CIRCULATION VARIABILITY REFLECTED IN ICE CORE AND LAKE RECORDS OF THE SOUTHERN TROPICAL ANDES

STEFAN HASTENRATH [1], DIERK POLZIN [1] and BERNARD FRANCOU [2]

[1] *Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, 1225 West Dayton Street, Madison, WI 53706, U.S.A.*
E-mail: slhasten@facstaff.wisc.edu

[2] *Institut de Recherche pour le Développement (IRD), Laboratoire de Glaciologie et de Géophysique de l'Environnement, Saint-Martin d'Hères, France*

Abstract. The circulation mechanisms of climate anomalies in the southern tropical Andes are of particular interest for the January–February core of the precipitation season. With this focus, we evaluate in context upper-air and surface analyses, water level measurements of Lake Titicaca, and records of net balance and δ^{18}O from ice cores. Precipitation is more abundant with enhanced and southward expanded easterlies through a deep layer of the troposphere over the southern tropical Andes. Concomitant with this is a southward displaced circulation system over the equatorial Atlantic, entailing reduced interhemispheric gradient of sea surface temperature (SST; cold/warm anomalies in the North/South), more southerly position of the surface wind confluence and Intertropical Convergence Zone, and thus more abundant rainfall in Northeast Brazil. Such ensemble of circulation departures in boreal winter is common to the high phase of the Southern Oscillation.

δ^{18}O in the ice cores from Peru's Quelccaya Icecap, as well as the cores from Sajama and Ilimani in Bolivia is more negative with more abundant precipitation, both in the same annual cycle and on interannual timescales. The large-scale circulation departures associated with the more negative δ^{18}O are in the sense as for anomalously abundant precipitation activity over the southern tropical Andes. The variability of δ^{18}O seasonally and interannually appears to be controlled mainly by the fate of the water vapor along its trajectory and over the Andes, rather than by the SST of the South Atlantic source region.

1. Introduction

A diversity of data sources, including upper-air analyses, surface climatological and hydrological series, along with ice core records, have progressively become available, and invite an actualistic evaluation in the context of climate dynamics. In particular, the ice cores taken in the southern tropical Andes, located in the transition from the tropical easterlies to the subtropical westerlies, sample a strategically important, climatically sensitive region.

The high mountain environment of the southern tropical Andes (Figure 1) experiences marked changes from year to year and on longer time scales. These have been themes of recent specialty symposia (Cadier et al., 1998; PAGES, 2001). A series of research papers over the past decades have recurrently addressed the circulation causes of anomalies in precipitation and the water level of Lake Titicaca

Climatic Change **64:** 361–375, 2004.

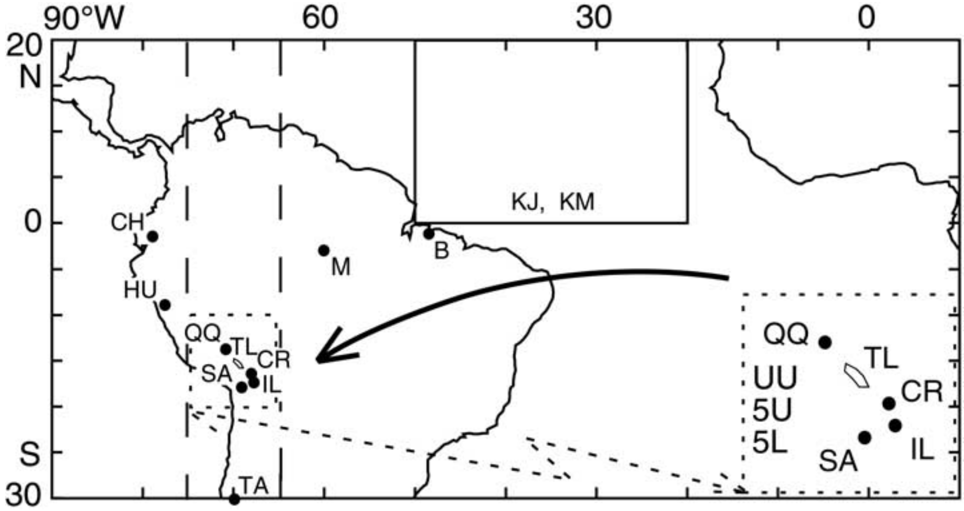

Figure 1. Orientation map. Dashed lines demarcate the meridional profiles in Figure 3, solid-line rectangle the domain in the Atlantic for which the SST indices KJ and KM were compiled, and dotted-line rectangle the domain of the indices of zonal wind UU, 5U, and LT. This rectangle is repeated at enlarged scale in lower right portion of the map. Solid curved arrow shows the direction of the lower-tropospheric water vapor transport. Dots indicate the sites of Chimborazo (CH), Huascarán (HU), Quelccaya (QQ), Lake Titicaca (TL), San Calixto (CR), Sajama (SA), Ilimani (IL), Cerro El Tapado (TA), Belém (B) and Manaus (M).

(Kessler, 1974, 1981, 1990; Jacobeit, 1991; Garreaud, 1999; Vuille, 1999; Vuille et al., 2000; Garreaud and Aceituno, 2001). It has also been recognized that the vast meridional chain of icecaps and glaciers holds promise for the extraction of ice cores for climate study (Thompson et al., 1984a). The first tropical ice cores were drilled on the Quelccaya Icecap of southern Peru a quarter-century ago (Thompson et al., 1979). The subsequent decade-long field effort culminated in the retrieval of deep cores with a record from AD 470 to 1984 (Thompson et al., 1984b, 1986). Since then, ice cores have been retrieved from Chimborazo in Ecuador, Huascarán in northern Peru (Thompson et al., 1995), Sajama (Thompson et al., 1998) and Ilimani in Bolivia (Ramirez et al., 2002), and Cerro El Tapado in northern Chile (Ginot et al., 2001). Regarding the exploration of the circulation mechanisms of regional climatic variability, new prospects have opened up with the recent release of the global upper-air dataset from the National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP-NCAR) 40-year Reanalysis (Kalnay et al., 1996).

With this background, the purpose of the present paper is to research the circulation mechanisms of climatic variability in the southern tropical Andes reflected in the water level of Lake Titicaca and in the ice core records of oxygen isotopes and net balance. Section 2 describes the data and analysis, Section 3 explores the large-scale circulation in relation to lake level, Section 4 examines the ice core records, and a synthesis is offered in the closing Section 5.

2. Data and Analysis

The data sources used in this study include global upper-air analyses, long-term surface ship observations, lake level measurements, raingauge series, and ice core records.

The National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., l996; Kistler et al., 2001) at a 2.5° latitude-longitude resolution was acquired for the years l958–1997. Data were processed into individual monthly mean fields. Of interest here is the wind at the levels 1000, 925, 850, 700, 600, 500, 300, 200, and 100 mb. For January–February the wind field was analyzed at the 500 mb level and along a meridional-vertical transect at 75–65° W. An index UU was compiled of the zonal wind speed in the domain 10–20° S, 75–65° W, 500–300 mb; an index 5U of the zonal wind in the domain 10–20° S, 75–65° W, at 500 mb; and an index 5L of the latitude position of the boundary between westerlies and easterlies at 75–65° W and 500 mb.

For the tropical Atlantic sector and the March–April core of the Northeast Brazil (Nordeste) rasiny season, two indices were available from earlier work (Hastenrath and Greischar, 1993; Hastenrath, 2000), namely, an index NB of Nordeste rainfall and an index LT of the latitude of the surface wind confluence at 40–20° W. From a dataset of sea surface temperature (SST) with a two degree square resolution prepared by Kaplan et al. (1998), the indices KJ for January–February and KM for March–April were compiled (domain 0–20° N, 50–20° W; see Figure 1). As in earlier work, the pressure difference Tahiti minus Darwin is taken as a measure of the phases of the Southern Oscillation (SO).

Records of water level of Lake Titicaca at Puno were available for the period from l915 onward. From the individual monthly values a series of an index TL was compiled, being the seasonal change of water level from December to March, indicative of the precipitation during the rainy season. Values are ascribed to the second of the two years (i.e., December 1961 to March 1962 is denoted as 1962). From this series the ten years of highest (HI = 1964, 66, 67, 80, 83, 87, 89, 90, 91, 92) and lowest (LO = 1960, 62, 63, 73, 74, 76, 79, 84, 85, 86) values of TL were identified.

The raingauge measurements at Observatorio San Calixto in La Paz began in 1898 and were available through 1968. The index CR represents June–May precipitation ascribed to the later year.

Ice core records of oxygen isotope ratios (δ^{18}O) and net balance are of particular interest. Ice core records were obtained from the website of the World Data Center for Paleoclimatology, Boulder, and NOAA Paeoclimatology Program: http://www.ngdc.noaa.gov. For Quelccaya, the name is ‘Quelccaya Ice Core Database’, and the suggested data citation ‘Thompson, L., 1992: Quelccaya Ice Core Database. IGBP PAGES/World data Center-A for Paleoclimatology Data Contribution Series #92–008, NOAA/NGDC Paleoclimatology Program, Boulder, Co., U.S.A.’. Ice core data were also retrieved from two journal publications on Quelccaya (Thompson et al., 1979, 1984b). For ‘Huascarán Ice Core Data’ the suggested data citation is ‘Thompson, L. G., 2001, Huascarán Ice Core Data, IGBP PAGES/World Data Center A for Paleoclimatology Data Contribution Series #2001–008, NOAA/NGDC Paleoclimatology Program, Boulder Co, U.S.A.’. From Edson Ramirez we obtained the δ^{18}O and net balance data of the Sajama and Ilimani ice cores, for the period 1947–1997 (Hoffmann et al., 2003). 1947–1998 records of net balance and deuterium are available for Chimborazo.

Records of oxygen isotope ratios (δ^{18}O) and rainfall for selected stations in the Amazon basin were obtained from the website of IAEA (2001) Isotope Hydrology Information System, the ISOHIS Database: http://isohis.iaea.org.

The NCEP-NCAR reanalysis serves to diagnose the large-scale upper-air circulation; compact indices describe surface conditions in the Atlantic sector; station data of isotopes in rainfall shed light on relationships prevailing in the Amazon lowlands; raingauge and lake records document the hydroclimatic conditions in the Andean highlands; and this ensemble of sources is used to evaluate the information in the tropical icecores. From the diverse observation periods of the various elements, two common base periods are used here. The time span 1958–1984 has complete records for the upper-air data, the five aforementioned ice core sites, the Titicaca water level, the SO index, and the Atlantic indices LT, NB, KJ and KM, although the San Calixto, La Paz, rainfall series (CR) is available only to 1968. The time span 1915–1957 has records complete for Titicaca, the ice core sites, SO, San Calixto (to 1968), KJ and KM (from 1917 onward), but no upper-air data.

3. Variability of Circulation and Lake Levels

The most essential circulation characteristics at the core of the precipitation season in the southern tropical Andes are captured by January–February maps of the mid-tropospheric wind field (Figure 2) and meridional-vertical cross sections of the zonal wind (Figure 3). The map of 500 mb flow (Figure 2a) shows at its northern and southern extremities the midlatitude westerlies, contrasting with easterlies in the tropical belt; over the southern tropical Andes the boundary between the easterly and westerly wind regimes being located near 21° S. Complementing Figure 2a, the cross section (Figure 3a) illustrates the strong equatorward slope of the anticyclonic axis of the boreal winter hemisphere, the deep easterlies in the tropics, and the margin of the austral summer hemisphere westerlies; with the southern tropical Andes being located near the southern margin of the tropical easterlies.

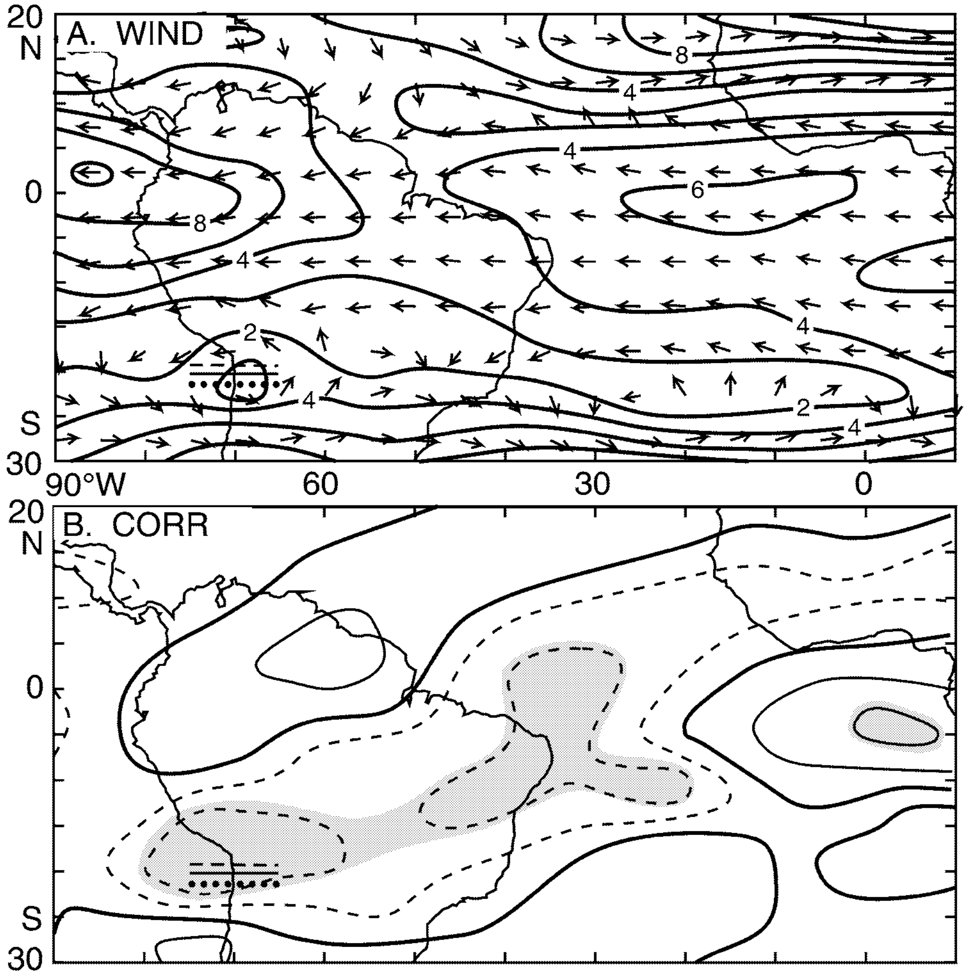

Figure 2. Maps of January–February wind at 500 mb during 1958–1984. (a) Mean, with arrows indicating wind direction and isotachs at spacing of 2 ms^{-1}. (b) Pattern of correlations of zonal wind component with TL, with spacing of 0.2 and dashed lines indicating negative values; shading represents 5% significance level.

The correlation patterns in the map of Figure 2b and the cross section of Figure 3b illustrate the association of the large-scale circulation with the variability of the seasonal change of water level of Lake Titicaca. The map Figure 2b shows stronger easterlies, and a more southerly location of the boundary between easterlies and westerlies, accompanying anomalously large seasonal rise of lake level. Complementing Figure 2b, the cross section Figure 3b also shows for the southern tropical Andes around 10–20° S strong negative correlations throughout the tropospheric column and especially in the upper troposphere, where they extend far northward. Figure 3b thus also indicates enhanced easterlies and a southward

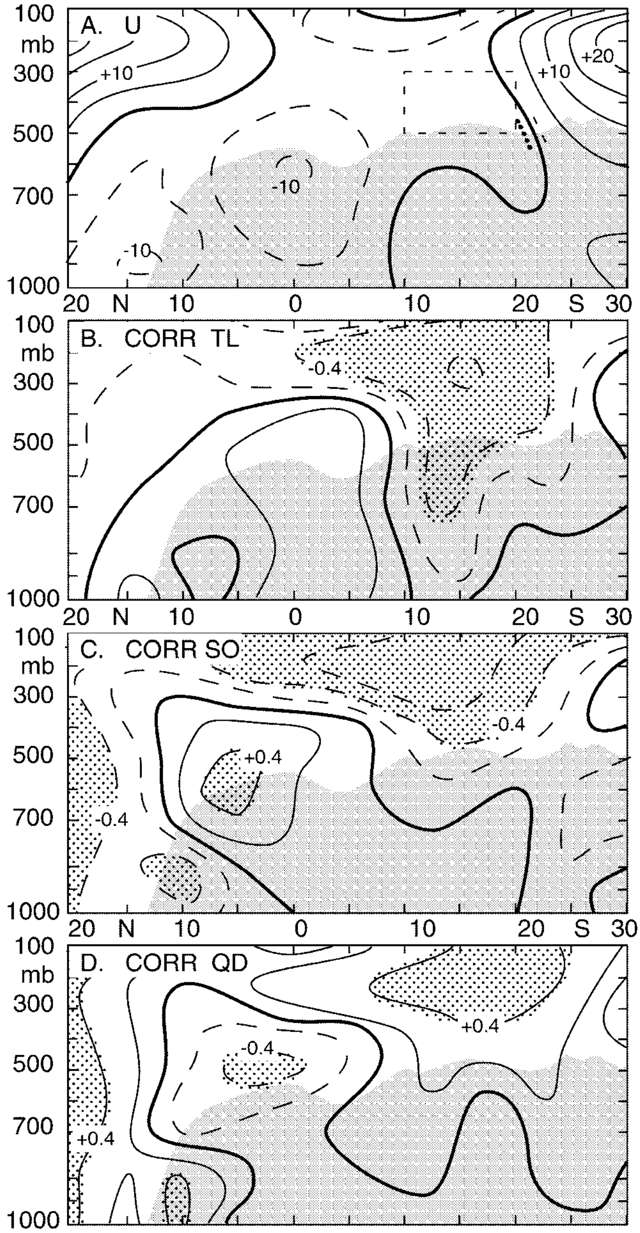

Figure 3. Meridional-vertical cross sections along 75–65° W for January–February 1958–1984. Shading indicates the surface topography of the Andes. (a) Mean zonal wind, with isotach spacing of 5 ms^{-1} and dashed lines indicating easterlies. The latitude position of the boundary between westerlies and easterlies at 500 mb and 75–65° W is indicated by dotted and dashed lines, respectively, for the ensembles of extremely high and low values of TL. Dotted-line rectangle shows domain of zonal wind index UU (ref. Table I). (b) Correlations of zonal wind versus TL, with isoline spacing of 0.2 and dashed lines indicating negative values. Dot raster shows significance at 5% level. (c) Correlations of zonal wind versus SO, with symbols as for (b). (d) Correlations of zonal wind versus QD, with symbols as for (b).

Table I

Matrix of correlation coefficients for 1958–1984 (in hundredths)

	TL	QA	QD	SA	SD	IA	ID	UU	5U	5L	SO	LT	NB	KJ
TL														
QA	+12													
QD	−58**	−02												
SA	+19	+48**	+07											
SD	−33	−17	+56**	−39*										
IA	−04	−22	+03	−38*	+38*									
ID	−38*	+16	+14	+15	+34	+09								
UU	−62**	+03	+47*	−15	+26	−15	+27							
5U	−43*	−02	+23	−01	+00	−04	+06	+72**						
5L	−32	+11	+15	−28	+28	+27	+32	+61**	+55**					
SO	+46*	+19	−41*	+06	+00	+28	−07	−64**	−30	−19				
LT	−36	−20	+41*	−32	+33	+21	+20	+56**	+40*	+47*	−55**			
NB	+23	+29	−31	+17	−22	+05	−12	−38*	−56**	−23	+45*	−59**		
KJ	−06	+15	+19	−14	+20	+28	+08	+41*	+31	+46*	−32	−58**	−19	
KM	−32	+07	+51**	−15	+29	+39*	+14	+60**	+29	+38*	−64**	−74**	−39*	+80**

* Significance at 5% level. ** Significance at 1% level. Indices are as follows: TL = December to March change of Lake Titicaca water level; QA = Quelccaya net balance, July to June; QD = Quelccaya δ^{18}O, July to June; SA = Sajama net balance, July to June; SD = Sajama δ^{18}O, July to June; IA = Ilimani net balance, July to June; ID = Ilimani δ^{18}O, July to June; UU = zonal wind in domain 10–20° S, 75–65° W, 500–300 mb, Jan–Feb; 5U = zonal wind in domain 10–20° S, 75–65° W, 500 mb, Jan-Feb; 5L = boundary between westerly and easterly wind at 75–65° W, 500 mb, Jan–Feb; S0 = Tahiti minus Darwin pressure difference, January–February; LT = latitude of surface wind confluence at 40–20° W, March–April; NB = rainfall in Northeast Brazil, March–April. KJ = SST in domain 0–20° N, 50–20° W, January–February; KM = SST in domain 0–20° N, 50–20° W, March–April

expansion of the easterly wind regime in years of anomalously large seasonal rise of lake level. Somewhat similar to Figure 3b, Figure 3c shows in the upper troposphere over the southern tropical Andes enhanced easterlies in the high phase of the SO. Figure 3d shall be discussed in Section 4 below.

The pictorial evidence in Figures 2b and 3b,c is complemented by the correlation matrix for the period 1958–1984 in Table I. For selected elements time series are also plotted in Figure 4. The strong positive correlation between TL and CR for 1915–1968 in Table II and Figures 4a,b indicates that the seasonal change in Lake Titicaca water level is a good measure of the regional precipitation conditions. Table I shows strong positive, mutual associations between lake level rise (TL), easterly wind (UU and 5U), southward extent of the easterlies (5L), and the high SO phase. UU may also be compared with TL and CR in Figures 4a,b,e.

In context this is broadly consistent with findings in earlier studies mentioned in the Introduction. Garreaud (1999) explains how enhanced upper-tropospheric easterlies, through vertical momentum exchange, stimulate the upslope flow of moisture from the lowlands on the Amazon side of the Andes, which serves to fuel the precipitation over the Altiplano. Also, the subtropical westerlies in the mid and upper troposphere are known to be weaker in the high SO phase.

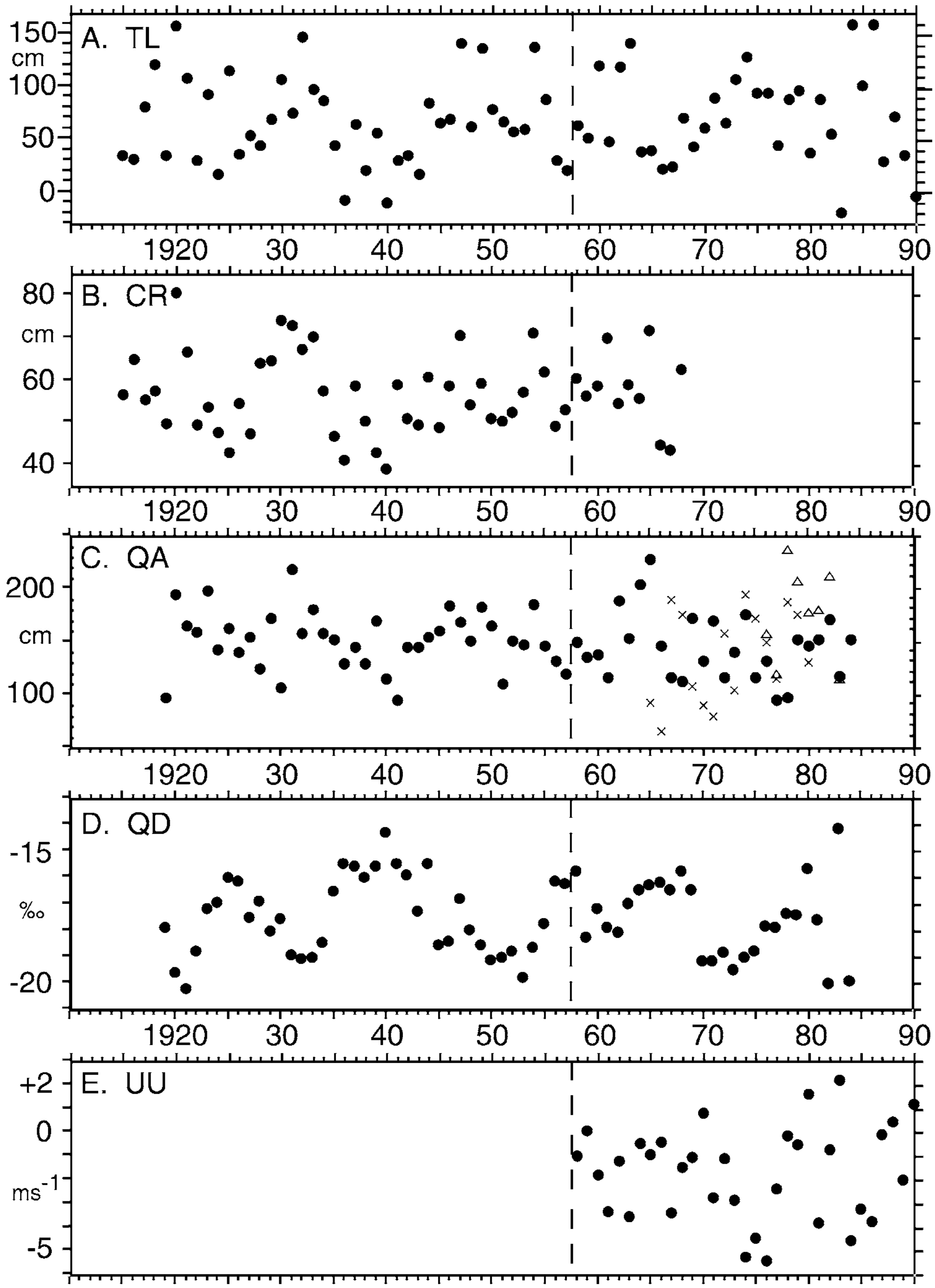

Figure 4. Time series plots of selected indices. (a) TL, December to March change in water level of Lake Titicaca, in cm; (b) CR June-May rainfall at San Calixto Observatory, La Paz, in cm; (c) QA, Quelccaya net balance, in cm of liquid water equivalent; dots denote values from icecore; for the period after 1964 crosses indicate values from crevasse wall, and for the period after 1974 triangles show values from snow pits; (d) QD, Quelccaya δ^{18}O values in per mil; (e) UU, 500–300 mb zonal wind, in ms^{-1}.

Table II
Matrix of correlation coefficients for 1915–1957

	TL	QA	QD	SD	ID	CR	SO	KJ
TL								
QA	+59**							
QD	−51**	−43**						
SD	−30	−14	+49**					
ID	−13	−25	+49**	+37*				
CR	+66**	+31	−57**	−50**	−16			
SO	+14	+13	−21	−23	−22	+15		
KJ	−45**	−29	+15	−17	+10	−23	−02	
KM	−35*	−26	+18	−29	+02	−15	−11	+85**

* Significance at 5% level. ** Significance at 1% level. Symbols as for Table I. 1915–1957 (except 1917–1984 for KJ and KM, and 1915–1968 for CR = rainfall at San Calixto (La Paz) Observatory, June–May)

Beyond the Andes, Table I contains the indices LT and NB from the tropical Atlantic sector. As shown in earlier work (Hastenrath and Greischar, 1993; Hastenrath, 2000), a southward displaced Atlantic near-equatorial wind confluence and Intertropical Convergence Zone (ITCZ) with the accompanying abundant Nordeste rainfall are a consequence of a steepened interhemispheric SST gradient in the tropical Atlantic (cold/warm in the North/South), which is largely controlled by the temperature variability in the tropical North Atlantic. This is reflected in Tables I and II, in particular the large negative correlations of KJ and KM with NB, and the positive correlation with LT. Correlations with the tropical South Atlantic (not shown here) are weak and positive with NB and TL. As apparent from Tables I and II, the correlations with NB, LT, and TL, tend to improve from January–February (KJ) to March–April (KM). The correlations with SO in Tables I and II are further consistent with earlier work (review in Hastenrath, 2000), which showed that late in the boreal winter half-year the near-equatorial wind confluence and associated ITCZ, the main rainbearing system for the Nordeste, tend to be displaced southward in the high SO phase.

Tables I and II also offer the large-scale circulation context for the cold anomalies in the tropical North Atlantic to accompany abundant precipitation in the Titicaca basin, as suggested by Mélice and Roucou (1998) and Baker et al. (2000) from data of the early to later part of the 20th century. Comparison of Tables II and I indicates that such relationship was stronger in the early than the later part of the record.

In synthesis from Figures 2 and 3 and Tables I and II, along with the earlier work, abundant precipitation at the core of the austral summer precipitation season in the southern tropical Andes is causally related to enhanced, and southward expanded, easterly flow through a deep layer of the troposphere, which favors the import of water vapor from the lowlands on the Amazon side (Garreaud, 1999) to fuel the precipitation activity. Such southward displacement of the wind regime in the realm of the southern tropical Andes is typically associated with likewise southward displaced circulation system in the tropical Atlantic sector: reduced interhemispheric meridional SST gradient (cold/warm anomaly in the North/South) entails southward displaced surface wind confluence and ITCZ, and hence anomalously abundant rainfall in Northeast Brazil. Such an ensemble of circulation departures over the southern tropical Andes as well as the equatorial Atlantic is during the boreal winter half-year common in the high SO phase.

Regarding the water vapor transport into the southern Amazon basin, recent studies (Rao et al., 1995; Curtis and Hastenrath, 1999) unambiguously identify a trajectory from the southern tropical Atlantic (Figure 1), although there seems to be some belief in a North Atlantic source region (Mélice and Roucou, 1998). More particularly, however, Garreaud (1999) points to the boundary layer over the lowlands on the Amazon side of the Andes as moisture source for the precipitation activity over the Altiplano.

4. Ice Cores

A quarter-century ago, the retrieval of the first tropical ice core from the Quelccaya Ice Cap in Peru (Thompson et al., 1979) led to the discovery of conditions contrastingly different from the pattern familiar from the polar regions: a seasonal spread in δ^{18}O values as large as the difference between ice age and modern conditions (and seasonal spread) in the polar ice cores; and the more negative values of δ^{18}O during the summer precipitation season. The latter peculiarity in particular was duly noted in later papers (Grootes et al., 1989; Thompson et al., 2000).

Given the marked negative association of precipitation and δ^{18}O in the annual cycle evidenced in the first shallow ice cores on Quelccaya (Thompson et al., 1979), it is interesting to compare the interannual variability of net balance and δ^{18}O in the later deep ice core. To that end, Tables I and II present, for the periods 1958–1984 and 1915–1957, correlations between QD and QA, and also with the precipitation indicators TL and CR. For the longer and earlier period 1915–1957 (Table II), a significant negative correlation is obtained between QD and QA, consistent with the findings of a quarter-century ago for the annual cycle relationship.

In contrast to Table II, however, for the shorter recent period 1958–1984 (Table I) the correlation between QD and QA is nil. This is all the more surprising in light of the highly significant negative correlations of QD with the precipitation indicators TL and CR from more distant locations for both periods (Tables I and II), and the highly significant positive correlation of the Quelccaya net balance QA with the regional precipitation indicator TL during 1915–1957 (Table II), although not during 1958-1984 (Table I). This raises the question of the quality of the QA record for the 1958–1984 period. In addition to the ice core record, published values (Thompson et al., 1984b) from pits and a crevasse are also plotted for part of the period. Figure 4c shows considerable differences between the three sets, and comparison with Figure 4a indicates a less good agreement of TL with the core than with the pit and crevasse values. This gives grounds for the conjecture that in the latter part of the Quelccaya ice core record QA was not well sampled, possibly due to spatial variability of net balance related to snow drift, wind scour, surface melt and sublimation, as well as ablation increasing in recent decades. Indeed, in addition to Quelccaya, the lack of correlation of net balance with δ^{18}O is also noted for Huascarán and Ilimani.

In contrast to QA, the series of QD has significant correlations not only with TL, but also with the large-scale circulation parameters SO, UU, and LT (Table I). In the same vein the cross-section Figure 3d, illustrating stronger easterlies over the southern tropical Andes with more negative QD, is consistent with Figure 3b showing greater seasonal rise of Lake Titicaca water level with stronger easterlies. Comparing QD with other ice cores, the δ^{18}O series of Sajama and Ilimani (Tables I and II) have positive correlations with the δ^{18}O of Quelccaya, and their correlations with the other elements are of the same sign as for Quelccaya, albeit weaker. Thus the Sajama and Ilimani series support the relationships obtained for the Quelccaya core. Similar to the l958–1984 portion of the Quelccaya record (Table I) discussed above, the Huascarán and Ilimani cores show no correlation between the isotope and net balance series. The Chimborazo core has over the 1947–1998 record a correlation of –0.19 between net balance and deuterium, while over the top 10 m deuterium and δ^{18}O are correlated at +0.99. Thus the correlation between δ^{18}O and net balance appears negative, similar to the other ice cores.

Complementing the correlation matrices in Tables I and II, the time series plots in Figure 4 illustrate the overall close relationship between the precipitation indices TL and CR, the circulation index UU, and the Quelccaya isotope record QD throughout, and for the 1915–1957 period also between QA versus QD and TL.

Considering the strong negative association of δ^{18}O in the Quelccaya ice cores with precipitation both in the annual cycle and on interannual time scales, a complementary appraisal of other sources is in order. Of interest in this respect is the network for measurement of isotopes in precipitation operated in the Amazon basin from the 1960s to the 1980s. For the two stations with more continuous record, Belém and Manaus (Figure 1), δ^{18}O is more negative in the season of largest rainfall in the annual cycle, and the spotty records also indicate a tendency for more negative δ^{18}O values in the years of more abundant rainfall. Processes which control the δ^{18}O in precipitation and Andean ice cores have been considered in various papers (Grootes et al., 1989; Pierrehumbert 1999; Hoffmann et al., 2003; Schotterer et al., 2003).

The recently available upper-air analyses in conjunction with the surface climatological and hydrological series allowed to examine the ice core evidence in the large-scale circulation context. Without such diagnostics of circulation processes, Diaz and Pulwarty (1994) had the Quelccaya δ^{18}O record among the several index series spanning the past millenium, which they subjected to spectral analysis; giving no phase relationships, they suggested that the ice core record showed preferred time scales of variability similar to El Niño. Likewise, without circulation diagnostics, Henderson et al. (1999) analyzed the Huascarán δ^{18}O series over the greater part of the past century, noted coincidences with the Pacific El Niño, and attempted to find associations with Atlantic SST. In the process they discussed at length earlier work on the climate dynamics of the tropical Atlantic sector and Nordeste rainfall, as did Baker et al. (2000). On the paleo time scale, Pierrehumbert (1999) proposed the Huascarán δ^{18}O record as an indicator of tropical climate during the Last Glacial Maximum. It may be noted that Huascarán and Chimborazo are not in pivotal location within the large-scale circulation, much in contrast to the southern tropical Andes (Figure 1).

In synthesis from Tables I and II and Figure 4, δ^{18}O on Quelccaya and Sajama, and to a lesser extent on Ilimani, has a negative association with the precipitation activity of the southern tropical Andes at large, and this in turn is modulated by large-scale circulation mechanisms discussed in Section 3. The Quelccaya, Sajama, and Ilimani drill sites, near the boundary between the tropical easterlies and the southern hemisphere subtropical westerlies, have a fortunate strategic position within the general circulation (Figures 1 and 2). The interannual variability of δ^{18}O in the three ice cores from the southern tropical Andes presented in Tables I and II cannot be accounted for by Atlantic SST. Accordingly, the fate of the water vapor along its trajectory from the Atlantic source region merits particular attention, including precipitation and evaporation processes over the Amazon lowlands, uplift at the Andes barrier, and precipitation over the highlands; essential being the observed more negative δ^{18}O with enhanced precipitation, both seasonally and interannually. By contrast, processes after deposition were found of little consequence for δ^{18}O (Schotterer et al., 2003; Hoffmann et al., 2003). A large-scale circulation perspective may be in order, appreciating in context the domain of zonal flow from the Atlantic over the Amazon lowlands to the Andes.

5. Conclusions

For the study of climatic change, various components of the environment may provide valuable indicators. The high mountain environment is recognized as particularly sensitive and is receiving increased attention in recent symposia (Institut Français d'Etudes Andines et IRD, 1998; PAGES, 2001). While the environmental response is conspicuous, the climatic forcing is not generally obvious. This poses the key task of inferring the general circulation causes of the observed environmental response. Crucial to such endeavors of 'actualistic' research into the circulation mechanisms of climatic variability are not only suitable upper-air and surface meteorological datasets but also field records from strategic locations and with sufficient resolution on interannual, if not seasonal, time scales.

The recently available NCEP-NCAR 40-year upper-air dataset (Kalnay et al., 1996) opens new prospects for the analysis of the atmospheric circulation. The southern tropical Andes are in a strategic position within the general circulation, as they are located within the transition from the tropical easterlies to the southern hemisphere subtropical westerlies. The long series of the water level variations of Lake Titicaca is a representative proxy of the regional precipitation activity. This provides a valuable complement for the Quelccaya, Sajama and Ilimani ice cores, of which net balance and δ^{18}O are of particular interest. These diverse sources have been evaluated in context, with focus on the circulation mechanisms of climatic variability in the southern tropical Andes.

The precipitation activity at the core of the rainy season in the southern tropical Andes is favored by enhanced and southward expanded easterlies through a deep layer of the troposphere. Concomitant with this is a notorious southward displacement of the circulation system over the equatorial Atlantic, which has been extensively explored in earlier work (references in Hastenrath and Greischar, 1993; Hastenrath, 2000). This entails reduced interhemispheric SST gradient (cold/warm in the North/South), more southerly position of surface wind confluence and Intertropical Convergence Zone, and abundant rainfall in Brazil's Nordeste. This Atlantic anomaly has, however, no direct influence on the southern tropical Andes. Such ensemble of circulation departures in the tropical Americas-Atlantic sector is common in the high SO phase.

This exploration of the circulation mechanisms of the precipitation variability in the southern tropical Andes provides a background for the appraisal of the oxygen isotope record in the ice core from Peru's Quelccaya Icecap, as well as the later cores from Sajama and Ilimani. Complementing the discovery a quarter-century ago (Thompson et al., 1979), δ^{18}O is more negative with more abundant precipitation, not only in the annual cycle but also on interannual time scales. More negative δ^{18}O is accompanied by circulation departures in the same sense as with anomalously abundant precipitation over the southern tropical Andes, namely enhanced and southward expanded tropical easterlies, and the southward displaced circulation system over the equatorial Atlantic. The source region of the water vapor transport into the southern Amazon lowlands is the South Atlantic, whose SST variability cannot account for the observed variations in δ^{18}O. The causes for the seasonal and interannual variability of δ^{18}O must be sought in processes along the moisture trajectory and in the precipitation over the Andes.

Acknowledgements

This study is supported by NSF Grant ATM-0110061. We thank Edson Ramirez for the Sajama and Ilimani icecore data, and Ulrich Schotterer and Paul Baker for exchanges of thought, and the anonymous reviewers for helpful comments.

References

Baker, P. A., Seltzer, G. O., Fritz, S. C., Dunbar, R. B., Grove, M. J., Tapia, P. M., Cross, S. L., Rowe, H. D., and Broda, J. P.: 2001, 'The History of South American Tropical Precipitation for the Past 25,000 Years', *Science* **291**, 640–643.

Cadier, E., Galárraga, R., Gómez, G., and Jauregui, C. (eds.): 1998, 'Conséquences Climatiques et Hydrologiques du Phénomène El Niño', Workshop of Quito, November, 1997, *Bulletin de l'Institut Français d'Etudes Andines* **27** (3), 423–896.

Curtis, S. and Hastenrath, S.: 1999, 'Trends of Upper-Air Circulation and Water Vapour over Equatorial South America and Adjacent Oceans', *Int. J. Clim.* **19**, 863–876.

Diaz, H. and Pulwarty, R.: l994, 'An Analysis of the Time Scales of Variability in Centuries-long ENSO-sensitive Records in the Last 1000 Years', *Clim. Change* **26**, 317–342.

Garreaud, R. D.: 1999, 'A Multi-Scale Analysis of the Summertime Precipitation over the Central Andes', *Mon. Wea. Rev.* **127**, 901–921.

Garreaud, R. D. and Aceituno, P.: 2001, 'Interannual Rainfall Variability over the South American Altiplano', *J. Climate* **14**, 2779–2789.

Ginot, P., Kull, C., Schiwkowski, B., Schotterer, U., and Gäggeler, H. W.: 2001, 'Effects of Post-depostional Processes on Snow Composition of a Subtropical Glacier (Cerro Tapado, Chilean Andes', *J. Geophys. Res.-Atmos.* **106** (D23), 32375–32386.

Grootes, P. M., Stuiver, M., Thompson, L. G., and Mosley-Thompson, E.: 1989, 'Oxygen Isotope Changes in Tropical Oce, Quelccaya, Peru', *J. Geophys. Res.-Atmos.* **94** (D1), 1187–1194.

Hastenrath, S.: 2000, 'Interannual and Longer-Term Variability of Upper-Air Circulation in the Northeast Brazil – Tropical Atlantic Sector', *J. Geophys. Res.-Atmos.* **105** (D6), 7327–7335.

Hastenrath, S. and Greischar, L.: l993, 'Circulation Mechanisms Related to Northeast Brazil Rainfall Anomalies', *J. Geophys. Res.-Atmos.* **98** (D3), 5093–5102.

Henderson, K. A., Thompson, L. G., andLin, P. N.: 1999, 'Recording of El Niño in Ice Core δ^{18}O Records from Nevado Huascarán, Peru', *J. Geophys. Res.-Atmos.* **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., and Werner, M.: 2003, 'Coherent Isotope History of Andean Ice Cores over the Last Century', *Geophys. Res. Lett.* **30** (4), 1179–1182.

Jacobeit, J.: 1991, 'Die grossräumige Höhenströmung in der Hauptregenzeit feuchter und trockener Jahre über dem südamerikanischen Altiplano', *Meteorol. Zeitschrift N.F.* **1**, 276–284.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D.: 1996, 'The NCEP/NCAR 40-Year Reanalysis Project', *Bull. Amer. Meteorol. Soc.* **77**, 437–471.

Kaplan, A., Cane, M. A., Kushnir, Y., Clement, A., Blumenthal, M. B., and Rajagopalan, B.: 1998, 'Analysis of Global Sea Surface Temperature 1856–1991', *J. Geophys. Res.-Oceans* **103** (C9), 18567–18589.

Kessler, A.: 1974, 'Atmosphärische Zirkulationsanomalien und Spiegelschwankungen des Titicacasees', *Bonner Meteorologische Abhandlungen* **17**, 361–372.

Kessler, A.: 1981, 'Wasserhaushaltsschwankungen auf dem Altiplano in Abhängigkeit von der atmosphärischen Zirkulation', *Aachener Geographische Arbeiten* **14**, part 2, 111–122.

Kessler, A.: 1990, 'Das El Niño – Phanomen und der Titicacaseespiegel', *Mainzer Geographische Studien* **34**, 91–100.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White. G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R., and Florino, M.: 2001, 'The NCEP-NCAR 50-year Reanalysis: Monthly Means CD-ROM and Documentation', *Bull. Amer. Meteorol. Soc.* **82**, 247–267.

Mélice, J. L. and Roucou, P.: 1998, 'Decadal Time Scale Variability Recorded in the Quelccaya Summit Ice Core δ^{18}O Isotopic Ratio Series and its Relation with the Sea Surface Temperature', *Clim. Dyn.* **14**, 117–132.

PAGES: 2001, *Workshop on Climate Change at High Elevation Sites: Emerging Impacts, Highest II*, June 2001, Davos, Switzerland, Abstract volume 143 pp.

Pierrehumbert, R. T.: 1999, 'Huascarán δ^{18}O as an Indicator of Tropical Climate during the Last Glacial Maximum', *Geophys. Res. Lett.* **26** (9), 1345–1348.

Ramirez, E., Hoffmann, G., Taupin, J. D., Francou, B., Ribstein, P., Caillon, N., Landais, A., Petit, J. R., Pouyaud, B., Schotterer, U., and Stievanard, M.: 2003, 'A New Andean Deep Ice Core from the Illimani (6350 m), Bolivia', *Ear. Plan. Sci. Lett.* **212** (3–4), 337–350.

Rao, V. B., Cavalcanti, I. F. A., and Hada, K.: 1996, 'Annual Variation of Rainfall over Brazil and Water Vapor Characteristics over South America', *J. Geophys. Res.-Atmos.* **101** (D21), 26539–26551.

Schotterer, U., Grosjean, M., Stichler, W., Ginot, P., Kull, C., Bonnaveira, H., Francou, B., Gaggeler, H. W., Gallaire, R., Hoffmannn, G., Pouyaud, B., Ramirez, E., Schwikowski, M., and Taupin, J. D.: 2003, 'Glaciers and Climate in the Andes between Equator and 30° S: What is Recorded under Extreme Environmental Conditions? *Clim. Change* **58**, 157–175.

Thompson, L. G., Hastenrath, S., and Morales-Arnao, B.: 1979, 'Climatic Ice Core Records from the Tropical Quelccaya Icecap', *Science* **209**, 1240–1243.

Thompson, L. G., Mosley-Thompson, E., Grootes, P. M., Pourchet, M., and Hastenrath, S.: 1984a, 'Tropical Glaciers: Potential for Ice Core Paleoclimatic Reconstructions', *J. Geophys. Res.-Atmos.* **89** (D3), 4638–4646.

Thompson, L. G., Mosley-Thompson, E., and Morales-Arnao, B.: 1984b, 'El Niño Southern Oscillation Events Recorded in the Stratigraphy of the Tropical Quelccaya Ice Cap, Peru', *Science* **226**, 50–53.

Thompson, L. G., Mosley-Thompson, E., Dansgaard, W., and 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., and Liu, K. B.: 1995, 'Late Glacial Stage and Holocene Tropical Ice Core from Huascarán, Peru', *Science* **269**, 47–50.

Thompson, L. G., Davis, M. E., Thompson, E. M., Sowers, T. A., Henderson, K. A., Zagorodnov, V. S., Lin, P. N., Mikhalenko, V. N., Campen. R. K., Bolzan, J. F., Cole-Dai, J., and Francou, B.: 1998, 'A 25,000 Year Tropical Climate History from Bolivian Ice Cores', *Science* **282**, l858–1864.

Thompson, L. G., Mosley-Thompson, E., and Henderson, K. A.: 2000, 'Ice-core Palaeoclimate Records in Tropical South America since the Last Glacial Maximum', *J. Quat. Sci.* **15** (4), 377–394.

Vuille, M.: 1999, 'Atmospheric Circulation Anomalies over the Bolivian Altiplano during Dry and Wet Periods and Extreme Phases of the Southern Oscillation', *Int. J. Clim.* **19**, 1579–1600.

Vuille, M., Bradley, R. S., and Keimig, F.: 2000, 'Interannual Climate Variability in the Central Andes and its Relation to Tropical Pacific and Atlantic Forcing', *J. Geophys. Res.-Atmos.* **105** (D10), 12447–12460.

(Received 7 August 2002; accepted 31 August 2003)