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 Maceió, 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 that 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–February) and fall (March–May). The stations with significant trends appear to be located closer to the west and east coasts of South America.

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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 50 yr (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 periods for 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 1946–99 (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 yr (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 1910–98, 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 1900–98; however, no consistent trends were found in extreme hot summer days (Bonsal et al. 2001).

For South America, there have been few published results on temperature changes and extremes that are available internationally. A few papers on temperature extremes in Argentina have been published recently. A comparison study of station temperature observations with National Centers for Environmental Prediction–National Center for Atmospheric Research (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–February, DJF) and winter (June–August, JJA) for 1959–98 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 analyzed 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 São Paulo and Rio de Janeiro (Marengo 2001, 2003; Sansigolo et al. 1992). In Colombia, nighttime temperature has increased steadily during the last 30–40 yr (Quintana-Gomez 1999). For the Amazon region, Victoria et al. (1998) have detected a warming of 0.56°C/100 yr until 1997, while Marengo (2003) has updated the trend to 0.85°C $(100 \text{ yr})^{-1}$ 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 2005, manuscript submitted to *Int. J. Climatol.)*.

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's (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 to develop a comprehensive list of indices meaningful over global regions and to coordinate a series of workshops for the preparation of climate change indices in the regions lacking daily climate observations. The key regions were Central and South America, Africa, and southern Asia (Easterling et al. 2003; Peterson et al. 2002). A weeklong workshop was held in Maceió, 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. 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

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

Country	Stations	Start	End	Lat (°)	Lon (°)	Elev (m)
Argentina	Ceres	1959	2001	−29.88	−61.95	88
	Esquel	1959	2002	−42.93	−71.15	785
	Jujuy	1959	2001	−24.38	−65.08	905
	Laboulage	1959	2001	−34.13	−63.37	137
	Del Plata Mar	1962	2001	−37.93	−57.58	21
	Mendoza	1959	2002	−32.83	−68.78	704
	Monte Caseros	1959	2001	−30.27	−57.65	54
	Neuquen	1959	2002	−38.95	−68.13	271
	Posadas	1960	2001	−27.37	−55.97	125
	Rio Gallegos	1959	2001	−51.61	−69.28	19
	Salta	1968	2001	−24.85	−65.48	1221
	Santiago	1959	2001	−27.77	−64.30	199
	Trelew	1959	2002	−43.20	−65.27	43
Bolivia	Arani	1976	2001	−17.57	−65.77	2740
	Misicuni	1979	2001	−66.30	−17.01	3500
	Patacamaya	1957	2000	−17.20	−67.92	3789
	Santa Cruz	1971	2001	−17.78	−63.17	416
	Tiraque	1957	2001	−65.70	−17.40	3220
Brazil	Agua Funda	1950	2003	−23.39	−46.37	779
	Bage	1960	2000	−31.33	−54.11	214
	Belem	1951	2000	−1.30	−48.50	10
	Caetite	1954	1978	−42.52	−14.05	882
	Cambara	1957	2003	−23.00	−50.03	450
	Campinas	1896	2003	−22.54	−47.05	694
	Curitiba	1961	2003	−25.43	−49.28	910
	Goias	1961	1978	−50.13	−15.92	495
	Guiaba	1961	1978	−56.12	−15.55	178
	Julio de Castilhos	1956	1999	−29.23	−53.68	514
	Manaus	1954	1999	−3.10	−60.00	67
	Passo Fundo	1956	2000	−28.26	−52.41	687
	Pelotas	1950	2000	−31.75	−52.35	7
	Ponta Grossa	1954	2003	−25.37	−50.00	880
	Sao Borja	1956	2000	−28.66	−56.00	99
	Sao Paulo	1961	1978	−46.60	−23.50	762
	Soure	1951	2000	−1.00	−48.00	11
	TreaLagoas	1961	1978	−51.70	−20.78	313
	Veranopolis	1956	1999	−28.94	−51.55	705
Chile	Antofagosta	1961	2003	−23.60	−70.30	120
	Arica	1961	2003	−18.20	−70.20	55
	Conception	1950	2003	−36.46	−73.02	11
	Coyhaique	1961	2003	−45.40	−72.10	310
	La Serena	1950	2003	−29.90	−71.10	146
	Pta Arenas	1961	2000	−53.00	−70.50	16
	Puerto Montt	1970	2003	−41.43	−73.10	58
	Santiago	1950	2003	−33.45	−70.76	520
	Valdivia	1970	2003	−39.40	−73.10	19
Ecuador	Galapos	1965	2001	−89.50	−0.90	6
	Izobamba	1966	2002	−0.35	−78.55	3058
	Loja Argelia	1964	2000	−4.04	−79.20	2160
	Pichilingue	1965	2002	−1.11	−79.48	120
Paraguay	Asuncion	1960	1999	−25.25	−57.51	101
	Concepcion	1960	1999	−23.43	−57.43	70
	Encarnacion	1951	1999	−25.32	−55.87	85
	Mariscal	1950	1999	−22.02	−60.60	165
	Pto Casado	1947	1999	−22.28	−57.93	80
	Villarrica	1956	1999	−6.67	−57.12	110

TABLE 1. *(Continued)*

Country	Stations	Start	End	Lat (°)	Lon (°)	Elev (m)
Peru	Canete	1937	2003	−13.07	−76.32	158
	Huayao	1950	2003	−12.03	−75.30	3308
	Imata	1936	2003	−15.83	−71.08	4519
	Iquitos	1957	1995	−3.45	−73.15	125
	Pampa de Majes	1950	2003	−16.30	−72.20	1434
	San Camilo	1954	2003	−14.00	−75.75	398
	Spiura	1955	1996	−5.08	−80.62	49
	Weberbauer	1965	2003	−7.17	−78.50	2536
Uruguay	Mercedes	1956	2000	−33.25	−58.07	17
	Paysandu	1950	2000	−32.50	−58.03	61
	Prado	1921	2000	−34.85	−56.20	16
	Rocha	1961	2000	−34.48	−54.30	18

of climate change indices. 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 that were prepared during the workshop in Maceió. The data and methodologies are discussed in section 2 and the analysis of trends is presented in section 3. A summary and conclusion follow in section 4. Results for the precipitation extremes are also presented in a companion paper by Haylock et al. (2006).

2. Data and methodologies

Country representatives brought daily precipitation, and maximum and minimum temperature data for at least five stations along 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 Fig. 1: very few stations are available with long records in the Amazon region of Brazil.

a. 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°C at Ponta Grossa, Brazil, on 11 November 1963. The problems were rare and only a few bad values were identified in some stations. All erroneous values were set to missing.

Homogeneity assessment and adjustment can be quite complex (Aguilar et al. 2003; Vincent et al. 2002) and it often requires close neighbor stations, detailed station history (metadata), and a great amount of time. Therefore, the objective was to identify only the potential major problems. 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 step in the tested series.

Stations with potentially large problems were tabulated and metadata were examined when available. From the 68 stations, there were 19 stations with a potential step in annual maximum temperature and 22

FIG. 1. Location of the 68 temperature stations. The three stations with given names are mentioned in section 3.

stations with a potential step in annual minimum temperatures. Historical explanations for the cause of the step, such as station relocation, were found for only five stations. 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 m) and the instruments were relocated in 1969 by only a few meters but with a significant change of exposure. The identified inhomogeneities can affect the trends calculated in some temperature indices; however, removing all suspicious sites could have resulted in far fewer stations for the analyses of trends in South America. Therefore, the homogeneity results were used for explaining the trends that were in disagreement with their surrounding stations.

b. *Definition of the temperature indices*

A set of 11 temperature indices was selected for this study and their description are given in Table 2. They are analyzed 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 nighttime temperature. For example, the nighttime temperature over land has increased by about twice the rate of the daytime temperature during the past 50 yr (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 1961–90. They are defined for every day of the calendar year 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 5-day window centered on each calendar day over

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	No. 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	No. 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	No. 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 during the year	°C

TABLE 3. Average of the indices values over the 1961–90 period for five stations in South America. The warmest day (coldest night) represents the highest (lowest) value over 1961–90.

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

1961–90. Recently, it was found that the methodology used 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 1961–90. The five stations were selected to represent different climate regions in South America. The warmest day represents the highest temperature value over 1961–90 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 at the Climate Research Branch of the Meteorological Service of Canada. It computes the 27 temperature and precipitation indices recommended by the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI). The indices were calculated on a monthly and/or annual basis. Monthly indices were obtained if no more than 3 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 is available at the ETCCDMI Web site.

c. *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 nonnormality 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 et al. 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

a. *Annual analysis*

Table 4 summarizes the findings by presenting the number of stations with significant decreasing trends,

TABLE 4. Number of stations with significant negative, nonsignificant, and significant positive trends for the annual temperature indices over 1960–2000 (significant at the 5% level). The numbers in boldface indicate that more than 25% of the stations have significant trends.

Indicator name	Negative	Nonsignificant	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

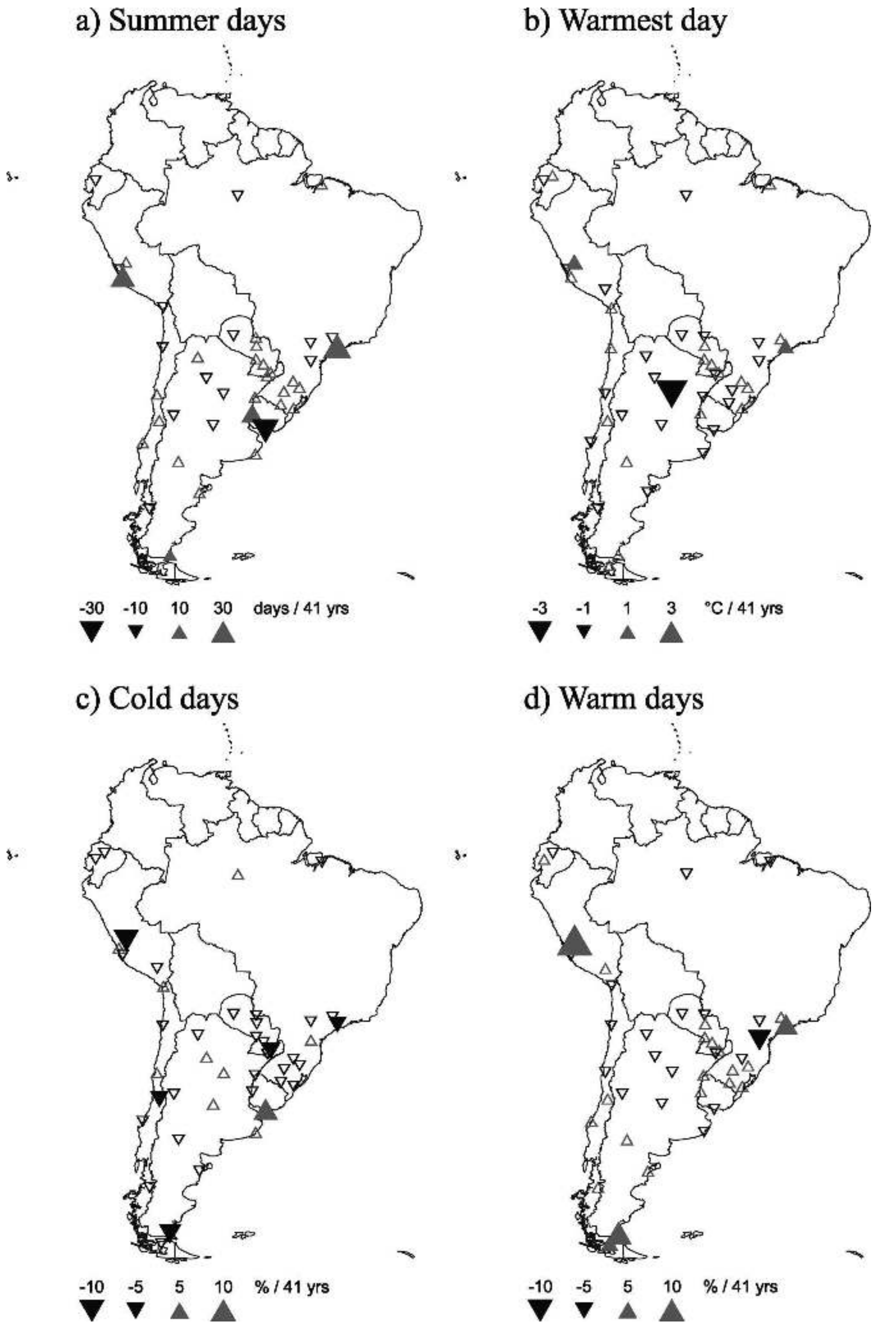


FIG. 2. Trends in four indices based on daily maximum temperature over 1960–2000. Upward (gray) and downward (black) pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the filled triangle is proportional to the magnitude of the trend: (a) summer days, (b) warmest day, (c) cold days, and (d) warm days.

no significant trends, and significant increasing trends for each temperature index. The results show that there are few 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 nonsignificant trends across the countries. It seems that some stations are in disagreement with their surroundings. For example, for Prado, Uruguay, significant decreasing and increasing trends are shown in the summer days

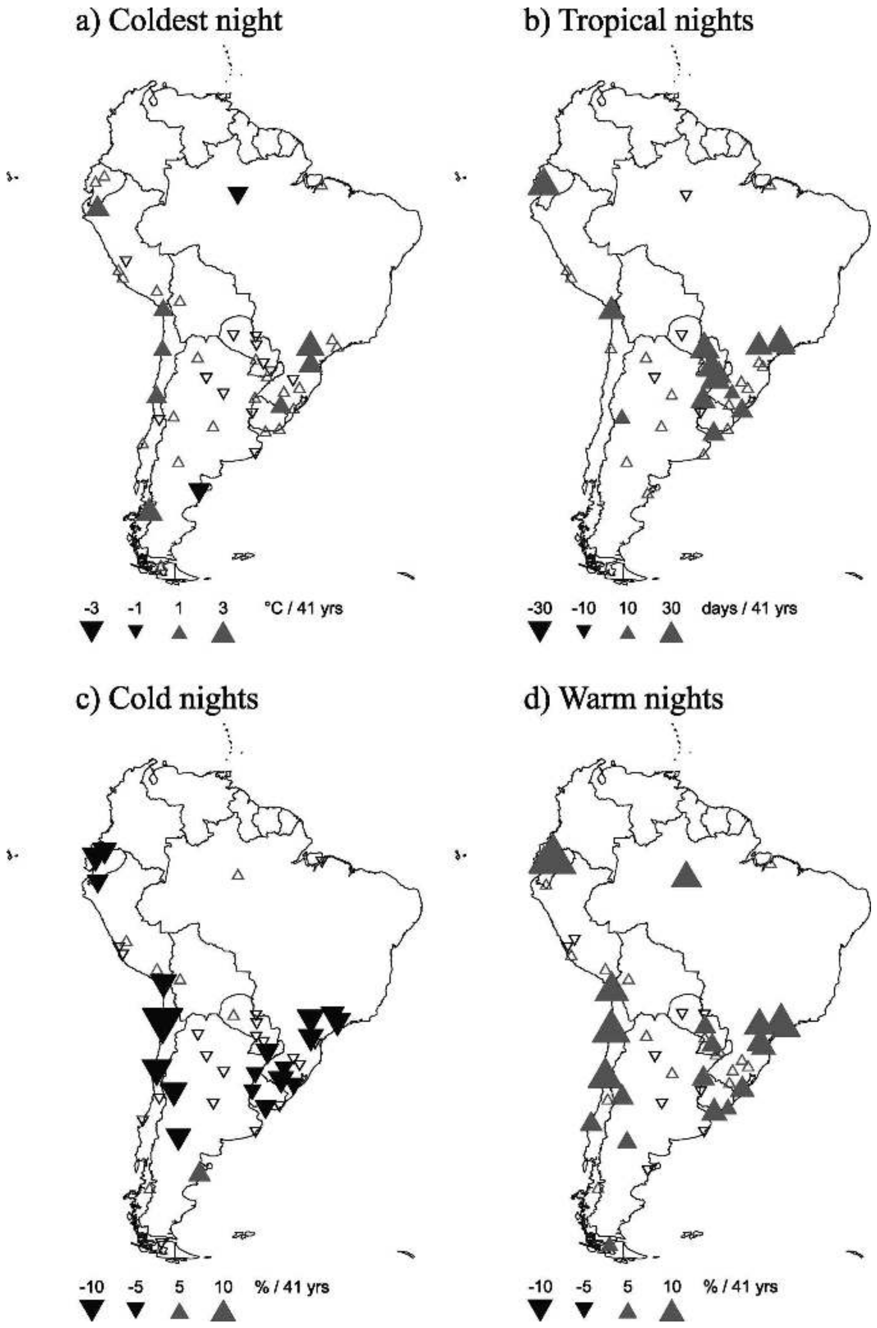


FIG. 3. Same as in Fig. 2 but for four indices based on daily minimum temperature: (a) coldest night, (b) tropical nights, (c) cold nights, and (d) warm nights.

and cold days, respectively. Homogeneity assessment indicated a potential step at this station in the annual maximum 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 northern 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 (Fig. 3). There are, as well, more tropical nights in

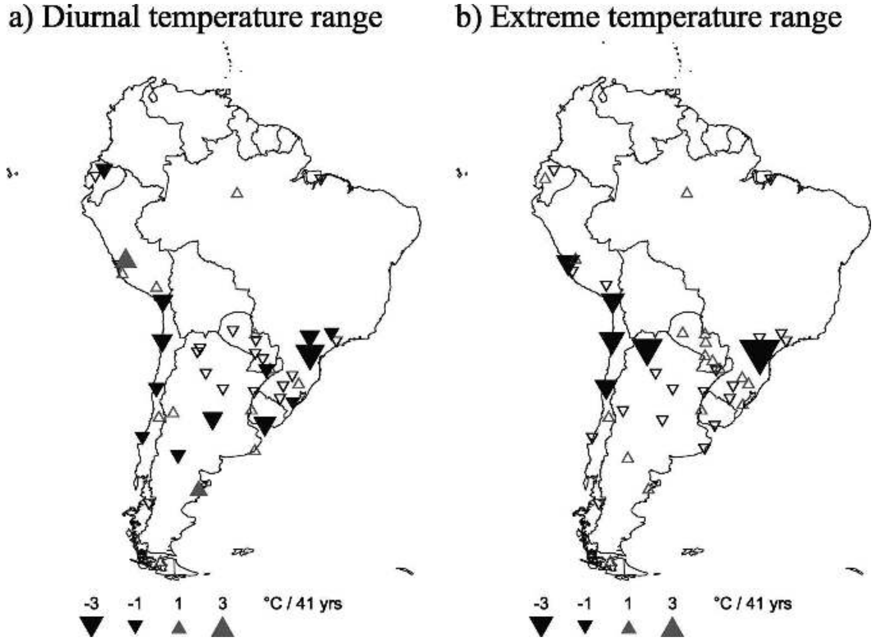
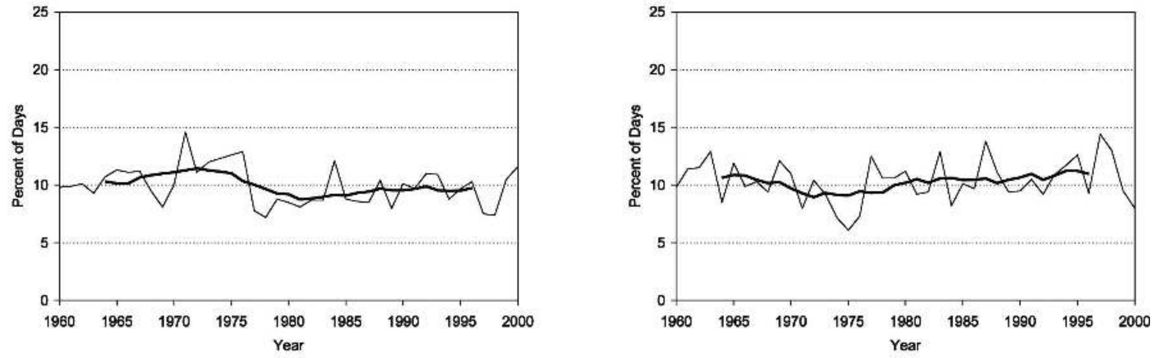


FIG. 4. Same as in Fig. 2 but for two indices based on both daily maximum and minimum temperature: (a) diurnal temperature range and (b) extreme temperature range.

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 the stations in the interior have smaller nonsignificant trends.

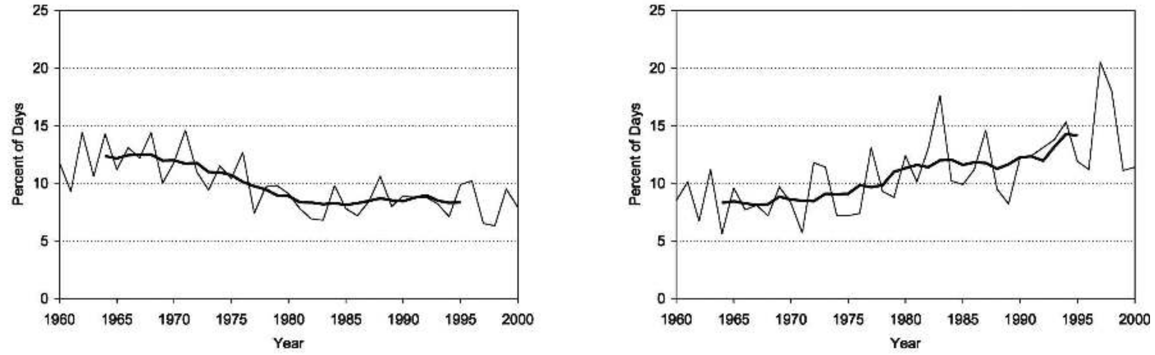
Several decreasing trends are observed in the indices based on both daily maximum and minimum temperatures (Fig. 4). The diurnal temperature range (mean of the difference between daily maximum and minimum) has decreased by 2°–3°C at many locations. However, there are fewer stations showing significant 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 values that have changed. These results also support the strong warming observed in the nighttime 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% 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 yr, respectively. It seems that the time series of the warm days and warm nights are influenced by the strong 1997–98 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.



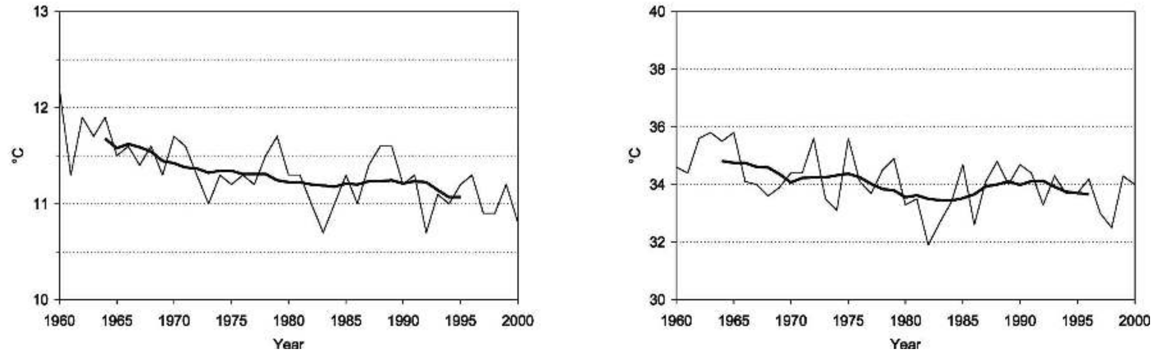
a) Cold days

b) Warm days



c) Cold nights

d) Warm nights



e) Diurnal temperature range

f) Extreme temperature range

FIG. 5. Regional time series for six temperature indices. The 9-yr running mean is given by the line in boldface: (a) cold days, (b) warm days, (c) cold nights, (d) warm nights, (e) diurnal temperature range, and (f) extreme temperature range.

b. 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–August), spring (September–November), summer (December–February), and fall (March–May). Table 5 provides the number of stations with significant negative, nonsignificant, 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 nighttime 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

TABLE 5. Number of stations with significant negative, nonsignificant, and significant positive trends for the seasonal temperature indices over 1960–2000 (significant at the 5% level). The numbers in boldface indicate that more than 25% of the stations have significant trends.

Indicator name	Season	Negative	Nonsignificant	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

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 indicates 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 southern 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 conclusions

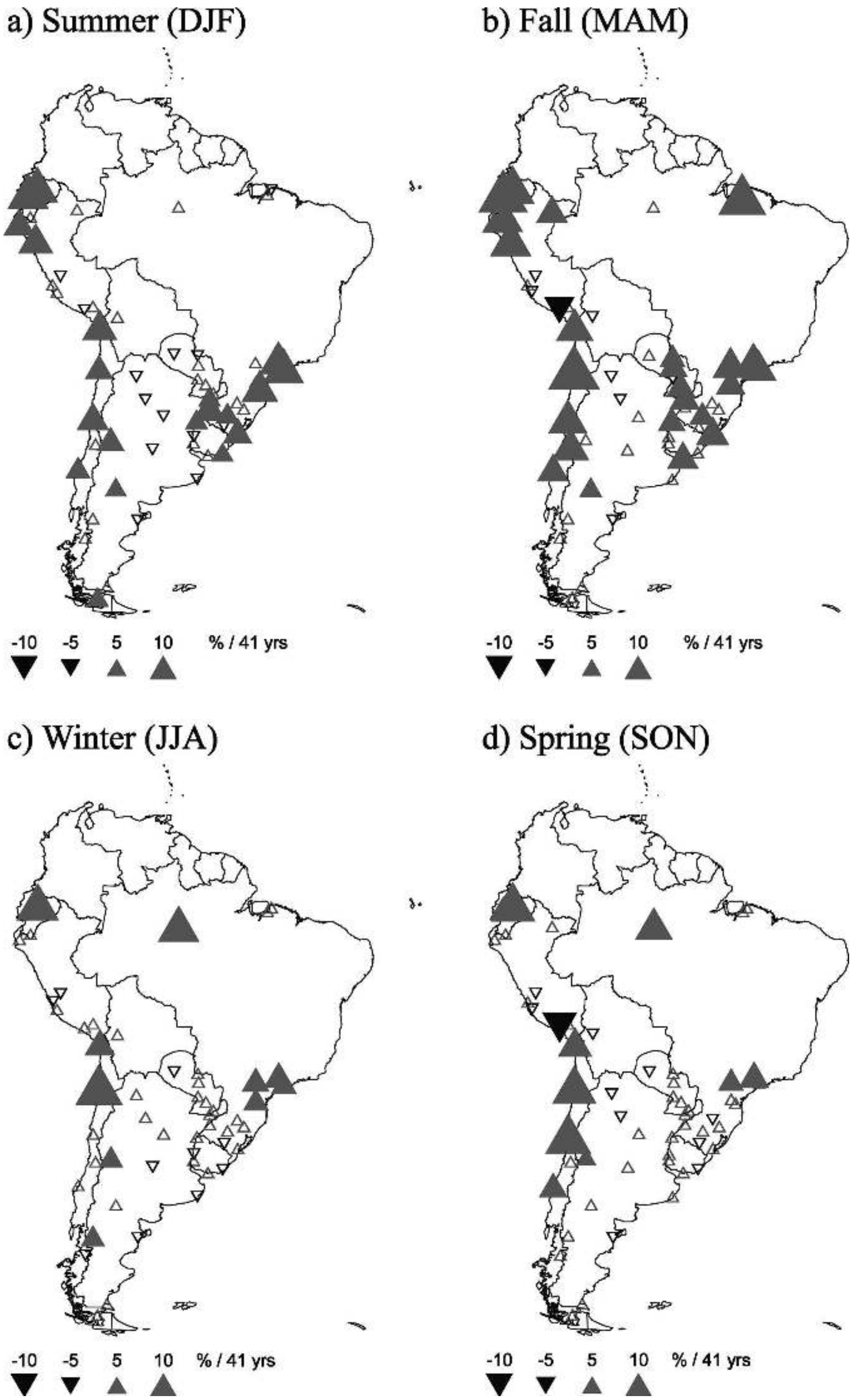
This study presents an examination of the trends in indices of daily temperature extremes for South America during 1960–2000. Data quality and homogeneity assessments are crucial before trends in climate indices are computed. Erroneous outlier values and artificial steps due to changes in instrument 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 results show that 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 and there are more tropical nights. The percentage of cold nights is decreasing while the percentage of warm nights is increasing, and these changes are more pronounced during the summer (DJF) and fall (MAM). The nighttime warming corresponds to a significant decrease 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 examine the relation between the circulation pattern and the land surface temperature and extremes over the entire South American landmass.

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 stations 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 has 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 nighttime 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 nighttime 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 Maceió, Brazil, has provided a great opportunity for establishing a strong sci-



a) Summer (DJF)

b) Fall (MAM)

c) Winter (JJA)

d) Spring (SON)

FIG. 6. Same as in Fig. 2 but for the seasonal warm nights: (a) summer, (b) fall, (c) winter, and (d) spring.

entific network in the region. The expertise of the participants allowed the production of reliable and valuable results for changes in climate extremes in a region where no such study had been 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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