An intercomparison of observed and simulated extreme rainfall and temperature events during the last half of the twentieth century: part 2: historical trends

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Abstract We analyze historical simulations of variability in temperature and rainfall extremes in the twentieth century, as derived from various global models run informing the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4). On the basis of three indices of climate extremes, we compare observed and modeled trends in time and space, including the direction and significance of the changes at the scale of South America south of 10° S. The climate extremes described warm nights, heavy rainfall amounts and dry spells. The reliability of the GCM simulations is suggested by similarity between observations and simulations in the case of warm nights and extreme rainfall in some regions. For any specific extreme temperature index, minor differences appear in the spatial distribution of the changes across models in some regions, while substantial differences appear in regions in the interior of tropical and subtropical South America. The differences are in the relative magnitude of the trends. Consensus and significance are less strong when regional patterns are considered, with the exception of the

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La Plata Basin, where observed and simulated trends in warm nights and extreme rainfall are evident.

1 Introduction

A primary concern in estimating impacts from climate change are the potential changes in variability and hence extreme events that could accompany global climate change. Short-scale extreme events have long been of interest to meteorologists because most of the meteorological-related human and monetary costs are usually incurred during the brief periods of these short-term events. Understanding the causal mechanisms for short-term events will yield insight into seasonal anomalies as well.

One of the most important questions regarding short-term extreme events is whether their occurrence is increasing or decreasing over time—that is, whether the shape of the distribution indicating whether these events occur more or less frequently is changing significantly. Statistically this can be thought of as resulting from changes in the variable's mean and/or other parameters of its distribution or climatologically as a result of changes in the frequency and intensity of the associated weather events themselves and/or the occurrence of the large-scale patterns conditioning these events. Thus a sequential analysis of time series can determine the existence of trends without giving any information on the underlying causes (even in the absence of abrupt changes which may have contributed).

Heat and cold waves, intense rainfall, floods, dry spells among other extreme events affect South America in all seasons, and their impacts vary according to the sector. Heavy or extreme precipitation events have important effects on society, since flash floods associated with intense and brief, rainfall events may be the most destructive of extreme events. Over many areas, the frequency of heavy precipitation events has increased, consistent with warming, and widespread changes in extreme temperatures have been observed over the last 50 years (Alexander et al. 2006; Marengo et al. 2008). Cold days, cold nights and frost have become less frequent; while hot days, hot nights, and heat waves have become more frequent (Vincent et al. 2005; Haylock et al. 2006; Caesar et al. 2006; Alexander et al. 2006; Rusticucci and Tencer 2008). Such changes in extremes have impacts on human activities such as agriculture, human health, urban development and planning and water resources management.

Several papers have documented observed trends in extreme air temperatures in South America. Nonetheless, the variation in methodologies employed by these studies makes intercomparison a difficult task. For example, studies using an index of temperature or precipitation extremes based on percentiles are likely to reach different conclusions than those that define extremes as some percent of a standard deviation or those considering thresholds (see reviews in; Barrucand and Rusticucci 2001; Rusticucci and Barrucand 2001, 2004; Marengo and Camargo 2007). Thus, the use of indices of extremes has been accepted as a possible solution for studies that can be integrated at regional and global scales.

In southeastern South America various studies on extremes, defined using different methodologies seem to agree with those derived using the Frich et al. (2002)

derived indices. The results of Rusticucci and Barrucand (2004) for Argentina Marengo and Camargo (2007) for Southern Brazil and of Rusticucci and Renom (2008) for Uruguay suggest warming in Southeastern South America, both in summer and winter and in the mean and extremes, with the warming being strongest during the winter than in the summer. In relation to precipitation, Liebmann et al. (2001), Doyle and Barros (2002), Carvalho et al. (2002, 2004), Penalba and Vargas (2004), Groissman et al. (2005), Penalba et al. (2005), Boulanger et al. (2005), Marengo (2007), Teixeira and Satyamurty (2007), and Penalba and Robledo (2008, this issue) have identified systematic increases of very heavy precipitation since the decade of 1950 in various regions of Southeastern South America. All of these studies agree with the tendencies identified in Vincent et al. (2005), Haylock et al. (2006), and Alexander et al. (2006) and Marengo et al. (2008), derived from the Frich indices.

For South America, projections for the twenty-first century are unanimous concerning the changes in most temperature indices that are expected within a warmer climate, with differences in the spatial distribution of the changes and in the rates of the trends detected across scenarios. Tebaldi et al. (2007), using an ensemble of eight IPCC AR4 global models for the A1B and A2 (transition and high emissions), and Marengo et al. (2008) using the PRECIS regional model system for the A2 and B2 scenarios, assessed projections of changes in climate extremes from an ensemble of eight global coupled models from IPCC-AR4 under scenario, and for the 2071–2100 time slice. They found warming in South America and increase in nighttime temperatures (and warm nights) in regions such as Southeastern South America, together with increase in frequency of intense rainfall events during the last 50 years or so. However, consensus and significance are less strong when it comes to regional patterns, and while all models show consistency in the warming signal, the same can not be said for rainfall extremes.

Because of their finite and still relatively coarse resolution, global climate models are not expected to represent extreme weather events with the same intensity and frequency as in observed data, particularly for precipitation-related events (Kiktev et al. 2003). Some efforts to downscale extremes in present and future climates (Marengo et al. 2008; Solman et al. 2007, 2008) have shown some agreement with the global model-derived projections, especially in data-rich regions such as Southeastern South America.

Therefore, we examine indices of temperature and rainfall extremes from seven IPCC AR4 coupled climate models for the twentieth century (referred as IPCC AR4 20C3M). Even though the simulations are available since 1900 (some of them go back to 1860), the modeled extreme indices are compared to observations for the 1960–2000 period only. This period was selected because of the availability of homogeneous and quality-controlled observed temperature and precipitation data was available for that period. The comparisons between observed and simulated indices are made to determine the plausibility of the simulated indices for present climate. Finally, we discuss the uncertainties in the predicted extremes rainfall changes and in their potential impacts on the regional climates and society.

This study is part of the CLARIS-EU project ("A Europe South America Network for Climate Change Assessment and Impact Studies"; Boulanger et al. 2008, this issue) aimed at strengthening collaborations between research groups in Europe and South America to develop common research strategies on climate change and impact issues in the subtropical region of South America through a multi-scale

integrated approach (continental–regional–local). The analyses of extreme climate, whether observed or simulated, represent one of the objectives of CLARIS-EU.

2 Data and methods

2.1 IPCC AR4 20C3M experiment and models used

The 20C3M experiment consists of mostly five-member ensemble simulations of the twentieth century climate (starting from mid-nineteenth century) by different state-of-the-art models. The goal of this study is to survey the most recent simulations of climate extremes for present times. From the models available for the 20C3M experiment in which Frisch-derived indices of extremes were computed we, used four runs from the PCM, three runs from each the MIROC3.2 (Med res), GFDL-CM2.0 and GFDL-CM2.1 models, and five runs from the MRI-CGCM2.3.2. The rest of the models have one run only. More information on the 20C3M experiment can be found at: http://www.ipcc-data.org/ar4/scenario-20C3M.html, and data from this experiment is provided by the US Department of Energy Program for Climate Model Diagnosis and Intercomparison (PCMDI).

The list of IPCC AR4 models that have available Frich indices of extremes in the 20C3M run (until February 2008, when this paper was written) can be found at http://www-pcmdi.llnl.gov/ipcc/data_status_tables.htm. The models used for this study are the DOE/NCAR Parallel Climate Model (PCM; Washington et al. 2006; Weatherly and Bitz 2001) and Coupled Climate System Model (CCSM3; available from http://www.ccsm.ucar.edu/publications), the CCSR MIROC medium and high resolution models (Hasumi and Emori 2004), INM-CM3 (Diansky and Volodin 2002), CNRM-CM3 (Déqué et al. 1994; Déqué and Piedelievre 1995), GFDL-CM2.0, GFDL-CM2.1 (Delworth et al. 2005) and MRI-CGCM2. Model grid resolutions vary from relatively coarse (INMCM3, $5° \times 4°$) to relatively finer (MIROC hires, 1.125°). We used the 1960–2000 period (see Section 2.4). See Meehl et al. (2007) for more details on the descriptions of the coupled global models.

2.2 Observations

For this study, long term temperature daily observational records from high quality stations covering as much as possible for the region were preferable. A total of 104 stations were closely examined for the preparation of the indices (Fig. 1). The period of record varied by station but it generally covered 1960–2000. On this study we used the minimum temperature and precipitation daily records of those 104 stations spread mostly in subtropical South America, with few ones in the Andean region, Amazonia, Northeast Brazil and the western coast of South America. Data from most of the stations used in this work are included in the data base created during the CLARIS-EU project (Boulanger et al. 2008, this issue). For details on the stations, quality control, and the times series, the reader is referred to Alexander et al. (2006), Haylock et al. (2006), Vincent et al. (2005), Rusticucci et al. (2009, this issue) and Penalba and Robledo (2008, this issue).
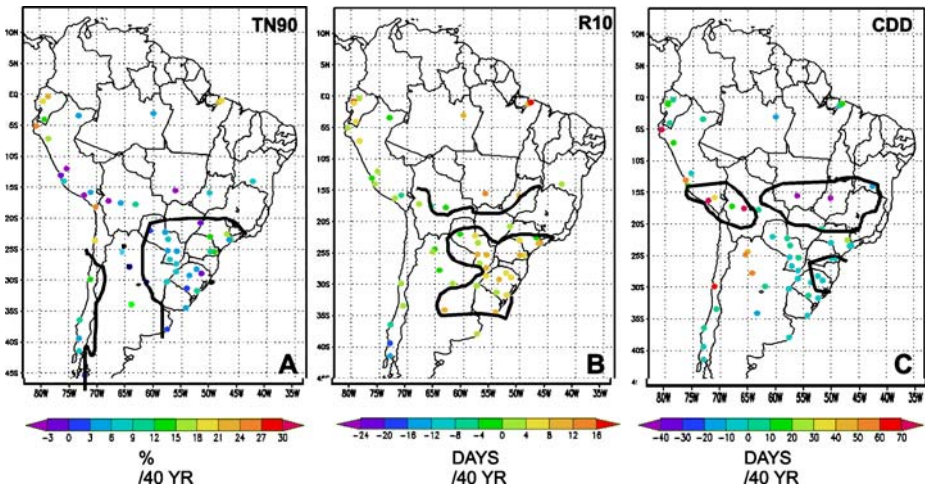
Fig. 1 Observed trends of extreme climate indices for 1960–2000. The trend is assumed as linear and represents the values of 2000 minus 1960. **a** TN90 in %/40 years; **b** R10 days/40 years; **c** CDD in days/40 years. *Black line* delimitates areas where the linear trend is statistically significant at 5% level using the Student *t*-test. *Maps* show indices at station level

The baseline period for calculations of anomalies is 1961–1990, so the last 10 years in the record are excluded. We are aware that this procedure may produce spurious results and introduces discontinuities resulting in an overestimated number of days outside of the base period. We refer the reader to Zhang et al. (2005) for more in depth analyses regarding this aspect. Nevertheless, we maintain this approach since it has been used by the IPCC (Trenberth et al. 2007) and several other papers, so direct comparisons can be made between our and previous results.

2.3 Indices of extremes

The indices used on this study were defined by Frich et al. (2002). These indices sample the extreme ends of a reference period distribution. Estimates of these indices were made available for the IPCC AR4 20C3M models mentioned before. Since the observed indices are available from 1960–2000 and the modeled indices are available for the twentieth century, we use the common period 1960–2000 considering 1960–1990 as reference period for calculations of anomalies.

The indices used are:

1. Warm nights, defined as the percentage of times in the year when minimum temperature is above the 90th percentile of the climatological distribution for that calendar day: TN90
2. Number of days with precipitation greater than 10 mm: R10
3. Maximum number of consecutive dry days (days with precipitation of less than 1 mm/day): CDD

The selection of these three indices from a list of 27 is based on the consideration that they represent situations such as heat waves, intense rainfall and dry spells, that

have important effects on human activities such agriculture, human health, urban development and planning and water resources management.

These indices do not represent extremely rare events, for which the computation of significant trends could be a priori hampered by the small sample sizes. From observations, we create programs to calculate those three indices based on Frich et al. (2002) and the input data was daily precipitation and maximum and minimum air temperatures. In the following we may be referring to intense precipitation as the R10 index.

2.4 Methodology

As a first step, the 104 stations available for this study were gridded over South America onto a regular $1° \times 1°$ grid using ordinary krigging for every index during the 40 years of study. Given the lack of stations in Amazon, we focus our study South of $10°$ S were stations are more concentrated. The Vebyk (Value Estimation BY Kriging) algorithm has been computed with no anisotropy and 20 stations are used for each interpolated data. The well-known exponential auto-covariance function has been chosen to fit the experimental covariance function. The correlation length has been set up to $100°$. This algorithm provided an estimation of the error (errovariance) at each grid box. These parameters have been chosen based on different simulations results so that to minimize the errovariance.

Because the stations are not evenly distributed, linear interpolation could lead to erroneous values. With this in mind, values whose errovariance was greater than a fixed value (1.5e-3) have been set up to undefined and have not been taken into account in following calculation. Once the grids were obtained, trends in the indices have computed over the 40 years at every grid box following Alexander et al. (2006) for both observed and simulated data. Trends have been estimated by fitting a straight line to the data. The statistical significance of such a trend is determined by conducting a Student's *t*-test. A Kendall's tau based slope estimator (Sen 1968) has been used to compute the trends since this method does not assume a distribution for the residuals and is robust to the effect of outliers in the series. The serial correlation in the residuals was considered when testing the statistical significance of trends, since a positive auto-correlation (which is usually present in time series of climate data) in the time series would make the test unreliable (e.g. Zhang and Zwiers 2004).

The analysis of the variability has been done by comparing the estimated Probability Density Functions PDFs of corresponding observational and model fields. A kernel smoothing method was used to obtain nice plots (Bowman and Azzalini 1997). All the observations and modeled fields have been resized onto a grid $1° \times 1°$ before doing those calculations, as each model resolution is different (but lower than $1° \times 1°$). We acknowledge that gridded $1° \times 1°$ resolution from the observation does not, in general, produce a data set comparable with that from models as gridded data are typically estimations for a point rather than area mean as is the case for the models.

On the comparison of the trends in the observed and simulated indices, and referring to the observed and simulated warming during the XX century discussed by Hegerl et al. (2007), we can consider that if observations and simulations have similar natural variability and anthropogenic influence (as detected from the beginning of the XX century to the 1970s), the only thing we could reasonably explain the

observed warming during the last 30 years of the XX century would be the strong anthropogenic climate change signal since natural forcing has not change that much. As the scales getting smaller, the natural variability or the noise will be very strong when compared with the signal. To quantify this comparison of observed and simulated linear trends for the extreme indices during the last 40 years, we determine the extent to which linear trends in station data and data from the models are correlated. It is clear that with these analyses we do not expect to see a clear separation between noise and signal at such very small scale and we will focus on larger patterns.

3 Results

3.1 Geographical patterns of observed trends in extremes

Figure 1 shows the observed trends of the three indices analyzed derived from observations at station level. Trends in the temperature index reflect an increase in minimum temperature, with significant change (Rusticucci and Barrucand 2004; Vincent et al. 2005; Obregon and Marengo 2007; Marengo and Camargo 2007). Figure 1 also shows very large increase in the occurrence of very warm nights in southern South America. The observed pattern of trends in TN90 was significant at the 5% level in some regions. There have been locally significant positive trends over southeastern South America and the west coast of southern Chile. There are examples of locally non significant decreases in the percentage of TN90 in the gridded observations in Bolivia, Southern Peru and Northern Argentina. Alexander et al. (2006) indicate that warming in TN90 trends is observed all year long in southern South America, and is higher in austral summer (December–February) and fall (March–May).

We found an increase of precipitation extreme trends. The observed fields show that the number of extreme daily rainfall events above 10 mm/day (R10) exhibits an increase during the last 40 years in regions such as the western coast of Peru and Ecuador, and southeastern South America. In Northern Peru there has been an increase of 4–8 days with heavy precipitation, while in southern Brazil, Uruguay and Paraguay this increase reaches up to 12 days with heavy precipitation. The presence of abundant rainfall during the strong El Nino events in the time from of 1961–2000 (1972, 1983, 1987 and 1998) on the otherwise arid South American west coast may have driven those trends. The tendency for increase in rainfall extremes in these regions have been documented in previous studies (Liebmann et al. 2004; Penalba et al. 2005; Groissman et al. 2005; Teixeira and Satyamurty 2007), using different criteria for defining extremes, may be linked to changes in the interannual variability due to El Nino/La Nina frequencies, or changes in the frequency of occurrences of cold front entrances, episodes of South Atlantic Convergence Zone SACZ and the South American Low Level Jet east of the Andes SALLJ variability.

The CDD observed index (Fig. 1) exhibits positive trends in the regions extending from western Ecuador (10–20 days), southern Peru, Bolivia and Northern Argentina (10–50 days), while negative trends reach field significance in west central Brazil, Paraguay and Southern Brazil and Uruguay, with reduction between 10 and 40 days, in agreement with Alexander et al. (2006) and Haylock et al. (2006).

3.2 Simulated geographical patterns of observed trends in extremes

The simulated trends for TN90 (Fig. 2) from six models are all positive, being higher (above 15% in 40 years) in tropical South America in the CCSM, CNRM, INM and MIROC-Med Res, while the GFDL2.0 and PCM show trends on the order of 3–6%. For the La Plata basin all models show positive trends reaching field significance in the CCSM and GFDL2.0 models in orders of magnitude comparable to observed trends (see Fig. 1). The CRNM, INM and MIROC-Med Res simulate quite well the large, positive trend. The observed trend in TN90 the northern coast of Peru and Ecuador and in the southern coast of Chile between 15° and 30° S is well simulated, even though the magnitude may be underestimated.

The simulated R10 index show positive trends in all models South of 35° S, and negative trends in southeastern Brazil around 20° S. Observed trends south of 35° S are in the interval −20 to +4, and are positive over southeastern Brazil. With the exception of the INM, PCM and CNRM, all models simulate the observed positive trends in the La Plata Basin. Observed trends there vary from 4–12 days (Figs. 1 and 2) and from −4 to 8 days in the models. The observed positive trends in the northern regions of Peru and Ecuador are not well simulated by the models and large positive
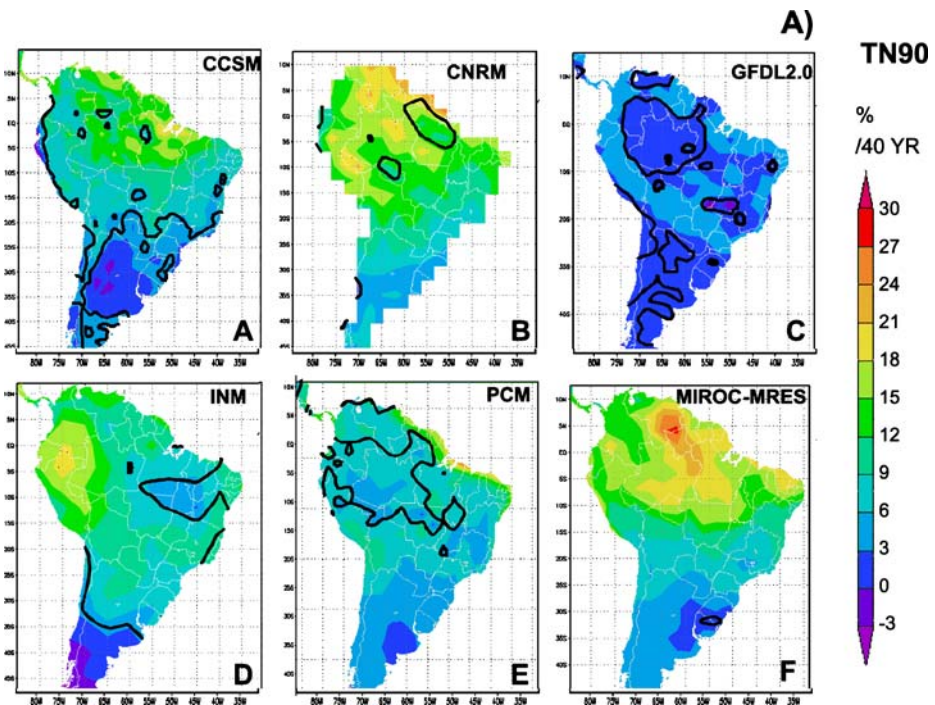
Fig. 2 Simulated trends of extreme climate indices for 1960–2000. The trend is assumed as the slope of the linear regression during 1960–2000. **a–f** TN90 in %/40 years; **g–l** R10 days/40 years; **m–r** CDD in days/40 years. *Black line* delimitates areas where the linear trend is statistically significant at 5% level using the Student *t*-test. Models used are CCSM, CNRM, GFDL2.0, INM, PCM and MIROC Med Resolution
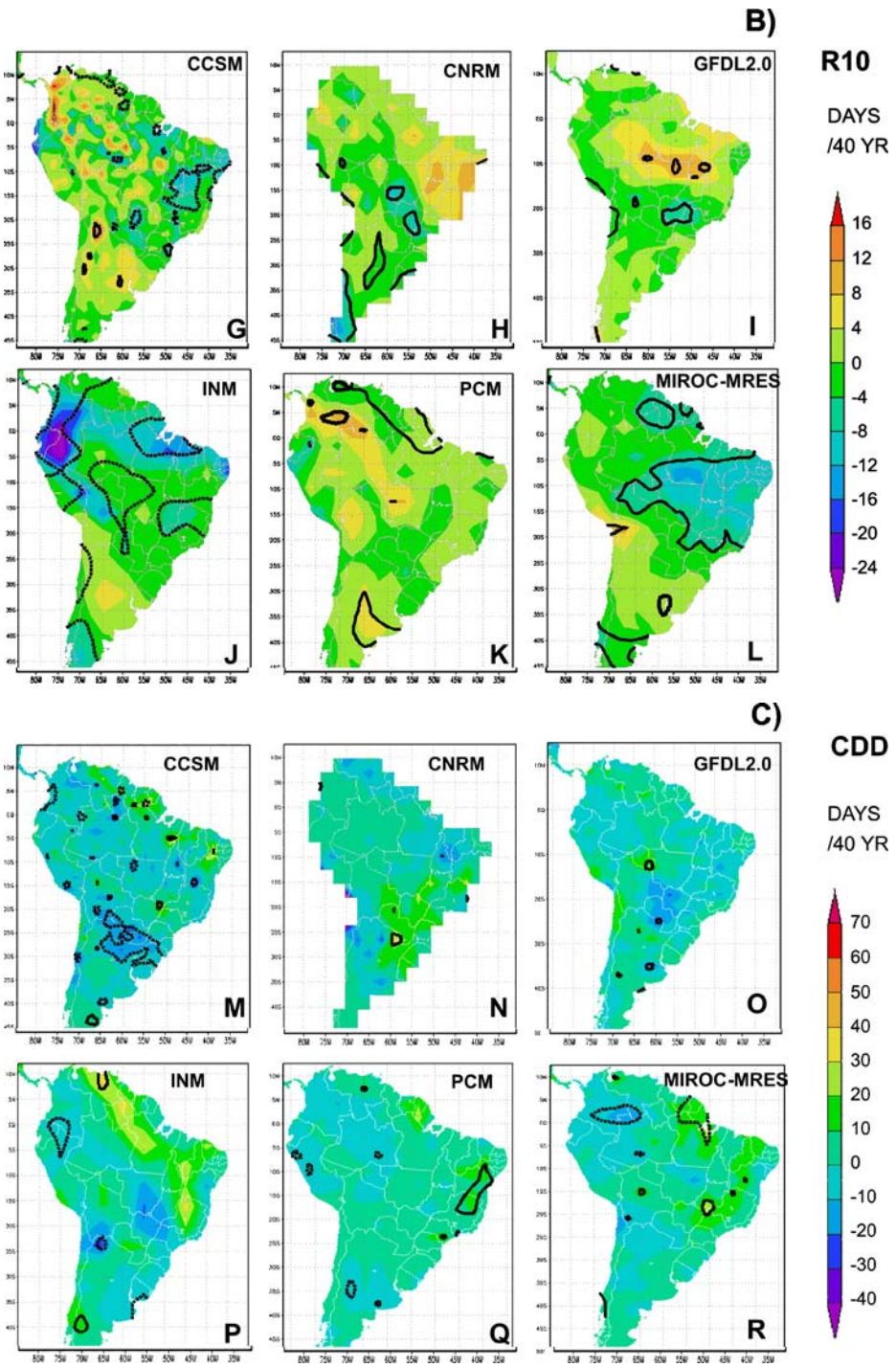
Fig. 2 (continued)

trends in tropical South America east of the Andes in the CNRM, GFDL2.0 and PCM, as well as the negative trends in the same region for the MIROC-MedRes cannot be validated due to lack of observations on those regions.

Figure 2 shows that the observed negative CDD trends in the La Plata Basin (over Southern Brazil, Paraguay, Uruguay and Eastern Bolivia are well simulated by the CCSM (reaching field significance of the region) and the INM and PCM show small positive trends. While positive trends are observed in Bolivia, Southern Peru and Northern Argentina, the CNRM, CCSM and MIROC models tend to simulate negative trends.

Comparing observations and models using the Spearman correlation analysis, Fig. 3 shows that the best agreement between all models and observations at station level is for TN90, especially in the La Plata Basin, Northwest Peru-Ecuador and southern Chile. In southern Peru, Bolivia and western and central Brazil, the negative correlation index suggests a conflicting pattern of observed and modeled TN90 trends. The R10 trends show good correspondence between observed and modeled trends in the La Plata Basin for the CCSM and CNRM models, where positive correlations can reach as high as 0.4–0.6. The other models show mostly
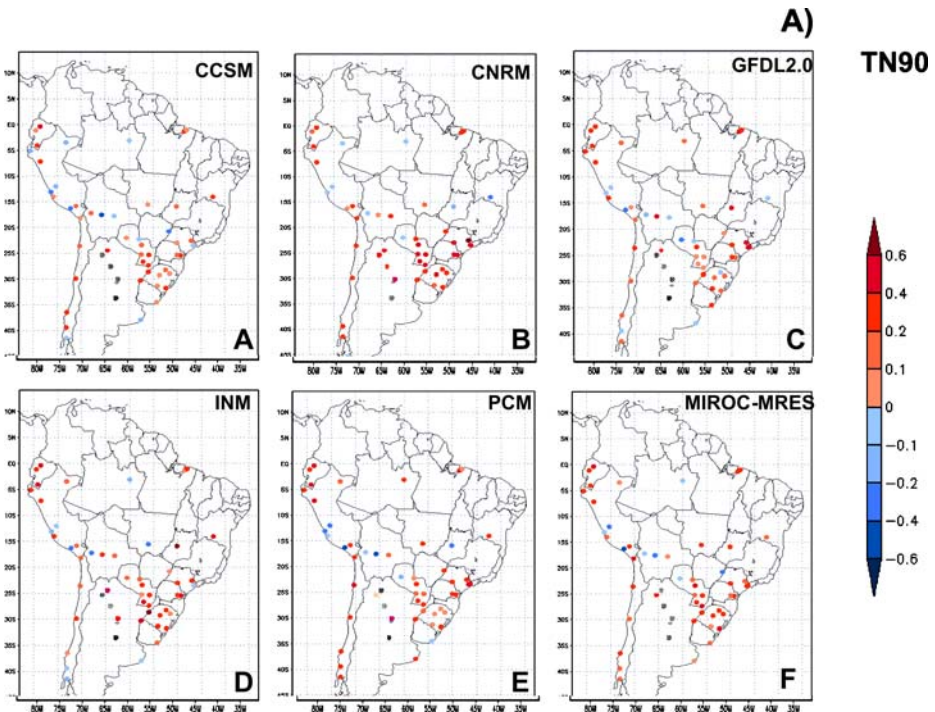

Fig. 3 Correlation coefficient between observed (station) and simulated trends of extreme climate indices for 1960–2000. **a–f** TN90 in %/40 years; **g–l** R10 days/40 years; **m–r** CDD in days/40 years. Models used are CCSM, CNRM, GFDL2.0, INM, PCM and MIROC Med Resolution. *Color scale* shows the values of the correlations. Values above 0.45 reach statistically significance at the 95% level 5%
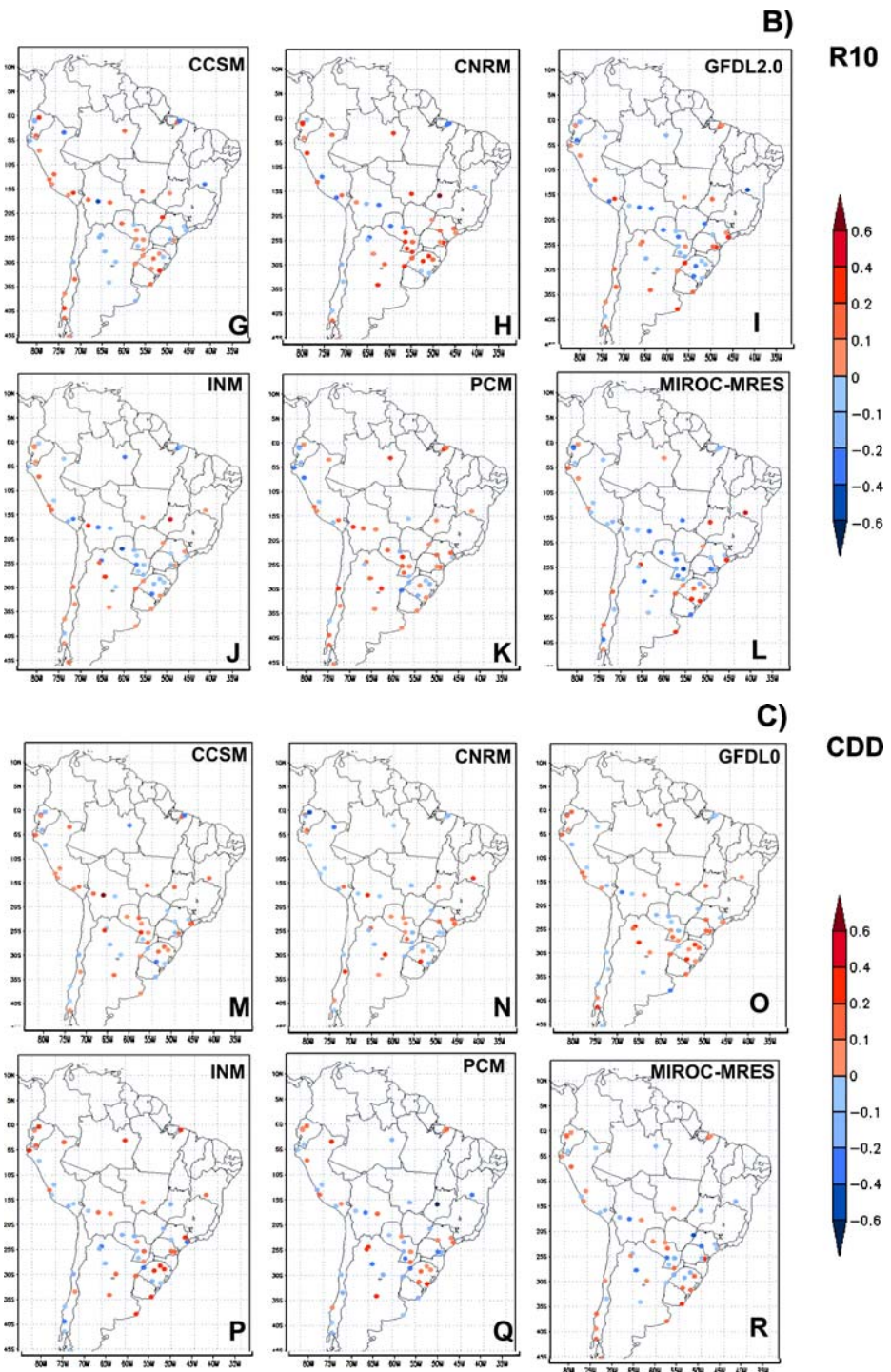
Fig. 3 (continued)

negative correlations, but also positive ones in some sections of the basin. In regions
such as north central Argentina, Bolivia, Paraguay, Peru and Ecuador there is an
indistinct pattern of correlations. In the CDD correlation fields map the spread
of positive and negative values all over South America show that it is hard to
get a conclusion on the agreements between the trends derived from models and
observations for 1960–2000. That could be because most of the models fail in
representing CDD values and tendencies (Rusticucci et al. 2009, this issue)

3.3 Time variability of modeled and observed indices of extremes

The time series considered for this analysis include observations (from station data
and from interpolated data to 1° × 1° using krigging) for regions that were selected
because of good data coverage. These are: southeastern South America, north
central Argentina and the southern coast of Chile. The regions and the times series of
observed and simulated indices are shown in Fig. 4. Each panel shows the observed
and simulated indices from the eight global models.

For the TN90 index, observations show strong interannual variability and the
largest TN90 values are detected since 1990, varying from 6–14% in the 1960s and
1970s to 14–18% during 1995–2000. The models show a large interannual variability,
and in general the order of magnitude of observed and simulated values of the
TN90 index in the three regions is comparable. In the three regions, models and
observations exhibit positive trends that are larger from 1990 to 2000 as compared to
the 1960s and 1970s.

In contrast, the R10 index derived from observations and models exhibit dif-
ferences in the values, sometimes of the order of ±100%. In Southeastern South
America, during 1960–1989 the observations and the series from the GFDL2.0 model
agree in magnitude, while after 1980 these models tend to overestimate observations.
The CCSM and PCM models strongly overestimation the observed indices in North
Central Argentina (by about 200%), the other models show similar values or slightly
underestimations. In those two regions, the models do not capture the observed,
slightly positive trend. In Southern Chile the MIROC hi res, GFDL and CMRM
overestimate the R10 index for the whole period, sometimes by more than 100%.
In this region, the R10 time series simulated by the models do not show any
unidirectional tendency, while observations show a slight negative trend.

The CDD observed time series also exhibit a large interannual variability, with
values varying from 40 to 80, while the models simulate values ranging from 20 to
almost 120 in the GFDL model in North Central Argentina. In this region the INM,
MIROC Hi and Med resolution model simulations of the CDD, indices harmonize
with observations, while the rest of models either over- or underestimate variability.
In Southeastern South America the CDD time series show large observed values that
are 2–4 times larger than the models, except the MIROC Med Res, where the values
are comparable. No clear trend is detected in the region. In Southern Chile, while all
models show values between 10–30 days, the observed values mean could be as high
as 40–50 days, varying from 10 to 90 along 1960–2000. In the three regions, the CDD
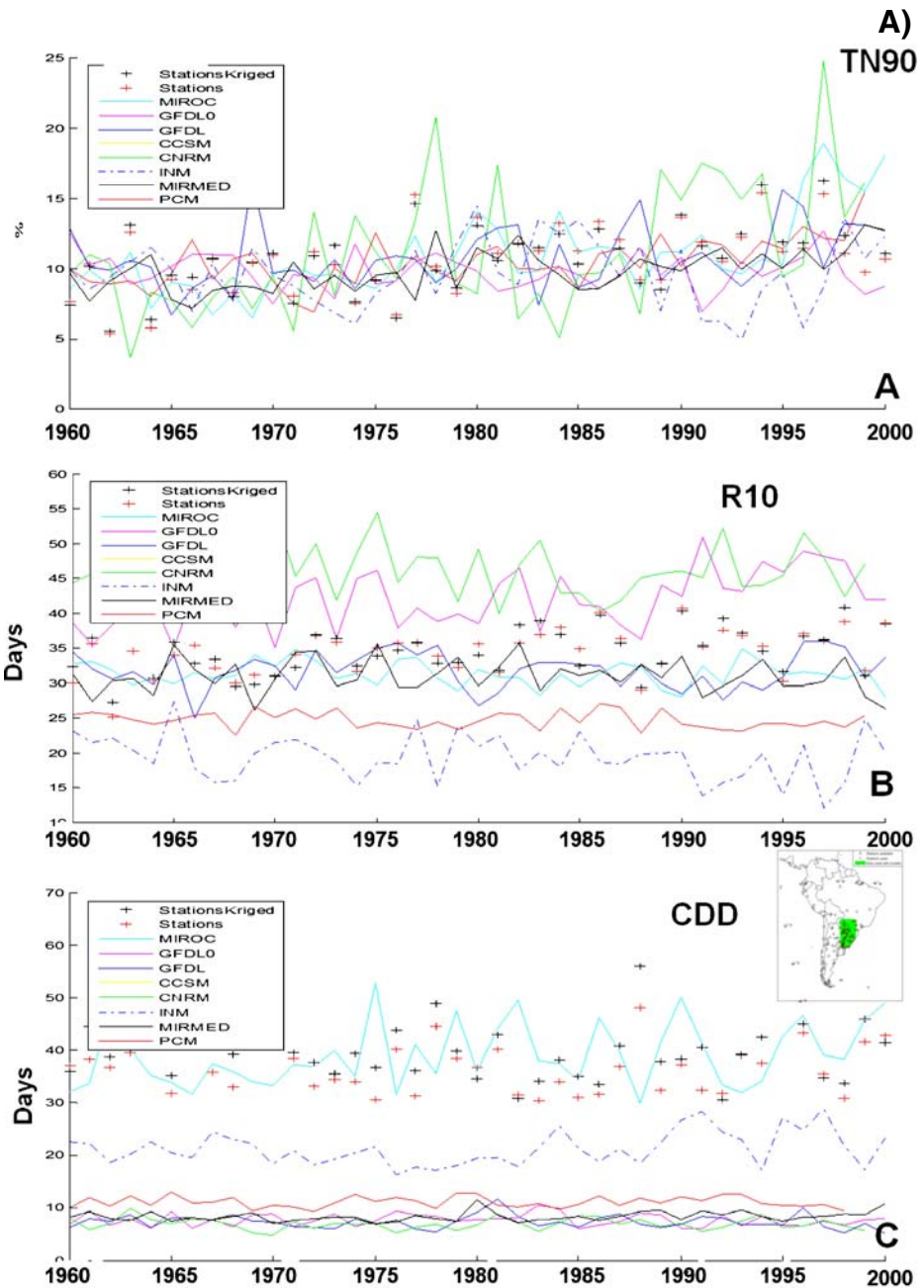observed and modeled time series do not have any particular unidirectional trend.

Fig. 4 Times series of observed and simulated TN90, R10 and CDD indices during 1960–2000 in various regions of South America: **a–c** for southeastern South America, **d–f** for North central Argentina, and **g–i** for southern Chile. Maps showing the location of the region appear in the CDD panel
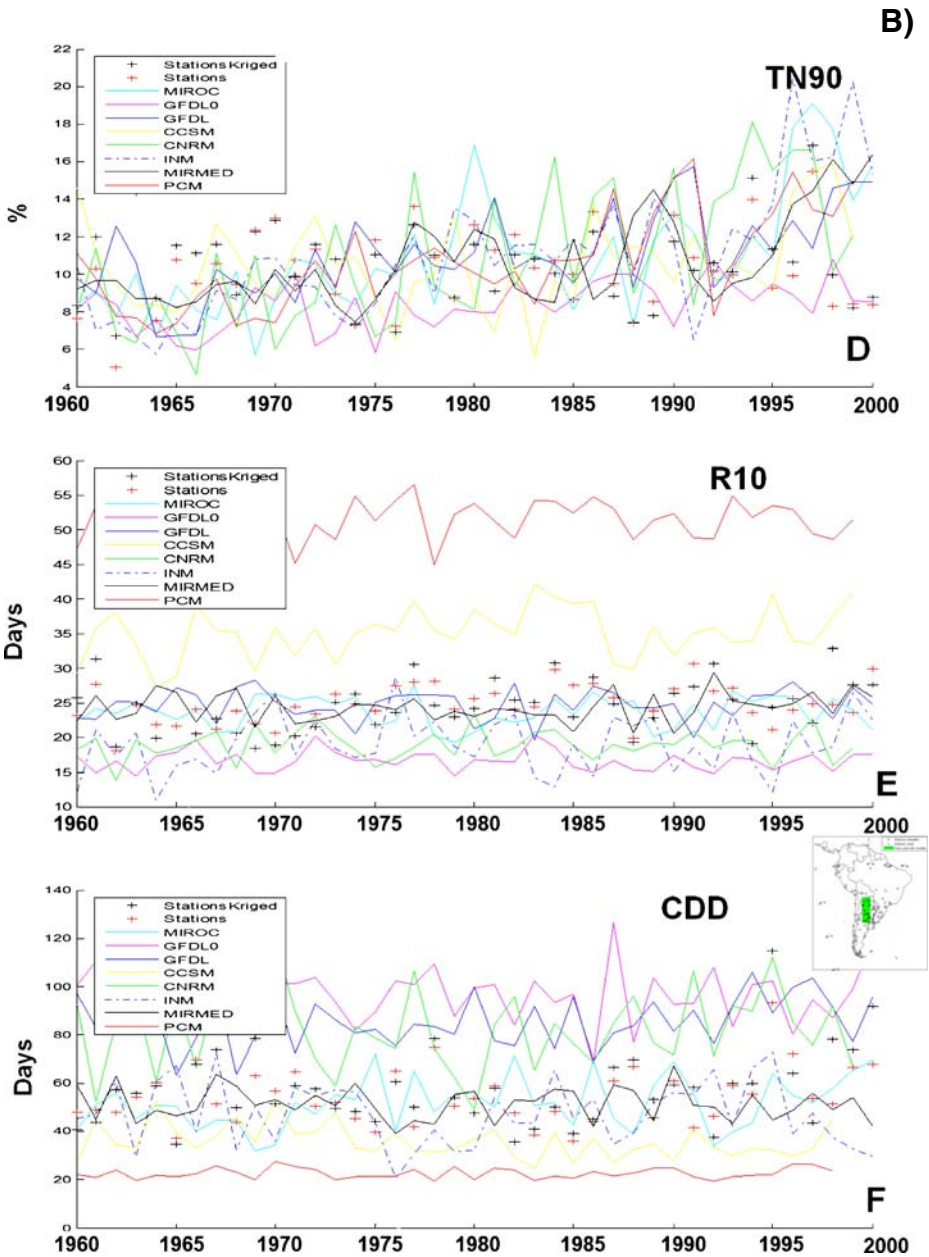
Fig. 4 (continued)

3.4 Changes on distributions of trends in extremes

To analyze the above results in historical context, we examined temporal changes in the indices for a subset of stations with complete coverage for 1960–2000. We compared the probability distributions of each of the indices for this period. Similar
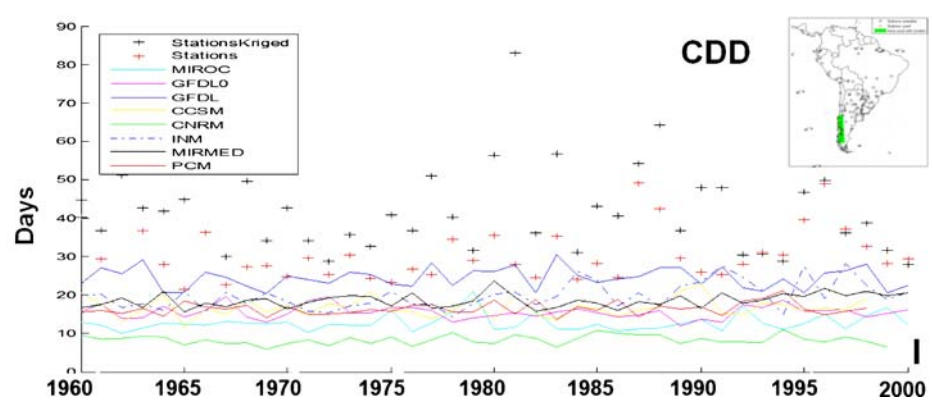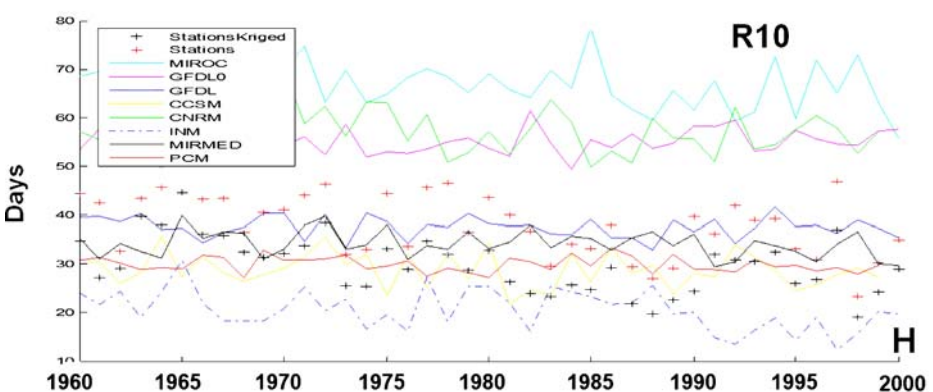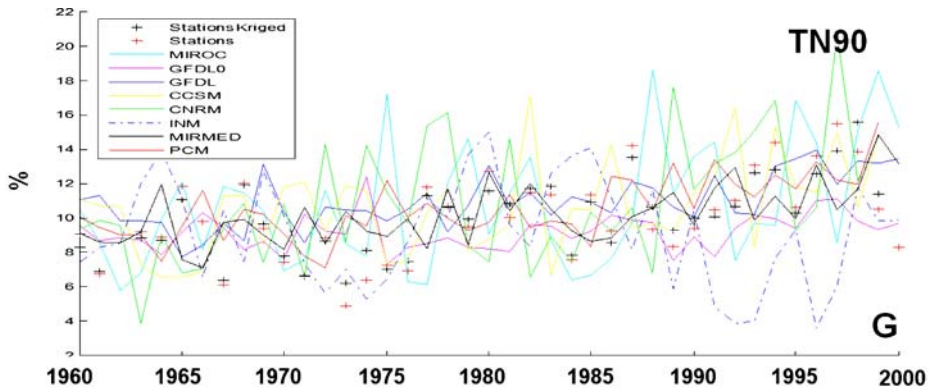
Fig. 4 (continued)

analysis was done by Alexander et al. (2006) and Caesar et al. (2006), who have brought regional results together, gridding the common indices or data for the period since 1946, considering stations worldwide for different periods of the twentieth

century. We focus on the 104 stations for 1960–2000 and the analyses will focus on the region south of 10° S, where data coverage is better

Gridded indices have been used to calculate the Probability Density Function PDFs. To minimize sampling error due to different spatial coverage in different periods, a fixed set of grid boxes which have no missing data over this period have been used (Alexander et al. 2006). The distributions of these indices using the fixed grids from observations and models are different (Fig. 5), with very notable shifts in the distribution of the modeled minimum temperature percentile-based index (TN90) to the right (with the exception of the GFDL model). Therefore, models and observations show a marked shift toward more warm nights, with models overestimating the observed trend to varying degree. Changes in TN90 (show a pattern of positive trends that may be over or underestimated in some regions (Fig. 1). The TN90 PDF curve show patterns of change consistent with a general warming, although the observed changes of the tails of the temperature distributions are often more complicated than a simple shift of the entire distribution to the right would suggest. In southern South America, significant positive trends were found in the occurrence of warm nights (TN90) and negative trends in the occurrence of cold nights, but no consistent changes were found in the indices based on daily maximum temperature (Marengo et al. 2008; Marengo and Camargo 2007). It is possible that, the dominant distribution change at rural stations for both maximum and minimum temperature involved a change in the mean in this region, affecting either one or both distribution tails without significant change in standard deviation (Griffiths et al.
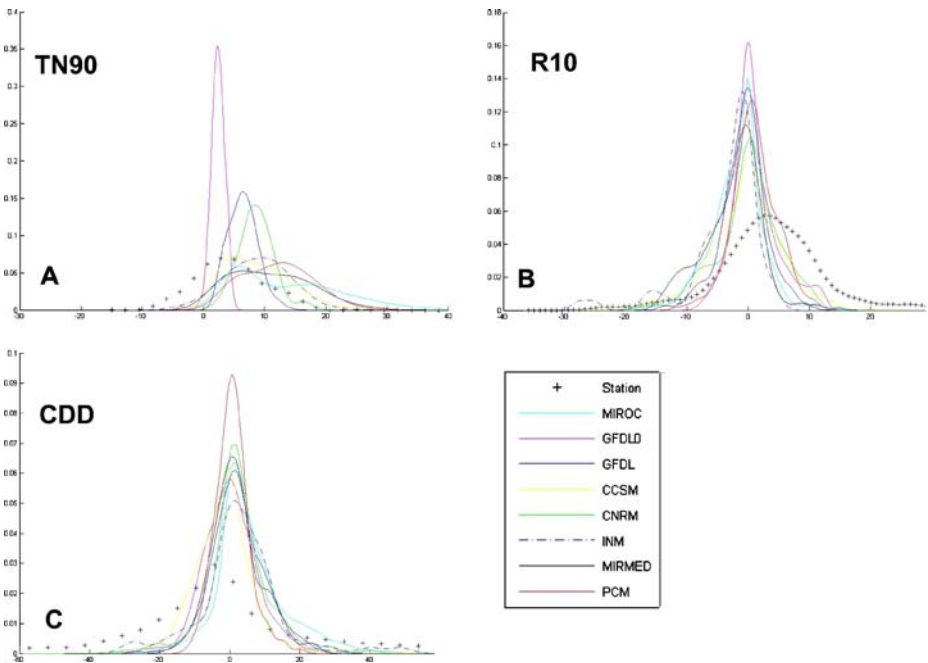

Fig. 5 Probability Density Function (PDF) for observed and simulated TN90, R10 and CDD trends during 1960–2000, for all models and observations

2005). For urbanized stations, however, the dominant change also involved a change in the standard deviation. This result was particularly evident in the case of minimum temperature.

A number of recent regional studies have been completed for southern South America (Haylock et al. 2006; Marengo et al. 2008), and the pattern of trends for rainfall extremes between 1960 and 2000 was generally the same as that for total annual rainfall (Haylock et al. 2006). The PDF of the rainfall based index R10 derived from the models for the whole South America South of 10° S show a shift to the left, suggesting a slight negative trend, while the PDF of the observations indicate a tendency toward positive trends. At the regional level, observations for the last 40 years of the century suggest a tendency towards increased extreme rainfall events in regions such as southeastern South America, North Central Argentina and Northwest Peru-Ecuador (Fig. 1), whereas the rest of South America South of 10 S show small negative trends.

The PDF of CDD shows that the models are slightly shifted to the right, suggesting mean positive trends for the entire region. By contrast, observations show a PDF shift to the left. As shown in previous figures, some regions exhibit positive or negative trends, but in general models do not show large scale, consistent trends towards more or less CDDs by the end of the twentieth century. The PDFs of rainfall derived indices clearly indicates that changes in precipitation extremes are much less coherent than for temperature.

In general, the peak of the PDFs from the three extreme indices simulated by the models during 1960–2000 are larger than those from observations, suggesting that the models exhibit a larger frequency of those extremes compared to observations, independent of the under- or over-estimation of the trends. We suggest that because the level of noise is so large, estimates of trends from global models may be complicated due to differences between models. Changes in the standard deviation of the TN90 could be due to the effect of urbanization, while the small changes in the standard deviation in the PDFs of R10 and CDD could be consequence of smaller internal variability of the models, as compared to observations.

4 Conclusions

Using station data from South America which has become available for the CLARIS-EU project, we have presented a detailed regional picture of changes in temperature and precipitation extremes during the last half of the twentieth century. During 1960–2000 a significant positive trend in the frequency of warm nights derived from observations is detected basically everywhere in South America South of 10° S. Positive trends in extreme rainfall events (R10) are also shown in southeastern South America, North Central Argentina, Northwest Peru and Ecuador, while negative trends are xxx in southern Chile. The pattern of observed trends in the CDD is less clear than the one from TN90 and R10, although, small negative trends are identified in a large part of southeastern South America and, to a smaller extent over Southern Peru, Northern Argentina and Bolivia are identified.

We find that all simulated indices of extremes exhibit differences due to the between models. Warming is apparent in observations and models, even though all models (but the GFDL2.0) tend to overestimate the magnitude of the TN90

positive trends, while trends in R10 tend to be underestimates in some regions. In Southeastern South America, both observations and simulations exhibit positive trends that reach field significance. These positive trends are consistent with the positive trends detected in observed and simulated total rainfall as documented on previous studies (See Section 1). Therefore, the observed increases in total rainfall may be due in part to an increase in the number of days with rainfall above 10 mm.

The warming in the probability distribution of TN90, and the trend analyses document a substantial rise in warm nighttime temperatures apparent over the 41 year period, and that is well captured by the models. The observed and simulated positive TN90 trends suggest that most of South America has warmed at a similar rate. Previous studies on annual and seasonal temperature trends (See Section 1) have shown that observed maximum temperature has increase, albeit to a lesser degree than mini the minimum temperature in some regions. The PDFs of rainfall derived indices clearly indicates that changes in precipitation extremes are much less coherent than for temperature.

Estimates of future potential changes in both temperature and precipitation extremes can provide essential to urban, regional and national adaptation and planning strategies. In this paper we attempt to assess the quality of the simulation of some of those extremes during the second half of the twentieth century, and show the geographical patterns of change in observed and simulated trends in extremes. This will be most useful in any assessment of projections of changes in extreme events in future climate change scenarios, changes with important consequences for agricultural production, human health, urban development and planning of water resource management.

References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank A, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Ambenje P, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson D, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:D05109. doi:10.1029/2005JD006290

Barrucand MG, Rusticucci MM (2001) Climatología de temperaturas extremas en la Argentina. Varibilidad temporal y Regional. Meteorológica 26:85–102

Boulanger JP, Leloup J, Penalba O, Rusticucci M, Lafon F, Vargas W (2005) Observed precipitation in the Paraná-Plata hydrological basin: long-term trends, extreme conditions and ENSO teleconnections. Clim Dyn 24:393–413

Boulanger JP, Brasseur G, Carril A, Castro M, Degallier N, Ereño C, Marengo J, Le Treut H, Menendez C, Nuñez M, Penalba O, Rolla A, Rusticucci M, Terra R (2009) The European CLARIS project: a Europe-South America network for climate change. Clim Change (this issue)

Bowman AW, Azzalini A (1997) Applied smoothing techniques for data analysis. Oxford University Press, Oxford

Caesar J, Alexander L, Vose R (2006) Large-scale changes in observed daily maximum and minimum temperatures: creation and analysis of a new gridded data set. J Geophys Res 111:D05101. doi:10.1029/2005JD006280

Carvalho LMV, Jones C, Liebmann B (2002) Extreme precipitation events in Southeast South America and large-scale convective patterns in the South Atlantic Convergence Zone. J Climate 15:2377–2394

Carvalho LMV, Jones C, Liebmann B (2004) The South Atlantic Convergence Zone: intensity, form, persistence, relationships with intraseasonal to interannual activity and extreme rainfall. J Climate 17:88–108

Delworth T, Broccoli AJ, Rosati A, Stouffer RJ, Balaji V, Beesley JA, Cooke WF, Dixon KW, Dunne J, Dunne KA, Durachta JW, Findell KL, Ginoux P, Gnanadesikan A, Gordon CT, Griffies SM, Gudgel R, Harrison MJ, Held IM, Hemler RS, Horowitz LW, Klein SA, Knutson TR, Kushner PJ, Langenhorst A, Chu Lee H, Lin S, Lu J, Malyshev SL, Milly PCD, Ramaswamy V, Russell J, Schwarzkopf MD, Shevliakova E, Sirutis JJ, Spelman MJ, Stern WF, Winton M, Wittenberg AT, Wyman B, Zeng F, Zhang R (2005) GFDL's CM2 global coupled climate models. Part I: formulation and simulation characteristics. J Climate 19:643–674

Déqué M, Piedelievre JP (1995) High resolution climate simulation over Europe. Clim Dyn 11: 321-339

Déqué M, Dreveton C, Braun A, Cariolle D (1994) The ARPEGE/IFS atmosphere model: a contribution to the French community climate modelling. Clim Dyn 10:249–266

Diansky NA, Volodin EM (2002) Simulation of present-day climate with a coupled atmosphere-ocean general circulation model. Izvestiya 38:732–747

Doyle ME, Barros VR (2002) Midsummer low-level circulation and precipitation in subtropical South America and related sea surface temperature anomalies in the South Atlantic. J Climate 15:3394–3410

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank AMG, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. Clim Res 19:193–212

Griffiths GM et al. (2005) Change in mean temperature as a predictor of extreme temperature change in the Asia-Pacific region. Int J Climatol 25:1301–1330

Groissman P, Knight P, Easterling D, Karl T, Hegerl G, Razuvaek V (2005) Trends in intense precipitation in the climate record. J Climate 18:1326–1350

Hasumi H, Emori S (2004) K-1 coupled model (MIROC) description, K-1 technical report, 1. Center for Climate System Research, University of Tokyo, Tokyo

Haylock MR, Peterson T, Abreu de Sousa JR, Alves LM, Ambrizzi T, Baez J, Barbosa de Brito JI, Barros VR, Berlato MA, Bidegain M, Coronel G, Corradi V, Garcia VJ, Grimm AM, Jaildo dos Anjos R, Karoly D, Marengo JA, Marino MB, Meira PR, Miranda GC, Molion L, Muncunil DF, Nechet D, Ontaneda G, Quintana J, Ramirez E, Rebello E, Rusticucci M, Santos JL, Varillas IT, Vincent L, Yumiko M (2006) Trends in total and extreme South American rainfall 1960-2000 and links with sea surface temperature. J Climate 19:1490–1512

Hegerl GC, Zwiers FW, Braconnot P, Gillett NP, Luo Y, Marengo Orsini JA, Nicholls N, Penner JE, Stott PA (2007) Understanding and attriuting climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Kiktev D, Sexton DMH, Alexander L, Folland CK (2003) Comparison of modeled and observed trends in indices of daily climate extremes. J Climate 16:3560–3571

Liebmann B, Jones C, de Carvalho LMV (2001) Interannual variability of extreme precipitation events in the State of São Paulo, Brazil. J Climate 14:208–218

Liebmann B, Vera C, Carvalho L, Camilloni I, Hoerling MP, Allured D, Barros V, Baez J, Bidegain M (2004) An observed trend in Central South American Precipitation. J Climate 17:4357–4367

Marengo J (2007) Integrating across spatial and temporal scales in climate projections: challenges for using RCM projections to develop plausible scenarios for future extreme events in South America for vulnerability and impact studies. In: Annals of IPCC TGICA expert meeting: integrating analysis of regional climate change and response, Nadi, Fiji, 20–22 June 2007

Marengo J, Camargo CC (2007) Surface air temperature trends in Southern Brazil for 1960–2002. Int J Climatol 28(2):893–904 doi:10.1002/joc.1584

Marengo J, Jones R, Alves LM, Valverde MC (2008) Future change of temperature and precipitation extremes in South America as derived from the PRECIS regional climate model system. Int J Climatol. doi:10.1002/joc.1863

Meehl G, Covey C, Delworth T, Latif M, McAvaney B, Mitchell JFB, Stouffer R, Taylor K (2007) The WCRP CMIP3 multimodel data set. A new era in climate change research. Bull Am Meteorol Soc 88(9):1383–1394 doi:10.1175/BAMS-88-9-1383

Obregon G, Marengo JA (2007) Caracterização do clima do Século XX no Brasil: Tendências de chuvas e temperaturas médias e extremas. Relatório 2, Ministério do Meio Ambiente - MMA, Secretaria de Biodiversidade E Florestas – SBF, Diretoria de Conservação da Biodiversidade – DCBio Mudanças Climáticas Globais e Efeitos sobre a Biodiversidade - Sub projeto: Caracterização do clima atual e definição das alterações climáticas para o território brasileiro ao longo do Século XXI.Brasília, Fevereiro 2007

Penalba OC, Robledo F (2008) Spatial and temporal variability of the frequency of extreme daily rainfall regime in LPB during the 20th century. The European CLARIS Project: a Europe-South America Network for Climate Change

Penalba OC, Beltran A, Messina C (2005) Monthly rainfall in Central–Eastern Argentina and ENSO. A comparative study of rainfall forecast methodologies. Revista Brasileira de Agrometeorología 13(2):49–61

Penalba O, Vargas W (2004) Interdecadal and interannual variations of annual and extreme precipitation over central-northeastern Argentina. Changes in the extreme precipitation seasonal cycle. Int J Climatol 24(12):1565–1580

Rusticucci M, Barrucand M (2001) Climatología de temperaturas extremas en la Argentina. Consistencia de datos. Relación entre la temperatura media estacional y la ocurrencia de extremos. Meteorológica 26:69–84

Rusticucci M, Barrucand M (2004) Observed trends and changes in temperature extremes in Argentina. J Climate 17:4099–4107

Rusticucci M, Renom M (2008) Variability and trends in indices of quality-controlled daily temperature extremes in Uruguay. Int J Climatol 28:1083–1095. doi:10.1002/joc.1607

Rusticucci M, Tencer B (2008) Observed changes in return values of annual temperature extremes over Argentina. J Climate 21:5455–5467

Rusticucci M, Marengo J, Penalba O, Renom M (2009) An intercomparison of model-simulated in extreme rainfall and temperature events during the last half of the XX century: part 1: mean values and variability. Clim Change (this issue)

Sen PK (1968) Estimates of the regression coefficient based on Kendall's Tau. J Am Stat Assoc 63:1379–1089

Solman S, Nuñez MN, Cabré MF (2007) Regional climate change experiments over southern South America, I: present climate. Clim Dyn. doi:10.1007/s00382-007-0304-3

Solman SA, Nuñez MN, Cabré MF (2008) Regional climate change experiments over southern South America, I: present climate. Clim Dyn 30:533–552. doi:10.1007/s00382-007-0304-3

Tebaldi C, Haohow K, Arblaster J, Meehl G (2007) Going to extremes. Am intercomparison of model-simulated historical and future changes in extreme events. Clim Change 79:185–121

Teixeira M, Satyamurty P (2007) Dynamical and synoptic characteristics of heavy rainfall episodes in Southern Brazil. Mon Weather Rev 135:598–617

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007) Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Vincent L, Peterson T, Barros VR, Marino MB, Rusticucci M, Miranda G, Ramirez E, Alves LM, Ambrizzi T, Baez J, Barbosa de Brito JI, Berlato M, Grimm AM, Jaildo dos Anjos R, Marengo JA, Meira C, Molion L, Muncunil DF, Nechet D, Rebello E, Abreu de Sousa J, Anunciação YMT, Quintana J, Santos J, Ontaneda G, Baez J, Coronel G, Garcia VL, Varillas IT, Bidegain

M, Corradi V, Haylock MR, Karoly D (2005) Observed trends in indices of daily temperature extremes in South America, 1960–2002. J Climate 18:5011–5023

Washington R, Harrison M, Conway D, Black E, Challinor A, Grimes D, Jones R, Morse A, Kay G, Todd M (2006) African climate change: taking the shorter route. Bull Am Meteorol Soc 87: 1355–1366

Weatherly JW, Bitz CM (2001) Natural and anthropogenic climate change in the Arctic. 12th Symposium on global change and climate variations, AMS

Zhang X, Zwiers FW (2004) Comment on "Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test" by Sheng Yue and Chun YuanWang. Water Resour Res 40:W03805. doi:10.1029/2003WR002073

Zhang X, Hegerl G, Kenyon J, Zwiers FW (2005) Avoiding inhomogeneity in percentile-based indices of temperature extremes. J Climate 18:1641–1651