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Cross-references

Beryllium-10
Carbon Dioxide and Methane, Quaternary Variations
Deuterium, Deuterium Excess
Dust Transport, Quaternary
Ice Cores, Mountain Glaciers
Oxygen Isotopes
Quaternary Climate Transitions and Cycles
SPECMAP

ICE CORES, MOUNTAIN GLACIERS

Introduction

With the help of recent innovations in light-weight drilling technology, ice core paleoclimatic research has been expanded from the polar regions to ice fields in many of the world's mountain ranges and on some of the world's highest mountains. Over the last few decades, much effort has been focused on the retrieval of cores from sub-polar regions such as western Canada and eastern Alaska, the mid-latitudes such as the Rocky Mountains and the Alps, and tropical mountains in Africa, South America, and China. Unlike polar ice cores, climate records from lower-latitude alpine glaciers and ice caps present information necessary to study processes where human activities are concentrated, especially in the tropics and subtropics where 70% of the world's population lives. During the last 100 years, there has been an unprecedented acceleration in global and regional-scale climatic and environmental changes affecting humanity. The following is an overview of alpine glacier archives of past changes on millennial to decadal time scales. Also included is a review of the recent, global-scale retreat of these alpine glaciers under present climate conditions, and a discussion of the significance of this retreat with respect to the longer-term perspective, which can only be provided by the ice core paleoclimate records.

Locations of mountain ice core retrieval

The sites from which many of the high-altitude ice cores have been retrieved are shown in Table I3. Among the earliest efforts to retrieve climate records from mountain glaciers were programs involving surface sampling on the Quelccaya Ice Cap (13°56′ S, 70°50′ W; 5,670 m a.s.l.) in southern Peru (1974–1979). The results from this preliminary research, conducted by the Institute of Polar Studies (now the Byrd Polar Research Center) at The Ohio State University, paved the way for the first high-altitude tropical deep-drilling program on Quelccaya in 1983, which yielded a 1,500-year climate record. Meanwhile, in western Canada, a 103-m ice core was drilled on Mt. Logan (60°35′ N, 140°35′ W; 5,340 m a.s.l.) by Canada's National Hydrology Research Laboratory. The record from this core extends back to 1736 AD. Recently, the ice caps on both these mountains have been redrilled, Mt. Logan in 2002 and Quelccaya in 2003. During the intervening decades, mountain ice core research has expanded significantly throughout the world, with programs successfully completed on the Tibetan Plateau and the Himalayas, the Cordillera Blanca of Northern Peru, Bolivia, East Africa, the Swiss and Italian Alps, Alaska, and the Northwest United States (Table I3).

Climatic and environmental information from mountain ice cores

The records contained within the Earth's alpine ice caps and glaciers provide a wealth of data that contribute to a spectrum of critical scientific questions. These range from the reconstruction of high-resolution climate histories to help explore the oscillatory nature of the climate system, to the timing, duration, and severity of abrupt climate events, and the relative magnitude of twentieth century global climate change and its impact on the cryosphere. Much of the variety of measurements made on polar ice cores, and the resulting information, is also relevant to cores from mountain glaciers. Researchers can utilize an ever-expanding ice core database of multiple proxy information (i.e., stable isotopes, insoluble dust, major and minor ion chemistry, precipitation reconstruction) that spans the globe in spatial coverage and is of the highest possible temporal resolution. The parameters that can be measured in an ice core are numerous and can yield information on regional histories of variations in temperature, precipitation, moisture source, aridity, vegetation changes, volcanic activity and anthropogenic input (Figure I4). Many of these physical and chemical constituents produce wet and dry/cold and warm seasonal signals in the ice, which allow the years to be counted back similar to the counting of tree rings.

Isotopic ratios of oxygen and hydrogen (δ^{18}O and δD, respectively) are among the most widespread and important of the measurements made on ice cores. Early work on polar ice cores on these "stable" (i.e., as opposed to unstable, or radioactive) isotopes indicated that they provide information on the precipitation temperature (Dansgaard, 1961), based on

Table I3 A sampling of mountain glaciers sites from which ice cores have been retrieved since 1980. This is by no means a complete inventory of all alpine ice cores ever collected

Mountain	Location	Elevation (m a.s.l.)	Year drilled	Leading organization	Length of core (m)	Length of record (yr)
Bona Churchill	61°24′ N, 141°42′ W	4,420	2002	BPRC	460	1700
Mt. Logan	60°35′ N, 140°35′ W	5,340	1980	NHRI	103	225
			2002	NGP, AINA	190	NA
				NIPR	220	NA
				IQCS, UNH	345	NA
Eclipse Dome	60°51′ N, 139°47′ W	3,017	1996	UNH	160	NA
Fremont Glacier	49°07′ N, 109°37′ W	4,100	1991	USGS	160	275,
			1998		50, 160	NA
Belukha	49°48′ N, 86°34′ E	4,062	2001	PSI, UNIBE	140	200+
Fiescherhorn	46°32′ N, 8°02′ E	3,880	1988	PSI, UNIBE	30	42
			2002		150	
Coropuna	15°32′ S, 72°39′ W	6,450	2003	BPRC	146.3, 34.3, 34.3	16,000+
Col du Dôme	45°50′ N, 6°50′ E	4,250	1994	LGGE, IFU	139	75
Mont Blanc	45°45′ N, 6°50′ E	4,807	1994	LGGE	140	200+
Djantugan	43°12′ N, 42°46′ E	3,600	1983	IGRAS	93	57
Gregoriev	41°58′ N, 77°55′ E	4,660	1991	IGRAS, BPRC	20, 16	53
			2001	IGRAS	21.5	NA
			2003	IGRAS	22	NA
Dunde	38°06′ N, 96°24′ E	5,325	1987	BPRC, LIICRE	138	10,000+
Malan	35°50′ N, 90°40′ E	6,056	1999	LIICRE	102	112+
Guliya	35°17′ N, 81°29′ E	6,200	1992	BPRC, LIICRE	302	110,000+
Puruogangri	33°55′ N, 89°05′ E	6,000	2000	BPRC, LIICRE	208	7000
Dasuopu	28°23′ N, 85°43′ E	7,200	1996	BPRC, LIICRE	162	1,000+
Qomolangma	27°59′ N, 86°55′ E	6,500	1998	UNH, LIICRE	80	154
Kilimanjaro	3°04′ S, 37°21′ E	5,895	2000	BPRC	52	11,700
Huascarán	9°06′ S, 77°36′ W	6,050	1993	BPRC	166	19,000
Quelccaya	13°56′ S, 70°50′ W	5,670	1983	BPRC	155, 164	1,500
			2003		168, 129	1780
Illimani	16°37′ S, 67°47′ W	6,350	1999	IRD, PSI	137, 139	18,000
Sajama	18°06′ S, 68°53′ W	6,540	1996	BPRC	132	20,000

NA: Data not available.

Abbreviations: *BPRC*, Byrd Polar Research Center, The Ohio State University (USA); *NHRI*, National Hydrology Research Institute (Canada); *NGP*, National Glaciology Program (Canada); *AINA*, Arctic Institute of North America, University of Calgary (Canada); *NIPR*, National Institute of Polar Research (Japan); *IQCS*, Institute for Quaternary and Climate Studies, University of Maine (USA); *USGS*, United States Geological Survey (USA); *PSI*, Paul Scherrer Institute (Switzerland); *IRD*, Institute of Research and Development (France); *LGGE*, Laboratoire de Glaciologie et Geophysique de l'Environnement (France); *IGRAS*, Institute of Geography, Russan Academy of Science (Russia); *IFU*, Institut für Umweltphysik (Germany); *UNIBE*, University of Bern (Switzerland); *LIICRE*, Key Laboratory of Ice Core and Cold Regions Environment (China); *UNH*, Institute for the Study of Earth, Oceans and Space, University of New Hampshire (USA).

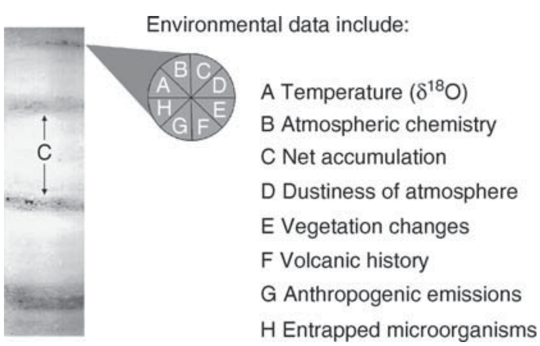

Figure I4 A large variety of environmental information can be obtained from high-altitude ice cores. On the *left* is an image of a core from a typical mountain glacier in Tibet. The dust bands were deposited during the dry seasons, and the space between them is cleaner ice from snow deposited during the wet seasons.

the fractionation of the oxygen and hydrogen atoms into their light and heavy isotopes (^{16}O and ^{18}O, ^{1}H and ^{2}H or deuterium (D)), and on the higher vapor pressure of $H_2{}^{16}O$ over $HD^{16}O$ and $H_2{}^{18}O$. The resulting ratios of the light and heavy isotopes of these elements act as recorders of temperature both at the moisture source and at the deposition site.

The use of $\delta^{18}O$ and δD as temperature proxies for polar ice is now widely accepted; however, it is still a source of controversy for lower-latitude cores. Some who have studied the problem suggest that $\delta^{18}O$, rather than being a temperature recorder at lower latitudes, is a function of precipitation amount (Rozanski et al., 1993; Dahe et al., 2000; Shichang et al., 2000; Baker et al., 2001; Tian et al., 2001). However, real-time comparisons of air temperature and $\delta^{18}O$ measured on precipitation on the Northern Tibetan Plateau reveal a very close relationship between the two (Yao et al., 1996). Correlations between ice core records from the Himalayas and the Northern Hemisphere temperature records show that on longer time scales (longer than annual) the dominant factor controlling mean $\delta^{18}O$ values in snowfall must be temperature rather than precipitation (Thompson et al., 2000; Davis and Thompson, 2003). On seasonal to annual time scales, both temperature and precipitation influence the local $\delta^{18}O$ signal (Vuille et al., 2003).

The annual precipitation rate on an ice cap, or net balance, can be reconstructed by measuring the length of ice between seasonal variations in one or more parameters (e.g., $\delta^{18}O$ indicating warm or cold seasons or high aerosol concentrations characterizing dry seasons, Figure I4) Since ice is viscous, it tends to flow not only horizontally but also vertically, resulting in annual layer thinning with depth. In order to correct for this deformation and reconstruct the original thickness of an annual layer at the time of its deposition in the past, vertical strain models are used that take into account the changing densities with depth, the thickness of the glacier, and the rate of thinning (Bolzan, 1985; Reeh, 1988; Meese et al., 1994).

Aerosols in the atmosphere are either deposited on mountain ice fields and glaciers as nuclei of snow (wet deposition) or carried by turbulent air currents to high altitudes (dry deposition). Either way, these insoluble mineral dust particles and soluble salts, such as chlorides, record variations in environmental conditions such as regional aridity. The concentration and size distribution of insoluble dust particles are also helpful for qualitative reconstructions of wind strength. Evidence of volcanic eruptions in the ice is provided by sulfate concentrations and/or the presence of microscopic tephra particles. If these volcanic layers are identifiable (e.g., the 1815 eruption of Tambora or the 1883 eruption of Krakatoa), they can serve as valuable reference horizons to calibrate the time scale. Biological aerosols, such as pollen grains (Liu et al., 1998) and nitrates that may have been injected into the atmosphere by vegetation upwind of a glacier (Thompson et al., 1995; Thompson, 2000), have been useful for reconstructing past climate and environmental changes that have had impacts on regional flora.

The record of human activity is also available from ice cores, although this type of research on high-altitude glaciers lags behind polar ice sheets. Research on heavy metal types and concentrations in high-altitude glaciers is relatively new, but what is available from Mont Blanc in the French-Italian Alps provides information about increasing industrial production and other activities associated with expanding populations and urbanization (Van DeVelde et al., 1999). Measurements of carbon dioxide and methane, as well as lesser gases, trapped in ice bubbles are not as extensive on ice from mountain glaciers as they are from polar cores; however, the research that has been done shows correlations of so-called "greenhouse" gas concentrations with the temperature proxy δ^{18}O (Yao et al., 2002a, b). The information from these ice core studies complements other proxy records that compose the Earth's climate history, which is the ultimate yardstick by which the significance of present and projected anthropogenic effects will be assessed.

The significance of climate records from mountain glaciers

Ice core records from high-altitude glaciers, when combined with high-resolution proxy histories such as those from tree rings, lacustrine and marine cores, corals, etc., provide an unprecedented view of the Earth's climatic history that can extend over several centuries or millennia. The longest of them have revealed the nature of climate variability since the Last Glacial Maximum (LGM), 18–20 thousand years ago, and even beyond. The more recent parts of the climate records, which are of annual and even seasonal resolution, can yield high-resolution temporal variations in the occurrence and intensity of coupled ocean-atmosphere phenomena such as El Niño and monsoons, which are most strongly expressed in the tropics and subtropics, and are of world-wide significance. This is particularly valuable information since meteorological observations in these regions are scarce and of short duration.

Four records from the Andes (Huascarán in Northern Peru, Coropuna in Southern Peru and Sajama and Illimani in Bolivia) and one from the Western Tibetan Plateau (Guliya) extend to or past the end of the last glacial stage and confirm, along with other climate proxy records (e.g., Guilderson et al., 1994; Stute et al., 1995), that the LGM was much colder in the tropics and subtropics than previously believed. Although this period was consistently colder, it was not consistently drier through the lower latitudes as it was in the polar regions. For example, the effective moisture along the axis of the Andes Mountains during the end of the last glacial stage was variable, being much drier in the north than in the Altiplano region in the central part of the range (Thompson et al., 1995, 1998; Ramirez et al., 2003). In another example in Western China, the Guliya Ice Cap is partly affected by the variability of the southwest Indian monsoon system, which was much weaker during the last glacial stage than during the Holocene. However, this region of the Tibetan Plateau also receives (and received) moisture generated from the cyclonic activity carried over Eurasia by the prevailing wintertime westerlies. Not only were lake levels in the Western Kunlun Shan higher than tropical lakes during the LGM (Li and Shi, 1992), but the dust concentrations in the Guliya ice core record were consistent with those of the Early Holocene when the summer Asian monsoons became stronger, suggesting that local sources of aerosols were inhibited during this cold period by higher precipitation and soil moisture levels (Davis, 2002).

Ice cores from the Andes can also contribute to what is known about past environmental and climatic conditions of the Amazon Basin. The extent of biological activity in the Amazon rainforest during the LGM is controversial, and the nitrate concentration record from the Huascarán ice core has been included in the argument (Colinvaux et al., 2000). Pollen studies from the Amazon Basin suggest that the extent of the rainforest has not changed much between the glacial maximum and the Holocene. However, proponents of the "refugia" theory (i.e., Clapperton, 1993) assert that the cold, dry climate in the tropics caused a major retreat of the rainforest flora into a small, geographically isolated area, leaving most of the Basin covered by grasslands. In the Huascarán core, the nitrate concentration profile is similar to the δ^{18}O levels throughout most of the record, and the very low concentrations of nitrate, which are concurrent with very depleted δ^{18}O, suggest that biological activity upwind of the Cordillera Blanca was impeded by the cold and dry climate $\sim$19,000 years ago.

Most of the deep cores from the low latitudes extend through at least the Holocene, and show spatial variations in climate, even between records from the same region. For example, the Holocene δ^{18}O profiles from Huascarán and Illimani, while similar to each other in that they show Early Holocene isotopic enrichment, are different from that on Sajama, which has a relatively stable isotopic record through the last 10,000 years. Although Sajama and Illimani, both in Bolivia, are geographically close to each other, they are on opposite sides of the Andean Mountains, with Illimani located in the eastern range. Like Huascarán far to the north, it received most of its precipitation from the northeast after it had been recycled through the Amazon Basin. Sajama, which is located on the high, dry Altiplano, is more subject to Pacific influences and local hydrological effects.

Holocene ice core records from mountain glaciers around the world show evidence of major climatic disruptions, such as droughts and abrupt cold events during this period, which previously was believed to have been stable. Major dust events, beginning between 4.2 and 4.5 ka and lasting several hundred years, are observed in the Huascarán and Kilimanjaro ice cores

(Thompson, 2000; Thompson et al., 2002, respectively), and the timing and character of the dust spikes are similar to one seen in a marine core record from the Gulf of Oman (Cullen et al., 2000) and a speleothem $\delta^{13}C$ record from a cave in Israel (Bar-Matthews et al., 1999). This dry period is also documented in several other proxy climate records throughout Asia and Northern Africa (see contributions in Dalfes et al., 1994). Two other periods of abrupt, intense climate change in east Africa are observed in the Kilimanjaro ice core at ~8.3 ka and 5.2 ka (Thompson et al., 2002). The latter event is associated with a sharp decrease in $\delta^{18}O$, indicative of a dramatic but short-term cooling.

More recently, a historically documented drought in India in the 1790s, which was associated with monsoon failures and a succession of severe El Niños, was recorded in the insoluble and soluble aerosol concentration records in the Dasuopu ice core (Thompson et al., 2000). Another recorded Asian Monsoon failure in the late 1870s (Lamb, 1982) is noticeable in the Dasuopu dust flux record, which is a calculation that incorporates both the dust concentration and the annual net balance. The dust concentration on Dasuopu is also linked to the magnitude of the Southern Oscillation and the phase of the Pacific Decadal Oscillation (Davis, 2002), thus indicating a linkage between these tropical processes. However, recent research on Tibetan Plateau ice cores drilled north of 32° N shows that their climate records are not only influenced by the South Asian Monsoon and other tropical coupled atmospheric-oceanic processes such as the El Niño-Southern Oscillation (ENSO), but also by atmospheric pressure variations such as those seen in the North Atlantic Oscillation (Davis and Thompson, 2003; Wang et al., 2004). Thus, the high resolution isotope, chemistry, dust, and accumulation records from ice cores retrieved from across the Plateau help us to reconstruct the spatial and temporal variability of the climate in this region.

There is little purpose in trying to reconstruct the history of global climate change from one ice core, especially at high resolution on short time scales. However, as discussed above, it is clear that certain parameters such as $\delta^{18}O$ do record large-scale regional variability in sea surface temperatures, while others such as aerosols may be more sensitive to local as well as regional conditions. Although the mountain ice core records that extend back through the last millennium show regional differences with each other and with the polar records, many of them also document common climatic variations on hemispheric, and even global, scales. This is illustrated in Figure I5, where composites of the decadally-averaged $\delta^{18}O$ profiles of three South American cores (Huascarán, Quelccaya, and Sajama) and three Tibetan Plateau cores (Dunde, Guliya and Dasuopu) show different interhemispheric trends (Thompson et al., 2003) (Figures I5a and I5b, respectively). For example, the "Little Ice Age," a cold event between the fifteenth and nineteenth centuries that is recorded in many Northern European climate records, is more evident in the South American ice core composite than in the Tibetan Plateau. The "Medieval Warming," a period before the "Little Ice Age," which appears in the Greenland ice core records, is also obvious in the Andean ice cores. However, both the composites show isotopic enrichment (indicating warming) beginning in the late nineteenth century and accelerating through the twentieth century. When all six of the profiles from these mountain glaciers are combined, the resulting composite (Figure I5c) is similar to the Northern Hemisphere temperature records of Mann et al. (1998) and Jones et al. (1998) covering the last 1,000 years (Figure I5d).

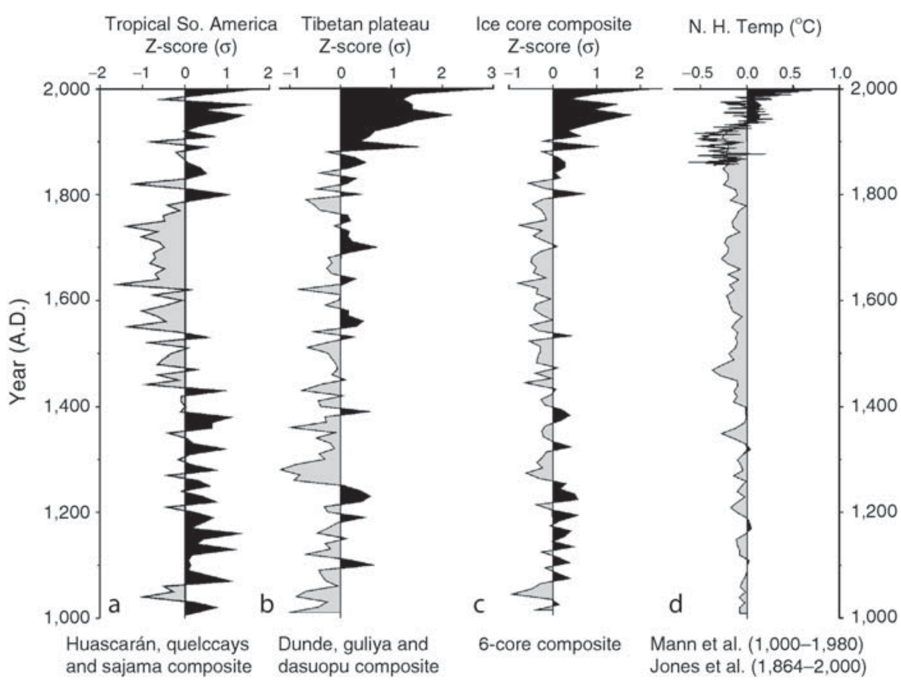

Figure I5 Composite records of decadal averages of $\delta^{18}O$ from ice cores from (**a**) the South American Andes (Huascarán, Quelccaya, Sajama) and (**b**) the Tibetan Plateau (Dunde, Guliya and Dasuopu) from 1000 AD to the present. All six ice-core records are combined (**c**) to give a total view of variations in $\delta^{18}O$ over the last millennium in the tropics, which is compared with the Northern Hemisphere reconstructed temperature record (**d**) (from Thompson et al., 2003).

Not only do these comparisons argue for the important role of temperature in the composition of oxygen isotopic ratios in glacier ice, but they also demonstrate that the abrupt warming from the late nineteenth century through the twentieth century (and continuing into this century) transcends regional variations, unlike earlier climatic variations. Indeed, on a global basis, the twentieth century was the warmest period in the last 1,000 years, which also encompasses the time of the "Medieval Warming."

The modern climate warming and its effects on mountain glaciers

Meteorological data from around the world suggest that the Earth's globally averaged temperature has increased 0.6° C since 1950. The El Niño year of 1998 saw the highest globally averaged temperatures on record, while 2002 (a non-El Niño year) was the second warmest, followed by 2003 and 2001 (a la Niña year). The recent warming of the past century, which has been accelerating in the last two decades, is recorded in alpine glaciers in other ways, both within the ice core records and by the rapid retreat of many of the ice fields. This glacier retreat is observed in almost all regions, from the Caucasus and other Eurasian mountain ranges in the mid-latitudes (Mikhalenko, 1997), to central Europe and western North America (Huggel et al., 2002; Meier et al., 2003), and to the Tibetan Plateau and the tropics (Thompson et al., 1993; Dahe et al., 2000; Thompson et al., 2000). In the Andes, on the Tibetan Plateau and in the East Africa Rift Valley region, this climate change has left its mark. The many ice fields on Kilimanjaro covered an area of 12.1 km^2 in 1912, but today only 2.6 km^2 remains (Figure I6). If the current rate of retreat continues, the perennial ice on this mountain will likely disappear within the next 20 years (Thompson et al., 2002).

Future priorities

Ice cores from mountain glaciers, especially those from the tropical and subtropical latitudes where most of the world's

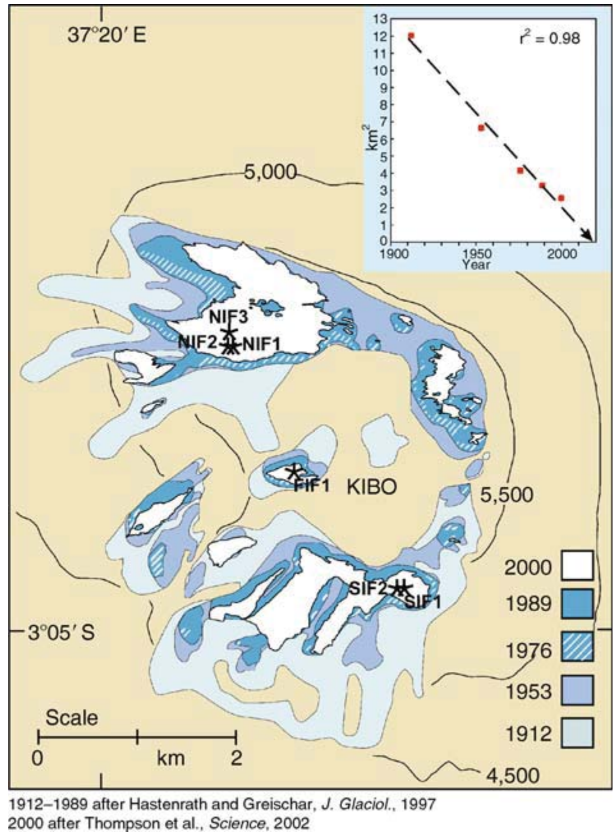

Figure I6 Retreat of ice fields in the Kibo Crater of Kilimanjaro, Tanzania. *Shaded areas* show "snapshots" of areas of ice cover at five times over the twentieth Century. At the rate of retreat shown here, all the ice on this mountain will disappear within the first half of the twenty first century (*insert*) (from Thompson et al., 2002).

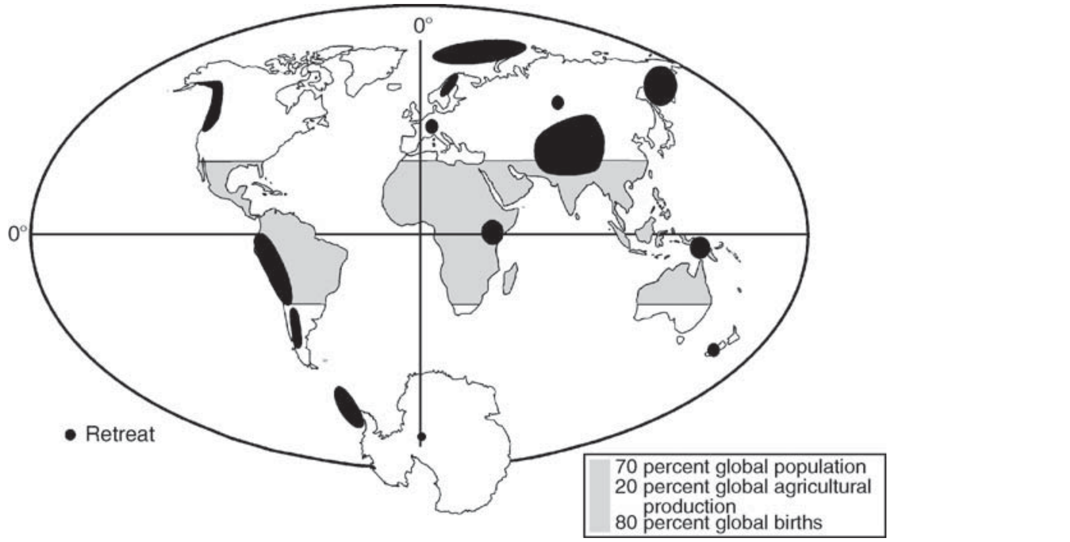

Figure I7 Map demonstrating the current condition of the Earth's cryosphere. *Dark shading* depicts regions where glacier retreat is underway. The light shading represents over land between 30° N and 30° S.

population is concentrated, provide unique and valuable archives of climate information because they are able to record variations in atmospheric chemistry and conditions. Since 1982, the El Niño-Southern Oscillation phenomenon has gained worldwide attention as populations and governments have come to realize the extent of its widespread and often devastating effects on weather. As we begin to understand how this coupled atmospheric-oceanic process works, we also see its linkages with other important systems such as the Asian/African Monsoons. Because both of these tropical systems influence precipitation and temperature over large regions, their effects are also recorded by the chemistry and the amount of snow that falls on alpine glaciers. Seasonal and annual resolution of chemical and physical parameters in ice core records from the Andes Mountains has allowed reconstruction of the variability of the ENSO phenomenon over several hundred years (Thompson et al., 1984, 1992; Henderson, 1996; Henderson et al., 1999). Because the effects of El Niño and La Niña events are spatially variable, ice core records from the northernmost (Colombia) and southernmost (Patagonia) reaches of the Andes Mountains will help further resolve the frequency and intensity of ENSO, along with temperature variations, from long before human documentation. This will aid in placing the modern climate changes and the modern ENSO into a more comprehensive perspective. Variability of the South Asian Monsoon is also of vital importance for a large percentage of the world's population that lives in the affected areas. Cores from the Tibetan Plateau have yielded millennial-scale histories of monsoon variability across this large region and information on the interaction between the monsoon system and the prevailing westerlies that are traced back to the Atlantic Ocean.

The clearest evidence for major climate warming underway today comes from the mountain glaciers, recorded in both the ice core records and in the drastic reductions in both total area and total volume. The rapid retreat causes concern for two reasons. First, these glaciers are the world's "water towers," and their loss threatens water resources necessary for hydroelectric production, crop irrigation and municipal water supplies for many nations. The ice fields constitute a "bank account" that is drawn upon during dry periods to supply populations downstream. The current melting is cashing in on that account, which was built over thousands of years but is not currently being replenished. As Figure I7 illustrates, almost all the Earth's mountain glaciers are currently retreating. The land between 30° N and 30° S, which constitutes 50% of the global surface area, is home to 70% of the world's population and 80% of the world's births. However, only 20% of the global agricultural production takes place in these climatically sensitive regions. The second concern arising from the disappearance of these ice fields is that they contain paleoclimatic histories that are unattainable elsewhere and, as they melt, the records preserved therein are forever lost. These records are needed to discern how climate has changed in the past in these regions and to assist in predicting future changes.

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Cross-references

Aerosol (Mineral)
Deuterium, Deuterium Excess
Ice Cores, Antarctica and Greenland
Little Ice Age
Medieval Warm Period
Monsoons, Quaternary
Mountain Glaciers
North Atlantic Oscillation (NAO) Records
Oxygen Isotopes
Paleo-El Niño-Southern Oscillation (ENSO) Records
Paleo-precipitation Indicators

"ICEHOUSE" (COLD) CLIMATES

Earth's climate has changed, within life-sustaining bounds, from warm to cool intervals, on scales from thousands to hundreds of millions of years. In the Phanerozoic Eon there have been three intervals of glaciation (Ordovician, Carboniferous and Cenozoic) lasting tens of millions of years, with ice down to sea level at mid-latitudes (Frakes et al., 1992; Crowell, 1999). These cool "icehouse" intervals were generally times of lower sea level, lower CO_2 percentage in the atmosphere, less net photosynthesis and carbon burial, and less oceanic volcanism than during alternating "greenhouse" intervals (Fischer, 1986). The transitions from Phanerozoic icehouse to greenhouse intervals were synchronous with some biotic crises or mass extinction events, reflecting complex feedbacks between the biosphere and the hydrosphere.

Figure I8 summarizes Earth's entire paleoclimate history, and Figure I9 shows the better-known Phanerozoic Eon, with carbon, strontium and sulfur isotopic ratios that are linked to major climate changes. Figure I10 shows an anti-correlation between atmospheric CO_2 levels and δ^{18}O values (proxy for oceanic temperature), which tracks the latitude of ice-rafted glacial debris.

The Cryogenian Period of Neoproterozoic time (about 750–580 Ma) contains rocks deposited in two or more severe Icehouse intervals (Harland, 1964; Knoll, 2000). Laminated cap carbonates with depleted δ^{13}C ratios are found on top of glacial marine diamictites in many successions (Kauffman et al., 1997). The sharp juxtaposition of icehouse versus greenhouse deposits has led some to suggest that rapid and extreme climate changes took place in Neoproterozoic time. The Snowball Earth hypothesis proposes that during these Neoproterozoic glaciations, the world ocean froze over. The cap carbonates are thought to have been deposited during a subsequent alkalinity event, caused by rapid warming and supersaturation of sea water on shallow continental shelves (Hoffman et al., 1998; Kennedy et al., 2001; Hoffman and Schrag, 2002).

The Earth's temperature has remained relatively constant for 3.8 by, within a range where life could exist (Figure I11), even though solar luminosity has increased and atmospheric