

# Determination of the Effects of Kelvin Radii and Bulk hygroscopicity on Atmospheric Aerosols Using MVN mix Ratios

Ayinde Akeem Shola, Jimoh Morufat Motolani, Aibinu Abdulmumin Taiye

Physical/Chemical oceanography, Nigerian Institute for Oceanography and Marine Research

DOI: 10.29322/IJSRP.9.02.2019.p8610

<http://dx.doi.org/10.29322/IJSRP.9.02.2019.p8610>

**Abstract-** Present work aims to determine the relationship between Kelvin radii and Bulk hygroscopicity factor, the effects of these factors on Kelvin effect and Water activity of atmospheric aerosol and investigate how both Kelvin effect and Water activities affect atmospheric processes based on (MVN mix ratios). In the present study, microphysical properties of aerosols were extracted from the Optical Properties of Aerosols and Clouds (OPAC) at seven relative humidity (50%, 70%, 80%, 90%, 95%, 98% and 99%) for ten aerosol models (Arctic, Antarctic, Continental clean, continental polluted, continental average, Desert, Maritime clean, maritime polluted, maritime tropical and Urban.). The parameters extracted were individual radii of the aerosols (both dry and wet), number concentrations, mass density, volume density, number mix ratio, mass mix ratio and volume mix ratio. The parameters were used to calculate effective radii and effective hygroscopic growth of the aerosols. These two calculated parameters were used in Köhler models to determine Kelvin radii (Kelvin effects) and bulk hygroscopicity factors (water activities) of the aerosols. It was discovered that the effective radii, effective hygroscopic growth factor, Kelvin effect and water activity all depends on aerosol composition and hygroscopicity. We also observed that the water activity values for all our aerosol models except the Urban were less than RH for number mix ratio, while the Maritimes, Antarctic and Arctic models are less than RH for volume mix ratio. And the Maritimes and Arctic models are less than RH for the mass mix ratio. The values of the Kelvin effect of all atmospheric aerosol models except the urban model, decreases with increase in RH and the Sahara model has a very high magnitude for the number mix ratio. While for the volume and mass mix ratios the Kelvin effects of all models decreases with increase in RH with very low magnitude for the Sahara model. We observed that as the ambient relative humidity (RH) changes, hygroscopic atmospheric aerosols can undergo phase transformation, droplet growth, and evaporation. Both Kelvin effect and water activity play important roles in atmospheric processes. These two quantities depend on Kelvin radii and bulk hygroscopicity factors of atmospheric aerosols.

**Index Terms-** Kelvin effect, water activity, relative humidity, effective radii, effective hygroscopic growth, Kelvin radii, bulk hygroscopicity.

## I. INTRODUCTION

Future climate predictions over the next century remain a scientific goal for most of the earth science community. Uncertainty in predicting climate change at 2100 mainly lies in the uncertainty associated with feedbacks in the carbon cycle (Gregory et al., 2009) and aerosol forcing (Forster et al., 2007). These feedbacks are the results of both natural and anthropogenic of land-atmosphere-ocean interactions. Atmospheric aerosols are suspended liquid or solid particles in the atmosphere originating from both natural and anthropogenic activities, affect local radiative forcing by scattering and absorbing of terrestrial radiation, thus, affects radiation balance of the earth and climate (Hess et. al., 1998). Radiative properties of clouds depend on the size and number concentration of droplets, which is governed by atmospheric conditions, such as the number of cloud condensation nuclei (CCN) and the supersaturation of water. The ambient relative humidity changes the microphysical and optical properties of hygroscopic atmospheric aerosols (Cheng et al., 2008), such as sea-salts and water soluble. These ambient atmospheric aerosols are external and internal mixtures of particles with different chemical compounds such as soot, sulphate, nitrate, organic carbon and mineral dust. The state of mixing of these components is crucial for understanding the role of aerosol particles in the atmosphere, As the ambient relative humidity (RH) changes, hygroscopic atmospheric aerosols can undergo phase transformation, droplet growth, and evaporation. Phase transformation from a solid particle to a saline droplet usually occurs spontaneously when the RH reaches a level called the deliquescence humidity and its values depend also on the chemical composition of the aerosol particle (Orr et al. 1958; Tang 1976). The chemical composition of aerosol undergoes spatio-temporal changes, hence characteristics such as Kelvin radii (Kelvin effects) and bulk hygroscopicity factors (water activities) are significantly different from places and particles (Mochida et al., 2006). Köhler equation is often used to describe both hygroscopic growth of aerosol particles and their activation to cloud droplets. It is divided into: (1) the Kelvin effect which is responsible for the increase in equilibrium water vapor pressure over a curved surface (Lewis, 2006); and (2) the Raoult effect which is the reduction in water activity associated with solute dissolution in terms of either effective hygroscopic growth and/or the effective radius of the mixtures at given RHs.

In the work of Kreidenweis et al. (2005a), the use of water uptake data for particles below water saturation to calculate the water activity as a function of solute weight percent, extrapolating to dilute solution concentrations relevant to describing equilibria at supersaturated vapor conditions was investigated. Water uptake data for RH below about 95% were obtained using the humidified tandem differential mobility analyzer (HTDMA). The HTDMA measures the water uptake of a nearly monodisperse aerosol at a controlled temperature and relative humidity. A method was outlined for determining  $a_w$  as a function of solution composition from HTDMA measurements (Brechtel and Kreidenweis, 2000b; Prenni et al., 2001; Rader and McMurry, 1986). The HTDMA measures the hygroscopic diameter growth factor,  $GF$ , of particles at  $RH < 95\%$ , where  $GF$  is defined as the ratio of the diameter in equilibrium with water vapor at the relative humidity, RH, to the dry diameter, the latter was measured at  $RH < 95\%$ . The use of HTDMA data for determining solution water activities was proposed by Brechtel and Kreidenweis (2000a, b); and their methodology was adapted to a different water activity expression. (B.I Tijjani and G.S.M Galadanci 2015) studied volume, mass and number base ratio for six aerosol type i.e. Arctic, Antarctic, Continental, Desert, Maritime and Urban, it was observed that hygroscopicity increases exponentially with relative humidity at every aerosol type.

In this study, nvm based microphysical properties such as individual radii of the aerosols (both dry and wet), number concentrations, mass density, volume density, number mix ratio, mass mix ratio and volume mix ratio were used to study ten types of atmospheric aerosols.

## II. METHODOLOGY

In the present study, microphysical properties of ten atmospheric aerosols type were extracted from Optical Properties of Aerosols and Clouds (OPAC) Table 2.1 and 2.2 shows composition and microphysical properties of aerosol types extracted from OPAC respectively. The *sol* and *ns* show that the aerosols are soluble and insoluble respectively; the *inso* represents the *water-insoluble* part of aerosol particles and consist mostly of soil particles with a certain amount of organic material. The *waso* represents the *water-soluble* part of aerosol particles that originates from gas to particle conversion and consist of various kinds of sulfates, nitrates and also organic water-soluble substances, thus, it contains more than only the sulfate aerosol that is often used to describe anthropogenic aerosols. The *soot* component is used to represent absorbing black carbon, carbon is not soluble in water and therefore the particles are assumed not to grow with increasing relative humidity. The *ssam* and *sscm* are *sea-salt accumulation and coarse modes* particles respectively and they consist of various kinds of salt contained in seawater. The *suso* is *sulfate* component (75%  $H_2SO_4$ ) used to describe the amounts of sulfates found in the Antarctic aerosols. *Mineral nucleation mode (minm)*, *Mineral accumulation mode (miam)*, and *Mineral coarse mode (micm)* are mineral aerosols or desert dusts produced in arid regions, they consist of a mixture of quartz and clay minerals and are modeled with three modes to allow considering increasing relative number of large particles for increasing turbidity. The *mitrate mineral transported (mitr)* is used to describe desert dust that is transported over long distances with a reduced number of large particles.

**Table 2.1 Composition of Aerosol Models at 50% RH**

Aerosol models	Components	$N_i$ (cm <sup>-3</sup> )	$M_i$ (μgm <sup>-3</sup> )	$V_i$ (μcm <sup>-3</sup> )	Number mix ratio ( $n_j$ )	Mass mix ratio ( $m_j$ )	Volume mix ratio ( $v_j$ )
Continental clean	waso (sol)	2600	5.2	3.66E+6	1.0	0.591	0.673
	inso (ns)	0.15	3.6	1.78E+6	5.77E-5	0.409	0.327
Continental average	waso (sol)	7000	14.0	9.85E+6	0.458	0.583	0.653
	inso (ns)	0.4	9.5	4.75E+6	2.61E-5	0.396	0.315
	soot (ns)	8300	0.5	4.97E+5	0.542	0.021	0.0329
Continental polluted	waso (sol)	15700	31.4	22.08E+6	0.314	0.658	0.707
	inso (ns)	0.6	14.2	7.12E+6	0.12E-4	0.298	0.228
	soot (ns)	34300	2.1	20.52E+5	0.686	0.044	0.0656
Urban	waso (sol)	28000	56.0	3.94E+7	0.177	0.563	0.606
	inso (ns)	1.5	35.8	1.78E+7	9.49E-6	0.358	0.274
	soot (ns)	1.3E5	7.8	7.78E+6	0.823	0.079	0.12
Sahara	waso (sol)	2000	4.0	2.81E+6	0.87	0.018	0.0177
	minm (ns)	269.5	7.5	2.88E+6	0.117	0.033	0.0331
	miam (ns)	30.5	168.7	6.49E+7	1.33E-2	0.747	0.746
	micm (ns)	0.142	45.6	1.77E+7	6.17E-5	0.202	0.203
Maritime clean	waso (sol)	1500	3.0	2.11E+6	0.987	0.071	0.0705
	ssam (sol)	20	38.6	3.0E+7	1.32E-2	0.908	0.909
	sscm (sol)	3.2E-3	0.9	6.64E+5	2.11E-6	0.021	0.0201
Maritime polluted	waso (sol)	3800	7.6	5.35E+6	0.422	0.160	0.16
	ssam (sol)	20	38.6	3.1E+5	2.22E-3	0.814	0.815
	sscm (sol)	3.2E-3	0.9	3.0E+8	3.56E-7	0.019	0.018

	soot (ns)	5180	0.3	6.64E+5	0.576	0.006	0.00653
Maritime tropical	waso (sol)	590	1.2	8.30E+5	0.983	0.058	0.0565
	ssam (sol)	10	19.3	1.50E+7	1.67E-2	0.928	0.927
	sscm (sol)	1.3E-3	0.3	2.70E+5	2.17E-6	0.014	0.0167
Arctic	waso (sol)	1300	2.6	18.29E+5	0.197	0.328	0.3804
	inso (ns)	0.01	0.2	11.87E+4	1.52E-6	0.029	0.03477
	ssam (sol)	1.9	3.7	28.48E+5	2.88E-4	0.544	0.5384
	soot (ns)	5300	0.3	31.69E+4	0.803	0.044	0.04643
Antarctic	suso (sol)	42.9	2.0	1.63E+6	0.998	0.910	0.9209
	ssam (sol)	0.5E-1	0.1	7.05E+4	1.09E-3	0.045	0.0411
	mitr (ns)	0.5E-2	0.1	3.24E+4	1.23E-4	0.045	0.03805

**Table 2.2 Microphysical Properties of Aerosol Models at 50% RH Extracted from OPAC.**

Aerosol models	Components	Minimum radius (µm)	Maximum radius (µm)	Density (gcm <sup>-3</sup> )	R <sub>mod</sub> (wet) (µm)	R <sub>mod</sub> (dry) (µm)
Continental clean	waso (sol)	6.0E-3	25	1.42	2.62E-2	2.12E-2
	inso (ns)	5.0E-3	20	2	4.71E-1	4.71E-1
Continental average	inso (ns)	5.0E-3	20	2	4.71E-1	4.71E-1
	waso (sol)	6.0E-3	25	1.42	2.62E-2	2.12E-2
	soot (ns)	5.0E-3	20	1	1.18E-2	1.18E-2
Continental polluted	inso (ns)	5.0E-3	20	2	4.71E-1	4.71E-1
	waso (sol)	6.0E-3	25	1.42	2.62E-2	2.12E-2
	soot (ns)	5.0E-3	20	1	1.18E-2	1.18E-2
Urban	waso (sol)	6.0E-3	25	1.42	2.62E-2	2.12E-2
	inso (ns)	5.0E-3	20	2	4.71E-1	4.71E-1
	soot (ns)	5.0E-3	20	1	1.18E-2	1.18E-2
Sahara	waso (sol)	6.0E-3	25	1.42	2.62E-2	2.12E-2
	minm (ns)	5.0E-3	20	2.6	7.0E-2	7.0E-2
	miam (ns)	5.0E-3	20	2.6	3.9E-1	3.9E-1
	micm (ns)	5.0E-3	20	2.6	1.9	1.9
Maritime clean	waso (sol)	6.0E-3	25	1.42	2.62E-2	2.12E-2
	ssam (sol)	7.7E-3	32.2	1.29	3.36E-1	2.09E-1
	sscm (sol)	7.7E-3	90.5	1.29	2.82	1.75
Maritime polluted	waso (sol)	6.0E-3	25	1.42	2.62E-2	2.12E-2
	soot (ns)	5.0E-3	20	1	1.18E-2	1.18E-2
	ssam (sol)	7.7E-3	32.2	1.29	3.36E-1	2.09E-1
	sscm (sol)	7.7E-3	90.5	1.29	2.82	1.75
Maritime tropical	waso (sol)	6.0E-3	25	1.42	2.62E-2	2.12E-2
	ssam (sol)	7.7E-3	32.2	1.29	3.36E-1	2.09E-1
	sscm (sol)	7.7E-3	90.5	1.29	2.82	1.75
Arctic	inso (ns)	5.0E-3	20	2	4.71E-1	4.71E-1
	waso (sol)	6.0E-3	25	1.42	2.62E-2	2.12E-2
	soot (ns)	5.0E-3	20	1	1.18E-2	1.18E-2
	ssam (sol)	7.7E-3	32.2	1.29	3.36E-1	2.09E-1
Antarctic	ssam (sol)	7.7E-3	32.2	1.29	3.36E-1	2.09E-1
	mitr (ns)	2.0E-2	5	2.6	0.5	0.5
	suso (sol)	7.3E-3	30.5	1.25	9.8E-2	6.95E-2

Generally, atmospheric aerosol is a mixture of different (soluble and insoluble) components. Therefore, the information on the hygroscopicity modes was merged into an “overall” or “bulk” or “effective” radius and hygroscopic growth factor of the mixture. From the hygroscopic data obtained from microphysical properties of aerosols extraction using optical properties of aerosols, the effective radius for all the aerosol models was calculated using the relation

$$r_{eff}(S) = (\sum_k x_k r_k^3)^{1/3} \tag{1}$$

where,  $S$  is taken for eight values 0%, 50%, 70%, 80%, 90%, 95%, 98% and 99% RH and the summation were performed over all compounds present in the particles and  $x_k$  represent their respective volume fractions or number fractions and mass fractions using the Zdanovskii-Stokes-Robinson relation (ZSR relation; Sjogren et al., 2007; Stokes and Robinson, 1966; Meyer et al., 2009; Stock et al., 2011).

The calculated effective radii for number, volume and mass mix ratios were plotted against relative humidity and observed. We defined aerosol hygroscopic growth factor as

$$g(S) = \frac{r(S)}{r(S=0)} \quad (2)$$

Where  $r(S)$  and  $r(S=0)$  are the radii of the wet and dry aerosols respectively. Now, the effective hygroscopic growth factor  $g_{eff}(S)$ , which represents the entire aerosol's particle population is given as:

$$g_{eff}(S) = (\sum_k x_k g_k^3)^{1/3} \quad (3)$$

Equation (3) were used directly to calculate the effective hygroscopic growth factor of the aerosol models. The calculated effective hygroscopic growth factors were plotted against RH and observed.

The growth of aqueous droplets in ambient is commonly described by Köhler theory (Köhler, 1936; Gysel et al., 2002; Kreidenweis et al., 2005). According to Köhler theory, the equilibrium water vapor saturation ratio,  $S$ , is given by

$$S = a_w K_e \quad (4)$$

where,  $a_w$  denotes the water activity or Raoult term, and  $K_e$  is the Kelvin effect.

The equilibrium water vapor saturation ratio for a droplet was described by Kreidenweis et al., 2005, as

$$\ln S = \frac{A}{D} - \frac{B}{D^3} \quad (5)$$

Where,  $D$  is aerosol particle diameter.

$$A = \frac{4\sigma MW_w}{RT\rho_w} \quad (6a)$$

$$B = \frac{6n_s M_w}{\pi\rho_w} \quad (6b)$$

Where  $R$  is the universal gas constant,  $T$  is the temperature,  $\sigma$  is the surface tension,  $M$ ,  $W_w$ ,  $\rho_w$ ,  $n_s$  are molar volume of pure water, molar volume of solute, density of the solute and particles number respectively.

Now, for our atmospheric aerosol models, Eq. (5) was adapted but rewritten to represents the property of the bulk components as

$$\ln S = \frac{A}{2r_{eff}(S)} + \frac{B}{8r_{eff}^3(S)} \quad (7)$$

Relationship between droplet radius-RH and  $A$  (Kelvin radius) and  $B$  (Bulk hygroscopicity factor) were established by computing multiple regression analysis with MS Excel for equation (7)

Comparing the first term on the right-hand side of Eq. (7) with Eq. (4), we obtain

$$\ln K_e = \frac{A}{2r_{eff}(S)} \quad (8)$$

Where  $A$  is the characteristic length for the effect of surface tension (or Kelvin radius)

Taking natural log of both sides of equation (8), we obtain

$$K_e = \exp\left(\frac{A}{2r_{eff}(S)}\right) \quad (9)$$

Also, comparing the second term on the right-hand side of Eq. (7) with Eq. (4), we get

$$\ln a_w = \frac{B}{8r_{eff}^3(S)} \quad (10)$$

The parameter  $B$  was described as the bulk hygroscopicity factor under subsaturation conditions (Mochinda et al., 2006).

This also implies,

$$a_w = \exp\left(\frac{B}{8r_{eff}^3(S)}\right) \quad (11)$$

The calculated Kelvin effects and water activities using Eq. (9) and Eq. (11) were substituted into Eq. (4) to calculate the saturation ratio; these parameters were plotted against RH and observed.

The relationship between growth factors, composition, and water activities are deduced and given in functional form as (Kreidenweis et al., 2005a):

$$g_{eff}(S) = \left[ 1 + (a + b \cdot a_w + c \cdot a_w^2) \frac{a_w}{1-a_w} \right]^{\frac{1}{3}} \quad (12)$$

This implies that,

$$g_{eff}^3(S) - 1 = (a + b \cdot a_w + c \cdot a_w^2) \frac{a_w}{1-a_w} \quad (13)$$

Where,  $a$ ,  $b$  and  $c$  are polynomial coefficients, which were determined by multiple regression analysis using MS Excel.

### III. RESULTS AND DISCUSSIONS

#### 3.1 Effective Radius ( $R_{eff}$ )

The effective radius of ten aerosol models was calculated using eq. (1). The calculated effective radii were plotted against the relative humidity and the graphs are shown in figures 1a, 1b & 1c.

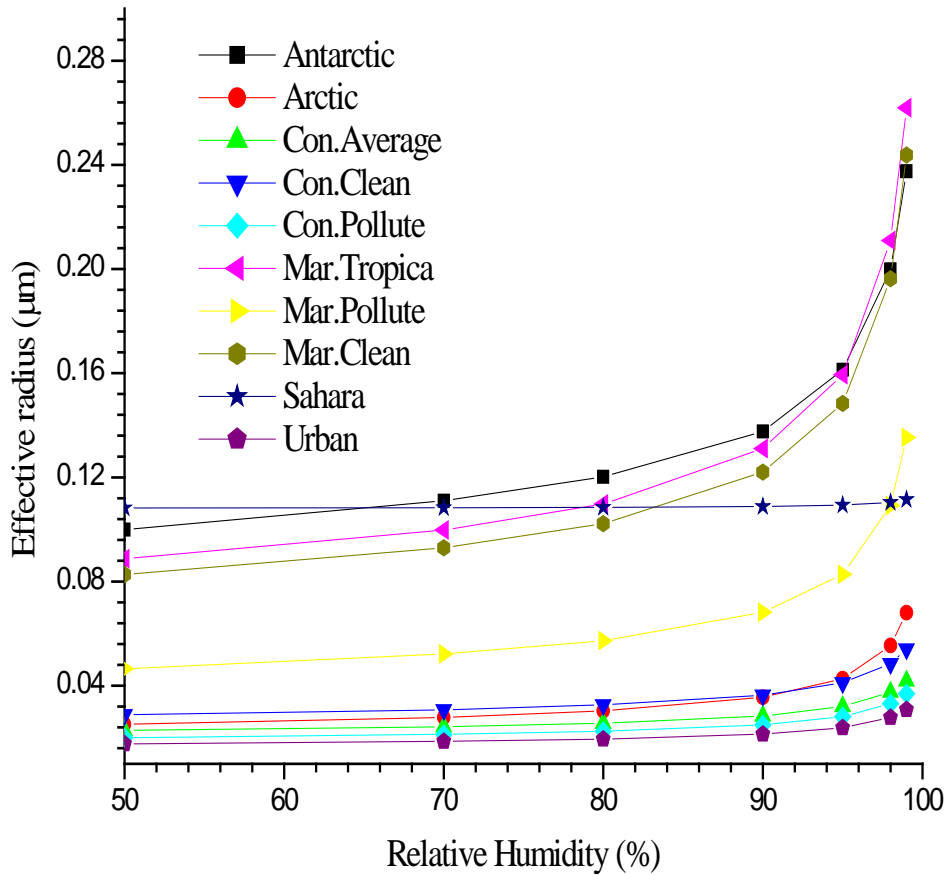
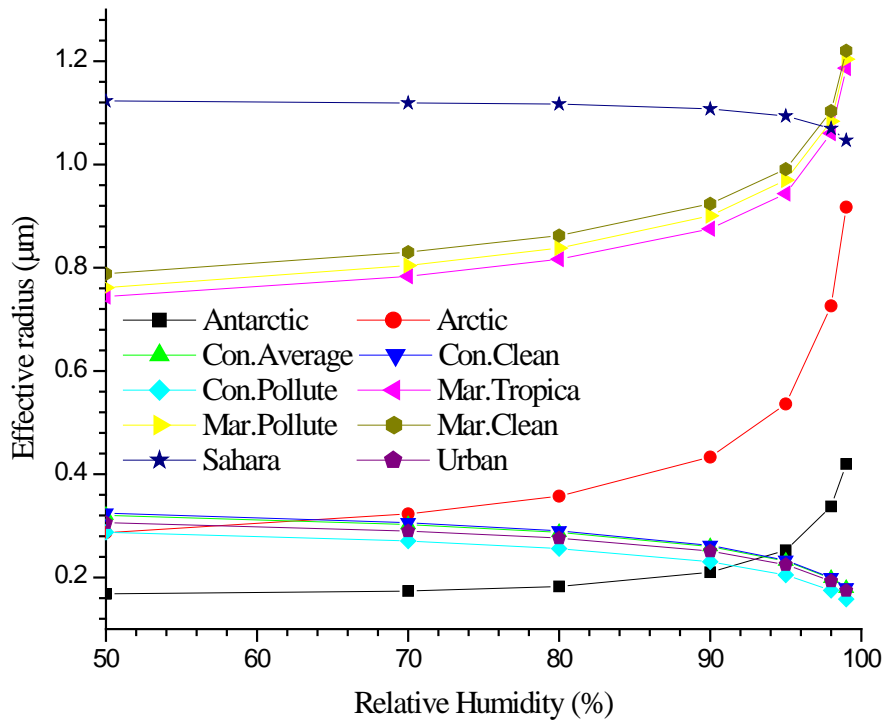
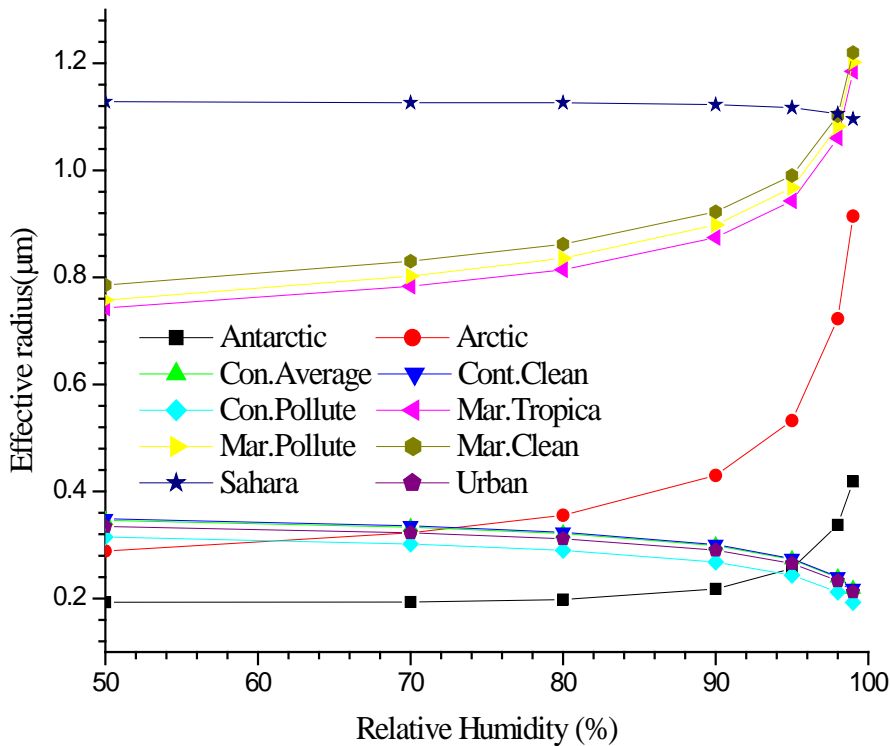


Figure 3.1a Effective Radius (number mix ratio) against RH using eq. (1)



**Figure 3.1b** Effective Radius (volume mix ratio) against RH using eq. (1)



**Figure 3.1c** Effective Radius (mass mix ratio) against RH using eq. (1)

3.2 Effective growth ( $g_{eff}$ )

The effective growth of the aerosol models were calculated from eq. (3.3). The graphs of effective growth against RH are shown in figures 4.2a, 4.2b & 4.2c.

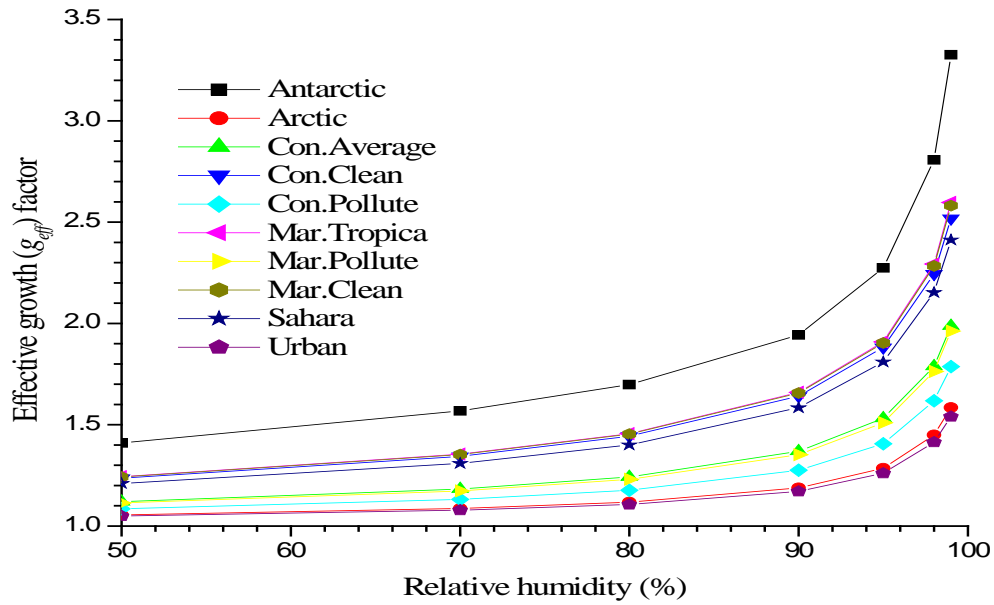


Figure 3.2a Effective Growth (number mix ratio) against RH using eq. (3)

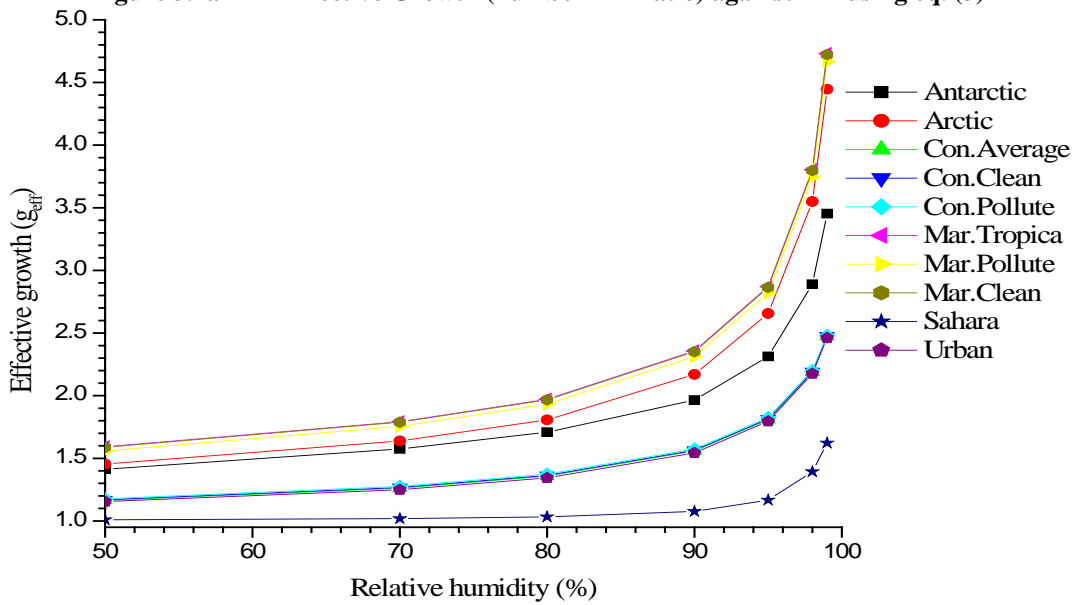
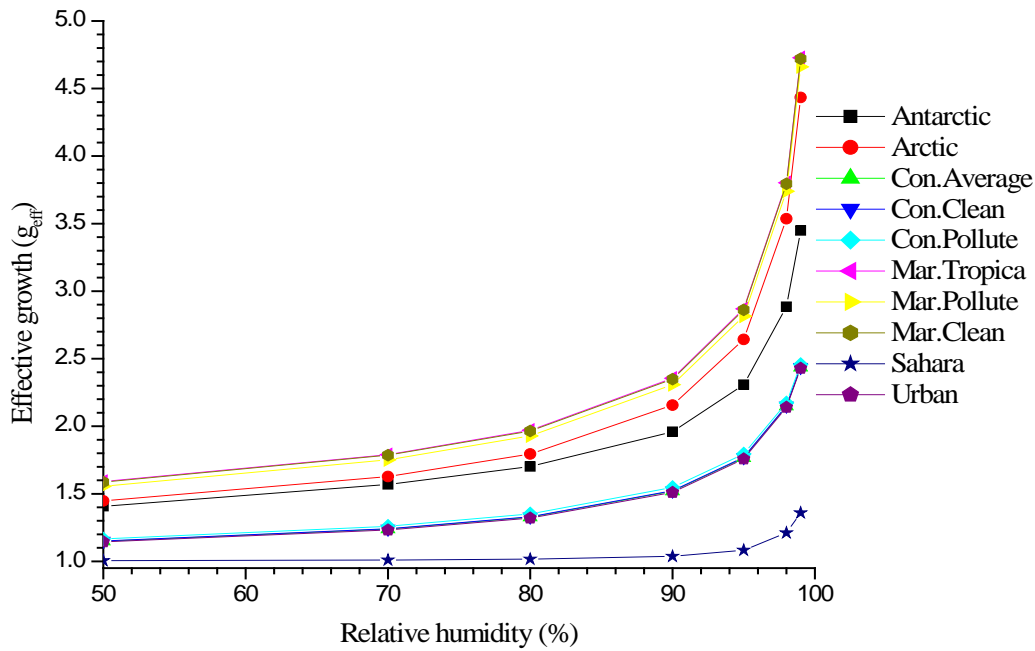


Figure 3.2b Effective Growth (volume mix ratio) against RH using eq. (3)



Figur3 4.2c Effective Growth (mass mix ratio) against RH using eq. (3)

### 3.3 WATER ACTIVITY ( $a_w$ )

The water activity of the aerosol models were calculated using equation (1). The graphs of water activity against RH are shown in figure 4.3a, 4.3b & 4.3c. The water activity curve of Sahara aerosol type could not be shown in the graphs because it's  $a_w$  values is not in the range of  $a_w$  values of other aerosol models (see appendix A).

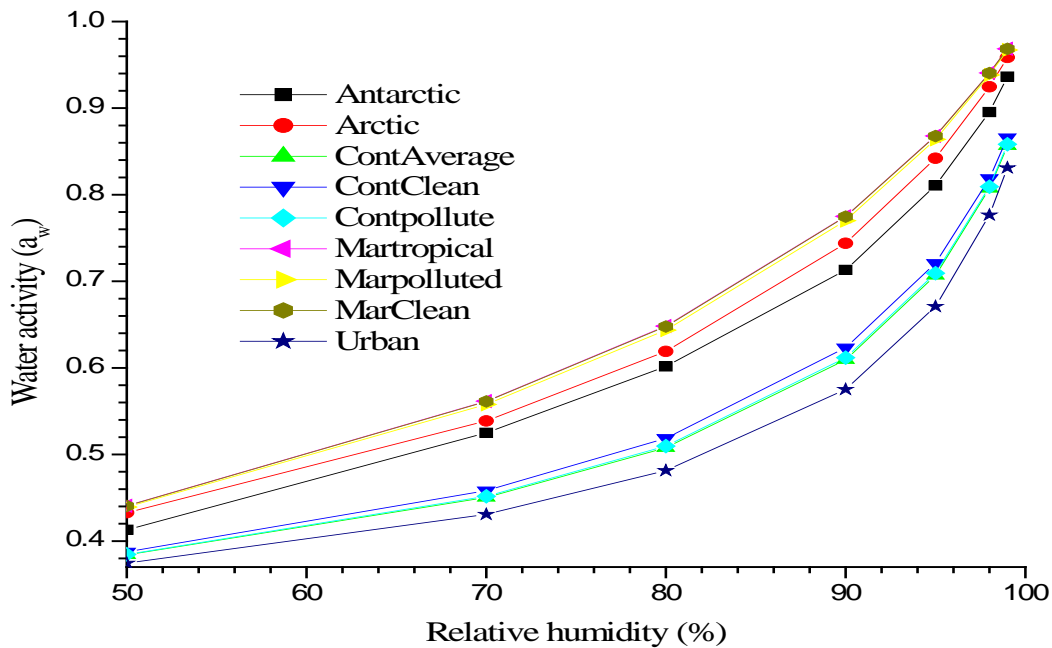


Figure 3.3a Water Activity (number mix ratio) against RH using eq. (11)



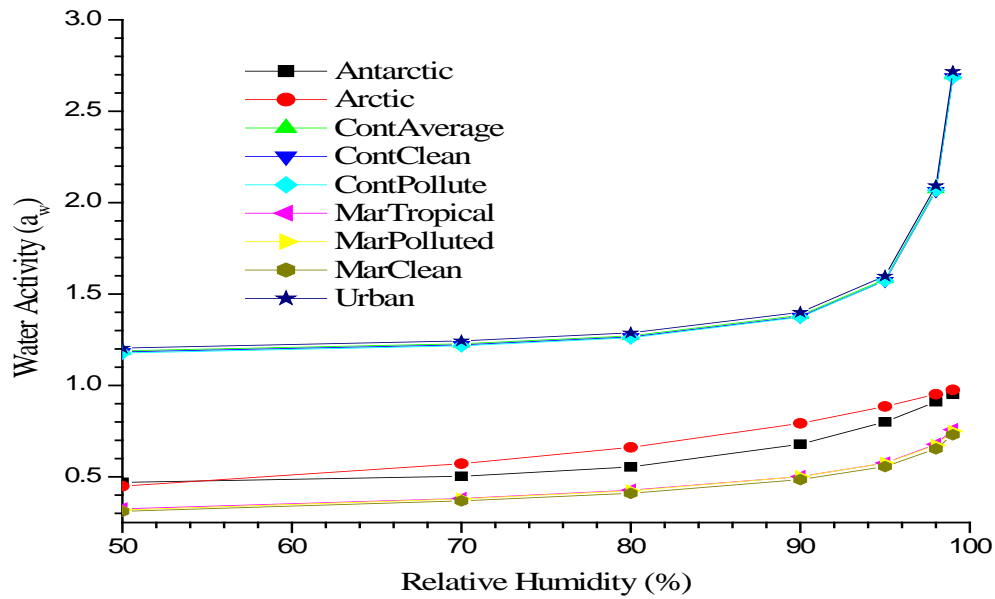


Figure 3.3b Water Activity (volume mix ratio) against RH using eq. (11)

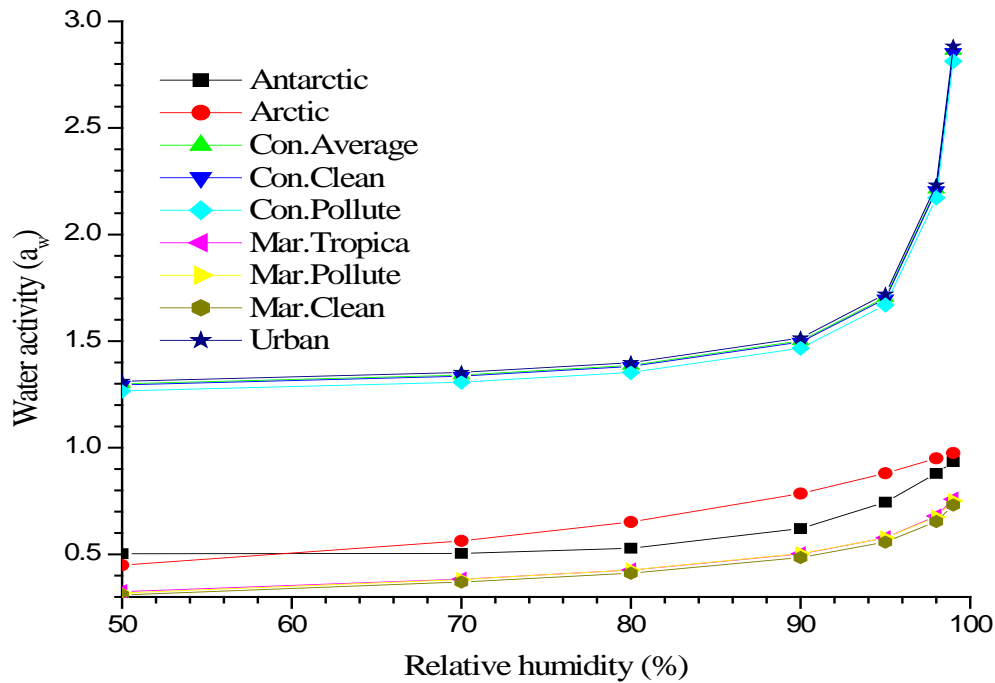


Figure 3.3c Water Activity (mass mix ratio) against RH using eq. (11)

### 3.4 KELVIN EFFECT ( $K_c$ )

Eq. (9) was used to calculate the Kelvin effect of all aerosol model types. The graphs of Kelvin effect against RH are shown in figure 4.4a, 4.4b & 4.4c. Kelvin effect curve of the Sahara model isn't included in the graphs because  $K_c$  values are not in range of the values of other aerosol models (see appendix B).

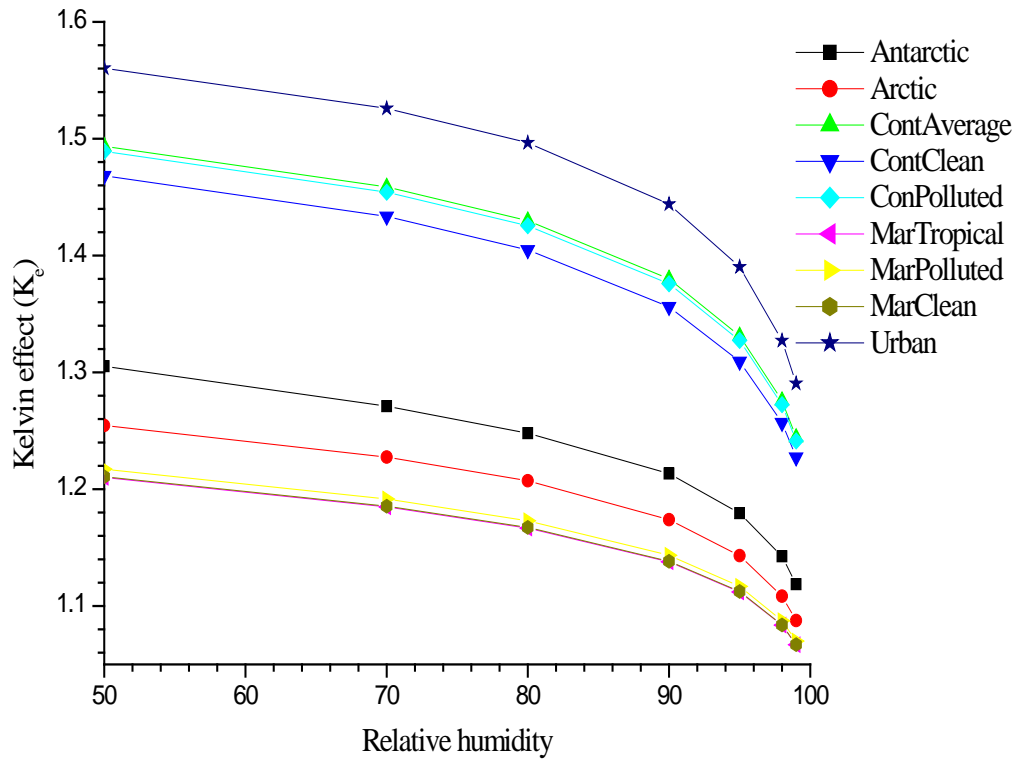


Figure 3.4a Kelvin Effect (number mix ratio) against RH using eq. (9)

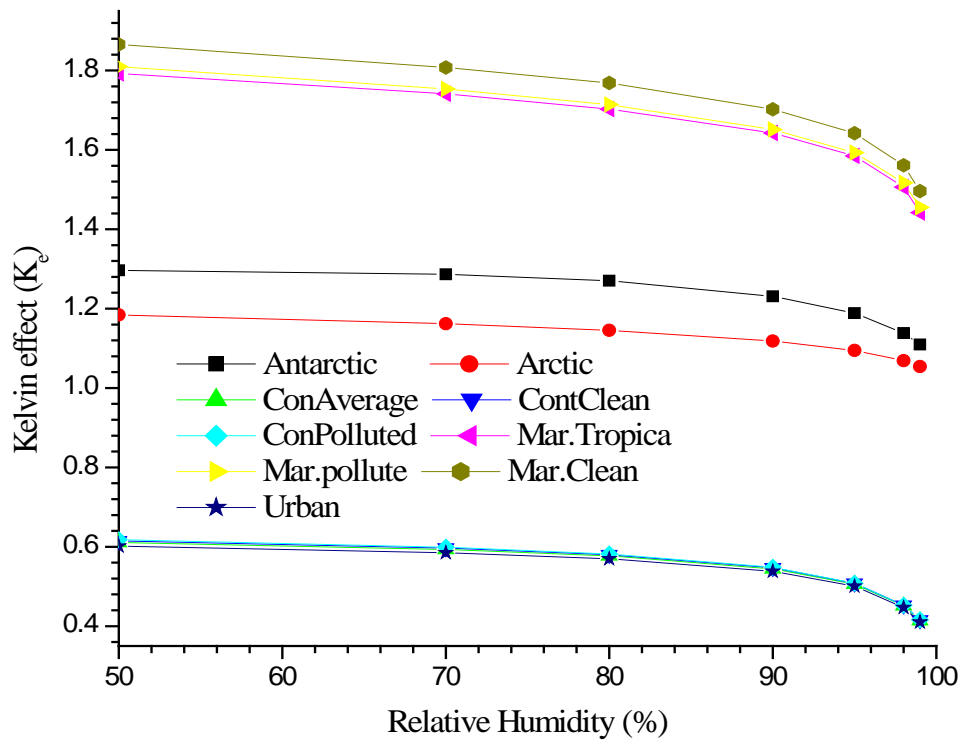


Figure 3.4b Kelvin Effect (volume mix ratio) against RH using eq. (9)

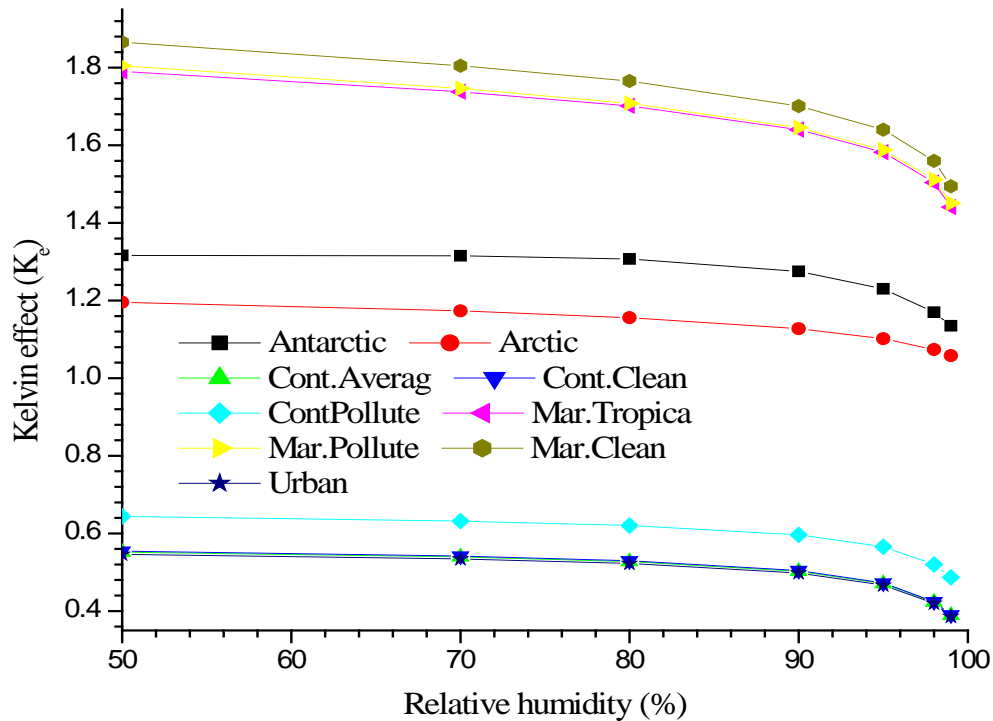


Figure 3.4c Kelvin Effect (mass mix ratio) against RH using eq. (9)

### 3.5 SATURATION RATIO (S)

The saturation ratio,  $S$ , of the aerosol model types are calculated using eq. (4). The following are the graphs of saturation ratio against RH.

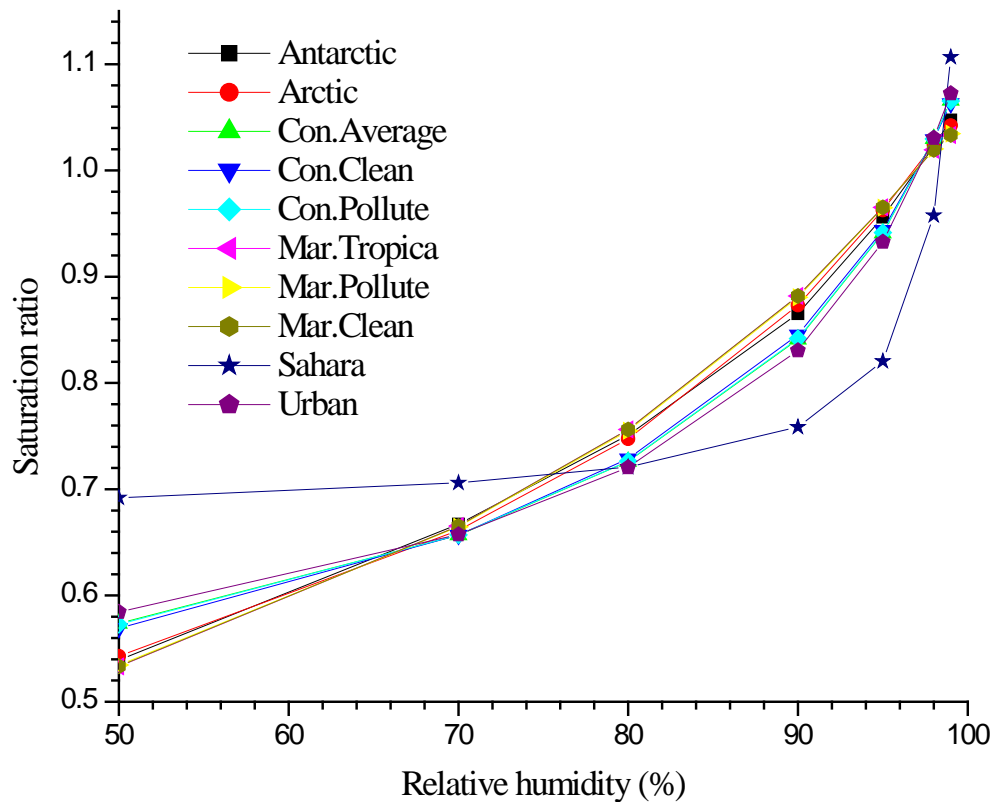
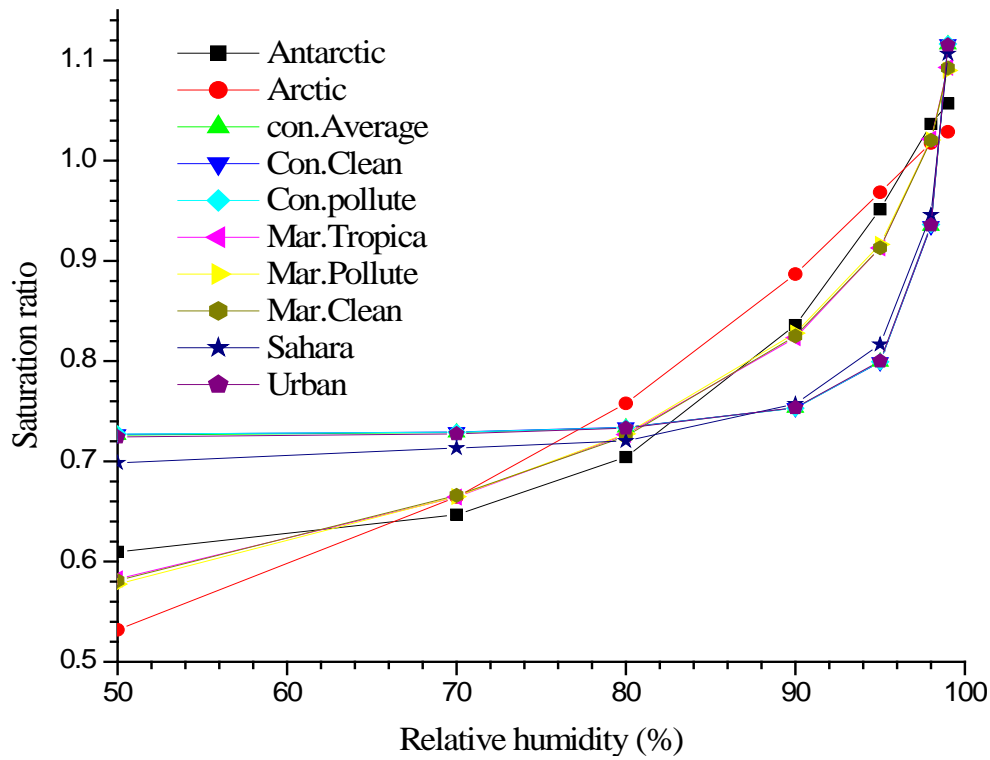
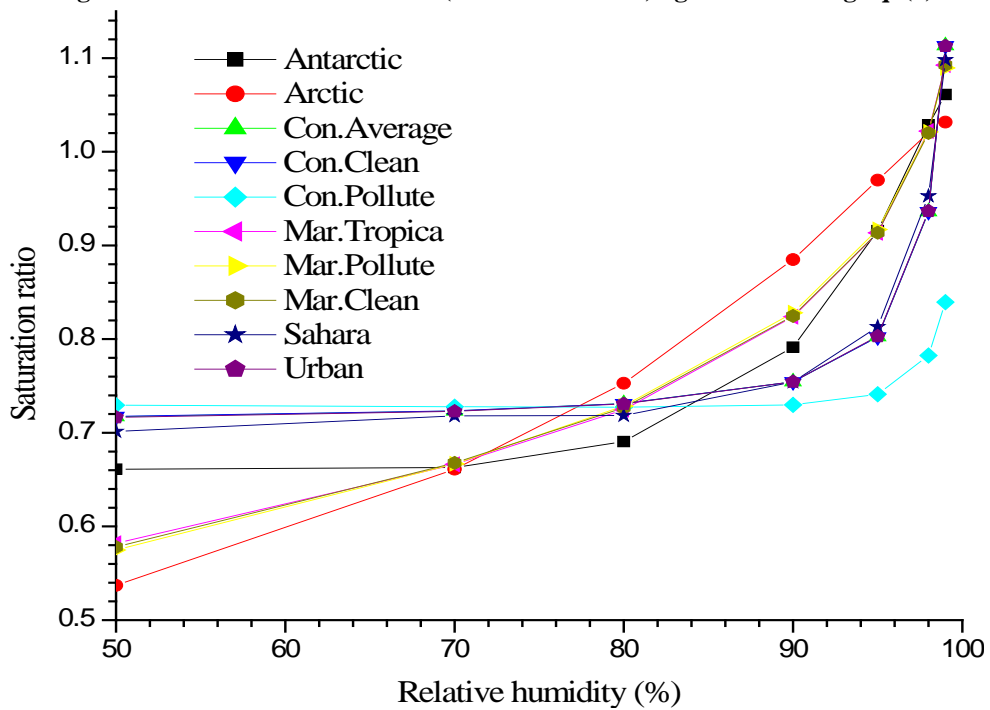


Figure 3.5a Saturation Ratio (number mix ratio) against RH using eq. (4)



**Figure 3.5b** Saturation Ratio (volume mix ratio) against RH using eq. (4)



**Figure 3.5c** Saturation Ratio (mass mix ratio) against RH using eq. (4)

3.6 Regression Analysis of Eq. (7)

From the regression analysis of Eq. (7) using the effective radii the calculated parameters A (Kelvin radii) and B (Bulk hygroscopicity factors) for all aerosol models are given below.

**Table 3.1a. Result of regression analysis of eq. (7) using the number mix ratio**

Aerosol Model	R squared	Significance F	A	P-value (A)	B	P-value (B)
Antarctic	0.972297	0.000497	0.053233	0.030835	-0.00705	0.000762
Arctic	0.969627	0.000598	0.011411	0.060082	-0.00011	0.001151
Continental Average	0.933104	0.002942	0.018293	0.046012	-9.10E-05	0.004664
Continental Clean	0.939013	0.00244	0.022165	0.043431	-0.00018	0.003841
Continental Polluted	0.934255	0.002841	0.015945	0.045431	-6.10E-05	0.004495
Maritime Tropical	0.979281	0.000277	0.033865	0.055035	-0.00459	0.000522
Maritime Polluted	0.977939	0.000314	0.018286	0.055487	-6.60E-04	0.000594
Maritime Clean	0.979171	0.00028	0.031613	0.05511	-0.00371	0.000528
Sahara	0.731737	0.051428	1.712919	0.080136	-0.084	0.07439
Urban	0.918251	0.00442	0.015732	0.051801	-4.30E-05	0.007077

**Table 3.1b Result of regression analysis of eq. (7) using the volume mix ratio**

Aerosol Model	R squared	Significance F	A	P-value (A)	B	P-value (B)
Antarctic	0.888709	0.008292	0.08741	0.230889	-0.02877	0.023721
Arctic	0.980669	0.000241	0.096982	0.071658	-0.15085	0.0005
Continental Average	0.662749	0.083703	-0.31584	0.032508	0.045547	0.065893
Continental Clean	0.661153	0.084555	-0.31616	0.032686	0.046059	0.066166
Continental Polluted	0.661029	0.084622	-0.27719	0.032462	0.03112	0.065497
Maritime Tropical	0.916052	0.004666	0.868893	0.031727	-3.70563	0.006399
Maritime Polluted	0.92314	0.0039	0.903454	0.025835	-4.0356	0.005094
Maritime Clean	0.917835	0.004466	0.983164	0.026847	-4.5716	0.005844
Sahara	0.717813	0.057242	-7.52069	0.063588	33.88249	0.075589
Urban	0.66658	0.081678	-0.31101	0.032119	0.04257	0.065269

**Table 3.1c Result of regression analysis of eq. (7) using the mass mix ratio**

Aerosol Models	R squared	Significance F	A	P-value (A)	B	P-value (B)
Antarctic	0.809861	0.025003	0.105974	0.341703	-0.03955	0.073584
Arctic	0.976038	0.000371	0.10311	0.084664	-0.15406	0.000823
Continental Average	0.680441	0.074584	-0.41129	0.032098	0.086766	0.064907

Continental Clean	0.679839	0.074885	-0.41174	0.032067	0.087687	0.064912
Continental Polluted	0.677036	0.076293	-0.35671	0.031799	0.059058	0.064615
Maritime Tropical	0.916581	0.004606	0.865396	0.031473	-3.68395	0.006308
Maritime Polluted	0.926023	0.003608	0.894618	0.024169	-3.97767	0.004648
Maritime Clean	0.921135	0.004109	0.980304	0.024741	-4.54907	0.005282
Sahara	0.711807	0.059857	-17.5557	0.078646	85.33011	0.084574
Urban	0.681981	0.073819	-0.4046	0.032085	0.081247	0.064719

3.7 Regression Analysis of Eq. (13)

Below are the results of the polynomial coefficients a, b and c of eq. (13) using multiple regression analysis with excel.

**Table 3.2a result of regression analysis of Eq. (13) using number mix ratio**

Aerosol Model	R squared	Significance F	a	P-value (a)	b	P-value (b)	c	P-value (c)
Antarctic	1.000000	3.55E-10	2.258894	3.03E-06	1.155791	1.66E-03	-1.03521	4.25E-04
Arctic	0.998979	3.60E-05	-0.44874	0.12032	2.115164	0.019178	-1.57617	0.009503
Continental Average	0.999984	6.95E-08	-0.20779	0.086153	2.942578	0.000395	-1.59061	0.001161
Continental Clean	0.999987	5.36E-08	-0.1696	0.396998	5.353031	0.000488	-2.86942	0.00139
Continental Polluted	0.999985	6.17E-08	-0.12856	0.099608	1.964976	0.000366	-1.0623	0.001063
Maritime Tropical	0.998721	5.05E-05	-2.22403	0.177093	10.2551	0.034009	-7.63885	0.016339
Maritime Polluted	0.998624	5.63E-05	-0.96965	0.162632	4.418218	0.03126	-3.28989	0.015095
Maritime Clean	0.998671	5.34E-05	-2.24926	0.174163	10.30879	0.033771	-7.67686	0.016242
Sahara	0.799435	1.35E-02	16758.88	0.002737	0	NA	0	NA
Urban	0.999975	1.38E-07	-0.2257	0.009318	1.705166	0.000316	-0.94508	0.000984

**Table 3.2b Result of regression analysis of Eq. (13) using volume mix ratio.**

Aerosol Model	R squared	Significance F	a	P-value (a)	b	P-value (b)	c	P-value (c)
Antarctic	0.999821	2.63E-06	-2.42427	0.11077	16.65941	0.005117	-12.6153	0.002462
Arctic	0.999996	9.93E-09	1.513417	0.013533	3.365144	0.016134	-2.77939	0.004772
Continental Average	0.997793	0.000114	3.148554	0.030978	-1.23197	0.349591	-1.21421	0.019165

Continental Clean	0.997756	0.000117	3.157237	0.030789	-1.25196	0.345211	-1.22135	0.019461
Continental Polluted	0.997832	0.000111	3.066829	0.031081	-1.15892	0.368995	-1.25533	0.016739
Maritime Tropical	0.999956	3.27E-07	12.89818	0.008075	-56.6944	0.003283	110.7113	0.000121
Maritime Polluted	0.999966	2.14E-07	21.3911	0.000671	-93.9456	0.000267	147.3837	2.25E-05
Maritime Clean	0.999973	1.55E-07	22.03662	0.000561	-100.822	0.000214	169.061	1.55E-05
Sahara	0.999093	3.01E-05	0.848412	0.138606	0.015413	0.664764	-0.00289	0.006445
Urban	0.997908	1.06E-04	3.122777	0.031067	-1.17733	0.360297	-1.19697	0.018055

**Table 3.2c Result of regression analysis of Eq. (13) using mass mix ratio**

Aerosol Model	R squared	Significance F	a	P-value (a)	b	P-value (b)	c	P-value (c)
Antarctic	0.999076	3.10E-05	-7.09648	0.080552	30.46983	0.01909	-21.2985	0.014383
Arctic	0.999996	7.71E-09	1.212138	0.020272	4.224447	0.005231	-3.29362	0.001804
Continental Average	0.99852	6.28E-05	3.907586	0.013857	-1.87589	0.142423	-0.9004	0.025742
Continental Clean	0.998525	6.25E-05	3.903243	0.013686	-1.87948	0.141688	-0.90922	0.025241
Continental Polluted	0.999116	2.90E-05	-6.31507	0.014498	15.6516	0.002324	-8.92964	0.000415
Maritime Tropical	0.999976	1.29E-07	14.58893	0.00165	-63.1731	0.000673	116.0725	2.93E-05
Maritime polluted	0.999978	1.13E-07	22.18538	0.000248	-96.6615	9.96E-05	148.3258	8.92E-06
Maritime Clean	0.999965	2.27E-07	21.23913	0.001033	-97.6174	0.000388	165.4878	2.69E-05
Sahara	0.999889	1.29E-06	0.144825	0.163241	0.000331	0.010656	-2.50E-07	7.04E-05
Urban	0.998583	5.89E-05	3.863578	0.01375	-1.81111	0.146171	-0.8949	0.023748

#### IV. DISCUSSIONS

##### 4.1 Effective Radius

The effective radius of aerosols is dependent on the composition of such aerosols, its hygroscopic nature and relative humidity. The effective radius (Figure 3.1a) of all aerosol models increases with increase in relative humidity. All aerosol models except the Maritimes and the Antarctic model only shows appreciable increase in their effective radius at relative humidity > 90%. Both effective radii (Figure 3.1b and figure 3.1c) curves are of the same pattern with difference only in their values. This is so because of the relation between mass and volume i.e. mass is directly proportional to volume. In both cases all the Continentals and Urban aerosols decreases with increase in relative humidity

while the remaining aerosol models increases with increase in relative humidity.

##### 4.2 Effective Growth Factor

This is the hygroscopic growth factor of aerosols. It is dependent on the hygroscopicity of the aerosols' composition, effective radius and relative humidity. In figure 3.2a, the effective growth factor of Antarctic aerosol has the highest value and is highly sensitive to RH than the other aerosols while the Urban aerosol model has the lowest values and less sensitive to RH. In the other two cases (figure 3.2b and figure 3.2c), the Maritime models possesses the highest value and more sensitive to RH than the other aerosol models while the Sahara has the lowest values and is less sensitive to RH.

#### 4.3 Water Activity

The water activity of aerosols is dependent on the effective radius and % water soluble of aerosols. The water activity (figure 3.3a) of all aerosol models are sensitive to RH, they increase with increase in RH (increases exponentially). The Sahara aerosol has the lowest value of  $a_w$ , while the Maritimes have the highest values of  $a_w$ . In the other two cases (figure 3.3b) and (figure 3.3c) the curves have same behavioural patterns. The aerosol models show observable dependency on RH at 90% RH and above. The Maritimes, Sahara and Urban show great sensitivity at RH > 90% while the remaining aerosol models are slightly sensitive at RH > 90%.

#### 4.4 Kelvin Effect

The Kelvin effect of aerosol is affected by the hygroscopic nature of the aerosol composition and its effective radius. The Kelvin effect (figure 3.4a) of all the aerosol models decreases with an increase in RH. The Maritime models have the lowest  $K_e$  values while the Sahara model has the lowest  $K_e$  values. All the aerosol models show high sensitivity to RH at RH > 90%. The other two cases (figure 4.4b and figure 3.4c) have similar curve patterns (also decreases as RH increases and high sensitivity to RH at 95% and above). The Maritime models show dependency on RH at all RH but the other aerosol models only show an observable dependency at RH > 80%.

#### 4.5 Saturation Ratio

The saturation ratio is the ratio of the vapor pressure of water over the drop to the saturation vapor pressure of water at that temperature and is equivalent to the product of water activity and Kelvin effect. It can be equated to the fractional ambient relative humidity if the droplet is in equilibrium with its surrounding. All the aerosol models are highly sensitive to RH (i.e. increase with increase in RH) except Sahara and Urban models (in figure 3.5a) and Sahara, Urban and the Continentals (in figure 3.4b and figure 3.5c) who only show a sharp increase in their saturation ratio at RH > 90%.

#### 4.6 Table 3.1a, 3.1b and 3.1c.

The significance  $F$  determines which of the mixing ratios is best suitable for determining the parameters if significance  $F < 0.05$  the mixing ratio is better but when it is greater than 0.05, the method is not suitable. The P-value determines the contribution of parameters in an equation. If P-value < 0.05, the parameters contributes significantly in the equation but, if P-value  $\geq 0.05$  the contribution of the parameters to the equation is insignificant. Also, from the values of Kelvin radii and Bulk hygroscopicity, the positive values are for concave curvature while negative values are for convex curvature.

From table 3.1a, 3.1b and 3.1c: (1) Antarctic model, both A and B of the number mix ratio contributed significantly to the equation. For the volume mix ratio, B contributed significantly while contribution of A to the equation is insignificant. Finally, for mass mix ratio, both A and B has insignificant contribution to the equation. Due to the significant  $F$ , all three mixing ratios are the suitable for determining A and B; (2) Arctic model, only B contributed to the equation in all three ways. Due to the significant  $F$ , all three mixing ratios are the suitable for determining A and B; (3) all Continental aerosol models, both A and B contributed

significantly to the equation in number mix ratio but, only A contributed to the equation in both volume and mass mix ratio. The number mix ratio is best suitable for determining A and B; (4) for all Maritime aerosol models, only B contributed significantly to the equation in number mix ratio while A and B contributed significantly to volume and mass mix ratio. All three mixing ratios are suitable for determining A and B; (5) Sahara model, contribution of A and B are insignificant in all three methods. All three mixing ratios may be used to determine A and B; finally (6) Urban model, only B contributed significantly to the equation in number mix ratio while, for both volume and mass mix ratio, only A has a significant contribution. The number mix ratio is preferable for determining A and B.

#### 4.7 Table 3.2a, 3.2b and 3.2c

From table 3.2a, 3.2b and 3.2c: (1) Antarctic model, a, b and c of number mix ratio contributed significantly to the equation, for both volume and mass mix ratio only b and c has significant contribution in the equation. All three mixing ratios are suitable for determining A and B; (2) Arctic model, for number mix ratio, only b and c contributed significantly to the equation, while in a, b and c contributed significantly to the equation in both volume and mass mix ratio. All three mixing ratios are suitable for determining A and B; (3) Continental average and Continental clean model, for number mix ratio, only b and c contributed significantly to the equation while only a and c contributed significantly to the equation for both volume and mass mix ratios. All three mixing ratios are suitable for determining A and B; (4) Continental polluted, only b and c has significant contribution in the equation for number mix ratio while, a and c contributed significantly to the equation for volume mix ratio but, for mass mix ratio, all the polynomial coefficient a, b and c contributed significantly to the equation. All three mixing ratios are suitable for determining A and B; (5) Maritimes models, in number mix ratio of all Maritimes models, only b and c contributed significantly to the equation while for both volume and mass mix ratio, all the polynomial coefficients contributed significantly to the equation. All three mixing ratios are suitable for determining A and B; (6) Sahara model, only a contributed significantly to the equation for number mix ratio while only c has a significant contribution to the equation in volume mix ratio but, both b and c contributed significantly to the equation for mass mix ratio. All three mixing ratios are suitable for determining A and B; lastly (7) Urban model, all the polynomial coefficients contributed significantly to the equation for number mix ratio, while for both volume and mass mix ratio, only a and c contributed significantly to the equation. All three mixing ratios are suitable for determining A and B.

## V. SUMMARY

The hygroscopicity data of aerosols were obtained from the microphysical properties of aerosols using Optical Properties of Aerosols and Clouds (OPAC). With these hygroscopic data, we were able to calculate the effective radii, effective growth factor, water activity, Kelvin effect and saturation ratio of ten different aerosol models using three mixing ratios: (1) number mix ratio; (2) volume mix ratio; and (3) mass mix ratio. Method (2) and (3) gives similar results because of the relationship between mass and



volume (both are directly proportional to each other). In all cases, the aerosols show smooth water uptake curve with no deliquescence or efflorescence behavior.

The effective radius of each aerosol is dependent on the compositions of such aerosol, its hygroscopic nature and relative humidity. The water activity is dependent on the effective radius and % water soluble of the aerosol. The Kelvin effect is affected by the hygroscopic nature of the aerosol compositions and its effective radius. The effective hygroscopic growth factor is dependent on the hygroscopicity of the aerosol compositions, effective radius and relative humidity. Both water activity and Kelvin effect were used to determine the saturation ratios.

It was observed that the water activity values for all our aerosol models except the Urban were less than RH for number mix ratio, while the Maritimes, Antarctic and Arctic models are less than RH for volume mix ratio. And the Maritimes and Arctic models are less than RH for the mass mix ratio. The values of the Kelvin effect of all atmospheric aerosol models except the urban model, decreases with increase in RH and the Sahara model has a very high magnitude for the number mix ratio. While for the volume and mass mix ratios the Kelvin effects of all models decreases with increase in RH with very low magnitude for the Sahara model.

## VI. CONCLUSION

From the analysis of our results, the magnitudes and consequences of both Kelvin effect and water activity are dependent on the aerosol models hygroscopicity i.e. the solute compositions and how they take up water which is due to the presence of water soluble. Some authors state that solution water activity is equal to RH when solution is in equilibrium with the vapor and Kelvin effect is negligible. But from the magnitude of our calculated water activities, we can state that at equilibrium solution with water vapor the Kelvin effects are significant.

From our observation some aerosol component like soot does not take up water thereby, contributing to global warming. Most literatures use the experimental methods in determining water activities of known constituents of atmospheric aerosol particles but we used the regression analysis to determined water activity of real aerosol particles. One clear advantage of this method is that for the mixed particles, whose components are only slightly soluble, their contributions to water activities are captured in the hygroscopic data. And we can determine water activities of aerosols of unknown constituents also, using this method.

## REFERENCES

[1] Akpootu, D.O., Gana, N.N. (2013): The Effect of Relative Humidity on the Hygroscopic Growth Factor and Bulk Hygroscopicity of water Soluble Aerosols. *IJES*, 2(11), 48-57.

[2] Asa-Awuku, A., Sullivan, A. P., Hennigan, C. J., Weber, R. J., and Nenes, A. (2008): Investigation of molar volume and surfactant characteristics of water-soluble organic compounds in biomass burning aerosol, *Atmospheric Chemistry and Physics*, 8, 799–812. <http://www.atmos-chem-phys.net/8/799/2008/>.

[3] Brechtel, F. J. and Kreidenweis, S. M. (2000a): Predicting particle critical supersaturation from hygroscopic growth measurements in the humidified TDMA, part I: Theory and sensitivity studies, *J. Atmos. Sci.*, 57(12), 1854-1871.

[4] Brechtel, F. J. and Kreidenweis, S. M. (2000b): Predicting particle critical supersaturation from hygroscopic growth measurements in the humidified

TDMA, part II: Laboratory and ambient studies, *J. Atmos. Sci.*, 57(12), 1872-1887.

[5] Charlson, R. J., S. E. Schwartz, J. M. Hales, R. D. Cess, J. A. Coakley, Jr., J. E. Hansen, and D. J. Hofmann, (1992): Climate Forcing by Anthropogenic Aerosol. *Science*, 255, 423-430.

[6] Cheng, Y.F., Wiedensohler, A., Eichler, H., Heintzenberg, J., Tesche, M., Ansmann, A., Wendisch, M., Su, H., Althausen, D., Herrmann, H., Gnauk, T., Brüggemann, E., Hu, M. and Zhang, Y.H. (2008): Relative Humidity Dependence of Aerosol Optical Properties and Direct Radiative Forcing in the Surface Boundary Layer at Xinken in Pearl River Delta of China: An observation Based Numerical Study. *Atmos. Environ.*, 42, 6373-6397. <http://dx.doi.org/10.1016/j.atmosenv.2008.04.009>

[7] Cohen, M. D., Flagan, R. C., and Seinfeld, J. H. (1987a): *Journal of Physics and Chemistry* 91:4563-4574.

[8] Dinar, E., Taraniuk, I., Graber, E. R., Anttila, T., Mentel, T. F., and Rudich, Y. (2007): Hygroscopic growth of atmospheric and model humic-like substances, *Journal of Geophysical Research Atmospheres*, 112, 1–13, doi: 10.1029/2006JD007442, 2007.

[9] Dubovik, O., Holben, B. N., Eck, T. F., Smirnov, A., Kaufman, Y. J., King, M. D., Tanré, D. and Slutsker, I. (2001): Variability of Absorption and Optical Properties of Key Aerosol Types Observed in Worldwide Locations, *J. of the Atmos. Sci.*

[10] Facchini, M., Mircea, S. Fuzzi, and R. J. Charlson, (1999): Cloud albedo enhancement by surface-active organic solutes in growing droplets. *Nature*, 401, 257–259. doi:10.1038/45758.

[11] Facchini, M. C., Decesari, S., Mircea, M., Fuzzi, S., and Loggion, G. (2000): Surface tension of atmospheric wet aerosol and cloud/fog droplets in relation to their organic carbon content and chemical composition, *Atmos. Environ.*, 34(28), 4853–4857.

[12] Gysel, M., Weingartner, E. and Baltensperger, U. (2002): hygroscopicity of aerosol particles at low temperature. 2. Theoretical and experimental hygroscopic properties of laboratory generated aerosols. *Environ. Sci. Technol.*, 36, 63-68.

[13] Heintzenberg, J., R. J. Charlson, A. D. Clarke, C. Liou, V. Ramaswamy, K. P. Shine, M. Wendisch, and G. Helas, 1997: Measurements and modeling of aerosol single scattering albedo: progress, problems and prospects. *Beitr. Phys. Atmos.*, 70, 249-263.

[14] Hess, M., P. Koepke, and I. Schult (1998), Optical properties of aerosols and clouds: The software package OPAC, *Bull. Am. Meteorol. Soc.*, 79, 831–844.

[15] Köhler, H. (1936): The Nucleus In and the Growth of Hygroscopic Droplets, *Trans. Faraday Soc.*, 32, 1152- 1161.

[16] Kreidenweis, S. M., Koehler, K., DeMott, P. J., Prenni, A. J., Carrico, C., and Ervens, B. (2005): Water Activity and Activation Diameters from Hygroscopicity data – Part I: Theory and application to inorganic salts, *Atmos. Chem. Phys.*, 5, 1357–1370. <http://www.atmos-chem-phys.net/5/1357/2005/>.

[17] Kumar, P. P., Broekhuizen, K., and Abbatt, J. P. D. (2003): Organic acids as cloud condensation nuclei: Laboratory studies of highly soluble and insoluble species, *Atmos. Chem. Phys.*, 3, 509–520, SRef-ID: 1680-7324/acp/2003-3-509.

[18] Lance, S., A. Nenes, and T. A. Rissman (2004): Chemical and dynamical effects on cloud droplet number: Implications for estimates of the aerosol indirect effect, *Journal of Geophysical Research: Atmospheres*, 109, D22208. doi:10.1029/2004JD004596.

[19] Lewis, E.R., (2006): The Effect of Surface Tension (Kelvin Effect) on the Equilibrium Radius of a Hygroscopic Aqueous Aerosol Particle. *Journal Aerosol Science*, 37, 1605 – 1617.

[20] McDonald, J. E. (1953): Erroneous cloud-physics applications of Raoult's law, *Journal of Meteorology*, 10, 68–70.

[21] Meyer, N.K., Duplissy, J., Gysel, M., Metzger, A., Dommen, J., Weingartner, E., Alfarra, M.R., Prevot, A.S.H., Fletcher, C., Good, N., McFiggans, G., Jonsson, A.M., Hallquist, M., Baltensperger, U. and Ristovski, Z.D. (2009): Analysis of the Hygroscopic and Volatile Properties of Ammonium Sulphate Seeded and Unseeded SOA Particles. *Atmospheric Chemistry and Physics*, 9, 721-732. <http://dx.doi.org/10.5194/acp-9-721-2009>.

[22] Mochida M., Kuwata M., Miyakawa T., Takegawa N., Kawamura K., and Kondo Y. (2006): Relationship Between Hygroscopicity and Cloud Condensation Nuclei Activity for Urban Aerosols in Tokyo. *Journal of Geophysical Research*, 111, D23204, doi:10.1029/2005JD006980.

- [23] Nenes, A., Ghan, S., Abdul-Razzak, H., Chuang, P.Y. and Seinfeld J.H. (2001): Kinetic Limitations on Cloud Droplet Formation and Impact on Cloud Albedo, *Tellus*, 53B, 133-149.
- [24] Nenes, A., R. J. Charlson, M. C. Facchini, M. Kulmala, A. Laaksonen, and J. H. Seinfeld (2002): Can Chemical Effects on Cloud Droplet Number Rival the First Indirect Effect?, *Geophysical Research Letters*, 29(17), 1848, doi:10.1029/2002GL015295.
- [25] Orr Jr., C., Hurd, F.K. and Corbett, W.J. (1958): Aerosol Size and Relative Humidity. *Journal of Colloid Science*, 13, 472-482. [http://dx.doi.org/10.1016/0095-8522\(58\)90055-2](http://dx.doi.org/10.1016/0095-8522(58)90055-2).
- [26] Ovadnevaite, J., D. Ceburnis, G. Martucci, J. Bialek, C. Monahan, M. Rinaldi, M. C. Facchini, H. Berresheim, D. R. Worsnop, and C. O'Dowd (2011): Primary Marine Organic Aerosol, A Dichotomy of Low Hygroscopicity and High CCN Activity, *Geophysical Research Letters*, 38, L21806, doi:10.1029/2011GL048869.
- [27] Prenni, A. J., Demott, P. J., Kreidenweis, S. M., Sherman, E. E., et. al. (2001): The Effects of Low Molecular Weight Dicarboxylic Acids on Cloud Formation, *J. Phys. Chem. A*, 105(50), 11240-11248.
- [28] Pruppacher, H. R. and Klett, J. D. (1997): *Microphysics of Clouds and Precipitation*, Dordrecht, Kluwer Academic Publishers.
- [29] Rader, D. J. and McMurry, P. H. (1986): Application of the Tandem Differential Mobility Analyzer to Studies of Droplet Growth or Evaporation, *J. Aerosol Sci.*, 17(5), 771-787.
- [30] Randles, C.A., Russell, L.M. and Ramaswamy, V. (2004): Hygroscopic and Optical Properties of Organic Sea Salt Aerosol and Consequences for Climate Forcing. *Geophysical Research Letters*, 31, Published Online <http://dx.doi.org/10.1029/2004GL020628>
- [31] Raymond, T.M. and Pandis, S.N. (2003): Formation of cloud droplets by multicomponent organic particles, *J. Geophys. Res.-A*, 108(D15), 4469-4476.
- [32] Seinfeld, J. H. and Pandis, S. N. (1998): *Atmospheric Chemistry and Physics: from air pollution to climate change*, John Wiley & Sons, INC.
- [33] Shulman, M.L., Jacobson, M.C., Carlson, R.J., Synovec, R.E., and Young, T.E. (1996): Dissolution behavior and surface tension effects of organic compounds in nucleating cloud droplets, *Geophys. Res. Lett.*, 23(3), 277-280.
- [34] Stokes, R.H. and Robinson, R.A. (1966): Interactions in aqueous nonelectrolyte solutions, I. Solute-solvent equilibria, *J. Phys. Chem.*, 70, 2126-2130.
- [35] Swietlicki, E., Hansson, H.C., Hameri, K., Svenningsson, B., Massling, A., McFiggans, G., McMurry, P.H., Petaja, T., Tunved, P., Gysel, M., Topping, D., Weingartner, E., Baltensperger, U., Rissler, J., Wiedensohler, A. and Kulmala, M. (2008): Hygroscopic Properties of Submicrometer Atmospheric Aerosol Particles Measured with H-TDMA Instruments in Various Environments: A Review. *Tellus B*, 60, 432-469. <http://dx.doi.org/10.3402/tellusb.v60i3.16936>
- [36] Sjogren, S., Gysel, M., Weingartner, E., Baltensperger, U., Cubison, M.J., Coe, H., Zardini, A.A., Marcolli, C., Krieger, U.K. and Peter, T. (2007): Hygroscopic Growth and Water Uptake Kinetics of Two-Phase Aerosol Particles Consisting of Ammonium Sulfate, Adipic and Humic Acid Mixtures. *Journal of Aerosol Science*, 38, 157-171. <http://dx.doi.org/10.1016/j.jaerosci.2006.11.005>
- [37] Stock, M., Cheng, Y.F., Birmili, W., Massling, A., Wehner, B., Müller, T., Leinert, S., Kalivitis, N., Mihalopoulos, N. and Wiedensohler, A. (2011): Hygroscopic Properties of Atmospheric Aerosol Particles over the Eastern Mediterranean: Implications for Regional Direct Radiative Forcing under Clean and Polluted Conditions. *Atmospheric Chemistry and Physics*, 11, 4251-4271. [www.atmos-chem-phys.net/11/4251/2011/](http://www.atmos-chem-phys.net/11/4251/2011/) <http://dx.doi.org/10.5194/acp-11-4251-2011>
- [38] Tang, I.N. (1976): Phase Transformation and Growth of Aerosol Particles Composed of Mixed Salts. *Journal of Aerosol Science*, 7, 361-371. [http://dx.doi.org/10.1016/0021-8502\(76\)90022-7](http://dx.doi.org/10.1016/0021-8502(76)90022-7).
- [39] Tang, I. N., and Munkelwitz, H. R. (1989). *J. Colloid Interface Sci.* 128:289-295.
- [40] Tang, I. N. and Munkelwitz, H. R. (1994): Water activities, densities, and refractive indices of aqueous sulfates and sodium nitrate droplets of atmospheric importance, *J. Geophys. Res.-A*, 99(D9), 18801-18808.
- [41] Tang, I. N., Tridico, A. C., and Fung, K. H. (1997): Thermodynamic and Optical Properties of Sea-salt Aerosols, *J. Geophys. Res.-A*, 102(D19), 23 269-23 275.
- [42] Tegen, I., A. A. Lacis and I. Fung, 1996: The influence on climate forcing of mineral aerosols from disturbed soils. *Nature*, 380, 419-422.
- [43] Thomson, S.W. (1871). On the equilibrium of vapour at a curved surface of liquid. *Philosophical Magazine*, 4, 448-452.
- [44]
- [45] Tijjani, B.I., Galadanci, G.S.M., Abubakar, A.I., Koki, F.S., Adamu, I.D., Nura, A.M., Saleh, M. and Uba, S. (2015): The Effect of Kelvin Effect on the Equilibrium Effective Radii and Hygroscopic Growth of Atmospheric Aerosols. *Journal of Natural Sciences Research*, 5, 22, 96-111.
- [46] Wise, M. E., Surratt, J. D., Curtis, D. B., Shilling, J. E., and Tolbert, M. A. (2003): Hygroscopic Growth of Ammonium Sulfate/dicarboxylic Acids, *J. Geophys. Res.-A*, 108(D20), 4638-4645.
- [47] Wright, H. L. (1936). The size of atmospheric nuclei: Some deductions from measurements of the number of charged and uncharged nuclei at Kew Observatory. *Proceedings of the Physical Society*, 48(5), 675-688.
- [48] Quinn, P. K., Bates, T. S., Baynard, T., Clarke, A. D., Onasch, T. B., Wang, W., Rood, M. J., Andrews, E., Allan, J., Carrico, C. M., Coffman, D. and Worsnop, D. (2005): Impact of particulate organic matter on the relative humidity dependence of light scattering: A simplified parameterization, *Geophys. Res. Lett.*, 32, art. no. L22809, doi:10.1029/2005GL024322.

#### AUTHORS

**First Author** – Ayinde Akeem Shola, MSc. Physics, Nigerian Institute for Oceanography and Marine Research, [ayindeas@niomr.gov.ng](mailto:ayindeas@niomr.gov.ng), [ayindeakeemshola@yahoo.com](mailto:ayindeakeemshola@yahoo.com)  
**Second Author** – Jimoh Morufat Motolani, MSc. Physics, [molaitanjimoh@gmail.com](mailto:molaitanjimoh@gmail.com)  
**Third Author** – Aibinu Abdulmumin Taiye, MSc. Physics, [t\\_aibinung@yahoo.com](mailto:t_aibinung@yahoo.com)

**Correspondence Author** – Ayinde Akeem Shola, [ayindeas@niomr.gov.ng](mailto:ayindeas@niomr.gov.ng), [ayindeakeemshola@yahoo.com](mailto:ayindeakeemshola@yahoo.com), [ayindeakeemshola@gmail.com](mailto:ayindeakeemshola@gmail.com), +2348081609213