Western Indian Ocean J. Mar. Sci. Vol. 9, No. 1, pp. 1-16, 2010


# Monthly Variations in Sea Level at the Island of Zanzibar

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***Keywords***: Zanzibar, sea level variations, climate, spectral analysis, multiple regression.

**Abstract—**Meteorological and tide gauge data were used to analyze correlations between climatic parameters and variations in mean sea level at Zanzibar for the period 1985-2004. This involved spectral and multiple regression analysis of the monthly variables, as well as harmonic analysis of hourly sea level. Air pressure and rainfall remained relatively constant during the 20-year study period, but there were trends in sea level, northeast winds, southeast winds and air temperature. Monthly variations in mean sea level, composed predominantly of semi-annual, annual and 4-year oscillations, were represented by the steric effect proxies of rainfall and air temperature (45%), southeast and northeast monsoon winds (41%), and air pressure (5%). The trend in sea level (9%) appeared to be mainly correlated with northeast winds. The annual cycle in sea level (36%) was represented to a certain degree by rainfall (11%), air temperature (10%), southeast winds (8%) and northeast winds (7%). The semi-annual component (28%) was best represented by southeast winds (15%), with the remaining 13% of the variability being equally represented by rainfall, northeast winds and air pressure. The 4-year oscillations, which accounted for about 27% of the variation in sea level, were mainly represented by air temperature (12%), rainfall (8%) and southeast winds (6%). There is a strong likelihood that physical processes other than meteorology and tides influenced the observed variations in sea level, especially in the 4-year cycle.

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# INTRODUCTION

Changes in monthly mean sea level reflect fluctuations in atmospheric pressure (the inverted barometer effect), wind regime, river runoff and steric effects due to changes in the specific volume of the ocean associated with shifts in water temperature and salinity (Tsimplis and Woodworth, 1994). The steric effect causes sea level to rise when the water is warm, or has low salinity, and vice versa. At low latitudes, variations in mean sea level are controlled to a very large extent by these steric effects and are mainly thermal (Pattullo *et al*., 1955; Lisitzin and Pattullo, 1961).

Variations in sea level off Tanzania have received very little attention. Pattullo *et al*., (1955) indicated that the sea level in Dar es Salaam (Fig. 1), which is about 80 km south of Zanzibar, is highest during March-May and lowest during July-September. The authors, however, did not outline factors that may be responsible for the observed seasonality. Using rainfall and sea level data from 1962 to1966, Ragoonaden (1998) observed that variations in monthly mean sea level at Tanga (about 120 km north of Zanzibar town) were mainly due to elevation of the sea surface resulting from changes in the current velocity off the coast, ruling out the effect of rainfall and river runoff as a significant factor. In this paper, the contribution of meteorology and long-term trends in tides to monthly variations in sea level is investigated off Zanzibar, contributing towards climate monitoring and coastal management.

The largest manifestation of seasonal change at the Island of Zanzibar (Fig.1) is the monsoon wind reversal and associated changes in climate. The northeast monsoon extends from January to February and is characterised by higher air temperatures, lower wind speeds and consequently calmer sea. The southeast monsoon begins in April, ends in November and is usually strong. Wind speeds are highest between June and October, and are lowest during the inter-monsoon months of March and December. The heavy (long) rains are experienced from March to May, while the light (short) rains fall during November and December.

The prevailing current along the Tanzanian coast is the East African Coastal Current (EACC), which flows northwards throughout the year. Apart from the EACC, winds and tides are the main forces that drive the oceanic circulation in the Zanzibar Channel (Mayorga-Adame, 2007). The Channel, which is about 35-40 km wide and 120 km long, is generally shallow with a depth of between 30-40 m in the middle (Shaghude & Wannäs, 1998). According to Harvey (1977) and Mohammed *et al*., (1993), the tidal circulation inside the Channel is complex. Flood streams enter and ebb streams exit the Channel at both its north and south entrances. While the Wami and Ruvu rivers on Mainland

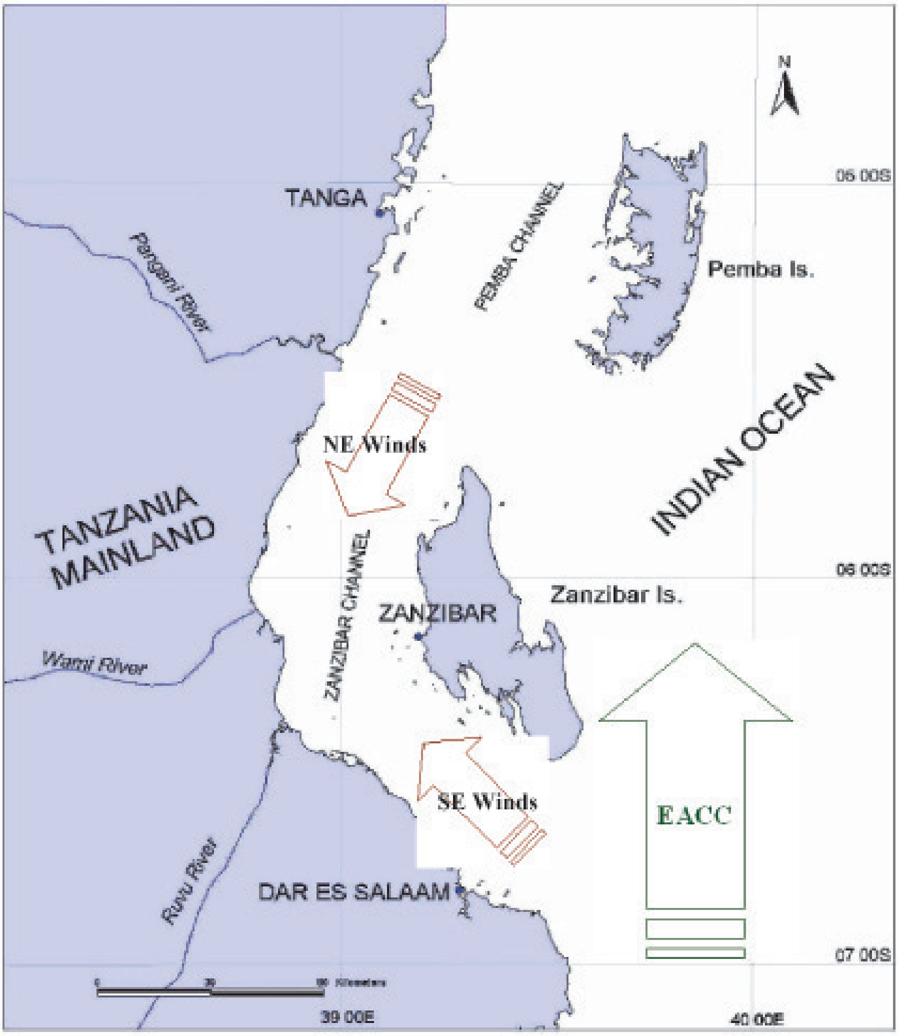


**Fig. 1: Map showing the island of Zanzibar, the major direction of the Southeast (SE) and Northeast (NE) Monsoon winds, and the direction of the East African Coastal Current (EACC).**

Tanzania discharge into the Zanzibar Channel directly opposite the island, there are no permanent rivers on Zanzibar. (Fig. 1).

The Zanzibar tide gauge is located on the seaward end of the main jetty in Zanzibar Harbour, on the western coast of Zanzibar town. The harbour is protected by a number of offshore islands, reefs and sandbanks that complicate current patterns in the vicinity of the harbour area (Shaghude *et al*., 2002; Mayorga-Adame, 2007). The tide gauge was commissioned in 1984, serving as one of the prime Indian Ocean stations for observation of global sea level change. The station has also been transmitting real-time sea level data for the Indian Ocean Tsunami Warning System (IOTWS) through the Global Telecommunications System (GTS) since December 2006.

## DATA AND METHODS OF ANALYSIS

Two sets of data were used in the investigation. The first included records of hourly and monthly sea level data from the Zanzibar tide gauge (1985-2004). These were obtained from the University of Hawaii Sea Level Centre (UHSLC), and can be accessed at www.ilkai.soest.hawaii.edu. The hourly data were subjected to harmonic analysis to obtain the amplitudes and phase lags of major tidal harmonics using the Sea Level Processing Software, SLPR2 (Caldwell, 1998).

The UHSLC computes monthly mean sea levels through simple averaging of the daily values. The daily series, on the other hand, are derived using a two-step filtering operation. First, the dominant diurnal and semidiurnal tidal components are removed from the quality-controlled hourly values. Secondly, the remaining higher frequency energy data are removed using a 119-point convolution filter (Bloomfield, 1976) to prevent aliasing when the data are computed to daily values.

The second group of data (1985-2004) consisted of mean monthly rainfall, air temperature, air pressure and winds (speed and direction) recorded at 1500 local time (GMT +3). Meteorological records were obtained from Chukwani station, about 5 km from the harbour and considered representative of the study area. The *MATLAB* "wind-rose" script was used to determine the main axes of the southeast and northeast monsoon winds at Zanzibar. These were oriented at 135° and 29° respectively from True North. The data on winds were then decomposed into these two major wind directions, which also conform to the general orientation of the northern and southern entrances of Zanzibar Channel (Fig. 1).

The contribution of steric effects to the observed sea level oscillations was not directly computed due to paucity of data on salinity and sea surface temperature along the coast. Consequently, the steric effect proxies of rainfall and air temperature were used. The above data sets were cleaned before analysis through removal of large spikes. These were outlying data points that were considered incorrect. Linear regressions of the monthly series were plotted by the method of least squares on *SIGMAPLOT* software to determine the presence of long term changes.

Spectral time series in the sea level and meteorological data were extracted using Fast Fourier Transform (FFT) in the *STATISTICA* software package which determined the significant spectrum peaks (Shumway, 1988). Prior to spectral analysis, the relatively few missing data were interpolated from linear trend regressions. The amplitude and phase lags in significant spectral cycles were computed by Discrete Fourier Transform (DFT) using a script downloaded from *www.mathworks.com\matlabcentral\fileexchange*. The Hamming window (Oppenheim & Schafer, 1989) was chosen to smooth the raw data for both the FFT and DFT analyses. The procedure involves weighted moving average transformation that assigns the greatest weight to the observations in the centre of the window, and increasingly smaller weights to values that are further away from the centre. This procedure was preferred to other lag windows as it provided better interpretation of the results. The amplitude, phase and nature of the meteorological oscillations were related to fluctuations in sea level.

*STATISTICA* was also used to calculate multiple regressions of time series of the meteorological parameters against monthly mean sea level (see e.g. Thompson, 1980; Abdelrahman, 1997; Vilibić, 2006). Prior to these calculations, the monthly sea level data were isolated in terms of cyclical trends, seasonal effects, and remaining (irregular) variability using the method known as seasonal decomposition, an algorithm described and discussed in detail in Makridakis & Wheelwright (1978, 1989). The moving average in the variable trend-cycle was determined using the Henderson curve moving average, which is a weighted moving average in which the magnitude in the weighting follows a bell-shaped curve. To avoid erroneous conclusions, residual analysis tests were carried out in STATISTICA to identify any violations of the assumptions after fitting the multiple regression equations through case-wise plots of the residuals, case-wise plots of outliers and normal probability plots of the residuals.

**Table 1: Main tidal components at Zanzibar Harbour, 1 Jan 2003–31 Jan 2004.**

| SN | Symbol | Period | (h/days) | Amplitude (cm) | Greenwich Phase (degrees) |
|---|---|---|---|---|---|
| 1 | SA | 365.3 | days | 2.0 | 84.5 |
| 2 | SSA | 182.6 | days | 2.9 | 81.4 |
| 3 | MF | 13.7 | days | 1.8 | 21.0 |
| 4 | Q1 | 26.9 | h | 2.5 | 31.9 |
| 5 | O1 | 25.8 | h | 11.2 | 42.7 |
| 6 | P1 | 24.1 | h | 5.6 | 39.3 |
| 7 | S1 | 24.0 | h | 2.7 | 0.2 |
| 8 | K1 | 23.9 | h | 18.4 | 41.0 |
| 9 | 2N2 | 12.9 | h | 2.1 | 44.0 |
| 10 | MU2 | 12.9 | h | 1.77 | 87.5 |
| 11 | N2 | 12.7 | h | 22.6 | 89.7 |
| 12 | NU2 | 12.6 | h | 4.6 | 92.4 |
| 13 | M2 | 12.4 | h | 120.4 | 112.4 |
| 14 | L2 | 12.2 | h | 4.3 | 120.2 |
| 15 | T2 | 12.0 | h | 4.1 | 157.9 |
| 16 | S2 | 12.0 | h | 60.9 | 154.6 |
| 17 | K2 | 12.0 | h | 16.7 | 151.6 |
| 18 | M4 | 6.2 | h | 1.56 | 354.8 |
| 19 | 2MN6 | 4.2 | h | 1.33 | 258.6 |
| 20 | M6 | 4.1 | h | 2.2 | 307.6 |

# RESULTS AND DISCUSSION

## Astronomic tides

The results of harmonic analysis of tides of amplitude >1 cm are listed in Table 1. The tides were strongly semidiurnal, with a Form Factor F (Pugh, 2004) of 0.16. The corresponding mean spring tidal range was 3.65 m, which compares well with previous observations (Odido and Francis, 1999). Table 1 also shows that most of the constituent harmonics were diurnal and semi-diurnal. Results of the tidal harmonic analysis for long-period tides (Sa and Ssa) between 1985 and 2004 are listed in Table 2. Whereas the Ssa tides occur every year, the Sa tides appear only once in every four years.

**Table 2: Amplitude and Greenwich Phases of long-period tidal components at Zanzibar.**

| Year | Sa | | Ssa | |
|---|---|---|---|---|
| | Amplitude (cm) | Phase (deg) | Amplitude (cm) | Phase (deg) |
| 1985 | 0 | - | 1.8 | 89.4 |
| 1986 | 0 | - | 1.6 | 44.3 |
| 1987 | 0 | - | 5.1 | 87.2 |
| 1988 | 3.6 | 128.1 | 0.9 | 332.5 |
| 1989 | 0 | - | 3.7 | 74.0 |
| 1990 | 0 | - | 3.4 | 70.7 |
| 1991 | 0 | - | 2.1 | 60.0 |
| 1992 | 3.0 | 109.0 | 1.0 | 70.5 |
| 1993 | 0 | - | 1.5 | 107.9 |
| 1994 | 0 | - | 2.2 | 157.4 |
| 1995 | 0 | - | 1.2 | 25.1 |
| 1996 | 5.3 | 80.5 | 1.0 | 78.1 |
| 1997 | 0 | - | 2.8 | 99.5 |
| 1998 | 0 | - | 2.5 | 8.0 |
| 1999 | 0 | - | 0.7 | 0.7 |
| 2000 | 2.2 | 26.3 | 1.2 | 110.6 |
| 2001 | 0 | - | 2.7 | 106.2 |
| 2002 | 0 | - | 3.1 | 53.0 |
| 2003 | 0 | - | 3.5 | 75.2 |
| 2004 | 3.6 | 38.7 | 2.8 | 104.2 |

## *Monthly variations*

Figure 2 illustrates monthly variations in the meteorological and sea level data. Atmospheric pressure, air temperature, the southeast winds and rainfall clearly manifested annual variability with low air temperatures corresponding to high air pressure and vice versa. The trends in sea level and northeast winds displayed inconsistent fluctuations throughout the observation period. With the exception of air pressure and rainfall, all the other meteorological parameters exhibited increasing trends over the 20-year study period (1985-2004). The mean sea level has also been declining consistently as indicated by the linear regression and Mahongo (2009) has noted that this parameter has been declining at Zanzibar at the rate of 3.6 mm/yr during this period.

Descriptive statistics of sea level and the meteorological parameters for the period 1985-2004 are presented in Table 4. The range between the lowest and highest sea levels (6.2 cm) is much smaller than that observed at higher latitude. For example, on the west coast of India, the amplitude in annual mean sea level is of the order of 20 cm (Wijeratne *et al*., 2008) while, in the Red Sea, amplitudes of about 40 cm have been recorded (Abdelrahman, 1997).

The solar annual (Sa) and the solar semi-annual (Ssa) tidal components were 3.5 cm and 2.3 cm in mean amplitude at Zanzibar respectively. This conforms to an observation by Tsimplis & Woodworth (1994) that, generally, semi-annual tidal amplitudes are much smaller than the annual component. Differences in atmospheric pressure at Zanzibar fell

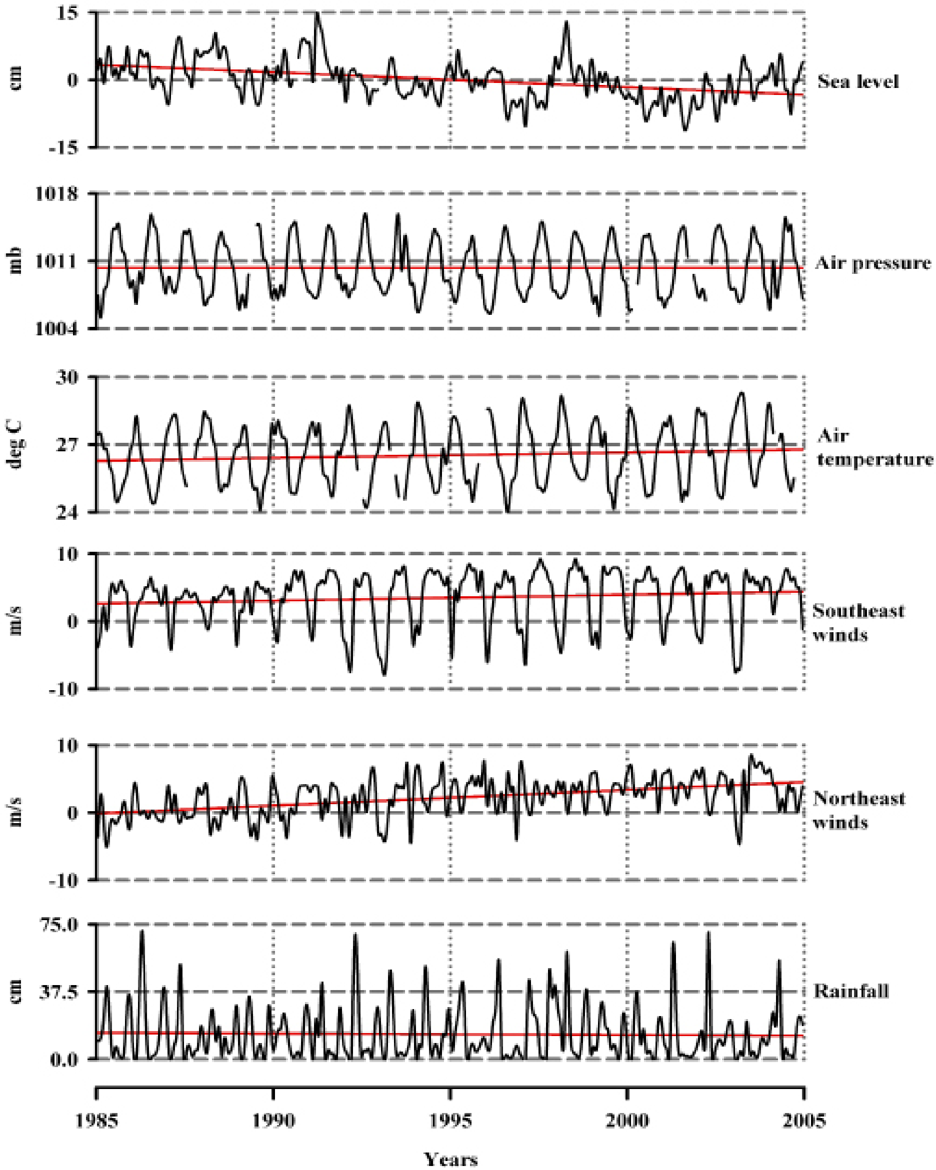


**Fig. 2: Monthly sea level and meteorological data for Zanzibar with linear regressions.**

within a range of 7.3 mb, this being small compared to higher latitudes such as the Arabian Sea, where differences >40 mb have been recorded (Sultan *et al*., 1995). The mean monthly air temperature was 26.5°C, ranging from a minimum of 24.7°C in July to a maximum of 28.2°C in February.

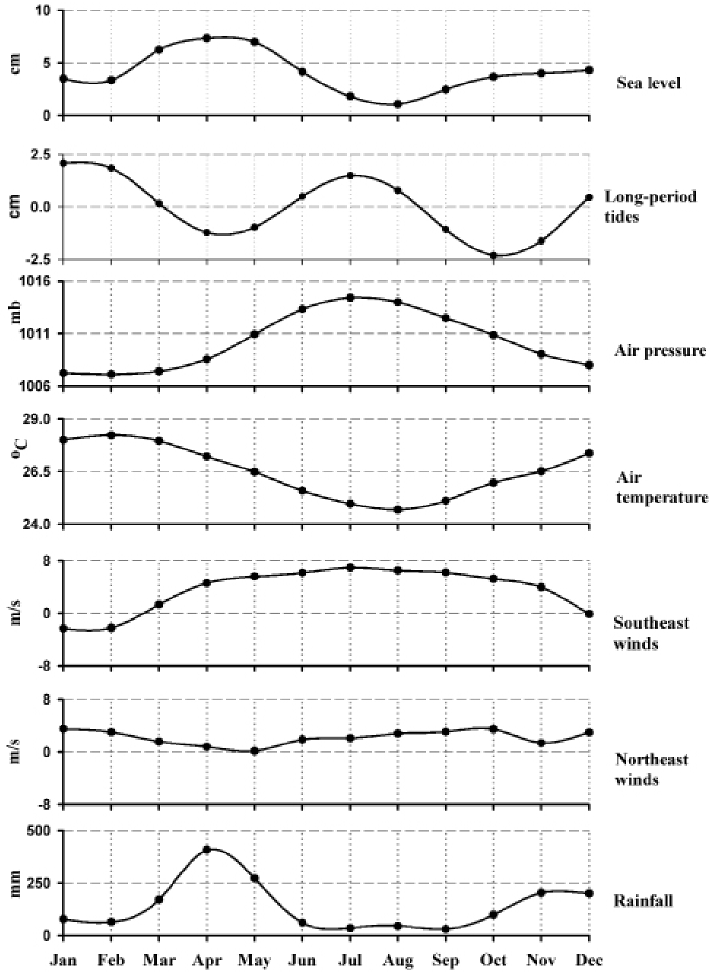


**Fig. 3: Monthly means of the sea level and associated meteorological parameters at Zanzibar (1985-2004).**

## *Monthly means*

Monthly means in sea level and the meteorological and oceanographic parameters are presented in Figure 3. These were obtained by averaging monthly series, e.g. January, over all the years in the record. The highest sea levels were observed during March-May, while the lowest occurred during July-September. The highest and lowest mean sea levels were recorded in April and August, respectively.

The mean monthly variations in sea level at Zanzibar conformed to those of Dar es Salaam on mainland Tanzania and Kilindini harbour in Mombasa, Kenya (Pattullo *et al*., 1955). However, the pattern differs at Tanga, which is closer to Zanzibar (Fig. 1), having the lowest levels in February-May and the highest in July-September (Ragoonaden (1988). This is rather surprising, since Tanga is sandwiched between Zanzibar and Dar es Salaam in the south and Mombasa in the north.

Mean variations representing the sum of the Sa and Ssa tides were highest in January and February, and lowest in October and November.

**Table 3: Analysis of spectral components in sea level and meteorological and tidal data at Zanzibar.**

| | | | Amplitude | | | | | |
|---|---|---|---|---|---|---|---|---|
| Period (yrs) N=240 (cm) | Sea level (mb) | Air pressure ($^oC$) | Air temp (mm) | Rainfall (m/s) | SE winds (m/s) | NE winds (cm) | Sa tide (cm) | Ssa tide (cm) |
| 0.5 | 1.6 | 0.6 | 0.1 | 125.1 | 1.8 | 0.9 | 0.0 | 1.6 |
| 1 | 2.1 | 3.9 | 1.9 | 89.9 | 5.2 | 1.0 | 0.9 | 0.0 |
| 4 | 2.7 | 0.4 | 0.1 | 18.8 | 1.0 | 0.6 | 0.4 | 0.1 |
| | | | Phase (degrees) as of January | | | | | |
| Period (yrs) N=240 | Sea level | Air pressure | Air temp | Rainfall | SE winds | NE winds | Sa tide | Ssa tide |
| 0.5 | 149.5 | 5.5 | 196.3 | 145.8 | 159.2 | 315.5 | 31.3 | 342.6 |
| 1 | 290.9 | 164.3 | 333.4 | 296.7 | 169.6 | 66.5 | 310.0 | 66.7 |
| 4 | 163.1 | 254.0 | 144.3 | 269.0 | 175.0 | 139.8 | 145.3 | 41.4 |

The mean atmospheric pressures were highest during May-October, whereas air pressures were lowest during November-April. As expected, the periods of high and low temperatures coincided with low and high pressure. The period with the lowest mean air temperature (i.e. August) also corresponded with the lowest mean sea level. However, higher air temperatures that occurred in February did not correspond with higher sea levels. The total annual rainfall over the study period averaged 168 cm, with the heaviest rainfall in April (42.3 cm) and the lowest in September (3.1 cm). The rainfall was highest during April and May, corresponding with the highest mean sea level. Rainfall in the region is bi-modal (falling twice a year), with a second but smaller peak in November and December. The southeast winds were generally stronger than the northeast winds, averaging 3.5 and 1.3 m/s, respectively (Table 4).

## *Spectral Analysis*

The results of spectral analysis of the various parameters are presented in Figure 4. In addition to annual and semi-annual variations, the sea level spectrum clearly displayed the prominence of a long-period cycle of four years. The annual and semi-annual oscillations were of the same order of magnitude, while the 4-yearly cycles were significantly larger. The spectra of air pressure, air temperature that influence the 4-year oscillations in sea level. Nevertheless, there was a cyclical trend in sea level which accounted for about 9% of the total variance in sea level, attributable and southeast winds largely manifested an annual cycle. In addition to the annual cycle, the southeast wind component also contained a small but significant

**Table 4: Descriptive statistics of monthly mean sea level and meteorological data at Zanzibar.**

| N=240 | Sea level (cm) | Air pressure (mb) | Air temp °C | Rainfall (cm) | SE winds m/s | NE winds m/s |
|---|---|---|---|---|---|---|
| Mean | 204.1 | 1010.3 | 26.5 | 13.8 | 3.5 | 1.3 |
| Min | 201.1 | 1007.1 | 24.7 | 2.9 | -2.3 | 0.1 |
| Max | 207.3 | 1014.4 | 28.2 | 40.7 | 6.9 | 3.5 |
| Range | 6.2 | 7.3 | 3.6 | 37.7 | 9.3 | 3.4 |
| STD | 4.5 | 2.8 | 1.3 | 14.9 | 4.0 | 3.0 |

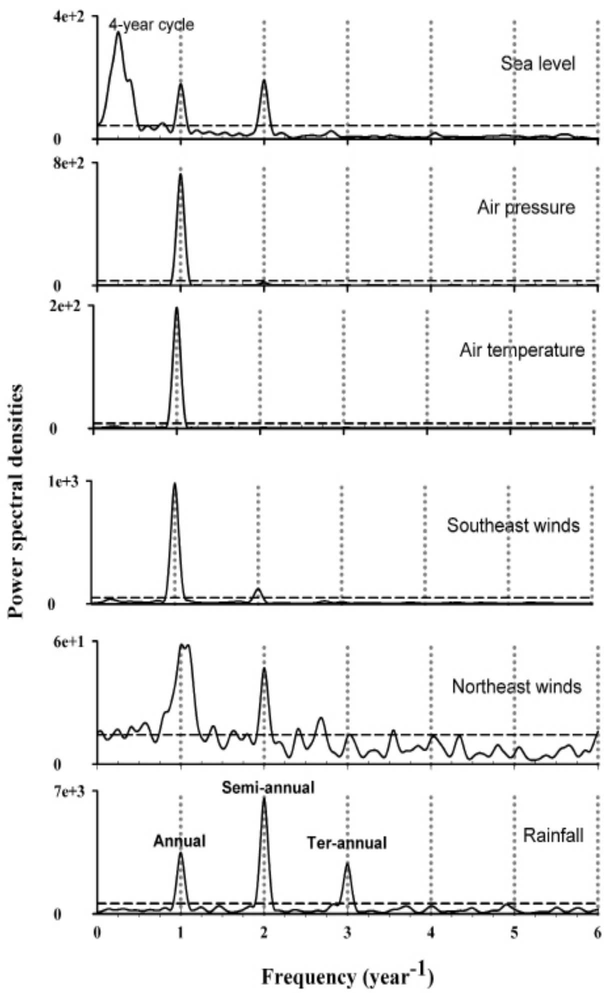


**Fig. 4: Spectral analysis of the sea level and meteorological data (1985-2004). Horizontal lines show the upper limit of the 95% confidence level.**

semi-annual signal at 95% confidence level.

The spectrum of the northeast winds was predominantly composed of annual and semi-annual signals, as well as numerous lower and higher frequency signals that were smaller. The rainfall spectrum contained three significant peaks (at 95% confidence level) at annual, semi-annual and 4-monthly periods with the semi-annual signal being more pronounced than the other two signals. Background noise of low energy oscillations in the sea level and rainfall spectra were of less significance.

## *Amplitude and phase lags*

Table 3 lists the amplitude of and phase lags in the meteorological and sea level variables corresponding to the spectral frequencies in sea level. In the semi-annual cycle, changes in sea level were nearly in phase with rainfall and southeast winds, but were about 1.6 months later in phase than air temperature. Air pressure and northeast winds were out of phase with changes in sea level by 4.8 and 5.5 months, respectively. Rainfall had the highest amplitude in the semi-annual cycle, yet the corresponding amplitude in sea level was smaller than in the annual cycle. This suggests that other physical processes are more important than rainfall as a cause or proxy of the semi-annual cycle in sea level. The solar semi-annual tide Ssa, with an amplitude of 1.6 cm (equal to that of sea level), was opposite in phase with sea level, preceding it by 6.4 months.

In the annual cycle, changes in sea level were almost in phase with rainfall and the solar annual tide, Sa. Again, changes in air temperature occurred 1.4 months earlier than those of sea level. Southeast winds, air pressure and northeast winds were out of phase with changes in sea level by 4, 4.2 and 7.5 months respectively. In the 4-year cycle, southeast winds, air temperature, northeast winds and the annual astronomic tides (Sa) were almost in phase with changes in sea level. Changes in sea level relative to air pressure and rainfall were out of phase by 3 and 3.5 months, respectively. Changes in sea level were of much higher amplitude in the 4-year cycle than in the annual and semi-annual cycles, yet the amplitude of the meteorological and tidal factors (that were in phase) were comparatively small. Hence, apart from meteorology and tides, it is very likely that other physical processes significantly influence the 4-year oscillations in sea level at Zanzibar. Seismic activity and oceanographic effects such as the El Niño Southern Oscillation can also contribute to variations in mean sea level (Aung *et al*., 1998).

## *Multiple regression analysis*

Regression coefficients, normalized regression coefficients, semi-partial correlations and percent variance in the meteorological data are listed in Table 5. The advantage of normalizing the regression coefficients was to compare the relative contribution of each meteorological variable in the prediction of sea level, regardless of the units used. The semi-partial correlation provided a measure of the correlation with each meteorological variable after eliminating the effects of the other variables.

In Table 5a-d, the variance in the meteorological variables fitted to that of sea level totalled 100%. The annual rainfall had a regression rate of 0.51 cm/10 cm. This implies that, at the recorded maximum rainfall of 42.3 cm, the sea level could increase by 2.2 cm. In the Adriatic, Vilibić (2006) obtained a corresponding rate of 0.53 cm/10 cm. The seasonal cycle of sea level, represented by the sum of semi-annual and annual oscillations, accounted for about 64% of the sea level variance at Zanzibar.

**Table 5: Results of multiple regressions of meteorological and sea level data (*not significant at 95% confidence level).**

(a) In the semi-annual cycle

| N=240, R = 0.64<br>Total variance = 28.2% | Regression coefficients | Normalized regression coefficients | Semi-partial correlations | Percent variance |
|---|---|---|---|---|
| SE winds | 0.203 ± 0.027 | 0.618 ± 0.081 | 0.39 | 14.9 |
| Rainfall | 0.023 ± 0.005 | 0.265 ± 0.062 | 0.22 | 4.6 |
| NE winds | -0.111 ± 0.027 | -0.241 ± 0.058 | -0.21 | 4.4 |
| Air pressure | -0.242 ± 0.059 | -0.513 ± 0.124 | -0.21 | 4.3 |
| Air temperature* | -0.039 ± 0.115 | -0.039 ± 0.114 | -0.02 | 0.0 |

(b) In the annual cycle

| N=240, R = 0.81<br>Total variance = 28.2% | Regression coefficients | Normalized regression coefficients | Semi-partial correlations | Percent variance |
|---|---|---|---|---|
| Rainfall | 0.051 ± 0.006 | 0.407 ± 0.047 | 0.33 | 11.0 |
| Air temperature | 1.022 ± 0.124 | 0.713 ± 0.087 | 0.31 | 9.9 |
| SE winds | 0.216± 0.029 | 0.460± 0.061 | 0.29 | 8.2 |
| NE winds | -0.192 ± 0.029 | -0.292 ± 0.044 | -0.25 | 6.5 |
| Air pressure* | -0.021 ± 0.064 | -0.032 ± 0.094 | -0.01 | 0.0 |

(c) In the 4-year cycle

| N=240, R = 0.62<br>Total variance = 28.2% | Regression coefficients | Normalized regression coefficients | Semi-partial correlations | Percent variance |
|---|---|---|---|---|
| Air temperature | 1.662 ± 0.245 | 0.789 ± 0.116 | 0.35 | 12.0 |
| Rainfall | 0.062 ± 0.012 | 0.336 ± 0.063 | 0.27 | 7.5 |
| SE winds | 0.275 ± 0.057 | 0.398± 0.082 | 0.25 | 6.1 |
| Air pressure* | 0.221 ± 0.126 | 0.223 ± 0.126 | 0.09 | 0.8 |
| NE winds* | -0.084 ± 0.057 | -0.086 ± 0.059 | -0.08 | 0.6 |

(d) In the trend cycle

| N=241, R = 0.33<br>Total variance = 28.2% | Regression coefficients | Normalized regression coefficients | Semi-partial correlations | Percent variance |
|---|---|---|---|---|
| NE winds | -0.378 ± 0.082 | -0.327 ± 0.071 | -0.3 | 8.1 |
| Air pressure* | -0.151 ± 0.181 | -0.127 ± 0.152 | -0.1 | 0.3 |
| Air temperature* | -0.278 ± 0.353 | -0.110 ± 0.140 | 0.0 | 0.2 |
| Rainfall* | -0.012 ± 0.017 | -0.052 ± 0.076 | 0.0 | 0.2 |
| SE winds* | -0.024 ± 0.082 | -0.030 ± 0.099 | 0.0 | 0.0 |

In other areas such as the Arabian Gulf, the corresponding variance is about 80% (Sultan *et al*., 1995). In the spectral analysis, the 4-year cycle was significantly larger than the annual cycle (at the 95% confidence level), yet the fitted variance was smaller. This again suggests the presence of factors other than meteorology largely to northeast winds.

Air temperature, rainfall and southeast winds appeared to increase the sea level as indicated by the sign of the regression and normalized regression coefficients (Table 5a-d). In contrast, the northeast winds and air pressure appeared to depress the sea level. According to Harvey (1977), the EACC flows faster during the SE monsoon (speed 1.5 - 2 m/s), being accelerated by the SE winds. During the NE monsoon, the current is retarded by the northeast winds to 0.5 m/s. The southeast monsoon winds thus increase the speed and consequently the geostrophic flow of the EACC, which flows permanently northwards parallel to the coast of Tanzania. As a result of the Coriolis Effect, water is pumped into the Zanzibar Channel through the southern entrance, thereby increasing the sea level. In contrast, the northeast winds reduce the geostrophic flow of the EACC, consequently reducing the sea level in Zanzibar Channel.

In the Maldives, Mőrner *et al.,* (2004) linked intensification of the northeast winds over a 30-year period to increased evaporation and a subsequent drop in sea level. The stronger winds observed over the 20-year study period have not had similar effects at Zanzibar; both the northeast and southeast winds have intensified at Zanzibar, but the southeast winds in the annual, semi-annual and the 4-year cycles were associated with an increase in sea level. The declining trend in sea level at Zanzibar is therefore best represented by strengthening of the northeast winds, which may have led to a decrease in the flow of the EACC and, consequently, a reduction in the trend of sea level. According to Han *et al*., (2010), the decrease in sea level at Zanzibar and the south tropical Indian Ocean is driven by changing surface winds associated with a combined invigoration of the Indian Ocean Hadley and Walker cells, which is partly attributable to rising levels of atmospheric greenhouse gases. Mid-latitude westerly winds have strengthened in both hemispheres since the 1960s as a result of climate change (Trenberth *et al*., 2007).

## CONCLUSIONS

In conclusion, analyses of the monthly means of sea level and meteorological parameters during 1985-2004 at Zanzibar revealed a large proportion (64%) of the spectral signal to be seasonal, essentially comprising the sum of the annual and semi-annual components. Seasonality was largely evidenced by changes in winds and the steric effect proxies of rainfall and air temperature. A 4-year cycle accounted for about 27% of the variance in sea level and was best represented by air temperature, rainfall, southeast winds as well as the annual astronomic tides. Long-term changes in sea level constituted about 9% of the total variance, apparently due to changes in the northeast winds. This corroborated an observation by Pattullo *et al*., (1955) that, in low latitudes, variations in mean sea level are regulated to a very large extent by steric effects.

Results of multiple regression analysis of the data generally conformed to the results of the spectral analyses. Discrepancies, especially in the 4-yearly cycle, were presumably attributable to the effects of other physical processes superimposed on the measured variables. The mean sea level, winds (NE and SE monsoons) and air temperature have been changing at Zanzibar steadily over the 20-year study period, probably as a consequence of the changing global climate.

***Acknowledgments***–We wish to express our sincere gratitude to the Western Indian Ocean Marine Science Association (WIOMSA) for providing a fellowship grant to present this paper at the Fifth WIOMSA Scientific Symposium in South Africa during October 2007. We also thank the Tanzania Meteorological Agency for the provision of atmospheric data, and the University of Hawaii Sea Level Centre (UHSLC) for making the data on sea level available. Prof. D.T. Pugh of the University of Liverpool (UK) provided useful comments and suggestions which have substantially improved the manuscript. Lastly, we appreciate the support of Online Access to Research in the Environment (OARE), and Access to Global Online Research in Agriculture (AGORA) for assistance in acquiring pertinent references.

# REFERENCES

Abdelrahman, S.M. (1997). Seasonal fluctuations of mean sea level at Gizan, Red Sea. *J. Coast. Res.* **13**: 1166-1178.

Aung, T. H., Kaluwin, C. & Lennon, G.W. (1998). *Climate Change and Sea Level, Part 1: Physical Science*, National Tidal Facility, The Flinders University of South Australia, Adelaide. 106 pp.

Bloomfield, P. (1976). *Fourier analysis of time series: An Introduction*. John Wiley & Sons, New York. 288 pp.

Caldwell, P. (1998) Sea Level Data Processing On IBM PC Compatible Computers Version 3.0 (Year 2000 Compliant). JIMAR Contribution No. 98-319. National Oceanographic Data Center and University of Hawaii Sea Level Center. 72pp.

Han, W., Meehl, G.A., Rajagopalan, B., Fasullo, J.T., Hu, A., Lin, J., Large, W.G., Wang, J., Quan, X., Trenary, L.L., Wallcraft, A., Shinoda, T. & Yeager, S. (2010) Patterns of Indian Ocean Sea-level Change in a Warming Climate. *Nature Geosci.* **3**: 546 - 550.

Harvey, J. (1977) Some Aspects of The Hydrography of the Water off the coast of Tanzania: A Contribution to CINCWIO. Univ. *Sci. J.* (University of Dar es Salaam) **3**: 53-92.

Lisitzin, E. & Pattullo, J.G. (1961) The Principal Factors Influencing the Seasonal Oscillation of Sea Level. *J. Geophy. Res.* **66**: 845-852.

Mahongo, S.B. (2009) The changing Global Climate and its Implication on Sea Level Trends in Tanzania and the Western Indian Ocean region. *Western Indian Ocean J. Mar. Sci.* **8**: 147-159.

Makridakis, S.G. & Wheelwright, S.C. (1978) Interactive Forecasting: *Univariate and Multivariate Methods* (2nd ed.). Holden-Day, San Francisco, CA. 650 pp.

Makridakis, S.G. & Wheelwright, S.C. (1989) *Forecasting Methods for Management* (5th ed.). John Wiley, New York. 241 pp.

Mayorga-Adame, C.G. (2007) Ocean Circulation of the Zanzibar Channel: A Modelling Approach. Technical Report for Theiss Research and IMS (Zanzibar). La Jolla, CA. 8 pp.

Mohammed, S., Ngusaru, A. & Mwaipopo, O. (1993) Determination of the Effects of Pollutants on Coral Reefs around Zanzibar Town. A Technical Report to NEMC. IMS, Zanzibar. 34 pp.

Mörner, N., Tooley, M & Possnert, G. (2004) New Perspectives for the Future of the Maldives. Global Planet. *Change* **40**: 177–182.

Odido, M. & Francis, J. (1999) Sea Level Measurement and Analysis in the Western Indian Ocean. Regional Report for IOC/UNESCO. 59 pp.

Oppenheim, A.V. & Schafer, R.W. (1989) *Discrete-Time Signal Processing*, Prentice-Hall. 870 pp.

Pattullo, J.G., W. Munk, R. Ravelle & Strong, E. (1955) The Seasonal Oscillations in Sea level. *J. Mar. Res.* **14**: 88-156.

Pugh, D.T. (2004) Changing Sea Levels: Effects of Tides, Weather, and Climate. Cambridge University Press, 265 pp.

Ragoonaden, S. (1998) Mean Monthly Sea Level Variation and its Relation to Large-scale Ocean Circulation in the Southwest Indian Ocean. *In:* Sherman, K. Okemwa, E.N. & Ntiba, M.J. (eds.) *Large Marine Ecosystems of the Indian Ocean: Assessment, Sustainability and Management*. Blackwell Science, Inc. Malden, MA. pp. 193-214.

Shaghude, Y. & Wannäs, K. (1998) Morphology and Sediment Distribution of the Zanzibar Channel. *Ambio* **27**: 729-733.

Shaghude, Y., Wannäs, K. & Mahongo, S. (2002) Biogenic Assemblage and Hydrodynamic Settings of the Tidally Dominated Reef Platform Sediments of the Zanzibar Channel. *Western Indian Ocean J. Mar. Sci.* **1**: 107-116.

Shumway, R.H. (1988) *Applied Statistical Time Series Analysis*. Prentice Hall. Englewood Cliffs, NJ. 379 pp.

Sultan, S.A.R., Ahmad, F., Elghribi N.M. & Al-Subhi, A.M. (1995) An Analysis of Arabian Gulf Monthly Mean Sea Level. *Cont. Shelf Res.* **15 (11/12)**: 1471-1482.

Thompson, K.R. (1980) An Analysis of British Monthly Mean Sea Level. *Geophys. J. R. Astron. Soc.* **63**: 57-13.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B. & Zhai, P. (2007) Observations: Surface and Atmospheric Climate Change. *In:* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (eds.) Climate Change 2007: *The Physical Science Basis. Contribution of Working Group I to the IPCC AR4.* Cambridge University Press. Cambridge, UK and New York, NY, USA. pp. 235-336.

Tsimplis, M.N. & Woodworth, P.L. (1994) The Global Distribution of the seasonal Sea Level Cycle Calculated from Coastal Tide Gauge Data. *J. Geophys. Res.* **99 (c8)**: 16031-16039.

Vilibić, I. (2006) Seasonal Sea Level Variations in the Adriatic. *Acta Adriat.* **47**: 141-158.

Wijeratne, E.M.S., Woodworth, P.L. & Stepanov, V.N. (2008) The seasonal Cycle of Sea Level in Sri Lanka and Southern India. *Western Indian Ocean J. Mar. Sci*. **7(1)**: 29-43.