Low latitude ice cores record Pacific sea surface temperatures

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[1] Oxygen isotope 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. Circulation anomalies associated with this variability control moisture flux from the equatorial and tropical Atlantic Ocean and Amazon Basin to the ice core sites. Below average SSTs lead to higher accumulation rates and isotopically lighter snow; such conditions are also associated with lower atmospheric freezing levels. During warm events, opposite conditions prevail. Oxygen isotope variations in an ice core in the Himalayas also reflect SST variations in the equatorial Pacific Ocean, pointing to the prospect of reconstructing low latitude circulation anomalies from a network of ice cores in selected locations. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 1833 Hydrology: Hydroclimatology; 1827 Hydrology: Glaciology (1863); 1620 Global Change: Climate dynamics (3309); 1655 Global Change: Water cycles (1836). **Citation:** Bradley, R. S., M. Vuille, D. Hardy, and L. G. Thompson, Low latitude ice cores record Pacific sea surface temperatures, *Geophys. Res. Lett.*, *30*(4), 1174, doi:10.1029/2002GL016546, 2003.

1. Introduction

[2] In recent years, a number of ice cores have been recovered from high elevation sites in the tropics. The primary parameter measured on these cores, for paleoclimatic purposes, is the relative abundance of oxygen isotopes (^{16}O and ^{18}O, expressed as $\delta^{18}O$). The precise interpretation of this parameter has been controversial. Contemporary measurements on precipitation collected at sites around the world indicate a strong $\delta^{18}O$ - temperature relationship at mid to high latitudes, reflecting Rayleigh fractionation and increasing depletion of the heavy isotope at lower temperatures. However in tropical and equatorial regions, this relationship does not hold. The isotopic composition of precipitation in these regions is a function of precipitation amount, which largely reflects fractionation in convective cloud systems. In such systems, precipitation is associated with towering cumulonimbus clouds in which fractionation takes place during vertical ascent of the air. Early expectations for isotopic change in ice cores from the Andes thus predicted that periods with large amounts of precipitation would be associated with the lightest isotopes [*Grootes et al.*, 1989]. Subsequent research on down-core isotopic variations and their relationship to other paleoclimatic records suggested that a more conventional temperature interpretation might be more appropriate, with lower isotopic values during the (presumed to be) cooler "Little Ice Age" and increasingly enriched precipitation during the 20th century warming phase [*Thompson*, 2001].

[3] Both of these conflicting interpretations suffer from inadequate calibration of the observed isotopic record, in relation to climatic conditions during periods of snow accumulation on the ice caps. Here, we use the results of on-site meteorological measurements to determine the seasonality of the ice core record, and then assess how the isotopic records relate to temperature, precipitation and the larger scale circulation associated with snowfall at these high elevation sites. We then extend the analysis to ice core records from the Asian monsoon region. This empirical approach to the interpretation of the isotopic record in low latitude ice cores complements theoretical studies by *Broecker* [1997] and *Pierrehumbert* [1999].

2. Meteorological Observations on Sajama Ice Cap, Bolivia

[4] An automated weather station was established on the summit of Sajama Ice Cap (6,515 m; 18°06' S and 68°53' W) in October 1996 [*Hardy et al.*, 1998]. As is typical throughout the Peruvian and Bolivian Altiplano, there is a strong seasonal cycle of precipitation on Sajama with the southern winter months (April–September) being the driest. At that time, the inter-tropical convergence zone (ITCZ) is far to the north, over northern South America, and upper level winds over the Altiplano are from the west or northwest. Moisture from the Pacific is inhibited by generally cool waters offshore and a strong trade wind inversion that limits convection along the coast. Inland, airflow convergence over the Andes also limits convection, so overall conditions are generally not conducive for the development of rain-bearing clouds. As the seasons change, the zones of maximum convection migrate southward across the Amazon Basin, and along the Andes. High pressure (the Bolivian High) develops in the upper troposphere south and southeast of the Altiplano, leading to enhanced easterly flow. Air (in the free atmosphere) at the elevation of the plateau (~600 hPa) is generally dry with humidities of <3g kg^{-1}. Significant amounts of precipitation only occur when low level moisture is advected into the area from the east which causes humidity to rise, leading to convective instability [*Lenters and Cook*, 1997; *Garreaud*, 2000]. This process occurs when strong mid and upper level tropospheric easterly winds develop in summer months, driving very moist air upslope, from the tropical lowlands east of the Andes. Modifications to this seasonal pattern occur when there are strong circulation anomalies in the Pacific, as a result of ENSO variability [*Garreaud and Aceituno*, 2001]. During La Niñas, enhanced easterly winds result in

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above-average precipitation and a prolonged summer wet season. Conversely, during El Niños, the Bolivian High is displaced northward, causing precipitation amounts to be lower than normal [*Vuille*, 1999].

[5] These seasonal and interannual changes were well recorded on the summit of Sajama ice cap over the past few years. Sonic ranging snow sensors enabled the timing and amount of snowfall and dry season ablation to be determined. This revealed that much of the late summer snowfall was lost via wind scour and sublimation during the winter (mid-April to September) dry season, so that only the early to mid-summer snowfall remained as *net accumulation* to form the ice core record. The exact amount of snow remaining at the end of each dry season varies from year to year (estimated to average ~53% of the original snowfall) but in all years, most of the late summer season (generally, February–March) snowfall is not retained (D. R. Hardy et al., Variability of snow accumulation and isotopic composition on Nevado Sajama, Bolivia, submitted to *Journal of Geophysical Research,* 2003, hereinafter referred to as Hardy et al., submitted manuscript, 2003). Inter-annual differences can be large. For example, during the El Niño of 1991–92, we estimate that snowfall on Sajama was 159 cm (41% of the 1948–49 to 1996–97 mean). By the end of the 1992 dry season, net accumulation was only ~21% of the original snow that fell on the summit in the preceding wet season, and that represented only a very short interval from early in the summer. Conversely, the La Niña event of 1974–75 resulted in heavy snowfall (estimated at 688 cm, 178% of average), 60% of which was retained, so that the overall period represented by the resulting net accumulation covers a longer season, extending into March or even later. These examples demonstrate that any calibration of stable isotopes in ice cores against instrumental data must take into account that the record is seasonally biased towards a period that generally extends from late October/early November to ~February.

[6] By taking such variations into account, we estimated the actual time window that each annual cycle of $\delta^{18}O$ in the Sajama ice core represents, over the past 50 years (Hardy et al., submitted manuscript, 2003). Within this window, we calculated precipitation-weighted mean $\delta^{18}O$ values for each year; overall, the period from November–February is the seasonal window that captures most of the variance in the ice core net accumulation. Correlation of these data with temperature and precipitation at nearby long-term weather stations (and NCEP temperature data averaged over 400 and 500 hPa) shows that there is a statistically significant (negative) relationship between $\delta^{18}O$ and precipitation amount ($r = -0.61$), and a weak, not significant (positive) relationship with NCEP temperature (Hardy et al., submitted manuscript, 2003). Thus, initial ideas about isotopic records from the tropics reflecting the "amount effect" appear justified. However, Altiplano temperature is inversely correlated with precipitation amount in this area, such that anomalies are generally warm and dry or cool and wet. To investigate this further, we examined the large-scale circulation controls on inter-annual variability of both parameters [cf. *Vuille et al.*, 2000]. We correlated the global SST field for November–February of each year with the net annual precipitation-weighted $\delta^{18}O$ reconstructed for Sajama, over the period 1960–61 to 1996–97 (Figure 1).

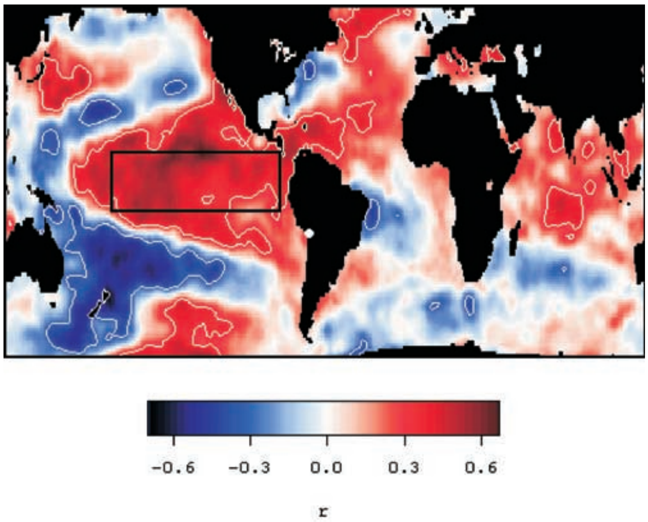

Figure 1. Correlation of global Nov–February SSTs with net accumulation-weighted $\delta^{18}O$ at Sajama, Bolivia (white dot), 1961–1997. Regions delimited by white line are correlated at the 95% significance level. The area used in the regression of Figure 3 is shown as a box in the central and eastern Equatorial Pacific.

This shows clearly that ENSO variability is a key control on isotopic composition of snowfall on Sajama, and that this signal is retained in the ice core record, even though the moisture source for precipitation is the Atlantic [*Vuille et al.*, 1998, 2003a]. A strongly positive correlation field extends across the equatorial Pacific to beyond the dateline, in a wedge separating two "wings" of negative correlation. This pattern is essentially the first EOF of global SSTs and demonstrates that oxygen isotopes in the Sajama ice core record capture a major mode of variability of the climate system, a mode which has global-scale impacts on temperature and precipitation variability [*Bradley et al.*, 1987; *Diaz*, 1996]. Studies of oxygen isotope records from Huascarán and Quelccaya Ice Caps (Peru) reveal a similar relationship; the first EOF of $\delta^{18}O$ in 3 ice cores (Huascarán, Quelccaya and Sajama) has a correlation with Nino 3.4 SSTs of 0.92 (1973–1984) [*Vuille et al.*, 2003b]. This confirms that there is a robust, regional control on isotopic values in the tropical and sub-tropical Andes driven by equatorial SSTs in the eastern Pacific. We also find that simulations with 2 AGCMs (NASA GISS and ECHAM4) employing modern SSTs, reproduce well the isotopic variability seen in ice cores over the last 20–30 years [*Vuille et al.*, 2003b]. We note, however, that precipitation amounts on Sajama are not always simply a function of SSTs in the eastern Equatorial Pacific: the geographic pattern of the SST change, and the strength and location of the low- to mid latitude temperature gradient are also important [*Rind*, 2000; *Charles et al.*, 2001]. For example, in 1972/73 and in 1988/89 the spatial pattern of tropical Pacific SSTs was anomalous, resulting in zonal wind anomalies (related to the changed meridional temperature gradient) being located anomalously far south, thus not affecting precipitation patterns in the Central Andes. This resulted in a warm but *wet* El Niño year (in 1972/73) and a cold but *dry* La Niña year (in 1988/89) [*Garreaud and Aceituno*, 2001]. Nevertheless such conditions are quite exceptional.

[7] Since there are well-known links between Equatorial Pacific SSTs and monsoon precipitation regimes [*Diaz and Kiladis*, 1992; *Kawamura*, 1998], we examined the relationship between SSTs and oxygen isotope variations in an ice core from Dasuopu, China [*Thompson et al.*, 2000]. As we have no basis for adjusting this record for ablation losses, we simply correlated the "mean annual" isotopic values with SSTs for the main snowfall season in that region (June–September). This reveals a very similar correlation pattern with the Pacific SST field as was found for Sajama (Figure 2), indicating the critical importance of Pacific SSTs in controlling the isotopic content of ice cores on both sides of the Pacific Basin. This may also help to explain the strong correlation between accumulation records in Peruvian and Tibetan ice cores pointed out by *Thompson* [1992]. In addition, we note that studies of a limited network of coral records from the Pacific Ocean, and tree-ring records from the western margin of the Americas also capture the main characteristics of SST variability in the Pacific, with a correlation field map almost identical to that in Figure 1 [*Evans et al.*, 2001]. All of these relationships point to the prospect of combining multi-proxy records to reconstruct at high resolution the variability of Pacific SSTs over recent centuries, with a high degree of fidelity.

[8] The regression of $\delta^{18}O$ at Sajama with SSTs averaged over 10°N–10°S, 85°W–180°W is shown in Figure 3. The relationship is statistically significant ($p < 0.002$) and indicates a 1°C increase in SSTs across this region corresponds to a change in $\delta^{18}O$ of ~1.58‰ at Sajama. Furthermore, high SSTs (associated with El Niño episodes, as in 1982–83) correspond not only to periods of well-below average accumulation but also to high freezing level heights in the atmosphere [*Diaz and Graham*, 1996]. Regression analysis shows that an increase of 1°C in Nino 3.4 SSTs (in the central Equatorial Pacific) corresponds to freezing level heights ~76 m above average over the entire inter-Tropical Andes [*Diaz et al.*, 2003]. Hence, any prolonged episode of high SSTs in the central and eastern Equatorial Pacific would lead to negative mass balance and glacier recession in the region (Figure 4).

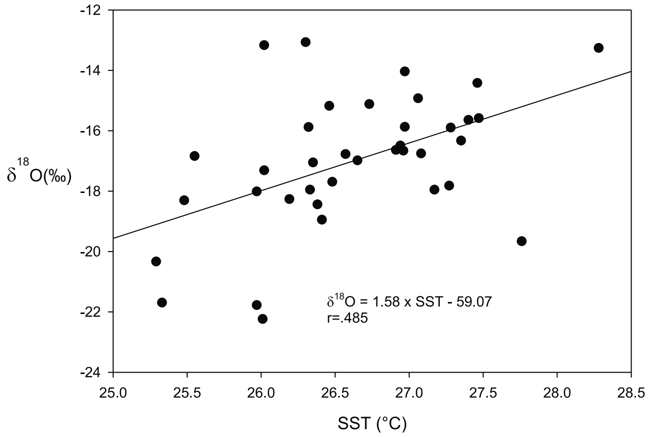

Figure 3. Regression of November–February SSTs averaged over the region 10°N–10°S, 180°W–85°W, with net accumulation-weighted oxygen isotope values at Sajama, 1961–1997.

[9] Based on the calibration outlined here, the long-term Sajama $\delta^{18}O$ record [*Thompson et al.*, 1998] can be interpreted as reflecting mean SSTs in the central and eastern Equatorial Pacific ~3.5°C lower than today during the LGM, resulting in heavy snowfall, low freezing levels in the atmosphere and strongly positive mass balance on glaciers and ice caps of the Bolivian Andes. This is consistent with studies of Lake Titicaca and other closed lakes in the region, which show high lake levels in the LGM, abruptly shifting to warmer and drier conditions by the early Holocene [*Baker et al.*, 2001]. During the Holocene, the Sajama record suggests SSTs varied by ±1°C, with higher variability and an overall higher mean temperature of ~0.8°C in the mid-to late Holocene, compared to the early Holocene. This differs from the Huascarán ice core record which suggests that the early Holocene was the warmest time in that region (~1.5–2°C warmer from ~11 ka–8 ka than in the late Holocene) [*Thompson et al.*, 1995].

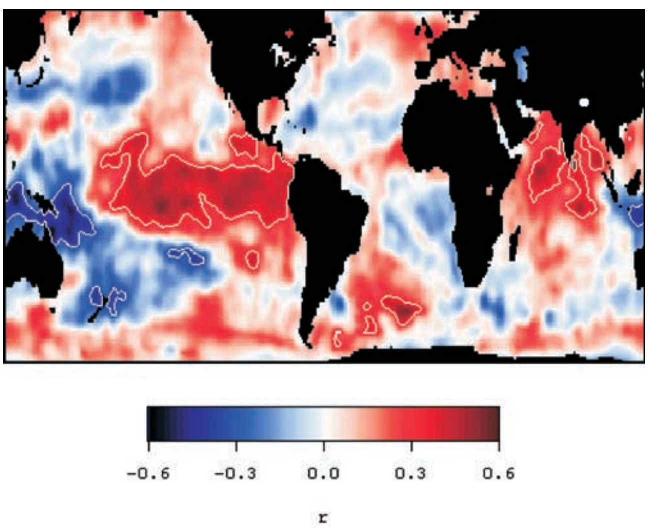

Figure 2. Correlation of global June–September SSTs with mean annual $\delta^{18}O$ at Dasuopu, China (white dot); mean of cores 2 and 3, 1961–1996.

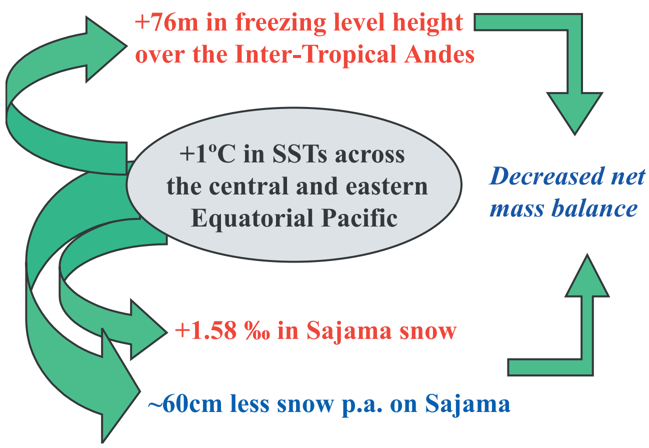

Figure 4. Schematic diagram summarizing links between central and eastern Equatorial Pacific SSTs, isotopic records at Sajama, and mass balance changes.

Studies of lake sediments in the Cordillera Real of Bolivia [*Abbott et al.*, 2000; *Wolfe et al.*, 2001] also indicate relatively dry conditions in the region from the mid to late Holocene, until the last 1500–2300 years, when renewed glaciation set in. We note the increased variability in late Holocene SSTs after ~5000 yr B.P., shown by the Sajama ice core isotopic record, in which short episodes with relatively high isotopic values punctuate longer periods when isotopic values trend towards lower values. Thus, warm, dry episodes may have alternated with longer, cool wet periods (consistent with the Sajama dust record which shows high variability during this period). Given the resolution of the ice core record, this does not shed light on the frequency of ENSO over time, only on overall changes in average SSTs in the central and eastern Equatorial region, but the ice core record, as interpreted here, is consistent with evidence for more El Niño-like episodes (i.e. relatively high SSTs across the region) after ~5000 yr B.P. [cf. *Sandweiss et al.*, 1996; *Rodbell et al.*, 1998; *Markgraf and Diaz*, 2000; *Clement et al.*, 2000; *Moy et al.*, 2002].

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