

ENSO AND RAINFALL ALONG THE ZONGO VALLEY (BOLIVIA) FROM THE ALTIPLANO TO THE AMAZON BASIN

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ABSTRACT

The location of eight rainfall stations in the Zongo valley (Eastern Cordillera – Bolivia) between 1195 and 4750 meters above sea level (masl) gives a unique opportunity to study the time-space rainfall variability between two regions, i.e. the Altiplano and the Amazonian lowlands of Bolivia, that are differently related to El Niño-Southern Oscillation (ENSO) events in the Pacific. In the central part of the lowlands, a La Niña/dry signal is observed during the peak of the rainy season (February) and around wintertime (May and September). Going toward the Andes and on the foothills up to 1500 masl, no ENSO signal has been found. On the median slopes of the Zongo valley, between 1800 and 3500 m, a strong Niño/dry signal is depicted on an annual timescale and during summer. In February, a Niña/wet signal is also significant. Going westward through the high Andes and the eastern Altiplano, this signal weakens. On the western edge of the Altiplano, an El Niño/dry and La Niña/wet signals are clearly identified.

In the central lowlands and on the western Altiplano, ENSO indexes account for nearly 25% of rainfall variability, and for as much as 50% along the median slopes of the eastern Cordillera, in the Zongo valley.

This finding deserves further study as previous researches have shown that in the Andes the best relationship between rainfall and equatorial Pacific sea-surface temperature (SST) is in the western Altiplano, far from the Amazonian source of moisture. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: rainfall; rainfall variability; ENSO; Andes; Altiplano; Amazon basin; Bolivia

1. INTRODUCTION

The Zongo river flows down the eastern Andean Cordillera in Bolivia. It is an effluent of Beni River, an Amazon tributary (Figure 1(a) and (b)). Its watershed has a WSW-ENE orientation and extends from the Zongo glacier (the southern glacier of the Huayna Potosi peak – 6088 meters above sea level (masl)) to the Yungas, the hot and wet valleys east of La Paz. Along the 50-km Zongo valley, eight hydropower plants located between 1195 and 4750 masl provide electric power to La Paz. In these plants, the Bolivian Company of Electric Energy (COBEE) has been measuring rainfall since the beginning of the seventies (Table I).

The data set offers an opportunity to analyze the altitudinal rainfall gradient in the eastern Andean Cordillera and the interannual rainfall variability in a valley located between two regions characterized by different El Niño-Southern Oscillation (ENSO) rainfall relationships.

Upstream, the Bolivian Altiplano receives less rainfall than average during El Niño events (Francou and Pizarro, 1985; Aceituno, 1988; Aceituno and Garreaud, 1995; Ronchail, 1998; Gallaire *et al.*, 2000), although little evidence of more rainfall during La Niña events has been reported. Vuille *et al.* (2000) noted a better ENSO–rainfall signal on the western side of the Altiplano than on its eastern side. The same signal is found in

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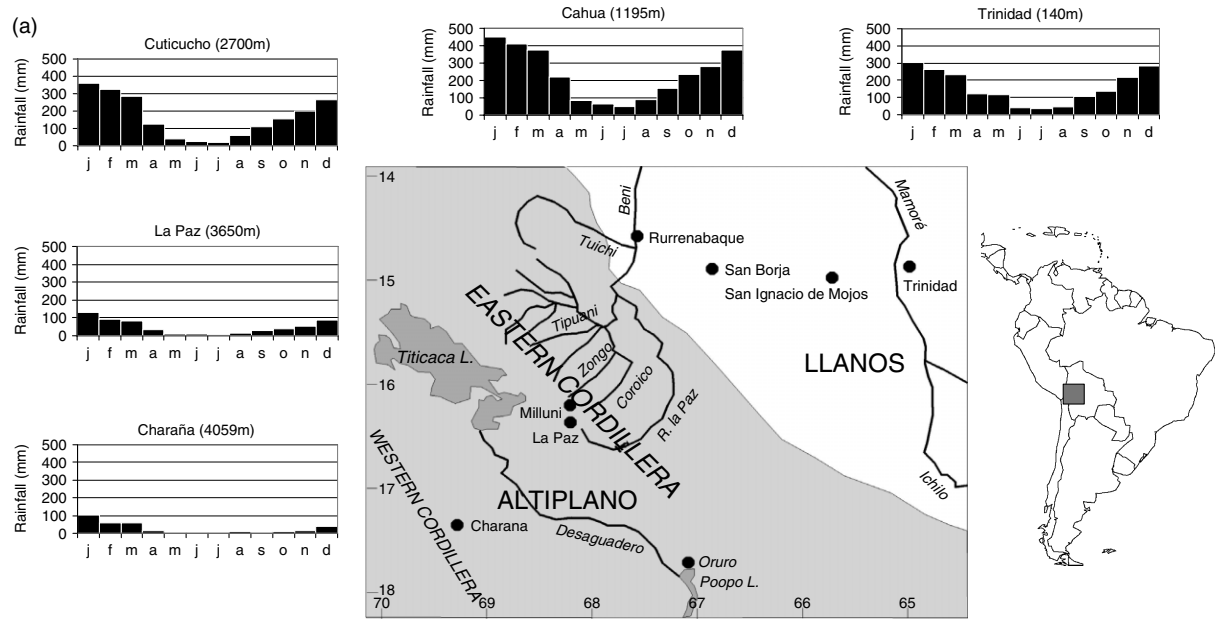


Figure 1. (a) Location of the Zongo valley in the eastern Andean Cordillera (Bolivia) and South–Western Amazonian basin. Rainfall regime (1971–2001) in Charaña and la Paz (Altiplano), in Botijlaca and Cahua (Zongo valley) and in Trinidad (Amazonian lowlands). Grey shading indicates regions higher than 500 m. (b) Bolivian company of electric energy (COBEE) panel showing the electric plants along the Zongo valley

Table I. Characteristics of stations: code, origin of data, altitude, annual rainfall, rainfall standard deviation, rainfall coefficient of variation and period of data availability. Mean annual rainfall is for the hydrological year (August–July)

	Code	Origin of the data	Altitude (m)	Annual rainfall (mm)	Rainfall std	Coefficient of variation	Period
Charaña	CH	SENAMHI	4059	311	116	0.37	1971–1995
Oruro	OR	SENAMHI	3709	412	113	0.27	1971–1996
La Paz	LP	SENAMHI	3650	583	85	0.15	1971–2001
Milluni	MI	COBEE	4650	556	172	0.31	1971–2001
Plataforma	PL	COBEE	4750	819	248	0.30	1971–2001
Botijlaca	BO	COBEE	3450	1062	187	0.18	1971–2001
Cuticucho	CU	COBEE	2700	1997	263	0.13	1971–2001
Santa Rosa	SR	COBEE	2500	1966	262	0.13	1971–2001
Sainani	AS	COBEE	2210	2074	235	0.11	1971–2001
Chururaqui	CQ	COBEE	1830	2062	275	0.13	1971–2001
Harca	HÁ	COBEE	1480	2167	268	0.12	1971–2001
Cahua	CA	COBEE	1195	2789	296	0.11	1981–2001
Rurrenabaque	RU	SENAMHI	280	2407	431	0.18	1971–2000
San Borja	SB	SENAMHI	190	1968	450	0.23	1971–2001
San I. de Moxos	SIM	SENAMHI	220	2093	392	0.19	1971–2000
Trinidad	TR	SENAMHI	140	1907	276	0.14	1971–2000

the discharge and suspended sediment yields of Rio Beni in Rurrenabaque on the edge of the Andes (Bourrel *et al.*, 2003; Ronchail *et al.*, 2005b). Aalto *et al.* (2003) report more events of frequent sedimentation in the Beni basin during La Niña events. These results are confirmed by the survey of glaciers in Bolivia (Francou *et al.*, 1995). Wagon *et al.* (2001) found a significant melting of the Zongo glacier during the 1997–1998 El Niño, and Francou *et al.* (2003) conclude that more frequent occurrences of El Niño since 1976 along with an increase of the global surface temperature have accelerated the retreat of the Chacaltaya glacier. Dry conditions during El Niño are associated with a weakening and northward displacement of the Bolivian High, with a strong westerly flow above the Altiplano that prevents the advection of moist air from the Amazon basin (Aceituno and Montecinos, 1993; Vuille *et al.*, 2000; Garreaud and Aceituno, 2001) and, as suggested by Lenters and Cook (1999), with the anomalous northward penetration of strong cold fronts. Also, Garreaud *et al.* (2003) report that as the western Altiplano is far from the Amazonian source of moisture, it is more sensitive to the reduced moisture transport aloft during El Niño events.

Downstream, in the lowlands of Bolivia, reduced rainfall is associated with La Niña (Ronchail, 1998; Ronchail *et al.*, 2002). During El Niño years, no significant signal is found; huge flooding in 1982–1983 or 1991–1992 occurred as well as a rainfall deficit (1997–1998) (Ronchail *et al.*, 2005a). The lowland of Bolivia is located between the northern Amazon basin and the southeastern South American region (SESA – southeast Brazil, Uruguay, northeast Argentina). These two regions experience opposite ENSO–rainfall signals (Aceituno, 1988; Grimm *et al.*, 1998; Montecinos *et al.*, 2000). Hence, during an El Niño event, the lowlands of Bolivia may experience either

- dryness due to an anomalous subsidence over tropical South America,
- or abnormally wet conditions owing to midlatitude blocking in the south Pacific, intense subtropical jet and persistence of active extra-tropical frontal systems (Kousky *et al.*, 1984). Lau and Zhou (2003) also conclude that anomalies in the South American monsoon system (SAMS) during ENSO episodes, with an enhanced (slower) low-level jet (LLJ) along the Andes during El Niño (La Niña) may be responsible for more (less) rainfall in SESA. Consistently, Grimm (2004) indicates that the perturbation in the Walker and Hadley circulation over the eastern Pacific and South America generates, during La Niña, a diversion of the northerly moisture inflow from the Atlantic toward the mouth of the Amazon, at the expense of the SESA region.

Here, the relationship between altitude and mean rainfall is first investigated. Then the altitudinal variability of the ENSO–rainfall relationship is reviewed from the Altiplano to the lowlands of Bolivia. Is the Altiplano's El Niño–dry signal also observed along the Zongo valley, as the ENSO–Beni discharge relationship in Rurrenabaque seems to suggest? Downstream, where does the La Niña/dry signal appear?

1.1. Climatological background

The climate of the region studied is tropical: austral winter, from May to August, is the dry season while austral summer, from December to March, is wet (Figure 1(a)).

In the lowlands, the warm land and the onset of South American monsoon in summer (trade winds deviated toward the south by the Andes) favor deep convection and rainfall, while dryness in winter is associated with a cooler land and the demise of the monsoon. In winter, rainfall in the lowlands and on the down slopes of the Andes may be associated with cold fronts and residual humidity that characterize this regularly inundated region (Ronchail, 1989; Ronchail *et al.*, 2005a). Summer convection variability is modulated by the activity and the position of the South American convergence zone (SACZ), a cloudy band that, on average, extends from central Amazon to the southern subtropical Atlantic (Garreaud and Wallace, 1998; Liebmann *et al.*, 1999; Seluchi and Marengo, 2000).

In the Andes, rainfall variability on an annual timescale is related to the seasonal heating and cooling of the land and to changes in the troposphere zonal wind; in summer the easterlies favor the entrance of moist air over the eastern Andes and the Altiplano while the westerlies in winter prevent it (Aceituno and Montecinos, 1993; Vuille, 1999; Garreaud and Aceituno, 2001). Intraseasonal and interannual rainfall variability is also associated with anomalies in the troposphere zonal wind.

2. DATA AND METHODOLOGY

Monthly rainfall data from COBEE is available in eight stations (from Plataforma to Cahua – Table I and Figure 1(b)) for the 1971–1972/2000–2001 period. Additional rainfall data in Milluni, La Paz, Oruro and Charaña on the Altiplano and in Rurrenabaque, Trinidad, San Ignacio de Moxos and San Borja in the lowlands (Table I and Figure 1(a)) is from SENAMHI (National Service of Meteorology and Hydrology). The hydrological year runs from August to July (Figure 1(a)).

The sea-surface temperature (SST) data is from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center. Monthly SSTs (1950–2002) were collected for Niño 1–2 (0–10° S; 90–80° W), Niño 3 (5° S–5° N; 150–90° W), Niño 3–4 (5° S–5° N; 170–120° W) and Niño 4 (5° S–5° N; 160° E–150° W) regions. The JMA SST anomalies, calculated in a 4° S–4° N, 150° W–90° W box, are from the Japan meteorological agency. The Southern Oscillation Index (SOI), the standardized difference of pressure between Tahiti and Darwin, and the multivariate ENSO index (MEI) that synthesizes atmospheric and oceanic data in the equatorial Pacific, are from the CDC–NOAA. NCEP/NCAR reanalysis is described in Kalnay *et al.* (1996).

Correlations and composites, tested using a two-sided Student's *t*-test approach, are employed to analyze the relationships between SSTs and rainfall. Correlations and differences are taken into account when they are significant, respectively at the 95 and 90% level.

3. RAINFALL AND ALTITUDE

In the lowlands, annual rainfall is about 2000 mm (Table I and Figure 2). As the relief uplifts the moist air, rainfall increases to a maximum 2800 mm at about 1000 masl. Then the moisture supply becomes inadequate and rainfall drops; 2000 mm are observed between 1500 and 2700 masl. The presence of heavy precipitations up to nearly 3000 masl is caused by the sharp topography (Roche *et al.*, 1990). A dramatic decrease can be noticed on the upstream slopes toward the passes of the eastern Cordillera: 800 mm are recorded in

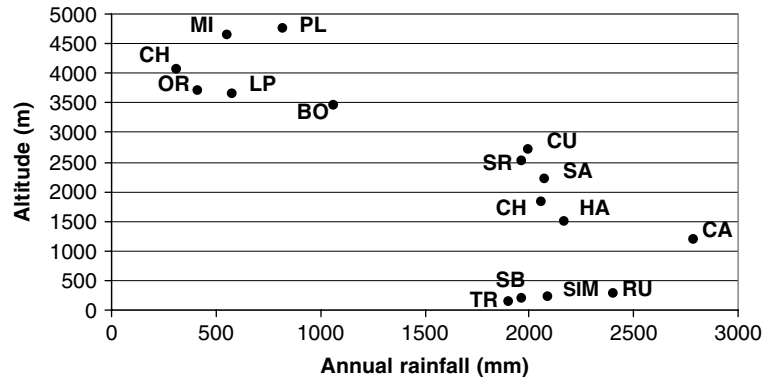


Figure 2. Mean annual rainfall (August–July) and altitude. See codes and periods in Table I

Plataforma (4750 masl). On the sheltered eastern side of the Altiplano, rainfall decreases again to 600 mm per year in La Paz and 300 mm in Charaña on the western edge of the Altiplano. On the Pacific slopes of the subtropical Andean Cordillera, rainfall increases with altitude up to 4000 masl (Patricio Aceituno, personal communication).

Although the decrease in the rainfall along the eastern slopes of the Andes is not regular, an altitudinal rainfall gradient is proposed for the Zongo valley: between Cahua and Plataforma, the rainfall decreases by 55 mm every 100 m and the altitude accounts for 89% of rainfall variability.

The proportion of summer rainfall (December–January–February (DJF)) in the annual rainfall also varies with altitude: the ratio is 40% in Rurrenabaque, 53% in La Paz and 66% in Charaña (Figure 1(a)). On the other hand, winter rainfall is more abundant in the lowlands, as a result of cold fronts.

Interannual variability of rainfall is stronger in the highest and the less rainy stations. On the Altiplano, the coefficient of variation is above 0.3, while it is less than 0.2 at a lower altitude (Table I). The lowest variability, below 0.15, is between Cuticucho (2700 masl) and Cahua (1195 masl). The highest rainfall variability occurs during the dry season (austral winter) while the lowest is in the rainy season (austral summer).

4. RAINFALL VARIABILITY AND ENSO EVENTS

The relationships between rainfall and ENSO events have been studied using correlation and composite analysis.

Correlation coefficients are computed between annual (August–July) rainfall and DJF ENSO indexes as ENSO events peak during this period. Results show significant relationships along the Zongo river, between Botijlaca (3450 masl) and Sainani (2210 masl) (Table II and Figure 3). During El Niño (La Niña), rainfall is less (more) abundant than usual. The strongest relationships can be observed with the SOI index. This index accounts for 46% of the annual rainfall variability in Santa Rosa (2500 masl, Figure 4). A similar relationship has been found in Charaña, on the western edge of the Altiplano, although it is less important. On the eastern edge of the Altiplano, the correlation between rainfall and ENSO indexes is not significant.

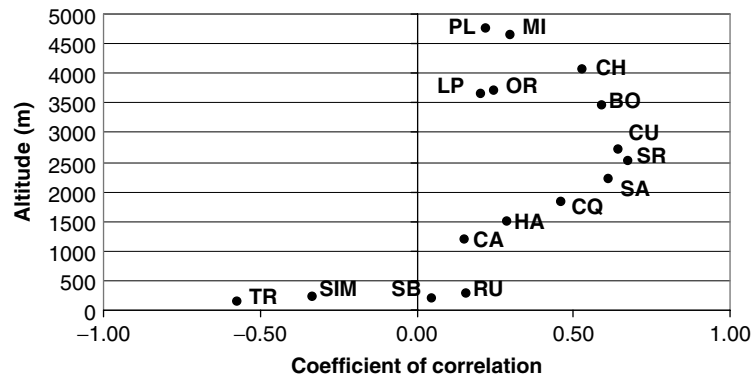
On the contrary, in the lowlands, an El Niño-wet/La Niña-dry signal has been reported and the SOI index accounts for about 33% of rainfall variability in Trinidad (Table II and Figures 3 and 4). It is noteworthy that this signal resembles that depicted in the SESA region (Aceituno, 1988; Grimm *et al.*, 1998; Montecinos *et al.*, 2000). A similar, but not significant, relationship is observed in San Ignacio de Moxos, near Trinidad.

Westwards in the lowlands (San Borja and Rurrenabaque) and in the Andes foothills, up to Harca (1480 masl), no ENSO signal is found.

The same analysis was performed using monthly and seasonal rainfall (December–January–February – DJF, March–April–May – MAM, June–July–August – JJA and September–October–November – SON).

Table II. Correlation values between annual rainfall (August–July) and DJF (December–January–February) ENSO indexes. Bold values are significant at the 95% level

	MEI	Niño4	Niño 3–4	Niño3	Niño 1–2	SOI	JMA
Charaña (4059 m)	−0.53	−0.53	−0.53	−0.49	−0.38	0.53	−0.50
Oruro (3709 m)	−0.33	−0.30	−0.32	−0.33	−0.43	0.25	−0.29
La Paz (3650 m)	−0.18	0.06	−0.16	−0.23	−0.31	0.21	−0.18
Milluni (4650 m)	−0.29	−0.15	−0.29	−0.34	−0.35	0.30	−0.30
Plataforma (4750 m)	−0.28	−0.11	−0.28	−0.33	−0.31	0.22	−0.30
Botijlaca (3450 m)	−0.59	−0.44	−0.55	−0.57	−0.54	0.60	−0.56
Cuticucho (2700 m)	−0.54	−0.37	−0.53	−0.53	−0.50	0.64	−0.51
Santa Rosa (2500 m)	−0.60	−0.59	−0.59	−0.53	−0.40	0.68	−0.52
Sainani (2210 m)	−0.52	−0.53	−0.50	−0.43	−0.32	0.62	−0.43
Chururaqui (1830 m)	−0.36	−0.43	−0.37	−0.28	−0.18	0.46	−0.27
Harca (1480 m)	−0.17	−0.23	−0.11	−0.02	0.01	0.29	−0.03
Cahua (1195 m)	−0.02	0.02	0.05	0.12	0.13	0.15	0.14
Rurrenabaque (280 m)	−0.16	−0.09	−0.06	−0.12	−0.27	0.16	−0.16
San Borja (190 m)	−0.09	0.07	−0.01	−0.09	−0.27	0.05	−0.11
San Ignacio de Moxos (220 m)	0.28	0.28	0.32	0.28	0.14	−0.33	0.28
Trinidad (140 m)	0.52	0.52	0.51	0.45	0.29	−0.57	0.47

Figure 3. Relationships between the altitude of stations and correlation between annual rainfall (August–July) and DJF (December–January–February) SOI. Significant values at the 95% level are above 0.42 and under -0.42 (except Cahua: 0.5 and -0.5). Station codes are listed in Table I

Along the Zongo valley, from Botijlaca (3450 masl) to Chururaqui (1830 masl), significant relationships are found between DJF rainfall, the peak rainfall season, and DJF SST; they are higher than those found with the annual timescale (Table III). In Cuticucho (2700 masl), the DJF SOI accounts for 50% of the DJF rainfall variability. Monthly analysis shows similar results in January and February and no relationships in December. In February, correlation values are significant in a wider range of stations (from Milluni to Harca) than in DJF and the values are often higher. Analyzing the climatological seasonal rainfall cycle and the interannual rainfall variability in the Altiplano, Lenters and Cook (1999) showed that the drier February month (compared to January) and El Niño years are related to a weakened and northward displaced Bolivian High and to drier and cooler conditions at the East of the Andes. This may be the reason for the tighter relationship between February rainfall and ENSO.

Similar results are observed in MAM, particularly in March and April, but correlation values are weaker and not significant on the western edge of the Altiplano (Table III).

In Trinidad, correlation between rainfall and ENSO indexes are significant just before and after wintertime (May; SON, in particular September). This indicates that the rain deficit (excess rain) during la Niña (El

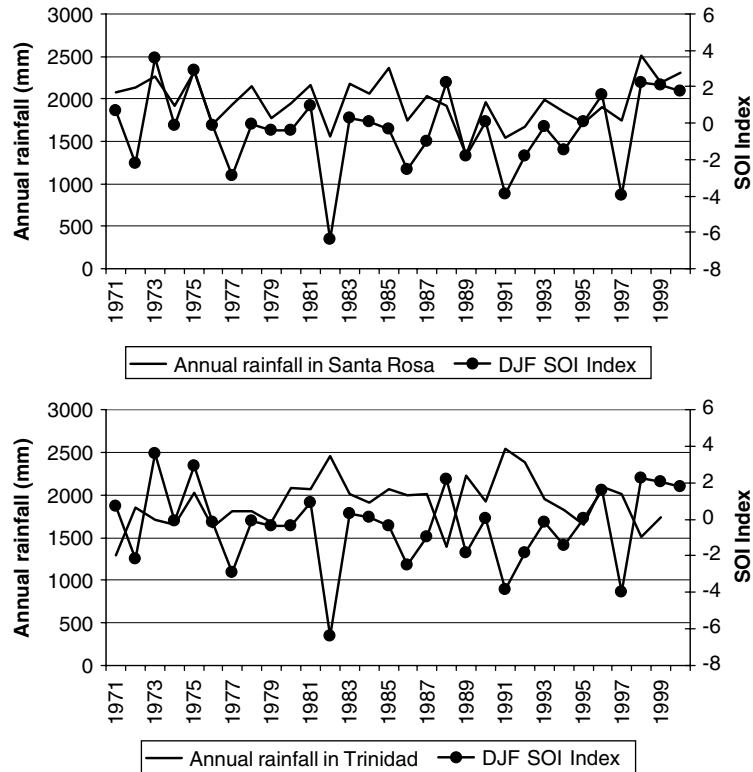


Figure 4. 1971–2001 evolution of annual (September–August) rainfall in Santa Rosa (2500 masl, above) and in Trinidad (140 masl, below) and of the DJF SOI Index

Niño) may be due to a low (high) frequency or intensity of cold fronts, as suggested by Kousky *et al.* (1984). This result was already mentioned in Ronchail (1998).

Moving correlations are calculated between annual SOI and annual rainfall. They show that the relationships between ENSO and rainfall are stationary in the Zongo valley while they become significant just after the beginning of the eighties in Trinidad (Figure 5). This is consistent with the ENSO-discharge correlation observed in the Mamoré River in Guayaramerin (Ronchail *et al.*, 2005b).

4.1. Composite analysis

Composite analysis does not entail linear relationships between ENSO indexes and rainfall; thus information about the symmetry of the ENSO–rainfall relationships turns out to be useful.

In Table IV, mean 1971–2001 rainfall and precipitations during El Niño and La Niña events (Trenberth, 1997) are compared. As the 1972–1973 El Niño event was unusually wet and the 1988–1989 La Niña dry, analyses were performed with and without these years. Results of a Student’s *t*-test give the probabilities of El Niño or La Niña rainfall not being different from the mean 1971–2001 rainfalls. Table IV also lists the percentage of enhanced or diminished rainfall during El Niño or La Niña episodes.

During El Niño, rainfall is lower than usual along the Zongo valley, from Plataforma (4750 masl) to Santa Rosa (2500 masl). When the 1972–1973 El Niño event is removed, the region with significant differences increases, including the downstream Sainani and Chururaqui stations and also the station of Charaña on the western edge of the Altiplano. El Niño years result in a 10 to 20% reduction of annual rainfall in the Zongo valley. The deficit reaches 35% in Charaña.

Table III. Correlation values between DJF (December–January–February), December, January, February, MAM (March–April–May), March, April, May, SON (September, October–November) rainfall and the DJF SOI or the Niño4 index. Bold values are significant at the 95% level

	DJF/ SOI	Dec./ SOI	Jan./ SOI	Feb./ Niño4	MAM/ SOI	March/ SOI	April/ Niño4	May/ SOI	SON/ Niño4
Charaña (4059 m)	0.54	0.16	0.41	-0.50	0.24	0.33	-0.28	0.05	0.25
Oruro (3709 m)	0.21	0.00	0.14	-0.38	0.40	0.25	-0.52	-0.09	-0.14
La Paz (3650)	0.25	0.16	0.09	-0.18	0.16	0.22	0.10	0.09	0.20
Milluni (4650 m)	0.35	0.07	0.25	-0.47	0.22	0.24	-0.12	0.15	-0.03
Plataforma (4750 m)	0.22	0.01	0.15	-0.34	0.24	0.24	-0.19	-0.18	0.11
Botijlaca (3450 m)	0.64	0.14	0.52	-0.71	0.50	0.44	-0.51	-0.18	0.20
Cuticucho (2700 m)	0.71	0.23	0.41	-0.72	0.39	0.37	-0.39	-0.37	0.22
Santa Rosa (2500 m)	0.65	0.15	0.54	-0.71	0.48	0.43	-0.52	-0.25	0.17
Sainani (2210 m)	0.57	0.14	0.45	-0.53	0.48	0.42	-0.55	-0.24	0.11
Chururaqui (1830 m)	0.43	-0.05	0.27	-0.65	0.45	0.43	-0.46	-0.31	-0.02
Harca (1480 m)	0.34	-0.06	0.22	-0.58	0.47	0.55	-0.27	-0.35	0.22
Cahua (1195 m)	0.22	-0.21	0.20	-0.48	0.50	0.41	-0.51	-0.56	0.06
Rurrenabaque (280 m)	0.33	0.38	0.24	0.11	-0.19	0.12	0.19	-0.41	-0.07
San Borja (190 m)	-0.05	0.37	-0.13	0.33	0.01	0.13	0.13	-0.18	0.15
San Ignacio de Moxos (220 m)	-0.13	0.07	-0.16	0.10	-0.27	-0.09	0.17	-0.37	0.23
Trinidad (140 m)	-0.27	0.16	-0.30	0.32	-0.38	-0.09	-0.12	-0.56	0.39

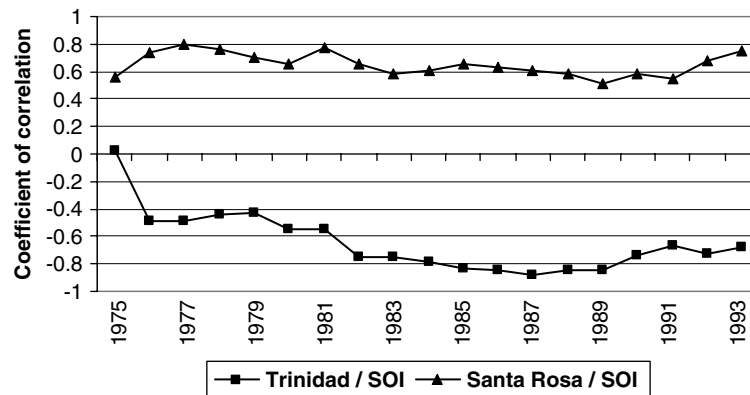


Figure 5. Evolution over time of the 11-year moving correlation between DJF (December–January–February) SOI and annual (August–July) rainfall in Santa Rosa (2500 masl) and Trinidad (140 masl). 1975 value is for the 1971–1981 period. Significant values at the 95% level are above 0.6 and below -0.6

During La Niña episodes, negative rainfall anomalies are not significant in the Zongo valley and the results are not improved when removing the dry 1988–1989 La Niña event (not shown). However, in Charaña, the excess rain during La Niña is significant and reaches 29% of the annual rainfall.

In Trinidad, an 11% rain deficit is significant during La Niña years.

Monthly composites of rainfall are given in Figure 6. In Santa Rosa (2500 masl) significant negative anomalies are observed in January (-26%), February (-21%) and April (-34%), while positive ones are highlighted in February (+24%). In Trinidad, negative and significant anomalies are depicted during the dry period, in May (-57%) and in September (-42%) after the peak of ENSO events and during the rainy season, in February (-24%).

Table IV. Mean annual (August–July) rainfall (mm) and mean rainfall during (1) El Niño years (2) El Niño years without 1972–1973, (3) La Niña years. In each case, the Student *t*-test probability and the percentage of enhanced or diminished rainfall are given. Bold values are significant at the 90% level

	Mean rainfall	El Niño years		El Niño years without 72–73			La Niña year			
		Mean rainfall	Prob.	%	Mean rainfall	Prob.	%	Mean rainfall	Prob.	%
Charaña (4059 m)	311	240	0.23	-0.23	201	0.03	-0.35	402	0.02	0.29
Oruro (3709 m)	412	352	0.22	-0.15	357	0.31	-0.13	469	0.42	0.14
La Paz (3650)	583	549	0.36	-0.06	546	0.37	-0.06	559	0.51	-0.04
Milluni (4650 m)	556	488	0.25	-0.12	468	0.16	-0.16	585	0.80	0.05
Plataforma (4750 m)	819	676	0.02	-0.17	670	0.02	-0.18	825	0.95	0.01
Botijlaca (3450 m)	1062	897	0.05	-0.16	844	0.00	-0.20	1149	0.28	0.08
Cuticucho (2700 m)	1997	1767	0.06	-0.12	1743	0.06	-0.13	2109	0.21	0.06
Santa Rosa (2500 m)	1966	1757	0.02	-0.11	1705	0.00	-0.13	2102	0.27	0.07
Sainani (2210 m)	2074	1917	0.14	-0.08	1851	0.02	-0.11	2192	0.29	0.06
Chururaqui (1830 m)	2062	1915	0.22	-0.07	1835	0.02	-0.11	2170	0.39	0.05
Harca (1480 m)	2167	2146	0.88	-0.01	2055	0.29	-0.05	2284	0.35	0.05
Cahua (1195 m)	2789	2722	0.69	-0.02	2722	0.69	-0.02	2698	0.68	-0.03
Rurrenabaque (280 m)	2407	2399	0.97	0.00	2373	0.88	-0.01	2491	0.72	0.03
San Borja (190 m)	1968	1867	0.53	-0.05	1868	0.54	-0.06	1888	0.57	-0.04
San I. Moxos (220)	2093	2160	0.70	0.03	2183	0.64	0.04	1932	0.21	-0.08
Trinidad (140 m)	1907	1997	0.51	0.05	2019	0.47	0.06	1692	0.05	-0.11

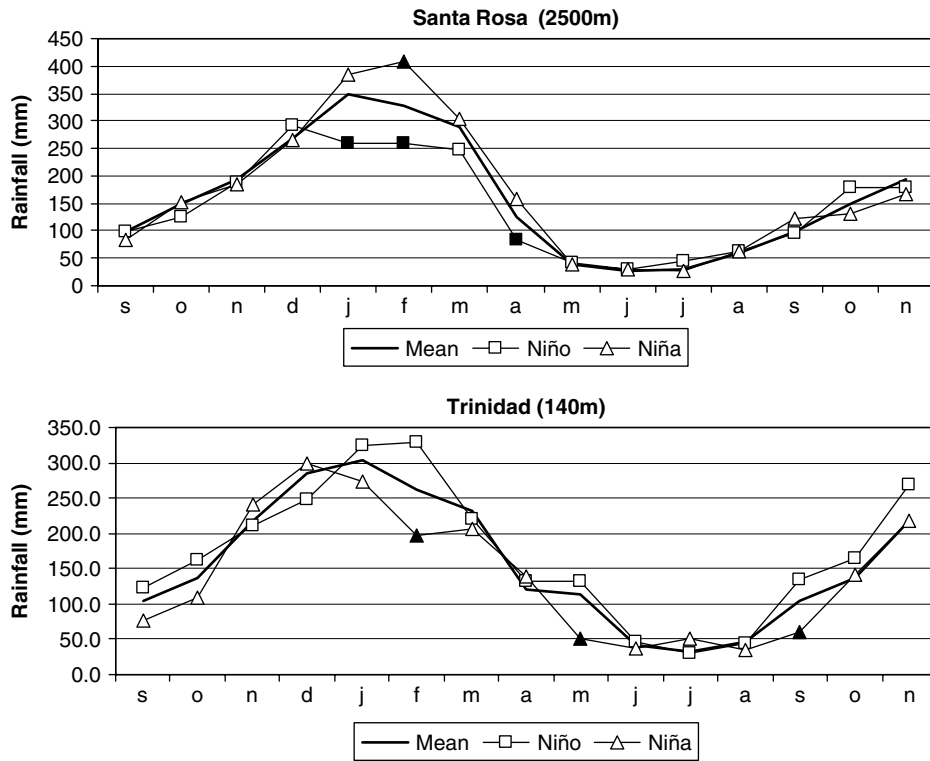


Figure 6. Mean rainfall during the period of study, during El Niño La Niña events, in Santa Rosa and Trinidad. Black points indicate that rainfall values are significantly different from the mean (at the 90% level)

5. DISCUSSION AND CONCLUDING REMARKS

Analysis of rainfall variability along a transect from the Amazonian lowlands to the Bolivian Altiplano has been conducted during the 1971–1972/2000–2001 period, using, in particular, the data of eight rainfall gauges located along the Zongo valley between 1195 and 4750 masl.

Rainfall increases from the lowlands to the foothills of the Andes. This increase is related to the topographic effect on rainfall.

Then, a global rainfall decrease is observed above 1000 m. Also, along the transect several stages are observed. A first decrease, from 2800 to 2000 mm/year, is found between 1000 and 1500 masl and another one up to 1000 mm/year is measured above 3000 masl. On the western edge of the eastern Cordillera, annual rainfall drops dramatically to 600 mm in the eastern Altiplano and 300 mm in the western Altiplano. The decrease in the rainfall can be associated with the cooling of the air with altitude and on the Altiplano, with the sheltering effect of the eastern cordillera.

Significant negative relationships between ENSO and rainfall, on the annual and seasonal (austral summer) timescale, are observed over the median eastern slopes of the eastern Andean Cordillera, between Botijlaca (3450 m) and Chururaqui (1830 m) and in the western Altiplano. ENSO indexes account for as much as 40% of the annual rainfall variability in the Zongo stations (and 50% of the summer rainfall variability) and 30% in Charaña (western Altiplano). These locations are characterized by significant rainfall deficit during El Niño and, by rainfall excess that is not regularly observed, except in Charaña, during La Niña. Analysis of monthly rainfall shows that the best correlations occur in February, as they are significant in all the stations above 1450 masl. Additionally, in February, rainfall anomalies in the Zongo valley are significant during El Niño and La Niña. The composite of the 200 hPa wind anomalies in February during El Niño episodes shows a western anomaly over the tropical Andes that prevents the advection of moist air from the Amazonian regions to the high slopes of the eastern Andes and the Altiplano (Figure 7(a)). The opposite occurs during La Niña events (Figure 7(b)). This result is in good agreement with previous data from Vuille *et al.* (2000) and Garreaud and Aceituno (2001).

In the lowlands (Trinidad), a significant La Niña/dry signal is observed in February, May, and September. In February, dryness during La Niña is associated with a low geopotential height over eastern Brazil, at low level, and a composite anomalous eastward wind from the Atlantic toward the mouth of the Amazon. It is accompanied by an anomalous southeastern wind over the lowlands of Bolivia. This composite signal is particularly strong during the 1980–2001 La Niña events, when the relationship between rainfall in Trinidad and ENSO indexes is significant (Figure 8(a)). Opposite features are observed during El Niño episodes, i.e. anomalous northern wind over the lowland of Bolivia (Figure 8(b)). These results are consistent with Zhou and Lau (2001) who found that during El Niño events, in response to subsidence over northern South America, there is a strengthening of the low-level flow along the eastern foothills of the eastern Andes, meaning an enhanced South American summer monsoon.

In May, a 56% shortage (50 mm above 114 mm, mean value) in Trinidad may be related to anomalously high geopotential height at low level over the southern part of the continent. This anomaly is observed during La Niña events over the whole 1971–2001 period, but it is stronger during the 80s and the 90s (Figure 9).

The La Niña/dry signal vanishes westward of Trinidad in the lowlands and in the downward slope stations of the Zongo valley.

Our results confirm previous reports: different ENSO–rainfall signals are found in the lowlands of Bolivia and on the Altiplano, and the ENSO–rainfall signal is better on the western edge of the Altiplano (here, Charaña) than on the eastern one. Our results also point to new elements. They highlight the rainfall–altitude relationships and a good ENSO–rainfall relationship along the median eastern slopes of the eastern Cordillera. This last result deserves further attention, as it does not match data from Garreaud *et al.* (2003) indicating that the best signals are in locations away from the Amazonian source of moisture.

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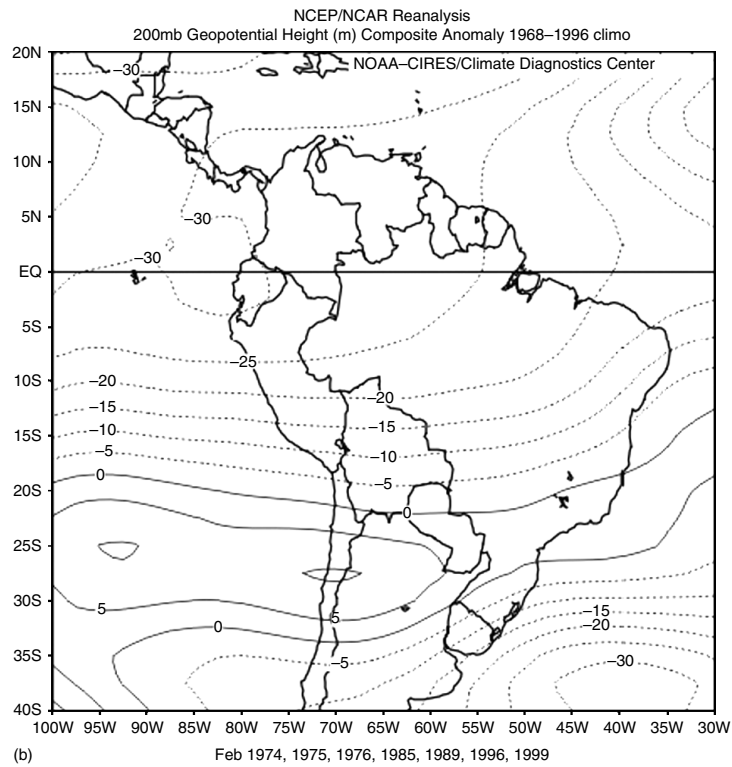
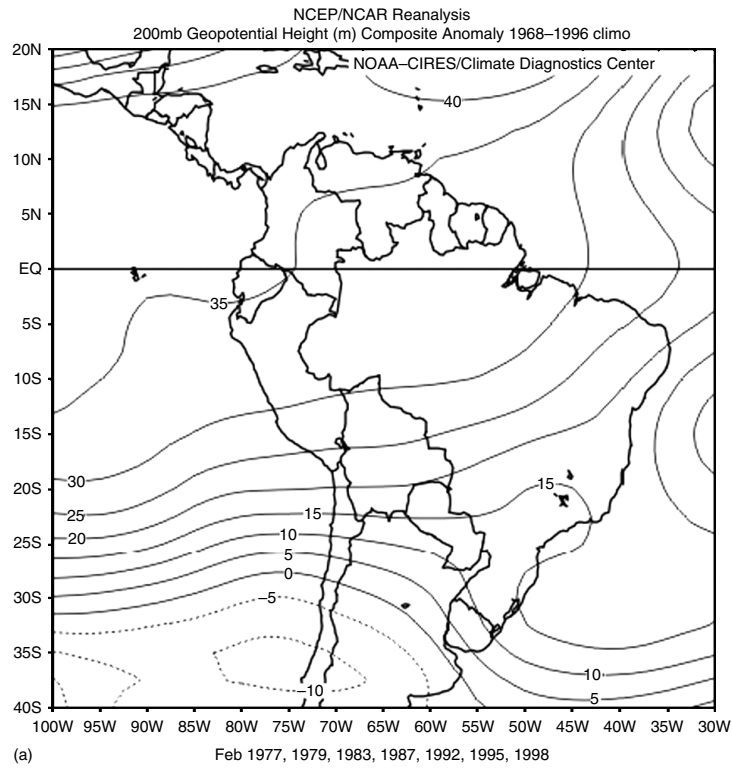


Figure 7. 200 hPa geopotential height (m) composite anomalies from the 1968–1996 mean for (a) El Niño in February, (b) La Niña in February, during the 1971–2001 period

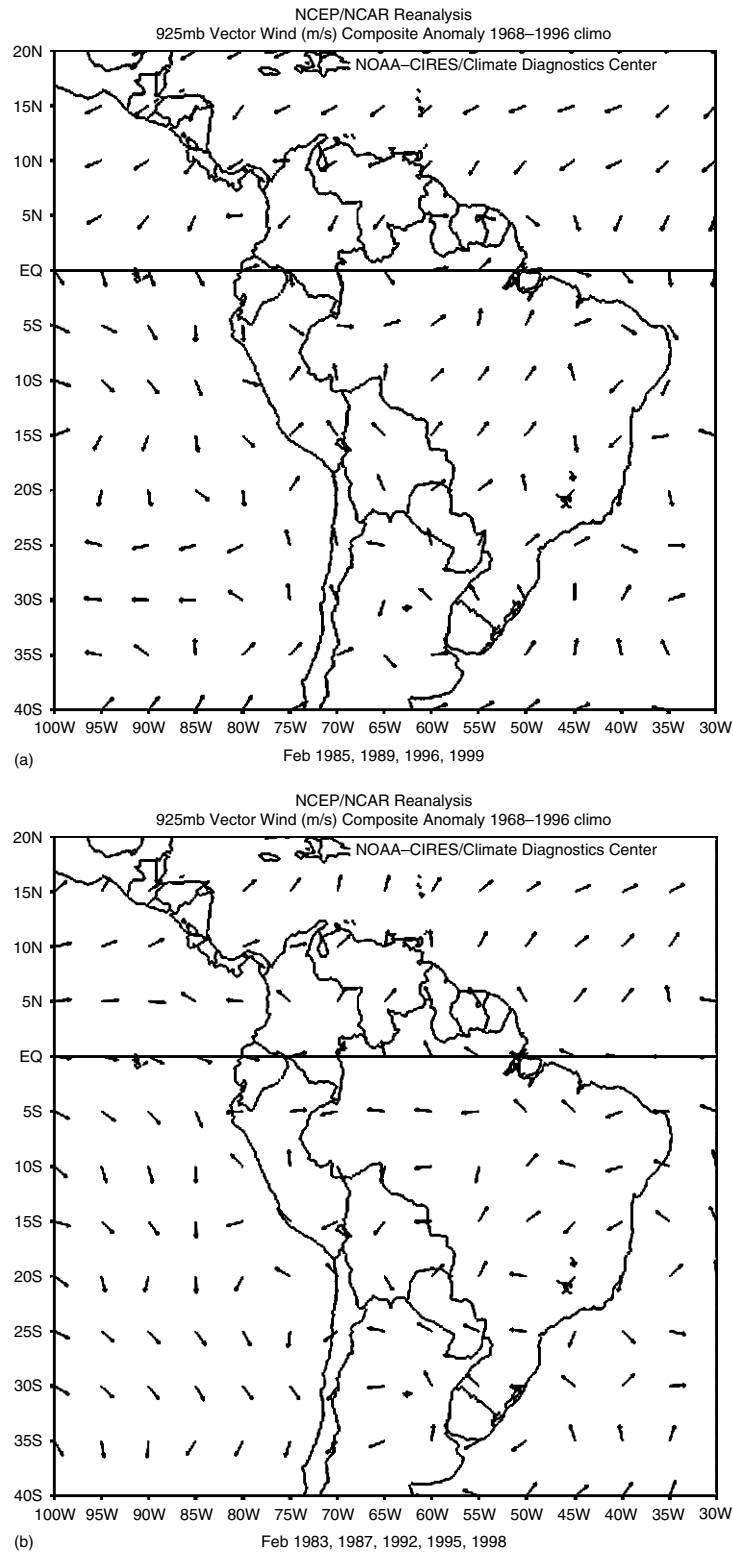


Figure 8. 925 hPa vector wind (m/s) composite anomalies from the 1968–1996 mean for (a) La Niña in February, (b) El Niño in February, during the 1980–2001 period

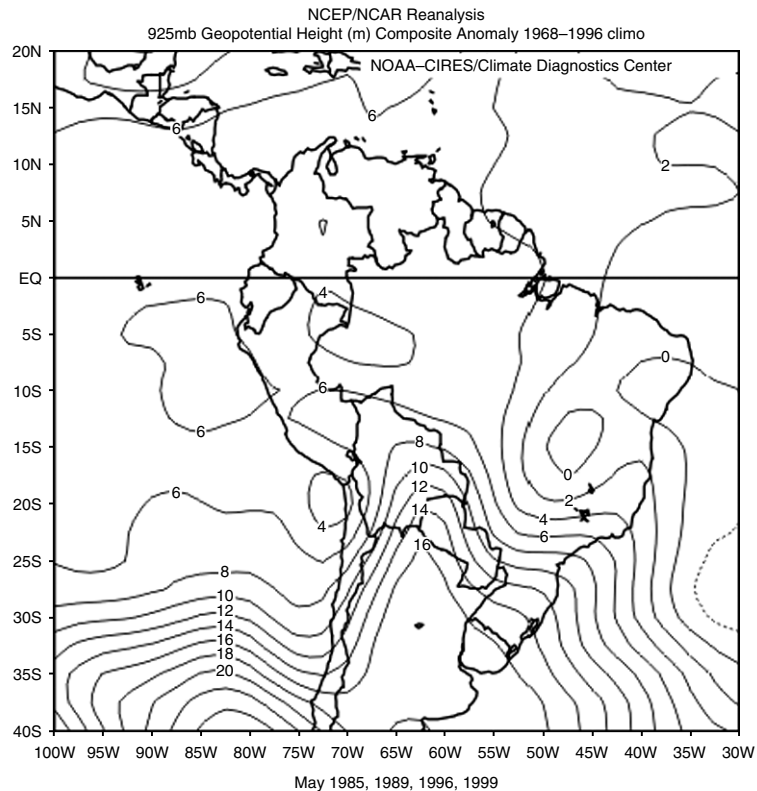


Figure 9. 925 hPa geopotential height (m) composite anomalies from the 1968–1996 mean for May La Niña during the 1980–2001 period

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