual precipitation at El Alto (La Paz, Bolivia), suggesting that the 1500-year net accumulation record from Quelccaya may serve as a proxy for water-level changes in Lake Titicaca. The ice-core record suggests that climatic variability, reflected in lake-level changes, has strongly influenced fluctuations in agricultural activity in southern Peru (Thompson et al., 1988a). The accuracy of precipitation reconstructions, particularly in the deeper core sections, depends on the appropriate constraints being applied to the ice flow model (Paterson and Waddington, 1984).

Climate, Man, and the Environment

In South America, no documentary records survive from before the incursion of the Spaniards in the mid-16th century. Knowledge of pre-Hispanic civilizations in this region comes largely from archaeological excavations, which may be supplemented by information recorded in the two ice cores drilled in the Quelccaya ice cap. A 1500-year record of particle concentrations and conductivity in these cores shows two major dust episodes, each lasting about 130 years, centered at A.D. 920 and 600. The examination of these dust events in light of oxygen isotope and net accumulation records suggests a correlation with pre-Incan agricultural activity.

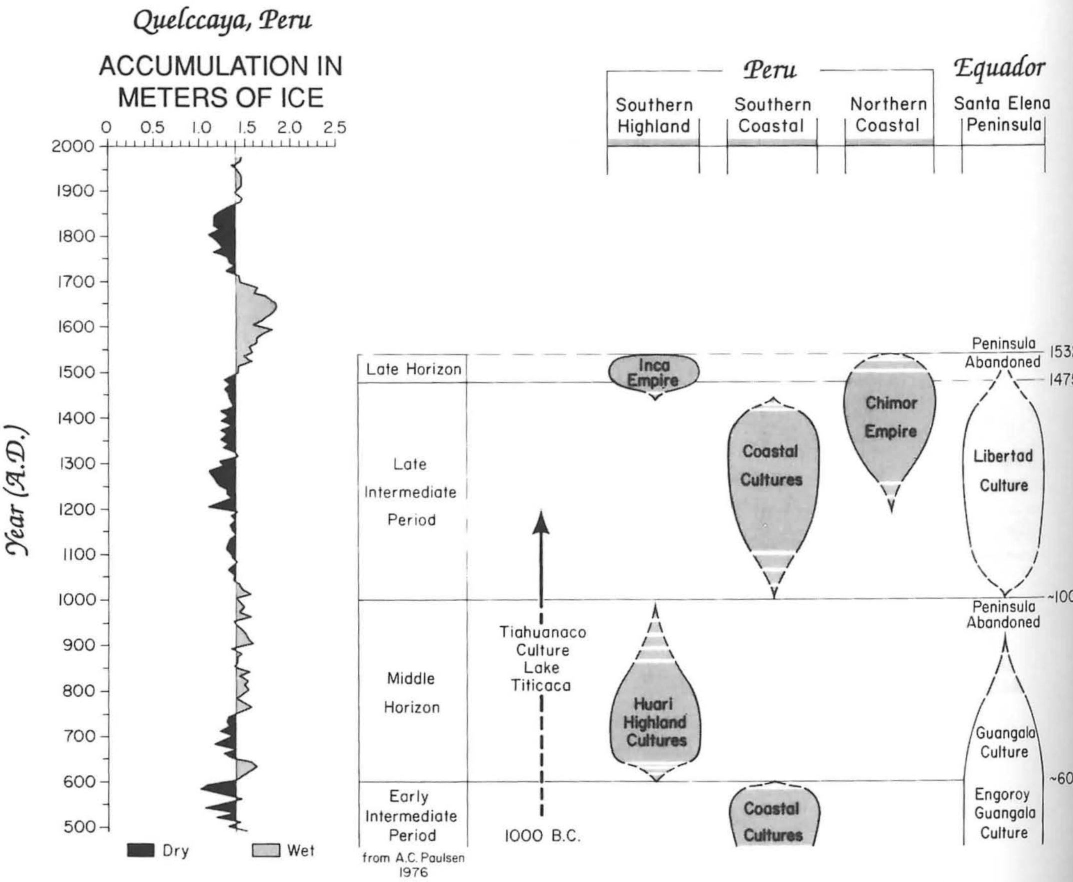

Figure 5. Decadal accumulation trends in meters of ice are presented as a composite of core 1 and summit core records. Wet and dry periods are indicated. On the right the periods of the rise and fall of coastal and highland cultures of Ecuador and Peru are indicated (taken mainly from Paulsen, 1976).

Over the last 1500 years of record in the Quelccaya ice cores, very marked dry periods are found: A.D. 540–610, 650–730, 1040–1490, and 1720–1860; two distinct wet periods occur from A.D. 760 to 1040 and A.D. 1500 to 1720, as illustrated in Figure 5. Both the prehistoric coastal and highland civilizations were largely agrarian-based, and both the coastal areas (due to dependence on a limited water supply) and the high plateau areas (being the upper limits of agriculture) are climatically very sensitive (Cardich, 1985).

Comparison of the records of accumulation from the Quelccaya ice cores with the archaeological history (Paulsen, 1976) demonstrates that highland cultures flourished during wet periods on the Bolivian-Peruvian plateau and, conversely, coastal cultures flourished when the highlands were dryer. Assuming that the same seesaw relationship which currently exists during ENSO events (Thompson et al., 1984) was valid over the longer periods of El Niño–like ocean and atmospheric circulation patterns, then wetter coastal conditions would be expected during periods of highland drought. The fact that coastal cultures flourished during the dryer highland periods implies that this seesaw relationship may exist over extended time periods.

The Global Perspective

The assimilation of multifaceted ice-core data sets from polar and nonpolar regions makes possible the determination of both temporal and geographical variability of any or all the individual ice core parameters, e.g., dust, chemistry, gases, isotopes, etc. The $\delta^{18}O$ records are discussed on a global scale by way of example in Figure 6. The ice-core oxygen isotope records reflect in varying degrees (1) air temperature at which condensation takes place, (2) atmospheric processes between the oceanic source of water vapor and the site of deposition, (3) local conditions under which the isotope signal is modified during firnification, (4) surface elevation of the depositional site, and (5) latitude of the site (see Dansgaard et al., 1973, and Bradley, 1985, for a review). Although the correlation of atmospheric temperatures with oxygen isotope ratios and its spatial representativeness is still under discussion, the method continues to be widely used as a proxy for climate and for temperature in particular (Dansgaard et al., 1973; Jouzel et al., 1983; Thompson et al., 1986; Peel et al., 1988). Figure 6 provides a preliminary global perspective of decadal and century-scale variations for periods ranging from 550 to 1000 years from five sites across the globe. The sites are, from north to south, Camp Century, Greenland (Johnsen et al., 1970); Dunde ice cap, China (this chapter); Quelccaya ice cap, Peru (Thompson et al., 1986); and South Pole and Siple Station, Antarctica (Mosley-Thompson et al., in press). In Figure 6, isotopically heavier and hence warmer periods are illustrated by shaded areas and isotopically lighter and hence colder periods are unshaded. The records show quite a large diversity in detail, not unlike that which would be found if only five widely dispersed meteorological stations were used to reconstruct global temperatures. However, several features stand out, such as the similarity of variability of isotopes in the two Northern Hemisphere sites with a rather pronounced ~180-year oscillation in the China decadal oxygen isotopic record. In the Southern Hemisphere there is a strong similarity in the oxygen isotopic records from the tropical Quelccaya ice cap, Peru, and South Pole, Antarctica. The Little Ice Age stands out as a period of more negative isotopic values from ~A.D. 1530 to 1900, while prior and subsequent to that both locations were generally isotopically less negative.

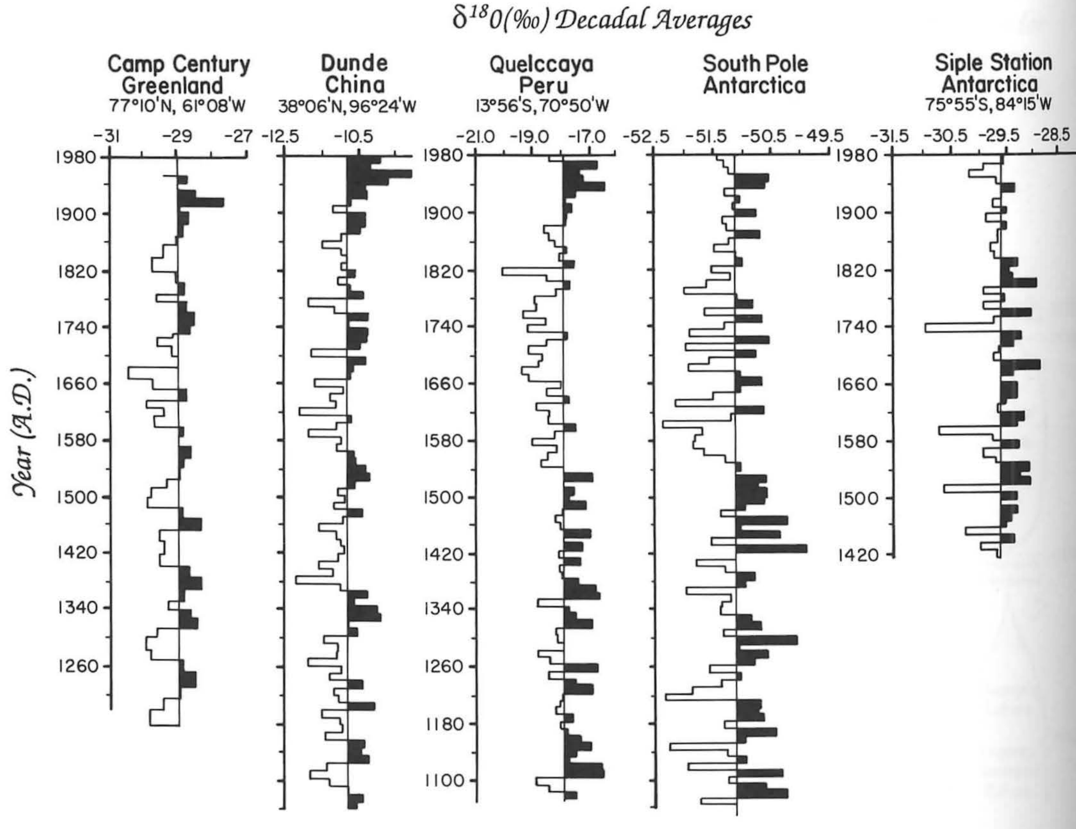

Figure 6. Decadal averages of the $\delta^{18}O$ records in a north-south global transect from Camp Century, Greenland, in the north to the South Pole. The shaded areas represent isotopically less negative (warmer) periods and the unshaded areas isotopically more negative (colder) periods relative to the mean of the individual records. Values shown with reference to the long-term mean at each station for the periods shown.

Of these five records, the Siple Station record is unique because during the Little Ice Age this site exhibits less negative oxygen isotopes and hence presumably warmer conditions. All sites show isotopically less negative conditions during the 20th century except Siple Station, which is, in general, isotopically more negative for the last 100 years. However, for the last 30 years the isotopic evidence (Peel et al., 1988; Mosley-Thompson et al., in press) indicates a general trend to less negative values and thus warmer conditions which is consistent with the warmer overall measured atmospheric temperatures in the Antarctic Peninsula from 1960 to 1980.

A most striking feature of the $\delta^{18}O$ records in Figure 6 is the extreme warmth in central China during the last 60 years, with the warmest decades being the 1940s, 1950s, and 1980s. Using the $\delta^{18}O$ record as a proxy for temperature, the last 60 years constitute one of the warmest periods in the entire record, equalling levels of the Holocene maximum 6000 to 8000 yr. B.P. (Thompson et al., 1989; Thompson et al., in press). Model results of Hansen et al. (1988) suggest that the central part of the Asian continent may be one of the first places to exhibit an unambiguous signal of the anticipated "greenhouse warming." Certainly the Dunde ice core results suggest that the recent warming on the Tibetan Plateau has been substantial. Recent radiosonde data from southern India (Flohn and Kapala, 1989) show that, in fact, the average tropospheric temperature has increased nearly 1°C since 1965. It must be cautioned that more robust temperature-isotope transfer functions must be developed for the Tibetan Plateau and, indeed, for all regions of the earth where isotopic ice-core records are being used as a proxy indicator of temperature.

In conclusion, the ice-core climatic and environmental records from low, mid- and high latitudes can greatly increase our knowledge and understanding of the course of climatic events of the past, which is essential to predicting future climatic oscillations, dominated as they may be by increasing greenhouse gases. The forcing factors, internal and external, which have operated in the past to prevent climatic stability will continue to operate and influence the course of events (Grove, 1988). The Dunde ice cap, China, cores yield the first ice-core record of the Holocene–late Pleistocene climate from the subtropics. The stable isotope record indicates that the last 60 years on the Tibetan Plateau have been one of the warmest periods in the entire record. Events such as the Little Ice Age are global in scale and thus must be caused by large-scale climatic forcing that influences the entire earth system. The manifestation of the Little Ice Age on any given record is quite variable and more distinct in the higher-elevation sites, such as Dunde, Quelccaya, and South Pole, than in the lower-elevation sites of Camp Century and Siple Station. This may indicate the importance of climatic change as a function of elevation as well as more subtle changes in climate like the Little Ice Age being more clearly recorded farther from the mitigating influence of the oceans. The high temporal resolution available from ice cores illustrates that the transition from climatic "norms" may be abrupt on the scale of the Little Ice Age and glacial/interglacial events. The tropical and subtropical ice-core records provide the potential to establish long records of ENSO events and monsoon variability which can yield information on variations in their magnitude and frequency through time and potentially provide information on the causes of these global-scale events. Moreover, a global array of cores can be used to establish changes in precipitation over the last 2000 years as well as to provide records of geographical variations in some of the greenhouse gases.

Recommendations for Further Research

There have been large perturbations of the environment during the last 100 years. In order to understand the consequences of these perturbations, it is necessary to have a time perspective—a frame of reference against which present and future changes can be compared. Specifically, we need to develop a 2000-year time series of the natural "background variability" of the undisturbed earth/atmosphere system. These data will be useful in understanding, for example, the consequences of a greenhouse warming, atmospheric chemistry changes, the El Niño phenomenon, or variations in global volcanism.

A global network of shallow and intermediate ice cores should be obtained in order to reconstruct a three-dimensional space/time history of environmental changes over the last 2000 years. Ice cores have already provided records of unparalleled quality for reconstructing past environments. Over 20 different types of measurements can be made to yield detailed information about changes in atmosphere composition, temperature, and moisture content. In addition to high-latitude sites, records can also be obtained from selected low-latitude and midlatitude alpine regions.

Approximately a dozen sites are needed to augment the handful of records currently available (Figure 7). Proposed areas for ice-core retrieval include the Andes, the central mountain areas of Asia, high-latitude island ice caps, Antarctica, and Alaska. Enough groundwork has been done to indicate that the goals of the initiative can be reached.

Specific foci for future ice-core research are listed below.

- *Ice-Core Process Studies.* Studies should be undertaken to develop more fully the transfer functions needed to interpret the archives by use of current meteorological observations and historical data for calibration. For example, the low average oxygen isotopes and large seasonal variations in oxygen isotopes on the Quelccaya ice cap could be quantitatively explained by factors such as variations in air mass stability over the Amazon Basin, the surface elevation of Quelccaya, and seasonal changes over the site. It has been found that seasonal changes in evaporation of snow on the surface of the ice cap amplify the seasonal oxygen isotope cycle. Thus, air circulation and air mass stability are important in determining the seasonal oxygen isotope cycle of Quelccaya and probably of other low-latitude sites (Grootes et al., 1989). In addition, documentation should be made of the modification of ice-core parameters that occurs within the upper layers of a glacier as snow is transformed into ice.

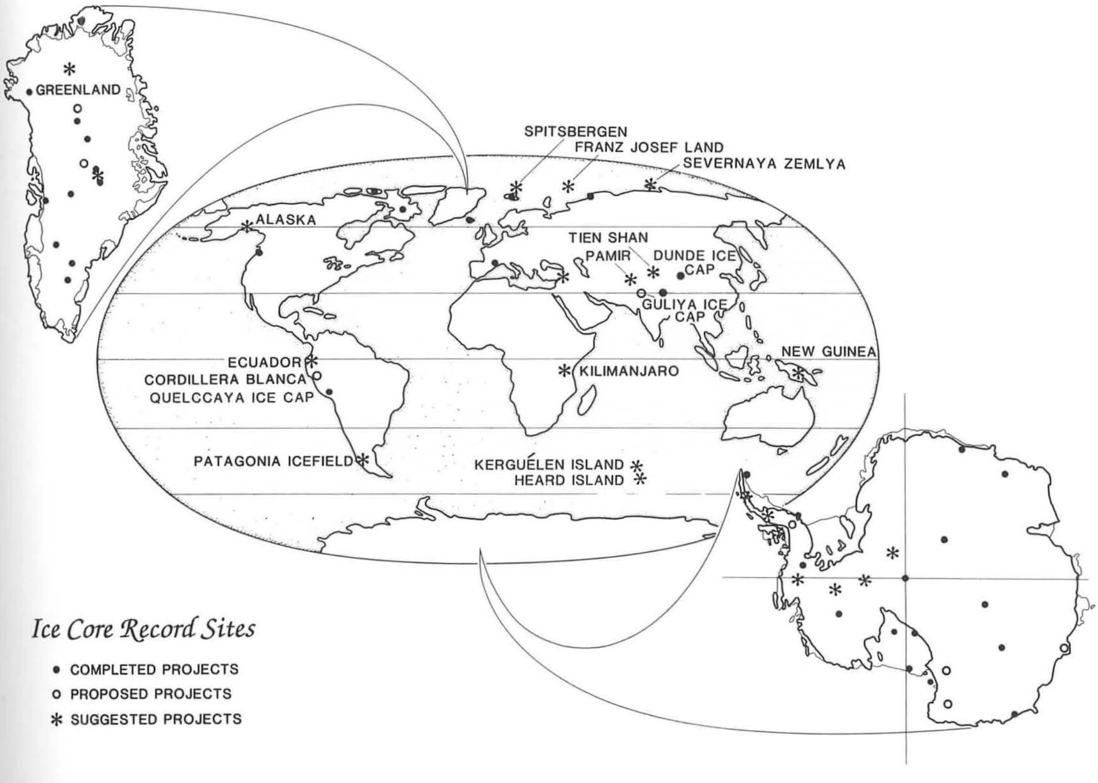

Figure 7. Proxy climate and environmental records from ice cores collected at the sites illustrated should contribute substantially to the reconstruction of such climatic events as the Little Ice Age, El Niño–Southern Oscillation, and monsoonal variations on a global scale. The timing, frequency, geographical extent, and possible causes of specific events may then be studied. The combination of these ice-core records with other proxy histories will make it possible to piece together a global record of climate over the last 2000 years on an annual scale. The most important causal mechanisms may then be identified and their relative importance determined. Filled circles indicate completed projects, open circles show proposed projects, and asterisks indicate suggested projects.

- *Geophysical Studies.* A properly conducted ice-core research program also requires a geophysical program aimed at determining the present ice dynamics, temperature regimes, and bottom topography in order to establish constraints for interpreting the ice-core record. Without the complete study of the glacier system the interpretation of ice-core parameters is substantially weakened. For any new site the climatological and glaciological conditions must be assessed to determine if conditions permit the climatic and environmental signals to be preserved before undertaking a larger-scale ice-core drilling program. It is important that at least two ice cores be drilled at each site and similarly analyzed to provide independent verification of physical and chemical records.

- *Little Ice Age.* The Little Ice Age, the most recent neoglacial event recorded in the Northern Hemisphere (from ca. A.D. 1450 to ca. 1890), was characterized by lower temperatures and expanded glaciers. This event is evident in the ice-core records from the tropics (Thompson et al., 1986) as well as globally (Grove, 1988). However, uncertainties exist as to the length, magnitude, timing, rate of onset and termination, and ultimate cause or causes of this event. One principal objective should be to recover and characterize the record of the Little Ice Age from various latitudes and to determine how this event is recorded in different climatic settings. Documenting climatic variations at different latitudes on both annual and decadal time scales is necessary in order to determine the latitudinal variations in the timing of the initiation and termination of the Little Ice Age and its degree of global synchrony.

- *Abrupt Climatic Change.* Since, as already mentioned, the total ecosystem and particularly the future well-being of man clearly is as much affected by the rate of climatic change as by the magnitude of the change which actually occurs, a principal objective should be to use the often annually resolvable ice-core records to document the rate of climatic change. These studies should be focused on the last 2000 years as well as on glacial/interglacial time scales.

- *ENSO and Monsoon Variability.* After the annual cycle, ENSO events are the dominant global climate signal on the time scale of a few months to a few years (Rasmusson, 1984). A major scientific objective for ice-core analyses from tropical and subtropical sites should be to isolate these events (where possible) and reconstruct their long time histories. These studies will extend the historic data set of ENSO events and assist in isolating long-term periodicities in the ENSO circulation. The perspective provided by a suite of long-term, high-temporal-resolution records should add to our understanding of the spatial patterns exhibited by historic ENSO events. However, since no two ENSO events are identical, their impact on the atmospheric circulation, precipitation, or snowfall at any single site will be different. In order to produce a long history of these ENSO events, a global record of associated parameters must be established.

Similarly, large sections of Africa, India, China, and Indonesia are under the influence of monsoonal circulation. The interannual variability of the summer monsoon rains over Southeast Asia has a profound socio-economic impact. The southwest and southeast monsoons are weakened during ENSO events. Ice cores from these regions may provide records of fluctuations in the monsoonal circulation through time (Thompson et al., 1988b, 1988c, 1989a; Thompson et al., in press). Ongoing and anticipated future programs in north central and western China and south central USSR should prove extremely valuable in this regard.

- *Linkage of Climate and Archaeology.* A 1500-year record of particle concentrations and conductivity in the Quelccaya cores shows that major dust episodes, each lasting about 130 years and centered on A.D. 920 and A.D. 600, are thought to be correlated with pre-Incan agricultural activity (Thompson et al., 1988a). In areas of the world where historical or archaeological records of the environment exist, i.e., largely low- and mid-latitude sites, linkages can be drawn between the ice-core climate record and man's activities. Further comparisons of ice-core and archaeological records, particularly for those times when civilizations seem to have come to an abrupt end, are well worth pursuing.

- *Multidisciplinary Studies.* Natural climatic variability over the last 2000 years is poorly documented and yet is most likely representative of the natural variability of the next few centuries. High priority must be placed upon the acquisition and analysis of ice cores from carefully selected sites on a global scale (Figure 7). Fortunately, proxy records are abundant within numerous natural systems that continuously record high-resolution climatic signals (see, for example, Bradley and Jones, in press). Further, it is imperative that the ice-core records be integrated with other proxy records such as those from corals, lacustrine sediments, and tree rings (Baumgartner et al., 1989). These proxy records, when coupled with available historical data, provide the wide geographical coverage essential in constructing a global picture of climatic changes. This cross-disciplinary approach overcomes the regional limitations imposed by the lack of coverage for any one natural recording system and the lack of historical data, which are particular problems in the Southern Hemisphere and the polar regions.

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