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The Scattering and Absorption Coefficients of Atmospheric Soot in the Hygroscopicity of Urban Aerosols

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Abstract
Aerosols are microscopic solid or liquid particles suspended in the atmosphere that have an impact on the Earth's radiative balance. This paper modeled and investigates the effect of scattering and absorption coefficients along with their respective hygroscopicity of atmospheric soot using extracted data from Optical Properties of Aerosols and Clouds (OPAC) incorporated with Fortran at spectral range of 0.25 to 1.00 μm for eight different relative humidities (RHs) (0, 50, 70, 80, 90, 95, 98 and 99%). The fine – mode and coarse – mode aerosol size distribution were also investigated. The particle number densities of soot were varied as 110,000 120,000 and 130,000 cm^{-3} while the water soluble and insoluble components were kept constant. The scattering coefficient decreases with RHs and also with wavelength in the form of power law at all RHs. The absorption coefficient increases with addition of soot, reflecting warming effect. In this study, it was observed that there is a pronounced hygroscopicity growth as from 95-99% RHs. The Ångström exponent decreases with increase in RHs for the case of scattering coefficient but varies for absorption coefficient; the curvature reveals the presence of both fine and coarse mode particles. The results of the turbidity coefficient (β) based on the scattering coefficient indicated that the atmosphere is relatively clear and hazy while the absorption coefficient indicated that the atmosphere is relatively clear at 0 – 99% relative humidity. The results in this study revealed that the coefficient of determination, $R^2 > 96\%$ for all the models (1 – 3).

Keywords: Coarse mode particles, fine mode particles, mass mix ratio, soot, volume mix ratio

INTRODUCTION
The natural and anthropogenic sources of atmospheric aerosols have important effects on the global and regional climate system since they scatter and absorb solar and thermal radiation (direct effect), modify the cloud optical properties by acting as cloud condensation nuclei

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(CCN) (indirect effect), and change atmospheric radiative budget (Bellouin *et al*., 2005; Rosenfeld, 2006). The climatic effects of the atmospheric aerosol are highly irregular due to the large variability of the aerosol physical and optical properties, which are attributed to a diversity of sources, and their dependence on the prevailing meteorological and atmospheric conditions (Satheesh and Krishna Moorthy, 2005). The aerosol optical properties are strongly dependent on relative humidity (Tijjani and Akpootu, 2013a).

The two most common forms of air pollution are Smog and Soot (Meseke *et al*., 2022). Soot aerosols also known as black carbon (BC) are produced when incomplete combustion takes place. The diesel engines, forest fires and biomass burning are the major sources of soot aerosols (BC) (Bond and Bergstrom, 2006). Soot consists of monodispersed spherical particles that collect into mass fractal aggregates having a broad size distribution, the primary soot particles are usually very small (Tijjani and Akpootu, 2013b). The role of soot particles in combustion remains as one of the main motivations of both experimental and theoretical studies of soot radiative properties (Akpootu and Momoh, 2013a). The presence of dust aerosol in the atmosphere during the harmattan season in the northern hemisphere is a familiar feature of the climate of most parts of West Africa (Akande *et al*., 2013). The huge amount of dust and sand particles raised and transported by the harmattan dust haze strongly reduces visibility and are estimated to reach about 6.0 km above sea level (Essienimo *et al*., 2016a; Essienimo *et al*., 2016b). Negative forcing such as scattering and reflection of solar radiation by aerosols and clouds tends to cool the earth's surface, while positive forcing such as the absorption of terrestrial radiation by greenhouse gases and clouds tends to warm it (Akpootu and Sharafa, 2013; Akpootu and Momoh, 2013b). The size distribution of a given suspended particle determines the life-span of the particle in the atmosphere and how far it can travel (Essienimo *et al*., 2015a; Essienimo *et al*., 2015b).

Chemical compositions of aerosol particles released from natural and anthropogenic sources are not homogeneous either locally or globally, hence characteristics such as hygroscopicity are significantly different from one particle to another, controlling the particle's ability to form cloud droplets. Furthermore, there is lack of information on the bulk hygroscopicity (i.e., solute effect) of organics also limits the prediction of cloud droplet formation. Only one constant value of hygroscopicity has been applied in global models dealing with direct and/or indirect effects of organic aerosols (Ghan *et al*., 2001).

Several researchers have carried out studies in related field. In the paper of Tijjani and Akpootu (2012), they modeled the optical depths, asymmetry parameters and single scattering albedos of urban aerosols using OPAC at the spectral range of 0.25 μm to 1.0 μm for eight different relative humidities (RHs). The radiative forcings (RF) and Ångström parameters were calculated in their studies. For the RF, they observed that as the RH increases there is a small increase in warming from 0 to 70% but as from 80 to 99% RH there is an increase in cooling from the first to the second and then to the third model adopted. Akpootu and Gana (2013) modeled the hygroscopicity properties of water soluble aerosols component based on microphysical properties of urban aerosols using data extracted from OPAC incorporated with FORTRAN program to determine the effect of relative humidity on hygroscopic growth factor and bulk hygroscopicity at spectral range of 0.25-1.00 μm for eight different relative humidities (RHs). Other studies include Ranjan et al. (2007), Akpootu and Muhammad (2013), Akpootu and Tijjani (2014), Contini et al. (2021), Meseke et al. (2022), Abdulkarim et al. (2022) to mention but a few.

The purpose of this paper is to (i) investigate the effect of scattering and absorption coefficients along with their respective hygroscopicity at spectral range of 0.25 to1.00 μm for eight

different relative humidities (RHs) (ii) determine the fine – mode and coarse – mode aerosol size distribution for atmospheric soot in urban region (iii) investigate the clearness and haziness of the atmosphere. This study is unique as OPAC software was used to investigate the properties of atmospheric soot of urban aerosol. The turbidity coefficient was also investigated using OPAC which has not been done in previous studies.

METHODOLOGY

The models extracted from OPAC are given in Table 1

Table 1: Compositions of aerosols types (Hess *et al*., 1998).

Components	Model 1	Model 2	Model 3
	No.density (cm^{-3})	No.density (cm^{-3})	No.density (cm^{-3})
Insoluble	1.5	1.5	1.5
Water soluble	20,000.00	20,000.00	20,000.00
Soot	110,000.00	120,000.00	130,000.00
Total	130,001.50	140,001.50	150,001.50

The data used for the urban aerosols in this study are derived from the Optical Properties of Aerosols and Clouds (OPAC) data set (Hess *et al*., 1998). In this, a mixture of three components is used to describe Urban aerosols: a water soluble (WASO) components consist of scattering aerosols that are hygroscopic in nature, such as sulphates and nitrates present in anthropogenic pollution, water insoluble (INSO) and Soot.

The spectral behavior of the aerosol optical thickness, scattering, absorption and extinction coefficients can be used to obtain some information regarding the size distribution by just looking at the Ångström coefficient exponent that expresses the spectral dependence of aerosol optical depth $\tau(\lambda)$, scattering σ_{scat} (λ), absorption σ_{abs} (λ) and extinction σ_{ext} (λ) coefficients, with the wavelength of light (λ) as inverse power law (Ångström, 1961, Akpootu and Sharafa, 2013; Akpootu and Momoh, 2013b).

$$X(\lambda) = \beta\lambda^{-\alpha} \quad (1)$$

where $X(\lambda)$ can be any of the parameters mentioned above. In this paper the scattering σ_{scat} (λ) and absorption σ_{abs} (λ) coefficients are used. The formula is derived on the premise that the extinction of solar radiation by aerosols is a continuous function of wavelength, without selective bands or lines for scattering or absorption (Ranjan *et al*., 2007).

The wavelength dependence of σ_{scat} (λ) and σ_{abs} (λ) are characterized by the Ångström parameter, which is a coefficient of the following regression as modified by Akpootu and Abdul salami (2013):

$$ln\sigma_{sca}(\lambda) = -\alpha \ln(\lambda) + ln\beta \quad (2)$$

and $ln\sigma_{abs}(\lambda) = -\alpha \ln(\lambda) + ln\beta$ (3)

where α and β are Ångström exponent and turbidity coefficient (Liou, 2002; O'Neill and Royer, 1993). The Ångström exponent itself varies with wavelength, and a more precise empirical relationship between aerosol extinction and wavelength is obtained with a 2nd-order polynomial (King and Byrne, 1976; Akpootu and Sharafa, 2013; Akpootu and Momoh, 2013b) as:

$$ln\sigma_{sca}(\lambda) = \alpha_2(ln\lambda)^2 + \alpha_1 ln\lambda + ln\beta \quad (4)$$

$$ln\sigma_{abs}(\lambda) = \alpha_2(ln\lambda)^2 + \alpha_1 ln\lambda + ln\beta \quad (5)$$

The coefficient α_2 accounts for "curvature" often observed in Sun photometry measurements. In case of negative curvature ($\alpha_2 < 0$) while positive curvature ($\alpha_2 > 0$). Eck et al. (1999) reported the existence of negative curvatures for fine mode and positive curvatures for significant contribution by coarse mode particles in the aerosol size distribution. Akpootu and Momoh (2013a) has reported that the turbidity coefficient (β) values of less than 0.1 are associated with a relatively clear atmosphere, and values greater than 0.2 are associated with a relatively hazy atmosphere.

The hygroscopicity was obtained using the equation (Akpootu and Abdul salami, 2013)

$$Hygroscopicity = \frac{\sigma_{sca}\,(RHref)}{\sigma_{sca}(RH=0)} \quad (6)$$

$$Hygroscopicity = \frac{\sigma_{abs}\,(RHref)}{\sigma_{abs}(RH=0)} \quad (7)$$

where RH_{ref} is the value of any RH other than at 0% RH while $RH = 0$ is the value of RH at 0%

RESULTS AND DISCUSSION

The scattering and absorption coefficients along with their respective hygroscopicity for the three models are presented graphically using origin software and were discussed accordingly. The tables showing the results of the Ångström exponent, curvature and turbidity coefficient was done using SPSS software and were discussed accordingly.

Comparing figures 1, 3 and 5 it was observed that the scattering coefficient tends to remain constant at all RHs except that at 50% RH and 98% RH in Figure 5 where there is a slight decrease in scattering, attributing warming effect. However, a rapid decrease in scattering coefficient with RHs was expected, though, not observed as a result of high percentage of volume and mass mix ratio of water soluble when compared to soot aerosol component at all RHs, this is in line with that reported by Akpootu and Sharafa (2013) shown in Table 8 (Analysis of volume mix and mass mix ratios). figures 2, 4 and 6 shows the graphs of their respective hygroscopicity. The hygroscopicity increases with increase in RHs from model 1 to model 3; however, the hygroscopic growth is more pronounced as from 95-99% RHs. Fitzgerald (1975) reported that in relation of scattering coefficients with RH is such that at the deliquescence point (90-99%) growth increases with higher RHs. In this study, hygroscopicity growth increases with RH as from 95-99% RHs.

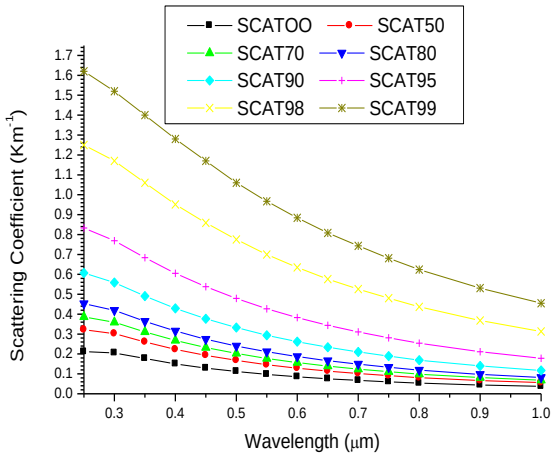

Figure 1: Scattering coefficient against wavelength based on model 1

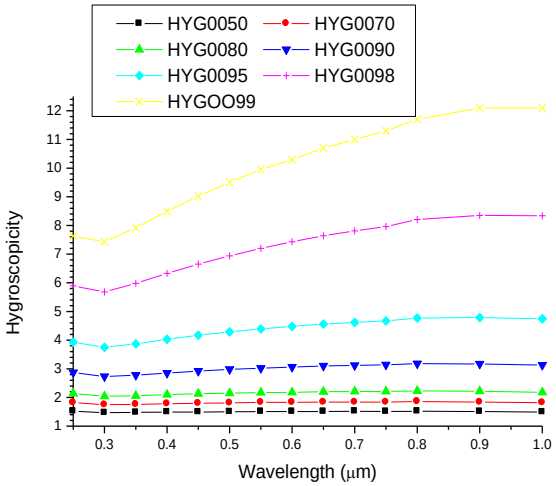

Figure 2. Hygroscopicity against wavelength based on model 1

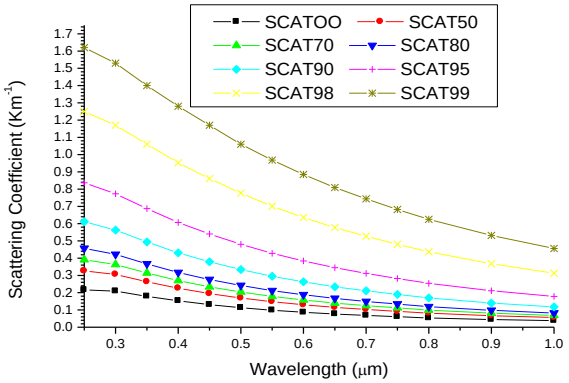

Figure 3: Scattering coefficient against wavelength based on model 2

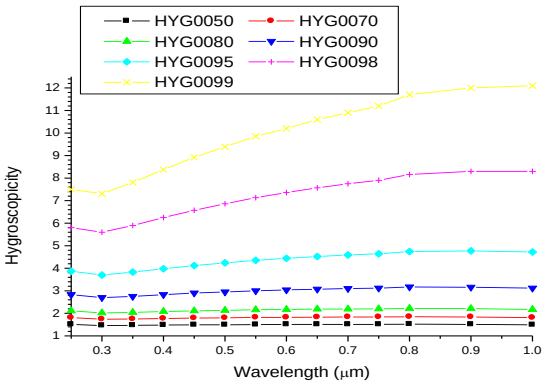

Figure 4: Hygroscopicity against wavelength based on model 2

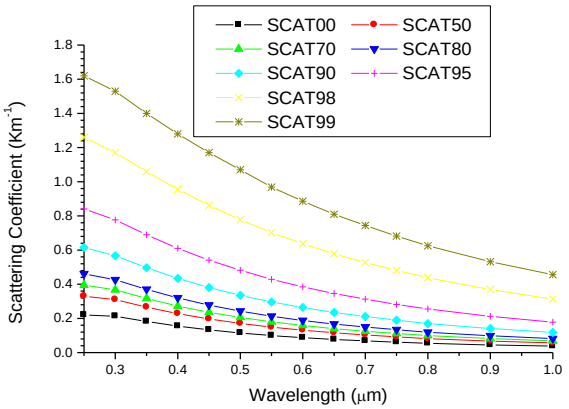

Figure 5: Scattering coefficient against wavelength based on model 3

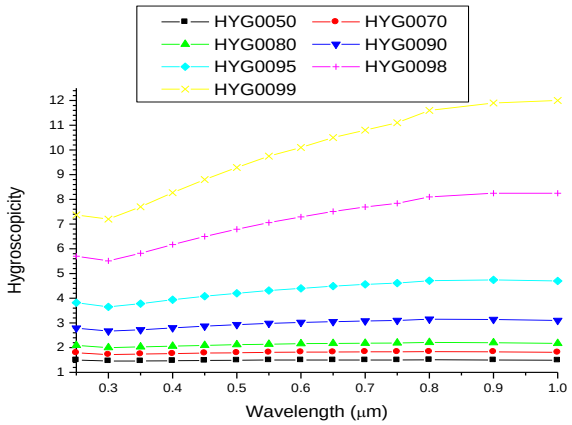

Figure 6: Hygroscopicity against wavelength based on model 3

According to Eck et al. (1999), Eck et al. (2001) and Ranjan (2007) positive values of Ångström exponent, α are characteristics of fine-mode dominated aerosols size distributions while near zero and negative values are characteristics of dominant coarse-mode, α_2 or bi-modal size distributions, with coarse-mode aerosols having significant magnitude. Tables 2, 3 and 4 show the values of the Ångström exponent, α and curvature, α_2 for the scattering coefficient. Comparing these Tables, the Ångström exponent, α, reflects the dominance of fine mode

particles which is verify by the curvature, α_2 at all RHs. However, the magnitude of α decreases with RH at all RHs indicating that higher fine mode particle are found at lower RH, this is in line with the results reported by Abdulkarim et al. (2022). Similarly, are the values for curvature. The values of the Ångström exponent, α indicating the fine – mode particle increases slightly from model 1 to model 3 while the values of the curvature indicating the fine – mode particle decreases slightly from model 1 to model 3. The coefficient of determination R^2 shows that the data fits excellently for the three models with the highest values recorded at 50% RH as 98.016%, 98.036% and 98.054% for model 1, model 2 and model 3 respectively. The turbidity coefficient (β) based on the analysis of the scattering coefficient shows that the atmosphere is relatively clear from 0 – 80% RHs and hazy from 98 – 99% RHs.

Table 2: The results of α and α_2 for scattering coefficient using equations (2) and (4) (model 1)

LINEAR				QUADRATIC			
RH(%)	R^2	α	β	R^2	α_1	α_2	β
0	0.97879	1.33365	0.04121	0.99726	-1.95957	-0.45916	0.03595
50	0.98016	1.32297	0.06231	0.99872	-1.9449	-0.45623	0.0544
70	0.98007	1.30326	0.07627	0.9991	-1.92359	-0.45506	0.06662
80	0.97959	1.27949	0.09186	0.99932	-1.89997	-0.45516	0.08023
90	0.97811	1.22117	0.13245	0.99962	-1.83982	-0.45382	0.11573
95	0.97548	1.14079	0.2016	0.9998	-1.75602	-0.45131	0.17627
98	0.97022	1.0177	0.35569	0.99991	-1.62591	-0.44616	0.31149
99	0.96517	0.92931	0.51817	0.99994	-1.53192	-0.44205	0.45433

Table 3: The results of α and α_2 for scattering coefficient using equations (2) and (4) (model 2)

LINEAR				QUADRATIC			
RH(%)	R^2	α	β	R^2	α_1	α_2	β
0	0.97909	1.34355	0.04146	0.99728	-1.96906	-0.45886	0.03617
50	0.98036	1.32975	0.06255	0.99871	-1.95121	-0.45588	0.05462
70	0.98027	1.30889	0.07652	0.99909	-1.92841	-0.45447	0.06684
80	0.97975	1.28444	0.09211	0.99932	-1.90456	-0.4549	0.08045
90	0.97830	1.22479	0.13271	0.9996	-1.84222	-0.45293	0.11599
95	0.97566	1.14364	0.20183	0.99979	-1.75795	-0.45064	0.17652
98	0.97039	1.01971	0.35590	0.9999	-1.62724	-0.44567	0.31172
99	0.96532	0.93081	0.51837	0.99994	-1.53307	-0.4418	0.45455

Table 4: The results of α and α_2 for scattering coefficient using equations (2) and (4) (model 3)

LINEAR				QUADRATIC			
RH(%)	R^2	α	β	R^2	α_1	α_2	β
0	0.9794	1.35336	0.04171	0.99729	-1.97825	-0.4584	0.03639
50	0.98054	1.33649	0.06279	0.99869	-1.95768	-0.45569	0.05484
70	0.9804	1.31464	0.07676	0.99908	-1.93448	-0.4547	0.06705
80	0.97991	1.28934	0.09235	0.9993	-1.90903	-0.45459	0.08067
90	0.97846	1.22873	0.13293	0.9996	-1.84575	-0.45263	0.11619
95	0.97581	1.14661	0.20204	0.9998	-1.76053	-0.45036	0.17671
98	0.97050	1.02156	0.35611	0.9999	-1.62903	-0.44562	0.31191
99	0.96549	0.93238	0.51855	0.99994	-1.53405	-0.44136	0.45476

Comparing figures 7, 9 and 11 there is a slight increase in absorption coefficient with increase in soot concentration which verify the effect of warming, though, rapid increase is expected. figures 8, 10 and 12 shows the graphs of their respective hygroscopicity, the hygroscopicity increases with RHs, though, there is a sharp fall of hygroscopicity with RH which tend to increase randomly indicating a more absorbing aerosol.

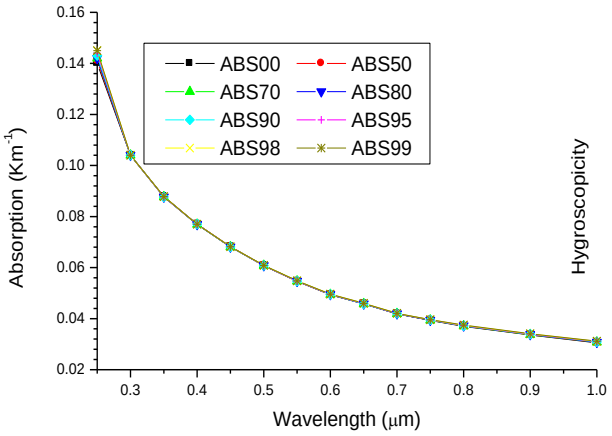

Figure 7: Absorption coefficient against wavelength based on model 1

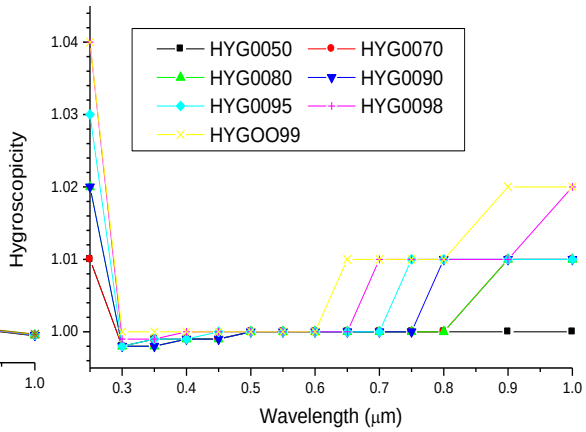

Figure 8: Hygroscopicity against wavelength based on model 1

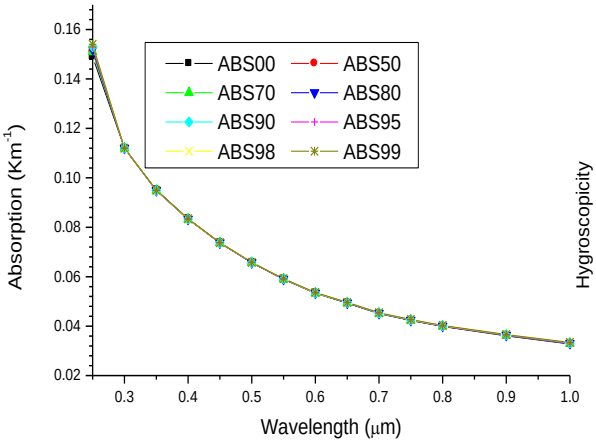

Figure 9: Absorption coefficient against wavelength based on model 2

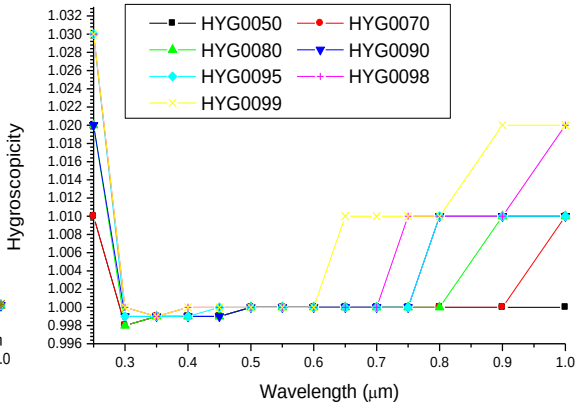

Figure 10: Hygroscopicity against wavelength based on model 2

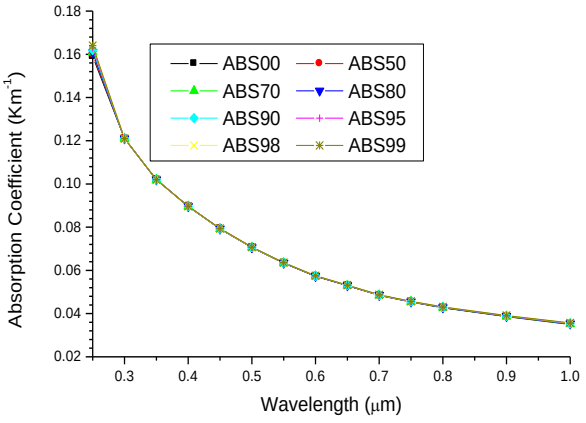

Figure 11: Absorption coefficient against wavelength based on model 3

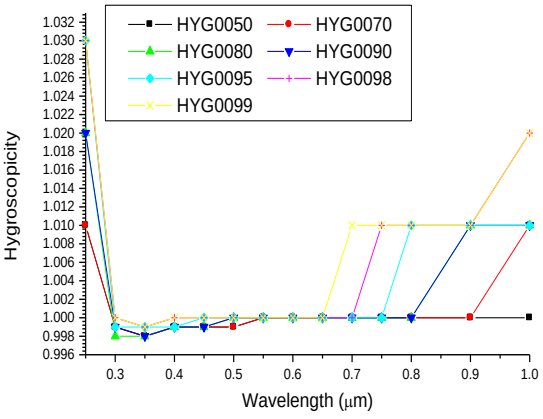

Figure 12: Hygroscopicity against wavelength based on model 3

According to Eck et al. (1999), Eck et al. (2001) and Ranjan (2007) positive values of Ångström exponent, α are characteristics of fine-mode dominated aerosols size distributions while near zero and negative values are characteristics of dominant coarse-mode, α_2 or bi-modal size distributions, with coarse-mode aerosols having significant magnitude. Tables 5, 6 and 7 show the values of the Ångström exponent, α and curvature, α_2 for the absorption coefficient. Comparing Tables 5, 6 and 7 the Ångström exponent, α, reflects the dominance of fine mode particles while α_2 reflects the dominance of coarse mode particles; this shows that the earth's atmosphere is composed of bimodal size distribution, that is consisting of both fine mode and coarse mode particles. The coefficient of determination, R^2 shows that the data fits excellently for the three models with the highest values recorded at 0% RH as 99.553%, 99.652% and 99.727% for model 1, model 2 and model 3 respectively. The turbidity coefficient (β) based on the analysis of the absorption coefficient shows that the atmosphere is relatively clear from 0 – 99% RHs.

Table 5: The results of α and α_2 for absorption coefficient using equations (3) and (5) (model 1)

LINEAR				QUADRATIC			
RH(%)	R^2	α	β	R^2	α_1	α_2	β
0	0.99553	1.07538	0.02913	0.9987	-0.86817	0.152	0.03047
50	0.99454	1.07526	0.02917	0.99841	-0.84635	0.16792	0.03066
70	0.99422	1.07518	0.02919	0.99832	-0.83911	0.17317	0.03073
80	0.99390	1.0754	0.02920	0.99824	-0.8326	0.17811	0.03079
90	0.99338	1.07541	0.02924	0.99809	-0.82251	0.18552	0.0309
95	0.99289	1.07497	0.02929	0.99795	-0.81267	0.19241	0.03101
98	0.99226	1.07456	0.02935	0.99781	-0.79997	0.20143	0.03116
99	0.99207	1.07356	0.02940	0.9978	-0.79468	0.20458	0.03124

Table 6: The results of α and α_2 for absorption coefficient using equations (3) and (5) (model 2)

LINEAR				QUADRATIC			
RH(%)	R^2	α	β	R^2	α_1	α_2	β
0	0.99652	1.07612	0.03138	0.9989	-0.89656	0.13172	0.03264
50	0.99572	1.07605	0.03142	0.99866	-0.87627	0.14655	0.03282
70	0.99545	1.07598	0.03144	0.99859	-0.86934	0.15159	0.03289
80	0.99519	1.07618	0.03146	0.99852	-0.86355	0.15598	0.03295
90	0.99478	1.0764	0.03149	0.99843	-0.85373	0.16335	0.03306
95	0.99438	1.076	0.03154	0.99832	-0.84452	0.16981	0.03318
98	0.99386	1.07572	0.0316	0.9982	-0.83287	0.17815	0.03332
99	0.99367	1.07451	0.03166	0.99815	-0.82794	0.18087	0.03341

Table 7: The results of α and α_2 for absorption coefficient using equations (3) and (5) (model 3)

LINEAR				QUADRATIC			
RH(%)	R^2	α	β	R^2	α_1	α_2	β
0	0.99727	1.07681	0.03364	0.99905	-0.92151	0.11393	0.0348
50	0.99662	1.07676	0.03368	0.99887	-0.90188	0.12829	0.03499
70	0.99641	1.07685	0.0337	0.99881	-0.896	0.13267	0.03506
80	0.99618	1.07677	0.03372	0.99873	-0.89055	0.13661	0.03512
90	0.99586	1.07672	0.03376	0.99867	-0.88142	0.14327	0.03523
95	0.9955	1.07674	0.0338	0.99857	-0.87253	0.14981	0.03534
98	0.99507	1.07638	0.03386	0.99846	-0.86151	0.15763	0.03549
99	0.99493	1.07542	0.03392	0.99845	-0.85661	0.16051	0.03557

Table 8 show the values of the water insoluble (INSO), water soluble (WASO) and soot for the volume and mass mix ratios at eight different RHs when the particle number density of soot was varied and the water insoluble and water soluble was kept constant using OPAC software. The results show that the values of water insoluble were found to be the highest and this was followed by the water soluble for the volume and mass mix ratios at 0% RH and 95% RH for the three models. The values of water soluble were found to be the highest and this was followed by the water insoluble for the volume and mass mix ratios at 50% RH, 70% RH, 80% RH, 90% RH, 98% RH and 99% RH for the three models.

TABLE 8: Analysis of Volume Mix and Mass Mix Ratios.

		Model 1		Model 2		Model 3	
RH (%) [%]	Comp.	Volume Mix Ratio	Mass Mix Ratio	Volume Mix Ratio	Mass Mix Ratio	Volume Mix Ratio	Mass Mix Ratio
	Inso	0.45300	0.51580	0.44620	0.51140	0.43960	0.50700
	Waso	0.37940	0.38880	0.37370	0.38540	0.36820	0.38210
0	Soot	0.16760	0.09540	0.18010	0.10320	0.19220	0.11080
	Inso	0.33900	0.43350	0.33510	0.43030	0.33140	0.42720
	Waso	0.53570	0.48640	0.52970	0.48290	0.52380	0.47940
50	Soot	0.12530	0.08012	0.13520	0.08677	0.14480	0.09332
	Inso	0.29380	0.39410	0.29090	0.39150	0.28810	0.38890
	Waso	0.59760	0.53310	0.59180	0.52960	0.58610	0.52610
70	Soot	0.10860	0.07282	0.11730	0.07892	0.12580	0.08494
	Inso	0.25720	0.35920	0.25500	0.35710	0.25290	0.35500
	Waso	0.64770	0.57440	0.64220	0.57090	0.63670	0.56750
80	Soot	0.09507	0.06638	0.10280	0.07198	0.11040	0.07752
	Inso	0.19710	0.29670	0.19580	0.29530	0.19450	0.29380
	Waso	0.73000	0.64840	0.72520	0.64520	0.72050	0.64200
90	Soot	0.07285	0.05483	0.07895	0.05952	0.08497	0.06416
	Inso	0.14390	0.23200	0.14320	0.23110	0.14250	0.23020
	Waso	0.80300	0.72520	0.79910	0.72230	0.79530	0.71950
95	Soot	0.05316	0.04286	0.05772	0.04658	0.06223	0.05027
	Inso	0.09219	0.15990	0.09191	0.15940	0.09163	0.15900
	Waso	0.87370	0.81060	0.87100	0.80840	0.86840	0.80630
98	Soot	0.03407	0.02954	0.03705	0.03214	0.04002	0.03473
	Inso	0.06780	0.12180	0.06764	0.12160	0.06749	0.12130
	Waso	0.90710	0.85570	0.90510	0.85390	0.90300	0.85220
99	Soot	0.02506	0.02251	0.02727	0.02451	0.02948	0.02649

CONCLUSION

In this study, there is no significant decrease in scattering coefficient with RHs as a result of high percentage of volume and mass mix ratios of water soluble when compared to soot. However, reflects the effect of warming. The absorption coefficient increases with addition of soot, reflecting warming effect. It was observed that there is a pronounced hygroscopicity growth as from 95-99% RHs. The regression analysis of the Ångström exponent, α and curvature, α_2 based on the scattering coefficient revealed that the fine – mode particle is dominant while for absorption coefficient revealed that the earth's atmosphere is composed of both fine – mode and coarse – mode particles. The highest values of the coefficient of determination for the scattering coefficient were found to be at 50% RH as 98.016%, 98.036% and 98.054% for model 1, model 2 and model 3 respectively. The highest values of the coefficient of determination for the absorption coefficient were found to be at 0% RH as 99.553%, 99.652% and 99.727% for model 1, model 2 and model 3 respectively. The turbidity coefficient (β) based on the analysis of the scattering coefficient showed that the atmosphere is relatively clear and hazy while the absorption coefficient indicated that the atmosphere is relatively clear at all relative humidity.

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