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THE GROWTH FACTOR AND BULK HYGROSCOPICITY OF ATMOSPHERIC SOOT OF URBAN AEROSOLS

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ABSTRACT

Aerosols within urban atmosphere can be composed of water-soluble aerosols from industrial emissions, insoluble and soot from biomass and bio-fuel emissions respectively. In this study, simulation was carried out using Optical Properties of Aerosols and Clouds (OPAC) to model the hygroscopic growth factor and bulk hygroscopicity of Soot at spectral range of 0.25 to 1.00 μm for eight different relative humidities. The results in this study revealed that the aerosol hygroscopic growth factor increases with relative humidity (RH) while the bulk hygroscopicity decreases with increase in RH from 50-99% RHs. The aerosol hygroscopic growth factor increases with increase in RH while the bulk hygroscopicity decreases with increase in RH for the number, volume and mass ratios. The aerosol growth factor revealed that the mixture is barely hygroscopic, less hygroscopic and more hygroscopic from 50 – 80% RH, 90 – 95% RH and 98 – 99% RH respectively for the number mix ratio. The aerosol growth factor revealed that the mixture is less hygroscopic, more hygroscopic and most hygroscopic from 50 – 80% RH, 90 – 95% RH and 98 – 99% RH respectively for the volume and mass mix ratios. The bulk hygroscopicity ranges between 0.02007 to 0.09456 for the number mix ratio from model 1 to model 3, the bulk hygroscopicity ranges between 0.13596 to 0.32956 for the volume mix ratio from model 1 to model 3 while the bulk hygroscopicity ranges between 0.12831 to 0.29925 for the mass mix ratio from model 1 to model 3.

Keywords: bulk hygroscopicity, hygroscopic growth factor, OPAC, relative humidity, soot

INTRODUCTION

The microscopic solid or liquid particles suspended in the atmosphere are called aerosols, these aerosols have effect on the radiative balance of the Earth and thus, the climatic system by interacting directly with solar and terrestrial radiation or changing the formation of clouds indirectly (Lohmann and Feichter, 2005; IPCC, 2013 ; Seinfeld *et al*., 2016). These aerosol climatic effects are highly irregular due to of the large variability of the physical and optical properties of aerosol, which are attributed to multiplicity 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 strong effect of aerosols on climate has not been given significant attention, which present significant uncertainty into climate predictions (IPCC, 2007).

The Smog and Soot which are also referred to as ground-level ozone and particulate matter respectively are the two most common forms of air pollution (Meseke *et al*., 2022). Soot aerosols also known as black carbon (BC) are formed when incomplete combustion takes place. The major sources of soot aerosols are forest fires, diesel engines and biomass burning. Absorption properties of soot particles depend highly on the combustion temperature and other material (e.g. organic carbon) emitted during the processes of combustion (Bond and Bergstrom, 2006). Soot is made up 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 is the major rationale of both experimental and theoretical investigation of soot radiative properties (Akpootu and Momoh, 2013a). The dust aerosol present in the atmosphere during the harmattan season in the northern hemisphere is a common feature of the climate of most parts of West Africa (Akande *et al*., 2013). The enormous amount of dust and sand particles raised and transported by the harmattan dust haze strongly decreases visibility and are estimated to reach about 6000 m above sea level (Essienimo *et al*., 2016a; Essienimo *et al*., 2016b)

The hygroscopic growth and the mixing state of aerosol particles play a significant role for various atmospheric effects like the direct aerosol effect on climate, visibility degradation, and cloud formation (Sloane and Wolff, 1985; Pandis *et al*., 1995; McFiggans *et al*., 2006). Through the interaction of atmospheric particles and cloud droplets with incoming shortwave radiation, the particle hygroscopic growth is one of the major parameters influencing the terrestrial radiation budget and climate (IPCC, 2007). Some uncertainties connect to the hygroscopic growth estimation and cloud condensation nuclei (CCN) activation for the complex chemical mixtures of aerosol particles found in the atmosphere. Other uncertainties relates to how hygroscopic growth and CCN activation can be parameterized for implementation in higher scale climate models. The scattering and reflection of solar radiation by aerosols and clouds tends to cool the earth's surface, and this referred to as negative forcing while in a situation when the absorption of terrestrial radiation by greenhouse gases and clouds tends to warm it is referred to as positive forcing (Akpootu and Momoh, 2013b; Akpootu and Sharafa, 2013; Essienimo *et al*., 2015a). The size distribution of any particular suspended particle determines the life-span of the particle in the atmosphere and the distance it can travel (Essienimo *et al*., 2015a; Essienimo *et al*., 2015b).

Numerous studies have been carried out to investigate the effect of atmospheric aerosols. In the paper of Tijjani and Akpootu (2012), they modeled the optical depths, asymmetry parameters and single scattering albedos of urban aerosols using Optical Properties of Aerosols and Cloud (OPAC) at spectral range of 0.25 μm to 1.0 μm for eight different relative humidities (RHs). The radiative forcings (RF) and Ångström parameters was computed from the obtained data. Based on the RF, they found 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 third model. Akpootu and Gana (2013) modeled the hygroscopicity properties of water soluble aerosols component based on microphysical properties of urban aerosols using OPAC to determine the effect of relative humidity on hygroscopic growth factor and bulk hygroscopicity at spectral range of 0.25-1.00 μm. Akpootu and Abdul salami (2013) describes the hygroscopicity properties of water soluble aerosols component based on optical and microphysical properties of urban aerosols using simulated data obtained from OPAC to determine the density mix ratio resulting from hygroscopic growth factor and bulk hygroscopicity at spectral range of 0.25-1.00 μm for eight different relative humidities (RHs). They found that the density mix ratio indicates that there is a steady increase in aerosol hygroscopic growth factor with RHs and decrease in the magnitude of bulk hygroscopicity. Other studies include Akpootu and Muhammad (2013), Akpootu and Tijjani (2014), Seinfeld et al. (2016) to mention but a few.

The aim of this paper is to investigate the effect of hygroscopic growth factor and bulk hygroscopicity of soot in relation to eight different relative humidities (0, 50, 70, 80, 90, 95, 98 and 99%) of urban aerosols using extracted microphysical properties of number mix ratio, volume mix ratio and mass mix ratio simulated from Optical Properties of Aerosols and Clouds (OPAC).

MATERIALS AND METHODS

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 urban aerosols data used in this study are derived from the Optical Properties of Aerosols and Clouds (OPAC) data set (Hess *et al*., 1998). A mixture of three components was 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 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 key parameter used to characterize the hygroscopicity of the aerosol particles is the aerosol hygroscopic growth factor gf(RH), which indicates the relative increase in mobility diameter of particles due to water absorption at a certain RH and has been defined as the ratio of the particle diameter at any RH to the particle diameter at RH = 0, the RH is taken for seven values 50%, 70%, 80%, 90%, 95%, 98% and 99% (Swietlicki *et al*. , 2008; Randles, *et al*., 2004; Akpootu and Gana, 2013):

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

The gf(RH) are subdivided into different classes with respect to hygroscopicity. One classification is based on diameter growth factor by Liu et al. (2011) and Swietlicki et al. (2008) 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).

Most of the atmospheric aerosols are externally mixed with respect to hygroscopicity, and consist of more and less hygroscopic sub-fractions (Swietlicki *et al*., 2008). The ratio between these fractions as well as their content of soluble material determines the hygroscopic growth of the overall aerosol. Particle hygroscopicity may change as a function of time, place, and particle size (McMurry and Stolzenburg, 1989; Swietlicki *et al*., 2008).

Estimation of hygroscopic growth factors with Köhler 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 calculated from the growth factors of the individual components of the aerosol and their respective volume fractions, V_k, by employing the Zdanovskii-Stokes-Robinson relation (ZSR relation) (Stokes and Robinson, 1966; Meyer *et al*., 2009; Sjogren *et al*., 2007; Stock *et al*., 2011; Akpootu and Gana, 2013):

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

where the summation was performed over all compounds present in the particles. Solute-solute interactions are neglected in this model while the volume additivity was 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.

This was also calculated using the corresponding number fractions n_k as (Meier *et al*., 2009; Duplissy *et al*., 2011; Akpootu and Gana, 2013).

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

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

The gf_{mix}(RH) as a function of mass mix ratio has been proposed by Tijjani and Uba (2013) as reported by Akpootu and Abdul salami (2013) to be

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

The subscript k in the above equations represents the different substances.

The RH dependence of gf_{mix}(RH) was parameterized in a good approximation by a one-parameter equation (Petters and Kreidenweis, 2007; Akpootu and Abdul salami, 2013):

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

Here, a_w is the water activity, which can be replaced by the relative humidity RH at equilibrium (Seinfeld and Pandis, 2006), if the Kelvin effect is negligible, as for particles with sizes more relevant for light scattering and absorption. The coefficient κ is a simple measure of the particle's hygroscopicity and takes into consideration all solute properties (Raoult effect).

Humidograms of the ambient aerosols obtained in different atmospheric conditions revealed that $gf_{mix}(RH)$ could as well be fitted well with a γ-law (Swietlicki *et al.*, 2000; Gysel *et al.*, 2009; Putaud, 2012; Akpootu and Abdul salami, 2013) 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 (Petters and Kreidenweis, 2007) and depends on the molar volume and the activity coefficients of the dissolved compounds (Christensen and Petters, 2012).

The bulk hygroscopicity factor under subsaturation RH conditions was determined using the following relation (Akpootu and Abdul salami, 2013):

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

where a_w is the water activity that is replaced by the relative humidity as previously explained from equation (5).

RESULTS AND DISCUSSION

Table 2: The growth factor and bulk hygroscopicity of aerosols using number mix ratio for model 1-3

	Model 1		Model 2		Model 3	
RH(%)	**gf_{mix}**	**Bulk Hyg**	**gf_{mix}**	**Bulk Hyg**	**gf_{mix}**	**Bulk Hyg**
50	1.04355	0.09456	1.04061	0.08792	1.03798	0.08201
70	1.06846	0.07839	1.06392	0.07287	1.05987	0.06797
80	1.09380	0.06886	1.08770	0.06401	1.08224	0.05971
90	1.15139	0.05546	1.14195	0.05154	1.13349	0.04808
95	1.23233	0.04470	1.21864	0.04154	1.20631	0.03875
98	1.37277	0.03206	1.35260	0.02979	1.33430	0.02779
99	1.48942	0.02316	1.46448	0.02152	1.44177	0.02007

Table 2 shows that there is an overall increase in aerosol hygroscopic growth factor for number mix ratio model with increase in relative humidity from 50-99% RHs in each model. The bulk hygroscopicity decreases with increase in RH from 50 – 99% RHs for all the three models used.

More so, it was observed that the growth factor decreases with RHs from 50-99% RHs when the models were compared from model 1 to model 3. Similarly, the bulk hygroscopicity decreases with RHs from model 1 to model 3. The aerosol growth factor revealed that the mixture is barely hygroscopic from 50 – 80% RHs, less hygroscopic from 90 – 95% RHs and more hygroscopic from 98 – 99% RHs for the number mix ratio. The bulk hygroscopicity ranges between 0.02316 to 0.09456 for model 1, 0.02152 to 0.08792 for model 2 and 0.02007 to 0.08201 for model 3.

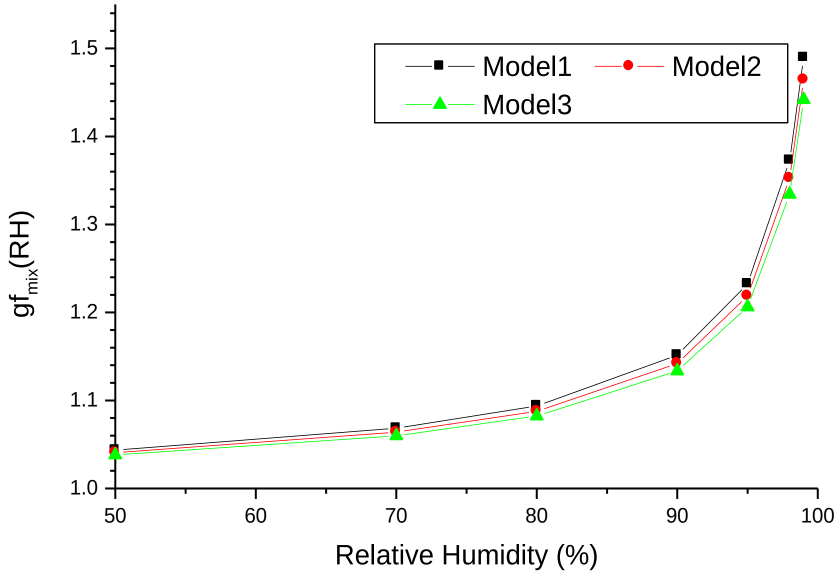

Figure 1: Growth factor of the mixture using number mix ratio (model 1-3)

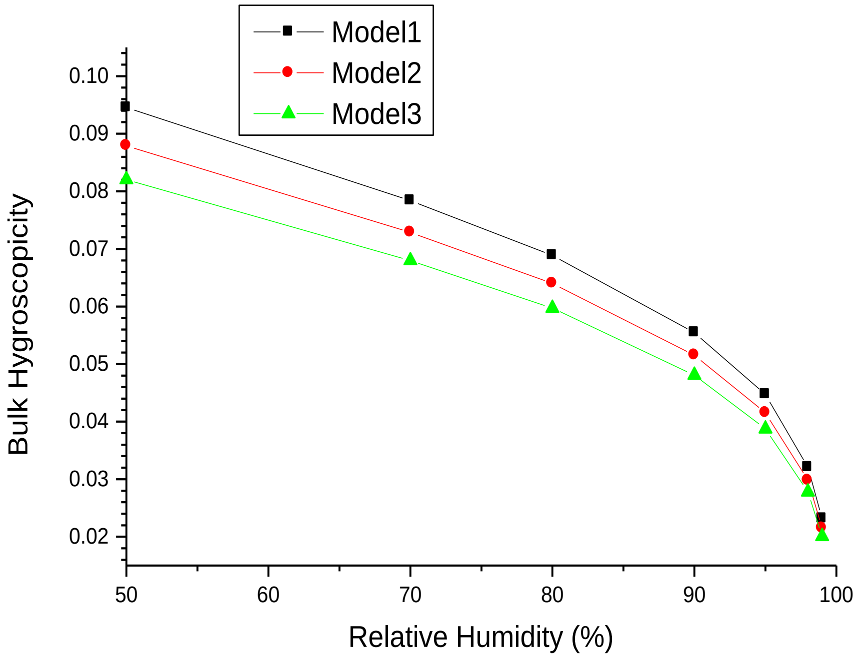

Figure 2: Bulk hygroscopicity of the mixture using number mix ratio (model 1-3)

Figure 1 depicts a non-linear increase in aerosol hygroscopic growth factor with RHs. The growth factor rise up steadily with increasing RH, this could be attributed to the fact that higher RH indicates more moisture content in the atmosphere which means the aerosol particles tends to absorb more water vapour in the atmosphere. The range of values estimated for the gf_{mix} shown in table 2 the mixture as shown in figure 1 are described as barely hygroscopic, less hygroscopic and more hygroscopic growth in accordance with the description for the range of values by Swietlick et al. (2008), Liu et al. (2011). The bulk hygroscopicity decreases with increase in RHs as displayed in figure 2 for the three models.

Table 3: The growth factor for number mix ratio using model 1

RH (%)	gf_{mix}	RH/(1-RH)	gf^3	ln(1-RH/100)	ln gf_{mix}
50	1.04355	1.00000	1.13642	-0.69315	0.04263
70	1.06846	2.33333	1.21978	-1.20397	0.06622
80	1.09380	4.00000	1.30861	-1.60944	0.08966
90	1.15139	9.00000	1.52639	-2.30259	0.14097
95	1.23233	19.00000	1.87145	-2.99573	0.20890
98	1.37277	49.00000	2.58699	-3.91202	0.31683
99	1.48942	99.00000	3.30406	-4.60517	0.39838

Table 4: The growth factor for number mix ratio using model 2

RH (%)	gf_{mix}	RH/(1-RH)	gf^3	ln(1-RH/100)	ln gf_{mix}
50	1.04061	1.00000	1.12684	-0.69315	0.03981
70	1.06392	2.33333	1.20429	-1.20397	0.06196
80	1.08770	4.00000	1.28683	-1.60944	0.08406
90	1.14195	9.00000	1.48918	-2.30259	0.13274
95	1.21864	19.00000	1.80978	-2.99573	0.19774
98	1.35260	49.00000	2.47462	-3.91202	0.30203
99	1.46448	99.00000	3.14086	-4.60517	0.38150

Table 5: The growth factor for number mix ratio using model 3

RH (%)	gf_{mix}	RH/(1-RH)	gf^3	ln(1-RH/100)	ln gf_{mix}
50	1.03798	1.00000	1.11832	-0.69315	0.03728
70	1.05987	2.33333	1.19057	-1.20397	0.05814
80	1.08224	4.00000	1.26756	-1.60944	0.07903
90	1.13349	9.00000	1.45631	-2.30259	0.12530
95	1.20631	19.00000	1.75538	-2.99573	0.18756
98	1.33430	49.00000	2.37555	-3.91202	0.28841
99	1.44177	99.00000	2.99704	-4.60517	0.36587

Tables 3, 4 and 5 shows the data estimated for the number mix ratio using equations (5) and (6). The results of the modeling using equations (12) and (13) are shown in table 6

Table 6: Summary of the results of R^2, k, c and γ for the number mix ratio.

Equations used	R^2	k	constant	γ	Models used
5	0.96171	0.02201	1.27405		Model 1
6	0.97935		-0.04843	-0.09252	
5	0.96171	0.02045	1.25472		Model 2
6	0.97787		-0.04831	-0.08879	
5	0.96171	0.01908	1.23761		Model 3
6	0.97645		-0.04804	-0.08532	

The fitted curve can be represented by any of the empirical parameters in the form of either equation (5) or (6) However, it was observed that equation (6) gives a higher coefficient of determination, R^2 as compared to equation (5) for the three models indicating that the growth factor is well fitted with the γ-law as compared to the parameterization by one – parameter equation.

Table 7: The growth factor and bulk hygroscopicity of aerosols using volume mix ratio for model (1-3)

	Model 1		Model 2		Model 3	
RH (%)	gf_{mix}	Bulk Hyg	gf_{mix}	Bulk Hyg	gf_{mix}	Bulk Hyg
50	1.13844	0.32956	1.13706	0.32587	1.13571	0.32224
70	1.22855	0.30471	1.22672	0.30175	1.22491	0.29884
80	1.32001	0.29009	1.3179	0.28763	1.31578	0.28517
90	1.51813	0.26328	1.51575	0.26155	1.51341	0.25985
95	1.77055	0.23341	1.76819	0.23227	1.76590	0.23117
98	2.15557	0.18214	2.15357	0.18158	2.15164	0.18104
99	2.44351	0.13658	2.44184	0.13628	2.44008	0.13596

Table 7 shows that there is a general increase in aerosol hygroscopic growth factor for the volume mix ratio model with increase in RHs from 50-99% RHs in each model. However, the bulk hygroscopicity decreases with increase in RH from 50 – 99% RHs for all the three adopted models.

It was observed that both the aerosol growth factor and bulk hygroscopicity decreases when compared from model 1 to model 3. The growth factor revealed that the mixture is less hygroscopic from 50 – 80% RHs, more hygroscopic from 90 – 95% RHs and most hygroscopic from 98 – 99% RHs for the volume mix ratio. The bulk hygroscopicity ranges between 0.13658 to 0.32956 for model 1, 0.13628 to 0.32587 for model 2 and 0.13596 to 0.32224 for model 3.

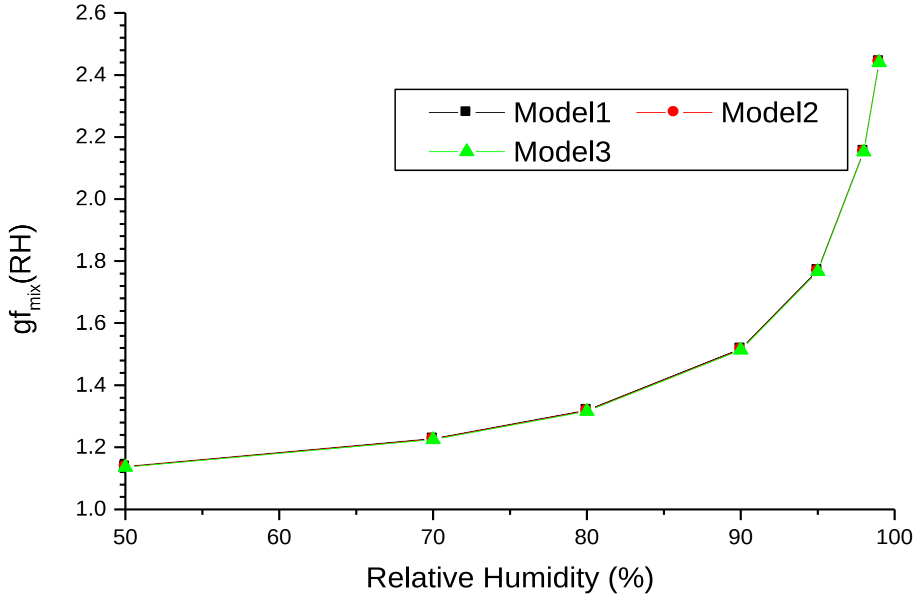

Figure 3: Growth factor of the mixture using volume mix ratio (model 1-3)

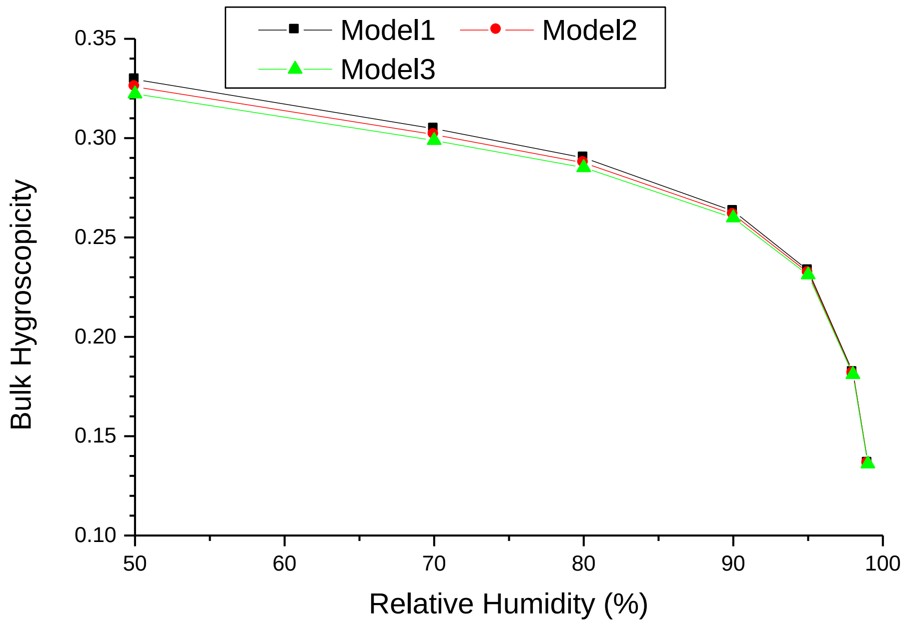

Figure 4: Bulk hygroscopicity of the mixture using volume mix ratio (model 1-3)

Figure 3 depicts a non-linear increase in aerosol hygroscopic growth factor with RHs, however, the rate of increase appears to be almost constant. The growth factor rises up steadily with increasing RH, this may be attributed to the fact that higher RH implies presence of more atmospheric moisture contents making the aerosol particles to absorb more water vapour. The range of values estimated for the gf_{mix} shown in table 7 the mixture as depicted in figure 3 are described as less hygroscopic, more hygroscopic and most hygroscopic growth in accordance with the description for the range of values by Swietlick et al. (2008), Liu et al. (2011). The bulk hygroscopicity decreases with increase in RHs as displayed in figure 4 for the three models.

Table 8: The growth factor for volume mix ratio using model 1

RH (%)	gf_{mix}	RH/(1-RH)	gf^3	ln(1-RH/100)	ln gf_{mix}
50	1.13844	1.00000	1.47546	-0.69315	0.12966
70	1.22855	2.33333	1.85430	-1.20397	0.20584
80	1.32001	4.00000	2.30001	-1.60944	0.27764
90	1.51813	9.00000	3.49884	-2.30259	0.41748
95	1.77055	19.00000	5.55042	-2.99573	0.57129
98	2.15557	49.00000	10.01579	-3.91202	0.76805
99	2.44351	99.00000	14.58963	-4.60517	0.89344

Table 9: The growth factor for volume mix ratio using model 2

RH (%)	gf_{mix}	RH/(1-RH)	gf^3	ln(1-RH/100)	ln gf_{mix}
50	1.13706	1.00000	1.47013	-0.69315	0.12845
70	1.22672	2.33333	1.84601	-1.20397	0.20434
80	1.31790	4.00000	2.28900	-1.60944	0.27604
90	1.51575	9.00000	3.48241	-2.30259	0.41591
95	1.76819	19.00000	5.52828	-2.99573	0.56996
98	2.15357	49.00000	9.98793	-3.91202	0.76713
99	2.44184	99.00000	14.55972	-4.60517	0.89275

Table 10: The growth factor for volume mix ratio using model 3

RH (%)	gf_{mix}	RH/(1-RH)	gf^3	ln(1-RH/100)	ln gf_{mix}
50	1.13571	1.00000	1.46489	-0.69315	0.12726
70	1.22491	2.33333	1.83786	-1.20397	0.20287
80	1.31578	4.00000	2.27796	-1.60944	0.27443
90	1.51341	9.00000	3.46634	-2.30259	0.41437
95	1.76590	19.00000	5.50676	-2.99573	0.56866
98	2.15164	49.00000	9.96119	-3.91202	0.76623
99	2.44008	99.00000	14.52822	-4.60517	0.89203

Tables 8, 9 and 10 shows the data obtained for the volume mix ratio using equations (5) and (6). The results of the modeling using equations (5) and (6) are shown in table 11.

Table 11: Summary of the results of R^2, k, c and γ for the volume mix ratio.

Equations used	R^2	k	constant	γ	Models used
5	0.97083	0.13455	2.08813		Model 1
6	0.99787		-0.0311	-0.201	
5	0.97105	0.13432	2.07683		Model 2
6	0.99781		-0.0328	-0.2012	
5	0.97123	0.13408	2.06598		Model 3
6	0.99775		-0.0345	-0.2013	

The fitted curve can be represented by any of the empirical parameters in the form of either equation (5) or (6) However, it was observed that equation (6) gives a higher coefficient of determination, R^2 as compared to equation (5) for the three models indicating that the growth factor is well fitted with the γ-law as compared to the parameterization by one – parameter equation.

Table 12: The growth factor and bulk hygroscopicity of aerosols using mass mix ratio for model (1-3)

	Model 1		Model 2		Model 3	
RH (%)	**gf_{mix}**	**Bulk Hyg**	**gf_{mix}**	**Bulk Hyg**	**gf_{mix}**	**Bulk Hyg**
50	1.12707	0.29925	1.12625	0.29706	1.12542	0.29487
70	1.20785	0.27183	1.20670	0.27004	1.20554	0.26823
80	1.29124	0.25726	1.28984	0.25569	1.28847	0.25418
90	1.47660	0.23385	1.47494	0.23270	1.47325	0.23154
95	1.72237	0.21079	1.72052	0.20995	1.71873	0.20913
98	2.10781	0.16899	2.10610	0.16853	2.10448	0.16809
99	2.39975	0.12884	2.39819	0.12857	2.39671	0.12831

Table 12 shows that there is a general increase in aerosol hygroscopic growth factor for the mass mix ratio model with increase in RHs from 50-99% RHs in each model. However, the bulk hygroscopicity decreases with increase in RH from 50 – 99% RH for all the three models.

It was observed that both the aerosol growth factor and bulk hygroscopicity decreases when compared from model 1 to model 3. The growth factor revealed that the mixture is less hygroscopic from 50 – 80% RHs, more hygroscopic from 90 – 95% RHs and most hygroscopic from 98 – 99% RHs for the mass mix ratio. The bulk hygroscopicity ranges between 0.12884 to 0.29925 for model 1, 0.12857 to 0.29706 for model 2 and 0.12831 to 0.29487 for model 3.

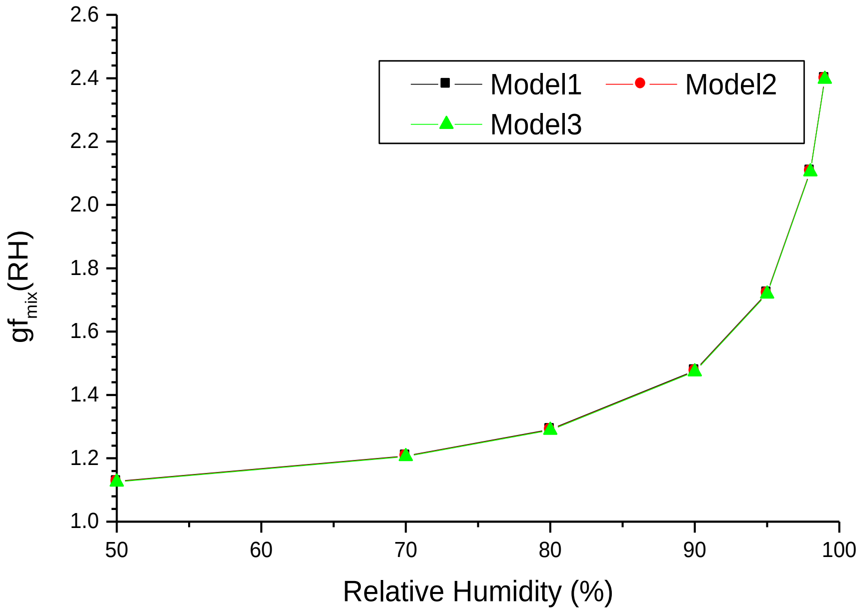

Figure 5: Growth factor of the mixture using mass mix ratio (model 1-3)

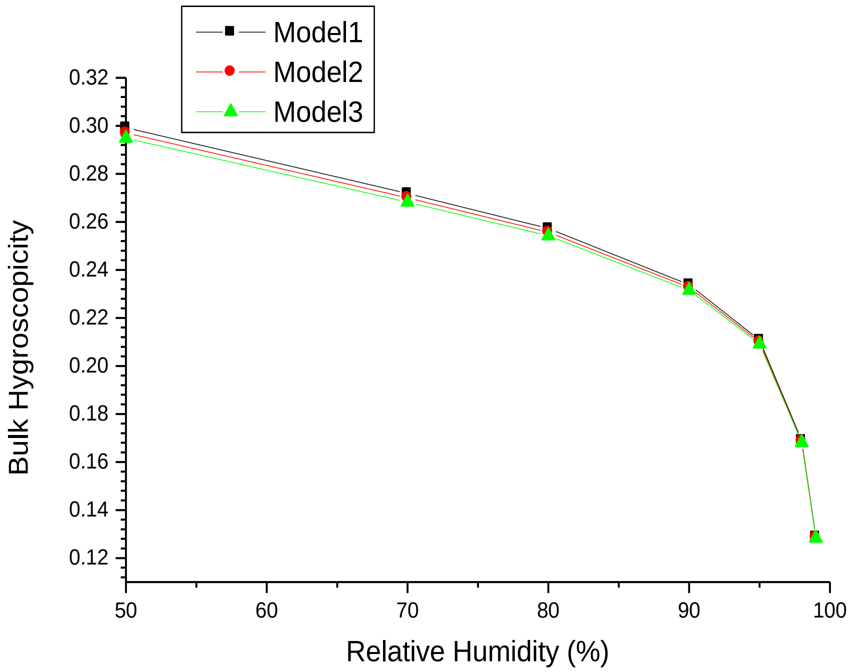

Figure 6: Bulk hygroscopicity of the mixture using mass mix ratio (model 1-3)

Figure 5 depicts a non-linear increase in aerosol hygroscopic growth factor with RHs, however, the rate of increase appears to be almost constant. The growth factor rises up steadily with increasing RH, this may be attributed to the fact that higher RH implies more atmospheric moisture content which makes the aerosol particles to absorb more water vapour on particle surface. The range of values estimated for the gf_{mix} shown in table 12 the mixture as depicted in figure 5 are described as less hygroscopic, more hygroscopic and most hygroscopic growth in accordance with the description for the range of values by Swietlick et al. (2008), Liu et al. (2011). The bulk hygroscopicity decreases with increase in RHs as displayed in figure 6 with almost constant rate for the three models under study.

Table 13: The growth factor for mass mix ratio using model 1

RH (%)	gf_{mix}	RH/(1-RH)	gf^3	ln(1-RH/100)	ln gf_{mix}
50	1.12707	1.00000	1.43172	-0.69315	0.11963
70	1.20785	2.33333	1.76212	-1.20397	0.18884
80	1.29124	4.00000	2.15289	-1.60944	0.25560
90	1.47660	9.00000	3.21949	-2.30259	0.38974
95	1.72237	19.00000	5.10955	-2.99573	0.54370
98	2.10781	49.00000	9.36473	-3.91202	0.74565
99	2.39975	99.00000	13.81964	-4.60517	0.87536

Table 14: The growth factor for mass mix ratio using model 2

RH (%)	gf_{mix}	RH/(1-RH)	gf^3	ln(1-RH/100)	ln gf_{mix}
50	1.12625	1.00000	1.42856	-0.69315	0.11889
70	1.20670	2.33333	1.75711	-1.20397	0.18789
80	1.28984	4.00000	2.14587	-1.60944	0.25451
90	1.47494	9.00000	3.20863	-2.30259	0.38861
95	1.72052	19.00000	5.09304	-2.99573	0.54262
98	2.10610	49.00000	9.34193	-3.91202	0.74484
99	2.39819	99.00000	13.79267	-4.60517	0.87471

Table 15: The growth factor for mass mix ratio using model 3

RH (%)	gf_{mix}	RH/(1-RH)	gf^3	ln(1-RH/100)	ln gf_{mix}
50	1.12542	1.00000	1.42541	-0.69315	0.11815
70	1.20554	2.33333	1.75203	-1.20397	0.18692
80	1.28847	4.00000	2.13908	-1.60944	0.25346
90	1.47325	9.00000	3.19761	-2.30259	0.38747
95	1.71873	19.00000	5.07716	-2.99573	0.54158
98	2.10448	49.00000	9.32035	-3.91202	0.74407
99	2.39671	99.00000	13.76718	-4.60517	0.87410

Tables 13, 14 and 15 shows the data obtained for the mass mix ratio using equations (5) and (6). The results of the modeling using equations (5) and (6) are shown in table 16.

Table 16: Summary of the results of $R^2, k, c\ and\ \gamma$ for the mass mix ratio.

Equations used	R^2	k	constant	γ	Models used
5	0.97531	0.12738	1.92953		Model 1
6	0.99622		-0.04749	-0.19923	
5	0.97546	0.12715	1.92241		Model 2
6	0.99615		-0.04852	-0.19927	
5	0.97560	0.12694	1.91534		Model 3
6	0.99608		-0.04956	-0.19932	

The fitted curve can be represented by any of the empirical parameters in the form of either equations (5) or (6) However, it was observed that equation (6) gives a higher coefficient of determination, R^2 as compared to equation (5) for the three models indicating that the growth factor is well fitted with the γ-law as compared to the parameterization by one – parameter equation.

CONCLUSION

The analysis in this study shows that the aerosol hygroscopic growth factor gf_{mix} increases with increase in RH while the bulk hygroscopicity factor decreases with increase in RH. The growth factor indicates that the mixture is barely hygroscopic, less hygroscopic, more hygroscopic for the number mix ratio and it's less hygroscopic, more hygroscopic and most hygroscopic for the volume and mass mix ratios. The bulk hygroscopicity ranges between 0.02007 to 0.09456 for the number mix ratio from model 1 to model 3, the bulk hygroscopicity ranges between 0.13596 to 0.32956 for the volume mix ratio from model 1 to model 3 while the bulk hygroscopicity ranges between 0.12831 to 0.29925 for the mass mix ratio from model 1 to model 3. The growth factor is well fitted with the γ-law as compared to the parameterization by one – parameter equation based on the coefficient of determination. The number mix, volume mix and mass mix ratios shows an increase in particle diameter with increase in RH with a steep curve of deliquescence found from 95-99% RHs. However, the volume mix ratio shows more increase in gf_{mix} with RHs and gives higher coefficient of determination when compared to the number mix ratio and mass mix ratio. The results showed that the coefficient of determination, $R^2 > 96\%$ for all the three models used in this study.

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