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Evidence of trends in daily climate extremes over southern and west Africa

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[1] There has been a paucity of information on trends in daily climate and climate extremes, especially from developing countries. We report the results of the analysis of daily temperature (maximum and minimum) and precipitation data from 14 south and west African countries over the period 1961–2000. Data were subject to quality control and processing into indices of climate extremes for release to the global community. Temperature extremes show patterns consistent with warming over most of the regions analyzed, with a large proportion of stations showing statistically significant trends for all temperature indices. Over 1961 to 2000, the regionally averaged occurrence of extreme cold (fifth percentile) days and nights has decreased by −3.7 and −6.0 days/decade, respectively. Over the same period, the occurrence of extreme hot (95th percentile) days and nights has increased by 8.2 and 8.6 days/decade, respectively. The average duration of warm (cold) has increased (decreased) by 2.4 (0.5) days/decade and warm spells. Overall, it appears that the hot tails of the distributions of daily maximum temperature have changed more than the cold tails; for minimum temperatures, hot tails show greater changes in the NW of the region, while cold tails have changed more in the SE and east. The diurnal temperature range (DTR) does not exhibit a consistent trend across the region, with many neighboring stations showing opposite trends. However, the DTR shows consistent increases in a zone across Namibia, Botswana, Zambia, and Mozambique, coinciding with more rapid increases in maximum temperature than minimum temperature extremes. Most precipitation indices do not exhibit consistent or statistically significant trends across the region. Regionally averaged total precipitation has decreased but is not statistically significant. At the same time, there has been a statistically significant increase in regionally averaged daily rainfall intensity and dry spell duration. While the majority of stations also show increasing trends for these two indices, only a few of these are statistically significant. There are increasing trends in regionally averaged rainfall on extreme precipitation days and in maximum annual 5-day and 1-day rainfall, but only trends for the latter are statistically significant.

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1. Introduction

[2] Since the second Intergovernmental Panel on Climate Change (IPCC, http://www.ipcc.ch) report highlighted the paucity of information on trends and variability in daily

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Table 1. Stations Included in Analysis[a]

Country	WMO Number	Station Name	Latitude	Longitude	Start Year	End Year
Botswana	68244	Gaborone	−24.4	25.55	1961	2000
Botswana	68054	Francistown	−21.1	27.31	1961	2000
Botswana	68148	Mahalapye	−23.07	26.5	1961	2000
Botswana	68226	Tshane	−24.01	21.53	1961	2000
Botswana	68328	Tsabong	−26	22.24	1961	2000
Malawi	67489	Mzuzu	−11.43	34.02	1961	2000
Malawi	67693	Chileka	−15.4	34.58	1938	2000
Seychelles	63980	Mahe-SIA	−4.4	55.3	1972	2003
Tanzania	63894	Dia	−6.8	39.1	1961	2003
Tanzania	63862	Dodoma	−6.17	35.77	1961	2003
Tanzania	63932	Mbeya	−8.93	33.47	1961	1990
Tanzania	63790	Moshi	−3.35	37.33	1961	1990
Tanzania	63856	Mwanza	−2.47	32.92	1961	1990
Tanzania	63971	Mtwara	−10.35	40.18	1961	1990
Tanzania	63832	Tabora	−5.1	32.8	1961	2003
Zambia	67561	Ndola	−13	28.4	1961	2000
Zambia	67743	Livingstone	−17.5	25.5	1961	2000
Zambia	67663	Kabwe	−14.45	28.47	1961	2000
Zambia	67475	Kasama	−10.13	31.1	1961	1999
Zambia	67461	Mansa	−11.1	28.85	1967	1999
Zambia	67551	Solwezi	−12.17	26.36	1961	1998
Zambia	67633	Mongu	−15.5	23.1	1961	2000
Zambia	67665	Lusaka	−15.32	28.45	1961	2000
Zambia	67581	Chipata	−13.55	32.6	1961	2000
Zimbabwe	67991	Beitbridge	−22.28	29.9	1951	2002
Zimbabwe	67774	Hre-Belvedere	−17.9	31.13	1951	2002
Zimbabwe	67983	Chipinge	−20.2	32.62	1951	2002
Zimbabwe	67964	Byo-Goetz	−20.02	28.61	1951	2002
South Africa	-	Addo	−33.97	25.7	1959	2000
South Africa	68816	Cape Town	−33.97	18.6	1956	2000
South Africa	-	Emarald Dale	−29.93	29.95	1960	2000
South Africa	-	Glen College	−28.95	26.33	1959	2000
South Africa	-	Langgewens	−33.28	18.7	1959	2000
South Africa	68842	Port Elizabeth	−33.98	25.62	1958	2000
South Africa	-	Pretoria PUR	−25.73	28.17	1959	2000
South Africa	68424	Upington	−28.42	21.27	1953	2000
Lesotho	68452	Mokhotlong	−29.28	29.07	1960	2001
Lesotho	-	Butha-Buthe	−28.76	28.4	1960	2001
Lesotho	68454	Maseru	−29.3	27.5	1960	2000
Lesotho	-	Teyateyaneng	−29.15	27.73	1960	2001
Lesotho	-	Leribe	−28.88	28.05	1960	2001
Uganda	63654	Masindi	1.68	31.72	1950	2003
Uganda	63682	Jinja Met St.	0.45	33.18	1903	2003
Uganda	63702	Mbarara met	−0.6	30.68	1951	2003
Uganda	63630	Gulu met St	2.78	32.28	1937	2003
Mozambique	67297	Beira	−19.8	34.9	1964	2003
Mozambique	67295	Chimoio	−19.08	33.5	1951	2003
Mozambique	67323	Inhambane	−23.9	35.5	1951	2003
Mozambique	67217	Lichinga	−13.22	35.18	1951	2003
Mozambique	67341	Maputo/Mavalane	−25.58	32.53	1951	2003
Mozambique	67237	Nampula	−15.1	39.3	1956	2003
Mozambique	67215	Pemba	−13	40.5	1951	2004
Nigeria	65208	Ibadan	7.43	3.9	1961	2000
Nigeria	65046	Kano	12.05	8.53	1961	2000
Nigeria	65201	Lagos Ikeja	6.58	3.33	1961	2000
Nigeria	65101	Ilorin	8.48	4.58	1961	2000
Gambia	61701	Yundum	13.35	−16.63	1945	2002
Gambia	61721	Janjanbureh	13.53	−14.77	1948	2002
Namibia	68110	Windhoek	−22.6	17.1	1913	2003
Namibia	68014	Grootfontein	−19.6	18.1	1917	2003
Namibia	68106	Gobabeb	−23.6	15.1	1962	2003
Namibia	68312	Keetmanshoop	−26.5	18.1	1949	2003
Mauritius	61988	Rodrigues	−19.7	63.4	1961	2004

[a] Those without WMO numbers are not listed in the WMO list of stations [*World Meteorological Organisation*, 2005].

climate and climate extremes [*Nicholls et al.*, 1996], a number of studies documenting such changes have emerged, both for specific countries [e.g., *Alexander et al.*, 2006; *Frei and Schar*, 2001; *Karl and Knight*, 1998; *Osborn et al.*, 2000; *Sen Roy and Balling*, 2004] and synthesizing information across regions and globally [*Alexander et al.*, 2006; *Frich et al.*, 2002; *Groisman et al.*, 1999; *Karl et al.*, 1995; *Kiktev et al.*, 2003; *Moberg et*

Table 2. Precipitation Indices Calculated by RClimDex RR is the Daily Rainfall Rate[a]

Index	Descriptive Name	Definition	Units
PRCPTOT	wet day precipitation	annual total precipitation from wet days	mm
SDII	simple daily intensity index	average precipitation on wet days	mm/d
CDD	consecutive dry days	maximum number of consecutive dry days	days
CWD	consecutive wet days	maximum number of consecutive wet days	days
R10mm	heavy precipitation days	annual count of days when RR >= 10	days
R20mm	very heavy precipitation days	annual count of days when RR >= 20	days
R95p	very wet day precipitation	annual total precipitation when RR > 95th percentile of 1961–1990 daily rainfall	mm
R99p	extremely wet day precipitation	annual total precipitation when RR > 99th percentile of 1961–1990 daily rainfall	mm
RX1day	maximum 1-day precipitation	annual maximum 1-day precipitation	mm
RX5day	maximum 5-day precipitation	annual maximum consecutive 5-day precipitation	mm

[a] A wet day is defined when RR >= 1 mm and a dry day when RR < 1 mm. All indices are calculated annually from January to December.

al., 2005]. These studies tended to concentrate on regions where the daily meteorological observations required for such analyses were already quality controlled and archived. An early initiative to fill the remaining gaps was the 1998 workshop on climate indices funded through the Asia-Pacific Network (APN) for Global Change Research [*Manton et al.*, 2001]. Building on this, the World Meteorological Organisation/Climate Variability and Predictability (WMO/CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) was charged with coordinating a series of regional workshops, where local scientists were supported in the quality control and analysis of daily temperature and precipitation data. (ETCCDMI is jointly sponsored by the WMO Commission of Climatology (CCl) and the CLIVAR project. On the CCl side, ETCCDMI is part of the CCl Open Programme Area Group on Monitoring and Analysis of Climate Variability and Change. See http://www.clivar.org/organization/etccd for more details.) By early 2005 workshops had been held in the Caribbean [*Peterson et al.*, 2002], North Africa [*Easterling et al.*, 2003], South and Central America [*Aguilar et al.*, 2005; *Vincent et al.*, 2005; *Haylock et al.*, 2006], southwest Asia, south Asia [*Peterson*, 2005], and southern Africa (this paper).

[3] There are numerous regional and national studies of recent trends and variability in monthly climate over Africa [e.g., *Fauchereau et al.*, 2003; *Hulme et al.*, 2001; *Kruger and Shongwe*, 2004; *Mahe et al.*, 2001; *Malhi and Wright*, 2004; *Misra*, 2003; *Moron*, 1997; *Schreck and Semazzi*, 2004; *Unganai and Mason*, 2001]. However, there has been little work on precipitation or temperature related extremes in Africa, primarily because of the lack of easily available daily data for the region. *Mason et al.* [1999] studied trends in extreme precipitation at south African stations that had not undergone location changes (but without testing for other inhomogeneities), identifying significant increases in the intensity of extreme rainfall events between 1931–1960 and 1961–1990 over 70% of the country. *Frich et al.*'s

Table 3. Temperature Indices Calculated by RClimDex[a]

Index	Descriptive Name	Definition	Units
SU	hot days	annual count when TX > 25°C	days
ID	cold days	annual count when TX < 0°C	days
TR20	warm nights	annual count when TN > 20°C	days
TXx	hottest day	monthly highest TX	°C
TNx	hottest night	monthly highest TN	°C
TXn	coolest day	monthly lowest TX	°C
TNn	coolest night	monthly lowest TN	°C
TN10p	cool night frequency	percentage of days when TN < 10th percentile of 1961–1990	%
TX10p	cool day frequency	percentage of days when TX < 10th percentile of 1961–1990	%
TN90p	hot night frequency	percentage of days when TN > 90th percentile of 1961–1990	%
TX90p	hot day frequency	percentage of days when TX > 90th percentile of 1961–1990	%
WSDI	warm spell	Annual count of days with at least 6 consecutive days when TX > 90th percentile of 1961–1990	days
DTR	diurnal temperature range	monthly mean difference between TX and TN	°C
CSDI[b]	cold spell	annual count of days with at least 6 consecutive days when TN < 10th percentile of 1961–1990	days
FD[b]	frost days	annual count when TN < 0°C	days
GSL[b]	growing season length	annual count between first span of at least 6 days with TG > 5°C after winter and first span after summer of 6 days with TG < 5°C	days

[a] TX is the daily maximum temperature; TN is daily minimum temperature; TG is daily mean temperature.
[b] Indices are included for completeness but are not analyzed further in this paper.

[2002] global analysis includes precipitation data from South Africa, Zimbabwe, Zambia, and Mozambique, and shows more variable patterns over this wider domain; the most consistent pattern is an increase in maximum 5-day rainfall during the second half of the twentieth century.

[4] This paper builds on these earlier findings for southern and west Africa, by examining trends in indices for extremes of daily precipitation and temperature at stations from these regions; the results arise from the WMO/CLIVAR and START cosponsored southern Africa climate extremes workshop, held in Cape Town, in June 2004. The workshop was attended by representatives from nine southern African and two west African nations, and provided the opportunity to quality control and analyze daily temperature and precipitation data from across the two regions. The results provide the first regional synthesis of trends in daily climate and extremes for southern Africa, and supplements the data for West Africa contributed at the earlier North African workshop [*Easterling et al.*, 2003].

2. Data and Methods

[5] Participants brought station records of daily precipitation, maximum temperature and minimum temperature for recent decades (Table 1). The data were supplemented by additional data for Mozambique, kindly provided by the Mozambique Meteorological Service, and for Namibia, obtained from the Global Climate Observing System (GCOS) Global Surface Network [*Alexander et al.*, 2006]. In all, 63 stations are included in the analysis.

[6] Data were analyzed using the RClimDex package (software and documentation available for download from http://cccma.seos.uvic.ca/ETCCDMI), which represents an enhancement of the EXCEL-based ClimDex software used in previous workshops [e.g., *Easterling et al.*, 2003]. Participants first used RClimDex for quality control of their data, through: (1) automated checking for erroneous data (e.g., negative precipitation, maximum temperature less or equal to minimum temperature); (2) automated searches for outliers, where thresholds/limits are defined by the user in terms of standard deviations from the long-term (typically 1961–1990) daily mean; experience from previous workshops has shown that a threshold of 3.5 standard deviations was appropriate (T. C. Peterson, personal communication, 2004) and was similarly adopted for this analysis; (3) through generation of data plots enabling visual inspection of the data; this allowed for an alternative check for erroneous data points, and local meteorological knowledge proved crucial in assessing a number of large precipitation outliers; the plots were also used to detect larger temporal inhomogeneities during the workshop; and (4) subsequent to the workshop, postprocessing of all data using the RHTest software (available for download from http://cccma.seos.uvic.ca/ETCCDMI), which uses a two-phase regression model to check for multiple step-change points that could exist in a time series [*Wang*, 2003].

[7] After quality control, RClimDex was used to calculate climate indices from the daily data; the indices are then used in subsequent analyses and made available to the global community through the ETCCDMI website. Use of indices overcomes the reluctance of many countries to release the original records of daily data; while the climate indices are valuable for climate monitoring, they are of little value for commercial activities such as weather forecasting. RClimDex calculates 10 precipitation and 16 temperature indices (Table 2 and Table 3), at annual and (where appropriate) monthly time steps. The aim of the ETCCDMI process is to collate a standardized set of indices enabling comparison across regions, but not all the indices are meaningful in an African context. For example, growing season length (GSL) is a temperature-dependent measure of growing season appropriate for mid to high latitudes, while growing season over much of Africa is defined by precipitation. In Tables 2 and 3 we provide summary information on all indices for consistency with other ETCCDMI workshops, but exclude GSL, ID (cold days), and FD (frost days) from further analysis.

[8] We use a nonparametric trend statistic, Kendall's tau for monotonic trends, which makes no assumptions about the distribution of the data or the linearity of any trends [*Hollander and Wolfe*, 1973, pp. 115–120]; although probably not a major problem when working with monthly and annual index data, the statistic is also robust in the face of outliers. Kendall's tau also standardizes the trend between −1.0 and 1.0, enabling comparison of trends across different parts of the region, where the absolute values of trends can vary. All trends are calculated over the standard period 1961–2000, with stations requiring at least 30 years of data in this period for a trend to be reported.

[9] As Kendall's tau does not give an indication of the magnitude of trend, we also calculate the least squares linear trends, both at individual stations, and for regionally averaged anomaly series for each index (Figure 1). The regionally averaged series were calculated as follows:

$$x_{r,t} = \sum_{i=1}^{n_t} \left(x_{i,t} - \bar{x}_i \right) \Big/ n_t$$

where

$x_{r,t}$ regionally averaged index at year t;
$x_{i,t}$ index for station i at year t;
$\bar{x}_i$ index mean at station i over the period 1961–2000;
n_t number of stations with data in year t.

For most indices, the regionally averaged series are expressed in the index units, but several of the precipitation indices that have millimeter units; here we standardize $x_{i,t} - \bar{x}$ by dividing by the station standard deviation to avoid the average series being dominated by those stations with high rainfall. Indices that were standardized are PRCPTOT, SDII, R95p, R99p, RX1day, and RX5day. Note that for similar reasons, linear trends for these indices at individual stations (auxiliary material[1]) are difficult to compare across the region; furthermore, linear trends in precipitation indices at individual stations may be affected by outliers (whether real or erroneous).

[10] Results for individual stations are available in the auxiliary material. Auxiliary material data include the mean and standard deviation of each index, the number of years

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/jd/2005jd006289.

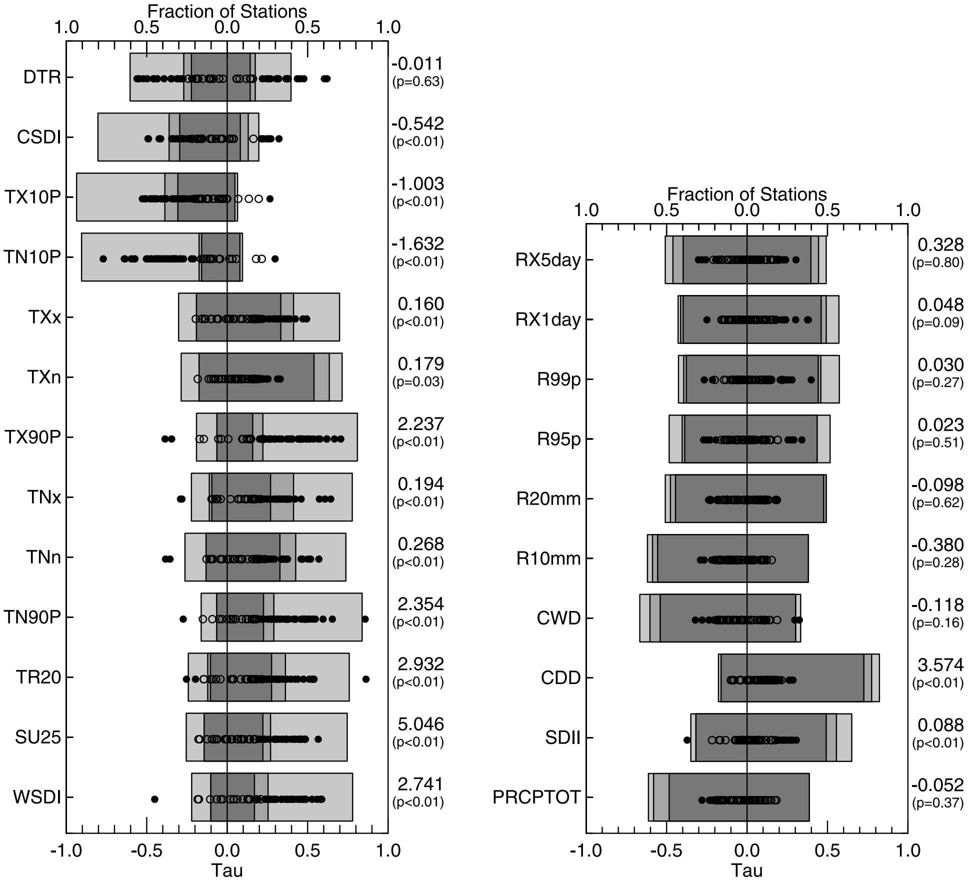

Figure 1. Summary of trends (Kendall's tau) for all indices. Bars show the fraction of stations with positive and negative trends. Shading indicates the proportion of stations with trends that are statistically significant. Dark gray, $p > 0.10$ (not significant); medium gray, $0.05 > p \geq 0.10$; light gray, $p \leq 0.05$. Trends for individual stations are shown by circles, with solid circles indicating $p \leq 0.10$. Numbers on the right axes show the liner trends for regionally averaged series, in absolute units per decade (see Table 1 for units; for example, the median trends for DTR and CSDI are −0.03°C/decade and −0.69 days/decade, respectively).

with data over 1961–2000, Kendall's tau, and the linear least squares trend, along with statistical significance.

3. Results

[11] Results for all indices are summarized over all stations in Figure 1, including the fraction of stations with trends that are significant at the 5% level, in the 5–10% range, and that are not statistically significant; in the sections that follow, we use a significance level of 10%, unless otherwise noted. Spatial patterns of trends and regional time series for individual indices are shown in subsequent figures. We describe results for indices related to temperature and precipitation in turn.

3.1. Temperature

3.1.1. Cold Extremes (TX10p, TN10p, TXn, TNn, CSDI)

[12] For indices of cold extremes, between 40% and 70% of stations show statistically significant decreasing trends (Figure 1). In particular, the percentage of days when maximum and minimum temperature is less than the 1961–1990 10th percentile (TX10p and TN10p) have changed, indicating that the number of cold days and nights has decreased; for cold nights, about 70% of stations have trends that are statistically significant. The regionally averaged linear trends (in percentage of days) for these two variables are −1.003 and −1.632 per decade, respectively; converting percentages to days, these correspond to trends of −3.7 and −6.0 days/decade. Similarly the temperatures of the coldest days and coldest nights in each year (TXn and TNn) show increasing trends at abut 70% of the stations, but with fewer statistically significant trends due to the higher variance of this statistic (recall from Table 3 that TNn and TXn are the coldest day and night of each year); regionally averaged trends in TNn and TXn are 0.179 and 0.268°C/decade. (Note that generally increasing trends in TNn and TXn are compatible with decreasing trends in TN10P and TX10P because the former indices are in absolute temperature units while the latter report frequency of days below a fixed threshold.) Cold spell duration (CSDI) has also generally decreased over the analysis period, at a regionally averaged rate of −0.54 days/decade; however, some stations do show a statistically significant increasing trend.

[13] The spatial patterns of trends are similar for all indices of cold extremes (Figure 2); as expected from the

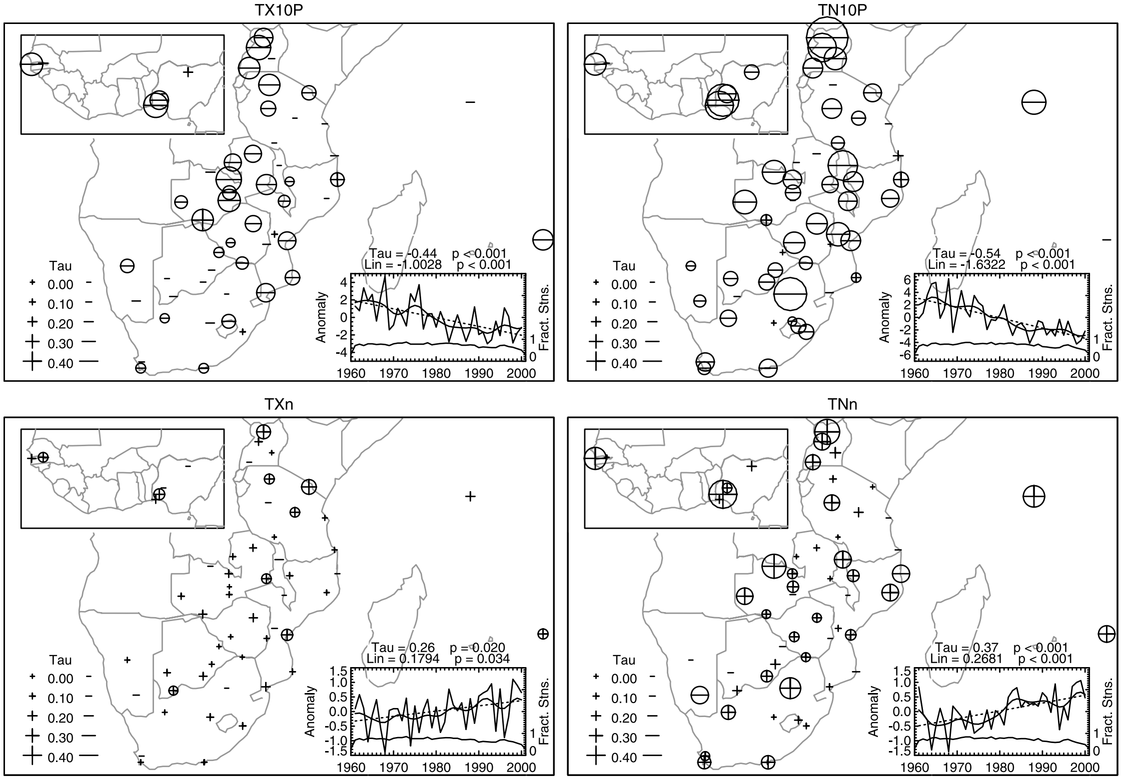

Figure 2. Spatial pattern of trends (Kendall's tau) and regionally averaged standardized series for indices of cold extremes. Positive trends are shown as pluses, negative trends as minuses. Trends that are significant at the 90% level are circled. Insets show the regionally averaged standardized anomalies relative to 1961–1990.

regionally averaged trends, the magnitudes of trends at individual stations generally larger for TX10p and TN10p than for TXn and TNn. There is also a tendency for trends to be strongest in the tropics and weaker in the extratropics. This is at least partly because emerging trends may be easier to detect against the lower interannual variability of temperature in the tropics, as evidenced from our analysis of National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis daily data (not shown), other global climate model analyses [e.g., *Paeth and Hense*, 2002] and for the station data analyzed here. The exception to this is CSDI, which shows a slight tendency for the greatest decreasing trends in the subtropics (Figure 3).

[14] Table 4 shows the proportion of stations where trends in indices are of a particular relative magnitude. About 60% of stations show larger magnitude trends in TX10p than TN10p, but there is no particular pattern across the region in

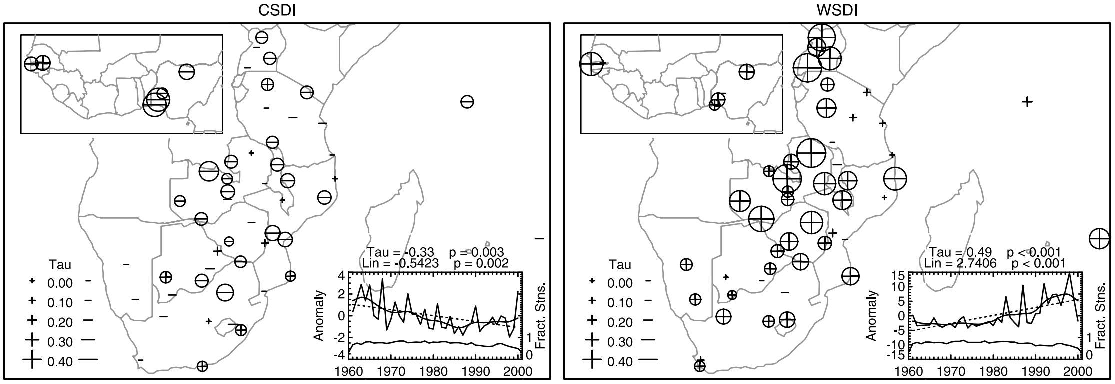

Figure 3. Same as Figure 2 but for trends in cold spell duration (CSDI) and warm spell duration (WSDI).

Table 4. Comparison of Trends at Individual Stations[a]

Index	Comparison[b]	Tau	Linear
TX90p > TX10p	abs	0.72	0.79
TN90p > TN10p	abs	0.38	0.47
TXx > TXn	rel	0.64	0.55
TNx > TNn	rel	0.56	0.46
TXx > TNx	rel	0.38	0.46
TXn > TNn	rel	0.46	0.45
WSDI > CSDI	abs	0.73	0.8
SU25 > TR20	abs	0.54	0.58
CDD > CWD	abs	0.55	0.81

[a] Proportion of individual stations where the trend in one index is of greater magnitude than trend in a second.

[b] Term abs indicates that the absolute magnitudes of trends are compared, rel indicates that the sign of the trends are retained during comparison.

the relative magnitude of trends (not shown). For TXn and TNn, 55% of stations have greater magnitude trends in TNn.

3.1.2. Diurnal Temperature Range (DTR)

[15] Approximately 60% (40% statistically significant) of stations show a decrease in diurnal temperature range (DTR; Figure 1). However, there are also some 25% of stations showing statistically significant increases. As a result the regionally averaged trend is only slightly negative, and not statistically significant. The sign of the trends in DTR vary considerably across the region (Figure 4), similar to previous analyses of diurnal temperature range [*Easterling et al.*, 1997]. However there is a tendency for increasing trends across Zimbabwe, Zambia and Mozambique, and for decreasing trends north and south of these areas. The increasing DTR trends in the center of southern Africa are associated with generally steeper trends in maximum temperature indices than minimum temperature indices.

3.1.3. Hot Extremes (TX90p, TN90p, TXx, TNx, TR20, SU25, WSDI)

[16] The remaining temperature indices are related to hot extremes, and in all cases show at least 65% of stations with positive trends (Figure 1), indicating that both daytime and nighttime hot extremes are increasing. Between 30 and 40% of the stations show statistically significant increasing trends, compared to 5–10% with statistically significant decreasing trends. The regionally averaged trends for the percentage of days exceeding the 90th percentiles (TX90p and TN90p) are 2.237 and 2.355 per decade; this corresponds to 8.2 and 8.6 days/decade, roughly similar for both indices. Regionally averaged trends in extreme temperatures (TXx and TNx) also show statistically increasing trends, of broadly similar magnitude (0.160 and 0.194°C/decade). As with the cold extremes, trends tend to be steeper in the tropics (Figure 5). The proportion of stations with greater magnitude trends in TX90p than TN90p is roughly equal (Table 4) and there are no areas of the region where the trends in one the indices are predominantly larger, reflecting the similar magnitude of the regionally averaged trends. For TXx and TNx, approximately 60% of stations have greater magnitude TNx trends, but again there is no strong regional pattern.

[17] Both warm nights (TR20) and hot days (SU25) have increased over the analysis period; however, here regionally averaged increase in the hot days (~5 days/decade) is greater than warm nights (~3 days/decade) (Figure 6). While there are marginally more stations with a larger trend in SU25, there is quite a strong spatial pattern in the relative magnitude of trends in these two indices: trends in SU25 are consistently larger across Namibia, Botswana, Zimbabwe, Zambia and southern Mozambique. Warm spells (WSDI) have also increased consistently across the region, with a regionally averaged increase of 2.4 days/decade (Figure 3).

3.1.4. Comparison of Hot and Cold Extremes

[18] It is useful to compare trends in hot and cold indices, as this provides information on the relative changes in the tails of the daily temperature distributions. The magnitude of the regionally averaged trend in TX90p is more than twice that of TX10p. This is reflected at individual stations, where some 70% of stations have larger magnitude trends in TX90p (Table 4). For TXx and TXn, regionally averaged trends are similar, although the trend in TXn is slightly greater than TXx (0.179 and 0.160°C/decade). At individual stations this pattern is reversed with about 60% of stations having larger magnitude TXx trends, and many more stations having statistically significant trends in TXx than in TXn. Thus the regional patterns are consistent with the comparison between the 90th and 10th percentile indices, where the trends in the hot tails of the maximum temperature distributions are on average of greater magnitude.

[19] For minimum temperatures, the regionally averaged trend in TN90p (2.354) is of greater magnitude than that of TN10p (−1.632), but the difference is not as marked as for maximum temperature. However, when looking at individual stations a greater proportion (60%) of stations do have trends in TN10p that are greater than TN90p. Those stations with greater magnitude TN90p trends are preferentially located to the NW of the region (Namibia, Zambia, Uganda and west Africa), while southern and east Africa tend to have stations where TN10p trends are of larger magnitude. Regionally averaged trends for TNx and TNn are similar, with TNn being slightly larger (Figure 1). At individual stations, roughly equal numbers of stations have greater magnitude trends in one or the other of these two indices.

[20] The regional trend magnitude for WSDI (2.741 days/decade) is about 5 times that of CSDI (−0.542). This result is repeated when individual stations are analyzed, with

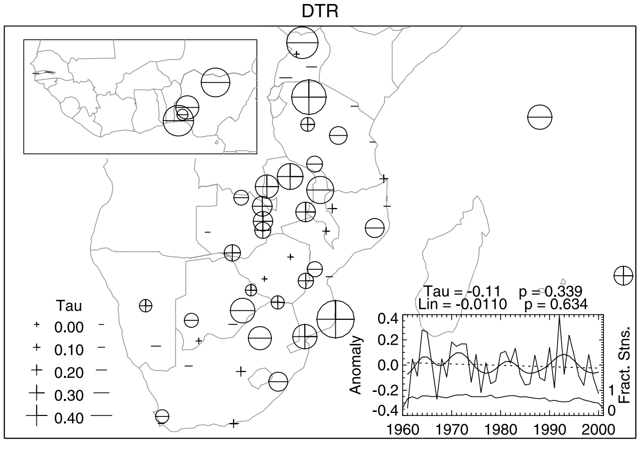

Figure 4. Same as Figure 2 but for trends in diurnal temperature range.

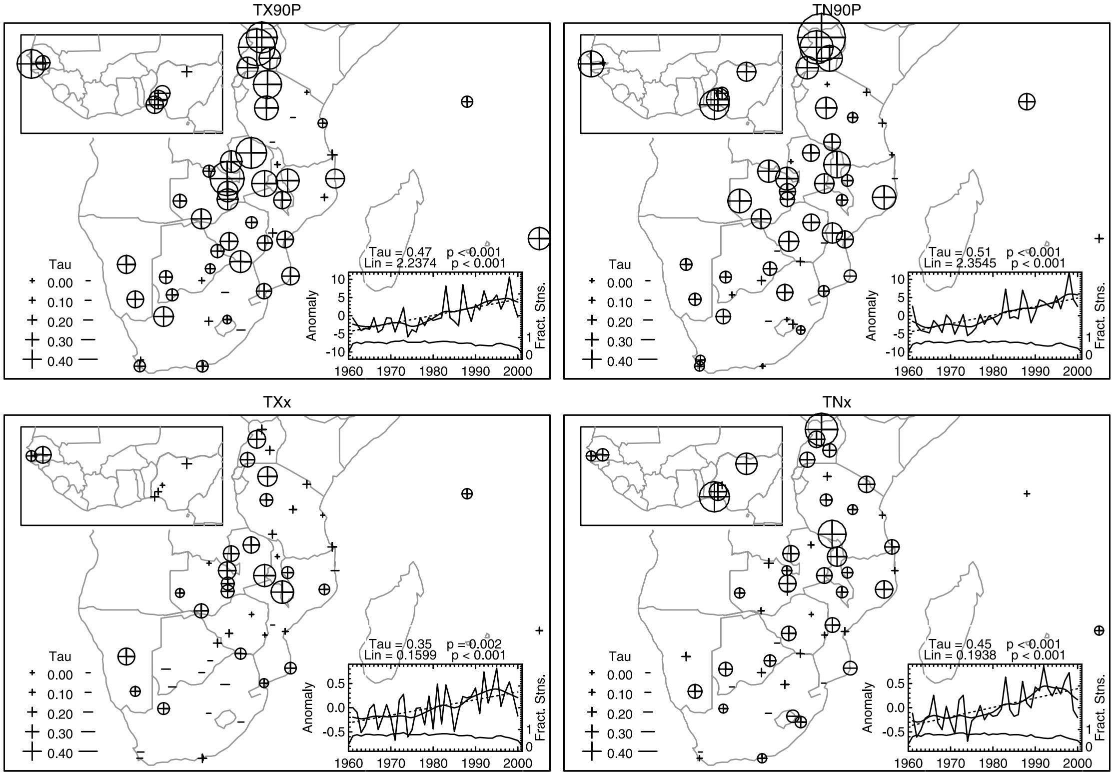

Figure 5. Same as Figure 2 but for trends in hot extreme indices.

approximately 80% of stations showing larger trend magnitudes for WSDI (Table 4).

3.2. Precipitation

[21] Most precipitation indices exhibit a roughly equal proportion of increasing and decreasing trends for the whole region (Figure 1); moreover, only a small fraction of station trends are statistically significant for any index. This is perhaps to be expected, as secular trends are difficult to detect against the large interannual and decadal-scale variability of precipitation over the region.

[22] When looking at the regionally averaged trends, only three indices have statistically significant trends: annual maximum 1-day precipitation (RX1day), average wet day precipitation (SDII) and maximum dry spell duration (CDD) all show statistically significant increasing trends. In addition, maximum 5-day precipitation (RX5day), total precipitation on extreme rainfall days (R95p and R99p) also show (nonsignificant) increasing regionally averaged trends. In contrast, there are (nonsignificant) decreasing trends for regionally averaged annual precipitation (PRCPTOT), heavy precipitation days (R10mm and R20mm) and consecutive wet days (CWD). Thus at the region-wide scale, there is a consistency between indices suggesting that average daily rainfall intensity has increased, along with the amount of rainfall on extreme rainfall days and periods, but that total rainfall and the number of days with heavy rainfall has decreased.

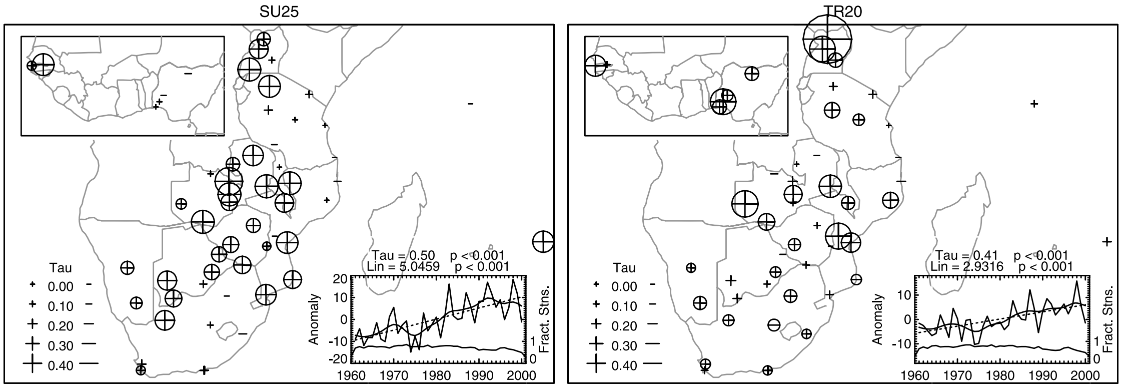

Figure 6. Same as Figure 2 but for trends in hot days (SU25) and warm nights (TR20).

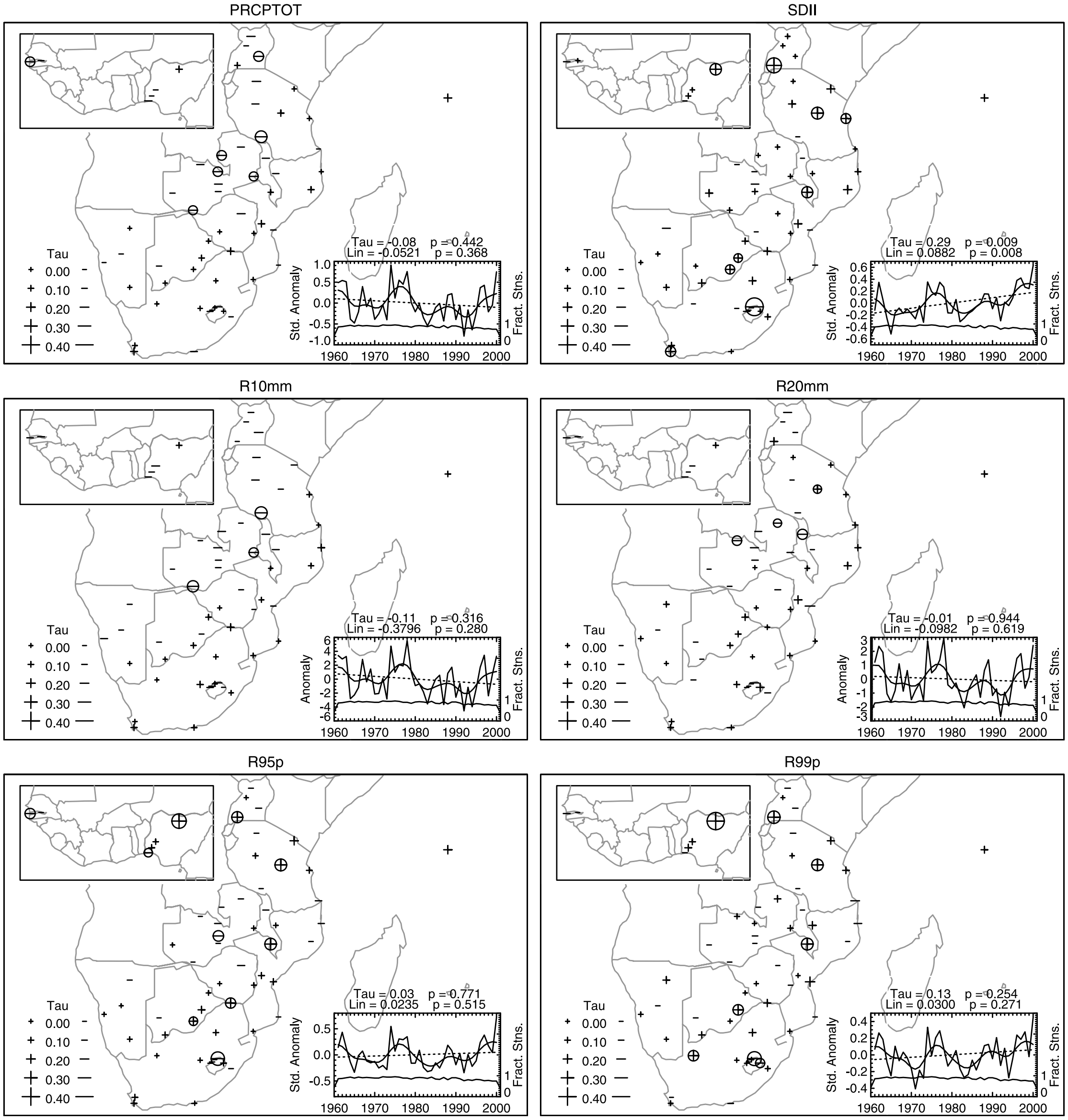

Figure 7. Same as Figure 2 but for trends in precipitation indices.

[23] Some of the precipitation indices show a difference between the north and south of the region (Figure 7): there is generally increased wet day precipitation and heavy precipitation days to the south of a line running SW-NE through southern Namibia, Botswana, Zimbabwe and Mozambique; to the north of this line, these indices generally show decreasing trends. However, it is also clear from Figure 7 that very few station trends are statistically significant. There are no consistent spatial patterns of trends in very wet day precipitation (R95p) and extremely wet day precipitation (R99p), as might be expected from the absence of significant regionally averaged trends.

[24] Consecutive dry days (CDD) is the only precipitation index showing a consistent trend over the region, with nearly all stations showing an increase (Figure 8). While only a few stations show statistically significant trends, the standardized regional series does show a significant increasing trend. It should be noted that CDD represents the increase in the longest dry spell in the year, which corresponds in most instances to dry season length, rather than dry spells in the rainy season, which is probably a more appropriate index. For regions in southern Africa experiencing one long rainy season this does however indicate a shortening of the rainy season, which is also implied by a recent trend toward later onset of the rainy season in southern Africa [*Tadross et al.*, 2005].

[25] In general, the sign of the trends of precipitation indices that measure precipitation amount and/or exceedance are correlated on a station-by-station basis (Table 5). For example, over 80% of stations have trends of the same sign for PRCPTOT and each of R10mm and R20mm; similarly over 65% of stations with the same sign of trend for PRCPTOT and each of R95p, R99p, RX1day and RX5day. At least 60% of stations have trends of the same

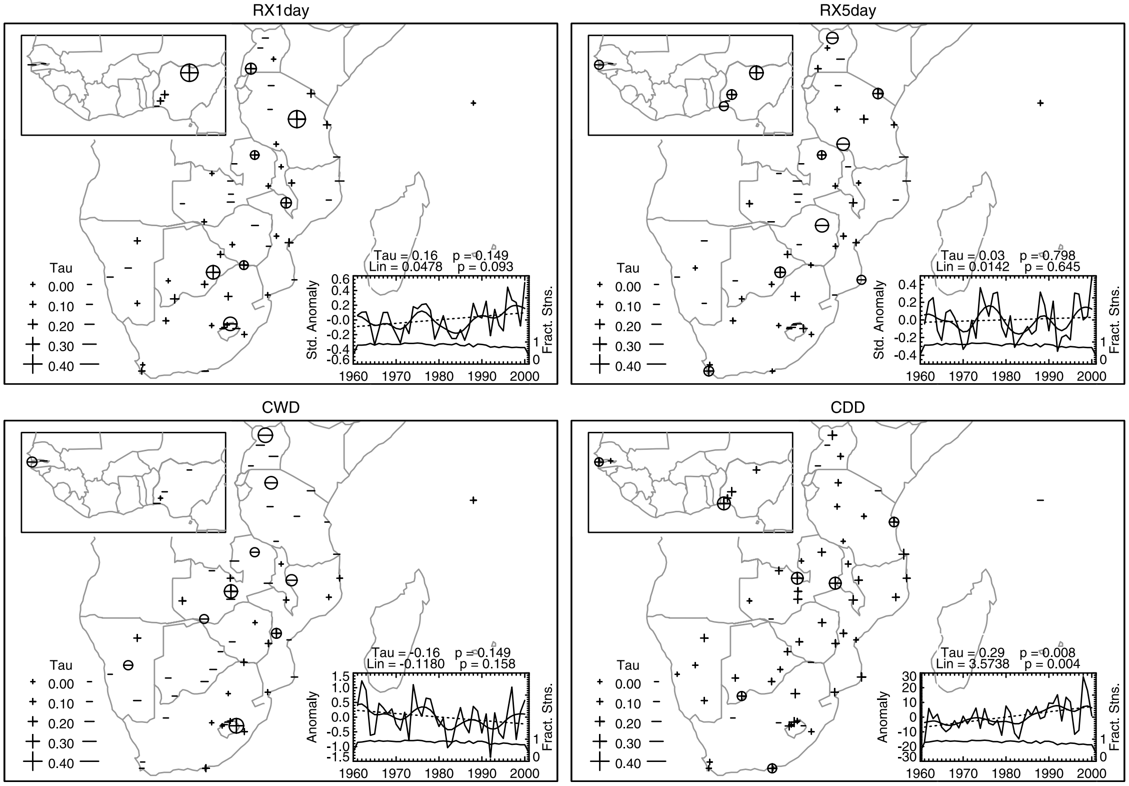

Figure 8. Same as Figure 2 but for trends in precipitation spell indices.

sign in SDII and each of PRCPTOT, R10mm, R20mm, R95p, R99p, RX1day and RX5day.

4. Conclusions

[26] We have described the results of an analysis of indices of extremes in daily climate data arising from a workshop attended by representatives of southern and west African meteorological agencies. The data, covering at least the period 1961–2000 were quality controlled by workshop participants, and indices calculated using the RClimdex software.

[27] There is a consistent pattern of trends in daily temperature extremes over the study area that is related to increasing temperatures. Extremely cold days and nights have decreased, and hot days and nights have increased. Moreover, hot extremes generally have trends of greater magnitude than their cold counterparts, suggesting that the warm tails of the daily temperature distributions are changing faster than the cold tails; this implies that the shape of the distribution of daily temperature is changing along with the mean. The statistical significance of most trends increases from subtropics to tropics, due to the lower

Table 5. Proportion of Stations Showing Trends of the Same Sign in Pairs of Precipitation Indices

	Trend	SDII	R10mm	R20mm	RX1day	RX5day	R95p	R99p	CDD	CWD
PRCPTOT	tau	0.597	0.806	0.823	0.661	0.742	0.754	0.677	0.355	0.597
	linear	0.565	0.839	0.806	0.694	0.758	0.738	0.661	0.355	0.661
SDII	tau		0.532	0.613	0.597	0.645	0.656	0.613	0.581	0.419
	linear		0.468	0.597	0.677	0.645	0.656	0.613	0.694	0.403
R10mm	tau			0.726	0.581	0.661	0.639	0.597	0.452	0.629
	linear			0.71	0.565	0.629	0.607	0.532	0.355	0.661
R20mm	tau				0.565	0.645	0.656	0.597	0.435	0.548
	linear				0.597	0.629	0.721	0.565	0.435	0.581
RX1day	tau					0.694	0.689	0.806	0.516	0.403
	linear					0.806	0.721	0.774	0.532	0.452
RX5day	tau						0.836	0.742	0.403	0.484
	linear						0.82	0.839	0.435	0.484
R95p	tau							0.77	0.443	0.443
	linear							0.738	0.475	0.541
R99p	tau								0.5	0.419
	linear								0.435	0.484
CDD	tau									0.371
	linear									0.323

variability of temperature in the latter. The magnitude of these trends does however vary spatially; this is to be expected in a region that stretches from the tropics to the extratropics, where an overall global or Africa-wide warming will be superimposed upon regionally specific variability and reorganization of regionally important processes that affect temperature extremes.

[28] Perhaps unsurprisingly for a continent where different factors affect regional rainfall, there are few consistent and statistically significant trends in precipitation indices. Regionally averaged dry spell length, average rainfall intensity and annual 1-day maximum rainfall all show statistically significant increasing trends, and a general pattern of increasing trends across the region, but few trends at individual stations are statistically significant. Additionally there is an indication of decreasing total precipitation, accompanied by increased average rainfall intensity; the fact that extreme precipitation indices (R95p, R99p, RX1day and RX5day) have on average increased while total precipitation and less extreme precipitation (R10mm and R20mm) have decreased suggests that increased average intensity is concentrated on extreme precipitation days. This indicates that time-averaged measures of rainfall may fail to capture these changes as increases in intensity may compensate for decreases in frequency.

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