Ice Cores from Tropical Mountain Glaciers as Archives of Climate Change

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1. Introduction

The 20[th] century has seen the acceleration of unprecedented global and regional-scale climatic and environmental changes to which humans are vulnerable, and by which we will become increasingly more affected in the coming centuries. One-half of the Earth's surface area lies in the tropics between 30°N and 30°S, and this area supports almost 70% of the global population. Thus, temporal and spatial variations in the occurrence and intensity of coupled ocean-atmosphere phenomena such as El Niño and the Monsoons, which are most strongly expressed in the tropics and subtropics, are of worldwide significance. Unfortunately, meteorological observations in these regions are scarce and of short duration. However, ice core records are available from low-latitude, high-altitude glaciers, and when they are combined with high-resolution proxy histories such as those from tree rings, lacustrine and marine cores, corals, etc., they provide an unprecedented view of the Earth's climatic history over several millennia. This paper provides an overview of these unique glacier archives of past climate and environmental 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

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retreat with respect to the longer-term perspective, which can only be provided by the paleoclimate records.

Over the last 25 years the principal objective of the Ice Core Paleoclimatology Research Group (ICPRG) at the Byrd Polar Research Center has been the acquisition and analysis of a global array of ice cores that can provide high-resolution climatic and environmental histories, which contribute to our understanding of the complex interactions within the Earth's coupled climate system. With the help of new lightweight drilling equipment, we have achieved one of our main scientific objectives by expanding our research from the polar regions to remote ice fields on some of the highest tropical and subtropical mountains. Ice core records from mountains in Africa, South America, and China make it possible to study processes in the subtropical and tropical latitudes where human activities are concentrated. We utilize an ever-expanding ice core database of multiple proxy information (i.e. stable isotopes of oxygen and hydrogen, or $\delta^{18}O$ and δD, respectively, 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 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, to the relative magnitude of 20th century global climate change and its impact on the cryosphere. 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.

2. Recent results

The sites from where the ICPRG has retrieved high-altitude ice cores are shown in Figure 1. The first program to drill a low-latitude mountain core to bedrock was carried out on the Quelccaya ice cap in southern Peru (14°S, 71°W) in 1983, and the most recent was accomplished in 2000 on the Puruogangri ice cap (34°N, 89°E) in the center of the Tibetan Plateau. In between, we have recovered cores (Dunde, Guliya, Dasuopu) from other regions of the Tibetan Plateau, from the Andes (Huascarán and Sajama) and from Kilimanjaro in East Africa. With the exception of Puruogangri, all the cores have been analyzed and their overall climate records have been published.

Low-latitude, high-altitude ice core records have revealed the nature of climate variability over both glacial and interglacial time scales, specifically from the Last Glacial Maximum (LGM) 18 to 20 thousand years ago, to the present. Two records from the South American Andes (Huascarán in northern Peru at 9°S, 78°W and Sajama in Bolivia at 18°S, 69°W) and one from the western Tibetan Plateau (Guliya at 35°N, 81°E) extend to or past the LGM and confirm, along with other climate proxy records (e.g. Guilderson et al. 1994; Stute et al. 1995; Colinvaux et al. 1996; Weyhenmeyer et al. 2000), that the LGM was much colder in the tropics and subtropics than previously believed (Thompson et al. 1995; 1997; 1998). Although this period was consistently

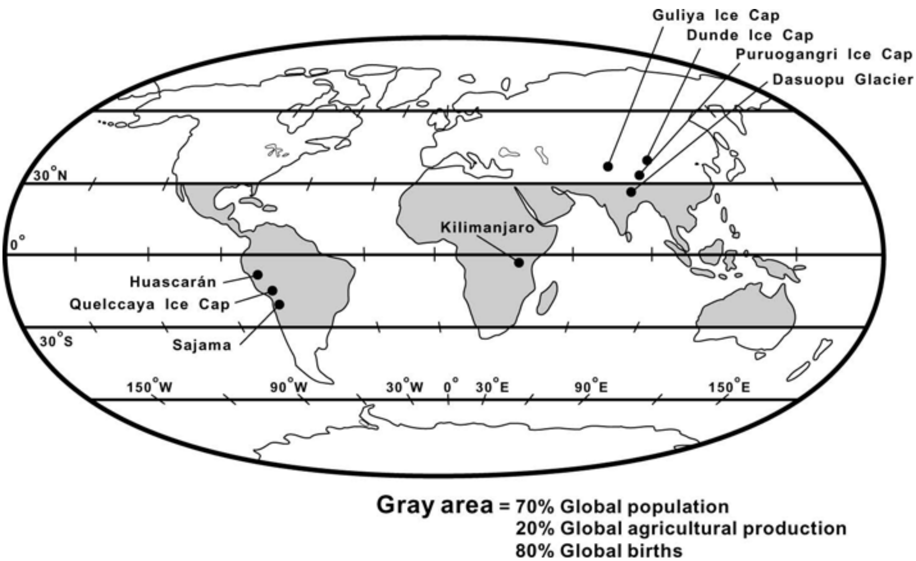

Figure 1: Locations of sites from where ice cores have been taken by the Ice Core Paleoclimate Research Group. The shading depicts the extent of the tropics over land from 30°N to 30°S.

colder, it was not consistently drier through the lower latitudes, unlike 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; Davis 2002). In another example, the Guliya ice cap is partly affected by the variability and strength 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 many lake levels in the western Tibetan Plateau higher than tropical lakes during the LGM (Li and Shi 1992), but the dust concentrations in the Guliya ice core record were comparable 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).

Tropical and subtropical ice core records during the Holocene show evidence of major climatic disruptions, specifically droughts. 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 spike is 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 δ¹⁸O, 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; Charles et al. 1997) is noticeable in the Dasuopu dust flux record (Davis 2002), which is a parameter that incorporates both the dust concentration and the annual accumulation rate of ice on the glacier surface.

High-resolution records of Late Holocene variations in temperature are available from low-latitude alpine ice cores. Composites of the $\delta^{18}O$ profiles of the South American cores (Huascarán, Quelccaya, and Sajama) and three of the Tibetan Plateau cores (Dunde, Guliya, and Dasuopu) show similar trends in decadal averages over the last millennium (Thompson et al. 2003) (Fig. 2). When all six of the records from these mountain glaciers are combined, the resulting composite is similar to the Northern Hemisphere temperature records of Mann et al. (1998) and Jones et al. (1998) covering the last 1000 years. As in polar ice cores, the dominant factor controlling mean $\delta^{18}O$ values in Andean snowfall on decadal, centennial, and millennial timescales must be temperature, while on seasonal to annual time scales both temperature and precipitation influence the local $\delta^{18}O$ signal (Vuille et al. 2003). $\delta^{18}O$ variations in ice cores from Bolivia and Peru are highly correlated with sea surface temperatures (SSTs) across the equatorial Pacific Ocean, which are closely linked to ENSO variability (Bradley et al. 2003). Likewise, $\delta^{18}O$ variations in the

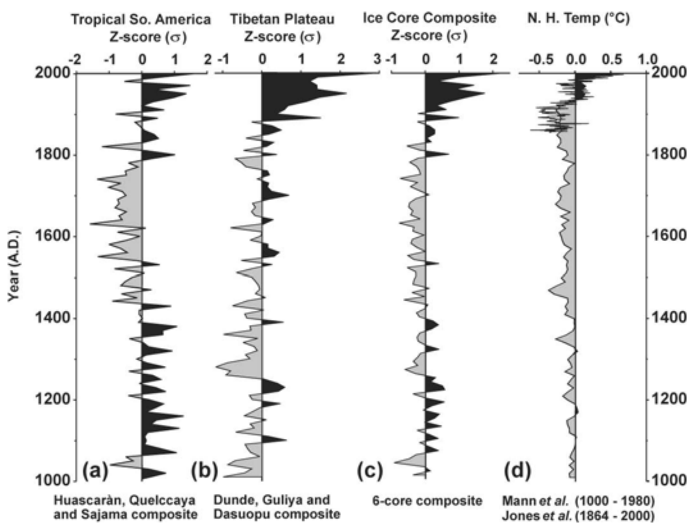

Figure 2: Composite records of decadal averages of $\delta^{18}O$ from ice cores from (a) the South American Andes (Huascarán, Quelccaya, Sajama) and (b) the Tibetan Plateau (Dunde, Guliya and Dasuopu) from A.D. 1000 to the present. All six ice-core records are combined (c) to give a total view of variations in $\delta^{18}O$ over the last millennium in the tropics, which is compared with the Northern Hemisphere reconstructed temperature record (d).

Dasuopu ice core from the Himalayas also reflect SST variations in the equatorial Pacific Ocean. The controlling factor on $\delta^{18}O$ is a matter of debate; however, 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 abrupt warming from the late 19th century through the 20th century. Indeed, they suggest that the 20th century was the warmest period in the last 1000 years in the tropics, which also encompasses the time of the "Medieval Warming".

The recent warming is recorded in tropical alpine glaciers in other ways, both within the ice core records and by the rapid retreat of many of the ice fields. In the Andes, on the Tibetan Plateau and in the East Africa Rift Valley region this climate change has left its mark. On the Tibetan Plateau, the trend is amplified and is accelerating with increasing elevation (Thompson et al. 2000). The lower elevation ice caps in the Andes are experiencing damage to their seasonal $\delta^{18}O$ signals from the lifting of the 0°C isotherm (Davis et al. 1995). For example, not only is the seasonal isotope signal on the Quelccaya ice cap at 14°S in southern Peru being smoothed out as meltwater percolates through the upper layers of the snow (Thompson et al. 1993), but the ice margins are undergoing rapid and accelerating retreat. The rate of this retreat from 1983 to 1991 (14 m/yr) was almost three times that between 1963 and 1983 (5 m/yr), and in the 2000/2001 year reached 205 m/yr. The many ice fields on Kilimanjaro covered an area of 12.1 km^2 in 1912, but today only 2.6 km^2 remains. 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).

3. Future Priorities

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. The marked warmth of the last two decades has contributed to the widespread melting of low-latitude, high-altitude glaciers. During this time, the ICPRG has been monitoring the accelerating retreat of this tropical ice in conjunction with its global ice core drilling and climate reconstruction program.

Seasonal and annual resolution of chemical and physical parameters in ice core records from the Andes Mountains have 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 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. The ICPRG has drilled four cores on the Tibetan Plateau that 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. Although marine cores from the Arabian Sea show that the intensity of the South Asian Monsoon has increased over the last four centuries (Anderson et al. 2002), the Dasuopu record from the Himalayas demonstrates that since the early 19^{th} century the amount of precipitation falling on this region has decreased (Thompson et al. 2000). However, the Dunde record from the north side of the Plateau shows an accumulation history that is opposite to that in the Himalayas (Davis and Thompson submitted). Like ENSO, therefore, the South Asian Monsoon systems have varying geographical effects. Retrieval of ice core records from the west side of the Himalayas, which is more directly affected by the SW Indian Monsoon than is the east side where Dasuopu is located, will provide a more comprehensive overview of the precipitation and temperature histories of the Himalayas as a whole. The glaciers on these mountains are vital sources of stream water for the populations of Nepal and India during the dry seasons, and their recent disappearance should be a source of great concern for these countries.

Compelling evidence for major climate warming underway today comes from the tropical glaciers, recorded in both the ice core records and in the drastic retreats of 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 3 illustrates, all the mountain glaciers in the tropical latitudes are currently retreating (see Kaser and Noggler 1991; Francou and Ribstein 1995; Mark and Seltzer, this volume), as are glaciers in middle and subpolar latitudes (Dyurgerov, Haeberli, both this volume). Although the land between 30°N and 30°S is home to most of the world's population and 80% of the world's births, the average gross domestic product per capita of the 72 tropical nations is only about one-third that of the 78 extratropical nations. Only 20% of the global agricultural production takes place in these climatically sensitive regions and the dwindling water resources for dry-season irrigation will further threaten this production.

The second concern that is brought about by 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.

The manifestations of the current global warming remain a topic of much debate, but the scientific evidence verifies that the Earth's globally averaged surface temperature is indeed increasing. At the same time, global water resources are at risk, and mountain glaciers and their unique climate histories are disappearing at an ever-increasing rate. In order to preserve these records that are essential for examining how climate has changed in the past and to predict future changes, we must accelerate the rate at which ice cores are being recovered and focus on those ice fields that are at the greatest risk.

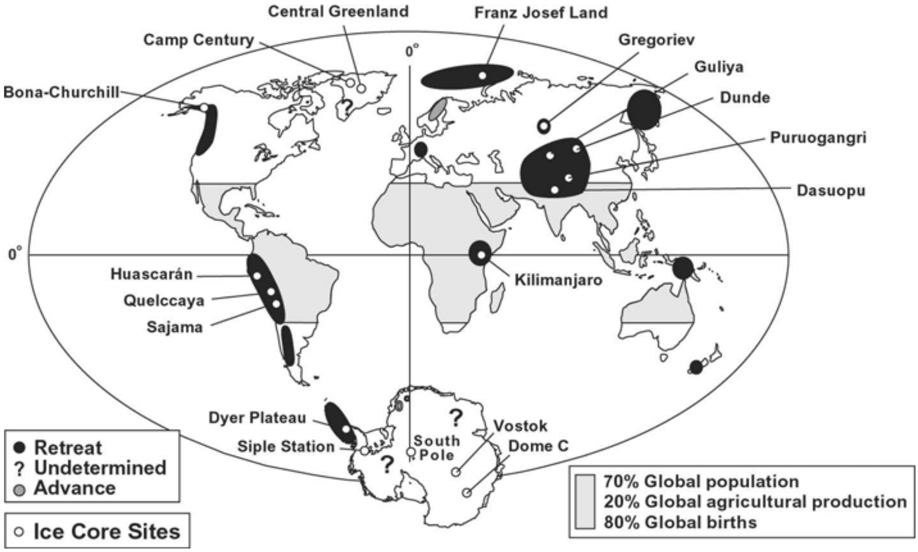

Figure 3: Map demonstrating the current condition of the Earth's cryosphere. Dark shading depicts regions where glacier retreat is underway, while lighter shading depicts where glacier advance is occurring. Shading over land between 30ºN and 30ºS indicates the tropical regions where much of human activity is currently concentrated.

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