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The Effect of Hygroscopic Growth on Urban Aerosols

B. I. Tijjani* and S. Uba**
*Department of Physics, Bayero University, Kano.
Emails: idrith@yahoo.com, , idrithtijjani@gmail.com
**Department of Physics, Ahmadu Bello University, Zaria

ABSTRACT

In this paper some microphysical and optical properties of urban aerosols were extracted from OPAC to determine the effect of hygroscopic growth at the spectral range of 0.25μm to 2.5μm and eight relative humidities (RHs) (0, 50, 70, 80, 90, 95, 98, and 99%). The microphysical properties extracted were radii, volume mix ratio, number mix ratio and mass mix ratio as a function of RH while the optical properties are scattering and absorption coefficients and asymmetric parameters. Using the microphysical properties, growth factors of the mixtures were determined while using optical properties we determined the enhancement parameters and were then parameterized using some models. We observed that the data fitted the models very well. The angstrom coefficients which determined the particles' sizes distribution increases with the increase in RHs except at the delinquent point where it decreases with the increase in RHs. The mixture was determined to have bimodal type of distribution with the dominance of fine mode particles.
Keywords: microphysical properties, optical properties, hygroscopic growth, parametrazition, enhancement parameters.

INTRODUCTION

Currently over half of the world's population lives in urban centers, and that fraction is increasing steadily [1]. Cities are major sources of particulate matter, which can be advected out of the boundary layer and remain aloft in the free troposphere for days to weeks [2-4], impacting Earth's radiative balance while undergoing intercontinental transport. Given the regional and global importance of urban aerosols, it is necessary that the interaction of urban aerosols with water vapor be well characterized. The hygroscopicity of aerosols are currently modeled in global climate models (GCMs), mostly to better predict the scattering properties and size distribution under varying humidity conditions [46].

A number of studies have focused on aerosol hygroscopicity in major urban areas. Because urban aerosol is, in part, an external mixture of organic and inorganic components, hygroscopic behavior is often complex, with several growth modes observed [5-11]. This implies that water uptake will typically be complex, with multiple growth modes comprised of hydrophobic, slightly hygroscopic, and hygroscopic modes, with as many as six growth modes observed periodically [5, 8]. Size-dependent hygroscopic properties are often observed, corresponding to distinct composition for Aitken and accumulation mode aerosol [9, 12]. While hygroscopic properties of inorganic species are well-characterized, organics can exhibit hygroscopic behavior ranging from hydrophobic to somewhat hydrophilic [12-14]. Increasing organic mass fraction is generally associated with suppressed water uptake [9, 15-17]. Oxidized, water soluble organic carbon can exhibit RH-dependent effects, with enhanced water uptake at lower RH (below 75%) and suppressed uptake at high RH (above 90%) [18, 19]. Because organics comprise the dominant fraction of most urban aerosols [20], the hygroscopicity of the urban organic fraction plays a key role in the overall hygroscopic behavior of the aerosol.

Globally, roughly one half of atmospheric aerosol mass is organic, a fraction which can be even higher in urban areas. Typically between 40 to 85% of organic carbon measured in different locations world-wide has been shown to be water-soluble [21-26].

According to Andreae and Gelencser [27], soot carbon particles, formed during combustion processes, consist of aggregates of spherules made of graphene layers, being almost purely carbon. Due to its morphology and relatively constant refractive index, the absorption spectrum of soot carbon is expected to exhibit Angstrom exponents of about 1.0±0.1 for particles with diameters in the range 10–100 nm [28, 29]. Measurements taken at urban areas support this statement [30-32]. In the two urban aerosol cases (TARFOX and ICARTT) the Angstrom exponent is close to 1 [33]. Moosmuller et al. [34] modeled the absorption spectra of homogeneous spherical brown carbon particles and found a decrease of Angstrom exponents for larger particle diameters (from 0.1 to 10 μm). A similar result has been found by Gyawali et al. [29] for uncoated black carbon spheres.

Several metrics exist for quantifying particle water uptake. The hygroscopic growth factor gf(RH), which is defined as the ratio of the particle diameter at any RH to the particle diameter at RH=0% is the most common

metric and provides a simple and intuitive measure of the magnitude of particle growth due to water uptake. It is used to characterize the change in the microphysical properties of the particles. The next is the resulting change in the optical properties which is described by the enhancement factor f(λ,RH), which, for a specific optical parameter χ, is defined as the ratio between its values determined in any conditions $\chi(\lambda,RH)$ and to those determined in dry conditions $\chi(\lambda,RH=0\ \%)$.
Observed gf(RH) in the less hygroscopic mode of urban aerosol range from 1.0 (no growth) to 1.4; for the more hygroscopic mode, GF ranges from 1.1 to 1.8 [35-38], while the measured and modeled enhancement factors for urban aerosols have been described in several previous studies [39, 40].
The aim of this study is to determine the aerosols hygroscopic growth and enhancement factors for urban aerosols from the data extracted from OPAC. One and two variables parameterizations models will be perform to determine the relationship of the particles' hygroscopic growth and enhancement parameters with the RH. Angstrom coefficients will be use to determine the particles' type and the mode size distributions.

METHODOLOGY

The models extracted from OPAC are given in table 1.

Table 1 Compositions of aerosol types [41].

Aerosol model type	Components	Concentration N_i (cm^{-3})
Urban	WASO	28,000.0
	INSO	1.5
	SOOT	130,000.0
	Total	158,001.5

where : N_i is the mass concentration of the component, water soluble components (WASO, consists of scattering aerosols, that are hygroscopic in nature, such as sulfates and nitrates present in anthropogenic pollution), water insoluble (INSO), soot (SOOT, not soluble in water and therefore the particles are assumed not to grow with increasing relative humidity).

The hygroscopic growth factor gf(RH), which indicates the relative increase in mobility diameter of particles due to water absorption at a certain RH and is defined as the ratio of the particle diameter at any RH to the particle diameter at RH=0 and RH is taken as [43, 44]:

$$gf(RH) = \frac{D(RH)}{D(RH=0)} \qquad (1)$$

where RH is taken for seven values 50%, 70%, 80%, 90%, 95%, 98% and 99%.
The gf(RH) can be subdivided into different classes with respect hygroscopicity. One classification is based on diameter growth factor by Liu et al [45] and Swietlicki et al., [43] as barely Hygroscopic (gf(RH) = 1.0–1.11), Less Hygroscopic (gf(RH) = 1.11–1.33), More Hygroscopic (gf(RH) = 1.33–1.85) and most hygroscopic growth (gf(RH) > 1.85).
Atmospheric particles of a defined dry size typically exhibit different growth factors. This is due to either external mixing of particles in an air sample or variable relative fractions of different compounds in individual particles (the latter here in after referred to as quasi-internally mixed). A mono-modal growth distribution without spread can only be expected in very clean and homogeneous air parcels. Most atmospheric aerosols are externally mixed with respect to hygroscopicity, and consist of more and less hygroscopic sub-fractions [43, 46]. The ratio between these fractions as well as their content of soluble material determines the hygroscopic growth of the overall aerosol. Particle hygroscopicity may vary as a function of time, place, and particle size [5, 35, 43].
The size and the solubility of a particle determine the response of an ambient particle to changes in RH. The water vapor pressure above a water droplet containing dissolved material is lowered by the Raoult effect. The equilibrium size of a droplet was first described by Kohler [42], who considered the Kelvin (curvature) and Raoult (solute) effect. Prediction of hygroscopic growth factors with Kohler theory requires detailed knowledge of particle composition as well as a thermodynamic model, which describes the concentration dependence of the water activity for such a mixture. The hygroscopic growth factor of a mixture, $gf_{mix}(RH)$, can be estimated from the growth factors of the individual components of the aerosol and their respective volume fractions, V_k, using the Zdanovskii-Stokes-Robinson relation [47-50]:

$$gf_{mix}(RH) = \left(\sum_k V_k gf_k^3\right)^{1/3} \qquad (2)$$

where the summation is performed over all compounds present in the particles. Solute-solute interactions are neglected in this model and volume additivity is also assumed. The model assumes spherical particles, ideal

mixing (i.e. no volume change upon mixing) and independent water uptake of the organic and inorganic components.

It can also be computed using the corresponding number fractions n_k as [9, 51];

$$gf_{mix}(RH) = \left(\sum_k n_k gf_k^3\right)^{1/3} \quad (3)$$

Where n_k is the number fraction of particles having the growth factor gf_k .

We now proposed the $gf_{mix}(RH)$ to be a function of mass mix ratio as

$$gf_{mix}(RH) = \left(\sum_k m_k gf_k^3\right)^{1/3} \quad (4)$$

where the subscript k represents the different substances.

The RH dependence of $gf_{mix}(RH)$ can be parameterized in a good approximation by a one-parameter equation, proposed e.g. by Petters and Kreidenweis [52]:

$$gf_{mix}(a_w) = \left(1 + \kappa \frac{a_w}{1-a_w}\right)^{\frac{1}{3}} \quad (5)$$

Here, a_w is the water activity, which can be replaced by the relative humidity RH, if the Kelvin effect is negligible, as for particles with sizes more relevant for light scattering and absorption. At equilibrium, it can be shown that, over a flat surface, the water activity equals the ambient relative humidity in the sub-saturated humid environment 53, 54]. The coefficient κ is a simple measure of the particle's hygroscopicity and captures all solute properties (Raoult effect).

Humidograms of the ambient aerosols obtained in various atmospheric conditions showed that $gf_{mix}(RH)$ could as well be fitted well with a γ-law [55-59] as

$$gf_{mix}(RH) = \left(1 - \frac{RH}{100}\right)^{\gamma} \quad (6)$$

Particle hygroscopicity is a measure that scales the volume of water associated with a unit volume of dry particle [52] and depends on the molar volume and the activity coefficients of the dissolved compounds [60].

The bulk hygroscopicity factor B under subsaturation RH conditions was determined using the relation:

$$B = (1 - gf_{mix}^3)/\ln a_w \quad (7)$$

where a_w is the water activity, which can be replaced by the RH as explained before.

The impact of hygroscopic growth on the aerosol optical properties is usually described by the enhancement factor $f_\chi(RH,\lambda)$:

$$f_\chi(RH,\lambda) = \frac{\chi(RH,\lambda)}{\chi(RH=0,\lambda)} \quad (8)$$

where $f_\chi(RH,\lambda)$ can be denoting the aerosol scattering and absorption coefficients, and asymmetry parameters. RH corresponds to any condition, and can cover the entire RH spectrum. In this paper we will only use scattering, absorption and asymmetric parameter. The reason for using asymmetric parameter is to determine its effect on forward scattering as a result of hygroscopic growth. This method was initially introduced by Covert et al. [61].

In general the relationship between $f_\chi(RH,\lambda)$ and RH is nonlinear (e.g. Jeong et al. [62]). In this paper we determine the empirical relations between the enhancement parameter and RH [63] as:

$$f_\chi(RH,\lambda) = \frac{\chi(RH,\lambda)}{\chi(RH=0,\lambda)} = \left(\frac{100 - RH_{ref}}{100 - RH_{high}}\right)^{\gamma} \quad (9)$$

where in our study RH_{ref} is 0%. The γ known as the humidification factor represents the dependence of aerosol optical properties on RH, which results from changes in the particle size and refractive index upon humidification. The parameter in our case was obtained by combining the eight $\chi(RH,\lambda)$ parameters at 0%, 50%, 70%, 80%, 90%, 95%, 98% and 99% RH. The use of γ has the advantage of describing the hygroscopic behavior of aerosols in a linear manner over a broad range of RH values; it also implies that particles are deliquesced [64], a reasonable assumption for this data set due to the high ambient relative humidity during the field study. The γ parameter is dimensionless, and it increases with increasing particle water uptake. From previous studies, typical values of γ for ambient aerosol ranged between 0.1 and 1.5 [64-66].

Two parameters empirical relation is also used [62, 67] as;

$$f_\chi(RH,\lambda) = a\left(1 - \frac{RH(\%)}{100}\right)^{b} \quad (10)$$

The model assumes equilibrium (metastable) growth of the aerosol scattering with RH such that the humidigraph profile does not display a deliquescent growth profile. For aerosol in a humid environment, this behavior will

hold true. Most aerosols are a mixture of metastable and deliquescent particles and will exhibit some deliquescent behavior.

The Angstrom exponent being an indicator of the aerosol spectral behaviour of aerosols [68], the spectral behavior of the aerosol optical parameter (X, say), with the wavelength of light (λ) is expressed as inverse power law [69]:

$$X(\lambda)=\beta\lambda^{-\alpha} \quad (11)$$

where X(λ) can represent scattering and absorption coefficients. The variable X(λ) can be characterized by the Angstron parameter, which is a coefficient of the following regression,

$$\ln X(\lambda) = -\alpha\ln(\lambda) + \ln\beta \quad (12)$$

However the Angstrom exponent itself varies with wavelength, and a more precise empirical relationship between aerosol extinction and wavelength is obtained with a 2nd-order polynomial [70-80] as:

$$\ln X(\lambda)=\alpha_2(\ln\lambda)^2 + \alpha_1\ln\lambda + \ln\beta \quad (13)$$

and then we proposed the cubic

$$\ln X(\lambda)= \ln\beta + \alpha_1\ln\lambda + \alpha_2(\ln\lambda)^2+ \alpha_3(\ln\lambda)^3 \quad (14)$$

where X(λ) can be any of the optical parameter, β, α, α_1, α_2, α_3 are constants that are determined using regression analysis with SPSS16.0.

We also determine the effect of hygroscopic growth on the effective refractive indices of the three mixed aerosols using the following formula [81]:

$$\frac{\varepsilon_{eff}-\varepsilon_0}{\varepsilon_{eff}+2\varepsilon_0}=\sum_{i=1}^{3} f_i\frac{\varepsilon_i-\varepsilon_0}{\varepsilon_i+2\varepsilon_0} \quad (15)$$

where f_i and ε_i are the volume fraction and dielectric constant of the i^{th} component and ε_0 is the dielectric constant of the host material. For the case of Lorentz-Lorentz [82, 83], the host material is taken to be vacuum, ε_0 =1.

RESULTS AND OBSERVATIONS

Table 2: the growth factor of the aerosols using number mix ratio (equation 3) *and Bulk hygroscopicity factor (equation 7)*

RH	50	70	80	90	95	98	99
gf_{mix}(RH)	1.0137	1.0199	1.0255	1.0365	1.0496	1.0687	1.0827
Bulk Hygroscopicity factor (B)	0.0290	0.0218	0.0175	0.0120	0.0080	0.0045	0.0027

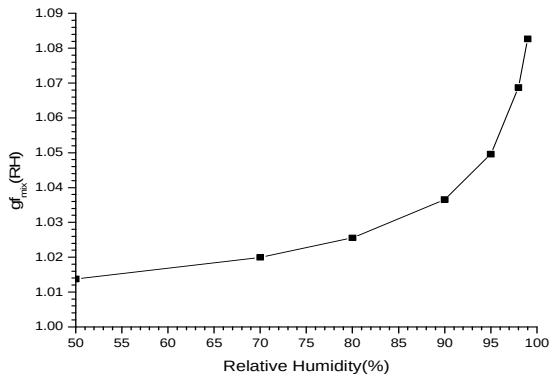

Figure 1; a graph of growth factor of the mixture using number mix ratio (equation 3)

Figure 1 shows a steep curve with deliquescence observed at relative humidities as from 90 to 99%RH. The smoothness of the curve shows that the mixture is internally mixed.
The results of the parameterizations by one parameter of equations (5) and (6) are:

C= 1.0769, k= 0.0022, R2= 0.8730 (equation 5)

γ= -0.0168, R2= 0.9985 (equation 6)

The fitted curve can be represented by one empirical parameters fit of the form of equations (5) and (6), though equation (6) has higher coefficient of determination.

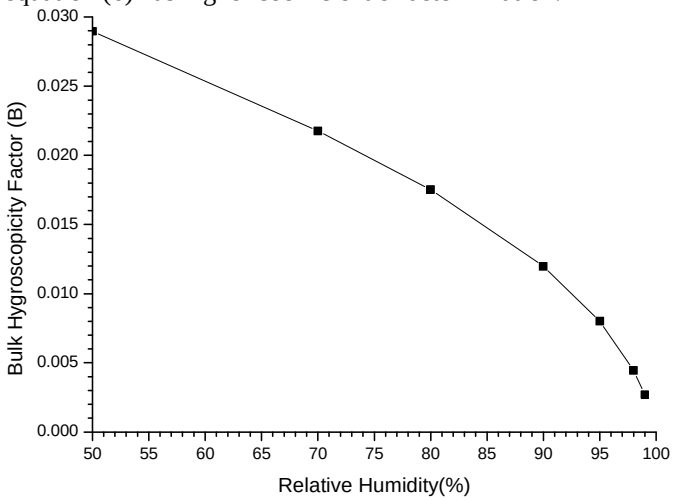

Figure 2; Bulk Hygroscopcity factor of the mixture using number mix ratio (equation 7)

Figure 2 shows non-linear relation B with RH, (a steep curve) with deliquescence observed at relative humidities as from 90 to 99% RH. The smoothness of the curve shows that the mixture is internally mixed.

Table 3: the growth factor of the aerosols using volume mix ratio (equation 2) *and Bulk hygroscopicity factor (equation 7)*

RH(%)	50	70	80	90	95	98	99
gf_{mix}(RH)	1.0456	1.0711	1.0955	1.1453	1.2039	1.2854	1.3409
Bulk Hygroscopicity factor (B)	0.0991	0.0816	0.0703	0.0529	0.0382	0.0227	0.0142

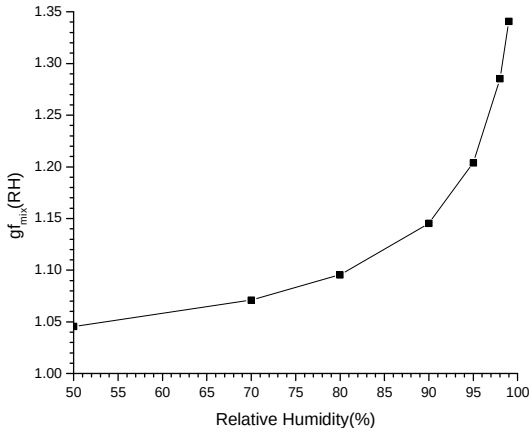

Figure 3; a graph of growth factor of the mixture using Volume mix ratio (equation 2)

Figure 3 shows a steep curve with deliquescence observed at relative humidities as from 90 to 99%RH. The smoothness of the curve shows that the mixture is internally mixed.

The results of the parameterizations by one parameter of equations (5) and (6) are:

C= 1.3110, k= 0.0125, R2= 0.8906 (equation 5)

γ= -0.0626, R2= 0.9987 (equation 6)

The fitted curve can be represented by one empirical parameters fit of the form of equations (5) and (6), though equation (6) is better because it has higher coefficient of determination.

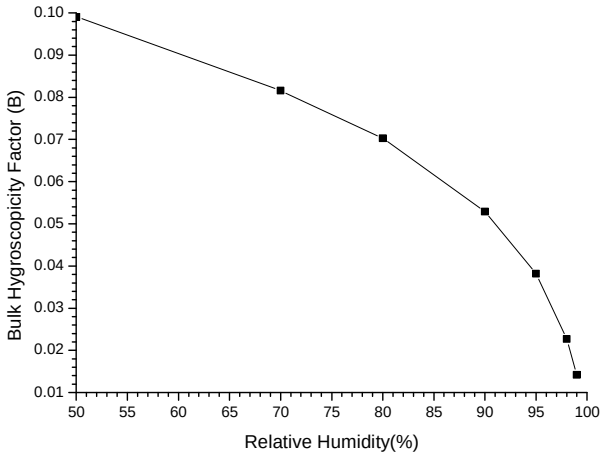

Figure 4; Bulk Hygroscopcity factor of the mixture using volume mix ratio (equation 7)

Figure 4 shows non-linear relation B with RH, (a steep curve) with deliquescence observed at relative humidities as from 90 to 99% RH.

Table 4: the growth factor of the aerosols using mass mix ratio (equation 4) *and Bulk hygroscopicity factor (equation 7)*

RH(%)	50	70	80	90	95	98	99
gf_{mix}(RH)	1.0425	1.0655	1.0878	1.1342	1.1911	1.2730	1.3298
Bulk Hygroscopicity factor (B)	0.0921	0.0747	0.0641	0.0483	0.0354	0.0215	0.0136

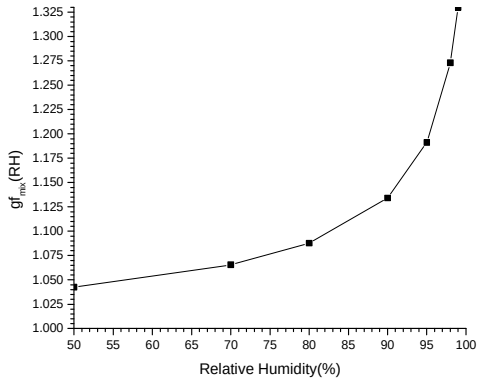

Figure 5; a graph of growth factor of the mixture using mass mix ratio (equation 4)

Figure 5 shows a steep curve with deliquescence observed at relative humidities as from 90 to 99%RH

The results of the parameterizations by one parameter of equations (5) and (6) are:

C= 1.2823, k= 0.0121, R2= 0.9011 (equation 5)

γ= -0.0599, R2= 0.9974 (equation 6)

The fitted curve can be represented by one empirical parameters fit of the form of equations (5) and (6), though equation (6) is better because it has higher coefficient of determination.

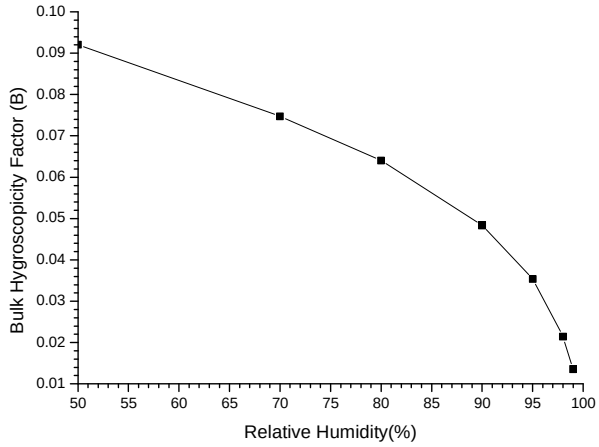

Figure 6; Bulk Hygroscopcity factor of the mixture using mass mix ratio (equation 7)

Figure 6 shows non-linear relation B with RH, (a steep curve) with deliquescence observed at relative humidities as from 90 to 99% RH.

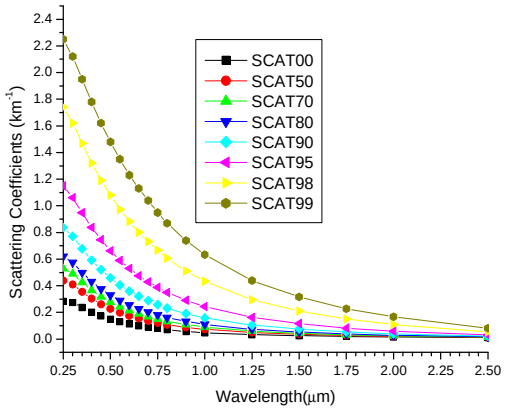

Figure 7: A plot of scattering coefficients against wavelength

Figure 7 shows that hygroscopic growth has more effect at shorter wavelengths and this indicates that it has more effect on smaller particles. Its relation with wavelengths shows a steep curve that satisfies power law. This increase is due to the growth of smaller particles to sizes at which they scatter more light being more pronounced than that for larger particles. At the deliquescence point (90 to 99%) this growth with higher humidities increases substantially, making this process strongly nonlinear with relative humidity [84, 85].

Table 5 The results of the Angstrom coefficients of scattering coefficients using equations (12), (13) and (14) for urban model at the respective relative humidities using regression analysis with SPSS16.0.

	Linear		Quadratic			Cubic			
RH(%)	R2	α	R2	α1	α2	R2	α1	α2	α3
0	0.9906	1.5018	0.9961	-1.5781	-0.1661	0.9993	-1.7201	-0.0041	0.2124
50	0.9853	1.5793	0.9986	-1.7040	-0.2714	0.9997	-1.7925	-0.1704	0.1324
70	0.9816	1.5962	0.9992	-1.7416	-0.3165	0.9998	-1.8045	-0.2447	0.0941
80	0.9779	1.6022	0.9995	-1.7647	-0.3537	0.9998	-1.8060	-0.3065	0.0618
90	0.9698	1.5917	0.9997	-1.7820	-0.4143	0.9997	-1.7851	-0.4107	0.0047
95	0.9602	1.5506	0.9995	-1.7641	-0.4648	0.9996	-1.7325	-0.5008	-0.0473
98	0.9469	1.4597	0.9988	-1.6925	-0.5067	0.9995	-1.6291	-0.5791	-0.0948
99	0.9373	1.3840	0.9983	-1.6243	-0.5231	0.9993	-1.5473	-0.6109	-0.1151

The values of α at linear part reflects the dominance of fine particles and the quadratic part re-affirmed the statement by Eck et al. [71] who reported the existence of negative curvatures for fine-mode aerosols and positive curvatures for significant contribution by coarse-mode particles in the size distribution. It can also be observed that, the hygroscopic growth as a result of increase in RH has caused increase in α, at the RH between 0 to 80% but decrease at the delinquent points (90 to 99%) α_2 increase throughout while α_3 change the sign from positive to negative and this shows increase in the dominance of fine mode particles with hygroscopic growth. The cubic part shows that the particles have bi-modal type of particle distributions with the dominance of fine mode distributions.

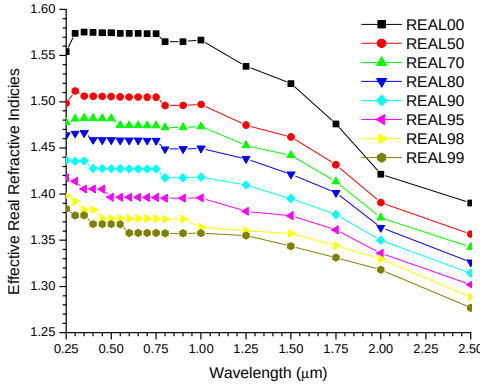

Figure 8: A plot of Effective real refractive indices against wavelength

Figure 8 shows that hygroscopic growth has caused decrease in the effective real refractive indices and decrease with wavelengths. The non-linearity of the plots with respect to wavelength shows the presence of non-spherical particles. The non-spherical nature increases with the increase in hygroscopic growth.

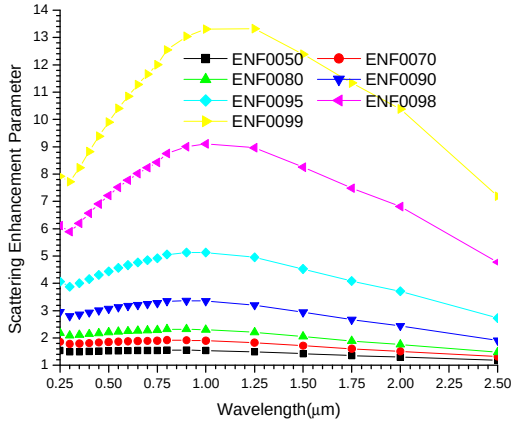

Figure 9: A plot of scattering enhancement parameters against wavelengths

Figure 9 shows that increase in hygroscopic growth has caused increase in enhancement parameters. It can be seen that it is more sensitive to medium wavelengths. But in relation to wavelengths, from 50 to 80%RH it almost constant, but started increasing with wavelength substantially from 90 to 99% and made this process strongly nonlinear with relative humidity [84, 85].

The results of the fitted curves of equations (9) and (10) are presented as follows;

For a single parameter using equation (9).

At λ=0.25μ, γ=0.463093, R^2=0.9980
At λ=1.25 μ, γ=0.547117, R^2=0.9982
At λ=2.50 μ, γ=0.375913, R^2=0.9737
For two parameters using equation (10).

At λ=0.25μ, a= 1.121402, b= -0.427208, R^2= 0.9991
At λ=1.25 μ, a= 0.919682, b= -0.573340, R^2= 0.9955
At λ=2.50 μ, a= 0.738665, b= -0.470782, R^2= 0.976390
Because of the very good correlations , they verify the non-linearity relation between the enhancements parameters and RH. The curve fitting by one and two empirical parameters fit show that they can be expressed of the form of equations (8) and (9) because of the high values of the coefficients of determinations.

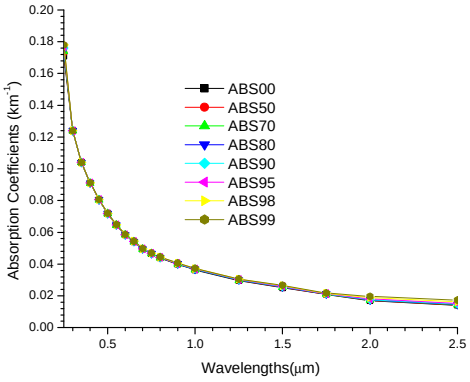

Figure 10: A plot of absorption scattering coefficients against wavelength

Figure 10 shows that absorption is almost independent of RH. This shows the increase in hygroscopic growth has little effect on absorption.

Several studies have shown that the aerosol absorption coefficient decreases monotonically with wavelength [33]. It is usual to approximate this wavelength dependence by a power-law expression.

Table 6 The results of the Angstrom coefficients of absorption coefficients using equations (12), (13) and (14) for urban model at the respective relative humidities using regression analysis with SPSS16.0.

	Linear		Quadratic			Cubic			
RH(%)	R2	α	R2	α1	α2	R2	α1	α2	α3
0	0.9958	1.0326	0.9971	-1.0072	0.0554	0.9989	-0.9344	-0.0277	-0.1089
50	0.9951	1.0269	0.9967	-0.9984	0.0620	0.9988	-0.9207	-0.0267	-0.1163
70	0.9948	1.0242	0.9966	-0.9941	0.0655	0.9987	-0.9156	-0.0241	-0.1174
80	0.9945	1.0216	0.9966	-0.9900	0.0688	0.9987	-0.9112	-0.0211	-0.1178
90	0.9940	1.0157	0.9965	-0.9806	0.0763	0.9986	-0.9029	-0.0123	-0.1162
95	0.9932	1.0067	0.9966	-0.9664	0.0877	0.9986	-0.8925	0.0034	-0.1105
98	0.9914	0.9889	0.9970	-0.9385	0.1097	0.9984	-0.8756	0.0380	-0.0940
99	0.9892	0.9716	0.9973	-0.9117	0.1304	0.9982	-0.8618	0.0734	-0.0746

The value of α at the linear part reflects the dominance of fine particles at 0% RH, but it can be observed that it decreases with the increase in RH. But α_2 at the quadratic part reflects the dominance of coarse particles. However, α_2 at the cubic part reflects the dominance of coarse particles.

The reason for reduced Angstrom exponents at the deliquescence RHs can be attributed either to the increase of particle sizes or increase in the non-spherical nature of the particles with RHs.

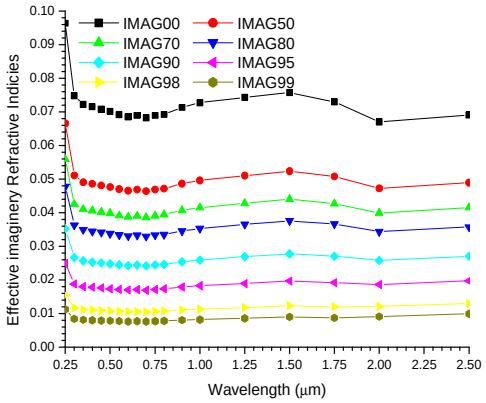

Figure 11: A plot of Effective Imaginary refractive indices against wavelength

Figure 11 shows decrease in imaginary refractive indices as a result of hygroscopic growth. From the figure it can be seen that the refractive indices are very small, of which that is the reason why the absorption is very small.

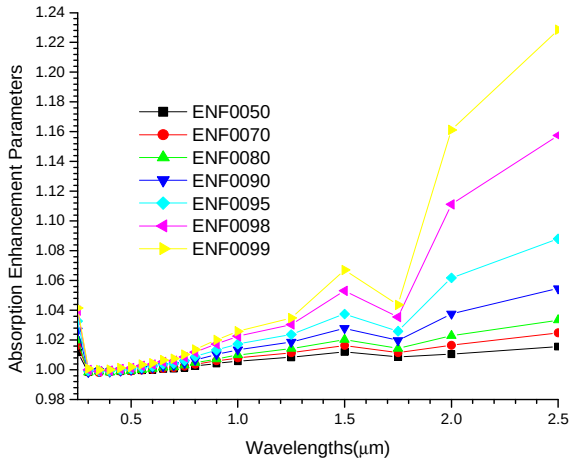

Figure 12: A plot of absorption enhancement parameters against wavelengths

Figure 12 shows a slight increase in enhancement factor at smaller wavelength, but it increases with the increase in wavelengths. This shows the dominance of coarse particles in absorption.

Enhancement factor as a function of RH shows a non-linear relation.
The results of the fitted curves of equations (9) and (10) are presented as follows:
For a single parameter equation (9).
At λ=0.25μ, γ=0.010039, R^2=0.9832
At λ=1.25 μ, γ=0.007763, R^2=0.9944
At λ=2.50 μ, γ=0.035953, R^2=0.9453
For two parameters equation (10).

At λ=0.25μ, a= 1.007288, b= -0.007765, R^2= 0.9842
At λ=1.25 μ, a= 1.003428, b= -0.006691, R^2= 0.9992
At λ=2.50 μ, a= 0.962464, b= -0.047935, R^2= 0.9397

Because of the very good correlations , they verify the non-linearity relation between the enhancements parameters and RH. The curve fitting by one and two empirical parameters fit show that they can be expressed of the form of equations (9) and (10) because of the high values of the coefficients of determinations.

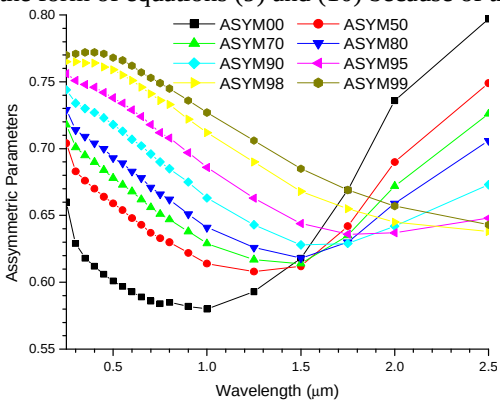

Figure 13: A plot of Asymmetric parameters against wavelengths

Figure 13 shows that increase in hygroscopic growth as a result of the increase in RH has caused smaller particles to scatter more in the forward of which that is the reason why the scattering is higher at smaller wavelengths. This shows that as the particles sizes increase, there is a decrease in scattering in the forward directions as the wavelength increases.

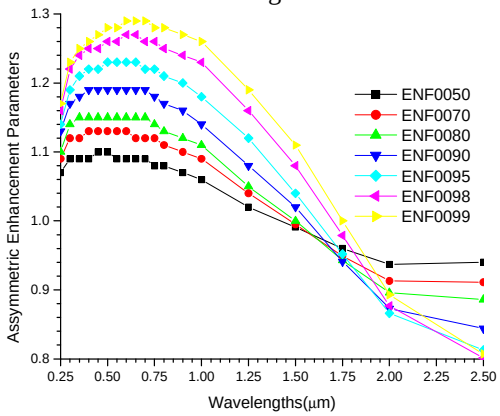

Figure 14: A plot of Asymmetric parameters enhancement parameters against wavelengths

Figure 14 shows that the enhancement factor is more on smaller particles and decreases as the particle size

increases as a result of hygroscopic growth increases and finally becomes less than one at higher wavelength.

Enhancement factor as a function of RH shows a non linear relation.
The results of the fitted curves of equations (9) and (10) are presented as follows:
For a single parameter using equation (9).

At λ=0.25μ, γ=0.041147, R2=0.9419
At λ=1.25 μ, γ=0.037260, R2=0.9982
At λ=2.50 μ, γ=-0.058162, R2=0.9642
For two parameters using equation (10).

At λ=0.25μ, a= 1.060538, b= -0.022738, R2= 0.9498
At λ=1.25 μ, a= 0.992577, b= -0.039594, R2= 0.9974
At λ=2.50 μ, a= 0.949436, b= 0.041912, R2= 0.8902

Because of the very good correlations, they verify the non-linearity relation between the enhancements parameters and RH. The curve fitting by one and two empirical parameters fit show that they can be expressed of the form of equations (9) and (10) because of the high values of the coefficients of determinations. It can also be observed that there is a change in the sign of γ and b.

CONCLUSION

From the three $gf_{mix}(RH)$ it can be concluded that the higher values are observed using volume and mass mix ratios because of the high density of WASO. This is in line with what Sheridan et al. [86] found, on the basis of analysis of in situ data collected at SGP in 1999, that aerosols containing higher fractions of smaller particles show larger hygroscopic growth factors. From our results despite soot being having the least size and higher in fractions shows that using volume mix and mass mix ratios, shows that the mixture is more hygroscopic. However, still in their they showed that aerosols containing higher fractions of more strongly absorbing particles exhibit lower hygroscopic growth factors, in our own case it shows that using number mix ratio.

The effect of hygroscopicity in the enhancement parameters show that it has more effect on the medium size particles for scattering while is higher for absorption by larger particles.

The effect of hygroscopicity on scattering shows that the mixture has more dominance of fine particles and that of absorption shows little absorption, while the effect on asymmetric parameter shows that for smaller particles the hygroscopic growth increase forward scattering while for coarse particle it decreases forward scattering.

The effect of hygroscopic growth shows that it increases growth factor, optical parameters and enhancement parameter to the extent that at the deliquescence point (90 to 99% RH) the increase is so substantial that the process become strongly nonlinear with relative humidity [84, 85].

Its effect on angstrom shows that it increases with the increase in RH, but as from the deliquescence point (90 to 99%), it decreases with the increase in RH.

It shows that increase in RH increases forward scattering because particle growth enhances forward diffraction [87] for smaller particles while in larger particles it causes increase in the backward scattering. It also shows that the mixture is internally mixed for smaller particles because of the increase in forward scattering as a result of the hygroscopic growth [88].

These hygroscopic growth behaviors also reveal an immense potential of light scattering enhancement in the forward direction at high humidities and the potential for being highly effective cloud condensation nuclei for smaller particles.

Finally, the data fitted our models very and can be used to extrapolate the hygroscopic growth and enhancements parameters at any RH.

The importance of determining $gf_{mix}(RH)$ as a function of RH and volume fractions, mass fractions and number fractions, and enhancement parameters as a function of RH and wavelengths can be potentially important because it can be used for efficiently representing aerosols-water interactions in global models.

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