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Wind Patterns of Coastal Tanzania: Their Variability and Trends

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Abstract—Patterns in Tanzanian coastal winds were investigated in terms of their variability at the weather stations of Tanga, Zanzibar, Dar es Salaam and Mtwara. Three-hourly data collected over a 30-year period (1977-2006) were used for the study. Statistical analyses included regressions, correlations, spectral analysis, wavelet analysis and partial correlations. Among the four stations, Mtwara proved to have the strongest winds, and Dar es Salaam the weakest. The study confirmed that NE winds prevail from November to March along the coast of Tanzania and SE winds from April to October. The monthly means were mainly composed of annual and semi-annual signals, as well as low frequency oscillations of different wavelength. Generally, the wind speeds were significantly correlated with the El-Niño Southern Oscillation and the Pacific Decadal Oscillation, while at Mtwara the winds were also correlated with the Indian Ocean Dipole. These correlations were higher during the SE Monsoon than during the NE Monsoon. Trends in the monthly mean and maximum wind speeds indicated that the winds have generally strengthened over the past three decades, the corresponding rates of increase being about 0.04-0.07 and 0.03-0.08 $m.s^{-1}.y^{-1}$ respectively, except for the monthly maximum speeds at Mtwara which declined at a rate of ~0.02. The maximum wind speed at Dar es Salaam remained almost unchanged.

INTRODUCTION

Wind patterns along the coast of Tanzania form part of the prevailing monsoon wind system (Schiller & Bryceson, 1978). The winds are influenced by seasonal shifts in the Inter-Tropical Convergence Zone (ITCZ), which is a low pressure system that encircles the earth roughly parallel to the equator. The ITCZ moves between the tropics of Cancer and Capricorn, usually with a seasonal lag of 4–6 weeks (Ker *et al*., 1978). When the ITCZ is in the south, the winds blow from the NE, and when it is in the north, the winds come from the SE. The SE trade winds originate from the semi-permanent South Indian Ocean

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anticyclone (Mascarene High), a centre of high atmospheric pressure that seasonally shifts its position between 31°S; 60°E in July, and 37°S; 80°E in March.

Conversely, the NE Monsoons originate from a semi-permanent high pressure system which is centred in the Arabian Gulf (Arabian High). This system, which is commonly referred to as the Arabian Ridge, is related to a pressure build-up over Siberia (Siberian High). At 850 mb (corresponding to about 1 500 m above sea level), the monsoonal air current circulating in East Africa (East African Low Level Jet) is characterized by very high speeds of between 25 and 50 $m.s^{-1}$ (Findlater, 1977). At the surface, however, the general tropospheric circulation has very low speeds which are also modified by the system of land and sea breezes at individual locations.

In coastal Tanzania, most authors consider the NE Monsoon to prevail from November to March, and the SE Monsoon from April to October (Iversen *et al*., 1984; Newell, 1957). The NE winds are lighter and predominantly northerly, while the SE winds are usually strong and predominantly southerly (Iversen *et al*., 1984). Occasionally, the SE Monsoons are associated with episodic events such as storms and cyclones. An extensive survey of south-west Indian Ocean tropical cyclones dating back to 1854 revealed that, although hurricanes are fairly common and frequently affect the region between Mozambique and the Mascarene Islands (averaging $3.y^{-1}$), they rarely occur along the coast of Tanzania. The only known cyclone of full intensity to strike the Tanzanian coast occurred at Lindi and Mtwara on 15 April 1952 (Blumel, 1984). Other cyclones that have affected coastal Tanzania occurred at Zanzibar and Bagamoyo in April 1872 and at Zanzibar again in August 1994 (Francis *et al*., 2001).

Various aspects of the wind patterns along the coast of Tanzania have been investigated. Dubi (2001) used data spanning 25 years to determine variations in maximum wind speed and their general trends along the coast. His results showed that Tanga, Dar es Salaam and Mtwara experienced peak speeds during July-August, while Zanzibar experienced peak speeds in January. He also noted that, at Mtwara, maximum wind speeds have increased linearly since 1972, whereas at the other three locations, the speeds revealed a decreasing trend.

Lwambuka (1992) compiled 18 years of wind data at several locations in Tanzania including Tanga, Zanzibar, Dar es Salaam and Mtwara. Using the method of moments, he found 50-year extreme gust speeds of 30$m.s^{-1}$ at Tanga, 29m.s-1 at Zanzibar, 2729 $m.s^{-1}$ at Dar es Salaam and 3829 $m.s^{-1}$ at Mtwara. In another study, Njau (1997) investigated the velocity characteristics of wind in Tanzania, including the coast. He observed that the wind speed at coastal stations displayed two clear minima in the year at March and in September-November.

Nieuwolt (1973) analysed sea breezes along the Tanzanian coast using four years of surface wind data from Dar es Salaam. He observed that, during the NE Monsoon, a sea breeze prevailed most of the time, while in the SE Monsoon, the main trend was from the land. A diurnal reversal of the sea and land breezes developed regularly only during the intermediate periods between the monsoons. However, the winds in the general circulation were often quite strong. Summer (1982) illustrated the importance of local diurnally-varying land and sea-breezes in Dar es Salaam using two years of surface wind data and at the 850 mb level. He observed a marked change in wind direction at the surface in all seasons, such that mean three-hourly data clearly depicted a regular alternation between land and sea breezes superimposed on and interacting with the prevailing general circulation.

In this study, wind patterns were investigated along the coast of Tanzania from Tanga, Zanzibar, Dar es Salaam and Mtwara, applying a variety of statistical technique such as spectral analysis, wavelet analysis, regressions, correlations and partial correlations to meteorological data spanning 28 years from 1977. The investigation aimed to contribute knowledge on the Tanzanian coastal climate system, and yield information for improved monitoring and management of the coastal environment. The specific objectives of the study were to explore the long-term directional and oscillatory patterns, and the extreme velocities, in Tanzanian coastal winds. The study also aimed at exploring any links with the large-scale climatic systems. A possible limitation in the study revolved around the assumption that data from land-based meteorological stations were representative of the wind field in the coastal domain. However, the coastal topography and other micro-climatic conditions were expected to differ only slightly between land and water.

DATA and ANALYTICAL METHODS

Wind speed and direction data for the coastal and island stations of Tanga, Zanzibar, Dar es Salaam and Mtwara (Fig. 1) were obtained from the Tanzania Meteorological Agency. The data, which spanned from 1977 to 2006, were recorded at three-hourly intervals by rotating cup anemometers at a height of 10 m. The instruments are serviced and calibrated annually, and are installed sufficiently distant from direct physical obstructions, making the data uniform in quality and comparable. Although the coastal topography and other micro-climatic conditions may differ slightly, these land-based and island station data were considered representative of the wind field over the near-shore coastal domain.

Prior to analysis, the data sets were cleaned by removal of spikes that stood out as outliers and the few missing data of one or two observations in each series were interpolated from adjacent data. Gaps of a few months in Zanzibar and Mtwara data were filled with seasonal ARIMA (Auto Regressive Integrated Moving Average) models (Box & Jenkins, 1976); see Box *et al*. (1994) for a detailed description of these models. The first analysis involved simple averaging of the three-hourly wind speeds at each station to obtain the corresponding daily values and monthly means. The daily maximum wind speed for each location was taken as the highest of the three-hourly observations. Similarly, the maximum values in each month were taken as the monthly maxima. Seasonality of wind speed was derived by averaging the monthly data, say January, for all the years on the record. Patterns in both wind speed and direction were further investigated through plots of wind rose diagrams that were plotted in MATLAB. The presence of long-term changes at each location was determined through linear regression of the monthly mean and maximum wind speeds.

Time series spectra of the monthly means were estimated using Fast Fourier Transform (FFT) in STATISTICA to determine the significant spectrum peaks. The Parzen window (Oppenheim & Schafer, 1999) was chosen for smoothing of the raw data sets. This window is a weighted moving average transformation that assigns the greatest weight to the observation being smoothed in the centre of the window, and diminishing weight to values that are further away from the centre. The Parzen window was preferred to other lag windows as it provided the best interpretation of the results.

Wavelet analysis was undertaken on the data to further explore the monthly mean and maximum wind speeds at each station. While the time-series may contain dominant periodic signals, these signals can vary in both amplitude and frequency over long periods. This technique therefore allows decomposition of the time-series in terms of frequency and shows the evolution in relative strength of the dominant modes with time. The analysis was undertaken using MATLAB (Torrence&Compo, 1998).

The relationship between local wind fields and the Indian Ocean Dipole (IOD), El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) was explored through partial correlations. The strength of an ENSO event is measured by the Ninõ-3 index, which is defined as the SST anomaly averaged over the eastern equatorial Pacific (5°N to 5°S and 150°W to 90°W). The index was derived from the US National Oceanic

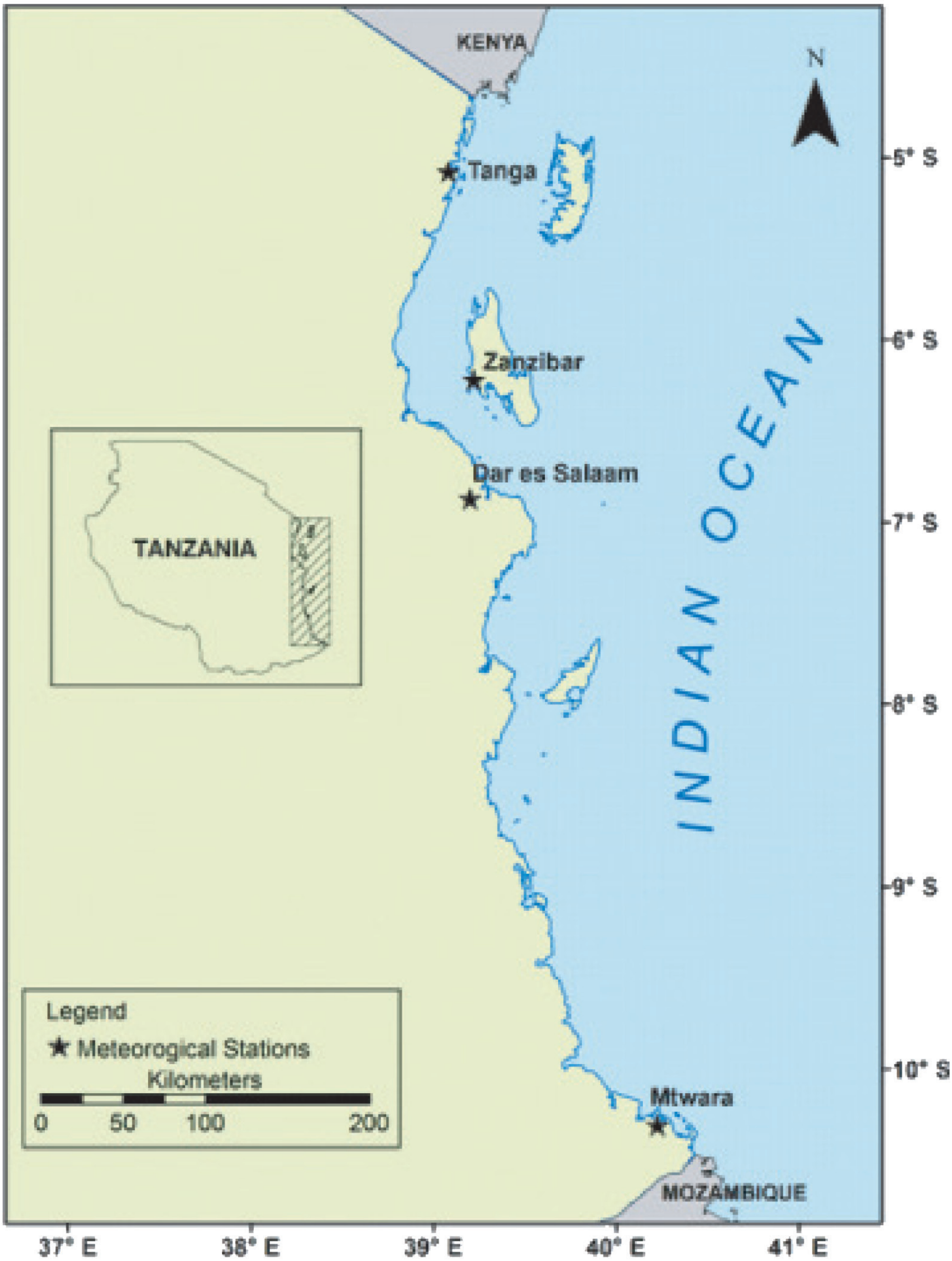

Figure 1. Location of Tanzanian coastal weather stations used in this study.

and Atmospheric Administration (NOAA) Climate Prediction Center website (http://www.cpc.ncep.noaa.gov/data/indices). Warm (positive) SST anomalies are associated with El Niño events, while La Niña events are typically associated with cold (negative) SST anomalies. The intensity of the IOD is represented by an anomalous SST gradient between the western equatorial Indian Ocean (50°E to 70°E and 10°S to 10°N) and the south eastern equatorial Indian Ocean (90°E to 110°E and 10°S to 0°N). This gradient is named the Dipole Mode Index (DMI) after Saji *et al*. (1999). The DMI was derived from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) website(http://www.jamstec.go.jp/frcgc/research/d1/iod/).

The PDO Index, as defined by Mantua *et al*. (1997), is the principal component of North Pacific monthly SST anomalies pole-ward of 20°N. The monthly mean global average SST anomalies are removed in the PDO Index so as to separate it from any "global warming" signal that may be present in the data. The data were derived from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) website (http://jisao.washington.edu/pdo/PDO.latest).

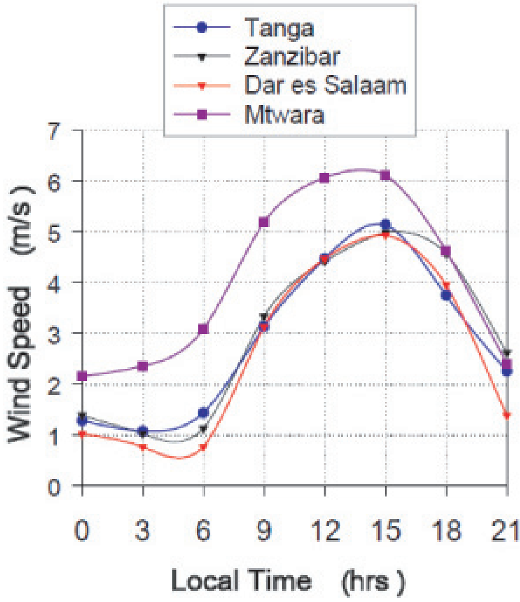

Figure 2. Mean three-hourly Tanzanian coastal wind speeds during 1977-2006.

The partial correlation of wind speed with the Niño-3 index was computed relative to the DMI and PDO, and tabulated for the seasons January to December (annual), November to March (NE Monsoon) and April to October (SE Monsoon). Likewise, the partial correlation was obtained for wind speed and DMI while excluding the influence of Niño-3 index and PDO. Similarly, the partial correlation of wind speed with the PDO was derived relative to the DMI and Niño-3 index. All computations for partial correlations were performed using STATISTICA.

RESULTS

The hourly variations in wind speed are presented in Figure 2. Higher wind speeds occurred during the day, with maximum speeds being generally attained at 15:00 local time (12:00 GMT). Thereafter, a steady, marked fall in wind velocity occurred between 18:00 and 21:00, while between 06:00 and 09:00, a steady rise was observed. From 21:00 to 06:00, the mean wind speeds were lower, with the minima occurring at 03:00. The average speed at night was ~1 m.s^{-1}at all the stations except Mtwara where it was higher, ranging between 2-3 m.s^{-1}. It is also worth noting that Mtwara had the highest diurnal speeds compared to the other stations, averaging ~12 m.s^{-1} in the afternoon. However, the plots of hourly mean wind speeds were quite similar, with troughs and crests occurring almost simultaneously at all the four stations. During the period of study, the daily mean wind speeds were about 5.0 m.s^{-1} (Dar es Salaam), 5.5 m.s^{-1} (Tanga), 5.7 m.s^{-1} (Zanzibar) and 7.8 m.s^{-1} (Mtwara).

The monthly variations in wind speeds are presented in Figure 3a. Again, the speeds were highest all year round at Mtwara. Generally, the months of June through September experienced strongest wind speeds during the SE Monsoon, with peaks in July averaging 6.0 m.s^{-1}(Mtwara), 3.9 m.s^{-1} (Zanzibar) and 3.7 m.s^{-1} (Tanga). There were also smaller peaks in January of ~5.1 m.s^{-1} (Mtwara), 3.1 m.s^{-1} (Zanzibar) and 3.0 m.s^{-1} (Tanga). In Dar es Salaam, however, the peaks occurred in January (3.6 m.s^{-1}) and June (2.5 m.s^{-1}). There were also two minimum monthly means at every station, generally occurring during the months of March and November during the NE Monsoon. However, monthly mean wind speeds recorded at 15:00 local time

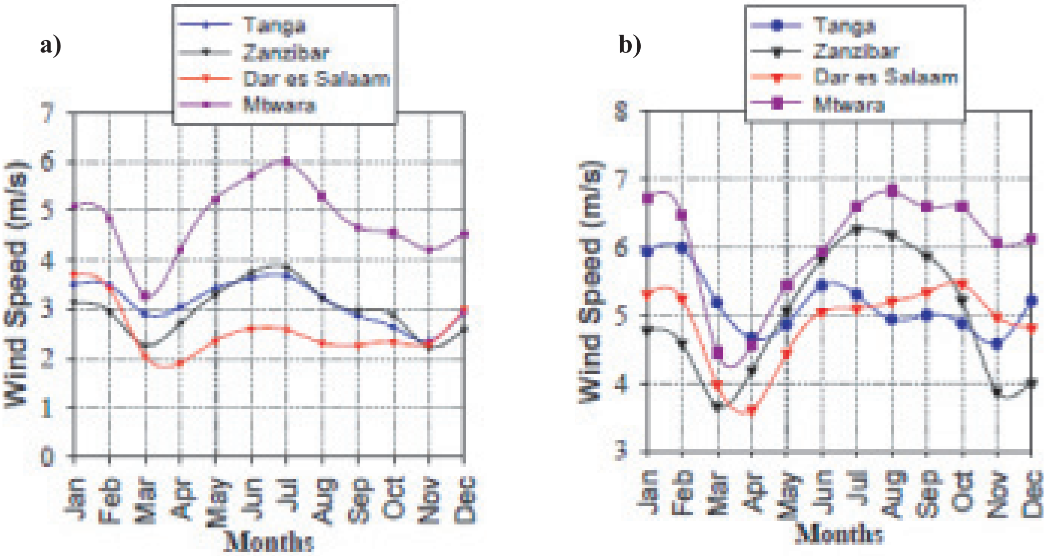

Figure 3. Mean monthly Tanzanian coastal wind speeds during 1977-2006 (a) and the mean monthly values at 15:00 (b).

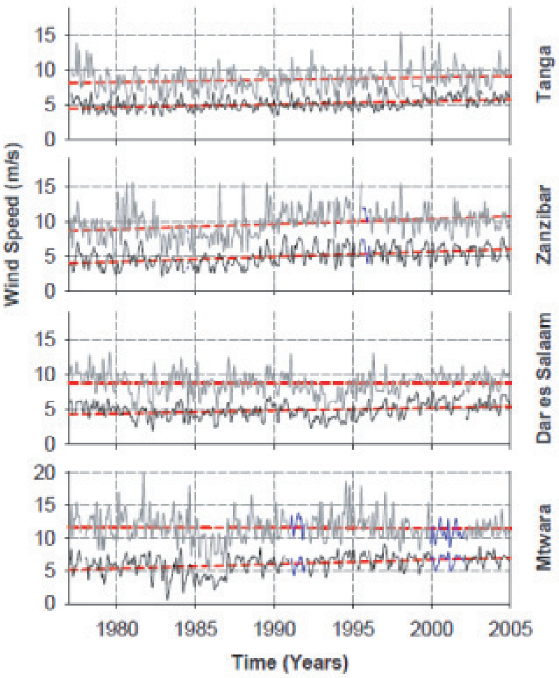

Figure 4. Monthly maximum (top, gray) and mean (bottom, black) Tanzanian coastal wind speeds ($m.s^{-1}$) during 1977-2006. Blue lines represent missing data that were fitted with an ARIMA (111) (012)s model in the case of Zanzibar, and ARIMA (011) (011)s model in the case of Mtwara. Red dashed lines are linear regressions.

were quite high, averaging about 6.8 $m.s^{-1}$ (Mtwara), 6.0 $m.s^{-1}$ (Tanga), 6.3 $m.s^{-1}$ (Zanzibar) and 5.5 $m.s^{-1}$ (Dar es Salaam) (Fig. 3b).

Figure 4 shows trends in the monthly mean and maximum wind speeds at each station. The results revealed a general rise in the wind speeds at all four stations during the period of observation. The only exception was a decline in maximum wind speeds at Mtwara. The plots also showed that Zanzibar experienced the steepest trends in both mean and maximum wind velocity. The annual rate of increase over the 28-year period was about 0.04$m.s^{-1}$at Dar es Salaam, 0.04 $m.s^{-1}$ at Tanga, 0.06 $m.s^{-1}$ at Mtwara and 0.07$m.s^{-1}$ at Zanzibar while Dar es Salaam recorded no change. The corresponding rate of increase in maximum wind velocity was about 0.03 $m.s^{-1}$ at Tanga and 0.08 $m.s^{-1}$ at Zanzibar, while the rate of decline at Mtwara was about 0.02 $m.s^{-1}$.

Figure 5 presents representative wind-rose diagrams, plotted using data recorded at 09:00 and 15:00 local time during the months of January and July. These results are further summarized in tabular form to reveal the predominant wind direction and the frequency of

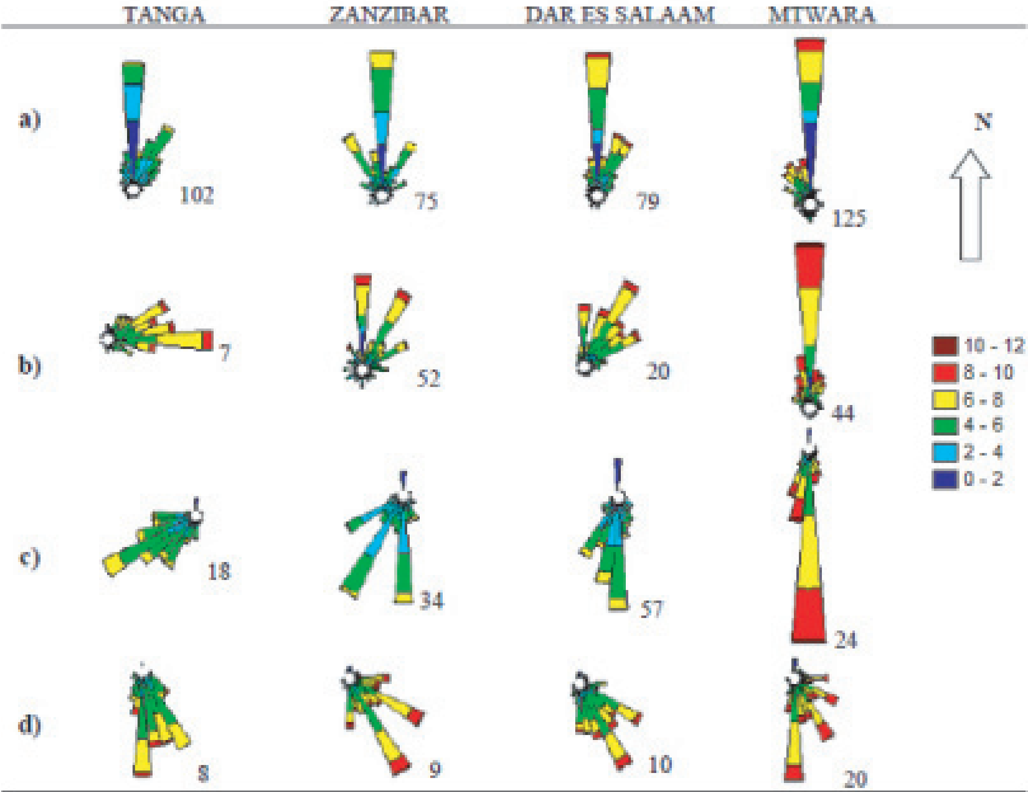

Figure 5. Wind rose diagrams plotted using Tanzanian coastal weather data for 1977-2006 in (a) January at 09:00, (b) January at 15:00, (c) July at 09:00 and (d) July at 15:00. The corresponding number of calms per month at each station is shown below the wind roses. The legend depicts wind speed in $m.s^{-1}$.

Table 1. Variations in monthly wind direction tabulated from wind-rose diagrams derived from Tanzanian coastal weather station data for 1977-2006. Entries marked in bold represent the predominant direction

STATION	Tanga		Zanzibar		Dar es Salaam		Mtwara	
TIME	09:00	15:00	09:00	15:00	09:00	15:00	09:00	15:00
Nov	N	S/SE/E	N/SW	SE/E/N	N/E/NE	NE/E	N/E	N/E/NE
Dec	N/NE	E/NE	N/NE	N/NE	N/NE	N/NE	N	N
Jan	N/NE	E/NE	N/NW/NE	N/NE	N/NE	N/NE	N/NW	N
Feb	N/NE	E/NE	N/NW/NE	N/NE	N/NE	N/NE	N/NW	N/NW
Mar	N	E/SE/S	N	N	N	N/NE	S/N	N
Apr	SW	S/SE	S/SW	S/SE	S/SW	S/SE	S	S/SE/E/N
May	SW	S/SE/SW	S/SW	S/SE	S/SW	S/SE	S	S/SE
Jun	SW	S/SE/SW	S/SW	S/SE	S/SW	S/SE	S	S/SE
Jul	SW	S/SE	S/SW	SE	S/SW	S/SE	S	S/SE
Aug	SW	S/SE	S/SW	SE	S/SW/SE	SE	S	S/E/SE
Sep	SW	S/SE	S/SW/SE	SE	S/SE	SE/E	S/E/N	E/SE/NE
Oct	S/SW/N	S/SE	S/SW/SE	SE/E	SE/E	E/SE/NE	E/S/N	N/E/NE

Table 2. Number of calm periods at Tanzanian coastal weather stations during 1977-2006.

STATION	Tanga		Zanzibar		Dar es Salaam		Mtwara	
TIME	09:00	15:00	09:00	15:00	09:00	15:00	09:00	15:00
Nov	263	15	133	74	147	30	116	28
Dec	146	7	117	79	136	37	107	47
Jan	102	7	75	52	79	20	125	44
Feb	125	6	58	36	90	19	111	38
Mar	209	12	139	85	222	71	169	116
Apr	68	20	87	63	119	67	75	88
May	33	21	42	20	74	31	34	31
Jun	30	2	24	5	53	14	27	18
Jul	18	8	34	9	57	10	24	20
Aug	62	2	49	4	148	11	57	6
Sep	99	1	58	11	134	8	89	5
Oct	180	4	84	33	106	7	77	7

calm conditions from January to December (Tables 1 and 2). The results can clearly be differentiated into two regimes with different characteristics, one running from November through March representing the NE Monsoon, and the other from April to October representing the SE Monsoon. In Table 1, it is notable that from November to March at 09:00, the diurnal winds were predominantly northerly, whereas at 15:00 they were predominantly northerly and north-easterly. It is also worth noting that the prevailing winds at 15:00 were generally more variable than those at 09:00.

The condition reversed completely during the period April to October, during which the winds at 09:00 were predominantly southerly and south-westerly, whereas at 15:00 they were predominantly southerly and south-easterly. There were two calm periods (Table 2) which generally occurred during the months of March and November, more so at 09:00 than at 15:00. Overall, the winds were calmer from November through March than April to October. The few disparities in the predominant wind direction are also noteworthy, especially at Tanga and Mtwara.

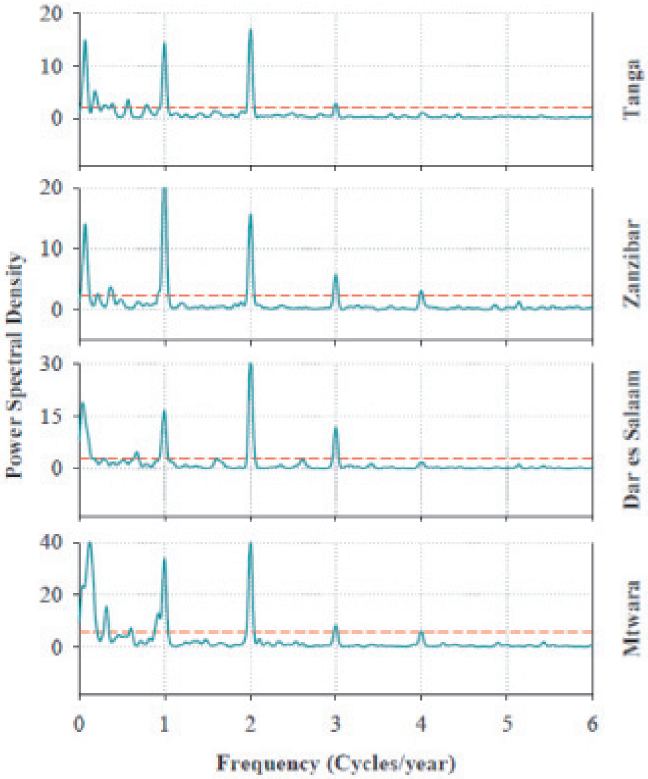

Figure 6. Spectral time series of monthly mean Tanzanian coastal wind velocities during 1977-2006. The red dashed line indicates the 95% Confidence Level.

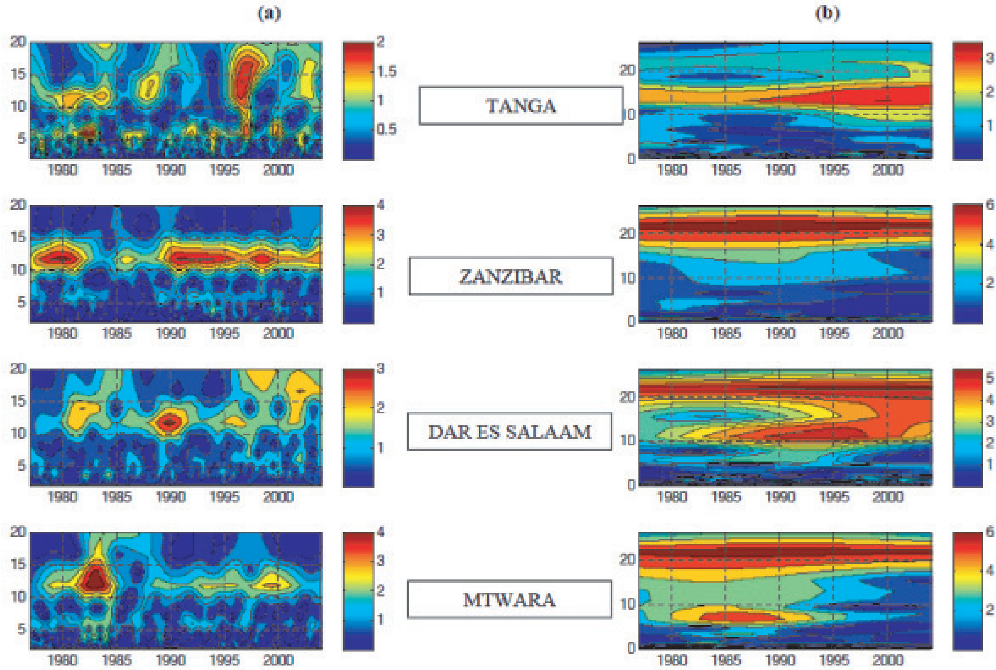

Figure 7. Morlet wavelet spectra representing (a) monthly maximum wind speeds and (b) low frequency oscillations in years along the Tanzanian coast. The legends indicate wind speed in $m.s^{-1}$.

Spectral analysis revealed annual and semi-annual patterns in the wind speeds (Fig. 6). These oscillations are clearly evident in the wavelet spectra in Figure 7a, as well as their temporal variation. It is interesting to note that the annual and semi-annual periods that correspond to the highest or lowest wind speeds differed appreciably from one station to another. In Figure 7a, peak wind speeds in the annual cycle occurred at Tanga during 1977-82, 1991-93 and 1996-97; at Zanzibar during 1977-82, 1989-92, 1993-96 and 2003-04; at Dar es Salaam during 1980-82, 1988-91, 1995-96 and 2001-02; and at Mtwara during 1978-83.The wavelet spectra in Figure 7b further reveal prominent low frequency cycles of variable wavelength at each station, with periods of 11-18 years (Tanga), 19-25 years (Zanzibar), 10-15 years and 20-24 years (Dar es Salaam), and 6-8 years and 15-25 years (Mtwara).

The matrix of correlation coefficients presented in Table 3 indicate that the monthly mean wind speeds at Mtwara and Zanzibar are highly correlated (r=0.58), followed by Dar es Salaam and Tanga (r=0.51) which, surprisingly, are relatively distant from each other. Conversely, the wind speeds at Dar es Salaam and Zanzibar, despite being very close, were the least correlated (r=0.23), followed by Dar es Salaam and Mtwara (r=0.28), which again are quite far apart.

The partial correlations of wind speed with the IOD, ENSO and PDO are presented in Table 4. It is noteworthy that the southernmost station of Mtwara was most significantly correlated with the ENSO (r=-0.36), and that the correlations generally decreased northwards. Mtwara

Table 3. Matrix of correlation coefficients for monthly mean Tanzanian coastal wind speeds during 1977-2006.

	Tanga	Zanzibar	Dar es Salaam	Mtwara
Tanga	1.00	0.45	0.51	0.45
Zanzibar	0.45	1.00	0.23	0.58
Dar es Salaam	0.51	0.23	1.00	0.28
Mtwara	0.45	0.58	0.28	1.00

Table 4. Correlations of Tanzanian coastal wind speed with Niño-3 (r_n), DMI (r_d), and PDO (r_p), in partial correlations with the effects of DMI and PDO, Niño-3 and PDO, and Niño-3 and DMI. The NE Monsoon is from November to March, and SE Monsoon is from April to October; values in bold are significant at the 95% Confidence Level.

Station	Latitude	Longitude	January – Dec			NE Monsoon			SE Monsoon		
			r_n	r_d	r_p	r_n	r_d	r_p	r_n	r_d	r_p
Tanga	5° 5.6'S	39° 4.3' E	0.03	-0.03	-0.16	0.05	-0.11	-0.01	0.01	0.05	-0.29
Zanzibar	6° 13.2 S	39° 13.4' E	-0.17	0.08	-0.07	0.05	-0.06	-0.21	-0.29	0.12	-0.10
Dar es Salaam	6° 52.4' S	39° 12.2' E	-0.31	0.09	-0.20	-0.25	-0.07	-0.07	-0.35	0.18	-0.32
Mtwara	10° 20.2' S	40° 10.9' E	-0.36	0.26	-0.09	-0.22	0.14	-0.14	-0.46	0.35	-0.07

was also the only station with wind speeds that were significantly correlated with the IOD (r=0.26). During the SE Monsoon, however, the winds at Dar es Salaam became significantly correlated with the IOD. Tanga and Dar es Salaam were also the only stations with wind speeds that were significantly correlated with the PDO (r=-0.16 and -0.20, respectively). The correlations between wind speed and any of these climatic phenomena were higher during the SE Monsoon than the NE Monsoon at each station.

DISCUSSION

The effects of breezes and earth rotation

Along tropical coastlines, sea breezes normally prevail during the day and land breezes during the night, due to pressure gradients caused by differential heating and cooling of the land surface and water (Qian, 2008). Generally, land breezes are weaker than sea breezes due to friction and rapid cooling of the land. While the effect of a sea breeze can be felt up to a distance of 50 km, a land breeze is generally not felt beyond 15 km (Nieuwolt, 1977). Diurnal variations in wind were investigated in this study in a manner similar to that employed by Nieuwolt (1973). He used the number of calms during the day and night in both the NE and SE Monsoons, as well as the orientation of the coastline, to investigate the local effects of breezes on the general circulation. He observed that, at Dar es Salaam, the sea and land breezes were strongest at around 15:00 and 09:00, respectively. Likewise, in this study, land breezes that prevailed during the night through early morning were strongest at 09:00, and the sea breezes at 15:00.

In this study, the small number of calm periods that were observed in the NE Monsoon (November to March) at 15:00 were attributable to sea breezes in the general surface circulation. In contrast, the general circulation is weakened by land breezes at 09:00, leading to a relatively large number of calms. Similarly, during the SE Monsoon (April to October), sea breezes enhanced the general circulation while land breezes weakened it. However, the effects of sea and land breezes were generally weaker during the NE Monsoon due to small temperature differences between the land and water during this season (Nieuwolt, 1973). The prevalence of north-west winds during the NE Monsoon at Mtwara, and south-west winds during the SE Monsoon at Tanga, Zanzibar and Dar es Salaam, may be attributed to the effect of the earth's rotation. In the south at Mtwara, which is relatively far from the Equator (10°S), the general circulation tends to veer from north and north-east to north-west during the NE Monsoon. Likewise, closer to the Equator, winds tend to veer from south and south-east to south-west during the SE Monsoon at the northern stations of Tanga, Dar es Salaam and Zanzibar.

Seasonal variations

The results presented in Tables 1a and b and Figure 5 shed light on the seasonality of winds at the local level in coastal Tanzania. Seasonality in wind on the coast is mainly driven by the general circulation at the surface, which is in turn modified by a combination of land and sea breezes of a strength that is determined by coastal morphology. This implies, therefore, that the seasonality in monsoons at the surface is not necessarily similar to that of the general circulation at 850 mb. Winds at the upper level can be measured by pilot balloons, radar and aircraft, as opposed to anemometers at the surface (Findlater, 1977). In most cases, balloon wind observations are recorded in East Africa at 09:00 and 15:00 (Anyamba & Kiangi, 1985; Findlater, 1971). More often, however, debate ensues as to when the NE and SE Monsoons prevailing over coastal Tanzania occur because of differences in the observations of wind patterns from one coastal location to another, and because measurements taken at the surface are different from those recorded at 850 mb.

For instance, most authors consider the NE Monsoon to prevail from November to March, and the SE Monsoon from April to October (Iversen *et al*., 1984; Newell, 1957). However, some authors believe that the SE Monsoon commences in February (Jury *et al*., 2010) or May (Ngusaru & Mohammed, 2002), and Nyandwi & Dubi (2001) believe that September signals its end. Then, there are those who believe that the NE Monsoon runs from December to April (Mtolera & Buriyo, 2004), October to March (Nyandwi & Dubi, 2001), November to April (Ngusaru, 2000), or December to February (Jury *et al*., 2010). However, results from this study confirm earlier observations by Newell (1957) and Iversen *et al*. (1984) that, at the surface, the NE winds along the coast of Tanzania prevail from November to March, while the SE winds blow from April to October.

Oscillatory patterns

The annual and semi-annual patterns in monthly mean wind velocity observed in this study can be elucidated in terms of changes in the prevailing wind regime. The annual cycle is associated with the monsoonal wind reversals, and the semi-annual cycle is associated with transitions between the two monsoonal wind systems (Steele *et al*., 2009). The 6-8 year timescale signal observed only at Mtwara (Fig. 7b) possibly corresponds to ENSO events. This agrees well with the significant correlation at this station between wind speeds and the Niño-3 Index, especially during the SE Monsoon.

The prominent decadal signals at timescales of 12-16 years (Tanga), 19-25 years (Zanzibar), 10-13 years and 20-24 years (Dar es Salaam), and 15-25 years at Mtwara (Fig. 7b) possibly relate to the Quasi Decadal Oscillation (QDO) and the PDO signals. The QDO has a typical period of 9-13 years (Warren *et al*., 2008), while the PDO has a period of 15-25 years (Mantua *et al*. 2002). These two large-scale systems are known to influence the world climate, including that of the Indian Ocean (e.g. Crueger *et al*., 2009). The PDO signals that have been observed at Zanzibar, Dar es Salaam and Mtwara possibly correspond to the 2-decade epochs that are described by Allan *et al*. (1995) and Reason (2000).

Long-term trends

The rates of annual increase in mean wind speeds observed in this study were similar to those observed in the nearby Mozambican Channel during1950-1987, which did not exceed 0.1 $m.s^{-1}$ (Bigg, 1992). According to Douglas (1992), however, a longer record of at least fifty years is needed to ascertain the relationship between observed trends and changes in the global climate system.

Our results on trends in maximum wind speeds differ with those of Dubi (2001), who analysed records from coastal locations between 1972 and 1996. He observed increasing wind velocities at Mtwara and a declining trend at Tanga, Dar es Salaam and Zanzibar. These differences are possibly attributable to different lengths in the records used in the two studies. In the present study, a longer record spanning 30 years from 1977 to 2006 was used and showed a declining trend at Mtwara station, and rising trends at the other three locations. However, our results of monthly mean wind velocity at Zanzibar were similar to recent observations by Mahongo and Francis (2010), who have also recorded an increasing trend during 1985 to 2004.

This increasing trend in wind velocity along the coast of Tanzania may be explained in terms of changes in global climate. Climate change is a complex and spatially heterogeneous process which, apart from global or regional warming, manifests itself through various other phenomena, including changes in the wind climate (Suursaal & Kullas, 2006). Significant changes in the regional wind regime over the past few decades have been recorded at other localities such as the North and Baltic Seas (Suursaal *et al*., 2006; Suursaal & Kullas, 2006). In the Maldives, Mörner *et al*. (2004) linked the intensification of NE winds in over 30 years from the 1970s to increased evaporation. According to Trenberth *et al*. (2007), mid-latitude, westerly winds have strengthened in both hemispheres since the 1960s as a result of climate change. In much of the tropical Pacific Ocean, Whysall *et al*. (1987) and Inoue and Bigg (1995) observed an apparent strengthening in the trade wind system over the past few decades.

Correlations, and links with large-scale climatic systems

Good correlations in monthly mean wind speeds between Mtwara and Zanzibar, and between Tanga and Dar es Salaam (Table 3) do not appear to be related to large scale climatic systems (Table 4), and to long period cycles (Fig. 7b). This implies that the correlations between these stations are largely due to local factors, presumably the degree of coastal exposure. Mtwara and Zanzibar are more exposed to winds prevalent in the general circulation, while Dar es Salaam and Tanga are shielded by the Islands of Zanzibar and Pemba, respectively.

Our results have demonstrated that the ENSO, IOD and PDO modes are more closely linked to the SE Monsoon than the NE Monsoon. This is illustrated by the much higher correlations between the indices of these climatic systems and the corresponding wind speeds at each station. Correlations between wind speed and the ENSO or IOD modes increase southwards from Tanga to Mtwara. It is also notable that, during the NE Monsoon, there is no correlation between wind speed along the coast with the IOD mode. There is also no clear relationship between station location and the corresponding correlations between wind speed and the PDO. An attempt was made in this study to correlate monthly mean wind speeds with the Southern Oscillation Index (SOI) in partial correlations with Niño-3, DMI and PDO indices. However, no significant correlation was found at any of the stations, implying that winds along the coast of Tanzania are not related to dynamic processes in the Southern Ocean. Whether the increase in extreme wind velocities we describe here is related to shifting and strengthening of the South Indian Ocean anticyclone as described in Allan *et al*. (1995) and Reason (2000) requires further investigation.

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