5.4.5 Ice-Core Records from Low Latitudes

Ice caps are not confined to polar regions; they also occur at very high elevations in many mountainous regions, even near the equator (Thompson et al., 1984a; Francou and Vincent, 2011). High-elevation ice cores provide invaluable paleoenvironmental information to supplement and expand upon that obtained from polar regions (Figure 5.2 and Table 5.2). However, establishing the chronology of ice cores from low latitudes is very difficult, especially in the deeper sections. In general, accumulation rates are high, so the bulk of the ice recovered only represents the last one or two millennia. The dating of older ice has relied on the identification of volcanic layers (such as the AD 1600 eruption of Huaynaputina in Peru) and correlation of isotopic features and/or gas content with polar ice cores or other paleoenvironmental records. This all leads to considerable uncertainty in low-latitude ice-core chronologies at depth. It is only at Sajama that a ^{14}C date of ~24 ka BP on organic material in the deepest section of the ice core provides a reliable marker in the LGM. Furthermore, thinning of the ice at depth means that the oldest sections are highly compressed. For example, in the Huascarán (Peru) and Illimani (Bolivia) ice cores (166 and 136.7 m in length, respectively), all of the pre-Holocene ice is in the lowest 2 m section, and so, it is not possible to determine in any detail the changes that occurred during that period (Thompson et al., 1995; Ramirez et al., 2003). Sajama provided more old ice at depth, so it has a more detailed LGM and late glacial record; it is also unique in that organic material (including an insect) was found in the ice at several levels, so that a chronology could be established, at least in part using radiocarbon dating (Figure 5.36). Radiocarbon dates were also obtained on organic debris in the ice core from Kilimanjaro's northern ice field, but these provided little guidance for the chronology as the resulting ages were not in stratigraphic order. Thompson et al. (2002) argued for a basal age of ~11,700 BP, based in part on a comparison with a speleothem isotopic record from Soreq Cave (Israel), but the chronology is quite uncertain and there may be discontinuities of unknown duration in the record.

In spite of these dating problems, the three long ice cores from South America provide important information about paleoclimate in the tropical Andes since the LGM (Figure 5.36) (Vimeux, 2009). LGM δ^{18}O values were more depleted by 4-6‰ relative to Holocene values, indicating that conditions at that time were wetter (assuming that the isotopes reflect an "amount effect," as shown in Figure 5.6). This finds confirmation in the more extensive playa lakes of the Altiplano and in speleothem records from Brazil, which all point to a more southerly mean position of the ITCZ and enhanced moisture flux from the Atlantic Ocean. In the Illimani and Huascarán cores, there was a shift to higher δ^{18}O beginning around 18 ka BP, which parallels changes seen in the EPICA Dome C record, with a reversal occurring after AIM1 at ~15 ka BP. At Sajama, the change to heavier isotopes is later and more abrupt; it is not clear whether such a change also occurred at Illimani and Huascarán, but if so, that detail has been lost by smoothing at depth in those highly compressed records. In any case, this change signifies a shift to drier conditions, as confirmed by an increase in Cl^- and dust in Sajama ice at that time. This may indicate that the ITCZ shifted north, before returning once again to a more southerly position during the Younger Dryas interval, when δ^{18}O once again became lower in the Andean ice cores. Finally, the Early Holocene was characterized by dry conditions and high values of δ^{18}O at Huascaran and Illimani, gradually becoming wetter in the Late Holocene. This contrasts with Sajama where the development of extensive playas in the Late Holocene led to high levels of dust reaching the ice cap.

In the Guliya ice core, from the western Qinghai-Tibetan Plateau, the ^{36}Cl profile in the core indicates that the oldest section of the record (below 300 m) may be >500,000 years old (Thompson et al., 1997). Much of the ice appears to date from the last glaciation, so details of conditions in this area at that time can be resolved in considerable detail (Thompson et al., 1997). The long-term record reveals several stadial-interstadial oscillations since the last interglacial (Figure 5.37) with δ^{18}O values in the interstadials reaching Holocene levels,

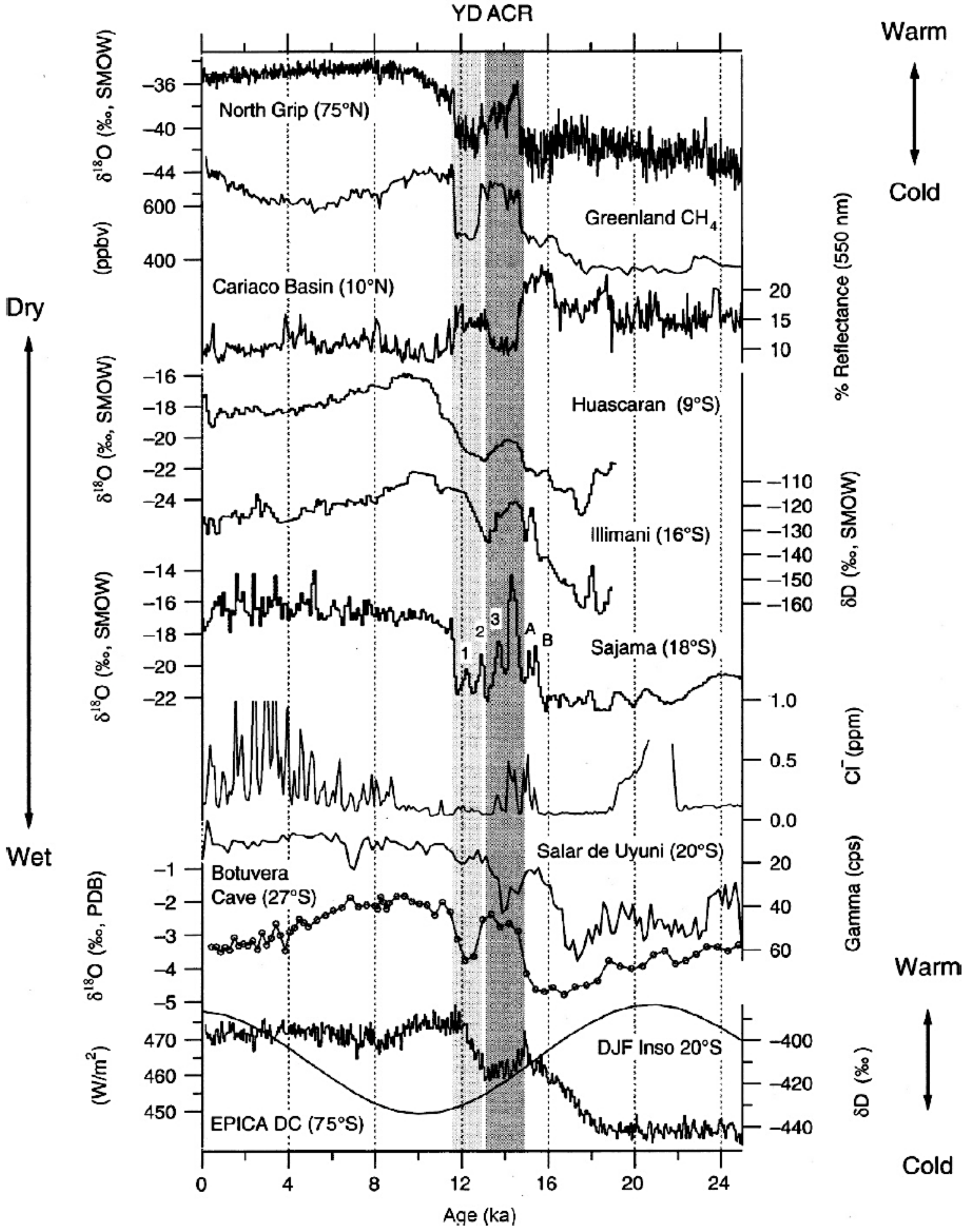

FIGURE 5.36 Records of $\delta^{18}O$ in the Huascarán (Peru) ice core, δD in Illimani (Bolivia) & $\delta^{18}O$ in Sajama (Bolivia) compared to other environmental records over the past 25,000 years: (above) NGRIP $\delta^{18}O$; Greenland CH_4; Cariaco Basin sediment reflectance. (below): chloride from Sajama ice; gamma density from the Salar de Uyuni playa lake basin sediment cores; Botuvera (Brazil) speleothem oxygen isotopes; EPICA Dome C δD, and December-February insolation at 20°S. The general interpretation of each proxy is indicated by the arrows on the left and right. The Sajama record has more ice in the LGM and late glacial section than the other tropical ice cores, and so the record is more detailed. *From Vimeux (2009).*

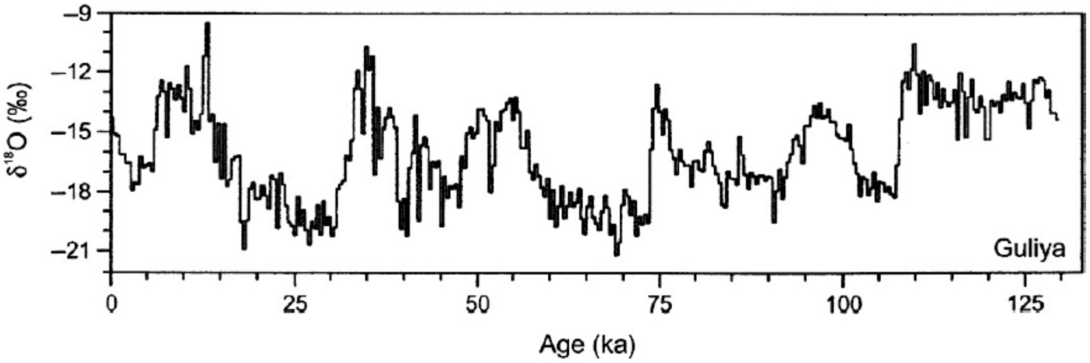

FIGURE 5.37 $\delta^{18}O$ in an ice core from Guliya Ice Cap, western Tibet (~35°N, 81°E). The 308m record was dated by correlating the CH_4 record from Vostok and GISP2 with the oscillations of $\delta^{18}O$. This assumes that the factors causing changes in $\delta^{18}O$ at Guliya would increase and decrease in phase with CH_4 (which is likely to be driven by low-latitude climatic changes). *From Thompson et al. (1997).*

around −13‰. Abrupt, high-amplitude changes in $\delta^{18}O$ occurred from ~15 to 33 ka BP, with an average length of ~200 years. These oscillations are much shorter than the Dansgaard-Oeschger oscillations seen in GISP2 and are associated with higher levels of dust, NH_4, and nitrate during higher $\delta^{18}O$ episodes (the opposite of what is seen in Greenland). This may indicate that warmer episodes occurred throughout the glacial stade, associated with less snow cover and more vegetation on the plateau.

In many ice cores from low latitudes, strong seasonal changes in dust and isotopes enable very reliable chronologies to be established for recent centuries by counting annual layers. For example, in the Quelccaya summit core (Cordillera Vilcanota, Peru: 168.68 m in length), dust levels increase in the dry season (June-September) when $\delta^{18}O$ values and conductivity levels are highest, providing a strong annual signal to a depth of 160m (AD 683 ± 5 years). A prominent conductivity peak resulting from a major eruption of the Peruvian volcano Huaynaputina (in February-March, 1600) provides an excellent chronostratigraphic check on the annual layer counts. No other ice core from the tropics has provided such a clear and detailed chronology (Thompson et al., 1986, 2013). $\delta^{18}O$ over the last 1000 years shows distinct variations in the Quelccaya core, with the lowest values from AD 1530 to 1900 (Figure 5.38). This corresponds to the "Little Ice Age" observed in many other parts of the world. Accumulation was well above average for part of this time (1530-1700) but then fell to levels more typical of the preceding 500 years. Accumulation was also slightly above the long-term mean from AD ~600 to 1000. Archeological evidence shows that there was an expansion of highland cultural groups at that time. By contrast, during the subsequent dry episode in the mountains (AD ~1040-1490), highland groups declined, while cultural groups in coastal Peru and Ecuador expanded (Thompson et al., 1988). This may reflect longer-term evidence for conditions that are common in El Niño years, when coastal areas are wet at the same time as the highlands of southern Peru are dry. Indeed, the Quelccaya record shows that El Niños are generally associated with low accumulation years (Thompson et al., 1984b). Figure 5.39 shows the correlation field between $\delta^{18}O$ at Quelccaya (1870-2009) and SSTs over the Pacific. This shows clearly that there is a strong imprint of ENSO variability on the isotopic record at Quelccaya, a point also noted by

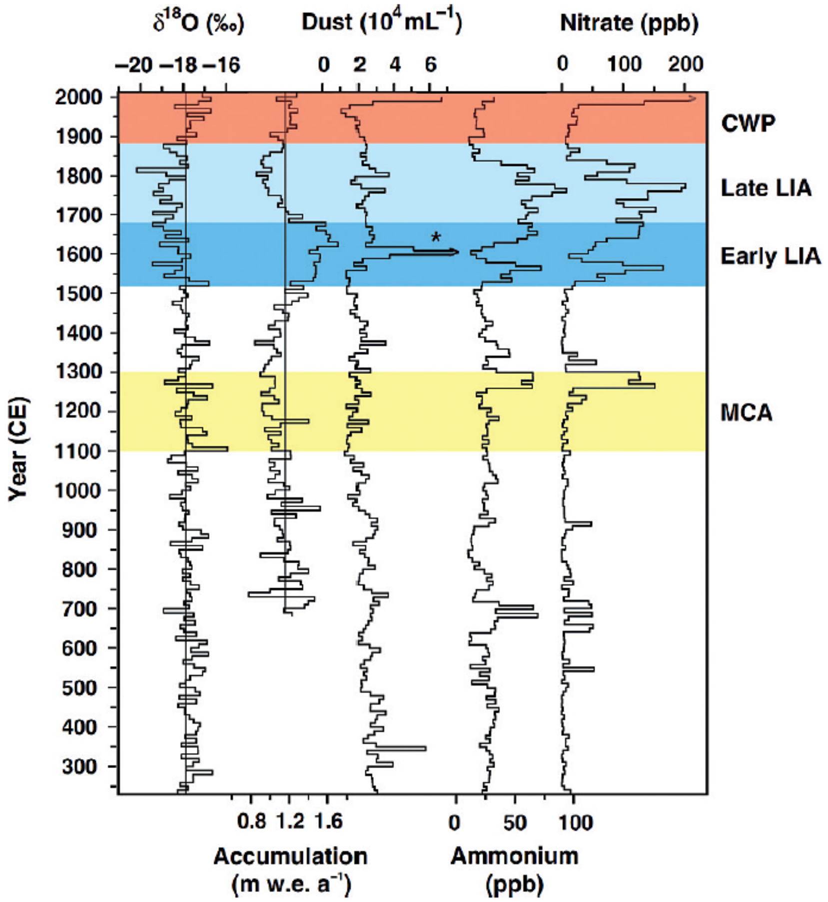

FIGURE 5.38 The record of $\delta^{18}O$, net accumulation, dust, NH_4 and NO_3 from the Quelccaya Ice Cap, southern Peru. The star on the dust profile indicates the eruption of Huaynaputina (Peru) in A.D 1600. m w.e. a^{-1}= meters of water equivalent per year. *From Thompson et al. (2013).*

Bradley et al. (2003b) and Francou et al. (2004) for Sajama Ice Cap (Bolivia) and Ecuadorian glaciers, respectively. This led Thompson to use the $\delta^{18}O$/SST regression to reconstruct Niño4 region SSTs over the last ~1500 years, which indicates that SSTs have rarely been higher than in recent years and that SSTs were 0.3-0.4 °C cooler during the Little Ice Age than in recent decades (Figure 5.39).

High-altitude regions of the tropics have experienced significant increases in temperature over the last few decades, resulting in glaciers and ice caps disappearing altogether in some places (Francou et al., 2003; Vuille et al., 2008; Braun and Bezada, 2013). At the Quelccaya Ice Cap, temperatures in the last 20 years have increased to the point that by the early 1990s, occasional surface melting had reached the Summit core site (5670 m) obscuring the detailed $\delta^{18}O$ profile that was clearly visible in cores recovered in 1976 and 1983 (Thompson et al., 1993). In the entire 1800-year record from Quelccaya, there is no comparable evidence for such melting at the Summit site. Ice cores from the Gregoriev Ice Cap (in the Pamirs) and Guliya and

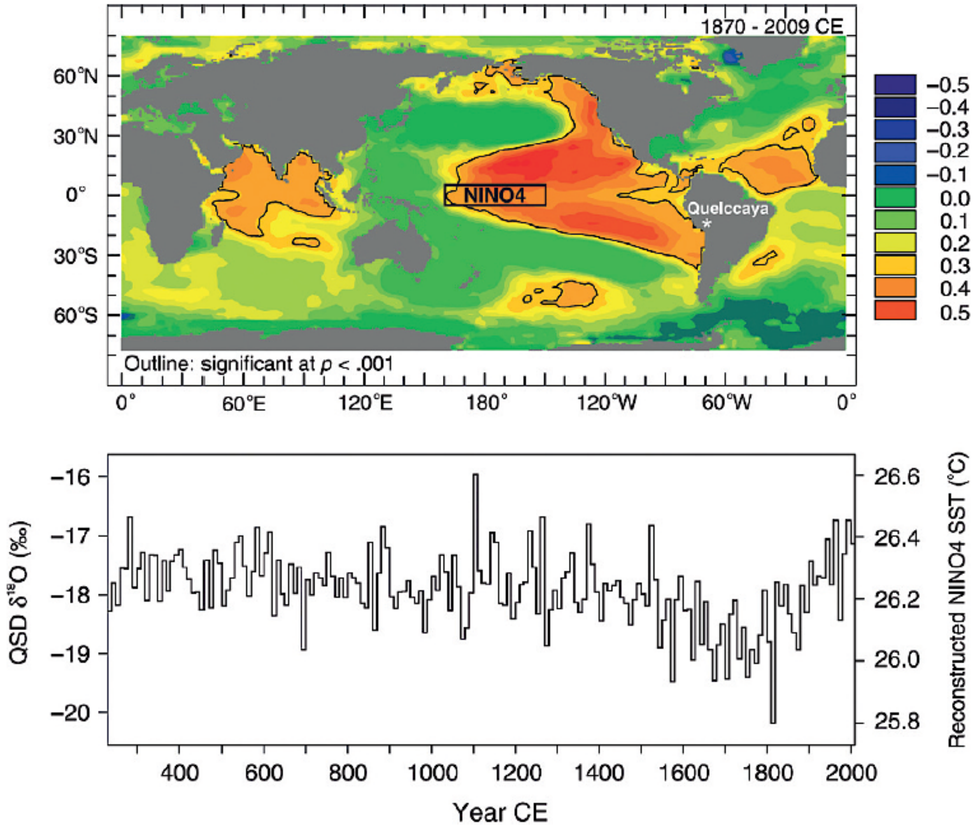

FIGURE 5.39 Map of the correlation field between δ^{18}O in the Quelccaya Summit Dome ice core and SSTs (1870-2009). This pattern shows the strong imprint of ENSO variability on the isotopic composition of the ice. The lower diagram shows reconstructed SSTs in the Niño4 area (see box on map) over the last ~1500 years, based on the δ^{18}O/SST regression equation. Although the spatial correlation pattern has not remained fixed in time, the general relationship between ENSO and δ^{18}O has remained strong. The reconstruction indicates that SSTs have rarely been warmer than in recent decades, and that SSTs were persistently below average during the Little Ice Age. *From Thompson et al. (2013).*

Dundee, western China, also show evidence of recent warming (Lin et al., 1995; Yao et al., 1995). On the northern ice field of Kilimanjaro, ablation has lowered the surface by several meters over the last decade, so that ice at the surface now dates from the nineteenth century or earlier (Hardy, 2011). These records, plus other evidence from short ice cores at high-elevation sites in Africa and New Guinea (e.g., Hastenrath and Kruss, 1992), demonstrate the dramatic nature of climatic change in recent decades, prompting concern over the potential loss of these unique archives of tropical paleoenvironmental history (Thompson et al., 1993, 2006).