

Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003

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[1] In November 2004, a regional climate change workshop was held in Guatemala with the goal of analyzing how climate extremes had changed in the region. Scientists from Central America and northern South America brought long-term daily temperature and precipitation time series from meteorological stations in their countries to the workshop. After undergoing careful quality control procedures and a homogeneity assessment, the data were used to calculate a suite of climate change indices over the 1961–2003 period. Analysis of these indices reveals a general warming trend in the region. The occurrence of extreme warm maximum and minimum temperatures has increased while extremely cold temperature events have decreased. Precipitation indices, despite the large and expected spatial variability, indicate that although no significant increases in the total amount are found, rainfall events are intensifying and the contribution of wet and very wet days are enlarging. Temperature and precipitation indices were correlated with northern and equatorial Atlantic and Pacific Ocean sea surface temperatures. However, those indices having the largest significant trends (percentage of warm days, precipitation intensity, and contribution from very wet days) have low correlations to El Niño–Southern Oscillation. Additionally, precipitation indices show a higher correlation with tropical Atlantic sea surface temperatures.

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1. Introduction

[2] During the last 3 decades, a great deal of work has been done analyzing changes in monthly total precipitation and monthly average maximum, minimum, and mean temperature for many areas of the globe using widely

available long-term monthly data [e.g., Peterson and Vose, 1997; Hansen et al., 2001; Jones and Moberg, 2003; Easterling et al., 1997; New et al., 2001]. However, changes in monthly values can only address a subset of climate change issues. Often changes in extremes can have more impacts than changes in mean values. Furthermore, changes

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Table 1. Stations List^a

Name	Latitude	Longitude	Elevation	WMO Number	First Year	Last Year	Use
PSWGIA01	17°32'	87°42'	5	78583	1961	2004	TP
SPANISHL	17°13'	87°01'	91		1968	2002	P
AEROPUERTO ELDORADO/BOGOTÁ	4°43'	74°09'	2547	80222	1972	2004	P
LAS GAVIOTAS	4°33'	70°56'	171	80241	1969	2004	P
AEROPUERTO ALFONSO BONILLA ARAGÓN/CALI	3°33'	76°23'	961	80259	1972	2004	P
AEROPUERTO ANTONIO NARIÑO/PASTO	1°24'	77°17'	1796	80342	1961	2004	P
AEROPUERTO VÁSQUEZ COBO/LETICIA	4°09'(S)	69°57'	84	80398	1969	2003	P
AEROPUERTO EL EDEN/ARMENIA	4°28'	75°46'	1204	80211	1961	2004	P
AEROPUERTO BENITO SALAS/NEIVA	2°58'	75°18'	439	80315	1970	2004	P
AEROPUERTO CAMILO DAZA/CÚCUTA	7°56'	72°31'	250	80097	1961	2004	TP
AEROPUERTO OLAYA HERRERA/MEDELLÍN	6°13'	75°35'	1490	80110	1969	2004	P
CATIE	9°54'	83°45'	0		1961	2004	TP
COTO47	8°03'	83°00'	0		1961	2004	P
FABIO BAUDRIT	10°00'	84°15'	0		1961	2002	TP
SAN JOSE	9°54'	84°06'	0		1961	1995	P
PUERTO LIMON	10°00'	83°03'	3	78767	1961	2004	P
CAMAGUEY, CAMAGUEY	21°24'	77°51'	122	78355	1961	2003	P
CASA BLANCA, LA HABANA	23°01'	82°21'	50	78325	1961	2003	P
LOS ANDES	13°53'	89°39'	1770	78652	1970	2001	TP
SAN MIGUEL/EL PAPALON	13°26'	88°09'	80	78670	1970	2000	TP
CAMANTULUL	14°02'	91°03'	280		1971	2003	P
ESQUIPULAS	14°32'	89°02'	950		1972	2003	P
LA FRAGUA	15°00'	89°03'	0		1972	2003	P
LABOR OVALLE	14°52'	91°31'	2380		1971	2003	TP
FLORES	16°31'	89°52'	123	78615	1974	2003	P
INSIVUMEH	14°35'	90°32'	1502	78640	1970	2003	TP
PUERTO BARRIOS	15°44'	88°35'	2	78637	1973	2003	P
HUEHUETENANGO	15°19'	91°03'	1870	78627	1970	2003	P
SAN JERONIMO	15°04'	90°15'	1000		1970	2003	P
MARALE	14°54'	87°01'	720		1971	2004	TP
VALLECILLO	14°31'	87°24'	107		1970	2004	P
CHOLUTECA	13°18'	87°11'	48	78724	1963	2004	P
TEGUCIGALPA	13°03'	87°13'	1007	78720	1961	2004	TP
LA CEIBA (AIRPORT)	15°44'	86°52'	26	78705	1965	2004	TP
TELA	15°43'	87°29'	3	78706	1961	2002	TP
LA MESA (SAN PEDRO SULA)	15°27'	87°56'	31	78708	1961	2004	TP
CATACAMAS	14°54'	85°56'	442	78714	1961	2004	TP
SANTA ROSA DE COPAN	14°47'	88°47'	1079	78717	1961	2004	TP
LA PAZ, LA PAZ	24°08'	110°02'	16		1961	2002	TP
CANDELARIA, CARMEN (SMN)	18°11'	91°03'	25		1961	2001	P
ESCARCEGA, ESCARCEGA SMN	18°37'	90°45'	85		1961	2001	P
CALLEJONES, TECOMAN	18°05'	103°04'	24		1961	2002	TP
ALTAMIRANO, ALTAMIRANO	16°42'	92°02'	1240		1961	2000	P
BOCHIL, BOCHIL	16°59'	92°53'	1200		1961	2003	P
EL BOQUERON, SUCHIAPA	16°38'	93°09'	480		1961	2001	TP
LAS FLORES, JIQUIPILAS	16°41'	93°33'	480		1961	2002	TP
OCUZOCUAUTLA	16°45'	93°22'	838		1961	2003	P
PUENTE COLGANTE	16°43'	93°03'	418		1961	2002	TP
TUXTLA GUTIERREZ (DGE)	16°45'	93°07'	530		1961	2003	TP
LA UNION, LA UNION	17°54'	101°47'	190		1961	2003	P
IGUALA, IGUALA (DGE)	18°25'	99°31'	751		1961	2003	TP
EJUTLA, EJUTLA	19°58'	104°02'	1120		1961	2003	P
PRESA DANXHO, JILOTEPEC	19°53'	99°12'	2435		1961	2000	P
CUITZEO, CUITZEO	19°58'	101°19'	1831		1961	2003	P
CHAPARACO, ZAMORA	19°57'	102°15'	1633	76577	1961	2002	P
HUINGO, ZINAPECUARO	19°55'	100°05'	1832		1961	2002	TP
PRESA GUARACHA, VILLAMAR	19°57'	102°34'	1570		1961	1999	TP
ATLATLAHUACAN, ATLATLAH.	18°56'	98°54'	1656	76405	1961	2001	TP
CUAUTLA, CUAUTLA (SMN)	18°49'	98°58'	1303		1961	2002	P
BOQUILLA NUN.I.NEJAPA DE	16°39'	95°56'	620		1961	2002	TP
CHICAPA, JUCHITAN DE Z.	16°35'	94°49'	30		1961	2002	TP
JUCHITAN DE ZARAGOZA,	16°26'	95°02'	46		1961	2002	TP
BENITO JUAREZ, CENTLA	18°28'	92°43'	18		1961	2002	TP
BOCA DEL CERRO (DGE)	17°26'	91°31'	100		1961	2000	P
MACUSPANA,MACUSPANA (DGE)	17°46'	92°35'	68		1961	2000	TP
PUEBLO NUEVO, CENTRO	17°05'	92°54'	60		1961	2000	TP
SAMARIA, CUNDUACAN	18°01'	93°16'	72		1961	2000	TP
TLAXCO, TLAXCO	19°38'	98°08'	2240	76833	1961	2002	P
ACTOPAN, ACTOPAN	19°29'	96°35'	311		1961	2002	TP
ATZALAN, ATZALAN	19°48'	97°13'	1842		1961	2001	TP
CD. ALEMAN, COSAMALOAPAN	18°11'	96°05'	29		1961	2002	P
COSCOMATEPEC BRAVO (SMN)	19°04'	97°02'	1588		1961	2002	P
CUATOTOLAPAN	18°08'	95°18'	14		1961	2002	P

Table 1. (continued)

Name	Latitude	Longitude	Elevation	WMO Number	First Year	Last Year	Use
HUATUSCO DE CHICUELLAR	19°09'	96°57'	1344		1961	2001	P
LOMA FINA,PASO DE OVEJAS	19°01'	96°18'	30		1961	2002	TP
RINCONADA, EMILIANO Z.	19°21'	96°33'	313		1961	2002	P
TEOCELO, TEOCELO	19°23'	96°58'	1218		1961	2002	TP
JOSE CARDEL, LA ANTIGUA	19°23'	96°23'	29		1961	2002	TP
LAS VIGAS, LAS VIGAS	19°39'	97°06'	2400		1961	2002	P
PICACHO (CHINANDEGA)	12°38'	87°08'	60	78739	1966	2004	P
MANAGUA A. C. SANDINO	12°08'	86°09'	56	78741	1961	2000	P
NANDAIME	11°43'	86°02'	95	78731	1961	2003	P
MASATEPE	11°54'	86°08'	450	78732	1963	2001	P
RIVAS	11°25'	85°05'	70	78733	1968	2003	TP
OCOTAL	13°22'	86°17'	612	78740	1961	2003	P
CONDEGA	13°12'	86°32'	560	78729	1961	2003	P
MUYMUY	12°28'	86°23'	320	78743	1970	2003	P
JUIGALPA	12°04'	86°19'	90	78735	1961	2003	P
JINOTEGA	13°03'	85°35'	1032	78734	1961	2004	P
BALBOA HEIGHTS	8°57'	79°33'	0		1961	2003	P
ANTON	8°21'	80°16'	33		1970	2004	TP
SANTA FE	8°03'	81°05'	0		1961	2004	P
TOCUMEN	9°03'	79°22'	14		1970	2004	P
EL COPE	8°42'	80°03'	0		1969	2002	P
DAVID	8°24'	82°25'	27		1968	2004	TP
BOCAS DEL TORO	9°02'	82°15'	2		1972	2004	P
CARACAS/MAIQUETIA Apt. BOLIVAR	10°36'	66°59'	48	80415	1961	2000	TP
SANTA ELENA DE UAIREN	4°36'	61°07'	907	80462	1961	2000	P
TUMEREMO	7°18'	61°27'	181	80453	1961	2000	TP
SAN FERNANDO DE APURE	7°54'	67°25'	48	80450	1961	2000	TP
MERIDA	8°36'	71°11'	1498	80438	1961	2000	TP
MENE GRANDE	9°49'	70°56'	28	80425	1961	2000	TP
CARACAS/LA CARLOTA	10°03'	66°53'	835	80416	1964	2000	TP
MARACAY - B.A. SUCRE	10°15'	67°39'	437	80413	1961	2000	TP
GUIRIA	10°35'	62°19'	14	80423	1961	2000	TP

^aLatitude and longitude are in degrees and minutes (north and west, except for where "(S)" indicates south); altitude is in meters; column USE indicates whether the station is employed for temperature and precipitation (TP) or precipitation only (P).

in extremes can be strong indicators of climate change as it has been hypothesized that in a warming world where the atmosphere can hold more water vapor, the hydrological cycle could become more active [Folland *et al.*, 2001].

[3] Unfortunately, the data necessary to analyze changes in extremes, namely long-term daily data, are not widely exchanged. A "global" analysis of changing extremes published in 2002 used no data from Central or South America and little data from Africa and southern Asia [Frich *et al.*, 2002]. To remedy this shortcoming in climate change knowledge the joint World Meteorological Organization Commission of Climatology (CCI) and the Climate Variability and Predictability (CLIVAR) Expert Team (ET) on Climate Change Detection Monitoring and Indices (ETCCDMI, <http://cccma.seos.uvic.ca/ETCCDMI>) has been coordinating a series of regional climate change workshops in underanalyzed regions modeled after the Asian-Pacific Network workshop [Manton *et al.*, 2001; Zwiers *et al.*, 2003; Expert Team for Climate Change Detection Monitoring and Indices, 2003]. At these workshops, participants analyze the daily data they brought with them to assess the data's quality and homogeneity and calculate a suite of climate change indices that primarily evaluate extremes. The regions covered by these workshops include the Caribbean, parts of Africa, the Middle East, south and central Asia, and the southern 7/8 of South America [Peterson *et al.*, 2002; Easterling *et al.*, 2003; Vincent *et al.*, 2005; Haylock *et al.*, 2005; S. Sensoy *et al.*, Workshop on enhancing Middle East climate change monitoring and

indices, submitted to *Bulletin of the American Meteorological Society*, 2005].

[4] This paper is a result of the workshop for Central and northern South America, a region where changes in extremes have not yet been assessed and one where sharing of long-term daily data outside the region is very limited. The workshop was funded by the U.S. State Department through the Global Climate Observing System (GCOS) and cohosted in Guatemala by the Costa Rican-based Comité Regional de Recursos Hidráulicos de Centro America (CRRH) and the Guatemalan Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología (INSIVUMEH). It took place in the second week of November of 2004. The workshop was organized following the established ETCCDMI model of a combination of seminars and hands-on data analysis. Experts from the U.K., Costa Rica and Spain joined participants from Mexico, Belize, Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, Panama, Cuba and Venezuela. Additional data for Colombia were provided after the workshop as the invited Colombian participants were unable to attend the workshop.

2. Data

[5] All participants were asked to bring daily temperature and precipitation time series representing the different climatic zones of their respective countries. The meeting preparation required a great effort by the participants. Many of them engaged in data digitization to produce a sufficient number of long-term data to be analyzed. The preexistent

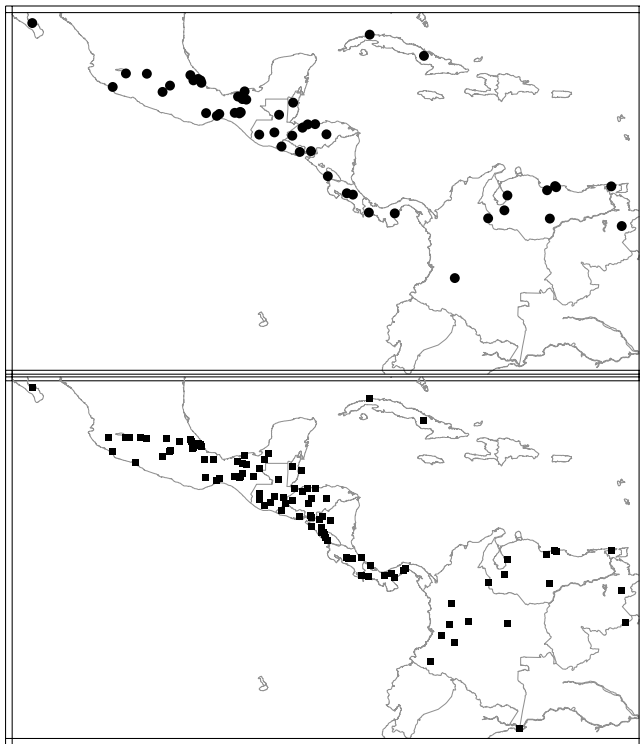


Figure 1. Location of the stations selected for indices calculation. (top) Temperature (circles) and (bottom) precipitation (squares).

spirit of cooperation between the different countries of the region, among other benefits, helped foster the interest for daily data archaeology and analysis of climate variability and change. The participants agreed on the need for further cooperation to establish a quality controlled and homogeneous data set.

[6] The network gathered in Guatemala included 200 stations. Although a few of them had observations back to the first third of the 20th century, most of the digital records began in the late 1950s or in the 1960s. For this reason, this paper focuses on the 1961–2003 period. Not all the stations had adequate quality, homogeneity or period of record. The analysis requires time series to have 80% or more of the data for the period 1971–2000. A list of the stations, the variables used, and their period of records are given in Table 1 and their locations are plotted in Figure 1. There are 105 precipitation stations and 48 temperature stations that met the data quality and completeness criteria. Figure 2 shows how the available data vary over time.

2.1. Quality Control

[7] About a half of the initial stations underwent preliminary quality control (QC) and homogeneity checks by the participants during the 5-day workshop. At the first stage, obviously wrong temperature and precipitation data, such as negative precipitation or $T_{\max} < T_{\min}$, were removed. For the second stage of QC, temperature outliers were identified using standard deviation thresholds. The variance of a station time series was calculated for each calendar day using the surrounding 5 days. All outliers greater than 4σ from the mean were evaluated, repeating the procedure a second time with a 3.5σ limit provided for a finer quality control of the data. In addition to these numerical checks, visual checks of data plots were made for both temperature and precipitation. Time series of daily T_{\max} , T_{\min} , diurnal temperature range (DTR which is simply T_{\max} minus T_{\min}), and precipitation were plotted. Examination of these plots revealed outliers as well as a variety of problems that cause changes in the seasonal cycle or variance of the data. Also, histograms of the data were created which revealed problems that show up when looking at the data set as a whole. The quality control software, indeed all the workshop software for QC, homogeneity testing and calculating indi-

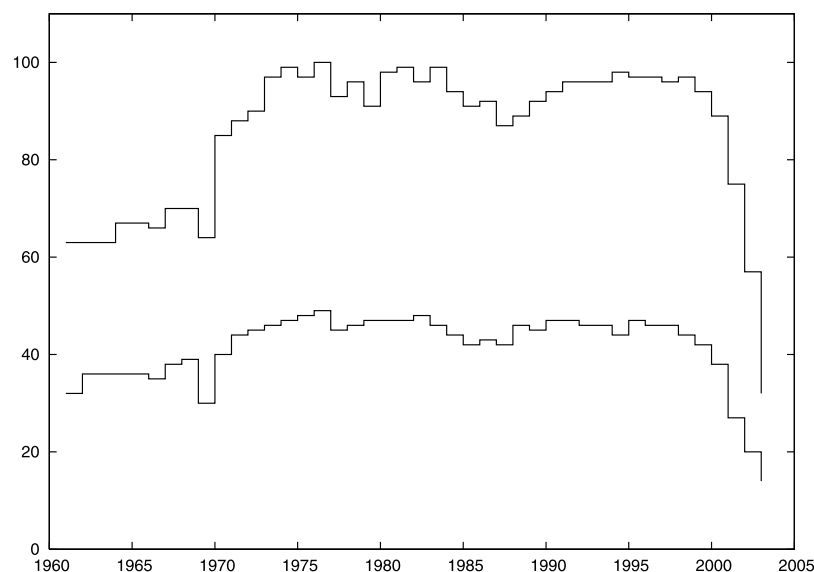


Figure 2. Number of stations per year for PRCPTOT (top line) and TX90p (bottom line). Stations considered for calculation had at least 80% of the data available for the reference period (1971–2000) and passed quality control procedures and homogeneity assessment. Annual values were calculated if no more than 15 days were missing in a year.

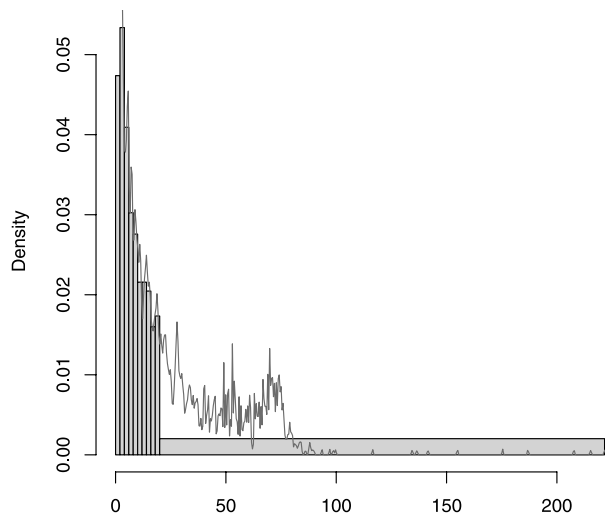


Figure 3. Example of precipitation successful quality control procedures using R-Climdex. Histogram (vertical bars) and Kernel-filtered density (line), showing an unexpected high density around 70–80 mm. It was found that relative humidity was erroneously digitized instead of rainfall values. The participants were able to replace the wrong data by the correct observations immediately.

ces, was written by Xuebin Zhang (Environment Canada) using the R statistical package (<http://www.r-project.org>) and is available from <http://cccma.seos.uvic.ca/ETCCDMI/>.

[8] Figure 3 is an example of one of the plots used to QC precipitation data. It explains the data density in two different ways: a histogram (bars) and a Kernel-filtered

estimate (line) which is a nonparametric approach to density fitting (see *Silverman* [1986] for further details). Both show an unexpected high density around 70–80 mm. Investigating this problem in the data revealed that 1 year had relative humidity erroneously digitized instead of rainfall values. The participants from that country were able to quickly replace the erroneous data with correct observations. Histograms of the 12 monthly distributions of maximum daily temperatures and minimum daily temperatures were also evaluated. Figure 4 shows a histogram of July minimum temperature for a rejected station. The bimodal distribution shown was due to the repetition in 1971 of maximum temperatures in the minimum temperature column.

[9] Outliers that were identified by either the statistical tests or examination of plots were evaluated by comparing their values to adjacent days, to the same day at nearby stations and, most importantly, to the knowledge of local experts, before being validated, edited or removed. In many cases, the location of a typing mismatch or a gap in the data led to an immediate query of the relevant archive and resulted in the addition of new information. The temperature QC procedure led also to the rejection of some stations which showed an excessive number of problems and to the identification of problems that were left unsolved, as they were believed not to affect the indices calculations. An example of a data problem that would be unlikely to adversely impact the indices would be rounding of temperature observations to the nearest half of a °C.

[10] Some other stations that were provided in Guatemala, but were not able to be analyzed at the meeting, were included in the analysis. After the workshop, all the time series went through a second quality control procedure that was more time consuming than the short workshop would

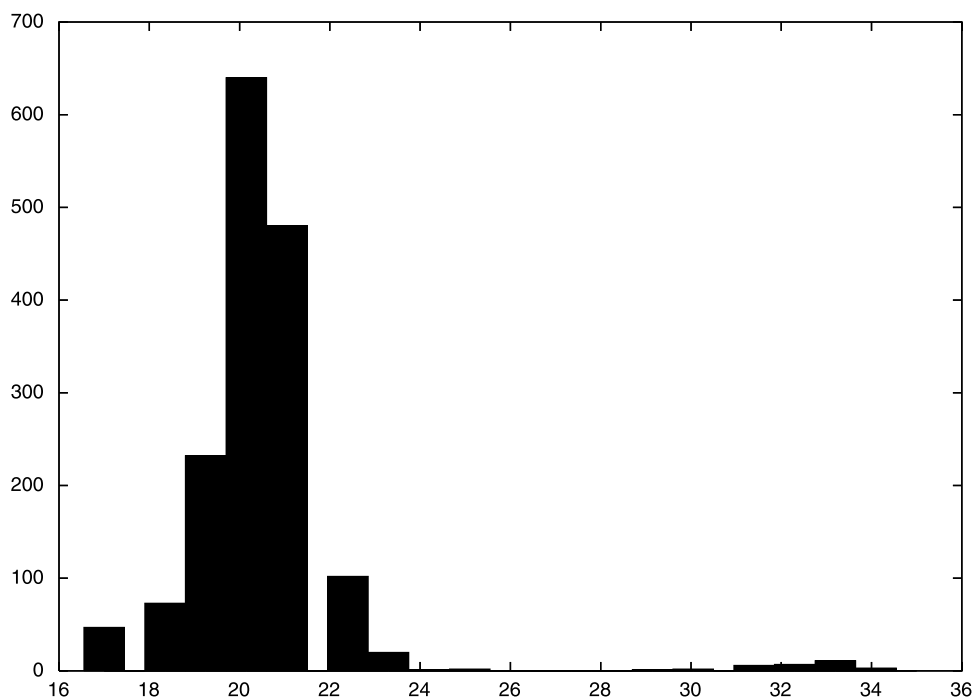


Figure 4. Histogram of July daily minimum temperature for a rejected station. The bimodal distribution shown (observations between 30° and 34°C) was due to the repetition in 1971 of maximum temperatures in the minimum temperature column.

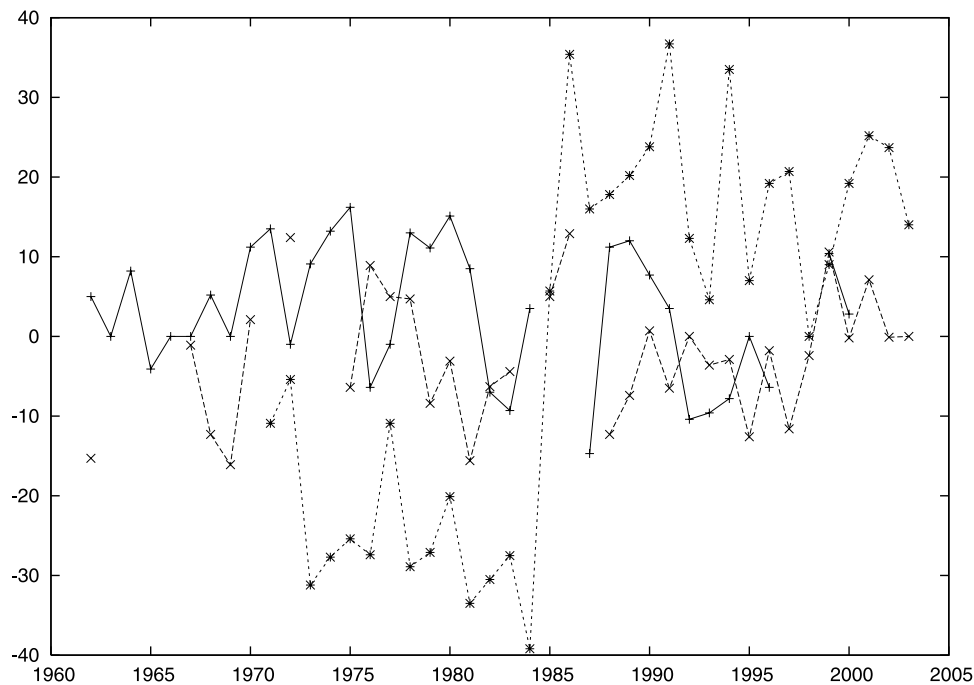


Figure 5. Example of homogenization procedures. Time series represent difference of the median value of a particular time series to a rough regional estimate, created by selecting for each year the median value among all the available stations. Solid line and dashed line with crosses represent homogeneous stations. Dashed line with asterisks represents an station with an inhomogeneity around 1985 and was rejected.

permit. In the case of precipitation all the observations above 200 mm were checked to insure that the adjacent values were not set to missing (i.e., to make sure that high values were not due to accumulation over several days). Also, suspiciously long spells of “0” values were evaluated. This procedure allowed for the detection of a few time series where monthly accumulations values were included in the daily time series. Subsequently, histograms of the annual statistical distribution of precipitation were drawn and the most extreme values for each station were checked against nearby locations. When this procedure would not lead into the validation of the event, different data sets were used, such as the hurricane tracks archives available from the National Climatic Data Center (<http://www.ncdc.noaa.gov>), the National Hurricanes Center (<http://www.nhc.noaa.gov/>) and the Desinventar (<http://www.desinventar.org/desinventar.html>) database, which collects information for different categories of catastrophic events in Central America and South America. Only those extreme temperature and precipitation observations that were positively identified as wrong were removed from the time series.

2.2. Homogeneity Checks

[11] Several different methods were employed to evaluate the homogeneity of the station time series. At the workshop, a two-phase regression based test [Wang, 2003] was employed. Metadata brought by the participants were also used in the identification and removal of different inhomogeneous stations. After the workshop, plots of mean values and indices of extremes were visually assessed for discontinuities in the time series at every station. To facilitate additional comparisons, approximate regional time series

of indices were created by calculating for each year, the median value of all available stations. Then the difference between this rough regional estimate and the single stations were plotted against time as in Figure 5. Again, identified inhomogeneities would lead to the rejection of that particular station.

3. Methods

3.1. Indices

[12] ETCCDMI has been coordinating a suite of 27 indices. Providing the exact formula and indeed software to calculate these indices allows regional analyses to fit seamlessly into a global whole. For percentile indices (e.g., the number of days exceeding the 90th percentile of minimum temperature) the methodology uses bootstrapping for calculating the base period values so there is no discontinuity in the indices time series at the beginning or end of the base period [Zhang *et al.*, 2005]. As some of the indices, such as the number of days below freezing, were not relevant to this region, a subset of 11 temperature and 10 precipitation indices were calculated for each of the stations that passed quality control and homogeneity testing. Table 2 provides a description of these indices. The selected base period for the percentile indices was 1971–2000, which maximized the number of stations meeting the strict data availability requirements.

[13] All of the indices were annual and some could also be calculated on seasonal or monthly bases. Although seasons lose a great part of their meaning in the tropical latitudes, boreal winter/spring and summer/fall were found to represent the mostly prevalent dry and wet seasons. For this reason

Table 2. Rainfall and Temperature Indices With Their Definitions and Units^a

ID	Indicator Name	Definitions	Units
<i>TXx</i>	max Tmax	annual maximum value of daily maximum temp	°C
<i>TNx</i>	max Tmin	annual maximum value of daily minimum temp	°C
<i>TXn</i>	min Tmax	annual minimum value of daily maximum temp	°C
<i>TNn</i>	min Tmin	annual minimum value of daily minimum temp	°C
<i>TN10p</i>	cool nights	percentage of days when TN < 10th percentile	% days
<i>TX10p</i>	cool days	percentage of days when TX < 10th percentile	% days
<i>TN90p</i>	warm nights	percentage of days when TN > 90th percentile	% days
<i>TX90p</i>	warm days	percentage of days when TX > 90th percentile	% days
WSDI	warm spell duration indicator	annual count of days with at least 6 consecutive days when TX > 90th percentile	% days
CSDI	cold spell duration indicator	annual count of days with at least 6 consecutive days when TN < 10th percentile	% days
<i>DTR</i>	diurnal temperature range	annual mean difference between TX and TN	°C
<i>RX1day</i>	max 1-day precipitation amount	annual maximum 1-day precipitation	mm
<i>RX5day</i>	max 5-day precipitation amount	annual maximum consecutive 5-day precipitation	mm
SDII	simple daily intensity index	annual total precipitation divided by the number of wet days (defined as precipitation ≥ 1.0 mm) in the year	mm/day
R10mm	number of heavy precipitation days	annual count of days when precipitation ≥ 10 mm	days
R20mm	number of very heavy precipitation days	annual count of days when precipitation ≥ 20 mm	days
CDD	consecutive dry days	maximum number of consecutive days with daily rainfall < 1mm	days
CWD	consecutive wet days	maximum number of consecutive days with daily rainfall ≥ 1 mm	days
R95p	very wet days	annual total PRCP when RR > 95th percentile	mm
R99p	extremely wet days	annual total PRCP when RR > 99th percentile	mm
PRCPTOT	annual total wet-day precipitation	annual total PRCP in wet days (RR ≥ 1 mm)	mm

^aTX is maximum daily temperature; TN is minimum daily temperature. Annual values are calculated from January to December. Indices in italic have been also calculated for standard seasons.

and for comparability to other existent and forthcoming studies, the standard 3-month seasons were also calculated for several indices.

3.2. Area Averaging

[14] Despite of the lack of data in the Yucatan Peninsula and a larger coverage in the Pacific side of the Isthmus, the stations are found to be reasonably well distributed across the area of study. For this reason, regional time series for 1961–2003 were created by averaging anomalies to the 1971–2000 base period by giving all the stations equal weight. Regional time series for precipitation indices were calculated twice: first, using simple anomalies and also dividing a station's index by its standard deviation during the reference period. This was made to insure that those stations with very high precipitation do not dominate in the time series. As the aspect and the trends in both cases lead to the same conclusions, the standardized series were discarded and the results of the more informative absolute anomalies are shown.

[15] Another concern in calculating the aggregate time series was the possible existence of large subregional asymmetries. This was evaluated for every index by comparing time series from different subregions. As the example in Figure 6 shows, the different regions have similar highly correlated behavior, so a single regional time series for each index was deemed appropriate to calculate and analyze. To explore spatial coherence of the trends calculated over the time series, a station by station analysis was made and mapped. Trends were calculated using the approach by Sen [1968], modified by Wang and Swail [2001] to account for time series autocorrelation. This approach, which is resistant to extreme values, results in robust significant trends.

3.3. Comparisons to SSTs

[16] Sea surface temperatures (SST) were compared to the regional time series of several indices by calculating the correlation between the index time series and the SST time

series at each grid box in the global ocean. The SST data set employed for the analysis, the Extended Reconstructed SST [Smith and Reynolds, 2003, 2004] which has a resolution of 2° latitude \times 2° longitude. The correlation index used was Kendall's Tau, a nonparametric approach employed in similar works [Haylock et al., 2005; Vincent et al., 2005] that meets the requirements of the generally non-Gaussian distributed indices and is less sensitive to the presence of outlying values.

4. Results

[17] The analysis of temperature and precipitation reveals a variety of changes in extreme values during the last 40 years in Central America and northern South America. Although this is true for both climate elements, changes in temperature have a much higher degree of spatial coherence. This comes as no surprise since precipitation in the region has more variability than temperature.

4.1. Temperature

[18] The analysis of the annual regional time series of the temperature indices indicates that changes in temperature extremes over the 1961–2003 reflect warming for the region as a whole. The regional temperature trends given in Table 3 have, in general, large spatial coherence. Regional series of indices based on percentile and station by station trends are shown in Figures 7 and 8.

[19] The annual percentage of warm days and nights, analyzed through the TX90p and TN90p indices, has significantly increased by 2.5% per decade and 1.7% per decade respectively. Conversely, the number of cold nights and days, analyzed through TX10p and TN10p, has decreased at a rate -2.2% per decade and -2.4% per decade. The trends for these indices have the same sign for each of the seasons but the magnitude of the changes is greater during JJA and SON than during the dry season of DJF and MAM. Spatial coherence is large for these four percentile-based indices, as can be seen in Figure 8. Also revealed by

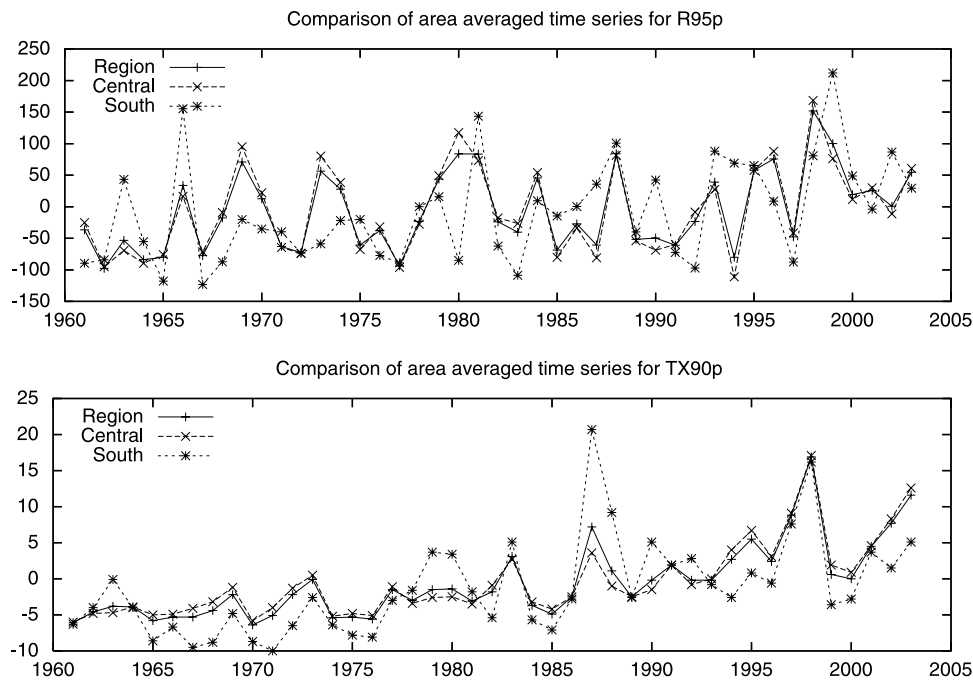


Figure 6. Comparison between regional (Region) and subregional (Central for stations in Central America and South for stations in northern South America) averaged time series for (top) R95p and (bottom) TX90p. The plots show a good correlation, although South series are impacted by larger interannual variability, as fewer stations configure them.

Figure 8 is the similarity between trends calculated for 1961–2003 and 1971–2003.

[20] Indices looking at the largest and lowest value of maximum and minimum temperatures have spatial cohesion similar to the indices plotted in Figure 8. The temperature extremes are increasing at significant rates of 0.2°C/decade to 0.3°C/decade. The higher values correspond to daily maximum temperature extremes (see Table 3). As suggested by the indices discussed so far, larger warming is found in measures of daily maximum temperatures. This results in a significant increase of regional DTR of around 0.1°C/decade, both for the annual and the seasonal scales. It needs to be mentioned, though, that the spatial coherence of the station trends is much lower for DTR. The final temperature indices evaluated are the number of days in cold and warm spells which are defined as at least 6 days in a row of temperatures exceeding the 90th or 10th percentile. The regional average of cold spell duration shows a significant decrease of –2.2 days/decade. It is noticeable that almost all of this trend is caused by changes occurring before 1980. A similar pattern is found for the duration of warm spells, although high values for the 1960s prevent the trend from achieving significance for 1961–2003.

4.2. Precipitation

[21] Regional time series of several precipitation indices can be seen in Figure 9 and the spatial distribution of station trends in Figure 10. Although most stations show nonsignificant trends for the different indices, due to the relatively short period of data and the large year to year variations in precipitation, the aggregated time series are able to highlight several features that well represent the hydroclimatological changes in the region (see Table 3).

[22] Regionally averaged total annual precipitation does not have a significant trend (Table 3 and Figure 9). Even though the number of stations with positive trends is larger, a considerable number of negative slopes are found, clustered around the northernmost stations in Mexico and around those located in the southwestern side of the Central

Table 3. Trend Analysis for 1961–2003 for Regional Time Series of Anomalies (Base Period 1971–2000) Indices^a

Index	Units	Trend, units/decade
<i>Temperature</i>		
TX90p	% of days	2.5
TN90p	% of days	1.7
TX10p	% of days	-2.2
TN10p	% of days	-2.4
DTR	°C	0.1
TXx	°C	0.3
TXn	°C	0.3
TNx	°C	0.2
TNn	°C	0.3
CSDI	number of days	-2.2
WSDI	number of days	0.6
<i>Precipitation</i>		
PRCPTOT	millimeters	8.7
SDII	millimeters	0.3
R95p	millimeters	18.1
R99p	millimeters	10.3
RX1day	millimeters	2.6
RX5day	millimeters	3.5
R10mm	number of days	-0.1
R20mm	number of days	0.1
CDD	number of days	0.4
CWD	number of days	-0.1

^aTrends in bold reached the 5% significance level.

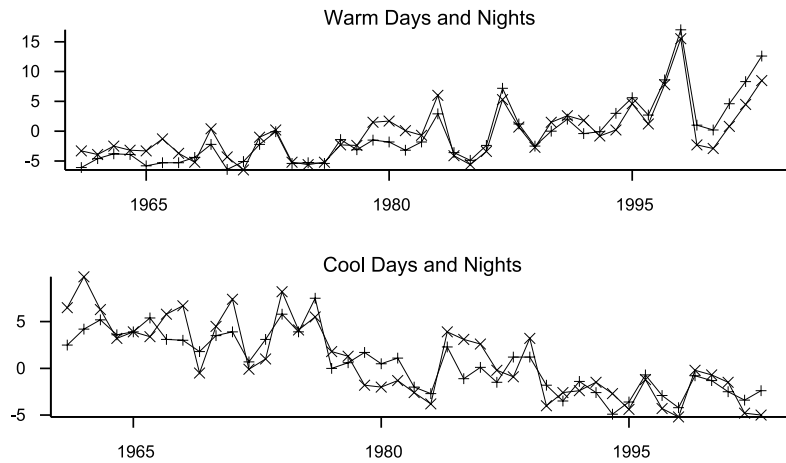


Figure 7. (top) Regional annual anomalies (% of days) to 1971–2000 for TX90p (pluses) and TN90p (crosses). (bottom) Regional annual anomalies (% of days) to 1971–2000 for TX10p (pluses) and TN10p (crosses).

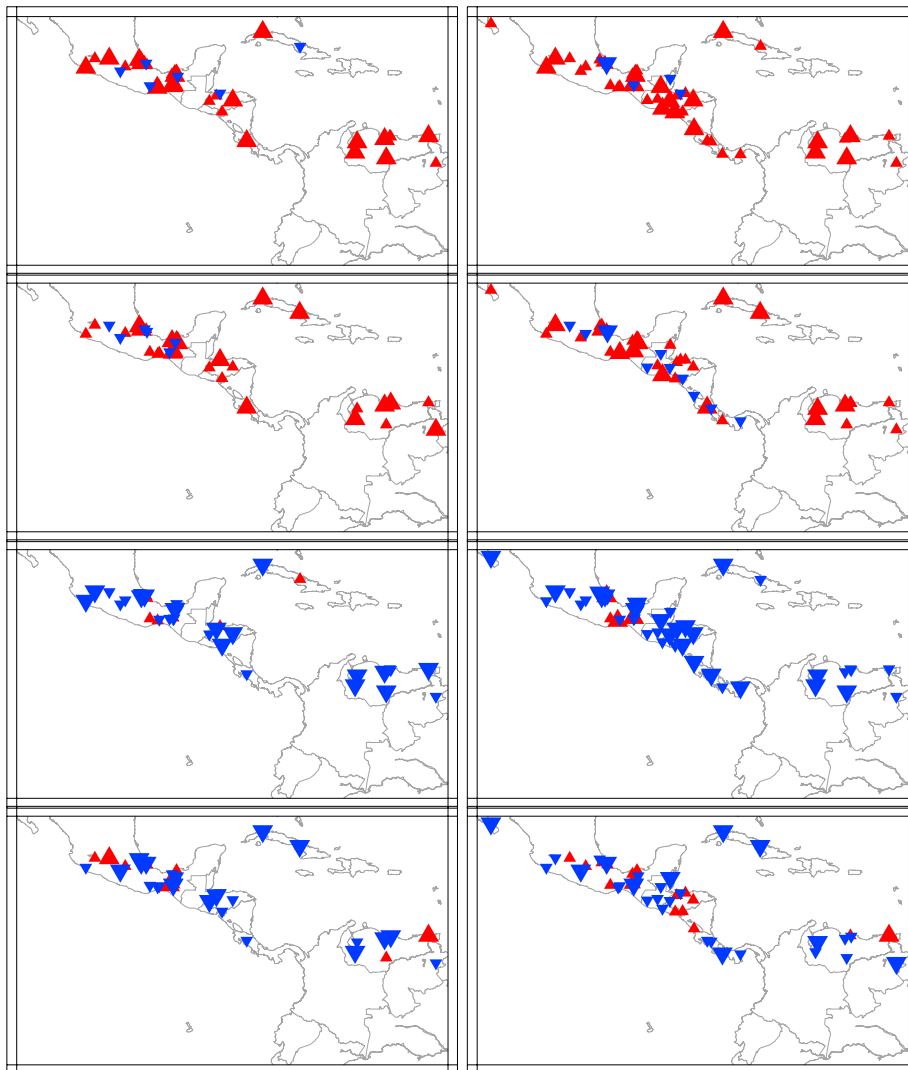


Figure 8. Trends for (left) 1961–2003 and (right) 1971–2003 for (from top to bottom) TX90p, TN90p, TX10p, and TN10p. Red large triangles indicate positive significant trends, red small triangles indicate positive nonsignificant trends, blue large triangles indicated negative significant trends, and blue small triangles indicate negative nonsignificant trends.

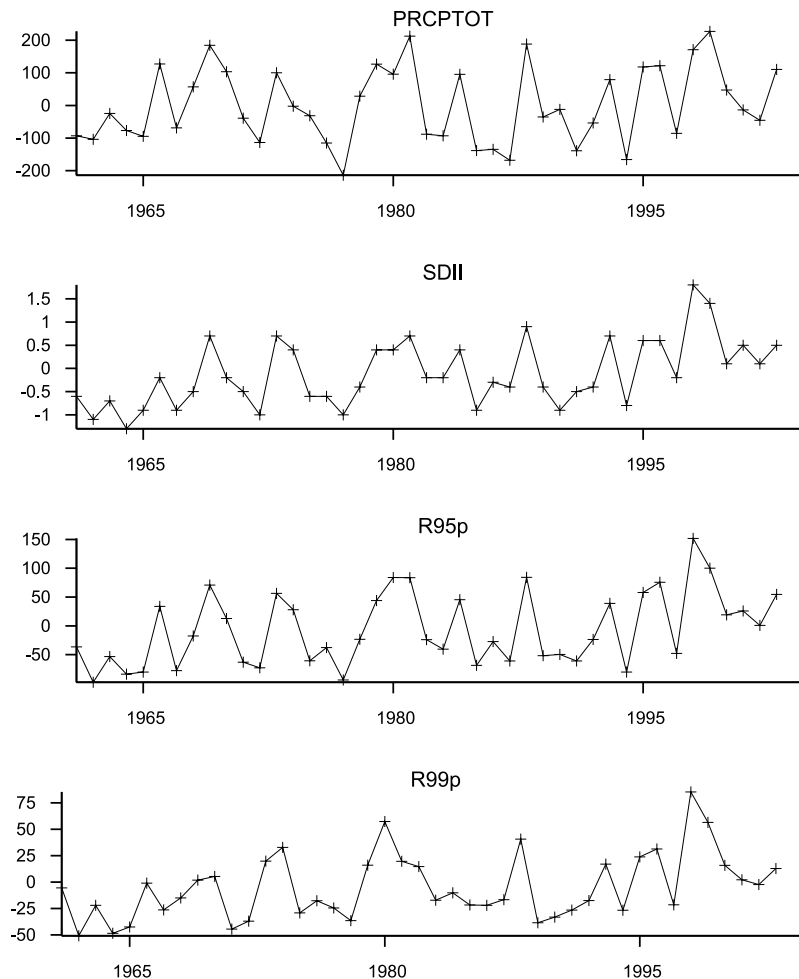


Figure 9. Regional annual anomalies (mm) to 1971–2003 for 1961–2003 and different precipitation indices.

American isthmus (Figure 11). This pattern averages out to a nonsignificant positive trend of 8.7 mm/decade from 1961 to 2003. It is interesting then to stress that there has not been a decrease in the annual amount of precipitation during the last 40 years in Central America.

[23] A different response is found for the indices looking at the amount of rainfall coming from extreme (R95p) and very extreme events (R99p). Although the spatial patterns somewhat resemble that described for the PRCPTOT index (Figure 11), more stations have positive trends than in the aforementioned index (increase from 60% to 70%). This situation led to significant increases in positive trends for the region wide time series of, respectively, 18.1 and 10.3 mm/decade (Table 3 and Figure 9). The same reasoning may be applied to SDII which indicates that on the days it does rain that precipitation amounts are increasing at a rate of 0.3 mm/decade.

[24] In this later case, seasonal analysis reveals positive trends for all seasons, although only summer reaches the 5% significance level. The winter trend is the lowest of all. The maximum amount of rain falling in 1 day (Figure 11) shows a significant trend of 11.1 mm for 1961–2003. The only season with a significant trend in maximum 1 day precipitation is JJA with 1.7 mm/decade. No significant trends were found for the maximum 5 day precipitation values.

[25] No region-wide significant changes are found in the number of consecutive dry days, CDD. Nevertheless, the analysis of station trend maps shows a pattern of decrease for the stations located in the central portion of the isthmus (mostly distributed on its Pacific side, see Figure 12) and the Colombian stations, located across the western portion of the South American landmass. In contrast, the northernmost stations in Mexico and those in the eastern/Caribbean portion of South America are characterized by increases in CDD. This pattern resembles the different effects of ENSO on precipitation that will be discussed later.

[26] The number of consecutive wet days shows a nonsignificant decrease in large parts of the area. Negative slopes dominate the trend maps, although scattered positive trends are found. Among those appears a cluster including again the Colombian stations near the Pacific. Finally, very mixed patterns and non significant trends are found also for the R10mm and R20mm indices (not shown). The clearest signal appears in Panama, with spatially consistent decreases in the number of precipitation events over these thresholds.

4.3. Relations With Sea Surface Temperatures

[27] Given the geographical location of the region, sea surface temperatures (SSTs) likely play a key role in the

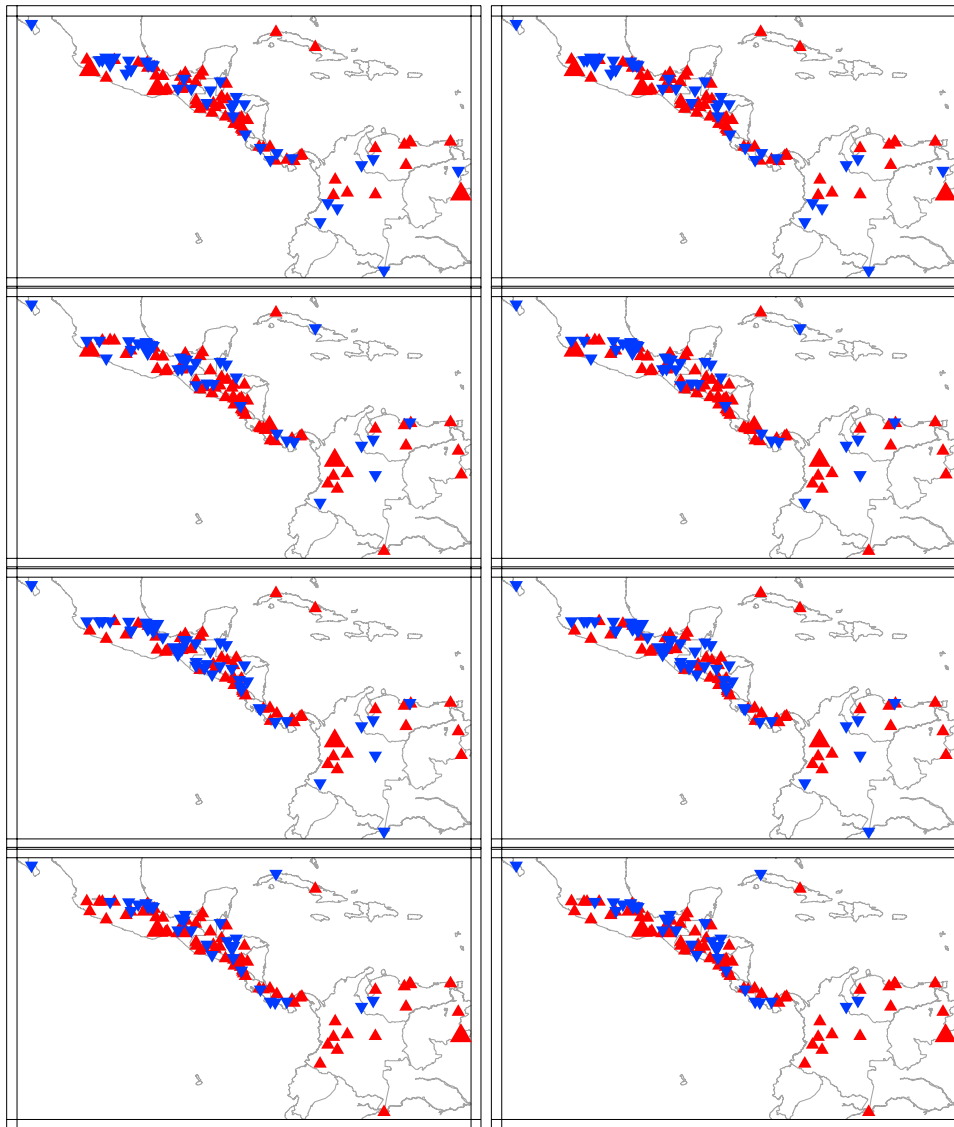


Figure 10. Trends for (left) 1961–2003 and (right) 1971–2003 for (from top to bottom) PRCPTOT, SDII, R95p, and R99p. Red large triangles indicate positive significant trends, red small triangles indicate positive nonsignificant trends, blue large triangles indicate negative significant trends, and blue small triangles indicate negative nonsignificant trends.

time evolution of temperature and precipitation in the area. Figures 13 and 14 show the values obtained when correlating annual averages of SST with the regional time series. The primary relationship with precipitation indices is a positive correlation with the tropical Atlantic Ocean. Temperature indices by contrast, reveal significant relationships to equatorial Pacific Ocean temperatures, including

patterns related to ENSO, in agreement with *Alfaro* [2000, Figure 14].

5. Discussion

[28] *Magaña et al.* [1999] studied the annual cycle of precipitation and temperature in the region. Precipitation is

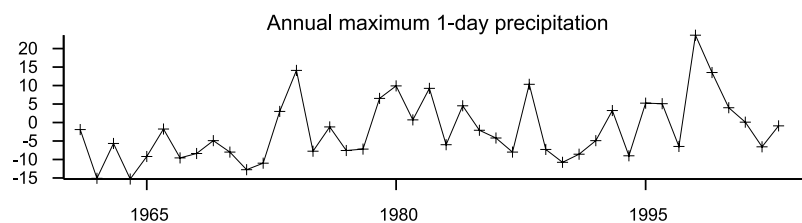


Figure 11. Regional annual anomalies (in mm) for to 1971–2000 for maximum 1-day rainfall (RX1day) for 1961–2003.

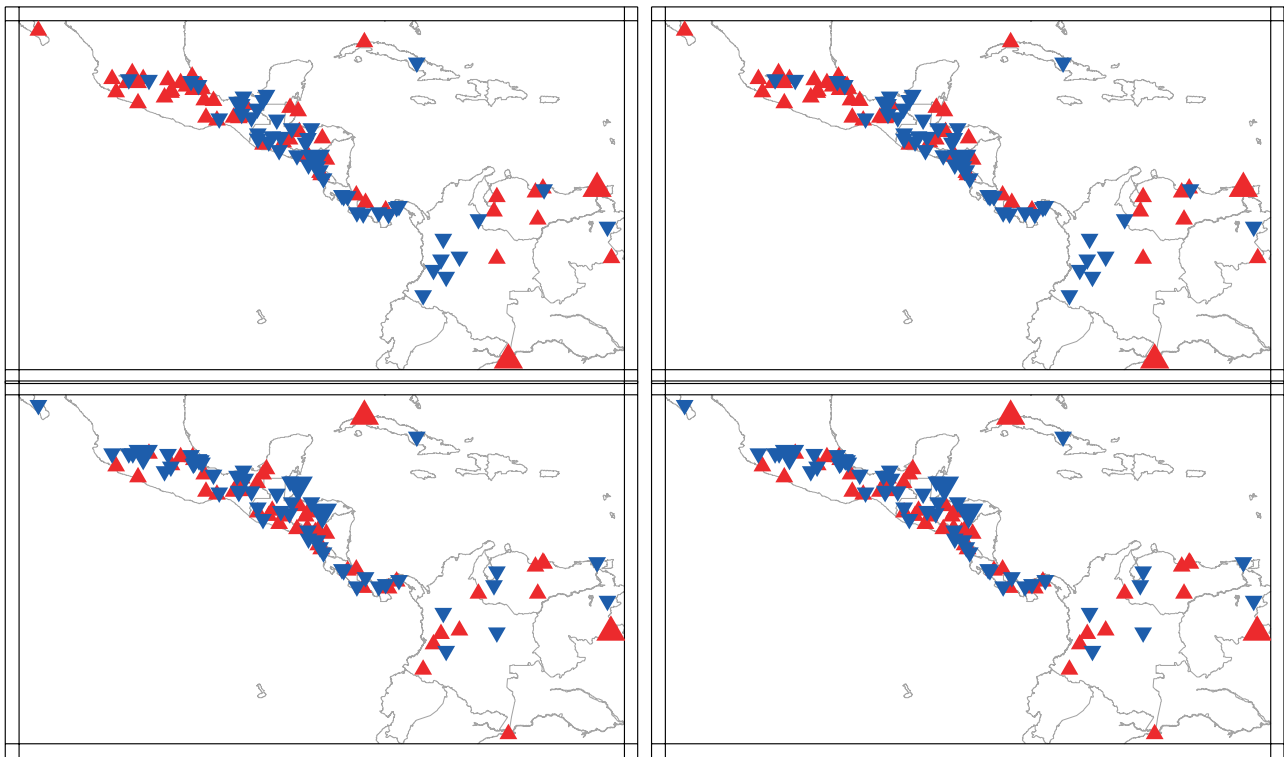


Figure 12. Trends for (left) 1961–2003 and (right) 1971–2003 for (from top to bottom) CWD and CDD. Red large triangles indicate positive significant trends, red small triangles indicate positive nonsignificant trends, blue large triangles indicate negative significant trends, and blue small triangles indicate negative nonsignificant trends.

dominated by a dry season extending from November to April/May and a wet season lasting for the rest of the year. The strengthening of the easterlies in July, produces a maximum in precipitation in most of the Caribbean side of Central America and southern Mexico, but results in a marked midsummer drought (MSD) in the Pacific coast. Stations in northern South America, closer to the equator, experience a smaller annual cycle in precipitation. Temperature regimes are strongly related to the described cycle of precipitation. Daytime temperatures reach their maximum values before the onset of the rainy season and decreases toward January, because of the combination of radiative forcing and latent heat release. Minimum temperatures show a different cycle, with maximum values in July when cloudiness associated to the rainy season reduces nighttime radiative cooling. The lowest minimum temperature values occur during the boreal winter, although most locations, especially those located in the Pacific coast, experience a secondary minima in phase with the midsummer drought. Stations in northern South America have less annual cycle than those farther north.

[29] In a region impacted by easterly trade winds, warmer oceanic surface to the east could be expected to increase precipitation as the correlation between several indices and SSTs implies. It is likely that this is partially due to increased evaporation off a warmer ocean leading to more water vapor available for precipitation but also to the potential relationship with a longer or more intense tropical cyclonic season. Several authors have considered the hypothesis that with warming of the SSTs, the tropical

North Atlantic is entering a phase of enlargement and intensification of the cyclonic season [Goldenberg *et al.*, 2001], which would lead to increases in all indices if no other factors changed.

[30] Correlations with the Atlantic waters reach maximum spatial extent with the SDII index. Their maximum is also displaced in this index, compared with PRCPTOT, from the Caribbean to the equatorial band. This might be related to the influence of the strength of the Intertropical Convergence Zone (ITCZ) as well as factors mentioned above. Enhanced easterlies, related to the positive North Atlantic Oscillation [Poveda *et al.*, 2005], would increase convection and thus the intensity of precipitation. Also, precipitation indices are well correlated with waters south of the Aleutians, an area affected by the Pacific-North American Pattern, which has been linked to the NAO/Northern Annular Mode [Wallace and Thompson, 2002].

[31] The Pacific waters also play a key role in precipitation, especially in modulating the increases in its amount [Magaña *et al.*, 2003]. The regional relationship between El Niño (La Niña) and dry (wet) years in the region is well known, although the Caribbean/Atlantic coast may experience opposite forcing, especially when the Atlantic is warm [Enfield and Mayer, 1997]. The larger negative correlation to the equatorial Pacific, very small when compared to those found in the Atlantic, corresponds to the PRCPTOT index, which showed a nonsignificant increase and large spatial variability, which would result as an effect of ENSO control of precipitation. On the contrary, those indices looking at the intensity of precipitation and the contribution from

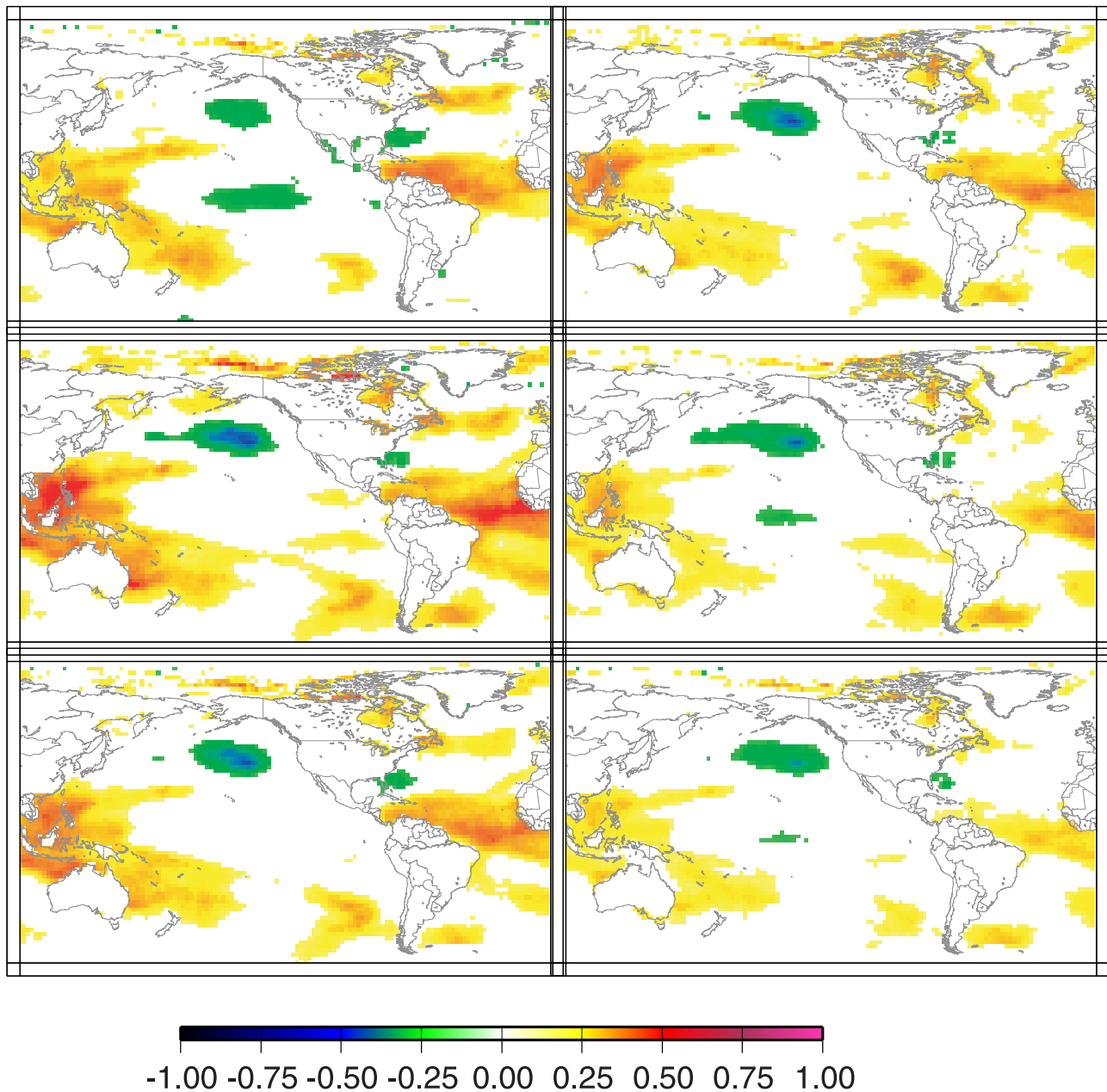


Figure 13. Kendall's Tau values for 1961–2003 between RSST and regional series of (top left) PRCTOP, (middle left) SDII, (bottom left) R95p, (top right) R99p, (middle right) RX1day, and (bottom right) RX5day. Only significant correlations appear colored in the maps.

extreme events (SDII, R95p and R99p) show no significant correlation with cold waters in the equatorial Pacific, although a direct and strong relation is found to the ENSO-related boomerang-shaped SST pattern in the western Pacific.

[32] Table 4 shows correlations between precipitation indices, the SOI and the number of named storms in the tropical Atlantic. Larger relations are found with the latter, similar to *Alfaro and Cid* [1999], who also stress the predominant impact of the tropical Atlantic on rainfall in the region. This indicates that longer rainy seasons are related to warm waters in the aforementioned basin, independent of the status of the El Niño3 region. Although, of course, ENSO has an impact over the different areas of the

region, its effects might be canceling each other when Central America is considered as a whole. In any case, El Niño Southern Oscillation seems to act as a modulator of precipitation trends in the region, as those indices better anticorrelated with the Southern Oscillation Index (SOI), show weaker trends. In any case, an intensified hydrological cycle with more rain coming from extreme events and more average rain per episode appears to characterize the region and does not appear to be linked to El Niño or dependant on the total amount of precipitation. This fits together well with the widespread increases found in the percentage of warm days during JJA and SON, roughly the wet season, which suggests more insolation and therefore less cloudy days. Fewer rainy days and more warm days would be expected

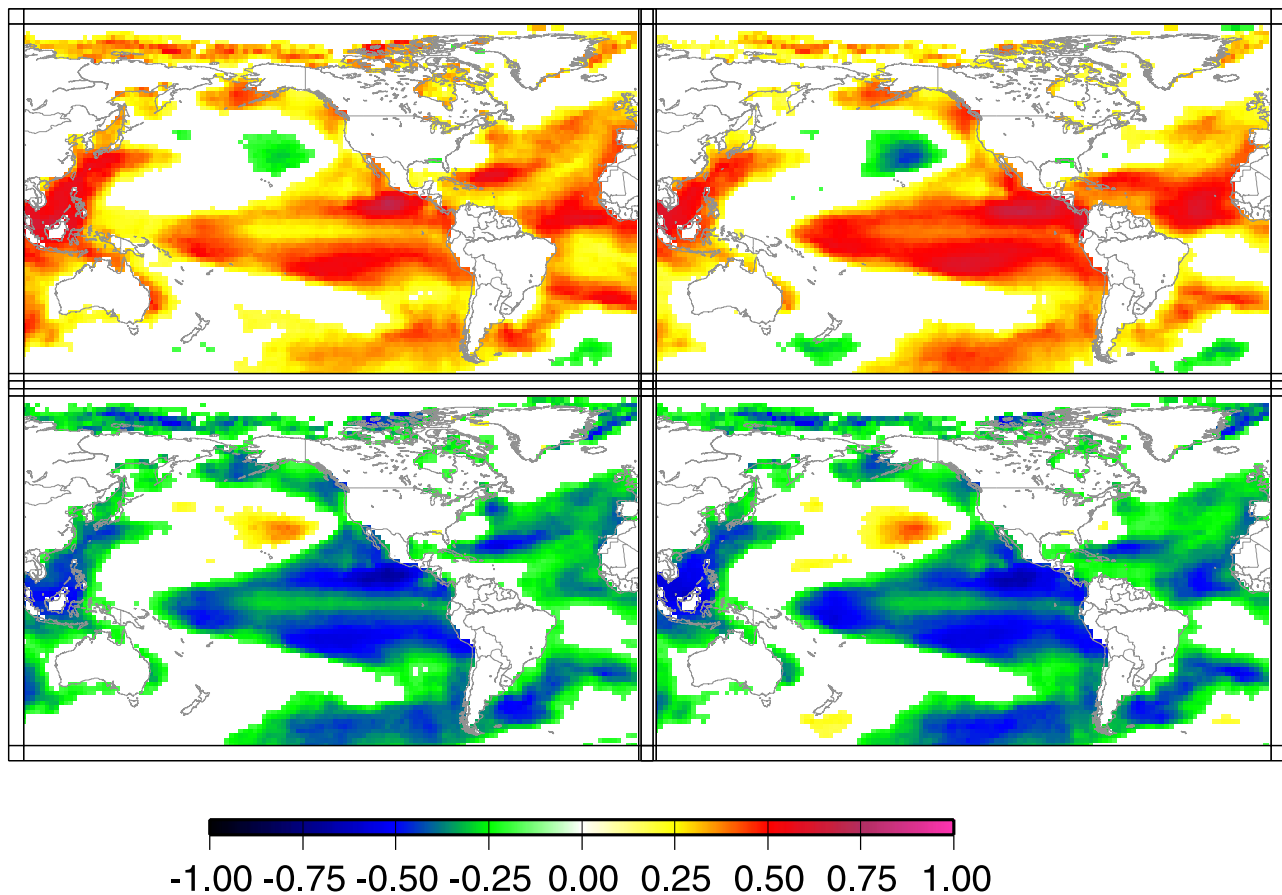


Figure 14. Kendall's Tau values for 1961–2003 between RSST and regional series of (top left) TX90p, (top right) TN90p, (bottom left) TX10p, and (bottom right) TN10p. Only significant correlations appear colored in the maps.

with precipitation not decreasing while precipitation intensity is increasing.

[33] Finally, a companion workshop which was held in Brazil for all South American countries except the northern tier which participated in this paper's analysis, found consistent changes in minimum temperature indices, but not in maximum temperature indices, relating warming to more warm nights and fewer cold nights during the summer and fall [Vincent *et al.*, 2005]. Regarding precipitation, Haylock *et al.* [2005] found an evolution toward wetter conditions in Ecuador, northern Peru, southern Brazil, Paraguay, Uruguay and northern and central Argentina; on the contrary, decreases in precipitation were found for Chile and southern Argentina. The pattern of extreme precipitation was in general similar to that for total rainfall.

6. Conclusions

[34] For the first time, analysis of changes in temperature and precipitation extremes is available for Central America and northern South America. The region is clearly warming over the last several decades and extremes of temperature are changing accordingly. Trends for the temperature indices show a large spatial coherence, with a larger increase in extremely high maximum temperatures than decrease in extremely cold maximum temperatures. This leads to an increased DTR. Temperature indices show larger warming

during the boreal summer and autumn, roughly the wet season in the region, reducing the seasonal contrast in the area.

[35] The spatial coherence of precipitation indices was much lower. A nonsignificant increase of precipitation is found, with very mixed spatial patterns of positive and negative trends when individual stations were studied. By contrast, the intensity of precipitation and the contribution of wet and very wet days, do have significant trends

Table 4. Kendall's Tau Correlations Between Precipitation Indices, the Southern Oscillation Index, the Pacific Decadal Oscillation and the Number of Named Storms in the Tropical Atlantic for 1961–2003^a

	SOI	Named Storms
PRCPTOT	0.27	0.432
SDII		0.334
R95p		0.367
R99p		0.233
RX1day		0.231
RX5day		0.21
R10mm		0.391
R20mm		0.426
CDD		
CWD	0.367	

^aIndices in bold show significant trend for 1961–2003; empty boxes indicate nonsignificant trends at the 5% level.

indicating that heavy precipitation events are increasing in the region.

[36] The analysis presented here was made possible by collaboration initiated by a regional climate change workshop. The data used have been restricted by the countries participating in this analysis so they are not available to outside researchers. However, at the workshop all the participants agreed to make the entire suite of time series of indices for each of the stations used in this analysis available to researchers. Please see <http://ccma.seos.uvic.ca/ETCCDMI/> for instructions on how to obtain these indices.

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