Ice Cores, High-Mountain Glaciers, and Climate

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Introduction

The near-global retreat of high-mountain glaciers and the shrinkage of ice fields and ice caps and retreat of their associated outlet glaciers are perhaps the most visible evidence for 20th-century climate change and the recent increase in the globally averaged near-surface temperatures of the Earth's surface. The loss of high-mountain glaciers—including ice fields, ice caps, and other glaciers—not only diminishes regional water supplies but also destroys the long, scientifically valuable, and often detailed climatic histories that are unavailable from any other terrestrial or marine record. The question arises as to the significance of 20th-century retreat of glaciers within a much longer perspective. In a few cases, the paleoclimate histories contained within ice cores from these shrinking ice fields and ice caps can provide this critical temporal context. The ongoing global-scale rapid retreat of mountain glaciers threatens freshwater supplies in many of the world's most populous regions while at the same time contributing to the rise in global sea level.

Innovations in lightweight drilling technology have enabled paleoclimatic research on ice cores to expand from the polar regions (for example, ice cores from the Greenland and Antarctic ice sheets) to ice fields and ice caps in many of the highest mountains on Earth. During the last few decades, much effort has been focused on retrieving ice cores from glaciers in subpolar regions, such as western Canada and eastern Alaska; from the mid-latitudes, such as the Rocky Mountains and the Alps; and from tropical mountains in Africa, South America, and China. Unlike climate records from polar ice cores, those from lower latitude high-mountain glaciers—including ice caps, ice fields, and other types of glaciers—present information necessary for studying climatic processes in areas where human activities are concentrated, especially in the tropics and subtropics, where 70 percent of the world's population lives. During the past 100 years, changes in global and regional-scale climates and environmental changes to which human beings are vulnerable have accelerated. These changes will increasingly affect us in the current century and in future centuries. The following overview of the archives of these past changes as held in high-mountain glaciers on millennial to decadal time scales includes a review of the recent, global-scale retreat of these high-mountain glaciers under present climate conditions. The significance of this retreat for the longer term perspective, which can be inferred only from paleoclimate records contained in ice cores, is also discussed.

Geographic Locations of Mountains Where Glacier Ice Cores Have Been Obtained

The sites where many of the high-altitude glacier ice cores have been retrieved are shown in figure 37 and listed in table 10. Among the earliest efforts to retrieve climate records from high-mountain glaciers were research

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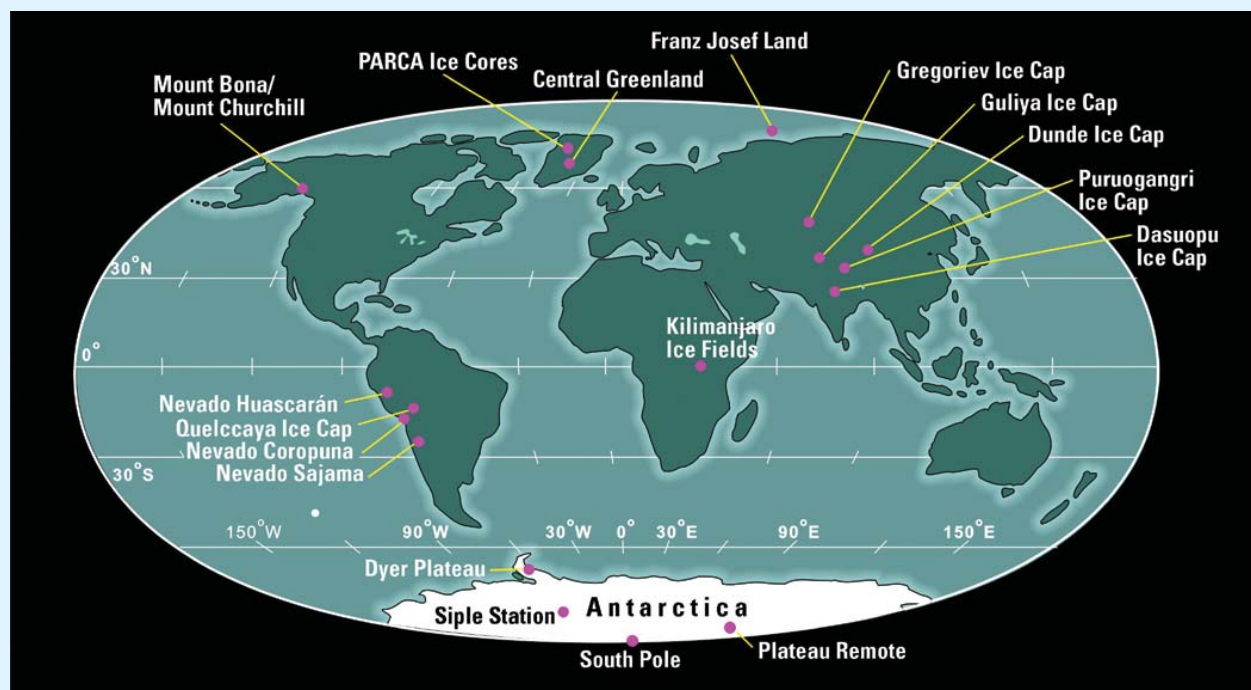
Figure 37.—*Geographic locations of sites where ice cores have been obtained by the ice-core paleoclimate research group at the Byrd Polar Research Center, The Ohio State University. PARCA, Program for Arctic Regional Climate Assessment.*

programs from 1974 to 1979, which involved surface sampling on the *Quelccaya Ice Cap* (5,670 m above sea level [asl]; lat 13°56' S., long 70°50' W.) in southern Perú. (See section on *Quelccaya Ice Cap* by Stefan Hastenrath in Chapter 1386–I, "Glaciers of South America," p. I64–I65, of this series (Morales-Arnao, 1998)). The results from this preliminary research by the Institute of Polar Studies (now the Byrd Polar Research Center, or BPRC) at The Ohio State University paved the way for the first tropical high-altitude, deep-drilling program on the *Quelccaya Ice Cap* in 1983, which yielded a 1,500-year climate record. Meanwhile, in western Canada in 1980, a 103-m ice core was drilled on Mount Logan (5,340 m asl; lat 60°35' N., long 140°35' W.) by Canada's National Hydrology Research Laboratory. The record from this core extends back to A.D. 1736. The ice caps on both mountains have been redrilled recently, Mount Logan in 2002 and *Quelccaya Ice Cap* in 2003. During the intervening decades high-mountain ice-core research has expanded significantly throughout the world, with programs successfully completed on the Tibetan Plateau, the Himalaya, the Cordillera Blanca of northern Perú, Bolivia, East Africa, the Swiss and Italian Alps, Alaska, and the Pacific Northwest of the United States. In 2002, the BPRC paleoclimate ice-core group succeeded in retrieving the deepest ice cores ever recorded (460 m) from the col between Mount Bona (5,008 m asl) and Mount Churchill (4,770 m asl) in the St. Elias Mountains of southeastern Alaska. (See descriptions of glaciers in this mountain range in Chapter 1386–K, "Glaciers of Alaska," of this series (Molnia, 2008).

Table 10.—*A selection of sites of high-mountain glaciers from which research organizations have obtained ice cores since 1980*

[NA, time series for this ice core is not yet available; place-name in italics indicates that it is informal usage (unapproved)]

Abbreviations for the organizations: BPRC, Byrd Polar Research Center (previously called the Institute of Polar Studies), The Ohio State University (USA) NHRC, National Hydrology Research Centre (Canada) NGP, National Glaciology Programme (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 (now called the CCI, Climate Change Institute), University of Maine (USA) USGS, U. S. Geological Survey (USA)	PSI, Paul Scherrer Institut (Switzerland) IRD, Institut de Recherche pour le Développement (France) LGGE, Laboratoire de Glaciologie et Géophysique de l'Environnement (France) IGRAS, Institute of Geography, Russian Academy of Science (Russia) IFU, Institut für Umweltphysik (Germany) UNIBE, Universität 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)

Name of glacierized mountain or glacier, and state or country	Location (latitude and longitude)	Elevation (meters above sea level)	Year drilled	Leading organization	Length of core (meters)	Length of record (years)
Mount Bona/Mount Churchill, Alaska	61°24′N. 141°42′W.	4,420	2002	BPRC	460	NA
Mount Logan, Canada	60°35′N. 140°35′W.	5,340	1980 2002	NHRC, NGP, AINA, NIPR, IQCS, UNH	103 190 220 345	225 NA NA NA
Eclipse Dome, Canada	60°51′N. 139°47′W.	3,017	1996	UNH	160	NA
Fremont Glaciers, Wyoming	43°09N. 109°37′W.	4,100	1991 1998	USGS	160 50, 160	275 NA
Gora Belukha, Kazakhstan/Russia	49°48′N. 86°34′E.	4,062	2001	PSI, UNIBE	140	200+
Fiescherhorner, Switzerland	46°32′N. 8°02′E.	3,880	1988 2002	PSI, UNIBE	30 150	42
Col du Dôme, France	45°50′N. 6°50′E.	4,250	1994	LGGE, IFU	139	75
Mont Blanc, France	45°45′N. 6°50′E.	4,807	1994	LGGE	140	200+
Djantugan, Russia	43°12′N. 42°46′E.	3,600	1983	IGRAS	93	57
Gregoriev, Kyrgyzstan	41°58′N. 77°55′E.	4,660	1991 2001 2003	IGRAS, BPRC IGRAS IGRAS	20, 16 21.5 22	53 NA NA
Dunde ice cap, China	38°06′N. 96°24′E.	5,325	1987	BPRC, LIICRE	183	10,000+
Malan ice cap, China	35°50′N. 90°40′E.	6,056	1999	LIICRE	102	112+
Guliya ice cap, China	35°17′N. 81°29′E.	6,200	1992	BPRC, LIICRE	302	110,000+
Purugangri ice cap, China	33°55′N. 89°05′W.	6,000	2000	BPRC, LIICRE	208	NA
Dasuopu glacier, China	28°23′N. 85°43′E.	7,200	1996	BPRC, LIICRE	162	1,000+
Qomolangma, Nepal/China	27°59′N. 86°55′E.	6,500	1998	UNH, LIICRE	80	154
Kilimanjaro ice fields, Tanzania	3°04′S. 37°21′E.	5,895	2000	BPRC	52	11,700
Nevado Huascarán, Perú	9°06′S. 77°36′W.	6,050	1993	BPRC	166	19,000
Quelccaya ice cap, Perú	13°56′S. 70°50′W.	5,670	1983 2003	BPRC	155, 164 168, 129	1,500 1,800
Nevado Illimani, Bolivia	16°37′S. 67°47′W.	6,350	1999	IRD, PSI	137, 139	18,000
Nevado Sajama, Bolivia	18°06′S. 68°53′W.	6,540	1996	BPRC	132	20,000

Climatic and Environmental Information from High-Mountain Ice Cores

The records within the Earth's high-mountain ice caps and other glaciers contain a wealth of data that contribute to a spectrum of critical scientific and societal issues. These data have enabled glaciologists to reconstruct high-resolution climate histories; explore the oscillatory nature of the climate system; estimate the timing, duration, and severity of abrupt climate events; and estimate the relative magnitude of 20th-century global climate change and its impact on the Earth's cryosphere, among other achievements. Many of the measurements made on polar ice cores (for example, from the Greenland and Antarctic ice sheets) and the resulting information are also relevant to ice cores from high-mountain glaciers. Researchers can utilize an ever-expanding ice-core database of multiple kinds of proxy information (for example, stable isotopes, insoluble dust and tephra, major- and minor-ion chemistry, precipitation reconstructions) that spans the globe in terms of geographic coverage and that is of the highest possible temporal resolution. Numerous parameters can be measured that yield information on regional histories of variations in temperature, precipitation, moisture source, aridity, vegetation changes, volcanic activity, and anthropogenic input (table 11). Many of these physical and chemical constituents yield signals in the ice of wet and dry or cold and warm seasons that allow the variations to be analyzed backward in time, much as does tree-ring analysis (dendroclimatology).

Isotopic ratios of oxygen ($\delta^{18}O$) and of deuterium (δD) in water are among the most widespread and important of the measurements made on ice cores. The information that $\delta^{18}O$ and δD provide is based on the fractionation of the oxygen and hydrogen atoms into their light and heavy isotopes (^{16}O and ^{18}O, and ^{1}H and ^{2}H or deuterium (D)) and on the higher vapor pressure of $H_2^{16}O$ over $HD^{16}O$ and over $H_2^{18}O$. Early work on these stable isotopes (as opposed

Table 11.—*Principal sources of paleoclimatic information from ice cores*

[A variety of environmental information can be obtained from high-altitude ice cores. In the low latitudes, pollen and entrapped microorganisms have been measured; insects and organic material are sources for accelerator mass spectrometer (AMS) carbon-14 dating (after Bradley, 1999). Abbreviations: δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; ^{10}Be, beryllium-10; SO_4, sulfate; CO_2, carbon dioxide; CH_4, methane; N_2O, nitrous oxide; ECM, electrical conductivity measurement]

Parameter	Analysis
Paleotemperatures:	
Summer	Melt layers
Annual? Days with snowfall?	δD, $\delta^{18}O$
Humidity	Deuterium excess (d)
Paleoaccumulation (net)	Seasonal signals, ^{10}Be
Volcanic activity	Conductivity, nonsea salt, SO_4
Tropospheric turbidity	ECM, microparticle content, trace elements
Wind speed	Particle size, concentration
Atmospheric composition: long-term and anthropogenic changes	CO_2, CH_4, N_2O content, glaciochemistry
Atmospheric circulation	Glaciochemistry (major ions)
Solar activity	^{10}Be

to unstable, or radioactive, isotopes) in polar ice cores resulted in transfer functions between the isotopic ratios and the water temperature at the moisture source and the atmospheric temperature as the water vapor condenses into precipitation (Dansgaard, 1961).

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 ice cores. Some geoscientists who have studied the problem believe that $\delta^{18}O$ is a function of the amount of precipitation rather than being a temperature proxy at lower latitudes (Rozanski and others, 1993; Kang and others, 2000; Qin Dahe and others, 2000; Baker and others, 2001; Tian and others, 2001). However, real-time comparisons of $\delta^{18}O$ measured on precipitation on the northern Tibetan Plateau and air temperature reveal a very close relation between the two (Yao and others, 1996). Correlations between ice-core records from the Himalaya and temperature records for the Northern Hemisphere show that the dominant factor controlling mean $\delta^{18}O$ values in snowfall on longer than annual time scales must be temperature, not precipitation (Thompson and others, 2000; Davis and Thompson, 2004; Thompson and Davis, 2005; Thompson and others, 2006). On seasonal to annual time scales, temperature and precipitation both influence the local $\delta^{18}O$ signal (Vuille and others, 2002, 2003, 2005).

The annual net balance[6] on an ice cap can be constructed by measuring the thickness of ice between seasonal variations in one or more parameters that indicate warm or cold seasons (such as $\delta^{18}O$) or that characterize wet or dry seasons (such as aerosol concentrations). Because ice is viscous, it tends to flow not only vertically but also horizontally, resulting in thinning of the annual layer with depth. To correct for this deformation so that the original thickness of an annual layer at the time of its deposition in the past can be reconstructed, 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 and others, 1994).

Aerosols in the atmosphere are either deposited on high-mountain ice fields, ice caps, and other 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 (chlorides, for example) record variations in environmental conditions such as regional aridity. The concentration and size distribution of insoluble dust are also helpful for qualitative reconstructions of wind speeds. Evidence of volcanic eruptions is found in sulfate concentrations and (or) the presence of microscopic tephra particles in the ice cores. If these volcanic layers are geochemically or petrologically identifiable (for example, as the 1815 eruption of Tambora or the 1883 eruption of Krakatoa, both in the East Indies), they can serve as valuable reference horizons to calibrate the time scale within and between ice cores (tephrochronology). Biological aerosols, such as pollen grains (Liu and others, 1998) and nitrates that may have been injected into the atmosphere by vegetation upwind of a glacier (Thompson and others, 1995; Thompson, 2000), have been useful for reconstructing past climate and environmental changes that caused changes in regional flora.

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[6] "The *balance* or *mass balance b* at any time is the algebraic sum of the accumulation and ablation… The mass balance at the end of the balance year is the *net balance* b_n for the year. It can be subdivided into a *winter balance* b_w which is positive, and a *summer balance* b_s which is negative." (Paterson, 1994, p. 28).

The record of human activity also is available from high-mountain ice cores, although this type of research lags behind that on analysis of ice cores from the polar regions. Analysis of heavy metals in high-mountain glaciers is relatively new, but what is available from Mont Blanc (Monte Bianco) in the Savoy Alps, on the border of France and Italy, provides information about increasing industrial production and other activities associated with expanding populations and urbanization (van de Velde and others, 1999). Measurements of carbon dioxide, methane, and other atmospheric gasses trapped in ice bubbles in low-latitude ice cores are not as extensive as they are from polar ice cores; however, the available measurements show that so-called greenhouse-gas concentrations correlate with the temperature proxy $\delta^{18}O$ (Yao, Duan, and others, 2002; Yao, Thompson, and others, 2002). The information from these studies complements other proxy records that define the Earth's climate history, the ultimate yardstick by which the significance of present and projected anthropogenic effects are being and will continue to be assessed.

The Significance of Climate Records from High-Mountain Glaciers

When ice-core records from high-mountain glaciers are combined with high-resolution proxy records such as those from tree rings, lacustrine and marine cores, corals, and other sources, geologists are afforded an unprec-edented examination of the Earth's climatic history. Such records can extend over several centuries or even millennia. The longest records have revealed the nature of climate variability since the Last Glacial Maximum (LGM), 18 to 20 ka (thousand years ago), and even longer ago (Thompson and others, 2006). The more recent parts of the ice-core records—which have annual and, in some cases, seasonal resolution—can yield high-resolution temporal variations in the occurrence and intensity of coupled ocean-atmosphere phenomena of global significance, such as El Niño[7] and monsoons; the latter are most strongly expressed in the tropics and subtropics. Such information is particularly valuable because long-term meteorological observations from these regions are scarce; most records are of short duration (decadal at most, as opposed to a century or more in the United States and Europe) and in many cases intermittent.

Three records from the Andes (Nevado Huascarán, northern Perú; and Sajama and Illimani, Bolivia) and one from the western Tibetan Plateau (Guliya ice cap) extend to or past the end of the last glacial stage (of the Pleistocene Epoch), along with other climate proxy records (for example, Guilderson and others, 1994; Stute and others, 1995). These records confirm that the LGM was much colder in the tropics and subtropics than previously believed (Thompson and others, 1995, 1997, 1998; Ramirez and others, 2003). Although this period was consistently colder, it was not consistently drier throughout the lower latitudes than it was in the polar regions. For example, the effective moisture along the axis of the Andes 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. Meanwhile, in western China, the southwest Indian monsoon system was much weaker during the last glacial stage than during the Holocene Epoch. However, the region of the Tibetan Plateau in which the Guliya ice cap is located also received (and receives) mois-

[7] [Editors' note: El Niño is defined as a phenomenon in a region of the equatorial Pacific Ocean characterized by a sea surface temperature that is ≥0.5°C warmer than normal, averaged over three consecutive months; this increase affects the global climate system.]

ture 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 in tropical lakes during the LGM (Li Shijie and Shi Yafeng, 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 higher precipitation and soil-moisture levels inhibited local sources of aerosols during this cold period (Davis, 2002).

Ice cores from the Andes can also contribute to our understanding of past environmental and climatic conditions of the Amazon Basin. The extent of the Amazon rainforest during the LGM is controversial, but the nitrate concentration record from the Nevado Huascarán ice core sheds some light on this debate (Colinvaux and others, 2000). Pollen studies from the Amazon Basin suggest that the areal extent of the rainforest has not changed much between the LGM and the Holocene. Proponents of the "refugia" theory (for example, Clapperton, 1993) assert, however, that the cold, dry climate in the tropics caused a major retreat of the rainforest flora (and associated fauna) into small, geographically isolated areas, leaving most of the Amazon Basin covered by grasslands. In the Nevado Huascarán ice core, the nitrate-concentration profile is similar to (although lagging behind) the $\delta^{18}O$ record throughout most of the ice core, and the very low concentrations of nitrate that are concurrent with very depleted $\delta^{18}O$ suggest that biological activity upwind of the Cordillera Blanca of Perú was impeded by the cold and dry climate ~19 ka. Limited evidence for tropical ecosystems suggests that rainforest and forest soils may be a major source of active species of atmospheric nitrogen such as NO and NH_3, which are precursors for NO_3^- and NH_4^+, which occur as aerosols. The low NO_3^- concentrations in Late Glacial Stage ice may imply that the forest cover was significantly reduced in response to dry conditions (Thompson and others, 1995).

Most of the deep ice cores from the low latitudes extend through at least the Holocene Epoch and show spatial variations in climate, even between records from the same region. For example, the Holocene $\delta^{18}O$ profiles from Nevado Huascarán, Perú, and from Nevado Illimani, Bolivia, which are similar in showing nearly identical early Holocene isotopic enrichment, differ from the profile from Nevado Sajama, Bolivia, which shows relatively low isotopic variability throughout the last 10,000 years. Although Nevado Sajama and Nevado Illimani are geographically close, they are on opposite sides of the Andes, with Nevado Illimani to the east in the Cordillera Real (Jordan, 1998; see especially fig. 17, p. I99). Like Nevado Huascarán far to the north, Nevado Illimani has long received most of its precipitation from the northeast after the water that makes up the precipitation has cycled through the Amazon Basin. Nevado Sajama, which is on the high, dry Altiplano, is more subject to Pacific influences, local hydrological processes, and sublimation.

Holocene ice-core records from high-mountain glaciers around the world show evidence of major climatic disruptions (droughts and abrupt cold events) during an epoch that geologists previously believed to have been stable. Beginning between 4.2 and 4.5 ka and lasting several hundred years, major dust events are observed in ice cores from Nevado Huascarán and from Kilimanjaro ice fields (in Africa) beginning between 4.2 ka and 4.5 ka (Thompson, 2000; Thompson and others, 2002, respectively), and lasting several hundred years. The timing and character of the dust spike are similar to those seen in a marine sediment-core record from the Gulf of Oman (Cullen and others, 2000) and in a speleothem $\delta^{13}C$ record from a cave in Israel (Bar-Matthews and others,

1999). This dry period is also documented in several other proxy climate records throughout Asia and North Africa (Dalfes and others, 1997). Two other periods of abrupt, intense climate change in East Africa are observed in the ice cores from the Kilimanjaro ice fields at ~8.3 ka and 5.2 ka (Thompson and others, 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 records of insoluble and soluble aerosol concentrations in the ice core from the Dasuopu glacier, China (Thompson and others, 2000). The ice core from the Dasuopu glacier recorded another Asian monsoon failure in the late 1870s (Lamb, 1982) in the dust-flux record, which is a calculation that incorporates both the dust concentration and the annual net balance. The dust concentration on the Dasuopu glacier is also linked to the magnitude of the Southern Oscillation[8] and the phase of the Pacific Decadal Oscillation (Davis, 2002), thus indicating a linkage between these two tropical processes. However, recent research on Tibetan Plateau ice cores drilled north of lat 32° N. shows that their climate records are influenced not only by the South Asian Monsoon and other tropical coupled atmospheric-oceanic processes such as the El Niño–Southern Oscillation (ENSO) (Davis and others, 2005) but also by atmospheric-pressure variations such as those seen in the North Atlantic Oscillation (NAO) (Wang and others, 2003; Davis and Thompson, 2004). Thus, the records from ice cores of high-resolution isotopes, chemistry, dust, and accumulation that were retrieved from across the Tibetan Plateau help us to accurately reconstruct the spatial and temporal variability of climate in this region.

Ice-core proxy records document local, regional, and larger scale environmental fluctuations. There is little purpose in trying to reconstruct the history of global climate change from a single ice core, especially at high resolution on short time scales. However, certain parameters, such as $\delta^{18}O$, clearly record large-scale regional variability in sea-surface temperatures (SSTs), whereas other parameters, such as aerosols, may be more sensitive to local and regional conditions. Although the high-mountain ice-core records that extend back through the last two millennia differ regionally from one another and from the polar records, many of them document common climatic variations on hemispheric and even global scales. For example, composites of the decadally averaged $\delta^{18}O$ profiles of three South American ice cores (Nevado Huascarán, *Quelccaya Ice Cap*, and Nevado Sajama) and three Tibetan Plateau ice cores (Dunde and Guliya Ice Caps and Dasuopu Glacier) show different interhemispheric trends during the last millennium (Thompson and others, 2003) (fig. 38). For example, the Little Ice Age, a cold event between the 15th and 19th centuries that is noted in many northern European climate records (Grove, 1988), is more evident in the South American ice-core composite than that from the Tibetan Plateau. The Medieval Warming, a period before the Little Ice Age that appears in the Greenland ice-core records, is also more evident in the Andes time series. However, both of the composites show isotopic enrichment (indicating warming) beginning in the late 19th century and accelerating through the 20th century.

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[8] [Editors' note: The Southern Oscillation describes changes in atmospheric air pressure above the Pacific Ocean.]

A. Locations of ice cores used in the ice core composite record
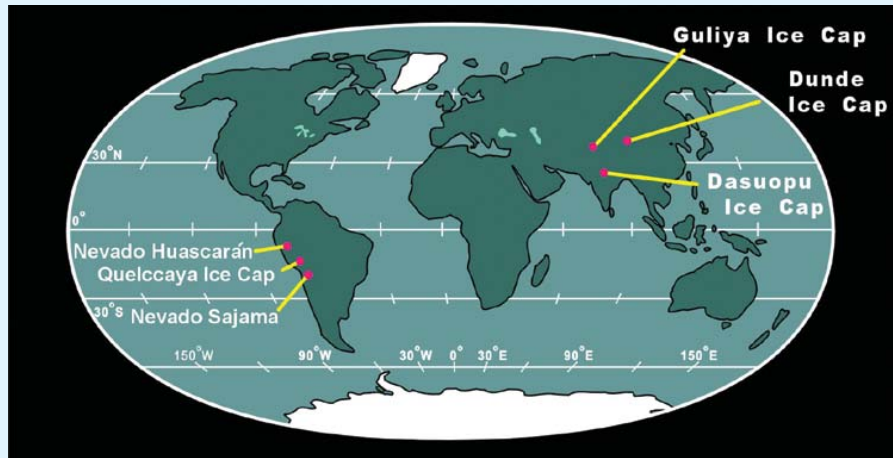
B. Reconstructed and observed Northern Hemisphere temperature record
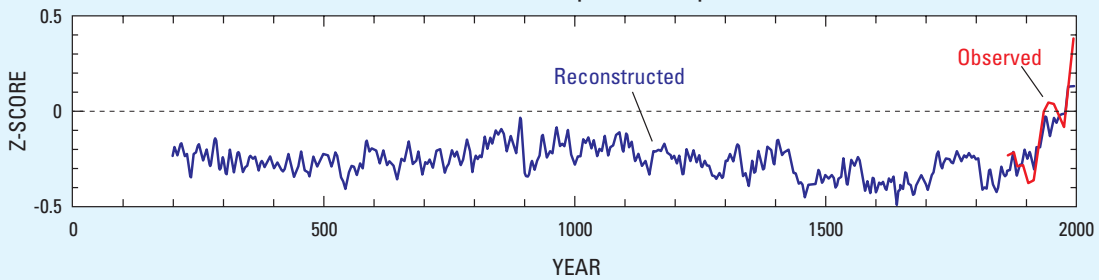
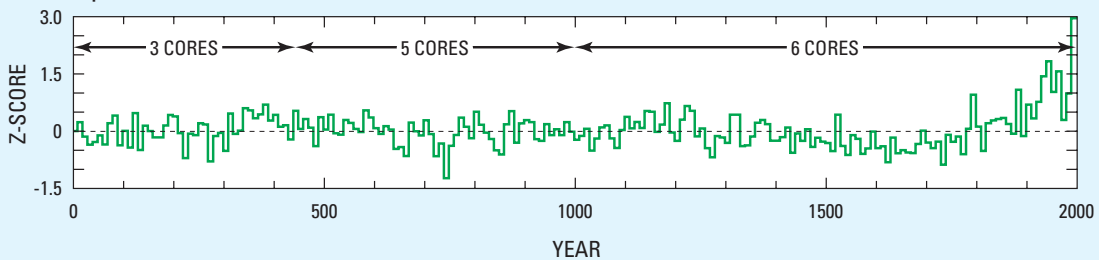**C.** Composite δ¹⁸O record from Andes Mountains and Tibetan Plateau ice cores

Figure 38.—**A**, *Geographic location of ice cores used in the ice-core composite record.* **B**, *Northern Hemisphere temperature records. The ice-core reference period for B is 1961–1990. The blue line is a reconstruction of temperature from Jones and Mann (2004); the short red segment of the line depicts the meteorological observations compiled by Jones and Moberg (2003).* **C**, *Composite of decadal averages of the isotope δ¹⁸O from ice cores from the Andes Mountains and Tibetan Plateau during the past two millennia. The Z score is the standard deviation from its respective mean (Mosley-Thompson and others, 2006). The ice-core reference period for C is the 2,000 years preceding the 21st century.*

When all six of the profiles from these high-mountain glaciers are combined, the resulting profile is similar to the Northern Hemisphere temperature records of Mann and others (1998) and Jones and others (1998), which cover the last 1,000 years (Thompson and others, 2003) (fig. 38). Not only do these comparisons argue that temperature plays the most important role in the composition of oxygen isotopic ratios in glacier ice but they also demonstrate that the abrupt warming beginning in the late 19th century through the 20th century (and continuing into the 21st century) transcends regional influences, unlike earlier climatic variations. Indeed, on a global basis, the 20th century was the warmest period in the last 1,000 years, a period of time that also encompasses the interval of the Medieval Warming.

To capture a larger temporal time scale, the composite record of decadal $\delta^{18}O$ averages from these six ice cores has been extended back another 1,000 years. The composite consists of all the ice cores for the last 1,000 years, five for the last 1,550 years, and three for the last 2,000 years (fig. 38). Because 70 to 80 percent of the snowfall over both the Tibetan Plateau and Andes arrives during the Northern Hemisphere summer and winter, respectively, combining the six isotopic time series results in a more representative history from high elevations situated in low latitudes. The combined Tibetan Plateau and Andes records of decadally averaged $\delta^{18}O$ are shown in figure 38, along with the 2,000-year Northern Hemisphere multiproxy climate history, coupled with meteorological observations since 1860 (Jones and Moberg, 2003; Jones and Mann, 2004). These records place the dominant signal, that of the 20th century warming, within a longer-term perspective. This global-scale, high-elevation warming is significant because, although seasonal and annual temperature variations are small in the tropics, the high-mountain ice fields, ice caps, and other glaciers in these regions experienced significant and rapid loss of mass in the past two decades (for example, accelerated thinning and retreat of termini and margins) and this rapid loss is currently continuing. (See also table 3.1 (p. 19) and fig. 3.1 (p. 20) in "The Distribution of Glaciers in the Tropics" (Kaser and Osmaston, 2002).) The changes in high-mountain glaciers are discussed more fully below.

Post-1950 Climate Warming and Its Effects on High-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, whereas 2002, a non-El Niño year, was the second warmest. The year 2003 was followed by 2004, a La Niña[9] year, and yet 2005 matched or exceeded the record temperature of 1998. The warming during the 20th century, which has accelerated during its last two decades, is recorded in high-mountain glaciers both within the ice-core records and by the rapid thinning and retreat of many of the ice fields, ice caps, and other glaciers. This glacier retreat is observed in almost all regions of the world:

- The Caucasus and other Eurasian mountain ranges in the mid-latitudes (Mikhalenko, 1997; Kotlyakov and others, 2010);

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[9] [Editors' note: La Niña is defined as a phenomenon in a region of the equatorial Pacific Ocean characterized by a sea surface temperature that is ≥0.5° C colder than normal, averaged for three consecutive months.]

- Central Europe (Williams and Ferrigno, 1993);

- Western North America (Haeberli and others, 1999; Huggel and others, 2002; Williams and Ferrigno, 2002; Hoelzle and others, 2003; Meier and others, 2003); Alaska (Molnia, 2008);

- Iceland (Sigurðsson, 1998, 2005, 2006; Sigurðsson and Williams, 1998; Sigurðsson, and others, 2007);

- Tibetan Plateau (Shi Yafeng and others, 2010) ;

- Tropics (Allison and others, 1989; Thompson and others, 1993, 2000; Qin Dahe and others, 2000);

- Andes (Williams and Ferrigno, 1998);

- Irian Jaya, Indonesia (Allison and Peterson, 1989; Prentice and others, 2003);

- New Zealand (Chinn, 1989, 1996);

- Great Rift Valley Region of East Africa (Young and Hastenrath, 1991).

The case of Kilimanjaro is worth remaking. In 1912, the many ice fields on Kilimanjaro covered an area of 12.1 km^2, but in 2000 the ice covered only 2.6 km^2 (fig. 39). If the current rate of retreat and thinning continues, the perennial glacier ice on this mountain is likely to disappear by 2020 (Thompson and others, 2002). When the 20th century shrinking of Kilimanjaro's ice fields is placed within a 11.7-ka interval, the perspective of the ice-core records shows that the current wasting of these ice fields is unprecedented during the Holocene Epoch, even within the context of the evidence of intense and abrupt climatic disruptions in the past. For example, the ice-core evidence reveals that a prolonged drought occurred ~4.5 to 4.0 ka, coincident with the greatest drought historically recorded for tropical Africa. Kilimanjaro's Northern Ice Field (NIF), nevertheless, survived this drying event. In the visible stratigraphy of the longest NIF core, no major melt features are visible throughout the core's length except in the topmost meter. Comparing the chemical and physical properties preserved in the NIF with those in the nearby rapidly shrinking Furtwängler Glacier, which is saturated with water (see map (figs. 7, 8) and Landsat images (figs. 6, 7, 9) in Young and Hastenrath, 1991, p. G58–G63), confirms that conditions similar to those today (2009) have not existed in East Africa during the past 11 millennia (Thompson and others, 2002).

The ongoing retreat of glaciers in the Andes is now well documented (Ames, 1998; Williams and Ferrigno, 1998; Thompson and others, 2003; Thompson, 2004) and can be placed within a longer time perspective. The retreat of Qori Kalis, the largest outlet glacier from the *Quelccaya Ice Cap*, has been studied by terrestrial photogrammetry since 1978; it has the best documented recent history of any tropical glacier (figs. 24 and 40). The rate of its retreat from 1983 to 1991 (14 m a^{-1}) was almost three times the rate of its retreat from 1963 to 1983 (5 m a^{-1}); during the 2000 and 2001 balance year, its rate of retreat reached 205 m a^{-1}. The retreat stopped during two periods (1991–1993 and 2002–2003), but the glacier resumed its retreat in subsequent years. Figure 40 is a 10-map sequence that documents the rapid and acceler-
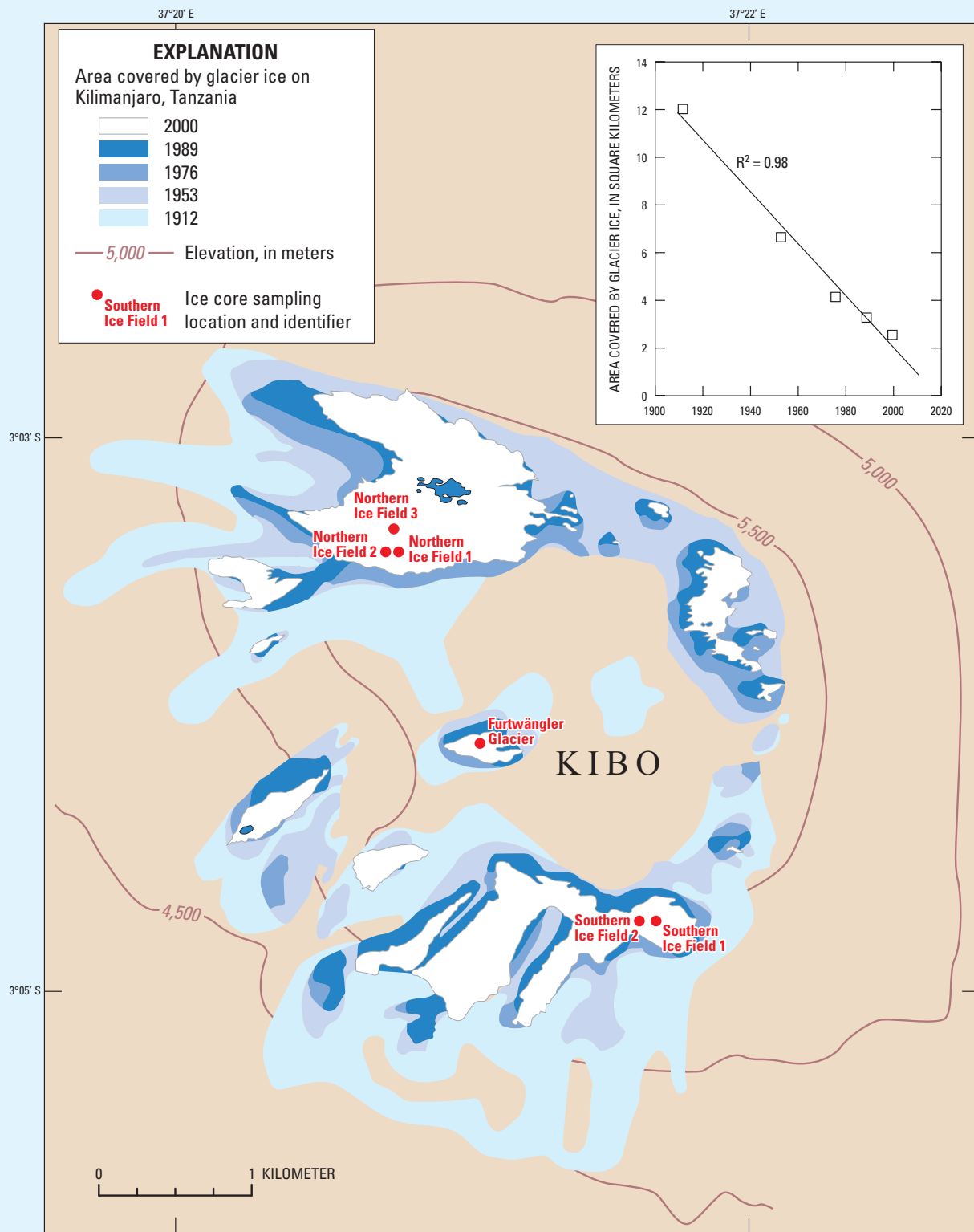
Figure 39.—Outlines of the Kilimanjaro Ice Fields in 1912, 1953, 1976, 1989, and 2000. The inset graph shows a least-squares regression line plot of the 5 discrete years of area calculations and the nearly linear (R², the coefficient of determination, is 0.98) decrease in ice area from 1912 to 2000. The red dots on the map indicate locations of ice-core sites, three from the Northern Ice Field, one from the Furtwängler Glacier, and two from the Southern Ice Field. See also Young and Hastenrath (1991) and Hastenrath and Greischar (1997).
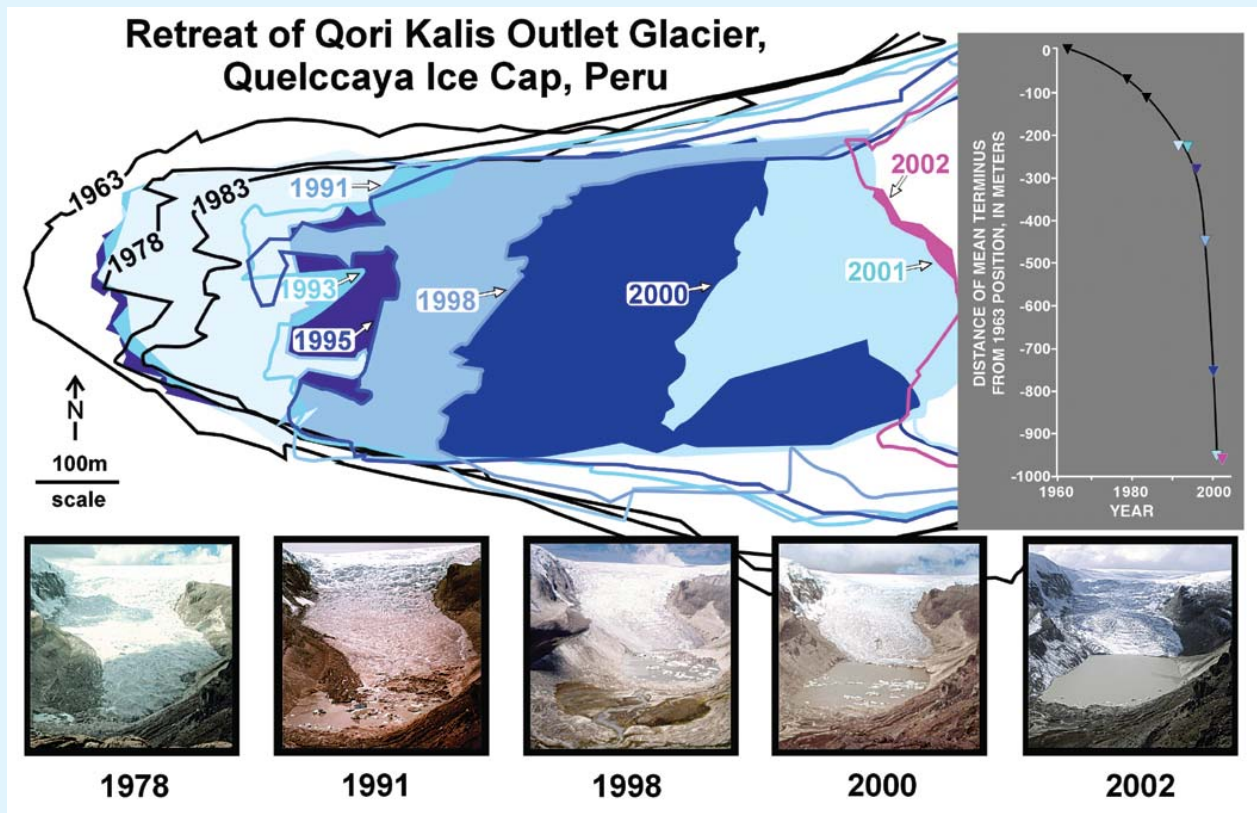
Figure 40.—*Photographic and cartographic history of the retreat of Qori Kalis, an outlet glacier from the Quelccaya Ice Cap, Perú, 1963–2002. Accompanying graph shows retreat of terminus during that period of time.*

ating wastage, in which the Qori Kalis outlet glacier terminus is receding about 10 times faster during the period from 1987 to 2002, than it receded during the initial measurement period from 1963 to 1978.

The shrinkage that is affecting the Qori Kalis outlet glacier is actually occurring around most of the margin of the *Quelccaya Ice Cap* (fig. 24), and the rapid melting of the ice is now exposing plant material that was buried between 5.2 and 4.8 ka (accelerator mass spectrometer ^{14}C dated), a time during the middle of the Holocene when glaciers throughout the Andes began expanding (Mark and others, 2002; Thompson, 2004). These localized data, coupled with the ~18,000-year δ^{18}O history from Nevado Huascarán (Thompson and others, 1995), suggest that warmer and drier conditions prevailed in the early Holocene (~11 to 6 ka) and that less extensive glacierization of high mountains accompanied the drought. Around 5 ka, cooler, wetter conditions prevailed, initiating the expansion of high mountain glaciers. Multiproxy studies of sediment from glacial lakes throughout the central region of the Andes corroborate an overall aridity through the late glacial stage and the early Holocene. After 4.8 ka, wetter conditions and glacier expansion followed, with the last 2,300 years being the wettest of the Holocene. Conditions were not always stable on centennial to millennial time scales, however, and considerable variability in climates is evident on the scale of decades to centuries (Abbott and others, 2003).

Future Priorities

Ice cores from high-mountain glaciers are unique and valuable archives of climate information because they record variations in atmospheric chemistry and conditions. Ice cores from the tropical and subtropical latitudes are especially valuable, because these latitudes comprise more than 50 percent of the Earth's surface area where the major energy that drives the global climate system is absorbed and where most of the world's population is concentrated. Since 1982, the phenomenon that combines El Niño and the Southern Oscillation has captured worldwide attention as populations and governments have come to realize the wide geographic extent of the phenomena's widespread and often devastating effects on the weather in many regions. As we begin to understand how this coupled atmospheric-oceanic process works, we also see its linkages with other important systems such as the Asia/African monsoons. Because both of these tropical systems influence precipitation and temperature over large regions, their effects are also recorded in the chemistry (and in the net accumulation) of snow that falls on high-mountain glaciers. Seasonal and annual resolution of chemical and physical parameters in ice-core records from the Andes have allowed glaciologists to reconstruct the variability of the ENSO phenomenon during several hundred years (Thompson and others, 1984, 1992; Henderson, 1996; Henderson and others, 1999). Because the effects of El Niño and La Niña events vary geographically, ice-core records are needed from the entire length of the Andes—from the Sierra Nevada de Mérida, Colombia, to the Cordillera Darwin of southern Patagonia—in order to more fully resolve both the temporal and spatial variability of the ENSO phenomenon, including their frequency and intensity, along with temperature variations that occurred long before human documentation.

The variability of the South Asian monsoon is also of vital importance for the large percentage of the world's population that lives in the affected areas. Cores from the Tibetan Plateau have yielded variability in the annual-to millennial-scale histories of monsoons across this large region, thereby affording us information on the interaction between the monsoon system and the prevailing westerlies that can be traced back (and linked by teleconnection) to atmospheric processes in the Atlantic Ocean. Recent research has suggested that the current warming trends may be affecting the strength of the Asia monsoon system (for example, Anderson and others, 2002) and that information about past climate on the Tibetan Plateau and its association with monsoonal strength can be gained from additional analyses of ice cores and from related glacier studies in the Himalaya.

Some of the most dramatic evidence for the warming of the global climate that is underway today (2012) comes from the drastic recession of both total area and total volume of high-mountain glaciers. This rapid retreat causes concern for two reasons.

First, these glaciers are regional "water towers," and their loss threatens water resources necessary for producing hydroelectric power, for crop irrigation, and for municipal water supplies in many nations. The high-mountain ice fields, ice caps, and other glaciers constitute a "savings account" that is drawn upon during dry periods to provide water supplies to human populations downstream. The accelerated melting of high-mountain glaciers is rapidly

depleting that "savings account," an "account" that was built up for hundreds to thousands of years but that current climatic conditions are not replenishing. Figure 41 illustrates, the current thinning and areal shrinkage of almost all the Earth's high-mountain glaciers. The land between latitudes 30° N. and 30° S., which constitutes 50 percent of the global surface area, is home to 70 percent of the world's population and to 80 percent of the world's growth in population (births). However, only 20 percent of global agricultural production takes place in these climatically sensitive regions.

The second concern that the disappearance of these high-mountain glaciers brings about is that they contain paleoclimatic histories that are unattainable from any other source. As the glaciers melt, the records of variability of the change in the environment and in the climate preserved within them are lost forever. Only these scientifically valuable records can assure that we accurately determine how climate has changed in the past in many regions and that we carefully assess the probable magnitude and rate of future changes.
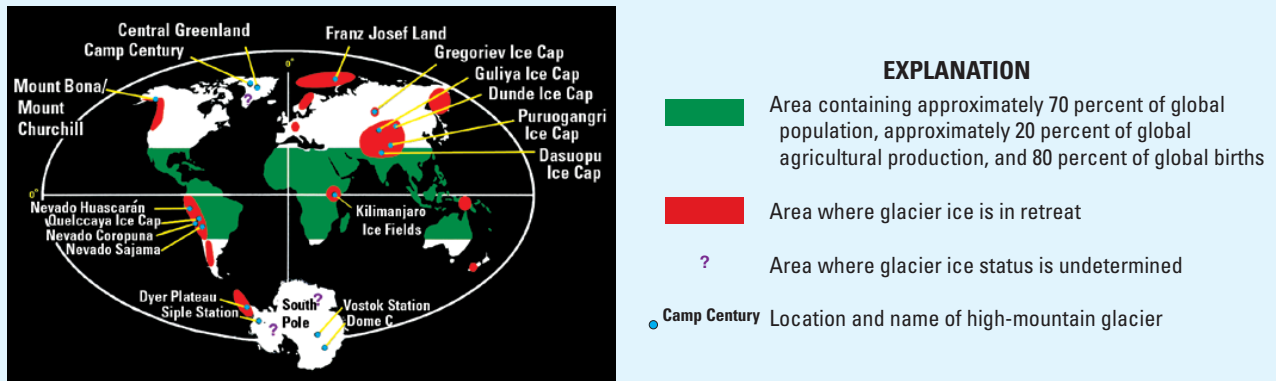

EXPLANATION

▬ (green) Area containing approximately 70 percent of global population, approximately 20 percent of global agricultural production, and 80 percent of global births

▬ (red) Area where glacier ice is in retreat

? Area where glacier ice status is undetermined

○ Camp Century Location and name of high-mountain glacier

Figure 41.—*Late 20th-century status (retreat or advance) of selected high-mountain glaciers of the Earth's cryosphere, the location of ice-core sites, and the contemporary location of important human activities.*