INFLUENCE OF OZONE IN THE TROPICAL TROPOPAUSE LAYER ON THE INDIAN OCEAN SURFACE TEMPERATURES

BY

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I56/68909/2013

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NAIROBI, KENYA.

A *DISSERTATION* SUBMITTED IN PARTIAL *FULFILLMENT* OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN METEOROLOGY

JULY, 2018

DECLARATION

I certify that this dissertation is my original work and has not been presented for a degree in any other university.

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DEDICATION

I dedicate this study to my Mother and late father, who inculcated in me a philosophy of reading, learning and being the best that I can be, thank you;

And my daughter Nicole, this one is for you. Work hard, at no time should you stop visualizing and trusting.

ACKNOWLEDGEMENT

I thank God the Almighty, for through Him, all things are possible. I devote this certificate to the following people who have marched with me in one way or another through this journey:

- My wife and Children who have been there for me and have tolerated and accommodated my unavailability, while I pursued completion of this course. Your strength and unwavering support inspire me.
- UON, Department of Meteorology, academic staff and non-academic staff, you were wonderful people to work with.
- My dearest *Msc* Meteorology classmates who continue to inspire me to even greater achievements, personally and professionally.
- My colleagues at KMD for affording me the time and space to conduct this research.

I am immeasurably appreciative for the leadership, direction and patience shown by my supervisors; Muthama, Ininda and Opijah, you were truly professional, fatherly and brotherly. You even went out of your busy schedules to look for me whenever I went off my study course.

God bless.

ABSTRACT

This study sought to investigate the distribution of ozone and temperature within the tropical tropopause layer and the linkages of ozone variability at the Chemopause level to sea surface temperature in Indian Ocean using ozonesonde data. The ozonesonde data sets were acquired from World Ozone and Ultra Violet radiation Data Center, Montreal, Canada and Southern Hemisphere Additional Data Ozonesonde while sea surface temperature (SST) data was obtained from the Hadley Centre hosted at United Kingdom Meteorological Office. Calculation of monthly and seasonal arithmetic mean, Potential temperature gradient, correlation, regression and multiplicative shift methods were used to realize the objectives of the study.

Mean monthly and seasonal ambient air temperature, potential temperature gradient change with geopotential height, and vertical ozone mixing ratios were computed over Watukosek, Nairobi, Sepang and Malindi. Gridded SST data were extracted from three Indian Ocean regions namely; 60°E-70°E, 3°N-20°N; 55°E-60°E°, 33°S-26°S and 30°E-60°0E, 44°-40°S which were considered relevant for the forecast of seasonal rainfall over Kenya. The data sets were subjected to correlation and regression to establish relationship between Ozone and ambient temperature at chemopause level. The result was then subjected to a statistical significance test at 95% confidence level with two degrees of freedom using student t_test statistic. The main convective out flow leve for Watukosek, Nairobi, Sepang and Malindi was found to be at 13.6, 13.4, 14.0 and 13.7 km, respectively, above sea level. Cold point temperature tropopause was 16.6km for Watukosek, 17.2km for Nairobi, 18.2km for Sepang and 16.8 km for Malindi. The seasonal variability of ozone was found to be compact in the troposphere and slight variability in the tropopause layer. There were marked fluctuations of ozone in the stratosphere. The months of December, January and February had the lowest ozone mixing ratios in the troposphere while June, July and August exhibited the highest ozone mixing ratios over Nairobi and Sepang.

It may be concluded that there is strong influence of SSTs at locations 60°E-70°E, 3°N-20°N, 55°E-60°E°, 33°S-26°S and 30°E-60°0E, 44°-40°S in Indian ocean to Nairobi equatorial continental ozone mixing ratios variability at 14.9km. Therefore, O_3 mixing ratios

may be used to predict seasonal weather/climate with a lead time of four months instead of SSTs over Kenya.

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ACRONYMS

AO: Arctic oscillations

BDC: Brewer Dobson circulation

Br: Bromine

BrO: Bromine Oxide

CCM: Chemistry Climate Models

CFCs: Chlorofluorocarbons

Cl: Chlorine

CLaMS: Chemical lagrangian model for Stratoshere

ClO: Chlorine Oxide

CO: Carbon Monoxide

CPT: Cold Point Temperature

CPTT: Cold Point Temperature Tropopause

CRED: Center for Research on the Epidiomology of Disasters

DU: Dobson Unity

ECC: Electrochemical Concentration Cell

ECMWF: European Centre for medium weather Forecasts

EOF: Eigen Orthogonal Functions

EP: Eliassen-Palm

FZ; Flux vector

GAW: Global Atmosphere Watch

GHG: Greenhouse gases

GSFC: Goddard Space Flight center

IOD: Indian Ocean Dipole

ITCZ: Intertropical Convergence Zone

JJA:	June, July and August
KMD:	Kenya Meteorological Department
LMS:	Level of Minimum Stability
LNB:	level of neutral buoyancy
MAM:	March, April and May
NAM:	Northern Annular Mode
NH:	Northern Hemisphire
NOx:	Nitrogen Oxide
O_3:	Ozone
OND:	October, November and December
PBL:	Planetary Boundary layer
QBO:	Quasi biennual Oscillations
SCO:	Stratospheric Column Ozone
SH:	Southern Hemisphere
SHADOZ:	Southern Hemisphere Additional Data Ozosondes
SLP:	Sea Level Pressure
SST:	Sea Surface Temperature
STE:	Stratosphere-troposhere Exchange
TCO:	Tropical Column Ozone
TEM:	Transformed Eurelian Mean
TOMS:	Total Ozone Mapping Spectrophotometer
TTL:	Tropical Tropopause Layer,
UON:	University of Nairobi
UT-Ls;	Upper trosphere-Lower Stratosphere
UV:	Ultraviolet

VSL	Very Short Lived
WMO:	World Meteorological Organisation
WOUDC:	World Ozone and Ultra Violet Radiation Data Centre

CHAPTER ONE

1.0 Introduction

This chapter provides a brief description on the study background, the objectives, the problem statement, significance and hypothesis of the study.

1.1 Background

Extreme climate and weather associated events have been the foremost cause of natural adversities over Kenya, in recent years. The country has witnessed repeated episodes of both excessive rainfall (floods) and deficient rainfall (drought). As earth surface temperatures continue to raise, the occurrence and intensity of rainfall is also predicted to change through variations in ozone, surface temperature in lowest atmospheric layers, together with water holding ability, (WMO, 2010). This is anticipated to alter the water cycle, with fluctuating impacts on ecosystem services and food security in Kenya, which is much reliant on rain fed agricultural activities.

Kenya Meteorological Department, KMD issues seasonal weather and climate forecasts limited to 3 months with uncertainty due to two factors namely, observational and scientific. Limited understanding of both the efficiency of deep convective transport, the rates of transport of minor gases e.g. Ozone, O_3 and water vapour through the tropical tropopause layer, TTL, boundary layer in the middle atmosphere and linkages of O_3 at chemopause (change of gradient of O_3), to Indian Ocean sea surface temperature (SSTs) contributes to our inability to forecast weather and predict climate beyond three months over Kenya and the East African region.

Earlier findings by Liu (2007), Bergman *et al* (2012) and Pan *et al* (2014), showed that most of tropospheric air that enter the stratosphere originates from deep convection that occurs in the tropics and detrains in the lower elevation portion of the TTL, an area separating troposphere and stratosphere. The photochemical budget of O_3 in the TTL is determined by the strength of inputs of chemical precursors from convection and lightning. Within the TTL, photochemical reactions and competing physical processes are important for chemical species whose lifetime is comparable to about 2 months that it takes for slow ascent to traverse the TTL. Fujiwara *et al.*, (2009) argues that in-mixing of air from subtropics will increase the age of the air in the TTL and could reduce the input of halogens to the stratosphere. Such in-mixing can also reduce the relative humidity and cloud formation in the TTL.

Understanding the distribution of O_3 and ambient temperature at the levels of deep convective discharge and cold point temperature tropopause and possible linkages of ozone in the middle atmosphere to SSTs in some selected regions in the Indian Ocean is important for understanding lead time evolution of SSTs and improving the length of seasonal forecasts in Kenya from the current three months to four or more. The fact that the overall transport of both aerial emissions from the boundary-layer to the stratosphere involves prompt transport by deep convection from the ground to the lower boundary of the TTL (time measures of minutes to hours), followed by slow ascent through the TTL (time scales of months) helps to emphasize the need to investigate linkages between O_3 and SSTs at the chemopause level.

Pan *et al.*, (2014), suggested that the dynamics on a huge array of space and time scales, from single convective air trails to global-scale motions play a major role in maintaining the thermal inconsistency in the TTL. Nonetheless, the influence of convective heat transfer to the chemistry of the upper troposphere is a high priority investigation area because of potential impacts of ozone on chemistry/climate coupling e.g., (Shepherd, 2008). Therefore, documenting and understanding the characteristics of Ozone mixing ratios and ambient temperature within the tropopause layer and the relationship between ozone mixing ratios and SSTs in selected regions in the Indian Ocean will assist to solve our current limitation of seasonal weather/climate forecast.

In this investigation, ozone is used as a stratospheric minor, (trace). Folkin *et al.,*, (2002) and Kley *et al.,*, (1996, 2007) found that the vertical contour of ozone minor is a suitable pointer to convection, thermally induced vertical mixing, in the tropics.

The use of SSTs as a predictor of seasonal climate has been a norm world over today, more so in East Africa, particularly in Kenya (Ininda 1989, Muthama *et al.,*, 2000 Indeje *et al.,* 2000, Kijazi and Reasons 2009). In addition, SSTs have been used to investigate the relationship between vertical ozone characteristic and SSTs, as in (Shepherd 2008). In this study, Indian Ocean SSTs at three selected regions forms the basis of investigating the relationship between vertical ozone and temperature at convective outflow in deep convective clouds at UT/LS.

1.2 Statement of the problem

Meteorological related events remain the leading causes of natural tragedies in Kenya. Since 1964 to 2015 a total of 101 disasters including droughts, floods and related epidemics have been recorded affecting a total, cumulatively, of 58.66 million people in Kenya (CRED, 2016). Changes in O_3 and tropospheric temperature are also predicted to modify the water cycle, with fluctuating impacts on ecosystem services and food security in the Country, which is much dependent on rain fed agricultural activities. Therefore, there is need in Kenya for continued study and documentation of better ways of improving weather forecast/climate prediction. Kenya Meteorological Department, KMD, which is charged with the responsibility of issuing now casting, daily, short and medium term and seasonal weather/climate forecasts and prediction, is limited to three months seasonal forecasts.

There has been limited research on the dynamics of boundary layer air into tropical tropopause layer both in terms of the height distribution of convective detrainment in the TTL and in terms of dilution of convective cores by entrainment throughout the free troposphere. South easterly and north easterly monsoon meeting zones have convective tops that rarely exceed 13.5 km, while a significant percentage of intertropical convergence zone, ITCZ convection about 3% reaches the tropopause. Entrainment of free tropospheric air into deep convection updrafts is important, particularly for the relatively small convective cores that occur in the tropical maritime regions. Thus, the mixture of air deposited in the TTL at the tops of convection will be a combination of upper troposphere and lower stratosphere composition and free tropospheric composition.

The characteristics and fluctuations of ozone (O_3) are fundamental to the atmospheric temperature variations, and it is at the upper troposphere lower stratosphere that O_3 distresses can apply their utmost influence on climate, (Thuburn and Craig, 2002). However, the variation of vertical O_3 and temperature at the deep convective outflow and cold point tropopause in Kenya whose weather/climate is also affected by the migration of ITCZ and SSTs has not been fully investigated. Previous studies looked at rainfall variability at seasonal, annual and decadal scales, but little work has been done on deep convective outflow. Therefore, the need to examine and document the variation of temperature and O_3 at the tropopause layer and the relationship of O_3 at the chemopause to SSTs over the Indian Ocean is overarching. Understanding the relationship concerning the variability of O_3 partial pressures in the tropical UT/LS and SSTs in the Indian Ocean will help to enhance the accuracy of weather forecasting and prediction but also the lead time evolution of SSTs as well as expected future climate changes in the Country. This will help enhance preparedness to mitigate climate induced hazards.

1.3 Main Objective

This was to investigate the behaviour of ozone in the tropical tropopause layer and its influence on the Indian Ocean surface temperatures using ozonesonde.

To help achieve this main objective, the following specific objectives guided the study:

1. To determine the tropopause, chemopause levels and deep convective outflow over Nairobi, Malindi, Sepang and Watukosek,
2. To characterize vertical temperature and Ozone structure over Nairobi, Malindi, Sepang and Watukosek ,
3. To evaluate the relationship between ozone mixing ratios and temperature in the lower stratosphere and upper troposphere
4. To examine the relationship between the variability of ozone concentration at the chemopause and Indian Ocean surface temperature.

1.3.1 Research questions

The following specific research questions were answered by this study,

1. What are the levels of Chemopause, cold point tropopause and deep convective outflow over Nairobi, Malindi, Sepang and Watukosek?
2. How coherent are variations in the ozone mixing ratios and ambient air temperature over Nairobi, Malindi, Sepang and Watukosek?
3. What is the relationship between O_3, and temperature in the lower middle atmosphere?
4. To what extent does the Indian Ocean SSTs variation affect ozone at the chemopause over Nairobi and Malindi?

1.4 Significance of the Study

The TTL is particularly important because it is the primary gateway to stratosphere (Fueglistaler *et al.*,, 2009). It is also at the upper troposphere and lower stratosphere that O_3 distresses utmost effect on climate. The significance of vertical and latitudinal distributions of temperature fluctuations commencing at the surface of the earth to the middle atmosphere as a basis of climate change detection and attribution has been appreciated (Thomson and Solomon, 2005 and Fu *et al.*, 2004). Understanding of the dynamics of vertical ozone and temperature at the tropical tropopause layer is necessary not only for the development of support programs for long term measurements over the region but also for the future monitoring of lead time evolution of sea surface temperature (SST) in the Indian Ocean. This will enhance KMD's current ability of seasonal weather/climate forecasting of three months lead time to more time in Kenya as well as regional references for atmospheric chemistry. It is hoped that the study will be useful to atmospheric scientists and modelers in trying to understand the variations, relationships and forcing of vertical ozone and temperature and possible linkages of ozone at the chemopause to sea surface temperature over the Indian Ocean.

The findings and recommendations of the study should also be useful to scientists and policy makers since the tropical differences of O_3 in the atmosphere is of vital significance for the radiative balance of the Earth-Atmosphere system and aid in discovering long-term trends of major significance.

The researcher hopes that the study will form a basis for further investigations on the atmospheric forcing over Kenya and East Africa to enhance the accuracy of weather/climate forecasting. The economy of the region is mainly dependent on agriculture and agro based industries which heavily rely on the amount and distribution of weather and climate. Improved accuracy will go a long way in helping planners, managers and policy makers of various sectors of the economy sensitive to weather and climate such as electricity production, transportation, tourism, forest resource management, and wildlife management plan better and formulate better policies to help in mitigation of climatic hazards.

CHAPTER TWO

2.0 Literature Review

In this chapter, the existing scientific research on how O_3 distribution in deep convective outflow at UT/LS in the ITCZ is affected by the Indian Ocean SSTs was examined.

2.0.1 Local research

Seasonal rainfall forecasting in Kenya is still limited to three months period besides being one of the most challenging problems. Understanding the linkages between ozone and temperature in deep convective outflow, cold point temperature tropopause and linkages of O_3 at the chemopause to the Indian Ocean SSTs will increase the lead time evolution of SSTs. This will enhance our current ability to forecast seasonal rainfall from three months to four months and beyond.

Though a number of scientific literature exist on the role played by O_3 and temperature on climate prediction, very little is still known in terms of the importance of ozone and temperature relation in climate prediction in the tropics and especially in Kenya and Africa. In Eastern Africa, Ayoma *et al.,* (2004) investigated the O_3 profile over, Nairobi, Cairo and Johannesburg based on vertical Ozone distribution measurements for the period 1998 to 2003. From their findings for Nairobi, it was established that minimum ozone values were at a height of 16 kilometres and maximum ozone values were at a level of 26 kilometres above mean sea level (ASL). They further found out that total maximum ozone mixing ratios occurred in September while total minimum values occurred in the month of April. In addition, monthly vertical ozone variations in each atmospheric layer indicated highest fluctuations in the TTL while the stratospheric ozone is comparatively the same throughout the year. This underscores the findings of (WMO 1989 and Muthama 1989).

Fioletov *et al.,* (2002) validated instu (ground based) and satellite measurements, 1964 to 2000 and established that the total column ozone data in the tropics and equatorial regions and that of Ozonesonde profile from southern hemisphere agree within 2 to 3%. Therefore, there is confidence using the ozonesonde data obtained from shadoz.

Muthama *et al.,*, (2000) using spearman's correlation method to analyze the relationship between total column Ozone and SSTs over western Indian Ocean found some significant relationship between ozone and SSTs. None of these studies have considered the relationship between vertical ozone and temperature at deep convective outflow and linkages of O_3 at the chemopause to SSTs in Indian Ocean.

In the recent few decades scientists have discovered the existence of a region separating UT/LS. Folkins *et al.,*, (2000) and Pan *et al.,*, (2014) suggested that this region may also be termed as a frontal transition area. They stated that this region was not adequately understood since it exhibits properties of both US and LS. They also observed that in the region latitudes 10° south and north of the equator, this transition layer extends vertically several kilometers. The available research works define this frontal area as the tropical tropopause layer, TTL. This frontal changeover area separating the troposphere and stratosphere is of great importance since it's the border between two different dynamical regimes of convective troposphere and radiative stratosphere besides acting as gateway into the stratosphere for minor gases in the atmosphere, i.e. water vapor and very short lived (VSL) substances. These tracer substances play a significant role in middle atmosphere interactions.

2.1 Intertropical convergence Zone

The weather and climate of Kenya are driven by the ITCZ, SSTs, atmospheric waves and topography. A study by Folkins *et al.,* (2002) on the genesis of temperature changes with height in the middle atmosphere, using five days ozonesonde datasets launched at Samoa in March 1996 suggested that further investigation be extended to other ITCZ or active convective regions. The study found that there is clamp down of deep convection at 14km.

The ITCZ is one of the synoptic scale structures categorized by the tropical atmosphere. According to Nicholson (1996) and Gitau (2010), ITCZ is a permanent low-pressure belt found in the tropical region and marks the meteorological equator. It is caught amid usually fine meteorological conditions to the north and south of the subtropical anticyclones related to the meeting of air flows originating from the subtropical high pressure belts. While Anyah and Semazzi, (2007) state that the ITCZ trails the movement of the overhead sun and is always characterized by turbulent activities within the belt, which at time leads to heavy convective activities. During development of such convective activities, latent heat is freed in the convective cloud systems during phase change. The exchange of energy during phase change is a significant process in the atmospheric energy balance (Mabuchi *et al.*,, 2005 and Otieno and Anyah 2012). The improved cloudy conditions accompanying these convective cloud structures deliver a significant input to the global albedo. The changes of heat, moisture, momentum, and radiation concerning the atmosphere and the earth vary intensively meridional in the ITCZ region and the belt northerly and southerly of the ITCZ, Nicholson, (1999). As a result, the position, configuration, and movements of the ITCZ contributes significantly in inducing the behaviour of ocean-atmosphere and land-atmosphere coupling on a limited scale; the flow of the tropical oceans on a basin scale, and amount of features of the Earth's climate on a universal scale. Folkins, (2002) argues that occasionally the tropics have a number of deep convective cloud systems that seem to be rather unsystematically disseminated through the equatorial belt. Usually, the further developed a convective system stands, the larger the horizontal magnitude. This is typically owing to the growth of high cirrus clouds in the convective outflow (discharge) area. In distinction to profound convective 'turrets', which normally have horizon levels in the order of 1–10 km and when found in segregation typically display undeveloped or developing convective schemes. Cirrus clouds can be seen to extend over thousands of kilometres and encompass tens or hundreds of convective turrets concurrently, Folkin et al.,, (2002). In addition, though almost all cloud systems in the tropics are produced by simple convective instability, probable in amalgamation with synoptic wavelike turbulences typical to the equatorial belt, the connotation of some schemes can be influenced by low-frequency phenomena which can enhance their longitudinal and latitudinal magnitude.

Therefore, it can be said that the ITCZ is a lifting mechanism as well as a barrier to deep convection affecting the distribution of O_3 in the US/LS in the tropics.

2.2 The tropopause level

Studies by Held, (1982) and Thuburn and Craig, (2000) assert that the thermal configuration in the UT/LS epitomizes radiative-convective equilibrium. These studies concluded firstly, that as portion of the radiative-convective balance, the sealing of the convective effect is approximately a few kilometers lower than the cold point temperature. Secondly, that a changeover separation also termed as TTL, extends after the end of deep convection to the cold point temperature. As a follow up to their earlier research works Thuburn and Craig, (2002) argued that the frontier boarder is subjective to the influence of both the stratospheric and tropospheric progressions. In their conclusion, they observed that the cold point temperature tropopause ciphers a sharp rise in stability, above which the potential temperature, (θ) profile is the same as radiative equilibrium. Gettelman and de F. Forster, (2002), while explaining the deep convective temperature signal within the TTL, considered the level of minimum stability, in the gradient of θ to symbolize the parting from the equilibrium of thermally induced vertical motion. They referred to this level as the secondary tropical tropopause. According to Paulik and Birner, (2012), this level is the convective discharge, in general and is lower than the level of neutral buoyancy (LNB) (which is related to the level of maximum detrainment of marine air and the upper limit of convective cloud tops, (Folkins, 2002 and Takahashi and Luo, 2012)

2.3 The deep convective outflow, superior and subordinate tropopause levels

Fueglistaler *et al.,*, (2009) while investigating tropical tropopause, proposed that TTL prolongs after the level of main convective discharge (outflow) about 200mb in the lower stratosphere around 70mb. The study also concluded that this level, TTL remains exclusive in that it has both tropospheric and stratospheric features, e.g. ozone rises speedily with increase in altitude beyond the point (height) of main convective outflow, while temperature keeps on declining up and around the cold point temperature tropopause (CPT), 100mb.

Significant prominence has been put upon this TTL by scientists, since it establishes the frontier circumstances for atmospheric minors coming into the stratosphere. Similarly, it is in this frontier that O_3 has largest inconsistency that impact climate. Therefore, the mass-flux description, defines a TTL (i.e. a level that functions as a border), through which the air agglomeration regularly enter the stratosphere. Folkins, (2002) projected that both the subordinate and superior limits of this frontier or boarder, to be at the temperature of 356 K, (about 15.0 km) and 375 K (about 16.6km) in appreciation of the circumstance that within this region, the mass fluxes for the Hadley (tropospheric) and Brewer-Dobson (stratospheric) circulations could be comparable. Fu *et al.,* (2007) confirmed these heights i.e. subordinate and superior altitudes centered on radiative mass flux arguments. Fueglistaler *et al.*, (2009), referred to the subordinate frontier as tropically mean height of nil net radiative heating for full sky (150 mb or 14 km), and the superior sealing referred to as the height where the local mass flux is similar to that of the Brewer-Dobson circulation (70 mb or 18.7 km). The balanced radiative heating for complete sky is importantly dissimilar from that of the clear sky situations, about 14 km against 15.5 km.

These borders are founded on mean situations that employ mutually limited (i.e. temperature and wind direction and speed at the superior sealing) and non-limited (i.e radiative heating as of tropical mean cloud spreading) evidence. The temperature description describes TTL such as changeover area in which the circumstantial thermodynamic configuration changes among the convectively controlled troposphere and the radiatively dominated stable stratosphere. According to this explanation, the upper and lower limits are recognized by the temperature ascents and obtained changes in temperature with height.

Atticks and Robinson, (1983), studied some features of the tropical tropopause and suggested that the cold point temperature tropopause and the level of minimum stability correspond to the superior and subordinate boundaries, respectively. This delineation trails the extensive past tropical measurements that prime to the official description of the tropical tropopause layer. The upper and lower limits in this example are locally defined and can be resulting from prompt measurements using Ozonesonde

2.4 Distribution of Ozone

The tropical distinction of atmospheric O_3 plays a fundamental significance aimed at the radiative stability of the Earth/Atmosphere system and aid in categorizing extensive period movements of key significance (IPCC, 2004). Ozone aids in supporting the stratospheric temperature characteristic. This warming is brought about by the immersion of solar ultraviolet (UV) energy by the O_3. Shepherd, (2008) states that the UT/LS is important for chemistry/climate coupling largely because of the significant radiative forcing caused by ozone, water vapour, clouds and aerosols in this region of the atmosphere

2.4.1 Sources and Sinks of Tropospheric Ozone

To gain some useful concerning the sinks and sources of atmospheric ozone science, it is important to look at the formation and removal reaction processes in the atmospheric air. The creation of ozone in the troposphere is a multifaceted procedure including the feedbacks of hundreds of antecedents. The major source of lower atmospheric O_3 is the stratosphere-troposphere exchange. Another source is the photochemical reactions, the higher the air pollution levels the higher the O_3 amounts. Anthropogenic emissions from biomass and fossil fuel burning produce O_3 precursor gases that enhance photolysis production of O_3.

2.4.2 Nitrogen Oxides and the Photo stationary-State Relationship of Ozone

The main components, (Finlayson-Pitts and Pitts 2000, and in Seinfeld and Pandis 1998), are deliberated in Equations (1-3). The realization of O_3 in the lower atmosphere is as a result of only a single known response; i.e. tallying of atomic oxygen (O) to molecular oxygen (O_2) in the existence of another third "body" indicated as M. Where M can be any "body" that has mass, predominantly nitrogen, (N) or oxygen (O_2) molecules, but can also be particles, minor gas molecules, and surfaces of big objects. The significance of M is absorption of heat; without this removal of heat, the combination of O and O_2 into O_3 will not be completed.

$$O + O_2 + M \rightarrow O_3 + M \qquad (1)$$

The O_2 atoms are made mainly from break down of NO_2 by the UV portion of short wave radiation, h.

$$NO_2 + h \rightarrow NO + O \qquad (2)$$

Equation 3 changes O_3 back to O_2 and nitrogen oxide back to Nitrogen dioxide, NO_2, concluding the "nitrogen cycle."

$$O_3 + NO \rightarrow NO_2 + O_2 \qquad (3)$$

Equations 1 and 3 occur fairly fast. Equation two which is the slower photolysis response is typically the factor limiting reaction for the nitrogen cycle and the cause why ozone is not created significantly at night. This is also one of the reasons why ozone amounts are high during the summer time months, when temperatures are high and solar radiation is intense. These equations 1, 2 and 3 occur within a short time. O_3 collects over numerous hours, subject to production frequencies and weather conditions. The combination of NO and NO_2 is referred to as Nitrogen Oxides NOX is essential of O_3 formation.

O_3 sinks include uptake by plants and also photochemical production of hydroxyl, OH, radicals. OH react with Methane CH_4 reducing the greenhouse effect that leads to Global warming.

2.5 The Tropics and Sub tropics Ozone

After the discovery of O_3 hole occurrence in the Polar Regions, (Farman 1985), investigations and observations have been dedicated to arctic and Antarctic regions of the World. However; the role of tropical dynamics on the distribution of Ozone cannot be ignored, given that much of the solar radiation is received within the tropics and subtropics and transported to the poles. This is dominated by meridional circulation from the equator to the poles transporting energy, momentum and moisture. The deep convection activities within the tropics are also phenomenon resulting in the discharge of huge amounts of latent heat in the UT/LS, (Shepherd, 2008)). The tropical atmosphere therefore, plays an important part in the universal Ozone chemistry, moisture and momentum distribution.

The critical role played by the tropical region is that the stratospheric Ozone is formed photo-chemically, for the reason that the incident short (Solar) wave radiation is more intense in the tropics. Latitudes 10° North and South of the equator receives higher solar radiation and the production of O_3 is maximum in the region. The reason for the maximum amounts for O_3 to occur in polar and mid latitudes is because of north-south (meridional) carriage away from the tropics by Brewer Dobson circulation (BDC) in the stratosphere. According to, (Fioletov, 2002)), the study concluded that near the equator (NH and SH) the overall quantities display less variability, statistically, but are also normally lower, about 220-280 Dobson DU, unit, (100 DU = 1mm) than in mid latitudes, where maxima are gotten during austral or boreal spring periods.

The air flow in the tropics is, largely affected by the ITCZ, wind shears, atmospheric waves, high pressure cells and SSTs. The South easterly, (SE) and the North easterly, (NE) trade winds originating from sub-tropical high pressure belts (STHPB) are sometimes embedded in the monsoons SE and NE meet at the equator driving the warm and light tropical air to rise. This certainly prevents atmospheric air in the lower atmosphere to mix uniformly, transversely at the equator. A study by Folkins, (2006) showed that in the lower atmosphere of the equatorial region the ITCZ creates (constitutes) an effective barrier between the Southern and Northern Hemispheres, permitting minor gases to possess different quantities. Apparently this is merely the state for low altitudes. The study still avers that due to fragmentation of the tropopause at about latitude 30 degrees, where the subtropical Jetstream is located, air from the troposphere can easily reach the stratosphere. Owing to the fact that the countries in the tropics are developing there is low emissions from industries and motor vehicles except in urban areas, therefore industrial and traffic effluents contribute less to atmospheric chemistry.

A study using in situ observations, (Thomson *et al.*,, 2002) has shown that there are quite a lot of exceptional issues in the equatorial region that are thought to impact ozone levels. Most noticeable, specifically in Africa, is biomass scorching to make plantations for agriculture. This largely comprises of biomass fires for the whole duration of the dry seasons, discharging enormous quantities of the O_3 antecedents e.g. NOX and CO in the planetary boundary layer, PBL, i.e. 1 to 3km. This puts the leading area of African biomass scorching in a strap in the Sahel and north of the equator extending all the way to Southern Africa. It springs from western Africa all the way to East Africa (Kenya and Uganda)

The region follows the matching sun as it oscillates from north to south with dry period as demarcated by the continually shifting ITCZ. Most of these fires are essentially not bushfires, but the consequence of agrarian left-over scorching as portion of small scale agriculture in a region of high grass production. The smoke trails from the fires are conveyed south-westerly (meridional) by the wind, getting to as far over as the Atlantic Ocean. As the plumes move upward in ITCZ, they formerly might even be transported over to the Southern Hemisphere, (Edwards *et al.*,, (2003)). Alternative source for nitrogen oxides over Africa is lightning, which is understood to be the major source of nitrogen oxides in the mid troposphere outside of the plantation scorching time of the year. Irregular differences of the global wind fields, like the Quasi-Biennial Oscillation, QBO, where winds in the stratosphere blow in westerly direction for one year and change to easterly for another one year with a mean period of about twenty eight months (Thompson *et al.*,, 2003b) and or the El-Nino Southern Oscillations (ENSO), may root differences of about five percent in stratospheric ozone totals and impact tropospheric ozone columns. ENSO also impacts tropospheric ozone when rainfall deficiency is followed by big fires. These phenomena occur in the tropical region.

2.6 Brewer-Dobson circulation

Brewer-Dobson circulation (BDC) refers to a unique prominent feature of the stratosphere and it normally defines the North-South (meridional) carriage of minor gases from the tropical region to the Arctic and Antarctic (Brewer, 1949 and Dobson, 1956). Studies by Haynes *et al.*,, (1991), Rosenlof and Holton, (1993), Newman *et al.*,, (2001) and Plumb, (2002) on BDC, refers to BDC as an overall air flow that is a relic of zonal and atmospheric waves in the extra tropics. The zonal and atmospheric waves interrupt BDC causing a slow meridional float. Wave-induced torques drives a middle atmosphere circulation with a strong seasonal dependence, mainly from Rossby waves in the stratosphere and also from gravity waves in the mesosphere. This is the origin of the stratospheric 'Brewer-Dobson circulation' that cools the tropics and warms the poles. However this circulation is today understood as a left over flow.

Waugh and Hall, (2002) observed that the conveyance period of circulation in the stratosphere beginning from the equator to the lower most Arctic and Antarctic stratosphere is about a few years. While Chipperfield and Jones, (1999) concluded that the transport of O_3 from the tropics to the poles is greatest in either the austral or boreal winter. Many of the climate replicas and chemistry climate replicas (CCR) illustrate that the power of the winter Brewer Dobson circulation will raise with cumulative greenhouse gas amounts(GHG) and accelerate the anticipated ozone rescue e.g. (Butchart *et al.*,, 2010, Garcia and Randel, 2008 Fomichev *et al.*,, 2007, ,). Engel *et al.*,, (2009) in their research using available data indicated that the stratospheric time of air (which should decrease if BDC is improved) did not vary in the latest years.

Existing research works by (Bönisch *et al.*,, 2011), where they used minor-minor correlation appears to show that at least in the narrow division of the BDC (closer to the Upper Tropospheric Levels at the tropics and subtropics), faster passage times are recently detected.

Newman *et al.*,, (2001) states that the global flow deed motivating the BDC is typically explained by the coming together of Eliassen-Palm (EP) flux. The meeting of the EP flux in the stratosphere is a quantification of easterly momentum dumped to relax the westerly, zonal flow in winter. According to Andrews *et al.*,, (1987) argues that geostrophic approximation needs a slight meridional flow component that initiates the north- south or residual circulation. The perpendicular vector of the EP flux trajectory, Fz, that is comparative to the eddy heat flux, is a measure of the upright spread of global waves from the troposphere. Both EP flux meets and the heat perturbations are regularly employed to define dissimilarities in the BDC driving. Fusco and Salby (1999) and Salby and Callaghan (2004a) observed that year to year difference of the heat perturbations associates with inter-annual variations of higher latitude total column O_3 and at the same time dissociates with O_3 differences in the tropics, specifying the inter-annual changes in hemispheric ozone transport.

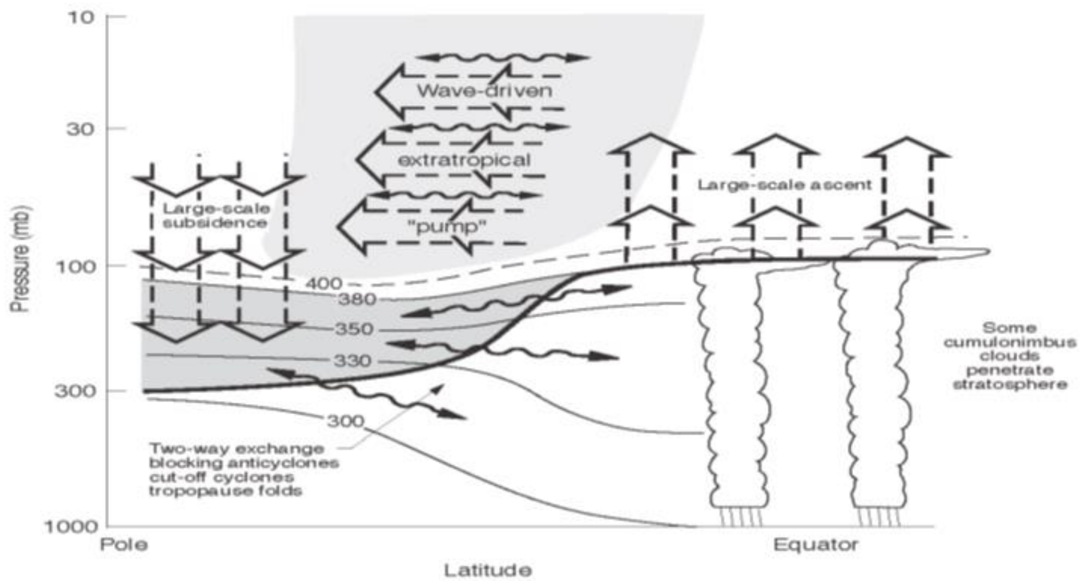


Figure 3 Schematic showing BDC circulation in the stratosphere with rising motion at the equator in the troposphere and sinking motion at the poles. The atmospheric waves drive this circulation. Source: Cohen, 2014

Diverse alternatives are being employed in the trend replicas distinctly and in mixture to explain dynamical ozone variations, identical to potential vorticity or tropopause height, teleconnection patterns, i.e. Arctic Oscillation (AO), equivalent latitude alternative, and heat perturbation. Appenzeller *et al.,*. (2001) concluded that the cold season AO guide represented variations in stratospheric dynamics and that the Oscillations related well with ozone fluctuations. The lasting variations in the AO index displayed conceivable lasting fluctuations in the Brewer-Dobson Circulation (Fusco and Salby, 1999), Randel *et al.,*, (2002)). The publication by Kiesewetter *et al.,*. (2010) revealed that for cold seasons in a high (low) annular mode state, negative (positive) larger stratospheric ozone irregularities in fall; accordingly, lead in small (great) column ozone irregularities in polar spring.

2.7 Troposhere/stratosphere exchange

According to Wang *et al.*, (2008), the circulation of atmospheric minor gases is occasioned by the proportion of production and removal as well as dynamic transport developments. Even though these progressions are intricate, various isolated atmospheric elements, have revealed a comparable circulation. Therefore, it looks as if atmospheric structures have a relaxed development of chemical alteration controlled by dynamics in its three-dimensional variations. Predominantly the exchange of stratosphere and troposphere requires passing within the tropopause interchange procedure penetrating into the stratosphere (troposphere) (Wang *et al.*, 1994, 2006 and 2008). Stationary steadiness in the troposphere is truncated; accordingly it merely requires numerous hours moving the surface air and effluents to the higher troposphere by wet convection procedure, and only numerous days by baroclinic wave action. Whereas stationary steadiness inside the stratosphere is great, the upward transport of comparable length may last a year or more, which should be complemented by radiative heating or cooling, (Bian, 2004). Hence, it is noteworthy to investigate the conversation of air pollution and chemical configuration in the UT/LS.

Wang, (2008), says that the procedure of stratosphere-troposphere exchange (STE) is an extremely significant aspect which determines the O_3 and water, H_2O in the higher troposphere/lower stratosphere. He continues to argue that the investigation of the STE may well aid in understanding in what ways mandatory impacts in tropopause influence the tropospheric flow and climate. Additionally, He states that the variations in the tropopause itself are an important signal in climate change investigation.

Wang *et al.,*, (2008) proposed that the temperature variation in the tropopause and dynamic processes of micro and macro scales are diligently connected to the UT/LS O_3 profile. When an air mass containing O_3 in the lower stratosphere moves to and from the troposphere, changes the variation of O_3 amount, and also causes the important chemical forcing of different radiative forcing effects, all of which will ultimately affect the tropospheric movement and climate,

2.8 Seasonal variation of ozone

Study of O_3 data by (Balos 2013), disclosed a great seasonal cycle with a typical slim upward increases rightly beyond the tropical tropopause. Randel *et al.,*. (2007) emphasized this characteristic and suggested that it was induced periodically in tropical upsurge acting on the robust O_3 background upward changes with height. Abalos *et al.,*. (2012) calculated the periodicity of the various terms in the renovated Eulerian mean (REM) transport balance using satellite data of O_3 and re-analysis atmospheric variables, and established that the periodicity in O_3 essentially followed the periodicity of upward transport by upsurge at heights with great upward gradients. Therefore, these investigations established that upward transport inside the tropics is the leading forcing of the O_3 periodicity at a stationary height in the REM context.

In addition, Konopka *et al.,*. (2009) studied the source of the O_3 yearly flows by means of a theoretical replica. Balos *et al.,*. (2010) also examined ozone periodicity beyond the tropical tropopause by means of simplistic tropical trace gas replica. Both studies suggested that quasi-horizontal carriage had a principal part in producing the ozone periodicity. However, Konopka *et al.,*. (2010) detected a strong summer maximum in isentropic ozone passage from the northern mid-latitudes into the tropics (in mixing) related to the Asian monsoon upper altitude flow, in general circulation replicas reproductions employing Chemical Lagrangian Model of the Stratosphere ClaMS. Ploeger *et al.,*. (2012) additionally stated that the O_3 yearly sequence beyond the tropical tropopause completely vanished if amalgamation was suppressed. Accordingly, from a Lagrangian angle, following air parcel paths, amalgamation of temperate air within the tropics seemed critical for elucidating tropical O_3 partial pressures, and mainly the O_3 summer maximum.

2.9 Sea Surface temperature

Sea surface temperatures (SSTs) are used in many places as predictors of seasonal climate, particularly in East Africa, (Ininda *et al.*, 2000)). Ininda (2002) argues that SSTs bear a huge effect on climate and weather of Kenya and the surrounding regions. E.g., around three to seven years, temperatures rise up by 2°C to 3°C in an extensive part of the Pacific Ocean along the equator. This warming up is a symbol of the climate pattern El Nino, which alters precipitation patterns all over the world.

On a reduced balance, ocean temperatures affect the growth of tropical cyclones also known as low depressions (hurricanes and typhoons), which pull energy from warm ocean waters to occur and strengthen. These low depressions have effect on the intra seasonal variability of precipitation over Kenya. Studies by Saji *et al.*, (1999); Webster *et al.*, (1999); Murtugudde *et al.*, (2000) state that the Indian Ocean Dipole (IOD) is connected with changes in SSTs at two regions (or ends, therefore a dipole); a western pole in the Arabian Sea, near Somalia (western Indian Ocean) and an eastern pole in the eastern Indian Ocean south of Indonesia (Sumatra). They also argue that the IOD has an effect on the climate of Kenya and other countries which border the Indian Ocean basin. It also contributes greatly to rainfall variability in East African region. In the equatorial Indian Ocean, IOD is understood to have a connection with ENSO episodes by way of the Walker Circulation to the west and accompanying Indonesian low flow. Saji *et al.,* (1999) observed that Positive Indian Ocean Dipole episodes are consistently connected with El Niño and negative events with La Niña. Ininda, (2002) concluded that when the Indian Ocean Dipole and ENSO are in period the effects of El Niño and La Niña phenomena are frequently greatest over, Kenya, i.e. when we have El Niño and positive IOD; while, when they are out of period the effects of El Niño and La Niña episodes can be weakened.

CHAPTER THREE

3.0 Area of Study, Data and Methodology

This chapter describes the area of study, data and the various methods used to realize the objectives of the study.

3.1 Area of Study

This study concerns the distribution of O_3 and temperature at Nairobi, Malindi, Sepang and Watukosek and linkages of O_3 at the Chemopause to SSTs at selected regions in Indian Ocean that are relevant to seasonal forecast of rainfall in Kenya. This is aimed at enhancing the accuracy of KMD's forecast of seasonal weather/climate in Kenya.

The Republic of Kenya is found on the East African Indian ocean coastal line and the equator splits it into two equal halves. Ethiopia and Sudan are the boarders on the northern side. On the east, it is bordered by the Indian Ocean and Somalia. Tanzania is found to the south, and Uganda and Lake Victoria to the west. Kenya covers a geographical area of 580 370 km^2 and its further sub-divided into 47 devolved Counties.

The geographical features of Kenya are assorted, e.g. the multifaceted high grounds are also the source of water towers for some of the leading rivers of the region, Krishnamurti and Ogallo (1989). The high grounds i.e. Mountains, form an essential part of the local water cycle Indeje (2000). Another exceptional physical characteristic of Kenya include the water bodies of Lake Victoria and Indian Ocean, the Western and Eastern Highlands, which degenerate, to a plateau towards the Indian Ocean. Sandwiched between these highlands, propagates the Great Rift Valley that slopes north/south across central Kenya into Tanzania. This configuration creates local mesoscale circulation of land/sea and land/lake breezes, as a consequence of the water and land temperature contrasts. This is owing to the differential solar heating and radiative cooling of water and land. Lake Victoria, for example, has a strong flow of its own with a quasi-permanent low that drifts from the land to lake and the lake to land during the night time and day time; respectively. The lake has an aerial extent of about 60, 000 km^2 (Indeje 1994; Mukabana and Pielke 1996; Indeje and Anyamba 1998). Lake Victoria is also the foundation of river Nile (the longest river in the world). The main climates of equatorial Kenya varies from cold polar type i.e.

lake Lewis, on top of Mt Kenya, humid equatorial and tropical climate, savannah grasslands, hot dry semi-desert among many others. The savannah climate that has one distinct dry/wet season is the home of most of the African wildlife and livestock. Tourism and wide range of agricultural activities are extensive in this Country. Most of the locations with equatorial climate are concentrated largely near the large water bodies and over the highlands. The semi-desert region covers the north and northeast Counties of Wajir, Mandera, Garissa, Lamu amongst others. A relatively moist zone covers the coastal belt of the Indian Ocean. Agriculture and utilisation of forest resources are the major socio-economic activities in Kenya. Soil erosion arising from such activities is however a major environmental problems in many Counties of the Country. Kenya has a shoreline on South East, on the Indian Ocean, which comprises swamps of East African mangroves. Inland are expansive plains, lakes and many hills and Mountains.

Central and Western Kenya regions are characterized by the Rift Valley home to Kenya's highest mountain, Mount Kenya (5199 m) and Mount Elgon (4321 m), on the borderline of Kenya and Uganda, Aberdare Rangers (3999 m) and the Mau escarpment (3098 m). Mount Kenya has enduring glaciers at its top and a glacier lake Lewis (whose snow cover is receding due to partly drying moisture, albedo and global warming), all through the year which brands the mountain as a distinct possible signs of regional and/or large-scale together with long-term climate variations. Kakamega Forest, in western Kenya stands out as leftover of an East African tropical forest. Greatly bigger is Mau Forest, the major forest intricate in East Africa (Indeje, 2000).

The Kenyan climate differs by position; ranging from ordinarily cool every day, to constantly warm/hot, (Greene, et al., 1991). The climate along the coastal strip is tropical and humidly. This implies that rainfall and temperatures are higher during the year especial higher altitudes and lower altitudes; respectively.

As one move further inside the Country, the drier the climate develops. A semi-arid and arid climate receives little to almost no rainfall, and temperature fluctuates broadly based on the prevailing time of the day/night.

Though Kenya is centred at the equator, it shares the seasons of both hemispheres. During the southern hemisphere summer, boreal winter, December, January, February and March, Kenya has the warmest summer season and the coolest winter season, austral winter, during the months of

June, July and August, with again differences in temperature fluctuating from place to place within the country.

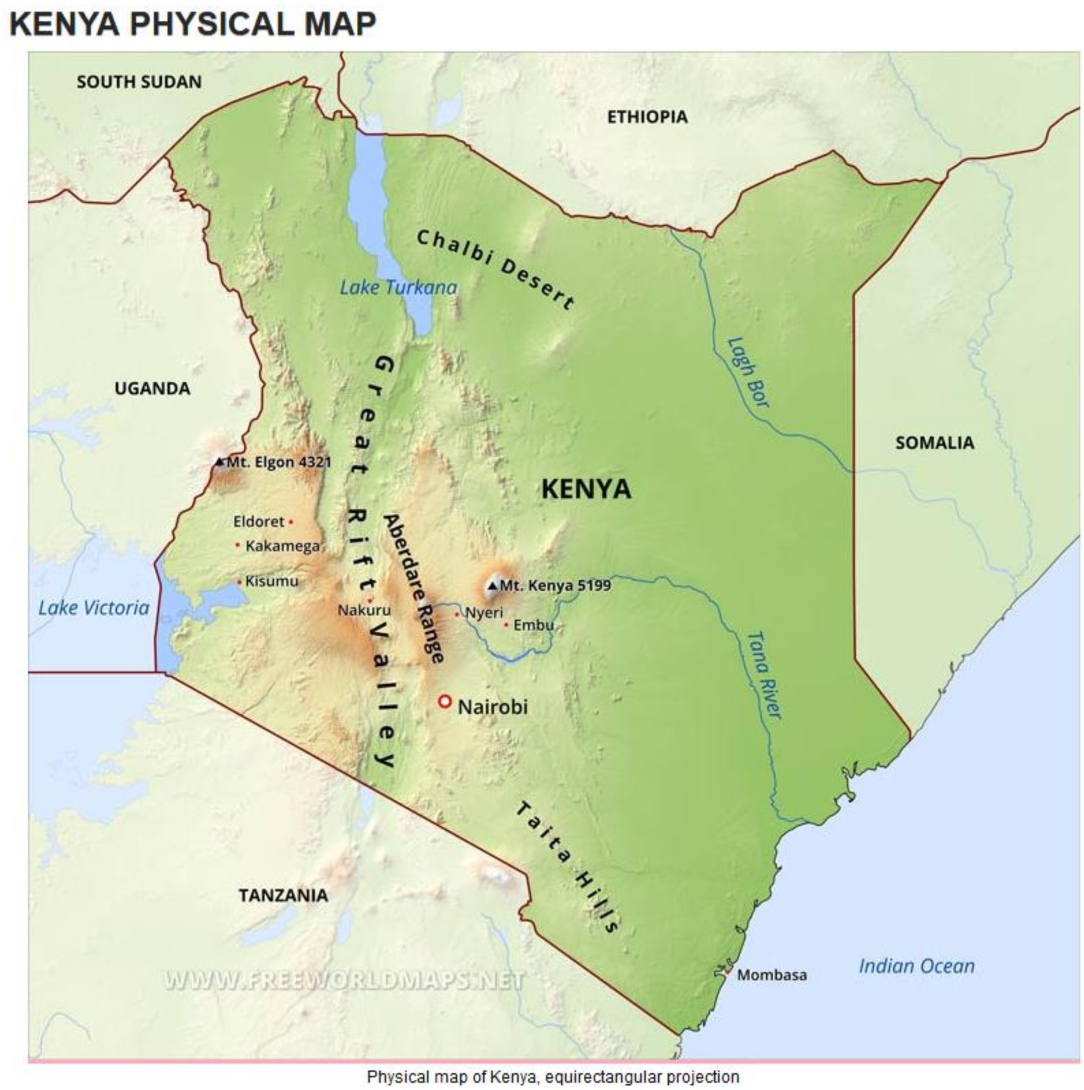


Figure 4: Schematic showing the aerial extent of Kenya, her neighbouring Countries and major geographical features. Source: Free world maps.net/Africa/Kenya/map.html

The mean yearly rainfall is 630 mm with fluctuations ranging from less than 200 mm in north eastern/western Kenya to above 1800 mm on the inclines of Mt. Kenya. The precipitation distinctive regimes is mostly twice a year with major rains falling from March, April, May and called long rain season, all through to June and short rains October and November, for most parts of the country. Nevertheless, Western and coastal region receive a third season of rainfall from June, July and August and therefore have a tri-modal rainfall regime. Kenya being a tropical country, her climate is generally affected by the inter-tropical convergence zone and topography, ranging from permanent snow above 4650 metres on Mt. Kenya to proper desert type in the Chalabi desert in the Marsabit County. Nearly three quarters of the country is arid and semi-arid, while about 17% is considered to be high prospective agrarian land, supporting livelihoods of about 75% of the inhabitants, Indeje (2000). The woodland cover is about 3% of the total acreage below the recommended universal coverage of 10 percent.

3.1.1 Distribution of Southern Hemisphere Additional Data on Ozone SHADOZ stations

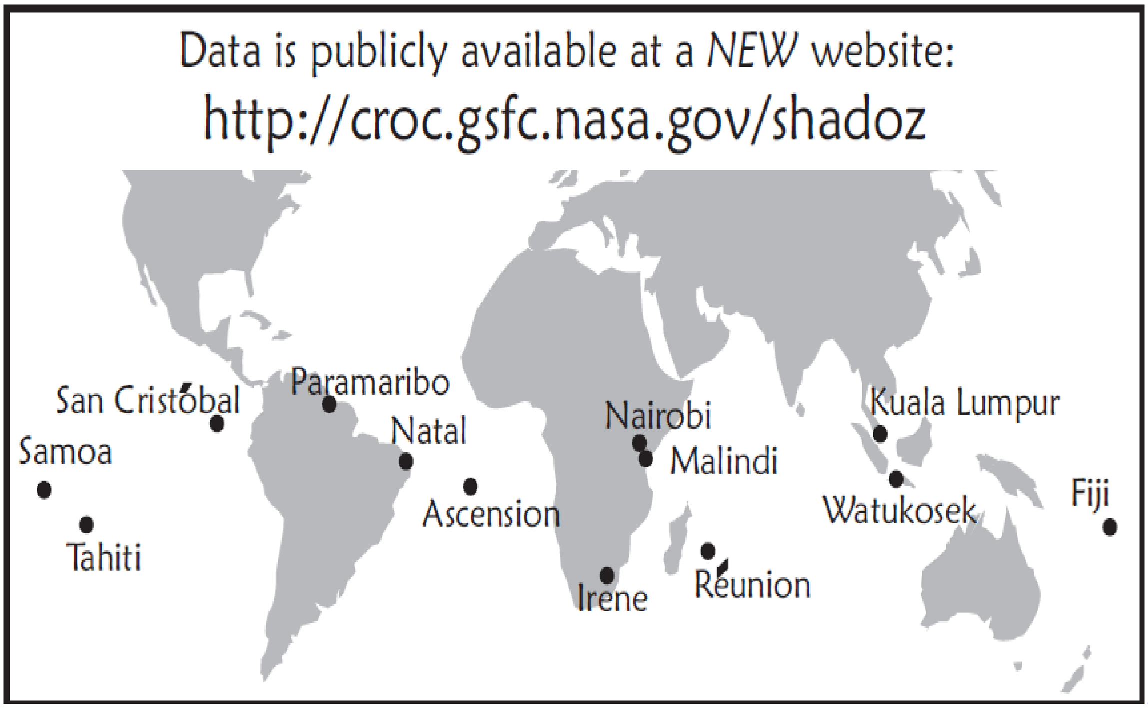


Figure 5: Map showing shadoz stations with Nairobi, Malindi; (Kenya), Watukosek, (Indonesia) and Sepang, (Kuala Lumpur), Malaysia stations whose data was used in the study. All stations are in the tropics facing Indian Ocean. Source:http://croc.gsfc.nasa.gov/shadoz.

Table 1: Shows the station name, geographic location, elevation(m) and Ozonesonde data time series used in analysis.

No	Station Name	Geographic location	Elevation (m asl)	Data time series
1	Nairobi	1.27°S and 36.8°E,	1795	1998 to 2014
2	Malindi	3° S and 40° E,	-6	1998 to 2005
3	Sepang (Kuala Lumpa)	2.73° N, 101.7° E	17.0	1993 to 2013
4	Watukosek	7.5°S, and 112.6°E	51	1988 to 2013

3.2 Data

The data that was used in this study included Ozonesonde data for Nairobi (1998-2014) and Malindi (1998-2005) Kenya, Sepang (1993-2013) Malasya, and Watukosek (1988-2013), Indonesia and SSTs data from three selected areas in the Indian Ocean relevant to weather forecasting in Kenya. The four stations were used because they were found to be the only stations in the tropics and close to the Indian ocean with weekly Ozonesonde data for five years and more.

3.2.1 Sea Surface Temperature (SST) data

SST data was acquired from Hadley Centre SST (HadISST: http://www.metoffice.gov.uk/hadobs/hadisst/). The SST data was extracted for three regions over the Indian Ocean 60°E-70°E, 3°N-20°N; 55°E-60°E, 3°S-26°S and 30°E-60°E, 44°S-40°S refer to figure four. The SSTs data was from 1961 to 2013 though corresponding data to Ozonesonde data time series as shown in table one above was used.

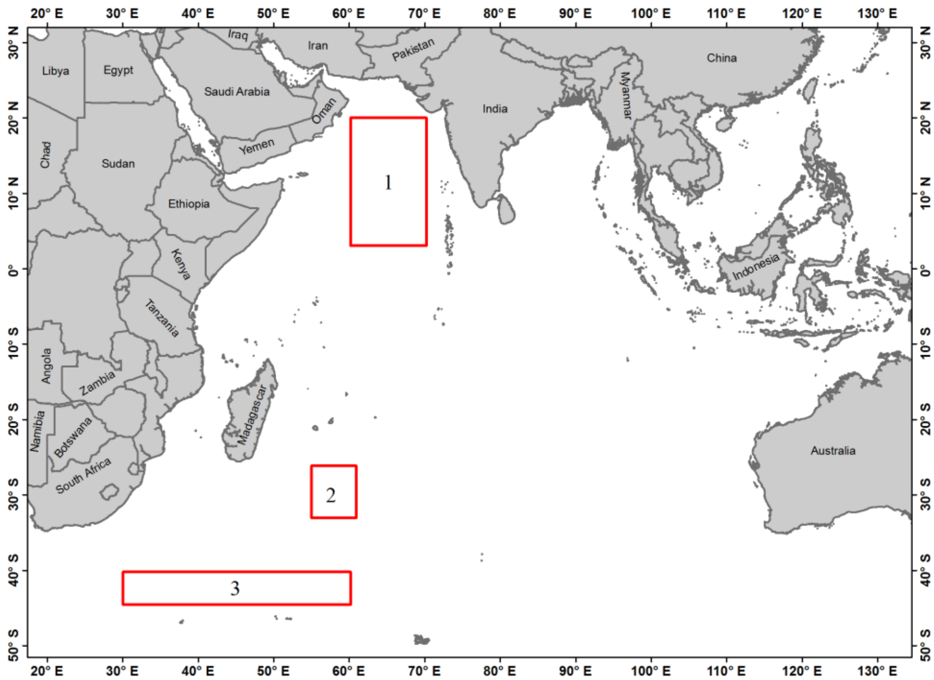


Figure 6: Map showing the location of three regions; region 1: 60°E-70°E, 3°N-20°N; region 2:55°E-60°E, 3°S-26°S and region 3:30°E-60°E, 44°S-40°S in Indian Ocean whose SSTs were used in regression. They are numbered and marked in red generated using arcgis 10.4 version

3.2. 2 Ozonesonde Data

The data sets for vertical ozone and ambient temperature profiles were obtained from Southern hemisphere additional Ozonesonde data (SHADOZ) and World ultra-violet and ozone data centre, WUODC, Montreal, Canada sites. The Ozone ambiguity is usually within 5-10% but is projected to be larger ~10-15% in the tropical tropopause region (Smit et al.,. 2007).

3.2.3 Moderate Resolution Imaging Spectroradiometer Data

MODIS is an abbreviation for Moderate Resolution Imaging Spectroradiometer. It’s a major device on-board the Terra Earth Observation Satellite (EOS AM) and Aqua (EOS PM) satellites. Terra's circumvolution round the Earth is prearranged so that it passes from north to south through the equator in the morning, ascending; while Aqua passes south to north over the equator in the afternoon, descending. The data resolution was at 1° by 1° and was used to determine spatial distribution of tropopause height over Kenya.

3.2.4 Grid Analysis and Display System Data

The Grid Analysis and Display System GrADS was used to extract mean monthly sea surface temperature data over the following regions in the Indian ocean which are relevant to seasonal rainfall prediction in Kenya, 60°E-70°E, 30°N-20°N, 55°E-60°E, 33°S-26°S and 3°E-35°E, 44°S-40°S, Muthama *et al.*, (2003).

3.3.0 Arcgis 10.3

This was used to indicate the following regions 60°E-70°E, 30°N-20°N, 55°E-60°E, 3°S-26°S and 3°E-35°E, 44°S-40°S on the geographical map.

3.3.1 To determine Tropopause and chemopause levels.

To realize the first and second objective the vertical mean monthly and annual temperature and ozone profiles were plotted against time to indicate the cold point temperature CPT which is the minimum in temperature profile. Chemopause levels were also determined as both the minimum and maximum ozone points in ozone profiles.

3.3.2 To determine second tropopause (deep convective outflow)

To fully achieve objective one, potential temperature θ were calculated based on the following formula and plotted against time.

$$\theta = T\left(\frac{P}{P_{00}}\right)^{k} \quad\text{...}(4)$$

In equation four, θ is potential temperature in Kelvin, T is the ambient temperature in kelvin, P is the reference pressure at 1000mb, P_{00} is the pressure at the ambient temperature and k =0.286 and is the Poisson constant which is the ratio of the gas constant to specific heat capacity at a constant pressure.

The gradient of potential temperature $\frac{d\theta}{dZ}$ was calculated and plotted against time to determine level of minimum stability (LMS) equation five which corresponds to level of convective outflow Pan *et al.*,, (2014).

$$\text{LMS}=\frac{d\theta}{dZ} = \frac{\theta 2-\theta 1}{Z2-Z1} \quad\text{...}(5)$$

In equation five, z is the geopotential height in metres and 1, 2, 3………n is the corresponding geopotential height.

3.3.3 Correlation Analysis

In this study, simple correlation was used to evaluate the level of association among the O_3 and temperature. A simple correlation coefficient of 1.0 and -1.0 denotes a perfect positive (direct) and negative (inverse) linear relationship in the observed ozone and temperature values while a correlation coefficient equal to 0.0 represents no association between the two variables. Biases may still occur with a perfect correlation coefficient because the coefficient is normalized by the overall mean of each variable whereas low values of the coefficient may result due to non-linear relationships (Bosire, 2012). The simple correlation coefficient may be given by the formula in Equation 6 below;

$$r = \frac{\sum_{z=1}^{N}(X_z - \bar{X})(Y_z - \bar{Y})}{\sqrt{\{\sum_{z=1}^{N}(X_z - \bar{X})^2\}\{(\sum_{z=1}^{N}(Y_z - \bar{Y}))^2\}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

In Equation (6), X_z and $Y_z$are ozone and temperature; respectively, at level z, and $\bar{X}$ and $\bar{Y}$arithmetic means of $X_z$and $Y_z$at level z. N is the record length. Estimation of the statistical significance of r was done through the use of student t-test given by the equation (7);

$$t_{N-2} = r\sqrt{\frac{N-2}{1-r^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

In Equation (7) t_{N-2} is the student t-distribution value with $N-2$ degrees of freedom and N is the total number of observations. Temporal and spatial variation of ozone mixing ratios over Nairobi, Malindi, Sepeng and Watukosek were correlated at various altitudes in the upper troposphere and lower stratosphere to corresponding ambient temperature and sea surface temperature of the three regions in the Indian Ocean.

Correlation was used to realize the third specific objective.

3.3.4 The Equation of Linear Regression

Linear regression is a method to establish the association among two variables. The equation is the slope formula. The equation has the form

$Y=\alpha+\beta X$, ... (8)

In Equation (8), Y is the dependent variable, SSTs X is the independent variable, O_3 mixing ratios, β is the slope of the line and α is the y-intercept.

$$\alpha = \frac{(\sum y)(\sum x^2)-(\sum x)(\sum xy)}{n(\sum x^2)-(\sum xy)^2} \quad \text{.........(9)}$$

$$\beta=\frac{n(\sum xy)-(\sum x)(\sum y)}{n(\sum x^2)-(\sum x)^2} \quad \text{.........(10)}$$

The primary stage in obtaining a linear regression equation is to find if there is a association among the two variables.

The linear regression analysis was used to realize the fourth specific objective.

3.3.5 Multiplicative Shift

$$x'_{corrected} = X_i \frac{x_{obs}}{x_{iFcst}} \quad \text{.........(11)}$$

In equation eleven x' is the corrected SST, X_i is the raw monthly SST, x_{obs} is observed long term monthly mean SST and x_{iFcst} Forecasted long term monthly mean forecasted.

i. The Multiplicative shift technique corrects only forecasted SSTs to replicate the long-term mean observed monthly SSTs, and therefore does not adjust any regular error in the intensity or distribution of SSTs. Equation 11 was used to reduce biases in the forecasted SSTs.

3.4 Limitations of the study

In this study, three limitations are discussed.

i. This study was conducted through correlation and regression analysis. Linear correlation is limited to abrupt changes like in temperature occasioned by global warming and O_3 due to pollution in troposphere, transboundary exchange and ozone hole in stratosphere

ii. This study was restricted to Ozonesonde data in the tropics 10° north and south of the equator and near or in the Indian Ocean. The SSTs regions were also restricted to Indian Ocean. Therefore this study cannot be applied to other regions

iii. The tropics are understudied due to lack or scarcity of Ozonesonde data. The stations used had ozonesonde data of five or more years with some long time data gaps e.g. at Malindi and Nairobi. The data was also collected weekly. Continuous data collected on daily basis would be most appropriate.

CHAPTER FOUR

4.0 Results and Discussions

This chapter presents and discusses the various results of the study.

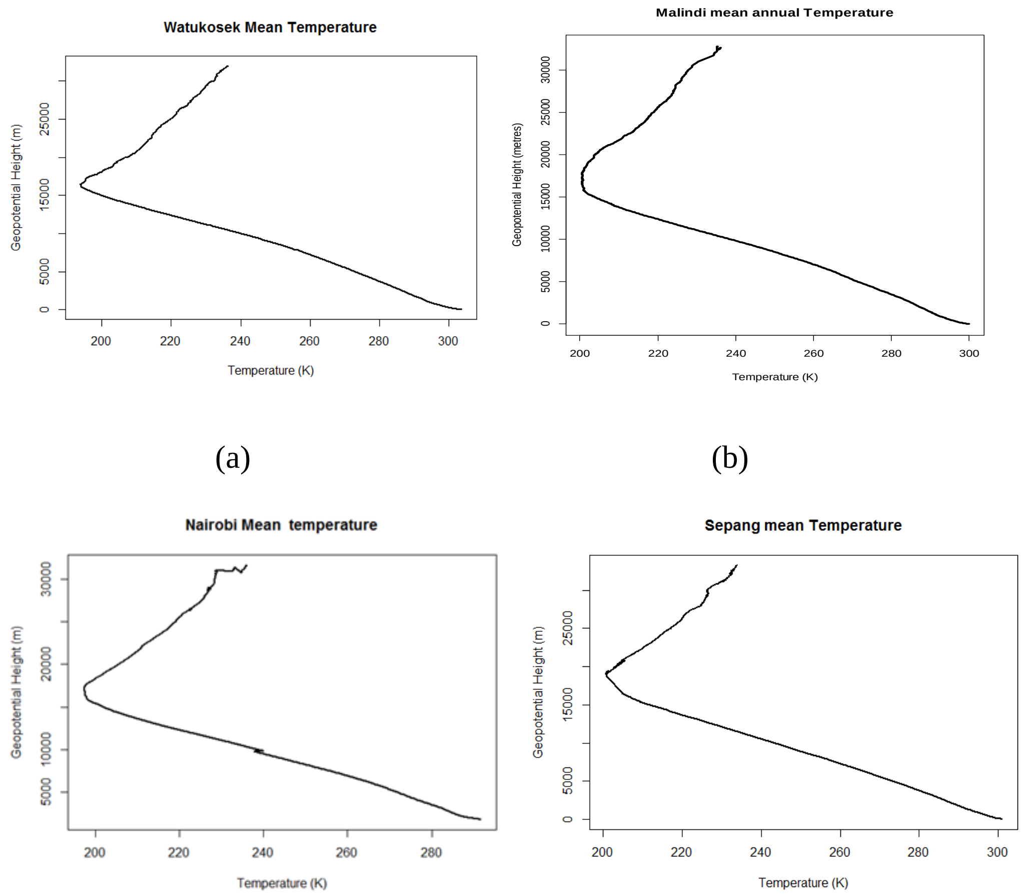
4.1.0 Determination of cold point tropopause

All weekly Ozonesonde data for Nairobi, Malindi, Sepang and Watukosek used in the analysis were checked for plausibility and were also visually inspected. The Ozonesonde data were pinned at an interval of 50 meters to reduce noise and have regular altitude. The SSTs data was also visually inspected. Ozonesondes are flown with standard vaisalla radiosondes to simultaneously measure vertical profiles of standard atmospheric physical variables (such as wind direction and speed, ambient air temperature, humidity and pressure).

Firstly the mean ambient temperature was calculated and plotted against the vertical height as shown in Figure 5. Monthly, seasonal and annual averages for ozone, temperature, potential temperature and level of minimum stability were calculated and plotted against geopotential height.

Figure 5, displays the ambient air temperature (T) at the four stations under investigation. Cold point temperature (CPT) corresponds to the minimum in temperature of the ozonesonde profile. Minimum temperature can be deduced at Watukosek, Malindi, Nairobi and Sepang to be at a mean height of 16.4, 16.8, 17.2 and 18.8 km ASL annually, respectively. The corresponding temperature at CPT is 194.0K, 200.4k, 197.2k and 200.4k, respectively. These cold point temperatures also mark the cold point temperature tropopause CPTT.

These height levels at Watukosek, Malindi, Nairobi and Sepang correspond to the upper sealing of the tropical tropause layer.



(a) (b)

(c) (d)

Figure 7: Display of mean ambient vertical profile of air temperature (k) at Watukosek (1988-2013), Malindi (1998-2005), Nairobi (1998-2014) and Sepang (1993-2013). The cold point temperature tropopause, CPTT is identified by the temperature minimum in the vertical profile.

4.1.1 Spatial distribution of tropopause over Kenya

The GES-DISC Interactive Online Visualization And Analysis Infrastructure (Giovanni) was used to explore MODIS satellite for tropopause height over Kenya. Figures 6 and 7 show day and night time tropopause height in Kenya. Higher tropopause levels are experienced in the Northern and coastal regions. This is because of intense insolation in these areas during the day and cooling at night. The time area averaged tropopause height map, figures 6 and 7 indicate high tropopause levels over Mandera, Laboi and Dif on the north eastern boarder of Kenya and Somalia having an average height of 16.5km.

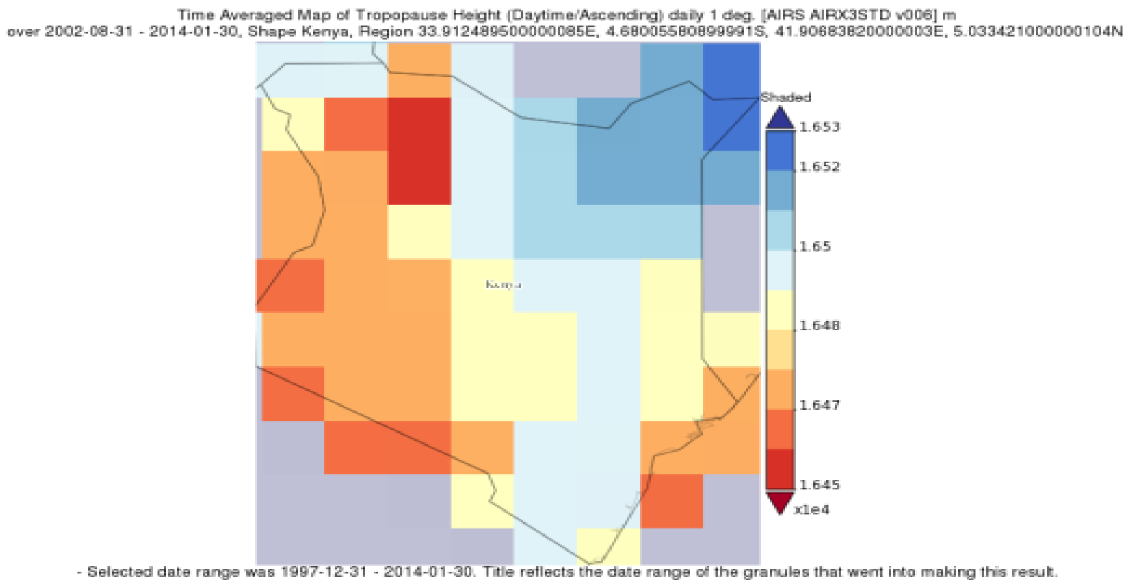


*Figure 8: Day time area averaged map of tropopause height over Kenya from 13/12/1997 to 30/01/2014. The scale unit is in Meters (1.0 *10^4). Generated using Giovanni*

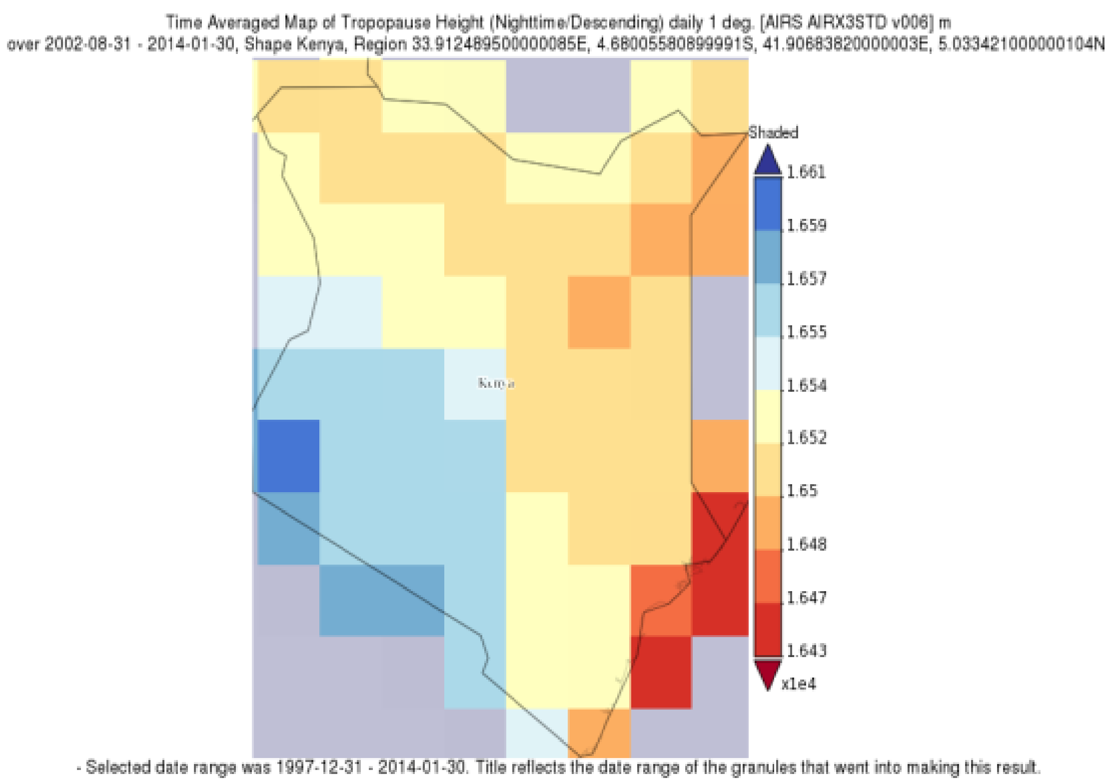


*Figure 9: Night time area averaged map of tropopause height over Kenya from 13/12/1997 to 30/01/2014. The scale unit is in Meters (1.0 *10^4). Generated using Giovanni.*

The rest of the Country shows low level tropopause height except the western part close to Lake Victoria and the highlands. This is due to active convective activities experienced in these areas due to intense radiation, the presence of the lake/ocean and topography. The rest of the Country experiences relatively low tropopause level ranging from 16.4 to 16.6 km during the day and slightly higher during the night.

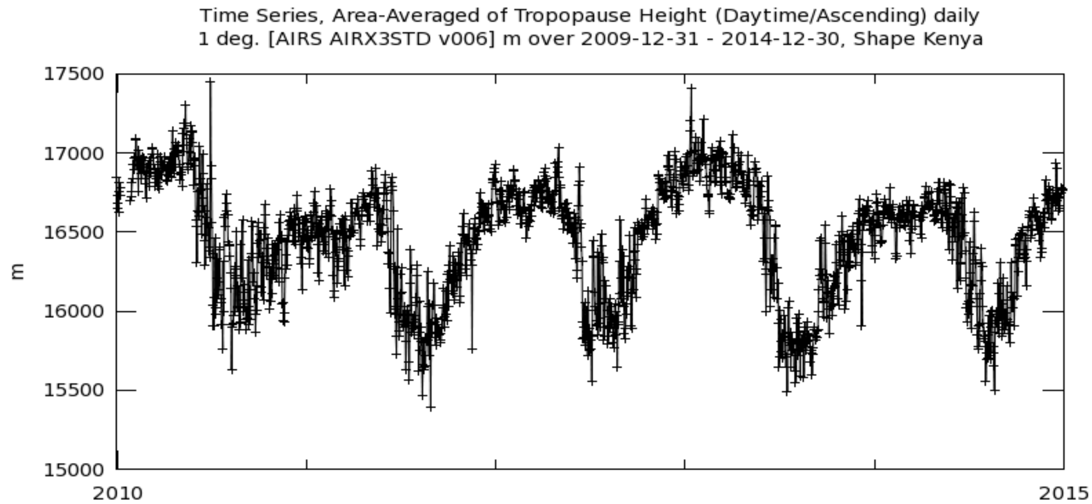


Figure 8: Temporary and spatial distribution of day and night time area averaged time series of tropopause level over Kenya from 13/12/1997 to 30/01/2014.Generated using giovanni.

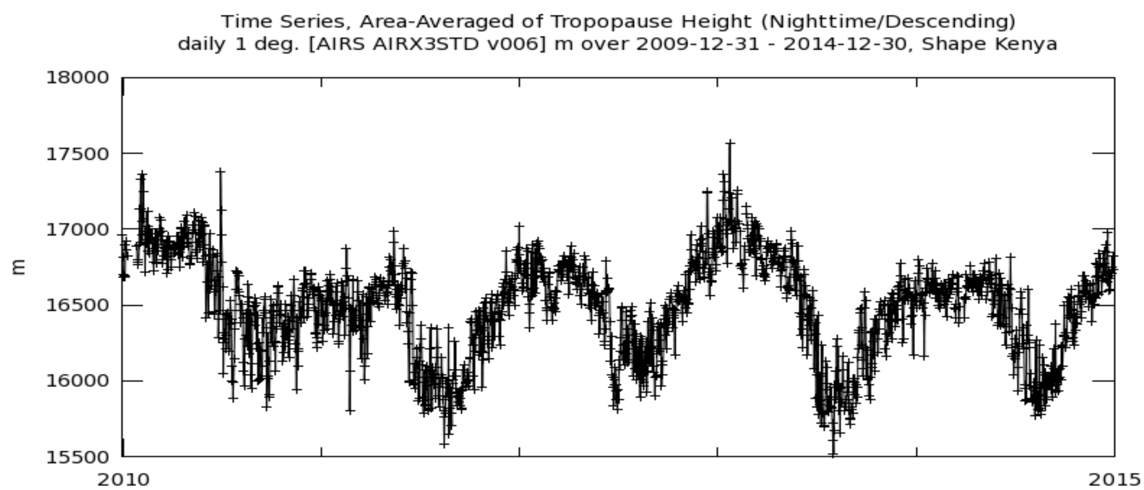


*Figure 9: Graphic display of time series (2010-2014) of area averaged night time tropopause level at 1 degree by 1 degree over Kenya. Vertical height in metres (1.0*10^2) produced using giovanni.*

Figures 8 and 9 indicate seasonal variability of the tropopause level over Kenya during the day and at night respectively. Minimum tropopause height is realized during the months of June to July during night time. This time of the year, there is cold temperature over most parts of the country due to advection of cold air mass from Southern Africa through Mozambique Channel towards Tanzanian coastal strip into the Country leading to very low temperatures and characterized by stable atmosphere. The maximum tropopause height values are attained from November to January. November to January period is generally dry and warm in the Country. These minimum and maximum tropopause height seasons correspond to minimum and maximum O_3 mixing ratios in the troposphere over Nairobi. The difference between the height levels of ascending (daytime) and descending (night-time) tropopause is minimal.

4.1.2 Deep convective outflow

Figure 10 shows is the plot of mean potential temperature against geopotential height in metres for Watukosek, Malindi, Nairobi and Sepang.

From the potential temperature plots figure 10 there is early change of gradient, i.e., before cold point temperature tropopause height at all the four stations. Malindi, Watukosek, Nairobi and Sepang change gradients at a mean altitude of 14.0, 14.6, 15.0 and 16.1 km asl; respectively. Watukosek, Malindi and Sepang have warmer air than Nairobi. This is evidenced by the high potential temperature at the same pressure (geopotential height) level. This is because Nairobi station is continental while Watukosek, Malindi and Sepang stations are close to Indian Ocean (Maritime).

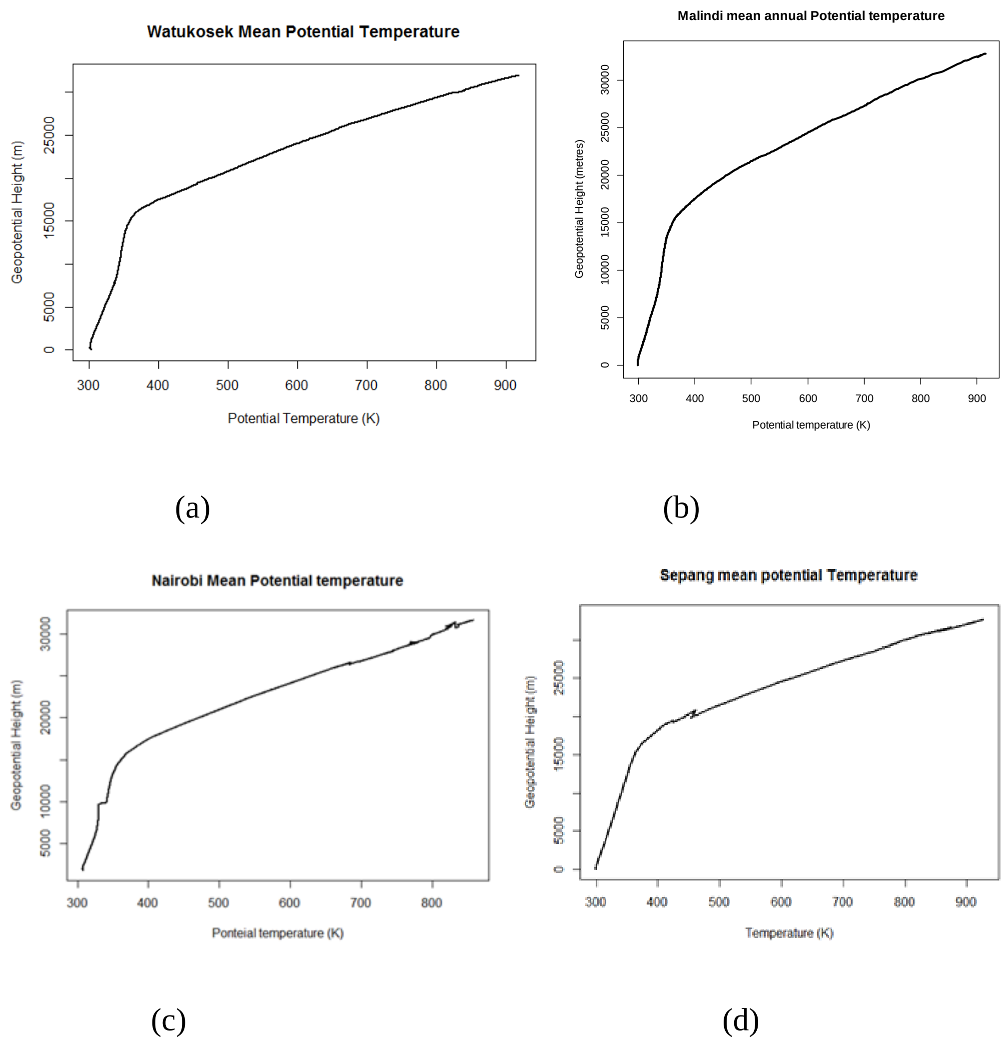
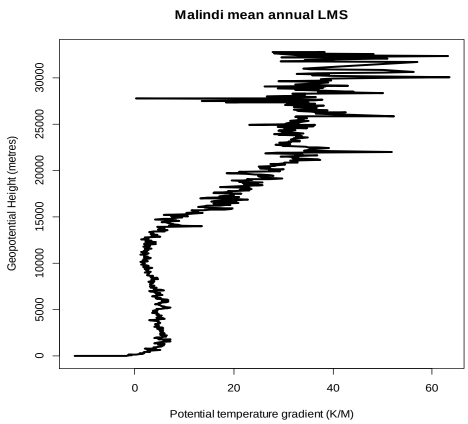


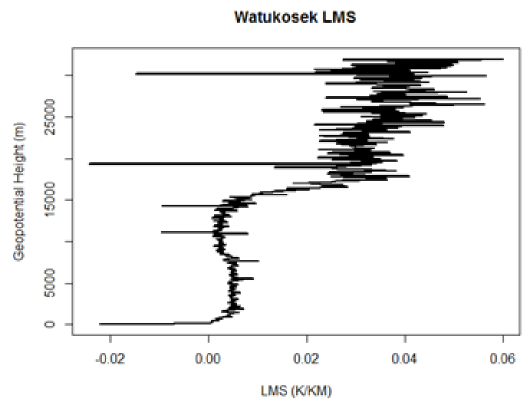
Figure 10: Distribution of mean potential temperature in Kelvin at Malindi (1998-2005), Watukosek (1988-2013), Nairobi (1998-2014) and Sepang (1993-2013). Change of gradient of potential temperature is clearly marked.

4.1.3 Level of Minimum Stability

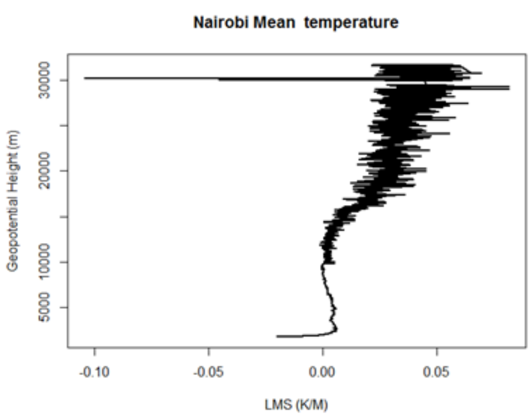
The level of minimum stability (LMS) is defined as the height at which there is minimum change in potential temperature gradient (dθ/dz) in kelvin per meter (k/m). Figure 11 shows the change in potential temperature gradient with geopotential height at Watukosek, Malindi, Nairobi and Sepang. From Figure 11, it can be concluded that LMS (k/m) shows greater variability at all the four stations, but averages to a mean minimum at an altitude of 13.7km, 13.6km, 13.4km and 14.0km asl for Malindi, Watukosek, Nairobi and Sepang respectively. This is in agreement with a recognized feature for the deep convective discharge (outflow) in the tropics and has been revealed to be consistent with the sea surface equivalent potential temperature circulations (Folkins *et al.*,., 1999; Folkins, 2002). These levels are also markedly below the CPT tropopause level. They signify the end of the height of the top of overshooting convective clouds and convective.



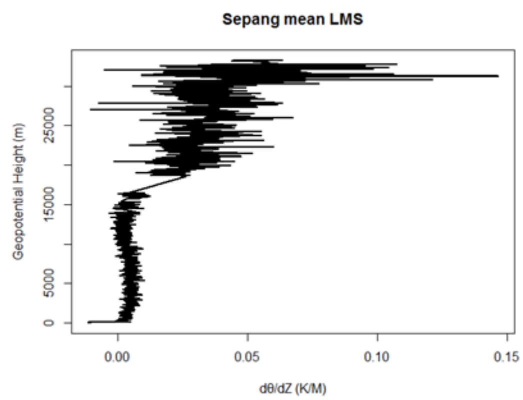
(a)



(b)



(c)

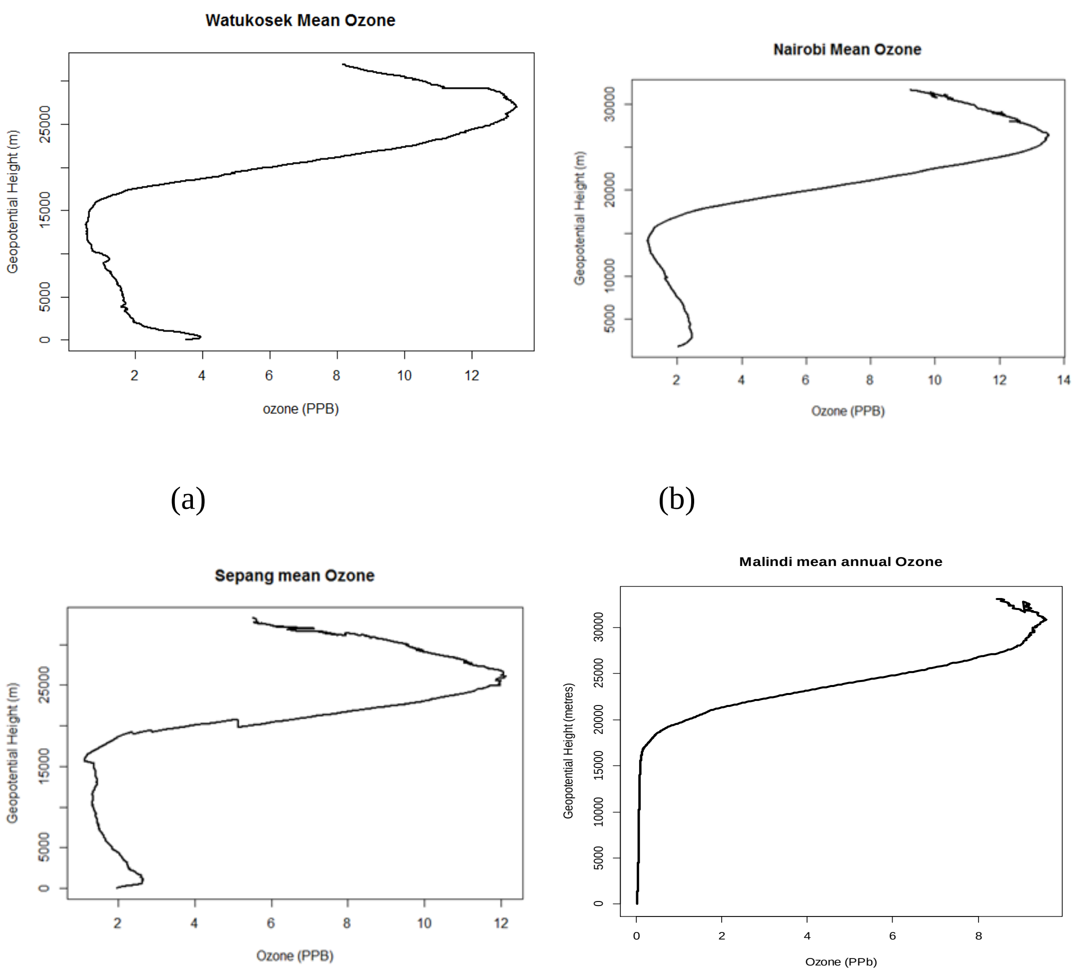


(d)

Figure 11: Graphical display of the change in potential temperature gradient with height over Malindi (1998-2005), Watukosek (1988-2013), Nairobi (1998-2014) and Sepang (1993-2013)

4.2 Determination of Chemopause Level

Chemopause refers to change of gradient in O_3 mixing ratios. In this case, there is minimum chemopause which corresponds to the lowest value at which O_3 mixing ratios change gradient and the maximum chemopause when O_3 mixing ratios change in gradient is maximum. Figure 12 shows a plot of mean ozone mixing ratios against the geopotential height for Malindi, Watukosek , Nairobi and Sepang .



(a) (b)

(c) (d)

Figure 102: Graphical presentation of mean Ozone mixing ratios vertical profile at *Malindi (1998-2005), Watukosek (1988-2013), Nairobi(1998-2014) and Sepang (1993-2013). The minimum and maximum chemopause levels are clear visible.*

From Figure 12, it is evident that ozone vertical profiles show clearly inverted S-shaped graphs with the minimum and maximum chemopause well-marked out. At Watukosek, Nairobi, Sepang and Malindi the mean minimum O_3 chemopause values are at 13.8, 14.9, 15.1 and 15.5 km ASL respectively. All the stations indicate that minimum ozone (Chemopause) occurs below the cold point tropopause CPT but slightly above deep convective outflow level. This is deduced to be the consequence of end of convection and main convective discharge level (Folkin 2002) and transboundary enhancement i.e. O_3 enhancement from the stratosphere due to atmospheric waves.

Table 2: Display of summary of the levels of minimum stability, minimum chemopause level and cold point temperature tropopause level in kms at Watukosek, Nairobi, Sepang and Malindi

No	Station	LMS (km)	Min chemopause(km)	CPTT (km)
1	Watukosek	13.6	14.2	16.6
2	Nairobi	13.4	14.9	17.2
3	Sepang	14.0	15.1	18.2
4	Malindi	13.7	15.5	16.2

4.3 Characterization of Vertical Temperature and Ozone

The mean seasonal variation of O_3 mixing ratios, Potential temperature and ambient temperature were calculated and plotted against geopotential height. The seasons were defined as follows and based on the known long rain season of March, April and May (MAM), June, July and August (JJA), September, October and November (SON) and December, January and February (DJF).

From Figure 13, Nairobi shows compacted (close) seasonal ozone profiles both in the troposphere and lower stratosphere. The seasonal ozone variations in both the troposphere and tropopause may be attributable to turbulent air motions which promote non-uniform distribution of ozone precusors and long range transport from biomass burning.

Similarly, Malindi profile depicts low ozone mixing ratios in the troposphere indicating clean maritime air and somewhat highly variabile flactuations of O_3 partial pressures in the lower stratosphere.

Watukosek shows seasonal fluctuations of Ozone in the stratosphere and showing the highest pollution levels in the free atmosphere amongst the four stations under investigation as shown by high ozone mixing ratios. SON season has the highest ozone mixing ratio of 5.0ppv followed by JJA season. The distribution in the stratosphere exhibits minimal flactuations of O_3 mixing ratios.

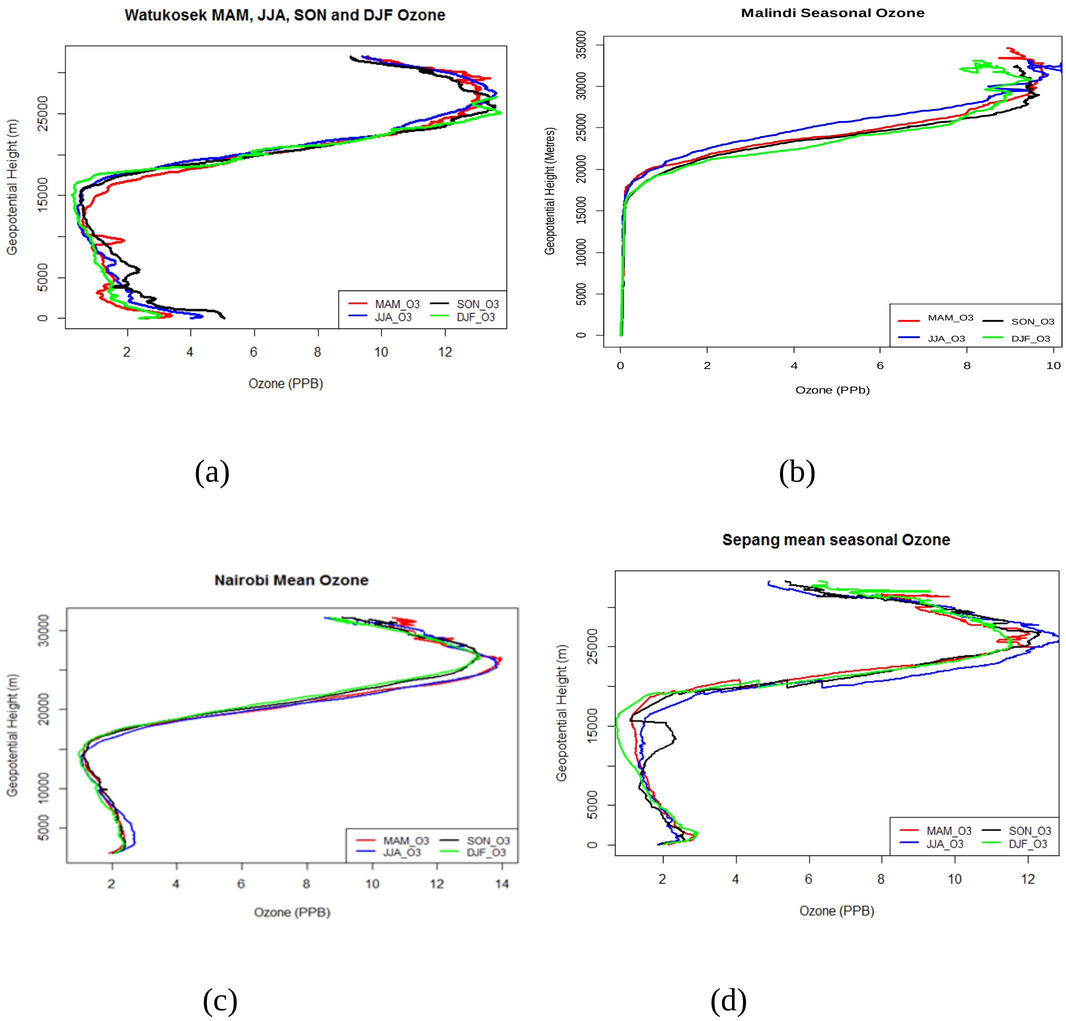


Figure 113: Display of seasonal i.e. DJF, MAM, JJA and SON, variation of vertical Ozone at Watukosek (1988-2013), Malindi (1998-2005), Nairobi (1998-2014) and Sepang (1993-2013).

Sepang shows high variability O_3 around the minimum chemopause. Also evident is the early change of gradient (Chemopause) due to ozone enhancement before cold point tropopause. This is attributable to incursion of O_3 from the stratosphere to the troposphere occasioned by the presence of breaking equatorial Kelvin waves which result in a descending motion leading to dilution of stratospheric air into the TTL and destruction of upward mixing associated with tropical deep convection above 14km. DJF season has the lowest Ozone mixing ratios among the four stations in the troposphere. The potential temperature at the four stations, indicate slight variability with early onset of the gradients before the tropopause as shown in figure 14. MAM has the highest values of pontential temperature in the stratosphere except at Sepang where DJF has the highest. Malindi exhibits the highest flactuations of potential temperature in the stratosphere.

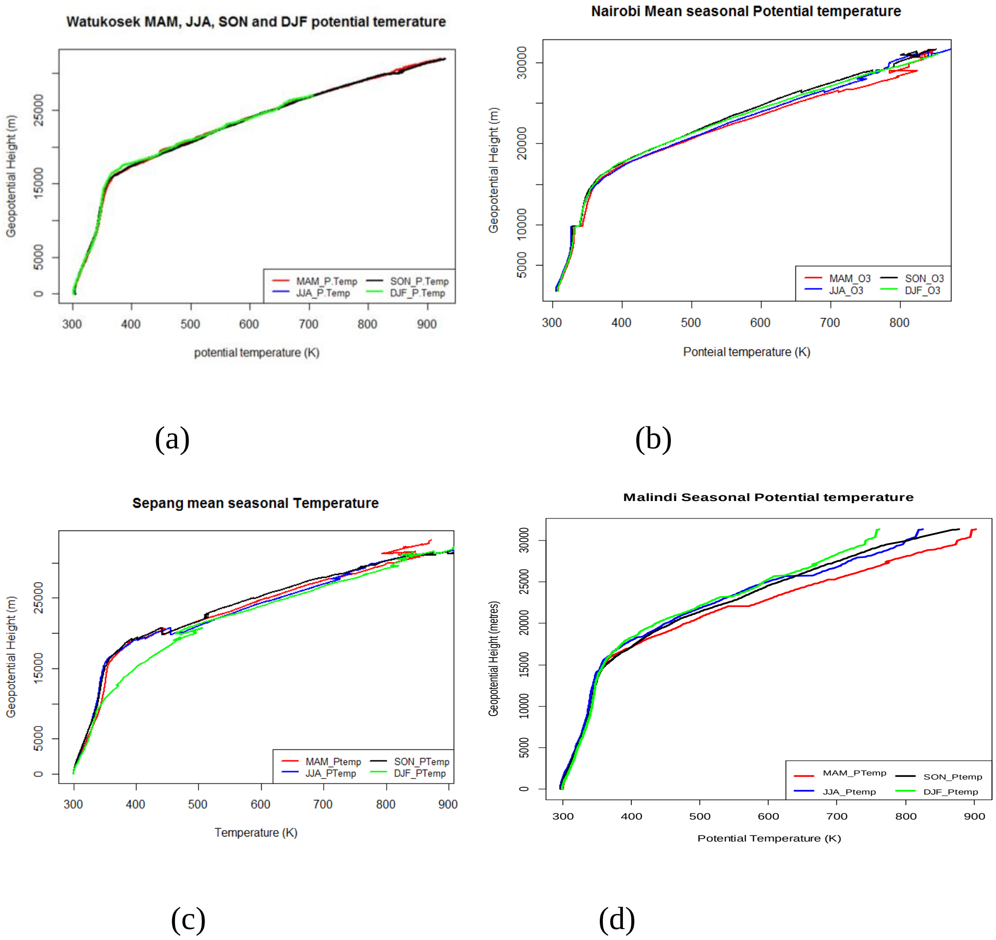


Figure 124: Display of vertical profiles of DJF, MAM; JJA and SON seasonal potential temperature (k) at Watukosek (1988-2013), Malindi (1998-2005), Nairobi(1998-2014) and Sepang (1993-2013).

Nairobi and Watukosek indicate almost slight seasonal temperature variability in the troposhere (Figure 15). The seasonal ambient air temperature at the two stations are close, an indication of slight seasonal variability in the lower atmosphere with clear seasonal variabilty of cold point tropapause discernable. Similarly, Malindi seasonal ambient air tempearture curves are close to each other with some noticeable seasonal variability towards cold point tropopause. However, there is some marked flactuations of ambient temperature in the lower stratosphere.

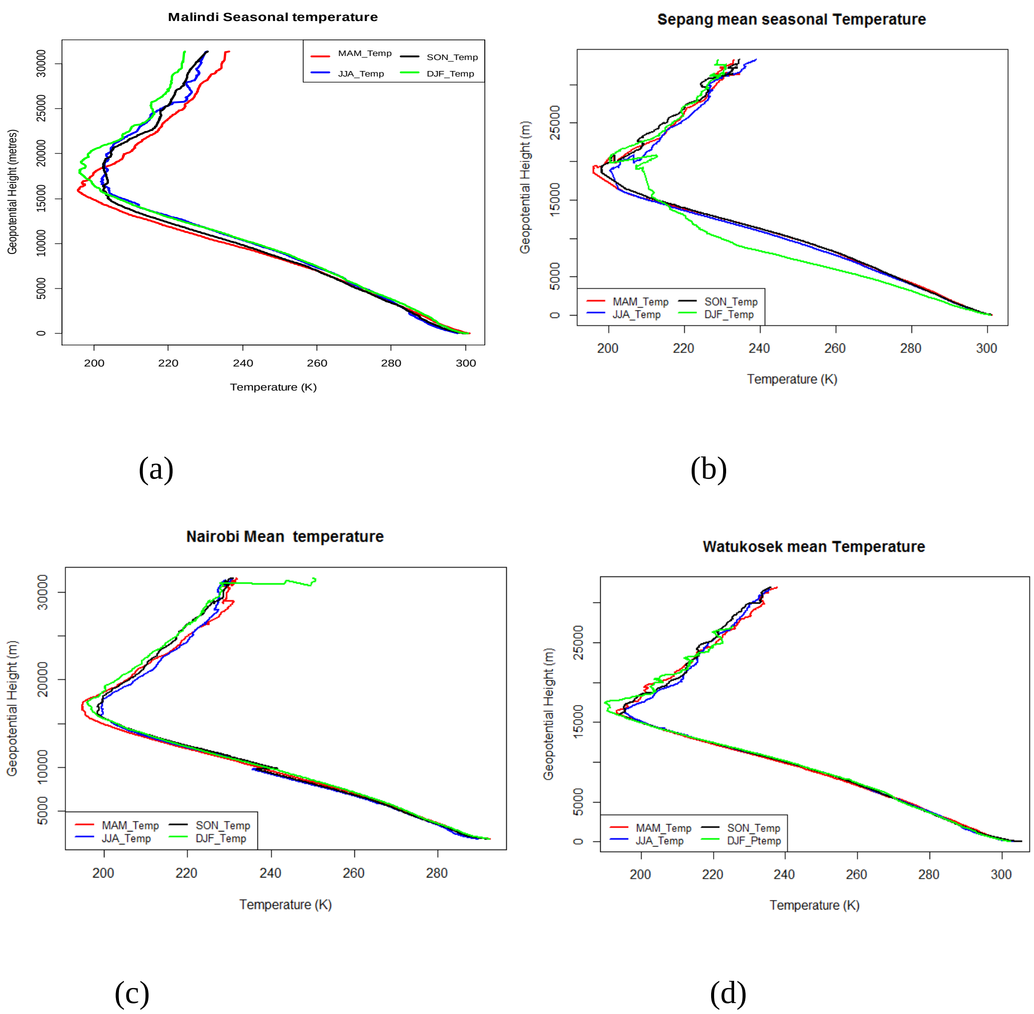


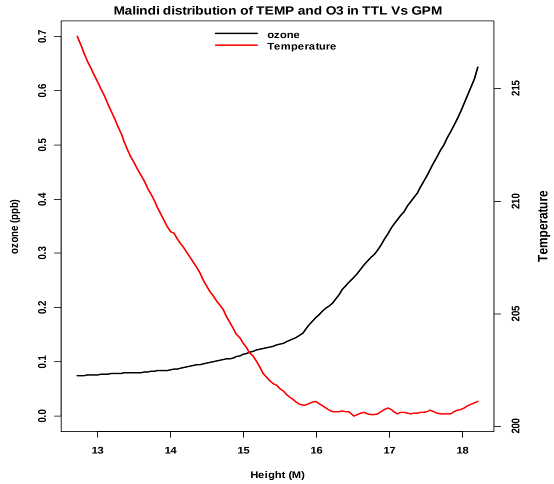
Figure 135: Graphical presentation of vertical profile of mean seasonal ambient air temperature (k) at Watukosek (1988-2013), Malindi (1998-2005), Nairobi (1998-2014) and Sepang (1993-2013).

The cause of these seasonal fluctuations of ambient air temperature is the non-uniform distribution of vertical water vapour, convection in the lower atmosphere and radiative in the middle atmosphere.

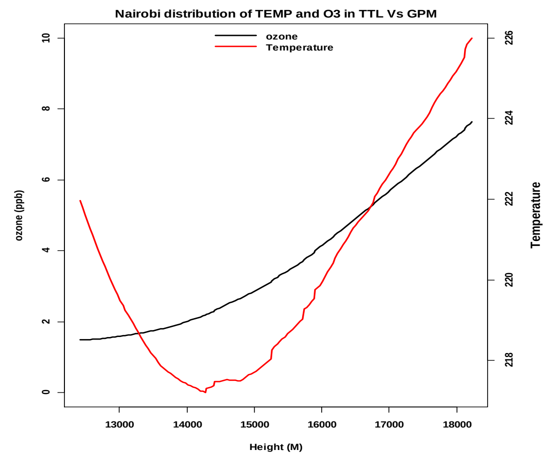
4.3.1 Investigation of Ozone and Temperature against height in TTL

The distribution of ozone mixing ratios and ambient temperature against height in the TTL at Watukosek, Malindi, Nairobi and Sepang was plotted. The results are displayed in Figure 16. This was achieved by reversing the axis i.e. height becoming the ordinate (y-axis) in order to gain much insight on how O_3 and ambient temperature curves behave in the TTL. From Figure 16, Malindi O_3 mixing ratios range between 0.1ppb and 0.7ppb and lowest O_3 values amongst the four stations. Nairobi exhibits the highest O_3 values ranging between 1.8ppb and 8.0ppb. The ambient air temperature ranges from 217k to 226k. Watukosek O_3 values are in the range of 0.5 to 2.1ppb while temperature ranges from 194 to 218k. Sepang O_3 values range from 0.8ppb to 2.0ppb and the temperature is between 200k and 216k.

At all the four stations, temperature continue to decrease as O_3 increases steadily and fast. This is due to intrusion of O_3 from the stratosphere into the troposphere caused by atmospheric waves. The other reason for start of O_3 increase in this region is the end of convective overshooting clouds.



(a)



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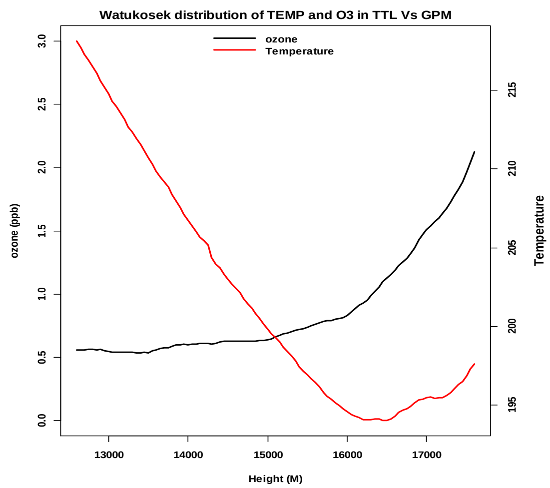

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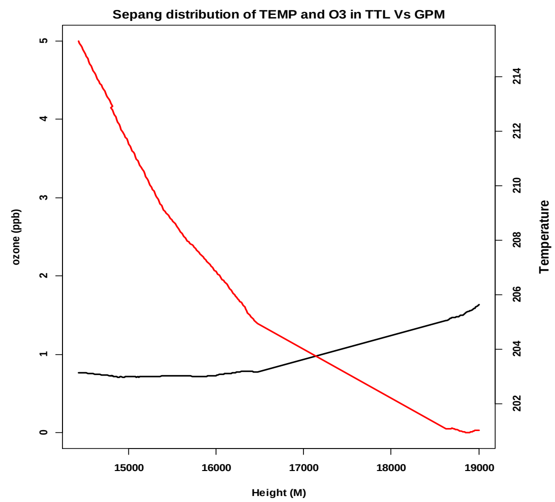


(d)

Figure 146: Display of O_3 mixing ratios (ppb) and ambient temperature (k) in the TTL at Watukosek (1988-2013), Malindi (1998-2005), Nairobi(1998-2014) and Sepang (1993-2013) verses geopotential height (m).

4.4 Correlation O_3 and Temperature at TTL

The correlation between O_3 and ambient temperature was computed for the four stations to determine any linear relationship at the LMS and CPTT. The correlation coefficients of Sepang, Watukosek and Malindi showed moderate negative linear relationship between Ozone mixing ratios and ambient temperature (Table 3). Nairobi indicated a strong positive linear relationship between the variables of Ozone mixing ratios and ambient temperature. This can be attributed to the climatology of the four stations. Nairobi is the only continental station and the other three, Malindi, Sepang and Watukosek are Maritime (close to Indian Ocean). This difference in climatology may account for the strong positive linear relationship of correlation coefficient of 0.8886 between Ozone and temperature obtained in Nairobi. The altitude of Nairobi is also high and therefore the station benefits from transboundary transport of O_3 and cross hemispheric flow since it is located on the equator. The increasing urban heat island and pollutants may also contribute to high O_3 values over Nairobi.

Table 3: Results of correlation coefficients of O_3 (ppb) and ambient temperature (k) in the TTL, values of t-computed and t_Critical for Watukosek, Nairobi, Sepang and Malindi

No	Station	r	t_computed	t_Critical
1	Watukosek	-0.4087	-4.225	-3.402
2	Nairobi	0.8886	28.273	3.39
3	Sepang	-0.5449	-14.719	-3.31
4	Malindi	-0.5182	-8.397	-3.357

Student t-test was used to test for the significance of relationships between ozone mixing ratios and ambient temperature at all the four stations at $\alpha=0.05$ (95%) confidence level using student t-test with 2 degrees of freedom. From table 2, the t_computed value for Nairobi is greater than the t_critical value. This means that the correlation between Ozone and temperature is statistically significant. Hence the null hypothesis was rejected. This observation at Nairobi may be due to convective, transboundary transport and detrainment of marine depleted air mass. However, for Sepang, Watukosek and Malindi, the t-computed was less than t-critical and therefore the correlation was not statistical significant despite big r values i.e. null hypothesis was accepted.

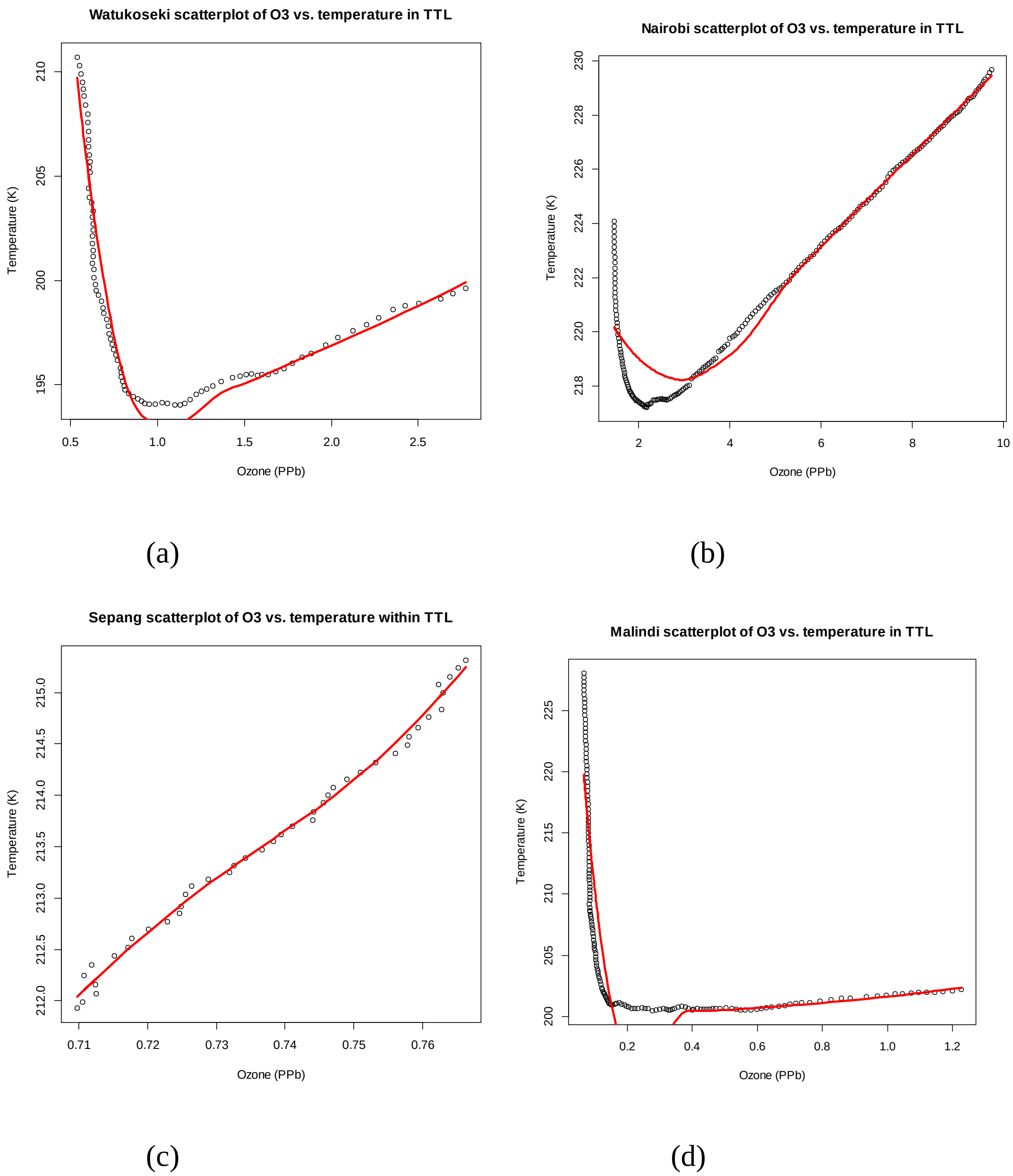


Figure 157: Scatterplots of O_3 (ppb) verses ambient temperature (k) within the TTL at, Watukosek, Nairobi, Sepang and Malindi. Red line is locally weighted least squares regression, Loess which was fitted to indicate any relationship between O_3 (ppb) and temperature (k).

From the Figure 17, scatterplots of O_3 mixing ratios against ambient temperature within the TTL, there is no linear relationship between ambient air temperature and O_3 mixing ratios from the four stations except Sepang. Therefore the assumption that the relationship between temperature and ozone variable is monotonic and constant across the domain and range of each variable (i.e. that as Ozone increases, temperature also increases at the same rate for all Ozone and temperature) is not true. Locally weighted least squares regression Loess, was used for smoothing at a span of 0.75. There was no known pattern that was again visible except at Sepang. Sepang displays a linear relationship.

4.4.1 Correlation of Ozone and ambient temperature between Level of Minimum Stability and Chemopause and Chemopause and Cold Point Temperature Tropopause

Further investigation of relationship between O_3 and ambient temperature from LMS to Chemopause was done as shown in table 4.

Table 4: Results of correlation coefficients of O_3 and temperature between LMS to Chemopause at Watukosek, Nairobi, Sepang and Malindi

No	Station	r_Chemo Pause	p-value	95 % confidence interval
1	Watukosek	-0.443	=1.559e-05	-0.658, -0.294
2	Nairobi	0.944	< 2.2e-16	0.929, 0.956
3	Sepang	0.994	= 0.0023	0.989, 0.997
4	Malindi	-0.921	< 2.2e16	-0.966, -0.920

Table 4 r values are significant, -ve at Malindi and Watukosek indicating strong –ve relationship between O3 and ambient temperature and +ve at Nairobi and Sepang and an indication of strong +ve relationship.

Table 5 has –ve r values at Watukosek and Malindi and +ve values at Nairobi and Sepang. Watukosek, Malindi and Nairobi indicate strong relationship between O3 and ambient temperature in the TTL.

The correlation coefficient of O_3 and ambient temperature between the LMS and the Chemopause at Watukosek, Nairobi, Sepang and Malindi is -0.443, 0.944, 0.994 and -0.921 respectively. Watukosek and Malindi have moderate and strong negative r values.

Table 5: Results of correlation coefficients between O3 and ambient temperature from chemopause to cold point temperature tropopause

No	Station	R_CPTT	p-value	95 % confidence interval
1	Watukosek	-0.498	= 0.0023	-0.6518, -0.1719
2	Nairobi	0.332	< 2.2e-16	0.300, 0.363
3	Sepang	-0.883	< 2.2e-16	-0.913, -0.842
4	Malindi	0.020	= 0.8495	-0.226, 0.187

This means that an increase in O_3 leads to a decrease in ambient temperature and an increase in ambient temperature corresponds to a decrease in O_3. Nairobi and Sepang have strong positive correlation coefficient, r, of O_3 and temperature between LMS stability and Chemopause level. This implies that both temperature and O_3 increase in this layer. Watukosek, Sepang and Malindi have very low p-value (probability of the four station have very small values. The null hypothesis is rejected from the layer between Chemopause and CPT i.e. the relationship between O_3 mixing ratios and ambient temperature is statistically significant.

Watukosek, has moderate negative r between LMS and Chemopause and Chemopause and CPTT. In both layers the relationship is statistically significant.

Malindi has strong negative r of 0.921 between LMS and Chemopause and week r between Chemopause and CPTT.

Nairobi has strong positive r of 0.944 between LMS and chemopause and moderate r from chemopause to CPT.

4.5 Lagged Correlation of Ozone at Chemopause and Sea surface temperature

The serial correlation of O3 at chemopause to SSts at three regions; namely, 60°E-70°E, 3°N-20°N, 55°E-60°E°, 33°S-26°S and 30°E-60°0E, 44°S-40°S was performed and results tabulated in Table 6

Cross correlation analysis was performed in order to find out if there was any cyclic pattern between O_3 and SSTs. This revealed repeating patterns reminiscent with annual seasons of three months. The r results indicate moderate negative and positive association between Nairobi O_3 at the Chemopause and SSTs

Table 6: Lagged correlation coefficient r for Nairobi and Malindi between O3 and SSTs for regions 60°E-70°E, 3°N-20°N; 55°E-60°E, 33°S-26°S and 3°0E-60°E, 44°S-40°S

Nairobi				Malindi		
Lag	r_7060	r_5560	r_3060	r_7060	r_5560	r_3060
0	0.38	-0.31	-0.32	-0.13	-0.15	0.27
1	0.34	-0.34	-0.35	-0.02	0.003	0.17
2	0.14	-0.27	-0.27	0.14	0.09	0.02
3	0.002	-015	-0.13	0.23	0.15	-0.1
4	0.08	-0.01	-0.01	0.22	0.2	-0.18
5	0.21	0.12	0.10	0.17	0.18	-0.2
6	0.13	0.24	0.2	0.1	0.11	-0.12
7	-0.16	0.33	0.27	0.01	0.03	-0.06
8	-0.42	0.32	0.32	0.1	-0.04	-0.06
9	-0.47	0.22	0.24	-0.16	-0.12	-0.03
10	-0.25	0.06	0.04	-0.17	-0.18	0.81
11	0.08	-0.13	-0.17	-0.12	-0.2	0.18
12	0.32	-0.29	-0.3	-0.06	-0.16	0.19
13	0.32	-0.34	-0.33	-0.03	-0.02	0.12
14	0.13	-0.29	-0.27	0.15	0.1	-0.02
15	0.01	-0.16	-0.15	0.28	0.22	-0.12

4.5.1 Regression of Ozone and Sea surface temperature at Chemopause

Three locations i.e. 60°E-70°E, 3°N-20°N, 55°E-60°E°, 3°S-26°S and 30°E-60°0E, 44°S-40°S located in Indian ocean whose SSTs are operationally used as predictors for East African seasonal rainfall prediction (Ininda, 1999 and 2000) were used in lagged regression for all the months with ozone partial pressures at chemopause as the predictor.

Nairobi and Malindi showed significant lagged correlation. The lagged r^2 values are generally persistently significant up to five months. This alludes to the long memory of the (water bodies), oceans.

Table 7: *Lagged regression coefficient r^2 for Malindi between O_3 at Chemopause level and SSTs 60°E-70°E, 3°N-20°N ; 55°E-60°E°, 33°S-26°Sand 30°E-60°0E, 44°-40°S regions in the Indian Ocean*

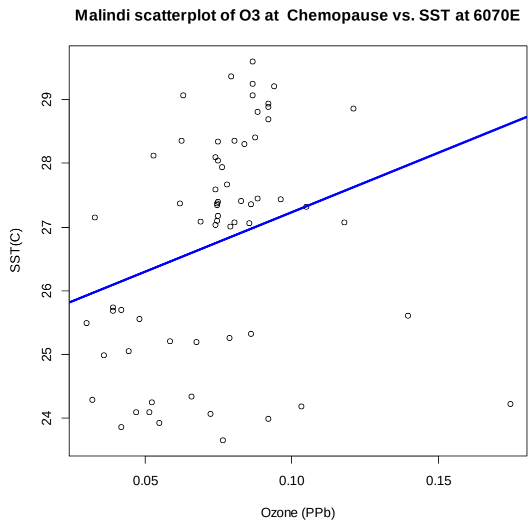
Malindi r^2	60°E-70°E, 3°N-20°N	55°E-60°E°, 33°S-26°S	30°E-60°0E, 44°-40°S
Lag 0	0.075	0.0254	0.0178
Lag 1	0.079	0.06123	0.0326
Lag 2	0.038	0.066	0.0416
Lag 3	0.005716	0.0539	0.0308
Lag 4	0.000319	0.0189	0.0163
Lag 5	-0.01785	0.0061	0.0004

The r^2 lagged values are insignificant, therefore Malindi O_3 at chemopause has no significant relationship with SSTs at the selected regions.

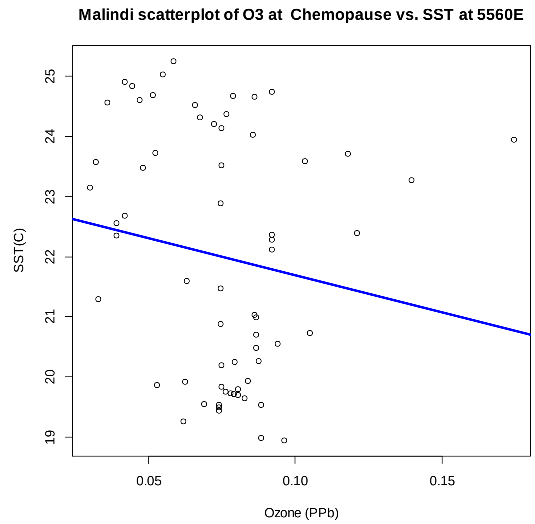
Table 8: Lagged regression coefficient r^2 for Nairobi between O_3 at Chemopause level and SSTs at 60°E-70°E, 3°N-20°N; 55°E-60°E°, 33°S-26°Sand 30°E-60°0E, 44°-40°S regions in the Indian Ocean

Nairobi r^2	60°E-70°E, 3°N-20°N	55°E-60°E°, 33°S-26°S	30°E-60°0E, 44°-40°S
Lag 0	0.012	0.141	0.105
Lag 1	0.053	0.024	0.037
Lag 2	0.213	0.0001	0.001
Lag 3	0.188	0.0348	0.052
Lag 4	0.026	0.093	0.093
Lag 5	-0.018	0.105	0.081

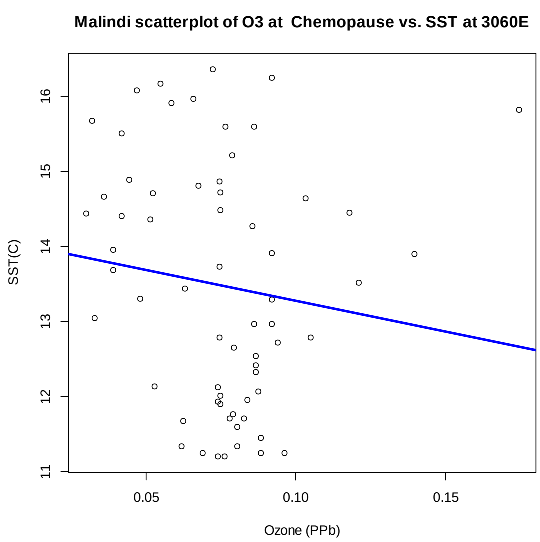
Table 8 shows r^2 lagged results for Nairobi and are values are also insignificant. Since the r^2 values are very insignificant for both Malindi and Nairobi, the null hypothesis is accepted that is there is no trend between O_3 mixing ratios and SSTs over 60°E-70°E, 3°N-20°N 55°E-60°E°, 33°S-26°Sand 30°E-60°0E, 44°-40°S in the Indian Ocean.



(a)



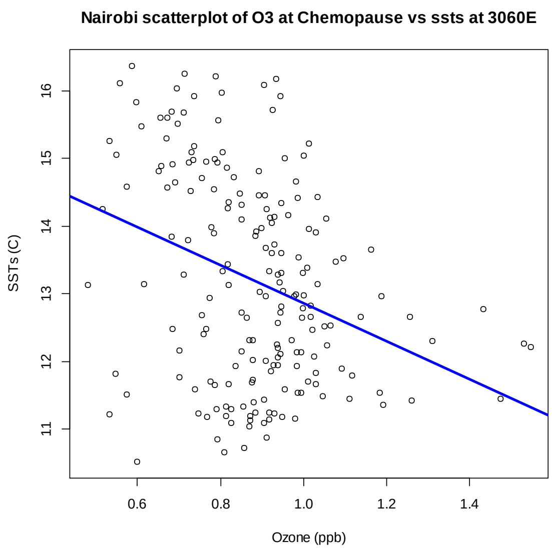
(b)



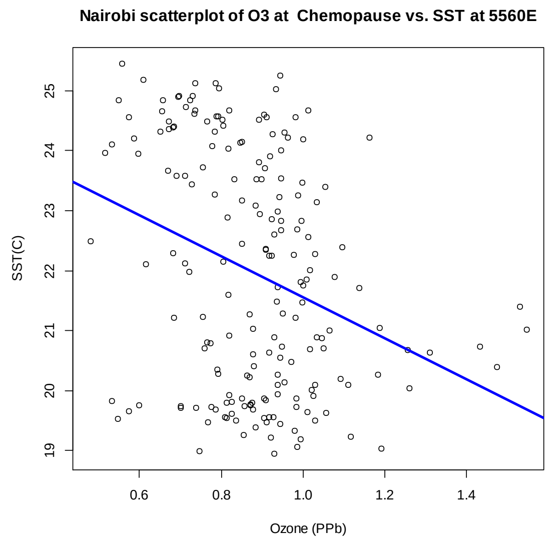
(c)

Figure 18: Malindi scatter plot of O3 and SSTs for 60°E-70°E; 33°N-20N, 55°E-60°E; 33°S-26°S and 30°E-60°E; 44°S-40°S

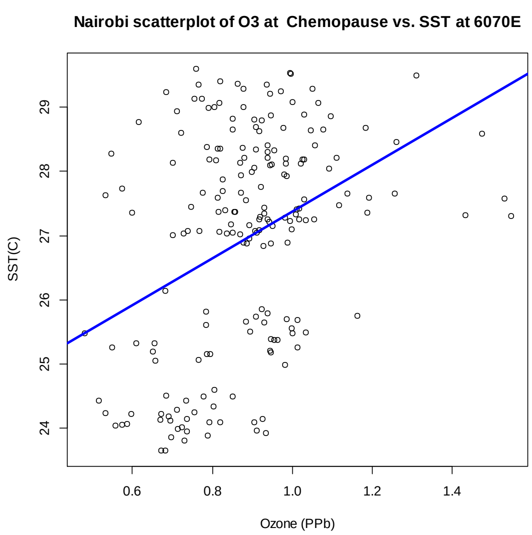
Figure 18a and b show two clusters up and bottom. Figure 18c and b indicate –ve relationship while 18a indicate +ve relationship. However the relationship are not statistically significant.



(a)



(b)



(c)

Figure 19: Nairobi scatter plot of O_3 (ppb) mixing ratios and SSTs (C)for regions 55°E-60°E; 33°S-26°S and 60°E-70°E;33°N-20°N in Indian ocean

Figures 18 and 19 are display of time series of scatter plots of ozone mixing ratios and SSTs for periods from 1998 to 2014 for Nairobi and 1998 to 2005 for Malindi. Also shown is an estimated regression lines. Figure 19c has two clusters up and bottom with –ve relationship suggesting non linearlity. While figures 18a and b have +ve relationship. Again the relationships are statistically insignificant.

Table 9: Results of α and β for Nairobi and Malindi between O_3 and SSTs for regions 60°E-70°E, 3°N-20°N; 55°E-60°E, 33°S-26°S and 3°0E-60°E, 44°S-40°S

	Nairobi			Malindi		
Region	60°E-70°E 3°N-20°N	55°E-60°E 33°S-26°S	30°E-60°E 44°S-40°S	60°E-70°E 3°N-20°N	55°E-60°E 33°S-26°S	30°E-60°E 44°S-40°S
α (y-intercept)	-1.625	4.889	3.923	-0.302	2.949	-6.813
β (slope)	3.6598	-3.414	-2.802	18.692	-12.335	0.618

From Figure 20a and c forecasted SSTs have no any graphical similarities with observed SSTs. 20b shows some graphical similarities but underestimates the forecasted SSTs.

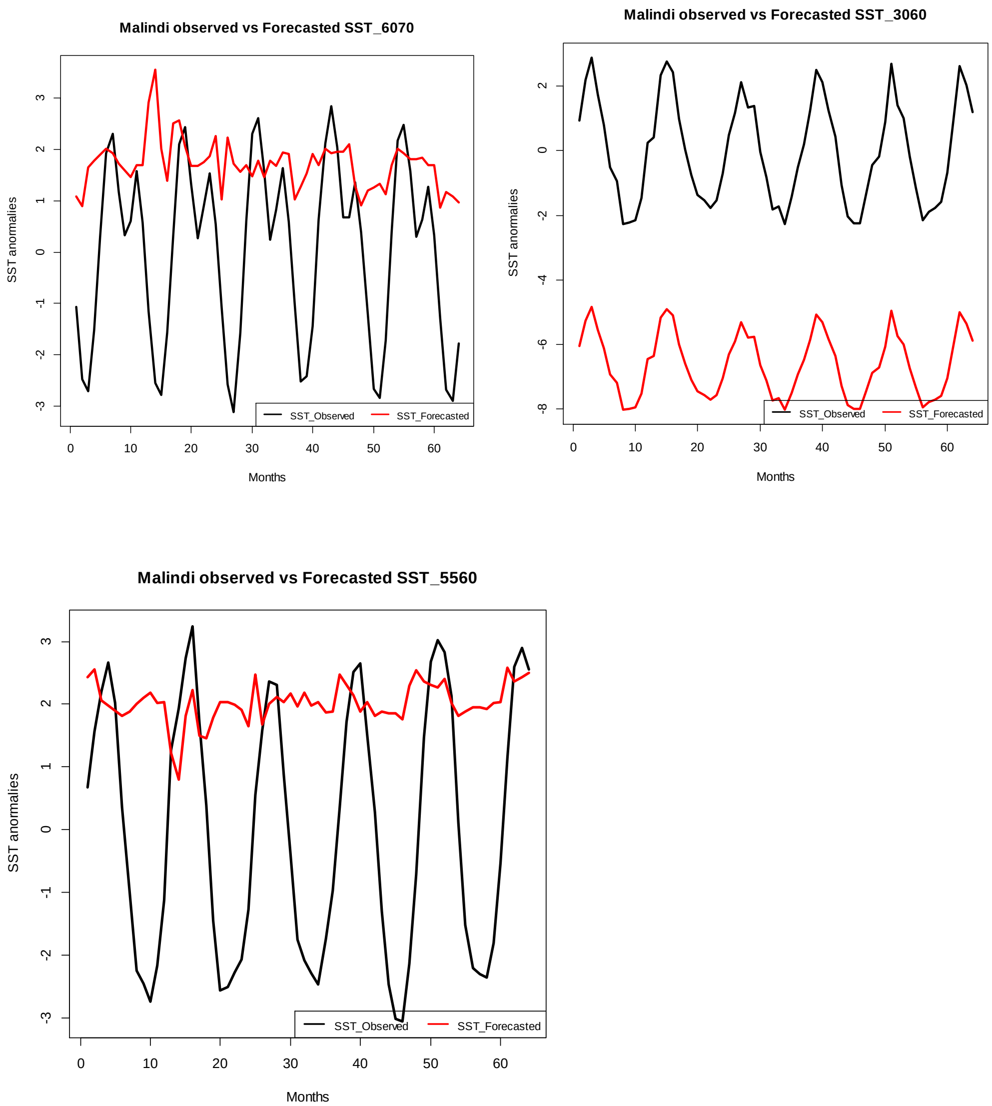


Figure 160: Malindi Graphs of observed and forecasted SSTs at 60°E-70°E, 33°N-20°N; 55°E-60°E°,33°S-26°S and 30°E-60°0E, 44S°-40°S using O_3 at Chemopause level.

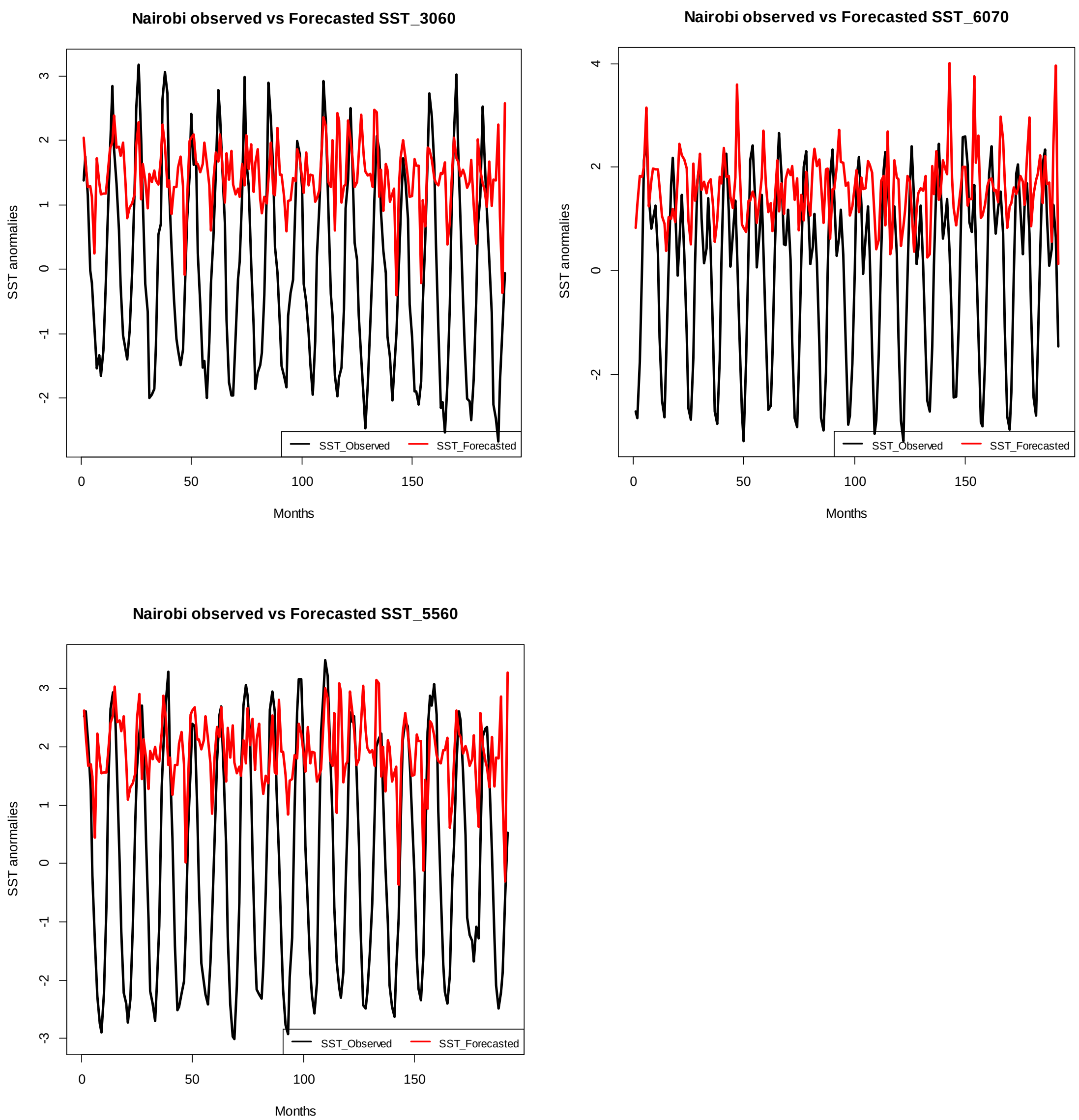


Figure 171: Nairobi Graphical display of observed and forecasted SSTs against time in Months for regions,60°E-70°E, 33°N-20°N; 55°E-60°E°,3

Though Nairobi model forecast is in phase with the observed, the model under estimated the SSTs for all the three regions of concern. The lagged regression coefficients were minimal and therefore not significant. The consistency of Nairobi models to forecast SSTs reveal that SSTs at those regions can be forecasted with a lead-time of several months an indication that the time evolution of the SSTs over these regions can be predicted using Nairobi O_3 at chemopause. Therefore Nairobi O3 at Chemopause can be used instead of SSTs and increase lead time to predict seasonal weather/climate over Kenya.

CHAPTER FIVE

5.0 Conclusion and Recommendations

This study has shown strong influence of rainfall over Kenya by SSTs at locations 60°E-70°E, 3°N-20°N, 55°E-60°E°, 33°S-26°S and 30°E-60°0E, 44°-40°S in Indian ocean whose SSTs are operationally used as predictors for Kenya's seasonal rainfall prediction, to Nairobi equatorial continental ozone mixing ratios variability. Also the study revealed statistically a significant strong positive correlation of 0.886 between Ozone and temperature at the upper troposphere and lower stratosphere over Nairobi. Therefore the variability of Ozone mixing ratios at 14.9km over Nairobi can be used instead of SSTs to predict seasonal weather/climate over Kenya.

Also revealed is the higher and lower boundaries of TTL layer over Nairobi, Malindi, Sepang and Watukosek as 13.4 to 17.2, 13.7 to 16.8, 14.0 to 18.2 and 13.6 to 16.6 km asl, respectively. Within this TTL, O_3 starts to increase while ambient temperature continues to decrease up to the higher boundary which corresponds to CPT. These levels also marked the subordinate and superordinate boundaries of TTL at the four stations.

5.3 Recommendations

In this research, four in situ ozonesonde measurement stations data were used; namely, Nairobi, Malindi, Sepang and Watukosek. Nairobi was the only continental station since the other three stations are close to Indian Ocean. In terms of altitude, Nairobi was also the highest station.

Therefore, this study strongly recommends establishment of more Ozonesonde stations in the tropics but inland i.e. away from the global oceans. This will ensure measurements of continental air mass whose O_3 is strongly affected by SSTs.

Further similar work needs to be undertaken for Pacific and Atlantic Oceans focusing on the behavior of O_3 in the TTL and possible linkages to SSTs and El Nino indices. More so continental stations should be investigated.

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