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MONITORING SPATIAL-TEMPORAL VARIABILITY OF AEROSOL OVER KENYA

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Abstract
This study sought to investigate the spatial and temporal variations of aerosols over Kenya based on Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor Aerosol Optical Depth (AOD) data for the period between 2001 and 2012. A Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used for trajectory analysis in order to reconstruct the origins of air masses and understand the Spatial and temporal variability of aerosol concentrations. Validation of MODIS AOD using Aerosol Robotic Network (AERONET) indicated that MODIS overestimated the aerosol loading over the study region. Space time variability of MODIS AOD measurements over Kenya showed a decreasing trend in aerosol loading with a long term mean of between 0.02 and 0.56. Mean monthly AOD values showed two peaks during the months of July and December while seasonal variations indicated high aerosol loading during the December –January –February (DJF) and June –July –August (JJA) season. Back trajectory analyses showed that aerosols mainly dust and sea salt reaching Kenya were transported from either Arabian or Indian sub continent or western parts of the Indian Ocean respectively. Therefore, long term and more comprehensive satellite AOD retrievals are necessary in order to achieve a better understanding of spatial and temporal variations in aerosols over Kenya

Key Words: *Aerosol Optical Depth, MODIS, Kenya*

Introduction

Atmospheric aerosols play a significant role in energy balance of the earth-atmosphere system. Changes in the atmospheric aerosol load, greenhouse gases, solar radiation, and land surface properties alter the energy balance of earth's atmosphere (Papadimas *et al*., 2008). According to IPCC (2007) report, aerosols have been recognized as a major factor in determining the global climate change in the last two decades as they play a crucial role in the solar and thermal radiative transfer in the atmosphere.

It is noted that aerosols not only affect the solar radiation budget at the surface of the earth and in the atmosphere but also on the hydrological cycle and precipitation rate (Lohmann and Feichter, 2005; Kosmopoulos *et al*., 2008). Moreover, dust particles modify the transmission of both short-wave and long-wave radiation through the atmosphere through atmospheric scattering and absorption processes (Otto *et al*., 2007) and consequently produce heating in the atmospheric column due to dust absorption (Haywood *et al*., 2001). Significant effects on non –climatic related processes such as human health and ecosystem services have been noted (Smart *et al*., 2011). Increasing aerosol loading has mainly been attributed to biomass burning and boreal forest fire aerosol events and thus exacerbated the existing problems associated with air quality and public health (Torres *et al*., 2002).

Several studies have used satellite measurements to monitor space time characteristics of aerosols, at both regional and global scales (Kaufman *et al*., 2005; Matheson *et al*., 2005). Satellite remote sensing technique allows both spatial and temporal pattern and properties of aerosols to be assessed (Kosmopoulos *et al*., 2008). The spatio-temporal processes involved can then be indirectly described and mapped through modelling techniques, e.g., by using the USA's National Oceanic and Atmospheric Administration (NOAA) HYSPLIT model (Draxler and Rolph, 2003). In several urban areas of Europe, the United States, Australia, and some regions of Asia, the mass concentration of ambient aerosol particles is routinely measured by ground stations. However, individual ground-based observations represent point measurements and do not have coverage required to map regional or

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global distributions of aerosols. One major advancement in this respect has been the introduction of the AERONET Aerosol Robotic Network (Holben *et al*., 1998), which means that satellite remote sensing of aerosols no longer needs to be largely independent but can be tied in to this coordinated and harmonized ground data.

Studies by Chu *et al*. (2003) and Wang and Christopher (2003) showed great potential for mapping the distribution and properties of aerosols, and for deriving indirect estimates of particulate matter using MODIS satellite data. Gupta *et al*. (2008) noted that sparse distribution of ground based measurements makes it inevitable for the use of satellite data as a proxy measure for the monitoring of particulate matter air quality. Concern about atmospheric particulate pollution is growing worldwide with abundance and compositions of aerosols differing due to physical processes and their origin (Mkoma and Mjemah, 2011) which influences their spatial and temporal variability. Moreover, Mkoma and Mjemah (2011) noted higher PM10 mass concentrations (45μg/m^3) during the 2005 dry season and the lowest (13 μg/m 3) during the 2006 wet season which were attributed to temperature inversions and absence of rain wash down. Other studies on transport and dispersion of aerosols based on satellite data exist (De Graaf *et al*., 2010; Mbithi, 2010).

Aerosol concentrations are continually increasing in virtually all urbanized and industrialized regions because of growing populations, rapid urbanization with consequent land use changes, increasing motorized traffic, and increasing industrialization within, and adjacent to, urban areas. There are, to date, relatively few studies on aerosols over Kenya. Nevertheless, ground-based measurements require expensive software or permanent automatic monitoring stations. Therefore, the study sought to investigate the spatio-temporal variability of aerosols based on MODIS AOD data over Kenya in order to understand the effects that aerosols have on the earth's climate system and human health they must be routinely monitored, both on a global scale and on regional or local scales, in particularly by analyzing their spatial and temporal patterns. This will provide a better understanding of spatial and temporal variations in aerosols which greatly impacts air quality and thus act as basis for development of air quality related policy in Kenya.

Area of Study

Kenya, lies between latitudes 5^o North and 5^o south and between longitudes 34^o and 42^o east. It has a land area of about 569,137 km^2 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).

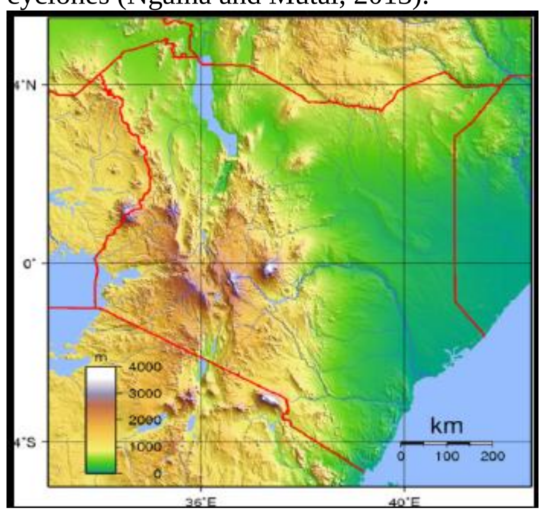

Figure 1: Topographic map of Kenya

Seasonal cycles of absorbing aerosols have distinct modes of residue distribution associated with dry periods and wet periods (De Graaf *et al*., 2010). During dry periods the residue varies freely, due to aerosol emissions from deserts and biomass burning events while during wet periods the residue depends linearly on the amount of precipitation, due to scavenging of aerosols and the prevention of aerosol emissions from the wet surface attributed to the sources and sinks of atmospheric aerosols being controlled directly by the local climate such as monsoonal precipitation

Possible sources of aerosols in Kenya are Middle East, Sahara and Arabian deserts in the Northern hemisphere during the month of February while the Congo rain forest, Kalahari and Namibian deserts, Southern Atlantic Ocean, South west Indian Ocean, Madagascar Island and South African regions during the month of July (Mbithi, 2010). The transport of aerosols and their dispersion patterns greatly depend on the season of the year together with the prevailing atmospheric conditions.

Materials and Methods

Satellite aerosol properties from MODIS sensors were used in this study (http://daac.gsfc.nasa.gov/MODIS/Terra/atmosphere/MOD08_M3.shtml) to understand and analyze the variability of aerosols over Kenya. Ground based AERONET AOD data was used to validate MODIS AOD which was obtained using Level-3 MODIS gridded atmosphere monthly global product 'MOD08_M3' at spatial resolution of 1^0x1^0 (Ichoku *et al*., 2004).

The AERONET CIMEL sky ground-based data are available at three levels; Level 1.0 (unscreened), Level 1.5 (cloud screened) and Level 2.0 (quality assured) (Holben *et al*., 1998), which can be downloaded from the AERONET website (http://aeronet.gsfc.nasa.gov/). The CIMEL sun/sky radiometer takes measurements of direct sun and diffuses sky radiances within the 340 -1020 nm and 440 -1020 nm spectral ranges, respectively (Holben *et al*., 1998). The sun/sky radiometer retrieval accuracy is comprehensively explained and discussed by Dubovik *et al*. (2000).Version 2 cloud screened daily mean AOD (500 nm) direct sun data over Nairobi (1^0S, 36^0E) and ICIPE-Mbita (0^0S, 34^0E) in Kenya from 2007 to 2012 were used in the study.

The daily mean AODs (500 nm) from AERONET were first interpolated to a common 550nm using the power law shown in equation 1.

$$AOD_{550nm} = AOD_{500nm}\left(\frac{550}{500}\right)^{-\alpha}$$

Where α is the (440 -870 nm) Angstrom exponent (Prasad *et al*., 2007).

Interpolated ground based AERONET AOD data were then used to validate MODIS AOD over Eastern Africa. This was based on Percentage difference in the MODIS retrieved and AERONET AOD data computed using the equation 2. Comparison was also done based on the coefficient of determination (R^2) values over the stations.

$$\%\ \text{difference} = \frac{AOD_{MODIS} - AOD_{AERONET}}{AOD_{AERONET}} \text{ x } 100$$

A positive value of the percentage difference implies an overestimation by MODIS.

Temporal variability was assessed using Mann Kendall Rank statistic while spatial analysis was based on Kriging method using Surfer software. In Mann Kendall trend tests, positive values are indicative of an increase in the constituent with time, whereas negative values indicate a decrease in the constituent with time with strength of the trend proportional to the magnitude of the Mann-Kendall Rank Statistic (Helsel and Hirsch, 1992).

A HYSPLIT model was used for backward trajectory analysis to compute simple air parcel and can be run interactively on the website (http://ready.arl.noaa.gov/HYSPLIT.php). A three day back trajectory analysis based on the NOAA HYSPLIT model (Draxler and Rolph, 2003) was used to understand the origins of the air masses arriving in region. The meteorological input for the trajectory model was the GDAS (Global Data Assimilation) dataset (reprocessed from National Centres for Environmental Prediction (NCEP) by Air Resources Laboratory).

Results and Discussion

Validation of MODIS AOD at 550 nm

MODIS AOD product over Eastern Africa was validated based on AERONET AOD data from ICIPE –Mbita and Nairobi stations (Figure 2).

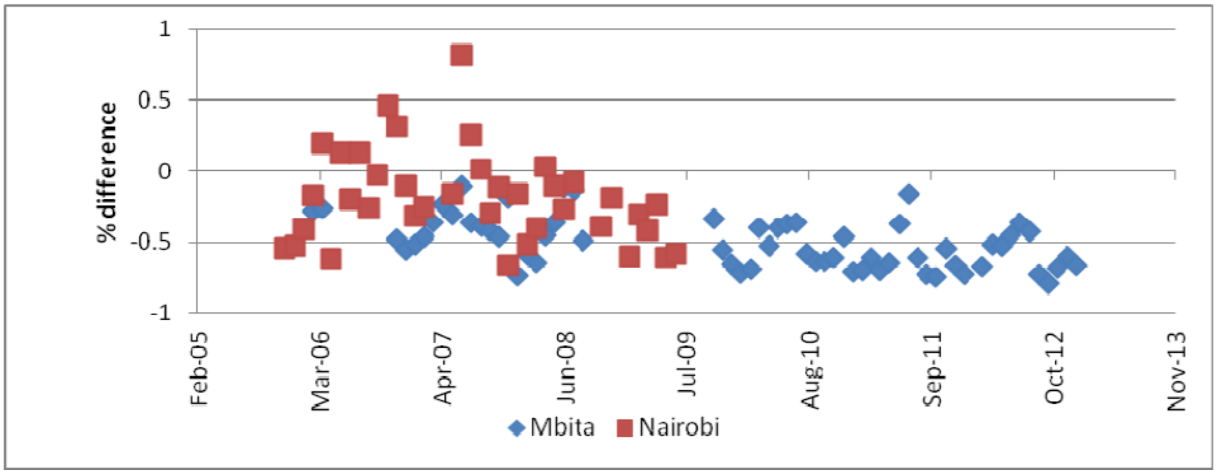

Figure 2: Percentage difference for AERONET and MODIS AOD over Mbita and Nairobi

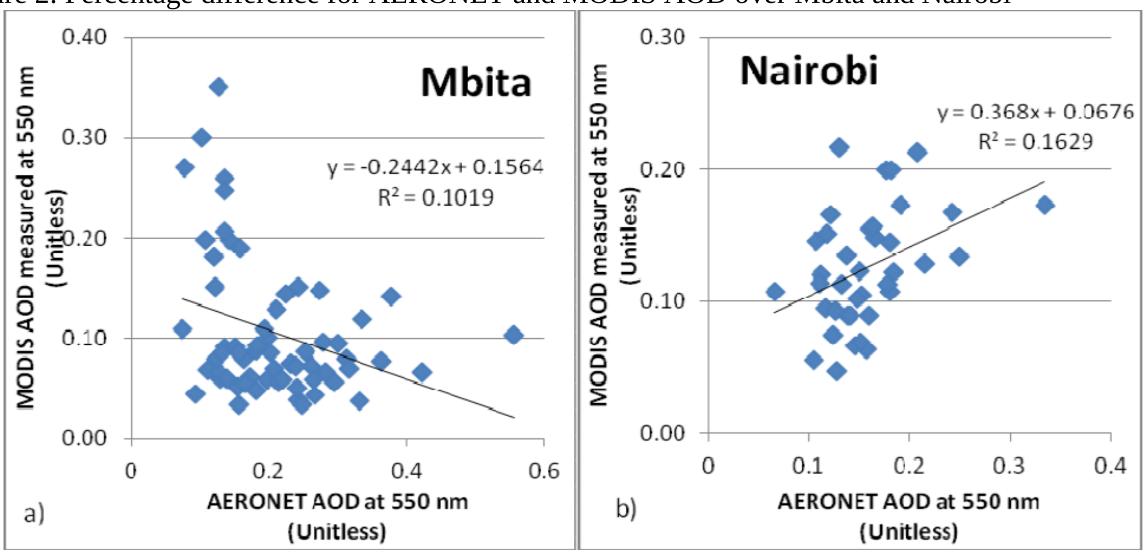

Figure 3: Validations of MODIS AOD with AERONET AOD at 550 nm, over a) Mbita and b) Nairobi stations

Graphical plot of percentage difference between MODIS and AERONET AOD data over Mbita and Nairobi were found to have a mean of -50% and -19% respectively. These negative values indicated that MODIS sensor underestimated the amount of aerosol over the two stations considered.

The correlation coefficient for Mbita and Nairobi was found to be 0.81 and 0.55. The t test showed that these values were all significant as the t computed were all greater than the tabulated for the stations. However, regression analysis of between AERONET and MODIS AOD (Figure 3) noted that more data points were comparable over Nairobi than Mbita attributed to R^2 values of 0.16 and 0.10 respectively. This implied that AOD estimates from MODIS over continental were better over terrestrial regions (Nairobi) than near water surfaces. This affirms results from Alam *et al.* (2011) which noted that MODIS AOD data provided better estimates over terrestrial and vegetated surfaces.

Overall, MODIS satellite were found to overestimate AOD values with observed differences attributed to issues such as consistency, revisit times, instrument calibration, sampling differences, and data availability (Liu *et al.*, 2007; Kahn *et al.*, 2007) for validation process

Trend analysis

Mann Kendall trend test (figure 4a) at 95% significance level showed that most stations over western Kenya had significant negative trend in time series of MODIS AOD as p values were lower than alpha (0.05) while stations to the east of Kenya had no significant trend. The negative trends were attributed to the influence of transported pollution inlands as the region due to dominant South Easterlies and North Easterlies during a greater period of the year (Ngaina and Mutai., 2013; Okoola 1999).

Annual and seasonal variations of AOD over Kenya

Over Kenya, annual mean values of AOD (figure 4b) ranged from 0.02 to 0.56. The high mean values close to the Indian Ocean were attributed to presence of high amounts of sea salt throughout the year while high AOD values over North and eastern parts of Kenya were attributed to dust.

Time series of mean monthly AOD values (figure 5) were noted to display two peaks during the months of July and December with the high aerosol loading linked to different process over different locations and times of the year. However, seasonal variations indicated high aerosol loading during DJF and JJA season (figure 6). The enhanced AOD loading were attributed to land clearing and agricultural fires that are widespread in the equatorial region during dry season (December January February) and dust storm events (Gautam *et al*., 2010) during monsoon seasons. Moreover, Rajeev *et al*. (2000) noted that in the western Indian Ocean and Arabian Sea, the high concentration of non-sea-salt aerosols were due to transport from the Indian subcontinent and Arabia.

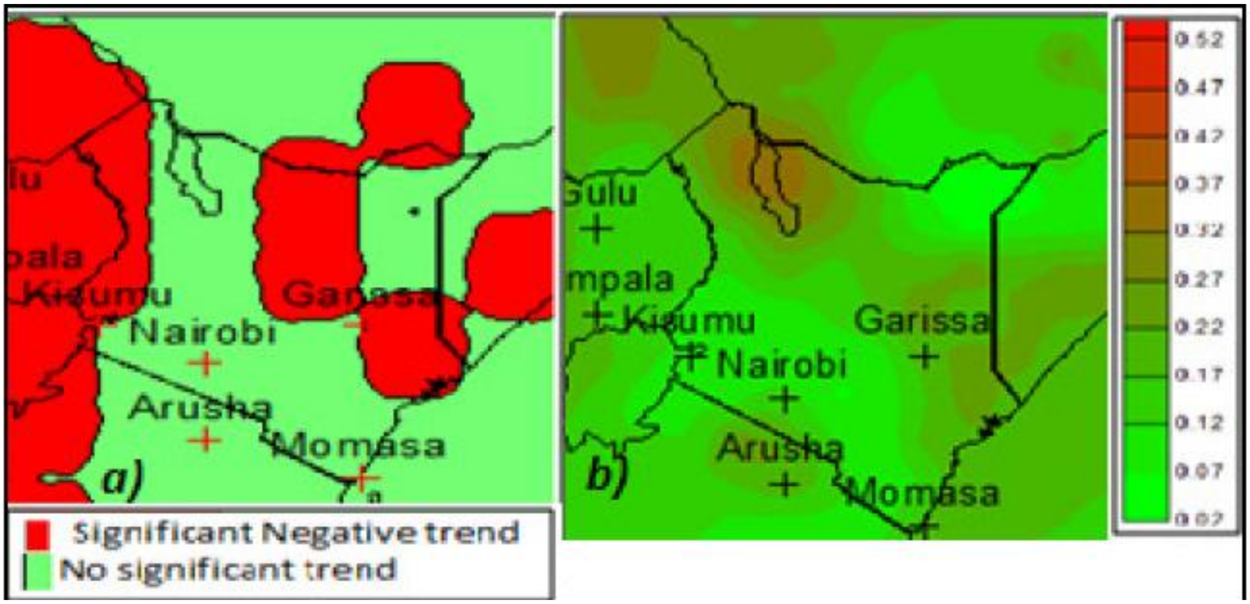

Figure 4: Spatial pattern of a) mean and b) long term AOD over Kenya

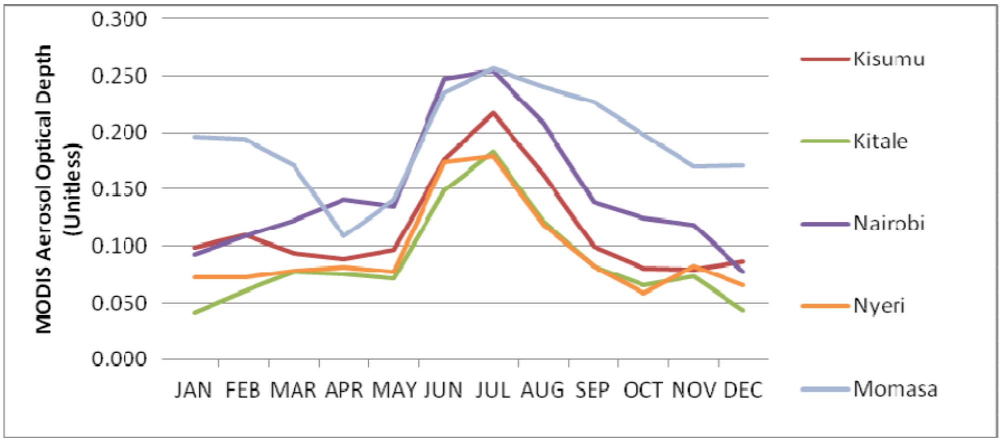

Figure 5: Annual variation of MODIS Aerosol Optical depth over Kenya

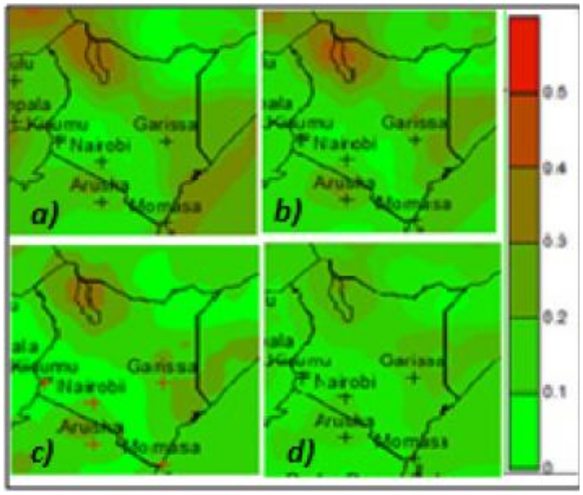

Figure 6: AOD over Kenya during a) DJF b) MAM c) JJA and d) SON season

Influence of meteorological parameters on atmospheric aerosols

Back trajectory analysis was computed at several altitudes (500 m, 1000 m, and 500 m) for January, April, July and October 2012 as representative periods for DJF, MAM, JJA and SON seasons as shown in (figure 7).

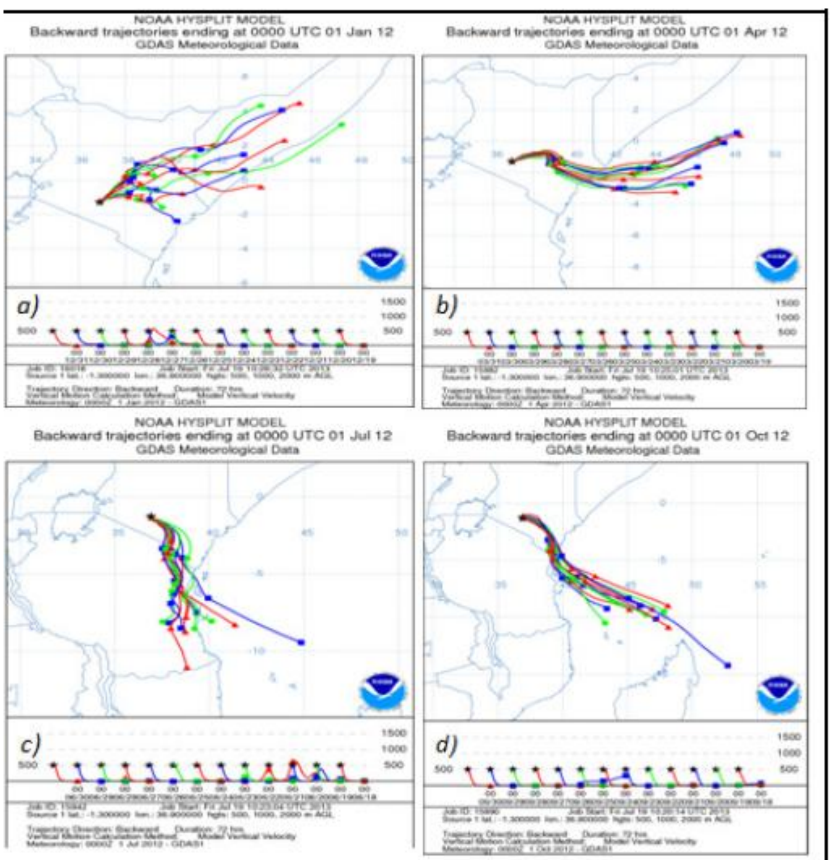

Figure 7: Back trajectories for a) DJF b) MAM c) JJA and d) SON over Kenya

The results indicated that the sources of pollutants during DJF and MAM were mainly from the Arabian highs and Indian Sub continent while sources of pollutants during the JJA and

SON season were mainly from the southwestern parts of the Indian Ocean. Studies by Gatebe *et al*. (2001) noted that aerosols measured depended critically on regional patterns of aerosol transport with interregional transfers seemingly a feature of the transport climatology with inter hemispheric transport across the equator in the region is observed.

Further, the study observed that at different levels above the ground, the atmospheric aerosol present in the atmosphere had same origins. It was assumed that these aerosols at from different origins underwent vertical mixing as they got advected inlands over the region. Therefore, these mixed aerosols accounted for enhanced aerosol loading and significant trend over western parts of the study.

Conclusion

Assessment of space and time variability of MODIS aerosol measurements over Kenya showed a decreasing trend in aerosol loading with a long term mean of between 0.02 and 0.56. Although validation of MODIS AOD using AERONET data from two stations (Nairobi and Mbita) indicated that MODIS overestimated the aerosol loading, the data confirmed that MODIS data performed well over vegetated regions than near large water bodies. Time series of mean monthly AOD values showed two peaks during the months of July and December while seasonal variations indicated high aerosol loading during DJF and JJA season. Backward trajectory analysis indicated that the sources of pollutants during DJF and MAM were mainly from the Arabian highs and Indian Sub continent while sources of pollutants during the JJA and SON season were mainly from the southwestern parts of the Indian Ocean. In order to obtain more comprehensive satellite AOD retrievals utilization of long time period AERONET is planned for future research projects aimed at achieving a better understanding of spatial and temporal variations in aerosols over Kenya.

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