GLOBAL and PLANETARY CHANGE

(This is a sample cover image for this issue. The actual cover is not yet available at this time.)

Warming and wetting signals emerging from analysis of changes in climate extreme indices over South America

María de los Milagros Skansi [a,*], Manola Brunet [b,c], Javier Sigró [b], Enric Aguilar [b],
Juan Andrés Arevalo Groening [d], Oscar J. Bentancur [e], Yaruska Rosa Castellón Geier [f],
Ruth Leonor Correa Amaya [g], Homero Jácome [h], Andrea Malheiros Ramos [i,j], Clara Oria Rojas [k],
Alejandro Max Pasten [l], Sukarni Sallons Mitro [m], Claudia Villaroel Jiménez [n], Rodney Martínez [o],
Lisa V. Alexander [p], P.D. Jones [c,q]

[a] Departamento Climatología, Servicio Meteorológico Nacional, 25 de Mayo 658 (C1002ABN), Ciudad Autónoma de Buenos Aires, Argentina
[b] Centre for Climate Change, Department of Geography, University Rovira i Virgili, Av. Catalunya, 35, 43071, Tarragona, Spain
[c] Climatic Research Unit, University of East Anglia, Norwich, NR4 7TJ, United Kingdom
[d] Instituto Nacional de Meteorología e Hidrología (INAMEH), Carretera Hoyo de la Puerta, Parque Tecnológico Sartenejas, Edificio INAMEH. Municipio Baruta, Estado Miranda, 1080 Venezuela
[e] Dpto. Biometría, Estadística y Computación, Facultad de Agronomía, UDELAR, Av. Garzón 780, Montevideo, CP.12900, Uruguay
[f] Unidad Climatologia, Institucion: Servicio Nacional de Meteorologia e Hidrologia (SENAMHI), Calle Reyes Ortiz No. 41 (Zona Central), La Paz, Bolivia
[g] Grupo de Gestión de Datos y Red Meteorológica, Subdirección de Meteorología, Instituto de Hidrología, Meteorología y Estudios Ambientales, IDEAM, Carrera 10 No. 20–30 Piso 6, Colombia
[h] Dpto. de Climatología, Instituto Nacional de Meteorología e Hidrología (INAMHI), Calle Iñaquito No. N36-14 y Corea, Codigo Postal No. 16-310, Quito, Ecuador
[i] Coordenação de Desenvolvimento e Pesquisa (CDP). Instituto Nacional de Meteorologia (INMET). Eixo Monumental, Via S1 Sudoeste. 70680-900, Brasília-DF, Brazil
[j] Geophysics Centre of Évora (CGE), University of Évora, Portugal. Rua Romão Ramalho, 59. 7000-671. Évora, Portugal
[k] Centro de Prediccion Numerica de la Direccion General de Meteorología, Servicio Nacional de Meteorologia e Hidrologia del Peru, Jr. Cahuide 785, Jesus Maria, Lima, Peru
[l] Direccion Nacional de Aeronautica Civil–Dirección de Meteorologia e Hidrología Gerencia de Climatologia e Hidrología, Departamento de Climatología, Cnel. Francisco Lopez 1080 c/ De La Conquista, Paraguay
[m] Meteorological Service Suriname, Magnesiumstraat 41, Paramaribo, Surinam
[n] Direccion Meteorológica de Chile, Subdepartamento de Climatología y Meteorología Aplicada, Seccion de Met. Aplicada — Oficina de Estudios, Av. Portales 3450, Estación Central, Santiago, Chile
[o] Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN), Escobedo 1204 y 9 de Octubre, P.O. Box 09014237, Guayaquil, Ecuador
[p] Climate Change Research Centre and Centre of Excellence for Climate Systems Science, University of New South Wales, Sydney NSW 2052, Australia
[q] Center of Excellence for Climate Change Research/Dept of Meteorology, Faculty of Meteorology, Environment and Arid Land Agriculture, King Abdulaziz University, P. O. Box 80234, Jeddah 21589, Saudi Arabia

ARTICLE INFO

ABSTRACT

Here we show and discuss the results of an assessment of changes in both area-averaged and station-based climate extreme indices over South America (SA) for the 1950–2010 and 1969–2009 periods using high-quality daily maximum and minimum temperature and precipitation series. A weeklong regional workshop in Guayaquil (Ecuador) provided the opportunity to extend the current picture of changes in climate extreme indices over SA.

Our results provide evidence of warming and wetting across the whole SA since the mid-20th century onwards. Nighttime (minimum) temperature indices show the largest rates of warming (e.g. for tropical nights, cold and warm nights), while daytime (maximum) temperature indices also point to warming (e.g. for cold days, summer days, the annual lowest daytime temperature), but at lower rates than for minimums. Both tails of night-time temperatures have warmed by a similar magnitude, with cold days (the annual lowest nighttime and daytime temperatures) seeing reductions (increases). Trends are strong and moderate (moderate to weak) for regional-averaged (local) indices, most of them pointing to a less cold SA during the day and warmer night-time temperatures.

* Corresponding author at: Departamento Climatología, Servicio Meteorológico Nacional, 25 de Mayo 658 (C1002ABN), Ciudad Autónoma de Buenos Aires, Argentina. Tel.: +54 11 51676767x18259/18273; fax: +54 11 51676709.
 E-mail addresses: mms@smn.gov.ar (M.M. Skansi), manola.brunet@urv.cat (M. Brunet), javier.sigro@urv.cat (J. Sigró), enric.aguilar@urv.cat (E. Aguilar), jarevalo@inameh.gob.ve (J.A. Arevalo Groening), obent@fagro.edu.uy (O.J. Bentancur), yaruska@senamhi.gob.bo (Y.R. Castellón Geier), rcorrea@ideam.gov.co (R.L. Correa Amaya), hjacome@inamhi.gob.ec (H. Jácome), andrea.ramos@inmet.gov.br (A. Malheiros Ramos), clara@senamhi.gob.pe (C. Oria Rojas), max.pasten@meteorologia.gov.py (A.M. Pasten), sukarnimitro@yahoo.com (S. Sallons Mitro), cvilla@meteochile.cl (C. Villaroel Jiménez), r.martinez@ciifen-int.org (R. Martínez), l.alexander@unsw.edu.au (L.V. Alexander), P.Jones@uea.ac.uk (P.D. Jones).

northeastern Brazil
western South America
southeastern South America

Regionally-averaged precipitation indices show clear wetting and a signature of intensified heavy rain events over the eastern part of the continent. The annual amounts of rainfall are rising strongly over south-east SA (26.41 mm/decade) and Amazonia (16.09 mm/decade), but north-east Brazil and the western part of SA have experienced non-significant decreases. Very wet and extremely days, the annual maximum 5-day and 1-day precipitation show the largest upward trends, indicating an intensified rainfall signal for SA, particularly over Amazonia and south-east SA. Local trends for precipitation extreme indices are in general less coherent spatially, but with more general spatially coherent upward trends in extremely wet days over all SA.

1. Introduction

The study of extreme weather and climate events is a current topic of higher scientific and societal interest. It is being fuelled by relevant scientific communities, including various climatological branches that assess climate change (e.g. observational, modeling, adaptation and impact sectors). This issue has been addressed recently by the Intergovernmental Panel on Climate Change (IPCC, 2012) in the Special Report on Extremes (SREX). This has provided the most comprehensive global review and assessment on the relation between climate extremes, their impacts and the strategies to manage associated perils.

A number of issues, however, constrain our current understanding and scientific confidence in the observed changes in extremes. Among others, availability and accessibility of long-term and high-quality climate series at the relevant time scales for assessing extremes (e.g. daily and sub-daily) is one of the most serious gaps, particularly over some regions of the world (often called climate-data-sparse regions), such as most of South America. The availability of climate series is also limited temporally, since for most of the world the length of digitized daily climate series (e.g. for temperature and precipitation) only goes back in time to the mid-20th century and for many regions is restricted to the 1970s onwards. In addition, there are also concerns regarding the quality and homogeneity of the available series, which could compromise the robustness of assessed changes. Many countries also restrict access to their higher temporal resolution time-series. In short, the quality and quantity of accessible climate series still limit our understanding of the observed changes in climate extremes, particularly over data-sparse regions (Trenberth et al., 2007: Appendix 3.B.2).

A number of international groups have made major efforts to advance both knowledge of global changes in climate extremes and to promote the recovery and development of climate data (i.e. ensuring data quality and homogeneity) over data-sparse regions. In this regard, the ETCCDI[1] has largely contributed to this effort by advancing knowledge on changes in climate extremes through the formulation of a suite of 27 core climate extreme indices calculated from daily temperature and precipitation data (http://cccma.seos.uvic.ca/ETCCDI/list_27_indices.shtml). They have also promoted the analysis and monitoring of extremes around the world through organizing regional workshops in data-sparse regions that have involved scientists from National Meteorological and Hydrological Services (NMHS) as part of ETCCDI's two-pronged approach (Peterson and Manton, 2008, p. 1266).

Contributions from the ETCCDI to filling in gaps in data-sparse regions and enhancing analyses of the global picture of changes in extremes (Trenberth et al., 2007, based on Alexander et al., 2006) have helped to improve knowledge and understanding about how and how much climatic extremes are changing under climate change. However,

the network of stations used in global analysis (e.g. Alexander et al., 2006; Vose et al., 2005 or Brown et al., 2008), are not globally uniform and contain irregular or limited data over northern Latin America and South America as a whole, Africa, parts of Australia, India, the Middle East and Southern Asia, which restricts our ability to estimate changes in extremes over these regions (Seneviratne et al., 2012: 123).

For South America (SA hereafter), some effort has been made to assess changes in climate extremes based on temperature and precipitation station data at the daily scale (for temperature extremes: Vincent et al., 2005; Alexander et al., 2006 and for precipitation extremes: Haylock et al., 2006; Khan et al., 2007; Sheffield and Wood, 2008; Grimm and Tedeschi, 2009; Dai, 2011; Mo and Berbery, 2011).

Parts of SA have been more intensively explored, such as SE SA for observed changes in temperature extremes (e.g. Rusticucci and Barrucand, 2004; Barrucand et al., 2008; Marengo and Camargo, 2008; Rusticucci and Renom, 2008; Marengo et al., 2009; Renom, 2009; Tencer, 2010; Rusticucci, 2012) or for precipitation extremes (e.g. Dufek and Ambrizzi, 2008; Dufek et al., 2008; Marengo et al., 2009; Pscheidt and Grimm, 2009; Penalba and Robledo, 2010; Llano and Penalba, 2011; Teixeira and Satyamurty, 2011). Other sub-regional studies are focused on NE Brazil for precipitation extremes (e.g. Santos and Brito, 2007; Silva and Azevedo, 2008; Santos et al., 2009) and over western SA for temperature extremes (Falvey and Garreaud, 2009) and for precipitation extremes (Dufek et al., 2008).

From these studies, there is a clear geographical imbalance in the assessments of one or another part of SA and in the number of stations employed. Most previous studies have focused on southern SA, with limited studies and data over the northern half of SA. Most analyses however point to observed changes in temperature extremes consistent with warming when averaged over the whole continent but with regional variations (Vincent et al., 2005: 5016–5020). However, while extreme indices based on minimum (i.e. night-time) temperature have warmed, those based on maximum (i.e. daytime) temperature show little change or have cooled, particularly over southern SA (Rusticucci, 2012, pp. 4–6).

The scientific confidence in the observed changes over SA, therefore, ranges from low to medium, depending on the region analyzed (Seneviratne et al., 2012: Table 3.2, p. 194). There is low confidence in the assessed changes in extremes based on either daily maximum or minimum temperature data over the northern half of SA, including Amazonia, due to the irregular network in these regions. In the southern half of SA (including NE Brazil, south, SE and west Coast of SA) there is medium confidence in the estimated extreme temperature trends. In the case of heat waves and warm spells, the confidence is low over all SA, including southern SA, due to either insufficient evidence or to spatially varying trends.

A similar uncertain picture is apparent when assessing changes in precipitation extremes over all SA, due to both the scarcity of studies and spatially incoherent trends in either heavy events (e.g. those defined as daily precipitation >95th or 99th percentiles) or in dryness (e.g. consecutive dry days — CDD, Palmer Drought Severity Index – PDSI – indices) reducing the scientific confidence in the estimated trends. There is medium confidence that there have been increases in heavy precipitation events over Amazonia and many parts of NE Brazil, but a few areas in the west (W) coast of SA indicate decreases or mixed

---

[1] Joint World Meteorological Organization (WMO) Commission for Climatology (CCl)/World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR)/Joint WMO–Intergovernmental Oceanographic Commission of the United National Educational, Scientific and Cultural Organization (UNESCO) Technical Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team on Climate Change Detection and Indices (ETCCDI: http://www.clivar.org/organization/etccdi).

results (Seneviratne et al., 2012: Table 3.2, p. 194, based on Haylock et al., 2006; Santos and Brito, 2007; Silva and Azevedo, 2008; Santos et al., 2009).

The scientific confidence provided by the SREX report for changes in dryness in SA is low either due to spatially varying trends or inconsistent results among assessments. Slight reductions in the CDD index have been estimated over Amazonia, but with inconsistent spatial signals. However the opposite signal (tenuous increases in dryness) has been found over southern SA and contrasting spatial signals and inconsistencies among studies over NE Brazil and W SA also return low confidence in the estimated trends in dryness (Seneviratne et al., 2012: Table 3.2, p. 194 based on Haylock et al., 2006; Dufek and Ambrizzi, 2008; Dufek et al., 2008; Sheffield and Wood, 2008; Llano and Penalba, 2011; Dai, 2011).

With the aim of improving both the spatial and temporal coverage of former assessments (e.g. Vincent et al., 2005; Haylock et al., 2006) and enhancing the global picture of changes in climate extremes over SA, a week-long ETCCDI regional workshop was held in Guayaquil (Ecuador) in the Centro Internacional para la Investigación del Fenomeno El Niño (CIIFEN) in January 2011. This workshop followed the "recipe" devised by the ETCCDI and enabled a more extended assessment (both spatially and temporally) of changes in climate extremes over SA.

Therefore, this study aims to analyze both local and regional/sub-regional changes in annual temperature and precipitation extremes over SA. This is done by calculating a core set of 27 ETCCDI extreme indices from high-quality daily weather data and estimating trends.

In the next sections we provide details of the network and indices used for assessing recent changes, the methodology applied for ensuring the quality and homogeneity of the final series employed for estimating local and regional annual trends. In addition, we discuss our findings and provide insights on the shortcomings that SA countries are still facing to gain a truly regional picture of the observed changes in extremes.

2. Data, methods, indices and trend estimation

2.1. Rationale for the ETCCDI regional workshop

In a previous ETCCDI regional workshop held in Brazil (Vincent et al., 2005; Haylock et al., 2006) in 2004, a network of 68 (54) temperature (precipitation) time-series covering the period 1960–2000 were analyzed, which enabled the first regional assessment on changes in extremes over SA as a whole to be produced (Rusticucci, 2012: p. 4).

The low density of stations employed in both studies supported the need for enhancing the spatial and temporal availability of high-quality daily time-series since only a limited assessment of observed changes could be performed. The ETCCDI regional workshop held in Guayaquil (Ecuador) in January 2011 presented an opportunity to extend the network for SA. Participants from mainly NMHS' in Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Surinam, Uruguay and Venezuela attended the workshop and brought their best, longest and most complete digital daily maximum temperature (TX), minimum temperature (TN) and precipitation (RR) time-series for analysis.

The participants brought daily records for 261 (262) TX (TN) series and 280 RR records from a selection of data available in their national databanks, representing well distributed stations and covering the main climatic types in their countries. During the workshop itself only about 15% of records could be analyzed, so intense post-workshop analysis was required. Many time-series were discovered to contain large data gaps or many missing values that compromised data completeness and their suitability for computing extreme indices. This is common among South American national networks.

2.2. Time-series quality control (QC), homogeneity testing and homogenization

Time-series were quality controlled using RClimDex. This software was developed by the ETCCDI and is freely available at http://cccma.seos.uvic.ca/ETCCDI/software.shtml. We complemented RClimDex with an additional QC procedure and software (also freely available at http://www.c3.urv.cat/data1.html along with the user manual (Aguilar et al., 2010)). The time-series were subjected to the QC procedures by the participants either during or after the workshop. This involved identifying and documenting potential non-systematic errors and ensuring that the time-series were reasonably free of gross errors, at the same time as ensuring internal, temporal and spatial consistency of the records.

RClimDex and the additional QC software provide several graphical and numerical output files which can be used in tandem to further assess the quality of the data. Graphical output includes monthly and interannual box-plots, which allow for the identification of outliers for RR, TX, TN and DTR series. Assessment can then be made as to the reliability of data by using expert judgment and by consulting original data sources. Details of all the additional numerical and graphical output is given in Aguilar et al. (2010: pp.4–6).

Once the QC exercise is complete, workshop participants can test their time series for consistency or "homogeneity". With the time-series quality controlled at the workshop, the attendees were trained in the application of two homogeneity tests: (i) RHtestV3 method and software (Wang et al., 2010: section 5, see http://cccma.seos.uvic.ca/ETCCDI/software.shtml) and (ii) an application of the Standard Normal Homogeneity Test (Alexandersson and Moberg, 1997) run in R and called RSNHT (available at http://www.c3.urv.cat/data1.html; Aguilar, 2010). RHtestV3 was used to test homogeneity on the RR series and RSNHT was used not only for testing homogeneity, but also for adjusting the TX/TN series at the monthly scale. The homogeneity testing of the RR series was also supported by visual inspection of the indices and looking for unusual behavior. After homogeneity testing of the RR time-series, 28 records were rejected for having too many break points and thus only 252 out of the original 280 RR series were used to compute the extreme indices.

The 261 (262) TX (TN) records were subjected to homogenization by using the RSNHT software. On average 1.1 (1.2) breaks in TX (TN) series were detected, validated and accounted for by interpolating monthly adjustments returned by the RSNHT to the daily scale following the procedure recommended by Vincent et al. (2002: pp. 1325–1326).

2.3. The network used, extreme indices and trend estimation

The network brought by the attendees to the workshop is shown in Table A in the supplementary information. This table provides the station names by country, start and end dates, geographical coordinates, elevation and the variables available at the station. Fig. 1 shows the location of the original station network assessed, depicting the final number of stations used for assessing extremes (circles) and those rejected (triangles), along with the borders of the fours sub-regions analyzed as adapted from the SREX report.

Following QC, homogeneity testing and homogenization, only 188 (252) temperature (precipitation) series were assessed to be suitable for computing extreme indices (those locations shown in Fig. 1); although for percentile indices only a maximum of 145 stations were considered suitable. The network includes records spanning the whole of the 20th century up to 2010, but with only a few records going back to the 1900s (e.g. in Surinam for RR records) or back to the 1930s and 1940s (e.g. in Argentina and Colombia for the three variables and decades respectively, and Venezuela for RR for the latter decade). Although about 28% of the stations start in the 1950s, it is not until the late 1960s that about 94% of the stations have data (see Table A in the supplementary data). This latter period allows a larger number of
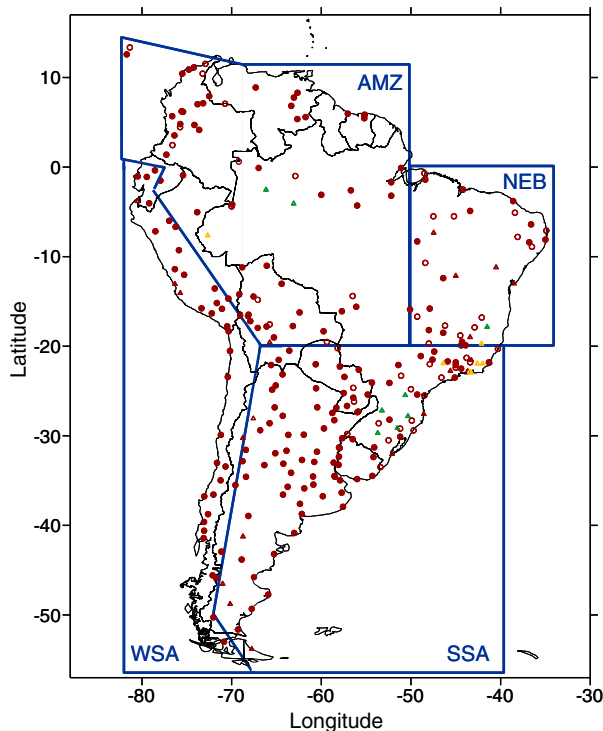
Fig. 1. Location map showing the network of stations assessed, including those used (circles) and not used (triangles). Stations with temperature and precipitation data are shown in red, while green (yellow) have only precipitation (temperature) series. Solid (empty) circles are those considered homogeneous or homogenized (not homogenized temperature records, only precipitation series used). Boxes identify the four SA sub-regions adapted from the SREX Report (see text for details).

indices to be calculated annually from stations mainly located in the northernmost part of SA where data availability is very limited in previous studies. This justifies the analysis periods used in this paper i.e. 1969–2009 for the common analysis of local trends and the 1950–2010 for the regional and sub-regional series of extreme indices assessment.

A visual comparison between our Fig. 1 and Figure 1 in Vincent et al. (2005: p. 5015), Figure 1 in Haylock et al. (2006: p. 1494) and Fig. 3, plots a–f, in Marengo et al. (2009, p. 2248) highlights the improvement in the spatial coverage of the data and indices used in this study. An enhanced spatial resolution is especially evident over the northern half of SA, including the whole W SA. The density of stations particularly over Brazil, Colombia, Surinam or Venezuela is somewhat better than that used in previous studies and in Ecuador, Peru, Chile it is remarkably better. This enables us to expand the analysis to these parts of SA, which have been highlighted in recent reviews as data-sparse areas (e.g. Rusticucci, 2012, p.2; Seneviratne et al., 2012: Table 3.2, p. 194).

The improvement in coverage of this study can also be seen over southern SA when compared with previous SA assessments (e.g. Vincent et al., 2005; Haylock et al., 2006). Over the western coast of SA, both studies have assessed relatively few numbers of records: 20 (16) temperature (precipitation) series. In this study we have analyzed 53 temperature and precipitation series over this sector, which also expands across Peru, Ecuador and Colombia where previous coverage was scarce.

Other studies focused on parts of SA use similar or reduced coverage than this study (e.g. Falvey and Garreaud, 2009: Table 1; Rosenbluth et al., 1997: Table Ia–b pp. 69–70 and Fig. 1, p.71; Rusticucci and Barrucand, 2004: Fig. 1, p. 4110; Barrucand et al., 2008: Fig. 1; Rusticucci and Renom, 2008: Fig. 1 in p. 1084 and pp. 1084–1085; Renom, 2009: p. 13 for temperature extremes over the southern part of

SA, likely the best analyzed region in SA so far). For analysis of precipitation extremes there has been much better coverage in previous analyses (e.g. Penalba and Robledo, 2010, Fig. 2, p. 534 and Table 1, p. 535–536 over the La Plata Basin; Teixeira and Satyamurty, 2011, Fig. 2, p. 1915 for southern and SE Brazil), but those time-series do not extend to recent years.

The authors are aware that even with the enhanced spatial and temporal coverage presented here, the complex topography and large variety of climates in this continent, make it difficult to comprehensively analyze observed changes in climate extremes at lower spatial scales (e.g. national, sub-regional). Our network is, nevertheless, large enough to improve the global picture over all SA. This is particularly the case over the northern half of SA, but also in the western part of SA. The new study also improves the temporal extent over all SA.

2.3.1. The ETCCDI extreme indices

As discussed elsewhere (e.g. Klein Tank et al., 2009; Zhang et al., 2011; Zwiers et al., 2011), the ETCCDI extreme indices were defined with the aim of both monitoring changes in "moderate" extremes and for enhancing climate change detection studies given their high signal-to-noise ratio (Zhang et al., 2011: p. 854).

To compute the ETCCDI extremes requires long, continuous, quality controlled and homogeneous daily time-series. This requirement is an issue in many parts of the world, including SA, where there is a lack of high-quality daily measurements covering several decades. Therefore, for indices calculation using RClimDex, a number of conditions have to be met. An annual value of an index will not be calculated if there are more than 15 days missing in a year. In addition, the percentile-based indices will only be calculated if at least 80% of the data are present in the reference period. These requirements for data completeness had an impact on the final number of extreme indices computed from the homogenized temperature series in this study, since only a maximum of 170 (145) locations could compute temperature (percentile-based) indices.

From the 27 core extreme or "moderately extreme" indices defined by the ETCCDI, we assess 13 (9) temperature (precipitation) indices in this assessment. Table 1 outlines index names, definitions, units and the number of stations for which each index has been calculated for both periods assessed. While the indices chosen can be calculated both annually and monthly by RClimDex, in this assessment we only consider the annual values.

Percentile indices are calculated using the 1971–2000 base period, in order that most series could be included in the trend analysis over the 1950–2010 period. To eliminate possible bias in the trend estimation of the percentile-based indices associated with the existing inhomogeneities at the limits of the reference period, the RClimDex software follows the bootstrapping approach proposed by Zhang et al. (2005: pp. 1643–1644).

2.3.2. Linear trend estimation of indices

Although the RClimDex software also produces trend files for each index, in this study the estimated change is explained by a linear trend fitted over two different periods: (i) a common period (1969–2009) used for assessing local trends and (ii) the period 1950–2010 for which the linear trends have been estimated on a regional (all SA) and sub-regional scales as defined by SREX (IPCC, 2012: Fig. 3–1, p. 123 and Appendix 3.A-2. See also Fig. 1).

Trends were calculated annually by adapting Sen's (1968) slope estimator, following the method proposed by Zhang et al. (2000) in a study of annual temperature and precipitation change over Canada. This more robust approach for trend estimation was adopted because the indices have mostly non-Gaussian distributions and also because daily data could contain large real outliers that could compromise the results returned by the non-resistant least squares method.

Table 1

Temperature and precipitation indices from the ETCCDI analyzed in this assessment with associated definitions and units (for further details see also http:// cccma.seos.uvic.ca/ETCCDI/list_27_indices.shtml), along with the number of stations for which each index has been computed for both periods: the 1950–2010 for area-averaged indices and 1969–2009 for station-based indices. All indices are calculated annually from January to December. Italics indicate those indices that are not percentile-based (see Section 2.3.2 for details).

ID	Index name	Indices definitions	Units	No. of stations	
				1969–2009	1950–2010
TXx	*Highest Tmax*	*Annual highest value of daily maximum temperature*	*C deg*	*133*	*150*
TNx	*Highest Tmin*	*Annual highest value of daily minimum temperature*	*C deg*	*136*	*148*
TXn	*Lowest Tmax*	*Annual lowest value of daily maximum temperature*	*C deg*	*133*	*148*
TNn	*Lowest Tmin*	*Annual lowest value of daily minimum temperature*	*C deg*	*137*	*149*
TN10p	Cold nights	Percentage of days when TN<10th percentile from the 1971–2000 reference period	% days	131	144
TX10p	Cold days	Percentage of days when TX<10th percentile from the 1971–2000 reference period	% days	127	145
TN90p	Warm nights	Percentage of days when TN>90th percentile from the 1971–2000 reference period	% days	131	145
TX90p	Warm days	Percentage of days when TX>90th percentile from the 1971–2000 reference period	% days	128	145
DTR	Daily temperature range	Annual mean difference between TX and TN	C Deg	121	170
SU25	*No. summer days*	*Annual count of days when TX>25 °C*	*Days*	*126*	*170*
TR20	*No. tropical nights*	*Annual count of days when TN>20 °C*	*Days*	*100*	*141*
WSDI	Warm spell duration index	Annual count of days with at least 6 consecutive days when TX>90th percentile from the 1971–2000 reference period	Days	145	145
CSDI	Cold spell duration index	Annual count of days with at least 6 consecutive days when TN<10th percentile from the 1971–2000 reference period	Days	145	144
Rx1day	*The highest 1-day RR amount*	*Annual maximum 1-day precipitation*	*mm*	*169*	*238*
Rx5day	*The highest 5-day RR amount*	*Annual maximum consecutive 5-day precipitation*	*mm*	*169*	*240*
SDII	*Simple daily RR intensity index*	*Annual total precipitation divided by the number of wet days (defined as precipitation≥1.0 mm) in the year*	*mm/ day*	*173*	*238*
R20	*No. of heavy RR days*	*Annual count of days when daily RR≥20 mm*	*Days*	*170*	*240*
CDD	*Consecutive dry days*	*Maximum number of consecutive days with daily rainfall<1 mm*	*Days*	*173*	*241*
CWD	*Consecutive wet days*	*Maximum number of consecutive days with daily rainfall≥1 mm*	*Days*	*174*	*242*
R95p	Very wet days	Annual total precipitation when RR>95th percentile from the 1971–2000 reference period	mm	171	241
R99p	Extremely wet days	Annual total precipitation when RR>99th percentile from the 1971–2000 reference period	mm	152	239
PRCPTOT	*Wet-days annual amount*	*Annual total RR from wet days RR>1 mm*	*mm*	*174*	*244*

Annual trends of all indices are tested for statistical significance at the 0.01 (0.05) confidence level for regional and sub-regional averaged indices (station-based trends) unless otherwise stated. The 95% confidence intervals for trend coefficients have also been estimated from tabulated values in Kendall (1955). Trends have only been estimated for an index if less than 25% of the annual values were missing. This has had an impact over the northern part of SA, particularly over Brazil, Colombia and Venezuela for temperature indices. This highlights the need to fill in gaps by recovering, digitizing and reconstructing long-term and high-quality climate records over these areas.

To provide a global picture of the sign and magnitude of the estimated changes in extreme indices over all SA and over its four sub-regions: Amazonia (region 7), the NE of Brazil (region 8), W SA (region 9) and SE SA (region 10) (see Appendix 3.A-2 of the IPCC, 2012 for coordinates and Fig. 1 for the adapted borders), we have calculated five (one for all SA and four for its regions) simple area-averaged indices from the available indices series estimated for each region. As stated, the indices trends have been estimated locally for the common period 1969–2009, which has been selected because it was the time interval that also returned a larger number of trends with better cover the northernmost part of SA. They are mainly used for assessing spatial coherency of the emerging signals.

To minimize latitudinal/longitudinal and altitudinal effects on trend estimation for area-averaged indices, we created anomalies with respect to a 1971–2000 reference period for each station series for all indices that are not based on percentiles and whose units are given in absolute quantities (those shown in italics in Table 1). This makes the assessments between stations more comparable given the rich climatic diversity in SA. Also, to adjust the variance bias associated with varying the sample size in these regionally/sub-regionally averaged series over time, we applied the approach developed by Osborn et al. (1997: pp. 92–93) to minimize this bias in the indices time-series.

3. Results and discussion

In this section, we describe the results of the analysis carried out for assessing changes in annual temperature and precipitation extremes over SA, both area-averaged and station-based. First, we examine the spatially-averaged trends for the extreme indices and, second, we provide the results for local trends to assess spatial coherency. Next, we discuss and put our findings in the context of previous assessments.

3.1. Regional and sub-regional trends

Table 2 (Table 3) shows the trend coefficients estimated, along with their significance levels, for each TX and TN (RR) area-averaged indices for the 1950–2010 period at both global-all SA- and sub-regional levels. The calculated ± standard errors for the 95% confidence interval of the extreme indices coefficient trend are given in brackets. Significant signals of warming (wetting and intensified rainfall events) are evident throughout the whole continent (mainly over the eastern part of SA, excluding NE Brazil).

Over all SA, the TN-based indices record faster rates of warming than TX-based indices. Strong reductions (increases) are estimated for cold nights (warm nights), while cold (warm) days shows moderate (weak) downward (upward) trends (significant at the 5% for the latter). Tropical nights (TR20) are also warming at higher rates than summer days (SU25), with TR20 (SU25) recording strong (moderate) upward trends (Table 2). Also the annual coldest night and day and the warmest night show a strong tendency toward higher temperatures, while the warmest day shows no significant change. Reductions in the duration of cold spells (a proxy for cold waves) are also significant over all SA, but increases in warm spells (a proxy for heat waves) are weak and do not reach statistical significance for the continent as a whole. As the TN-based indices change at higher rates than the TX indices, the annual Diurnal Temperature Range (DTR) shows a moderate downward trend over all SA.

Fig. 2 shows annual anomaly series for cold nights and days (Fig. 2a and c) and warm nights and days (Fig. 2b and d) averaged over all SA, depicting the warming signal over the continent as a whole. Fig. 3

Table 2
Annual trends (in days/decade) for the period 1950–2010 for regionally and sub-regionally averaged temperature indices using a robust linear trend estimate along with the ± standard errors in brackets using a 95% confidence interval (see Section 2.3.2 for details). Bold (italic) indicates significance at 0.01 (0.05) levels. AMA stands for Amazonia, NEB for NE Brazil, WSA for western South America and SESA for SE South America.

Index	All SA	AMA (region 7)	NEB (region 8)	WSA (region 9)	SESA (region 10)
TXn	**0.20** (0.11/0.28)	**0.19** (0.09/0.29)	**0.30** (0.14/0.45)	0.07 (−0.03/0.16)	**0.20** (0.05/0.33)
TXx	−0.05 (−0.15/0.06)	**0.12** (0.04/0.18)	**0.34** (0.23/0.46)	0.11 (−0.01/0.24)	*−0.14* (−0.27/−0.01)
TNn	**0.20** (0.09/0.31)	**0.32** (0.24/0.41)	**0.56** (0.37/0.73)	**0.19** (0.07/0.30)	0.13 (0/0.27)
TNx	**0.18** (0.13/0.22)	**0.24** (0.17/0.31)	**0.34** (0.27/0.40)	**0.22** (0.15/0.28)	**0.13** (0.06/0.20)
TX10p	**−0.61** (−0.988/−0.43)	**−0.85** (−1.28/−0.35)	**−2.09** (−2.56/−1.62)	−0.53 (−1.16/0.13)	**−0.52** (−0.83/−0.26)
TX90p	*0.62* (0.10/1.04)	**1.20** (0.67/1.73)	**3.05** (1.94/4.09)	**1.18** (0.61/1.86)	0.44 (−0.05/0.86)
TN10p	**−1.77** (−2.11/−1.49)	**−2.27** (−2.85/−1.81)	**−4.50** (−5.36/−3.68)	**−1.60** (−2.02/−1.10)	**−1.43** (−1.75/−1.13)
TN90p	**1.54** (1.17/1.90)	**2.28** (1.73/2.87)	**4.02** (3.41/4.71)	**1.60** (1.07/2.06)	**1.30** (0.98/1.58)
SU25	*1.26* (0.20/2.18)	**1.60** (0.65/2.44)	**6.94** (5.07/8.71)	**1.46** (0.63/2.37)	0.68 (−0.52/2.14)
TR20	**4.68** (3.81/5.61)	**1.67** (1.32/2.07)	**10.61** (8.61/12.11)	**2.86** (2.02/4.04)	**2.84** (2.13/3.58)
WSDI	0.09 (−0.44/0.72)	**1.05** (0.31/2.13)	**1.78** (0.65/3.90)	0.35 (0.05/0.66)	−0.25 (−0.77/0.30)
CSDI	**−1.09** (−1.45/−0.83)	**−1.92** (−2.94/−1.09)	**−3.74** (−5.50/−2.12)	**−0.81** (−1.24/−0.45)	**−0.64** (−0.84/−0.44)
DTR	**−0.12** (−0.16/−0.07)	**0.40** (0.30/0.56)	−0.07 (−0.19/0.06)	**0.17** (0.07/0.28)	−0.03 (−0.10/0.04)

shows annual time-series for the annual coldest night (Fig. 3a) and coldest day (Fig. 3b), tropical nights (Fig. 3c) and summer days (Fig. 3d). All these indices clearly point to higher temperatures in these annual coldest events and an increasing in the number of days recording values exceeding the 20 °C (25 °C) during night-time (daytime).

On sub-regional scales the largest trends have been estimated over NE Brazil for cold nights (about 27% days decrease in frequency) and warm nights (about 24% days increase in frequency), followed by Amazonia for both indices by averaging 17 and 23 stations respectively. Also increases (decreases) in warm (cold) days are remarkable over NE Brazil: 18% (13%) more (less) frequent and Amazonia with 7% (5%) more (less) frequent. Moderate reductions (increments) in cold (warm) nights and days are evident over W and SE SA, where a network of 26 and 79 stations respectively have been used. Tropical nights and summer days increase over the four sub-regions with lower rates of change for the latter index. Tropical nights (summer days) change faster over NE Brazil and W and SE SA (NE Brazil, Amazonia and W SA). Cold spells show significant reductions over the four sub-regions with the highest rates being estimated over NE Brazil (about 22 days shorter at present than in the 1950s), while warm spells increase significantly over NE Brazil (about 11 days longer), Amazonia and W SA, with the latter being significant at the 5% level. Finally, DTR increased strongly (slightly) over Amazonia (W SA), while weak and non-significant downward trends are estimated over the two remaining regions (Table 2).

Clear and significant wetting and intensified rainfall signals emerge from the analysis of precipitation extreme indices averaged over all SA over 1950 to 2010 (Table 3). Annual total precipitation is strongly increasing when averaged over the whole continent (about 92 mm more rain at present than in the 1950s), which is being accompanied by high rates of upward trends in heavy events. This is particularly evident for increases in events exceeding the 95th percentile (about 92 mm more intense nowadays than in the 1950s), followed by the highest 5-day consecutive rainfall amounts (11 mm more), extremely

wet days (about 36 mm more) and the highest 1-day precipitation (5 mm more intense). Weak increases in the number of consecutive rainy days (0.24 days longer) and in the simple daily intensity (about 0.50 mm more intense wet days) indices cannot explain the strong upward trend in the total amount of annual rainfall, which is more likely related to the intensification seen in the heaviest events, although we have not explored this further. Also, consecutive dry days are increasing though not significantly, suggesting that a wetter continent might be more likely associated with rainfall intensification rather than with an increment in the frequency of wet days >1 mm. Finally, the number of heavy rain (RR > 20 mm = R20) events also moderately increase over all SA (Table 3).

Fig. 4 shows the time-varying annual anomalies for total annual rainfall (Fig. 4a), annual wettest consecutive 5-day precipitation (Fig. 4c), very wet days (Fig. 4b) and extremely wet days (Fig. 4d). All of them show long-term, steady increases between 1950 and 2010. Annual precipitation totals have seen a strong increase up to the mid-1970s followed by stagnation in higher amounts until 2010. Fig. 5 shows the annual anomaly series for R20 (Fig. 5a) and the annual wettest 1-day (Fig. 5b), both recording increases over all SA.

Sub-regional signals show SE SA (103 stations) as the region with the highest rates of change for annual rainfall (about 158 mm wetter than it was in the 1950s), followed by Amazonia (77 stations and about 97 mm higher), while W SA (NE Brazil) sees moderate (weak) but non-significant reductions estimated from a network of 32 and 30 stations respectively. Very wet days and extremely wet days show upward trends that are related to significant increases over Amazonia (SE SA) with about 192 (87) mm higher amounts than in the 1950s. These events are also increasing over W and NE Brazil but they are not statistical significant. The annual wettest day only increases significantly at the 5% level over SE SA (6.24 mm wetter) and Amazonia (4 mm wetter), but over W SA (NE Brazil) the estimated upward (downward) trends are non-significant. For the annual wettest consecutive 5-day events

Table 3
The same as Table 2, but for precipitation indices.

| Index	All SA	AMA (region 7)	NEB (region 8)	WSA (region 9)	SESA (region 10)
Rx1day	**0.86** (0.33/1.37)	*0.67* (0.09/1.1.9)	−0.52 (−2.14/1.10)	0.63 (−0.31/1.64)	*1.04* (0.09/1.97)
Rx5day	**1.86** (0.91/2.72)	*1.10* (0/2.13)	0.29 (−3.58/3.73)	−0.78 (−3.00/1.55)	**2.40** (0.73/3.99)
R20	**0.23** (0.10/0.36)	0.09 (−0.20/0.35)	0.16 (−0.68/0.79)	−0.10 (−0.34/0.11)	**0.52** (0.28/0.79)
CDD	0.25 (−0.27/1.00)	−0.23 (−1.04/0.62)	**−5.58** (−8.98/−2.68)	1.12 (−1.01/3.10)	0.41 (−0.34/1.34)
CWD	0.04 (−0.02/0.11)	0.08 (−0.02/0.16)	−0.07 (−0.17/0.14)	0.02 (−0.17/0.22)	0.05 (0/0.10)
R95p	**15.29** (11.42/19.50)	**32.02** (24.02/39.77)	9.86 (−7.00/25.27)	4.55 (−4.77/12.15)	**14.49** (7.07/21.15)
R99p	**5.95** (3.86/7.52)	**10.65** (7.50/13.75)	5.76 (−1.49/12.63)	1.45 (−2.27/5.52)	**5.66** (3.11/8.33)
SDII	**0.09** (0.03/0.15)	−0.06 (−0.11/0)	0.01 (−0.16/0.18)	0 (−0.15/0.15)	**0.19** (0.08/0.30)
PRCPTOT	**15.40** (5.83/22.71)	**16.09** (0.33/31.85)	−1.42 (−41.71/40.63)	−13.97 (−33.34/3.80)	**26.41** (11.71/42.89)
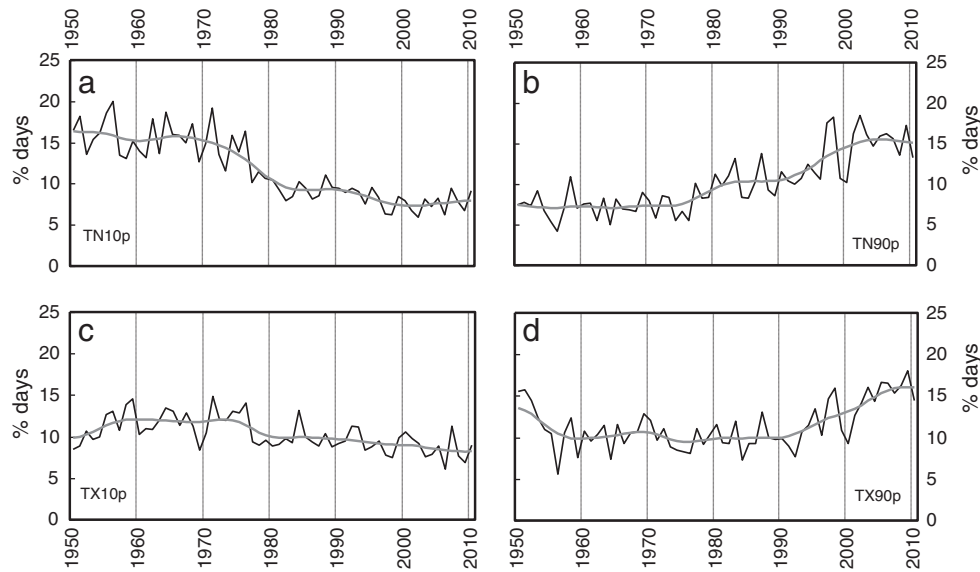
Fig. 2. Annual time-series (1950–2010) of area-averaged temperature indices over all South America for cold nights (Fig. 2a), warm nights (Fig. 2b), cold days (Fig. 2c) and warm days (Fig. 2d). The indices are smoothed with a 13-year Gaussian filter. See Section 2.3.2 for details on trend estimation and adjustment of variance bias associated with varying sample size in the area-averaged indices.

significant increases are found over SE SA and Amazonia (the latter significant at the 5% level), while over W SA (NE Brazil) they are decreasing (increasing) but non-significant. Consecutive wet days (CWD) show weak and non-significant upward trends over the four sub-regions except NE of Brazil. CDD, a proxy for dryness, shows significant reductions over the NE of Brazil (33 days longer than in the 1950s) and Amazonia (although non-significant) and over W and SE SA consecutive dry days are increasing but not significantly. The SDII index increase only over SE SA (about 3 mm more intense), while weak but non-significant increases are seen in the remaining sub-regions except W SA where no change is

found. A similar signal is found for heavy events (RR > 20 mm), with a moderate upward trend over SE SA (3 days more than in the 1950s), while in the other sub-regions except W SA, heavy rainfall events are increasing but not significantly (Table 3).

3.2. Local trends for temperature and precipitation extreme indices

A summary of the sign of the trend and its significance for all the locally estimated indices are given in Table 4. Indices that represent warming such as cold night reductions, warm night and tropical night
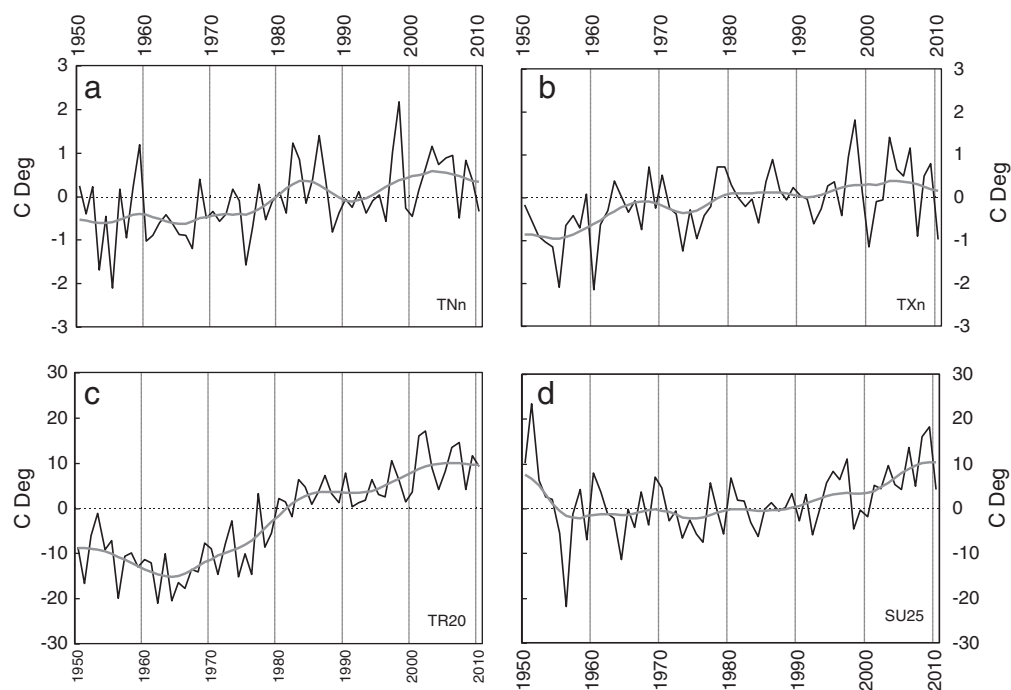

Fig. 3. Annual anomaly (with respect to the 1971–2000 reference period) between 1950 and 2010 of area-averaged temperature indices for South America and for the annual lowest night-time (Fig. 3a) and daytime (Fig. 3b) temperatures, tropical nights (Fig. 3c) and summer days (Fig. 3d).
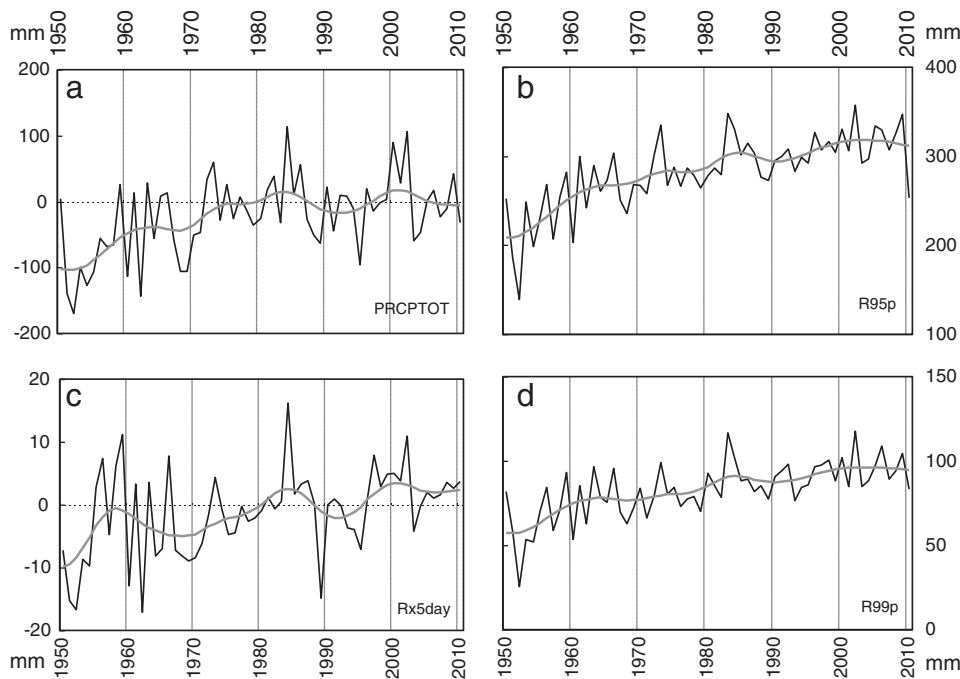
Fig. 4. The same as Fig. 3 but for total annual rainfall (Fig. 4a) and annual maximum consecutive 5-day precipitation (Fig. 4c), and the same as Fig. 2 but for very wet days (Fig. 4b) and extremely wet days (Fig. 4d) indices.

increases have more significant than non-significant local trends. No rain-based index shows more significant than non-significant trends.

Fig. 6 shows local trends for cold nights and days and for warm nights and days. Both generalized reductions (increases) in the frequency of cold (warm) nights and days over most of the South American locations are evident with a high spatial coherency of the signals, particularly for cold nights. Downward trends are strong over the northern and western parts of SA, while SE SA also sees moderate and weak reductions, some of them not significant. A few differences to this are the local non-significant trends seen over eastern Uruguay, south Argentina, Chile, Paraguay, Peru and northwest Brazil (Fig. 6 upper left plot). Further research is required to assess whether this is due to the complex topography at these stations or whether homogenization issues could explain them. Similar spatial patterns and signals, although weaker, have been established for cold days (Fig. 6 upper right panel) with strong negative trends in the northern part of SA, while the southern part sees mostly non-significant reductions. Similar patterns (strong increases in the north and weak in the southern parts of SA) are found for warm nights (Fig. 6 bottom left panel). Warm days show a general increase over the northern part of SA, while the southern part has mostly non-significant (both increasing and decreasing) trends (Fig. 6 bottom right plot).

Fig. 7 shows local trends for tropical nights, summer days and the annual lowest night-time and daytime temperatures. Tropical nights

mostly record increases, with a few spatially incoherent trends in southern Paraguay and central Argentina (Fig. 7 upper left panel). Generalized and significant increases are estimated for summer days, except for a subset of stations (Fig. 7 bottom left panel). A stronger warming signal is seen over SE Brazil and over southern SA with a similar spatial pattern to that estimated for tropical nights. TNn (upper right panel) and TXn indices (bottom right panel) show consistent and generalized changes toward higher values of both the annual lowest nighttime and daytime temperatures over all SA, particularly in the northern half of the continent with most being moderate and significant upward trends. This indicates a consistent warming signal in warmest nights and days.

Trends (both upward and downward) in precipitation indices at station locations are mostly non-significant. This much more contrasting pattern compared to the temperature indices is expected given that precipitation has higher temporal and spatial variability. This characteristic, however, does not contradict the clear wetting signal that emerged from our assessment at the regional and sub-regional scales, since averaging across locations increases the signal to noise ratio.

Fig. 8 shows rates of change for PRCPTOT (which can be used as baseline to place observed changes in other precipitation extreme indices in context), heavy events (such as the R95p, Rx1day, R99p or Rx5day) and CDD indices.
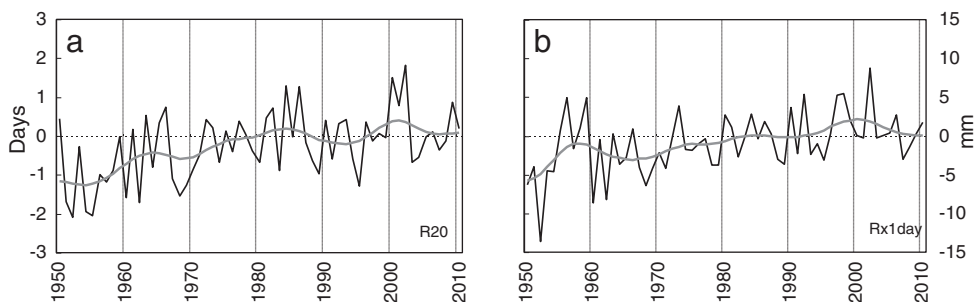

Fig. 5. The same as Fig. 3 but for the number of heavy rainy days >20 mm (Fig. 5a) and the annual wettest day (Fig. 5b).

Table 4

Number of stations for which each index has returned significant negative and positive trends (at the 5% level), along with non-significant trends for the annual temperature and precipitation station-based indices over 1969–2009.

Index ID	Negative	Positive	Non-significant
TXx	3	41	89
TNx	1	54	81
TXn	0	28	105
TNn	3	41	93
TN10p	91	1	39
TX10p	50	2	75
TN90p	0	83	48
TX90p	2	53	73
DTR	31	6	84
SU25	2	37	89
TR20	2	52	46
WSDI	–	19	44
CSDI	1	5	10
Rx1day	3	6	161
Rx5day	4	10	155
SDII	7	16	151
R20	5	16	149
CDD	3	16	154
CWD	6	6	160
R95p	3	12	156
R99p	1	13	138
PRCPTOT	5	11	158

For PRCPTOT (Fig. 8 upper left panel), both strong to moderate (moderate to weak) upward (downward) trends, mostly non-significant, are evident. In general there are widespread mostly non-significant increases over SA in very wet days and extremely wet days (Fig. 8 upper middle panel and upper right panel respectively). Very wet days have a less spatially consistent wetting signal than extremely wet days, since the latter records general upward trends over all SA with a few significant and moderate trends. Changes in both extreme indices are clear and spatially coherent indicators of the intensification of the heaviest events over the continent.

The annual wettest consecutive 5-day and 1-day precipitation have less spatially consistent patterns (Fig. 8 bottom left panel and bottom middle panel respectively). The dominant signal is a tendency toward higher amounts in both indices despite many moderate to low (low to moderate) and non-significant downward trends in Rx5-day (Rx1-day). Finally, local trends for consecutive dry days (Fig. 8 bottom right panel) show mostly upward trends, some significant with strong rates of change, although downward non-significant trends are also present.

3.3. Discussion

Previous studies of South American temperature and precipitation extremes have used a variety of networks and time periods for their assessments. This study can be used to highlight some of the similarities and differences with those other assessments where either similar timescales or similar networks were used.

Reasonable agreement with our findings for temperature indices and those reported by Vincent et al. (2005) is found. This is particularly true for cold and warm nights and to a lesser extent for cold days mainly over southern and western SA (see Fig. 3c, 3d p. 5018 and Fig. 2c p. 5017 in Vincent et al., 2005). However, this cannot be stated for changes in warm days (Vincent et al., 2005: Fig. 2d, p. 5017). Our findings point to strong warming over northern SA and weak upward trends over southern SA in contrast to the previous study which showed mixed signals (both warming and cooling) over all SA, especially over Argentina where we have mainly estimated weak upward trends. For the regionally averaged indices, there is good agreement for cold and warm nights (Vincent et al., 2005, Fig. 5c and 5d, p. 5020 respectively), while cold and warm days (Fig. 5a and b p. 5020) show less vigorous warming than in this study. Good agreement is also found between both assessments for upward trends in tropical

nights and summer days (Vincent et al., 2005: Fig. 3b p. 5018 and Fig. 2a p. 5017), although some disagreement in a few Argentinean, Paraguayan and Uruguayan locations can be seen for summer days.

Comparing findings for smaller scales (e.g. for Uruguay from Rusticucci and Renom, 2008: p. 1086, 1088), similar weak downward (upward) trends for cold nights and days (warm nights) to our findings are seen, although neither study finds statistical significance. Also our findings point to weak and non-significant increases in warm days, while their assessment indicated decreases. However, the highlighted differences in trends between our study and the previous studies discussed can be explained not only by the different networks used, but also because of the differences in length of periods assessed.

Also, there is good agreement between our results for local trends in precipitation indices when compared with those from Haylock et al. (2006) for all SA, bearing in mind the differences highlighted above on the variety of locations and periods assessed. Most of the local trends for PRCPTOT, Rx1day, Rx5day, R95p and CDD indices in Haylock et al. (2006: Fig. 2, p. 1497) show strong similarities to our findings. However, for the R99p index, our results indicate general increases across SA while the previous study showed mixed trends. They show similar contrasting spatial patterns with mixed upward and downward trends, although differences between statistical significance of trends between both assessments must be highlighted, since the previous study estimated more significant local trends than those calculated by us.

Other agreement also occurs in the annual evolution of area-averaged precipitation indices between both assessments. Haylock et al., 2006 (Fig. 3 p. 1498 and Fig. 4 p. 1499) show time-series of R20 and R99 indices for the four quadrants of the continent (NW, NE, SE and SW) and found significant trends over the SE quadrant for both indices, while in our assessment both indices show upward and significant trends over SE SA, although they are stronger over Amazonia (a region with a non-significant trend in the previous study due to the highly sparse data).

4. Summary and outlook

In this study we have analyzed changes in temperature and precipitation extremes by using an extended network of daily quality controlled, homogeneity tested or homogenized records over South America covering the 2nd half of the 20th century up to 2010. The time-series assessed, however, present a number of problems.

Lack of multi-decadal time-series at the daily scale over most of the SA countries is one issue which is still hampering our knowledge on how and by how much extremes are changing under climate change. Another serious problem in the continent is climate series completeness, since large amounts of missing periods and values are a common characteristic of South American daily data. This has had a negative impact on the computation of the ETCCDI extreme indices used in our study, especially for temperature-based indices in general and percentile-based indices in particular.

Despite WMO Resolution 40 on the free exchange of meteorological and related historical data, accessibility of long-term and high-quality climate records with an appropriate time resolution is a major issue, since data sharing is restricted due to national policies that preclude data exchange. Access to these data is an essential requirement before we can confidently detect or predict climate variability and change (e.g. Brunet and Jones, 2011: pp. 30–34; Thorne et al., 2011: pp. 4–6). Therefore, there is still a need to promote data rescue and data development activities at both the international and national level in order to improve observed and projected changes in extremes over SA.

Even given the above mentioned problems, this assessment has improved our knowledge of the spatial and temporal changes in temperature and precipitation extremes over all SA and its regions than was possible in previous studies. Nevertheless, we are aware that our study and findings are limited both in time and space, since we
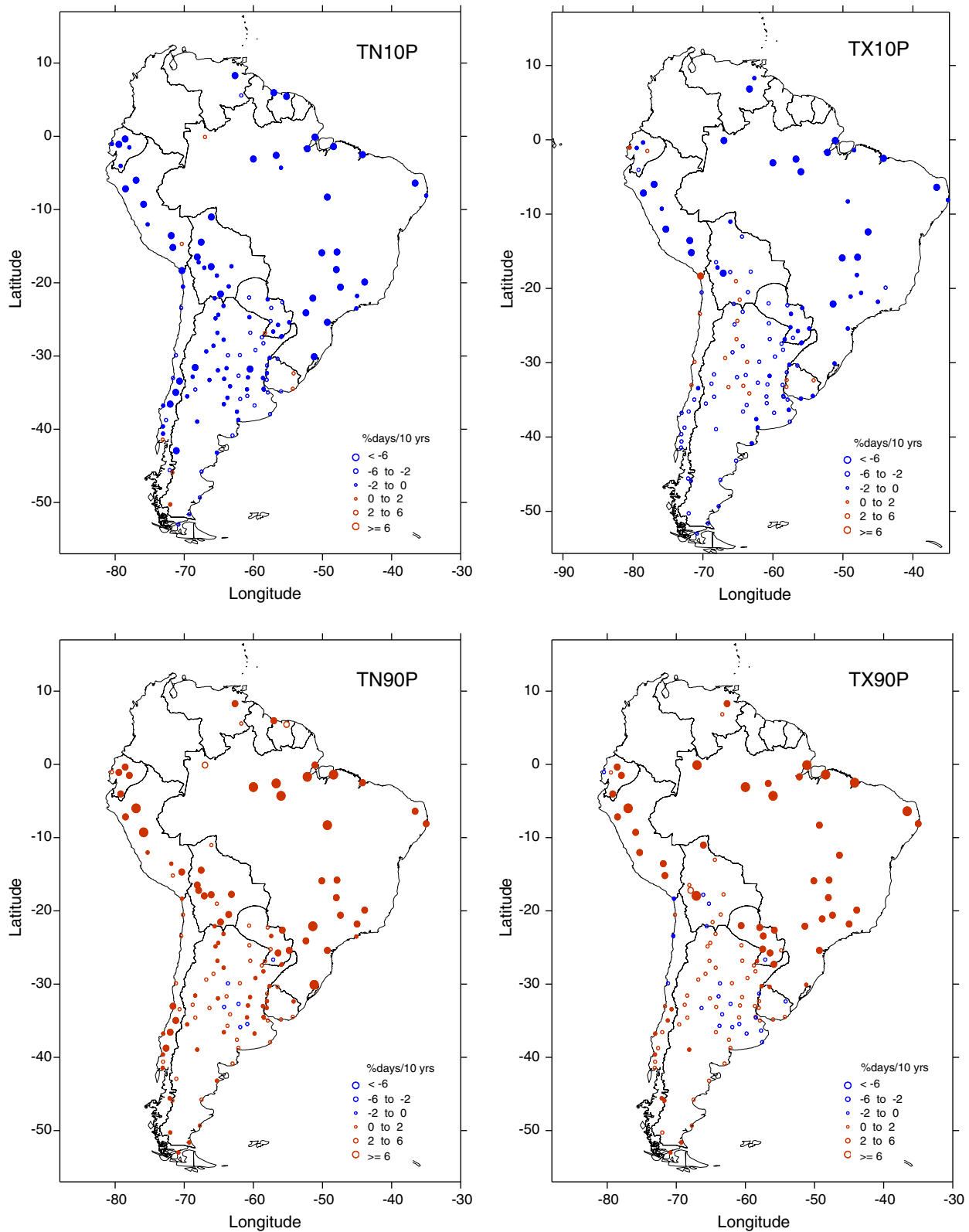
Fig. 6. Local robust trends estimated annually for the 1969–2009 period for cold nights (upper left plot), cold days (upper right panel), warm nights (bottom left panel) and warm days (bottom right panel), all showing warming. See Section 2.3.2 for details on trend estimation.

do not explore changes at the intra-annual scale (e.g. monthly and seasonal), or using the whole distribution of data, or provide results at fine spatial scales (e.g. national and sub-national).

In line with global assessments (Alexander et al., 2006; Donat et al., submitted for publication) which found that the world is becoming substantially less cold, SA has experienced widespread decreases in cold extremes (e.g. cold nights and days, the annual lowest TN and TX values, cold spells) along with increases, although less marked, in warm extremes (e.g. warm days, the annual highest TX and TN values or warm spells).
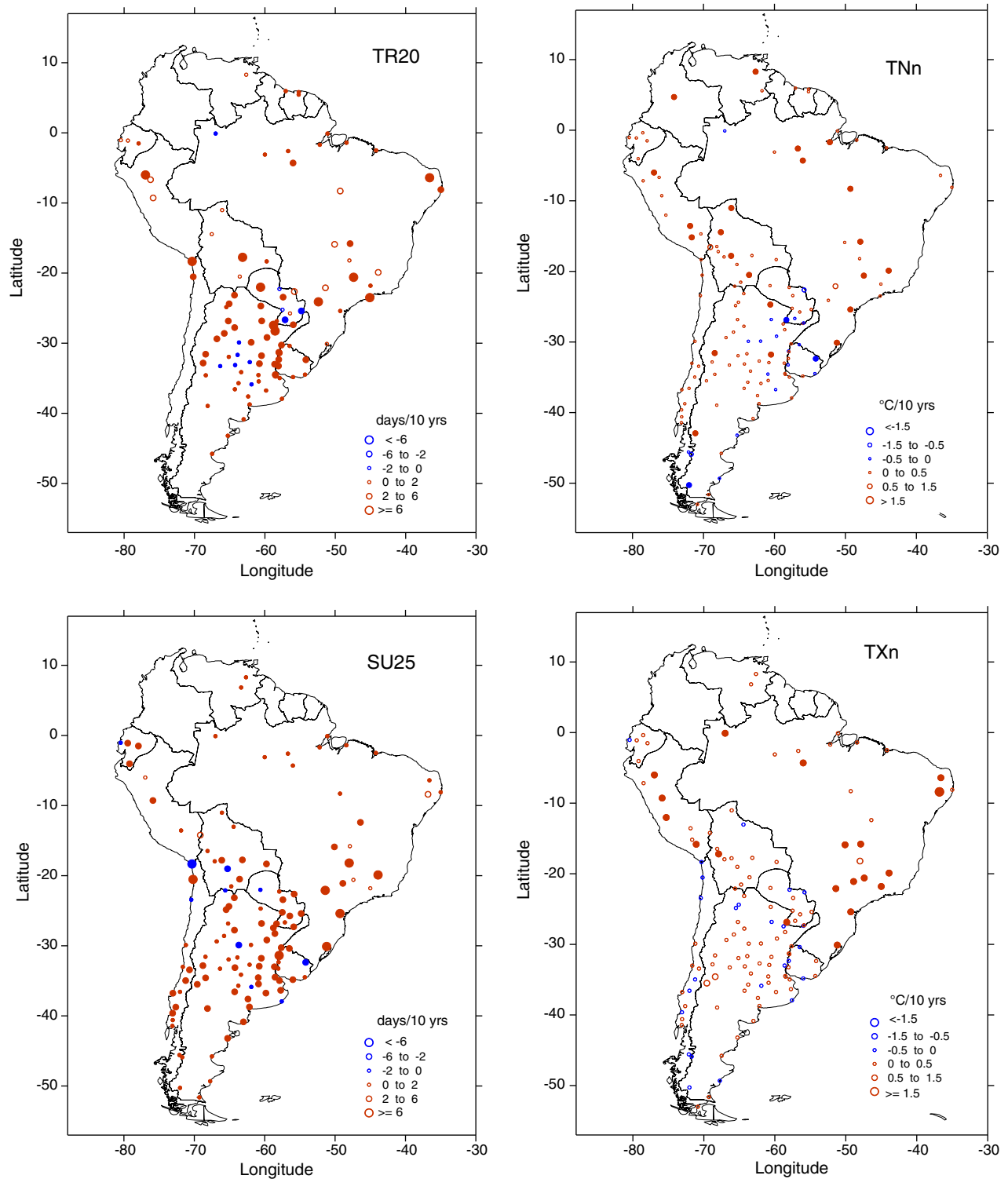
Fig. 7. The same as Fig. 6 but for tropical nights (upper left panel), summer days (bottom left panel), and the annual lowest night time (upper right plot) and daytime (bottom right plot) temperatures.

SA is also becoming wetter as a whole, with Amazonia and SE SA leading the increases in the total amount of annual precipitation. This upward trend seems to be more related to intensification of heavy rainfall (particularly over Amazonia and SE SA) than to increases in the duration or frequency of consecutive wet days. Significant increases in consecutive dry days also point to this feature.

Many of the principal findings on global changes in climate extremes have resulted from ETCCDI regional workshops. It is hoped that in the near future that up-to-date data availability and accessibility will evolve towards accessible and user-friendly platforms such as those produced for the European Climate Assessment and Dataset (ECA&D) project for Europe (http://eca.knmi.nl/). There are potential opportunities to build up a South American portal using the same
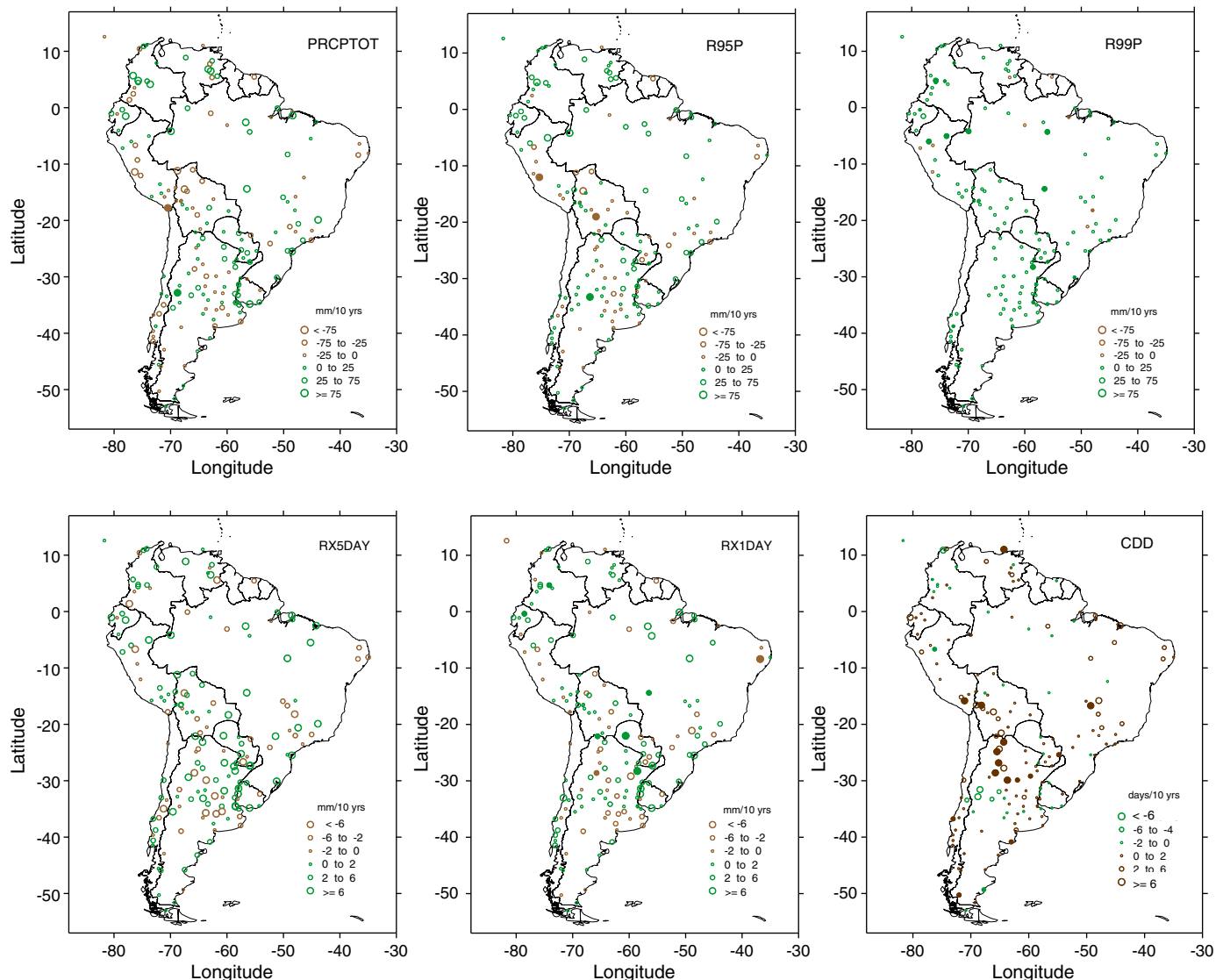
Fig. 8. The same as Fig. 6 but for annual total rainfall (upper left panel), very wet days (upper central panel), extremely wet days (upper right panel), annual maximum consecutive 5-day precipitation (bottom left panel), annual maximum 1-day precipitation (bottom central panel) and consecutive dry days (bottom right panel).

technology, software and experience as in ECA&D. This endeavor will need both adequate support and increased interaction with all South American NMHSs to ensure adequate data provision to enable a robust climate service to a wide community of users.

Finally, the climate series used in this study are accessible from the websites of the Brazilian, Chilean and Venezuelan NMHSs, while those belonging to the NMHSs in Bolivia, Colombia, Ecuador and Peru will be made accessible through the WSACAD (Western South America Climate Assessment & Dataset) portal once implemented on-line. Finally, the series from Argentina, Paraguay, Suriname and Uruguay NMHSs are accessible under request from the relevant NMHS.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gloplacha.2012.11.004.

References

Aguilar, E., 2010. Manual de uso de RSNHT.R (software de homogenización del Center for Climate Change, URV, Tarragona, España), Centre for Climate Change self-editing, Tarragona. (12 pp. Available at: http://www.c3.urv.cat/data/manual/manual_rsnht.pdf and accessed on the 20th July 2012).

Aguilar, E., Sigró, J., Brunet, M., 2010. RCLIMDEX con funcionalidades extras de Control de Calidad. Manual de Uso, versión 1.0, Centre for Climate Change self-editing, Tarragona. (20 pp. Available at: http://www.c3.urv.cat/data/manual/Manual_rclimdex_extraQC.r.pdf and accessed on the 20th July 2012).

Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A.M.G., Haylock, M., Collins, D., Trewin, B., Rahimzdeh, F., Tagipour, A., Kumar Kolli, R., Revadekar, J.V., Griffiths, G., Vincent, L., Stephenson, D.B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M., Vazquez Aguirre, J.L., 2006. Global observed changes in daily climate extremes of temperature and precipitation. Journal of Geophysical Research-Atmospheres 111, D05109 http://dx.doi.org/10.1029/2005JD006290.

Alexandersson, H., Moberg, A., 1997. Homogenization of Swedish temperature data. 1. Homogeneity test for linear trends. International Journal of Climatology 17, 25–34.

Barrucand, M., Rusticucci, M., Vargas, W., 2008. Temperature extremes in the south of South America in relation to Atlantic Ocean surface temperature and Southern Hemisphere circulation. Journal of Geophysical Research 113, D20111 http://dx.doi.org/10.1029/2007JD009026.

Brown, S.J., Caesar, J., Ferro, C.A.T., 2008. Global changes in extreme daily temperature since 1950. Journal of Geophysical Research-Atmospheres 113, D05115.

Brunet, M., Jones, P.D., 2011. Emerging data rescue initiatives: bringing historical climate data into the 21st century. Climate Research 47, 29–40 http://dx.doi.org/10.3354/cr00960.

Dai, A., 2011. Drought under global warming: a review. Wiley Interdisciplinary Reviews: Climate Change 2 (1), 45–65.

Donat, M.G., Alexander, L.V., Yang, H., Durre, I., Vose, R., Dunn, R. Willett, K., Aguilar, E. Brunet, M., Caesar, J., Hewitson, B., Jack, C., Klein Tank, A.M.G., Kruger, A.C., Marengo, J., Peterson, T.C., Renom, M., Oria Rojas, C., Rusticucci, M., Salinger, J., Sekele, S.S., Srivastava, A.K., Trewin, B., Villarroel, C., Vincent, L.A., Zhai, P., Zhang, X., Kitching, S., submitted for publication. Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. Journal of Geophysical Research — Atmospheres.

Dufek, A.S., Ambrizzi, T., 2008. Precipitation variability in Sao Paulo State, Brazil. Theoretical and Applied Climatology 93 (3–4), 167–178.

Dufek, A.S., Ambrizzi, T., da Rocha, R.P., 2008. Are reanalysis data useful for calculating climate indices over South America? Trends and Directions in Climate Research: In: Gimeno, L., Garcia-Herrera, R., Trigo, R.M. (Eds.), Annals of the New York Academy of Sciences, New York, NY, USA, vol. 1146, pp. 87–104.

Falvey, M., Garreaud, R.D., 2009. Regional cooling in a warming world: recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006). Journal of Geophysical Research 114, D04102 http://dx.doi.org/10.1029/2008JD010519.

Grimm, A.M., Tedeschi, R.G., 2009. ENSO and extreme rainfall events in South America. Journal of Climate 22, 1589–1609 http://dx.doi.org/10.1175/2008JCLI2429.1, 2009.

Haylock, M.R., Peterson, T.C., Alves, L.M., Ambrizzi, T., Anunciação, Y.M.T., Baez, J., Barros, V.R., Berlato, M.A., Bidegain, M., Coronel, G., Corradi, V., Garcia, V.J., Grimm, A.M., Karoly, D., Marengo, J.A., Marino, M.B., Moncunill, D.F., Nechet, D., Quintana, J., Rebello, E., Rusticucci, M., Santos, J.L., Trebejo, I., Vincent, L.A., 2006. Trends in total and extreme South American rainfall 1960–2000 and links with sea surface temperature. Journal of Climate 19, 1490–1512.

IPCC, 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA (582 pp.).

Kendall, M.G., 1955. Rank Correlation Methods. Oxford Univ. Press, New York.

Khan, S., Kuhn, G., Ganguly, A.R., Erickson III, D.J., Ostrouchov, G., 2007. Spatio-temporal variability of daily and weekly precipitation extremes in South America. Water Resources Research 43, W11424 http://dx.doi.org/10.1029/2006WR005384.

Klein Tank, A.M.G., Zwiers, F.W., Zhang, X., 2009. Guidelines on Analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation, WMO-TD No. 1500/WCDMP-No. 72, Geneva . (52 pp.).

Llano, M.P., Penalba, O.C., 2011. A climatic analysis of dry sequences in Argentina. International Journal of Climatology 31, 504–513 http://dx.doi.org/10.1002/joc.2092.

Marengo, J.A., Camargo, C.C., 2008. Surface air temperature trends in southern Brazil for 1960–2002. International Journal of Climatology 28, 893–904 http://dx.doi.org/10.1002/joc.1584.

Marengo, J.A., Rusticucci, M., Penalba, O., Renom, M., 2009. An intercomparison of observed and simulated extreme rainfall and temperature events during the last half of the twentieth century: part 2: historical trends. Climatic Change 98 (3–4), 509–529.

Mo, K.C., Berbery, E.H., 2011. Drought and persistent wet spells over South America based on observations and the U.S. CLIVAR Drought Experiments. Journal of Climate 24, 1801–1820 http://dx.doi.org/10.1175/2010JCLI3874.1.

Osborn, T.J., Briffa, K.R., Jones, P.D., 1997. Adjusting variance for sample-size in tree-ring chronologies and other regional mean time series. Dendrochronologia 15, 89–99.

Penalba, O.C., Robledo, F.A., 2010. Spatial and temporal variability of the frequency of extreme daily rainfall regime in the La Plata Basin during the 20th century. Climate Change 98 (3–4), 531–550.

Peterson, T.C., Manton, M.J., 2008. Monitoring changes in climate extremes: a tale of international collaboration. Bulletin of the American Meteorological Society 2008, 1266–1271 http://dx.doi.org/10.1175/2008BAMS2501.1 (September).

Pscheidt, I., Grimm, A.M., 2009. Frequency of extreme rainfall events in southern Brazil modulated by interannual and interdecadal variability. International Journal of Climatology 29, 1988–2011 http://dx.doi.org/10.1002/joc.1799.

Renom, M., 2009. Temperaturas extremas en Uruguay. Análisis de la variabilidad temporal de baja frecuencia y su relación con la circulación de gran escala, Ph.D. thesis, Universidad de Buenos Aires, Buenos Aires (Argentina), 166 pp. Available at: www.digital.bl.fcen.uba.ar and accessed on the 20th July 2012.

Rosenbluth, B., Fuenzalida, H.A., Aceituno, P., 1997. Recent temperature variations in southern South America. International Journal of Climatology 17 (1), 67–85.

Rusticucci, M., 2012. Observed and simulated variability of extreme temperature events over South America. Atmospheric Research 106 (2012), 1–17 http://dx.doi.org/10.1016/j.atmosres.2011.11.001.

Rusticucci, M., Barrucand, M., 2004. Observed trends and changes in temperature extremes over Argentina. Journal of Climate 17 (20), 4099–4107.

Rusticucci, M., Renom, M., 2008. Variability and trends in indices of quality controlled daily temperature extremes in Uruguay. International Journal of Climatology 28 (8), 1083–1095.

Santos, C.A., Brito, J.I.B., 2007. Análise dos índices de extremos para o semiárido do Brasil e suas relações com TSM e IVDN. Revista Brasileira de Meteorologia 22 (3), 303–312.

Santos, C.A.C., Brito, J.I.B., Rao, T.V.R., Meneses, E.A., 2009. Tendências dos Índices de precipitação no Estado do Ceará. Revista Brasileira de Meteorologia 24 (1), 39–47.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association 63, 1379–1389.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., 2012. Changes in climate extremes and their impacts on the natural physical environment. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109–230.

Sheffield, J., Wood, E.F., 2008. Global trends and variability in soil moisture and drought characteristics, 1950–2000, from observation-driven simulations of the terrestrial hydrologic cycle. Journal of Climate 21 (3), 432–458.

Silva, A.G., Azevedo, P., 2008. Índices de tendências de Mudanças Climáticas no Estado da Bahia. Engenheiria Ambiental 5, 141–151.

Teixeira, M.S., Satyamurty, P., 2011. Trends in the frequency of intense precipitation events in southern and southeastern Brazil during 1960–2004. Journal of Climate 24 http://dx.doi.org/10.1175/2011JCLI3511.1.

Tencer, B., 2010. Variabilidad de los eventos extremos de temperatura observados y modelados en el sudeste de Sudamérica, y sus proyecciones ante un escenario de cambio climático, Ph.D. thesis, Universidad de Buenos Aires, Buenos Aires (Argentina), 100 pp. Available at: www.digital.bl.fcen.uba.ar and accessed on the 20th July 2012.

Thorne, P.W., Willett, K.M., Allan, R.J., Bojinski, S., Christy, J.R., Fox, N., Gilbert, S., Jolliffe, I., Kennedy, J.J., Kent, E., Klein Tank, A., Lawrimore, J., Parker, D.E., Rayner, N., Simmons, A., Song, L., Stott, P.A., Trewin, B., 2011. Guiding the creation of a comprehensive surface temperature resource for 21st century climate science. BAMS http://dx.doi.org/10.1175/2011BAMS3124.1.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Solden, B., Zhai, P., 2007. Observations: surface and atmospheric climate change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, pp. 235–336.

Vincent, L.A., Zhang, X., Bonsal, B.R., Hong, W.D., 2002. Homogenization of daily temperatures over Canada. Journal of Climate 15, 1322–1334.

Vincent, L.A., Peterson, T.C., Barros, V.R., Marino, M.B., Rusticucci, M., Carrasco, G., Ramirez, E., Alves, L.M., Ambrizzi, T., Berlato, M.A., Grimm, A.M., Marengo, J.A., Molion, L., Moncunill, D.F., Rebello, E., Anunciação, Y.M.T., Quintana, J., Santos, J.L., Baez, J., Coronel, G., Garcia, J., Trebejo, I., Bidegain, M., Haylock, M.R., Karoly, D., 2005. Observed trends in indices of daily temperature extremes in South America 1960–2000. Journal of Climate 18, 5011–5023.

Vose, R.S., Easterling, D.R., Gleason, B., 2005. Maximum and minimum temperature trends for the globe: an update through 2004. Geophysical Research Letters 32, L23822.

Wang, X.L., Chen, H., Wu, Y., Feng, Y., Pu, Q., 2010. New techniques for the detection and adjustment of shifts in daily precipitation data series. Journal of Applied Meteorology and Climatology 49, 2416–2436 http://dx.doi.org/10.1175/2010JAMC2376.1.

Zhang, X., Vincent, L.A., Hogg, W.D., Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean 38, 395–429.

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

Zhang, X., Alexander, L.V., Hegerl, G.C., Klein-Tank, A., Peterson, T.C., Trewin, B., Zwiers, F.W., 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. Wiley Interdisciplinary Reviews: Climate Change 2, 851–870 http://dx.doi.org/10.1002/wcc.147.

Zwiers, F.W., Alexander, L.V., Hegerl, G.C., Knutson, T.R., Naveau, P., Nicholls, N., Schär, C., Seneviratne, S.I., Zhang, X., 2011. Community paper on climate extremes. Challenges in Estimating and Understanding Recent Changes in the Frequency and Intensity of Extreme Climate and Weather Events, World Climate Research Programme Open Science Conference, 24–28 October 2011, Denver, CO, USA (45 pp. Available at http://www.isse.ucar.edu/extremevalues/wcrpextr.pdf and accessed on the 20th July 2012).