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Statistical downscaling estimation of recent rainfall trends in the eastern slope of the Andes mountain range in Argentina

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Abstract Statistical models for rainfall downscaling based on multiple linear regression techniques have been developed and tested in the Andean Region of west Argentina, an extended mountainous region where three different rain regimes predominate and rainfall has great spatial and temporal variability. The verification procedure was focused on the model's ability to reproduce observed rainfall trends in recent decades. In the northwest of Argentina, domain of the tropical summer rain regime, the monthly rainfall variance accounted for by downscaling models was 77% on average and models reproduced satisfactorily the negative linear trend observed in the last two decades of the past century. In the arid central-west Argentina, a region of rapid transition between two different rain regimes, model performance was rather poor (an average of 50% of explained variance), even so models were able to capture outstanding differences in the linear trend between the northern and southern sectors of the region. In the southwest of Argentina, domain of the mid-latitude winter rain regime, the monthly variance accounted for by downscaling models was 71% on average and models were capable to reproduce a singular change in the onset of the rainy season that occurred during the 1990s. The results achieved demonstrate that it is feasible to establish significant and useful statistical relationships between atmospheric variables and rainfall at monthly and river basin scales, even for a topographically complex region like western Argentina.

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1 Introduction

Those who develop regional climate change scenarios as well as those who conduct impact studies and make use of results from such scenarios likely consider the following key questions during the process: are the methods currently used to estimate future local or regional climate changes able to reproduce the most outstanding variations that occurred in the recent past? If so, what are their potentialities and limitations? This paper presents the results obtained during the development and validation stages of statistical models based on multiple linear regression for estimating local/regional rainfall from available atmospheric data. Models were calibrated in the mountainous region of western Argentina, where three different precipitation regimes can be distinguished, using monthly rainfall data from stations near the Andes mountain range and atmospheric data from reanalysis. The emphasis of this study was put on the assessment of model ability to reproduce rainfall trends observed in the last decades of the past century.

The rainfall records of the main meteorological stations in Argentina show significant regional changes during the past century toward more humid conditions in the northern and central zones and drier ones in the extreme southwest (Haylock et al. 2006a). The total annual rainfall series of these regions exhibit quite different non-linear long-term variations throughout the twentieth century (Minetti et al. 2004). The inter-annual streamflow variability of river courses on the eastern slope of the Andes together with recurrent drought and flood episodes that severely affect lives and economy of foothill inhabitants are closely related to variations in the large-scale atmospheric circulation that impact the amount of rain captured in the main river basins (Compagnucci et al. 2002). Some of these variations have

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been identified as natural low-frequency phenomena, such as the 18-year periodicity in rainfall in the Cuyo Region, which has been known for a long time (Vines 1982). Other variations, however, might be early manifestations of a climate change process, a possibility that is a matter of intense debate and research nowadays.

Simulations of the future climate performed with atmosphere–ocean general circulation models (AOGCM), under the assumptions of plausible carbon dioxide and sulfate aerosols emission rates and atmospheric concentrations, indicate that significant continental-scale rainfall changes are likely to occur in South America throughout this century (Boulanger et al. 2007; Labraga and López 1997). However, current AOGCM spatial resolutions—on the order of hundreds of kilometers—hamper the representation of the local physiographic characteristics that condition the spatial distribution of rainfall on the local/regional scale. Then, it is not possible to obtain reliable basin-scale rainfall estimates directly from these model outputs, a relevant piece of information for many impact studies.

A large variety of procedures is currently used to specify local climate characteristics starting from low-resolution atmospheric data obtained from reanalysis of observations or AOGCM simulations. These climate regionalization procedures are usually referred to as downscaling techniques and are based on the assumption that the local climate is conditioned by interactions between the large-scale atmospheric and oceanic circulations and small-scale characteristics of each site, such as topography, distribution of water bodies, vegetation cover and land-use practices (von Storch 1999). This sort of approach has been in use for several decades to enhance local weather information from regional or global weather forecast models (Klein and Glahn 1974). Downscaling procedures have aroused considerable interest during recent years because of their potential applications in the development of climate change scenarios and related impact studies.

The most frequently used downscaling methods in climate change studies are usually grouped into two categories: (1) dynamical methods, which obtain local climate information from simulations performed with high-resolution atmospheric models (on the order of tenths of kilometers) over limited areas, or global models with variable resolution, or limited area models with uniform high resolution. The necessary boundary conditions for the regional model sub-domains are provided by low-resolution AOGCMs simulations or by the analysis of observed data (Leung et al. 2004); (2) statistical methods, which use historical observed data to develop statistical models that relate local climate variables with a set of variables that suitably characterize the large-scale state of the atmosphere. These statistical models can be used in combination with AOGCMs or regional model outputs to obtain local climate features beyond the limits imposed by the resolution of dynamical models (Salathe 2003; von Storch et al. 2000; Wilby et al. 1998).

The state-of-the-art of the most frequently used methods relative to this matter is summarized in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Christensen et al. 2007). Some of the most recent work on the intercomparison of dynamical and statistical methods examine a wide range of features, which include the ability to reproduce characteristics of the contemporary climate, the similarity between climate change patterns obtained from model outputs, the influence of topography, and climate extremes (Busuioc et al. 2006; Haylock et al. 2006b; Schmidli et al. 2006), but they usually focus on a limited number of climate variables and regions of the globe.

The interaction between the atmospheric circulation and the Andes in South America has a strong influence on the climate of the region and generates a variety of rainfall regimes on both sides of the Andes and along their north–south extent (Prohaska 1976). This physiographic aspect might pose a major challenge for the success of any downscaling procedure, either dynamical or statistical. An additional challenge is posed by the scarcity of surface and upper-air observing stations in this part of South America, most of which are scattered over a wide area with varying climate characteristics, and with frequent temporal and spatial discontinuities in the rainfall series. These are all factors that can adversely affect the performance of any downscaling approach.

With regard to previous applications of statistical downscaling methods for rainfall in Argentina, the work of Cavazos and Hewitson (2005) is one of the few in the literature that reports on the relative efficiency of several atmospheric predictors of the daily rainfall for a single site far away from the Andes. On the other hand, there are numerous references to statistical models developed for mountainous regions of the world similar to that of western Argentina (Uvo et al. 2001; Dehn and Buma 1999; Fischlin and Gyalistras 1997; Busuioc and von Storch 1996). Kidson and Thompson (1998) evaluated the relative merits of a statistical method based on the multiple linear regression technique and a dynamical method based on a meso-scale atmospheric model applied to the mountainous region of New Zealand and found that both had comparable performance regarding the estimation of daily and monthly rainfall anomalies.

A detailed description of the study region and the downscaling procedure applied is presented in the following section. A simple statistical method was purposely selected to avoid the sensitivity of more elaborate methods to factors such as the particular choice of boundaries for the study region or the uneven spatial distribution of rain gauge stations, which could blur the validation procedure. The distinctive characteristics of rainfall regimes prevailing in western Argentina are described in Section 3. Section 4 presents the main results achieved in model development and verification. The potential and limitations of the methodology in the region of concern are discussed and summarized in the final section.

The ultimate goal of this paper, to develop robust rainfall downscaling models suitable for the particular physiographic characteristics and data availability in western Argentina, is linked to the goal of the next stage of this research project: to obtain reliable estimates of future rainfall rates in this region under different greenhouse gas emission scenarios for the current century.

2 Study area, materials, and methods

The Andes mountain range in South America is the natural frontier between Argentina and Chile and extends in the north-south direction for more than 3,700 km (Fig. 1). The area of study is located on the eastern slope of this mountain range, extending from 22° S to 45° S and divided into the three main regions detailed in Fig. 1, according to the dominant rainfall regimes described in the following section. Between 22° S and 29° S, the Northern Region, the average height is 4,250 m and the average width about 500 km, with a peak at 6,893 m (Ojos del Salado, 27°06′ S 68°32′ W). In the Central Region, between 30° S and 36° S, the average altitude is 3,500 m and the average width is 250 km. One of the highest peaks in the world, the Aconcagua (6,962 m, 32°39′ S 70°00′ W), stands out in this section of the Andes. In the Southern Region, between 36° S and the southern boundary of the study area, 45° S, the Andes becomes even narrower (less than 150 km) and the average height continues its decrease to 1,100 m.

Eighty-seven carefully controlled monthly rainfall series were selected from the observing networks of the Secretariat of Water Resources (SHR) and the National Meteorological Service (NMS) of Argentina for this study. The distribution of rain gauge stations is shown in Fig. 1. Continuity in the operation of the stations, requiring less than 15% missing data, and the best possible coverage of the main river basins on the eastern slope of the Andes were some of the selection criteria. Stations whose location changed significantly were discarded. Both the SHR and the NMS apply quality control routines to detect invalid data. Nevertheless, cross-controls between neighboring stations were carried out to identify outliers and examine the homogeneity of the series. No attempt was made to apply heterogeneity corrections in the time series when minor changes in the observation sites, instrument types or observational practices were detected.

In the Northern Region (upper right box in Fig. 1), the Bermejo, San Francisco, Juramento, Pasaje-Salado, and Sali-Dulce are among the most extensive river basins. Most of the 50 rain gauge stations in this region are located at heights that range from 500 to 2,500 m amsl on a narrow meridional band of 150 km width.

Nineteen of the selected rain gauge stations are distributed in the San Juan, Mendoza, Tunuyan, Diamante, and Atuel river basins in the Central Region at heights ranging from 500 to 1,500 m amsl (upper left box in Fig. 1). The remaining 18 stations are distributed in the extended Neuquen, Limay, and Chubut river basins and the smaller Futaleufu and Manso-Puelo river basins in the Southern Region (lower left box in Fig. 1).

The number and distribution of available observing stations in the study region are not sufficient to accurately estimate the total rainfall captured by each river basin. The average of all time series within each river basin is the best available indicator to study long-term rainfall variations at this scale.

Statistical comparison of the series revealed a few cases in which remarkable differences in rainfall behavior between sectors of the same river basin were evident. They are probably associated with local differences in the orientation of valleys and mountain chains relative to the large-scale atmospheric circulation. A cluster analysis applied on the set of series in each river basin made it possible to identify homogeneous subgroups of series, which were then averaged and the resulting local rainfall indexes assigned to the average latitude and longitude of the corresponding stations. Downscaling models are developed based on these rainfall indexes and for these locations. Homogeneous groups of stations within the same river basin are identified in Fig. 1 by means of different marker types and named accordingly (e.g., West San Francisco, square markers; East San Francisco, circular markers).

The statistical model for estimating the monthly average rain P in each river basin (or basin sector) was developed following a multiple linear regression technique (Wilks 2006). The predictand is $P^{1/3}$ and the independent variables were selected among a set of 14 atmospheric variables, whose performance as potential predictors is adequate according to our previous testing and the results of others (Cavazos and Hewitson 2005). To identify the factors that contribute significantly to the variance in the model response, the forward stepwise regression procedure was used, which combines forward selection steps with backward elimination steps (von Storch and Zwiers 2001), having established a maximum of eight independent variables. The basic criterion is that a variable is included in the model if it contributes a significant (1% level) amount of variance, for which a standard F-test for the ratio of the variances is conducted.

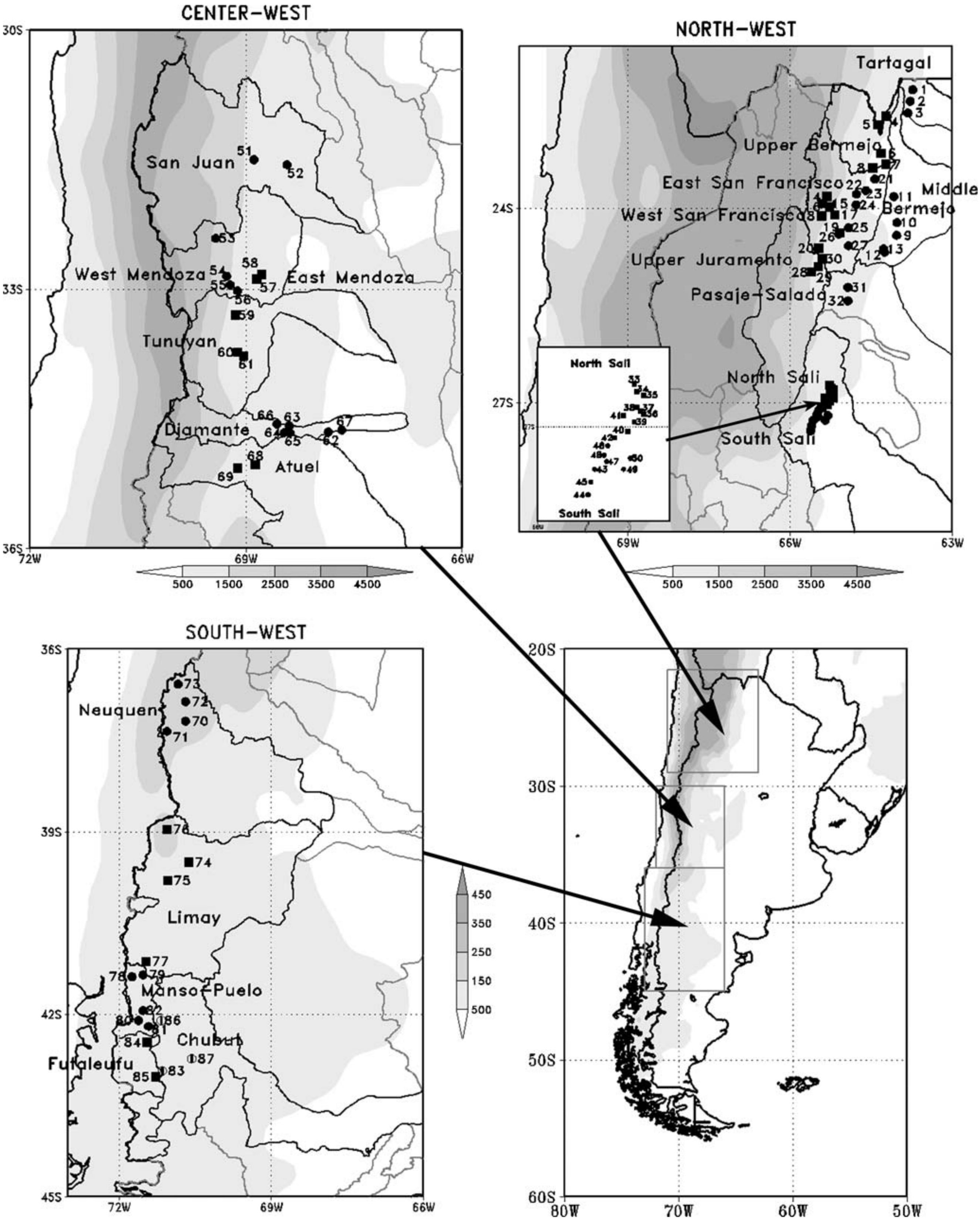

Fig. 1 Location of the rain gauge stations in the Northern, Central, and Southern Andean Regions of study (*boxes*). Boundaries of the main river basins are indicated with *solid black lines* and the scheme of the Andes topography is *shaded in gray* scale

The set of potential predictors includes only those variables that usually compose (or can be derived from) AOGCM outputs and have relevance in rain-producing processes such as convection, moisture advection, and topographic uplift. The predictor variables are: precipitable water (PW); temperature at 850 and 700 hPa (T_{850}, T_{700}); 500 hPa geopotential height (H_{500}); 500–1,000 hPa thickness (DPTH); zonal and meridional wind components at 850 hPa (U_{850}, V_{850}); mean sea level pressure (P_{MSL}); vorticity at 700, 500, and 250 hPa (VR_{700}, VR_{500}, VR_{250}); divergence at 700 and 250 hPa (DV_{700}, DV_{250}); and the zonal component of the wind at 250 hPa (U_{250}). The values of these variables were obtained from the NCEP–DOE Atmospheric Model Intercomparison Project Reanalysis (R-2) dataset (Kanamitsu et al. 2002) and bilinearly interpolated from the 2.5° latitude×2.5° longitude grid points to the modeling points in each river basin.

The use of the cube root of the rain rate, $P^{1/3}$, proved to be a very effective method for reducing the deviations of regression residuals with regard to normality; a result verified by plotting the standardized residuals from the regression against the quantiles of the standard normal distribution (von Storch and Zwiers 2001).

Previous experimentation has shown the convenience of developing regression models for each season separately. This approach produces a small but still appreciable improvement in the performance with regard to models developed with the total annual data (performance measured in terms of explained variance and mean absolute error). However, the main reason for assuming this approach is that it allows a safe treatment of outliers, particularly in those sites where different rain-producing mechanisms prevail along the year. It also makes possible to guess more coherent physical interpretations of the relationship between predictors and predictand.

The statistical models were developed using 11 to 13 years of observed monthly rainfall data (predictand) and monthly mean values of reanalyzed atmospheric variables (predictors). Model verification was accomplished using independent 10-year series of the same variables. The lengths of development and verification periods vary slightly across the study region according to rainfall data availability and both periods are indicated for each sector in the captions of Tables 1 to 3. The percentage of the monthly rainfall variance accounted for by the regression model and the mean absolute error, calculated in the independent period, were the statistical measures used to validate and compare the performance of the models in different regions. Other and not less important measures of performance taken into account in this study were the model's capability to reproduce the seasonal rainfall distribution and its variation during the study period and the long-term linear trends of the annual rainfall.

3 Characteristics of the rainfall regimes in the study region

A brief description of the main rain regimes and associated large-scale circulation patterns that predominate in the study region are presented here. This description will provide a basis for later interpretation of the physical associations between predictors and predictand in the multiple regression models and will highlight those aspects of the rainfall climate that models should be able to reproduce.

The stations located in the Northern Region (upper right box in Fig. 1) belong to the tropical summer rain regime. This is characterized by abundant precipitation within a rather brief humid season that extends from December to March and its almost total absence in the rest of the year. The annual totals can vary widely from place to place. Thus, we can find less than 350 mm in La Quiaca and more than 1,100 mm in San Miguel de Tucumán within the same rain regime. The annual rainfall averaged over the main river basins of the region is shown in Table 1. The frequent arrival of warm, humid and convectively unstable air in this region during summer is related to the persistent northerly circulation over the continent that develops between a low-pressure system located over the South American Chaco (the extended region between the Andes and the Paraguay River that comprises eastern Bolivia, western Paraguay, and northwestern Argentina) and the quasi-stationary high-pressure center in the subtropical South Atlantic Ocean (Prohaska 1976). The great availability of water vapor is also related to the efficient southward transport of moisture from tropical latitudes by the South American low-level jet: a poleward warm and moist current frequently observed in the lower troposphere immediately east of the Andes during the wet season (Saulo et al. 2000). A sub-ensemble of extreme low-level jet cases designated the Chaco Jet (Salio et al. 2002) occurs only 17% of the summer days, but contributes between 30% and 55% of the summer rain in northern Argentina. The interaction between circulation and topography in the Northern Region can play an important role in producing locally heavy rainfall due to forced uplift of the humid tropical air.

Seluchi et al. (2003) differentiate two components in the above-mentioned low-pressure system that is frequently observed east of the Andes between 15° and 32° S: the Chaco Low (CHL) located between Bolivia, Paraguay, and extreme northwest Argentina, and the Northwest Argentina Low (NAL) located south of about 27° S. Among the aspects that differentiate both systems, the authors indicate that anticyclonic circulation is frequently observed in the upper levels of the troposphere in summer over the CHL, which weakens towards the south until vanishing over the NAL. Both depressions are deep and frequent in summer,

Table 1 Performance of rainfall downscaling models in the Andean Region of Northern Argentina

River basin	Monthly rainfall			Annual rainfall					
	EV_V (%)	EV_D (%)	MAE_V (%)	Mean (mm)	St. Dev. (mm)	EV_V (%)	MAE_V (%)	LT_O (mm $year^{-1}$)	LT_M (mm $year^{-1}$)
Tartagal	77	80	35	1,121	239	43	14	−7.0	−5.2
Upper Bermejo	77	79	33	1,172	178	26	12	−14.8	−2.8
Middle Bermejo	76	77	35	948	175	64	8	−6.5	−1.5
West S. Francisco	80	86	33	968	314	79	12	**−37.4**	**−37.1**
East S. Francisco	71	75	40	798	217	60	15	**−20.9**	**−20.4**
Upper Juramento	81	85	34	745	142	51	8	−8.0	−8.5
Pasaje-Salado	71	75	31	721	194	57	16	**−17.1**	**−13.0**
North Salí-Dulce	82	85	37	527	120	57	21	+5.6	−1.9
South Salí-Dulce	75	78	37	1,086	248	46	14	**−14.8**	−9.1

Percentage of explained variance by the multiple linear regression models in the verification period 1992–2001 (EV_V) and development period 1979–1991 (EV_D). Mean absolute error in the verification period (MAE_V) expressed as percentage of the monthly or annual mean value. Observed (LT_O) and modeled (LT_M) linear trend in the entire study period (in mm $year^{-1}$). Significant values $p<0.05$ are indicated in boldface. The distribution and time variability of rainfall is characterized by means of the annual mean and standard deviation over each river basin

but while the first one is practically absent in winter, the second also appears intermittently in the lower troposphere during the cold season. The description of typical NAL cases for summer and winter are described by Seluchi et al. (2003). In both cases, migratory troughs approaching the continent from the Pacific Ocean south of 40° S seem to be a factor concurrent with the deepening of the NAL. According to the authors, the deepening of the NAL in summer is due mainly to the sensible heating at the surface, other favorable factors being the latent heat release during intense convective activity and the Foehn effect. Forced subsidence and warming leeward of the Andes is frequently associated with strong westerly winds across the mountains during the transit of upper-level baroclinic disturbances and dominates the intermittent NAL development in winter. The horizontal thermal advection cannot contribute to its deepening during these episodes because it is predominantly negative (cold) just above the NAL, although positive (warm) to the east of the NAL, according to the above referred study. The thermal character of the NAL becomes evident by the increase of the 600–900 hPa thickness, along with a strong negative trend in the 900 hPa height and a slightly negative trend in the 600 hPa height, throughout its development.

The continental subtropical summer rain regime extends to the east of the Andes between about 29° and 35° S. In general, annual rainfall totals are low east of the Andes—e.g., less than 100 mm in San Juan and 370 mm in San Rafael (representative annual mean values are shown in Table 2). The very moist air that reaches the region comes from the tropical zone of the continent and is advected by the same mechanisms acting in northwest Argentina, but the rain-producing convective processes in these latitudes can be as much frontal as non-frontal with an estimated proportion of 3:2 (Prohaska 1976). Rainfall distribution during summer months is better in this than in the previously described

Table 2 Performance of rainfall downscaling models in the Andean Region of Central Argentina

River basin	Monthly rainfall			Annual rainfall					
	EV_V (%)	EV_D (%)	MAE_V (%)	Mean (mm)	St. Dev. (mm)	EV_V (%)	MAE_V (%)	LT_O (mm year–^{1})	LT_M (mm year–^{1})
San Juan	44	57	66	107	33	10	27	**−1.6**	**−2.0**
West Mendoza	37	42	60	232	57	41	81	−0.3	−0.8
East Mendoza	53	60	53	256	86	38	61	1.4	1.1
Tunuyan	50	61	53	332	97	24	63	1.3	1.1
Diamante	63	66	43	370	106	67	104	**4.1**	**5.5**
Atuel	53	64	60	220	49	45	64	**11.4**	**12.1**

Symbols EV, MAE, LT_O and LT_M like in Table 1. The model development and verification periods are 1981–1991 and 1992–2001, respectively

Table 3 Performance of rainfall downscaling models in the Andean Region of Southern Argentina

River basin	Monthly rainfall			Annual rainfall					
	EV_V (%)	EV_D (%)	MAE_V (%)	Mean (mm)	St. Dev. (mm)	EV_V (%)	MAE_V (%)	LT_O (mm year^{-1})	LT_M (mm year^{-1})
Neuquen	83	83	36	679	220	77	12	−2.4	−1.9
Limay	78	81	36	829	208	54	13	+2.4	+7.2
Manso-Puelo	76	80	32	1,164	229	54	20	**−12.4**	**−9.4**
Futaleufu	62	62	40	774	172	41	13	−3.4	−2.5
Chubut	55	57	50	412	131	42	20	5.1	2.4

Symbols EV, MAE, LT_O and LT_M like in Table 1. Model development and verification periods are 1979–1994 and 1995–2004, respectively.

regime and the more frequent synoptic perturbations in winter, although weak and of low humidity content, contributes some rain during the dry season.

Precipitation in the cold semester (April–September) shows a remarkable spatial coherence and significant correlation between points located on both sides of the mountain range between 30° and 40° S, according to Compagnucci and Vargas (1998). An important fraction of winter high altitude precipitation occurs in the form of snowfall, which produces the spring–summer runoff in most Andean rivers. Results of the above study indicate that above (below) average streamflows are more probable during the mature phase of El Niño (La Niña) years, which implies more (less) frequent or intense snowfall in the previous winter. Compagnucci and Vargas (1998) show that large-scale circulation in humid winters is characterized by stronger meridional flow and weaker zonal flow. The opposite happens in relatively dry winters.

The dominance of the mid-latitude winter rain regime expands to the south of 35° S. A two season rainy regime with peaks in autumn and spring becomes evident in the transition zone from the subtropical regime. The annual cycle observed in the intensity and latitude of the westerly wind maximum in the upper troposphere is closely associated with a similar cycle in the frequency of synoptic disturbances, which determines a greater amount of precipitation from May to September to the south of 38° S.

4 Results

4.1 The Northern Region

The performance of the linear regression models in the nine rainfall downscaling sites representative of the major river basins in the Northern Region was satisfactory. The monthly variance accounted for by the models in the verification period ranged from 71% to 82% (Table 1). These values are comparable to or higher than those obtained by other authors (Uvo et al. 2001; Kidson and Thompson 1998) in topographically similar regions. The difference in percentage of explained variance between model development and verification periods is only 5% on average (Table 1), which suggests that the models are also stable. The mean absolute error of the monthly estimates is large and ranges from 30% to 40% of the observed monthly mean rainfall in each downscaling site (Table 1).

The composition and relative importance of the independent variables in the models is depicted in Fig. 2, which shows the frequency of each independent variable in the models composition in the region (the total number of models is equal to the number of sites times the number of seasons). It also shows the percentage of the rainfall variance explained by each variable, obtained from the R^2 change due to the successive inclusion of predictor variables in the stepwise regression procedure.

The precipitable water makes one of the largest contributions to the explained variance (17% on average) and is included in all the models of the Northern Region except in Tartagal.

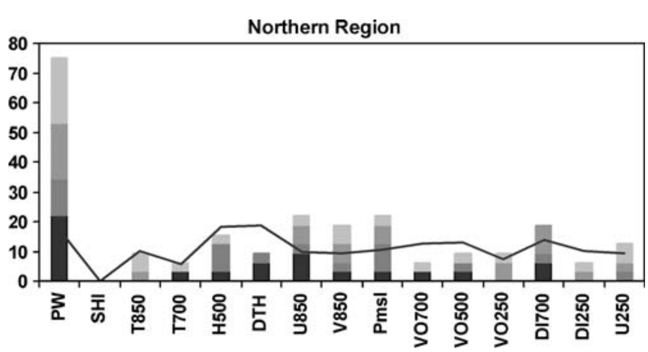

Fig. 2 The *stacked bars* indicate the frequency of each predictor variable in the models composition in the Northern Region (the total number of models is equal to the number of sites times the number of seasons), discriminated by season from winter (*dark gray*) to fall (*light gray*). The *solid line* indicates, on the same scale of the *left-hand side axis*, the percentage of the rainfall variance explained by each variable averaged over the subset of models where they participate

The msl pressure or 500 hPa geopotential height are rain predictor variables in several northern sites, contributing on average 22% and 16% of the explained, respectively. The 250 hPa vorticity goes together with one of the previous variable in three of the sites and produces a relatively lower contribution to the explained variance (7%). In Section 3, it was pointed out that the intensity of the Chaco Low is a crucial factor in the channeling of wet air masses of tropical origin into northern Argentina during the rainy season. This low-pressure system is shallow (thermal low) and an anticyclonic circulation develops in the upper levels of the troposphere. This explains the negative sign obtained in the regression coefficient of the first two variables and the positive sign in the latter.

The meridional wind component at 850 hPa is the second in importance predictor variable in the models of two sites and the first one in Tartagal. The negative sign of the related regression coefficient indicates that abnormally intense northerly wind is associated with rainfall excess, in correspondence with described low-level circulation characteristics (see South American low-level jet and Chaco jet in Section 3) that lead to enhanced water vapor flux toward subtropical Argentina during spring–summer season. This variable contributes less than 10% of the explained variance when located in the second place and almost 50% as one of the summer leading variables in Tartagal and the south of Sali-Dulce River Basin.

The rainfall index series for the east San Francisco and upper Juramento River Basins were obtained by averaging data from seven and three rain gauge stations, respectively (Fig. 1). The corresponding observed and simulated monthly series in the verification period are shown in Fig. 3a and b to illustrate the performance of downscaling models in the Northern Region. The estimated annual series reproduce more than 50% of the observed variability and the mean absolute error is less than 15% of the annual mean value in most of the sites (Table 1). For instance, the annual series shown in Fig. 3c and d illustrate that 1984 was one of the rainiest years in the last two decades of the past century, while 1992–1993 was well below the long-term mean rainfall. Both characteristics were also evident in the other river basin of the region and well captured by the models.

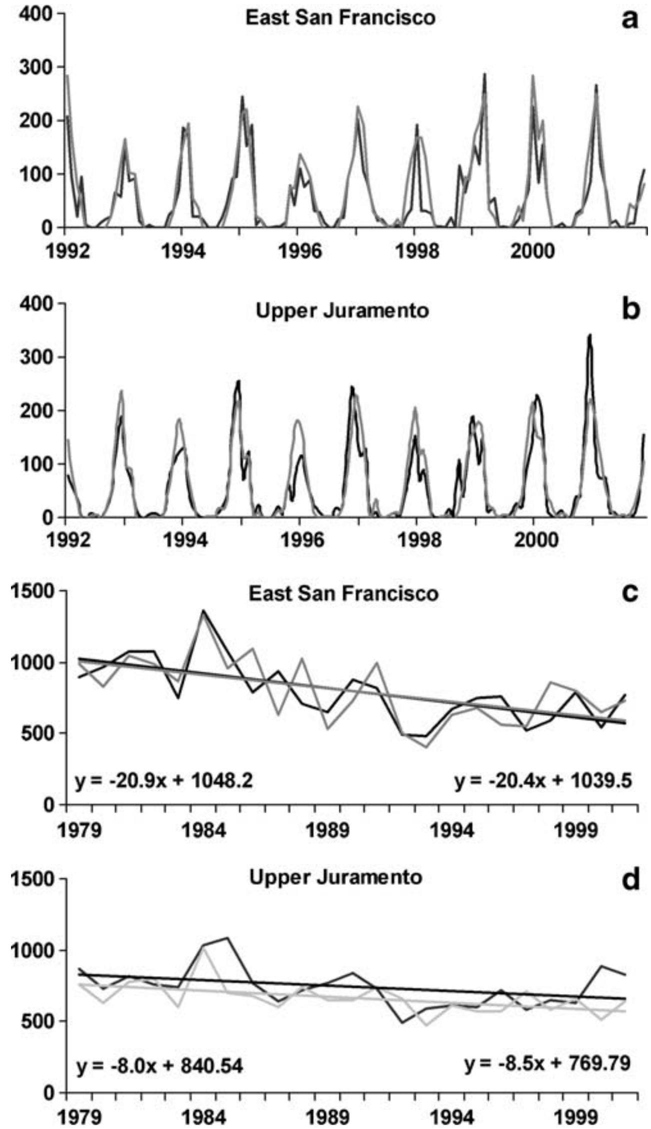

Fig. 3 Observed (*black line*) and modeled (*gray line*) rainfall series in the San Francisco and Juramento River Basins in the Northern Region; **a** and **b** monthly series for the model verification period 1992–2001; **c** and **d** annual series for the entire study period 1979–2001. The linear trend of the entire period and corresponding equations for observations (*left*) and estimations (*right*) are also shown in (**c**) and (**d**)

4.1.1 Simulation of recent rainfall trends in the Northern Region

The series of total annual rainfall in the northwest of Argentina have registered a remarkable increasing trend during the period 1930–2000. However, two interdecadal variations are discernible: one is the sudden shift to higher rainfall in the 1950s; the other is the beginning of a negative trend period by the middle of the 1980s (Minetti et al. 2004). Accordingly, our data indicate that the linear trend in rainfall was negative in the period 1979–2000 in most river basins of the region and reached statistical significance ($p<0.05$) in the east and west sectors of the San Francisco River Basin and in the Pasaje-Salado River Basin (Table 1). Computed linear trends of the annual series obtained from addition of monthly estimates are in close agreement with the observed values (Table 1), particularly where linear trends are statistically significant. The nine statistical models were able to reproduce quite important local differences as well as the slowly decreasing magnitude in the negative rainfall trend towards the south of the

Northern Region in the last two decades of the twentieth century.

It seems reasonable to ask how rainfall seasonal distribution varied in the Northern Region during the period of rain diminution, and if downscaling models were able to reproduce this variation. In order to answer both questions, the mean annual cycles of decades 1979–1988 and 1992–2001 were compared. The results obtained in different downscaling sites are similar and are exemplified in Fig. 4 with the San Francisco River Basin, where negative trend reached statistical significance and the Juramento River Basin, where trend was negative too but did not reach statistical significance.

The concentration of most of the annual rainfall from December to April that characterizes the tropical regime of summer rains in northwest Argentina is very well reproduced by the regression models (Fig. 4). Rainfall decreased in the months of the humid season during the last two decades of the past century and there is no evidence of other changes in the rest of the year, characteristic quite well-reproduced by the statistical models (Fig. 4).

4.2 The Central Region

The performance of the rainfall downscaling models developed for representative sites in the six main river basins of the Central Region (Fig. 1) was far below those for the Northern Region. The percentage of the observed monthly variance accounted for by the multiple linear regression equations ranged from 37% to 63% in the verification period (Table 2). The mean absolute error of the monthly estimates is relatively large, 56% of the local monthly mean rainfall averaged over the set of downscaling sites (Table 2). Additionally, the models seem to be less stable since the explained variance decreases nearly 10% between development and verification periods (Table 2). Nevertheless, the models were able to reproduce other climatic features like the observed local trends and low-frequency fluctuations of rainfall, as will be shown later.

Precipitable water is the predictor variable present in the models of most of the sites in each season (Fig. 5). However, compared to the previous region, it can be located between the first and third place with regard to its relative contribution to rainfall variation (12% of the explained variance on average). As expected, the corresponding regression coefficient is always positive. This variable is absent only in the San Juan model.

The sign of the regression coefficient of the 850 hPa temperature indicates that colder than normal low-level troposphere is significantly associated with excessive rainfall in six of the models. This variable alternates in the hierarchy of predictors with the precipitable water and contributes 15% to the explained variance on average. The

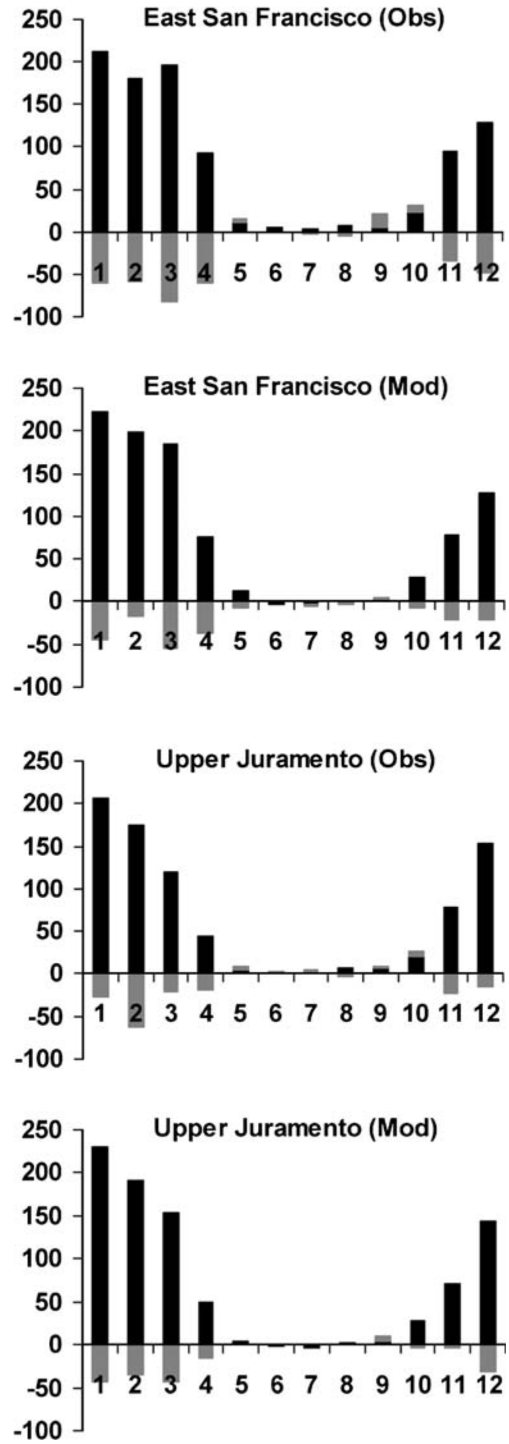

Fig. 4 Annual rainfall cycle in the San Francisco and Juramento River Basins averaged over decade 1979–1988 (*black bars*) and interdecadal variation (decade 1992–2001 minus decade 1979–1988 indicated by *stacked gray bars*, according to observations (*Obs*) and model data (*Mod*), in mm)

meridional wind component at 850 hPa makes a non-negligible contribution to rainfall determination in several models of the Central Region, contributing 21% of the explained variance. The negative sign of the corresponding

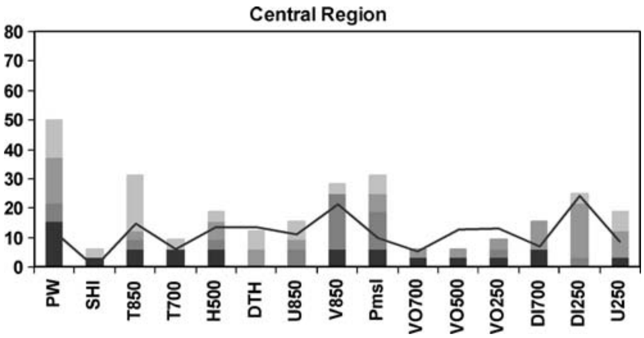

Fig. 5 The same as in Fig. 2, but for the Central Region

regression coefficient suggests an association between abnormal northerly flow and excessive rainfall, which could be attributed to the same reason stated for the Northern Region.

The contribution of the independent variables 700 and 250 hPa flow divergence to the explained rainfall variance in two of the sites is 7% and 24%, respectively. The opposite signs of the corresponding regression coefficients between both atmospheric levels suggest that anomalous convergent flow in the lower troposphere and/or divergent flow aloft are frequently concurrent with excessive rainfall.

The association between temperature, divergence, and rainfall previously indicated is coherent with the role of transient cyclonic perturbations as secondary mechanism for producing rain in the region. The primary mechanism is the local convection originated in atmospheric instability. However, the instability index or other linear combinations of atmospheric variables are not able to capture the associated rainfall variability.

As an example of performance of the rainfall downscaling models, the Mendoza and Diamante River Basins observed and modeled rainfall series are shown in Fig. 6. The large variability of rainfall in one of the most arid zone of Argentina is partly captured by the models. For instance, the rainfall deficit during 1994 and the noticeable excess in February 1998 (four times the monthly mean), were reproduced and can be seen in the series shown in Fig. 6a and b.

In the west sector of the Mendoza River Basin, located at higher altitude than the east sector, the performance of the downscaling model is not good enough, considering the low percentage of explained monthly variance and, concurrently, the large mean absolute error (Table 2).

4.2.1 Simulation of recent rainfall trends in the Central Region

The annual rainfall in western Argentina near the Andes, between 30° and 36° S (Fig. 1), showed a remarkable increasing trend from 1930 to 1980, which though at a much smaller rate remained positive up to the end of the past century according to Minetti et al. (2004). Our results agree that rainfall in the period 1981–2000 had a relatively small positive linear trend, which did not reach statistical significance in the Mendoza and Tunuyan River Basins located in the center of Cuyo Region. However, north of the Cuyo Region, in the San Juan River Basin, the trend was negative and significant, a behavior quite similar to that observed in the neighboring Northern Region. On the other hand, in the Diamante and Atuel River Basins in the south of the Cuyo Region, the rainfall trend was significantly positive. The statistical downscaling models were able to

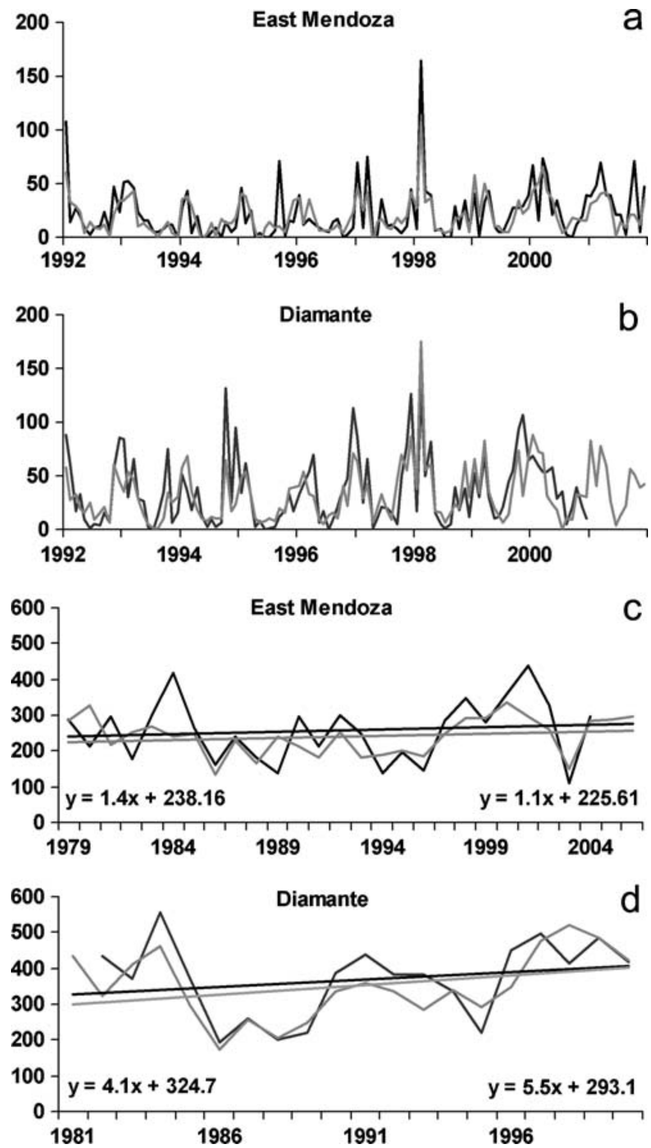

Fig. 6 Observed (*black line*) and modeled (*gray line*) rainfall series in the East Mendoza and Diamante River Basins in the Central Region (Cuyo Region); **a** and **b** monthly series for the model verification period 1992–2001; **c** and **d** annual series for the entire study period 1981–2001. The linear trend of the entire period and corresponding equations for observations (*left*) and estimations (*right*) are also shown in (**c**) and (**d**)

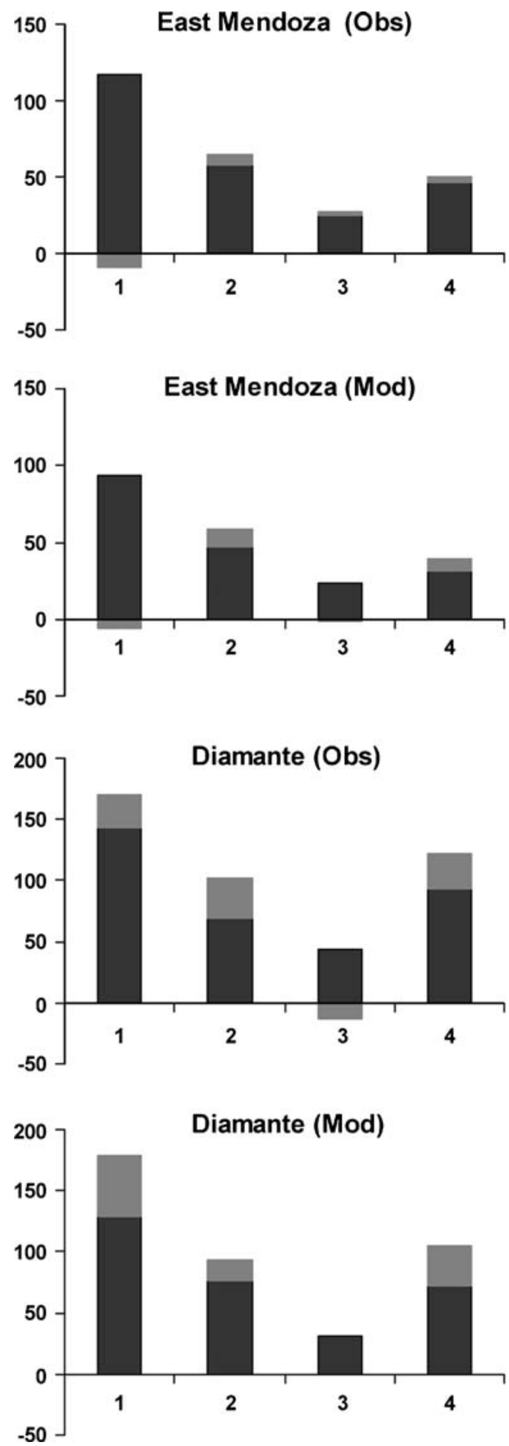

Fig. 7 Seasonal rainfall cycle (*1* DJF, *2* MAM, *3* JJA y, *4* SON) in the east Mendoza and Diamante River Basins averaged over decade 1981–1990 (*black bars*) and interdecadal variation (decade 1992–2001 minus decade 1981–1990) indicated by *stacked gray bars*, according to observations (*Obs*) and model data (*Mod*), in mm

reproduce these local differences in the sign, magnitude, and statistical significance of linear trend observed within relatively short distances quite accurately, as can be seen in Table 2.

According to Prohaska's (1976) classification, the San Juan and Mendoza River Basins belong to the subtropical continental summer rainfall regime. The Diamante and Atuel River Basins belong to the regime of transition toward the winter rains of the temperate latitudes, which is characterized by the appearance of a secondary maximum in June or July, much smaller than the absolute maximum in December or January. The existence of such a transition zone may explain some of the characteristics shown next.

The significant negative trend that occurred by the end of the past century in the San Juan River Basin was the result of the diminution of summer rains exclusively (not shown in figures), like what occurred in the Northern Region. East of the Mendoza River Basin, however, the diminution of the summer rains was slightly exceeded by its increment in autumn and spring (Fig. 7), which caused a non-significant positive trend in the annual rain. Finally, the positive rainfall trend in the Tunuyan, Diamante, and Atuel River Basins was caused by the increase of precipitation in spring, summer, and autumn, as shown in Fig. 7 for the second of these river basins. These local variations in the annual rainfall cycle in the last two decades of the past century were very well represented by downscaling in spite of the low percentage of monthly variance accounted for by the statistical models. Consequently, these rainfall changes are likely associated with low-frequency variations in the atmospheric circulation, variables included in the statistical models.

4.3 The Southern Region

The performance of the models in the river basins of the Andean Region of southern Argentina between 36° and 45° S is superior to that of the central region and reaches levels comparable to those of the Northern Region, with a monthly variance accounted for by the models ranging from 55% to 83% in the independent period (Table 3). The mean absolute error of the monthly estimates is slightly larger than in the Northern Region and ranges from 32% to 50% of the monthly mean rainfall in each downscaling site (Table 3).

The arrangement of model predictor variables is quite different from the other two regions (Fig. 8). The msl pressure is the variable that most strongly affects rainfall in the six downscaling sites, contributing 30% of the explained monthly variance on average. The second variable in importance in five of the modeling sites is the 250 hPa zonal wind component, which adds 15% to the explained variance. There are non-negligible contributions to the explained variance in two of the sites by the 500 hPa geopotential height, 850 hPa meridional wind component, and 250 hPa vorticity (20%, 6%, and 7% on average, respectively).

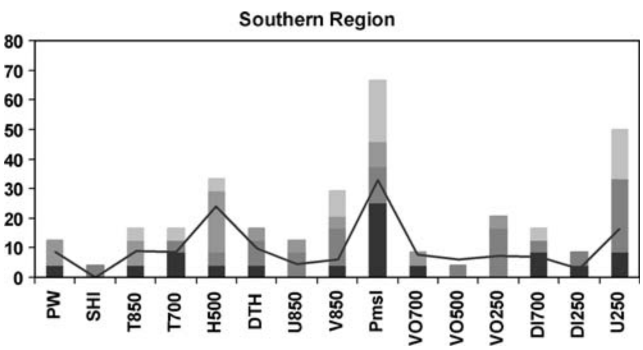

Fig. 8 The same as in Fig. 2, but for the Southern Region

The negative signs obtained in the msl pressure and 500 hPa geopotential height regression coefficients are coherent with the expected relationship between the frequency of cyclonic perturbations and the amount of rainfall in the mid-latitudes winter rains regime. The same reasoning is valid for the negative sign in the regression coefficient of the 250 hPa vorticity, predictor variable selected in most of the models of the southern sites in spring. It seems logical the positive sign obtained for the 250 hPa zonal wind component regression coefficient, since the baroclinic instability increases with the vertical shear of the flow in the vicinity of the upper troposphere jet stream.

To illustrate the performance of downscaling models in the Southern Region, Fig. 9 shows observed and estimated monthly and annual rainfall series for the downscaling sites in Neuquen and Chubut River Basins. Large monthly rainfall totals observed from 2000 to 2003 in the Neuquen site were effectively captured by the model, as can be seen in Fig. 9a. Also, the remarkable rainfall deficit observed in 1988, 1989, and 1998 in both river basins was reproduced quite accurately, as can be seen in the annual series in Fig. 9c and d.

4.3.1 Simulation of recent rainfall trends in the Southern Region

The already mentioned study by Minetti et al. (2004) on rainfall trends in Argentina and Chile states that the region between the Colorado and Deseado riverheads (between 36° and 46° S approximately) experienced a continuous decrease in the annual total rain between 1931 and 1999. Our analyses corroborate that in the period 1979–2004 a progressive decrease in rainfall occurred in the Neuquén, Manso-Puelo, and Futaleufú River Basins. However, increasing annual totals were registered in the Limay and Chubut River Basins, located also within the above-mentioned latitude interval, as it is demonstrated by the linear trends in the study period shown in Table 3. Our study is based on a larger number of series in this region, which makes it possible to demonstrate that rainfall behavior was not uniform. The regression models captured these regional differences in the signs of the rainfall trend, even though in general the magnitude was small and did not reach statistical significance (Table 3).

Only in the relatively small Manso-Puelo River Basin, located further west and higher on the eastern slope of the Andes, the negative trend reached statistical significance and was rather underestimated by the downscaling procedure. This region represents the southern end of an extensive pattern of decreasing rain that according to Minetti et al. (2004) dominated the central area of Chile and the heights of the Andes mountain range during the past century.

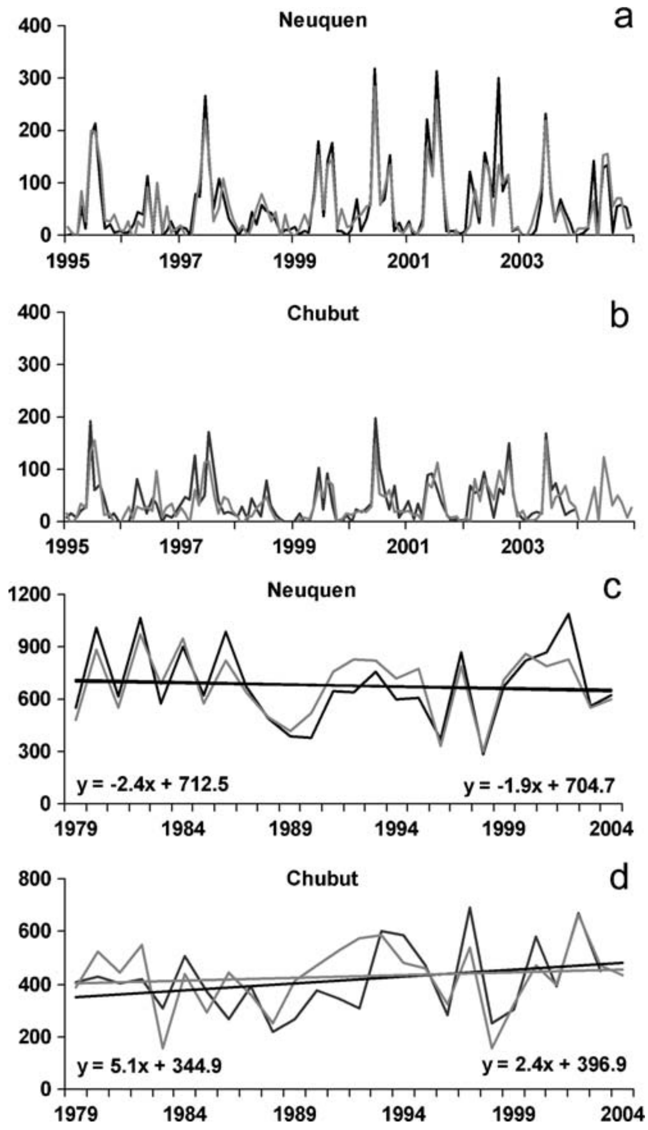

Fig. 9 Observed (*black line*) and modeled (*gray line*) rainfall series in the Neuquen and Chubut River Basins in the Southern Region; **a** and **b** monthly series for the model verification period 1995–2004; **c** and **d** annual series for the entire study period 1979–2004. The linear trend of the study period and corresponding equations for observations (*left*) and estimations (*right*) are also shown in (**c**) and (**d**)

A singular change in the annual rainfall distribution took place in the southern Andean Region within the period of study and it was very well reproduced by the statistical models. The onset of the winter rainy season, which in the long-term average can be located in May, shifted toward June by the end of the past century. This characteristic can be appreciated in Fig. 10, which shows changes in the observed and modeled annual rainfall cycles in the Neuquén and Chubut River Basins, located in the northern and southern ends of this region, respectively. The same shift appears in the other three basins, independently of the sign of the linear trend observed in the period. This rainfall change, which may be located at the beginning of the 1990s, is linked to changes in atmospheric circulation and was captured by downscaling from variations in the 250 hPa zonal wind component, which is discussed in the next section.

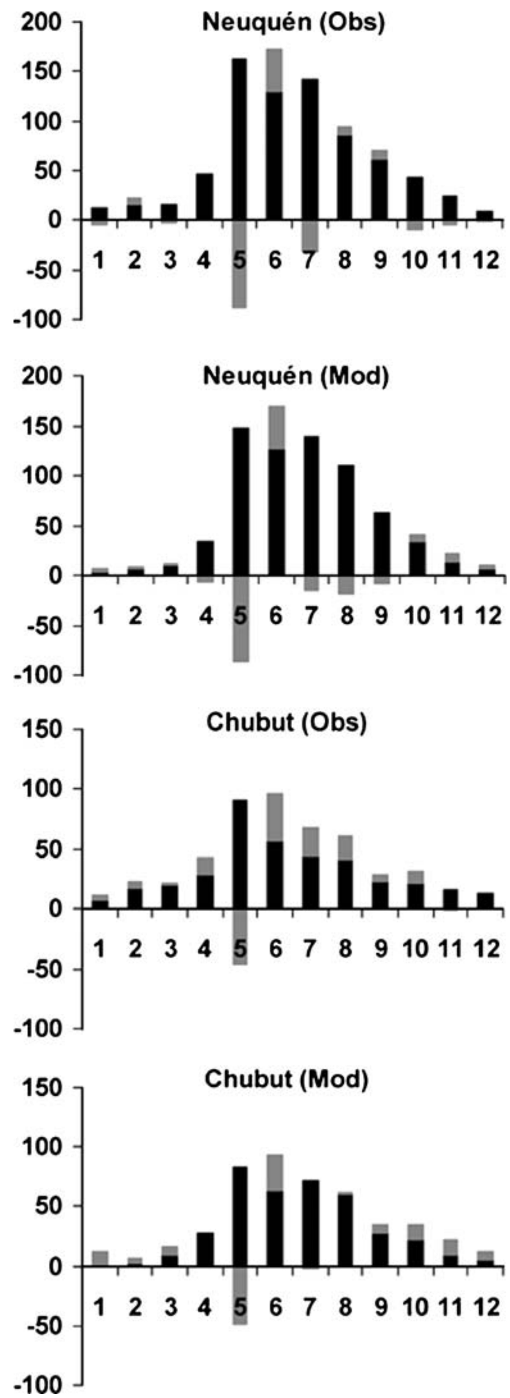

Fig. 10 Annual rainfall cycle in the Neuquen and Chubut River Basins, averaged over decade 1979–1988 (*black bars*) and interdecadal variation (decade 1995–2004 minus decade 1979–1988) indicated by *stacked gray bars*, according to observations (*Obs*) and model data (*Mod*), in mm

5 Discussion and conclusions

Statistical models for rainfall downscaling based on a multiple linear regression technique have been developed and tested in the Andean Region of west Argentina, a mountainous zone with great spatial and temporal rainfall variability, where different precipitation regimes coexist and the available observed data exhibit non-uniform distribution. A crucial aspect of the verification procedure has been testing the ability of the method to reproduce the important changes in rainfall trends observed in the recent past. The future application of the models here presented is oriented to produce reliable estimates of local rainfall variations that are likely to occur throughout the current century as a result of the global warming, an important piece of information for life and economy of vast populations that are critically dependent on water availability.

The models developed have shown quite different levels of performance, as well as noticeable differences in the structure and composition of the set of predictor variables, in each of the three rainfall regimes that prevail throughout the study region:

1. In the Northern Region, domain of the tropical summer rain regime, the correspondence between observed and modeled values is very good. The model variables that most effectively condition rainfall occurrence— which is predominantly convective— are the precipitable water, 850 hPa meridional wind component, 500 hPa geopotential height, msl pressure, and 250 hPa vorticity.
2. In the Central semi-arid region, the performance of the models in the estimation of monthly rainfall values is relatively poor. Even so, the models demonstrated ability to capture different signs and magnitudes in the local long-term trends and regional changes in the annual rainfall cycles observed toward the end of the past century. The most important predictor variables are the precipitable water, 850 hPa temperature and meridional wind component and 700 and 250 hPa flow divergence.

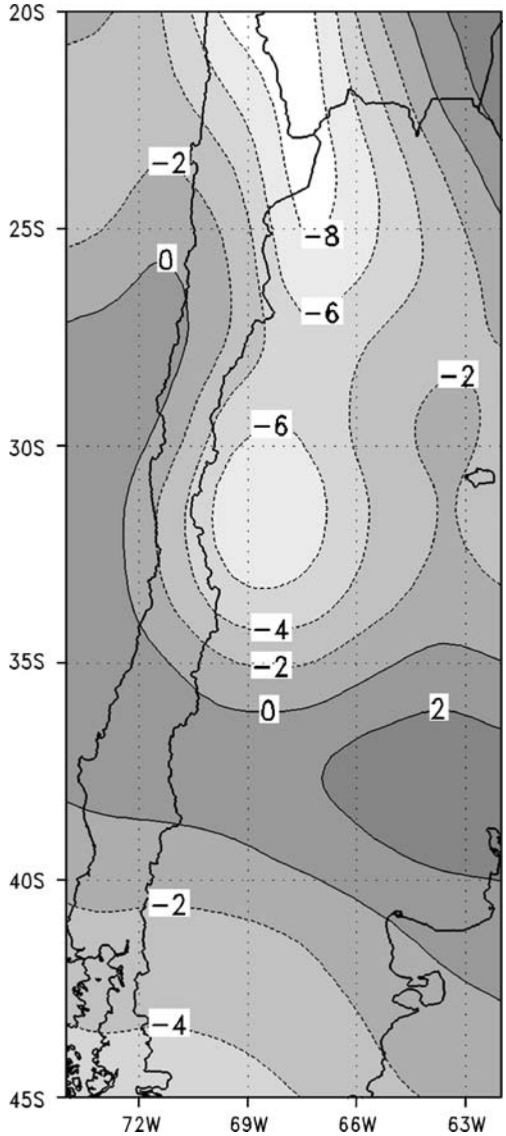

Fig. 11 Fractional changes in precipitable water in the Andean Region of west Argentina: 1996–2001 mean minus 1979–1984 mean as a fraction of the latter. Data from Reanalysis 2 (Kanamitsu et al. 2002)

3. In the Southern Region, model performance is good and comparable to that obtained in the Northern Region. In this mid-latitude zone, rains are produced mainly by transient synoptic disturbances. Consistently, dynamic variables such as the msl pressure, 250 hPa zonal wind component and vorticity, 500 hPa geopotential height, and 850 hPa meridional wind component, have an even greater influence on rainfall than precipitable water.

The mean values of the explained variance in each region (77% in the Northern, 50% in the Central and 71% in the Southern) are higher than the mean value obtained by Kidson and Thompson (1998) with individual regression models for 78 stations in a mountainous region like New Zealand (36.4%).

The deficient performance of the models in central-western Argentina may be attributed to errors in the reanalysis (Kanamitsu et al. 2002), which are the source of the predictor variables. These inaccuracies might be related to the rapid transition between the subtropical continental circulation and the mid-latitude westerly circulation that occurs in this region and the concurrent scarcity of upper-air observations. In addition, the steep Andes mountain range is an important obstacle to atmospheric circulation, difficult to represent even for high-resolution models. The development of regression models for each season separately let us explain coherently the physical relationships between predictors and predictand on the basis of observed regional circulation features and the sign of regression coefficients.

Precipitable water turned out to be an important predictor variable in most of the northern and central sites. Water vapor is one of the most sensitive atmospheric variables to the effects of global warming. Therefore, it seems advantageous to include this variable in downscaling models that will be used to estimate future climate changes. However, the accuracy of atmospheric humidity estimates in global or regional models should be evaluated before using them for downscaling procedures.

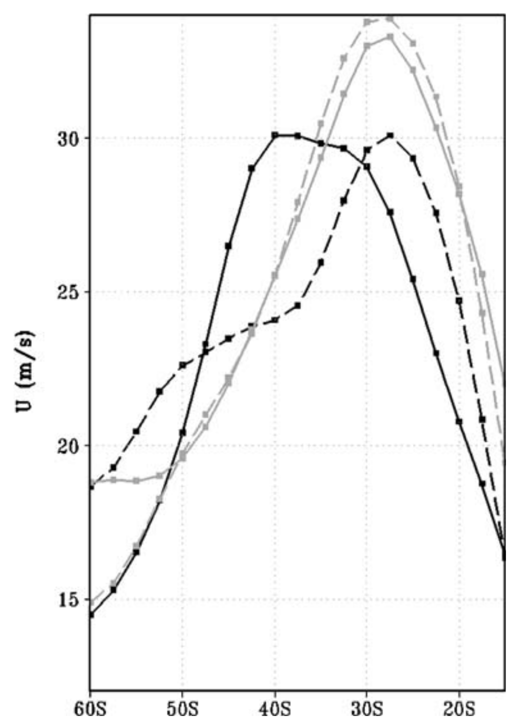

Fig. 12 Zonal wind component at 250 hPa and 70° W in m s^{-1}. Mean values for May (*black lines*) and June (*gray lines*). The average of the period 1979–1988 is indicated by *solid lines* and the average of the period 1995–2004 by *dashed lines*

Considerable emphasis was put on verifying the models' capability to simulate the observed long-term trends in the past century. Our results show that multiple regression models are able to reproduce satisfactorily the negative linear trend in northwest Argentina observed during the last two decades of the past century. The estimates of precipitation in this region are determined largely by the moisture available in the atmosphere. Thus, the average of precipitable water over the period 1979–1984, near the time of the maximum rainfall, was compared with the average over the period 1996–2001 (Fig. 11). The northwest of Argentina and the north of the Cuyo Region (up to 35° S) experienced a 2% to 6% drop in precipitable water, with a maximum located at the heights of the Andes mountain range. Between the same periods, the 500–1,000 hPa thickness also decreased, with a maximum centered over the mountain range and at 27° S approximately (not shown in figures), which indicates a regional cooling of the lower troposphere compatible with the reductions in atmospheric water vapor content and rainfall.

The shift in the onset of the winter rainy season we found in the Southern Andean Region in the 1990s is a climatic feature that statistical models were able to reproduce mainly through changes registered in the 250 hPa zonal wind predictor variable. In the Southern Hemisphere winter, the subtropical jet stream is located between 25° and 30° S over South America. Figure 12 shows that the mean location of the maximum in the upper-troposphere zonal wind component over the Andes (70° W) in May was located further north at the end of the study period than at the beginning. The storm tracks in the Southern Hemisphere are located frequently just south of the jet stream maximum due to the large transport capacity of transient eddies and the inherent baroclinicity of the flow (Trenberth 1991). The northward shift of the subtropical jet may explain the diminution of rains in May by the end of the past century in river basins of the Andean Region south of 36° S (see Neuquen in Fig. 10). On the other hand, in June the mean latitude of the jet stream maximum did not change but its intensity increased, which could explain the increase of rain in that month. Similarly, the positive sign in the rainfall trend observed and modeled in the last two decades of the past century south of the Cuyo Region between 34° S and 36° S (see Diamante in Fig. 7) could be attributed to the northward shift of the storm tracks in autumn.

The capacity of the downscaling models described here to estimate regional rainfall from the analysis of observed atmospheric data provides a measure of confidence for rainfall estimations based on climate conditions different from current ones, which could be obtained from global or regional model simulations of the future climate. The results achieved demonstrate the feasibility to establish significant statistical relationships between atmospheric variables and rainfall at monthly and river basin scales. In this sense, models based on multiple linear regression techniques offer an efficient alternative with relatively low computational cost, even in topographically complex regions. However, the application of this type of statistical model can be considered safe within the range of variations registered in the calibration period only. For greater variations, the use of dynamical downscaling techniques is advisable.

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