EFFECTS OF URBANIZATION ON WINDS OVER DAR ES SALAAM

by

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Declaration

This research project was carried out and presented for examination for the Postgraduate Diploma in Meteorology by me Abel Nkuba at the University of Nairobi.

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This research project has been submitted for examination with our approval as supervisors:

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Dr. F.J. Opijah

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Dr. R.E. Okoola

Abstract

This study sought to investigate the effect of urbanization on urban winds over Dar es Salaam based on observed maximum temperature, minimum temperature, wind speed and wind direction between the periods 1981 to 2012 while Population and Global Data Assimilation System (GDAS) data covered the period 2002 -2012 and 2004 -2012 respectively. Single mass curve was used for data quality control while time series, wind rose and correlation analysis were used to achieve the objectives of the study.

Data quality control indicated that the datasets were homogeneous. Results showed that population, maximum temperature, minimum temperature and wind speed at 0600Z and 1200Z were increasing with minimum temperature showing most significant increase in trend with coefficient of determination at 82.8%. The change in minimum temperature was observed to be higher than the change in maximum temperature owing and attributed to urbanization effects. Temperature was highly correlated with population with values above 0.5 which were significant. A Comparison of wind speeds between current and past years showed an increasing pattern. Results from wind roses analysis showed that the predominant winds were mainly south easterlies and their direction was noted to have slightly changed between the two periods considered.

The study noted that modification of both wind speeds and direction was a result of horizontal thermal gradients due to the urban heat island and less due to urbanization. Therefore, urban planners should consider modification due to urbanization for proper planning of residential and industrial places to ensure thermal comfort.

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CHAPTER ONE

1.1 Introduction

Urban and suburban centers are observed to grow as a result of population growth; it involves land-use changes as a result of human activities. According to García et al., (2009), urbanization in many parts of the world is evident due to the increase in population in cities. This process creates climate of its own by producing a change in the nature of the surface and atmospheric properties of a region. Rapid urbanization and industrialization have resulted in changes in land cover that affects the urban climate (Robaa, 2013).

Urban and rural environments differ substantially in their micro-climate which is primarily caused by the earth surface fluctuation due to anthropogenic activities and subsequent release of energy into the environment. In urban areas vast amount of heat energy is added to local energy balance via heating of the building, transportation and industrial activities. In rural areas cooling process of the land surface and local atmosphere is carried out through evaporation and transpiration from various natural surfaces. Such differences make urban areas to be warmer than the surrounding rural areas due to the fact that the differences in temperature are observed at night under stable condition with minimum atmospheric mixing. These create a phenomenon called urban heat island (UHI) in meteorological studies.

According to Oke (1973), urbanization effects on weather and climate are noticeable even in population settings of as small as 1000 people and the intensity of urban heat island (UHI) is linearly correlated with the logarithms of the population. The potential for steadily increasing temperatures and air pollution coupled with a projected doubling of the global urban population by 2030 (UN, 2001), greatly elevates the need for inhabitants, public health officials, planners and decision makers to devise effective strategies of managing climate in large cities. The study of the effects of land surface change on the climate of a given area is thus very important

A better scientific understanding of the physics of urban environmental meteorology may help optimize urban planning to prevent the occurrence of local meteorological conditions that are adverse to human populations (Steeneveld et al, 2011).

1.2   Problem statement

Urbanization in many parts of the world is evident due to increased population growth in the cities. In urban areas, effects of complex geometry of the urban surface, shape and orientation of the buildings, over concentration of manmade structures, peculiar thermal and hydrological properties of the urban morphology, heat generated by the many forms of combustion processes, traffic and industries, and the amount of pollutants released into the city's atmosphere all combine to modify the urban climate. These modifications include changes in near surface atmospheric parameters such as winds, air temperature, humidity, precipitation, visibility and surface energy fluxes and thus create a climate of its own. Moreover, modification of urban wind results to changes in the concentration of suspended particulates in the air and the surface roughness over the urban area. These changes may have adverse impacts on human health.

1.3   Hypothesis

In this study, hypothesis was stated that changes in urbanization indicators (population) will result to changes urban winds.

1.4   Objective of the study

The main objective is to study the effect of Urbanization on winds over Dar es Salaam area. The specific objectives are;

1. To determine the time variability of population, temperature and winds over Dar es Salaam

2. To find the relationship between population and meteorological variables.

3. To determine the effect of urbanization on winds over Dar es Salaam.

1.5   Justification

Dar es Salaam is experiencing rapid urbanization growth just like many other developing countries in Africa. In Tanzania, it is ranked the first in terms of urbanization level (Muzzini and Lindeboom, 2008). The effect of urbanization on the microclimate of cities are mostly due to the

changes in the various land uses to which urban areas are put to, especially when these cities are compared to their surrounding countryside (Nduka and Abdulhamed, 2011).

Modification of urban wind coupled with changes in air pollution levels and projected doubling of the urban population greatly elevates the need for inhabitants, public health officials, planners and decision makers to devise effective strategies of managing climate in Dar es Salaam and thus will enhance human comfort as well as ensure environmental sustainability. However, little research have been carried out to observe influence of urbanization on urban winds over Dar es Salaam city and hence the purpose of the study.

1.6   Study area

The study focuses on Dar es Salaam, the commercial city of Tanzania, located between 6.36^{o}S and 7°S and between longitudes 33.33^{o}E and 39°E (Figure 1). It borders with Coast Region in the North, West and South while to the East, the Indian Ocean. The city has a population of 4,364,541 people with a growth rate of 5.6% and administratively divided into three municipalities namely Kinondoni, Temeke and Ilala (Census, 2012).
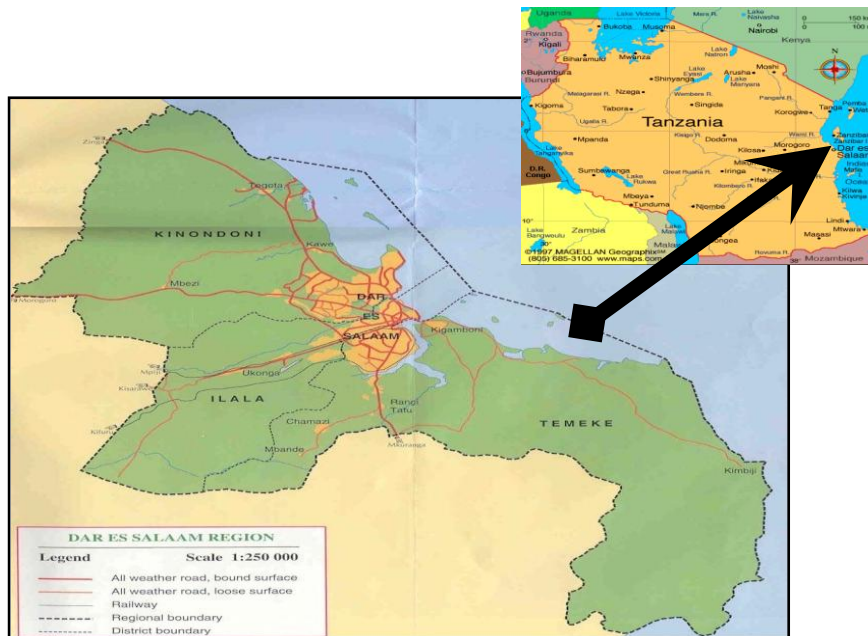

Figure 1: Map of Dar es Salaam

Dar es Salaam experiences a modified type of equatorial climate which is hot and humid throughout the year. The mean daily temperature is about 26° C, the mean seasonal range is about 4° C, and the mean daily range is about 8^oC. Generally, air temperatures vary from less than 22^oC to more than 30^oC and the mean humidity from 63% to 95%. The climate is also influenced by monsoons that have an influence on wind direction and strength, temperature and rainfall, among others. There are two monsoon seasons, namely the Northeast monsoon (Kaskazi) which prevails from November to February and is characterized by higher air temperatures (> 30°C) and weaker winds, and the Southeast monsoon (Kusi) which lasts from April to September and is marked by lower air temperature (approximately 25 °C) as well as stronger winds. Occasionally, the Southeast monsoons are associated with epidemic events such as storms and cyclones. The months of March/April and October/November are the inter-monsoon periods and usually are the calmest. June and July are the windiest months while March, April and November experience the lowest and most variable wind speeds (UNEP, 2001).

The wind speed in Dar es Salaam is lowest during the rainy season when the maximum speed is 3-5 m/s. The speed is greatest in the months of December/January and July/August during the first weeks of the monsoon, ranging from 5 to 8 m/s. (Nhnyete and Mahongo, 2007).

Furthermore the sea and land breezes vary with the seasons. During the northeast monsoon a sea breeze trend prevails most of the time, while in the southeast monsoon season the mainly from from the land. Only during the intermediate periods between the monsoons a diurnal reversal of sea and land breezes develops regularly (Nieuwolt, 1973).

CHAPTER TWO

2 Literature Review

The chapter reviews previous studies in the evidence of urbanization effects on the urban winds of the cities and adjacent locations. A comprehensive understanding of urban wind is important for many real-world applications such as understanding and modelling the dispersion of air pollutants or wind engineering practice for the design and construction of tall buildings.

2.1 Urbanization effects on wind

Modified surface heating and increased friction in urban areas lead to changes in the mean wind and turbulence. These changes are most observed within canyons and just above where the presence of sharp-edged buildings directly affects the airflow. The changed density and characteristics of the roughness elements cause the friction of the urban surface to vary as well as the vertical turbulent transport of heat, mass (*e.g.* moisture, CO_2) and momentum through increased mechanical and thermal mixing. The increased roughness and warmth of the city surface come together to make a normally less stable atmosphere and encourage stronger interaction between the near surface air and the rest of the UBL which results in an increase of the mixed layer.

The presence of tall buildings in urban areas provides surfaces for multiple reflection and absorption of sunlight thus increasing the heating efficiency. In addition tall buildings cause blocking of winds which may inhibit cooling by convection thus modifying patterns of airflow over the city (Daniele, 2010).

Saadatabadi &Bidokhti (2011) in their study on urbanization effect on local climate in Tehran Megapolis reveals that the interaction of mountain and country breeze circulations influence urban heating which may lead to further complication of the urban climate. Also the presence of early morning low level local winds under stable conditions reduce the temperature of the urban areas by mixing cold air near the surface with warm air above and ventilating the city.

The coastal areas are exposed to frequent sea breezes due to presence of ocean that may cause higher humidity for most of hours of the diurnal cycle. Rizwan et al (2009) in their study on an

investigation of urban heat island intensity as an indicator of urban heating observe that during daytime there is higher relative humidity in the urban but lower in the night.

Furthermore an increase in temperature in urbanized area is due to horizontal heat transport by the sea breeze; the sea breeze that has moved over the urbanized area for a long time accumulates heat within its layer and results in the highest temperature in the urban area.

2.2 Urbanization effects on temperature

During the daytime in absence of clouds, urban surfaces are warmed due to absorption of solar radiation which generates convective winds within the urban boundary layer resulting in atmospheric mixing that causes air temperature fluctuations to be minimum however surface temperature reaches extremely high levels (Renganathan, 2008). At night the atmospheric convection decreases due to absence of solar radiation which causes urban boundary layer to be stable. Stabilization leads to the formation of inversion layer which traps urban air near the surface and keeping surface air warm forming the night time warmer air temperatures within urban areas. Furthermore at night, surfaces lose heat by nocturnal radiation at low wind speed and cloudless sky which is blocked by the buildings in urban areas.

The height and spacing of buildings affect the amount of radiation received and emitted by urban infrastructure. In addition presence of buildings cause large amount of solar energy to be stored during the day but during the night lower rates of radiant cooling are observed. Furhermore the presence of higher buidings retard ground level wind speed as well as increases roughness that can affect urban heat island (Giannaros et al, 2012).

Reduced vegetation in urban areas reduces the natural cooling effect from shade and evapotranspiration. In addition presence of paved areas relative to soil and vegetation causes decreasing in rate of evaporation which result in more net radiation available for surface heating (Elsayed, 2012) .

The production of anthropogenic heat due to space heating, air conditioning, transportation, cooking and industrial processes increases urban air pollution which can reduce solar radiation during the day therefore promoting higher nocturnal temperatures due to absorption and re-emission of outgoing solar radiation at night (Shahmohamadi et al, 2010).

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CHAPTER THREE

3   Data and Methodology

This chapter includes data and methodology.

3.1   Data

Two types of datasets were used. These include meteorological datasets (winds and temperature) and urbanization indicator (population) as discussed in the following subsections.

3.1.1   Meteorological data

The data used in the study included maximum and minimum temperatures, wind speed and direction collected at Julius Nyerere international airport dating from 1981 to 2012.These datasets were sought from Tanzania Meteorological Agency. Three hourly wind data sourced from the National Centers for Environmnetal Prediction (NCEP) was utilized dating from 2004 to 2012.

Table 1: Location of station used in the study

Station Name	Latitude (S)	Longitude (E)	Elevation (m)
Julius Nyerere International Airport	06°52'	39°12′	53

3.1.2   Urbanization indicators

Population data was used as an urbanization indicator and was obtained from the Tanzania National Bureau of Statistics dating 2001 to 2011 for the population census results of 2002 and 2012 and population projections for years between the census years.

3.1.3   Data quality control

Data quality control involves homogeneity test.

3.1.3.1 Homogeneity Test

The quality of the estimated data will be examined using single mass curve. This will involve the plotting of the station rainfall totals against time. In this study single mass curve may be used to indicate data homogeneity for a station.

3.2   Methodology

Data analysis was conducted using standard statistical methods. These include time series, correlation and wind rose plots analysis

3.2.1   Time series Analysis

Time series analysis utilized graphical analysis to investigate the trend of meteorological parameters and urbanization indicator (population) over the area of study. This was be done by plotting maximum and minimum temperature, magnitudes of wind speed and direction and population against time for stations used.

3.2.2   Wind rose plots

Wind roses were used to identify and study changes in wind speed and direction. This was done by comparing the wind speeds of the past years with an equal number of current years. Wind class frequency distributions were similarly produced for the past and an equal number of recent years to study change in wind speeds.

Wind Rose Plot (WRPLOT) View was used. WRPLOT is a windows program that generates wind rose statistics and plots for user-specified date and time ranges (Lakes Environmental, 2000). The software has a frequency count that displays in tabular form the number of occurrences of winds in each of 16 direction sectors and 6 wind speed classes for a given location and time period. It also has a frequency distribution tab which gives a table displaying

the normalized frequency of occurrences of winds in each of 16 directions and 6 wind speed classes.

3.2.3   Correlation Analysis

Correlation analysis was used to find out the relationship between urbanization (population) and meteorological variables (temperature and winds). Pearson's correlation coefficient r is a statistical measure of the strength of a linear relationship between paired data.

In a sample it is denoted by r and is given by equation 1;

$$r_{xy} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..1$$

Where r_{xy} is the correlation coefficient, n is the size of the sample, x_i and y_i are parameters being correlated, are mean values of variables being correlated.

The test of significance of computed correlation values were done by using the student t test at 95% confidence level as shown in the formula below (equation 2);

$$t_{n-2} = r\sqrt{\frac{n-2}{1-r^2}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..2$$

Where t is the value of the student t- test, n is the number of observations and r is the correlation being tested.

CHAPTER FOUR

4 Results and Discussion

This chapter discusses results based on time series, correlation and wind roses analysis.

4.1 Data Quality control

The study noted that in all stations used, less than 10% of data were missing. Therefore, missing data were estimated using arithmetic mean method. Single mass curves were used to test for homogeneity of datasets used and results presented in Figures 2 to Figures 8.
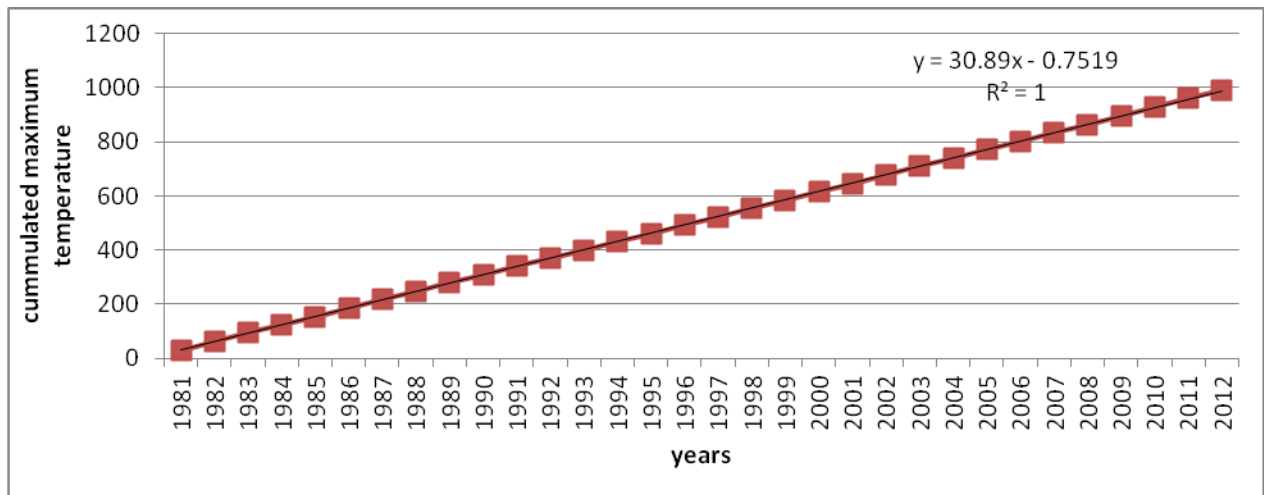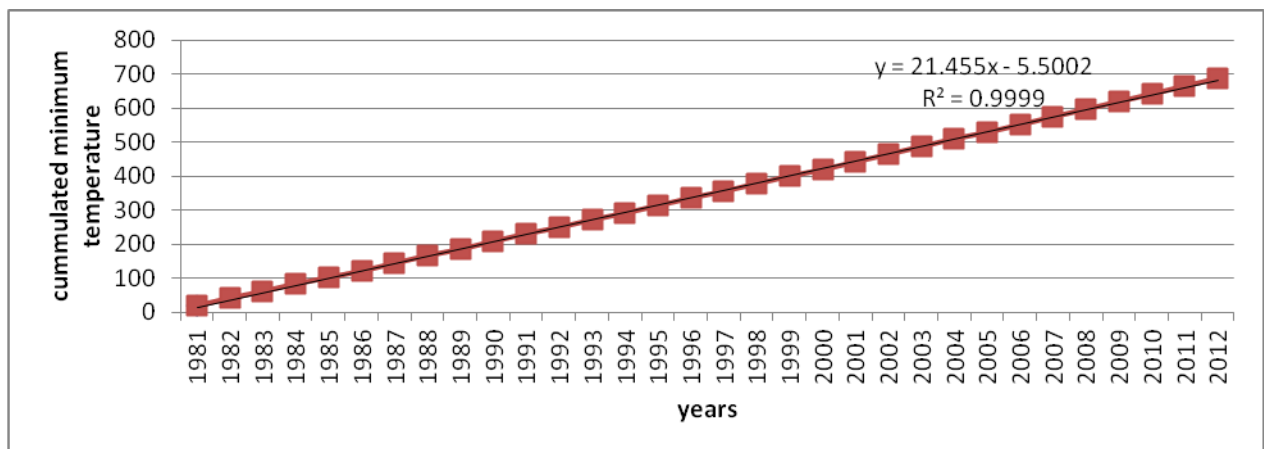

Figure 2: Single mass curve for maximum temperature over Dar es Salaam (1981-2012).

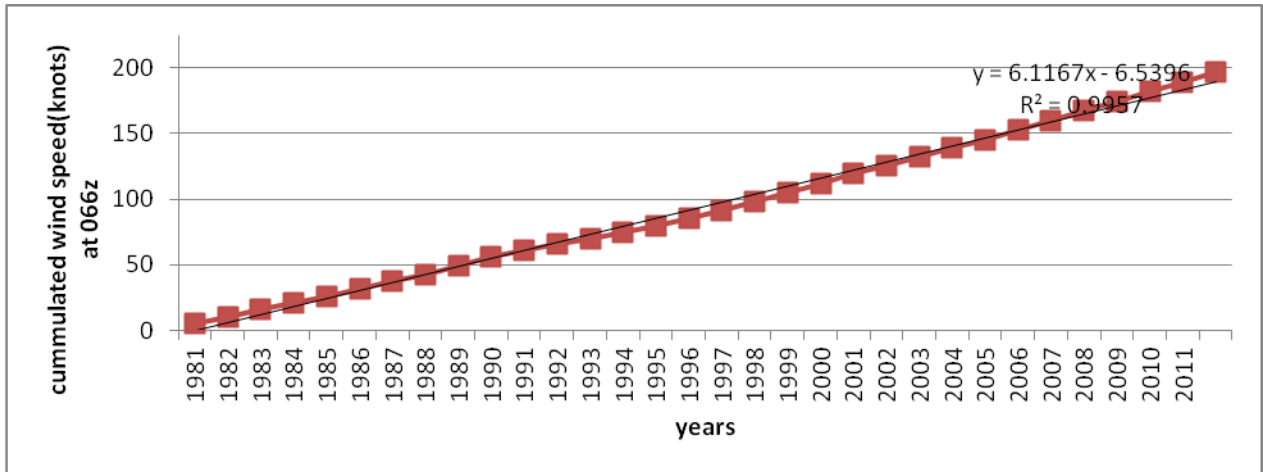Figure 3: single mass curve for minimum temperature over Dar es Salaam (1981-2012).

Figure 4: single mass curve for wind speed at 0600Z over Dar es Salaam (1981-2012).
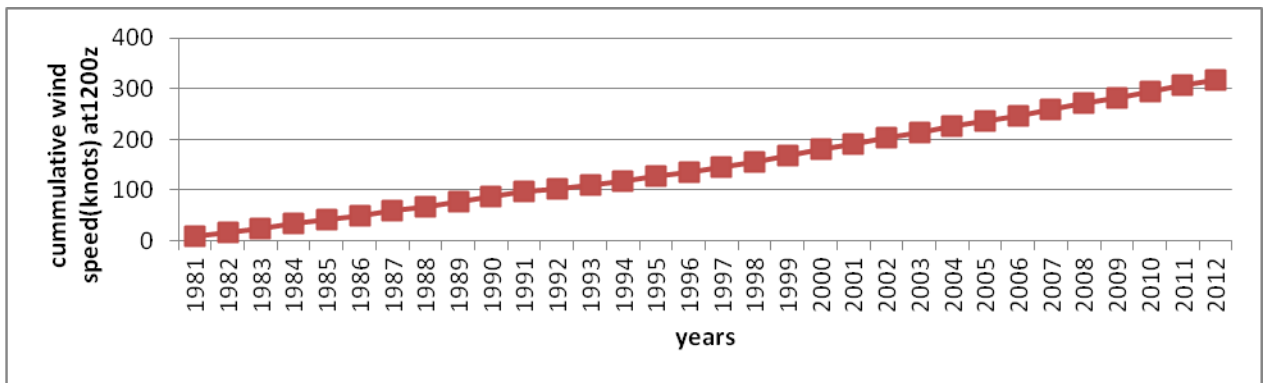

Figure 5: single mass curve for wind speed at 1200Z over Dar es Salaam (1981-2012).
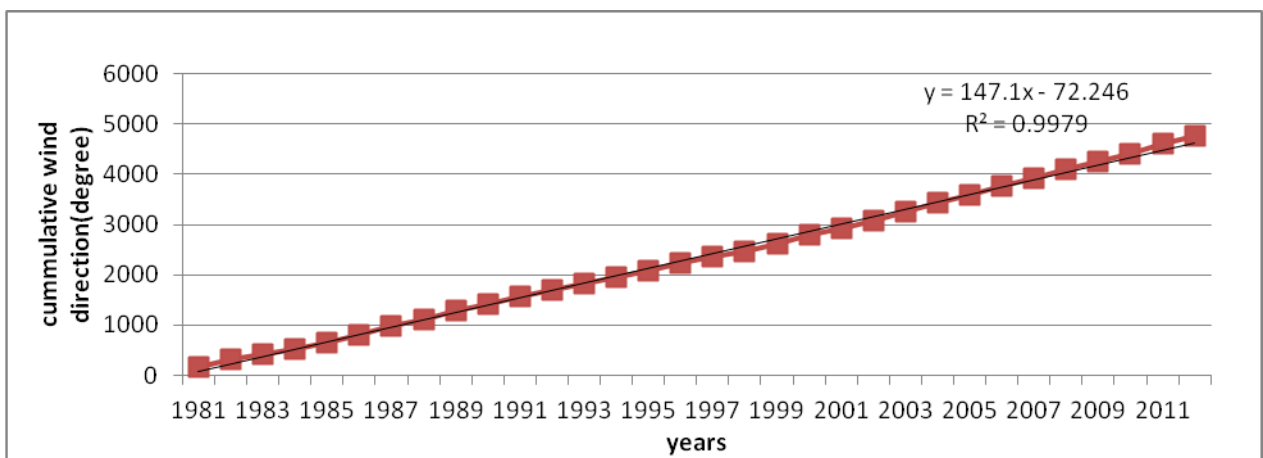

Figure 6: single mass curve for wind direction at 0600Z over Dar es Salaam (1981-2012).
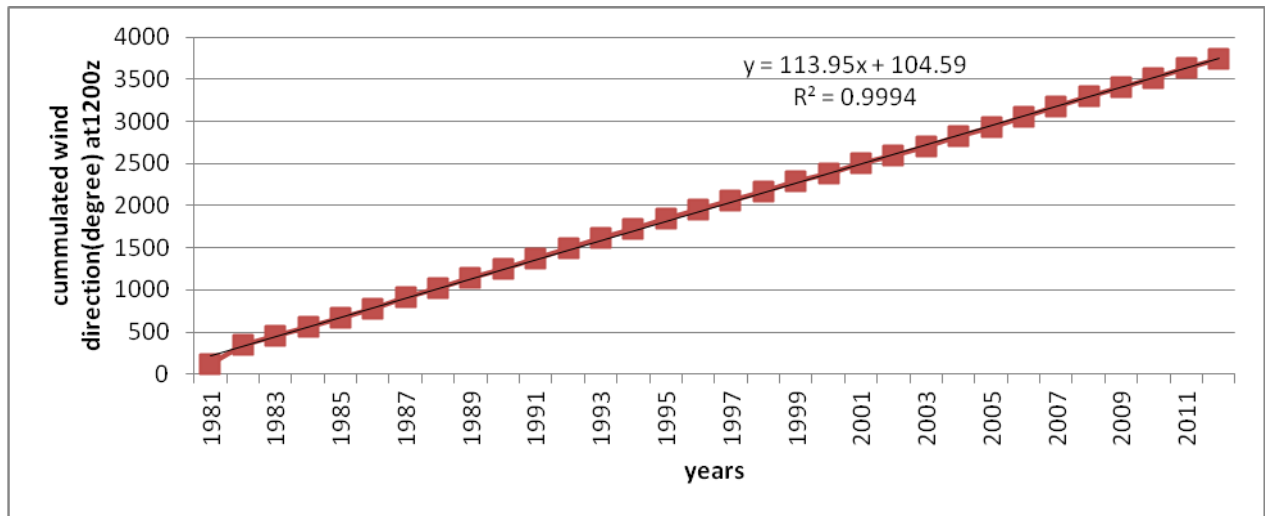
Figure 7: Single mass curve of wind direction at 1200Z over Dar es Salaam (1981-2012).
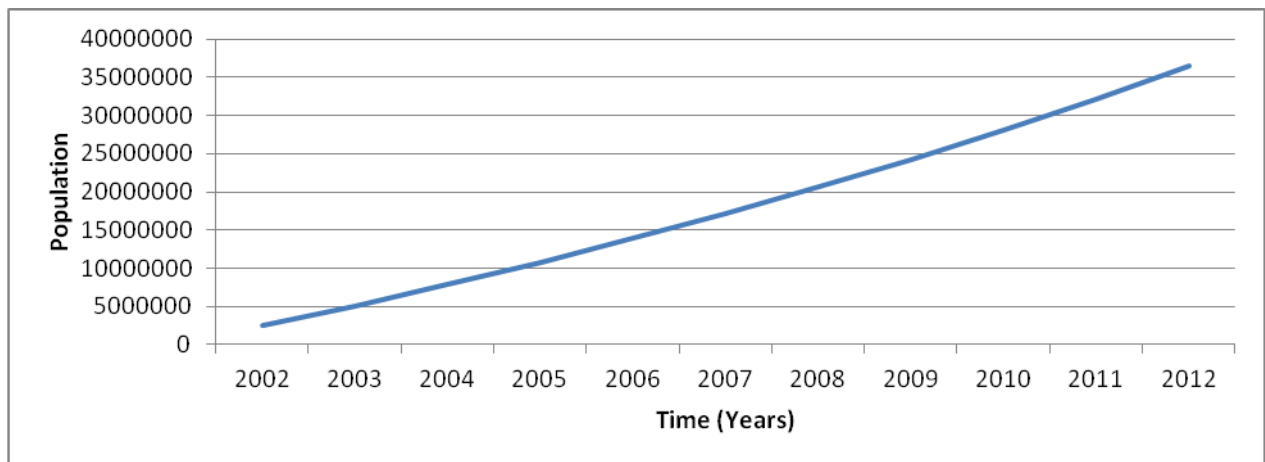

Figure 8: Single mass curve of population over Dar es Salaam region (2002-2012).

The graph of cumulated population, winds and temperature indicated a homogeneous dataset with coefficient of correlation (R^2) approximately equal to 1. These implied that the datasets available was good for further analysis.

4.2   Temporal Variability of Population, Temperature and Winds over Dar es Salaam

Graphical analysis was used to investigate the space time characteristic of population, temperature and magnitudes of winds over Dar es saalam. The results are presented in the following sub sections.

3.2.1 Population

Population was increasing at the rate of 5.6% over Dar es Salaam from 2.5 million in 2002 to 4.4 million in 2012 as shown in Figure 9. This accounted for 10% of the total Tanzania Mainland population(Census,2012).
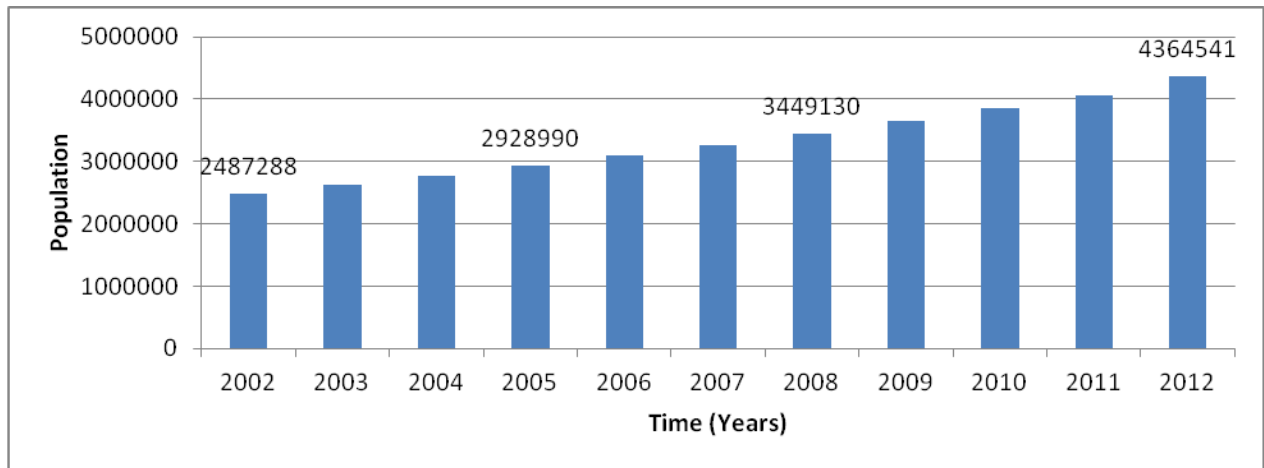

Figure 9: Time series of population over Dar es Salaam (2002-2012).

4.2.2   Wind speed and Direction

The temporal variation of Wind Speed and Direction over Dar es Salaam city is presented in Figures 10-13.
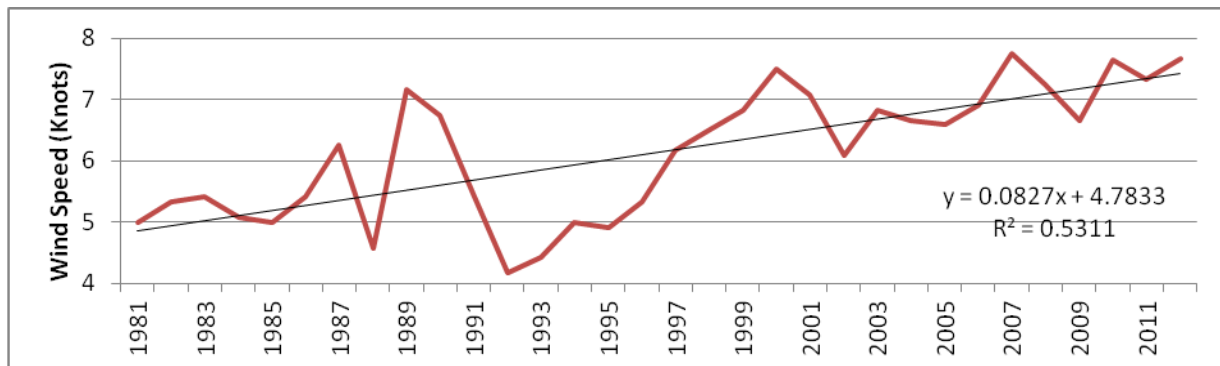

Figure 10: Time series of Wind Speed at 0600Z over Dar es Salaam (1981-2012)**.**

Figure 11: Time series of Wind Speed at 1200Z over Dar es Salaam (1981-2012)**.**
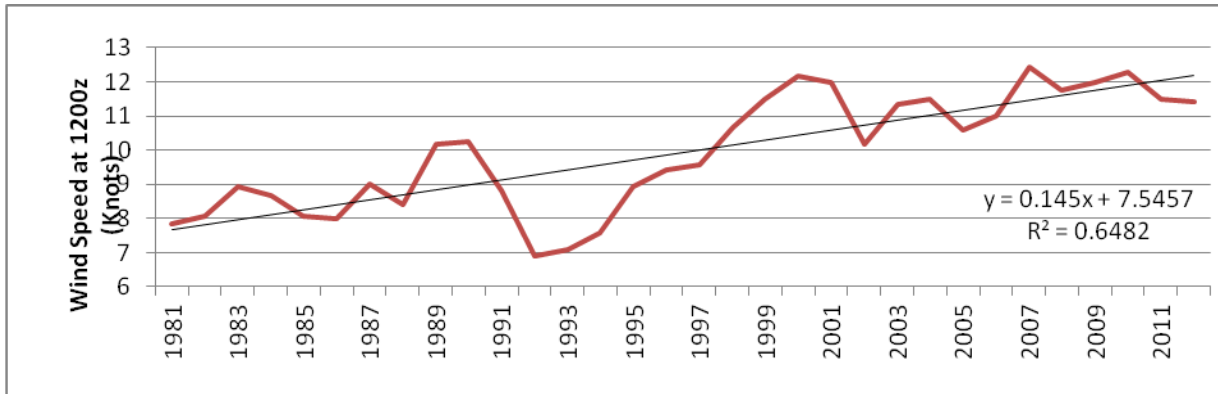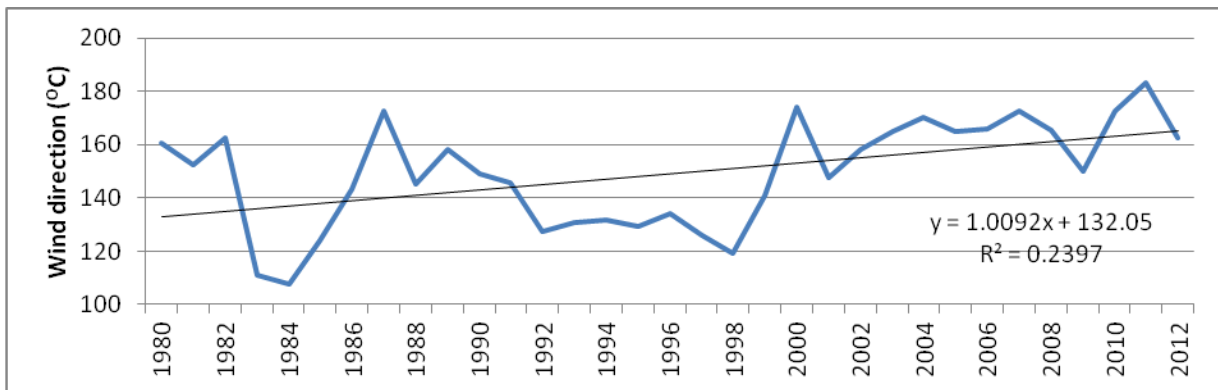

Figure 12: Time series of Wind direction at 0600z over Dar es Salaam (1981-2012)**.**
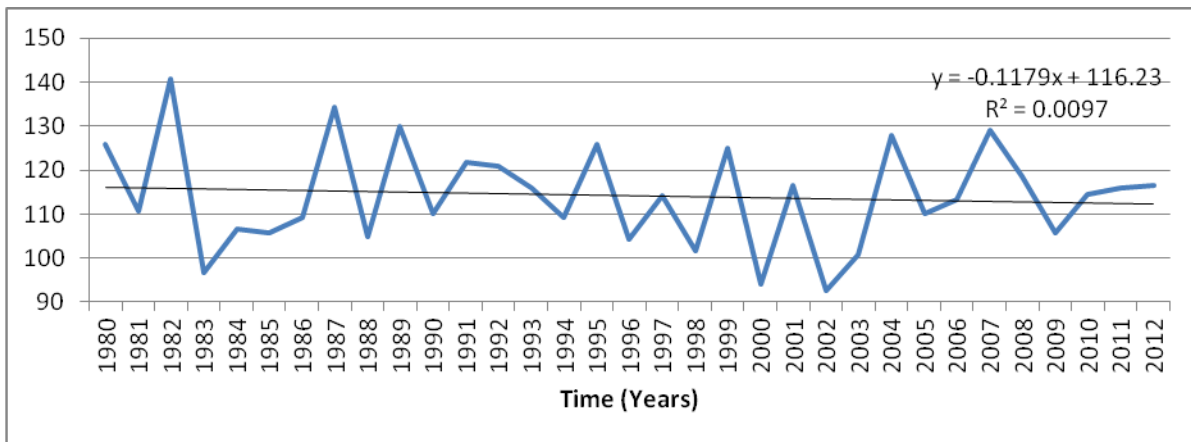

Figure 13: Time series of Wind direction at 1200z over Dar es Salaam (1981-2012)**.**

Trend analysis of wind speeds showed significant increases at both 0600 and 1200 over Dar es Salaam evidenced by the high coefficient of determination of 53.1% and 64.8% at 0600 and

1200UTC respectively. Wind direction showed significant change in trend at 0600 noted by a 23.9% coefficient of determination. However, the decreasing trend at 1200 was noted to be less significant as the coefficient of determination was approximated at 0.9%.

4.2.3 Maximum and Minimum Temperature

The figure 14 and figure 15 shows time series analysis of temperature over Dar es Salaam.
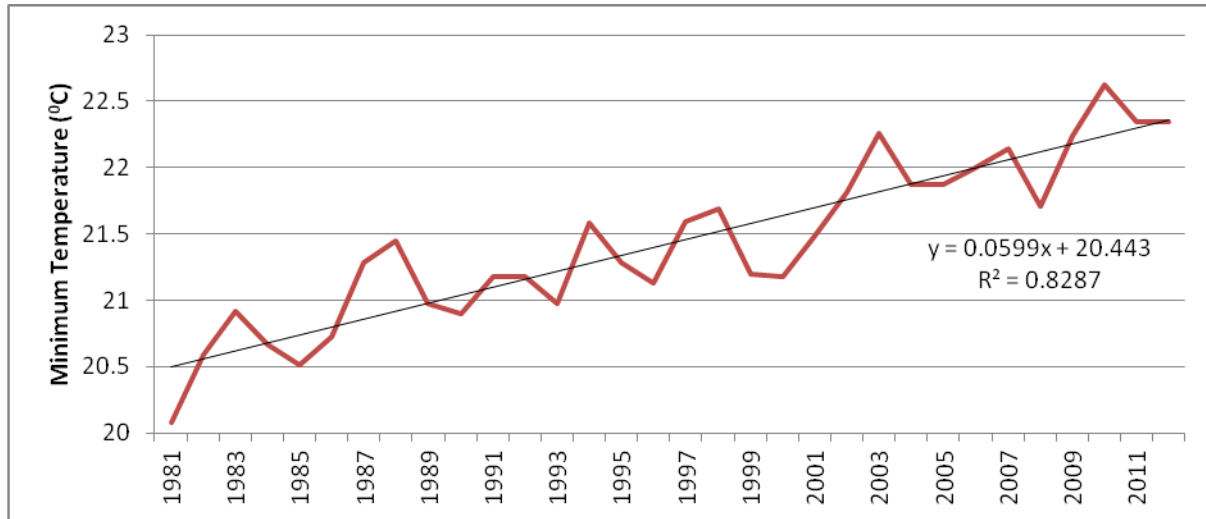

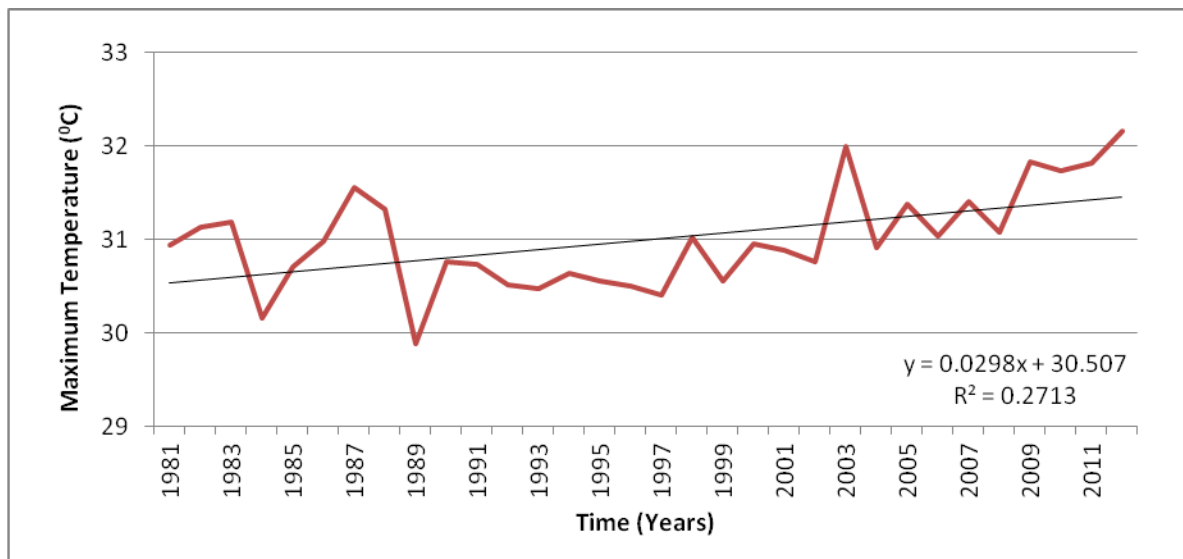Figure 14: Time series of minimum temperature over Dar es Salaam (1981-2012).

Figure 15: Time series of Maximum temperature over Dar es Salaam (1981-2012).

Minimum temperature showed the most significant increase in trend with coefficient of determination at 82.8% while maximum temperature had a coefficient of determination of 27.1%.

4.3 Effects of Urbanization on temperature and winds

The effects of urbanization on temperature and winds were investigated using correlation and wind roses analysis.

4.3.1 Correlation Analysis

The effects of urbanization on temperature and winds were investigated through correlation analysis. The results are presented in Table 2 below;

Table 2: Correlation Analysis between population and meteorological variables

Variable	Pearson correlation Coefficient, *r*	Student t test	
		t computed	t tabulated
Tmax/ Population	0.64	2.506	2.262
Tmin/ Population	0.63	2.430	2.262
WS-06/ Population	0.74	3.272	2.262
WS-12/ Population	0.53	1.852	2.262

Tmax and Tmin represent maximum temperature and minimum temperature respectively.

WS-06 and WS-12 represent wind speeds at 0600Z and 1200Z respectively.

Correlation analysis showed that wind speed at 0600 and 1200 and maximum and minimum temperature were highly correlated with population with values above 0.5. A test of significance using student t test showed that correlation between wind speeds at 0600, maximum temperature

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and minimum were significant with the t computed greater than the t tabulated. These results implied that changes in urbanization indicated by changes in population would result to significant changes in wind speeds at 0600UTC and both maximum and minimum temperature over Dar es Salaam.

4.3.2   Wind rose analysis

The 3-hour wind speed and direction data measured at a height of 10 m is shown in the wind rose plot for the past years with an equal number of current years are shown in Figure 16. Wind class frequency distributions were similarly produced as shown in figure 17 for the past and an equal number of recent years to study change in wind speeds.
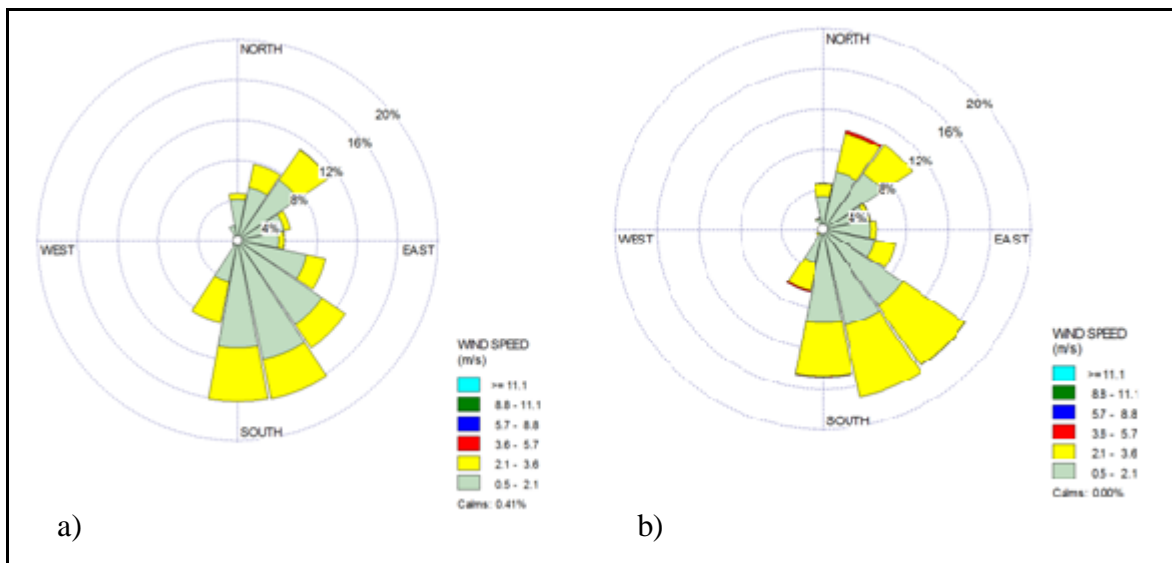

Figure 16: Dar es Salaam City wind roses for (a) 2005 -2006 and (b) 2010 -2011
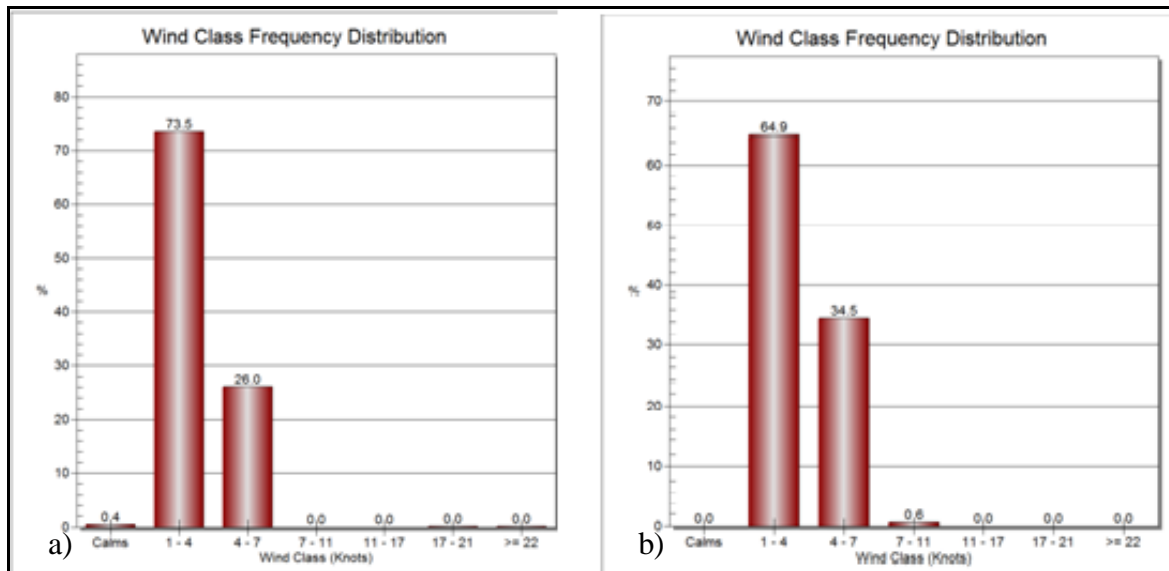
Figure 17: Dar es Salaam City wind class frequency distribution for (a) 2005 – 2006 and (b) 2010 –2011.

The predominant winds over Dar es Salaam are generally Easterlies and thus transport and dispersion of pollutants from the city are mainly to westward (Figure 16a and 16b). However, the direction of dominant wind speeds was noted to have slightly changed comparing the past years (2005 -2007) and the current years (2010 - 2011).

Over the Dar es Salaam city , the wind speed class of highest frequency in the past years of 2005 to 2006 was 1-4 knots at 73.5 per cent followed by 4 -7 knots at 26.0 per cent while calm winds were approximated at 0.4 per cent (Figure 17 a).

In the recent years; 2010 to 2011, the predominant wind speed class was 1 -4 knots at 64.9 percent followed by 4 -7 knots at 34.5 per cent while 7 -11 wind class frequency had a 0.6 percent (Figure 17 b). There was a notable increase in wind speeds when comparing the wind speeds of the past years and wind speeds of the recent years with the highest frequency of wind speeds changing from wind class of 4 -7 knots in the past years to 7 -11 knots in the recent years which probably could be attributable to horizontal thermal gradients of the urban heat island between rural and urban environments.

On the contrary, Ongoma et al. (2013) noted decreasing wind speeds over the urban centers in Kenya as owing to the increased roughness and frictional drag. These differences could be

explained in terms of data used for windrose analysis which spanned a period of two years only and the fact that wind speed and direction were measured at 10 m which are usually higher than winds at ground level due to less effects of surface roughness or turbulence effects.

Chapter Five

5   Summary, Conclusions and Recommendations

This chapter provides the summary, conclusions and recommendation of the study.

5.1   Summary and conclusion

The study investigated changes in wind flow and temperature over Dar es Salaam city due to urbanization. Data quality control indicated that all the datasets used were homogeneous and thus consistent and valid for further analysis.

The graph of cumulated population, winds and temperature indicated a homogeneous dataset with coefficient of correlation (R^2) approximately equal to 1. Trend analysis of wind speeds showed significant increases at both 0600 and 1200 over Dar es Salaam evidenced by the high coefficient of determination of 53.1% and 64.8% at 0600 and 1200UTC respectively. Wind direction showed significant change in trend at 0600 noted by a 23.9% coefficient of determination. However, the decreasing trend at 1200 was noted to be less significant as the coefficient of determination was approximated at 0.9%. Minimum temperature showed the most significant increase in trend with coefficient of determination at 82.8% while maximum temperature had a coefficient of determination of 27.1%.

Correlation analysis showed that wind speed at 0600 and 1200 and maximum and minimum temperature were highly correlated with population with values above 0.5. A test of significance using student t test showed that correlation between wind speeds at 0600, maximum temperature and minimum were significant with the t computed greater than the t tabulated.

The predominant winds over Dar es Salaam are generally Easterlies and thus transport and dispersion of pollutants from the city are mainly to westward. Over the Dar es Salaam city , the wind speed class of highest frequency in the past years of 2005 to 2006 was 1-4 knots at 73.5 per cent followed by 4 -7 knots at 26.0 per cent while calm winds were approximated at 0.4 per cent. In the recent years; 2010 to 2011, the predominant wind speed class was 1 -4 knots at 64.9 percent followed by 4 -7 knots at 34.5 per cent while 7 -11 wind class frequency had a 0.6 percent. There was a notable increase in wind speeds when comparing the wind speeds of

the past years and wind speeds of the recent years with the highest frequency of wind speeds changing from wind class of 4 -7 knots in the past years to 7 -11 knots in the recent years which probably could be attributable to horizontal thermal gradients of the urban heat island between rural and urban environments.

5.2   Recommendations

Results from the present study indicated that Dar es Salaam city is becoming more urbanized. Obeserved urbanization is accompanied with modification in wind speed and direction which necessitates land use planning and risk reduction strategies to the ever increasing population through formulation of relevant policies to promote sustainable development and urban planning.

Following the observed modification on urban winds by urbanization, the environmental effect of such modification on human comfort is thus inevitable. This information is therefore of value to building designers, city dwellers, event organizers, health practitioners, city planners among others to enhance safe stay and environmental sustainability. The awareness created by climate modification calls for environmentally conscious land use planning and risk reduction strategies. Planners should also factor wind in the allocation of different economic activities to minimize pollution.

The study also recommends that the Dar es Salaam's industries and factories should be located to the western parts of the city to minimize the exposure of city residents to the pollutants.

Further studies should consider more urbanization indicators such as land surface reflectivity, roughness length and albedo from high resolution satellites in order to investigate detailed effects of urbanization effects on winds over Dar es Salaam region.

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