Observed trends in indices of daily temperature extremes in South America 1960-2000

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ABSTRACT

A workshop on enhancing climate change indices in South America was held in Maceio, Brazil in August 2004. Scientists from eight southern countries brought daily climatological data from their region for a meticulous assessment of data quality and homogeneity, and for the preparation of climate change indices which can be used for analyses of changes in climate extremes. This study presents an examination of the trends over 1960-2000 in the indices of daily temperature extremes. The results indicate no consistent changes in the indices based on daily maximum temperature while significant trends were found in the indices based on daily minimum temperature. Significant increasing trends in the percentage of warm nights and decreasing trends in the percentage of cold nights were observed at many stations. It seems that this warming is mostly due to more warm nights and fewer cold nights during the summer (December, January, February) and fall (March, April, May). The stations with significant trends appear to be located closer to the west and east coasts of South America.

1. Introduction

Extreme temperature events, through the occurrence of prolonged hot or cold spells, can have serious impacts on our environment and society. Analyses of observed temperature in many regions of the world have already shown some important changes in the extremes. The global average surface temperature has increased by about 0.6°C over the twentieth century and many areas have experienced significant warming during the last fifty years (Folland et al. 2001). This warming may not be spatially or temporally uniform, but it is projected to continue and will likely be accompanied by more extreme climate events. Our society and infrastructure are becoming more vulnerable to severe and intense weather and it is essential to closely monitor the extreme events and to continue to search for evidence of changes in climate extremes.

Until now, issues regarding quality and availability of daily temperature data and the lack of consistency in methods and analyses have made it difficult to compare and interpret the results of many studies from various regions of the globe. Overall, the findings revealed a significant decrease in the number of days having extreme cold temperatures but it seems that no consistent changes were found in the frequency of extreme warm days. Recent investigation of the trends in temperature indices over Europe has indicated a symmetric warming of the cold and warm tails of the daily minimum and maximum temperature distributions during 1946-1999 (Klein Tank and Können 2003). The frequency of cold days has decreased in northern China while the number of hot days has also decreased in the eastern part of the country over the past 40 years (Zhai et al. 1999). Over Australia and New Zealand, the frequency of warm days and nights has increased while the frequency of extreme cool days and nights has decreased since 1961 (Plummer et al, 1999). For the United States, the number of frost days has slightly decreased over 1910-1998, while a small downward trend was also observed in the frequency of days with maximum temperature above the 90th percentile (Easterling et al. 2000). For southern Canada, the findings show increasing trends in the 5th and 95th percentiles of the daily minimum and maximum temperature over 1900-1998, however, no consistent trends were found in extreme hot summer days (Bonsal et al. 2001).

For South America, there have been little published results on temperature changes and extremes which are available internationally. A few papers on temperature extremes in Argentina have been published recently. A comparison study of station temperature observations with NCEP-NCAR reanalysis datasets has shown the ability of reanalysis data to reproduce extreme warm and cold events (Rusticucci and Kousky 2002). The relation between warm/cold events and sea surface temperatures was also examined (Rusticucci et al. 2003). The trends in means, standard deviations and extremes were evaluated for the summer (December, January, February) and winter (June, July, August) for 1959-1998 in the same country (Rusticucci and Barrucand 2004). The results show negative trends in the number of cold nights and warm days while the number of warm nights and cold days has increased at several locations mostly during the summer.

Temperature trends were also analysed in other regions of South America. Warming was identified in various parts of Brazil and it was sometime attributed to the changes in land use, including the development of large cities such as Sao Paulo and Rio de Janeiro (Marengo 2003, 2001; Sansigolo et al. 1992). In Colombia, night-time temperature has increased steadily during the last 30 to 40 years (Quintana-Gomez, 1999). For the Amazon region, Victoria et al. (1998) have detected a warming of 0.56°C/100 years until 1997, while Marengo (2003) has updated the trend to 0.85°C/100 years until 2002. In Southern Brazil, the temperature trends since the 1960s indicate stronger warming of the minimum temperatures compared to the maximum mainly in the winter (JJA) resulting in a decrease in the diurnal temperature range (Campos and Marengo 2004).

A near-global analysis was undertaken by Frich et al. 2002 to provide a coherent study of the changes in climatic extremes for the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report. Their results indicated that there were large regions of the world where no digital daily data were readily available for analysis. The Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) was established by the WMO Commission for Climatology (CCl) / World Climate Research Program project on Climate Variability and Predictability (CLIVAR) to develop a comprehensive list of indices meaningful over continental to global regions. They also coordinate a series of workshops for the preparation and analysis of climate change indices in the regions lacking daily climate observations and analyses.

The key regions were Central and South America, Africa and southern Asia. In 2001, a first workshop was held in Jamaica to cover the Caribbean region (Peterson et al. 2002), and a second one was in Morocco to cover the northern African countries (Easterling et al. 2003). Five more workshops were planned for 2004-2005: in Cape Town, South Africa for southern African countries; in Maceio, Brazil for southern South American countries; in Alanya, Turkey for western Asian countries; in Guatemala City, Guatemala for Central and northern South American countries; and in Pune, India for South Central Asian countries.

A weeklong workshop was held in Maceio Brazil in August 2004. It was attended by 28 scientists from eight countries in South America: Argentina, Bolivia, Brazil, Chile, Ecuador, Paraguay, Peru and Uruguay. Country representatives came from a university or the national weather service in order to promote research in both the educational and government streams. The participants brought their best digital long-term daily climatological data from their respective regions for meticulous assessment of the data quality and homogeneity, and for the computation of climate change indices. The workshop started with various presentations describing the purpose of the workshop, how the climate is projected to change and the methodologies that were going to be used. Most of the time was devoted to data analyses by the participants using several customized computer programs. The objectives of the workshop were to establish a network of scientists working in climate change analyses in this region and to provide a consistent methodology for studying the climate extremes across South America.

This paper presents the trends in indices of daily temperature extremes over 1960-2000 which were prepared during the workshop in Maceio. The data and methodologies are discussed in section 2 and the analysis of trends is presented in section 3. A summary and conclusions follow in section 4. Results for the precipitation extremes are also presented in a companion paper by Haylock et al. (2004).

2. Data and methodologies

Country representatives brought daily precipitation, maximum and minimum temperatures for at least five stations with any metadata available for those stations. Long digital temperature records from high quality stations covering as much as possible of the country were preferable. A total of 68 stations were closely examined for the preparation of the indices (Table 1). The period of record varied by station but it generally covered 1960-2000. The stations with shorter records were not used for the computation of the trends but they were still useful for assessing data quality and homogeneity at nearby stations. The station locations are presented in Figure 1: very few stations are available with long records in the Amazon region of Brazil.

2.1 Data quality and homogeneity

Data quality assessment is an important requirement before the calculation of indices since any erroneous outlier can have a serious impact on the trends in extremes. All suspicious daily temperatures were identified: maximum temperatures less than minimum temperatures and daily values outside of four standard deviations from the mean for that time of year. They were visually assessed to find out if they were part of a cold or warm spell and unusual high values were occasionally compared across nearby stations. Sometimes digitizing errors occurred: for example, 17.8°C was digitized as 178.1 at Ponta Grossa, Brazil, on November 11, 1963. The problems were rare and only a few bad values were identified in some stations. All erroneous values were set to missing.

Temperature observations can be very sensitive to station relocation and in particular to changes in instrument exposure and observing practices. Therefore it was necessary to spend some time for homogeneity assessment. A proper homogeneity assessment of a climatological time series requires close neighbour stations and detailed station history (metadata). A candidate station is compared to a reference series computed from the neighbouring stations and a statistical procedure is used to detect steps and trends (inhomogeneities) at the candidate series. The potential causes of the inhomogeneities are then assessed using the metadata. Statistical procedures can also be applied to adjust daily temperature in order to produce a homogeneous time series (Vincent et al. 2001).

Homogeneity assessment and adjustment of daily data can be quite complex (Aguilar et al. 2003), therefore the objective was to identify only the most significant problems. A preliminary assessment was performed as follows. Each station annual mean maximum and minimum temperature time series was tested separately using a two-phase regression model. The model was first proposed to test the homogeneity of a climatological series by Easterling and Peterson 1995 and by Vincent 1998, and the model and statistical test were revised by Lund and Reeves 2002, and by Wang 2003. The procedure consists of the application of two regression models. The first model describes an overall trend in the tested series. The second model describes an overall trend divided by a potential step at an estimated date. The models are compared using an F-test to determine if the step substantially improves the fit of the model. When the F-statistic is greater than the 95th percentile (Wang 2003), the second model is accepted and it is concluded that there is a potential step in the tested series.

Stations with potentially large problems were tabulated and metadata was examined when available. Over the 68 stations, there were 19 stations with a potential step in annual maximum temperature and 22 stations with a potential step in annual minimum temperatures. History support, such as station relocation, was found for only 5 stations. These results were used during the trends analysis in order to explain the trends in disagreement with their surrounding. For example, a decreasing step was identified in 1969 in the annual mean minimum temperature at Patacamaya, Bolivia. Patacamaya is located in the mountains at high altitude (3789 metres) and the instruments were relocated in 1969 by only a few metres but with a significant change of exposure. A decreasing step was also detected in 1973 in the annual mean maximum temperature at Prado, Uruguay. Prado was closed in 1974 and relocated in 1981 by about one kilometre west of Montevideo City (Prado). The inhomogeneities identified in the annual values of Patacamaya and Prado can affect the trends obtained in various temperature indices.

2.2 Definition of the temperature indices

A set of 11 temperature indices was selected for this study and their description is given in Table 2. They are analysed and presented by climate element (i.e. indices based on daily maximum temperature, on daily minimum temperature and on both). The reason for this is that the temporal variations of the daytime temperature can be different from those of the night-time temperature. For example, the night-time temperature over land has increased by about twice the rate of the daytime temperature during the past 50 years (Folland et al. 2001). The selected indices were calculated on a monthly and/or annual basis. They describe warm and cold temperature extremes. Some are based on a fixed threshold (e.g. summer days, frost days) and their impacts are easy to understand and to evaluate. Others are based on threshold defined as percentiles (e.g. warm days, cold nights) and they are used to facilitate the comparison between stations. Some indices are also computed from both daily maximum and minimum temperatures to provide a measure of extreme temperature variability.

The temperature indices based on percentiles are calculated as percentage of days (in a month or year) above or below the 90th or the 10th percentile. The percentiles are calculated from the reference period 1961-1990. They are defined for every day of the calendar and do not represent only the extreme hot days of the summer or the extreme cold days of the winter (Jones et al. 1999). They are obtained from 150 values: a five-day window centered on each calendar year over 1961-1990. Recently, it was found that the methodology to obtain the percentile during the reference period could create artificial jumps at the beginning and the end of this period and a bootstrap resampling procedure was developed to better estimate the percentiles during the reference period (Zhang et al. 2004).

Table 3 lists some averages of the indices values over 1961-1990. The five stations were selected to represent different climate regions in South America. The warmest day represents the highest temperature value over 1961-1990 while the coldest night is the lowest temperature value. For the indices based on the 10th and 90th percentiles, an almost consistent value of 10% is found throughout the table as a direct consequence of the definition of these indices. The table shows the wide range of temperatures over the whole region, for example, the coldest night of 17.8°C in Manaus, Brazil and of -16.4°C in Punta Arenas, Chile.

Data quality assessment and calculation of the indices were performed using the computer program RClimDex developed by X. Zhang and Y. Feng from the Meteorological Service of Canada. The source code was prepared using the computer language "R" which provides a robust environment for statistical computing and graphics and which can run under various operating systems. RClimDex computed the 27 temperature and precipitation indices recommended by the Expert Team. The indices were calculated on monthly and/or annual basis. Monthly indices were obtained if no more than three days were missing in a month and annual values were calculated if no more than 15 days were missing in a year. Threshold indices were computed if at least 70% of the data were present in the reference period. RClimDex is user-friendly and it is available for free download from the ETCCDMI global climate indices website (http://cccma.seos.uvic.ca/ETCCDMI/).

2.3 Trend estimation

The best-fit linear trend is often used to describe the change in a climatological series. However, it is also influenced by outliers such as large values produced during El Niño years and by the non-normality of the distribution which is often found in extreme values. In this study, an estimator of the slope proposed by Sen (1968) and based on the Kendall's rank correlation was used instead. The estimator is the median of the slopes obtained from all joining pairs of points in the series. The confidence interval is calculated from tabulated values (Kendall, 1955). This procedure was adapted and applied to estimate the change in annual temperature and precipitation (Zhang 2000) and in extreme wave heights (Wang and Swail 2001). In this work, the trends were computed for the period 1960-2000 only if less than 20% of the values were missing. The statistical significance of the trends was assessed at the 5% confidence level.

3. Trends analysis

3.1 Annual analyses

Table 4 summarizes the findings by presenting the number of stations with significant decreasing trends, no significant trends, and significant increasing trends for each temperature index. The results show that there are not many stations with either significant negative or positive trends in the four indices based on daily maximum temperature. Figure 2 presents the map of the trends for these four indices and shows a mixture of not significant trends across the countries. It seems that some stations are in disagreement with their surrounding. For example, for Prado, Uruguay, blue and red dots are shown in the summer days and cold days respectively; for Huayao, Peru, blue and red dots are identified in the cold and warm days; and for Ponta Grossa, Brazil, a decreasing trend is found in the warm days. Homogeneity assessment has revealed a potential step at these stations in either their annual maximum or minimum temperature with an estimate date of a step closely corresponding to the year of a station relocation. On the other hand, a significant decreasing trend is found in the warmest day for Ceres, in the north of Argentina, for which the annual maximum temperatures were considered homogeneous.

Contrary to the indices based on daily maximum temperatures, many significant trends are observed in the indices based on daily minimum temperatures (Table 4). Significant increasing trends in the coldest night (coldest night getting warmer) are found at several stations located along the west coast of South America, and a few are also identified in southern Brazil (Figure 3). There are as well more tropical nights in southern Brazil, Paraguay and Uruguay. The most profound changes are observed in the percentage of days with extreme cold and warm nights. Over 40% of the stations show significant decreasing trends in the percentage of cold nights and significant increasing trends in the percentage of warm nights. This means that many stations have seen fewer cold nights and more warm nights during the past four decades. Some stations show a decrease (or increase) of over 10% in the percentage of days with cold nights (or warm nights). In other words, there is a decrease of more than 36 extreme cold nights (or an increase of more than 36 extreme warm nights) over 1960-2000 at many stations in South America. The stations with significant trends are mostly located closer to the west and east coasts, and that the stations in the interior have smaller not significant trends.

Several decreasing trends are observed in the indices based on both daily maximum and minimum temperatures (Figure 4). The diurnal temperature range (mean of the difference between daily maximum and minimum) has decreased by 2 to 3°C at many locations. However, there are fewer stations showing significant decreasing trends in the extreme temperature range (difference between the highest daily maximum and lowest daily minimum during the year) which indicates that it is not necessarily the highest or lowest value that has changed. These results also support the strong warming observed in the night-time temperature.

Since the stations are fairly well distributed over the eight countries, a regional time series for South America (south of the equator) was obtained for each temperature index. The regional time series was produced by simply computing the numerical average from each station with values available. Figure 5 presents the regional time series of six temperature indices. The estimator of the slope by Sen (1968) and its statistical significance were also obtained to provide an estimate of the linear change over 1960-

2000. The regional time series of the percentage of days with extreme cold and warm temperatures fluctuate around the 10 percent line and indicate very little change over the four decades; the trends are also not significant at the 5% level. However, the regional trends of the percentage of nights with extreme cold and warm temperature show considerable change with significant trends of -5.5% and 5.6% for the 41 years, respectively. It seems that the time series of the warm days and warm nights are influenced by the strong 1997-1998 El Niño event, with the values of 1997 and 1998 quite high particularly for the warm nights. On the other hand, it seems that this major event has not affected the series of the cold days and cold nights. The diurnal temperature range has substantially decreased over 1960-2000 with a significant trend of -0.6°C, while the extreme temperature range has also slightly decreased although the trend is not significant at the 5% confidence level.

3.2 Seasonal analysis

Seasonal trends were examined to determine whether there is any season with significant changes in the indices based on daily maximum temperature and if the warming observed in the annual indices based on the daily minimum can be attributed to a particular season. Seasons were defined as follows: winter (June, July, August), spring (September, October, November), summer (December, January, February) and fall (March, April, May). Table 5 provides the number of stations with significant negative, not significant, and significant positive trends for the seasonal temperature indices. Once again, there are not many stations with any significant trends in the seasonal indices based on daily maximum temperatures. However, over 35% of the stations show significant trends in the indices based on the minimum temperature during the summer and fall. It seems that the warming observed in the extreme night-time temperature is mostly due to more warm nights in the summer and fall and to less cold nights during the summer, fall and, to a lesser extent, the spring. Figure 6 shows the seasonal trends in warm nights over 1960-2000. Many of the stations with a significant increase are located near the west and east coasts. In the summer and fall, many stations experience trends greater than 15% which indicate an increase of more than 13 warm nights during the past four decades. In the fall and spring, there are suspicious significant decreasing trends at Pampa de Majes, in the south of Peru, which also corresponds to a strong deceasing step identified in the annual minimum temperatures. The cause of the step was however not established.

4. Summary and conclusion

This study presents an examination of the trends in indices of daily temperature extremes for South America during 1960-2000. Data quality and homogeneity assessments are crucial before trends in climate indices are computed. Erroneous outlier values and artificial steps due to changes in instrument exposure will affect the trends in temperature extremes. In addition, it is essential to use a consistent methodology to define and calculate the climate extremes for a better comparison across regions. The procedures used to produce the temperature extremes were recommended by the CCl/CLIVAR Expert Team on Climate Change Monitoring Detection and Indices.

The results show that the temperature extremes are changing in South America. The findings reveal no consistent changes in the indices based on daily maximum temperature. However, significant trends were observed in the indices based on daily minimum temperatures. The coldest night of the year is getting warmer at many stations and there are also more tropical nights. The most important changes are observed in the percentage of extreme cold and warm nights. The regional trends show a decrease of

5.5% in the percentage of cold nights while an increase of 5.6% was found in the percentage of warm nights for 1960-2000. The change in the extreme night-time temperature is more pronounced during the summer (DJF) and fall (MAM). This warming also corresponds to a significant decrease of 0.6°C in the diurnal temperature range over the continent. Since the stations with significant trends appear to be located closer to the west and east coasts of South America, future work could involve an analysis of the correlation between the sea surface temperature and the land temperature extremes. In addition, since ENSO events seem to have considerable impact on the surface temperature in the southern part of the continent (Barros et al. 2002), further work could also examine the relation between the circulation pattern and the land surface temperature and extremes over the entire South America.

These results generally agree with what has been observed in many other parts of the world. The near-global analysis by Frich et al. 2002 has indicated an increase in the frequency of warm nights, a decrease in the extreme temperature range and also a decrease in the number of frost days. Frost days is not a representative index for South America since the temperature remains above 0°C almost everywhere with the exception of the stations located in the high mountains of Ecuador, Peru and Bolivia, and for those located in the southern part of Argentina and Chile. The results from the Caribbean region have indicated that the frequency of warm nights and warm days have significantly increased since the late 1950s while it seems that in South America only the warm nights have increased. The difference may be due to the daily temperature of the Caribbean Island stations being closely related to the sea surface temperature (SST) with extreme warm days related to warmer SST (Peterson et al. 2002). For Argentina, the analysis of the trends in temperature extremes has also indicated a strong warming of the night-time temperature with fewer cold nights and more warm nights (Rusticucci and

Barrucand 2004). However, increasing cold days and decreasing warm days were also found mostly in the summer whereas in this study no significant changes were observed. The definition of the extremes and the procedure to calculate trends were similar but not identical. This provides further evidence for the strong warming in the night-time temperature extremes and the weaker changes in the daytime temperature extremes.

This study presents the first analyses of the trends in temperature extremes in South America (south of the equator). The workshop in Maceio has provided a great opportunity for establishing a strong scientific network in the region. All participants gained valuable knowledge about the methodologies recently developed to assess and analyse daily climatological data, and the cross-border analysis has provided a better understanding of the climate variations over the continent. The expertise and enthusiasm of all participants have allowed the production of reliable and valuable results for changes in climate extremes in a region where no such study was done before on a continental scale. The indices produced during the workshop will be used for a global analysis being prepared for the next IPCC assessment report.

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Table 1. Period of data, location and elevation for the 68 stations.

Country	Stations	Start	End	Longitude	Latitude	Elev. (m)
Argentina	Ceres	1959	2001	-61.95	-29.88	88
	Esquel	1959	2002	-71.15	-42.93	785
	Jujuy	1959	2001	-65.08	-24.38	905
	Laboulage	1959	2001	-63.37	-34.13	137
	Mar Del Plata	1962	2001	-57.58	-37.93	21
	Mendoza	1959	2002	-68.78	-32.83	704
	Monte Caseros	1959	2001	-57.65	-30.27	54
	Neuquen	1959	2002	-68.13	-38.95	271
	Posadas	1960	2001	-55.97	-27.37	125
	Rio Gallegos	1959	2001	-69.28	-51.61	19
	Salta	1968	2001	-65.48	-24.85	1221
	Santiago	1959	2001	-64.30	-27.77	199
	Trelew	1959	2002	-65.27	-43.20	43
Bolivia	Arani	1976	2001	-65.77	-17.57	2740
	Misicuni	1979	2001	-17.01	-66.30	3500
	Patacamaya	1957	2000	-67.92	-17.20	3789
	Santa Cruz	1971	2001	-63.17	-17.78	416
	Tiraque	1957	2001	-17.40	-65.70	3220
Brazil	Agua Funda	1950	2003	-46.37	-23.39	779
	Bage	1960	2000	-54.11	-31.33	214
	Belem	1951	2000	-48.50	-1.30	10
	Caetite	1954	1978	-14.05	-42.52	882
	Cambara	1957	2003	-50.03	-23.00	450
	Campinas	1896	2003	-47.05	-22.54	694
	Guiaba	1961	1978	-15.55	-56.12	178
	Curitiba	1961	2003	-49.28	-25.43	910
	Goias	1961	1978	-15.92	-50.13	495
	Julio de Castilhos	1956	1999	-53.68	-29.23	514
	Manaus	1954	1999	-60.00	-3.10	67
	Passo Fundo	1956	2000	-52.41	-28.26	687
	Pelotas	1950	2000	-52.35	-31.75	7
	Ponta Grossa	1954	2003	-50.00	-25.37	880
	Sao Borja	1956	2000	-56.00	-28.66	99
	Sao Paulo	1961	1978	-23.50	-46.60	762
	Soure	1951	2000	-48.00	-1.00	11
	TreaLagoas	1961	1978	-20.78	-51.70	313
	Veranopolis	1956	1999	-51.55	-28.94	705
Chile	Antofagosta	1961	2003	-70.30	-23.60	120
	Arica	1961	2003	-70.20	-18.20	55
	Conception	1950	2003	-73.02	-36.46	11
	Coyhaique	1961	2003	-72.10	-45.40	310
	La Serena	1950	2003	-71.10	-29.90	146
	Pta Arenas	1961	2000	-70.50	-53.00	16
	Puerto Montt	1970	2003	-73.10	-41.43	58
	Santiago	1950	2003	-70.76	-33.45	520
	Valdivia	1970	2003	-73.10	-39.40	19
Ecuador	Galapos	1965	2001	-0.90	-89.50	6
	Izobamba	1966	2002	-78.55	-0.35	3058
	Loja Argelia	1964	2000	-79.20	-4.04	2160
	Pichilingue	1965	2002	-79.48	-1.11	120
Paraguay	Asuncion	1960	1999	-57.51	-25.25	101
	Concepcion	1960	1999	-57.43	-23.43	70
	Encarnacion	1951	1999	-55.87	-25.32	85
	Mariscal	1950	1999	-60.60	-22.02	165
	Pto Casado	1947	1999	-57.93	-22.28	80
	Villarrica	1956	1999	-57.12	-26.67	110
Peru	Canete	1937	2003	-76.32	-13.07	158
	Huayao	1950	2003	-75.30	-12.03	3308
	Imata	1936	2003	-71.08	-15.83	4519
	Iquitos	1957	1995	-73.15	-3.45	125
	Pampa de Majes	1950	2003	-72.20	-16.30	1434
	San Camilo	1954	2003	-75.75	-14.00	398
	Spiura	1955	1996	-80.62	-5.08	49
	Weberbauer	1965	2003	-78.50	-7.17	2536
Uruguay	Mercedes	1956	2000	-58.07	-33.25	17
	Paysandu	1950	2000	-58.03	-32.50	61
	Prado	1921	2000	-56.20	-34.85	16
	Rocha	1961	2000	-54.30	-34.48	18

Table 2. Definition of the temperature indices used in this study. Tmax and Tmin are daily maximum and minimum temperature respectively.

Element	Indicator name	Definitions	Units
Tmax	Summer days	Number of days with Tmax > 25°C	days
	Warmest day	Highest daily maximum temperature	°C
	Warm days	Percentage of days with Tmax > 90th percentile	%
	Cold days	Percentage of days with Tmax < 10th percentile	%
Tmin	Frost days	Number of days with Tmin < 0°C	days
	Coldest night	Lowest daily minimum temperature	°C
	Cold nights	Percentage of days with Tmin < 10th percentile	%
	Warm nights	Percentage of days with Tmin > 90th percentile	%
	Tropical nights	Number of days with Tmin > 20°C	days
Both	Diurnal temperature range	Mean of the difference between Tmax and Tmin	°C
	Extreme temperature range	Difference between highest Tmax and lowest Tmin	°C

Table 3. Average of the indices values over the 1961-1990 period for five stations in South America. The warmest day (coldest night) represents the highest (lowest) value over 1961-1990.

Indicator name	Manaus Brazil	San Camilio Peru	Asunción Paraguay	Rocha Uruguay	Punta Arenas Chile	Units
Summer days	363.7	300.3	267.3	102.5	0.2	days
Warmest day	38.0	36.8	41.7	39.5	27.8	°C
Warm days	10.2	9.8	11.0	10.4	9.9	%
Cold days	10.4	10.0	10.3	10.4	9.5	%
Frost days	0.0	0.0	0.1	5.1	79.6	days
Coldest night	17.8	3.8	-0.6	-5.8	-16.4	°C
Cold nights	9.8	10.2	10.3	10.1	10.1	%
Warm nights	10.8	10.1	10.6	10.0	9.3	%
Tropical nights	363.4	9.2	152.6	15.1	0.0	days
Diurnal temperature range	8.3	14.8	10.3	10.4	7.0	°C
Extreme temperature range	16.3	28.7	37.2	38.5	32.0	°C

Table 4. Number of stations with significant negative, not significant, and significant positive trends for the annual temperature indices over 1960-2000 (significant at the 5% level). The numbers in bold indicate that more than 25% of the stations have significant trends.

Indicator name	Negative	Not Sign.	Positive
Summer days	1	35	4
Warmest day	1	40	2
Warm days	1	38	4
Cold days	5	37	1
Frost days	5	27	1
Coldest night	2	35	9
Cold nights	**19**	26	1
Warm nights	0	25	**21**
Tropical nights	0	22	**14**
Diurnal temperature range	**13**	28	2
Extreme temperature range	6	36	0

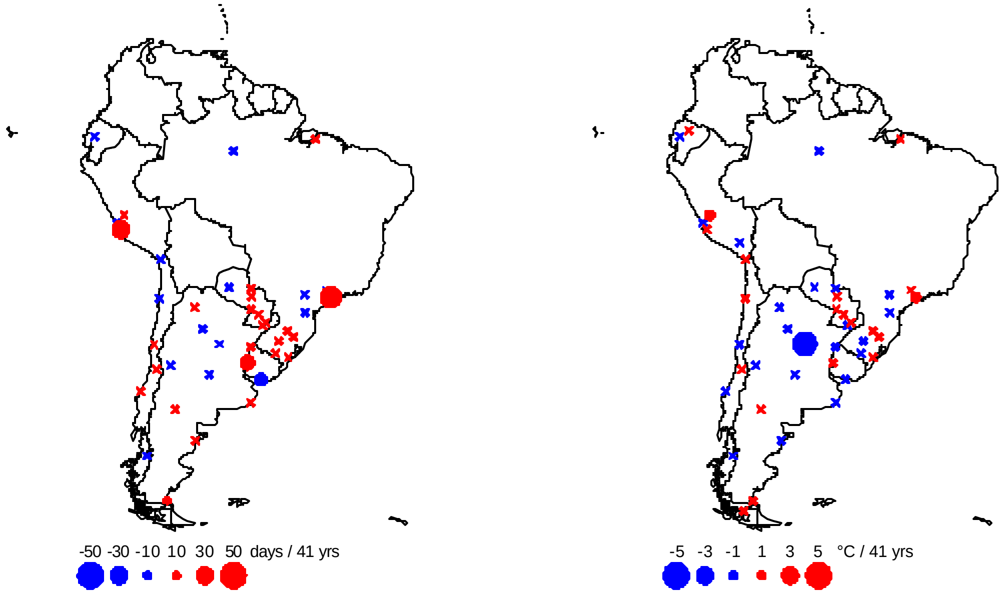
Table 5. Number of stations with significant negative, not significant, and significant positive trends for the seasonal temperature indices over 1960-2000 (significant at the 5% level). The numbers in bold indicate that more than 25% of the stations have significant trends.

Indicator name	Season	Negative	Not Sign.	Positive
Warm days	Summer	5	47	3
	Fall	3	46	6
	Winter	1	49	4
	Spring	1	48	5
Cold days	Summer	6	48	1
	Fall	4	51	0
	Winter	5	50	2
	Spring	4	48	1
Warm nights	Summer	0	35	**20**
	Fall	1	29	**25**
	Winter	0	43	10
	Spring	1	43	10
Cold nights	Summer	**22**	33	0
	Fall	**20**	33	2
	Winter	8	43	2
	Spring	**14**	38	2

Figure 1. Location of the 68 temperature stations.

a) Summer days

b) Warmest day



c) Cold days

d) Warm days

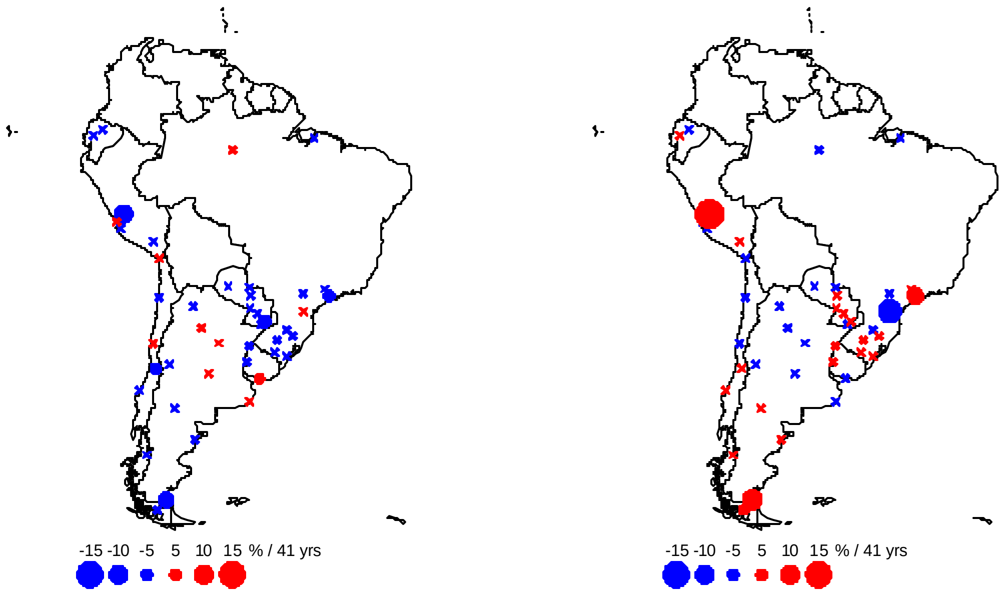
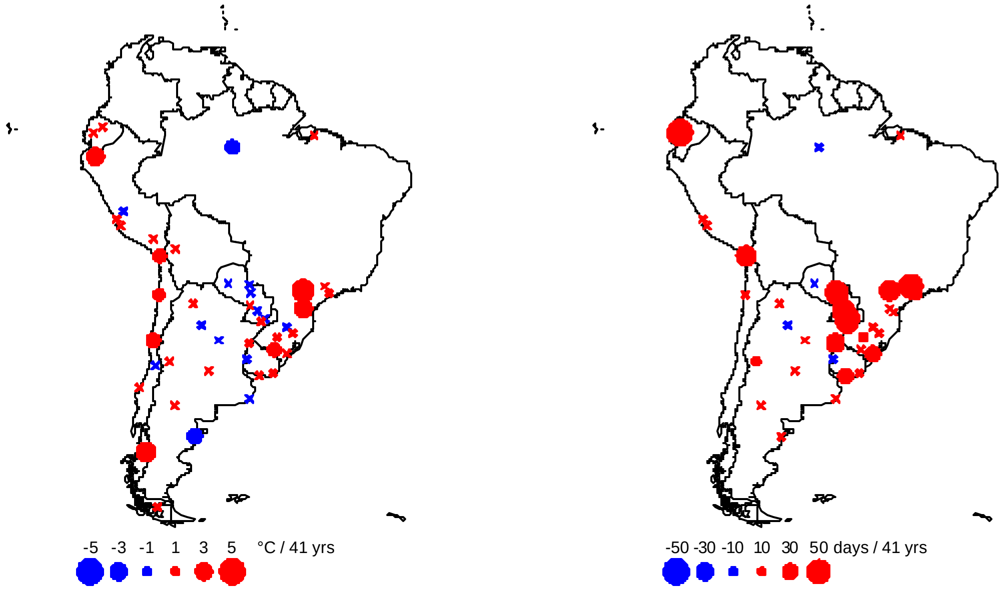
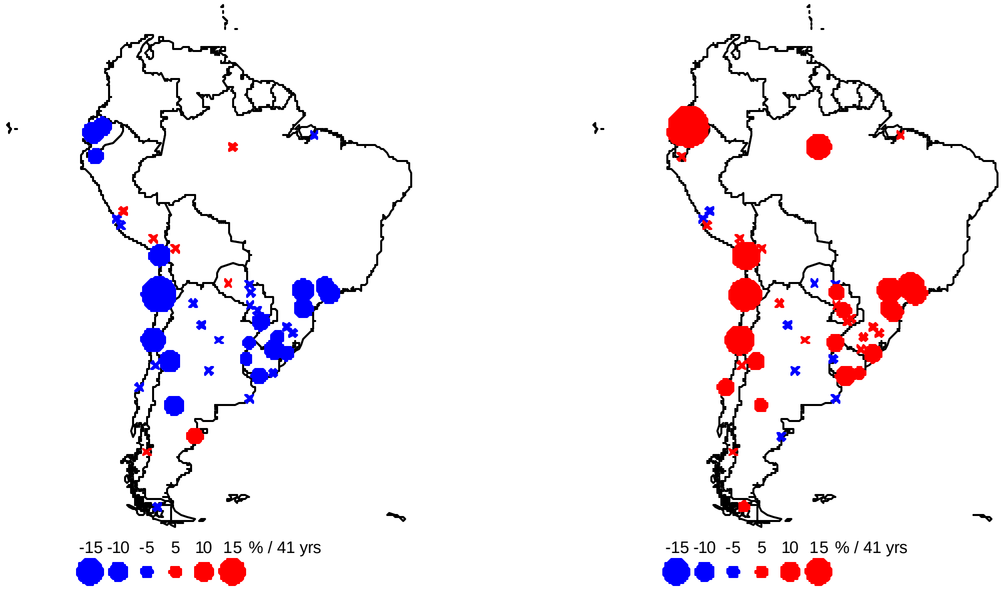


Figure 2. Trends in four indices based on daily maximum temperature over 1960-2000. Red (blue) dots indicate significant increasing (decreasing) trends. Crosses indicate non-significant trends at the 5% level.

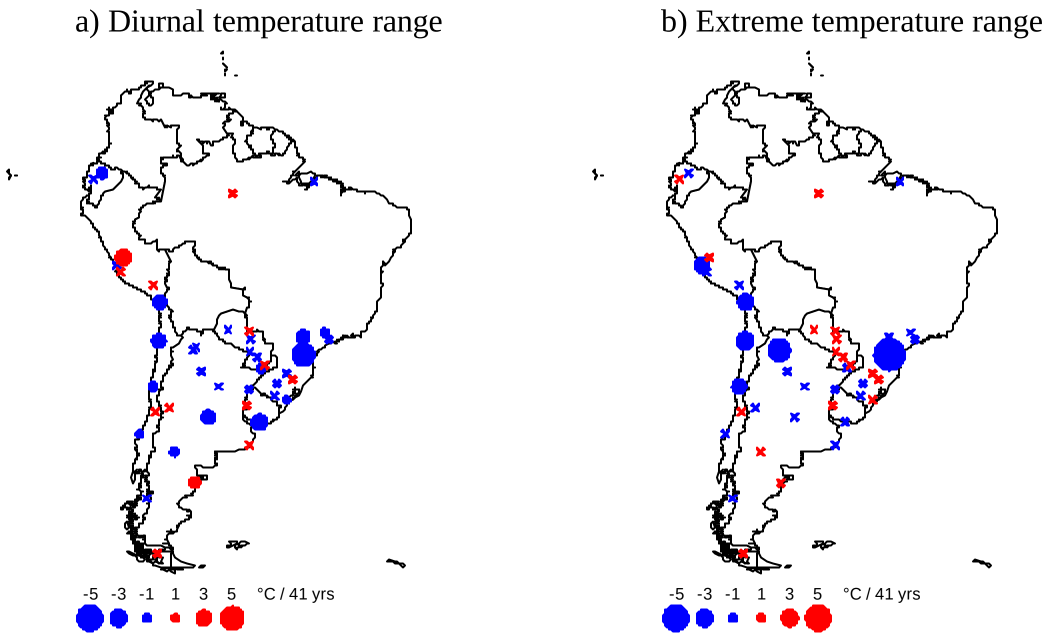

a) Coldest night

b) Tropical nights


c) Cold nights

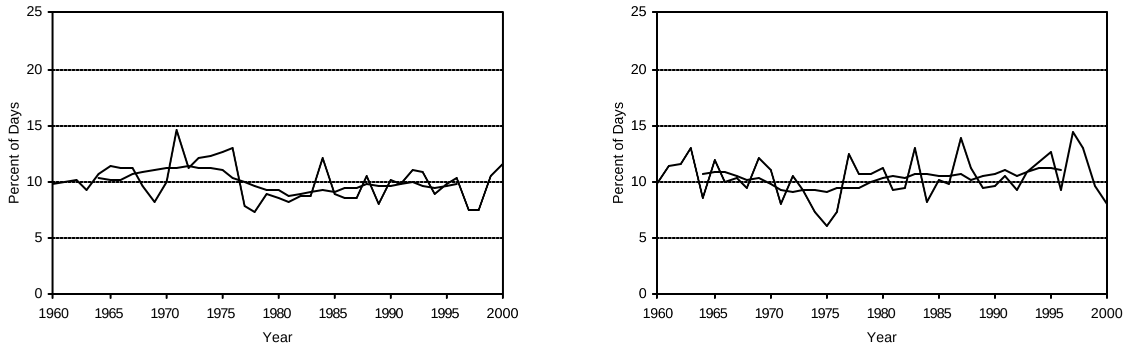
d) Warm nights

Figure 3. Trends in four indices based on daily minimum temperature over 1960-2000. Red (blue) dots indicate significant increasing (decreasing) trends. Crosses indicate non-significant trends at the 5% level.

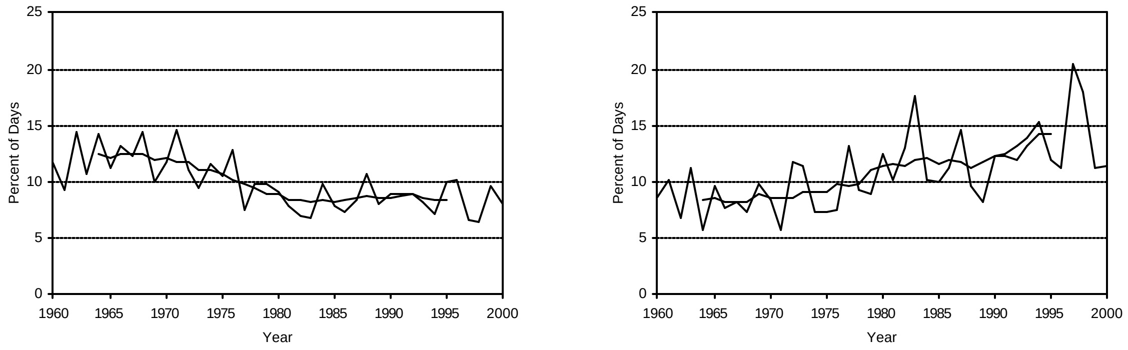

a) Diurnal temperature range

b) Extreme temperature range

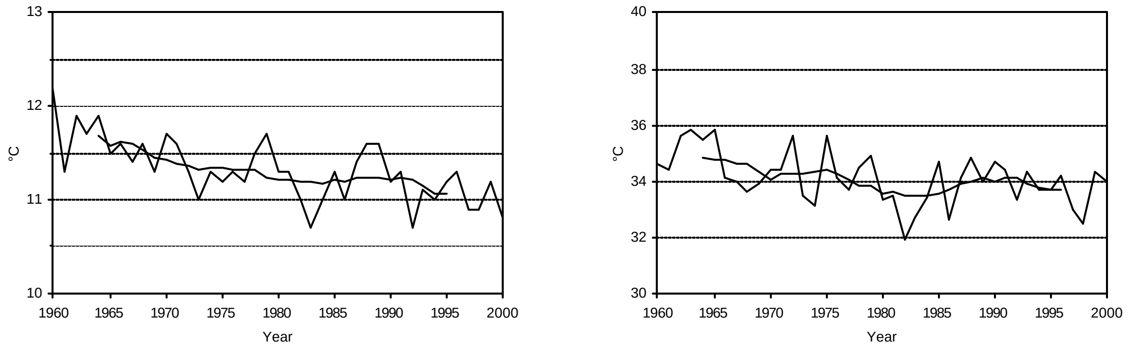
Figure 4. Trends in two indices based on daily maximum and minimum temperature over 1960-2000. Red (blue) dots indicate significant increasing (decreasing) trends. Crosses indicate non-significant trends at the 5% level.


a) Cold days

b) Warm days

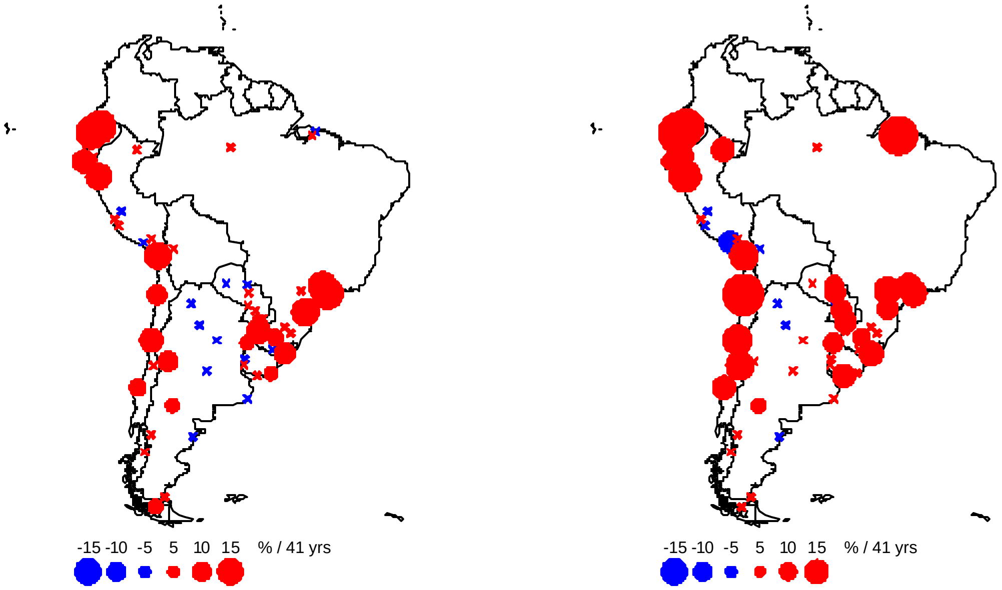

c) Cold nights

d) Warm nights


e) Diurnal temperature range

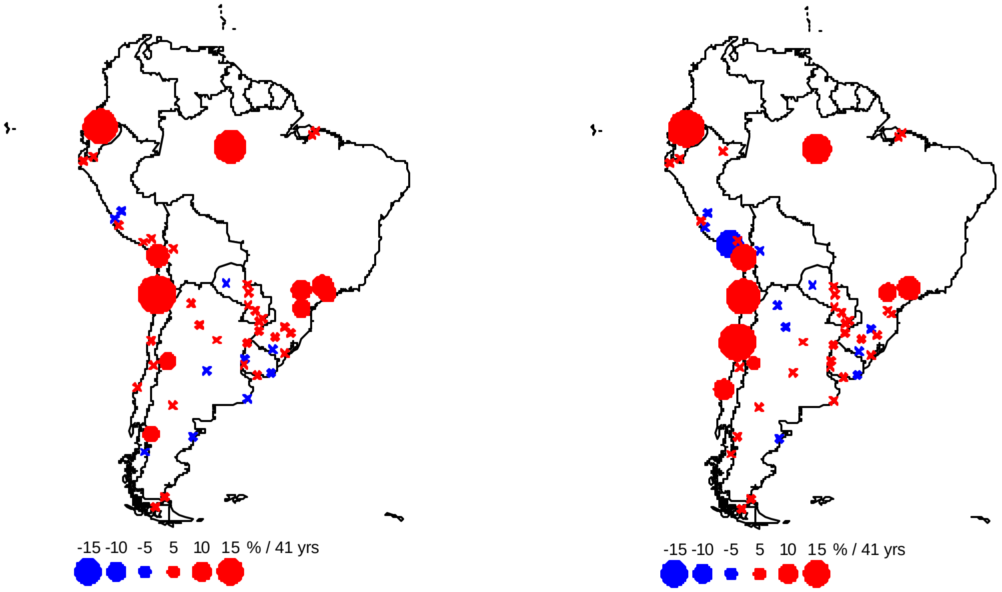
f) Extreme temperature range

Figure 5. Regional time series for six temperature indices. The nine-year running mean is given by the line in bold.



a) Summer (DJF)

b) Fall (MAM)



c) Winter (JJA)

d) Spring (SON)

Figure 6. Seasonal trends in warm nights over 1960-2000. Red (Blue) dots indicate significant increasing (decreasing) trends. Crosses indicate non-significant trends at the 5% level