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Climate in the Monte Desert: Past trends, present conditions, and future projections

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ABSTRACT

This paper documents the main features of climate and climate variability across the Monte Desert for the Last Glacial Maximum, the Glacial–Interglacial transition, and the Holocene on the basis of proxy records and for the 20th century using instrumental observations. The climate in the Monte is determined by interactions between regional physiography and atmospheric circulation in the 25–45°S sectors of South America. Although arid and semi-arid conditions prevail across the Monte, its large latitudinal extent and complex topography introduce many particularities at local scales. Paleoclimatic records and model simulations of past climates suggest significant variations in the atmospheric circulation, temperature and rainfall patterns since the Last Glacial Maximum. High-resolution proxy records east of the Andes support the existence of complex climatic patterns with similar temperature changes across the whole region but opposite precipitation variations between subtropical and mid-latitude sectors in the Monte during the past millennium.

The present-day climate is depicted in terms of the space and time variability of the near-surface temperature, rainfall and tropospheric wind patterns. Uneven temperature trends over the Monte were recorded for two separate (1920–44 and 1977–2001) global warming periods in the 20th century. Additional warming evidence in the region is provided by extreme temperature records. The non-homogeneous regional pattern of precipitation shows a positive long-term increase between 30 and 40°S during the interval 1985–2001. Ensemble of climate experiments accomplished with general circulation models provide the most likely changes in temperature and rainfall to occur by the end of this century in relation to present climate. Temperature increases, larger in summer than in winter, will be concurrent with more abundant precipitations in summer, but almost no changes or even small reductions in winter across the Monte.

1. Introduction

The Monte biogeographical province extends as a latitudinal wedge crossing Argentina from the foothills of the Andes in Salta (24°30′S) to the Atlantic coast in Chubut (44°20′S). Along this biogeographical band the topography is highly variable including plains, inter-mountain valleys, foothills, alluvial fans, and plateaus. Although the Monte is dominated by arid and semi-arid conditions, its large latitudinal extent and complex topography introduce many particularities in the climate at the local level. Diversity of temperature and precipitation in the Monte region should be interpreted in terms of its large meridional extent, the disruption of the large-scale circulation by the Andes Cordillera, and the transitional position between subtropical and mid-latitude circulation features in South America.

The latitudinal extension of the Monte and its proximity to the Andes in the northern and central sectors determine temperature gradients in both north–south and east–west directions. With elevations exceeding 4 km north of 35°S, the Andes represent a formidable barrier for the tropospheric flow. Most precipitation north of this latitude is related to Atlantic air masses. South of 40°S, due to lower elevations (<2 km) of the Andes, the Pacific air masses dominate.

This paper documents the main features of climate and climate variability over the Monte Desert on the basis of proxy records for the recent geological past and of instrumental observations during the 20th century. General circulation models are used to provide the most probable climatic scenarios in the Monte biogeographical province during the next 100 years.

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2. Large-scale temperature and precipitation patterns in the Monte

The distribution of the mean annual temperature in the Monte is influenced by the marked variations in elevation in the vicinity of the Andes Cordillera and, to a lesser extent, by the wide latitudinal range of the region (from 24°35′S to 44°20′S; Morello, 1958). Except in the northern sector where the temperature pattern is largely affected by the mountainous topography, the western and southern limits of the Monte are largely coincident with the 12 °C annual isotherm (Fig. 1a). Table 1 shows some basic climate statistics for nine meteorological stations in the Monte, which provide information on the spatial variations of temperature and rainfall across this biogeographical region. The north–south variation in the mean annual temperature is exemplified by the difference of 3.6 °C between Chilecito (17.1 °C) and Trelew (13.5 °C), distance 1545 km, whereas the strong east–west variation in the mountainous northern–central Monte is illustrated by the difference of 5 °C between La Paz (16.6 °C; 506 m asl) and Uspallata (11.6 °C; 1891 m asl), distance 180 km in east–west direction. San Carlos, at 940 m elevation between the localities of La Paz and Uspallata, has a mean annual temperature of 12.8 °C. The annual thermal amplitude (i.e., the difference in mean temperatures between the warmest and coldest months of the year) reaches 17 °C in the central sector of the region (Fig. 1b). The daily thermal amplitude (not shown in the figures) reaches 15 °C during most of the year in the northern part, an indication of the continental nature of the climate in the Monte. The absolute maximum temperature recorded in the northern sector is 48 °C, whereas the absolute minimum in the continental-southern sector is −17 °C (Le Houérou, 1999).

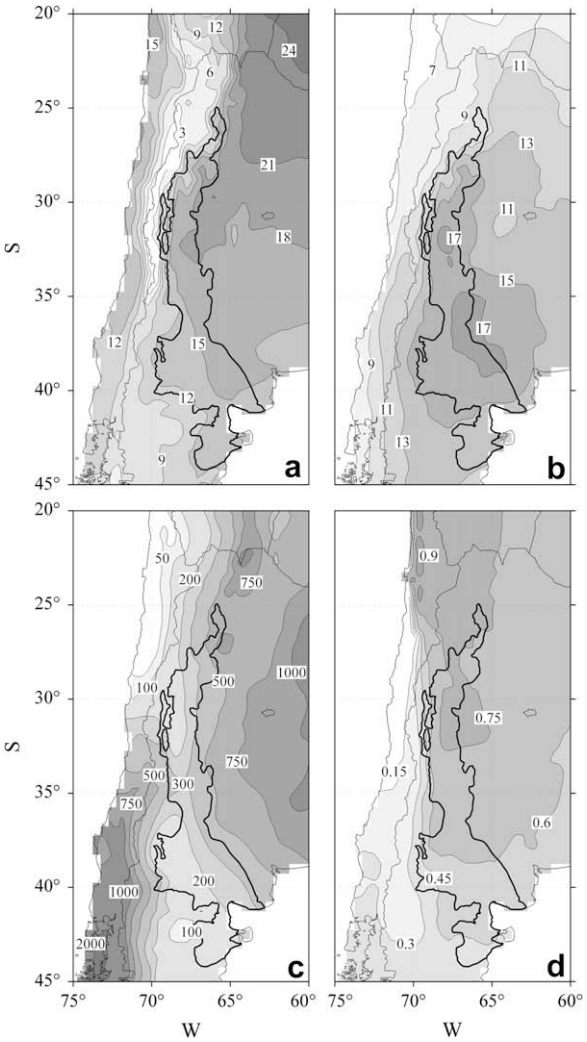

Fig. 1. Distribution patterns of (a) mean annual temperature, (b) annual thermal amplitude (°C), (c) total annual rainfall (mm) and (d) ratio between the spring–summer and total annual rainfall (%) for the 1961–1990 period. Data from CRU TS 2.1 Climate Research Unit dataset (Mitchell and Jones, 2005).

The rain is scarce in the whole region and the total annual precipitation ranges between 100 and 350 mm in most of the area (Fig. 1c, Table 1). The ratio between precipitation and potential evapotranspiration ranges between 0.05 and 0.5, indicating a marked water deficit for the whole area (Rundel et al., 2007). Precipitation is extremely reduced in the central Monte, between southern La Rioja and northern Mendoza, and in the Uspallata–Calingasta–Iglesia valleys due to the rainshadow effect of the Andean Precordillera (Fig. 1c, Table 1).

The frequent arrival of warm, humid and convectively unstable air to the subtropics in Argentina during summer is related to the persistent continental-scale northerly circulation with monsoonal characteristics (Zhou and Lau, 1998). The thermo-orographic low-pressure system located over the Chaco and northwestern Argentina intensifies in summer and increases the ingressions of air masses from the quasi-stationary high-pressure system over the subtropical South Atlantic Ocean and the Amazon Basin (Prohaska, 1976). This mechanism is reinforced by the southward transport of humidity by the Chaco low-level jet, a sub-synoptic scale low-level circulation system that develops to the east of the Andes. Although the low-level jet occurs on average in 17% of the days in summer, it accounts for a maximum of 55% of the rainfall in the northeast, and between 30% and 35% in the northwestern Argentina (Salio et al., 2002). Both mechanisms contribute to the subtropical regime of summer rains, which produces 70–75% of the precipitation in the Monte north of about 35 °S during spring–summer months (Fig. 1d). The rainfall gradient across the northern Monte is largely zonal (decreasing from east to west), which is clearly indicated by the rainfall variation from La Paz (250 mm) to Uspallata (147 mm) located both at approximately 33°S (Table 1).

A transitional zone from the summer rain toward the winter-rain domains, characteristic of the southern Pacific coast and Patagonia, is observed south of 35°S. Across continental Patagonia, precipitation is mainly concentrated from May to October and is associated with the increase in the frequency of Pacific synoptic perturbations during these months of the year (Prohaska, 1976). The southern sector of the Monte, located within a transitional zone to the Atlantic coast, has a relatively uniform annual distribution of rains with relative minor maxima in fall and spring months.

The storm tracks, the region where mid-latitude cyclones are most frequently observed, are usually located on the polar side of the jet stream throughout the year (Trenberth, 1991). The average speed of the jet stream in high levels of the troposphere reaches in summer a maximum value of 25 m s^{-1} and crosses the southern part of the continent between 45°S and 50°S, far south from the Monte (Fig. 2a). In winter, however, the maximum is located between 25°S and 30°S over the Monte desert and its average speed rises to 35 m s^{-1} (Fig. 2b). Thus, the jet stream and the corresponding storm tracks location influence rains in the central and southern part of the Monte during winter.

In the north and central sectors of the region, dominant winds in the lower troposphere are from the northeast in summer and from northwest in winter, whereas in the south they are from the west throughout the year (Fig. 2a and 2b). The summer rainfall, maximum over the northern and central zone of the Monte Province is caused by horizontal convergence of the northeasterly water vapor flux and by the orographic uplift on the eastern foothills of the Andes (Labraga et al., 2000).

Table 1
Mean annual temperature, mean maximum temperature, mean minimum temperature and total annual rainfall at nine meteorological stations located across the Monte.

Station	Coordinates Lat S, Lon W	Elevation (m)	Mean temp. (°C)	Max. temp. (°C)	Min. temp. (°C)	Precipitation (mm)
Andalgalá	27.56, 66.32	1072	17.9	27.0	11.5	308
Chilecito[a]	29.17, 67.51	1170	17.1	25.5	10.4	194
Jachal	30.25, 68.75	1165	16.3	–	–	119
Uspallata[b]	32.60, 69.33	1891	11.6	–	–	147
La Paz	33.44, 67.62	506	16.6	–	–	250
Mendoza (Obs.)	32.88, 68.85	828	16.0	22.7	10.9	210
San Carlos[b]	33.77, 69.06	940	12.8	–	–	346
Neuquen	38.95, 68.13	271	14.4	20.2	7.1	188
Trelew	43.23, 65.27	43	13.5	20.4	7.5	176

Statistics were calculated for the period 1961–1990.
[a] Average for 1941–1960.
[b] Average for 1971–1990.

3. Past climate trends

3.1. Glacial and Holocene climates

Paleoecological and geological records suggest that present climatic conditions in the Monte developed in the past 3000–4000 years (Grimm et al., 2001; Mancini et al., 2004; Markgraf, 1993; Muhs and Zarate, 2001). Consequently, the intensity and temporal persistence of the atmospheric circulation patterns that control climate variations today might have been substantially different across the region during the Glacial, Glacial–Interglacial transition, and early Holocene times.

The information on climate conditions during the Last Glacial Maximum (LGM, approximately 21,000 years ago) across the Monte is fragmentary and from diverse sources, which complicates the interpretation of climatic variations from these records. In general, most pollen and lake level records suggest that climate during the last glacial period was very cold, dry and likely windier than today. For instance, the high proportion of *Gramineae* and herbaceous pollen in Gruta del Indio (37°S) during the glacial period has been interpreted as a northward shift of the Patagonian steppe formation or a shift downslope in the Andes of *Graminae* species in response to cooler climates (Markgraf, 1989, 1993).

The paleoclimatic records are consistent with model simulations of past climates suggesting that mid-latitudes in the Southern Hemisphere were colder and drier during the LGM and the late glacial period (Kutzbach et al., 1993; Otto-Bliesner et al., 2006). In the LGM simulations from the Community Climate System Model version 3 (CCSM3; Collins et al., 2006), greatest cooling occurs at mid-high latitudes in South America concurrent with the expansion of sea ice in the Southern Oceans (Fig. 3a). Sea ice area simulated by CCSM3 for the LGM doubles in the

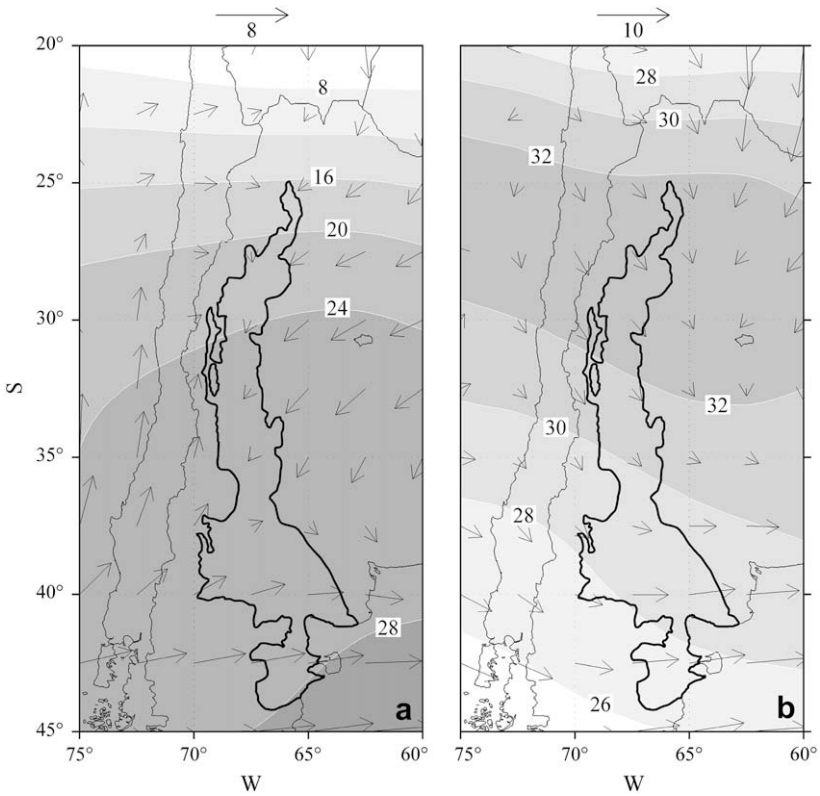

Fig. 2. Mean tropospheric circulation over the Monte in (a) summer and (b) winter for the 1961–1990 period. The wind field at the 950-hPa level is indicated by vectors (the vector scales in m s^{-1} are shown in the upper part of the figures). The zonal wind velocity (in m s^{-1}) at the 250-hPa level is indicated with gray scale. Data were obtained from NCAR/NCEP Reanalysis (Kalnay et al., 1996).

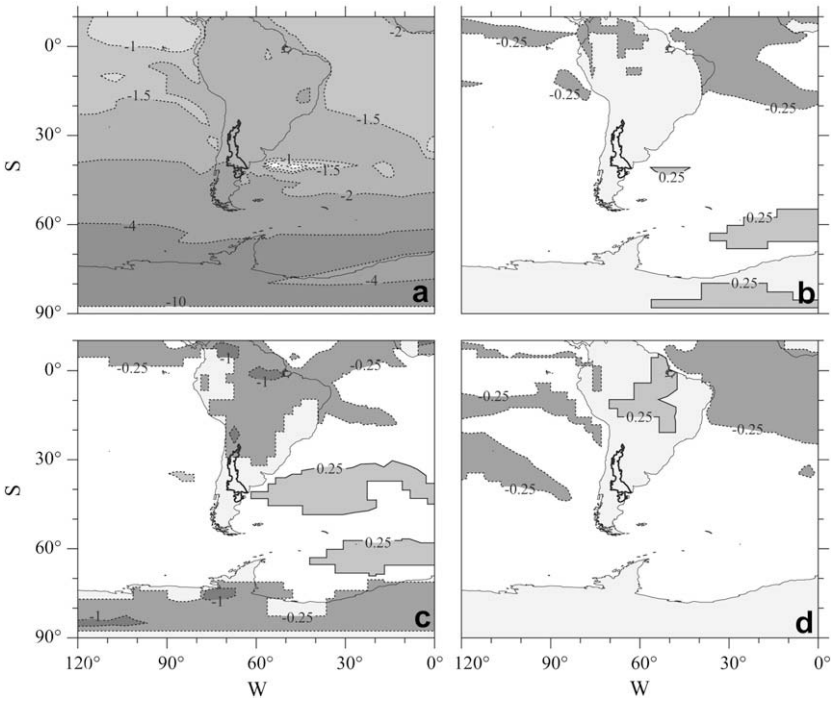

Fig. 3. Surface temperature changes (°C) in relation to Preindustrial Period (PI) simulated for the Last Glacial Maximum (LGM) and the mid-Holocene (6 K) using the Community Climate System Model version 3 (CCSM3; Collins et al., 2006). (a) Annual mean temperature, LGM minus PI, (b) annual mean temperature, mid-Holocene minus PI, (c) summer (DJF) mean temperature, mid-Holocene minus PI simulation, and (d) winter mean temperature (JJA), mid-Holocene minus PI. Only differences significant at 95% are shown. Modified from Otto-Bliesner et al. (2006).

Southern Hemisphere (Otto-Bliesner et al., 2006). A major difference with present climate displayed by COHMAP and CCSM3 simulations is the westerly dominant nature of winds. Although the westerly flow might has been seriously affected on surface and low elevations by the Andes, particularly north of 37°S, western upper-air flow was more intense and persistent during the LGM than today. These simulations are consistent with south-westerly paleowinds derived from extensive loess and aeolian sand fields east of the Andes between 34°S and 38°S (Muhs and Zarate, 2001).

The lack of a well-defined summer-wet season during the LGM might have had a major impact on the subtropical Monte vegetation. In comparison with present day conditions, a decrease in annual rainfall of 25–35% during the LGM has been simulated for tropical South America using a regional climate model with 60-km resolution (Cook and Vizy, 2006). The primary cause of this decrease was a delayed onset of the rainy season, so that the dry season was about twice as long as in the present day. The low-level inflow from the tropical-subtropical Atlantic onto the South American continent was weaker than in the present day simulation due to reduced evaporation from cooler Atlantic waters. Other regional responses in the LGM simulation include a weakening of both the Chaco low and the South America low-level jet, features of South American circulation related to a reduced inflow of Atlantic-wet air masses over the continent.

After 12,000 years BP, the increase in summer-rain desert taxa, especially therophytes, has been related to a substantial temperature increase coupled with a shift to more abundant summer precipitation (Markgraf, 1993). However, although temperature and summer precipitation were higher at 12,000 BP than in the LGM, they remained lower than today. Even in the early Holocene 8000 years ago, arid conditions with temperature not higher than today prevailed across the Monte (Fig. 3b–d). Vegetation of Andean–Patagonian affinity (*Schinus, Nassauvia, Chuquiraga, Verbena* shrub and *Ephedra frustillata*), mixed with *Larrea* shrublands, were the dominant species in the Precordillera (Mancini et al., 2004). Patagonic shrubs associated with *Ephedra frustillata*, and halophytes (*Chenopodiaceae*) developed in the fluvial valleys. The records show low values of *Poaceae* and Monte taxa at that time (Zárate and Páez, 2002). For instance, the pollen record at 8000 years BP in the Gruta del Indio is dominated by *Asteracea* (steppe); *Larrea* represents 20% of the total pollen rain, whereas only traces of *Prosopis* and *Cercidium* are recorded. According to Mancini et al. (2004), the type of vegetation present at 8000 years ago was still different from the Monte vegetation recorded today.

Most paleo-environmental records from the mid-Holocene suggest a warm, humid period (Muhs and Zarate, 2001). About 6000 years BP, tree taxa in Gruta del Indio increased in response to a relatively humid interval during the Mid-Holocene (Markgraf, 1993). Based on paleorecords, it is difficult to estimate if the Mid-Holocene climate was wetter than today. On the other hand, COHMAP simulations indicate that subtropical South America east of the Andes was warmer but drier (Kutzbach et al., 1993), whereas recent simulations suggest cooler and drier conditions across the Monte during the Mid-Holocene than today. Negative solar anomalies, as compared to present, occurred in both hemispheres in December–February during the mid-Holocene (Otto-Bliesner et al., 2006). Modest cooling in simulations occurs in response to reduced solar radiation over South America and Antarctica (Fig. 3c, d). Since monsoonal circulation in summer is the primary source of rainfall for the Monte region (Agosta et al., 1999; Vuille and Keiming, 2004), reductions in summer precipitation might be expected from a cooler continent (0.5–1 °C) concurrent with lower temperatures across tropical–subtropical Atlantic. However, although summer precipitation in the Monte may have been slightly lower than today during the Holocene, water deficit might have been compensated by cooler summers. Thus, as effective moisture has remained more or less the same, it might have facilitated the expansion of the Monte vegetation during the past 4000 years.

3.2. The last millennium

High-resolution proxy records in subtropical South America show complex patterns of timing and climate variability during the past 1000 years. Tree-ring records from northern Patagonia suggest the existence of cold intervals concurrent with the Little Ice Age events around the world (Grove, 2004). The most striking feature in the millennium temperature reconstructions for the eastern side of the northern Patagonian Andes (Villalba, 1990; Villalba et al., 2003) is a long, cold interval that extends from ca. 1500 to 1660. Severe, cold summers were particularly frequent during 1630–1660. The occurrence of this century-long cold interval is consistent with the glacial record, which indicates that the maximum extent of the Frías Glacier (41°S) during the last millennium was between ca. 1660 and 1670 at the end of this cold period (Villalba et al., 2005). This interval of low temperatures in Northern Patagonia during the past 1000 years was also registered in subtropical latitudes. Based on historical records, three (1627, 1649 and 1651) of the four coldest years during the XVII century in Mendoza were recorded during the same interval (Prieto, 1983). Glacier advances from the second half of the XV to the middle XVII century have also been reported at 34–35°S in the Central Andes (Espizua, 2005).

In contrast to a similar pattern of temperature variations from subtropical to mid-latitudes in the eastern flanks of the Andes, precipitation variations during the past centuries show a dominant opposite pattern between these regions. Historical records from northwestern Argentina show the occurrence of severe droughts from the end of the XVI to middle XVII centuries. Following this dry interval, precipitation was abundant in northwestern Argentina from 1660 to the beginning of the XVIII century. Concurrent with this wet interval, frequent floodings changed many river courses such as those registered for the Salado river in 1703 and 1709 (Prieto et al., 2000). Opposite patterns in precipitation variations have been recorded in northern Patagonia east of the Andes. According to Villalba et al. (1998), the wettest 50-year-long interval in a precipitation reconstruction for Patagonia during the past 4 centuries was recorded between 1604 and 1653. The 1669–1718 ranks second among the driest five intervals over the past 4 centuries.

In summary, the scarce high-resolution records east of the Andes suggest significant climatic changes across the Monte during the past millennium. In most past scenarios, temperature changes were similar across the whole region, whereas precipitation variations show opposite (dry subtropical and wet northern Patagonia or *vice versa*) patterns between subtropical and mid-latitude sectors in the Monte region. These observations are somewhat consistent with circulation models, which suggest that reduced precipitation in northern Patagonia triggered by weaker Westerlies, are coincident with intervals of abundant rainfall in the subtropics resulting from a stronger monsoon-like circulation reinforced by a warmer continent.

4. Climate trends during the 20th century

4.1. Temperature trends in the 20th century

In this section, we used instrumental records to examine temperature variations during the past century in the Monte in the context of climate variations at continental and global scales. The analysis of temperature trends from Jones and Moberg (2003), henceforth JM2003, shows that the global (continents and oceans) mean rate of warming in the last century was 0.066 °C decade^{-1}. This rate was not uniform in this period. The lineal positive trend was significant (95% significance level) in the early and latter parts of the century, centered in the intervals 1920–1944 and 1977–2001, with 0.154 °C and 0.165 °C decade^{-1} respectively, separated by a relatively stationary period (−0.005 °C decade^{-1}).

In the period 1901–2000, the continental South America experienced a warming rate of 0.060 °C decade^{-1}, similar in magnitude to the global mean rate. The rate of temperature increase was greater than the global mean in the period 1920–1944 (0.249 °C decade^{-1}) and smaller than the global mean in the period 1977–2001 (0.125 °C decade^{-1}), being the linear trend in both cases significant at the 95% level.

Temperature variations during the last century were not uniform across the continent, and the warming reached statistical significance only in few sectors of South America. According to JM2003, surface temperature trends in southern Brazil and northeastern Argentina during the period 1920–1944 were significant, reaching values greater than +0.25 °C decade^{-1}. The warming was less intense in northwestern and central zones of Argentina. Northern Patagonia experienced a significant temperature increase, larger than +0.25 °C decade^{-1}, during the same period (Fig. 4a). Therefore, positive trends of about +0.25 °C decade^{-1} in the south sector of the Monte, contrast with almost null trends in the central and north part of the region during the 1920–1940 warming interval (Fig. 4a). This warming was not uniform throughout the year, in fact the greater increases of temperature happened in winter (JM2003). In the 1977–2001 warming period, temperatures in the central and northern sectors of the Monte showed a non-significant positive trend (+0.1 °C decade^{-1}), less than the continental mean value (Fig. 4b).

The signal of the warming was evident also in the maximum and minimum temperature records in the Monte. Eleven indices, based on daily extreme temperatures, from 68 homogeneous records in South America south of the equator were used by Vincent et al. (2005) to characterize temperature variations during the period 1960–2000. The warming signal is relatively weak in most indices based on daily maximum temperatures. However, numerous and coherently spatially grouped stations registered significant positive trends in minimum temperatures. More than 40% of the stations registered significant negative trend in the percentage of cold nights (percentage of days with T_{min}<10th percentile) and significant positive trend in the percentage of warm nights (percentage of days with T_{min} >90th percentile) in the last 4 decades of the 20th century. Mendoza and Neuquén meteorological stations in the central sector showed noticeable nocturnal warming, whereas Trelew in the extreme southeastern sector of the Monte registered an opposite trend.

Previous results based on indices derived from daily minimum temperatures are consistent with Rusticucci and Barrucand (2004) study on temperature variations for the period 1959–1998 in 54 stations distributed across Argentina. However, in contrast to Vincent et al. (2005), a significant decrease in diurnal maximum summer temperatures in central Argentina and a significant increase in the diurnal maximum winter temperatures in Patagonia, were reported by Rusticucci and Barrucand (2004). These authors stated that estimates of future changes in mean temperature are not enough to properly evaluate future changes in extreme temperatures in the region. In summer, correlations between daily mean temperatures and the number of warm days or nights are significant in most of the country, reaching values of r=0.6 and 0.7 in the Monte region. However, correlations between mean temperatures and the number of cold nights or days are less and even not significant in some regions. In winter these correlations are smaller, particularly in our study region.

4.2. Precipitation trends in the 20th century

In South America, the most significant and persistent increase in precipitation since the mid of the 20th century has been recorded

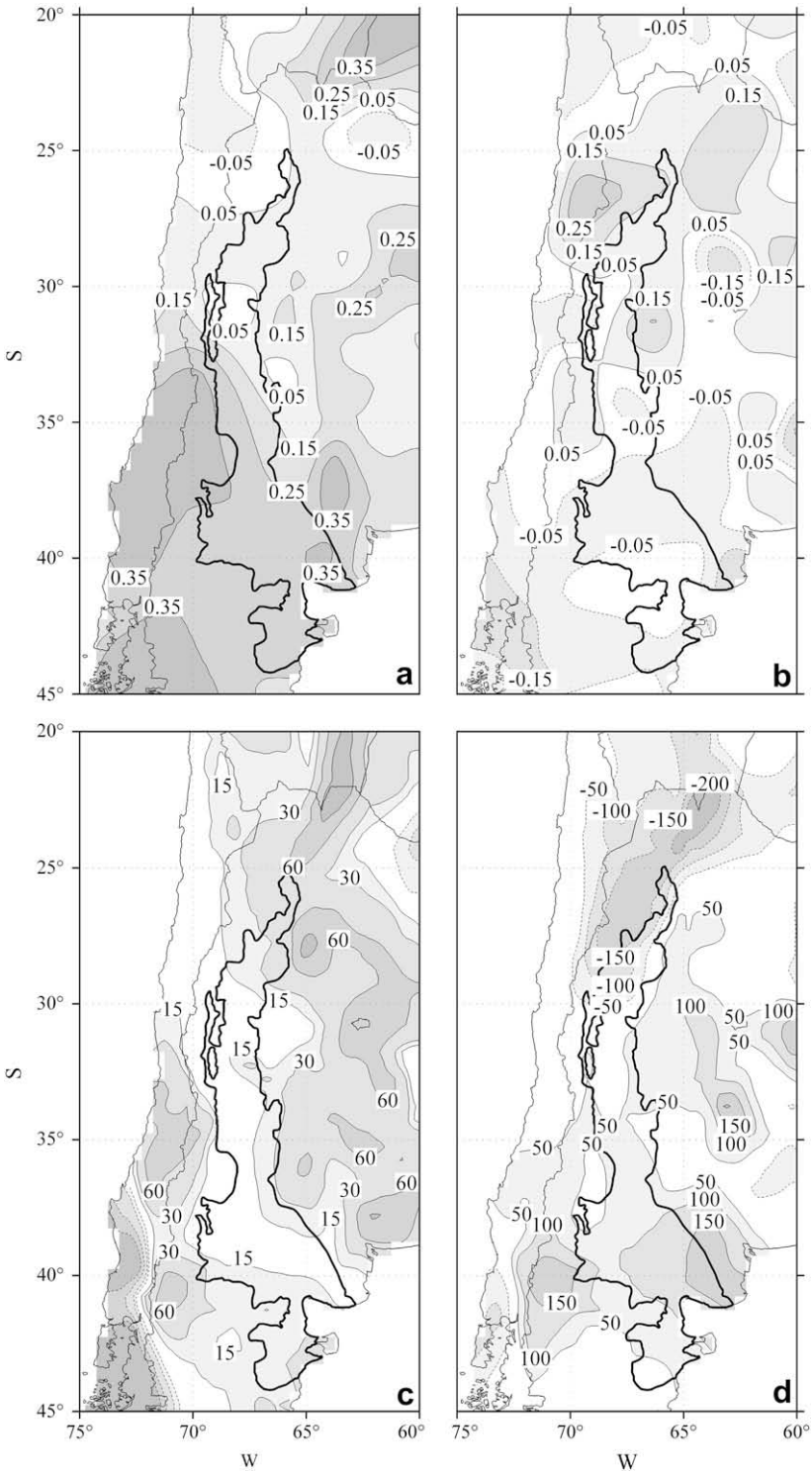

Fig. 4. Annual mean temperature trends in the periods (a) 1920–1944 and (b) 1977–2001 (°C decade^{-1}). Annual total rainfall trend in the periods (c) 1955–1984, (d) 1985–2001 (mm decade^{-1}). Data from CRU TS 2.1 Climate Research Unit dataset (Mitchell and Jones, 2005). Negative trends are indicated with dotted contour lines.

in southern Brazil (25°S). This positive trend in rainfall, which strengthens in the last quarter of the 20th century, has also affected northeastern Argentina and eastern Paraguay (Liebman et al., 2004). Rainfall increases have been less conspicuous toward the western and southern sectors of the continent. The rainfall increase appears to be related to a positive trend in sea surface temperatures (SSTs) in the subtropical Atlantic Ocean in response to the weakening of the atmospheric circulation in the west border of the Atlantic anticyclone.

Haylock et al. (2006) analyzed the rainfall variations in South America during the last 40 years of the 20th century using 54 reliable records of stations distributed south of the equator. Using these data, they computed 12 annual indices: 10 of them referred to extreme precipitation and the remaining to annual mean precipitation. The patterns of rainfall trends obtained for the extreme indices were very similar to those for total annual rainfall and exhibited large regions with homogeneous behaviors. The referred study confirmed the tendency toward more

humid conditions in southern Brazil during the period 1960–2000 reported by Liebman et al. (2004) and showed that this pattern also included the north and central sectors of Argentina. The total annual precipitation index and four of the extreme-rain indices showed coherent positive trends, significant at 95% level, in the two stations located in the Monte between 32 and 38°S (Fig. 2 in Haylock et al., 2006).

Relationships between rainfall indices and SSTs in the surrounding oceans were determined using canonical correlation analysis. The higher frequency of El Niño events in the last quarter of the century largely contributed to the rainfall increase in the southeast of the continent, in response to a southeastward shift of the South Atlantic Convergence Zone during warm ENSOs (Haylock et al., 2006).

Haylock et al. (2006) also reported on a consistent decrease in total and extreme rain events south of 40°S in southern Chile and southwestern Argentina. It is likely that this reduction in precipitation is also affecting the southwestern sector of the Monte. However, due to the scarce number of stations in this particular region, it is difficult to evaluate the consistence of this rainfall reduction across regions. The negative precipitation trend is attributed to a southward displacement of the storms track, associated with increasing mean sea level (MSL) pressure in middle latitudes. In consequence, this regional climatic change is coherent with the observed variations in the Southern Annular Mode, a measure of differences in MSL pressure anomalies between mid- and high-latitudes in the Southern Hemisphere. These MSL pressure changes has been associated with stratospheric ozone depletion across Antarctica (Thompson and Solomon, 2002) and increasing concentrations of greenhouse gases worldwide (Kushner et al., 2001).

A non-linear trend analysis of total annual rainfall between 1931 and 1999 was conducted by Minetti et al. (2004) to detect low-frequency variations in rainfall in Argentina. The northern sector of the Monte showed a positive trend up to middle 1980s followed by a reduction in precipitation after that (Fig. 4c and d). The central part of the Monte experienced a positive precipitation trend throughout the past century, whereas in the southeastern sector the positive trend intensifies during the past decades (Fig. 4c and d).

Based on long-term precipitation series from eight stations located between 29° and 36°S, a consistent 18–21-year-period has been detected in summer precipitation (Compagnucci et al., 1982, 2002). This lower frequency variation produces alternating episodes of above and below normal rainfall each lasting roughly 9 years. This quasi-fluctuation appears to be shared with the summer rainfall region of South Africa and was in-phase related to one another until mid-1970s (Vines, 1982). According to Agosta et al. (1999), the increase in summer precipitation in the last 20 years of the 20th century cannot be attributed to the 18–21 year oscillation, but to increased temperatures on the subtropical Atlantic. After a climatic jump recorded in the mid-1970s, the coherence in summer precipitation variations between Central Argentina and South Africa broke apart (Compagnucci et al., 2002).

The global analysis of extreme rainfall events using Parallel Climate Model simulations for the period 1979–1999 indicates that the 20-year return value of the annual maximum daily precipitation in the Monte region ranges between 30 and 45 mm day^{-1} (Wehner, 2004). Seasonal return values are generally less than the annual values. However, in the Monte, the 20-year return values for summer (DJF) and spring (SON) are very close to the annual value, whereas those of winter and autumn are lower. This suggests that the probability of heavy daily precipitation events in the Monte is higher in spring and summer.

5. Projected changes in temperature and rainfall during the 21st century

The Intergovernmental Panel on Climate Change (IPCC) has developed a large family of emission scenarios for greenhouse gases and sulfate aerosols based on future demographic, economic and technological growths (*Special Report on Emission Scenarios, SRES,* Nakicenovic and Swart, 2000). The SRES scenarios A2, A1B and B1 (or B2), associated with 'high', 'mean' and 'low' greenhouse gas emission rates, respectively, are among the most frequently used by diverse research groups to simulate future climatic scenarios during the 21st century. Suitable procedures have been developed to describe the future climate in terms of the most probable ranges in climate variables of concern together with reliability measures for the estimates, which take into account the diversity of emission scenarios, models and climate experiments currently available.

Giorgi and Mearns (2002) have developed a method for calculating means, uncertainty ranges, and reliability measures of regional climate changes from an ensemble of experiments with different climate models. Weighted averages take into account individual model performances for current climate simulations and the convergences of simulated changes across models. This procedure was applied to simulations of A2 and B2 SRES emission scenarios performed with nine coupled atmosphere—ocean models. The authors also provide a measure of collective reliability of the simulated changes, which ranges from 0 to 1. Estimated climate changes are expressed by the difference in mean temperature patterns between the periods 2071–2100 (future climate) and 1961–1990 (contemporary climate). Results for southern South America based on the emission scenario A2 indicate temperature changes of 3.4±0.9 °C and 2.2±0.6 °C with reliability indexes of 0.3 and 0.6, for DJF and JJA, respectively. These values exceed the natural variability of temperature in the region, which is about 0.5 °C. The ratio between temperature changes in scenarios A2 and B2 for southern South America is approximately 1.4 in summer as well as in winter.

On the other hand, climate projections from Boulanger et al. (2006) take into account the A2, A1B and B1 scenarios and use neural networks and Bayesian statistics to calculate weighted averages from an ensemble of seven climate model simulations. According to their results, the largest warming rate in South America takes place in the Amazon basin and its intensity diminishes faster toward the south of the continent than toward the Atlantic coast. Although the warming accelerates during the second half of the century, the spatial pattern across South America remains mostly unchanged with the final amplitude varying according to the emission scenario. By the end of this century, projections for the scenario A1B attain 80 to 90% of the amplitude of those for scenario A2, whereas estimates for scenario B1 reach almost half of the amplitude for scenario A2. Results for scenario A1 indicates that annual mean temperature increases between 2.5 and 3.5 °C are likely to occur toward the end of the 21st century in the northern and central Monte, which are among the largest increases in the southern part of South America.

Fig. 5a and b shows the estimates of mean temperature variations for summer (DJF) and winter (JJA) towards the end of this century based on five global climate models. Whereas in the Amazonia the seasonal thermal amplitude tends to decrease due to a more intense warming in winter than in summer, the annual thermal amplitude increases from the Bolivian Altiplano to Patagonia due to a larger warming in summer than in winter. The increase in the amplitude of annual temperature will affect the westernmost continental sector of Argentina and particularly the Monte region. Results from Boulanger et al. (2006) agree in general with those presented by Ruosteenoja et al. (2003).

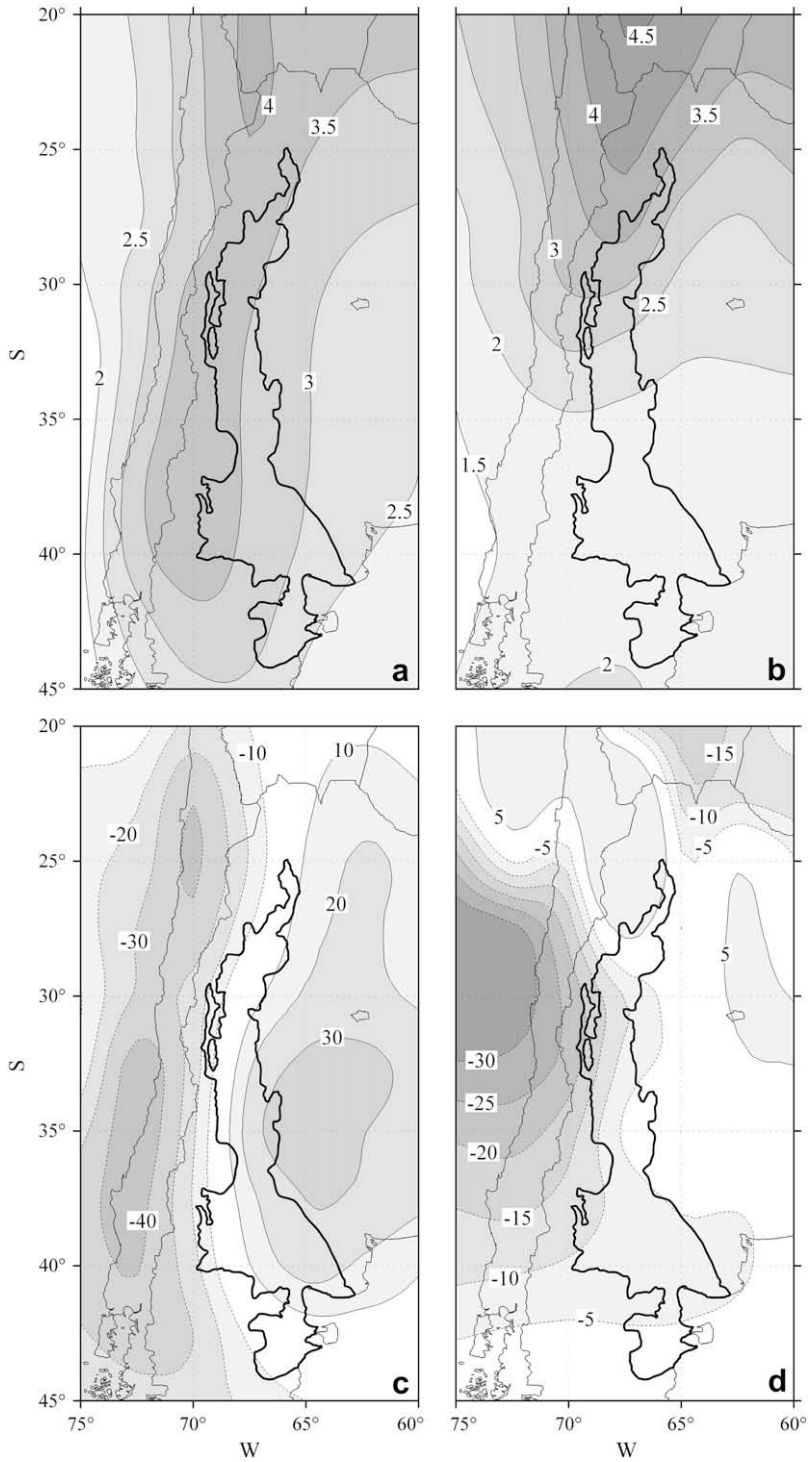

Fig. 5. Mean temperature changes (°C) between the 2071–2100 and 1979–2000 periods for (a) summer (DJF) and (b) winter (JJA). Total seasonal precipitation changes (%) between the same periods for (c) summer and (d) winter. Climate changes were calculated with the ensemble mean of the output from four models (CCC, CSIRO, HADCM3 and MPI), available at the IPCC Data Distribution Centre.

Regarding precipitation in southern South America, Giorgi and Mearns (2002) estimate for scenario A2 a regional mean change between 1961–1990 and 2071–2100 of 10±4% for DJF and 5±6% for JJA, with reliability indexes of about 0.6 in both seasons. Only the estimated summer variation exceeds the range of natural variability (3% in DJF and 12% in JJA). In southern South America, the ratio of precipitation changes between scenarios A2 and B2 varies from 2.5 in DJF to 0.8 in JJA.

Precipitation variations estimated by Boulanger et al. (2007) indicate that the increase in rainfall registered in southeastern South America (south of Brazil, northeast and central sectors of Argentina and Uruguay) in the past 30 years are likely to continue in this century. A persistent positive trend could increase summer rainfalls between 5% and 30% in the southeastern band of the Monte (Fig. 5c). On the other hand, summer rainfall decreases of about 5–20% are likely to occur in the Andean domain, which in

turn may affect the inter-mountain valleys in the western border of the region (Fig. 5c). According to Boulanger et al. (2007), rainfall in the Cuyo region could decrease 5–20% during winter. The overall reliability of rainfall projections for the narrow region of the Monte is rather low due to the significant bias in most model simulations introduced by the vicinity of the elevated Andes mountain range.

The statistical analysis of extreme rain events requires the combination of long time instrumental series and a dense network of stations to properly characterize the real nature of this small-scale phenomenon. Unfortunately, meteorological records in the Monte region are sparse and rarely longer than 60 years. In consequence, testing the validation of extreme events from model simulations with real data is extremely difficult today in the Monte region.

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