Coherent isotope history of Andean ice cores over the last century

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[1] Isotope records from Andean ice cores provide detailed and high-resolution climate information on various time scales. However, the relationship between these valuable isotope records and local or regional climate remains poorly understood. Here we present results from two new drillings in Bolivia, from the Illimani and the Sajama ice caps. All four high altitude isotope signals in the Andes now available (Huascarán, Quelccaya, Illimani and Sajama) show near identical decadal variability in the 20th century. Comparison with general circulation model results and meteorological data suggest that the Andean high altitude records are primarily controlled by precipitation variability over the Amazon basin. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3319 Meteorology and Atmospheric Dynamics: General circulation; 1827 Hydrology: Glaciology (1863); 1854 Hydrology: Precipitation (3354). **Citation:** Hoffmann, G., et al., Coherent isotope history of Andean ice cores over the last century, *Geophys. Res. Lett.*, *30*(4), 1179, doi:10.1029/2002GL014870, 2003.

1. Introduction

[2] There is an increasing need for highly resolved quantified climate proxies in the tropics. This is mainly because the convectively active regions in the tropics are key regions for the global hydrological cycle. In addition, the number of long-term meteorological stations at low latitudes is small compared to high northern latitudes. Determining the cause of ongoing climate shifts is therefore particularly difficult in this part of the world.

[3] The spatial significance and calibration of various paleo proxies measured in Andean ice cores, such as stable water isotopes and dust content of ice, is an important point of concern. In their pioneering papers on Andean ice cores from Bolivia [*Thompson et al.*, 1998] and from Peru [*Thompson*, 1995; *Thompson et al.*, 1985]. Thompson and colleagues discuss climatic changes on various time scales mainly deduced from the stable water isotope record ($\delta^{18}O$ or δD). The water isotopes integrate climate information from the evaporation source to the location of condensation and final deposition. Potentially they are sensitive to climate quantities such as air temperature or precipitation amount over the entire trajectory of a vapor parcel.

[4] The lack of a direct calibration of water isotopes from tropical and subtropical glaciers against measured meteorological variables has led to strongly divergent interpretations [*Broecker*, 1997; *Pierrehumbert*, 1999; *Thompson et al.*, 2000]. When analysing isotope signals in modern precipitation samples globally, two mechanisms dominate: At high latitudes, temperature controls the spatial and temporal pattern of the water isotopes (the global spatial "temperature effect" amounts to $\sim$0.6–0.7‰/°C, see [*Dansgaard*, 1964; *Rozanski et al.*, 1993]). At low latitudes, the relation between the water isotopes and temperature breaks down and the amount of precipitation becomes dominant ("amount effect", see citations above). For high elevation of tropical glaciers, however, it is not yet clear which effect dominates at the relevant time scale. For instance, the "amount effect" may dominate seasonal variations, whereas temperature may control interannual variations. Atmospheric circulation may also play an important role. Situated near one of the centers of action of the ENSO system, a link between the Andean isotope records and this dominant tropical climate oscillation was expected but only appears weakly [*Henderson et al.*, 1999]. Nevertheless, the isotopic content of the ice is thought to give us an important hint of the hydrological cycle in the tropics/subtropics in general [*Grootes et al.*, 1989; *Thompson et al.*, 2000].

2. The Data

[5] In this paper, we present two new high-resolution ice cores from Bolivia (see Figure 1). In 1997 the first drilling was performed on Sajama (6542 m,18°06′S, 68°53′W), a long inactive volcano in the Cordillera Occidental. The core was drilled down to 40 m depth, a couple of meters next to a deep drilling site, which reached the bedrock at 132.4 m [*Thompson et al.*, 1998]. Sajama is located about 150 km southwest of the Lake Titicaca approaching the extremely dry central part of the Bolivian Altiplano. Despite of its proximity to the Pacific Ocean ($\sim$100 km) this region only sporadically receives water from this nearby moisture source. About 80% of the precipitation falls in austral summer (December to February) when strong convective activity over the Altiplano is triggered by intense summer insolation [*Aceituno and Montecinos*, 1993].

[6] Two years later (1999) a second core was drilled on Illimani (6350 m, 16°37′S, 67°46′W), this time down to bedrock at 136.7 meter. The bottom part of the ice core dates back to the last glacial [*Ramirez et al.*, 2002]. Climatologically, Illimani is quite different relative to Sajama. Located within the Cordillera Oriental on the eastern side of the Andes next to La Paz and to the lake Titicaca, it is much more directly exposed to the humid and warm moisture flux

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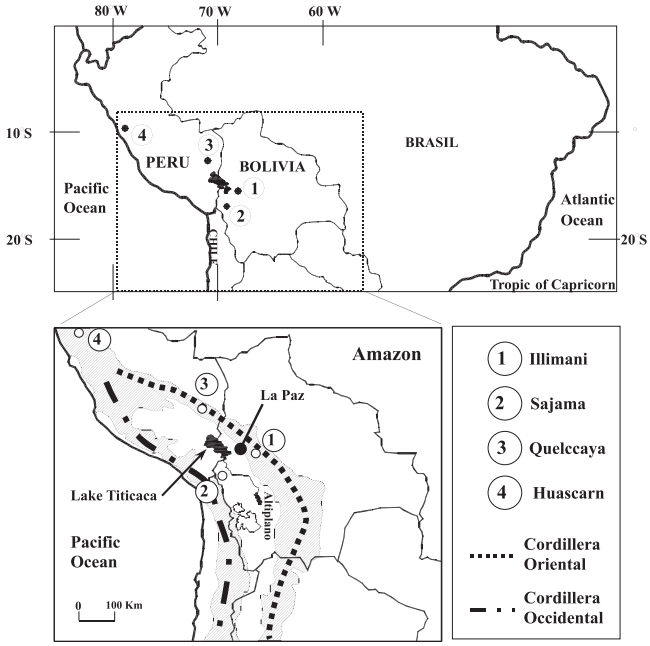

Figure 1. Map of the Andes including the four drilling sites of high altitude ice-cores discussed in this study. The Illimani glacier is situated right on the natural frontier of the Amazon and the Central Andes, 50 km next to La Paz city and 180 km to the Lake Titicaca. The Sajama glacier is located in the eastern part of the Andes, that is 160 km to the Pacific Ocean and 200 km to the Illimani glacier. Two other isotope records from ice cores in Peru, the Huascarán [*Thompson et al.*, 1995] and Quelcaya [*Thompson et al.*, 1985], are also used in this study.

coming from the Amazon basin. Though both ice cores are taken at about the same altitude, the annual accumulation is much stronger on Illimani (640 mm/year [Simões, personal communication, 2002] and 580 mm/year [*Knüsel et al.*, 2002]) than on Sajama (440 mm/year [*Thompson et al.*, 1998]). The slightly different accumulation rates for Illimani are based on using two different cores drilled next to each other and dating these cores with slightly different methods. However, the numbers for Illimani and Sajama should be accepted with care since the corresponding periods are not exactly the same.

[7] Two other isotope records from high altitude sites (see Figure 1) are discussed in this paper: Huascarán (6048 m, 9°06′S, 77°36′W, [*Thompson et al.*, 1995]) and Quelccaya (5670 m, 13°56′S, 70°50′W, [*Thompson et al.*, 1985]). Both Peruvian sites are subjected to more humid climate conditions, with a much shorter and less pronounced dry periods (only ∼3 months at the Huascarán) compared to Sajama (∼9 months).

[8] The Illimani core was first analysed for its electric conductivity and subsequently cut into pieces of 10 cm (from the top to 40 m), of 7 cm (from 40 m to 120 m), of 3 cm (from 120 m to 133 m) and of 1 cm (over the last 3 m). Subsequently dust content, chemical properties and the isotopic composition of the ice ($\delta^{18}O$) was measured in the laboratory. A similar procedure was chosen for the analysis of the Sajama core. The isotopic measurements are given here as deviations in per mil from the Vienna Standard Mean Ocean Water (V-SMOW) [*Craig*, 1961]. The experimental precision of the isotope analysis amounts to 0.8‰ for the Deuterium and 0.05‰ for the ^{18}O.

[9] Here we focus on the upper part of both cores (Illimani and Sajama) which were dated by counting annual layers apparent within a set of tracers: conductivity related to the acidity of the ice, dust content, Ca^{+} concentration and isotopic composition of the ice. The seasonality of all four quantities down to a depth of about 40 meters is well preserved. Furthermore, a number of fix points have been used: three peaks in conductivity can be associated with well-known volcanic eruptions of the last forty years (Pinatubo, 1991; El Chichón, 1982; Agung, 1963). A peak in the ^{137}Cs and Tritium content of the ice at the depth of about 33.5 meters can be associated with the strongest bomb tests in the Northern Hemisphere in year 1964. The estimated uncertainty of the multi proxy approach amounts to ±2 years down to 40 meters. However, the uncertainties increase rapidly with depth as the shape of the peaks associated with volcanic eruptions becomes less well defined (±7 years at 60 meters, which approximately corresponds to 1900).

3. Discussion

[10] In Figure 2a the resolved records from the Huascarán [*Thompson et al.*, 1995] and the Quelccaya [*Thompson et al.*, 1985] are compared to the upper parts of the Sajama and Illimani records (this study). All records were seasonally dated using a multi-proxy approach with at least 10 measurements per annual cycle. There is a striking correspondence between all four high-resolution records on time scales longer than about 3 years. The various isotope records are correlated with an r value ranging between 0.5 and 0.9 when restricted to the common period from 1968–1982 and 0.2 to 0.7 when taking the complete records into account. This is extremely high given that even temperature records from weather stations in the area have smaller correlations when treated in the same manner. In the following, we define the average isotope record (see Figure 2a) as the Andean Isotope Index (AII) covering the period from 1909–1998.

[11] The coherency of Andean isotope variations in the last century argues for the existence of a climate signal over a broad region in South America including a wet tropical site at 9°S and a dry subtropical site at 20°S. The common

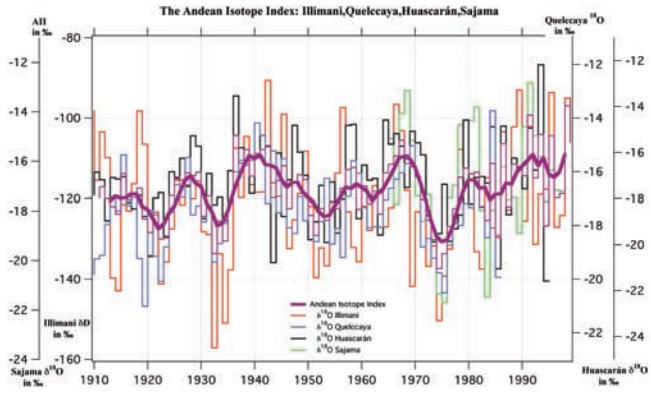

Figure 2a. Isotope records from Huascarán [*Thompson et al.*, 1995], Quelccaya [*Thompson et al.*, 1986], Illimani, Sajama (this work) and the Andean Isotope Index defined as the arithmetic mean of the four records.

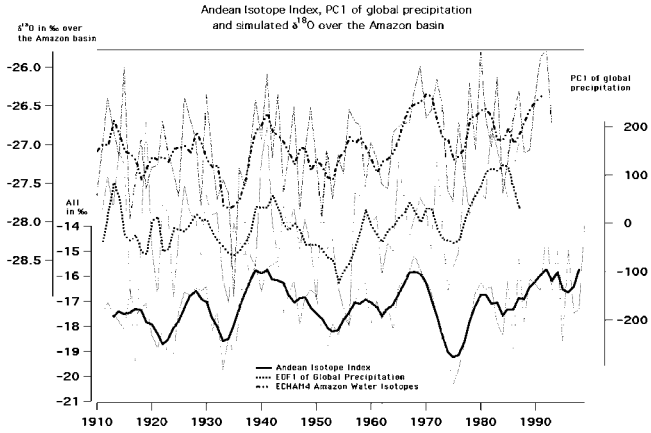

Figure 2b. Andean Isotope Index (arithmetic mean of Andean high resolution isotope records: Huascarán [*Thompson et al.*, 1995], Quelccaya [*Thompson et al.*, 1986], Illimani, Sajama, time scale was shifted by 2 years), PC1 *1000. of global precipitation [*Dai et al.*, 1997] and $\delta^{18}O_{Vap}$ averaged over the Amazon basin (5°N–20°S;70°W–30°W) at the 500Hpa level as simulated by the ECHAM4 GCM. The broader curves correspond to the 5-year running mean of each of the three quantities. Less (more) depletion of the water isotopes correlates well with anomalously dry (wet) conditions over the Amazon in agreement with the isotopic amount effect [*Dansgaard*, 1964].

and dominant moisture source for the Andes at these latitudes is the Amazon basin, and ultimately the tropical Atlantic. In order to better understand the origin of the observed isotope variability and to determine the regions that influence the AII, we compare the AII with global precipitation data for the last century [*Dai et al.*, 1997]. The global precipitation data were homogenized and analysed for the period from 1900 to 1988. Figure 2b shows the principal component (PC) of the first EOF of the observed annual precipitation anomalies. In *Dai et al.* [1997] the authors associate the EOF1 (explaining about 10% of the observed variability in the tropics and 6% globally) with ENSO related climate variability. EOF1 is marked by anomalously dry conditions in the Amazon basin.

[12] Figure 2b also shows isotope variations within a 92-year integration of the ECHAM general circulation model [*Roeckner et al.*, 1996] forced by observed sea surface temperatures and sea ice distributions (GISST2.2 data set, [*Hurrell and Trenberth*, 1999]). The model uses a T30 resolution corresponding to an approximate resolution of 3.75° on a physical grid and a 30 minutes time step. Atmospheric concentrations of greenhouse gases (CO_2, CH_4, N_2O) were also prescribed according to the observations [*IPCC*, 1995]. The model contains a sub-module allowing the calculation of the water isotopes in parallel to the model's hydrological cycle [*Hoffmann et al.*, 1998]. The simulated water isotope signal was checked against modern observations of the Global Network of Isotopes in Precipitation (GNIP). In Figure 2b, the isotopic composition of water vapour, $\delta^{18}O_{Vap}$, on the 500 HPa level regionally averaged between 5°N–20°S and 70°W–30°W is shown.

[13] A better comparison between the model, precipitation data and the AII record can be obtained when the AII time scale is shifted by two years (+2 years). Figure 2b demonstrates that the shifted AII is in good agreement with both the leading mode of tropical precipitation anomalies and the simulated isotope signal. Dry conditions occur within Amazon basin during the high phase of EOF1, producing less intense rainout and therefore less depleted water vapor (isotopic amount effect [*Dansgaard*, 1964]).

[14] The simulated $\delta^{18}O_{Vap}$ signal over the Amazon basin at the 500HPa level, which is the level of strongest water vapor transport, showed the strongest correlations with central Pacific SSTs (up to r = 0.5) resembling a decadal ENSO SST pattern (results not shown here). The Amazon isotope record further correlates well with negative precipitation anomalies over the tropical Atlantic and the Amazon basin (r = −0.5). However, neither the observed (AII) nor the simulated isotope record correlates extremely well with typical time series describing the ENSO phenomenon (SOI, Nino3). This is most probably due to the variable relation between individual El Niño/La Niña events and South American precipitation. The timing of such events relative to the main rain season is crucial for their impact on precipitation [*Montecinos et al.*, 2000].

[15] From the comparison between the simulated and the observed isotope signal, several conclusions can be drawn. First, the convincing agreement between the shifted AII and both direct observations and model results implies a systematic error of 2 years in the dating of the ice cores. The two years shift is within the uncertainty range of the ice cores. The high noise level in the upper firnal part of the cores (see Figure 2a) and the large accumulation variations in some ENSO years [*Vuille*, 1999] might be responsible for that. Second, the spatial relevance of the AII extends over an area even larger than the Andes between 10°S–20°S. Intense water recycling in the Amazon basin smoothes out the isotope signal over the entire region. It is this large-scale signal that is recorded by our high altitude sites. Third, the ECHAM model is capable of describing much of the decadal variability of the hydrological cycle in the tropics/subtropics. The data used to force the ECHAM were completely independent of the AII and therefore the comparison between the ECHAM and the AII represents an independent test of the GCM. Fourth, our results suggest that the reconstructed SST forcing is realistic, even in this part of the global ocean (tropical Pacific and Atlantic) and even over time-periods where reliable SST observations were lacking. However, before 1930 the model-observation agreement (see Figure 2b) is not as good implying possible problems with the quality of the reconstructed SSTs at the beginning of the record. A comparison between tropical temperatures (global average between 10°N and 10°S) shows even some resemblance to the AII (not shown here). This is not surprising since tropical temperatures on interannual to interdecadal timescales are controlled by the depth of the thermocline in the Pacific varying with the ENSO phase. The influence of the latter on the Hadley/Walker circulation and therefore on the described precipitation anomalies over South America is well known [*Rao Brahmananda et al.*, 1998].

[16] In our interpretation precipitation variability in the Amazon basin, the principal source region for precipitation on the Altiplano, is the leading factor controlling the AII and not local temperature trends. However, these two factors are not entirely decoupled. ENSO variability exerts a large influence on both quantities. As was shown in *Vuille*

and Bradley [2000] there is a statistically robust rising temperature trend of about 0.1°C per decade in the tropical Andes. When analysing meteorological data starting in 1939 the authors concluded that most of the temperature trend is taking place in the period from 1974–1995 (0.34°C per decade) roughly coinciding with the rising trend in the AII. However the observed temperature trend decreases significantly at high altitudes. From 1974–1995 we estimate therefore an approximate mean temperature rise of 0.5°C at the height of the Andean glaciers. The AII rises over the same period by about 3‰. This results in a hypothetical sensitivity of the water isotopes of 3‰/0.5°C = 6‰/°C which would be a gradient that cannot be explained by our actual understanding of water isotopic fractionation (the modern spatial gradient amounts to 0.6–0.7‰/°C see above).

[17] Alternatively the AII can be related to the observed precipitation variations. A linear regression between the AII and the PC of EOF1 (see Figure 2b) yields a relation of 0.2‰ per unit. With a mean amplitude of about 4 of the first EOF averaged over the Amazon basin [*Dai et al.*, 1997] and a precipitation variance of about 80 mm/year the relation between the water isotopes and ENSO related precipitation anomalies in the Amazon yields 1‰ per 0.2*4*80 mm/year $\sim$ 0.0167‰ for every mm/year. This result of a simple first order estimate is within the observed range of today's amount effect [*Rozanski et al.*, 1993].

[18] Though there is a slight accumulation of high isotopic anomaly within the AII in the most recent period, overall the mean Andean isotope signals seem to be relatively stable during the 20th century. The last decade in the record (1985–1995) do not look exceptional and the AII is not dominated by a rising trend. In future studies, more high-resolution ice records from the Andes will be stacked in order to extend a reliable isotope signal several centuries back in time and to compare quantitatively the 20th century with former centuries. The correspondence between the AII, independent observations, and GCM results over the last century is a promising starting point for future studies on long-term decadal/inter-decadal variability of the hydrological cycle in the tropics.

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References

Aceituno, P., and A. Montecinos, Circulation anomalies associated with dry and wet periods in the South American Altiplano, in *Fourth International Conference on Southern Hemisphere Meteorology and Oceanography*, Am. Meteorol. Soc., Boston, Mass., 1993.

Broecker, W. S., Mountain Glaciers: Recorders of atmospheric water vapor content?, *Global Biogeochem. Cycles*, *11*(4), 589–597, 1997.

Craig, H., Standard for reporting concentrations of deuterium and oxygen-18 in natural water, *Science*, *133*, 1833–1834, 1961.

Dai, A., I. Y. Fung, and A. D. Del Genio, Surface observed global precipitation variations during 1900–88, *J. Climate*, *10*, 2943–2962, 1997.

Dansgaard, W., Stable isotopes in precipitation, *Tellus*, *16*, 436–468, 1964.

Grootes, P. M., M. Stuiver, L. G. Thompson, and E. Mosley-Thompson, Oxygen isotope changes in tropical ice, Quelcaya, Peru, *J. Geophys. Res.*, *94*, 1187–1194, 1989.

Henderson, K. A., L. G. Thompson, and P.-N. Lin, The recording of El Niño in ice core $\delta^{18}O$ records from Nevado Huascaráan, Peru, *J. Geophys. Res.*, *104*, 31,053–31,065, 1999.

Hoffmann, G., M. Werner, and M. Heimann, The Water isotope module of the ECHAM atmospheric general circulation model - A study on time scales from days to several years, *J. Geophys. Res.*, *103*, 16,871–16,896, 1998.

Hurrell, J., and K. Trenberth, Global sea surface temperature and analyses: Multiple problems and their implications for climate analysis, modeling, and reanalysis, *Bulletin of the American Meteorological Society*, *80*(12), 2661–2678, 1999.

IPCC, *Climate Change 1995*, Intergovernmental Panel on Climate Change, Cambridge, 572 pp., 1995.

Knüsel, S., P. Ginot, U. Schotterer, M. Schwikowski, H. W. Gäggeler, B. Francou, J. R. Petit, J. C. Simões, and J.-D. Taupin, Dating of two nearby ice cores from the Illimani, Bolivia, *J. Geophys. Res.*, in press, 2002.

Montecinos, A., A. Diaz, and P. Aceituno, Seasonal diagnostic and predictability of rainfall in subtropical South America based on tropical Pacific SST, *J. Clim.*, *13*, 746–758, 2000.

Pierrehumbert, R. T., Huascaran $\delta^{18}O$ as an indicator of tropical climate during the Last Glacial Maximum, *Geophys. Res. Lett.*, *26*, 1341–1344, 1999.

Ramirez, E., G. Hoffmann, J. D. Taupin, B. Francou, P. Ribstein, N. Caillon, A. Landais, J. R. Petit, B. Poyaud, U. Schotterer, and M. Stievenard, A new Andean deep ice core from Illimani (6350 m), Bolivia, *Earth and Planetary Science Letters*, submitted, 2002.

Rao Brahmananda, Y., S. R. Chapa, and I. F. A. Cavalcanti, Moisture Budget in the tropics and the Walker circulation, *J. Geophys. Res.*, *103*, 13,713–13,728, 1998.

Roeckner, E., K. Arpe, L. Bengtsson, M. Christoph, L. Dümenil, M. Esch, M. Giorgetta, U. Schlese, and U. Schulzweida, The Atmospheric General Circulation Model ECHAM-4: Model Description and Simulation of Present-Day Climate, Max-Planck Institut für Meteorologie, Hamburg, 1996.

Rozanski, K., L. Araguas-Araguas, and R. Gonfiantini, Isotopic patterns in modern global precipitation, in *Climate Change in Continental Isotopic Records*, edited by P. K. Swart, K. C. Lohmann, J. MacKenzie, and S. Savin, AGU, Washington, D.C., 1–37, 1993.

Thompson, L. G., M. E. Davis, E. Mosley-Thompson, T. A. Sowers, K. A. Henderson, V. S. Zagorodnov, P. N. Lin, V. N. Mikhalenko, R. K. Campen, J. F. Bolzan, J. Cole-Dai, and B. Francou, A 25,000-year tropical climate history from Bolivian ice cores, *Science*, *282*, 1858–1864, 1998.

Thompson, L. G., E. Mosley-Thompson, J. F. Bolzan, and B. R. Koci, A 1500 year record of tropical precipitation recorded in ice cores from the Quelccaya ice cap, *Science*, *229*, 971–973, 1985.

Thompson, L. G., E. Mosley-Thompson, M. E. Davis, P. N. Lin, K. A. Henderson, J. Cole-Dai, J. F. Bolzan, and K.-B. Liu, Late glacial stage and Holocene tropical ice core records from Huascaran, Peru, *Science*, *269*, 46–50, 1995.

Thompson, L. G., E. Mosley-Thompson, and K. A. Henderson, Ice-core palaeoclimate records in tropical South America since the Last Glacial Maximum, *Journal of Quaternary Science*, *15*(4), 377–394, 2000.

Vuille, M., Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the Southern Oscillation, *International Journal of Climatology*, *19*, 1579–1600, 1999.

Vuille, M., and R. Bradley, Mean annual temperature trends and their vertical structure in the tropical Andes, *Geophys. Res. Lett.*, *27*(23), 3885–3888, 2000.

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