Clim. Past Discuss., 4, 173–211, 2008
www.clim-past-discuss.net/4/173/2008/

Climate of the Past Discussions

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Response of regional climate and glacier ice proxies to El Niño-Southern Oscillation (ENSO) in the subtropical Andes

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Received: 11 January 2008 – Accepted: 18 January 2008 – Published: 14 February 2008

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

El Niño-Southern Oscillation (ENSO) is an important element of earth's ocean-climate system. To further understand its past variability, proxy records from climate archives need to be studied. Ice cores from high alpine glaciers may contain high resolution ENSO proxy information, given the glacier site is climatologically sensitive to ENSO. We investigated signals of ENSO in the climate of the subtropical Andes in the proximity of Cerro Tapado glacier (30°08′ S, 69°55′ W, 5550 m a.s.l.), where a 36 m long ice core was drilled in 1999 (Ginot, 2001). We used annual and semi-annual precipitation and temperature time series from regional meteorological stations and interpolated grids for correlation analyses with ENSO indices and ice core-derived proxies (net accumulation, stable isotope ratio $\delta^{18}O$, major ion concentrations). The total time period investigated here comprises 1900 to 2000, but varies with data sets. Only in the western, i.e. Mediterranean Andes precipitation is higher (lower) during El Niño (La Niña) events, especially at higher altitudes, due to the latitudinal shift of frontal activity during austral winters. However, the temperature response to ENSO is more stable in space and time, being higher (lower) during El Niño (La Niña) events in most of the subtropical Andes all year long. From a northwest to southeast teleconnection gradient, we suggest a regional water vapour feedback triggers temperature anomalies as a function of ENSO-related changes in regional pressure systems, Pacific sea surface temperature and tropical moisture input. Tapado glacier ice proxies are found to be predominantly connected to eastern Andean summer rain climate, which contradicts previous studies and the modern mean spatial boundary between subtropical summer and winter rain climate derived from the grid data. The only ice core proxy showing a response to ENSO is the major ion concentrations, via local temperature indicating reduced sublimation and mineral dust input during El Niño years.

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1 Introduction

El Niño-Southern Oscillation (ENSO) is a quasi-regular and highly variable ocean-atmosphere oscillation with a periodicity of two to seven years, which plays an important role in the natural interannual climate variability on earth (Allan, 2006; Labeyrie et al., 2003; Sheinbaum, 2003). El Niño (La Niña) events are defined as positive (negative) sea surface temperatures anomalies (SSTA) in the central equatorial Pacific, which change regional precipitation and temperature worldwide by altering global oceanic and atmospheric circulation (Ropelewski and Halpert, 1987; Kiladis and Diaz, 1989; Rasmusson and Arkin, 1993; Trenberth et al., 2005). As strong events may result in high social and economic costs (Glantz, 1996; Pfaff et al., 1999; Cavazos and Rivas, 2004), it is an exigency to study ENSO's past variability in order to understand its future response to global climate change.

Ice cores from high-alpine glaciers are potential natural archives for the reconstruction of paleoclimatic variability. They may preserve high resolution proxy records provided these glaciers are not disturbed by post-depositional processes such as melting, sublimation and wind erosion (Eichler et al., 2001; Stichler et al., 2001; Hardy et al., 2003). Located in an ENSO-sensitive region ice-core derived proxies may be used to reconstruct regional and local climate including information about past ENSO variability (Knüsel et al., 2005; Hoffmann et al., 2003; Bradley et al., 2003). One of those regions is Mediterranean Chile (Kiladis and Diaz, 1989; Rasmusson and Arkin, 1993), i.e. the western part of the subtropical Andes, located at about 29° to 35° S and 68° to 72° W in the semi-arid transition area between low and mid latitude atmospheric circulation in southern South America (Fig. 1). Along the Pacific coast, precipitation ranges from less than 400 mm/a at 30° S to 4000 mm/a at 40° S (Veit, 1992; Schmidt, 1999).

One of the northernmost cold glaciers in the high cordillera south of the hyperarid Atacama Desert suitable as climate archive is located on the Chilean Cerro Tapado (30°08′ S, 69°55′ W) in the border region of Mediterranean Chile and north-western Argentina (Fig. 1). In its accumulation area at 5550 m a.s.l., a 36 m long ice core

(27.9 m water equivalent [m weq]) was drilled to bedrock in 1999 (Ginot, 2001). It has already been used for studying post-depositional processes such as sublimation and dust accumulation as well as for the reconstruction of the glacier‘s past mass balance (Ginot et al., 2001, 2002, 2006; Stichler et al., 2001).

As Cerro Tapado is located in a climatic transition area between austral winter and summer precipitation regimes, moisture may be provided from both the western and the eastern part of southern South America (Schotterer et al., 2003). Occurrence and amount of precipitation strongly fluctuate on interannual time scales as typical for a (semi-) arid climate (Weischet, 1995; Schmidt, 1999). Nevertheless, the main source of precipitation is supposed to be the Pacific Ocean and west wind frontal circulation during the austral winter months similar to Chilean coastal Mediterranean areas (Ginot et al., 2006). In austral summer, the extension of the South Eastern Pacific Anticyclone (SEPA) causing dry and stable weather conditions with southerly winds over the cold Humboldt Current off the Chilean coast impedes the jet stream and, thus, frontal activities from advancing to the north (Gallego et al., 2005). However, some moisture may be provided from tropical South America in connection with the northwest Argentinean low pressure system at around 25° S and 65° W (i.e. Chaco Low; Seluchi and Marengo, 2000), as already known from the adjacent Atacama Desert and the eastern Andean forelands (Vuille and Ammann, 1997; Grimm et al., 2000). Supporting this, an automatic weather station installed at Cerro Tapado from March 1998 to February 1999 registered greater relative humidity in December and January 1998/99 compared to the austral winter months August to October 1998 (Begert, 1999). Additionally, meteorological data from along the Chilean Elquí Valley and a classification of precipitation events in the higher altitudes aided by satellite images from 1995 to 1997 (Begert, 1999) suggested an increasing share of convective summer precipitation in total precipitation with increasing elevation. Nevertheless, due to the limited duration of this investigation and to the altogether sparse local meteorological information neither the dominant climatic influence on the Tapado glacier could be ascertained, nor the local ENSO response.

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The ENSO-influence on regional climate in southern South America is highly variable depending on the timing and intensity of the development of a particular event (ENSO's "different flavours", Trenberth and Stepaniak, 2001) as shown by Grimm et al. (2000). Nevertheless, some general characteristics illustrate the sensitivity of Mediterranean Chile with regard to ENSO: The influence of ENSO on regional precipitation is well known for lower Chilean altitudes (approx. 0–1000 m a.s.l.) around 33° to 35° S (Aceituno, 1988; Rutllant and Fuenzalida, 1991; Aceituno and Montecinos, 1993; Grimm et al., 2000; Montecinos et al., 2000; Montecinos and Aceituno, 2003). In this area higher (lower) than normal winter precipitation was observed in El Niño (La Niña) years due to a northward (southward) shift of the subtropical jet stream and a less (more) intense SEPA, which is part of the positive (negative) phase of the Pacific-South American (PSA) pattern (Mo and Higgins, 1998; Carleton, 2003). The same mechanisms cause higher snow accumulation and a positive mass balance of some glaciers between 32° and 34° S in the higher altitudes of the subtropical Andes (>1000 m a.s.l.) during El Niño events (Cerverny et al., 1987; Escobar et al., 1995; Leiva and Cabrera, 1996; Escobar and Aceituno, 1998; Leiva et al., 2007; Gallego et al., 2007).

ENSO also alters regional air pressure and temperature at the eastern slopes of the subtropical Andes, i.e. in north-western Argentina, where negative and positive anomalies in El Niño winters were found, respectively (Barros and Scasso, 1994; Grimm et al., 2000). This seems to be due to an intensification of the convective Chaco Low and to the advance of warm tropical air masses from the Amazon Basin and the Atlantic Ocean (Barros and Scasso, 1994; Grimm et al., 2000; Seluchi and Marengo, 2000) as Hadley and Ferrel Cells are weaker in El Niño years over the South Atlantic Ocean compared to the South Pacific Ocean (Yuan, 2004).

However, the relation between ENSO and air temperature in the investigation area as well as the ENSO-link to precipitation in north-western Argentina have not been studied in sufficient detail for adequately interpreting natural climate archives. Most studies on ENSO in southern South America are based on meteorological station data which have a poor coverage and short records in the remote and high-alpine border region of Chile and Argentina (Barros and Scasso, 1994; Gallego et al., 2007), where there are potential glacier archives.

The aim of this study is to investigate the regional ENSO response in the area of Cerro Tapado using grid and point meteorological data in order to establish a relation between ENSO and climate proxies conserved in the Tapado ice core.

2 Material and methods

2.1 Data sets

Different ENSO indices were chosen to study the particular influence of ENSO's oceanic and atmospheric manifestation on the subtropical Andean climate. As a representation of the SSTA in the equatorial Pacific we selected the Niño 3.4 index of Trenberth and Stepaniak (2001), which showed the closest relation to Central Chilean climate in a comparison of different oceanic indices (Ziessler, 2007). Furthermore, we used the Southern Oscillation Index (SOI) of Ropelewski and Jones (1987) and Allan et al. (1991), which indicates anomalies in atmospheric sea level pressure difference between Papete, Tahiti and Darwin, Australia. As a third ENSO index, we selected the Coupled ENSO Index (CEI) of Gergis and Fowler (2005), which contains both the oceanic (Niño 3.4) and the atmospheric (SOI) signal of ENSO. This has the advantage that times of strongly and loosely coupled ocean-atmosphere variability are represented showing negative (positive) values during El Niño (La Niña) events like the SOI (Gergis and Fowler, 2005).

To decipher the ENSO impact on the climate of the subtropical Andes, we tested two different grid data types. The spatially interpolated precipitation and temperature data of Willmott and Matsuura (2001) have a grid resolution of 0.5° longitude to latitude and are interpolated monthly from all available meteorological stations data worldwide, covering the time span from 1950 to 1999. This "Willmott data" set was obtained for the area 29° S to 35° S and 71.5° W to 67° W, including the western and eastern forelands

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of the subtropical Andes (Fig. 1). The second grid type was the vertically differentiated NCEP/NCAR-reanalysis data (Kalnay et al., 1996) with a resolution of 2.5° longitude to latitude covering the period 1960 to 2004. Here, monthly climatological data such as air temperature, precipitable water content, relative and specific humidity were considered.

Monthly temperature and precipitation data sets of the four meteorological stations La Serena, Santiago (Chile) and San Juan, Mendoza (Argentina) obtained from the Global Climate Perspectives System (Baker et al., 1995) and the Global Historical Climate Network (Vose et al., 1992) were also used in the correlation analysis. Table 1 summarises their varying qualities and time periods.

As potential ENSO ice core proxies we selected net accumulation, the stable isotope ratio $\delta^{18}O$ and a bulk parameter of major ion concentration. Net accumulation as derived from annual layer thickness represents either annual or seasonal precipitation, depending on the precipitation distribution around the year. Net accumulation is sensitive to post-depositional effects such as wind drift of snow or sublimation (Hardy et al., 2003; Ginot et al., 2006).

$\delta^{18}O$ [‰ SMOW] of ice cores has been used as an integrated proxy either for temperature or for precipitation, depending on latitude and the dominant isotope fractionation processes (Rozanski et al., 1993). In the tropics, precipitation amount and re-evaporation processes in the course of air mass trajectories seem to be the main factors controlling the isotopic composition in ice cores (Rozanski et al., 1993; Vimeux et al., 2005). At higher latitudes, air temperature during precipitation dominates the isotopic fractionation of snow (Dansgaard, 1964, 1985). In the transition area of subtropical Chile the importance of air temperature in fractionation processes was shown by Rozanski and Araguas-Araguas (1995) for low altitudes. $\delta^{18}O$ signals may also be altered post-depositionally, e.g. by diffusive mixing between firn and snow (Johnson et al., 1977) or removed by mass loss (Schotterer et al., 2003).

The major ion concentrations of the Tapado ice core are assumed to reflect intense post-depositional effects during dry periods. High values represent high input of mineral dust by dry deposition (especially Na^+, Ca^{2+} and Mg^{2+}) and/or an enrichment of some major ions (K^+, SO_4^{2-} and Cl^-) due to strong sublimation processes (Ginot et al., 2001), whereas low values are characteristic of precipitation during extended wet periods.

Major ion concentrations of the Tapado ice core were analysed using ion chromatography (Ginot et al., 2001) and $\delta^{18}O$ with stable isotope ratio mass spectrometry (Stichler et al., 2001). From these records only the upper 23.5 m weq and 20.1 m weq depth were used because of a hiatus at 23.5 m weq (Ginot et al., 2002) and a too low resolution of the $\delta^{18}O$-record beyond 20.1 m weq, respectively (Ginot, 2001).

2.2 Data preparation and statistical methods

Missing values in the meteorological data sets were replaced by the appropriate long term monthly mean. Missing data in the Mendoza Observatory time series was substituted using data from Mendoza Airport (Table 1); this composite and enlarged record is referred to as "Mendoza". The data of the four Willmott-grids closest to Cerro Tapado were averaged and are referred to as Willmott glacier data.

To determine how well regional climatic variability was represented by Willmott- and NCEP/NCAR-grids, a correlation analysis was conducted with available instrumental data from meteorological stations (Table 2).

In order to investigate the connection between regional climate and ENSO in a temporal way, annual and semi-annual time series were used. A year is defined from May to April and the austral winter (summer) term from May to October (November to April). Time periods used in linear correlation analyses depended on the maximum length of the available data set overlap. This was 1900 to 2000 for precipitation data (La Serena to 1992), whereas for temperature time periods varied (Table 1). Finally, correlation coefficients (r) and their respective explained variance ($r^2 \times 100$) were tested for significance using a standard Student's t-test. Results are only discussed when they reached significance at a certain level as stated below.

Furthermore, correlation analyses were performed using non-moving three-year averages of instrumental precipitation and temperature time series starting at 1901 to see whether ENSO-teleconnections differed with time scale.

To retrieve an integrated record of the ionic composition of the Tapado ice core, we calculated the first principal component (PC1) of the standardised concentrations of sulphate, calcium, nitrate, chloride, natrium, ammonium, potassium and magnesium (ordered from high to low average concentrations in the ice core) which accounts for 66.8% of their variability. The ice core was dated by annual layer counting of PC1 and the δ^{18}O record with maxima assumed to occur in January. Dating was supported by a comparison of tritium activity in the ice core with the tritium activity in precipitation at Kaitoke meteorological station, New Zealand, resulting from the nuclear testing in the 1960s (U. Morgenstern, GNS NZ, personal communication). No correction for layer thinning was needed as the glacier was too shallow (Ginot, 2001).

The estimated dating error is +/– 2 years for the time period of 1921 (1937) to 1998 of dated PC1 (δ^{18}O), in accordance to Ginot et al. (2005). After dating, the annual net accumulation [mm/a] was calculated using layer thickness between the annual maxima in PC1. However, this approach is more sensitive to errors than annual averages of other proxies in attributing summer horizons (Henderson et al., 2006). In order to account for the dating uncertainty non-moving three-year averages of ice core proxies were used for correlation analyses (Fig. 2). The averaging process is supposed not to dampen the ENSO-signal which has an interannual periodicity of 2.5 to 7 years (Allan, 2006).

3 Results

3.1 Representation of regional climate in grid data

Precipitable water content, relative and specific humidity as well as air temperature time series of the NCEP/NCAR-model were either negative or uncorrelated with the respective instrumental precipitation and temperature data (not shown). Thus, they could not reflect the regional climatic variability. Reasons for this might be the too low spatial resolution and/or a too simple approximation of global-scale climate models to adequately represent the small-scale climate gradients of the subtropical Andean mountains, reaching altitudes of 6000 m within east-west distances of around 100 to 200 km in this area (Fig. 1). They were not further used.

In contrast, the variability of the instrumental time series was in good agreement with the respective Willmott grid interpolation (Appendix A, Table A1). In addition, Willmott data clearly represented the climatological transitions with altitude in temperature and with latitude in precipitation patterns (Fig. 3). Another feature, the "Arid Diagonal" from northwest to the southeast of the region as caused by the SEPA and the Andean lee was reflected in smaller precipitation quantity (Fig. 3). This suggests a high suitability of the Willmott data to represent the climatic variability of the subtropical Andes.

3.2 Regional climate and ENSO

3.2.1 ENSO-related climate patterns: grid data

Correlation analyses of annual Willmott data and ENSO in the time period 1950 to 1999 at the 95% significance level showed clear seasonal and spatial teleconnection patterns consistent for all ENSO indices. Correlation results with the Niño 3.4 index were principally positive, when SOI and CEI were negative. However, there were differences in the strength of teleconnection depending which ENSO index was used, e.g. lowest r^2 were typically yielded with the Niño 3.4 index. To avoid redundancy, patterns are only presented with the CEI (Fig. 4), whereas those with the Niño 3.4 index and the SOI are shown in Appendix B (Figs. B1, B2).

In accordance to Aceituno (1988), Grimm et al. (2000) and Montecinos et al. (2000), among others, there was a strong connection between ENSO and precipitation in the Mediterranean part of the subtropical Andes especially during winter terms. At around 31.5° S to 33.5° S and 70° W to 71° W the highest variance of annual and winter precipitation could be explained by ENSO variability (Fig. 4a). The maximal r of −0.59 and

−0.65, respectively, were much higher than the correlation coefficient of $r=-0.45$ obtained by Aceituno (1988) for the July–August averages of precipitation in Santiago with the SOI. Apparently, higher altitudes receive more precipitation during El Niño events, while there are no effects at the coast. The cordillera east of Santiago did not show a connection between precipitation and ENSO suggesting that the ENSO influence on annual precipitation weakens at around 33.5° S in a narrow corridor (Fig. 4a). Furthermore, annual precipitation in the eastern forelands was connected to ENSO only south of 33.5° S, explaining up to 15% of its variance in the considered time period. However, this appears to be the result of a connection between summer precipitation and ENSO in this area, though it was visible only in the correlation analysis with the CEI and not with the SOI or Niño 3.4 index (Fig. 4a, Figs. B1, B2). No further relation existed between precipitation and ENSO in the summer term.

Concerning ENSO-related temperature patterns, we found similarly strong correlations as for precipitation, but in contrast they covered almost the entire subtropical Andes (Fig. 4b). Air temperature was higher (lower) in El Niño (La Niña) years. The temperature teleconnection pattern consisted of a decreasing gradient in correlation strengths from northwest to southeast of the region (Fig. 4b). Thus, ENSO explained up to 42% of winter temperature variance in the north-westernmost grids. This pattern also persists in summer in the northwest with still up to 34% of explained variance, indicating a seasonally more stable linkage of ENSO to temperature than to precipitation. Only by using CEI, among all ENSO indices, this summer pattern was found to extend further south along the highest cordillera.

At Cerro Tapado, both precipitation and temperature could partially be explained by ENSO variability. Local temperature was all year long and in average over all Willmott glacier grids more closely connected to ENSO than local precipitation (Fig. 4a, b). Correlation analysis using three-year averaged time series yielded similar but less significant results mainly due to reduced time series.

3.2.2 ENSO-related climate patterns: point data

Correlation analyses for point data from meteorological stations and ENSO indices principally yielded the same results at the 95% significance level as the corresponding Willmott data, with some variations due to longer and different time periods (Fig. 5). In accordance to the results using Willmott data the linkage of ENSO teleconnection to the winter season persisted at the Chilean stations. Precipitation of Santiago correlated with slightly higher r^2 than the one of La Serena unlike their temperature series (Fig. 5). In Argentina, station's precipitation and temperature did not show any correlation to ENSO contrary to the Willmott-data with the exception of San Juan's winter temperatures. Differences depending on the type of ENSO index used were only small (Fig. 5).

Correlation analyses using three-year averaged meteorological data mainly resulted in similar teleconnection patterns. However, higher correlations to ENSO were observed at the Chilean stations even though time series were reduced due to averaging (Fig. 6). Whether the changes in signal strength are part of different ENSO "flavours" described by Trenberth and Stepaniak (2001) and, therefore, an actual change in teleconnection processes or simply an artefact may not be stated from this study.

3.3 The Tapado ice-core derived proxies, regional climate and ENSO

3.3.1 General climatic situation at Cerro Tapado

The climatic divide between subtropical winter and summer rain climate generally follows the continental watershed and is situated east of Cerro Tapado (Fig. 7). As a first estimate obtained from the Willmott glacier grids, winter precipitation accounts for 69 to 88% of the mean annual precipitation around Cerro Tapado (Fig. 7), in accordance to the suggested winter rain regime of the region (Ginot et al., 2006). As a proxy for mean annual precipitation, the mean annual total accumulation was calculated to be 515 mm/a for the time period of 1921 to 1998 (in accordance to Ginot et al., 2006),

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corrected for sublimation as estimated after Ginot (2001). This is approximately 2.5 times the mean annual precipitation of 202 mm/a at La Laguna, a Chilean meteorological station around 3 km southwest of Cerro Tapado at 3100 m a.s.l. (time period: 1964–1997; Begert, 1999).

The discrepancy may be explained by an altitudinal effect as well as by the particular geomorphic setting of the Tapado glacier located in a southerly exposed cirque. There, lower insolation reduces sublimation compared to glacier‘s vicinity, thus preserving precipitation at the glacier. However, also a higher influence of summer precipitation via convection of tropical moisture may be possible.

3.3.2 Climate signals in the Tapado ice-core proxies

The Tapado ice-core proxies net accumulation, major ion concentration and δ^{18}O are independent from each other, suggesting that they are triggered by different climatological processes during proxy record genesis. None of the proxies is correlated neither with climate data of the western Andean stations, winter precipitation or annual temperature at the eastern Andean stations, nor with winter climate of local Willmott glacier data at the 90% significance level as would be expected in a dominant winter precipitation regime (Fig. 8).

Nevertheless, net accumulation is weakly positively correlated with annual and summer precipitation of San Juan and Mendoza and negatively correlated with Argentinean summer temperature time series (Fig. 8). Additionally, high local summer precipitation of Willmott glacier data was associated with high net accumulation in the ice core (Fig. 8). However, no correlation was found between net accumulation and ENSO indices (Table 3), in contrast to Piloto glacier (32° S, Leiva et al., 1999) and Echaurren glacier (33° S, Escobar et al., 1995) located south of Cerro Tapado.

Though fractionation processes may differ from low Mediterranean altitudes supporting the role of temperature as a controlling factor (Rozanski and Araguas-Araguas, 1995), the Tapado δ^{18}O-record correlated with local summer temperature (Fig. 8), whereas no significant correlation was found with precipitation or ENSO (Table 3).

PC1 of major ion concentrations was low when annual and summer precipitation in San Juan were high (Fig. 8). Additionally, PC1 is anticorrelated with annual and summer temperatures of the local Willmott data. There are further positive connections between PC1 and winter (summer) temperature in Mendoza (San Juan). The ionic composition of the Tapado ice core is the only proxy to correlate with annual and seasonal ENSO time series, with low ion concentrations during El Niño years (Table 3). Highest connections were found in the summer term and with the SOI, whereas lowest linkage existed to the Niño 3.4 index and in winter (Fig. 8). Up to 25% of major ion variability in the ice core could be explained by ENSO variability.

4 Discussion

4.1 ENSO-related regional climate patterns

Annual and semi-annual precipitation and temperature behave differently in ENSO-teleconnection patterns. This allows us to discuss the kind of influence ENSO has on climatic parameters in this region and finally on the Tapado ice core. High correlation is interpreted as a high sensitivity to ENSO during all events, whereas low correlations suggest a response to strong events at most.

ENSO-related precipitation is mainly driven by the northward shift of the subtropical jet stream, which results in higher wind velocities, more intense frontal activity and above average precipitation in El Niño years (Rutllant and Fuenzalida, 1991; Grimm et al., 2000; Gallego et al., 2005). In this study, we found the most sensitive region to these change around 32.5° S. The effect appears more pronounced at higher altitudes, for example in the coastal cordillera at and south of Santiago, than at the coast due to advective processes. Farther north only shifts of the westerlies during strong El Niño events result in anomalously high precipitation at the western slopes of the Andes, as may be concluded from slightly lower correlations between precipitation and ENSO north of Cerro Tapado (Fig. 4a) and from comparing the results of La Serena and

Santiago (Fig. 5a). South of 35° S a more persistent influence of the subtropical jet is to be expected (Gallego et al., 2005) which reduces the sensitivity to an ENSO-related shift of the westerlies, as shown by Escobar and Aceituno (1995) for winter snow accumulation. In our study, we noticed this effect only in the small corridor of the cordillera east of Santiago (Fig. 4a). However, our study reveals a region south of Mendoza responding to El Niño with higher precipitation in summers when ocean and atmosphere anomalies are strongly coupled, whereas in the study of Grimm et al. (2000) precipitation anomalies in this region were observed in winter at most. This could be due to a change in moisture advection from the south in association to polar outbreaks (Seluchi and Marengo, 2000), though their connection to ENSO has not been studied yet.

Temperature is strongly influenced by ENSO in most of the region as well. Until now, this has been shown only for the eastern part of the region (Barros and Scasso, 1994) and the Atacama Desert (Garreaud et al., 2003; Rutllant et al., 2004), but it appears even more consistent and seasonally stable in the (north-) western part of the studied area. This might be explained by stronger Hadley and Ferrel Cell activity transporting more latent heat from the tropics to high latitudes over the Pacific in El Niño years (opposite in La Niña years; Yuan, 2004). However, due to the teleconnection gradient from northwest to southeast, which is consistent with higher r^2 for La Serena compared to Santiago, we suggest a dominant influence of the SEPA via a regional water vapour feedback (Manabe and Wetherald, 1967; Soden et al., 2002; Philipona et al., 2005). During El Niño events the SEPA weakens horizontally and vertically. Then, a reduced upwelling of the Humboldt current, which gets warmer and releases latent heat (Rutllant et al., 2004), balances a decreased air mass warming due to less air descent (Holton, 2004). As the heat flux between ocean and atmosphere is altered mainly by vertical and horizontal temperature advection (Holton, 2004), the water vapour content in the boundary layer rises over the ocean and can be transported overland due to zonal wind anomalies. Increased water vapour in the unsaturated subtropical air reduces the emittance of long wave radiation and, thus, raises temperature (Hall and

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Manabe, 1999; Soden et al., 2002), maybe independent from changes in cloud cover (Philipona et al., 2005). However, latent heat is also released during cloud formation, but the effect is more efficient if water vapour is not removed by precipitation as indicated by the discrepancy between regions with highest correlation patterns of ENSO and precipitation versus temperature in our study. Furthermore, reduced meridional wind lowers the adduction of cold air from mid latitudes (opposite processes during La Niña events). As this regional water vapour feedback seems to be primarily driven by the extension of the SEPA as indicated by the northwest to southeast teleconnection gradient, it will be denoted as "SEPA-feedback" further on.

Evidences for further precipitation and temperature teleconnection patterns revealed in this study provide additional clues on this feedback. In El Niño winters, moisture from the Pacific may favour ENSO-related temperature anomalies via the SEPA-feedback not only at the sensitive western Andean slopes, but also in regions where no correlation with precipitation could be found, e.g. at the coast.

At the eastern Andean slopes, San Juan's temperatures correlate stronger than Mendoza's with ENSO suggesting a similar regional water vapour feedback with a humidity advection from Amazonia. The Chaco Low generally interacts with the SEPA generating a dipole separated by the Andean range (Grimm et al., 2000; Seluchi and Marengo, 2000). During El Niño winters, Barros and Scasso (1994) observed low pressure anomalies, i.e. an enhancement of the Chaco Low. Resulting northerly winds transport more water vapour to the eastern subtropical Andean forelands fostering a temperature increase during convection without precipitation anomalies. However, the major part of annual precipitation and water vapour input at the eastern slopes is in summer, which prevents an ENSO-related moisture feedback to significantly change temperatures. In contrast, SEPA and Pacific SSTA would remain in their anomalous state during the maturation of an ENSO event around December and still influence the regional water vapour content and temperature at the (north-)western subtropical Andean slopes in ENSO-summers. At the same time, the wave shift of the subtropical jet had already swung back to the south, reflected by normal precipitation patterns. Fur-

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thermore, we find a lower temperature teleconnection in the south of the subtropical Andes closer to the persistent frontal activity with generally higher water vapour in the atmosphere. Here, the SEPA-feedback might not change water vapour content significantly. Indirectly, this supports a lower ENSO sensitivity south of 34.5° S (see above), which then is more expressed in temperature than in precipitation patterns.

4.2 Ice core proxy genesis and regional climate

We observed a strong connection of all ice-core derived proxies to summer temperature and precipitation in the northwest Argentinean region. Net accumulation is high when eastern Andean summer temperatures are low suggesting a better preservation of winter precipitation on the glacier when sublimation is reduced. Furthermore, a main humidity input at Cerro Tapado from the east and from tropical circulation may be reflected in the dependence of net accumulation on summer precipitation. This is supported by PC1 which is low during wet summers suggesting a reduced sublimation and mineral dust input.

The δ^{18}O-record appears to conserve mainly local fractionation processes dominated by summer temperatures. How far this shows a post-depositional alteration during summer and/or an influence of summer precipitation cannot be stated from this study. This shows, first, a general problem of glaciers located at climatic divides, where the dominating climate regime is difficult to predict and second, the necessity to evaluate the actual importance of winter and summer precipitation as well as seasonal processes of post-depositional alteration at a given site.

Finally, we only found a significant relation between Tapado's major ion concentrations and ENSO. Their connection might be caused by changes in local summer temperature, which themselves may be influenced by the SEPA-feedback. Thus, there would be a high input of mineral dust and an enrichment of some major ions due to intense sublimation processes under cold conditions driven by an intensified SEPA and a high water vapour gradient between snow and air during La Niña years (opposite in El Niño years). This is in accordance to the high sublimation rates suggested for La Niña

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years by Ginot et al. (2006). Furthermore, high PC1 is associated with low summer precipitation in San Juan indicating reduced moisture advection from the northeast.

Hence, high local temperatures can drive intense sublimation and alter net accumulation in non-ENSO-years, whereas in El Niño years they are associated with decreased sublimation due to increased moisture in the air. Therefore, we suggest independent atmospherical processes trigger local temperature and alter post-depositional processes in dependence on ENSO and the regional water vapour feedbacks discussed above.

5 Conclusion

In this study we showed the subtropical Andes to be an ENSO-sensitive region based upon grid and point meteorological data. Precipitation anomalies along the western and central Andes differ with altitude and respond to a latitudinal shift of the subtropical jet and frontal activity. However, the ENSO influence on temperature is geographically dispersed due to changes in regional water vapour advection and gradients in association to the ENSO-related variability of the SEPA, Humboldt-current's SSTA and the Chaco Low. This specifies the teleconnection processes proposed by Grimm et al. (2000) for precipitation patterns in southern South America, but further studies on regional water vapour transport should follow. Then, these mechanisms might be interesting also for studying other regions in the subtropics and in the context of more frequent El Niño events in times of global warming (Timmermann et al., 1999; Vecchi et al., 2006). Further analyses of ENSO teleconnections should apply the CEI by Gergis and Fowler (2005), which may reveal climatic regions which are influenced only during ENSO related in-phases change of ocean and atmosphere.

At Cerro Tapado, both temperature and precipitation respond to ENSO. However, major ion concentrations are the only Tapado ice core records to represent these responses, with low (high) ion concentrations during El Niño (La Niña) years. There are many possible reasons, why other Tapado ice core-derived proxies do not correlate with ENSO. The correlation analyses with gridded local and meteorological station data suggest a dominant influence of summer precipitation in this region, which itself is independent of ENSO. How far data from lower altitudes actually represent local climate at 5500 m a.s.l. cannot be answered from this study, though the influence of summer climate seems to be a consistent feature.

However, ice-core derived proxies may intensively be altered by secondary processes, whose influence on the Tapado glacier is not totally determinable. Especially the mass loss due to sublimation plays an important role at Cerro Tapado. The intensity of those processes is best recorded in major ion concentrations, whereas the δ^{18}O-record tends to be smoothened making annual layer counting complicated (Fig. 2). The most sensitive proxy towards dating errors is net accumulation (Henderson et al., 2006), which may additionally be altered by wind erosion. This indicates the limits of the Tapado ice core in representing regional climate and ENSO.

Further south and with much less intense post-depositional effects compared to the Tapado glacier, a new, 104 m long ice core from Cerro Mercedario (Bolius et al., 2006) may offer a better chance for reconstructing ENSO variability in general and further in the past. In the Mercedario ice core the first ENSO response may be expected from major ion concentrations, though a less disturbed δ^{18}O-record seems also quite promising to learn more about ENSO variability.

Appendix A

Validation of gridded data

Table A1 shows the results of the correlation analyses comparing Willmott data and the instrumental time series for precipitation and temperature. They are highly and positively correlated suggesting a good representation of regional climate variability.

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Appendix B

Further correlation analysis

Figures B1 and B2 show the results of the correlation analyses of Willmott data with the SOI and Niño 3.4 index.

Acknowledgements. We would like to thank U. Morgenstern for helping with the tritium data and J. L. Gergis for providing the CEI. We are particularly grateful to U. Schotterer for his helpful comments on the manuscript.

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Table 1. Time period and quality of meteorological temperature and precipitation time series used in this study.

Meteorological station	Location	Height [m a.s.l.]	Time period		Missing data [%]	
			Precipitation	Temperature	Precipitation	Temperature
La Serena (Chile)	29.9° S, 71.2° W	146	1869–1993[1]	1901–1948[1]	1.3	0.5
Mendoza Obs	32.9° S, 68.9° W	827	1892–1989[1]	1905–1988[1]	1.9	0.01
Mendoza Aero	32.8° S, 68.8° W	704	1951–2003[2]	–	4.6	–
San Juan Aero	31.6° S, 68.7° W	630	1876–2003[2]	1901–1985[1]	5.0	0.0
Santiago	33.5° S, 70.7° W	520	1867–2003[2]	1945–1998[3]	2.6	0.0

Time period refers to the longest overlap of meteorological and ENSO indices time series. Sources: [1] Baker et al. (1995), [2] Vose et al. (1992), [3] Jorge Carrasco, DGA (personal communication).

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Table 2. Meteorological stations used for validation of the gridded climate data from Willmott and Matsuura (2001) and NCEP/NCAR-reanalysis.

Meteorological station		Willmott-Data[1]		NCEP/NCAR-Data[2]		Meteorological variable to be compared
Name	Height [m a.s.l.]	Southern Latitude [°]	Western Longitude [°]	Grid	GPH [hPa]	
Cristo Redentor	3832	33.25	70.25	7172	700	Temperature
Hd. San Agustin	1020	31.75	70.75	7028	925	Temperature
Mendoza (Aero)	704	32.75	68.75	7173	925	Temperature, Precipitation
San Juan	630	31.75	68.75	7029	925	Precipitation
Santiago	520	33.75	70.75	7172	1000	Precipitation

GPH...Geopotential Height. Sources: [1] Willmott and Matsuura (2001), [2]Kalnay et al. (1996).

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Table 3. Results of correlation analyses of the ice-core derived proxies net accumulation (Net Acc), first principal component of major ion concentrations (PC1) and δ^{18}O-records with ENSO indices.

	Annual			Winter			Summer		
	Net Acc	PC1	δ^{18}O	Net Acc	PC1	δ^{18}O	Net Acc	PC1	δ^{18}O
CEI	−0.16	0.43**	0.05	−0.19	0.38*	0.05	−0.13	0.47**	0.05
SOI	−0.33	0.48**	−0.01	−0.29	0.41**	0.02	−0.33	0.51**	−0.05
Niño 3.4	0.00	−0.34*	−0.12	−0.03	−0.37*	−0.10	0.03	−0.29	−0.14

Given are r at the **...95%, *...90% significance levels. Calculation on basis of Gergis and Fowler (2005), Allan et al. (2006), Trenberth and Stepaniak (2001).

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Table A1. Results of the correlation analyses of monthly, semi-annual (i.e. composite of winter and summer term averages) and annual time series between point and gridded meteorological data at different stations for validation purposes.

Meteorological station	Variable	Time series		
		monthly	semi-annual	annual
Cristo Redentor	Temperature	0.94**	0.98**	0.34*
Hd. San Agustin	Temperature	0.88**	0.91**	0.27
Mendoza-Aero	Temperature	0.99**	1.00**	0.91**
Mendoza-Aero	Precipitation	0.95**	0.97**	1.00**
Santiago	Precipitation	0.94**	0.97**	0.89**
San Juan	Precipitation	0.50**	0.64**	0.17

Given are r at the **...95%, *...90% significance levels. Calculation on basis of Vose et al. (1992), Baker et al. (1995), Willmott and Matsuura (2001).

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Fig. 1. Image of South America with the region of interest and geographical location of the meteorological stations used in this study (LS. . . La Serena, SA. . . Santiago de Chile, SJ. . . San Juan, ME. . . Mendoza). The drilling site on Cerro Tapado (CT, 5500 m a.s.l.) is located close to the border between Chile and Argentina at 30°08′ S and 69°55′ W. DEM and Blue Marble Image were provided by NASA Earth Observatory.

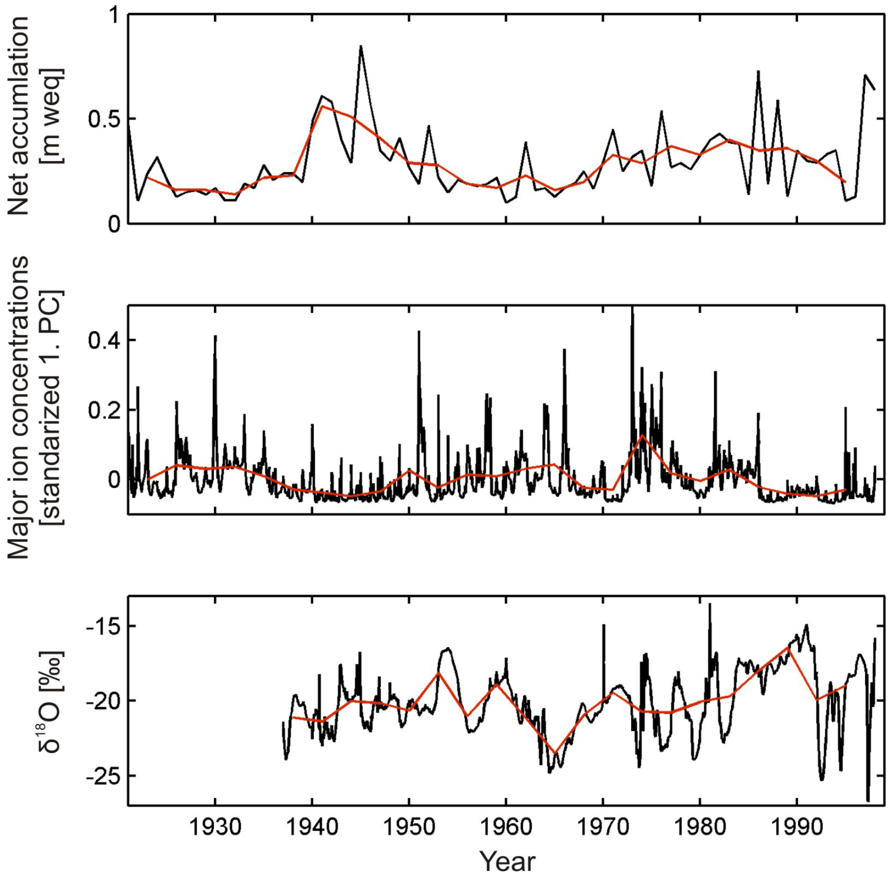

Fig. 2. Records of Cerro Tapado ice core proxies net accumulation, first PC of major ion concentrations and the δ^{18}O-record (from top to bottom). Original data sets in black and three-year non-moving averages ending 1995 in red.

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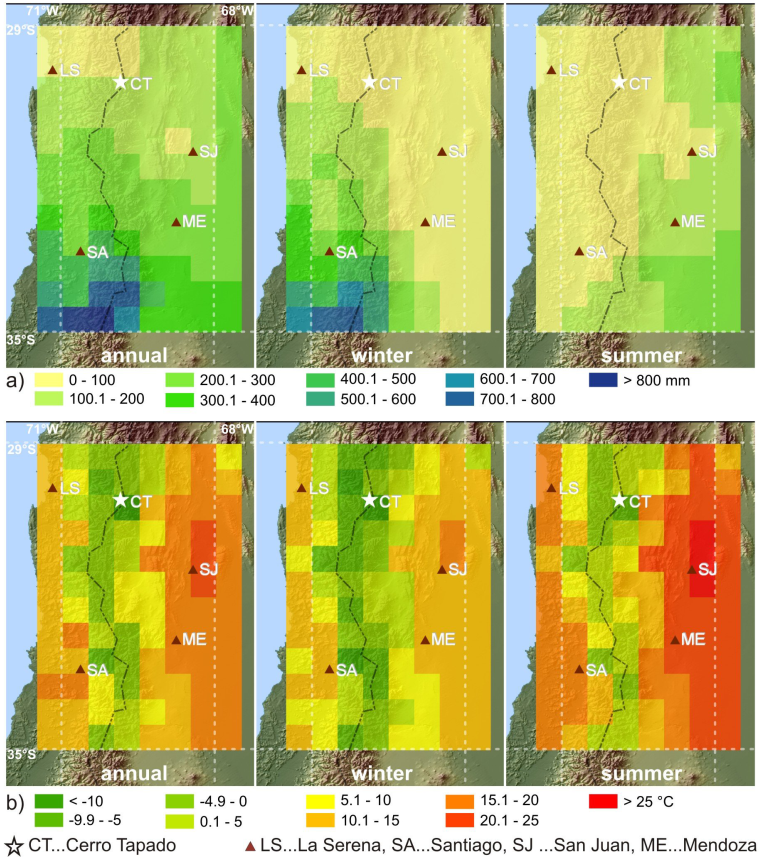

Fig. 3. Mean regional annual as well as winter and summer **(a)** precipitation amounts (mm) and **(b)** averaged temperatures (°C) in the subtropical Andes. Data after Willmott and Matsuura (2001) for the time period 1950 to 1999.

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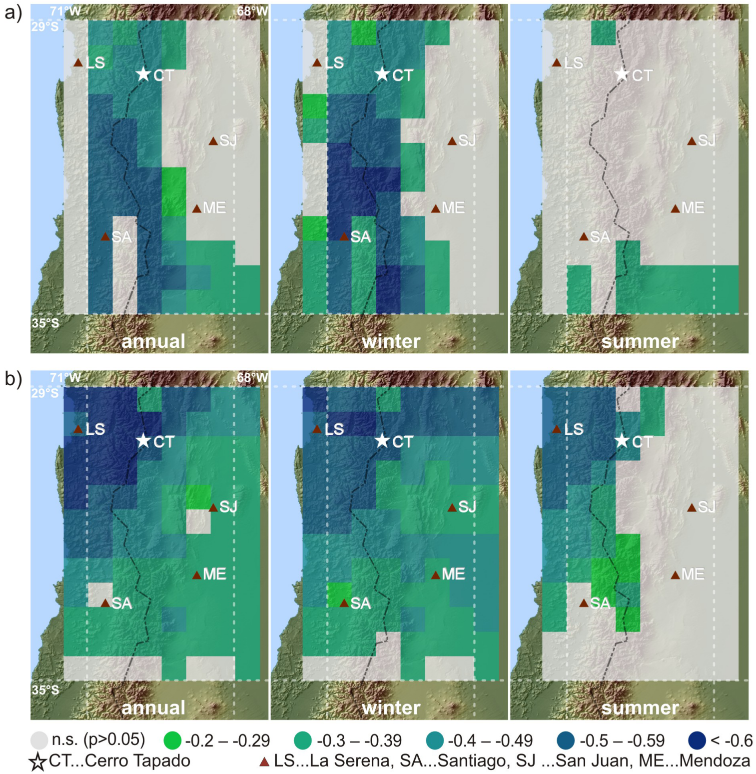

Fig. 4. Coefficients of the correlation analyses between annual as well as winter and summer **(a)** precipitation and **(b)** temperature time series after Willmott and Matsuura (2001) and the CEI of Gergis and Fowler (2005) for the time period 1950 to 1999.

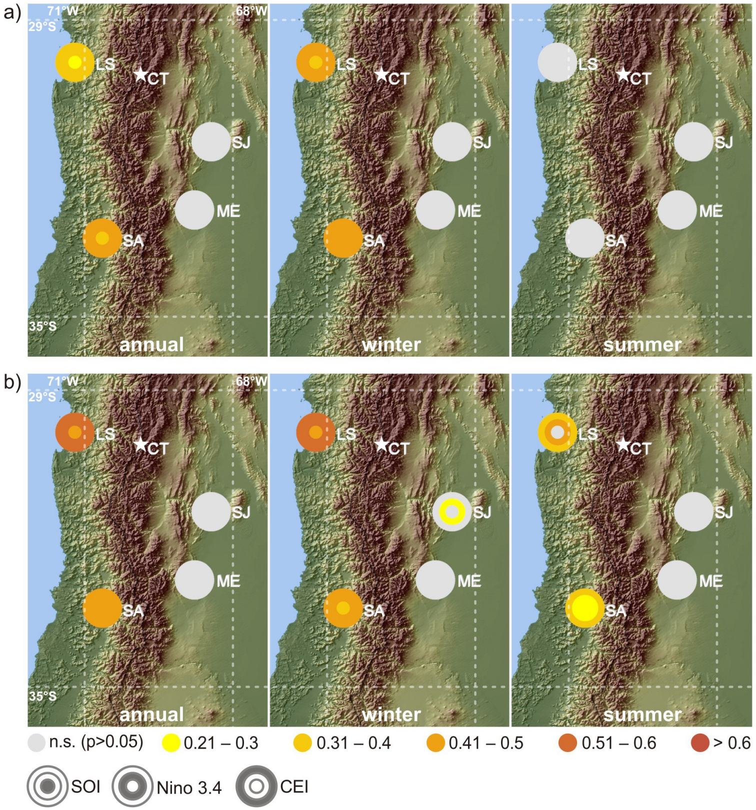

Fig. 5. Coefficients of annual correlation analyses between all ENSO indices (inner to outer ring: SOI, Niño 3.4 index and CEI) and meteorological station data of **(a)** precipitation and **(b)** temperature. Results are inversed for SOI and CEI. Abbreviations as in Fig. 4.

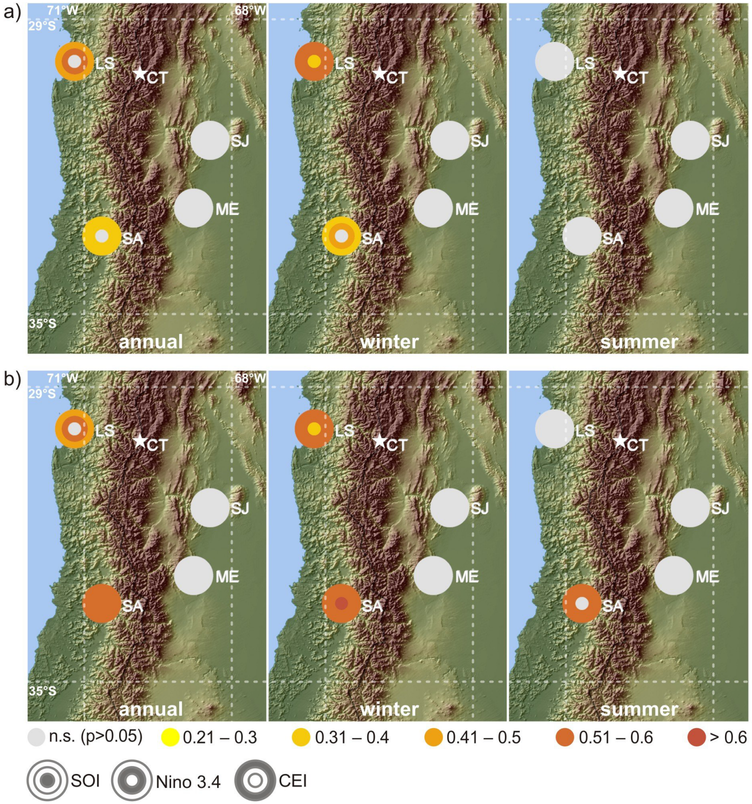

Fig. 6. Coefficients of three-year averaged correlation analyses between all ENSO indices (inner to outer ring: SOI, Niño 3.4 index and CEI) and meteorological station data of **(a)** precipitation and **(b)** temperature. Results are inversed for SOI and CEI. Abbreviations as in Fig. 4.

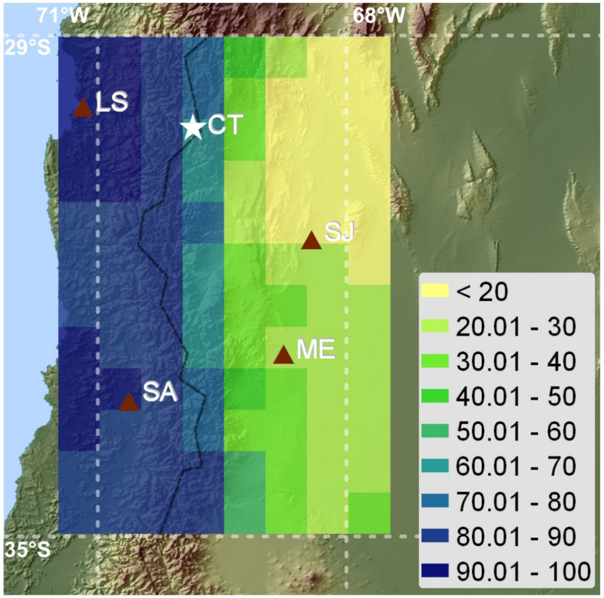

Fig. 7. Percentage winter precipitation of total annual precipitation in the subtropical Andes indicate the boundary between Mediterranean climate at the western and summer rain climate at the eastern Andean slopes (data: Willmott and Matsuura, 2001). Abbreviations as in Fig. 4.

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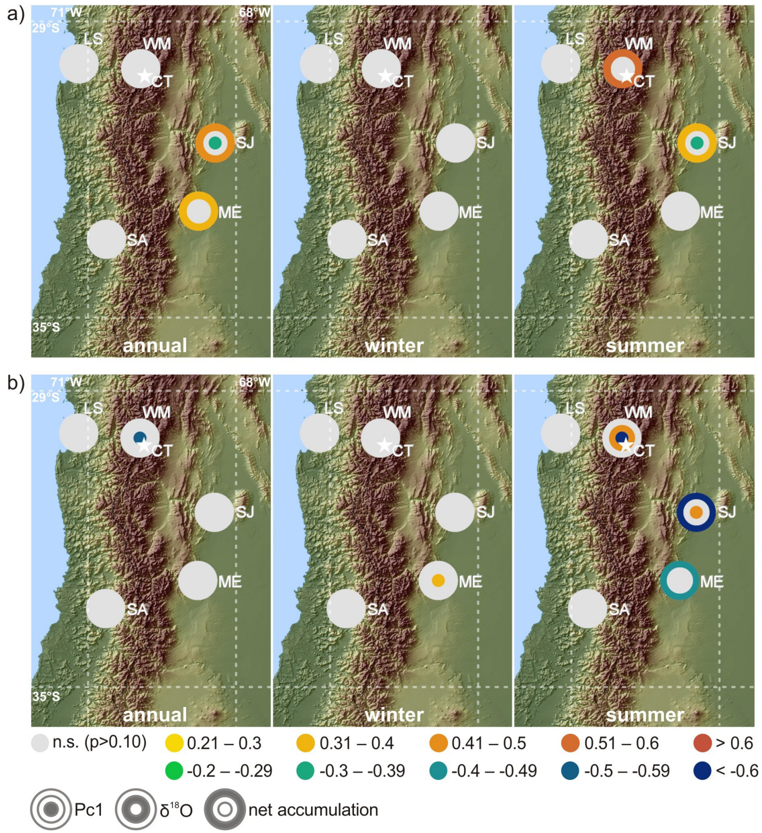

Fig. 8. Coefficients of correlation analyses between Tapado ice core proxies (inner to outer ring: PC1 of the major ion concentrations, δ^{18}O and net accumulation) and meteorological data of **(a)** precipitation and **(b)** temperature. WM: glacier grids after Willmott and Matsuura (2001, see text), other abbreviations as in Fig. 4.

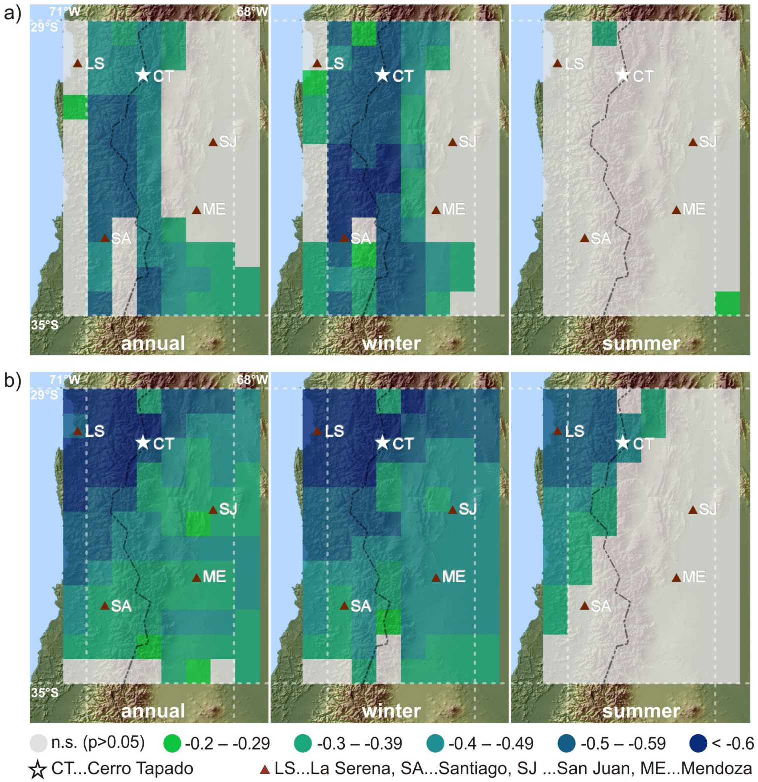

Fig. B1. Coefficients of the correlation analyses between annual as well as winter and summer **(a)** precipitation and **(b)** temperature after Willmott and Matsuura (2001) and the SOI of Allan et al. (1991) for the time period 1950 to 1999.

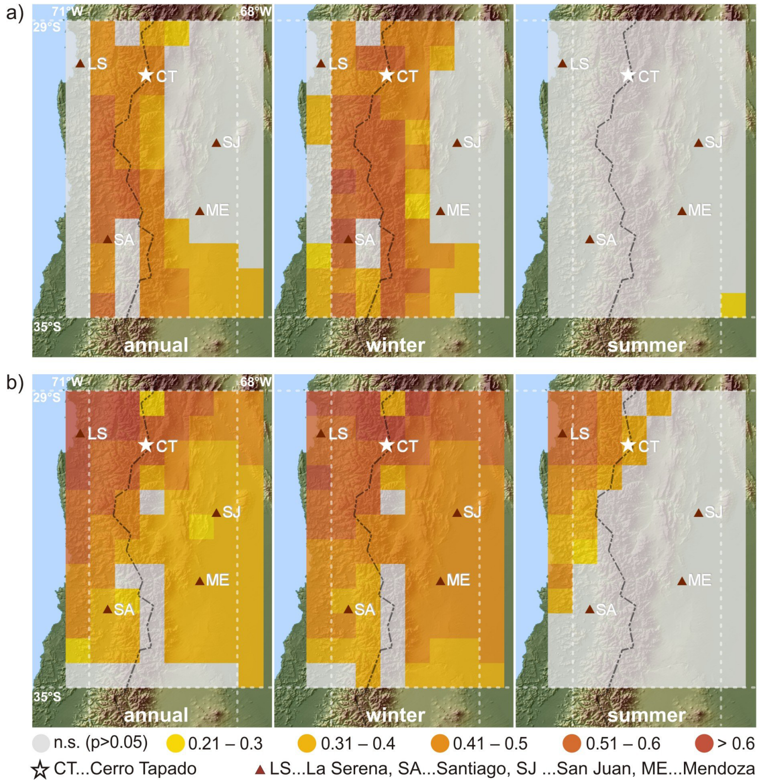

Fig. B2. Coefficients of the correlation analyses between annual as well as winter and summer **(a)** precipitation and **(b)** temperature after Willmott and Matsuura (2001) and the Niño 3.4 index of Trenberth and Stepaniak (2001) for the time period 1950 to 1999.