AN INTERCOMPARISON OF MODEL-SIMULATED IN EXTREME RAINFALL AND TEMPERATURE EVENTS DURING THE LAST HALF OF THE XX CENTURY: PART 2: HISTORICAL TRENDS

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Abstract.

Projections of changes in climate extremes are critical to assessing the potential impacts of climate change on human and natural systems. Therefore, especial care should be put on the validation of those extremes derived for present climate in both spatial and temporal variability. We analyze historical simulations of three such indicators as derived from seven GCMs contributing to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4) for the XX century. Our focus is on the consensus in the geographical and temporal variability of temperature and rainfall extreme trends between observations and the GCMs, in terms of direction and significance of the changes at the scale of South America south of 10 ^{o}S.

The climate extremes described by the 3 indices include warm nights, heavy rainfall amounts and dry spells. The observed historical trends in extremes generally agree with previous observational studies that used other indicators of extremes, and the favorable comparison in the warm nights and extreme rainfall in some regions provides a basic sense of reliability for the GCM simulations. For any specific temperature index, minor differences appear in the spatial distribution of the changes across models in some regions, while substantial differences appear in regions in interior 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 La Plata Basin, where observed and simulated trends in warm nights and extreme rainfall are evident. This analysis provides a first overview of simulated trends in extremes for present climates, and further work is focused on projected changes in climate extremes from the IPCC-AR4 models.

1. Introduction:

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 envelope within which these events preferentially occur is experiencing a trend on present climate. Variability and changes in the intensity and frequency of extreme events depend not only on the rate of change of the mean of a selected variable but also on whether there are changes in the statistical parameters that determine the distribution of that variable.

The most difficult trend analysis is that of extreme precipitation because of the small radius of correlation of many precipitation events. Therefore, reliable estimates of trends in extreme precipitation events are possible only for regions with dense networks that have remained stable over time.

In earlier global analysis of extreme indices by Groisman et al. (1999) and Frich et al. (2002), and Kiktev et al. (2003) there were almost no data for most of South America and Africa. A lack of long-term observations over large parts of South America is the biggest obstacle in quantifying the change in extremes during the past century. Previous studies on air temperature trends in South America have been more comprehensive for mean seasonal and annual air temperatures, and warming trends have been identified in various regions of tropical and subtropical South America (Hoffman et al 1997, Rosembluth et al. 1997; Victoria et al. 1998; Duursma 2002; Marengo 2007). Most of these studies did not include an analysis of extreme air temperatures (maximum and minimum) or using indices of extremes.

Several papers have documented tendencies and trends on extreme air temperatures in the region. Nonetheless, the variation in methodologies employed by these studies makes an intercomparison a difficult task. For example, studies using an index of temperature extremes based on percentiles (e.g., the number of days daily temperature is greater than the 90th percentile) are likely to reach different conclusions than those that define extremes as some percent of a standard deviation or those considering thresholds. Barrucand and Rusticucci (2001) analyze extreme temperatures in Argentina during 1959-98, and they found strong regional differences and a marked annual cycle, with the summer temperatures being more sensitive that the winter temperatures in relation to the occurrence of extremes. In particular, the increase of mean summer air temperature in southern Argentina is due to a reduction of cold events than the increase in the number of warm events. Rusticucci and Barrucand (2004) investigated observed changes in air temperature trends during 1959-98 in Argentina, detecting large positive trends in minimum air temperature, whereas the standard deviations decreases. Similar conclusions were found by Marengo and Camargo (2007) for extreme temperatures in southern Brazil

At a regional scale, Vincent et al. (2005), Alexander et al. (2006) and Marengo et al. (2008) used the indices for extreme temperatures defined by Frich et al. (2002), and identified steep positive trends in minimum air temperatures and the negative trends in the diurnal temperature range DTR in Southeastern South America, consistent with Marengo and Camargo (2007) and Rusticucci and Barrucand (2004) that were based on temperature thresholds. Vincent and collaborators identify positive trends in the frequency of warm nights (% of days with TMin>90th, tropical nights (days with TMin>20 C), and negative trends in the frequency of cold nights (% days with TMin<10th) and in the DTR in most of the southeastern South America over 1960-2000. They also found positive and significant trends in the frequency of warm nights during summer DJF and winter JJA, as well as negative but non significant trends in the frequency of cold days(% of days with

TMax<10th). The frequency of warm days(% of days with TMax>90th) shows a mixture of positive and negative non significant trend, suggestion a non-clear regional signal of change on this index. Other results from these studies include a decrease in the percentage of cold night and an increase in the percentage of warm nights. Similar results were found by Rusticuccci and Renom (2007) for Uruguay, using the same extreme temperature indices definition, the most profound change was detected in the percentage of days with cold nights (TN10), which shows the most decreasing trend in 1961-2002 with respect to the other periods considered. The only index showing a positive trend was TN90, but not significant. All of this evidence suggests warming in Southeastern South America, both in summer and winter and in the mean and extremes, being stronger during winter as compared to summer.

In relation to precipitation, Groissman et al (2005), Marengo (2007), and Marengo et al. (2008) in the subtropical part of Brazil and Penalba and Vargas (2004) for Northeastern of Argentina found that there was a systematic increase of very heavy precipitation since the decade of 1950, and in southeastern Brazil they obtained an increase in the frequency of extreme rainfall events. For southern and southeastern Brazil, Liebmann et al. (2001), Carvalho et al. (2002, 2004), Doyle and Barros (2002), Penalba et al. (2005), Boulanger et al. 2005 and Teixeira and Satyamurty (2007) found that extreme rainfall events exhibit an interannual variability linked to El Niño and La Niña, as well as intra-seasonal variations associated with the activity of the South Atlantic Convergence Zone (SACZ) and the South American Low Level Jet (SALLJ).

Haylock et al. (2006) assessed trends in annual total and rainfall extremes in South America, and found that the pattern of trends for the extremes was generally the same as that for total annual rainfall, with a change to wetter conditions in the region of southern

Brazil, Paraguay, Uruguay and northern and central Argentina. They identified positive significant trends for annual indices of number of days with heavy precipitation (R10mm), very heavy precipitation (R20mm), very wet precipitation (R95P) and extremely wet precipitation (R99P), during the period 1961-2000. These trends suggest an increase in frequency and intensity of rainy days in the southeastern South America. Alexander et al. (2006) and Marengo (2007b) analyzed extreme trends during 1950-2003 and they found a pattern of positive trends in extreme rainfall events and nighttime temperatures in the same region, and also found decadal changes in the probability density function during the relatively colder period 1951-1978 as compared to the warmer period 1979 – 2003. Penalba and Robledo, (2008, this issue) analyze trends in the period 1961-2000 and decadal variability in the frequency of rainy days for two thresholds: 0.1 mm and percentile 75th in the La Plata Basin region. Increases in the annual frequencies were observed in spatially coherent areas. This coherence is more marked in summer, autumn and spring. During these seasons, the biggest increases and significant were observed in southern Brazil. In winter, the low and middle basins of the Rio Uruguay and Rio Paraná have negative trends, some of which are significant.

For South America, projections for the XXI century are unanimous in 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) and Marengo (2008) assessed worldwide projections of changes in climate extremes from an ensemble of eight global coupled models from IPCC-AR4 under the A1B and A2 (transition and high emissions) scenario for the 2071-2100 time slice. However consensus and significance are less strong when regional patterns are concerned, and while all models show consistency in the warming signal, the same can not be said for rainfall extremes.

Therefore, on this paper we examine temperature and rainfall extreme indices available from seven IPCC AR4 coupled climate models for the XX Century (referred as IPCC AR4 20C3M). Even though the simulations are available since 1900 (some of them go back to 1860), trends of the modeled extreme indices are compared to observations during 1960-2000. 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 reasonableness of the simulated indices for present climate. Finally, we discuss the uncertainties in the predicted extremes changes rainfall changes and their potential impacts on the regional climates and their consequences in 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

The 20C3M experiment consists of 5-member ensemble simulations of the 20th Century climate (starting from mid-19th Century). The forcing agents of the experiment are the historical record of (or estimated) greenhouse gases (CO2, CH4, N2O and CFCs), sulfate aerosol direct effects, volcanoes and solar forcing. The column total sulfate mass loading with a geographical distribution is specified and vertically distributed with a homogeneous mixing ratio in the lowest 740 m thickness of the atmosphere. The temporal variation is included with multiplying a weighting time-series based on the historical emission record. Only the direct effect for shortwave radiation is included in the model. The sulfate mass loading data is from Mitchell and Johns (1997). The effect of solar activity is input by specifying the solar constant. The effect of stratospheric aerosols due to the volcanic activity is reflected with substitution as the solar irradiance reduction at the model's top of atmosphere (by changing the solar constant). Data from the 20C3M experiment is provided by the U.S. Department of Energy Program for Climate Model Diagnosis and Intercomparison (PCMDI).

2.2 Models used

The IPCC AR4 20C3M models with extremes indices currently available are: GFDL-CM2.0 (Delworth et al.2005); MIROC3-2-HIRES and MIROC3-2-MEDRES (Hasumi and Emori, 2004); NCAR-CCSM3.0 (available from http://www.ccsm.ucar.edu/publications); CNRM-CM3 (Déqué et al., 1994; Déqué and Piedelievre, 1995;); INM-CM3.0 (Diansky et al., 2002), and NCAR-PCM1 (Weatherly, et al. 2001). Projections of indices of extremes are used for the 1960-2000 period (see Section 2.4). Refer to Meehl et al. (2007) for more details on the descriptions of the coupled global models.

2.3 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. Most of the stations used in this work it comprises of the data base created and consisted during 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) and Rusticucci et al. 2008 (this issue).

2.4 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. Model 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 20th Century, we use the common period 1960-2000 considering 1960-90 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: CDD

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. The selected indices were calculated on monthly and/or annual basis. They describe warm minimum temperature extreme. Some are based on a fixed threshold (ex. 10 mm/day) and their impacts are easy to understand and to evaluate. Others are based on threshold defined as percentiles (ex. warm nights) and they are used to facilitate the comparison between stations.

2.5 Methodology

As a first step, the 104 stations available for this study were gridded over South America onto a regular 1º x 1º 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 10º South 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 degrees. This algorithm provided an estimation of the error (errovariance) at each grid box. These parameters have been chosen based on different simulations results based on the errovariance. Information about this algorithm and thesis diploma of Rolf Sidler can be downloaded at http://www.aug.geophys.ethz.ch/people/rolf/rolf.html

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 obtained, trends have computed the 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). An iterative procedure, originally proposed by Zhang et al. (2000), was used to compute the magnitudes of trends and to test their statistical significance

The analysis of the variability has been done by comparing the estimated Probability Density Functions PDFs of corresponding 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 1º x 1º before doing those calculations as each model resolution is different (but lower than 1º x 1º).

4. Results

a. Geographical Patterns of observed trends

Figs. 1 and 2 shows the observed trends of the three indices analized derived from observations at station level and interpolated at 1^{o} x1^{o}, respectively. Trends in temperature index reflect an increase in minimum temperature, with significant change (Rusticucci and Barrucand 2004, , Vincent et al. 2005, Obregon and Marengo 2006, Marengo and Camargo 2007). The two figures show very large increase in the occurrence of very warm nights in southern South America. The observed pattern of trends in TN90 was field significant at the 5% level in some regions. There have been locally significant positive trends over southeastern South America and the west coast of Chile and west central Argentina. There are no examples of locally significant decreases in the percentage of TN90 in the gridded observations, with non significant reductions in TN90 have been detected in Bolivia 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 (Penalba et al. 2005, Teixeira and Satyamurty 2007, Liebmann et al 2004, Groissman et al 2005), defined 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 SACZ and the SALLJ variability.

The CDD observed index (Fig. 1) exhibits positive trends in the regions extending from western Ecuador, southern Peru, Bolivia and Paraguay, while negative trends reach field significance in west central Brazil, Northern Argentina and Southern Brazil and

Uruguay, in agreement with Alexander et al (2006). We must admit that trends in CDD mat be dominated by the wetter regions in South America.

b. Simulated geographical patterns of observed trends

The simulated trends for TN90 (Fig. 3) from the six models all show positive trends, 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 of the order of 3-6%. All models show for the La Plata basin positive trends reaching field significance in the CCSM, and GFDL2.0 model with orders of magnitude that are comparable to the observed trends in Fig 1. The CRNM, INM and MIROC-Med Res simulates quite well the large positive. Even though our analyses is focused South of 10 ^{o}S, it is interesting to see TN90 trends in the northern coast of Peru and Ecuador, as they underestimate the observed trends in the southern cost of Chile between 15 and 30º S even the tendency is well simulated.

The simulated R10 index show positive trends in all models South of 15º S, and observations for present not always agree quite well. In the La Plata Basin all models simulate the observed positive trends, which in the observations vary from 4-12 days (Figs. 1 and 2) and in the models vary from 0 to 8 days. The observed positive trends in northern Peru-Ecuador are not well simulated by the models, and large positive trends in tropical South America east of the Andes in the CNRM, GFDL2.0 and PCM, and well as the negative trends in the same region for the MIROC-MedRes can not be validated due to lack of observations on those regions.

Fig. 3 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, Paraguay and Northern Argentina, the CNRM, PCM and MIROC models tend to simulate negative trends.

Comparing observations and models using the Spearman correlation analysis, Fig 4 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 west 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, while the other models show mostly 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. The CCD correlation fields are very conflicting between observations and all models, and the spread of positive and negative values all over South America 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 (Rusticucci et al, 2008)

c. Time variability of modeled and observed trends

The time series considered for this analysis include observations (from station data and from interpolated data to 1° x 1° using krigging) and from the models, and 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 trends are shown in Fig. 5. Each panel shows the observed and simulated trends from the 8 global models. In general, all models show the positive TN90 trends in the three regions, varying from 6-12% in the 1960´s and 1970´s to 14-16% during 1995-2000. Some 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 contrast, the R10 index derived from observations and models exhibit differences in the values, sometimes of the order of ± 100, and the slightly positive observed trends are not simulated by the models. During 1960-89 the observations and the series from the GFDL2.0 models agree in magnitude, while after 1980 these models tend to overestimate observations. 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.

The observed TN90 positive trends in North Central Argentina exhibit similar order of magnitude of the simulated values, and even though both models and observations show positive trends, some of them statistically significant, it is detected a large interannual variability among models. Large observed and modeled values are detected after 1990. The R10 series exhibit small positive trends in both observations and models, and while the CCSM and PCM models shows a large overestimation of the observed trends (about 200%), the other show similar values or slightly underestimations. The CCD observed and modeled time series do not have any particular trend, and a large interannual variability is detected in all series. The INM, MIROC- and Med resolution model simulations of the CDD indices and trends show similar orders of magnitude with observations, while the rest of models exhibit either over or underestimations.

d. Changes on distributions of trends

In order to put the above results in a historical context, we examine temporal changes in the indices for a subset of stations with complete coverage for 1960–2000. We compare the probability distributions of each of the indices for this period. Similar analysis was done by Alexander et al (2006) considering stations worldwide and for station and interpolated data, for different periods of the XX Century. We focus on the 104 stations for this period and the analyses will focus on the region south of 10º S, where data coverage is better.

When comparing PDFs within 1960-2000 we use a larger data sample. Gridded indices have been used to calculate 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. 6), with very notable shifts in the distribution of the modeled minimum temperature percentile-based index (TN90) to the right show (with the exception of the GFDL model). Models and observations show a marked shift toward more warm nights, with models overestimating in more or less degree the observed trend. Changes in TN90 as shown in Figs.1-3 show a pattern of positive trends that may be over or underestimated in some regions.

The PDF of the rainfall based index R10 suggest that while observations show a shift to the right suggesting a positive trend on intense rainfall, models do not show this trend, in fact the mean for the South America South of 10º S suggest no trends. While some of the observed trends suggest a tendency for increase of extreme rainfall events in the last 40 years in regions such as southeastern South America and Northwest Peru-Ecuador, the PDF shows almost no trends, it may be stated that models underestimate trends in R10 in general. This can be observed in some regions, as shown in Fig. 5. The PDF of CDD shows that the curve from observations is shifted to the left, suggesting mean negative trends for the entire region, while the models do not show any significant trend towards over or underestimation of the trends. As shown in previous figures, some regions exhibit positive or negative trends, but in general models do not show a large scale pattern of consistent trends towards more or less CDDs by the end of the XX Century.

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 as compared to observations, independent of the under or overestimation of the trends.

5. Conclusions

Using station data from South America which have 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 XX century. We show that during 1960-2000 observations show a significant positive trend in the frequency of warm nights basically everywhere in the region of study, South America South of 10º S, as well as positive trends in extreme rainfall events (R10) in southeastern South America, Northwest Peru and Ecuador and southern Chile. The CCD trends are as not revealing as those in TN90 and R10.

Using a fixed set of complete grid boxes, we find that all indices exhibit differences between observations and 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 the observed positive R10 trends tend to be underestimates at regional level. However, in regions such as Southeastern South America the positive trends reach field significance.

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. The trend analyses suggest that most of the South American continent has warmed at a similar rate, and previous studies (See section 1) has shown that maximum temperature extremes have also increased but to a lesser degree in some regions. In Southeastern South America, most precipitation indices show a tendency toward wetter conditions but not all show statistically significant changes, and this agree with the observed tendencies of increase in seasonal and annual rainfall, reported in the references in Section 1. In that case, the observed increases in total rainfall may be due in part to an increase of the number of days with rainfall above 10 mm.

Estimating future potential changes in both temperature and precipitation extremes provide essential input to urban, regional and national adaptation and planning strategies. In this paper we attempt to asses the simulation of some of those extremes during the second half of the XX century, and also to show geographical patterns of observed and simulated trends, to detect areas of agreement as well as uncertainty. This will be most useful in any assessment of projections of changes in extreme in future climate change scenarios.

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Figures:

Figure 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.

Figure 2. 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. Map show indices interpolated at 1x1 latitude longitude grids using krigging.

Figure 3. Simulated trends of extreme climate indices for 1960-2000. The trend is assumed as linear and represents the values of 2000 minus 1960. (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.

Figure 4. 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.

Figure 5. Times series of observed and simulated TN90, R10 and CDD trends during 1960-2000 in various region 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.

Figure 6. Probability Density Function (PDF) for observed and simulated TN90, R10 and CDD trends during 1960-2000, for all models and observation at the level of station.

Figure 1

Fig 1

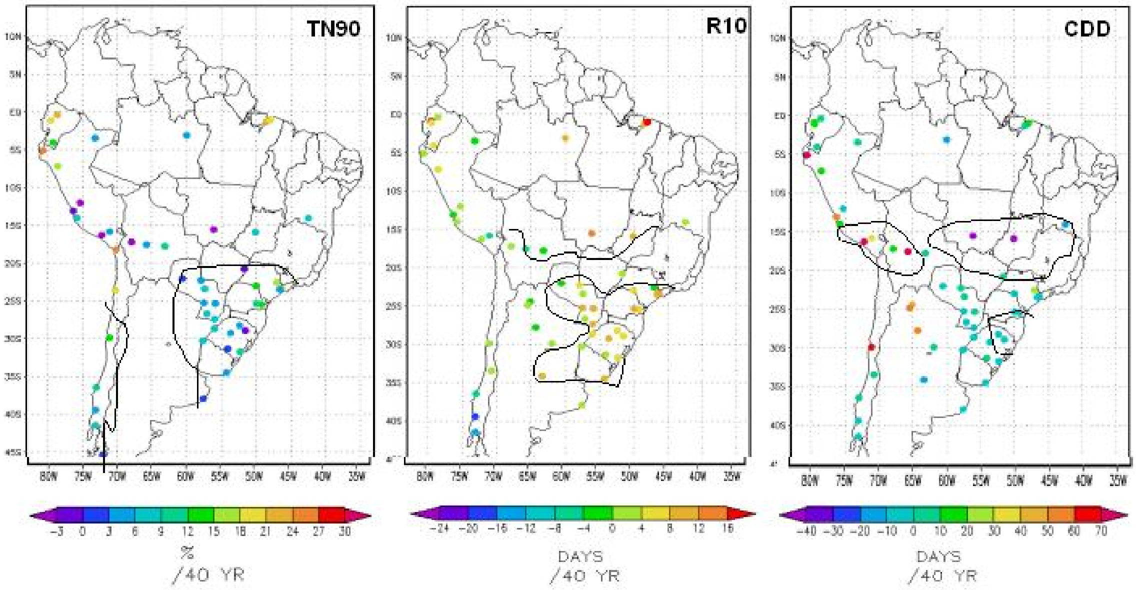


Figure 2

Fig 2

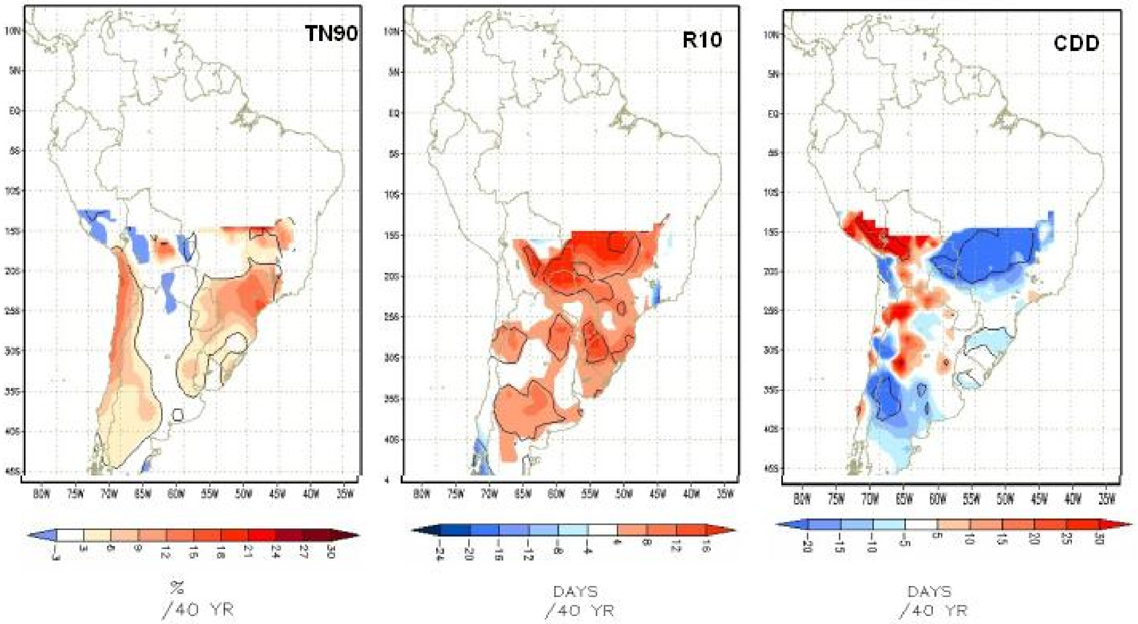


Figure 3

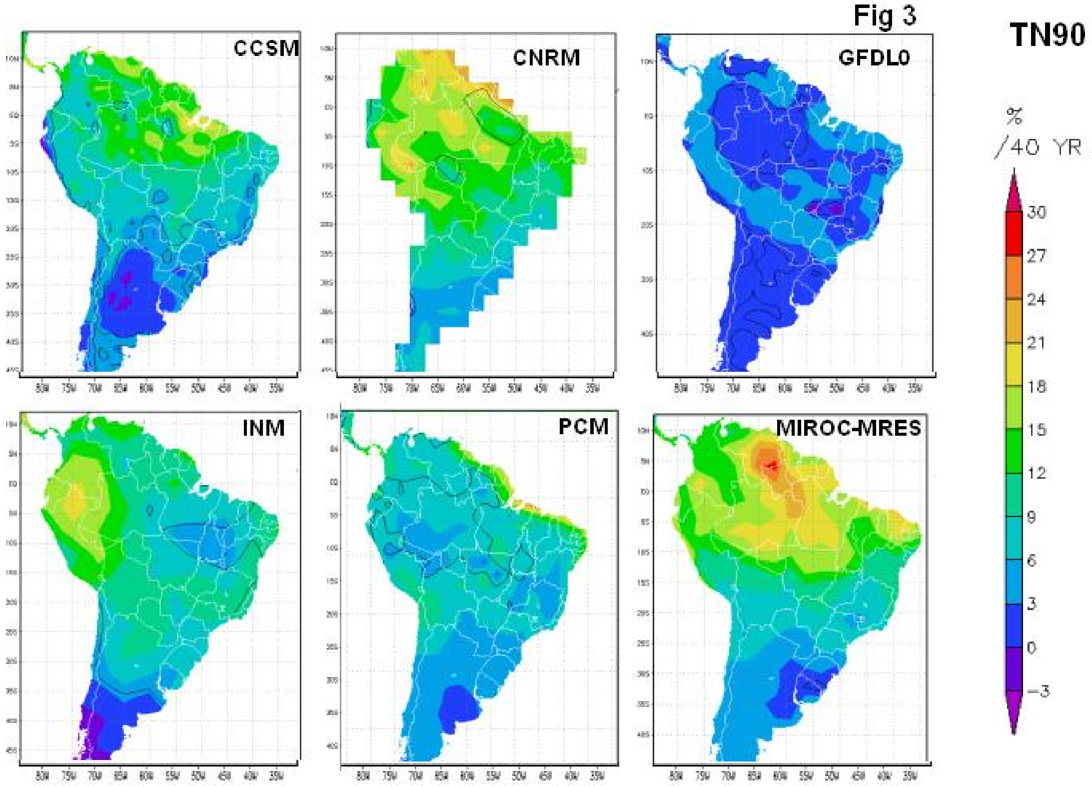
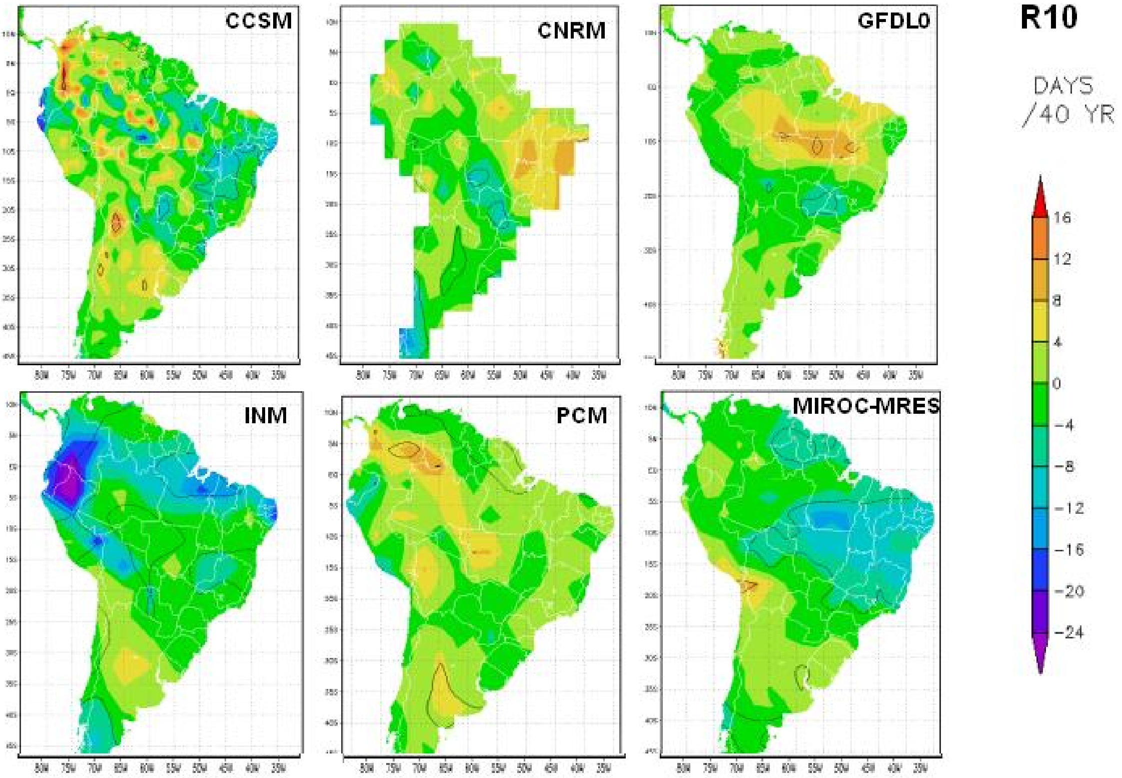


Fig 3
TN90
CCSM
CNRM
GFDL0
INM
PCM
MIROC-MRES
%
/40 YR
30
27
24
21
18
15
12
9
6
3
0
-3
80W
75W
70W
65W
60W
55W
50W
45W
40W
35W


CCSM
CNRM
GFDL0
INM
PCM
MIROC-MRES
R10
DAYS
/40 YR
16
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-4
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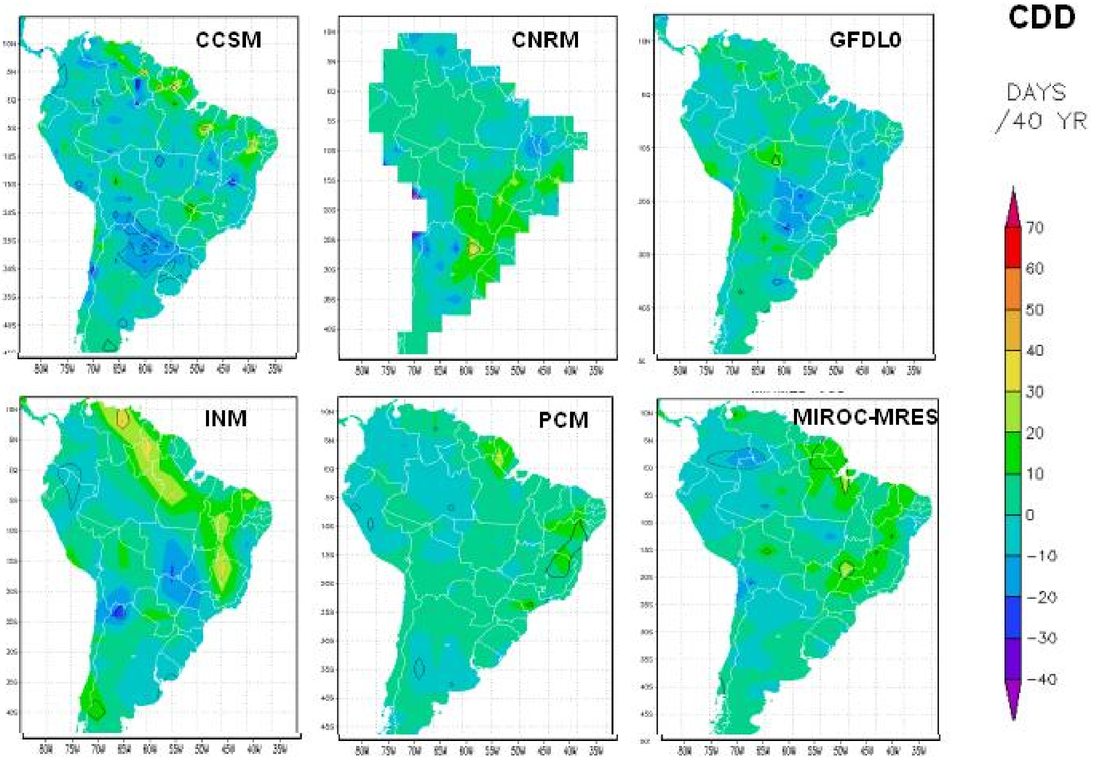
-12
-16
-20
-24
80W 75W 70W 65W 60W 55W 50W 45W 40W 35W


CCSM
CNRM
GFDL0
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PCM
MIROC-MRES
CDD
DAYS
/40 YR
70
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50
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10
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-10
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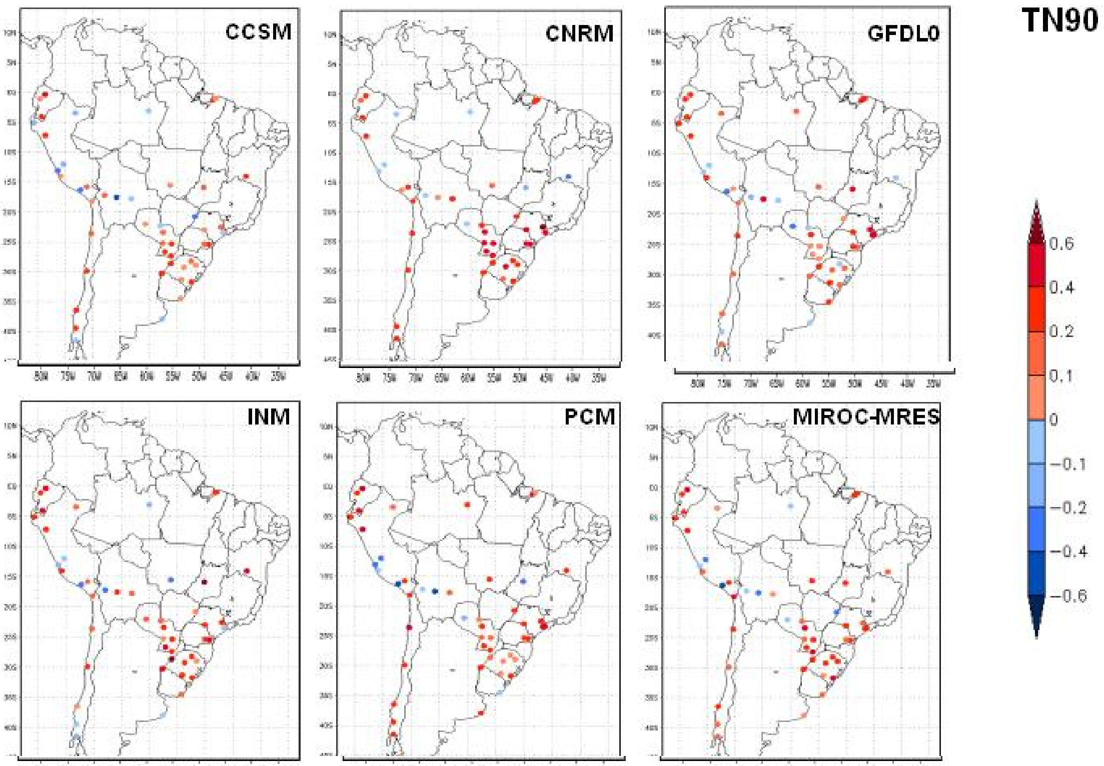
Figure 4



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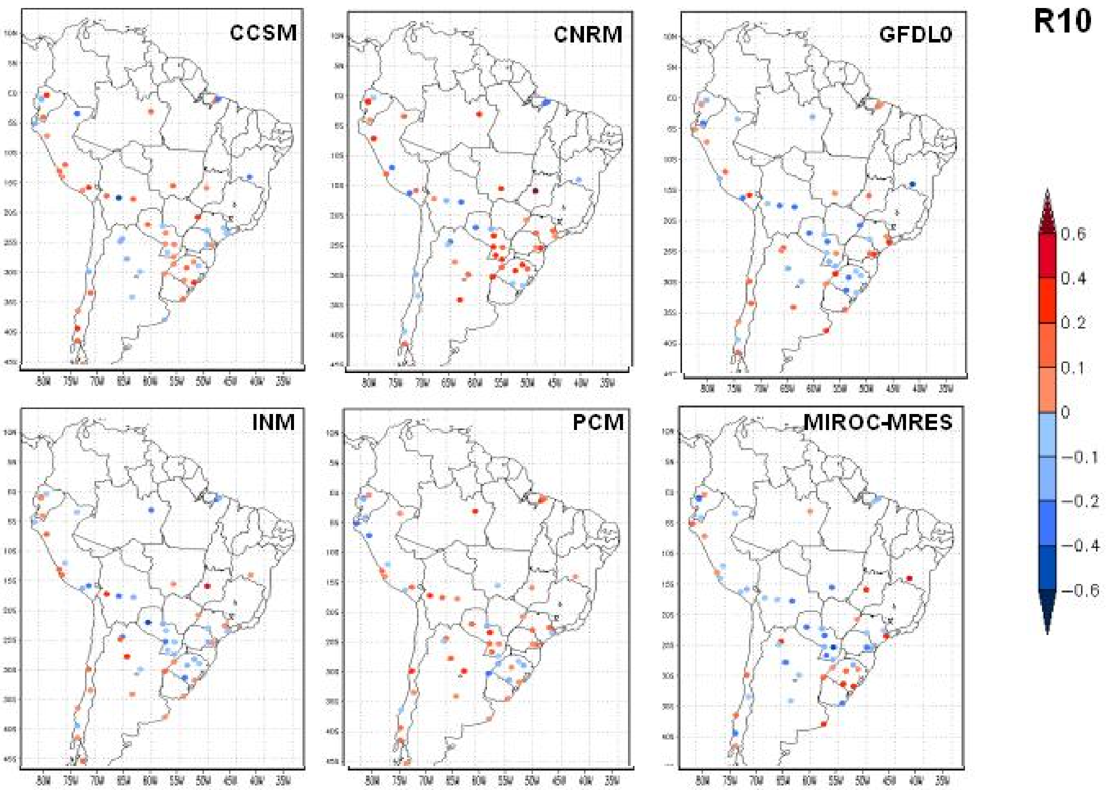
R10
CCSM
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0.6
0.4
0.2
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−0.2
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−0.6
10N
5N
EQ
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10S
15S
20S
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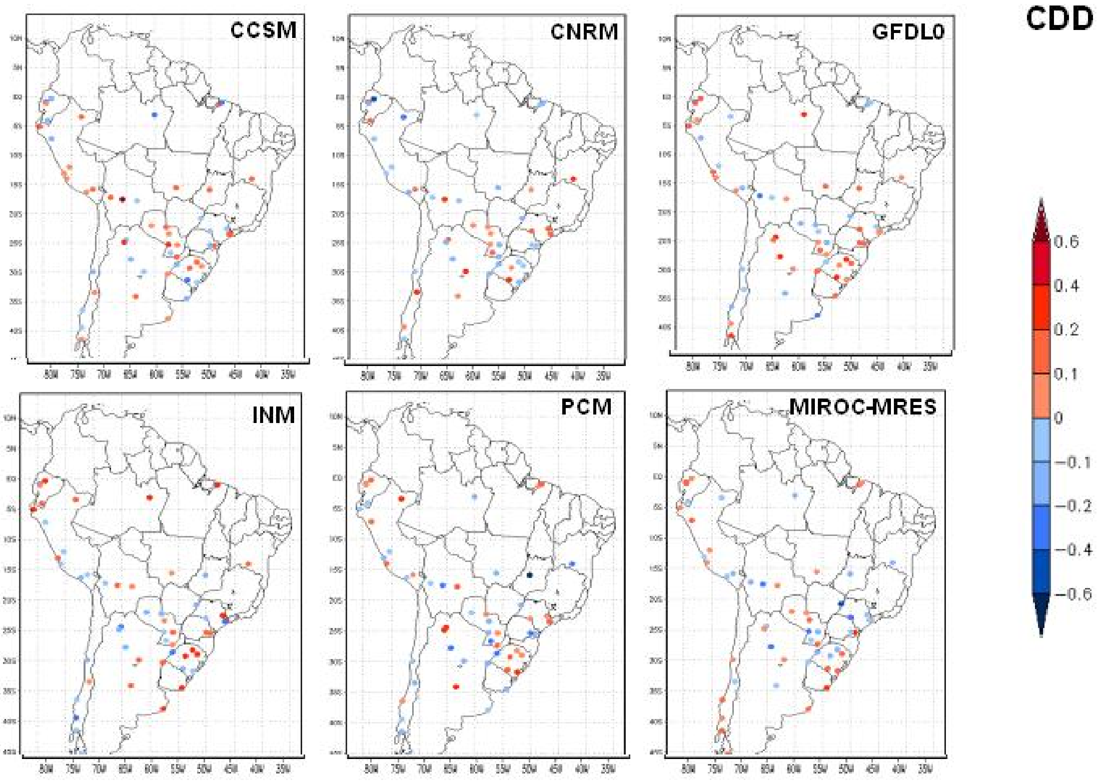
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MIROC-MRES
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−0.2
−0.4
−0.6
10N
5N
EQ
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15S
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25S
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Figure 5

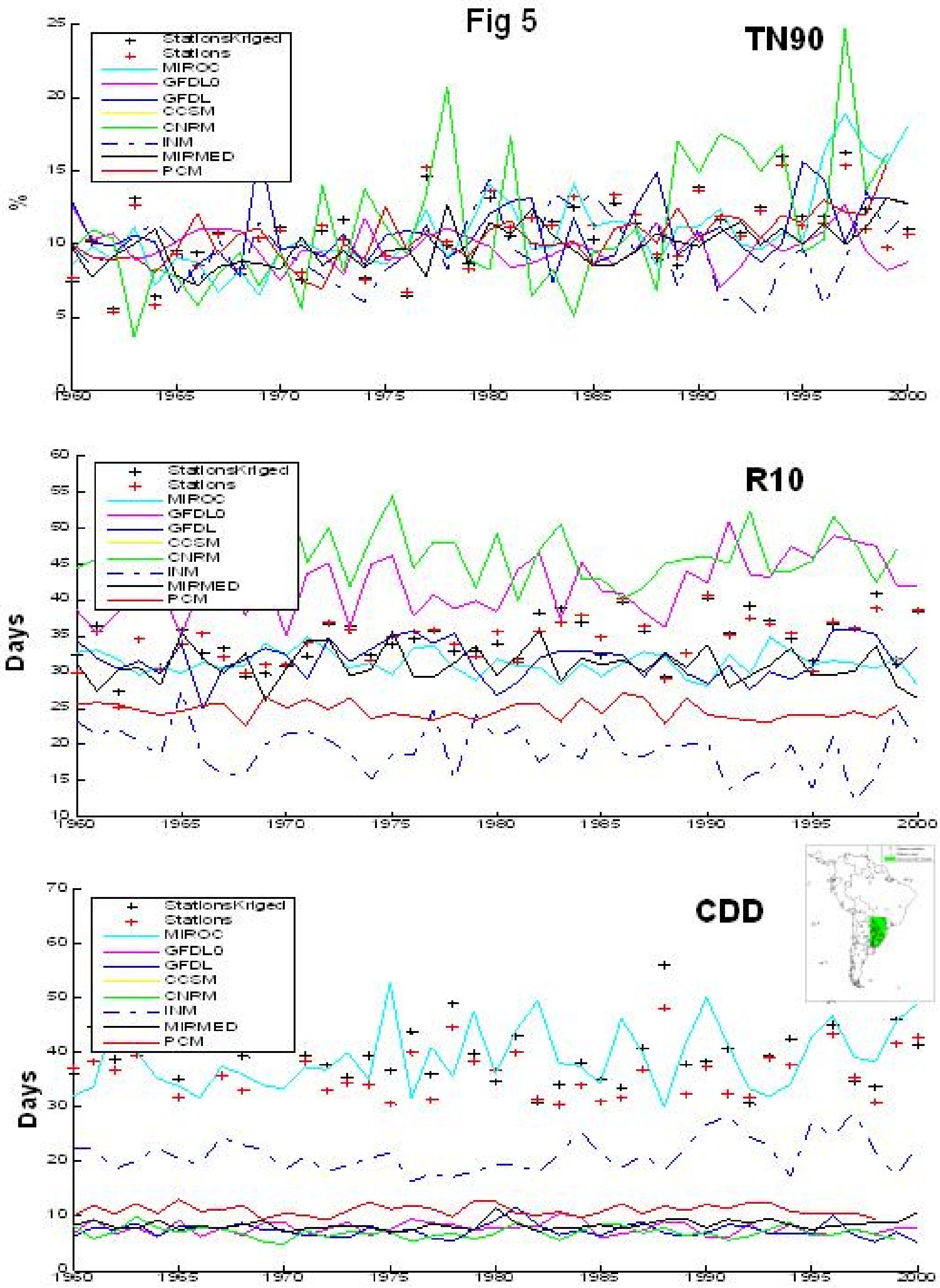
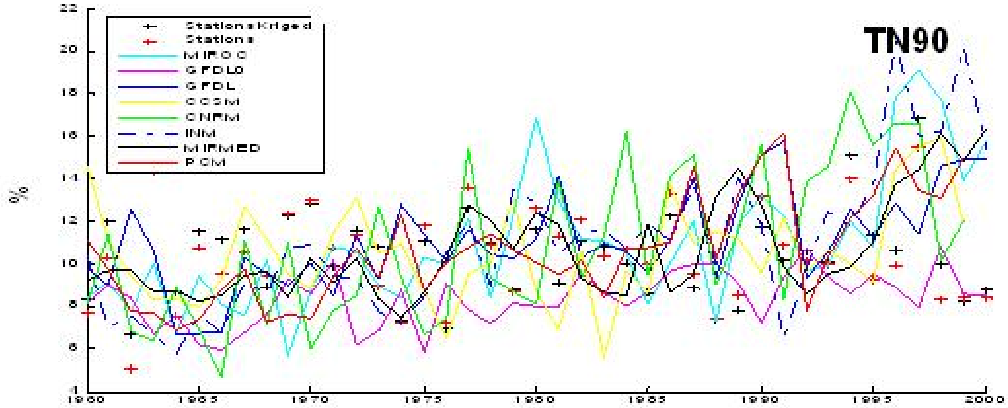


Fig 5
TN90
%
R10
Days
CDD
Days
StationsKriged
Stations
MIROC
GFDL0
GFDL
CCSM
CNRM
INM
MIPMED
PCM
1960
1965
1970
1975
1980
1985
1990
1995
2000


TN90
StationsKriged
Stations
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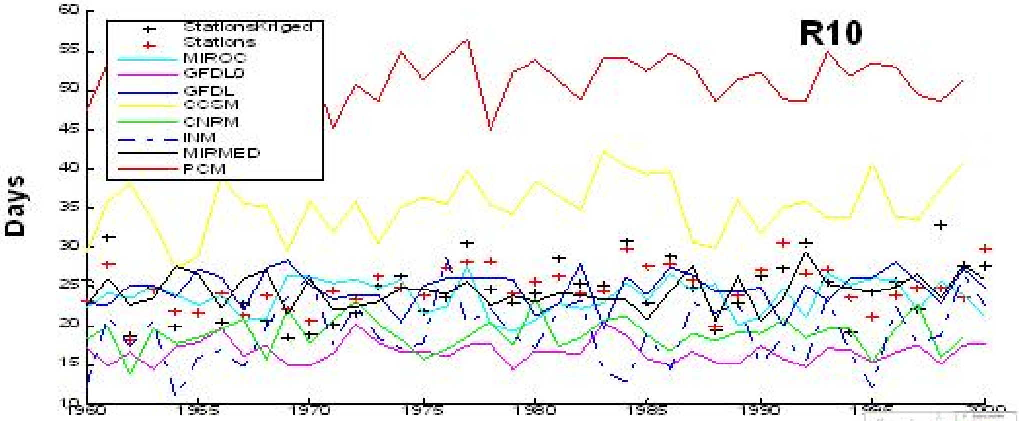
R10
StationsKriged
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MIROC
GFDL0
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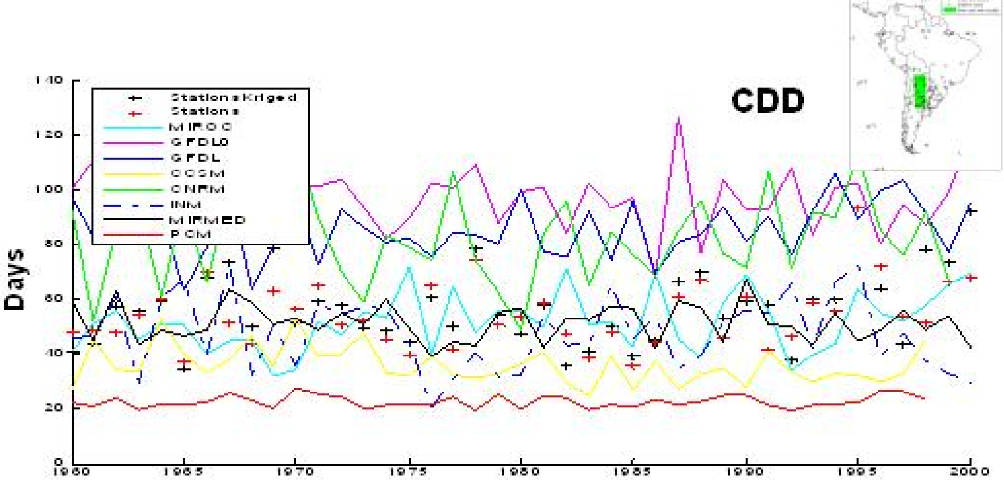
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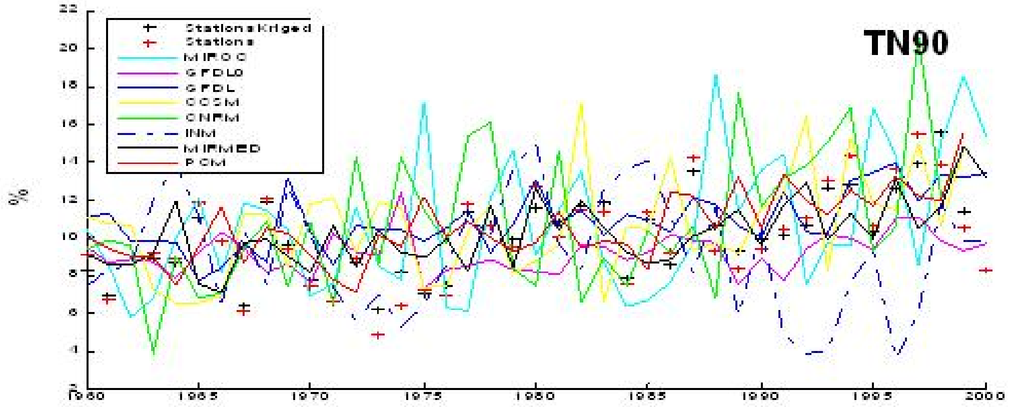
TN90
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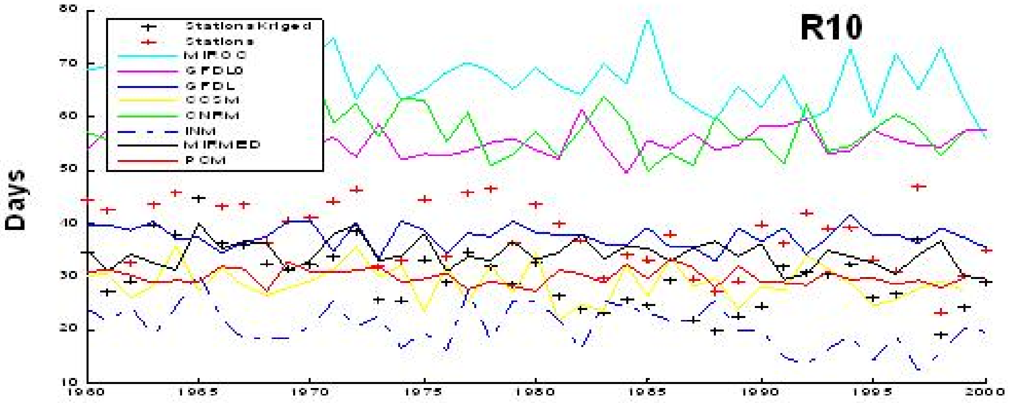
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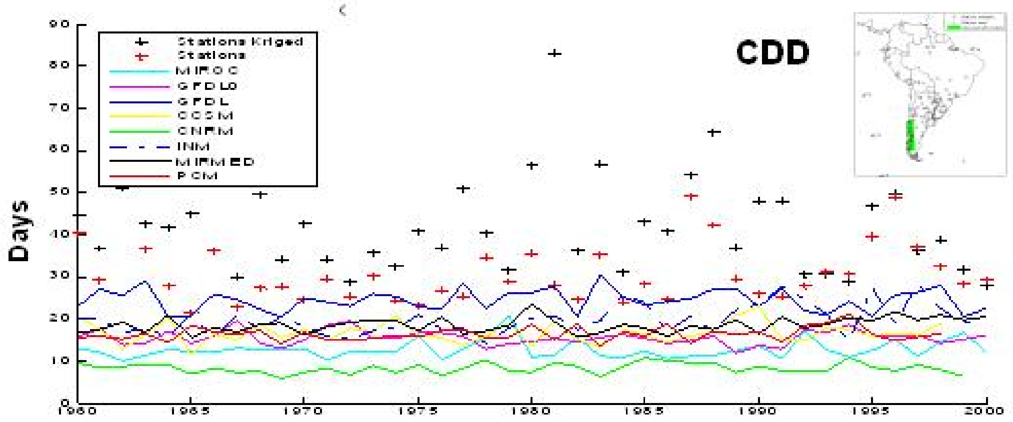
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Figure 6

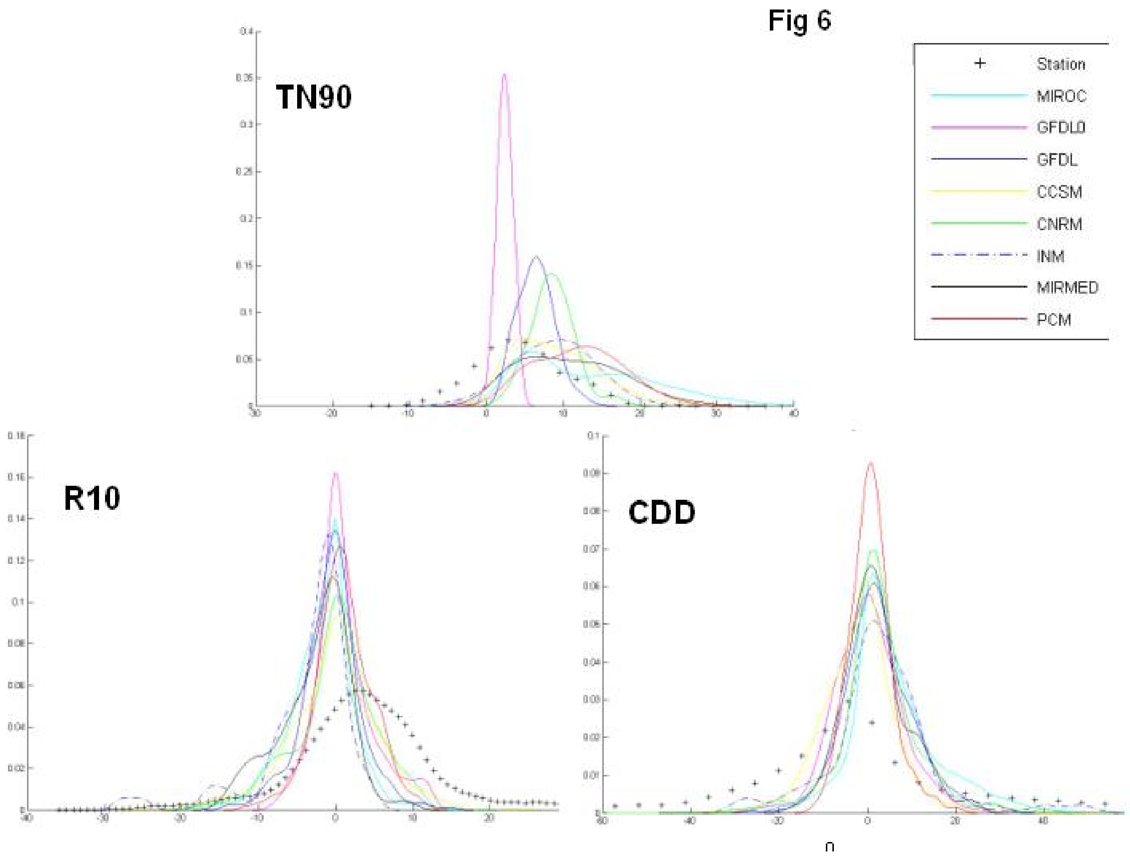
Fig 6
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R10
CDD
Station
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GFDL0
GFDL
CCSM
CNRM
INM
MIRMED
PCM
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0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-30
-20
-10
0
10
20
30
40
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-40
-30
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-10
0
10
20
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-60
-40
-20
0
20
40