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Rising Dust Aerosol Pollution at Ilorin in the Sub-sahel Inferred from 10-year Aeronet Data: Possible Links to Persisting Drought Conditions

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Abstract: AERONET Aerosol Optical Depth (AOD) and Angstrom Exponent (α) data of Ilorin in the sub-Sahel region of Nigeria (8º32′N; 4º34′E) for the first 10 years of measurements (April 1998-April 2008) are analyzed with the aim of deducing recent trends in dust aerosol loading in the area. The data indicates averagely increasing trends in AOD for both the dry and wet seasons. Analysis of the α data for two halves (1998-2002/03 and 2003-2007/08) of the progressive 10-year data span (1998-2008) reveals a slight increase (of ~ 8%) in the probability density of the dominant mode of the smaller α ($\alpha<1$) fraction (associated with dust aerosols) in the second part (2003-2007/08) compared to its value in the first part (1998-2002/03). The α peak also shifted to a lower value during the second half of the series suggesting increased coarseness of particles possibly due to presence of more dust aerosols. Considering that Sahara dust and biomass burning aerosols are both usually not significant in the wet season, the observed growing AOD trends in both seasons and then the α variability pattern suggest possible intensification of local dust pollutions at the site within the 10 year period considered. These possibilities are linked to the persistent long-term drought and resulting aridity of the area. Given a scenario where aerosol loading might inhibit rainfall, as some studies suggest, a reciprocal (positive feedback) action of the form; dust loading ↔ drought is probably intensifying in the area.

Key words: AERONET, atmospheric pollution, drought, dust aerosol, sub-Sahel, West Africa

INTRODUCTION

Changing concentrations and composition of atmospheric aerosol particles immensely influence the global climate system in a number of ways especially due to aerosol radiative and microphysical properties (Charlson *et al*., 1992; Giorgi *et al*., 2002).

Growing possibilities for aerosol loading changes are mostly found in regions such as West Africa being the location of the world's biggest natural reservoir for dust (The Sahara). In the sub-Sahel region of West Africa there is growing interest amongst climate scientists on account of the extraordinary aerosol production mechanisms encountered (Nwofor, 2009). The harmattan wind deposits Sahara aerosols during the dry period (Adeyewa and Balogun, 2003; Utah, 1995; Pinker *et al*., 1994) and transports same to various parts of the globe (Kaufman *et al*., 2005; Perrone *et al*., 2005).

The Sahara has encroached into previously forested areas in what seems to be the world's most accelerated desertification process, and this has been accompanied by exceptional rise in dust aerosol loading (Anuforom *et al*., 2007), with severe consequence for the weather and climate system.

One of the most critical challenges facing atmospheric research in Africa has to do with understanding the intricate links between the highly variable rainfall patterns in the Sahel and sub-Sahel area and the increasing atmospheric aerosol loading trends being reported in many parts of the region (Marticorena and Cairo, 2006).Desertification in the sub-Sahara region is usually a combination of drought-driven aridity and increasing deforestation arising from farming, grazing and fuel wood collection occasioned by increasing population (Nwofor, 2009, 2010).

It is well known that desertification leads to an upsurge in wind-assisted erosion of the topsoil which increases atmospheric dust load. Brooks and Legrand (2003) using the Infra-Red Difference Dust Index (IDDI) data set have established that decreasing rainfall totals in the Sahel area increased dust production in the later part of the following dry season . This is well understood to be a result of the combination of increased surface dryness and reduction in land cover from reduced rainfall. Reduction in land cover in particular has the long-term effect of reducing biomass burning aerosols which are very much produced in the West Africa region (Marticorena and Cairo, 2006; Kaufman *et al*., 2005)

The potential impacts of aerosol loading scenario in parts of the Sahel and sub-Sahel of West Africa and the association to desert encroachment have necessitated continuous monitoring of aerosol optical and particulate properties by the National Aeronautics and Space Administration (NASA) Aerosol Robotic Network

Fig. 1: Map of Nigeria showing the location of Ilorin

(AERONET) of ground-based sun photometers (Holben *et al*., 1998).The Ilorin AERONET site located in the sub-Sahel region of Nigeria, since inception about 10 years ago, is providing data on aerosol concentration as well as optical and size distribution characteristics which are invaluable for the validation of the Earth Observation System (EOS) datasets with respect to aerosol climatology and desert encroachment (http://www.atmos.umd.edu/~srb/eos/index.htm). These data provides a reliable tool for assessing the relationships between aerosol loading and rainfall dynamics (Pinker *et al*., 2006).

In this study, Aerosol Optical Depth and Angstrom Exponent data of Ilorin AERONET station since inception (~ 10 years i.e., 1998-2008) are examined to infer any possible changes in dust aerosol loading at Ilorin in the West African sub-Sahel (8º32′N; 4º34′E during the period. Thereafter, the resulting trends are discussed against the background of the now popular sub-Sahel drought using a century-long rainfall data.

METHODOLOGY

For this study, aerosol optical depth (AOD), Angstrom Exponent (AE) and Precipitable Water (PW) data sets from the National Aeronautics and Space Administration (NASA) Aerosol Robotic Network (AERONET); http://aeronet.gsfc.nasa.gov/, for Ilorin Nigeria (8º32′N; 4º34′E) (Fig. 1), were utilized. The site has been described in details in previous reports (Nwofor *et al*., 2007). The AOD data used for the investigations were the 340 nm level 2.0 data (cloud-screened).

The Aerosol Optical Depth (AOD) is an integrated aerosol column extinction property. Its temporal variability provides a reliable direct inference of particle concentration when the aerosol burden has insignificant temporal variations in chemical composition and size distribution. The daily average values were available for 10 years (April 1998-April 2008) covering the first ten years of AERONET data acquisition at the site. However due to instrument failures which are common with AERONET data, several gaps at times spanning many days often occur in the AOD data series (Nwofor and Chineke, 2007), thus making the use of monthly averages more reliable than daily averages for evaluating long-term trends with the data. Additional trends were therefore evaluated using annual averages instead of monthly averages and these were calculated separately for each season (the wet and dry seasons). The wet season months are chosen to span April, May, June, July, August and September, while the dry season months are October, November, December, January, February and March.

The Angstrom Exponent (α) is known to contain size information on all optically active aerosols sensed by a photometer (O'Neill *et al*., 2001). Hence α is a simple parameter for making direct inference on size distribution from optical depth data and this is useful for the characterization of aerosol particle sources. A large Angstrom exponent (typically $\alpha \geq 1$) implies scattering dominated by sub-micron particles while a distribution dominated by coarse particles has α typically <1 (Lesins and Lohmann, 2003). Analyses of the frequency distribution of α at Ilorin was employed previously by Nwofor *et al*. (2007) to conclude that two major modes occur in the dry season which represent coarse particles (Sahara and local dust likely) and fine particles (likely from biomass burning) and one coarse mode in the wet season (from local dust). The temporal evolution of α

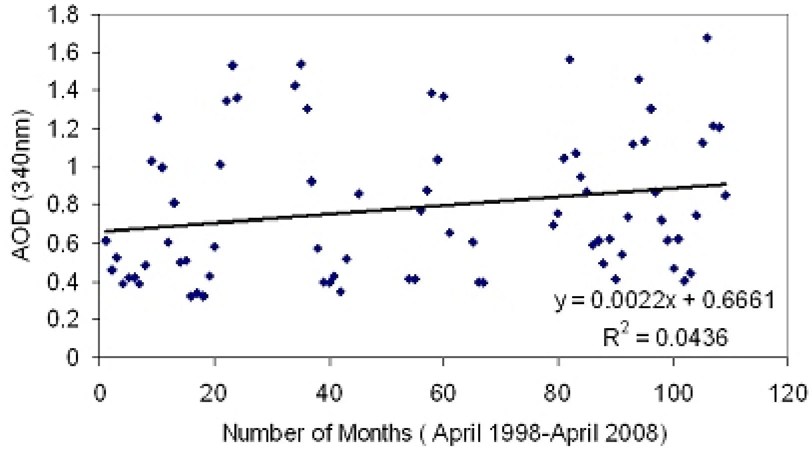


Fig. 2: Scatter plots of monthly averages of Ilorin AERONET AOD (340nm) from April 1998 to April 2008 and fitted trend line and R^2 (suggesting low correlation with data. Large gaps between some AOD values are periods without data

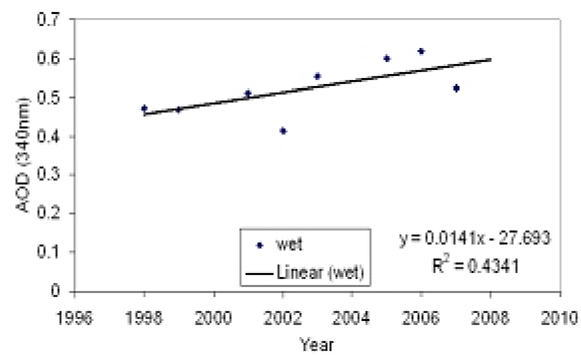
statistical distribution over a given time range can therefore justifiably define any changes in intensity and in the relative significance of aerosol particles of different origins at the site. This technique has been employed to assess such changes. The 10-year α data, for the 440-870 nm spectral intervals was divided into two time ranges: The first for 1998-2002/03 and the second for 2003-2007/08. The α probability densities were then evaluated for both time ranges and then plotted.

Monthly average rainfall data which were used to assess the nature of long-term wetness at the site were obtained from International Water Management Institute (IWMI) for ~ 100 years (1901-2002). The IWMI Integrated Database Information System (IDIS) is assessable on the website: http://dw.iwmii.org/IDIS_DP/clickandplotaspx and is designed to provide handy data for global water-related studies accounting for over 300 journal publications in the last two years alone (Nwofor *et al.*, 2010).

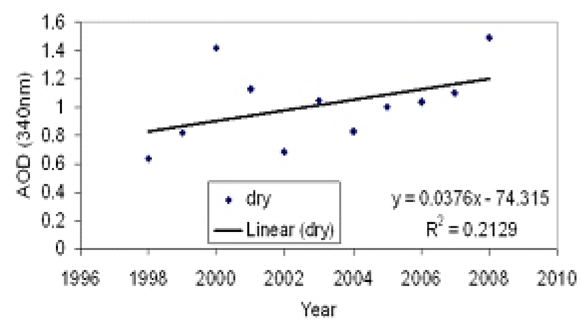
RESULTS

Aerosol optical depth: Plotted in Fig. 2 are the monthly averages of AOD from April 1998 to April 2008, with fitted trend line and correlation with data (R^2~0.04). The evaluated trend in the figure is positive but certainly made unreliable by the huge gaps in the data series which tend to occur more at periods of low AODs. Better trend fits using seasonal data are presented in Fig. 3a, b. Figure 3a, b with better correlation (R^2 = 0.43: 0.21), than that in Fig. 2 show more convincingly that aerosol loading may indeed be on the increase at the location and these occurred in both the wet and the dry seasons.

Angstrom exponent: The statistical distributions of the Angstrom Exponent have been used to infer the temporal trends in the size modes and by implication the aerosol types (Fig. 4a, b). It is shown that in the first period of the data range (1998-2002/03; Fig. 4a), the highest peak of

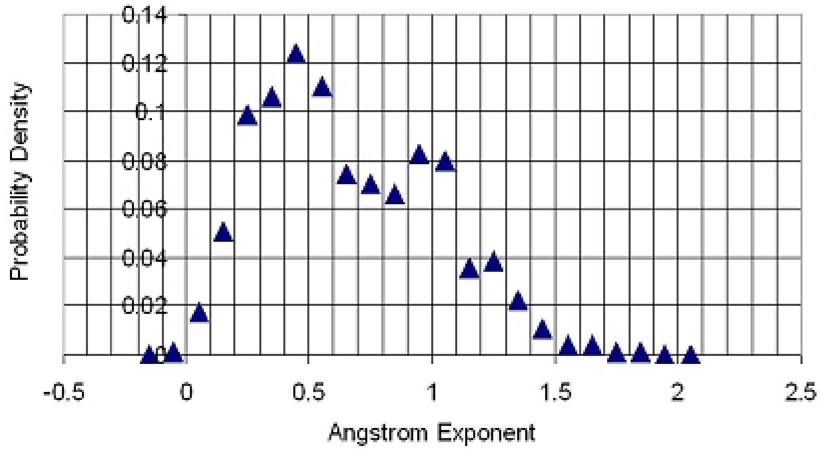


(a)

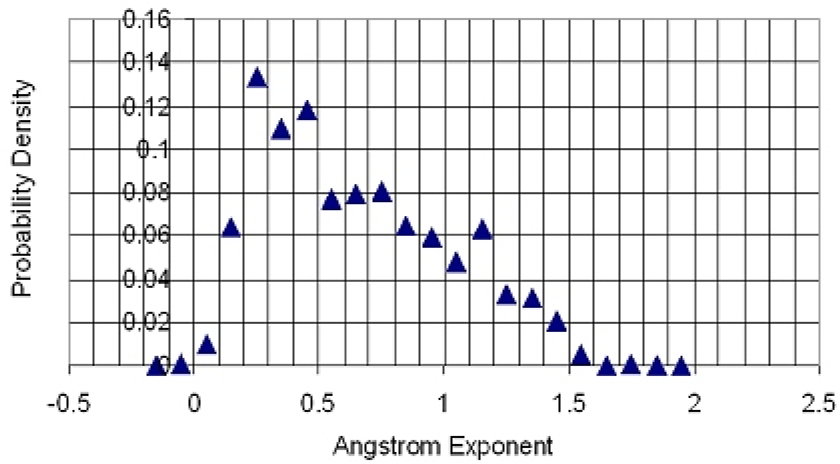


(b)

Fig 3: Scatter plots of yearly averages of Ilorin AERONET AOD (340 nm) from April 1998 to April 2008 and fitted trend line with improved correlation with data: (a) AOD for only wet season months, (b) AOD for only dry season months



(a)



(b)

Fig. 4: Angstrom Exponent Probability Density; (a) first part of the 10-year period (1998-2002), (b) second part of the 10-year period (2003-2007)

the lower α fraction (α< 1) - associated with dust-, occurs at α = 0.45 with probability density ($\alpha_{prob\text{-}density}$) = 0.12. In the second part of the data range (2003-2007/08; Fig. 4b), there is increased occurrence of multiple modes in the lower α fraction with the highest peaking at α = 0.25 and with $\alpha_{prob\text{-}density}$ = 0.13. This signifies the likely presence of coarser dust particles and some growth in the average probability of occurrence of dust particles during the second period of the 10-year data available. Considering the higher α fraction ($\alpha \geq$ 1)-associated with biomass burning aerosols-, it is evident that a greater number of modes occur in the first part of the data (1998-2002/03; Fig. 4a) than in the second part (2003-2007/08; Fig. 4b). The highest probability of occurrence ($\alpha_{prob\text{-}density}$ = 0.08) is located at α = 1. In the second period with less number of visible modes, the highest probability of occurrence ($\alpha_{prob\text{-}density}$ = 0.06) is at a value lower than what it was at the first period and occurs at α = 1.15 which suggests increased presence of finer biomass burning particles.

DISCUSSION

Temporal changes in AOD and α as observed in this study suggests variability in concentration or size of aerosol particles as inferred. The detected changes within the 10-year period of AERONET data series at Ilorin is likely a result of rising volume in internally generated dust particles in addition to the advected particles from the Sahara. This conclusion follows from the observation of increased AOD (aerosol concentration) in the dry season when Sahara dust is encountered as well as in the wet season (when Sahara dust particles are usually absent). Furthermore the Angstrom Exponent analyses indicating changes in coarseness or particle radii during different halves of the 10-year period signify possible introduction of multiple dust sources in the aerosol population.

(More local dust probably added to the dominant Sahara dust). The data also imply possible reduction in biomass aerosol production since the major mode associated with this fraction (α = 1) slightly dropped in intensity in the second half of the period considered.

Association to drought and aridity: It is clearly understood from AERONET data that dust and biomass burning particles are the major aerosol sources in the West African sub-Sahel region with loading characteristics highly determined by parameters of the annual monsoon cycle such as the wind vector and rainfall intensity (Pinker *et al*., 1994, 2006; Nwofor *et al*., 2007). This established dependence of temporal variability of aerosol loading in the region to meteorological conditions especially rainfall makes it imperative that the long-term variability of rainfall should be linked to any observed changes in aerosol loading. Apart from Sahara dust advected to most parts of West Africa during the *harmattarn* period, dust raised locally during the later part of the dry season and in the wet season is mostly affected by rainfall statistics as rainfall acts as the major sink for wet season particles and also affects the uplift of particles. Since dust is less likely lifted from a wet surface than from a dry one, the degree of water logging of the earth surface is very important in local dust production (Nicholson *et al*., 1998; Brooks and Legrand, 2003).

It is noteworthy that the Guinea (sub-Sahel) Savanna where Ilorin is located starts in the middle belt area of Nigeria towards the north (Fig. 1). It is distinguished from the Sahel Savanna by its more trees. Rainy seasons decline correspondingly in length as one moves north from the sub-Sahel (Akintola, 1986). The greatest total and heaviest precipitation is generally in the southern forested location, where mean annual rainfall is more than 4,000 mm and heaviest rainfall reaches between 700-800 mm/month. Towards the Sahel (Sokoto for example), the total rainfall, the length of the rainy season and the heaviest rainfall classes decline steadily. From the above discussion a change in rainfall pattern is therefore an established precursor of land cover change and changing dust aerosol loading. It is found from empirical data that both the mean rainfall and heavy rainfall classes have been on the decline at the site in the last 100 years.

Mean rainfall variations at Ilorin (1901-2002): In Fig. 5a, data of the mean monthly rainfall (mm) from January 1901 to December 2002 are presented. The raw rainfall data contains a total of 1224 data values. These

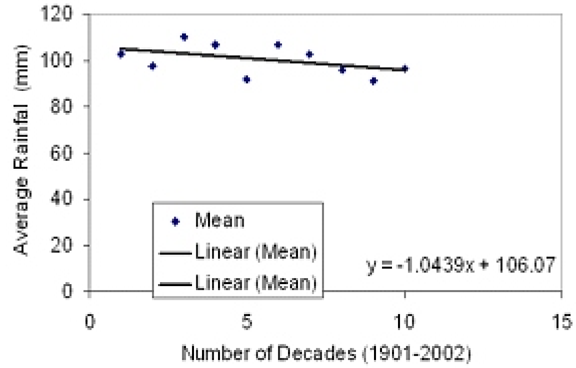


Fig. 5a: Decadal averages of rainfall (1901-2002) at Ilorin

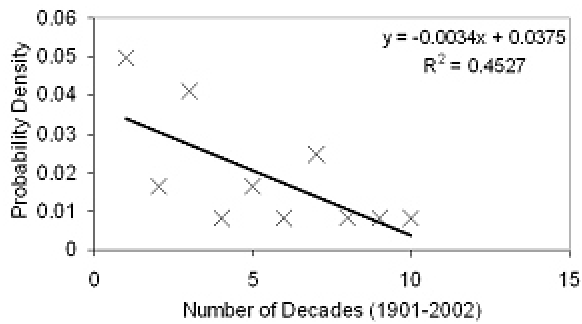


Fig. 5b: Probability density of decadal averages of rainfall within the heavy rainfall class ($\geq$ 300mm/month) at Ilorin and fitted linear trend

values have been used to compute the averages for each decade from 1901 to 2002 which therefore gives a 10-point decadal time series of the mean rainfall over the century. The major features of this variation are the clear swings although with no definite periodicity between wet and dry periods in the last century. It is equally obvious from the plot that each successive dry or wet period occurred at a value lower than it did at the previous period. The resulting long-term trend line fitted to the decadal variations shows a declining average rainfall from 1901 to 2002 of ~ 10mm. This figure therefore indicates a long-term centennial drought condition at this sub-Sahel location. It is however observed from the curve that in the last ten years, the mean decadal rainfall seems to be pick up from the trend of the preceding decade i.e. the 80s. This behavior has often been reported to imply some recovery from the prolonged drought situation of the 80s (Held *et al*., 2005).Weather or not this trend will be sustained can only be ascertained in the next decades or so when more measurements would be available to sufficiently prove such.

"Heavy" rainfall variations at Ilorin (1901-2002): Rainfall in most of West Africa and other areas can be discussed in terms of the "duration" and "intensity" of given rainfall events which jointly determine the "mean" rainfall. In fact agriculture and forestry growth and sustenance are very much dependent on both the duration and the intensity. It is however the later i.e., the intensity that determines the degree of flooding and water logging of the surface which is very influential to dust aerosol lifting. Hence declining trends in both average and "heavy" rainfall are complementary indicators of dryness and drought. It is noted in Fig. 5b that the probability of what is termed here as "heavy" rainfall (i.e., $\geq$300 mm/month), has just like the average rainfall been on the decline in the last 100 years. There are also visible inter-decadal fluctuations in the heavy rainfall trend similar to that observed in the average rainfall data- but the long-term decline (trend line has R^2~0.45) is phenomenal giving a long-term change from 1901 to the year 2002 of up to 50%.

These declining long-term rainfall trends are more influential to forestry growth and sustenance than the high frequency inter-decadal oscillations generally found in rainfall time series in West Africa (which seems to show apparent signs of recovery in the last 2 decades) and therefore a major cause of the growing aridity and local dust production.

Increasing trends in internally generated dust may arise from increasing surface area of the arid portions or from reduced surface water logging or both. These two possibilities can principally arise from declining precipitation trends which easily cause increased aridity, or loosening of the top soil.

Implications for dust-rainfall reciprocal action in the sub-Sahel: Nicholson (1992) has given a comprehensive schematic representation of land surface processes and feedback associated with drought and desertification. The schematic intrinsically connects decreased rainfall and reduced land cover giving rise to reduced soil moisture and evapo-transpiration and hence increased dryness and increased aerosol loading. The potential of dust particles to inhibit rainfall have been raised by Rosenfield *et al.* (2001) and corroborated by Rotstayn and Lohmann (2002). The implication is that a reciprocal action or positive feedback between dust aerosol and drought could be intensifying in the sub-Sahel- in which increasing drought supports intensification of dust aerosol loading first by increasing the aridity (thereby exposing more surfaces for mechanical erosion). Increasing dust atmospheric loading may in turn suppress rainfall. The schematic will be that shown in Fig. 6.

Impression from AOD/Precipitable water patterns: By measuring atmospheric optical depth at separate wavelengths within the atmospheric windows and comparing with those made at the water vapor absorption band, it is possible to retrieve atmospheric Precipitable Water (PW) which can serve as a good tracer for rainfall. Idemudia and Aro (1997) have used atmospheric

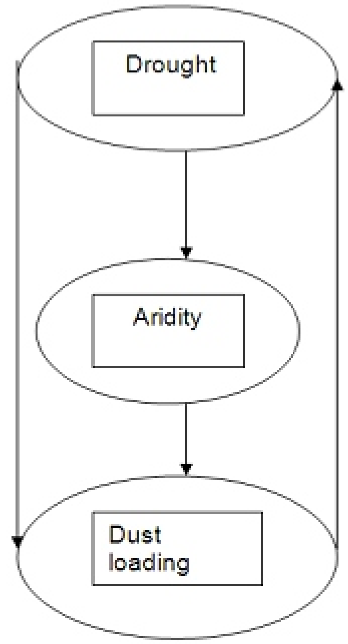


Fig. 6: Schematic of expected drought-dust reciprocal action in the sub-Sahel

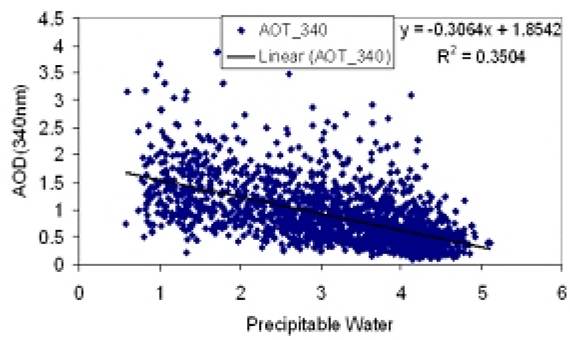


Fig. 7: Relation between aerosol optical depth and precipitable water at the site

precipitable water measurements to reproduce rainfall variations accurately at Ilorin Nigeria. Figure 7 is the plot of the PW/AOD_{340} relation using ten years AERONET data. The PW/AOD_{340} scatter-gram (R^2 = 0.35) shows an inverse relationship between aerosol loading and PW (rainfall probability). This relation is significant for the dust-drought reciprocal action in this region.

CONCLUSION AND OUTLOOK

From the analyses presented in this paper it is inferred that:

- There is increasing dust aerosol loading (for both the wet and dry seasons) from a generally increasing trend in the aerosol optical depth at Ilorin Nigeria in

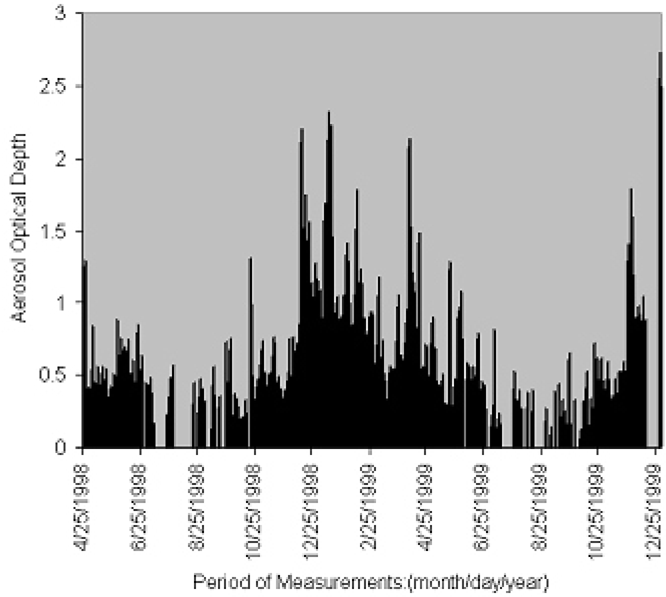


Fig. 8a: Time series of AOD (540 nm) of Ilorin for the period April 23 1999-December 31st 1999-a period that witnessed large data density permitting the fitting of a periodic cycle

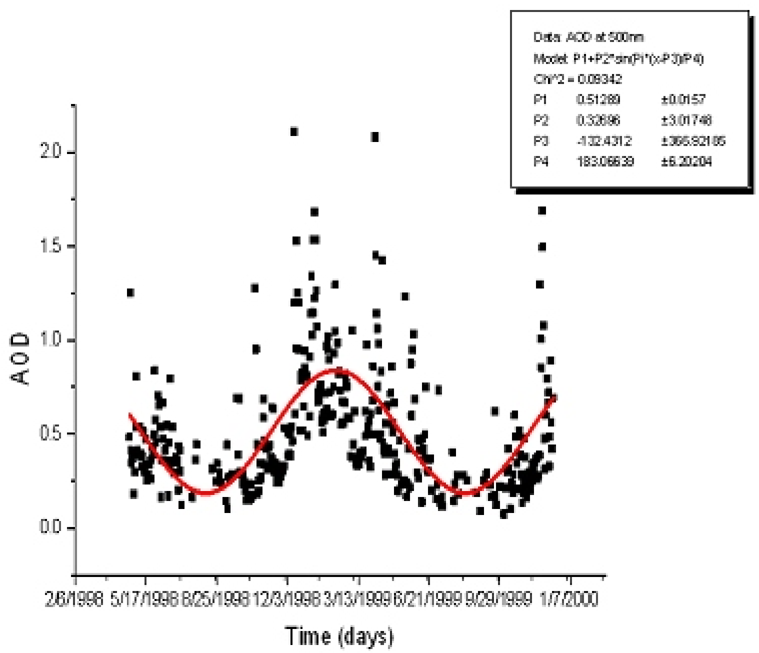


Fig. 8b: The fitted sine wave periodic cycle with fit parameters shown

sub-Sahel West Africa during the first ten years of AERONET measurements

- There is increased dust intensity and an additional coarser mode in the second half of the last 10 years of the data record compared to the first half. (Angstrom Exponent analysis).
- Since Sahara dust and biomass burning in this area occur mainly in the dry season (*Harmattan* and farming period respectively) while local dust occurs in both seasons, increasing local dust loading is most likely inferred in the observed aerosol optical depth trend in the wet season in particular.
- A declining long-term trend in the average rainfall of ~ 10 mm from 1901-2002 and also a drop in the probability of "heavy" rainfall which shows a long-term decline of ~ 50% from 1901 to 2000 are likely contributions to the observed rising local dust aerosol loading as the observed declining trends in rainfall at

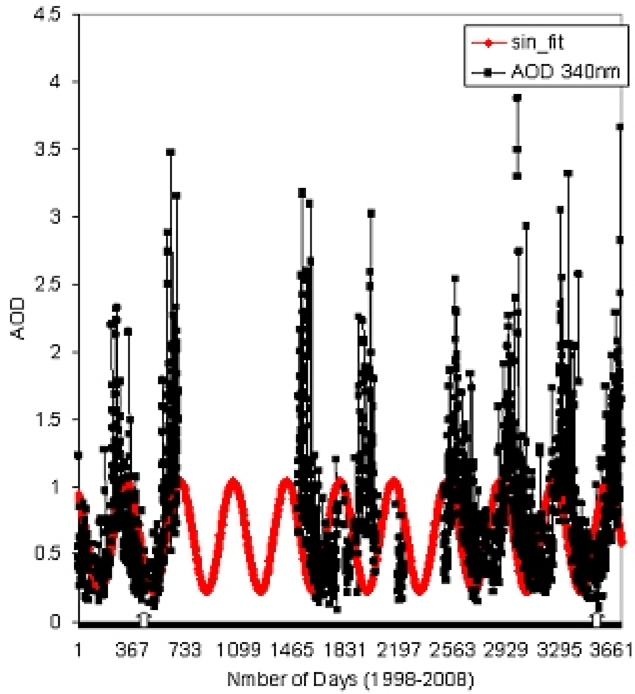


Fig. 9: Relation between observed AOD (340nm) for ten years (April 23,1998-December 31st 2008) and extrapolated sine model generated from the least square fit for the first cycle 23 April 1998-November 11,1999)
The AOD follows an annual cycle of dry season highs and wet season lows. In the data above a first arrow is positioned at the trough of the second annual cycle of the observations and again at the trough of the tenth cycle. Comparison of the two arrows with respect to the trough of the sine wave model indicates (although inclusively at this stage that a lag of the model with respect to the observed series appears to be developing

the site could intensify the aridity and surface dryness thus making more dust available for uplift.

- Since the quantity of biomass burnt depends on availability of forests, declining rainfall and consequently declining forest volume imply some decline in biomass burning aerosols relative to dust as was observed in this study.

An approach is being explored for examining the relative stability of the AOD and monsoon cycles at the site to assess how one affects the other. Preliminary analysis shows that the AERONET 10-year data of optical depth cycle of highs and lows might not be stable with time. This was investigated by fitting periodic functions based on a least square best fit to the daily AOD from 25th April 1998-31st December, 1999 (which has high data density to permit such a fit; (Nwofor, 2006; Nwofor and Chineke, 2007) using a relation of the form; $Y = P_1 + P_2 \sin(\pi(x-P_3)/P_4)$ where Y is the AOD, x is the chronological time of measurement and the parameters P_1, P_2, P_3 and P_4 represent the annual average, amplitude of the seasonal modulation, the phase and the period respectively and then extrapolating this over a 10-year period (1998-2008). The biennial data series is shown in Fig. 8a, while the periodic fit is shown in Fig. 8b. The observed AOD series and the projected function over a ten-year period are shown in Fig. 9. The AOD follows an annual cycle of dry season highs and wet season lows. In the data a first arrow is positioned at the trough of ~ the second annual cycle of the observations and again at the trough of ~ the tenth cycle. Comparison of the troughs of the observed series as indicated by the two arrows with respect to the trough of the sine wave model indicates that a lag of the model with respect to the observed series appears to be developing. Although for this short data length this disparity is not obvious. One however expects that with more data accumulating, it will become possible to establish if the observed AOD cycle propagates in response to the changing lengths of dry spells already reported for most of West Africa for instance by Chineke *et al.* (2010).

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courtesy of the International Water Management Institute (IWMI) via the website: http://dw.iwmii.org/IDIS DP/clickandplotaspx/

REFERENCES

Adeyewa, Z.D. and E.E. Balogun, 2003. Wavelength dependence of aerosol optical depth and the fit of the Angstrom law. Theor. Appl. Climatol., 74: 105-122.

Akintola, J.O., 1986. Rainfall Distribution in Nigeria 1892-1983. Impact Publishers, Ibadan.

Anuforom, A.C., L.E. Akeh, P.N. Okeke and F.E. Opara, 2007. Inter-annual variability and long-term trend of UV-absorbing aerosols during the harmatttarn season in sub-Saharan West Africa. Atmos. Environ., 41(7): 1550-1559.

Brooks, N. and M. Legrand, 2003. Dust Variability over Northern Africa and Rainfall in the Sahel. In: Mclaren, S.J. and D.R. Kniveton (Eds.), Advances in Global Change Research: Linking Climate Change to Land Surface Change. Springer Netherlands, pp: 1-25.

Charlson, R.J., S.E. Schwartz, J.M. Hales, R.D. Coakley, J.E. Hansen and D.J. Hoffman, 1992. Climate forcing by anthropogenic aerosols. Science, 255: 423-430.

Chineke, T.C., S.S. Jagtap and O. Nwofor, 2010. West African monsoon: Is the August break “breaking” in the eastern humid zone of Nigeria? Climatic Change, (In press). doi: 10.1007/s10584-009-9780-2.

Giorgi, F., X. Bi and Y. Qian, 2002. Direct radiative forcing and regional climatic effects of anthropogenic aerosols over East Asia: A regional coupled climate-chemistry/aerosol model study. J. Geophys. Res., 107(D20): 4439. doi: 10.1029/2001JD001066, 2002.

Held, I.M., T.L. Delworth, J. Lu, K.L. Findell and T.R. Knutson, 2005. Simulation of sahel drought in the 20th and 21st centuries. Proc. Nat. Acad. Sci. USA, 102(50): 17891-17896.

Holben, B.N., T.F. Eck, I. Slutsker, D. Tanre, J.P. Buis, A. Setzer, E. Vermonte, J.A. Reagan, Y.J. Kaufman, T. Nakajima, F. Lavenu, I. Jankowiak and A. Smirnov, 1998. AERONET - A federated instrument network and data archive for aerosol characteristics. Remote Sens. Environ., 66: 1-16.

Idemudia, G.O. and T.O. Aro, 1997. Measurements of atmospheric precipitable water vapor at micrometer wavelengths over a tropical station. Nig. J. Phys., 9: 100-105.

Kaufman, Y.J., I. Koren, L.A. Remer, D. Tanre, P. Ginoux and S. Fan, 2005. Dust transport and deposition observed from the Terra-MODIS spacecraft over the Atlantic Ocean. J. Geophys. Res., 110(D10S12): 1-16. doi: 10.1029/2003JD004436.

Lesins, G. and U. Lohmann, 2003. GCM aerosol radiative effects using geographically varying aerosol sizes deduced from AERONET measurements. J. Atmos. Sci., 60: 2747-2763.

Marticorena, B. and F. Cairo, 2006. EOP/LOP Aerosols Monitoring and Radiation (TT2b). AMMA International Implementation Plan-Version 2.0, 4: 2-15.

Nicholson, S.E., 1992. Prediction of trace gas emissions and their climatic impacts: some geographical considerations. Ecol. Bull., 42: 12-23

Nicholson, S.E., S.E. Nicholson, C.J. Tucker and M.B. Ba, 1998. Desertification, drought and surface vegetation; an example from the West African Sahel. Bull. Am. Meteorol. Soc., 79(5): 815-829.

Nwofor, O.K., 2006. Seasonality of aerosol optical depth over Ilorin Nigeria. Unpublished Ph.D. Dissertation, Imo State University Owerri, Nigeria.

Nwofor, O.K., 2009. Global Atmospheric Changes from Aerosol Emissions: Why is West Africa so Important? In: Chih-Hao, Y. (Ed.), Atmospheric Science Research Progress. Nova Science, New York, pp: 89-104.

Nwofor, O.K., 2010. Pondering a future of severe aerosol pollutions in Nigeria and the need for a monitoring network. Int. J. Environ. Waste Manage., 6(3/4): 364-376.

Nwofor, O.K. and T.C. Chineke, 2007. Mathematical representation of seasonal cycles of aerosol optical depths at Ilorin Nigeria using AERONET data. Global. J. Pure. Appl. Sc., 3(1): 285-293.

Nwofor, O.K., T.C. Chineke and R.T. Pinker, 2007. Seasonal characteristics of spectral aerosol optical properties at a sub-saharan site. Atmos. Res., 85: 38-51.

Nwofor, O.K., T.C. Chineke, U.K. Okoro and V.N. Dike, 2010. Interdecadal characteristics and spectral features of centennial (1901-2000) monthly average rainfall series of a sub-Sahel location. Submitted to Geofizika.

O’Neill, N.T., O. Dubovick and Eck, 2001. Modified Angstrom Exponent for the characterization of sub-micrometer aerosols. Appl. Optic., 40(15): 2368-2374.

Perrone, M.R., M. Santese, A.M. Tafuro, B. Holben and A. Smirnov, 2005. Aerosol load characterization over South-East Italy for one year of AERONET measurements. Atmos. Res., 75: 111-133.

Pinker, R.T., O. Idemudia and T.O. Aro, 1994. Characteristics of aerosol optical depths during the Harmattarn season in sub-Saharan Africa. J. Geophys. Res., 21: 685.

Pinker, R.T., Y. Zhao, C. Akoshile, J. Janowiak and P. Arkin, 2006. Diurnal and seasonal variability of rainfall in the sub-Sahel a seen from observations, satellites and a numerical model. Geophys. Res. Lett., 33: LO7806. doi: 10.1029/2005GLO25192.

Rosenfield, D., Y. Rudich and R. Lahav, 2001. Desert dust suppressing precipitation a possible desertification feedback loop. Proc. Nat. Acad. Sc. USA, 98: 5975-5980.

Rotstayn, L.D. and U. Lohman, 2002. Tropical rainfall trends and the indirect aerosol effect. J. Climate, 15(15): 2103-2116.

Utah, E.U., 1995. Aerosol optical density during the harmattarn at Jos, Nigeria. Nig. J. Phys., 7: 67-71.