Western Indian Ocean J. Mar. Sci. Vol. 13. No. 2, pp. 109 - 124, 2014

Annual to Inter-Decadal Variability in Surface Air Temperature Along the Coast of Tanzania

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Keywords: Surface temperature, low frequency oscillations, climatic systems, Tanzanian coast

Abstract — Patterns in atmospheric surface temperature along the coast of Tanzania were investigated for variability and trends over the last 50 years (1960-2009). Various statistical tools were employed in the study, including non-parametric models as well as trend, spectral and wavelet analyses. The results revealed that the ENSO was generally the most important climate phenomenon affecting the inter-annual surface temperature variations. Seasonally, the influence of the ENSO was most prominent around equinoxes, and was also significant around solstices as well as during October-December. At the decadal timescale, surface temperatures were generally composed of two low frequency oscillations at about 24-year and 50-year periodicities. Each of these oscillations had alternate epochs of low and high temperatures which were directly related to decadal oscillations in the IOD. A key finding of this study was the revelation of significant warming trends in surface temperatures along the coast. The increases per decade were consistent with global trends, being generally greater in minimum temperature (0.14-0.72°C) than in maximum temperature (0.07-0.13°C). Shifts in minimum surface temperature generally coincided with cool phases of the 50-year oscillations at the beginning of the record, and with warm phases at the end of the record. An increase in cloud cover over the coast of Tanzania during the observation period may have contributed to this disparity. Within the last half century, the warmest years in minimum temperature differed slightly between stations but all fell within the last decade (2000-2009). The last decade, which generally coincided with warm phases of the decadal oscillations in surface temperature and the IOD, was also the warmest.

INTRODUCTION

Global average surface temperatures have increased by about 0.074°C per decade over the period 1901 to 2010 (Morice *et al*., 2012). Over the last three decades (1979-2010), the rate of warming has more than doubled to about 0.169°C per decade. According to Trenberth *et al*. (2007), the global rise in minimum temperature per decade during the last half

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century (1950 to 2004) was 0.20°C, much higher than that of maximum temperature which was only 0.14°C. The decade 1991-2000 was the warmest of the previous 150 years, and the warmest 22 years have occurred since 1980, while 1998 and 2005 were the two warmest years on record (Ehrhart & Twena, 2006; Trenberth *et al*., 2007). It has also been observed that eleven of the last twelve years between 1995 and 2006 rank among the 12 warmest years in the instrumental record of global surface temperatures since 1850 (Trenberth *et al*., 2007). The consensus is that this warming trend has been triggered by anthropogenic emissions of greenhouse gases. Some of the global rates have recently been updated in the IPCC AR5 reports, extending the period of observations up to 2012 (Hartmann *et al*. 2013).

The warming trend, however, has not been continuous but has been interspersed by cooling periods due to natural climate variability such as the El Niño – La Niña cycle in tropical ocean temperature (Hansen *et al*., 2010). During the period of instrumental records, episodes of cooling included an abrupt drop in sea surface temperature around 1970 (Thompson *et al*., 2010) when both the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) were in their cool phases (Obeysekera *et al*., 2007). The recent hiatus in the rate of global warming has prompted much discussion. The increase in global mean surface temperatures was lower between 1997 and 2013 (0.07±0.08°C per decade) than over the last 50 years (0.16±0.02°C per decade) (Schmidt *et al*., 2014). This phenomenon has been attributed to natural variability in the climate system, whereby a short period of cooling (about a decade or two) is superimposed on the longer-term warming trend (Easterling & Wehner, 2009).

Other oceanographic parameters such as the well-known El Niño Southern Oscillation (ENSO) also play a role in global climate. The strength of ENSO events is measured by the Ninõ-3 index (McPhaden *et al*., 2006), which is defined as the SST anomaly averaged over the eastern equatorial Pacific region (5°N-5°S and 150°W-90°W). The ENSO is near global in extent but it appears to wax and wane on decadal to multi-decadal timescales (Allan, 1993). The Indian Ocean Diploe (IOD) constitutes the difference between an SST anomaly in the western equatorial Indian Ocean (50°E-70°E and 10°S-10°N) relative to the south eastern equatorial Indian Ocean (90°E-110E and 10°S-0°N). This difference is named the Dipole Mode Index (DMI; Saji *et al*., 1999). A positive IOD event is marked by a drop in SST in the south-eastern part of the Indian Ocean, counteracted by an SST increase in the western equatorial Indian Ocean, i.e. off the eastern coast of Africa from the northern part of Madagascar to the northern edge of Somalia, and vice versa for a negative IOD event (Marchant *et al*., 2006). The DMI index is archived at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (http://www.jamstec.go.jp/frcgc/research/d1/iod/). The Pacific Decadal Oscillation (PDO) Index (Mantua *et al*., 1997) is the leading principal component of North Pacific monthly SST anomalies poleward of 20°N. Monthly mean global average SST anomalies are removed from the PDO Index so as to separate it from any "global warming" signal that may be present in the data.

The climate of East Africa is regulated by a number of factors, including the Inter-Tropical Convergence Zone (ITCZ), subtropical anticyclones, tropical cyclones, monsoon wind systems, the African jet streams, easterly-westerly wave perturbations, and teleconnections between regional and large-scale quasi-periodic climate systems like the quasi-biennial oscillation, intra-seasonal waves, the ENSO and the IOD, among others (King'uyu *et al*., 2000). The teleconnection between the ENSO and the Western Indian Ocean is well documented in analyses of instrumental sea surface temperature (SST) and East African rainfall records (e.g. Hastenrath *et al*., 1993). ENSO events have usually occurred with an average return period of about 2–7 years (McPhaden *et al*., 2006).

Generally, the dominant variability in surface air temperature is assumed to come from slowly varying SSTs (Chelliah & Bell, 2004). However, low frequency decadal to multi-decadal fluctuations in the climate system are often related to large scale ocean-atmosphere exchanges involving changes in mass water transport, the oceanic thermohaline circulation, and deep water formation (Allan *et al*., 1995).

One of the key studies on trends in mean surface air temperatures over eastern Africa was undertaken by King'uyu *et al*. (2000). These authors used daily and monthly minimum and maximum temperature records from 71 locations (both coastal and inland) covering the period between 1939 and 1992. Their investigation encompassed two of the four stations included in the present study (Dar es Salaam and Tanga). Another key investigation was that of Christy *et al*. (2009) who used several global datasets to investigate trends in maximum and minimum temperatures from 118 coastal and inland locations in East Africa over a 100-year period (1904-2004). In the earlier study, the results revealed an increase in both maximum and minimum temperatures. In the later study, the maximum temperatures were relatively unchanged, but there was evidence of an accelerated rise in minimum temperatures.

The objectives of the present study were to determine the annual to decadal variability and trends in surface air temperatures along the coast of Tanzania. The investigation was undertaken using temperature data recorded in the last half century.

METHODS

Monthly maximum and minimum temperature data were obtained from the Tanzania Meteorological Agency (TMA), which is the custodian of all meteorological data in the United Republic of Tanzania. The data were collected from the key meteorological stations of Tanga, Dar es Salaam and Mtwara along the mainland coast, and from the major offshore island of Zanzibar (Fig. 1). The data covered 50 years, extending from 1960 to 2009. Table 1 presents geographical information on the meteorological stations used in the study. They are all installed sufficiently distant from physical obstructions, despite the Dar es Salaam station being located in an urban setting, making the data uniform in quality and comparable. The instruments are also serviced and calibrated annually to ensure reliability in the data collected.

Although the coastal topography and the micro-climatic conditions may differ slightly between land and water surfaces, the land-based stations were considered representative of the temperature field in the near-shore coastal domain. This is an assumption which poses a possible limitation in the study given the strong diurnal cycle (land-sea breezes) along the coast of Tanzania (Summer, 1982).

The first analysis involved simple averaging of the monthly means of maximum and minimum temperatures at each station to obtain annual series in each. The annual means could not be calculated for years with missing monthly data (which were few). Trends in the series were then computed from the annual means. Many statistical tests are available to detect trends in time series but the trend magnitudes can often be determined reliably using combinations of parametric and non-parametric techniques (Partal & Kahya, 2006).

Trend analyses were thus undertaken employing a variety of techniques including the least-squares linear regression, Kendall's τ statistic and the Spearman's rank correlation test. Kendall's τ statistic is a non-parametric test which can be used to test for the presence of a

Table 1. Geographic information on the Tanzanian coastal meteorological stations.

Station	Latitude	Longitude	Altitude above sea level (m)	Urban/Exposed
Tanga	05.05°S	39.04°E	49	Exposed
Zanzibar	06.13°S	39.13°E	18	Exposed
Dar es Salaam	06.53°S	39.12°E	53	Urban
Mtwara	10.21°S	40.11°E	113	Exposed

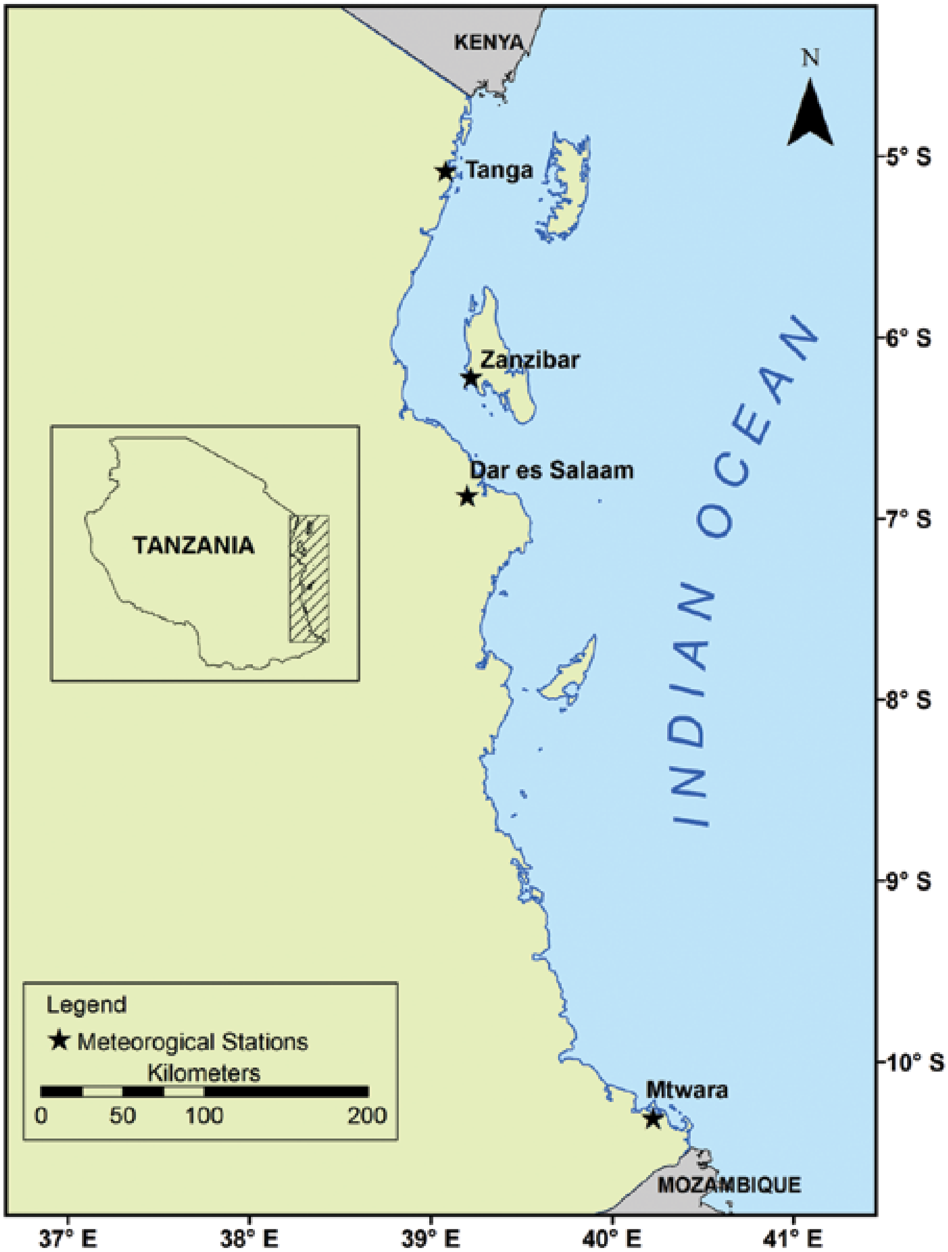

Figure 1. Map of coastal Tanzania showing the sites of the meteorological stations.

linear trend, while the Spearman's test validates the result (Mitchell *et al*., 1969). Kendall's τ statistic has been widely used in particular to test for randomness in trends in climatology and hydrology (Partal & Kahya, 2006). A disadvantage of a simple linear regression approach is that it may fail to detect trends that are nonlinear but still monotonic and unidirectional. The Kendall's τ test and the Spearman rank correlation can detect trends that are monotonic but not necessarily linear, and only indicate the direction, and not the magnitude, of the trends.

Time series spectra of the monthly means were thus estimated using Fast Fourier Transform (FFT) in the STATISTICA software package to determine the significant spectral peaks. The Parzen window (Oppenheim & Schafer, 1999) was used to smooth the raw data sets in preference to other approaches as it provided better interpretation of the results.

Wavelet analysis was used to further test for the presence of low frequency oscillations and temporal peaks in the monthly maximum and minimum temperatures as it constitutes the best tool to detect relatively slow changes in the frequency content of non-stationary series. While the time series may contain dominant periodic signals, the oscillations can vary in both amplitude and frequency over a longer time period. This technique therefore permits decomposition of the time series into time-frequency space, revealing the evolution in relative strength of the dominant modes with time. The analysis (Torrence & Compo, 1998) was undertaken using MATLAB to determine continuous wavelet transformation in the time series.

The relationship between local surface temperatures and the large scale climatic systems was explored in partial correlations. The Ninõ-3 index was obtained from the US National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/indices). The PDO index was obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) (http://jisao.washington.edu/pdo/PDO.latest). Partial correlation of local temperatures with Niño-3 was computed by isolating the effects of the DMI and PDO. Likewise, the partial correlation of maximum and minimum temperatures with the DMI (PDO) was determined by isolating the effects of the Niño-3 (DMI) and PDO (Niño-3), respectively. All computation of partial correlations was performed using STATISTICA software. Prior to analysis, missing data were interpolated from adjacent points.

RESULTS

The average monthly maximum and minimum air temperatures along the coast of Tanzania were about 30.5°C and 21.5°C respectively (Table 2). Temperatures generally increased northwards along the coast towards the equator. The coolest temperatures ranged from 12.8°C to 16.7°C during the southeast monsoon. The warmest monthly maximum temperatures were between 32.7°C and 34.5°C during the northeast monsoon.

The mean temperature in the coolest year at each station was about 20°C except at Zanzibar where it was only 17°C. The annual mean temperatures in the warmest years at each station were between 31°C and 32°C in 2003 at Zanzibar and Dar es Salaam, and at Tanga and Mtwara in 1983 and 1961 respectively. The warmest minimum temperatures were all recorded during the last decade, between 2003 and 2007.

Table 2. Mean and peak maximum and minimum temperatures (°C) recorded on the Tanzanian coast during 1960-2009.

Station	Mean monthly max temp	Mean min temp	Warmest monthly max temp	Coldest monthly min temp	Warmest monthly annual max temp	Coldest annual min temp	Warmest annual min temp
Tanga	30.6	22.2	34.5	16.4	31.2	20.2	23.3
(Period)			(Mar 1987)	(Sep 1973)	(1983)	(1973)	(2006)
Zanzibar	30.6	21.7	34.1	12.8	31.4	16.6	23.3
(Period)			(Feb 1982)	(Aug 1966)	(2003)	(1966)	(2003)
D' Salaam	30.8	21.1	34.1	16.7	32.0	20.0	22.3
(Period)			(Mar 2003)	(Jul 1981)	(2003)	(1980)	(2003)
Mtwara	30.1	21.0	32.7	16.7	30.9	19.9	22.1
(Period)			(Dec 1960	(Aug 1971)	(1961)	(1971)	(2007)

Time series of maximum and minimum temperatures clearly revealed a progressive northward increase in the amplitude of maximum temperatures along the coast (Fig. 2). Conversely, corresponding variations in the amplitude of minimum temperature increased southwards. All the sites manifested an increasing trend in both the maximum (daytime) and minimum (night-time) temperatures according to the Loess fit to the data. This also showed that the rises in minimum temperature were generally higher than that in maximum temperature. There was a large drop in minimum temperatures at Zanzibar between 1965 and 1970, and at Tanga between 1970 and 1975 (Fig. 2).

Linear regressions of the annual maximum and minimum temperature time series yielded warming trends at all stations (Table 3). Increases in minimum temperature were greater than that in maximum temperature. The greatest change in maximum temperature occurred at Dar es Salaam (0.65°C) while the smallest was recorded at Zanzibar (0.35°C). The greatest change in minimum temperature occurred at Zanzibar (3.59°C) and the smallest at Mtwara (0.7°C). The trends in both maximum and minimum temperatures were found to be statistically significant using Kendall's τ statistic and the Spearman rank test. The corresponding maximum and minimum temperature changes per decade averaged 0.07-0.13°C and 0.14-0.72°C respectively.

Decadal means of both maximum and minimum temperatures (Table 4) were highest during the last decade (2000-2009). The highest decadal maximum and minimum temperatures of 31.2°C and 23°C were recorded at Dar es Salaam and Zanzibar respectively. The corresponding lowest maximum and minimum temperatures of 30.0°C and 20.0°C were recorded at Mtwara

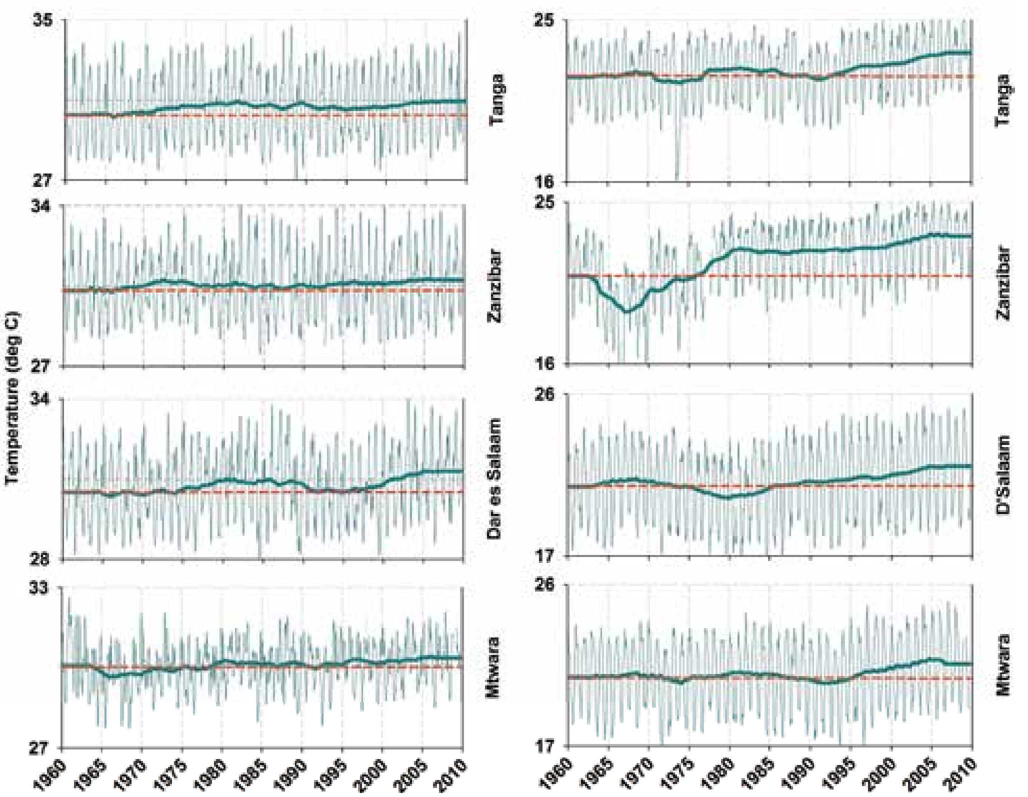

Figure 2. Monthly variation in maximum (left) and minimum (right) temperatures at the four study sites. Bold lines represent the Loess fit and red dashed lines correspond to the mean 1960 level.

Table 3. Regressions and trends in surface temperatures (°C) for the Tanzanian coast during 1960 to 2009. All correlations were significant at the 95% level.

Station	Parameter	Regression coefficient	Kendall τ	Spearman's R	Total change (°C)	Change decade (°C.decade^{-1})
Tanga	Max temp	0.01	0.33	0.47	0.50	0.10
	Min temp	0.02	0.44	0.62	1.15	0.23
Zanzibar	Max temp	0.01	0.23	0.32	0.35	0.07
	Min temp	0.07	0.68	0.87	3.59	0.72
Dar es Salaam	Max temp	0.01	0.32	0.45	0.65	0.13
	Min temp	0.02	0.39	0.55	1.05	0.21
Mtwara	Max temp	0.01	0.21	0.30	0.40	0.08
	Min temp	0.01	0.29	0.41	0.70	0.14
7°30S, 39°30E	SST	0.01	0.10	0.15	0.62	0.12

(1960-1969 and 1970-1979) and Zanzibar (1960-1969) respectively.

The time series spectra (Fig. 3) indicated that the annual cycle was the dominant mode of oscillation at all the stations. A small semi-annual signal was also prominent in the maximum temperature at Mtwara, which was expected because, in equatorial regions, the sun crosses its zenith twice a year, leading to weak double maxima in the air temperature cycle (Legates & Willmott, 1990). A semi-annual signal is also believed to be associated with the position of the rising branch of the Hadley circulation twice a year (Van Loon & Jenne, 1970). The maximum temperature at Mtwara and the minimum temperature at Zanzibar were also indicative of the existence of relatively small non-stationary signals in the time series spectra.

Wavelet analysis of the monthly time series indicated that the strength of the annual cycle varied throughout the record, clearly showing the presence of warm and cold spells in different periods at each site (Figs 4 and 5). An abnormally cold spell was discernible in the annual minimum temperature cycle at Zanzibar during the period 1976-1978. A weak, semi-annual signal was also apparent in both the maximum and minimum temperatures and, as in the spectral analyses, the signal was

Table 4. Mean decadal surface temperatures (°C) recorded on the Tanzanian coast during 1960-2009.

		1960-1969	1970-1979	1980-1989	1990-1999	2000-2009
Tanga	Max temp	30.3	30.6	30.7	30.6	30.9
	Min temp	21.9	21.8	22.1	22.2	22.9
Zanzibar	Max temp	30.4	30.6	30.4	30.6	30.7
	Min temp	20.0	21.1	22.3	22.5	23.0
Dar es Salaam	Max temp	30.5	30.6	30.9	30.6	31.2
	Min temp	21.1	20.7	20.7	21.3	21.8
Mtwara	Max temp	30.0	30.0	30.2	30.2	30.3
	Min temp	21.0	20.8	21.0	20.8	21.6
7°30S, 39°30E	SST	27.0	27.3	27.4	27.45	27.51

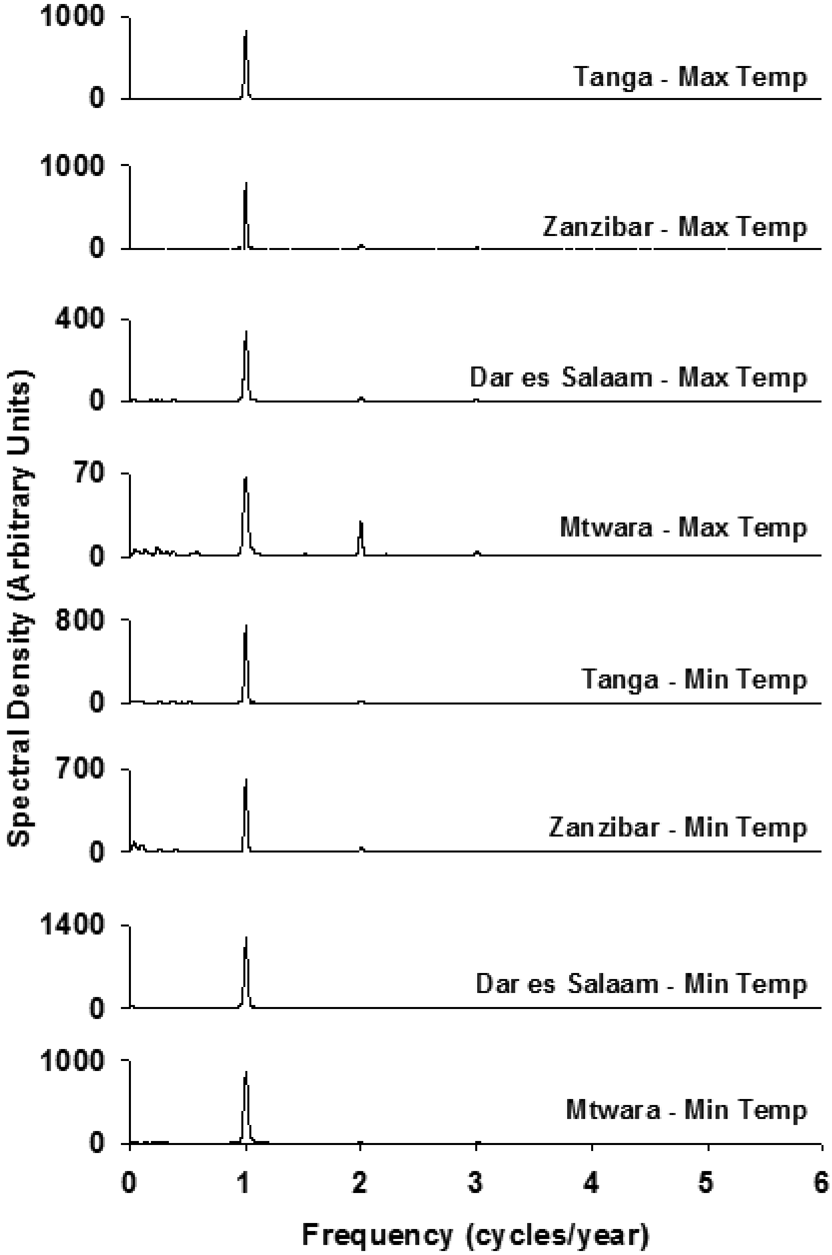

Figure 3. Time series spectra of annual cycles in maximum and minimum temperatures at each station.

only prominent in the maximum temperature records for Mtwara. Although the Zanzibar and Dar es Salaam stations are only about 35 km apart, the wavelet spectra for these two stations differed slightly, possibly due to different degrees of exposure to the land and ocean. This consequently appeared to lead to somewhat different surface temperature regimes.

At the inter-annual timescale (Figs 6 and 7), spectral analysis revealed significant energy at an ENSO interval of 2-8 yrs (see e.g. D'Arrigo *et al*., 2005), especially in the maximum temperatures. Strong La Niña events (1984/85) and El Niño (1987/88) were clearly evident in the wavelet spectra of maximum temperatures at each of the sites.

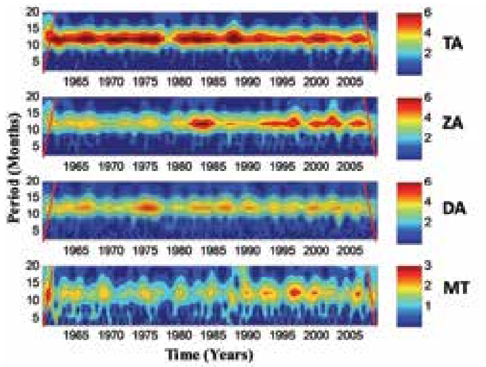

Figure 4. Wavelet spectra of annual cycling of maximum temperatures at Tanga (TA), Zanzibar (ZA), Dar es Salaam (DA) and Mtwara (MT). Red solid lines represent the Cone-of-Influence. Colour scales = standard deviations.

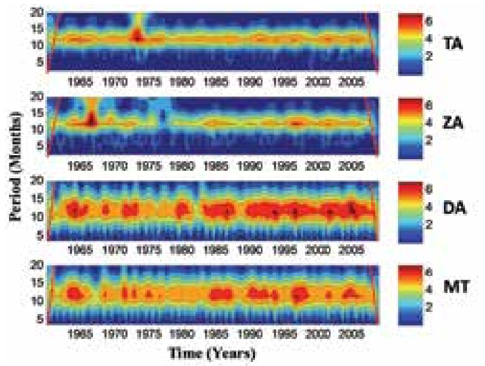

Figure 5. Wavelet spectra of annual cycling of minimum temperatures at Tanga (TA), Zanzibar (ZA), Dar es Salaam (DA) and Mtwara (MT). Red solid lines represent the Cone-of-Influence. Colour scales = standard deviations.

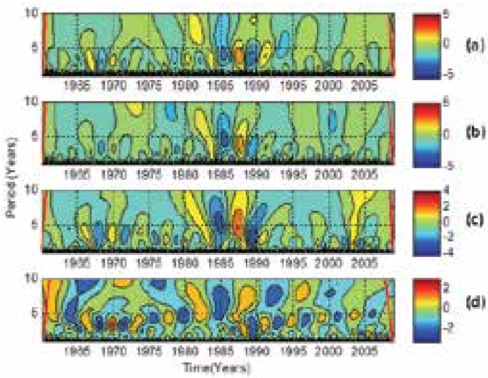

Figure 6. Wavelet spectra of ENSO timescale signals for maximum temperatures at a) Tanga, b) Zanzibar, c) Dar es Salaam and d) Mtwara. Red solid lines represent the Cone-of-Influence. Colour scales = standard deviations.

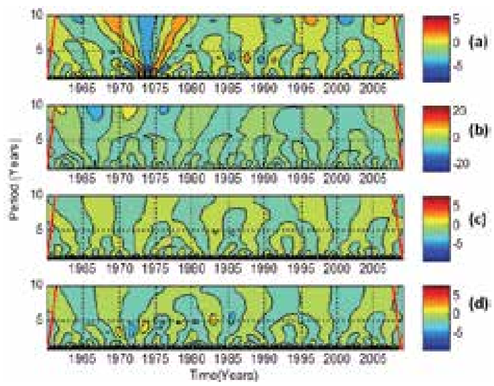

Figure 7. Wavelet spectra of ENSO timescale signals for minimum temperatures at a) Tanga, b) Zanzibar, c) Dar es Salaam and d) Mtwara. Red solid lines represent the Cone-of-Influence. Colour scales = standard deviations.

Strong and alternating La Niña and El Niño episodes were also evident in the minimum temperatures at Tanga between 1971 and 1976. There were no prominent peaks at the ENSO timescale in the minimum temperature records at the other sites.

At the decadal timescale, there was a prominent signal in the minimum temperatures at each station, as well as in the maximum temperatures at Mtwara, with a period of about 50 years (Figs 8 and 9). The signal had alternate epochs of warm and cool temperatures, each with a period of about 25 years. The decadal signal was directly related to the IOD low frequency oscillation which was also revealed through wavelet analysis (Fig. 10). Generally, cold phases prevailed in the 50-year periodicity during the first half of the records, and warm phases in the second half.

The maximum and minimum temperatures also revealed prominent peaks with a periodicity of about 24 years at most stations and an inter-annual timescale signal in the minimum temperatures at Dar es Salaam alone (Figs 8 and 9). Alternating phases of low and high temperatures occurred during the 24-year periodicity, closely related to the bi-decadal signal of the IOD in Figure 10.

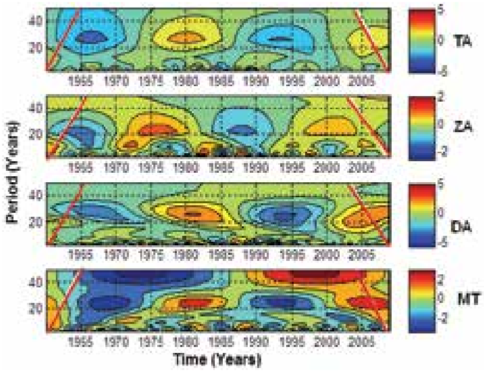

Figure 8. Wavelet spectra of low frequency decadal oscillations in maximum temperature at Tanga (TA), Zanzibar (ZA), Dar es Salaam (DA) and Mtwara (MT). Red solid lines represent the Cone-of-Influence. Colour scales = standard deviations.

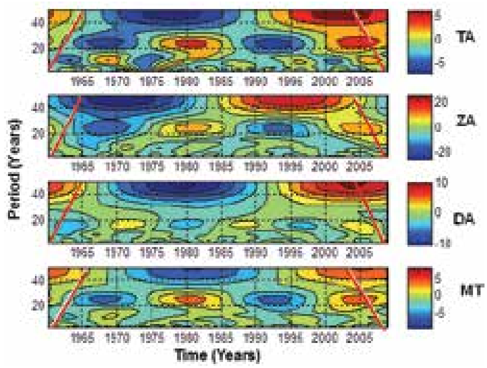

Figure 9. Wavelet spectra of low frequency decadal oscillations in minimum temperature at Tanga (TA), Zanzibar (ZA), Dar es Salaam (DA) and Mtwara (MT). Red solid lines represent the Cone-of-Influence. Colour scales = standard deviations.

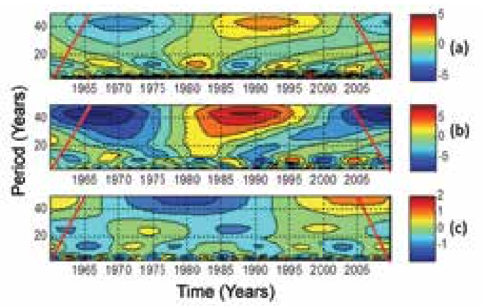

Figure 10. Wavelet spectra of low frequency (decadal) oscillations of a) the ENSO, b) the PDO and c) the IOD. Red solid lines represent the Cone-of-Influence. Colour scales = standard deviations.

Partial correlation analysis between surface temperatures and the large-scale climatic systems resulted only in weak and unsystematic relations in the monthly data (Table 5). The partial correlations were also generally weak during the northeast and southeast monsoons as well as in the long rainfall season of March-May. However, significant partial correlations were found between minimum temperatures and the ENSO during October-December, but these relationships were much stronger around equinoxes (Feb-Apr and Aug-Oct). Generally, the surface temperatures were directly influenced by ENSO at equinoxes, and appeared indirectly influenced by the IOD and the PDO. Conversely, the maximum temperatures were indirectly influenced by the ENSO at solstices (May-Jul and Nov-Jan). The partial correlations of surface temperature with the ENSO were the most significant, making it the most important climate phenomenon that affects inter-annual surface temperatures along the coast of Tanzania.

DISCUSSION

Changes in air temperature have implications on the coastal environment such as an increase in the thermal expansion of the ocean and, hence, changes in mean sea level which affect coastal and marine ecosystems. An assessment of air temperature variability and trends in the coastal climate is thus important in elucidating local and regional climatic systems.

The results of this study indicate that variations in inter-annual surface temperature are modified by low frequency oscillations at decadal timescales which are superimposed on the annual signal. For instance, the cool episode in the minimum temperature record at Zanzibar during the late 1960s (Figs 2 and 5) resulted from a co-occurrence of cool epochs in both the 24-year and 50-year periodicities which emerged from the data (Fig. 9). This notable finding concurs with global observations, which indicate the presence of a weak worldwide cooling from the 1960s to the early 1970s (Baines & Folland, 2007). Inter-annual oscillations have also been

Table 5. Partial correlations of temperature with Niño-3 (r_n), DMI (r_d) and PDO (r_p), after isolating the effects of the DMI and PDO, Niño-3 and PDO, and Niño-3 and DMI respectively for monthly data and for the period October-December (OND), the equinoxes (Feb-Apr & Aug-Oct), the solstices (May-Jul & Nov-Jan), MAM (Mar-Apr-May) and regional SST in each season. Partial correlation coefficients significant at the 95% level are in bold.

	Monthly						OND					
	Max temp			Min temp			Max temp			Min temp		
Station	r_n	r_d	r_p	r_n	r_d	r_p	r_n	r_d	r_p	r_n	r_d	r_p
Tanga	**0.25**	-0.02	0.06	**0.41**	0.06	**0.10**	0.05	-0.15	0.11	**0.29**	0.16	0.13
Zanzibar	0.07	-0.05	0.03	**0.42**	0.04	**0.22**	-0.09	**-0.21**	0.13	**0.24**	0.16	0.14
Dar es Salaam	**-0.21**	0.00	0.03	0.02	0.06	-0.07	0.09	-0.15	**0.21**	**0.18**	**0.18**	-0.03
Mtwara	**-0.12**	**0.09**	0.02	0.01	0.03	-0.04	0.03	0.03	0.00	**0.21**	0.07	0.12
	Equinoxes						Solstices					
Tanga	**0.64**	**-0.19**	**-0.17**	**0.74**	**-0.12**	-0.07	**-0.28**	0.07	0.09	-0.08	0.08	0.06
Zanzibar	**0.39**	0.07	**0.15**	**0.62**	**-0.14**	0.09	**-0.29**	0.05	0.05	0.05	0.03	**0.18**
Dar es Salaam	**-0.12**	**-0.14**	**-0.22**	**0.55**	**-0.14**	-0.03	**-0.38**	**0.12**	**0.13**	**-0.38**	**0.19**	0.03
Mtwara	**0.55**	-0.01	**-0.22**	**0.50**	-0.06	**-0.17**	**-0.37**	**0.17**	0.10	**-0.37**	**0.16**	0.05

	MAM						Monthly			
	Max temp			Min temp				SST		
Station	r_n	r_d	r_p	r_n	r_d	r_p	Season	r_n	r_d	r_p
Tanga	0.15	0.01	0.11	**0.23**	0.00	**0.21**	Monthly	**0.49**	0.01	**0.12**
Zanzibar	0.13	0.01	0.08	**0.24**	-0.09	**0.40**	Equinoxes	**0.80**	**-0.30**	**-0.28**
Dar es Salaam	**0.22**	0.02	**0.20**	0.16	-0.04	0.03	Solstices	-0.03	0.05	0.05
Mtwara	0.13	0.04	0.14	0.13	-0.09	0.04	MAM	**0.35**	0.00	**0.22**

observed to be associated with the solar passage (equinoxes and solstices). This may be attributable to the fact that solar radiation in equatorial regions tends to increase close to the equinoxes when the sun crosses the equator northwards in March, and southwards in September (Ashkenazy *et al*., 2010).

Decadal oscillations with a 24-year periodicity in the surface temperatures under consideration are comparable to those in East African coral oxygen isotope records, which were found to fluctuate at 18-25-year decadal timescales (Zinke *et al*., 2009). The results also concur with SST observations by Royer (1989), who detected prominent peaks at 20 to 30-year cycles in the northeast Pacific.

One lingering question is whether the observed oscillations over coastal Tanzania are related to natural internal oscillations of the Indian or Pacific Ocean climate systems. Warm (positive) SST anomalies are associated with El Niño events, while La Niña events are typically associated with cold (negative) SST anomalies. According to Ware & Thomson (2000), the decadal oscillations in the northeast Pacific are probably caused by natural internal oscillations of the north Pacific climate system. During this century, the PDO was predominantly negative (cool conditions) between 1947 and 1976, positive (warm conditions) between 1977 and 1998, and has been negative since 1999 (Mantua *et al*., 1997, Mantua & Hare, 2002). The timing of these PDO shifts is in agreement with the results of wavelet analysis of the PDO in this study (Fig. 10), confirming that our wavelet analysis method was effective in extracting low frequency oscillations from the surface temperature time series.

Wavelet analysis revealed that the decadal oscillations in minimum surface temperatures at 50-year and 24-year periodicities, as well as in the maximum surface temperature at Mtwara (Figs 8 and 9), coincided with similar cycles in the Indian Ocean Dipole (Fig. 10). This coincidence clearly suggests that these decadal oscillations and the IOD are strongly linked. It follows, therefore, that the decadal oscillations in surface temperature along the coast of Tanzania are probably caused by natural internal oscillations in the Indian Ocean. Similar decadal and multi-decadal peaks of the IOD were found by Ashok *et al.* (2004) in data from 1950 to 1999.

There was a mismatch between the decadal surface temperature oscillations (Figs 8 and 9) and those of the decadal ENSO and PDO indices (Fig. 10) in our data. The decadal oscillation period of surface temperature was, for instance, about 50 years, while that of ENSO events, which co-occurred with the PDO, was only about 40 years. Nevertheless, the decadal oscillation periodicity of 24 years in surface temperatures was shorter than that of the ENSO and PDO decadal timescale signal. This implies that the PDO and ENSO decadal oscillations have little influence on variations in the decadal surface temperatures. The fact that the decadal oscillations in surface temperature are in turn related to those of the IOD is in agreement with the findings of Ashok *et al.* (2004), who found no consistent phase relationship of the IOD with the Niño-3 index of the ENSO.

The existence of decadal variability in the IOD was first investigated by Ashok *et al.* (2004), who revealed decadal IOD peaks at 8 to 13-year and 8 to 32-year oscillations that were associated with decadal modulations of the inter-annual IOD. Accordingly, the decadal oscillations of surface temperatures along the coast of Tanzania found in this study may also be related to decadal modulations in inter-annual surface temperature variability and the IOD, due to a strong association between decadal variability in surface temperature and decadal IOD cycles. According to Ashok *et al.* (2004), the decadal signal of the IOD index is related to the 20°C isotherm depth anomaly, indicating that ocean dynamics is involved in decadal IOD fluctuations.

Decadal signals with about a 60-80 year period such as those observed by Ware & Thomson (2000) in the Northeast Pacific were not considered in this investigation. The record was too short (50 years) and could not resolve such lower frequency components. In the Northeast Pacific, the 60-80-year decadal signal has been the dominant mode of oscillation during the past four centuries (Ware & Thomson, 2000).

It would be of interest to show that changes in surface air temperatures in the study area follow that of SSTs. This was assessed by extracting SSTs from monthly gridded global temperature data (Rayner *et al*., 2003) from the UK Hadley Centre's Sea-Ice and Sea Surface Temperature record (HadISST1) at a location centred around 7°30 S and 39°30 E. Sea surface temperatures increased by about 0.12°C per decade during the period 1960-2009 (Table 3) and, as with the surface air temperatures, have risen consistently over the last five decades (Table 4). Partial correlations of SST with the large scale climatic systems (Table 5) also revealed that, in the study area, they were significantly correlated with ENSO events, and indirectly with the IOD and PDO, especially during equinoxes ($R = 0.80$, -0.30 and -0.28 at $p<0.05$, respectively). The relationships of SSTs with large scale climatic systems were thus similar to those observed with surface air temperature.

Records for the months of January to March were extracted and wavelet spectra were plotted (results not shown) for comparison with plots of 21-year epochs of SST in the wider Indian Ocean described by Allan *et al.* (1995). The resulting spectra for coastal Tanzania were not remarkably different from those shown in Figures 8 and 9. In their investigation, Allan *et al.* (1995) showed graphically that the epoch of 1963-1983 was relatively warmer than the preceding epoch (1942-1962) along the coast of Tanzania. It must be noted, however, that the timing of epochs described by Allan *et al.* (1995) does not match with the decadal timescale oscillations observed in this study. In the case of minimum temperatures, for instance, the period 1963-1983 almost coincided with cold phases in the decadal timescale signal (Fig. 9). The same was also true for the maximum temperatures at Mtwara (Fig. 8).

The changes in surface air temperature detected in this study agree closely with global observations of warming trends in both maximum and minimum temperatures (Trenberth *et al*., 2007). The warming rates for the maximum and minimum temperatures on the Tanzanian coast of 0.07-0.13°C and 0.14-0.72°C per decade respectively over the period 1960-2009, were generally similar to the global increases of 0.12°C and 0.20°C per decade over the period 1950-2004 (Trenberth *et al*., 2007). The present results are also similar to other observations in the region, such as those in South Africa and Ethiopia, where warming trends in both maximum and minimum temperatures have been recorded (Conway *et al*., 2004; Kruger & Shongwe, 2004).

Forster *et al*. (2007) have suggested that minimum temperatures are warming faster than maximum temperature, presumably as a result of the 'urban heat island' effect. This emanates partly from physical properties of the urban landscape and partly from the anthropogenic release of heat into the environment from the use of energy in appliances and vehicles. Solar radiation heat stored during the day is slowly released at night as long-wave terrestrial radiation which keeps the minimum temperature higher than in rural areas. In the recent past, Tanzania has experienced a massive construction boom and the import of numerous vehicles as a result of rapid economic growth. All the study sites are located in cities, the largest being Dar es Salaam followed by Zanzibar, Tanga and Mtwara.

According to Trenberth *et al*. (2007), however, the urban heat island effect is localized and has negligible overall influence. At the global level, it contributes >0.006°C per decade to warming over land and zero over the ocean (Forster *et al*., 2007). The extent of urbanization does not necessarily match with the rate of warming along the coast of Tanzania. For instance, the city of Dar es Salaam has expanded extensively over the recent past, more than any other city in Tanzania, but the rate of change in the minimum temperature per decade at Dar es Salaam was lower than that at Zanzibar and Tanga. King'uyu *et al*. (2000) similarly found no differences in the inter-annual temperature patterns between rural and urban locations in East Africa. It therefore seems plausible that factors other than urbanization must be considered in explaining the anomaly in the rates of increase of surface temperatures.

Christy *et al*. (2009) suggested that the relatively recent and rapid rise in minimum temperature may be attributable to changes in the surface characteristics and the boundary layer atmosphere. Normally, maximum temperatures occur during daytime when the surface is vertically connected to a mixed layer 1.5-2.5 km in depth. In contrast, minimum temperatures occur during the night, through early morning, characterising temperature in a thin boundary layer of air (Pielke Sr. *et al*., 2007). The minimum temperature is therefore sensitive to local land surface properties due to strong vertical gradients and its determination on measurement heights. Nevertheless, the horizontal footprint of minimum temperatures is smaller than that of maximum temperature since the former is more localised than the latter (Christy *et al*., 2009).

The results of this study strongly suggest that the faster rate of increase in minimum temperatures over maximum temperatures along the coast of Tanzania are most probably associated with natural decadal oscillations in the climate system. It is notable that cool epochs in the 50-year oscillations occurred during the first half of the record and warm epochs during the second half of the records, both in minimum temperatures at each site as well as in the maximum temperature at Mtwara. Correspondingly, warm epochs in both the 24-year and 50-year periodicities co-occurred during the last decade (Fig. 9).

Apart from decadal oscillations, changes in cloudy conditions are another factor worth considering for the accelerated rise in minimum temperatures. This is evident in the ship-based Extended Edited Cloud Reports Archive (EECRA), which indicate that there was an increase in cloud cover over Tanzania during the period 1954–2008 (Bellomo *et al*., 2014). These authors also showed that there has been an increase in cloud cover, mainly in the northern sector of the country, according to the Coupled Model Intercomparison Project (CMIP5). Cloud cover during the night prevents heat from being radiated from the earth's surface into the upper atmosphere. The minimum temperature, which is generally recorded before the sunrise, thus goes up. Similarly, cloudy conditions do not allow the sun's rays to enter the earth surface, leading to drop in the daytime temperature.

In conclusion, the warmest years in terms of minimum temperature along the coast of Tanzania differed slightly between stations but occurred within the last decade. These results are similar to those observed in other parts of the region. For example, the warmest years in terms of SST fell within the last decade (2003 and 2004) at Pointe des Galets at Reunion Island (François *et al*., 2007). Surface temperatures appeared to be largely influenced by ENSO events at the inter-annual timescale, as well as by the IOD at the decadal timescale. Seasonally, a combination of the large scale climatic systems (the ENSO, PDO and IOD) as well as solar intensity was the main driver of inter-annual variations in surface temperature. A greater increase in minimum temperature over maximum temperature during the last half century was associated with warm epochs in 50-year oscillations at the end of the records, and with the increase in cloud cover during the study period. In view of the changing global climate, the rise in surface temperatures is likely to continue and this must be taken into consideration in terms of coastal resilience, adaptation and mitigation strategies.

Acknowledgements – Climate data were provided by the Tanzania Meteorological Agency (TMA). I wish to thank Professor Philip Woodworth of the National Oceanographic Data Centre (UK) for providing useful comments on the draft manuscript.

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