Past, Present, and Future of Glacier Archives from the World's Highest Mountains[1]

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Introduction

The ice core paleoclimate research program at the Byrd Polar and Climate Research Center (BPCRC), formerly the Institute of Polar Studies, of The Ohio State University (OSU) began in 1974 as an outgrowth of the U.S. polar ice core drilling initiative. The first tropical ice cap drilled to bedrock was Quelccaya in the Andes of southern Peru. This ice core yielded a 1,500-year record of regional climatic and environmental variations and provided the first evidence of the occurrence of the Little Ice Age in the Southern Hemisphere Tropics. The innovative lightweight, solar-powered drilling system developed specifically to drill Quelccaya was instrumental in showing the way for continued drill development, which led to subsequent drilling projects on high-altitude glaciers in the central Andes, the Tibetan Plateau, the Alps, southeastern Alaska, tropical East Africa, and the mountains of Papua, Indonesia. Most of the resulting ice core records extend back many millennia, and several extend back into or through the last glacial cycle. The oldest of these records (>100 ky) is from the Guliya ice cap on the far western Tibetan Plateau, which was drilled in 1992 and again in 2015 with the anticipation of extending its time scale further. Examination of ice core–derived climate records from opposite sides of the Pacific Ocean resulted in the discovery of large-scale teleconnections between the Andes and the Himalaya through processes involving the tropical Pacific atmosphere and sea surface temperatures. However, these high-altitude tropical glaciers and ice caps are under threat from the warming that has progressed over the last several decades. Their loss will not only destroy the climate histories they contain, but will

1 Read on 28 April 2017 as part of the *Observed Climate Change* symposium.

PROCEEDINGS OF THE AMERICAN PHILOSOPHICAL SOCIETY VOL. 161, NO. 3, SEPTEMBER 2017

threaten the livelihood and even the lives of populations that rely on glacial-fed streams for agriculture, power generation, and municipal water supplies.

History of the Ice Core Drilling Program at the Byrd Polar and Climate Research Center

The U.S. ice core drilling program began in the polar regions shortly after the 1957–1958 International Geophysical Year (IGY), although joint European drilling programs had been ongoing in Antarctica. During and after the IGY, the United States, United Kingdom, Scandinavian nations, and former Soviet Union conducted numerous drilling projects in Greenland, Antarctica, and the Russian Arctic, which benefited from logistical support from American, European, and Soviet governmental organizations. In 1966, the first deep core to bedrock was completed at Camp Century, Greenland, and two years later an ice core was drilled to bedrock at Byrd Station, Antarctica. During this time, polar glaciology and climatology were rapidly developing disciplines and all the pioneers in these fields were in their prime. As a graduate student at OSU, I analyzed the mineral dust concentrations and morphologies from the Camp Century and Byrd cores and based a major part of my Ph.D. dissertation on the results. We all anticipated the data that would come from the new field of ice core paleoclimatology, and the excitement that came with the revelation of the records was infectious.

Despite this rapid development of ice core research, until the mid-1970s no one had considered drilling tropical mountain glaciers. Only in retrospect do we see the importance of a nexus of events that occurred in 1973. As a graduate student working with my advisor Colin Bull and early mentors like John Mercer, I was a member of a small group at the Institute of Polar Studies (IPS)[2] at OSU who considered the possibility of connecting ice core records from Antarctica and Greenland with those from the lower latitudes. John Mercer had obtained aerial photos of glaciers during his previous position at the American Geographical Society, and among these were images of the Quelccaya ice cap in the southern Peruvian Andes. In 1974 the U.S. National Science Foundation provided a limited amount of funding[3] for a reconnaissance of Quelccaya. With no experience on tropical mountains and facing many unknowns, it was not obvious to me that I was about to launch both my career and a new field of

2 The Institute of Polar Studies was renamed the Byrd Polar Research Center in 1987, which in 2015 was renamed the Byrd Polar and Climate Research Center (BPCRC).

3 Approximately $7,000 remained in the budget after the polar projects were funded.

Figure 1. Lightweight, solar-powered drilling systems (Quelccaya 1983, left; Huascarán 1993, right), which made deep drilling on high-elevation tropical glaciers possible.

research—tropical alpine glaciology. From the first expedition in 1974 and several subsequent expeditions, we determined that, just as in the polar ice sheets, a viable climate signal was preserved in this tropical ice (Thompson 1980; Thompson, Mosley-Thompson, and Arnao 1984). Despite initial reservations among some polar researchers concerning the ability of humans and drilling systems to work at such a high elevation (5,670 meters above sea level), we successfully drilled the summit of Quelccaya to bedrock in 1983. The resulting ice cores yielded an annually dated 1,500-year record of climatic and environmental variations from what was a relatively data-poor area (Thompson et al. 1985). The major revelations from the Quelccaya project included the first evidence of the Little Ice Age in the Southern Hemisphere Tropics (Thompson et al. 1986). In addition, the ice core records confirmed an early archeological hypothesis that decadal- to centennial-scale climatic variations may have been a major cause for the rise and fall of highland and lowland pre-Hispanic central Andean civilizations (Paulsen 1976). Later, we expanded this hypothesis by linking these variations to the frequency and intensity of El Niños (2014; Thompson and Kolata 2017). From 1974 to 2016 we conducted 24 expeditions to Quelccaya, including a second deep drilling program in 2003, making it the longest-studied tropical ice cap on Earth.

In order to drill at this altitude, a lightweight, innovative solar-powered system was developed that could be disassembled and backpacked in pieces up the ice cap (Figure 1). After the 1983 deep drilling on Quelccaya, high-altitude drilling technology continued to improve as lighter materials such as Kevlar for drilling cables and more efficient energy sources became available. Although the early portable drilling systems were designed and built by the Polar Ice Coring Office (PICO) at the University of Nebraska (later at the University of Alaska at

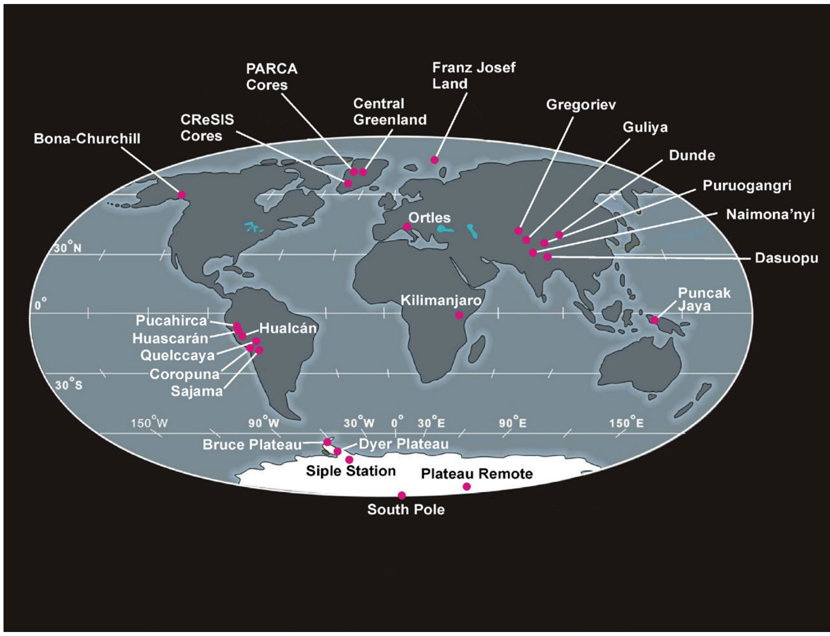

FIGURE 2. Locations of sites from the equator to the polar regions where ice cores have been drilled from 1983 to 2015 by the Institute of Polar Studies, renamed the Byrd Polar Research Center and later the Byrd Polar and Climate Research Center.

Fairbanks),[4] newer systems were designed and built at the Byrd Polar Research Center at OSU after 1995. In addition, improvements in shipping logistics ensured that frozen ice cores could be transported from anywhere in the world to the laboratories at OSU. We have used the lightweight systems to drill to bedrock on high-altitude tropical glaciers and ice caps in the Andes, Tibet, Indonesia, and East Africa, but have also drilled cores ranging from 100 meters to over 460 meters in Greenland, Antarctica, southeast Alaska, and the Russian Arctic (Figure 2). This drilling technology and improvements in transportation logistics have allowed us to develop a global perspective of climate over several millennia, and many of the records even extend back into the last ice age.

GLACIERS AS RECORDERS AND INDICATORS OF CLIMATE CHANGE

Glaciers capture and preserve everything that is in the atmosphere above them, including dust, salts, volcanic and biological emissions,

4 Although the first solar-powered thermal drill was built at PICO, it was tested in 1983 on top of a parking garage at OSU. A solar panel array was assembled on the roof, and the drill cut through blocks of ice stacked at the base of the garage.

pollen, plants and insects, and of course snow, which contains stable (nonradioactive) isotopes of hydrogen and oxygen. After snow falls on the surface of a glacier, it is buried and compacted to form firn. At the point when individual pores are isolated from each other (at a density of 830 kg/m^3) the firn turns to ice, which retains the chemistry of the atmosphere (from gases trapped in bubbles) and the precipitation. This transition from firn to ice takes years to centuries, depending on the precipitation rate and the atmospheric temperature.[5] Ice fields in regions that are under the influence of monsoon climates that are characterized by well-defined wet and dry seasons contain easily discernible seasonal dust layers that can be counted, much like tree rings, to produce reasonably precise time scales. Net accumulation, or net balance, is the amount of snow deposited in a year minus that lost by ablation processes such as wind scour, sublimation, and melting. Such accumulation records are produced by measuring the ice thicknesses between dust layers, and then adjusting the layer thicknesses to account for the thinning that occurs as ice is compressed while it is buried deeper over time. The interpretation of stable isotopes of hydrogen and oxygen (δD and $\delta^{18}O$, respectively) as temperature recorders in polar ice cores is widely accepted (Dansgaard 1964); however, this relationship is more complicated in tropical records (Thompson 2000; Vuille et al. 2003; Yao et al. 1996, 2006; Hurley et al. 2015). Net balance and stable isotopes provide histories of temperature, moisture sources, and precipitation intensity, while dust concentration and size, major ion concentrations, and trace element ratios provide information about environmental aridity, and wind intensity and trajectory.

Ice cores drilled on the Quelccaya ice cap in 1983 and 2003 provide examples of high-resolution records of temperature and precipitation through the last millennium. Oxygen isotope ($\delta^{18}O$) and net balance time series from cores drilled 20 years apart at the summit and a 2003 core from the north dome show high reproducibility (Figure 3). A warm, arid period (less negative $\delta^{18}O$ and low net balance) occurred from 1000 CE to approximately 1550 CE, followed by a cool and wet phase of the Little Ice Age from 1550 to 1700 CE and a cool and arid climate from 1700 to the beginning of the 20th century. The conditions of the 20th century are unique in these records; at no other time in the last 1,000 years was the climate in this region of the Andes as warm and wet over a sustained period.

5 For example, at Vostok Station in East Antarctica, where the snow accumulation rate and temperatures are very low, the firn/ice transition occurs at around 90–95 meters depth, corresponding to several thousand years in the Vostok ice core (Salamatin et al. 1998). On the tropical Quelccaya ice cap (high accumulation, warmer climate) the transition is at 18 meters depth (~10 years).

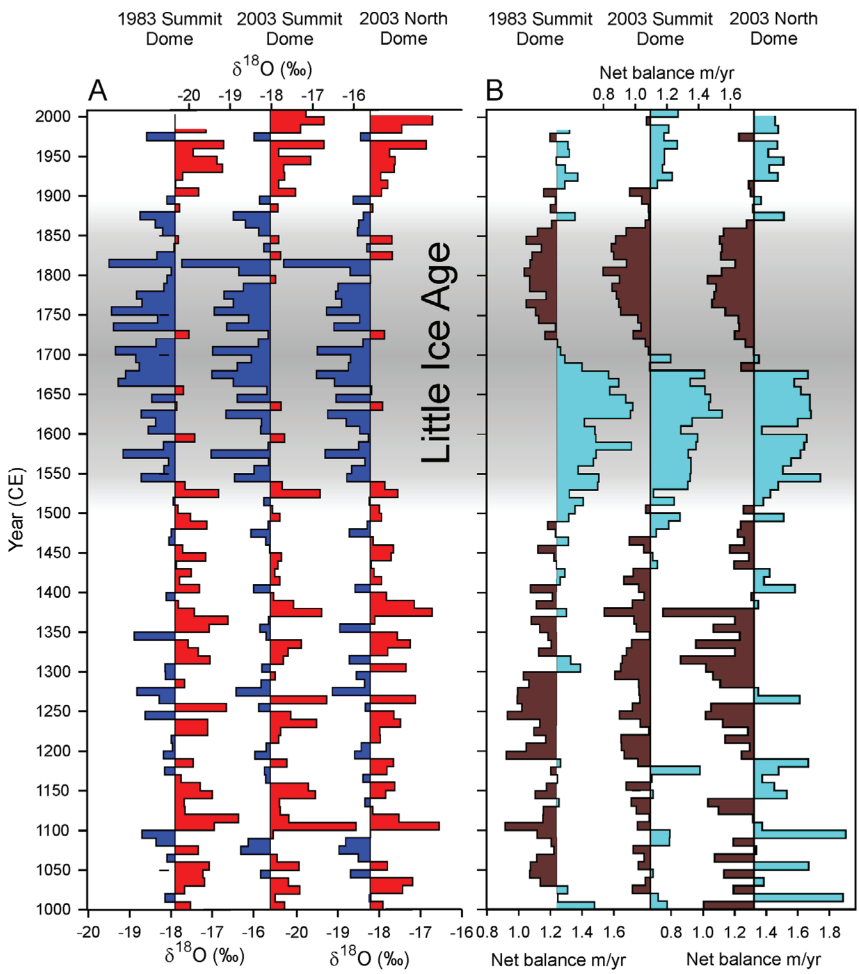

FIGURE 3. Climate records from the Quelccaya ice cap from cores drilled in 1983 and in 2003. The data are calculated as decadal averages of (A) $\delta^{18}O$ and (B) net balance from the summit dome (1983 and 2003) and the north dome (2003). The Little Ice Age is shaded.

EVIDENCE OF LARGE-SCALE CLIMATE TELECONNECTIONS FROM ICE CORE RECORDS

Ice cores that have been collected from around the world not only provide histories of regional climate change; combined records from different continents also help us reconstruct past hemispheric to global-scale atmospheric and oceanic processes. One of the most important of the linked oceanic/atmospheric processes is the El Niño-Southern Oscillation (ENSO). ENSO has two opposite phases, one marked by warming of the surface of the east equatorial Pacific Ocean (El Niño) (Figure 4a) and the other by cooling in this region (La Niña). Very strong El Niños and La Niñas are responsible for severe meteorological disruptions (e.g., flooding, droughts, heat waves, blizzards) throughout much of the world. In many regions of the tropics such as South Asia and the highlands of southern Peru, the occurrence of strong El Niños often results in monsoon weakening (Krishna Kumar et al. 2006; Thompson et al. 2017). Ice core–derived climate records from the Andes, including those from Quelccaya and Coropuna in southern Peru (Figure 2), contain evidence of ENSO events in their ice chemistry. On the opposite side of the Pacific Basin, cores from the Dasuopu glacier in the central Himalaya contain similar ENSO signatures. Spatial correlation fields between tropical sea surface temperatures and a composite of the $\delta^{18}O$ time series from Quelccaya, Coropuna, and Dasuopu from 1870 to 2002 shows a large region of significant positive correlations in the east tropical Pacific Ocean, which bears a strong resemblance to the El Niño warm pool in the same location (Figure 4b).

Longer-term records from these three cores also contain evidence of a series of very strong El Niños in the late 18th century. Large, sustained peaks in chloride in the 1790s (Figure 5) may be attributed to extreme aridity in the central Andes and in India and the Himalaya, which are regions that are highly susceptible to the effects of El Niño (Thompson et al. 2017). This late 18th-century climate event, recorded in both geological and historical records from many regions around the world, occurred at a time of hardship and social upheaval for particularly vulnerable populations. In South Asia, it coincided with the "East India Drought" with the 1791 El Niño at its core, which resulted in the deaths of ~11 million people in this region (Grove 2007). Geological and historical evidence also exists for severe droughts in Java, Australia, Mexico, the Caribbean, and Egypt at the same time (Grove and Chappell 2000; Rodysill et al. 2013; Thompson et al. 2017), which are also regions that are vulnerable to strong El Niños.

The Quest for the Oldest Ice Core–Derived Paleoclimate History from Outside the Polar Regions

Since 1984 the BPCRC has been investigating and coring ice fields around the Tibetan Plateau in collaboration with the Lanzhou Institute of Glaciology and Geocryology and the Chinese Academy of Science's Institute of Tibetan Plateau Research (ITPR). The results of this three-decade partnership include several ice cores drilled to bedrock on five ice caps around the Tibetan Plateau, the climate records from

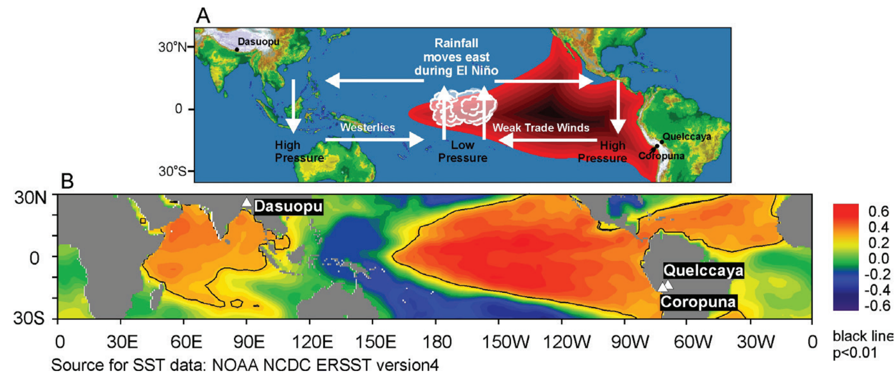

FIGURE 4. (A) Schematic of El Niño oceanic and atmospheric conditions, showing the east tropical Pacific warm pool (in red) and the Walker circulation during this phase of ENSO with weakened low-level easterly trade winds, strengthened westerlies, and the center of ascending air in the tropical Pacific located eastward of its La Niña and ENSO-neutral positions. (B) Correlation fields between sea surface temperatures and a composite of $\delta^{18}O$ records from the Quelccaya, Coropuna, and Dasuopu ice cores. Glacier locations are shown as black dots in (A) and as white triangles in (B).

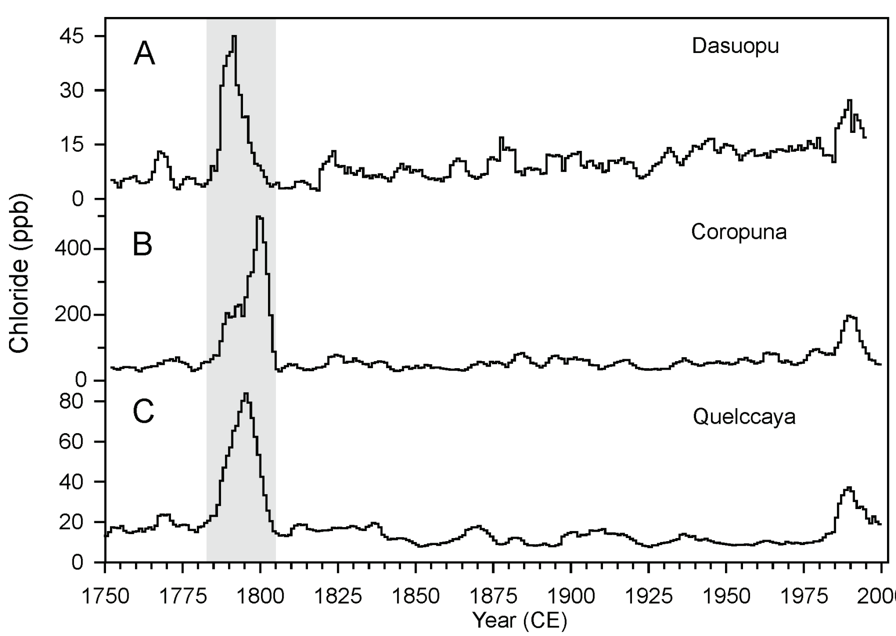

FIGURE 5. Time series of chloride concentrations, shown as five-year running means from the (A) Dasuopu, (B) Coropuna, and (C) Quelccaya ice cores from 1750 to the top of each record (1997 for Dasuopu; 2003 for the Andean cores). The late 18th-century El Niño–linked drought event is shaded.

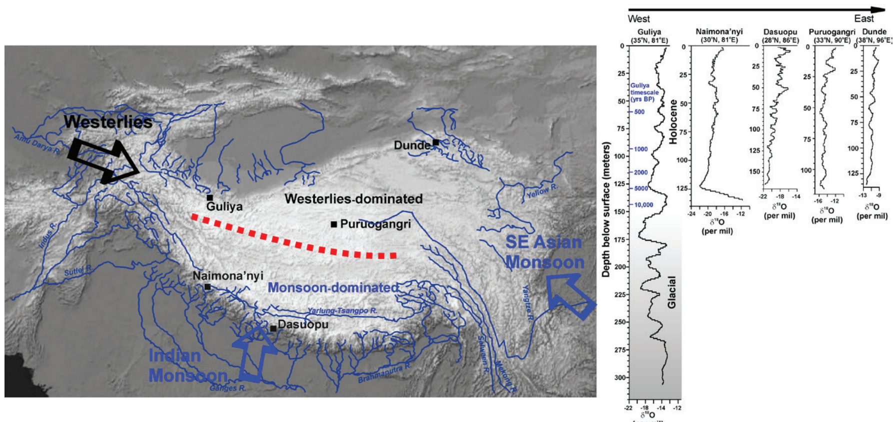

FIGURE 6. Relief map of the South Asian region, with the Tibetan Plateau highlighted. The two major climate regimes (monsoon and westerlies-dominated) are shown, along with major river systems that arise from glaciers on the Plateau. Ice core sites are marked by squares. The $\delta^{18}O$ records from these five ice caps and glaciers (on the right) are arranged from west to east.

which extend through at least the middle of the Holocene and show regional centennial-scale differences but millennial-scale similarities (Figure 6). Only the Guliya ice cap in the far west, drilled in 1992 to bedrock at 308 meters, appears to have existed throughout the last glacial cycle (Thompson et al. 1997), which makes it the oldest non-polar ice field known to date. The $\delta^{18}O$-derived climate record from this large ice field resembles those from polar ice cores, especially from Greenland (Grootes et al. 1993; Thompson et al. 1997), which may be the result of westerly airflow from the North Atlantic to Central Asia and the northern Tibetan Plateau. In both the Greenland and Guliya records, the $\delta^{18}O$ transitions from the cold stadials to the warm interstadials of the last glacial cycle are about 5.4 per mille in magnitude and are evidence of the climatic influence of the precession cycle (~22,000 years). These interstadials in the Guliya core also show similar variability to the methane concentrations in polar cores, which suggests connections between global methane levels and the tropical hydrological cycle.

Despite several lines of evidence indicating that the Guliya ice core is at least 110,000 years old, the bottom 40 meters of the 1992 core could not be dated with the analytical techniques available at the time. Another limitation was the amount of ice available for analysis, since Chinese and American collaborators split the single deep ice core between them. However, over the last two decades, BPCRC has obtained the equipment and expertise to make several new measurements on glacier ice, and the U.S. and international ice core communities have developed new techniques to constrain the age of ice over millennial time scales. Therefore, in 2015, BPCRC and ITPR returned to Guliya and recovered three cores to bedrock from the summit (6,700 masl) of the ice field (which was not logistically possible in 1992) and two cores from the plateau (one to bedrock) below the summit close to the 1992 drill site. Analyses are currently underway to confirm and further constrain the original time scale as well as expand the original records of climatic and environmental variation through the last glacial cycle in the remote western Tibetan Plateau.

The Recent Warming and Its Amplification at High Elevations in the Tropics

Instrumental data over the last century show that Earth has been warming, a trend also reflected in ice core $\delta^{18}O$ records (Figure 7a). A composite of $\delta^{18}O$ time series from four Andean cores and four Tibetan Plateau cores shows a significant correlation ($R=+0.86$, $p<.01$) with Northern Hemisphere temperature anomalies[6] from 1880 to 2005. A composite of seven $\delta^{18}O$ records from the Peruvian/Bolivian Andes and the Tibetan Plateau provides a longer perspective of this recent warming (Thompson et al. 2006). The ice core composite shows the warm Medieval Climate Anomaly and the cooler Little Ice Age (Figure 7b), as well as the strong warming trend of the 20th century. These features are also recorded in the reconstructed temperatures of the Northern Hemisphere since 200 CE (Jones and Moberg 2003; Jones and Mann 2004). Despite the controversy over the primary influences on stable isotopes in tropical precipitation, this recent increase is unprecedented in the last 2,000 years, indicating that significant and relatively rapid changes in climate are underway in the tropical and subtropical latitudes where 70 percent of the world's population lives.

Ice can be considered to be nature's best thermometer, perhaps the most sensitive and unambiguous indicator of climate change (Pollack 2009). The recent warming in the tropics is observed not only in ice core chemistry, but also in the retreat of the ice fields themselves. Low- and mid-latitude glaciers and ice caps serve as first responders to climate change as they expand when it is colder and/or wetter and

6 We use Northern Hemisphere temperature anomalies for the comparison despite the inclusion of Southern Hemisphere (Andes) ice core records in the $\delta^{18}O$ composite. Much of the snow that falls on the glaciers in the northern and central Andes ultimately originates in the tropical North Atlantic, and sea surface temperatures in this region have a large influence on $\delta^{18}O$ values in this precipitation. This can be observed in the tropical North Atlantic correlation fields in Figure 4b.

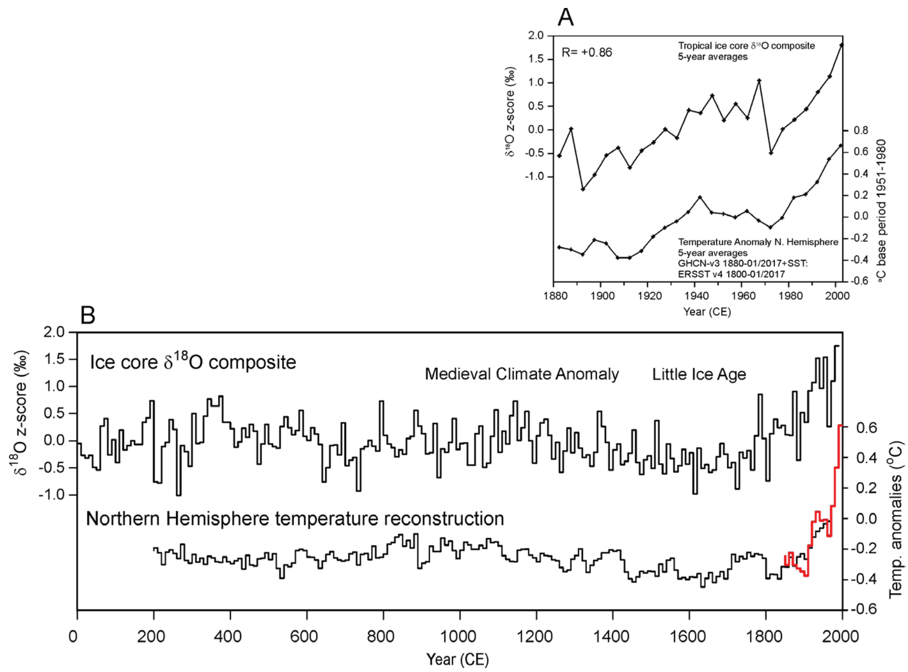

FIGURE 7. (A) Five-year averages of a composite of tropical ice core $\delta^{18}O$ records (Guliya, Dunde, Purougangri, and Dasuopu from the Tibetan Plateau, and Quelccaya, Sajama, Hualcán, and Huascarán from the Andes; see Figure 2 for locations) compared with five-year averages of Northern Hemisphere temperature anomalies. (B) Top: decadal averages of a composite of tropical ice core $\delta^{18}O$ records (all those listed in A except Hualcán) over the last two millennia (Thompson et al. 2006). Bottom: decadal averages of reconstructed Northern Hemisphere temperatures from 200 CE to 1980 CE (Jones and Mann 2004), on which are superimposed decadal averages of Northern Hemisphere temperature anomalies (red curve) based on meteorological observations from 1860 to 2000 (Jones and Moberg 2003).

retreat when it is warmer and/or drier much faster than the large polar ice sheets. Ground observations, aerial photography, and satellite-borne sensors monitor numerous high-altitude glaciers throughout the world. From all these analyses there is a consensus that virtually without exception these ice fields are retreating at an accelerating rate (Coudrain, Francou, and Kundzewicz 2005; Thompson et al. 2006, 2009, 2013).

Ground-based monitoring of tropical glaciers began in 1912 with the photographing of the Kilimanjaro ice fields in the early 20th century and the glaciers of Papua in 1936, although written documentation of the existence of these features exists from long before. IPS (later BPCRC) began monitoring the Quelccaya ice cap in 1978, when we photographed a margin wall in which distinct annual layers of ice were easily discernible. By 2002 this wall had melted and thinned considerably (Figure 8a). Since 1978 photogrammetric techniques have been used to document the retreat of the Qori Kalis outlet glacier on the western margin of the ice cap. Just like the vertical margin, this glacier that originally extended through its valley had diminished to about one-third of that length by 2016 (Figure 8b). The lake that has replaced the ice started forming in 1991 and now covers over 0.34 km^2 (84 acres) and is over 60 meters deep.

Similar glacier loss is occurring in many regions of the tropics. The Himalaya is not only warming but also is experiencing decreasing precipitation over recent decades (Yao et al. 2012). Bolch et al. (2012) documented mass loss of glaciers in the central Himalaya region, while in the western Himalaya the Naimona'nyi glacier is retreating not only along the margins but also from the surface down (Kehrwald et al. 2008). Based on 30 years of satellite, topographic map, and in situ ground studies, Yao et al. (2013) determined that glacier retreat on the Tibetan Plateau is most intense in the Himalaya, although glaciers are actually expanding in the Pamirs and Karakorum because of increased precipitation. On the other hand, Matsuo and Heki (2010) used Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry to measure accelerating ice loss on the Tibetan Plateau and surrounding high mountains and concluded that the rate of ice loss in the Himalaya has been decreasing. Nevertheless, the rate of the recent warming is accelerating at higher altitudes on the Tibetan Plateau as demonstrated by instrumental data (Liu and Chen 2000; Pepin et al. 2015).

The summit of Mount Kilimanjaro, located at 3°S in East Africa, contains ice fields that have been monitored since 1912 and that continue to shrink and thin. In the last few years the Furtwängler glacier in the center of the Kibo crater has bifurcated, which is accelerating the melting rate (Figure 8c). This also is happening to the ice fields in Papua, Indonesia near Puncak Jaya. These are the only glaciers that exist between the Himalaya and the Andes and here the ice is disappearing at a very rapid rate, as shown by photos of the Northwall Firn taken in June 2010 and November 2016 (Figure 8d). At the current retreat rates many tropical ice fields are destined to vanish soon: the Indonesian ice fields within the next few years (Permana 2015),[7] those on Kilimanjaro within the next few decades (Thompson et al. 2009),

7 In fact, Meren glacier near the Northwall Firn disappeared between 1997 and 2000 (Prentice and Hope 2007).

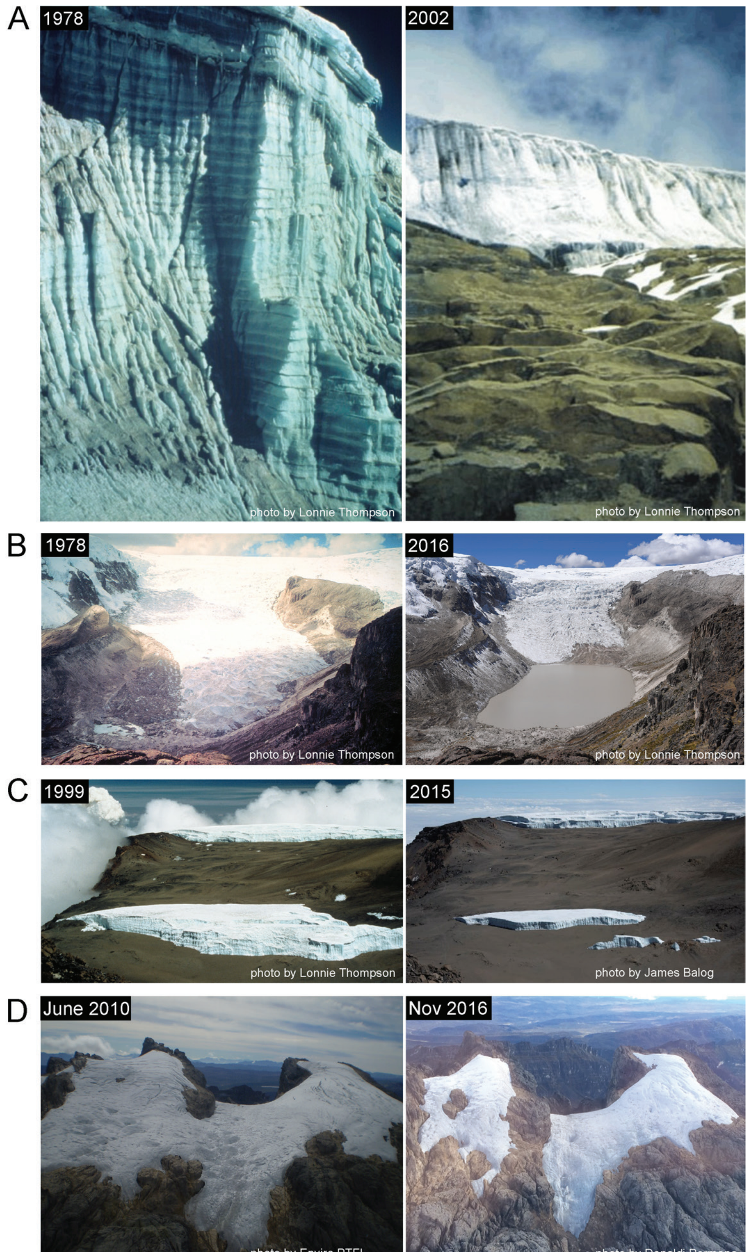

FIGURE 8. Photographs of glacier retreat of (A) a margin of the Quelccaya ice cap, (B) the Qori Kalis outlet glacier on the western margin of Quelccaya, (C) the Furtwängler glacier (foreground) on the summit of Kilimanjaro, and (D) the Northwall Firn near Puncak Jaya, Papua in Indonesia.

and Quelccaya, the largest tropical ice field in the world, in 50–60 years (Albert et al. 2014).

From a societal perspective, the disappearance of the ice from Kilimanjaro and Papua is not immediately detrimental to water resources for agriculture and hydropower, although the melting of the ice fields is symptomatic of the warming and elevation of ecologic zones that may damage the forests at the base of these mountains. However, the disappearance of glaciers in the Andes and the Himalaya is a great cause for concern for the populations of these regions. Over half of Peru's electricity is generated from hydropower (Vergara et al. 2007), and the source of much of the water is the mountain glaciers. The Tibetan Plateau contains 46,000 glaciers covering more than 100,000 km^2 (Yao et al. 2012) and is referred to as "Asia's water tower" as its glaciers are major contributors to South and Central Asia's major rivers that sustain ~1.5 billion people in 10 countries. The Tibetan Plateau is home to millions of people and provides the resources they need for daily life. Because it is the highest and largest (5 million km^2) of Earth's elevated regions, it plays a significant role in regional environmental changes and in the Earth's climate system. In addition, warming of mountain glaciers can result in geohazards such as glacier collapse (Tian et al. 2016), rock and ice avalanches, and flooding from glacial lake outbursts (Richardson and Reynolds 2000; Yao et al. 2007; Bajracharya and Mool 2009; Anacona, Mackintosh, and Norton 2015).

Afterword

Scientists measure and record the changes that occur all around us. For over 40 years the ice core group at BPCRC has measured and recorded changes in glaciers throughout the world, using our knowledge of geology, chemistry, physics, and engineering. We have reported our observations and hypotheses in peer-reviewed literature, adding to the growing body of knowledge about the natural and human-driven changes that the world's population is facing and will face in the relatively near future. Earth scientists, especially climatologists, have reached a consensus that climate change is real, that modern climate change is in large part human-driven, that it is accelerating, and that it will have to be addressed. Unfortunately, governments tend to be rather static entities that are not inclined to be proactive, partly because humans have evolved to be reactive rather than proactive. We tend not to address an issue until it becomes a crisis.

Thus far, most of the attempts to mitigate climate change have come from grassroots organizations, i.e., from the bottom up rather than from the top down. I believe that once the hazards that the world faces become undeniably obvious and public reaction reaches a critical level, major corporations and governments will adjust their attitudes and act responsibly. However, the window is closing, since the consequence of climate change is evolving from what we thought was a distant concern to a phenomenon that we are beginning to experience now. Although we may be "hardwired" by human evolution to procrastinate over problems that do not have immediate effects, we can overcome our conditioning through education and critical reasoning. Currently our federal and many of our state and local governments are de-emphasizing and de-funding secondary and college education in the environmental sciences, which will impact future university students and young researchers and teachers trying to establish careers in the field. Until and even after this attitude changes, it is imperative that the private sector and general public step forward to inspire and support the next generation of climatologists and Earth scientists.

Acknowledgments

I wish to acknowledge the efforts of dedicated teams of scientists, technicians, engineers, postdoctoral fellows, students, mountaineers, and porters that have worked diligently on alpine glacier reconnaissance and deep drilling in 16 countries over the last four decades, and on the laboratory analysis, data interpretation, and manuscript preparation. I also would like to acknowledge our collaborators in China and Peru who have arranged logistics and helped obtained permits for the drilling programs. Funding for the reconnaissance and drilling programs from 1974 to 2015 was provided by the National Science Foundation, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, National Geographic, and The Ohio State University. This is contribution C-1570 of the Byrd Polar and Climate Research Center.

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