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Analysis of Rainfall Variations and Trends in Coastal Tanzania

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Abstract—Rainfall records (1960-2009) for coastal Tanzania were investigated for variability and trends from seven key weather stations. Results indicated that the island of Mafia receives the highest amount of rainfall (1879 mm p.a.) while Kilwa Masoko receives the lowest (1029 mm p.a.). Generally, precipitation on the islands is heavier than on the mainland coast due to moisture convergence in sea breezes. Monthly series indicated a predominance of annual and semi-annual oscillations in the northern sector, while the annual signal was the most dominant on the southern coast. Partial correlation analysis revealed a significant influence of the El Niño Southern Oscillation (ENSO) on annual rainfall. However, the effects of the Pacific Decadal Oscillation (PDO) and the Indian Ocean Dipole (IOD) were smaller. At the seasonal scale, the effects of large scale climatic phenomena were smaller during the two wet seasons and in the northeast (NE) monsoon, but significantly greater during the southeast (SE) monsoon. Linear regressions of the monthly rainfall series portrayed a general downward trend at each station, but all the trends were insignificant at the 95% level. Inter-annual and decadal variations showed that the year 2003 and the last decade (2000-2009) were the driest in the last half century.

INTRODUCTION

Tanzanian coastal rainfall exhibits certain features that are unique to East Africa, with changes caused by local diurnally-based circulation altering the larger-scale rain-producing mechanisms (Summer, 1982). On the northern coast (4-8^{o}S), this circulation undergoes changes that are represented by two distinct (bimodal) rainy seasons. The heavy or "long" rains fall between March and May (MAM) and the light or "short" rains between October and December (OND). The heavy rains are more abundant, while the short rains are more variable. The two rainy seasons are respectively associated with the northward or southward movement of the Inter-tropical Convergence Zone (ITCZ). In the southern

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sector (8-12°S), only one (unimodal) rainfall season occurs during the year, from November through April (Kijazi & Reason, 2009).

The El Niño Southern Oscillation (ENSO) has been identified as the dominant climate signal that affects the weather and climate worldwide (Behera & Yamagata, 2003). However, the Indian Ocean Dipole (IOD) is an El Niño-like temperature anomaly in the Indian Ocean that affects the regional climate. A positive IOD event is marked by a fall in SST in the south-eastern part of the Indian Ocean, counteracted by an SST increase in the western equatorial Indian Ocean and vice versa (Marchant *et al*., 2006). This mainly affects the short rains (Saji *et al*., 1999). An increase in SST leads to heavy rainfall over the coast of east Africa and severe droughts and forest fires over Indonesia. Warm (positive) SST anomalies are associated with El Niño events, while La Niña events are typically associated with cold (negative) SST anomalies. Extremes in these climate phenomena cause extreme weather in many regions of the world. They are also influenced by the Pacific Decadal Oscillation (PDO) Index, as defined by Mantua *et al*. (1997), the leading principal component in North Pacific monthly SST anomalies pole-ward of 20°N.

In East Africa, positive and negative phases of ENSO are respectively accompanied by above-normal (flood) and below-normal (drought) conditions (Indeje *et al*., 2000). The intensity of an IOD is represented by an anomalous SST gradient between the western equatorial Indian Ocean (50°E-70°E and 10°S-10°N) and the south eastern equatorial Indian Ocean (90°E-110E and 10°S-0°N). This gradient was named the Dipole Mode Index (DMI) by Saji *et al*. (1999).

Apart from the ENSO, IOD, ITCZ and their teleconnections, several other systems also control the spatial and temporal characteristics of the East African climate. These include the intensity, location and orientation of the monsoonal wind systems, subtropical anticyclones, tropical cyclones, jet streams, easterly-westerly wave perturbations, extra-tropical weather systems, mesoscale systems like land-sea breeze effects, solar forcing and global warming. A considerable body of literature provides a detailed account on these factors and how they affect the climate of East Africa, (e.g. Findlater, 1974; Hastenrath, 2000; Kabanda & Jury, 1999; Mutai & Ward, 2000; Ogallo, 1989; Schreck III & Semazzi, 2004; Summer, 1983).

IPCC regional climate projections for the 21st century indicate that there will be an increase in the annual mean rainfall over East Africa (Christensen *et al*., 2007; Meehl *et al*., 2007). However, specific projections for the coast of Tanzania illustrate a declining trend in rainfall from June-August and an increasing trend from December to February. Globally, however, there are substantial discrepancies in predicted trends in annual precipitation, these being indicative of the difficulty in monitoring a variable that manifests considerable variability in both space and time.

Several studies have been carried out on various aspects of rainfall in East Africa, including Tanzania (e.g. Behera *et al*., 2005; Marchant *et al*., 2006; Mutai & Ward, 2000). Other studies have considered some parts of the country (e.g. Kabanda & Jury, 1999; Kijazi & Reason, 2009), while only a few have focused on the entire coastal environment (e.g. Kijazi & Reason, 2005; Summer, 1982). Some past analyses have also focused on the influence of the ENSO and IOD (.e.g. Behera *et al*., 2005; Behera & Yamagata, 2003; Kijazi & Reason, 2005), but none have considered the simultaneous effects of the ENSO, IOD and PDO phenomena and their effect on the monsoonal wind seasons. More importantly, most past analyses have utilized data that do not extend up to the end of the last decade.

The present study was thus undertaken to address these gaps through investigation of various aspects of variability and trends in rainfall along the coast of Tanzania (Fig. 1). This was considered imperative since fluctuations in rainfall along the coast play an important role in terrestrial and marine ecosystems, water supply, agriculture, human health and other socio-economic issues.

Many statistical tests are available for the detection of trends in time series, but there has been little consensus on suitable methods for trend analysis. For a more thorough review of the various methods that are utilized for the assessment of rainfall trends, see Lloyd (2009). Trend magnitudes can often be determined with considerable certainty using different combinations of parametric and non-parametric techniques (Partal & Kahya, 2006). Kendall's τ statistic has, in particular, been widely used to test for randomness in trends in climatology and hydrology (Partal & Kahya, 2006). Both it and the Spearman rank correlation can detect trends that are monotonic but not necessarily linear and were applied here.

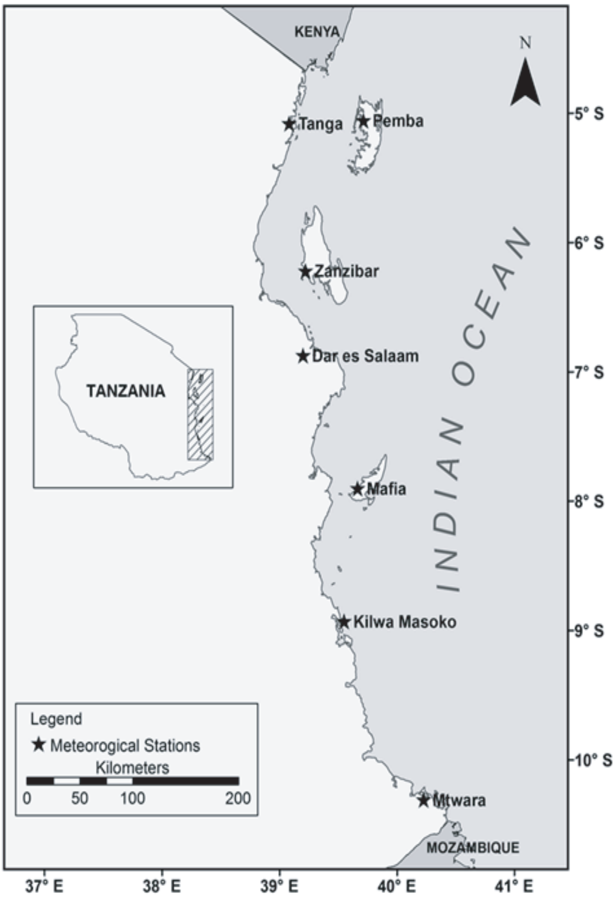

Figure 1. Map of the coastal Tanzania showing the location of the meteorological stations.

MATERIALS and METHODS

The study sites

Data on total monthly rainfall from 1960 to 2009 were used in the investigation. These were obtained from the Tanzania Meteorological Agency (TMA) for the key meteorological stations at Tanga, Dar es Salaam, Kilwa Masoko (hereinafter referred to as Kilwa) and Mtwara on the mainland coast, and from the major islands of Pemba, Zanzibar and Mafia (Fig. 1). Data from Pemba span only from 1974 to 2009. There were gaps of a few years in the rainfall series at each station, especially Mafia and Kilwa. Small gaps of a few months were interpolated from adjacent points using STATISTICA (http://www.statsoft.com) but large gaps were excluded from the analyses.

Trend analysis was undertaken on simple averages of the monthly means of rainfall at each station. Significance in the trends was assessed by non-parametric statistical tests that were enhanced with least squares linear regression models to determine their magnitude. Kendall's τ statistic was used to test for the existence of a linear trend and Spearman's test to verify the results (Mitchell *et al*., 1969).

Significant spectral peaks were estimated using the method of Fast Fourier Transform (FFT) in STATISTICA (Shumway, 1988). The presence of low frequency oscillations in rainfall was further explored through wavelet analysis (Torrence & Compo, 1998). This analysis was carried out in MATLAB (www.mathworks.com) to determine continuous wavelet transformation in the corresponding time series. The wavelet software was provided by C. Torrence and G. Compo, and is available at http://paos.colorado.edu/research/wavelets/

The relationship between local rainfall and the coupled ocean atmosphere systems were explored through partial correlations. The strength of ENSO events was measured by the Ninõ-3 index, which is defined as the average SST anomaly over the eastern equatorial Pacific (5°N-5°S and 150°W-90°W). Monthly time series data for the index (McPhaden *et al*., 2006) were obtained from the US National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/indices). Monthly time series data for the DMI index, used as a measure of the IOD, were collected from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (http://www.jamstec.go.jp/frcgc/research/d1/iod/).

Monthly mean global average SST anomalies were removed from the PDO Index to separate it from any “global warming” signal that may be present in the data. Data for the index were obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) (http://jisao.washington.edu/pdo/PDO.latest/).

Partial correlations of local temperatures with Niño-3 were computed by partialing out the DMI and PDO. Likewise, the partial correlations of maximum and minimum temperatures with DMI (PDO) were determined by partialing out the Niño-3 (DMI) and PDO (Niño-3), respectively. All computations for partial correlations were performed using STATISTICA (http://www.statsoft.com).

RESULTS

It is clearly evident from Table 1 that the island stations receive the highest amount of rainfall along the Tanzanian coast. The island of Mafia ranks first, with an annual total rainfall averaging 1879 mm p.a., followed by Zanzibar (1670 mm p.a.) and Pemba (1610 mm p.a.). Kilwa receives the lowest rainfall, averaging only 1029 mm p.a. Linear regressions of the monthly rainfall series revealed a downward trend at all seven stations (Fig. 2). In this regard, both the Kendall τ and Spearman’s rank tests showed positive but insignificant trends (at the 95% level) at Zanzibar (Table 1). At Mafia, the Spearman’s rank test yielded no trend, while the Kendall τ test showed a negative trend. The trends for all the other stations were also insignificant at the 95% level when tested using Kendall’s τ statistic and the Spearman’s rank test.

In Table 2, the highest amount of rainfall recorded in a single month in the last 50 years occurred at Mafia Island in April 1975 (1082 mm). This was followed by Pemba Island which, in April 1978 (1052 mm), corresponded to the 1977/1978 El Niño. The highest monthly rainfall records at all stations were observed in either March or April during the “long” rainy season, except at Tanga when this occurred in October during the “short” rainy season. Likewise, the highest annual total rainfall occurred at Pemba Island in 1978 (2668 mm), again corresponding to the

Table 1. Results of statistical tests for rainfall at coastal weather stations in Tanzania.

Station	Data span (Years)	Annual mean (mm)	Regression coefficient	Kendall τ	Spearman R	Significant at 95% level
Tanga	50	1289	-4.48	-0.13	-0.15	N
Pemba	35	1610	-14.93	-0.21	-0.31	N
Zanzibar	50	1670	-0.79	0.02	0.02	N
D’Salaam	50	1136	-2.30	-0.06	-0.09	N
Mafia	50	1879	-2.00	-0.01	0.00	N
Kilwa	50	1029	-0.53	-0.02	-0.02	N
Mtwara	50	1109	-3.85	-0.16	-0.23	N

Table 2. Statistics of extreme wet and dry coastal conditions in Tanzania for the period 1960-2009.

Station	Max monthly rainfall (mm)	Month occurred	Max annual rainfall (mm)	Year occurred	Min annual rainfall (mm)	Year occurred
Tanga	814	Oct 1997	2018	1968	692	2003
Pemba	1052	Apr 1978	2668	1978	800	1974
Zanzibar	871	Mar 1962	2802	1979	704	2003
Dar es Salaam	569	Apr 2002	1693	1961	585	2003
Mafia	1082	Apr 1975	2664	2002	1075	1987
Kilwa	562	Mar 1997	1645	1963	298	2003
Mtwara	756	Mar 1978	1685	1967	515	2003

1977/78 El Niño, followed by Mafia in 2002 (2664 mm). A Loess fit illustrates the remarkable rise in rainfall at most of the stations during the El-Niño events in 1978/79 and 1997/98 (Fig. 2).

Table 3 shows decadal averages of rainfall during the observation period. It is notable that the past decade (2000-2009) was the driest, followed by 1970-1979. The lowest decadal average was 954 mm which was recorded at Kilwa during 1980-89. The corresponding highest decadal record was 1905 mm which was observed at Mafia during 1960-1969.

Plots of the monthly and annual rainfall series spectra (figures not displayed) revealed that the major offshore islands (Pemba, Zanzibar and Mafia) manifested significant annual, semi-annual and terannual (four-monthly) oscillations. At the mainland coastal stations, the terannual signals were of less significance than were the annual and semi-annual oscillations. The northern mainland coastal stations (Dar es Salaam and Tanga) were mainly subjected to annual and semi-annual cycles, typical of a bimodal rainfall pattern. At the southern mainland stations (Kilwa and Mtwara), the annual cycles were the only significant sources of variation, typical of a unimodal rainfall pattern. There were significant spectral frequencies at periods of 2.2-2.4 years,

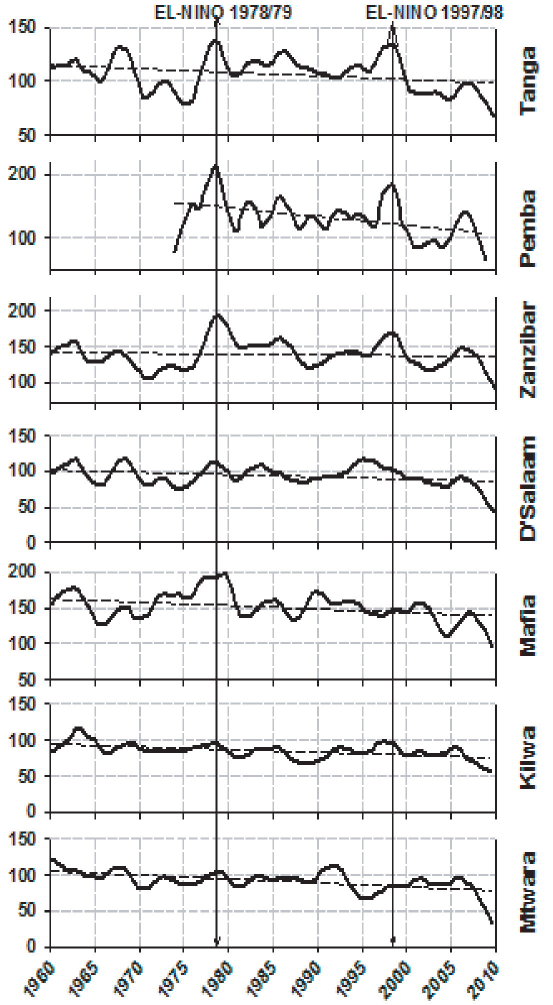

Figure 2. Loess smoothing of the monthly rainfall series at each station (solid lines). The linear regression trends are shown in dashed lines while solid arrows indicate the occurrence of major El Niño events.

Table 3. Decadal averages of total rainfall (mm) at coastal weather station in Tanzania.

Station	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009
Tanga	1393	1227	1358	1380	1065
Pemba	-	-	1628	1688	1243
Zanzibar	1690	1653	1727	1745	1536
Dar es Salaam	1226	1093	1114	1235	995
Mafia	1905	-	1797	1812	-
Kilwa	-	1042	954	1033	-
Mtwara	1227	1103	1119	1033	1002

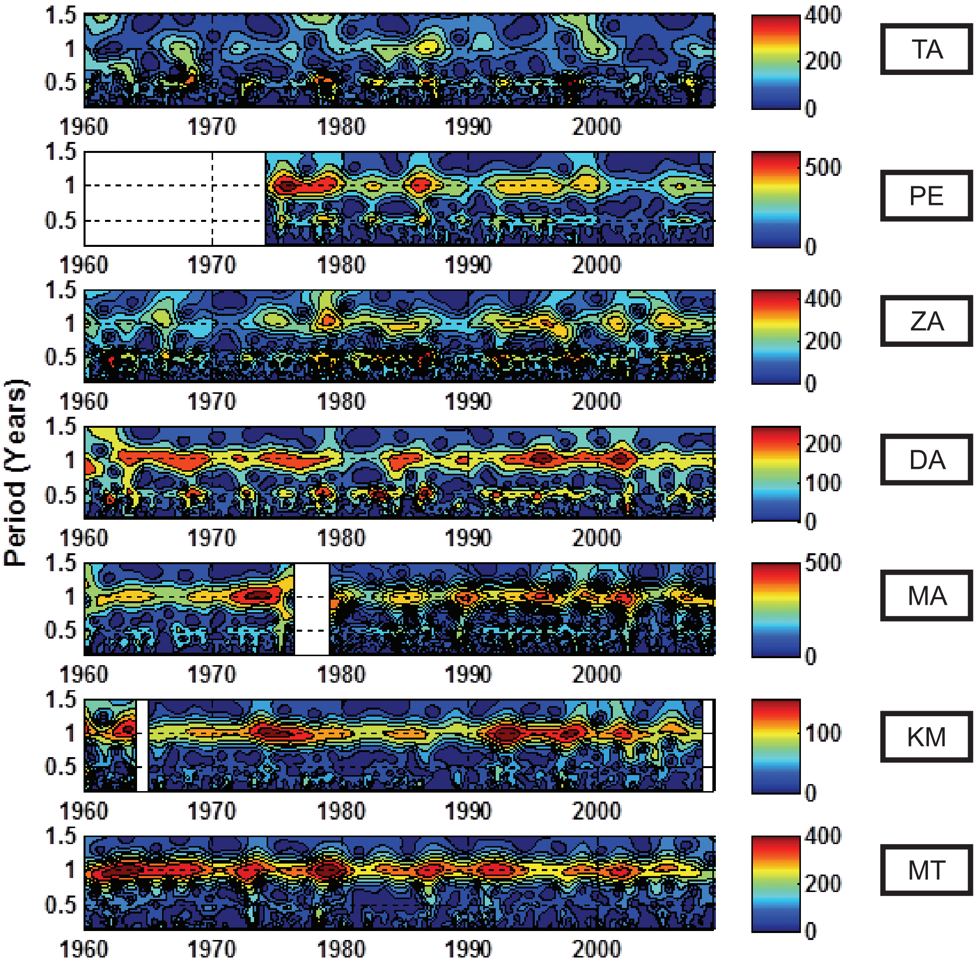

Figure 3. Wavelet spectra depicting the annual and semi-annual timescale signals of rainfall at Tanga (TA), Pemba (PE), Zanzibar (ZA), Dar es Salaam (DA), Mafia (MA), Kilwa Masoko (KM) and Mtwara (MT). The colour scale bar on the right shows the amount of rainfall (mm).

3.2-3.4 years and about 6.9 years in the annual rainfall spectra at all stations except Pemba where the annual rainfall series were not long enough to establish the detailed shape of its annual spectrum.

Results of the wavelet spectral analysis at the annual timescale are presented in Figure 3, and also manifested annual and semi-annual signals. At the inter-annual timescale (Fig. 4), all sites showed evidence of oscillations that were characteristic of the ENSO timescale signal. In Figures 2 and 4, the major El-Niño events of 1978/79 and 1997/98 are clearly discernible, especially in the northern sector.

Rainfall was significantly correlated with ENSO events (at 95% level) at all seven stations (Table 4), with correlation coefficients ranging between 0.28 and 0.52. Table 4 also shows a coherent inverse relationship between rainfall and PDO, but the correlation coefficients were generally less than those observed between rainfall and ENSO, the largest coefficient being only 0.21. Correlations of rainfall with IOD were also negative but less important than those with either ENSO or PDO (Table 4; correlation coefficients <0.14).

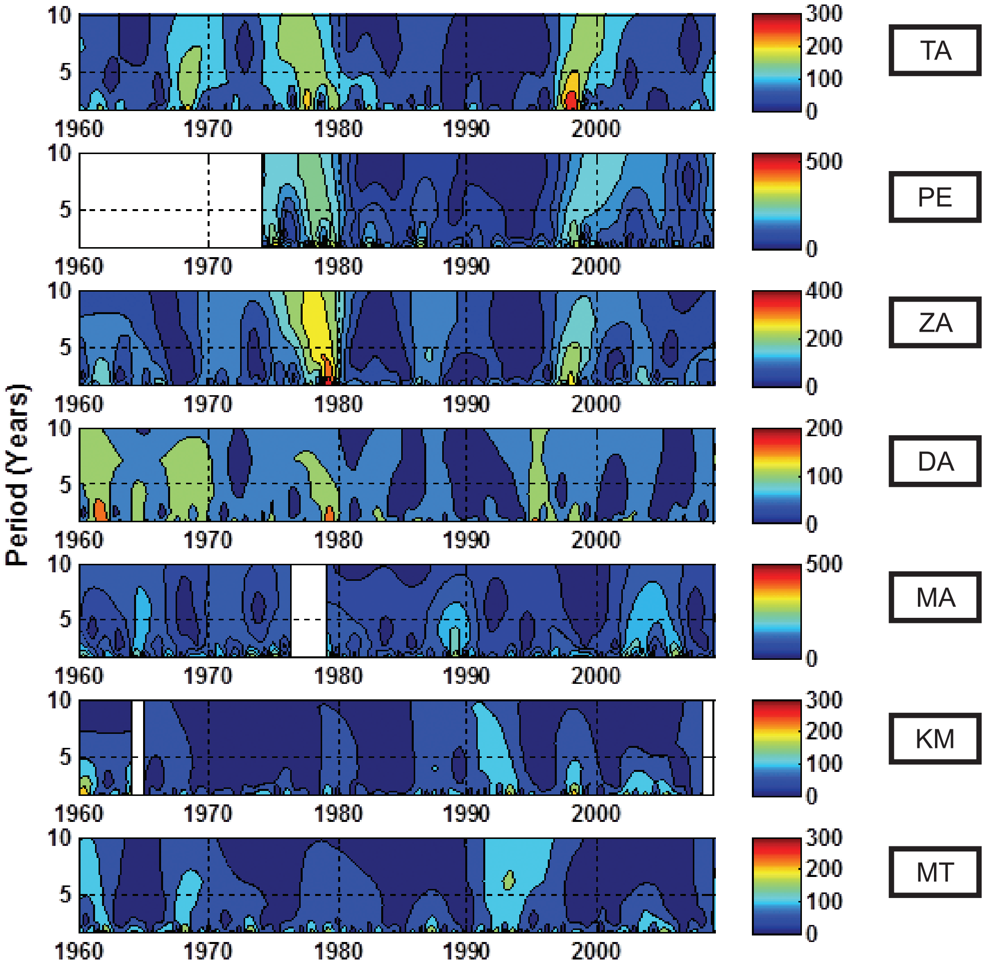

Figure 4. Wavelet spectra depicting the ENSO timescale signals of rainfall at Tanga (TA), Pemba (PE), Zanzibar (ZA), Dar es Salaam (DA), Mafia (MA), Kilwa Masoko (KM) and Mtwara (MT). The colour scale bar on the right shows the amount of rainfall (mm).

Table 4. Correlation of Tanzanian coastal rainfall with Niño-3 (r_n), DMI (r_d) and PDO (r_p), after partialing out the effects of DMI and PDO, Niño-3 and PDO, and Niño-3 and DMI, respectively during January-December and October-December (OND). Correlation coefficients in bold are significant at the 95% confidence level.

Station	Latitude	Longitude	January - December			October - December		
			r_n	r_d	r_p	r_n	r_d	r_p
Tanga	5^o 5.6 S	39^o 4.3 E	**0.28**	**0.09**	-0.06	0.12	**0.30**	-0.06
Pemba	5^o 21 S	39^o 38 E	**0.47**	**-0.11**	-0.09	**0.20**	0.18	-0.01
Zanzibar	6^o 13.2 S	39^o 13 E	**0.36**	-0.02	**-0.10**	0.14	**0.21**	-0.12
Dar es Salaam	6^o 52 S	39^o 12 E	**0.42**	-0.03	**0.17**	**0.22**	**0.18**	**-0.22**
Mafia	7o 57 S	39^o 45 E	**0.52**	**-0.14**	**-0.21**	0.16	0.14	-0.06
K/Masoko	8^o 54 S	39^o 30 E	**0.39**	-0.08	**-0.15**	**0.18**	0.07	-0.07
Mtwara	10^o 20 S	40^o 11 E	**0.36**	**-0.08**	**-0.13**	**0.21**	0.01	-0.04

At the seasonal timescale, the relation between rainfall and the three climate phenomena was generally stronger during the SE monsoon than during MAM, OND and the NE monsoon (Tables 4 and 5). This is reflected by the magnitude of the correlation coefficients which were generally larger in the SE monsoon than during the other three seasons. For instance, the correlation coefficients between rainfall and ENSO varied from 0.42 to 0.64 in the SE monsoon, whereas the coefficients did not exceed 0.3 in the other seasons. As in the annual cycle, there was an inverse relationship between rainfall and PDO in all four seasons, and the IOD during the SE monsoon. The correlation coefficients were positive during the short rains in OND and the NE monsoon, whereas the IOD did not exert any significant influence on rainfall at the 95% level during the heavy rains in MAM.

Table 5. Correlation of Tanzanian coastal rainfall with Niño-3 (r_n), DMI (r_d) and PDO (r_p), after partialing out the effects of DMI and PDO, Niño-3 and PDO, and Niño-3 and DMI, respectively during March-May, the NE Monsoon (November-March) and SE Monsoon (April-October). Correlation coefficients in bold are significant at the 95% confidence level.

Station	March-May			NE Monsoon			SE Monsoon		
	r_n	r_d	r_p	r_n	r_d	r_p	r_n	r_d	r_p
Tanga	0.03	-0.13	0.11	0.02	**0.19**	-0.06	**0.42**	0.04	-0.07
Pemba	0.04	-0.05	0.18	0.14	0.14	-0.02	**0.63**	**-0.24**	**-0.15**
Zanzibar	**0.19**	-0.02	0.06	-0.06	**0.20**	-0.02	**0.57**	**-0.14**	**-0.12**
D‘ Salaam	**0.20**	0.00	-0.05	**0.13**	**0.19**	**-0.13**	**0.58**	**-0.15**	**-0.17**
Mafia	**0.20**	-0.13	**-0.20**	**0.25**	0.09	-0.09	**0.64**	**-0.24**	**-0.25**
K/Masoko	**0.26**	-0.12	**-0.20**	**0.20**	**0.14**	-0.01	**0.55**	**-0.21**	**-0.21**
Mtwara	0.16	-0.16	-0.11	**0.33**	0.05	-0.06	**0.54**	**-0.23**	**-0.21**

DISCUSSION

There appears to be no literature that defines the Tanzanian coast and offshore islands as a homogeneous rainfall region owing to their differing climatic regimes (see e.g. Basalirwa *et al*., 1999; Nieuwolt, 1974). The present results indicate that the island stations receive higher rainfall than any of the mainland coastal stations, probably due to the effect of moisture convergence in Indian Ocean sea breezes which is more pronounced over the islands than on the continental mainland. In this regard, offshore winds often produce intense sea breezes, of which the extent of inland penetration is not great (Estoque, 1962). For instance, Qian (2008) observed intense rainfall on the small islands of Southeast Asia that was predominantly caused by sea-breeze convergence over the islands, reinforced by mountain–valley winds and further amplified by the cumulus merger processes.

The declining trends in rainfall along the coast of Tanzania seem to be in agreement with an earlier study that revealed downward trends over Tanzania during the period 1979-2001 (Bowden *et al*., 2005). The present study, however, confirmed that the downward trends are insignificant at the 95% level. Rothe & Virji (1976) also found no apparent long-term trend in the rainfall records for the Tanzanian coast using data collected between 1922 and 1973.

However, results of the current study seems to differ from several climate modelling studies which predict that global warming will enhance the atmospheric storage of moisture, resulting in significant increases in global net precipitation (Huntington, 2006; Rawlins *et al*., 2006). Surface air temperatures along the coast of Tanzania have been increasing significantly over the past 50 years (Mahongo, submitted) but this has not been matched by any increase in rainfall. This is in contrast to IPCC regional climate projections (Christensen *et al*., 2007) of an increase in annual mean rainfall in East Africa, emanating from changes in the global climate.

The observed spectral frequencies in the annual series seem to concur with an earlier study by Rothe & Virji (1976) who observed periodicities of 2-2.5 years, ~3.5 years and 5-5.5 years. These oscillations represent ENSO timescale signals in both the quasi-biennial (1.5-4 years) and lower frequency (3-6.7 years) bands defined by Moron *et al*. (1998).

The present study yielded wavelet analysis and partial correlations through Loess smoothing that showed that annual rainfall generally is significantly correlated with ENSO events. This implies that El Niño is associated with above average rainfall and La Niña with below average rainfall. Although the ENSO timescale signal was only apparent at the northern stations (Figs 2 & 4), its effect was significantly reflected at all the stations, especially during the SE monsoon (Tables 4 & 5). Seasonally, however, the influence of ENSO events on rainfall was not spatially coherent during the MAM and OND rains and, in general, its effect on the two rainfall seasons did not seem to differ appreciably.

Partial correlations between ENSO and rainfall (Table 4) also indicated that an early onset of rainfall during OND and a late onset during MAM can lead to years with higher than normal rainfall (El-Niño). Both seasons extend into the SE monsoons when rainfall was significantly correlated with ENSO events. Conversely, years with an early onset of rainfall during MAM, and longer than normal precipitation during OND were associated with reduced rainfall (La Niña). These seasons extended into the NE monsoons when rainfall was less correlated with ENSO events, which concurs with Kijazi & Reason's (2005) observations on the Tanzanian north coast.

Analysis of the influence of the IOD on rainfall can also be deduced from Table 4. Extended precipitation during OND, and an early onset of rain during MAM which impinges into the NE monsoon season, can lead to years with above normal rainfall at some stations. However, an extended MAM season and early onset of the OND season can lead to years with below normal rainfall at almost all the stations. Behera *et al*. (2005) have observed that the correlation between ENSO events and short rains (OND) becomes insignificant when the influence of the IOD is excluded. However, closer examination of Table 4 indicates that this is only true for Tanga and Zanzibar and does not hold true for Pemba, Dar es Salaam, Kilwa Masoko or Mtwara.

The influence of the PDO can also be inferred from Table 4, with extended MAM rains and an early onset of rainfall in OND possibly leading to years with below normal rainfall. However, the PDO may have little or no effect during an early onset of the MAM season, in longer than normal OND seasons, or during normal MAM and OND rainfall seasons. CLIVAR-VACS (cited in WCRP, 2007) showed that, in parts of East Africa, decadal rainfall signals are linked with PDO during the OND rainfall season. In the present case, this was only true of the station at Dar es Salaam, and during an early onset of the OND rains when the PDO was associated with reduced rainfall at all stations except Tanga.

These findings that rainfall is directly affected by large-scale climate phenomena are consistent with past work which indicated that precipitation in East Africa is impacted by ENSO events at the inter-annual timescale (Indeje *et al*., 2000; Kijazi & Reason, 2005), and by the IOD in the short OND rainy season (Behera *et al*., 2005; Black, 2005; Mapande & Reason, 2005; Marchant *et al*., 2006; Ummenhofer *et al*., 2009). The effect of the PDO on phase changes in East African rainfall was first reported by CLIVAR-VACS (cited in WCRP, 2007), but more evidence for Pacific decadal modulation has recently emerged through reconstruction of past changes in river runoff in corals (Grove *et al*., 2012), and through delineation of decadal rainfall zones by rotated principal component analysis (Omondi *et al*., 2012a; Omondi *et al*., 2012b). The current study further confirmed the influence of PDO on rainfall in East Africa, and establishes that precipitation which occurs during the SE monsoon season is influenced more by the large-scale climatic systems than rainfall which occurs during both MAM and OND.

In conclusion, a general decline in rainfall has been measured over coastal Tanzania during the last half century which, although statistically insignificant, is in contrast to the IPCC global climate projections of a likely increase in rainfall over East Africa during the 21st century. Major climatic phenomena clearly play a role in regional precipitation and, while this downward trend in rainfall serves as an indicator of climate change, its consequences require appropriate planning to cope with on-going reductions in precipitation.

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