JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, D10108, doi:10.1029/2010JD015303, 2011

Observed trends in indices of daily and extreme temperature and precipitation for the countries of the western Indian Ocean, 1961–2008

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Received 5 November 2010; revised 23 February 2011; accepted 3 March 2011; published 24 May 2011.

[1] A workshop on climate change indices was held at the Mauritius Meteorological Services in October 2009 to produce the first analysis of climate trends for the countries of the western Indian Ocean. Scientists brought their long-term daily temperature and precipitation for a careful assessment of data quality and homogeneity, and for the preparation of climate change indices. This paper reports on the trends in daily and extreme temperature and precipitation indices for 1961–2008. The results indicate a definitive warming of surface air temperature at land stations. Annual means of the daytime and nighttime temperatures have increased at a similar rate, leading to no discernible change in the diurnal temperature range. Significant increasing trends were found in the frequency of warm days and warm nights, while decreasing trends were observed in the frequency of cold days and cold nights. Moreover, it seems that the warm extremes have changed more than the cold extremes in the western Indian Ocean region. Trends in precipitation indices are generally weak and show less spatial coherence. Regionally, a significant decrease was found in the annual total rainfall for the past 48 years. The results also show some increase in consecutive dry days, no change in daily intensity and consecutive wet days, and a decrease in extreme precipitation events. Temperature indices are highly correlated with sea surface temperatures of the region, whereas weak correlations are found with the precipitation indices.

Citation: Vincent, L. A., et al. (2011), Observed trends in indices of daily and extreme temperature and precipitation for the countries of the western Indian Ocean, 1961–2008, *J. Geophys. Res.*, *116*, D10108, doi:10.1029/2010JD015303.

1. Introduction

[2] Extreme climate events should be closely monitored and analyzed since they can have overwhelming impact on our society and environment. Changes in temperature and precipitation extremes have been assessed for many parts of the world during the past century [*Alexander et al.*, 2006]. However, little is known about climate trends in the western Indian Ocean region. This is, to some extent, due to the various countries covered in the region, some of them limited in data access, and a lack of published studies available internationally. The region is particularly vulnerable to climate change as a result of its many low-lying islands, exposure to tropical cyclones and limited resources. Projected climate change will have adverse implications on the natural and human systems of this region. The frequency of hot days, heat waves and heavy precipitations are expected to increase. These events, along with rising sea levels, will exacerbate floods and erosion, threatening vital infrastructure and water quality [*Intergovernmental Panel on Climate Change*, 2007].

[3] A number of workshops have taken place during the past decade in order to promote analysis of climate extremes in regions where international data sets of long-term daily observations were unavailable [*Peterson and Manton*, 2008]. The purpose of these workshops was not only to improve our understanding of changes in the extremes in these regions, but also to establish a network for scientists working on climate change, provide basic training in quality control and homogenization of climate data, and provide a consistent methodology for studying climate extremes across the world. The regions that have been covered by these

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workshops include the Caribbean [*Peterson et al.*, 2002], South America [*Aguilar et al.*, 2005; *Vincent et al.*, 2005; *Haylock et al.*, 2006], parts of Africa [*New et al.*, 2006; *Aguilar et al.*, 2009], the Middle East [*Zhang et al.*, 2005], central and South Asia [*Klein Tank et al.*, 2006], and Southeast Asia and South Pacific [*Griffiths et al.*, 2005; *Manton et al.*, 2001]. Overall, the outcomes of these workshops have shown a decrease in cold extremes and increases in warm extremes over the past 50 years. However, changes in precipitation total amounts, intensity and extremes were generally weaker with little spatial coherence.

[4] This study presents the results of a workshop held at the Mauritius Meteorological Services in Vacoas, Mauritius, in October 2009. It was organized by the Commission de l'Océan Indien (COI) using the format prepared by the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection Monitoring and Indices (ETCCDI, http://cccma.seos.uvic.ca/ETCCDI/). ETCCDI was established to develop a comprehensive list of indices meaningful over the globe and coordinate a series of workshops for the preparation of climate change indices. Representatives from five countries in the western Indian Ocean participated in the workshop in October 2009, including Comoros, Madagascar, Mauritius, Reunion (France) and Seychelles. The participants brought their best digital long-term daily climatological data from their respective countries and undertook meticulous assessments of data quality and homogeneity, and computation of indices. It was the first time that representatives from these countries collaborated for an analysis of climate change in this region. Although most of the data assessment was performed during the workshop, some postworkshop data processing was required to assure that no major problems remained. Since the calculation of indices developed by ETCCDI is also used in other regions, results of analyses are comparable. This paper presents the observed trends in daily and extreme temperature and precipitation indices for the countries of the western Indian Ocean.

2. Data and Methodologies

[5] Participants brought daily maximum and minimum temperature and precipitation data for several stations along with any metadata available. A total of 68 stations were closely examined for the preparation of indices (Table 1). The period of available recorded data varied by station and several locations did not have any data recorded of daily temperature. Overall, there were enough stations with sufficient daily data to compute trends from 1961 to 2008; however, a second analysis of trends was also produced for 1975–2008 involving more stations. In Comoros, daily observations of Ouani and Hayaha were joined together in 1980 to create a longer record for the computation of trends from 1961 to 2008 as there was little land data available. The station locations are presented in Figure 1.

2.1. Data Quality and Homogeneity

[6] The purpose of data quality control (QC) is to identify errors in daily data sets that may potentially interfere with the correct assessment of the extremes. These errors are sometimes introduced during data processing, such as digitization. For temperature, values outside of five standard deviations from the daily mean were noted. These values were manually checked on a case-by-case basis to determine if they were part of a cold or warm spell by comparing them with neighboring stations. Daily maximum temperatures that were below its daily minimum temperature counterpart were as well identified. This occurred at a few stations for which the observations were freshly digitized because data in the input data sets were in the wrong order. For precipitation, negative values and daily observations above 200 mm were detected. However, in the countries of the western Indian Ocean, daily precipitation above 200 mm is not uncommon; therefore, local climatological knowledge was essential in the assessment of large precipitation events. All suspicious values were set to missing or corrected by the workshop attendees who are familiar about their own climate. Visual inspection of the data plots was also useful in assessing data QC. The computer software RClimDex was used for the quality control of daily climatological data. Software and documentation are available on the ETCCDI website at http://cccma.seos.uvic.ca/ETCCDI/.

[7] Homogeneity assessment consists of the detection of shifts in climate time series which are often due to station relocation, changes in instruments, observation practices, and automation. These nonclimatic shifts can affect the proper assessment of any climate trends in the data sets. An in-depth homogeneity assessment can be tedious since it requires detailed station history (metadata), close neighbor stations and a great amount of time [*Aguilar et al.*, 2003; *Vincent et al.*, 2002]. The methodology for the detection of shifts in climate data sets has certainly evolved since the first workshop held in Australia in 1999 [*Manton et al.*, 2001]. However, currently there is still a great deal of uncertainty on how to adjust daily climate data for detected shifts. For this study, only major inhomogeneities have been adjusted.

[8] The monthly means of the daily maximum temperature, minimum temperature and the monthly total precipitation were carefully examined for homogeneity using the software package RHtestsV3 developed by Xiaolan Wang and Yang Feng of the Climate Research Division of Environment Canada [*Wang and Feng*, 2009; *Wang*, 2008a]. This package was prepared for use in the workshops coordinated by ETCCDI (software and documentation available at the ETCCDI website). The procedure is based on regression models for the identification of shifts in individual station time series [*Wang et al.*, 2007; *Wang*, 2008b]. For example, a shift was detected in 1976 in the monthly mean of the daily maximum temperature at the station Plaine-des-Cafres, Reunion (Figure 2). This shift is most likely due to a change in exposure caused by a replacement of the thermometer screen (which houses the thermometers). The latest version of RHtestsV3 also allows for the detection of shifts in the difference between candidate and neighbors series which is a considerable improvement from the approach used in previous workshops.

[9] Many shifts were detected in the temperature series. For example, shifts in 1963 and 1983 were common at several stations in the region; however, adjustments were not applied to these shifts since metadata was not available to support the data and shifts were likely due to climate variations. Only a few shifts had historical explanations. Adjustments were applied to 9 (8) stations for daily maxi-

Table 1. List of Stations

Country	Station Name	Latitude (°S)	Longitude (°E)	Altitude (m)	Period[a] Temperature Start	Temperature End	Precipitation Start	Precipitation End
Comores	Hayaha	11°52′	43°30′	50	1981 03	2007 11	1981 04	2007 11
	Moroni	11°42′	43°13′	6	1960 01	2000 12	1960 01	2000 06
	Ouani	12°7′	44°25′	12	1960 01	1997 02	1960 01	1997 02
Madagascar	Ambohitsilaozana	17°37′	48°30′	780	1961 01	2008 01	1961 01	2006 12
	Analalava	14°37′	47°46′	57	1961 01	1994 07	1961 01	2003 12
	Antananarivo	18°53′	47°31′	1310	1961 01	2008 12	1961 01	2008 12
	Antsirabe	19°52′	47°4′	1540	1961 01	2009 08	1961 01	2007 12
	Antsiranana	12°21′	49°17′	105	1961 01	2009 08	1961 01	2008 12
	Besalampy	16°45′	44°28′	36	1961 01	1996 12	1961 01	2003 12
	Farafangana	22°48′	47°49′	6	1961 01	2007 02	1961 01	2006 12
	Fianarantsoa	21°27′	47°6′	1106	1961 01	2008 03	1961 01	2007 12
	Mahajanga	15°40′	46°21′	22	1961 01	2009 08	1961 01	2007 05
	Mananjary	21°12′	48°22′	6	1961 01	2004 10	1961 01	2005 12
	Morondava	20°16′	44°17′	7	1961 01	2007 05	1961 01	2007 12
	Ranohira	22°33′	45°23′	824	1961 01	2009 08	1961 01	2008 12
	Sainte-Marie	17°4′	49°49′	3	1961 01	2004 02	1961 01	2009 12
	Toamasina	18°7′	49°23′	6	1961 01	2009 08	1961 01	2009 08
	Toliary	23°22′	43°43′	8	1961 01	2009 08	1961 01	2009 08
Maurice	Agalega	10°22′	56°36′	3	1951 01	2008 12	1951 01	2008 12
	Fuel	20°13′	57°40′	146	1958 01	2008 12	1958 01	2008 12
	Medine	20°16′	57°22′	91	1962 01	2008 12	1962 01	2008 12
	Pamplemousses	20°6′	57°34′	79	1961 02	2008 12	1961 02	2008 12
	Plaisance	20°25′	57°40′	49	1951 01	2008 12	1951 01	2008 12
	Pointe Canon	19°40′	63°25′	58	1961 01	2008 12	1961 01	2008 12
	Vacoas	20°18′	57°28′	424	1951 01	2008 12	1951 01	2008 12
Reunion	Bagatelle	20°55′	55°34′	262			1956 01	2008 12
	Beauvallon	21°0′	55°42′	16			1952 01	2008 12
	Bois-Rouge	20°55′	55°37′	3			1952 01	2008 12
	Chaudron	20°53′	55°30′	38			1967 01	2008 12
	Cilaos	21°7′	55°28′	1197	1969 01	2008 12	1952 01	2008 12
	Colimaçons	21°7′	55°17′	798	1964 01	2008 12	1964 01	2008 12
	Dos D'Ane	20°58′	55°22′	915	1967 01	2008 12	1967 01	2008 12
	Gillot Aeroport	20°53′	55°31′	8	1953 01	2008 12	1953 01	2008 12
	Grand Galet	21°19′	55°37′	505			1953 08	2008 12
	La Crete	21°19′	55°40′	650			1969 01	2008 12
	Le Gol	21°16′	55°23′	31			1953 01	2008 12
	Le Port	20°57′	55°16′	9	1974 01	2008 12	1974 01	2008 12
	Le Tremblet	21°19′	55°47′	90			1953 01	2008 12
	Les Avirons	21°13′	55°19′	180			1952 01	2008 12
	Ligne Paradis	21°19′	55°28′	156	1966 01	2008 12	1966 01	2008 12
	Menciol	20°58′	55°37′	181	1961 01	2008 12	1953 01	2008 12
	Pamandzi	12°48′	45°16′	7	1951 01	2008 12	1949 01	2008 12
	Pierrefonds Aeroport	21°19′	55°25′	21	1951 01	2008 12		
	Pierrefonds Cirad	21°19′	55°25′	61			1953 01	2008 12
	Plaine des Cafres	21°13′	55°34′	1560	1965 01	2008 12	1952 01	2008 12
	Plaine des Palmistes	21°7′	55°37′	1032	1961 01	2008 12	1952 01	2008 12
	Ravine Citrons	21°15′	55°28′	487			1967 01	2008 12
	Saint Benoit	21°4′	55°43′	43			1954 01	2008 12
	Saint Joseph	21°22′	55°36′	17			1961 01	2007 12
	Saint Philippe	21°22′	55°46′	30	1966 01	2008 12	1970 01	2008 12
	Tromelin	15°52′	54°31′	7	1955 01	2008 12	1955 01	2008 12
Seychelles	Anse Forbans	4°46′	55°31′	5			1975 01	2009 07
	Anse Royale (Police)	4°43′	55°31′	5			1975 08	2009 07
	Anse Royale Waterwork	4°43′	55°31′	5			1979 08	2009 07
	Belombre	4°37′	55°25′	25			1976 01	2009 07
	Bon Espoir	4°42′	55°28′	240			1975 02	2009 07
	Cascade	4°40′	55°28′	110			1975 02	2009 07
	Hermitage	4°37′	55°27′	85			1979 05	2009 07
	La Gogue	4°34′	55°25′	120			1977 03	2009 07
	La Misere (Fairview)	4°39′	55°28′	335			1975 01	2009 06
	Le Niol	4°37′	55°25′	205			1975 01	2007 07
	Praslin Airstrip	4°12′	55°27′	4			1977 02	2009 05
	Quatre Bornes	4°46′	55°30′	85			1977 03	2009 07
	Rawinsonde Station	4°40′	55°31′	4			1976 05	2009 07
	Rochon	4°37′	55°27′	170			1975 01	2007 07
	St Louis	4°37′	55°25′	185			1975 02	2009 07
	Seychelles Intl Airport	4°40′	55°31′	4	1972 01	2008 12	1972 01	2008 12
	Tea Factory	4°39′	55°25′	390			1975 02	2009 07

[a]Dates given as year and month.

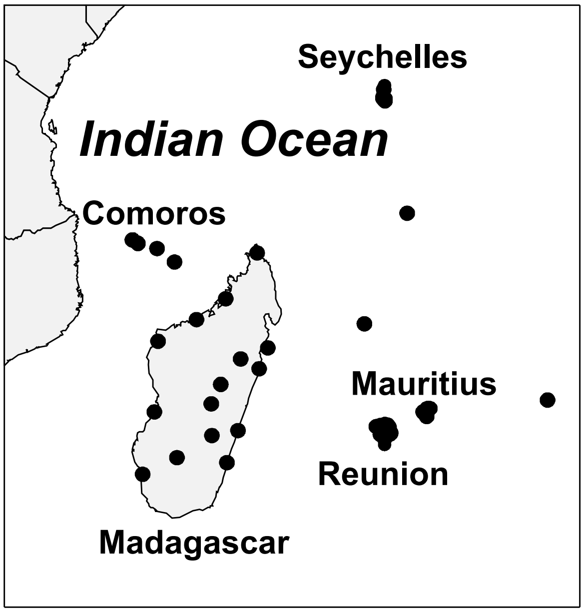

Figure 1. Station locations.

mum (minimum) temperatures using the Quantile Matching (QM) algorithm [*Wang et al.*, 2010]. This procedure was recently developed for adjusting daily data so the empirical distributions of all segments of the detrended series match each other. Although this new algorithm has not yet been entirely validated, trends after the adjustments were more consistent with the trends of the surrounding stations. For precipitation, the log transformation was applied to the wet months before homogeneity testing and none of the stations revealed inhomogeneity using this method.

2.2. Indices

[10] After QC and homogeneity assessment, 27 indices were calculated using RClimDex. These indices can be used in subsequent analyses and they are made available to the global scientific community through the ETCCDI website. Many meteorological and hydrometeorological services in developing countries do not have the capacity or mandate to disseminate daily data. As such, climate indices prepared during the ETCCDI workshops are valuable for climate monitoring and trend computation. Since not all the indices were meaningful in the western Indian Ocean context, 13 temperature and 8 precipitation indices were selected for this study and their descriptions are given in Table 2.

[11] All chosen indices were calculated on an annual basis. For temperature, they described changes in means as well as in cold and warm extremes. They are based on fixed thresholds (e.g., summer days) and on thresholds defined as station percentiles (e.g., warm days) to facilitate comparisons between stations. These percentiles are defined for each calendar day and these indices do not necessarily represent the summer hot days or the winter cold days. The thresholds are obtained from a 5 day window centered on each calendar day over the reference period of 1961–1990. Extreme temperatures such as the highest and lowest daily values of the year were also examined. For precipitation, the amount, intensity and extremes were analyzed as well as the maximum consecutive dry and wet days observed during the year. Annual indices were calculated if no more than 15 days were missing in a year, and percentiles were computed if no more than 20% of the data were missing in the reference period.

2.3. Regional Average Indices

[12] To provide an overview of the climate variations for the western Indian Ocean region, a regional average series was produced for every index. To avoid producing a series dominated by stations with very high temperature and precipitation, it was computed as the mean of the station indices departures from the reference period 1961–1990. For precipitation indices PRCPTOT, RX1day and RX5day, the departures were divided by the 1961–1990 mean due to very large precipitation amounts occurring in some years. For a better spatial coverage, average series were first computed for stations of the main islands of Reunion, Mauritius and Seychelles, since these stations are closely located together (Figure 1). Subsequently, their averages and averages from all other stations were used to obtain the regional average series. A second regional series was also produced for 1975–2008 as several stations covered shorter periods of time, particularly in Reunion and Seychelles. Regional average indices were only computed for stations having less than 20% of missing values in the analyzed periods.

2.4. Trend Estimation

[13] Trends for individual stations and regional series were calculated using a Kendall's tau-based slope estimate following an approach by *Sen* [1968]. The significance of the trend was assessed using the Kendall's test since it does not assume that the data are normally distributed and it is robust to the effect of the outliers in the series. The slope estimate is the median of the slopes calculated from all joining pairs of points in the series and the confidence interval was obtained from the tabulated values of *Kendall* [1955]. Since serial correlation might be present in the indices series, the procedure was applied to take into

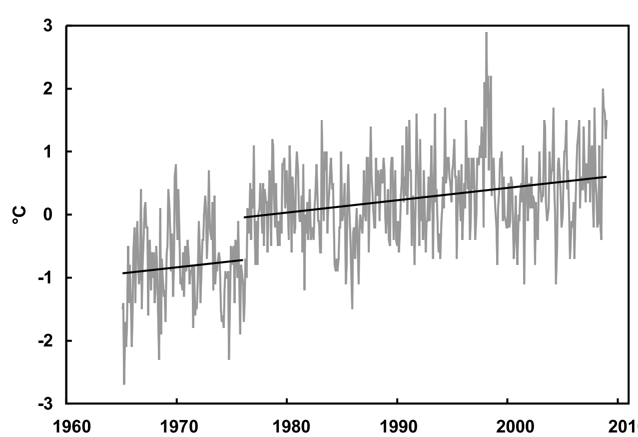

Figure 2. Step identified in 1976 in the monthly mean anomalies of the daily maximum temperature of the station Plaine-des-Cafres, Reunion.

Table 2. Definition of the Temperature and Precipitation Indices Used in This Study[a]

Element	Index	Descriptive Name	Definition	Unit
Temperature	TXMean	Annual maximum temperature	Annual mean of TX	°C
	TNMean	Annual minimum temperature	Annual mean of TN	°C
	DTR	Diurnal temperature range	Annual mean of difference between TX and TN	°C
	SU25	Summer days	Annual count when TX > 25°C	days
	TR20	Tropical nights	Annual count when TN > 20°C	days
	TX90P	Warm days	Percentage of days when TX > 90th percentile	%
	TX10P	Cold days	Percentage of days when TX < 10th percentile	%
	TN90P	Warm nights	Percentage of days when TN > 90th percentile	%
	TN10P	Cold nights	Percentage of days when TN < 10th percentile	%
	TXx	Highest TX	Annual highest value of TX	°C
	TXn	Lowest TX	Annual lowest value of TX	°C
	TNx	Highest TN	Annual highest value of TN	°C
	TNn	Lowest TN	Annual lowest value of TN	°C
Precipitation	PRCPTOT	Annual precipitation	Annual total precipitation	mm
	SDII	Simple daily intensity index	Annual precipitation divided by number of wet days	mm
	CDD	Consecutive dry days	Maximum number of consecutive dry days (RR < 1 mm)	days
	CWD	Consecutive wet days	Maximum number of consecutive wet days (RR ≥ 1 mm)	days
	R10mm	Days above 10 mm	Annual count of days when RR > 10 mm	days
	R20mm	Days above 20 mm	Annual count of days when RR > 20 mm	days
	RX1day	Maximum 1 day precipitation	Annual highest daily precipitation	mm
	RX5day	Maximum 5 days precipitation	Annual highest 5 consecutive days precipitation	mm

[a]TX, daily maximum temperature; TN, minimum temperature; RR, rainfall; PRCP, total precipitation.

account of the first lag autocorrelation. This approach was used in other works describing changes in climate extremes [*Aguilar et al.*, 2005; *Zhang et al.*, 2005; *Vincent et al.*, 2005; *Aguilar et al.*, 2009] and a detail description of the procedure is provided by *Wang and Swail* [2001]. In this study, the trends were computed for the periods 1961–2008 and 1975–2008 only if more than 80% of the values were present. The statistical significance of the trends was assessed at the 5% level.

3. Results

[14] The analysis of the temperature and precipitation indices reveals some consistent changes in means and extremes during the past 48 years in the countries of the western Indian Ocean. However, observed changes in temperature indices have a better spatial coherence than in precipitation indices, and this is mainly due to higher spatial and temporal variability in precipitation as compared to temperature. Table 3 presents the regional trends per decade for 1961–2008 and 1975–2008 for each of the chosen indices.

3.1. Temperature Means

[15] Since it is the first analysis of climate trends in the region, the annual mean of the daily maximum and minimum temperature (TXMean and TNMean) are first examined. Warming is observed in the countries of the western Indian Ocean for the past five decades. Regional average series indicate significant trends of 0.19 and 0.21°C per decade from 1961 to 2008 for TXMean and TNMean, respectively (Table 3), and the regional series show a gradual increase for the last 48 years (Figure 3). At a majority of the stations, an increase of 0.15 to 0.25°C per decade is observed over 1961–2008 in their daytime and nighttime temperatures and trends are significant at most stations (Figure 4). No spatial coherent change is observed in the diurnal temperature range (Figure 4); the regional average series suggests a small and insignificant decrease of 0.03°C per decade for the past 48 years (Table 3 and Figure 4). The results for 1975–2008 are very similar for these three temperature indices.

[16] Summer days (SU25) and tropical nights (TR20) occur very often in this part of the world. They are observed almost all year around in the countries closer to the equator such as Seychelles and Comoros, but almost never at stations located at high altitudes such as in Madagascar and Reunion. Regional trends suggest 4.72 more summer days and 5.14 more tropical nights per decade in this region for 1961–2008, although these increases are less when 1975–2008 is considered (Table 3). The increase in SU25

Table 3. Trends per Decade for the Region[a]

Element	Index	1961–2008	1975–2008	Unit
Temperature	TXMean	**0.19**	**0.17**	°C
	TNMean	**0.21**	**0.20**	°C
	DTR	−0.03	−0.04	°C
	SU25	**4.72**	**3.20**	days
	TR20	**5.14**	**4.32**	days
	TX90P	**3.75**	**5.37**	%
	TX10P	−1.28	−0.44	%
	TN90P	**3.83**	**5.65**	%
	TN10P	**−1.03**	−0.12	%
	TXx	**0.23**	**0.33**	°C
	TXn	**0.09**	0.05	°C
	TNx	**0.21**	**0.28**	°C
	TNn	**0.25**	0.17	°C
Precipitation	PRCPTOT	**−2.63**	−0.20	%
	SDII	−0.09	−0.01	mm
	CDD	1.94	−0.48	days
	CWD	0.04	0.09	days
	R10mm	−1.22	−0.63	days
	R20mm	−0.75	−0.40	days
	RX1day	−1.77	−1.26	%
	RX5day	−1.22	1.31	%

[a]Values for trends significant at the 5% level are shown in boldface.

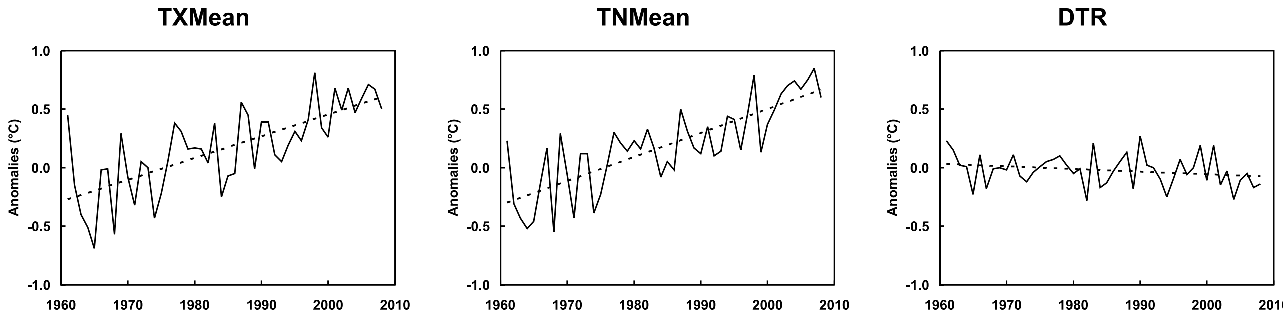

Figure 3. Regional average of the station's anomalies for TXMean, TNMean, and DTR. Dashed line represents the linear trend for 1961–2008.

and TR20 is significant at almost every station except for those for which these events occur nearly all the time or almost never (figures not presented here).

3.2. Temperature Extremes

[17] Changes in temperature extremes are spatially coherent across the region. Overall, changes are more pronounced in the extreme highs than the extreme lows. The regional average series indicate that the warm days (TX90P) and warm nights (TN90P) have significantly increased by 3.75 and 3.83% per decade, respectively, over 1961–2008 and these increases are even more pronounces for the past 34 years (Table 3 and Figure 5). Significant increasing trends ranging from 2 to 6% were also found at most stations (Figure 6). Observed changes in cold extremes are smaller than in warm extremes. The regional average series show an insignificant decrease of 1.28% per decade in the percentage of cold days (TX10P) while a significant decrease of 1.03% per decade is found in the percentage of cold nights (TN10P), over 1961–2008 (Table 3 and Figure 5); these decreases are less pronounced and insignificant over the last 34 years (Table 3). Most stations show a coherent pattern of decreasing trends ranging from −1 to −3% per decade and these trends are also mainly significant (Figure 6).

[18] The analysis of the annual highest and lowest daily maximum and minimum temperatures confirm the previous results. Changes in extreme high values are larger than in extreme low values (Table 3), with the exception of the nighttime temperatures for which low extremes are slightly increasing more than the high extremes but only for the longer period. The regional average series suggest significant increases of 0.23 and 0.21°C per decade in the annual high maximum (TXx) and minimum (TNx) temperatures, respectively, while significant increases of 0.09 and 0.25°C per decade are observed in the annual low maximum (TXn) and minimum (TNn) temperatures over the past 48 years. Many stations show significant trends in their annual extreme high and low temperatures (figures not presented here).

3.3. Precipitation Total and Intensity

[19] The results for the precipitation indices show less evidence of changes and spatial agreement compared to the temperature indices. The regional average series indicate a significant decrease in the annual total precipitation amount (PRCPTOT) of 2.63% per decade over 1961–2008 (Table 3 and Figure 7). Most stations show decreasing trends ranging from −2 to −6% per decade but few stations report a sig-

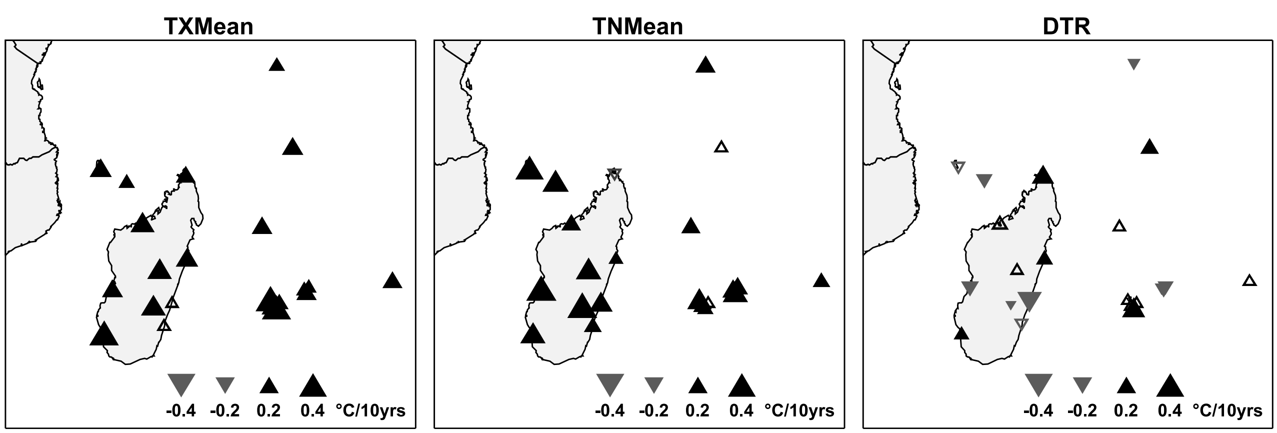

Figure 4. Trends in TXMean, TNMean, and DTR for 1961–2008. Upward (black) and downward (gray) pointing triangles indicate positive and negative trends, respectively. Solid triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend.

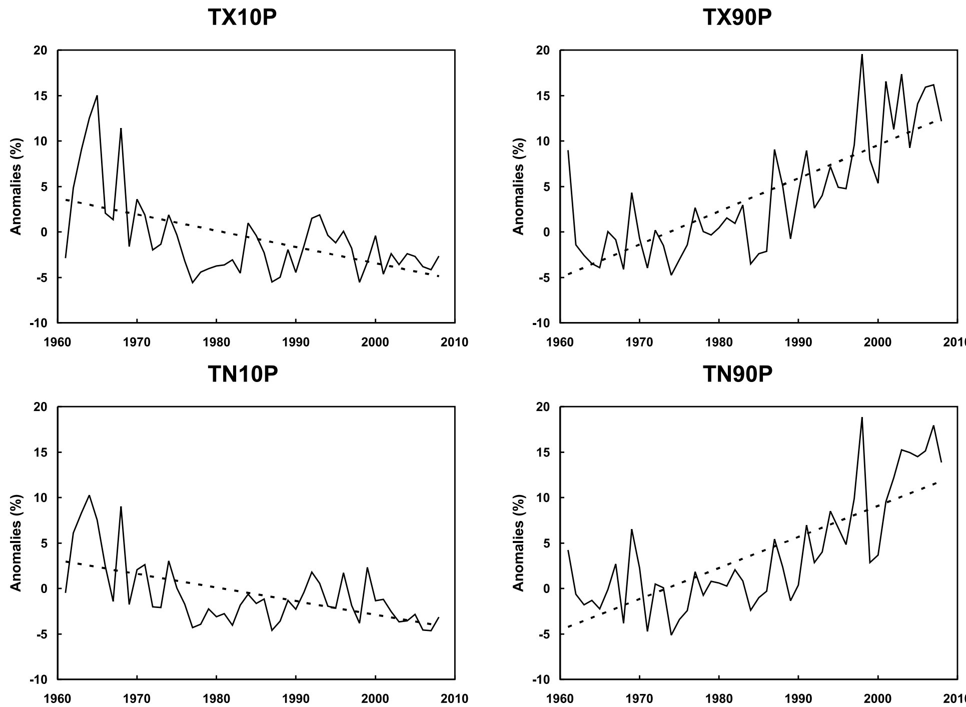

Figure 5. Regional average of the station's anomalies for TX10P, TX90P, TN10P, and TN90P. Dashed line represents the linear trend for 1961–2008.

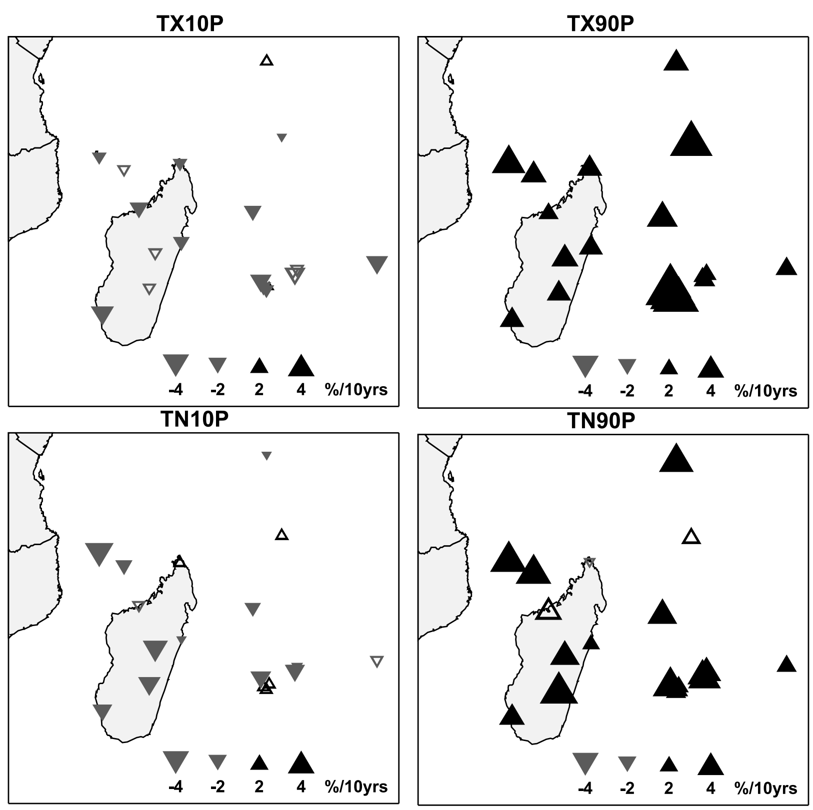

Figure 6. Same as Figure 4 but for trends in TX10P, TX90P, TN10P, and TN90P for 1961–2008.

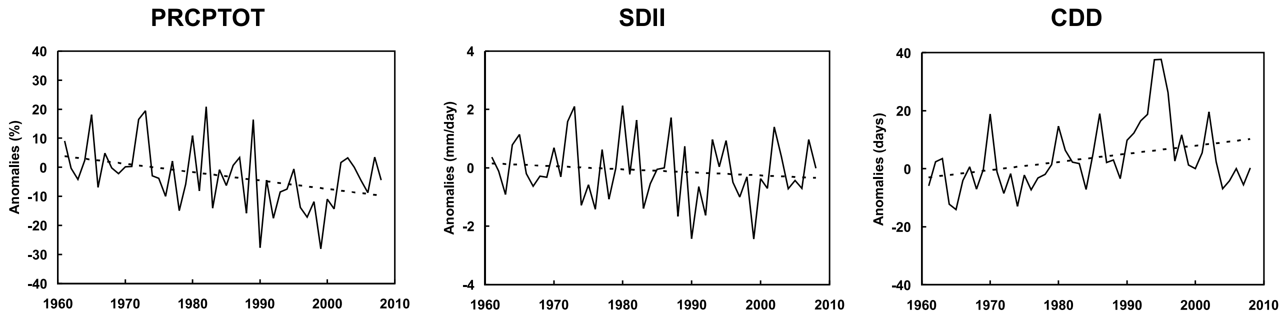

Figure 7. Regional average of the station's anomalies for PRCPTOT, SDII, and CDD. Dashed line represents the linear trend for 1961–2008.

nificant decrease (Figure 8). Some weak increasing trends were also found at some stations in Madagascar and Seychelles. The annual precipitation intensity (SDII) shows very little change with an insignificant regional trend of −0.09 mm per decade (Table 3 and Figure 7). Individual stations indicate either an insignificant positive or negative trend across the region (Figure 8). Consecutive dry days (CDD) have increased by 1.94 days per decade during 1961–2008 but the trend is not significant (Table 3 and Figure 7). It is important to notice that consecutive dry days have mainly increased over land as seen in Madagascar (Figure 8). The consecutive wet days (CWD) do not show any evidence of change (figures not presented here). The trends for 1975–2008 indicate similar results and all trends are not statistically significant.

3.4. Precipitation Extremes

[20] Overall, the results show small and insignificant decreases in precipitation extremes for both periods of 1961–2008 and 1975–2008. Regional average series indicates fewer days with rain above 10 and 20 mm (R10mm and R20mm); however, trends are not significant at the 5% level for both periods (Table 3 and Figure 9). Most individual stations show a decrease of 1 to 3 days in R10mm and R20mm and several significant decreasing trends are found across the region (Figure 10). A decrease is also observed in the regional series of the annual highest daily precipitation (RX1day) and the highest 5 consecutive days of precipitation (RX5day); however, these trends are not significant (Table 3 and Figure 9). In addition, an increase is reported in RX5day for 1975–2008. Stations show both increasing and decreasing insignificant trends across the region although more decreasing trends are observed (Figure 10).

4. Discussion

[21] The results presented in this study are in agreement with many other findings on changes in daily and extreme temperature and precipitation indices. The current study shows that the annual means of daytime and nighttime temperature have increased at similar rates, leading to no noticeable change in the diurnal temperature range (DTR) over the past five decades. Similar findings were also observed in central and southern Africa, where small insignificant trends were found in the DTR over comparable periods of time [*Aguilar et al.*, 2009; *New et al.*, 2006; *Kruger and Shongwe*, 2004]. However, significant decreasing DTR trends were established in the Middle East and central and South Asia [*Zhang et al.*, 2005; *Klein Tank et al.*, 2006]. Furthermore, almost 40% of land stations have indicated a significant decrease in DTR for the past 40 to

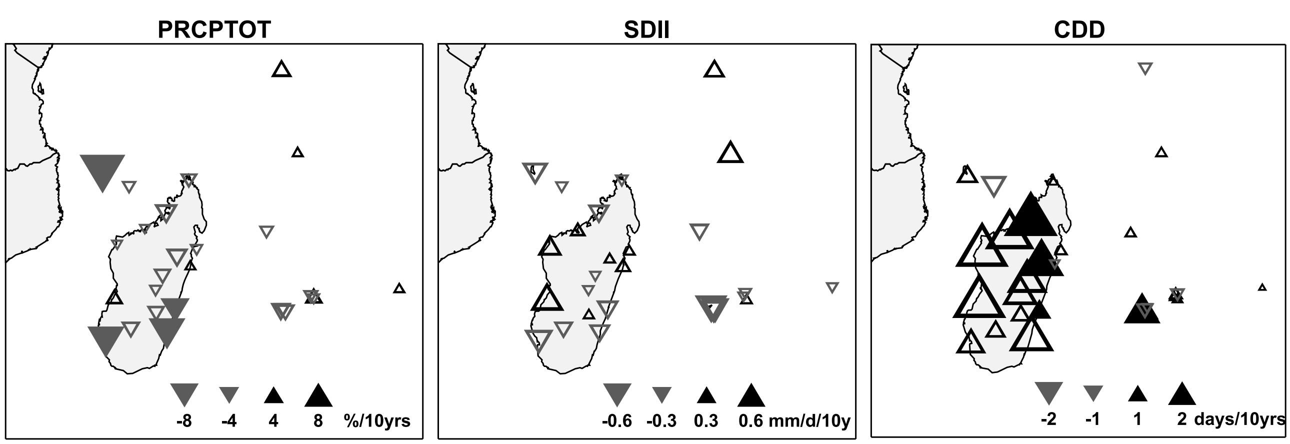

Figure 8. Same as Figure 4 but for trends in PRCPTOT, SDII, and CDD for 1961–2008.

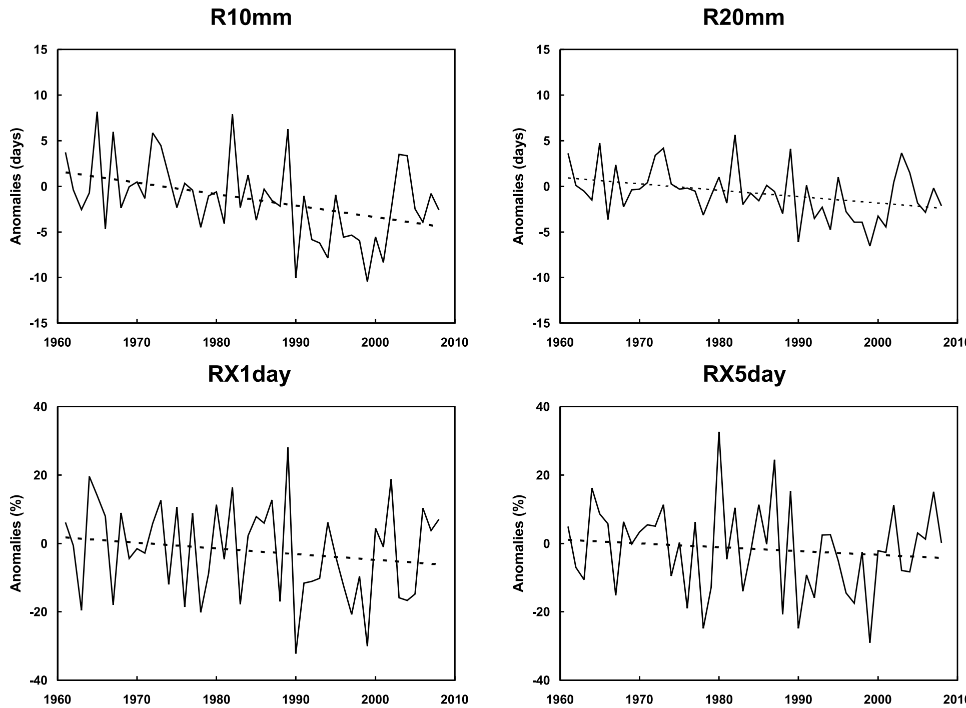

Figure 9. Regional average of the station's anomalies for R10mm, R20mm, RX1day, and RX5day. Dashed line represents the linear trend for 1961–2008.

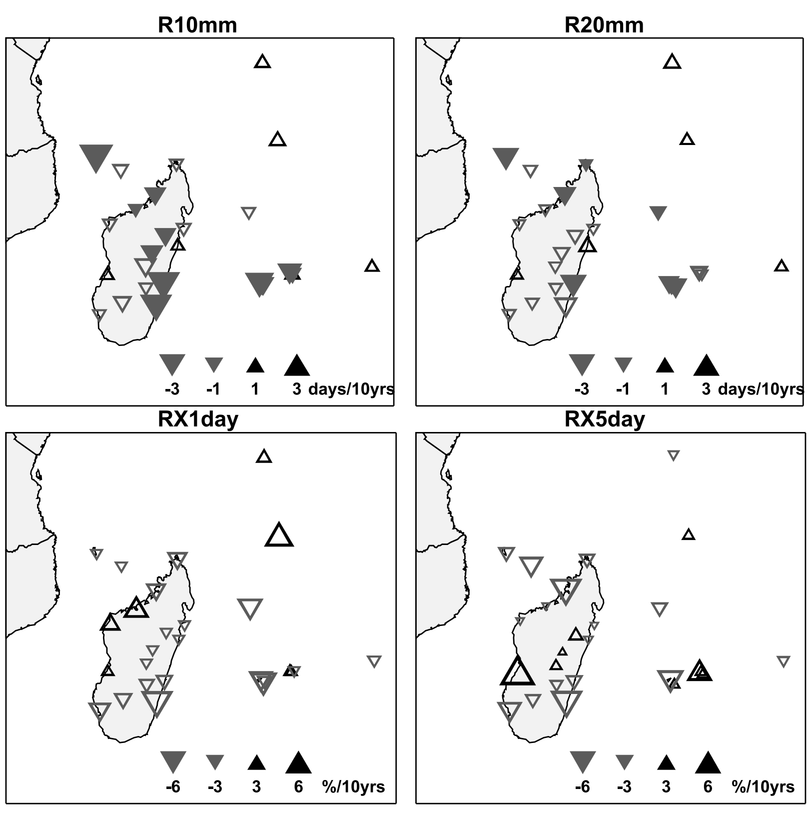

Figure 10. Same as Figure 4 but for trends in R10mm, R20mm, RX1day, RX5day, for 1961–2008.

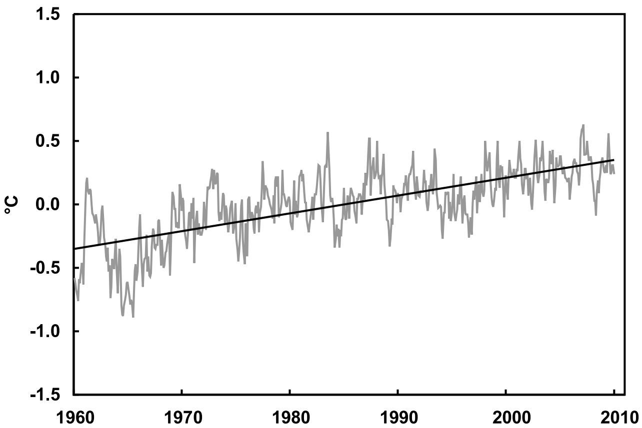

Figure 11. Sea surface temperature monthly anomalies averaged for the grid points between 30°E and 70°E and between 40°S and the equator.

50 years due to a warming more pronounced in nighttime temperature than in daytime temperature [*Alexander et al.*, 2006].

[22] The current study also suggests fewer cold extremes and more warm extremes for the past 48 years. This result is consistent with extreme temperature trends observed around the world [*Alexander et al.*, 2006]. The current analysis indicates that changes are more pronounced in warm extremes than cold extremes. This finding was also found in several parts of central and southern Africa [*Aguilar et al.*, 2009; *New et al.*, 2006] and in the Middle East and central and South Asia [*Zhang et al.*, 2005; *Klein Tank et al.*, 2006]. Globally, it is the nighttime warm and cold extreme temperatures that have changed the most for the past five decades and the global analysis has indicated that more than 70% of land area has significant trends in their warm and cold nighttime extreme temperatures [*Alexander et al.*, 2006].

[23] A small but statistically significant reduction was found in the annual total precipitation (PRCPTOT) for the countries of the western Indian Ocean during the past 48 years; for 1975–2008, the annual precipitation trend is still negative but statistically insignificant. No significant changes were observed in the other precipitation indices although several stations showed increasing trends in consecutive dry days (CDD), decreasing trends in the number of days above 10 and 20 mm (RR10mm, RR20mm), and extreme precipitation amounts (RX1day, RX5day). Thus, at a region-wide scale, there is agreement between the station indices which suggest less annual total and daily extreme rainfall. In several countries of central and southern Africa, many stations have also indicated insignificant decreasing trends in annual precipitation (PRCPTOT), days above 10 and 20 mm (RR10mm, RR20mm) and extreme amounts (RX1day, RX5day), while increasing trends were found in daily intensity (SDII) and consecutive dry days (CDD) for the past four decades [*Aguilar et al.*, 2009; *New et al.*, 2006].

[24] Sea surface temperature (SST) can be closely related to some of the changes seen in temperature and precipitation indices. Therefore, an analysis was done comparing each regional averaged index with the SST of the area. The Extended Reconstructed Sea Surface Temperature (ERSST.v3b) was used to prepare a single SST series for a window ranging from 30°E to 70°E and from 40°S to the equator [*Smith et al.*, 2008]. Monthly departures from 1960 to 2009 were first computed at each of the 2 degree grid points, then averaged together to produce a single annual SST series. Correlation was used to determine the linear association between each regional index and the annual SST. Furthermore, coefficients of determination were obtained to provide a measure of the reduction in total variation in each regional index associated with the use of the annual SST.

[25] Sea surface temperatures for the western Indian Ocean show an increase of 0.12°C per decade over 1960–2009 (Figure 11). The land surface temperature for the same region has indicated an increase of about 0.20°C per decade, almost twice the rate of SST during the same period of time. Homogeneity assessment of this SST series revealed an inhomogeneity at the beginning of the 1960s, which also corresponds to the shift detected in 1963 in many temperature station series and confirms the hypothesis that this shift is most likely due to climate variations. However, no other statistically significant shift was identified in the SST series while 1983 was detected as a second step in many temperature station series.

[26] Table 4 shows that the annual mean of daily maximum and minimum temperature (TXMean and TNMean) and number of summer days and tropical nights (SU25 and TR20) are highly correlated with the annual average of SST of the area and correlation coefficients range from 0.85 to 0.87. The correlation between warm and cold extremes (TX90P, TX10P, TN90P and TN10P) and SST vary from 0.66 to 0.84 (cold extremes have negative correlations). The highest and lowest values of the year (TXx, TXn, TNx and

Table 4. Correlation Between Each Index and the Regional Average Annual Anomalies SST Computed Over the Western Indian Ocean Region[a]

Element	Index	Correlation	Percent of Variability Explained by SST
Temperature	TXMean	0.87	75.0
	TNMean	0.85	71.8
	DTR	0.02	0.3
	SU25	0.86	73.5
	TR20	0.85	74.0
	TX90P	0.74	54.1
	TX10P	−0.84	70.2
	TN90P	0.66	43.0
	TN10P	−0.80	63.5
	TXx	0.66	43.5
	TXn	0.65	42.8
	TNx	0.60	35.5
	TNn	0.61	37.5
Precipitation	PRCPTOT	−0.25	6.4
	SDII	−0.05	0.3
	CDD	0.22	4.7
	CWD	0.03	0.1
	R10mm	−0.25	6.4
	R20mm	−0.18	3.4
	RX1day	−0.21	4.5
	RX5day	−0.11	1.1

[a]Percentage of the total variability in each index accounted for by the relation between SST and the index.

TNn) have lower correlation with SST and their values range from 0.60 to 0.66. Coefficients of determination (values multiplied by 100 in Table 4) indicate that 75% of the total variation in TXMean is explained by SST.

[27] Table 4 also indicates that there is almost no evidence of linear association between precipitation indices and the annual SST. Similar results were found indicating that the Indian summer monsoon is weakly linked to the Indian Ocean SSTs [*Bollasina and Nigam*, 2009]. However, in the climate extremes study of the Caribbean, the daily intensity (SDII) was the precipitation index with the strongest correlation with SST, and the correlations computed at each grid point have reached as high as 0.5 in the southern Caribbean Sea [*Peterson et al.*, 2002]. The relation between precipitation indices and SSTs could be further investigated for the western Indian Ocean region using seasonal precipitation and grid point SSTs; however, this is beyond the scope of this paper.

5. Summary and Conclusion

[28] This study presents the trends in daily and extreme temperature and precipitation indices for the countries of the western Indian Ocean from 1961 to 2008 (and 1975–2008). Data was carefully examined for quality and homogeneity by local experts and a consistent methodology was applied for the preparation and investigation of the temperature and precipitation indices. This study provides, for the first time, an analysis of the climate trends and extremes using many long-term land stations from all countries of the region.

[29] The results show warming of the surface air temperature at land stations. The annual mean of daily maximum and minimum temperature (TXMean and TNMean) have increased by 0.19 and 0.21°C per decade, respectively, for the past 48 years, leading to no discernable change in the diurnal temperature range. Summer days and tropical nights have became more frequent, changing at a rate of about 5 days per decade. The percentage of warm days and warm nights (TX90P, TN90P) have increased by almost 4% per decade, while the percentage of cold days and cold nights (TX10P, TN10P) have decreased by about 1% per decade. Overall, warm extremes have changed more than cold extremes and this was also seen in the highest and lowest temperatures of the year.

[30] Precipitation indices show less evidence of coherent changes. Regionally, only the annual total precipitation (PRCPTOT) has indicated a significant change, with a decrease of 2.63% per decade over 1961–2008. There is an indication of more consecutive dry days (CDD), especially in Madagascar, but there were no changes in consecutive wet days (CWD) and daily precipitation intensity (SDII). Although no significant change was detected regionally for the extremes, fewer days above 10 and 20 mm (R10mm, R20mm), and a decrease in the annual highest daily amount (RX1day) and highest 5 consecutive days (RX5day) of precipitation were found at many stations.

[31] The workshop in Mauritius has provided a great opportunity for establishing a strong scientific network in the region. The expertise of the participants enabled the generation of reliable climate change indices in a region where no such study had been done before. This study represents an important contribution to climate change research in the region. The indices will be made available to the international research community on the ETCCDI website at http://cccma.seos.uvic.ca/ETCCDI/.

[32] **Acknowledgments.** This workshop would not have been possible without the financial support of Les Fonds Français pour l'Environnement Mondial. Workshop attendees greatly appreciated organization provided by Brice Montfraix and Isabelle Lebreton from La Commission de l'Océan Indien (COI) in Mauritius, who implement the project "Renforcement des Capacités de la COI dans le domaine de l'Adaptation au Changement Climatique (ACCLIMATE)." The participants also enjoyed the hospitality provided by the Mauritius Meteorological Services and, in particular, by Yadowsun Boodhoo, director of the Meteorological Services in Mauritius. Appreciation is as well given to Xuebin Zhang, Xiaolan Wang, and Feng Yang, of the Climate Research Division of Environment Canada, for the preparation of the software packages RClimDex and RHtestsV3, which were used during the workshop. The authors are also grateful to Xuebin Zhang, Xiaolan Wang, and two anonymous reviewers for their helpful comments that contributed to an improved version of the paper.

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