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SIMULATION OF RADIATIVE FORCING DUE TO AEROSOLS OVER SOME COUNTIES IN KENYA

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ABSTRACT

The Coupled Ocean and Atmosphere Radiative Transfer (COART) model solved a radiative transfer equation from aerosol optical thickness data derived from Moderate Resolution Imaging Spectroradiometer (MODIS) spanning 2000 to 2015.

The temporal and spatial variation of aerosols optical depth was determined on Giovanni platform. Trajectory modelling was carried out using Hybrid Single Particle Langrangian Model (HYSPLIT). Integrated fluxes were generated from COART model. Counties investigated are Mombasa, Lamu,Nairobi, Kakamega, Bungoma, Nyeri, Meru, Machakos, Turkana, Tranzoia, Baringo, Nakuru, Narok, Kisumu, Kisii, Nyamira and Busia. Simulation of future warming over Kenya was also done using MAGGIC SCENGEN model under two scenarios.

Results of the study revealed that Turkana, ASAL and Maritime Counties had the highest aerosols loading while Kisii County had the lowest aerosols loading respectively and that aerosol loading was highest during the JJA season and that Garrissa County had the highest interannual variability of aerosols. The study revealed that aerosol loading across all Kenyan counties is reducing and that long distance transport and dispersion of aerosols was facilitated by low level winds over Kenya. It was observed that Kisii County had higher radiative forcing estimate due to aerosols while counties in the ASAL, Maritime counties and Turkana County had relatively lower corresponding estimates. It was also noted that forcing due to aerosols over Kenya is reducing and lies in the range of -0.187 to -0.05 w/m^2. SCENGEN Projections gave a warming of 0.17 ^{0}C, 0.45 ^{0}C, and 2.96 ^{0}C by the year 2000, 2015 and 2100 respectively due to aerosols and sulphates induced warming of 0.1 and 0.25 ^{0}C under two scenarios.

KEYWORDS: Aerosols, Radiative Forcing, Warming, Counties, Kenya

INTRODUCTION

Aerosols in the atmosphere strongly influence the transfer of radiant energy and the spatial distribution of latent heating through the atmosphere, despite their mass or volume fraction, thereby influencing the weather and climate.

According to fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the total anthropogenic Effective radiative forcing (ERF) over the industrial era is 2.3 (1.1 to 3.3) W m^{-2}. The ERF due to aerosol–radiation interactions (ERFari) that takes rapid adjustments into account is assessed to be –0.45 (–0.95 to +0.05) W m^{-2}. The radiative forcing (RF) from absorbing aerosol on snow and ice is assessed separately to be +0.04 (+0.02 to +0.09) W m^{-2}. Prior to adjustments taking place, the RF due to aerosol–radiation interactions (RFari) is assessed to be –0.35

(–0.85 to +0.15) W m^{-2}.The assessment for RFari is less negative than reported in fourth assessment report because of a re-evaluation of aerosol absorption. The uncertainty estimate is wider but more robust, based on multiple lines of evidence from models, remotely sensed data, and ground-based measurements. Fossil fuel and biofuel emissions contribute to RFari via sulphate aerosol: –0.4 (–0.6 to –0.2) W m, black carbon (BC) aerosol: +0.4 (+0.05 to +0.8) W m^{-2}, and primary and secondary organic aerosol: –0.12 (–0.4 to +0.1) W m^{-2}. Forcing agents consequently include as aerosols and GHGs.

Globally, the total ERF due to aerosols (ERFari+aci, excluding the effect of absorbing aerosol on snow and ice) is assessed to be –0.9 (–1.9 to –0.1) W m^{-2} with medium confidence. Persistent contrails from aviation contribute a RF of +0.01 (+0.005 to +0.03) W m^{-2} for year 2011, and the combined con -trail and contrail-cirrus ERF from aviation is assessed to be +0.05 (+0.02 to +0.15) W m^{-2}. Biomass burning +0.0 (–0.2 to +0.2) W m^{-2}, nitrate aerosol: –0.11 (–0.3 to –0.03) W m^{-2}, and mineral dust: –0.1 (–0.3 to +0.1) W m^{-2} (IPCC, 2013).

Recent studies had suggested that 20 up to 50 of the total mineral dust in the atmosphere originate from anthropogenic activities, the precise fraction of mineral dust of anthropogenic origin being extremely difficult to determine. Only the radiative forcing from this anthropogenic component is considered as there is no evidence that the naturally occurring component has changed since 1750. The assessment of the climatic effects of an aerosol with a large variability like mineral dust requires some approximations (Claquin, 1998).

Regionally, Studies by Makokha (2013) revealed a negative radiative forcing estimate due to aerosols over three cities in Kenya. Kenya has been devolved into 47 counties and the quantification of aerosols optical depths at County level together with the corresponding radiative forcing estimates is lacking. This study tries to provide climate monitoring information by determining estimates of radiative forcing due to aerosols in some counties

Radiative forcing by natural and anthropogenic aerosols presently presents one of the most uncertain aspects of climate models due to its dependence on various atmospheric processes e.g., coagulation, cloud cycling and aerosol long distance transport Variations in the radiative characteristics of aerosols can be used to quantify their effects on climate (Makokha, 2013).

The physical and chemical properties of atmospheric aerosols depend on their origin; for instance, aerosols in an urban environment had a higher concentration of sulfur and heavy metals as compared to those from rural environments. (Latha *et al.*, 2005).

Aerosol and ozone exhibit a strong regionality in climate forcing (Monks 2009).Air pollution can alter concentrations of greenhouse gases such as troposphere ozone directly or indirectly via changes in the OH free radical concentration (Mayor 2000). Kenya exhibits high trends of between 0.02-0.56 AOD due to presence of high amounts of sea salt from the indian ocean throught the year (Ngaina et al. 2014).Land clearing and Agricultural fires can enhance AOD (Ngaina et al., 2014).

Aerosols and Greenhouse gases impact on the temperature and forcing respectively. Ozone is not directly emitted and its abundance in the troposphere is determined from a balance of its budget terms: chemical production and influx from the stratosphere, versus chemical loss and deposition to the surface. The magnitudes of these terms are sensitive to the prevailing climate, and the levels and locations of ozone precursor emissions, such as nitrogen oxides (NO and NO_2; referred to as NOx), carbon monoxide (CO) and volatile organic compounds (VOCs), including methane (e.g. Wild, 2007). Ozone concentration in the troposphere is highly variable, ranging from 10 ppb (parts per billion) over the tropical oceans to 100 ppb over land, and can even exceed this last value in polluted urban areas (Denman, 2007). Its variability is dependent on available solar radiation, temperature fluctuations, winds, seasons and altitude, among other factors (IPCC, 2014).

Further, studies between aerosol indices showed a significant relationship in most of the months except for Mombasa city in the month of April where the relationship between absorbing and rainfall was insignificant. In Mombasa city the relationship between non absorbing and rainfall was weak. During the month of April the winds blowing into kenya are south easterlies and hence a station west of Nairobi for, example Kisumu city, showed significant relationship. While this did not demonstrate that one is a cause of the other and vice versa, the relationship suggest a contributing factor of aerosols to rainfall patterns (Mbithi, 2010).

Studies using backward air trajectory analysis showed that the possible sources of aerosols in the NH are Middle East, Sahara and Arabian deserts during February, whereas in the SH, the possible sources are the Congo rain forest, Kalahari and Namibian deserts, Southern Atlantic Ocean, South west Indian Ocean, Madagascar Island and South African region during July. Also, computed was the forward air trajectory analysis over the same locations. The findings of this study established that long distance transport of aerosols and their dispersion through low level winds is responsible for the aerosols affecting the EA region. This greatly depends on the season of the year together with the prevailing atmospheric conditions (Mbithi, 2014)

The eastern Indian Ocean is influenced by the transport from the Indian subcontinent and Southeast Asia, particularly from Indonesia. (Ramathan *et al*, 2001)

Radiative forcing

Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism (IPCC, 2007).

It is an externally imposed perturbation in the radiative energy budget of the Earth’s climate system. Such a perturbation can be brought about by secular changes in the concentrations of radiatively active species (e.g., CO_2, aerosols), changes in the solar irradiance incident upon the planet, or other changes that affect the radiative energy absorbed by the surface (e.g., changes in surface reflection properties). This imbalance in the radiation budget has the potential to lead to changes in climate parameters and thus result in a new equilibrium state of the climate system.

Black carbon in soot is the dominant absorber of visible solar radiation in the atmosphere. Anthropogenic sources of black carbon, although distributed globally, are most concentrated in the tropics where solar irradiance is highest. Black carbon is often transported over long distances, mixing with other aerosols along the way. The aerosol mix can form transcontinental plumes of atmospheric brown clouds, with vertical extents of 3 to 5 km. Because of the combination of high absorption, a regional distribution roughly aligned with solar irradiance, and the capacity to form widespread atmospheric brown clouds in a mixture with other aerosols, emissions of black carbon are the second strongest contribution to current global warming, after carbon dioxide emissions (Ramanathan, 2008).

Until about the 1950s, North America and Western Europe were the major sources of soot emissions, but now developing nations in the tropics and East Asia are the major source regions of black carbon.

Local wind blown dust related to agricultural activities and fire burning has been found to dominate the lower tropospheric aerosols in Nanyuki Kenya. There is no conclusive evidence of long range-transported aerosols being moved by night transport from the middle to the lower parts of the troposphere. Influence of the Indian Ocean marine aerosol is suggested (Gatari, 2001)

A comparison experiment varying trace gas forcing suggests that negative forcing by troposphere aerosols (and perhaps volcanoes, ozone, and land use changes) has been about −1.2 W m^{-2} since 1700, implying approximately equal contribution from direct and indirect tropospheric aerosol effects (Rind, 2012)

Using a radiative transfer model embedded in a general circulation model, It was found that dust from disturbed soils causes a decrease of the net surface radiation forcing of about l Wm^{-2}, accompanied by increased atmospheric heating that may be a significant forcing of atmospheric dynamics. These findings suggest that mineral dust from disturbed soils needs to be included among the climate forcing factors that are influenced by human activities (Tegen, 2012).

Studies between December 2010–May 2011 over Pune in India show significant day to day variability and covaries with AOD as a result of the ant correlation between aerosol direct radiative forcing (ADRF)/AOD, and also the differences in the daily maximum minus minimum relative humidity and temperature. Specifically, at Nowrosjee Wadia College, ADRF ranges between –37.7 W/m^2 (highest) and –5.9 W/m^2 (lowest). For 500 nm, ADRF takes values in the range –17.3 ± 7.1 W/m^2 to 54.2 ± 5.5 W/m^2 at Pune University, whereas the corresponding values at IGO are –15.1 ± 2.1 W/m 2and –36.6 ± 6.4 W/m^2(Pawar et al.,2012). A study over Pune in India using a multiplatform measurements show that maximum AOD values and minimum perceptible water were observed during a drought year (2009) when compared to normal monsoon years (2008 and 2010) (Vijayakumar et al.,2012). Radiative transfer modeling through the Dust and Biomass-burning Experiment (DABEX) by Johnson et al (2009) over West Africa suggested a 130–160 W/m^2instantaneous reduction of down welling solar radiation by aerosol columns (15–18% of the total flux).

Studies over Hyderabad, India reveal that tropospheric aerosol loading has significant impact on the solar irradiance reaching urban environments (Badarinath et al., 2007). A dimming of about 7 W/m^2 per decade at land surface stations worldwide was observed between 1961 and 1990 (Gilgenet al., 1998; Power and Mills, 2005). A study by Alpert et al. (2005) also indicates that stations from which the analysis took place were predominantly urban, hence, it was expected that dimming could be less or even missing in rural areas. (Makokha *et al*., 2013).

AREA OF STUDY

Kenya, lies between latitudes 5° North and 5o south and between longitudes 34° and 42° East. It has a land area of about 569,137 km2 with great diversity of landforms ranging from glaciated mountain peaks with permanent snow cover, through a flight of plateaus to the coastal plain.

The country is split by the Great Rift Valley into the Western part which slopes down into Lake Victoria from the Mau ranges and Mount Elgon (4,300m) and the Eastern part which is dominated by Mt. Kenya and the Aberdare ranges that rise to altitudes of 5,200m and 4,000m respectively. It has got a distinct bimodal rainfall pattern which is influenced by the Inter Tropical Convergence Zone (ITCZ), global oceans, the tropical high pressure systems (Mascarene, St. Helena, Azores and Arabian), tropical monsoons and tropical cyclones (Ngaina and Mutai, 2013).

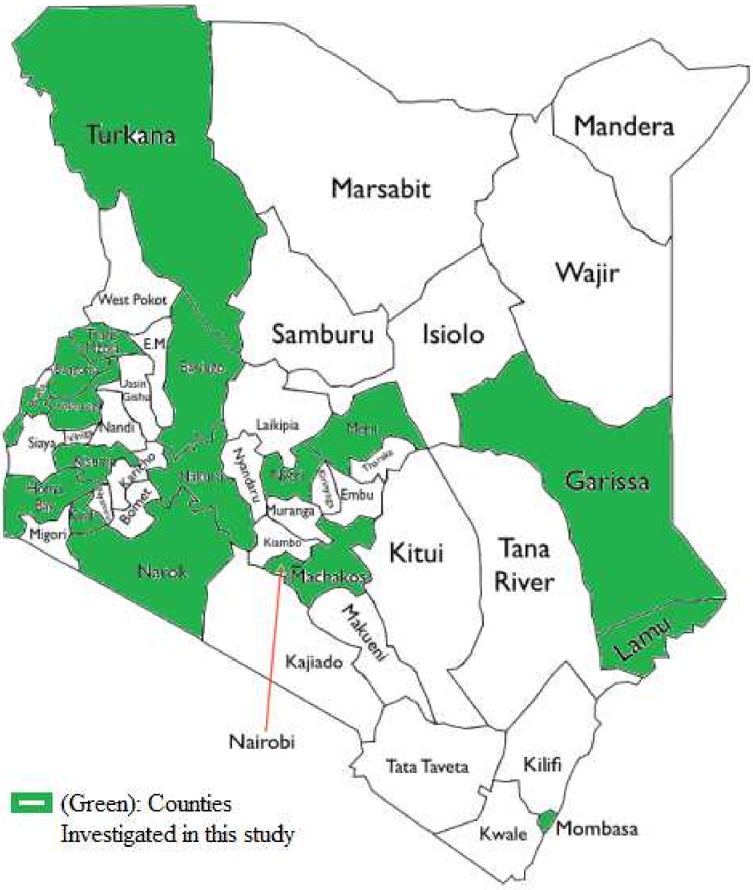


Figure 1: Map of Kenyan Counties (Source: Geocurrents)

Objectives of the study

The main objective of this study was to analyze radiative forcing simulations due to aerosols over some Counties in Kenya.

Specific objectives

In order to achieve the main objective, the following specific objectives were pursued;

- To determine spatial and temporal characteristics of aerosols Over Kenya
- To determine spatial and temporal variation of radiative forcing due to aerosols over Kenyan Counties.
- To simulate future climatic warming based on the radiative forcing estimates over Kenya under two scenarios.

Data Type and Source

Satellite measurements for the period 2000 to 2015 for the areas considered in this study were obtained from the National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS)-Aqua MODerate resolution Imaging Spectroradiometer (MODIS) via a Giovanni platform. Giovanni provides a World Wide Web (WWW) interface that enables access to global data sets from NASA Earth remote-sensing missions and other environmental data sets.

Methodology

The methodology employed included designing the theoretical framework, data quality control, and estimation of missing data. Coupled Ocean and Atmosphere Radiative Transfer (COART) was used to solve a radiative transfer equation. Time series analysis, correlation analysis was also done. Modelling of aerosols was done using Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT). Model for the Assessment of Green House Gas-Induced Climate Change, A Regional Climate Scenario generator (MAGGIC SCENGEN) was used for temperature projections. Surfer software was used to map AOD and corresponding radiative forcing over the counties of study.

COART Model Assumptions

The following are the assumptions in the solution of RTE in COART.

- Only solar radiation is considered. emission is neglected
- The land surface is assumed to be flat
- Assumes a non-vertically stratified system and therefore assuming that the atmosphere –land system has similar radiative properties
- Atmospheric perturbations are as a result of aerosols only. However, the model isolates any other interacting species by their radiative properties
- RTE is solved in plane parallel geometry
- Assumes that aerosols and surface have combined reflectance

RESULTS

Spatial Characteristics of Aerosols

The spatial variation of AOD over Kenya is as shown in Figure 2. It can be seen clearly from the Figure that the north-western and coastal Counties observed the highest aerosol loading. This may be attributed to the dust and sea spray in the respective regions.

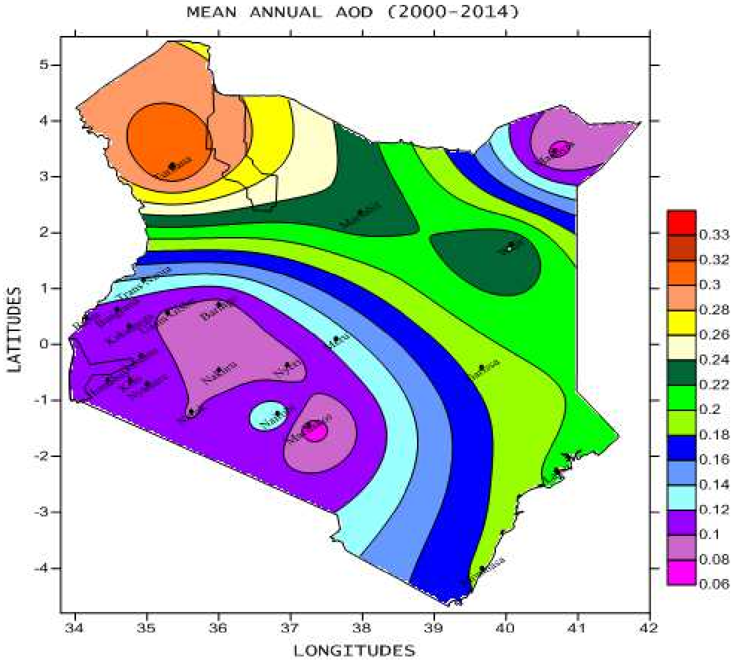


Figure 2: Variation of AOD over Kenyan Counties spanning 2000-2014

Figure 3 below also show the seasonal variation of AOD in DJF season in 2001 and 2007 respectively. It can be observed that there is minimum loading of aerosols during the DJF seasons with comparatively higher levels of aerosol loading in Turkana, Lamu, Kilifi, and Kwale Counties. This is due to a possibility of increasing anthropogenic petroleum exploration activities in Turkana County that can be possible sources of aerosols alongside carbonaceous aerosols from the alkaline Lake Turkana. Results from figure 3 also show the seasonal variation of AOD in DJF and MAM seasons in 2014 and 2007 respectively. It can be seen that aerosol loading has been decreasing spatially during the DJF season over the most recent years. It can also be seen that Turkana, Garrissa and maritime Counties had relatively high AOD spatial coverage possibly due to reasons explained above and high dust and sea salt over Garrisa and Maritime counties respectively.

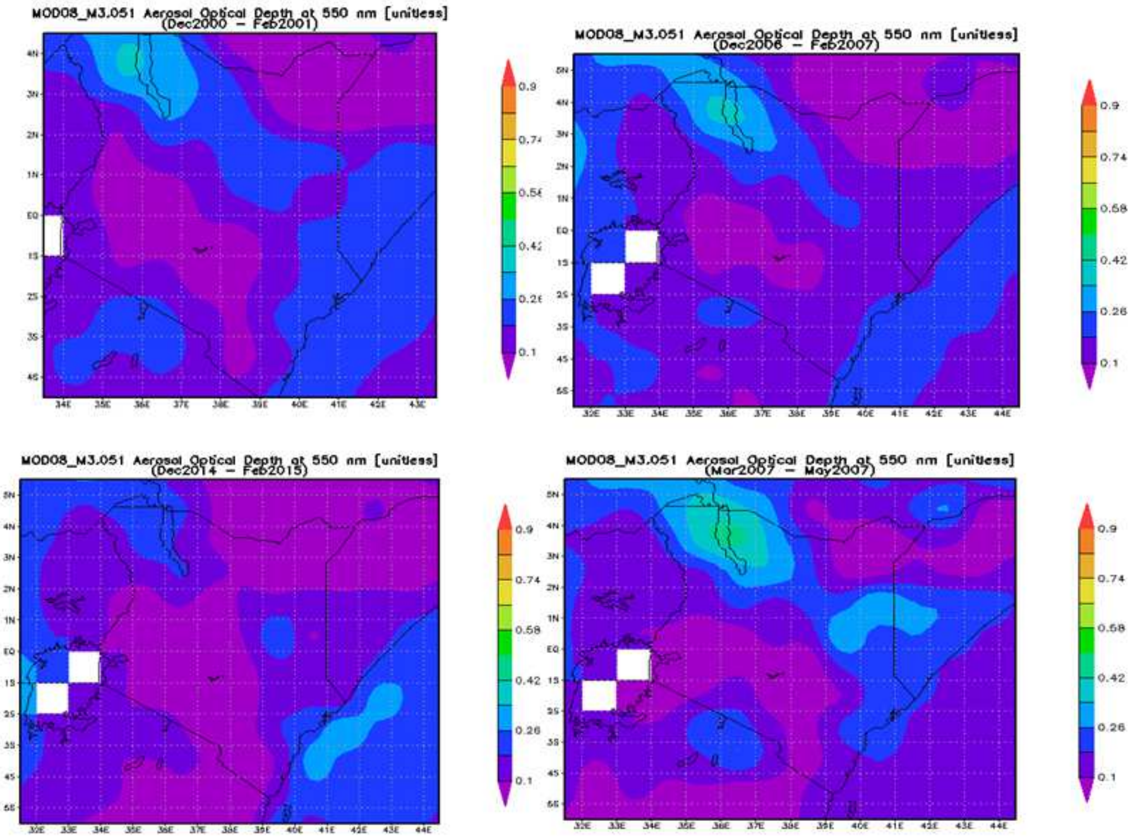


Figure 3.Variation of AOD in the DJF and MAM 2007 Seasons

Figure 4 show the variation of AOD in the MAM season in 2014 and JJA season in 2000 respectively. The results show that AOD loading has been reducing spatially over Kenya. Tana River County, Garrisa and Turkana counties had high relative aerosol loading in the MAM season. During the rainy months of March, April and May (MAM) and October, November and December (OND), it can be clearly noted that the AOD values are extremely low. This is due to cloud formation processes and wet deposition. Wet deposition is the removal of air pollution components by the action of rain. It can also be seen that JJA season is associated with the highest aerosol loading most likely due to reduced wash-out of aerosols due to minimum precipitation.

Dominant south easterly winds during the JJA season whose air masses transport aerosols from the Indian Ocean is another possible reason. The region is, also, generally under an inversion condition for a long period, that is, June, July and August

Results from figure 4 also show the Variation of AOD in the JJA season in 2014 and SON season in 2005.It can be seen that there is decreasing AOD loading over all counties. Turkana county is still at the centre of higher AOD loading compared to other counties followed by Maritime counties. Garrissa and Tana river had higher aerosols loading but the loading has been reducing during the most recent year.

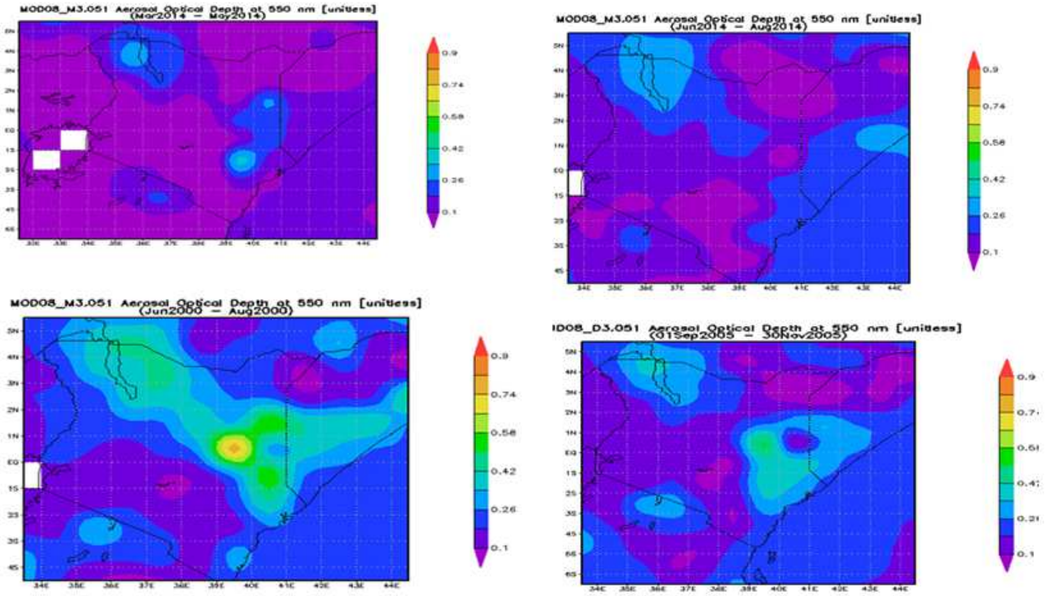


Figure 4: Variation of AOD in the MAM, JJA, and SON 2005 Seasons

Results from figure 5 show the Variation of AOD during SON season in 2014.Results show increasing AOD loading over all Kenyan Counties in the most recent years. In general, Turkana county and maritime counties recorded higher levels of AOD over Kenya. The results show a possible influx of aerosols from the Arabian Sea into Kenya via Somalia.

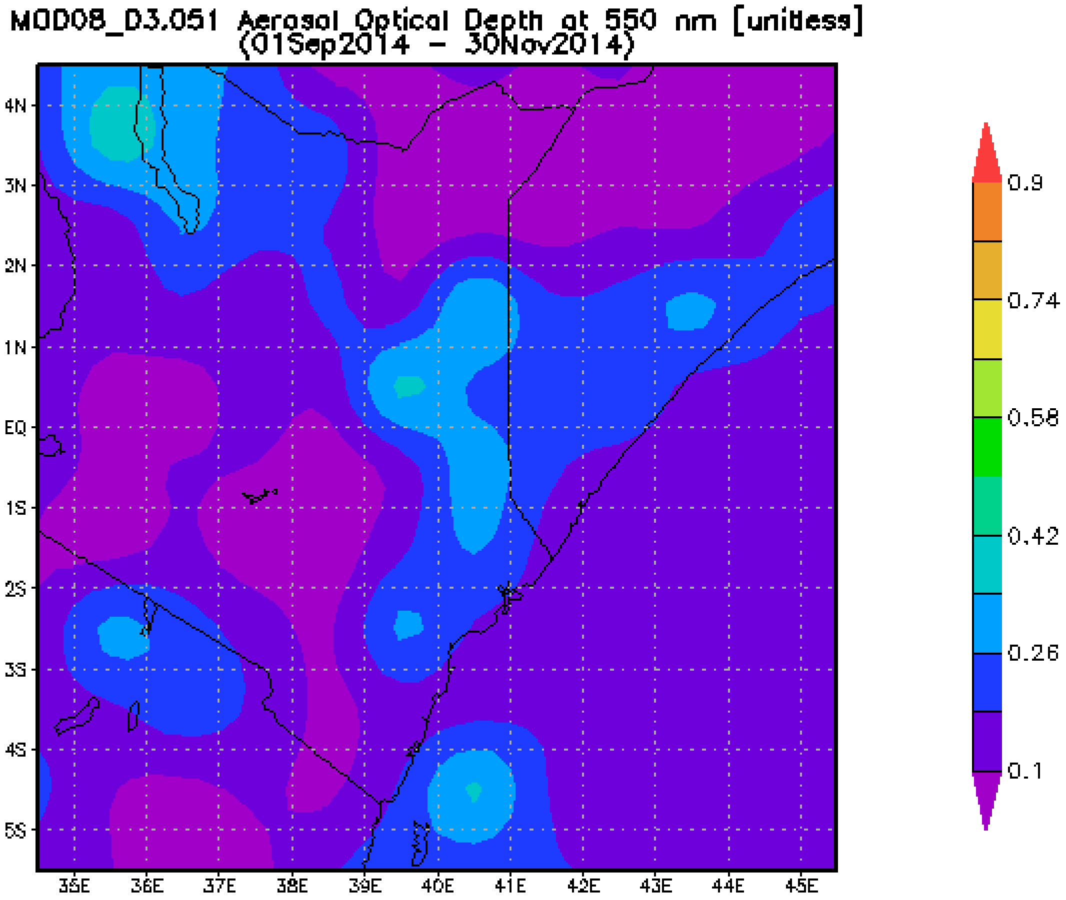


Figure 5: Variation of AOD during SON Season in 2014

Temporal Characteristics of Aerosols

Figures 8 below shows temporal variation of AOD over Mombasa County. Results show slightly decreasing trends of AOD over the county.There is a possibility of dominant south easterly winds ‘air masses carry aerosols from the Indian Ocean to the maritime counties.

Theoretically, the non-sea-salt component of AOD is inferred to be more than 3 times that of the estimated wind-dependent sea salt component. In the western Indian Ocean and Arabian Sea the high concentration of non-sea-salt aerosols are due to transport from the Indian subcontinent and Arabia. The eastern Indian Ocean is influenced by the transport from the Indian subcontinent and Southeast Asia, particularly from Indonesia.The results also agree with the findings of Kaskaoutis (2014) that there was an extremely high aerosol loading in the Arabian Sea in 2007/2008.The Arabian Sea, according to HYSPLIT trajectory analysis below is a possible source of aerosols into Kenya.

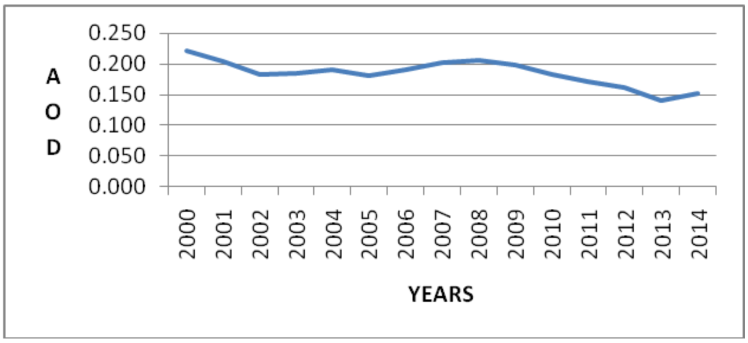


Figure 8: Variation of AOD over Mombasa County

Figure 9 below shows variation of AOD over Garrisa County. The results reveal higher variability in AOD possibly due to high levels of mineral aerosols characteristic of arid and semi arid areas. A southward displacement of the convergence zone is associated with both increased near-surface flow and decreased precipitation over the dust source regions of the southern Saharan desert, Sahel and Lake Chad (.O. M. Doherty et al., 2014).This in turn reduces soil moisture and vegetation, furthering the potential for dust emission. Therefore the coupling of changes in near-surface winds with changes in precipitation in source regions driven by a southward movement of the convergence zone most directly influence dust load in the ASAL counties.

During El Nino conditions, warm SST anomalies cause the zonal circulation to become pronounced with well-defined areas of rising and sinking motion along a mean air flow driven by convection at the west (the Arabian Peninsula), and subsidence to the east (Indian subcontinent). These intense westerlies at 700 hPa altitude transport large quantities of aerosols from the Arabian Peninsula towards the east and deposit them over the Indian .This explains high AOD in 2007.

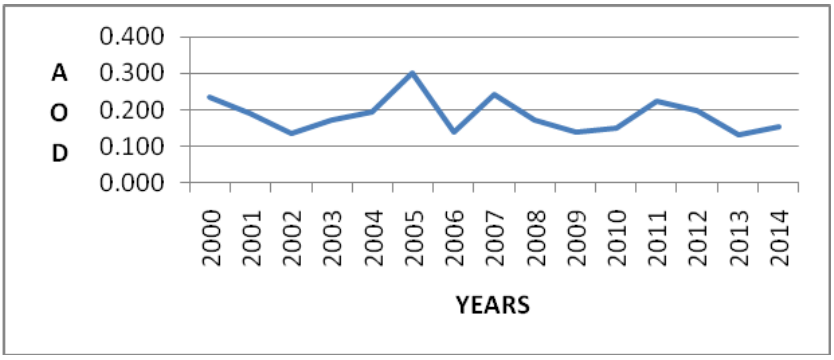


Figure 9: Variation of AOD over Garrisa County

Figures 10 and 11 below show temporal variation of AOD over Meru and Tranzoia respectively

The results show decreasing aerosol loading across meru and Tranzoia Counties but with more variability in meru. This can be attributed to decreasing aerosols ‘contribution from land use activities in the region.

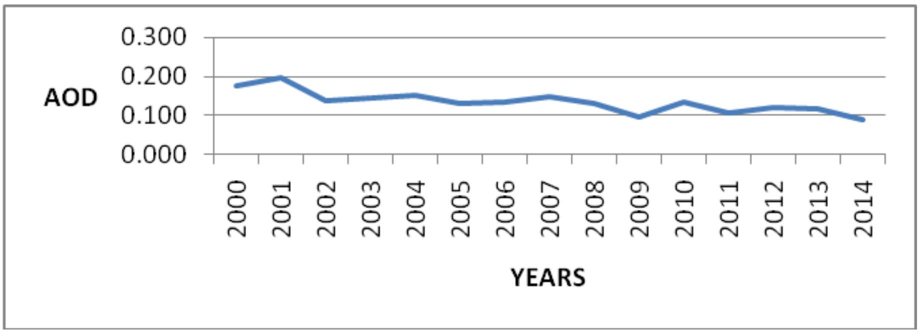


Figure 10: Variation of AOD over Meru County

Results shown in figure 11 below show variation of AOD over Tranzoia county.The results reveal that aerosols'loading has been decreasing over meru county.This can be attributable to increasing use of organic fertilizers in wetern Kenya that is reducing the use of persistent organic aerosols from pesticides.

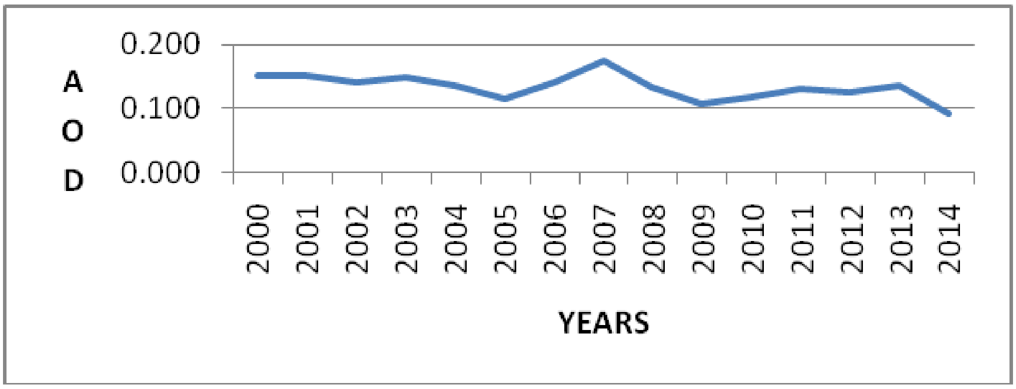


Figure 11: Variation of AOD over Tranzoia County

Figure 12 below show temporal variation of AOD over Turkana County. Results show decreasing trends in AOD loading over the county. However, there is more variability in Turkana County that can be associated with carbonaceous aerosols from the alkaline Lake Turkana and increasing petroleum mining activities becoming sources of aerosols from the surface.

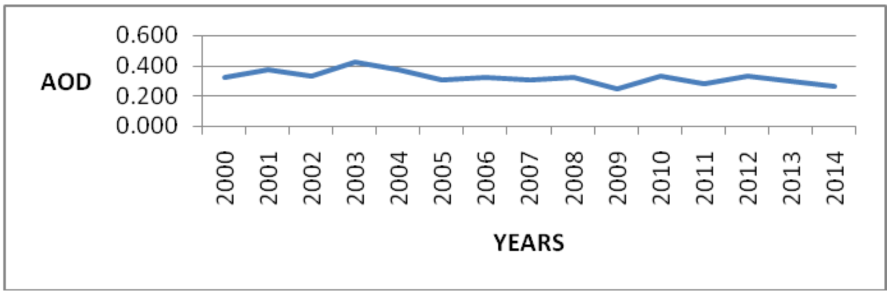


Figure 12: Variation of AOD over Turkana County

Figure 13 below show temporal variation of AOD over Nyeri County. The results reveal a decreasing trend of aerosols over Nyeri County with a tail in 2007 attributable to the possibility that most aerosols are non-persistent and easily washed out by rain water hence the effect of the 2007 El Niño event.

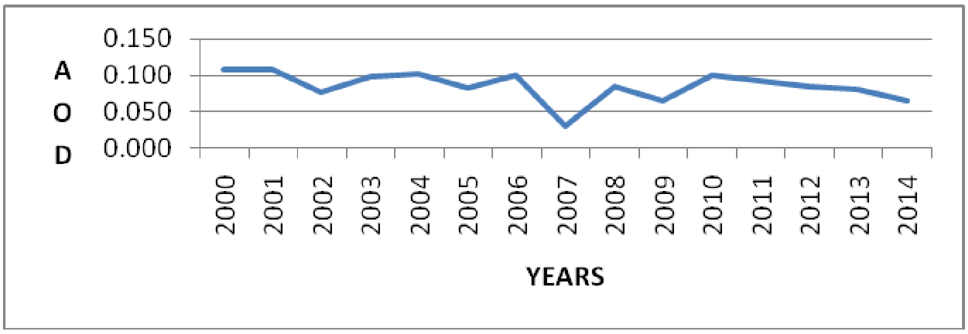


Figure 13: Variation of AOD over Nyeri County

Figures 14 and 15 show temporal variation of AOD over Nakuru and Narok Counties respectively. Results show a decreasing trend in AOD loading over the counties. This can be attributed to natural factors.

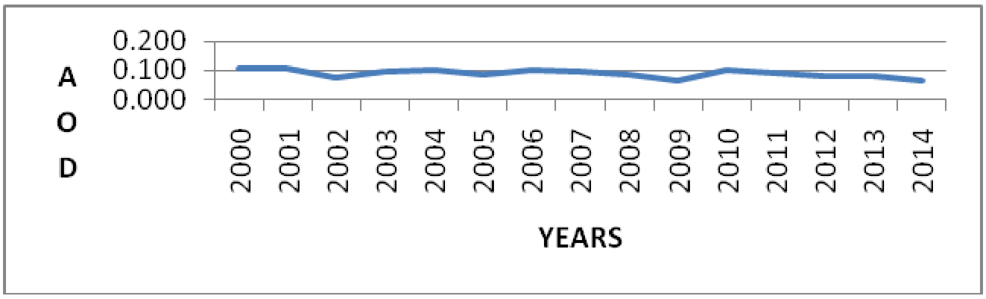


Figure 14: Variation of AOD over Nakuru County

Results in figure 15 show the variation of AOD over Narok County.The results reveal that there is minimum variability of aerosols over the county.However,the aerosols'loading is fast decreasing in the most recent years. This can be attributable to the regulatory framework in the Mau forest that has cut down buring of fossils and other anthropogenic activities in the vast forest.

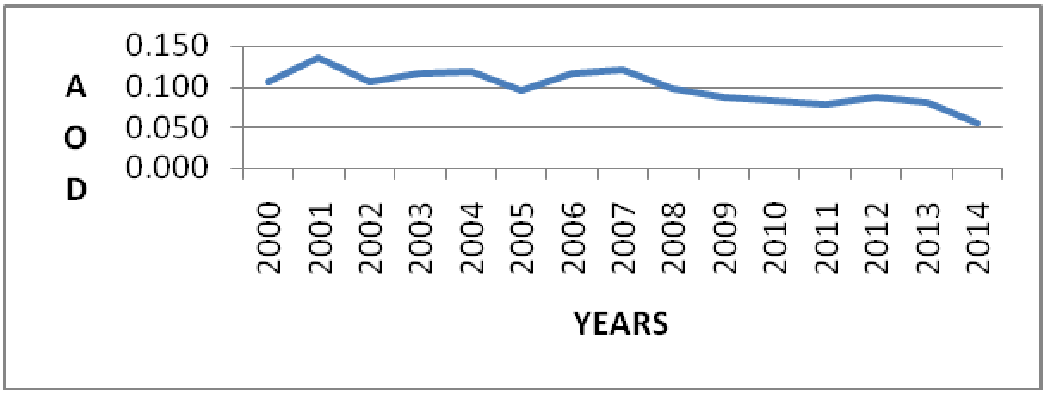


Figure 15: Variation of AOD over Narok County

Figure 16 below show temporal variation of AOD over Baringo County. Results show a decreasing trend over the county. This can be explained by the possibility that residents of the rift valley are increasingly embracing modern soil conservation methods and desisting from deforestation, Forest fires and other aerosols causing anthropogenic activities.

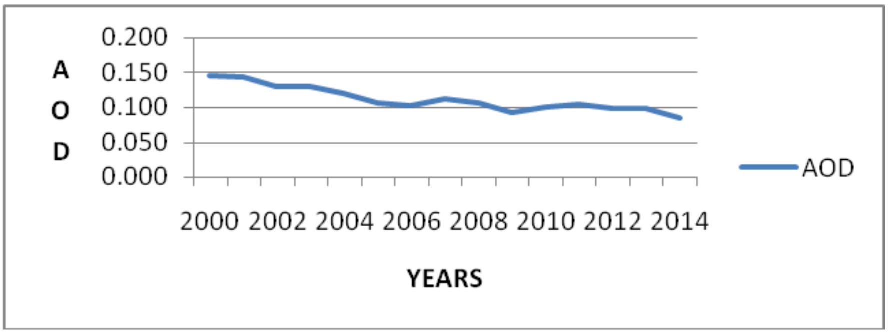


Figure 16: Variation of AOD over Baringo County

Figure 17 below show aerosols loading over counties of western Kenya namely Busia,Bungoma and Kakamega. Results show that aerosols loading in these counties is minimum and reducing in the most recent years attributable to fair land use activities over the region. The climate of these counties is also characterized with significant amounts of precipitation increasing wet deposition processes.

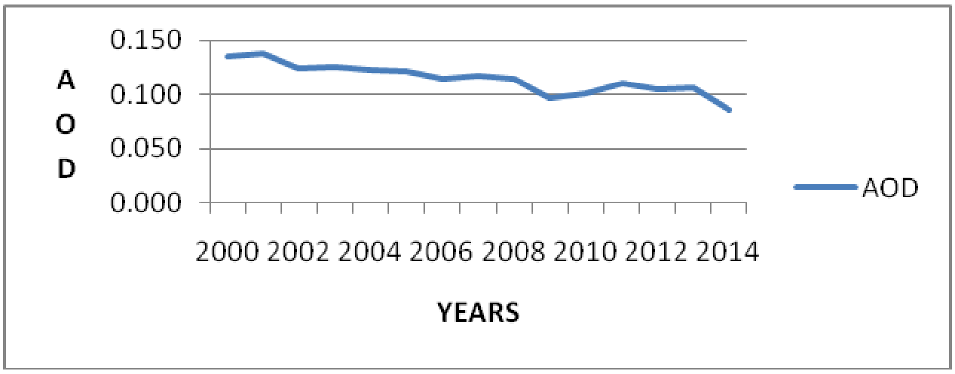


Figure 17: Variation of AOD over Western Kenya Counties

Figures 18 below show temporal variation of AOD over Machakos County.Results reveal a decreasing but highly varying AOD in Machakos County attributable to increased cement, stone, gravel, sand mining activities in the region..

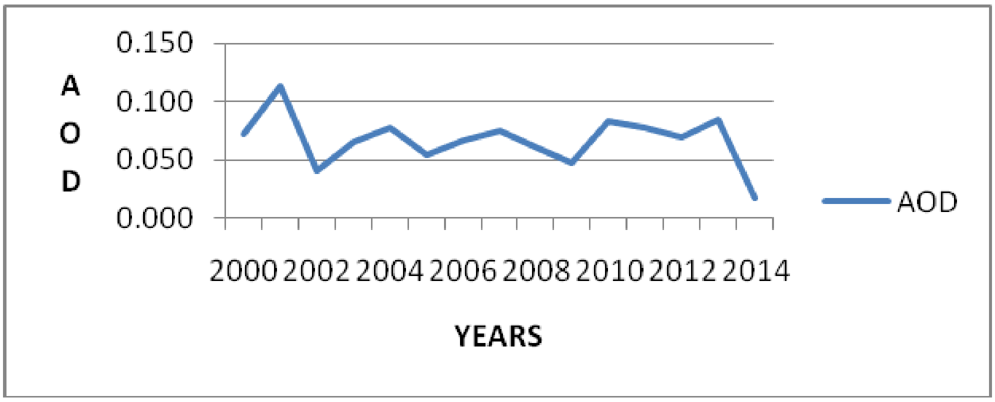


Figure 18: Variation of AOD over Machakos County

Figures 19 below show temporal variation of AOD over Lamu County. Lamu being a maritime county is associated with high AOD loading from the Indian Ocean. There is a possibility of dominant south easterly winds 'air masses carrying aerosols from the Indian Ocean to the maritime counties, mainly sea salt and non-sea salt aerosols.

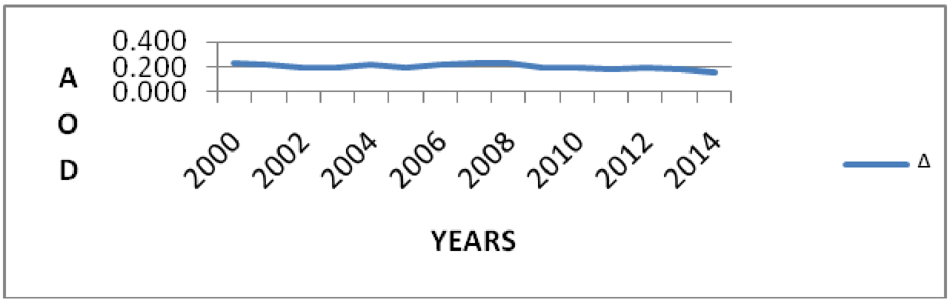


Figure 19: Variation of AOD over Lamu County

Figure 20 below show temporal variation of AOD over Kisumu, kisii, Homabay, Nyamira Counties respectively. Results show that AOD loading in kisumu and kisii, Nyamira, Homabay is exhibiting same trend and is decreasing. However, there are slightly high AOD values attributable to aerosols sources from the Lake Victoria.

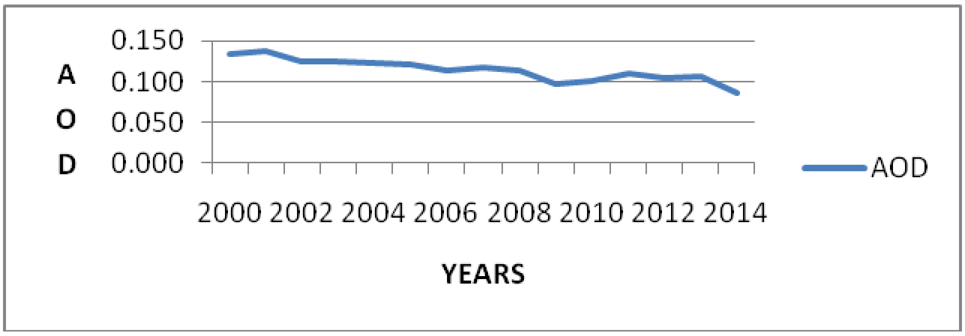


Figure 20: Variation of AOD over Kisumu,Homabay,Nyamira and Kisii Counties

Figures 21 below show backward trajectory of a location in Mombasa County. It can be seen that the Arabian and Indian sea sprays are the main sources of aerosols to the Kenyan Maritime Counties. This can be attributable to the fact that low level winds possibly transport dust and salt from Asian deserts namely Rajasthan, Trans-Himalayas and Kutch respectively.

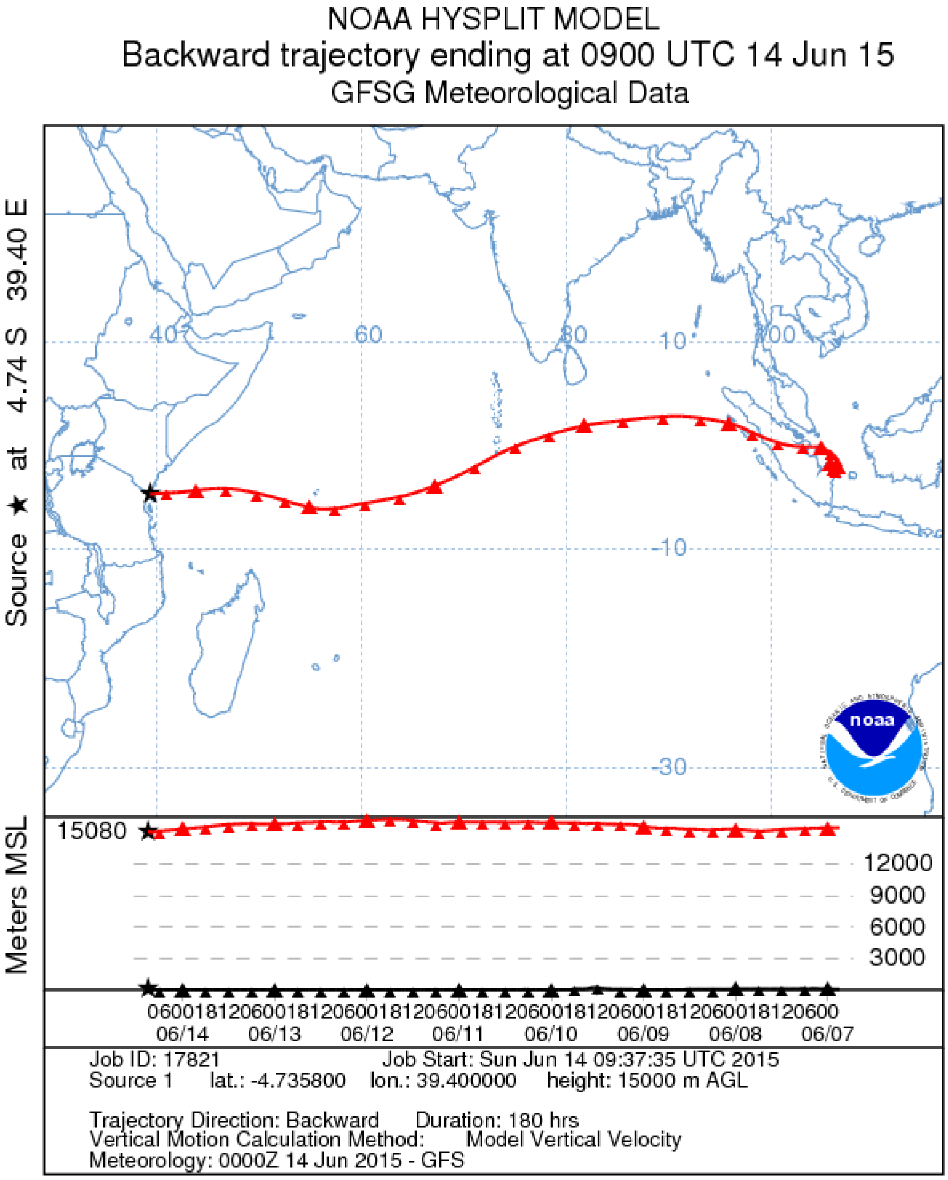
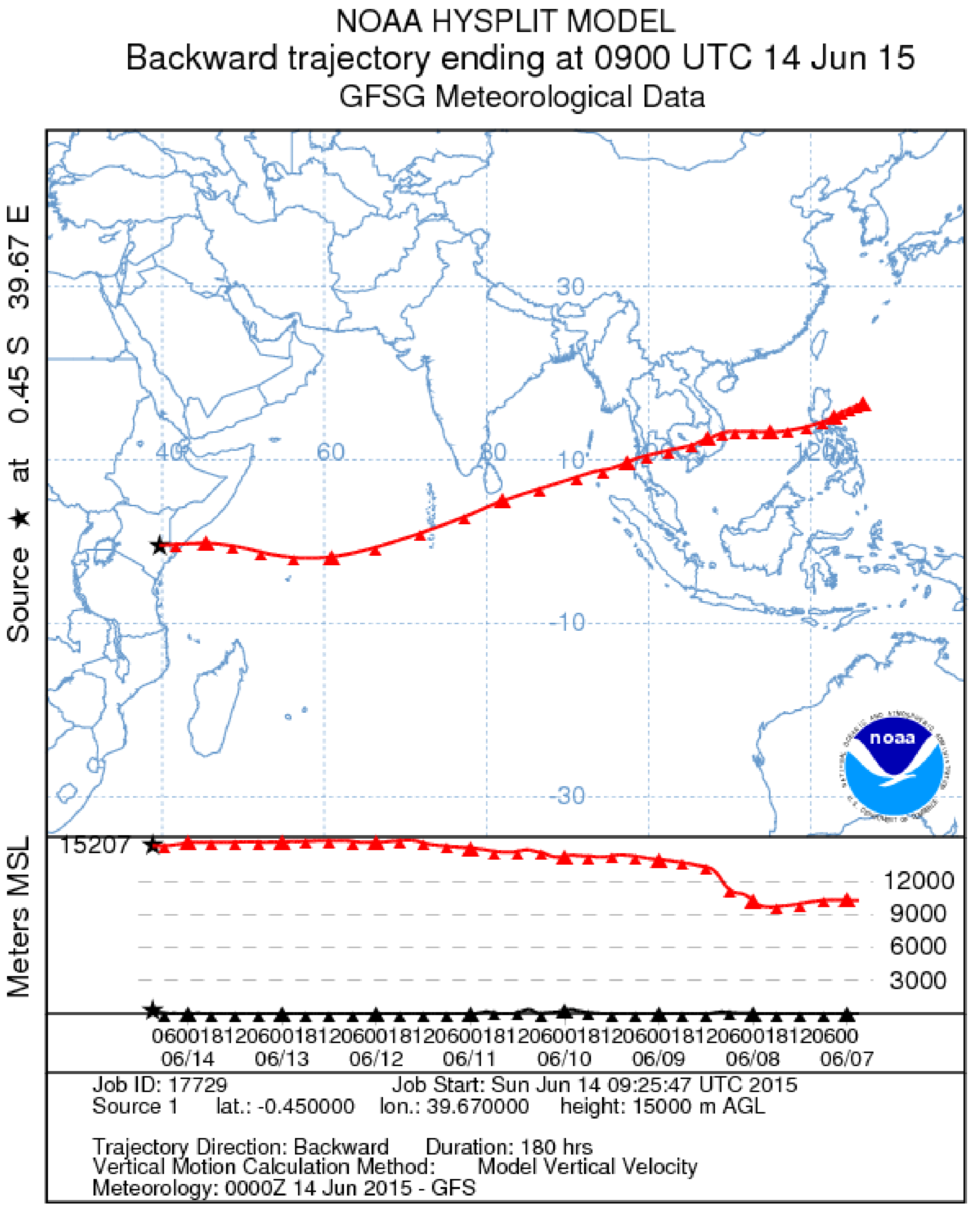


Figure 21: Backward trajectory at 15km above ground level, Mombasa County

Figures 22 below show backward trajectory of a location in Garrissa County. It can be seen that the Arabian Sea spray is a possible source of aerosols in the Kenyan ASALs. The aerosols can be traced as far as western part of India and the Philippines Sea. This can be attributable to the possibility that long distance air masses associated with low level winds transport aerosols to the ASALs.

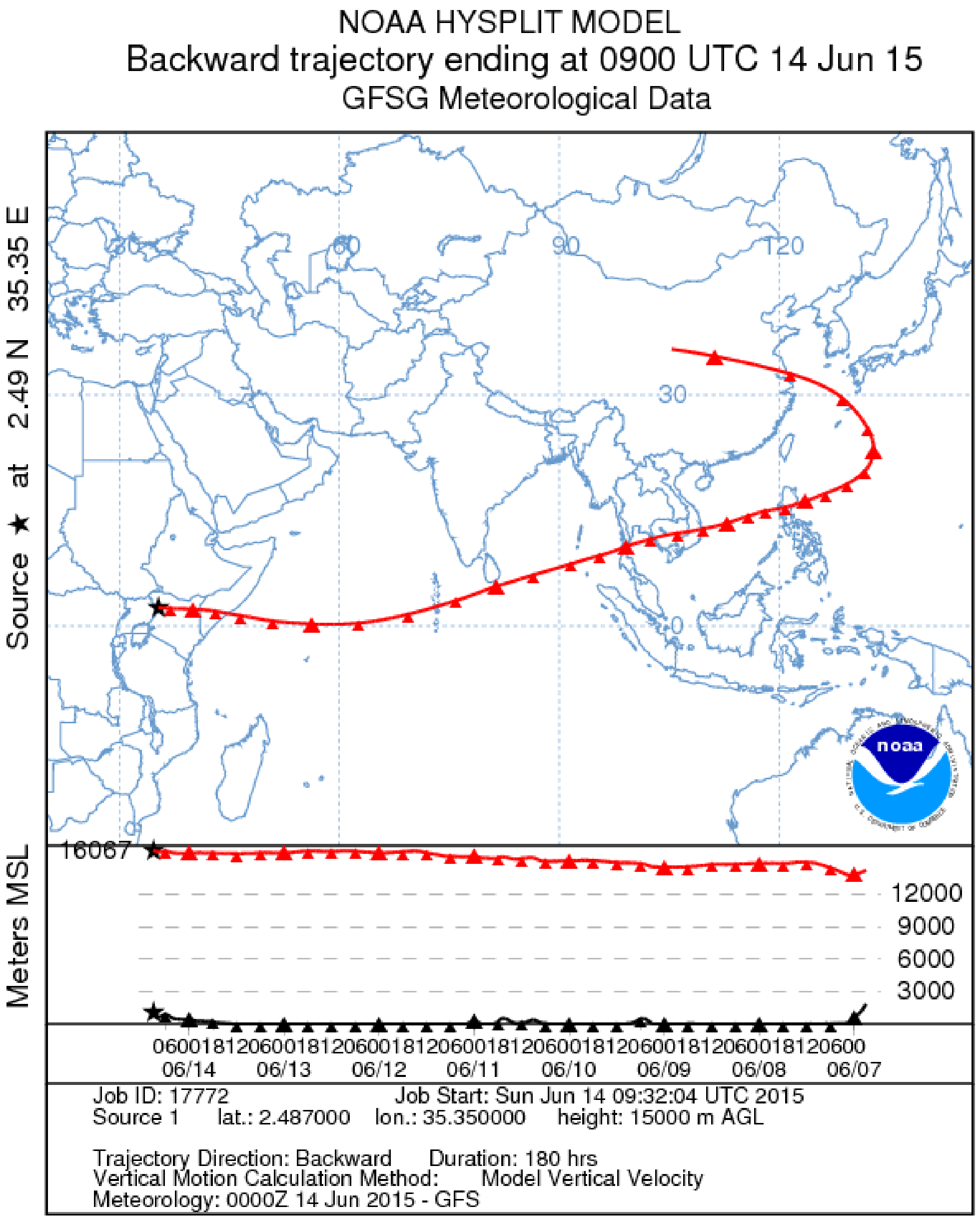


Job ID: 17729 Job Start: Sun Jun 14 09:25:47 UTC 2015
Source 1 lat.: -0.450000 lon.: 39.670000 height: 15000 m AGL

Trajectory Direction: Backward Duration: 180 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 14 Jun 2015 - GFS

Figure 22: Backward Trajectory at 15km above Ground level, Garrissa County

Figure 23 below shows a backward trajectory of a location in Turkana County.It can be seen that Turkana County experiences dust sprays sourced from as far as China’s Taklimakan desert via the Arabian Sea. This is also attributable to long distance transport of aerosols by low level winds.



Job ID: 17772 Job Start: Sun Jun 14 09:32:04 UTC 2015
Source 1 lat.: 2.487000 lon.: 35.350000 height: 15000 m AGL

Trajectory Direction: Backward Duration: 180 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 14 Jun 2015 - GFS

Figure 23: Backward Trajectory at 15km above Ground Level, Turkana County

Spatial Characteristics of Radiative Forcing due to Aerosols

COART model results show that radiative forcing due to aerosols is highest in kisii County followed by counties in Riftvalley, Nakuru, Machakos, Nyeri, Western Counties respectively. Radiative forcing due to aerosols is highest in Mombasa, Nairobi, Garrisa, Lamu, and Turkana respectively at the Top of surface. Radiative forcing is also highest in Mombasa, Turkana, Garrissa, Nairobi, Nakuru, Kisumu respectively at the Surface. All counties depicted low radiative forcing in the atmosphere led by kisumu, Lamu, Nakuru, Mombasa and Counties in the ASALS.

This is consistent with the findings that the Indo-Asian aerosols impact the radiative forcing through a complex set of heating (positive forcing) and cooling (negative forcing) processes Ultimately, the effect of haze is the large negative forcing at the surface and comparably large atmospheric heating at higher altitudes (Ramanathan et al., 2001).

In general, counties with the highest AOD recorded the lowest radiative forcing values due to aerosols. This can be attributable to the fact that aerosols scatter and/or absorb radiation and the net effect is either cooling or warming. In this case, it can be seen that the cooling effect is more dominant over Kenya.The results figure 24 below show that Mombasa, Turkana, Garrisa, Wajir Lamu, Nairobi had the lowest radiative forcing due to aerosols respectively while Kakamega, Bungoma, Busia, Kisii, Kisumu had the highest radiative forcing due to aerosols. This is consistent with the fact that aerosols scatter or absorb short wave radiation preventing it from reaching the surface and therefore minimizing the intensity of long wave radiation reflected back in space. Consequently, Most Counties with high AOD recorded comparatively lower radiative forcing estimates and vice-versa. Natural processes can also contribute to change in RF.

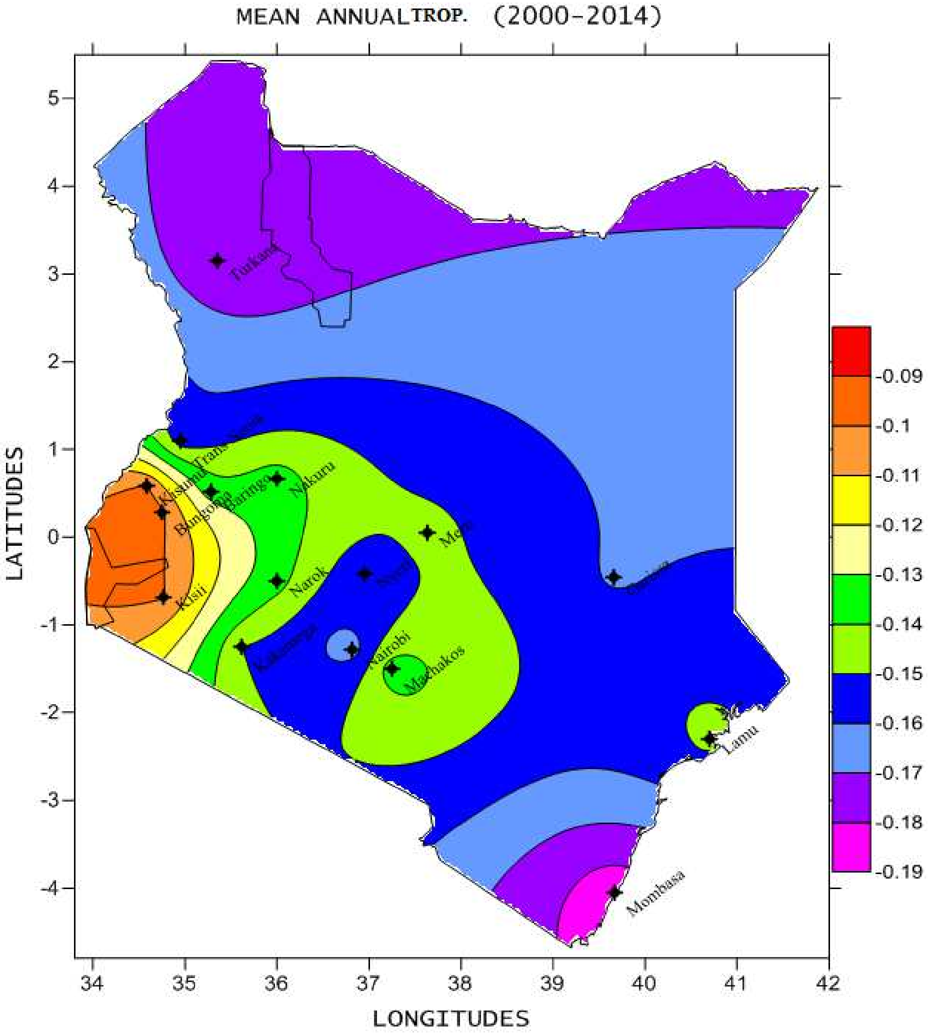


Figure24: Map Showing the Distribution of Radiative Forcing Due to Aerosols Over Kenyan Counties

Temporal Characteristics of Radiative Forcing due to Aerosols

Figure 25 below shows the temporal variation of forcing over Garissa County. The results show that radiative forcing due to aerosols has been increasing in intensity and variability. This is attributable to highly varying surface albedo characteristic of the ASALS and other natural processes.

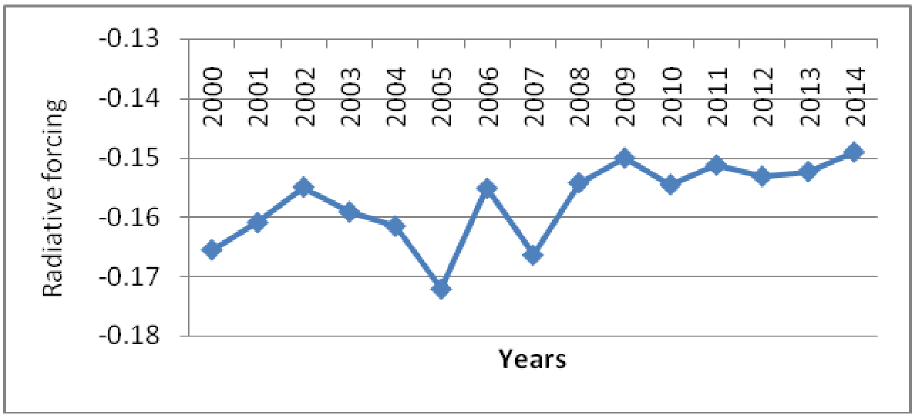


Figure 25: Graph Showing Variation of Radiative Forcing Due to Aerosols Over Garrisa County

Figure 26 below shows radiative forcing due to aerosols over Meru County. The results show that radiative forcing due to aerosols has been increasing over the county. This is attributable to decreasing direct effect of aerosols due to reduction in AOD loading and other natural processes.

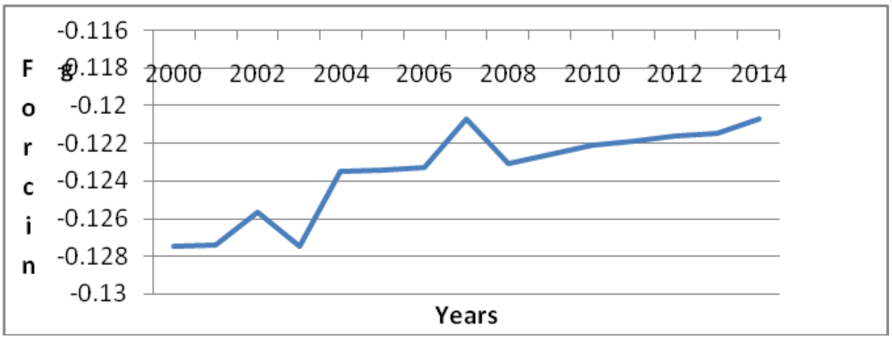


Figure 26: Graph Showing Variation of Radiative Forcing Due to Aerosols Over Meru County

Figure 27 below shows radiative forcing due to aerosols over Turkana County. The results show that radiative forcing due to aerosols has been increasing over the county. This is attributable to decreasing AOD loading. The results also reveal an increasingly varying trend of radiative forcing due to aerosols, a possible indicator of the anthropogenic perturbation to the atmosphere by land use activities in Turkana County. Other natural processes can also contribute to the observed trends.

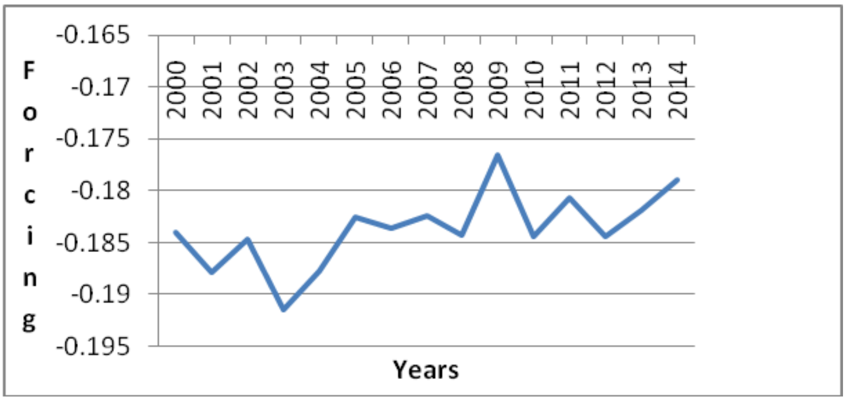


Figure 27: Graph showing Variation of Radiative Forcing Due to Aerosols Over Turkana County

Figure 28 below shows radiative forcing due to aerosols over Nyeri County. The results show that radiative forcing due to aerosols has been increasing over the county. This is attributable to decreasing AOD loading attributable to improved land use activities and minimum mineral aerosols associated with relatively high precipitation over the area of study. Natural processes can also be contributory.

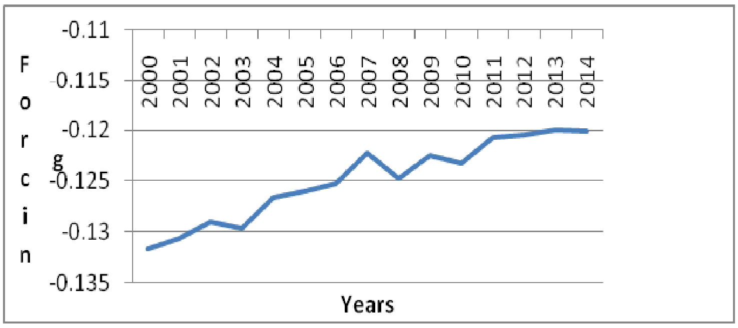


Figure 28: Graph Showing Variation of Radiative Forcing Due to Aerosols Over Nyeri County

Figure 29 below shows radiative forcing due to aerosols over Tranzoia County. The results show that radiative forcing due to aerosols has been increasing over the county. This is attributable to decreasing AOD loading. A peak in 2007 is attributable to increased aerosols wash out processes during the 2007 *El Niño* and natural processes.

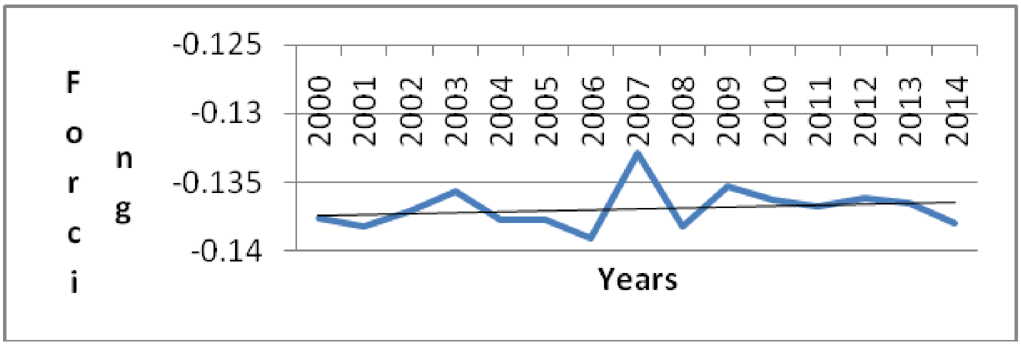


Figure 29: Graph Showing Variation of Radiative Forcing Due to Aerosols Over Tranzoia County

Figure 30 below shows radiative forcing due to aerosols over Nakuru county. The results show that radiative forcing due to aerosols has been increasing over the county. This is attributable to decreasing AOD loading. A peak in 2007 is attributable to increased aerosols wash out processes during the 2007 El Niño and natural processes.

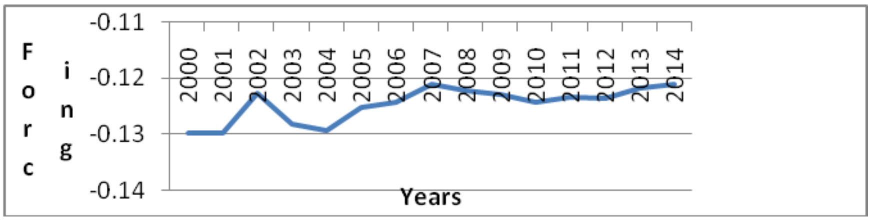


Figure 30: Graph Showing Variation of Radiative Forcing Due to Aerosols Over Nakuru County

Figure 31 below shows radiative forcing due to aerosols over Narok County. The results show that radiative forcing due to aerosols has been increasing over the county. However, radiative forcing due to aerosols was decreasing up to around 2003. This is attributable to the possibility that the indirect effect of aerosols to forcing was high or aerosols' loading from anthropogenic activities in the Mau Forest was slightly high leading to a net decrease in the forcing up to the year 2002/2003 when the Kenya Government formed a climate Change secretariat and implemented conservative land use activities in the Mau Forest. Natural processes can also contribute to the observed trends.

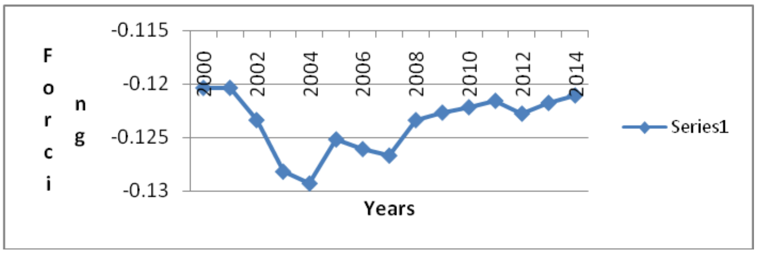


Figure 31: Graph Showing Variation of Radiative Forcing Due to Aerosols Over Narok County

Figure 32 below shows radiative forcing due to aerosols over Kakamega,Busia and Bungoma Counties respectively. The results show that radiative forcing due to aerosols has been increasing over the counties. This is attributable to increasing indirect effect of aerosols due to clouds associated with higher precipitation in the counties, and also due to reduced aerosols ‘loading over the counties due to increased aerosols ‘wash out activities due to characteristic precipitation levels. Natural processes can also contribute to the observed trends.

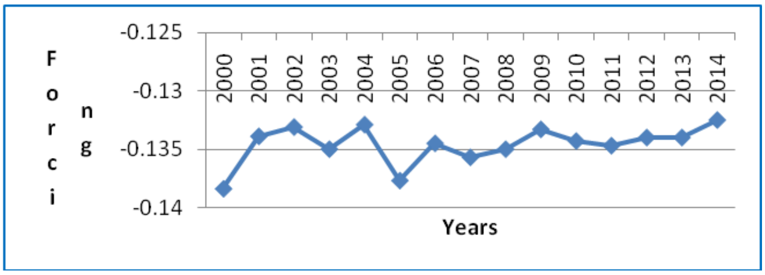


Figure 32: Graph Showing Variation of Radiative Forcing Due to Aerosols Over Kakamega County

Figure 33 below shows radiative forcing due to aerosols over Nairobi County respectively. The results show that radiative forcing due to aerosols has been increasing over the county. This is attributable to reducing aerosols’ loading over the county. Nairobi county is highly industrialized and can be a major source of anthropogenic aerosols that scatter or absorb shortwave radiation and therefore resulting in relatively low radiative forcing due to aerosols.

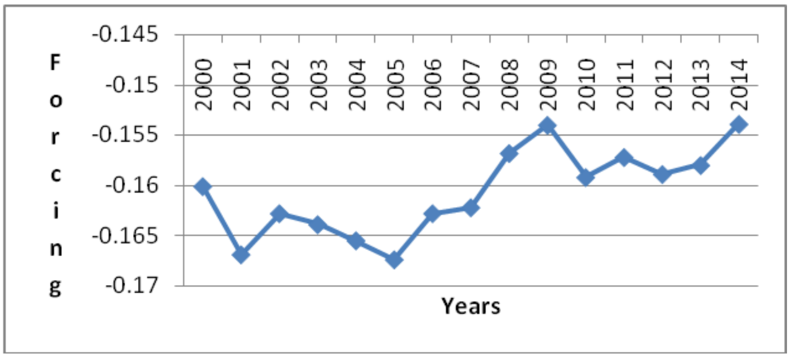


Figure 33: Graph Showing Variation of Radiative Forcing Due to Aerosols Over Nairobi County

Warming Projections over Kenya

MAGGICSCENGEN model output results reveal a warming over Kenya of 0.17 ^{0}C by the year 2000, 0.45 ^{0}C by the year 2015 respectively. This can be attributable to the possibility that there will be future variability in aerosols over the country in general due to both anthropogenic activities and natural factors leading to warming.

CONCLUSIONS

Results of the spatial characteristics of aerosols revealed that Turkana, ASAL and Maritime Counties had the highest aerosols loading while Kisii County had the lowest aerosols loading respectively. The study also noted that Turkana County, Maritime Counties and ASAL counties had the highest AOD respectively across all seasons. Results from this study show that aerosol loading is highest during the JJA season.

Results from the temporal characteristics of aerosols noted that Garrissa County has the highest interannual variability of aerosols. The study revealed that aerosol loading across all Kenyan counties is reducing and that long distance transport and dispersion of aerosols is facilitated by low level winds for aerosols affecting Kenya. The study noted that Indian Ocean and Arabian sea are possible sources of aerosols in the ASALS, Maritime and Neighbouring Counties

Results from spatial variation of radiative forcing due to aerosols noted that Kisii, Baringo, Machakos, Nyeri, Kakamega had high radiative forcing due to aerosols respectively . ASAL counties, Maritime counties and Turkana County had relatively lower radiative forcing due to aerosols.

Results from temporal variation of radiative forcing due to aerosols noted that the forcing over Kenya is reducing and lies in the range of -0.187 to -0.05 w/m^2

Model simulation results noted that Kenya has experienced warming by a value of 0.17 ^{0}C, 0.45 ^{0}C by the year 2000, 2015 respectively due to aerosols and is likely to experience a warming of 2.96 ^{0}C by the year 2100.The study also noted sulphates induced warming of 0.1 and 0.25 ^{0}C under reference and policy scenarios respectively. The study also noted that warming due to bio-aerosols is negligible by the year 2100 under both scenarios.

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