Palaeogeography, Palaeoclimatology, Palaeoecology 281 (2009) 229–241

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Climate variability during the last 1000 years inferred from Andean ice cores: A review of methodology and recent results

Françoise Vimeux [a,b,*], Patrick Ginot [c], Margit Schwikowski [d], Mathias Vuille [e], Georg Hoffmann [b], Lonnie G. Thompson [f], Ulrich Schotterer [g]

[a] Institut de Recherche pour le Développement (IRD), UR Great Ice, Paris, France
[b] IPSL, Laboratoire des Sciences du Climat et de l'Environnement (LSCE), CEA-CNRS-UVSQ, CE Saclay, Orme des Merisiers, Bât 701, 91191 Gif-sur-Yvette Cedex, France
[c] Institut de Recherche pour le Développement (IRD), UR Great Ice, La Paz, Bolivia
[d] Paul Scherrer Institut (PSI), Villigen, Switzerland
[e] Department of Earth and Atmospheric Sciences, University at Albany, State University of New York, Albany, USA
[f] Byrd Polar Research Center, The Ohio State University, Columbus, USA
[g] Climate and Environmental Physics, Physics Institute, University of Bern, Switzerland

A R T I C L E I N F O

Article history:
Received 25 May 2007
Accepted 13 March 2008
Available online 7 September 2008

Keywords:
Andean ice cores
South American high-altitude climate
Last millennium
Andean Isotopic Index
Little Ice Age
ENSO

A B S T R A C T

Andean ice core investigations began approximately 30 years ago. Today, 10 drilling sites, from 0° to 52°S, have been explored for paleoclimate reconstructions. Most of the ice cores reaching the bedrock cover the last 20,000 years with seasonal resolution over the last few centuries to the last 1000 years for the Quelccaya site. We discuss both the potential and the limitations of tropical ice cores as climate archives with regard to the collaborative effort to reconstruct past climate variations in South America over the last 1000 years. We point out the uniqueness of South American ice cores, due to their location at high altitude, and also their two main limitations, which are related to (i) the interpretation of certain proxies in terms of climate and (ii) the relatively poor dating when seasonal cycles are no longer resolved. In addition, we present an overview of the proxies that have been used so far to analyze tropical climate dynamics. Finally we discuss records of ENSO, the Little Ice Age and the 20th century decadal variability, including the anthropogenic period, which are all preserved in ice cores.

1. Introduction

1.1. Motivation for a review on Andean ice cores

Greenland and Antarctic ice cores have provided a wealth of quantitative paleoclimate and paleoenvironmental information, both at orbital and millennial timescales, back to 800,000 years BP (hereafter 800 ka) for the oldest ice core (EPICA community members, 2004). A well-known and robust example is the temperature reconstruction based on the modern linear relationship between the isotopic composition of surface snow (deuterium and oxygen-18) and the surface temperature at high latitudes.

Motivated by the demonstrated potential of this polar archive, exploration of tropical ice cores started about 30 years ago in the tropical South American Andes, where high altitude glaciers contain well-preserved ice, suitable for paleoclimate investigations. By now, a large number of firn and deep ice cores have been extracted along the South American Andes from 0 to 52°S. This has resulted in new and important paleoclimate information, which we review here.

The critical review of available ice core data sets and their interpretation is the first step in assessing their potential for use in future regional climate reconstruction following the methodologies by Mann et al. (1999), Luterbacher et al. (2004) and Moberg et al. (2005). Hence, this article gives an overview of the current understanding regarding Andean ice core analysis, and reviews both their unique potential and their limitations. We point out the peculiarities of this climate archive compared with other proxies presented in the accompanying articles (this special issue). We also discuss how they might contribute to ongoing efforts of reconstructing climate in South America over the last 1000 years. Finally, we discuss the main results regarding mechanisms of climate change that have emerged from Andean ice core studies. We discuss whether these records provide information on global or rather regional and/or local paleoclimate. Our discussion generally covers the last 1000 years with an emphasis on the last few centuries.

1.2. What Andean ice core records exist?

The ideal ice core drill site does not exist, but some boundary conditions need to be fulfilled: the drill site should be located in the accumulation area of a cold glacier on a site with minimal ice flow (e.g., on a saddle or a dome). Between the equator and 35°S, glaciers are generally located at an altitude above 5000 m, offering cold sites

* Corresponding author. IRD UR Great Ice/IPSL-LSCE, Orme des Merisiers, Bât 701., 91191 Gif-sur-Yvette Cedex. Tel.: +33 1 69 08 57 71; fax: +33 1 69 08 77 16.
E-mail address: Francoise.Vimeux@lsce.ipsl.fr (F. Vimeux).

0031-0182/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2008.03.054

with good potential to extract high-quality ice cores for paleoclimate purposes. In Patagonia, the snowline altitude is much lower and drops to sea level for most regions (Casassa et al., 1998). Most of the glaciers in Patagonia are temperate and a suitable site for ice core drilling (i.e., a plateau of a cold glacier) is, therefore, difficult to find.

Below, we list the different Andean sites from 0°S to 50°S where deep or shallow ice cores have been extracted (Fig. 1 and Table 1), including a brief description of the sites and expeditions.

1.2.1. Chimborazo: Ecuador

In December 1999, a 16 m shallow firn core was extracted from the Chimborazo summit (1°30' S, 78°36' W, 6268 m.a.s.l.) by the joint groups Institut de Recherche pour le Développement/Universität Bern/Paul Scherrer Institut (IRD/UB/PSI), followed by a deep drilling campaign in December 2000. Several ice cores were extracted; the longest at Cumbre Ventimilla reached bedrock at 54 m depth. A drilling attempt in the depression between Cumbre Ventimilla and Cumbre Ecuador was stopped at 25 m by water-saturated firn. The 54 m-long ice core covers the last 120 years with annual resolution (Ramirez, 2003).

1.2.2. Huascarán: Peru

The saddle of Huascarán (9°06' S, 77°36' W, 6048 m.a.s.l.) was selected for deep drilling after five shallow ice cores confirmed the potential for a well-preserved stratigraphic record. In 1993, two ice cores reached bedrock at 160.4 m and 166.1 m respectively, reaching back into the Late Glacial Stage (Thompson et al., 1995).

1.2.3. Quelccaya: Peru

Quelccaya ice cap (13°56' S; 70°50' W, 5670 m.a.s.l) was drilled in 1983 using the first solar-powered drill. The recovered ice cores cover the last 1500 years with excellent annual resolution (±2 years at AD 1500). In July 2003, the Ohio State University (OSU) team returned to the ice cap to drill a new set of ice cores down to bedrock. The new cores cover a similar period as the previous ones, but also include the intervening 20 years up to the year 2003 AD (Thompson et al., 2006a).

1.2.4. Coropuna: Peru

In June and August 2003, Coropuna (15°30' S, 72°40' W, 6434 m) was drilled twice, both by IRD and OSU. IRD recovered a 45 m ice core from the saddle (6080 m.a.s.l.). The drilling was stopped by water-

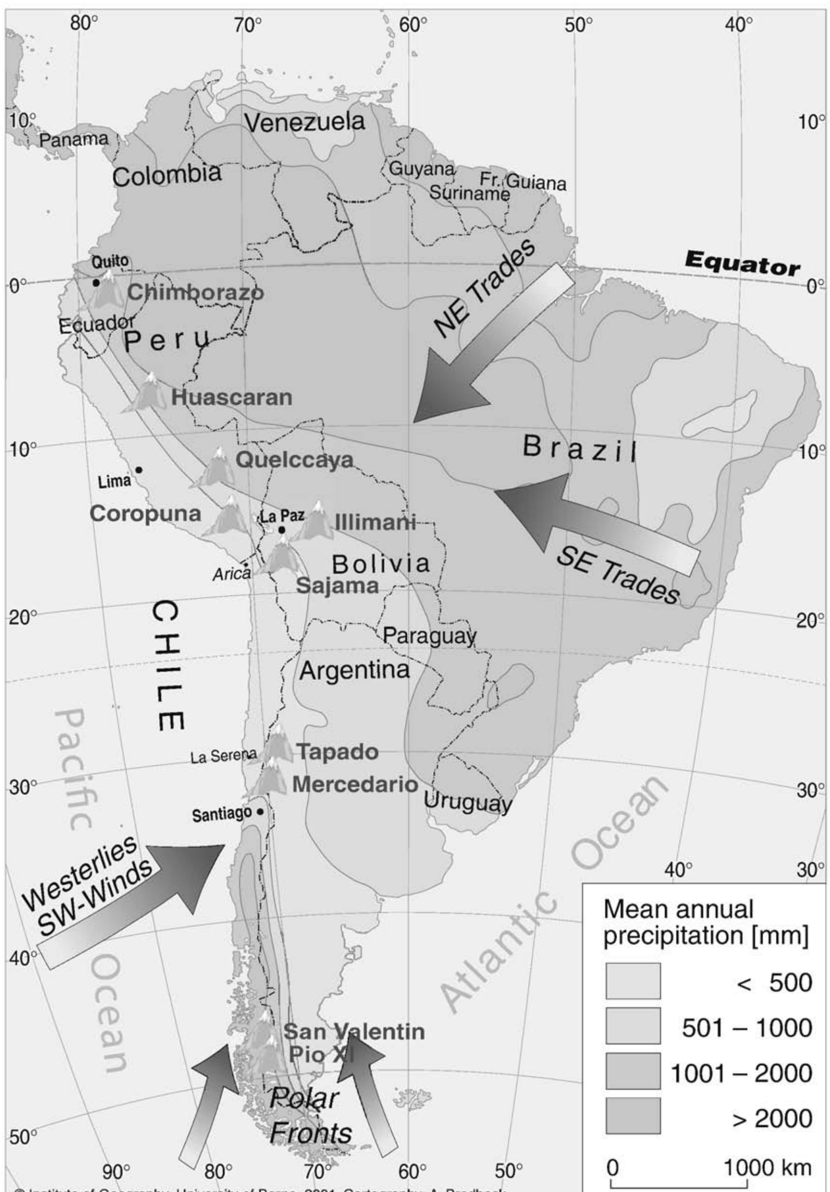

Fig. 1. Map of South America with the locations of Andean summits where ice cores have been extracted. Major atmospheric circulation paths are indicated.

Table 1
Andean ice cores characteristics.

Site name drilling date	Latitude longitude altitude	Core depth (m) * bedrock	Annual mean net accumulation (m w.eq.)	Seasonal precipitation maxima	Dominant wind direction	Length of data series	Resolution at the top of the core	Dating	Key references
Chimborazo 2000	1°30' S 78°36' W 6268 m	54*	0.5	March–May Oct–Nov	E or W ITCZ dependent	2000–1881	Annual	ALC, ^{210}Pb, ^{3}H	(Schotterer et al., 2003)
Huascarán 1994	9°07' S 77°37' W 6050 m	160*, 166*	1.3	Nov–March	NE–SE	1993–1719 LGM at bottom	Annual	ALC	(Henderson et al., 1999; Thompson et al., 1995)
Quelccaya 1983–2003	13°56' S 70°50' W 5670 m	155*, 164* –170*, 129	1.2	Nov–March	NE–SE	2003–488	Annual	ALC, beta activity	(Thompson et al., 1984, 1985, 2006b)
Coropuna Col–Summit–Crater	15°32' S 72°39' W 6072 m	40–34*–146*	0.4–0.12–1.2	Jan–Feb	NE–SE	20 ka at bottom	Annual	^{3}H	(Thompson et al., 2006b)
Illimani 1999	16°37' S 67°46' W 6350 m	137*, 139*	0.58	Nov–March	NE–SE	1999–1921 18ka at bottom	Annual	ALC, ^{3}H, ^{210}Pb	(Hoffmann et al., 2003; Knüsel et al., 2003; Ramirez et al., 2003)
Sajama 1997	18°06' S 68°53' W 6542 m	40 132*, 133*	0.44	Nov–March	NE–SE Westerlies	25 ka at bottom	Annual	ALC, ^{3}H, ^{14}C	(Thompson et al., 1998)
Tapado 1999	30°08' S 69°55' W 5550m	36*	0.31	May–Sept	Westerlies	1999–1962 1920 or older at bottom	Annual	ALC, ^{3}H, ^{210}Pb	(Ginot et al., 2006)
Mercedario 2005	31°58' S 70°07' W 6100 m	104	0.3	May–Sept	Westerlies	Analysis on-going	Annual	ALC, ^{210}Pb	(Bolius et al., 2006)
San Valentin 2005	46°35' W 73°19' W 3747 m	20, 55, 70, 122*	0.20	Annual	Westerlies Polar	2005–1965	Annual	ALC, ^{210}Pb, ^{137}Cs	(Vimeux et al., 2008)
Pio XI 2006	49°16'S 73°21'W 2600 m	51	Analysis on-going	Annual	Westerlies Polar	Analysis on-going	Annual	ALC, ^{210}Pb	

a) Site name and drilling dates; b) coordinates of the drill sites; c) core length (m); d) annual mean net accumulation (w.eq.) averaged over a few decades (mostly between Tritium horizon and the surface); e) monthly precipitation maximum; f) dominant wind direction g) length of temporal series; h) top temporal resolution; i) dating method; j) references.

saturated firn. OSU drilled two cores to bedrock, one from the summit crater rim at 6434 m.a.s.l. (34 m long) and another deep 145 m core to bedrock from the crater at 6350 m.a.s.l. The saddle core covers approximately the last 100 years. The summit core contains ice layers from the last 20 ka but with some temporal gaps. The crater core is still being analyzed.

1.2.5. Illimani: Bolivia

Two parallel ice cores were extracted from the saddle on Illimani (16°37' S, 67°46' W, 6300 m.a.s.l.) in June 1999 by IRD/UB/PSI. Both 135 m-long cores cover the whole glacier thickness and contain the climate history of the last 18 ka (Knüsel et al., 2003; Ramirez et al., 2003).

1.2.6. Sajama and Pomerape: Bolivia

The ice cap on the highest summit of Bolivia, Sajama (18°06' S, 68°53' W, 6542 m.a.s.l.), was drilled in June 1997 by OSU/IRD. Two 132 m-long ice cores to bedrock and an additional shorter ice core (40 m) were extracted. The last 25 ka are recorded in the longer cores (Thompson et al., 1998).

In November 2005, IRD tried to drill the volcano Pomerape (18°07' S, 69°07' W, 6215 m.a.s.l.) in the vicinity of Sajama, however, temperate firn with thick ice layers stopped further coring.

1.2.7. Cerro Tapado: Chile

Shallow and deep ice cores were extracted from Cerro Tapado glacier (30°08'S, 69°55'W, 5550 m.a.s.l.) in 1998 and 1999 by UB/PSI/IRD. Bedrock was reached at 36 m depth. The extremely dry conditions at this site were investigated by surface snow experiments and detailed in situ meteorological data in order to quantify sublimation processes during the drilling period (Ginot et al., 2001; Stichler et al., 2001). The deep core covers the 20th century, but older ice separated by a hiatus was identified in the basal layer.

1.2.8. Mercedario: Argentina

Two ice cores, 13 m and 104 m long, were recovered from La Ollada glacier on Cerro Mercedario (31°58'S, 70°07'W, 6100 m.a.s.l.) in 2003 (Bolius et al., 2006) and 2005, respectively, by PSI in collaboration with the Centro de Estudios Cientificos, Chile (CECS). The ice thickness at the drill site is about 140 m. Borehole temperatures (−18.5 to −16.7 °C, see Fig. 8) are the lowest obtained so far from Andean glaciers. The core should contain climate information covering several centuries.

1.2.9. San Valentín and Pio XI: Patagonia, Chile

The Patagonian Andes represent the third-largest ice field worldwide with an area of 19,500 km^2. It is divided into the Northern Patagonian Icefield (4200 km^2), the Southern Patagonian Icefield (13,000 km^2) and the 2300 km^2 ice field of Cordillera Darwin in the southern corner of Tierra del Fuego (Williams and Ferrigno, 1998). Since 1985, several drilling programs have tried to extract suitable ice cores (Yamada, 1987; Aristarain and Delmas, 1993; Matsuoka and Naruse, 1999; Shiraiwa et al., 2002;) but have always encountered temperate ice, which is not suitable for climate reconstructions.

In 2005, a 16 m firn core was taken by IRD from the San Valentín summit glacier (46°35'S, 73°19'W, 3747 m.a.s.l.) covering the last 40 years. The −11 °C borehole temperature and the 160 m ice thickness indicated high potential for successful deep drilling (Vimeux et al., 2008). In April 2007, a collaborative team from IRD and CECS drilled a 122 m ice core to bedrock, and collected two firn cores (55 and 70 m), as well as several 20 m shallow cores.

In August 2006, a 51 m ice core was recovered from the upper accumulation area of Pio XI glacier (49°16' S, 73°21' W, 2600 m.a.s.l.) within the framework of a PSI/CECS collaboration. Pio XI is the largest glacier of the Southern Patagonian Icefield. This site was selected based on a recent study (Schwikowski et al., 2006). Ice thickness at the drill site was 170 m, but drilling was stopped once temperate ice was reached.

2. Andean ice cores: potential and limitations

In this section, we review both the potential and the limitations of Andean ice cores to explore past climate variations. We demonstrate the uniqueness of Andean ice cores to study past climate in South America and we also mention some caveats that have to be accounted for when Andean ice cores are considered in future regional climate reconstructions.

2.1. Uniqueness of Andean ice cores

The uniqueness of Andean ice cores as a paleoclimatic archive is related to both their geographic setting and their specific properties as a glacial archive:

2.1.1. Unique geographic settings

(1) Andean ice cores provide original information on the evolution of two dominant climate modes in South America, the El Niño-Southern Oscillation (ENSO) and the Antarctic Oscillation (for a review see Garreaud et al., 2009-this issue).

(2) Thanks to the longitudinal extension of the Andes, South America is the only continent in the southern hemisphere where a paleoclimate transect based on the same archive can be established from the equator to high latitudes (55°S). This transect enables the documentation of South American paleoclimate at different temporal and spatial resolution and the linking of these records with those of the Antarctic Peninsula (and Antarctica), where a number of ice core records are already available (see the paleoclimate transect to the Pole that started in 2005, the CACHE-PEP program, http://www.antarctica.ac.uk/bas_research/current_programmes/cache.php). Thus, ice cores along the Andes provide a unique opportunity to explore tropical-high latitude interactions and teleconnections that affect South American climate.

(3) Due to the high-elevation of the drill sites, ice cores also offer the unique opportunity to assess climate change in the, often neglected, vertical dimension, as the ice cores provide a glimpse into how mid-tropospheric (5000–7000 m) climate and circulation have varied in the past. For example, we still know very little about how tropical climate at high altitude responds to well-known northern hemisphere and global climate anomalies, such as the Little Ice Age.

(4) Due to their location in pristine and remote environments, Andean ice cores can provide insight into climate from regions that would otherwise be completely void of data.

(5) Finally, Andean ice cores, combined with mass balance studies, should help understand if and how the recent Andean glacier retreat, and southern hemisphere climate in general, is linked to global climate change (Francou et al., 2003).

2.1.2. Unique glacial archives

(1) Ice cores sites are currently undergoing very rapid changes as a result of which these natural archives may soon be lost forever.

(2) Ice cores provide a unique set of proxy records complementing and adding to other existing sources of paleoclimatic information in South America. They are unique in that they provide a wide variety of different proxies (water stable isotopes, pollen, dust, net accumulation, major ions and trace elements, etc.), which can be used for climate reconstructions, provided their climatic sensitivity is adequately understood.

(3) They also allow for continuous, high-resolution (seasonal to annual) analysis, at least over the last few decades, but in some cases (Quelccaya) even millennia. They should, therefore, be considered potential candidates for global climate reconstruction efforts covering the last 1000 years with seasonal to decadal resolution.

2.2. The last 1000 years in Andean ice cores: important caveats and limitations

Despite the unique potential of Andean ice cores for climate reconstructions, some caveats must be mentioned when considering them for multi-proxy climate reconstructions over the last 1000 years:

(1) Due to the high accumulation rates in Andean ice cores, the climate variations of the last 1000 years constitute the major part of the ice core: this time period is roughly contained in the upper 115 m and 70 m at Illimani and Sajama, respectively. The last few meters of the cores contain between 10,000 and 15,000 years of climate history. Consequently, the dating is accurate at the surface (about ± 2 years over the last 10 years) and can be estimated downcore to roughly ± 10 years around 100 years BP (Knüsel et al., 2003; comparison of two parallel cores on Illimani). However, the loss of annual resolution after a few centuries (except at Quelccaya) makes it unsuitable to use such archives in multi-proxy reconstructions for the last 1000 years if one follows Mann et al.'s (1999) approach. An analysis of the spectral properties at decadal or centennial timescales, however, is still possible and could be useful if one uses Moberg et al.'s (2005) approach to merge different archives with climate variability at different frequencies and variable resolution.

(2) There are also still significant uncertainties and disagreements regarding the interpretation of some of the geochemical constituents, in particular stable water isotopes (hydrogen and oxygen). In the past, the isotopic composition of Andean ice cores (δD and $\delta^{18}O$, hereafter combined and cited as δ) was used as a proxy for temperature (e.g. Thompson et al., 1995) and has recently been included in global temperature reconstructions (Mann et al., 1999; Mann and Jones, 2003). However, as pointed out by the National Research Council (2006), Andean ice core proxies (and tropical ice core proxies in general) may be more complex than previously thought. In Section 3, we review the different opinions on this issue for the interpretation at different timescales (interannual to centennial). We propose potential approaches to address and solve some of the problems for future interpretations.

(3) Isotopic diffusion processes have not been explored in Andean glaciers yet. The isotopic diffusion in firn (diffusion in the vapour phase) and in the deeper ice (diffusion in single ice crystals, in water films or veins along crystal boundaries) can smooth the isotopic profiles and perturb the dating, so that a quantified interpretation of (rapid) isotopic variation, based on modern calibration, would be biased. A reliable study estimating the diffusion length should be helpful. Additionally, we do not know the effects on diffusion caused by the temperature gradient in the proximity of the bedrock, which is revealed by borehole temperature profiles in the lower part of some of the ice cores (see Section 4 and Illimani and Coropuna profiles in Fig. 8).

(4) Some sites undergo important post-deposition processes, which complicate the interpretation of isotopic and/or chemical profiles. We discuss the main studies that have been carried out to quantify post-deposition effects in Section 3.

3. How to interpret proxy records from Andean ice cores

3.1. Dating methods

The limited ice thickness of Andean glaciers, combined with the higher accumulation compared to polar regions, does not allow reconstruction of climate on glacial-interglacial timescales. Most records from the Andes cover the last 20 ka, with seasonal to decadal resolution over the last 1000 years.

An accurate chronology is crucial to correctly interpret paleoclimatic signals from ice core isotopic and chemical records. Various methods exist, such as counts of seasonal layers, reference horizons, radiogenic decay of suitable radionuclides and comparison with other proxy-archives.

3.1.1. Annual layer counting

The most accurate method for ice core dating is the multi-proxy annual layer counting (ALC), which is based on the seasonal variation of insoluble particles and the isotopic composition of the ice. However, it is necessary to first understand these signals and their suitability for ALC, as they are site-dependent.

First, in the tropical Andes seasonal variations of the isotopic composition of precipitation (δ) are related to the amount effect (Rozanski et al., 1993), and are thus sufficiently different from the dry to the wet season to allow ALC (the seasonal δ^{18}O variation is about 10‰, one hundred times higher than the analytical accuracy). For Andean ice cores, the application of this method can be complicated when (i) snow deposition occurs only during a short wet season (4–5 months), as is the case at Cerro Tapado, which makes the detection of a seasonal isotopic cycle difficult and, (ii) when the seasonal δ amplitude is of the same order as a intra-seasonal δ amplitude, as, for example, on Chimborazo. At this site, the annual course of convective activity associated with the South American summer monsoon leads to a bimodal precipitation distribution, which is reflected in a precipitation δ double peak over Ecuador (Garcia et al., 1998) and in the Chimborazo ice (Ginot et al., 2002). This annual double peak is also apparent in some chemical components like Ca^{2+} and NO_3^- (Fig. 2), which severely complicates ALC dating at inner-tropical sites.

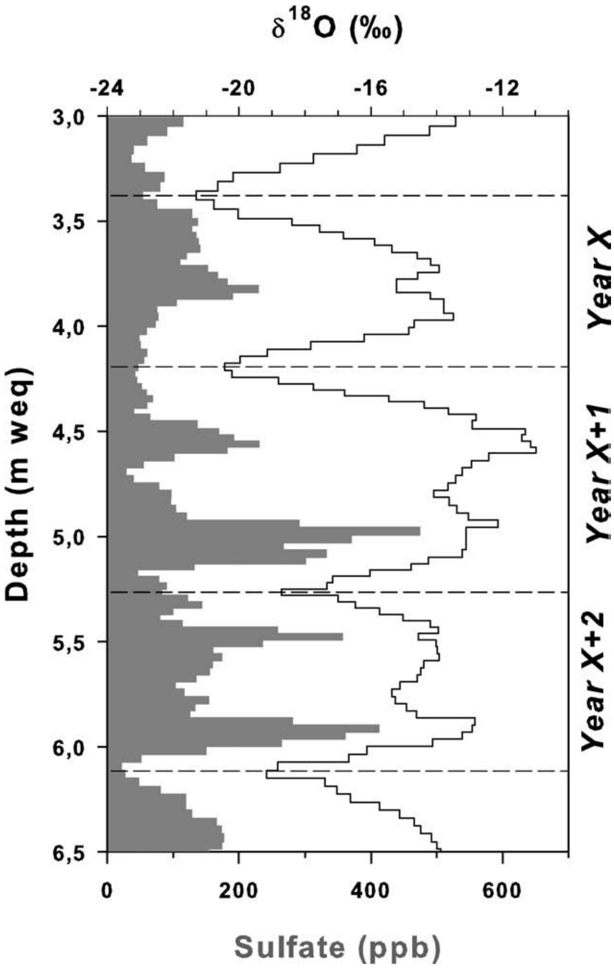

Fig. 2. Details of sulfate (grey bars) and δ^{18}O (black line) from the Chimborazo shallow ice core drilled in 1999 illustrate clearly the annual double-peak variations associated with the annual course of convective activity.

Second, the relative aridity of the Altiplano, combined with the pronounced unimodal precipitation distribution, contributes to a well-marked seasonal signal of dust content in the snow layers for most locations. During the summer, convective precipitation minimizes the dust content, while the following dry season is characterized by dry deposition of surrounding mineral particles and primary aerosols on the snow surface. Several proxies for dust content are appropriate. Calcium (Ca) is a major component of erodible soils and because of the high solubility of calcium-containing minerals, it is commonly used as a marker of eolian dust deposits. As seawater contains calcium salts, the contribution resulting from marine primary aerosol input must be discriminated from total calcium in order to assess the soil dust mobilization component. The latter, usually called non sea-salt calcium, $_{nss}Ca^{2+}$, is calculated using the sodium concentration as the marine primary aerosol reference and the bulk seawater calcium-to-sodium ratio, according to $_{nss}Ca^{2+} = Ca^{2+} – Na^{+} * (Na/Ca)_{sea\ water}$. This led us to assume that high-frequency oscillations in $_{nss}Ca^{2+}$ are related to seasonal changes in aerosol production, and thus that every firn layer containing one relative maximum surrounded by two relative minima, corresponds to one annual layer.

Third, Electric Conductivity Measurement (ECM) is a technique that delivers an extremely high-resolution (1 mm) continuous profile along the ice core and has the advantage of being a non-destructive technique. Initially developed for polar ice cores to estimate acidity (Hammer, 1980), the method was also applied on, for example, the Illimani ice core, where it was assumed that annual variations in the ECM record are due to varying H^+, microparticle and major ion concentrations, whereas large ECM peaks are related to high H^+ concentrations (Knüsel et al., 2003).

Finally, snow stratigraphy can also be used if the density varies within the year (Thompson et al., 2006a).

3.1.2. Dating by reference horizons: tritium, volcanic layers

In order to independently verify and crosscheck the ALC dating, reference horizons that document past atmospheric perturbations can be used. On a short timescale, radioactive fallout from nuclear weapon tests between the 1950's and 1970's can be detected by measuring tritium content or total-beta activity (today mainly ^{137}Cs activity), as the radioactive debris was spread across the planet via stratospheric-tropospheric exchanges. In the southern hemisphere, the tritium maximum occurred between 1964 and 1967. It has been used as an absolute chronological reference horizon for the ice cores from Chimborazo, Huascarán, Quelccaya, Coropuna, Illimani, Sajama, Tapado and San Valentin. Due to its well-known seasonal behaviour tritium was used to examine how well the seasonality was preserved in several cores during the maximum fall-out period.

Large volcanic eruptions have also provided numerous reference horizons. In the Illimani ice core, for example, the fallout from Pinatubo (1991 AD), Agung (1963 AD) and Tambora (1815 AD) were identified based on their ash, the chloride and fluoride signature and the sulfur isotopic composition (De Angelis et al., 2003; Ramirez, 2003). From the ECM profile, strong acid levels related to volcanic SO_2 emissions were identified and related to these eruptions. In addition, the eruptions of El Chichón (1982 AD), Krakatoa (1883 AD) and an unknown eruption (1258 AD) were found. Local volcanic eruptions such as Huaynaputina (1600 AD), which deposited a 3 cm thick ash layer on Sajama (Thompson et al., 1998), have also been identified.

3.1.3. Dating by radioactive decay: ^{210}Pb and ^{14}C

The radioactive isotope ^{210}Pb can be used where most of the conventional dating methods fail. ^{210}Pb (half-life of 22.3 years) is a decay product of ^{222}Rn (half-life of 3.83 days), which emanates continuously from the earth's crust into the atmosphere. Attached to aerosol particles, ^{210}Pb reaches the glacier surface by dry or wet deposition after an atmospheric residence time of a few days to a few weeks. ^{210}Pb dating has been applied to the ice cores from Cerro Tapado (Ginot et al., 2006), Illimani (Knüsel et al., 2003), Chimborazo, Coropuna, San Valentin (Vimeux et al., 2008) and Mercedario. ^{210}Pb activity at the glacier surface ranged from 60–100 mBq kg^{-1}. With a blank of a few mBq kg^{-1}, the time period that can be dated corresponds to 5–6 times the half-life. Lowest surface activity values were observed in the Mercedario and Cerro Tapado cores (after correction for the enrichment by sublimation; Ginot et al., 2006).

Radiocarbon (^{14}C) dating was used for the Sajama ice core, confirming that the core contains LGM ice (Thompson et al., 1998). The radiocarbon method could be applied because sufficient quantities of plant material and insect fragments were present for ^{14}C-AMS measurements. This is not normally the case for ice cores.

3.1.4. Dating accuracy: how to improve Andean ice core dating

It is important to mention that the dating accuracy depends on the site and how well the seasonal cycle is resolved. Thus the dating accuracy becomes very poor in the deeper part of the ice cores. For example, at Illimani, the dating accuracy over the last 10 years can be estimated to ± 2 years. However, this decreases rapidly with depth and reaches roughly ± 10 years around 100 years BP (Knüsel et al, 2003), although seasonal cycles are still preserved.

As annual resolution is limited to the last few decades or centuries (with the exception of Quelccaya, which provides more than 1000 years of annually resolved information), the application of high-resolution analytical methods developed for sites with low accumulation rates will be an important step to extend the seasonal reconstructions back in time. However, in order to make a competitive contribution to multi-proxy climate reconstructions, dating of Andean ice core records over the last 1000 years needs to be improved. This may be achieved by developing a specific Andean chronology of volcanic eruptions, similar to that used in polar ice cores. Such a chronology would facilitate cross-comparison of different ice cores, and could be backed-up with the new ^{14}C technique, which uses carbonaceous particles scavenged from the atmosphere during snowfall and subsequently preserved in ice (Jenk et al., 2007). However, this method has not yet been tested on ice cores from South America.

Since ice cores can provide complementary information to other natural archives such as tree rings, a more precise dating will allow for a much better multi-proxy reconstruction. This would be the best way to ensure that Andean ice cores are reliably included in ongoing efforts aimed at accurately reconstructing the climate history of the last 1000 years.

3.2. Accumulation processes

The interpretation of Andean ice cores as climate archives depends on the accumulation characteristics, related to both the seasonal distribution of precipitation and the length of the dry season. In the case of the Cerro Tapado, precipitation occurs between May and September followed by a long dry season that is characterized by strong ablation and sublimation (Ginot et al., 2002; Ginot et al., 2006). In this extreme situation, the preserved snow represents only a short time of the year, but some additional information about the dry season is recorded in the surface snow layers that are exposed to the atmosphere for a long time (see Section 3.3). For Sajama, Hardy et al. (2003) demonstrated that the ice in the core represents a relatively short period of time centred around the months of January or February and, therefore, the record cannot be interpreted in terms of annual mean conditions. The situation is different on Illimani, where convective precipitation originating from the Amazon basin can provide snow deposition on the glacier also during the dry season (Bonnaveira, 2004). Thus, information from different seasons is potentially recorded in the ice.

Based on the deposition/ablation processes observed at the different drill sites, it is clear that some sites are more appropriate to reconstruct the interannual snow accumulation history than others. The most suitable sites present a high accumulation/ablation ratio and a simple ice flow as a consequence of their location (best on a flat area on a summit or in a pass). Such conditions can be found at four Andean sites. We present here the annually resolved accumulation records for Illimani (1999–1880), Chimborazo (2000–1881), Quelccaya (1984–1880) and Huascarán (1993–1890; Fig. 3). The net accumulation was measured based on annual layer counting, whereby the dry-to-dry hydrological season was used. In order to establish the original thickness of the annual layers, which are compressed and stretched with depth and time, a glaciological flow/compaction model was applied (Nye, 1963). Such a model considers an exponential decrease in layer thickness with depth and time. Another way to correct the accumulation is to fit the layer thickness ($p_i - p_{i-1}$, in water equivalents w.eq.) versus depth (p_i) with the best fit exponential regression [$p_i - p_{(i-1)} = a * \exp(-bp_i)$; a and b being constants], and to use this regression equation as correction $\text{accu}_{pi} = (p_i - p_{i-1}) a * \exp(-b) / a * \exp(-bp_i)$ (Nye, 1963). This method draws attention to the interannual variability but hides the trend over the complete time range.

Despite these corrections, questions remain as to how representative and useful the net accumulation is as climate information. Net accumulation is the result of total accumulation controlled by precipitation and wind drift, minus the ablation (sublimation, evaporation, wind erosion). The accuracy of using net-accumulation as a proxy for "precipitation amount", for example, depends also on the respective seasonality of total accumulation and ablation. For sites like Cerro Tapado, combining both low net-accumulation (0.31 m w.eq./year) and strong sublimation (0.33 m w.eq./year) over a long dry season, the calculated net accumulation cannot be interpreted as

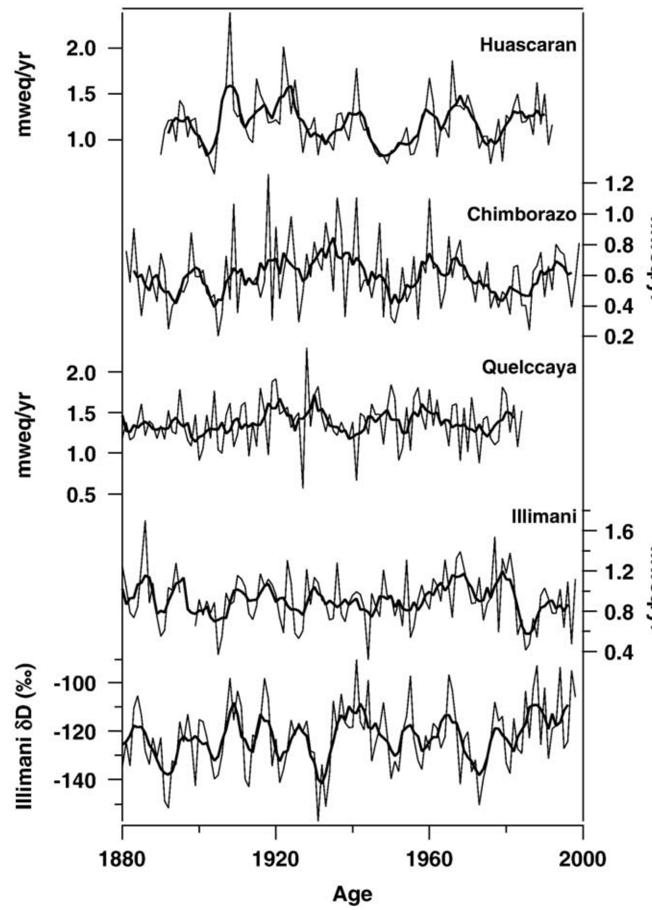

Fig. 3. Net accumulation reconstructions (in m w.eq. yr^{-1}) on Illimani, Quelccaya, Chimborazo and Huascarán over the last 120 years at annual resolution (thin line) and with a 5-year running average (thick line). The isotopic composition (δD, ‰) of Illimani ice is shown.

representative of the "amount of precipitation" (Ginot et al., 2006). At Sajama, Hardy et al. (2003) show that a substantial fraction of the snow falling at the drill site is lost due to wind scour and sublimation. Sites, such as Illimani, on the other hand are different. First, precipitation is distributed over about 9 months of the year. Second, the accumulation is higher (0.58 m w.eq./year. i.e. around 1.6 mm w.eq./day) and, although the sublimation rate can reach about 1 mm w.eq./day during the dry season (Wagnon et al., 2003), this process only extends over a short period (Bonnaveira, 2004). Moreover, Bonnaveira (2004) showed that (i) wind-driven snow transport is relatively reduced and (ii) precipitation and ablation seasons are relatively distinct so that the annual signal is largely preserved. The only time window that is potentially missing in the ice core record is the end of the rainy season. This represents 10% of the annual accumulation (0.06 m w.eq. loss by ablation was measured between May and October 2002). In such a case, net accumulation could be discussed: in Fig. 3 we show the isotopic composition of Illimani ice. No correlation between δD and accumulation rate appears from 1880 AD, in both long-term trends and high frequency variations. If net accumulation rate was dominantly controlled by precipitation, we would expect a significant negative covariation between both parameters (see Section 3.4.). Thus net accumulation depends on numerous parameters and its interpretation is very difficult and site dependent.

3.3. How do post-deposition processes affect chemical and water stable isotope records?

An underlying uncertainty is the representativeness of the regional climate by an ice core of about 100 mm diameter extracted from a glacier that has been chosen based on its physical characteristics. Indeed, some local parameters, like wind exposure or surface slope, may affect the accumulation/erosion processes and thus contribute to variations in the net-accumulation and proxy reconstructions. The formation of "sastrugi" (ridges formed by wind erosion and redeposition of fresh snow) is an appropriate example. The first step in understanding those post-deposition processes is to check the reproducibility of proxies through comparison with other shallow cores extracted adjacent to the principal coring site. For most of the drilling sites, such a spatial exploration has been carried out.

Most Andean sites undergo annual or seasonal surface temperatures close to 0 °C. Here we discuss the two contrasting sites of Cerro Tapado and Illimani where on-site surveys have been carried out. Based on observations from Chimborazo in 2000, we also introduce the influence of volcanic eruptions on snow chemistry.

Surface snow experiments performed on Cerro Tapado during the dry season show that the chemical composition is affected by strong sublimation (1.9 mm w.eq./day), which leads to a concentration of conservative chemical species (Ginot et al., 2001). In arid regions with long dry seasons, dry deposition also plays an important role in surface snow composition. However, if these processes are sufficiently understood for a specific site, it is possible to quantify their impact by estimating the ice volume lost due to sublimation and thus to reconstruct the complete original mass balance parameters (Ginot et al., 2006). On-site experiments revealed that mass loss on Cerro Tapado is "evaporative" (with a liquid film at the surface), which induces a strong enrichment of the isotopic composition of the surface snow and thus impacts the isotopic record. However, there are two important points to note: (i) the diffusion in ice is very slow, so even if the sublimation impact is strong at the surface, it does not affect the whole record unless sublimation occurs throughout the year and (ii) sublimation is not a linear process and not constant throughout the year. Rather, it preferentially impacts a certain season, thereby introducing a seasonal bias to the isotopic records, which is potentially significant.

On Illimani, the snow composition was surveyed throughout an entire year by sampling 4 snow pits (Bonnaveira, 2004). At this site, it appears that the post-deposition effects are rather low and occur mostly due to the different seasonality of accumulation and sublimation as described above. In contrast to Cerro Tapado, the isotopic composition of the surface snow does not reveal any perturbation, suggesting that the sublimation is a real snow-gas transfer, i.e., a non-fractionating process.

On Chimborazo, the comparison of two shallow ice cores recovered in 1999 and 2000 from the same place revealed information on the influence of the Tungurahua volcanic eruption on chemical records in ice. In December 2000, the glacier surface on Chimborazo was completely covered by ash from the nearby Tungurahua eruption (Schotterer et al., 2003). The surface snow melting and water percolation induced by the ash deposition caused a preferential elution and re-localization of ionic species.

3.4. How to interpret the isotopic composition of the ice

The isotopic composition of Andean ice cores has been measured using the same methods as those used for polar ice cores. In Antarctica, a robust relationship exists between surface temperature and the isotopic composition of snow (Jouzel et al., 2003). However, in the first global analysis of water stable isotopes in precipitation (Dansgaard, 1964; review by Rozanski et al., 1993) it was noted that this temperature control breaks down for low latitudes, where cloud systems are dominantly of convective character and the influence of surface or near-surface temperature on the formation of precipitation becomes spurious. Spatially, a weak correlation between the isotopic composition and the amount of precipitation (amount effect, Dansgaard, 1964) has been found in modern precipitation data (IAEA/WMO, 2004). The atmospheric water cycle in the tropics is highly complex (e.g., Garreaud et al., 2009-this issue), and thus our current knowledge about fractionating versus non-fractionating recycling, transpiration, partial evaporation of condensates and equilibrium with surrounding vapour is limited. There is no single controlling factor that dominates the impact of climate on the water isotopes and, consequently, there is a need for a full understanding of local and regional dynamic factors controlling the water isotopes.

Recent studies have focused on exploring the different climate controls on δ using modelling studies, including water stable isotope fractionations (Vuille and Werner, 2005; Sturm et al., 2007a,b, for recent overviews) or based on direct modern observations (Hardy et al., 2003; Vimeux et al., 2005; Villacis et al., 2008). These studies conclude that the isotopic composition of Andean precipitation is mainly controlled by local precipitation and rainout upstream (in the Amazon basin and the tropical Atlantic Ocean) at the seasonal and inter-annual timescales. Further, they discuss the possible origin of the precipitation anomalies and so the original, but indirect, cause of the isotopic variability. Part of the precipitation variability originates from a change in location and intensity of the ascending convective branch of the Hadley–Walker cell over tropical South America, affecting the South American Summer monsoon variability. The Hadley–Walker cell motion is perturbed by Pacific SST anomalies and hence by El Niño-Southern Oscillation (Bradley et al., 2003; Vuille et al., 2003a,b; Vuille and Werner, 2005; Sturm et al., 2007b). However, Atlantic SST variations also have a large impact on the South American Monsoon. It could therefore, be difficult to separate the Atlantic from the Pacific SST impact when interpreting the isotopic composition of Andean ice, particularly without any further comparison with other climate archives. Future modelling studies should help to distinguish between these two impacts by separately forcing only the Atlantic or Pacific basins.

Thompson and Davis (2007) suggest also a major influence of local/condensation temperature on the isotopic composition of Andean precipitation, as it is the case for polar δ signals. Thompson et al. (2000) underline the importance of tropospheric temperature gradients on convection and the mean condensation level (MCL), although inter-annually, such an influence is of minor importance. At present, there is no observational or model based evidence for the importance of such a mechanism. It is also not clear if such variations in the MCL are dynamically linked to the local convection strength changes, and hence the precipitation intensity, while surface temperature does not change.

Nudged (paleo)-simulations with mesoscale models, which include a water stable isotopic module, could also help to further constrain the control of precipitation on the isotopic composition at different timescales. So far, only a 5 year simulation, forced with the ECHAM atmospheric model implemented with water isotopes, has been performed with the mesoscale REMOiso model (Sturm et al., 2007a,b). The results support our observations that the isotopic composition of precipitation is linked with the degree of rainout at seasonal and annual timescales. However, a better understanding of the influence of convection on isotopes is needed. A 1D vertical radiative-convective model, implemented with water stable isotopes, is being developed to explore the impact of convection on the isotopic composition of precipitation (S. Bony, pers. comm.).

We also suggest that detailed studies dealing with comparisons between the isotopic composition of shallow firn cores and precipitation over the last decades (back to 1970) with meteorological or reanalysis data, could improve our understanding of how the isotopic signal is preserved in the ice and how it is linked with meteorology and climate.

3.5. Trace species concentration records

The analysis of chemical trace species in ice may help identify atmospheric transport processes, the origin of air masses, and air pollution or environmental changes in the past. However, only a few studies have focused on Andean ice cores. Mineral dust is generally the dominant component of chemical impurities in Andean glaciers. It originates from nearby arid areas. This was demonstrated by trace element analyses in the Illimani (Correia et al., 2003) and the Sajama ice cores (Ferrari et al., 2001). Comparison of glaciochemical records from Chimborazo, Illimani and Cerro Tapado showed that the input of mineral dust, as indicated by calcium and magnesium, is strongest on Cerro Tapado, where net accumulation rates are lowest (Ginot et al., 2002).

The overwhelming mineral dust signal in Andean ice cores complicates the identification and contribution of other aerosol sources. Nevertheless, by investigating the elemental composition of ice deposited on Illimani during the wet season, Correia et al. (2003) observed high crustal enrichment factors. Mining-related species were more enriched at Illimani than Sajama, in particular in the beginning of the 20th century. Marked temporal trends from the onset of the 20th century to more recent years were identified for the concentrations of several trace species of anthropogenic origin, especially for Cu, As, Zn, Cd, Co, Ni and Cr. In contrast, P and K showed moderate average wet season enrichment factors, suggesting an impact of natural biogenic emissions from the Amazon Basin (Correia et al., 2003). Additionally, Ginot et al. (2002) detected elevated amounts of biomass emission tracers (ammonium, formate, acetate, oxalate, potassium) in the Illimani and Chimborazo cores. This was interpreted as a dominant contribution of precipitation originating from the Amazon Basin. Conversely, high concentrations of sea salt components and methanesulfonate (MSA) indicated prevailing Pacific moisture sources on Cerro Tapado.

Detailed glacio-chemical studies of Andean ice cores are still limited and published records cover no more than the last century.

4. Most relevant results and discussion

In this section, we focus on some important features of climate variability during the last 1000 years (Fig. 4), which have been addressed from the start of Andean ice core investigations.

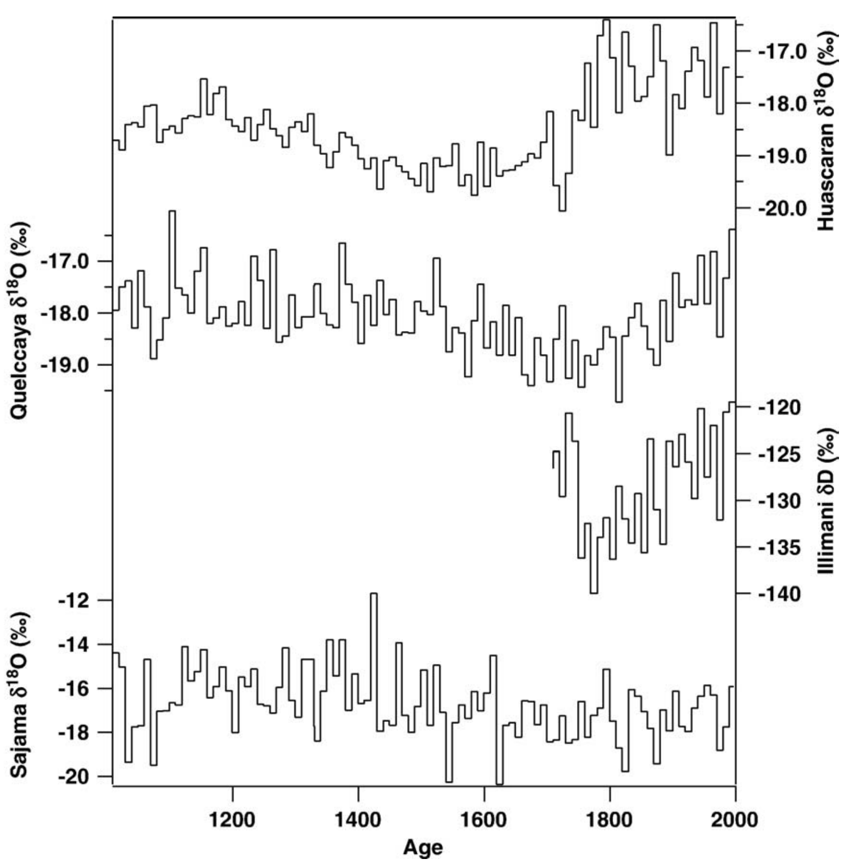

Fig. 4. 1000-year isotopic records from (top to bottom) Huascarán, Quelccaya, Illimani and Sajama with a 10-year average. The Illimani dating is too uncertain before AD 1700 to be plotted as a function of the age.

4.1. Is ENSO variability recorded in Andean ice cores?

ENSO signals have been detected in stable isotopic records ($\delta^{18}O$) from ice cores of Sajama (Bradley et al., 2003; Hardy et al., 2003), Quelccaya (Thompson et al., 1984; Diaz and Pulwarty, 1992), in the 1st EOF from the combined Huascarán, Quelccaya and Sajama records (Vuille et al., 2003b), and the Andean isotope index (Hoffmann et al., 2003). At all of these sites the stable isotopic composition tends to be enriched during El Niño events and depleted during La Niña events. On Sajama, an ENSO signal has also been found in the within-ice pollen concentration (Liu et al., 2007). On Illimani, an ENSO signal was found in the first principal component (PC) of ionic species (Knüsel et al., 2005), but was not detected in the stable isotope record.

It may seem counterintuitive that the robust regional interannual control on isotopic values in the tropical and subtropical Andes be driven by tropical Pacific SSTs since the moisture source for these ice core sites lies to the east in the South American continent and ultimately the tropical Atlantic. It is, however, consistent with the dominant influence of the tropical Pacific on interannual climate variability in this part of the world (Garreaud et al., 2003; 2009-this issue and references therein). Interannual variability of precipitation and large-scale atmospheric circulation in the tropical Andes is primarily a response to changes in the meridional baroclinicity over the Pacific Ocean in response to ENSO (Garreaud and Aceituno, 2001). Also, temperature follows closely tropical Pacific SSTs as the tropical troposphere warms up in response to increased latent heat release during El Niño events (Vuille et al., 2000a,b). Indeed, as shown by Vuille et al. (2003b), the large-scale dynamics of the atmospheric circulation associated with isotopic variability in tropical Andean ice cores is almost identical to the one described by Garreaud et al. (2003) from rainfall data from the Altiplano. This suggests that the stable isotopic composition is a faithful recorder of atmospheric circulation anomalies, including remote forcings from the tropical Pacific.

There are a number of reasons why the ENSO signal is more prominent in some ice core records than in others. First of all, detection of an ENSO signal requires very precise dating, given the inter- to multi-annual character of ENSO variability. An off-set of the ice record by only 1-2 years is sufficient to completely blur the ENSO signal, as ENSO tends to switch rapidly from the warm to the cold phase and vice-versa. Secondly, ENSO is phase-locked to the seasonal cycle and tends to peak at the end of the calendar year. Therefore, sites such as Sajama, where snowfall is limited to the period between November and February, are much more likely to record an ENSO signal than, for example, Illimani, which also receives significant amounts of snowfall early and late in the wet season, i.e., before or after the mature phase of ENSO. In addition, sites located in the western Cordillera (e.g., Sajama and Coropuna) are more sensitive to ENSO-induced circulation anomalies than sites located closer to the moisture source to the east (e.g., Illimani). As shown by Vuille and Keimig (2004) the most significant circulation changes (as indicated by the upper-air zonal wind component) develop over the Altiplano itself and, hence, do not affect sites to the east nearly as much as sites downstream of the circulation anomaly farther west. Finally, it is important to recognize that the ENSO impact on Andean climate is by no means perfectly linear. Precipitation anomalies on the Altiplano, for example, are highly sensitive to the exact location and intensity of the zonal wind anomalies, which in turn result from changes in the meridional baroclinicity between tropical and subtropical latitudes (Garreaud and Aceituno, 2001). Each ENSO event has its own flavour and the individual spatial pattern of the SST anomalies in the tropical Pacific will result in an individual anomalous location of the zonal wind anomalies over the Altiplano. This explains, for example, why the 1972/73 El Niño event was wet and the 1988/89 La Niña phase was dry in the central Andes (Garreaud and Aceituno, 2001). Such breakdowns in the ENSO-climate relationship are also likely to be visible in the isotopic record.

4.2. Is there a LIA signature in Andean ice cores?

In the north Atlantic, Europe and Greenland, the Little Ice Age (LIA) represents a cold period from the 15th to the end of 19th century. The geographical extent and nature of this anomaly is still debated. In the Andes, records of LIA imprints are scarce (Thompson et al., 1986; Rabatel et al., 2005, 2006; Solomina et al., 2007; Jomelli et al., 2008). The isotopic composition of Andean glaciers shows a significant decrease in $\delta^{18}O$ (~0.5–1‰), which lasted for several decades (see Jomelli et al., 2009-this issue). The $\delta^{18}O$ depletion begins earlier, around AD 1600 at the Quelccaya and Huascarán sites, whereas it begins at around AD 1650 on Illimani (Figs. 4 and 5). This isotopically depleted period lasts until around AD 1780 (Ramirez et al., 2003; Thompson et al., 2006a). For example, in the Quelccaya ice core the mean oxygen-18 isotopic composition is −17.90‰ between AD 1450–1600, −18.77‰ between AD 1600–1780, and −17.96‰ between 1800–1950 (with a similar standard deviation of about 1.6‰ for the three periods). This isotopic depletion, combined with dust depletion on Huascarán, suggests that this period is characterized by both cooler and moister conditions in the high Andes. This result might reflect an intensification of the South American summer monsoon with a reorganization of the atmospheric circulation and convective activity upstream the Andean summits, along air mass trajectories. A detailed comparison between ice core results and glacier advances may help to better describe and understand regional climate during the LIA (Jomelli et al., 2009-this issue).

4.3. The last century: a common decadal variability across the Andes

Over the last 100 years, four Andean ice cores (Huascarán, Quelccaya, Illimani and Sajama) show common trends in decadal variability, which allows the construction of a robust Andean Isotope Index (AII, Hoffmann et al., 2003). The AII is defined as the arithmetic mean of the four isotopic signals, shifted by two years compared with the original timescales in order to best match the isotopic composition of precipitation as simulated by the atmospheric general circulation model ECHAM-4 (Fig. 6). The comparison of the AII with the temporal evolution of the

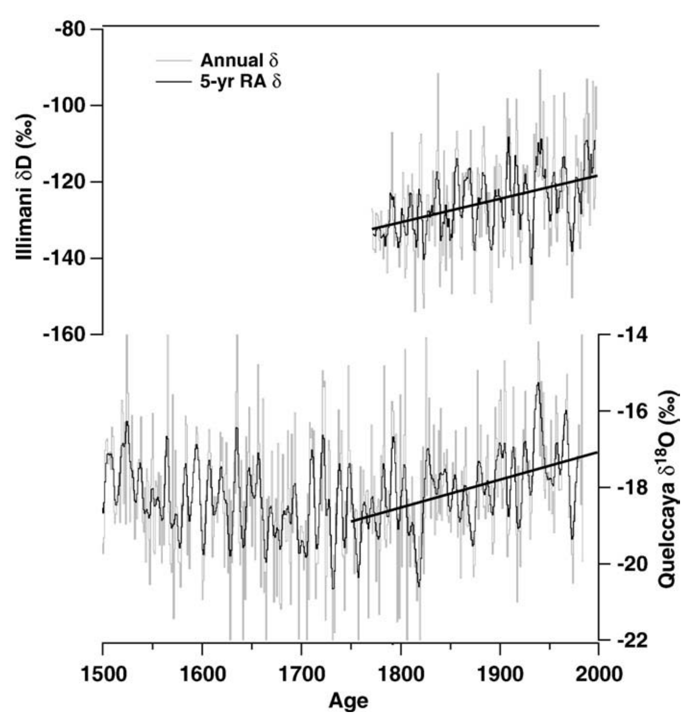

Fig. 5. Annual (grey line) and 5-year running average (black line) isotopic records from Illimani and Quelccaya. The linear trends since AD 1750 are shown.

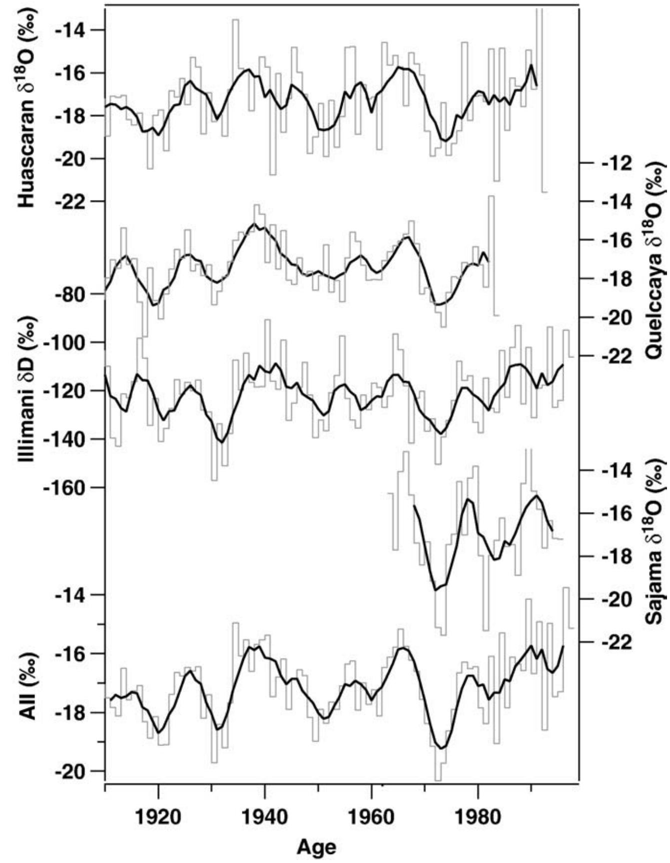

Fig. 6. Isotopic composition of ice at (top to bottom) Huascarán, Quelccaya, Illimani and Sajama at annual resolution (thin line) and with a 5-year running average (thick line) as used to construct the Andean Isotopic Index (Hoffmann et al., 2003). The latter is defined as the arithmetic mean of the four records and is shifted by +2 years to offer the best correlation with the modelled ECHAM Amazon oxygen-18 record over this period (see Hoffmann et al., 2003 for details).

leading mode of global precipitation (which explains 10% of the variability in the tropics) provides clear evidence for the influence of regional convective precipitation on δ. Comparison of the AII with the recent temperature evolution in the Andes (Vuille and Bradley, 2000) shows no correlation between δ and local temperature from 1940 to the mid-1970's. The AII shows a decreasing trend until 1953 and then a significant increase to a maximum in 1968, followed by a sudden drop until 1975. In contrast, the temperature clearly decreases from 1940 to 1948, remains stable until 1955, increases until 1960 and again remains stable until the mid 1970's. From 1975 onward, the AII and temperature show a common increase, but with a slope of 6.2‰/°C that cannot be explained by our current understanding of the stable water isotope–temperature relationship. However, in the mid-1970's, a large-scale ocean-atmospheric reorganization took place in the tropical Pacific, which affected both temperature and precipitation variability in South America until 2000 (Garreaud et al., 2009-this issue). At the decadal timescale, the increasing trend in temperature starts in 1950. This trend is absent in the AII (Fig. 7). We note that, while water isotopes do not record this temperature increase, it is well recorded in the Illimani borehole temperatures above ~40 m depth (which corresponds to an age of about 1950).

Furthermore, the comparison of the AII with SSTs from the central equatorial Pacific shows that, on interannual-decadal timescales, precipitation and temperature act in concert between the warm/dry mode (El Niño) and the cold/wet mode (La Niña) to produce the Andean isotopic signal (Hoffmann et al., 2003). Hence, as air temperature and δ are both closely tied to tropical Pacific SSTs, they are at times significantly correlated with one another, although there seems to be no direct cause-effect relationship between the two variables (Bradley et al., 2003; Hoffman et al., 2003; Vuille et al. 2003a,b).

4.4. The last 250 years: a common isotopic feature?

The Quelccaya $\delta^{18}O$ and the Illimani δD record exhibit a significant linear increase from about AD 1750 to present-day, with a slope of 0.7‰/100 years and 6‰/100 years, respectively (hence a total increase of 1.8‰ and 15‰ respectively since AD 1750; Fig. 5). This trend does not appear in the Sajama isotopic records (Thompson et al., 2006a). On Huascarán, an abrupt $\delta^{18}O$ increase occurs at the end of the LIA but no enrichment can be seen over the last 200 years (Thompson et al., 2006a). These discrepancies raise the questions, why the records are so different over the last 250 years and whether there is any relationship between this trend and global warming. Such

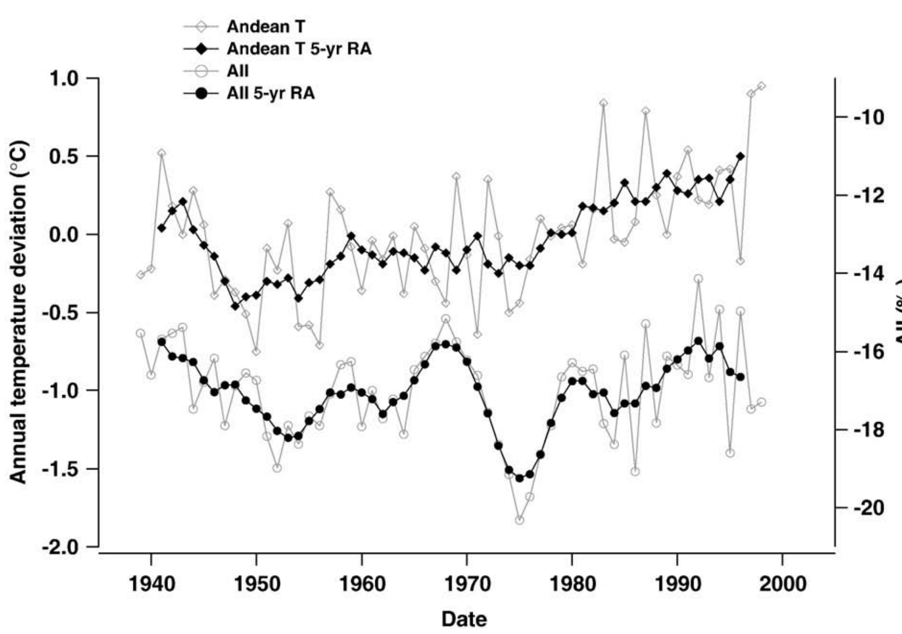

Fig. 7. Comparison between the Andean temperature (deviations from the 1961–1990 average in tropical Andes 1°N–23°S) from Vuille and Bradley (2000), and the Andean Isotopic Index (AII) from Hoffmann et al. (2003).

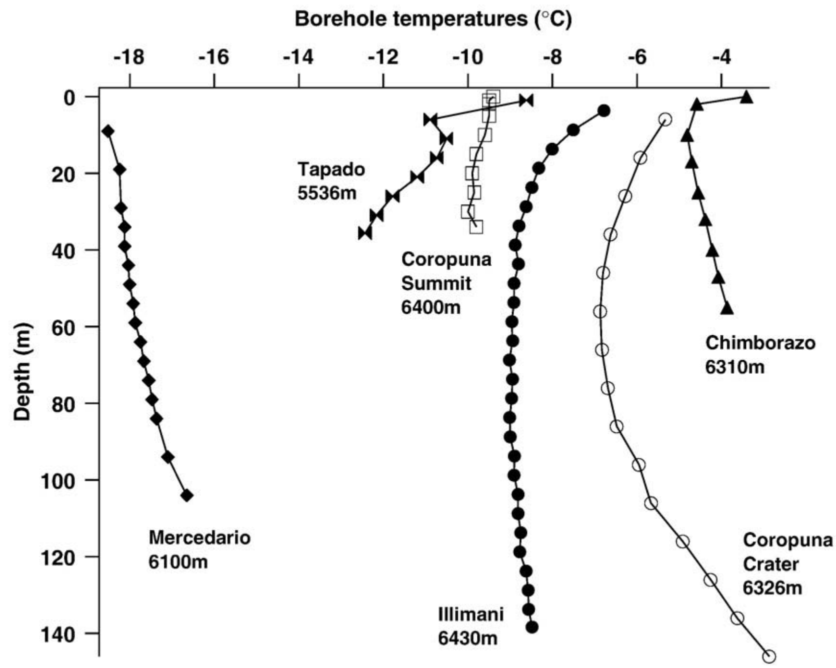

Fig. 8. Borehole temperature profiles from Mercedario, Tapado, Coropuna, Illimani and Chimborazo sites from the surface to the bedrock.

a strong trend in the isotopic record can be found at no other time in the last 1000 years. The answers to these questions remain elusive.

Fig. 8 shows borehole temperature profiles that can be used to infer past climate changes in very high mountain glaciers and polar regions (Ritz, 1989). The increasing temperature observed in the lower part of the ice cores near bedrock is related to geothermal heat flux. The sharp increase observed in the upper part (up to 40 m depth) on Illimani, Coropuna and Tapado might be related to atmospheric warming during the last decades. However, it is worth noting that the $\delta^{18}O$ trend observed over the last 250 years at Illimani is not recorded by borehole temperature reconstructions, which start to increase only after 1965.

5. Conclusions and perspectives

It is worth noting that Andean ice cores have recorded well-known climate events and anomalies that occurred in the past 1000 years, such as anomalies associated with the Little Ice Age. Therefore, ice cores have the potential to contribute important information on mechanisms of global climate change and of tropical-high latitude teleconnections, and to provide targets for future paleoclimate model simulations over the last millennium.

In addition to providing a review of the main results emerging from Andean ice core studies in terms of climate, one of the goals of this paper is to answer (or to propose possible approaches to solve) some of the main questions regarding Andean ice cores: what are the potentials and limitations of Andean ice cores? Where are the major gaps in our understanding? What needs to be improved for a better incorporation of ice cores in a regional or global high-resolution climate reconstruction? What experiments/observational studies do we need to improve calibration methods? Are there new perspectives for future isotope tracer modelling on the horizon?

We describe the unique potential of Andean ice cores regarding their use in regional climate reconstructions over the last 1000 years. We also mention the two main limitations, (i) uncertainties regarding the climatic interpretation of physico-chemical proxies in the ice (in particular regarding water stable isotopes) and (ii) the poor dating when seasonal cycles are no longer resolved. We list some potential directions for future research to help addressing these problems (long past simulations with mesoscale models including water stable isotopes, detailed studies aiming at comparing the isotopic composition of firn cores with the isotopic composition of precipitation over the same period, a new dating technique with ^{14}C, development of a reliable volcanic chronology).

We also show that most of the climate information over the last 1000 years inferred from Andean ice cores is derived from the isotopic composition of the ice and, therefore related to the atmospheric water cycle. Other proxies have not yet been fully explored. However, developments are being made in the evaluation of further parameters related to accumulation rates and chemical composition (e.g., $_{nss}K$; Kaspari et al., 2007). Merging all these parameters into a multi-proxy data set is important to advance the paleoclimatic value of Andean ice cores. This is imperative not only for single-parameter climate reconstructions (e.g., precipitation or temperature), but ultimately also for large-scale environmental reconstructions (e.g., fire history or deforestation in the Amazon basin).

Finally, two questions remain: are there key sites for future drilling? Do we need additional Andean ice cores? The northern part of the Andes between Ecuador and Bolivia, which receives moisture from the Atlantic Ocean and recycled moisture from the Amazon basin, has been the target of many studies over the past decades. Most of the highest glaciers suitable for ice core investigations have been examined. To the north of Ecuador, in Colombia and Mexico, some high volcanoes have iced areas that are potentially suitable for further studies. Between southern Bolivia and about 28°S in Chile/Argentina, the highest summits of the arid diagonal are ice-free. To the south, near 30°S, the highest peaks have only small iced areas that are characterized by strong ablation processes, in particular, sublimation. However, even if continuous climate reconstructions are not possible from this material, the preserved ice layers could still provide important information on different glaciation stages and their chronology. The southern part of the Andes, including the Patagonian icefields and "Tierra del Fuego", presents a real challenge in the recovery of an ice core, as a consequence of execrable weather conditions and very few suitable sites. In this area, the site of San Valentin seems to be the best place. First results from a recently recovered ice core are very promising (Vimeux et al., 2008).

Acknowledgements

We deeply thank R. Villalba and M. Grosjean for the organization of the fruitful PAGES meeting at Malargüe in October 2006 that initiated this work. We thank Karl Kreutz and an anonymous reviewer for fruitful comments. MV was partially funded by NSF EAR-0519415. Part of the work done by FV, PG and GH was funded by IRD, the Programme National d'Etude de la Dynamique du Climat (PNEDC-Amancay) and the Programme Les Enveloppes Fluides et l'Environnement (LEFE-Amancay 2).

References

Aristarain, A.J., Delmas, R.J., 1993. Firn-core study from the southern Patagonia ice cap, South America. J. Glaciol 39 (132), 249–254.
Bolius, D., Schwikowski, M., Jenk, T., Gäggeler, H.W., Casassa, G., 2006. A first shallow firn core record from Glaciar La Ollada on Cerro Mercedario in the Central Argentinean Andes. Ann. Glaciol. 43, 14–22.
Bonnaveira, H., 2004. Etude des phénomènes de dépôt et post-dépôt de la neige andine sur un site tropical d'altitude (Illimani-Bolivie-6340 m) en vue de l'interprétation d'une carotte de glace. Ph.D. Thesis, Université Joseph Fourier. Grenoble, France.
Bradley, R.S., Vuille, M., Hardy, D., Thompson, L.G., 2003. Low latitude ice cores record Pacific sea surface temperatures. Geophys. Res. Lett. 30 (4), 1174. doi:10.1029/2002GL016546.
Casassa, G., Espizua, L.E., Francou, B., Ribstein, P., Ames, A., Alean, J., 1998. Glaciers in South America. In: Haeberli, W., Hoelzle, M., Suter, S. (Eds.), Into the second century of world-wide glacier monitoring: prospects and strategies. A contribution to the International Hydrological Programme (IHP) and the Global Environment Monitoring System (GEMS). UNESCO, Paris.
Correia, A., Freydier, R., Delmas, R.J., Simões, J.C., Taupin, J.-D., Dupré, B., Artaxo, P., 2003. Trace elements in South America aerosol during 20th century inferred from a Nevado Illimani ice core, Eastern Bolivian Andes (6350 m a.s.l.). Atm. Chem. Phys. 3, 2143–2177.
Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16 (4), 436–468.
De Angelis, M., Simões, J.C., Bonnaveira, H., Taupin, J.D., Delmas, R.J., 2003. Volcanic eruptions recorded in the Illimani ice core (Bolivia): 1918–1998 and Tambora periods. Atm. Chem. Phys. 3, 1725–1741.
Diaz, H., Pulwarty, R.S., 1992. A Comparison of Southern Oscillation and El Niño signals in the tropics. In: Diaz, H.F., Markgraf, V. (Eds.), El Niño. Historical and paleoclimatic aspects of the Southern Oscillation. Cambridge University Press, pp. 175–192.
EPICA community members, 2004. Eight glacial cycles from an Antarctic ice core. Nature 429, 623–628.
Ferrari, C.P., Clotteau, T., Thompson, L.G., Barbante, C., Cozzi, G., Cescon, P., Hong, S., Maurice-Bourgoin, L., Francou, B., Boutron, C.F., 2001. Heavy metals in ancient tropical ice: initial results. Atm. Env. 35, 5809–5815.
Francou, B., Vuille, M., Wagnon, P., Mendoza, J., Sicart, J.E., 2003. Tropical climate change recorded by a glacier in the central Andes during the last decades of the 20th century: Chacaltaya, Bolivia, 16°S.J. Geophys. Res. 108 (D5), 4154. doi:10.1029/2002JD002959.
Garcia, M., Villalba, F., Araguas-Araguas, L., Rozanski, K., 1998. The role of atmospheric circulation patterns in controlling the regional distribution of stable isotope contents in precipitation: preliminary results from two transects in the Ecuadorian Andes. Isotope Techniques in the Study of Environmental Change. Proc. Series, International Atomic Energy Agency, Vienna.
Garreaud, R., Aceituno, P., 2001. Interannual rainfall variability over the South American Altiplano. J. Climate 14, 2779–2789.
Garreaud, R., Vuille, M., Clement, A., 2003. The climate of the Altiplano: observed current conditions and mechanisms of past changes. Palaeogeogr. Palaeoclimatol. Palaeoecol. 194, 5–22.
Garreaud, R., Vuille, M., Compagnucci, A., Marengo, J., 2009. Present-day South American Climate. Palaeogeogr. Palaeoclimatol. Palaeoecol. 281, 180–191 (this issue).
Ginot, P., Kull, C., Schwikowski, M., Schotterer, U., Gäggeler, H.W., 2001. Effects of post-depositional processes on snow composition of a subtropical glacier (Cerro Tapado, Chilean Andes). J. Geophys. Res 106 (D23), 32375–32386.
Ginot, P., Schwikowski, M., Schotterer, U., Gäggeler, H.W., Gallaire, R., Pouyaud, B., 2002. Potential for climate variability reconstruction from Andean glaciochemical records. Ann. Glaciol. 35, 443–450.
Ginot, P., Kull, C., Schotterer, U., Schwikowski, M., Gäggeler, H.W., 2006. Glacier mass balance reconstruction by sublimation induced enrichment of chemical species on Cerro Tapado (Chilean Andes). Clim. Past 2, 21–30.
Hammer, C.U., 1980. Acidity of polar ice cores in relation to absolute dating, past volcanism, and radioechos. J. Glaciol 25 (93), 359–372.
Hardy, D.R., Vuille, M., Bradley, R.S., 2003. Variability of snow accumulation and isotopic composition on Nevado Sajama, Bolivia. J. Geophys. Res. 108 (D22). doi:10.1029/2003JD003623.
Henderson, K.A., Thompson, L.G., Lin, P.N., 1999. Recording of El Niño in ice core $\delta^{18}O$ records from Nevado Huascarán, Peru. J. Geophys. Res 104 (D24), 31053–31065.
Hoffmann, G., Ramirez, E., Taupin, J.D., Francou, B., Ribstein, P., Delmas, R., Dürr, H., Gallaire, R., Simões, J., Schotterer, U., Stievenard, M., Werner, M., 2003. Coherent isotope history of Andean ice cores over the last century. Geophys. Res. Lett. 30 (4), 1179. doi:10.1029/2002GL014870.
IAEA/WMO, 2004. Isotope hydrology information system. The ISOHIS Database. IAEA, Vienna. http://isohis.iaea.org.
Jenk, T.M., Szidat, S., Schwikowski, M., Gäggeler, H.W., Bolius, D., Wacker, L., Synal, H.A., Saurer, M., 2007. Microgram level radiocarbon (^{14}C) determination on carbonaceous particles in ice. Nucl. Instr. Meth. Phys. Res. B. 259, 518–525.
Jomelli, V., Favier, V., Rabatel, A., Brunstein, D., Hoffmann, G., Francou, B. 2009. Fluctuations of Glaciers in the tropical andes over the last millennium and paleoclimatic implications: a review. Palaeogeogr. Palaeoclimatol. Palaeoecol. 281, 269–282 (this issue).
Jomelli, V., Grancher, D., Brunstein, D., Solomina, O., 2008. Recalibration of the yellow Rhizocarpon growth curve in the Cordillera Blanca (Peru) and implications for LIA chronology. Geomorphology 93, 201–212.
Jouzel, J., Vimeux, F., Caillon, N., Delaygue, G., Hoffmann, G., Masson-Delmotte, V., Parrenin, F., 2003. Magnitude of isotope/temperature scaling for interpretation of central Antarctic ice cores. J. Geophys. Res. 108. doi:10.1029/2002JD002677.
Kaspari, S., Mayewski, P., Kang, S., Sneed, S., Hou, S., Hooke, R., Kreutz, K., Introne, D., Handley, M., Maasch, K., Qin, D., Ren, J., 2007. Reduction in northward incursions of the South Asian monsoon since ~1400 AD inferred from a Mt. Everest ice core. Geophys. Res. Lett. 34, L16701. doi:10.1029/2007GL030440.
Knüsel, S., Ginot, P., Schotterer, U., Schwikowski, M., Gaeggeler, H.W., Francou, B., Simões, J.C., Petit, J.R., Taupin, J.D., 2003. Dating of two nearby ice cores from the Illimani, Bolivia. J. Geophys. Res. 108 (D6), 4181.
Knüsel, S., Brütsch, S., Henderson, K., Palmer, A.S., Schwikowski, M., 2005. ENSO signals of the 20th century in an ice core from Nevado Illimani, Bolivia. J. Geophys. Res. 110, D01102. doi:10.1029/2004JD005420.
Liu, K.-B., Reese, C.A., Thompson, L.G., 2007. A potential pollen proxy for ENSO derived from the Sajama ice core. Geophys. Res. Lett. 34, L09504. doi:10.1029/2006GL029018.
Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., Wanner, H., 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303, 1499–1503.
Mann, M.E., Bradley, R.S., Hughes, M.K., 1999. Northern hemisphere temperatures during the past Millenium: inferences, uncertainties and limitations. Geophys. Res. Lett. 26 (6), 759–762.
Mann, M.E., Jones, P.D., 2003. Global surface temperatures over the past two millennia. Geophys. Res. Lett. 30, 1820.
Matsuoka, K., Naruse, R., 1999. Mass balance features derived from a firn core at Hielo Patagonico Norte, South America. Arc. Antarct. Alp. Res 31 (4), 333–340.
Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., Karlen, W., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433, 613–617.
National Research Council Report, 2006. Surface temperature reconstructions for the last 2000 years. The National Academies Press, Washington D.C.
Nye, J.F., 1963. Correction factor for accumulation measured by the thickness of the annual layers in an ice sheet. J. Glaciol. 4, 785–788.
Rabatel, A., Jomelli, V., Francou, B., Naveau, P., Grancher, D., 2005. Dating Little Ice Age in the tropics from the moraines of Charquini glaciers (Andes of Bolivia, 16°S). CRAS Géosciences 337, 1311–1322.
Rabatel, A., Machaca, A., Francou, B., Jomelli, V., 2006. Glacier recession on Cerro Charquini (Bolivia, 16°S) since the maximum of the Little Ice Age (17th Century). J. Glaciol 52 (176), 110–118.
Ramirez, E., Hoffmann, G., Taupin, J.D., Francou, B., Ribstein, P., Caillon, N., Ferron, F.A., Landais, A., Petit, J.R., Pouyaud, B., Schotterer, U., Simões, J.C., Stievenard, M., 2003. A new Andean deep ice core from Nevado Illimani (6350 m), Bolivia. Earth Planet. Sci. Lett. 212, 337–350.
Ramirez, E., 2003. Interprétation de la variabilité climatique enregistrée dans les carottes de glace à partir des isotopes stables de l'eau: cas des Andes tropicales. Ph.D. Thesis, Université Paris 6- Pierre et Marie Curie, France.
Ritz, C., 1989. Interpretation of the temperature profile measured at Vostok, East Antarctica. Ann. Glaciol. 12, 138–144.
Rozanski, K., Araguas-Araguas, L., Gonfiantini, R., 1993. Isotopic patterns in modern global precipitation. In: Swart, P.K., Lohmann, K.C., MacKenzie, J., Savin, S. (Eds.), Climate Change in Continental Isotopic Records. AGU Geophys. Monogr. Ser., vol. 78, pp. 1–37.
Schotterer, U., Grosjean, M., Stichler, W., Ginot, P., Kull, C., Bonnaveira, H., Francou, B., Gäggeler, H.W., Gallaire, R., Hoffmann, G., Pouyaud, B., Ramirez, E., Schwikowski, M., Taupin, J.D., 2003. Glaciers and climate in the Andes between the Equator and 30°S: what is recorded under extreme environmental conditions? Clim. Change 59, 157–175.
Schwikowski, M., Brütsch, S., Casassa, G., Rivera, A., 2006. A potential high-elevation ice core site at the Southern Patagonian Icefield. Ann. Glaciol. 43, 8–13.
Shiraiwa, T., Kohshima, S., Uemura, R., Yoshida, N., Matoba, S., Uetake, J., Godoi, M.A., 2002. High net accumulation rates at Campo de Hielo Patagonico Sur, South America, revealed by analysis of a 45.97 m long ice core. Ann. Glaciol. 35, 84–90.
Solomina, O., Jomelli, V., Kaser, G., Ames, A., Berger, B., Pouyaud, B., 2007. Lichenometry in the Cordillera Blanca, Peru: "Little Ice Age" moraine chronology. Glob. Planet. Change 59 (1-4), 225–235.
Stichler, W., Schotterer, U., Fröhlich, K., Ginot, P., Kull, C., Gäggeler, H.W., Pouyaud, B., 2001. The influence of sublimation on stable isotope records recovered from high altitude glaciers in the tropical Andes. J. Geophys. Res. 106 (D19), 22613–22621.
Sturm, K., Hoffmann, G., Langmann, B., 2007a. Climatology of stable water isotopes in South America: comparing general to regional circulation models. J. Clim. 20, 3730–3750. doi:10.1175/JCLI4194.1.
Sturm, K., Vimeux, F., Krinner, G., 2007b. Intra-seasonal variability in South America recorded in stable water isotopes. J. Geophys. Res. 112, D20118. doi:10.1029/2006JD008298.
Thompson, L.G., Mosley-Thompson, E., Arnao, B.M., 1984. El Niño-Southern Oscillation events recorded in the stratigraphy of the tropical Quelccaya ice cap, Peru. Science 226, 50–52.

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

Thompson, L.G., Mosley-Thompson, E., Dansgaard, W., Grootes, P.M., 1986. The Little Ice Age as recorded in the stratigraphy of the tropical Quelccaya ice cap. Science 234, 361–364.

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

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

Thompson, L.G., Mosley-Thompson, E., Henderson, K.A., 2000. Ice core paleoclimate records in tropical South America since the Last Glacial Maximum. J. Quat. Sci. 15 (4), 377–394.

Thompson, L.G., Mosley-Thompson, E., Brecher, H.H., Davis, M.E., Leon, B., Les, D., Ping-Nan, L., Mashiotta, T.A., Mountain, K.R., 2006a. Abrupt tropical climate change: past and present. Proc. Natl. Acad. Sci. 103 (28), 10536–10543.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Buffen, A., 2006b. Glaciological evidence of temporal and spatial tropical climate variability. Amer. Geophys. Union Fall Meeting, San Francisco, GC23C-02.

Thompson, L.G., Davis, M.E., 2007. Ice core records, South America. In: Elias, S.E. (Ed.), Encyclopedia of Quaternary Science. Elsevier, Amsterdam, pp. 1233–1242.

Villacis M., Vimeux F., Taupin J-D., 2008. Analysis of the climate controls on the isotopic composition of precipitation (δ18O) at Nuevo Rocafuerte (74,5°W; 0,9°S; 250m) Ecuador, Compte Rendu de Géosciences 340, 1–9.

Vimeux, F., Gallaire, R., Bony, S., Hoffmann, G., Chiang, J., Fuertes, R., 2005. What are the climate controls on isotopic composition (δD) of precipitation in Zongo Valley (Bolivia)? Implications for the Illimani ice core interpretation. Earth Planet. Sci. Lett. 240, 205–220.

Vimeux F., de Angelis M., Ginot P., Magand O., Pouyaud B., Casassa G., Johnsen S., Falourd S., 2008. A promising location in Patagonia for paleoclimate and environmental reconstructions revealed by a shallow firn core from Monte San Valentin (Northern Patagonia Icefield, Chile), J. Geophys. Res. 113, D16118. doi:10.1029/2007JD009502.

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

Vuille, M., Bradley, R.S., Keimig, F., 2000a. Climate variability in the Andes of Ecuador and its relation to tropical Pacific and Atlantic sea surface temperatures anomalies. J. Climate 13, 2520–2535.

Vuille, M., Bradley, R.S., Keimig, F., 2000b. Interannual climate variability in the Central Andes and its relation to tropical Pacific and Atlantic forcing. J. Geophys. Res. 105, 12,447–12,460.

Vuille, M., Bradley, R.S., Werner, M., Healy, R., Keimig, F., 2003a. Modeling δ^{18}O in precipitation over the tropical Americas: Part I. Interannual variability and climatic controls. J. Geophys. Res. 108 (D6), 4174. doi:10.1029/2001JD002038.

Vuille, M., Bradley, R.S., Healy, R., Werner, M., Hardy, D.R., Thompson, L.G., Keimig, F., 2003b. Modeling δ^{18}O in precipitation over the tropical Americas, Part II, Simulation of the stable isotope signal in Andean ice cores. J. Geophys. Res. 108 (D6), 4175. doi:10.1029/2001JD002039.

Vuille, M., Keimig, F., 2004. Interannual variability of summertime convective cloudiness and precipitation in the central Andes derived from ISCCP-B3 data. J. Climate 17, 3334–3348.

Vuille, M., Werner, M., 2005. Stable isotopes in precipitation recording South American summer monsoon and ENSO variability: observations and model results. Clim. Dyn. 25, 401–413. doi:10.1007/s00382-005-0049-9.

Wagnon, P., Sicart, J.-E., Berthier, E., Chazarin, J.-P., 2003. Wintertime high-altitude surface energy balance of a Bolivian glacier, Illimani, 6340 m above sea level. J. Geophys. Res. 108 (D6), 4177. doi:10.1029/2002JD002088.

Williams, R.S., Ferrigno, J.G., (Eds.), 1998. Satellite image atlas of glaciers of the world; North America: U.S. Geological Survey Professional Paper 1386-J (Glaciers of North America), USGS, Washington.

Yamada, T., 1987. Glaciological characteristics revealed by 37.6-m deep ice core drilled at the accumulation area of San Rafael Glacier, the Northern Patagonian Icefield. Bull. Glacier Res. 4, 59–67.