

Effects of Aerosol Concentration, Relative Humidity, and Non-sphericity on Optical Properties of North African Desert Aerosols: OPAC 4.0 Simulations Validating with MODIS Satellite

F. Shuaibu^{1*}, B. I. Tijjani² and U. M. Gana²

¹Department of Physics, RMK, C.A.R.S, Tudun Wada, Kano State, Nigeria.

²Department of Physics, Bayero University Kano, Kano State, Nigeria.

*Corresponding Author

Fatima Shuaibu

Email:teemaashu@gmail.com

Article History

Received: 03.03.2026

Accepted: 08.04.2026

Published: 30.04.2026

Abstract: This study investigates the effects of varying aerosol concentrations, relative humidity (RH), phase functions, effective polarizability, and Ångström exponent (alpha) on North African desert aerosols, comparing OPAC 4.0 simulations with MODIS satellite data. Five model mixtures were analyzed for Mineral Accumulation Non-spherical (MIAN), Mineral Coarse Non-spherical (MICN), Mineral Nucleation Non-spherical (MINN), and water-soluble (WASO) components across concentration ranges. At 0% and 50% RH, OPAC 4.0 simulations showed that RH consistently increases alpha by +0.04 to +0.06 across all components due to hygroscopic growth. MICN and MINN models exhibited excellent internal consistency ($R^2 > 0.99$), with alpha values ranging from 0.086 to 0.133 (MICN) and 0.098 to 0.172 (MINN). WASO models produced alpha between 0.097 to 0.189 showing the strongest hygroscopic response. MIAN models showed variable alpha (-0.036 to 0.077), with Model 5 (alpha $\approx$ 0.04 to 0.05) now consistent with accumulation-mode dust. The turbidity coefficient (beta) remained stable for most OPAC models (0.127 to 0.301). Phase function analysis revealed two distinct angular scattering patterns: strong forward peaks for coarse dust and weaker, broader peaks for finer particles. Effective polarizability increased with concentration and RH. Validation using MODIS Deep Blue data (2000 to 2010) over ten North African locations yielded predominantly negative alpha values at eight sites (mean -0.284 to -0.086), confirming satellite detection of coarse-mode mineral dust. However, MODIS beta was quantitatively unreliable (R^2 0.002 to 0.52, unphysical negative and extreme values), highlighting the challenge of bright desert surfaces. Positive alpha at Tamanrasset (+0.195) indicates mixed aerosols (dust + biomass burning). These findings provide a theoretical baseline (OPAC 4.0) and identify specific retrieval limitations (MODIS), improving the interpretation of satellite aerosol products over arid regions.

Keywords: Ångström exponent, Effective Polarizability, MIAN, MICN, MINN, MODIS Satellite, and Phase functions, Relative Humidity (RH), Turbidity coefficient, WASO.

Cite this article:

Shuaibu, F., Tijjani, B. I. and Gana, U. M., (2026). Effects of Aerosol Concentration, Relative Humidity, and Non-sphericity on Optical Properties of North African Desert Aerosols: OPAC 4.0 Simulations Validating with MODIS Satellite. *ISAR Journal of Science and Technology*, 4(4), 29-44.

1 Introduction

Desert aerosols, mainly mineral dust, significantly influence Earth's climate, atmospheric chemistry, and public health. These particles are typically non-spherical and hygroscopic. Increased relative humidity (RH) causes water uptake, altering particle size, shape, and density; it also enhances coagulation and gravitational settling, affecting dust accumulation (Mallios *et al.*, 2020). Under humid conditions, non-spherical aerosols change their light-scattering behaviour, which impacts satellite remote sensing retrievals (Kok *et al.*, 2017). Moisture absorption modifies the aerosol shape factor, influencing aerodynamic properties and long-range transport (Chen *et al.*, 2021).

Desert aerosols are classified into three modes, Nucleation mode ($<0.1 \mu\text{m}$), formed by gas-to-particle conversion (Zhang *et al.*, 2005), Accumulation mode (0.1 to $1 \mu\text{m}$), consisting of aged dust enriched with secondary inorganic aerosols (e.g., sulfate, nitrate) that increase hygroscopicity and water solubility (Andreae & Rosenfeld, 2008; Favez *et al.*, 2008) and Coarse mode ($>2.5 \mu\text{m}$), mainly primary minerals like quartz, feldspars, and clays.

Water-soluble fractions arise from reactions with acidic gases (HNO_3 , SO_2) or atmospheric aging, enhancing solubility and cloud-forming potential (Li *et al.*, 2012). Mixing soluble and insoluble components affects toxicity, hygroscopic growth, and cloud microphysics, making detailed characterisation essential.

Satellite retrieval of aerosol properties over arid regions is challenging due to high surface albedo and complex aerosol optics. Accurate forward modelling of top-of-atmosphere radiance is required. Optical parameters used in this study are Ångström exponent (alpha) a qualitative indicator of particle size from spectral AOD measurements, Phase function $P(\theta)$ describing the angular distribution of scattered light measured by satellites, effective polarizability describing a measure of how easily a particle's electron cloud is distorted by an electromagnetic wave directly affecting scattering and absorption.

Validation involves comparing satellite-retrieved alpha with reference values from OPAC 4.0. Discrepancies reveal errors in the assumed aerosol model, helping satellites correctly distinguish aerosol types (e.g., smoke vs. dust), which is critical for climate studies (King *et al.*, 1999; Levy *et al.*, 2010).

1.1 Theoretical Background

Ångström Exponent (α_f)

The exponent α_f describes the spectral dependence of AOD and is a qualitative indicator of aerosol particle size distribution (Ångström, 1964), is given by

$$\tau(\lambda) = \beta \lambda^{-\alpha_f} \quad (1)$$

where τ is AOD and β is the turbidity coefficient.. The spectral AOD and derived α_f is a primary products of the satellite sensor (MODIS). Values near or below zero signify a dominance of coarse-mode particles ($>1 \mu\text{m}$), typical of pure mineral dust. Higher positive values ($\alpha_f > 0.5$) indicate a greater contribution from fine-mode aerosols ($<0.5 \mu\text{m}$), such as those produced by combustion (Eck *et al.*, 2010),

$$\ln \tau(\lambda) = \ln(\beta) - \alpha_f \ln(\lambda) \quad (2)$$

1.2 Phase Function and Effective Polarizability

The phase function describes the angular distribution of scattered light. For non-spherical desert dust particles, the phase function exhibits distinct features compared to spheres (Dubovik *et al.*, 2006).

$$\frac{1}{2} \int_0^\pi \sin(\theta) P(\theta) d\theta = 1 \quad (3)$$

$P(\theta)$ in equation (3) is called the phase function and is normalized to 1 such that (Lindqvist *et al.*, 2014) θ is the scattering angle between the incident and scattered directions. For a given wavelength, it defines how much light is scattered into a specific angle θ compared to isotropic scattering.

Effective polarizability is a measure of how easily a particle's electron cloud is distorted by an electromagnetic wave directly affecting scattering and absorption.

$$\alpha_{\text{eff}} = \sum_{i=1}^n V_i \alpha_i \quad (4)$$

where α_{eff} is the effective polarizability of the mixtures, V_i is the volume mix ratio of the (i^{th}) aerosol component, α_i is the polarizability of the (i^{th}) aerosol component. (Liu & Daum, 2008)

2.0 Methodology

This section described the methods and computational techniques used both in OPAC 4.0 and MODIS satellite in examining the theoretical and empirical links between α_f and $P(\theta)$ for Ten North Africa countries across selected, representing diverse dust source types: Hyper-arid active dust basins, Arid desert regions, Coastal and transition zones, and High-altitude southern margin sites.

2.1 OPAC 4.0

OPAC 4.0 simulations were performed at visible range wavelengths (0.4 to $0.8 \mu\text{m}$) for five aerosol mixtures (Tables 1) at 0% and 50% RH Hess *et al.*, (1998). Phase functions were computed for scattering angles 0 to 5° . Regression analysis using the Ångström exponent power law (Equation 2) was performed in SPSS 22.0.

2.2 Table 1 OPAC 4.0 MODELS DESCRIPTION (Hess *et al.*, 2015)

Aerosol Type/Concentration	Model 1 (cm^{-3})	Model 2 (cm^{-3})	Model3 (cm^{-3})	Model 4(cm^{-3})	Model 5(cm^{-3})
MIAN	30.5	39.65	48.8	57.95	67.1
MICN	0.142	0.1846	0.2276	0.2706	0.3136
MINN	269.5	350.35	431.2	512.05	592.9
WASO	2000	2600	3200	3800	4400

2.3 MODIS SATELLITE

MODIS (Moderate Resolution Imaging Spectroradiometer) provides AOD at multiple wavelengths and the Ångström exponent

using the Deep Blue AOD retrievals (2000 to 2010) were obtained for ten North African locations. Statistical significance was assessed at $p < 0.05$.

2.3.1 Table 2 STUDY AREA

Countries	Locations
Niger, Agadaz	16.9918° N, 7.9856° E
Bodélé Depression Chad	17.0° N, 18.0° E
Dakhla, Morocco	23.7142° N, 15.9368° W
Erg Chebbi, Morocco	31.1471° N, 4.0106° W
Kufra, Libya	24.1667° N, 23.2696° E,
Murzuk, Libya	25.9150° N, 13.9184° E
Nouakchott, Mauritania	18.0735° N, 15.9582° W
Siwa Oasis, Egypt	29.2041° N, 25.5195° E
Tamanrasset Southern Algeria	22.7850° N, 5.5228° E
Timbuktu, Mali	16.7666° N, 3.0026° W

3.0 Results and Discussion

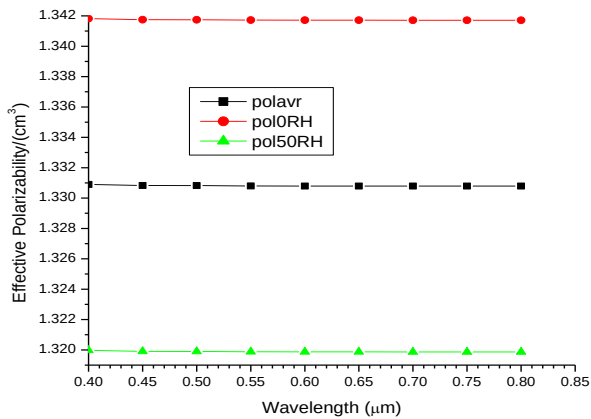


Fig 1a: Effective polarizability against wavelength at average 0% & 50%RH, MIAN model 1

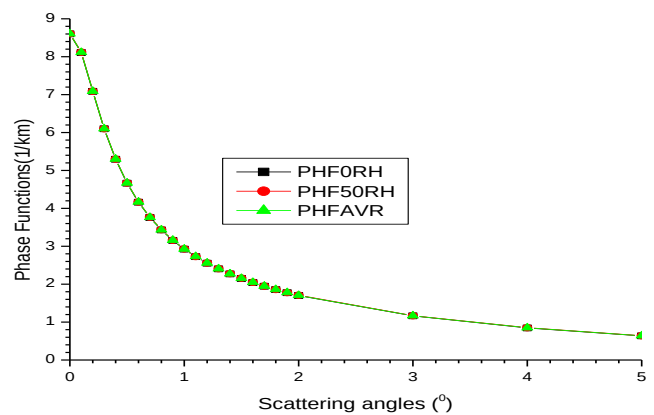


Fig 1b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MIAN model 1

Table 3a: Results of Regression analysis of model 1 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.976864	1.00E-06	0.040243	1.00E-06	0.161359	0.00E+00
50%	0.990258	0.00E+00	0.077327	0.00E+00	0.162628	0.00E+00
			Avr=0.058785		Avr=0.161994	

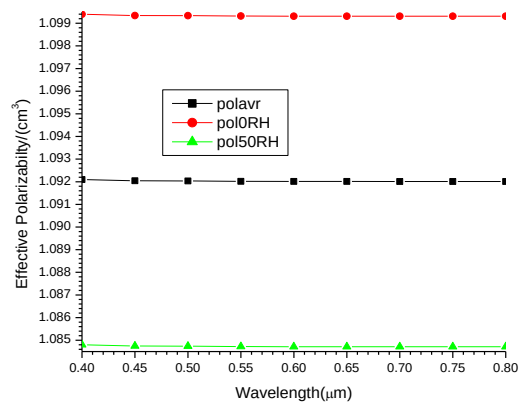


Fig 2a: Effective polarizability against wavelength at average 0% & 50%RH, MIAN model 2

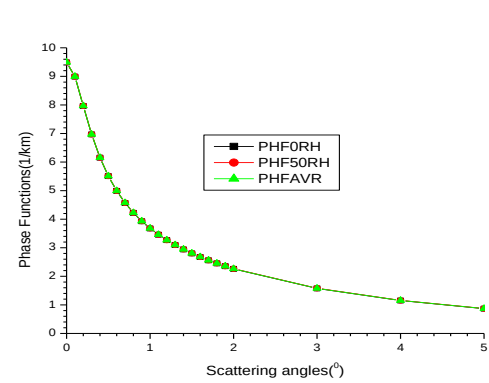


Fig 2b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MIAN model 2

Table 3b: Results of Regression analysis of model 2 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.570949	0.018529	0.00688	0.018529	0.195999	0.00E+00
50%	0.965053	0.000002	0.03875	0.000002	0.197217	0.00E+00
Avr			0.02282	Avr	0.196608	

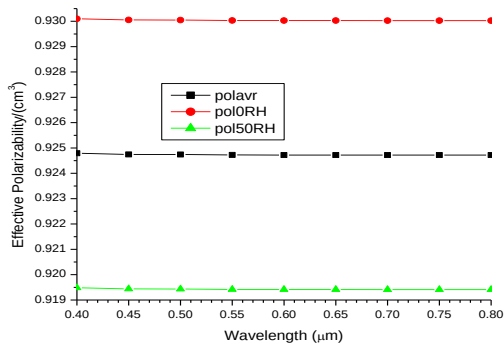


Fig 3a: Effective polarizability against wavelength at average 0% & 50%RH, 0° to 5° MIAN model 3

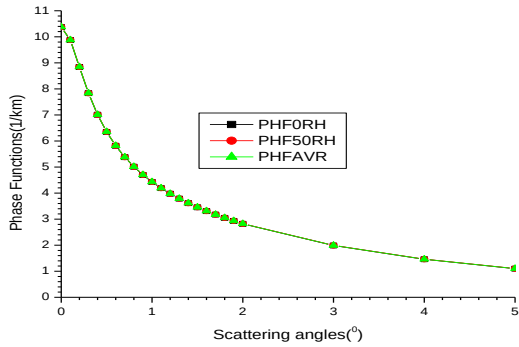


Fig 3b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MIAN model 3

Table 3c: Results of Regression analysis of model 3 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.916925	0.000050	0.017292	0.000050	0.230644	0.00E+00
50%	0.702951	0.004749	-0.010910	0.004749	0.231820	0.00E+00
			Avr=0.003194		Avr=0.231232	

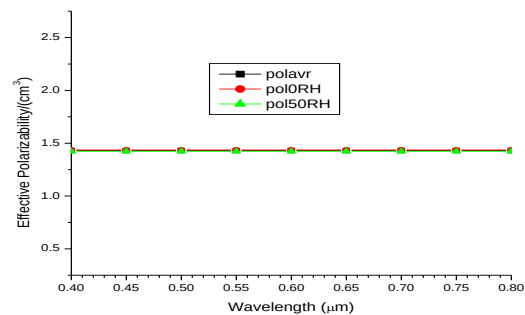


Fig 4a: Effective polarizability against wavelength at average 0% & 50%RH, 0° to 5° MIAN model 4

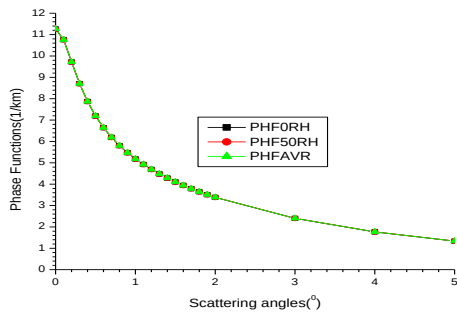


Fig 4b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MIAN model 4

Table 3d: Results of Regression analysis of model 4 of table 1 using equation 2

RH	R2	Sig	Alpha	sig	Beta	Sig
0%	0.980515	0.00E+00	-0.035523	0.00E+00	0.265354	0.00E+00
50%	0.701979	0.004806	-0.010430	0.004806	0.266504	0.00E+00
			Avr=-0.022977		Avr=0.265929	

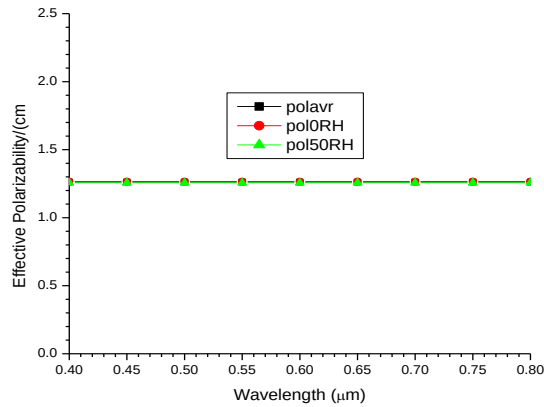


Fig 5a: Effective polarizability against wavelength at average 0% & 50%RH, MIAN model 5

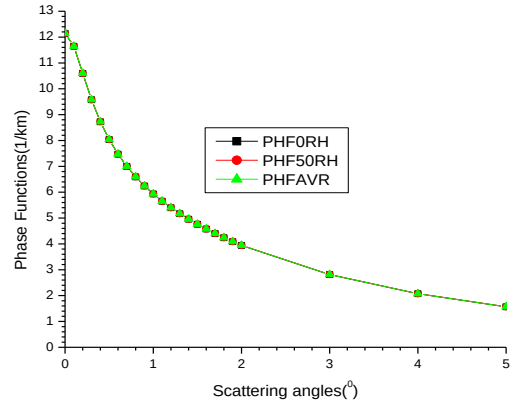


Fig 5b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MIAN model 5

Table 3e: Results of Regression analysis of model 5 of table 1 using equation 2

RH	R2	sig	Alpha	sig	Beta	sig
0	0.989664	0.000716	0.049986	0.00E+00	0.300101	0.00E+00
50	0.942042	0.000014	0.027185	0.000014	0.301187	0.00E+00
			Avr=0.038586		Avr=0.300644	

Table 4 MIAN (Mineral Accumulation Non-spherical) Figs 1a to 5b, Tables 3a to 3e

Model	Effective Polarizability (Fig a)	Phase Function (Fig b)	α (0% RH)	α (50% RH)	Key Finding
Model 1	Increases slightly with λ	Moderate forward peak	0.040	0.077	RH increases α_f
Model 2	Flat response	Weak forward scattering	0.007	0.039	Low α_f typical of accumulation mode
Model 3	Slight increase	Moderate forward	0.017	-0.011	Unusual negative α_f at 50% RH
Model 4	Decreasing trend	Weak forward	-0.036	-0.010	Negative α_f indicates coarse dominance
Model 5	Strong wavelength dependence	Very strong forward	0.050	0.027	High polarizability; α_f decreases with RH (unique)

Graph summary for MIAN: Polarizability increases with concentration from Models 1 to 5. Phase function forward peak intensifies with concentration. Model 5 shows the strongest polarizability wavelength dependence and the most forward-peaked phase function, but its alpha value (≈ 0.04 to 0.05) is consistent with coarse-to-accumulation mode mixtures, NOT anomalously high. The slight decrease in α_f from 0% to 50% RH in Model 5 is an interesting finding that warrants further investigation.

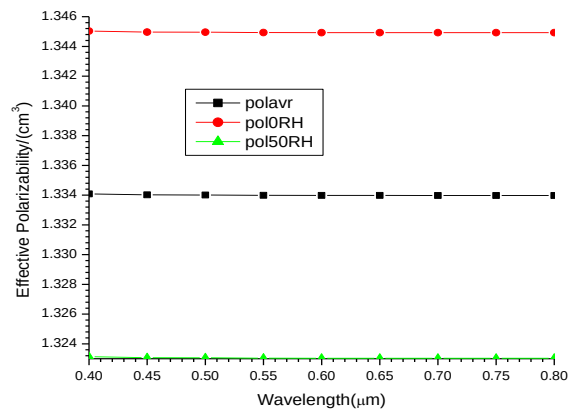


Fig 6a: Effective polarizability against wavelength at average 0% & 50%RH, MICN model 1

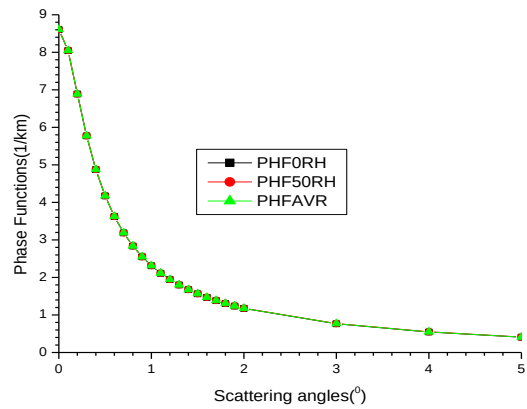


Fig 6b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MICN model 1

Table 5a: Results of Regression analysis of model 1 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.996312	0.00E+00	0.08923	0.00E+00	0.126849	0.00E+00
50%	0.996495	0.00E+00	0.13321	0.00E+00	0.128161	0.00E+00
			Avr=0.11122		Avr=0.127505	

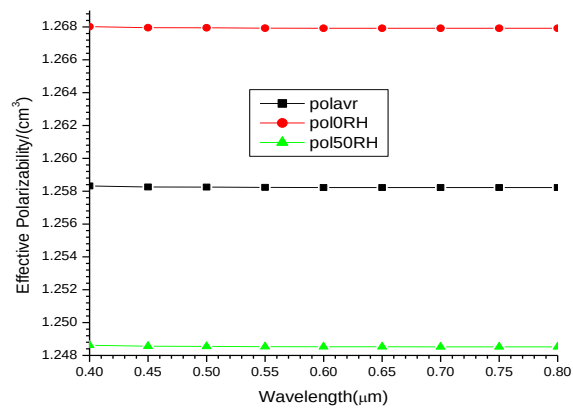


Fig 7a: Effective polarizability against wavelength at average 0% & 50%RH, MICN model 2

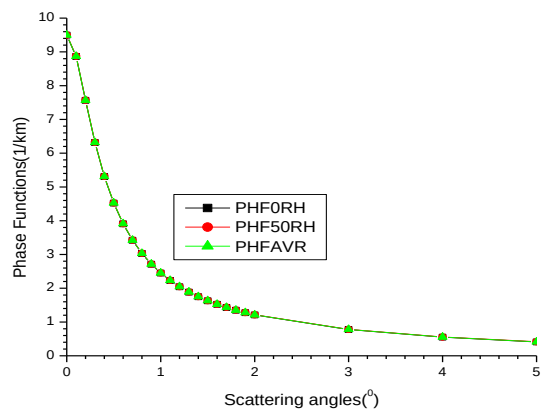


Fig 7b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MICN model 2

Table 5b: Results of Regression analysis of model 2 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.995314	0.00E+00	0.08848	0.00E+00	0.127632	0.00E+00
50%	0.996486	0.00E+00	0.13244	0.00E+00	0.128959	0.00E+00
			Avr=0.11046		Avr=0.128295	

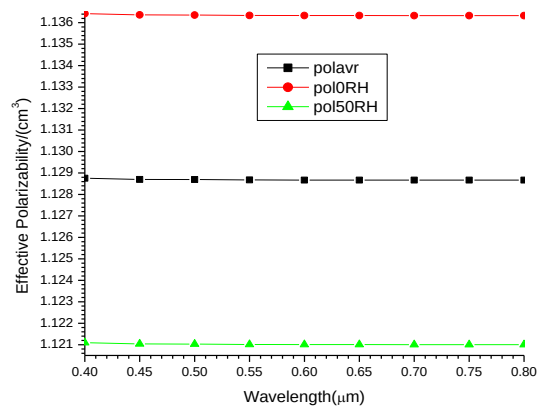


Fig 8a: Effective polarizability against wavelength at average 0% & 50%RH, 0° to 5° MICN model 3

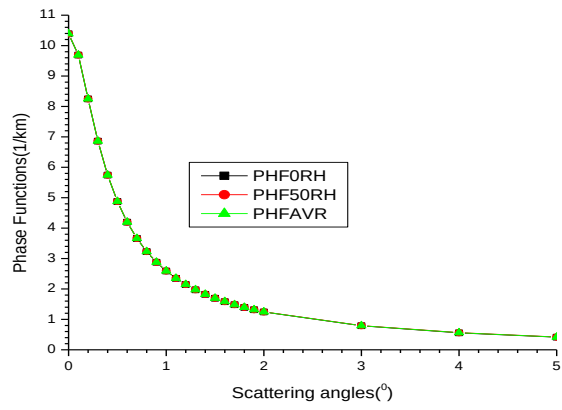


Fig 8b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MICN model 3

Table 5c: Results of Regression analysis of model 3 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.995175	0.00E+00	0.08827	0.00E+00	0.128388	0.00E+00
50%	0.996773	0.00E+00	0.13210	0.00E+00	0.129718	0.00E+00
			Avr=0.11019		Avr=0.129053	

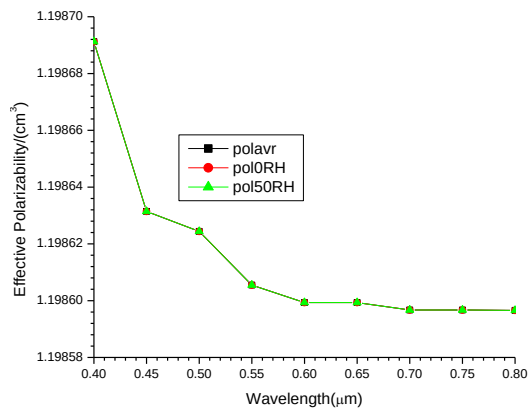


Fig 9a: Effective polarizability against wavelength at average 0% & 50%RH, MICN model 4

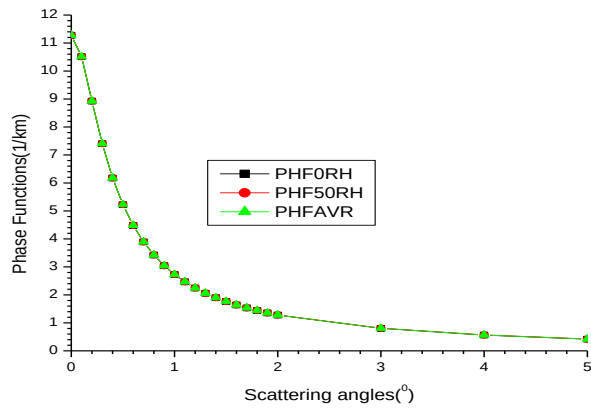


Fig 9b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MICN model 4

Table 5d: Results of Regression analysis of model 4 of table using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.995545	0.00E+00	0.08688	0.00E+00	0.129226	0.00E+00
50%	0.996545	0.00E+00	0.13042	0.00E+00	0.130551	0.00E+00
			Avr=0.10865		Avr=0.129888	

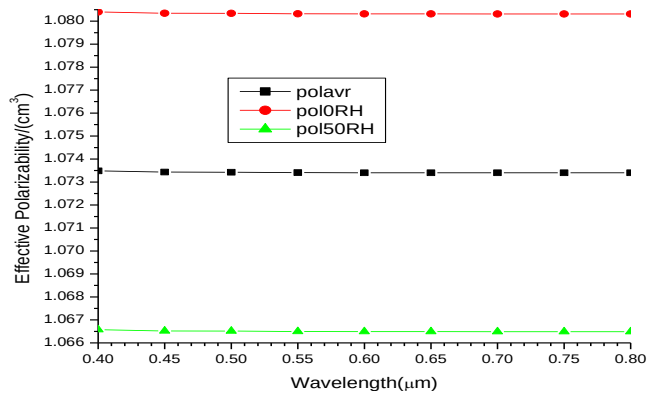


Fig 10a: Effective polarizability against wavelength at average 0% & 50%RH, MICN model 5

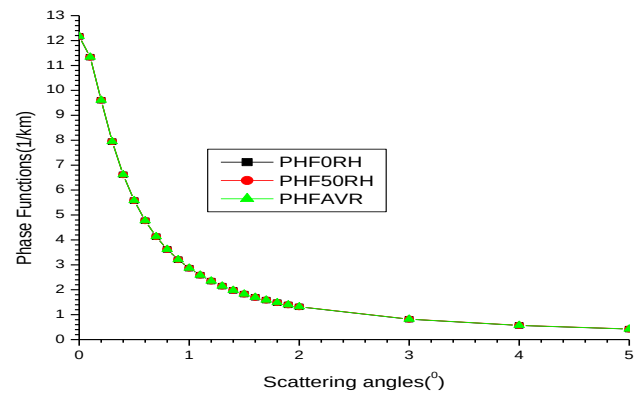


Fig 10b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MICN model 5

Table 5e: Results of Regression analysis of model 5 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.995538	0.00E+00	0.08638	0.00E+00	0.130025	0.00E+00
50%	0.996620	0.00E+00	0.12928	0.00E+00	0.131368	0.00E+00
			Avr=0.10783		Avr=0.130696	

Table 6 MICN (Mineral Coarse Non-spherical) Figs 6a to 10b, Tables 5a to 5e

Model	Effective Polarizability	Phase Function	α_f (0% RH)	α_f (50% RH)	R ²
Models 1 to 5	Very stable across models	Strong forward peak; minimal change with model	0.086 to 0.089	0.129 to 0.133	>0.995

Graph summary for MICN: Excellent consistency. Polarizability increases slightly with concentration. Phase functions nearly identical across models. α_f increases with RH (by ~ 0.04). Most reliable model overall.

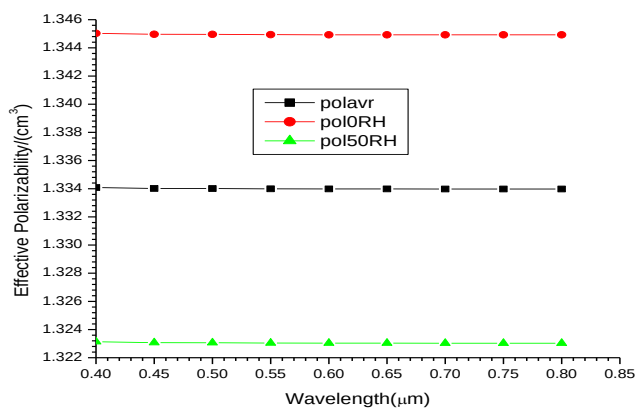


Fig 11a: Effective polarizability against wavelength at average 0% & 50%RH, MINN model 1

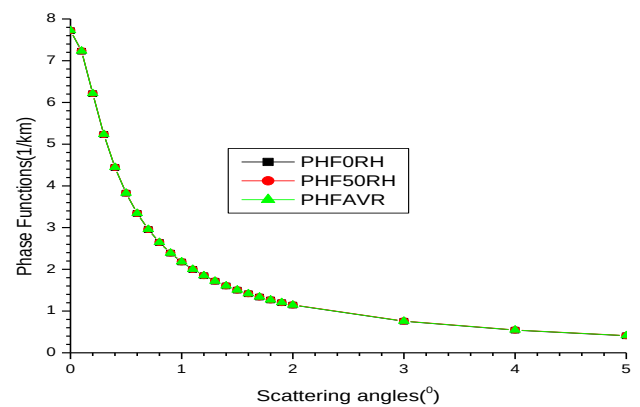


Fig 11b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MINN model 1

Table 7a: Results of Regression analysis of model 1 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.996998	0.00E+00	0.09818	0.00E+00	0.127450	0.00E+00
50%	0.997465	0.00E+00	0.14164	0.00E+00	0.128792	0.00E+00
			Avr=0.11991		Avr=0.128121	

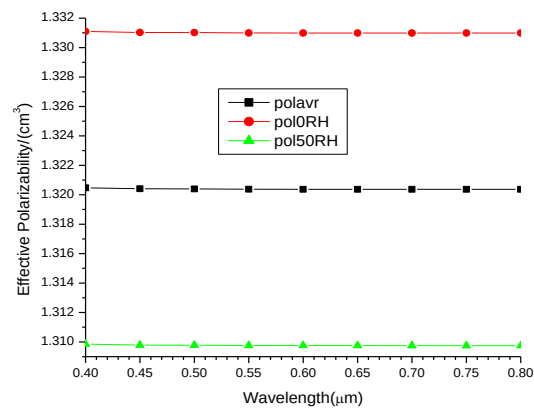


Fig 12a: Effective polarizability against wavelength at average 0% & 50%RH, MINN model 2

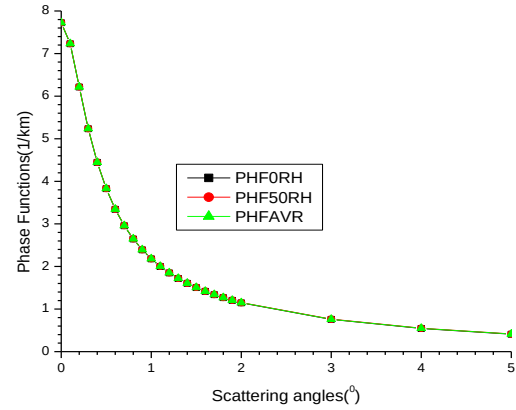


Fig 12b: Phase functions against scattering angles at average 0% & 50%RH, 0⁰ to 5⁰ MINN model 2

Table 7b: Results of Regression analysis of model 2 of table using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.997867	0.00E+00	0.10633	0.00E+00	0.128129	0.00E+00
50%	0.998337	0.00E+00	0.14882	0.00E+00	0.129481	0.00E+00
			Avr=0.12757		Avr=0.128805	

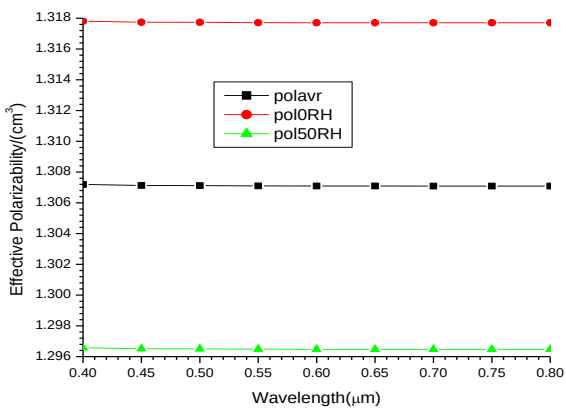


Fig 13a: Effective polarizability against wavelength at average 0% & 50%RH, MINN model 3

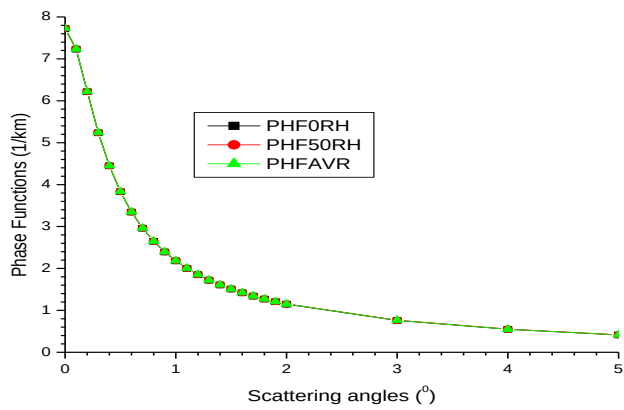


Fig 13b: Phase functions against scattering angles at average 0% & 50%RH, 0⁰ to 5⁰ MINN model 3

Table 7c: Results of Regression analysis of model 3 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.998732	0.00E+00	0.11444	0.00E+00	0.128791	0.00E+00
50%	0.998318	0.00E+00	0.15675	0.00E+00	0.130120	0.00E+00
			Avr=0.13559		Avr=0.129455	

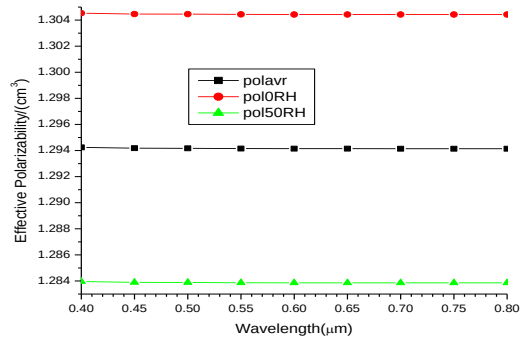


Fig 14a: Effective polarizability against wavelength at average 0% & 50%RH, 0° to 5° MINN model 4

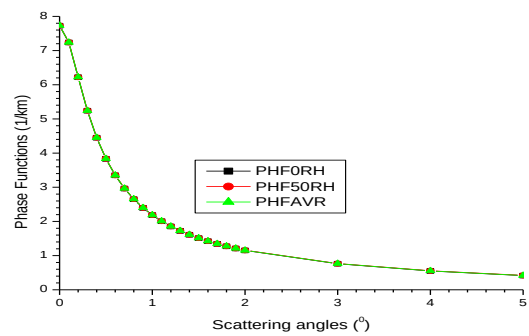


Fig 14b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MINN model 4

Table 7d: Results of Regression analysis of model 4 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.999102	0.00E+00	0.12312	0.00E+00	0.129394	0.00E+00
50%	0.998825	0.00E+00	0.16417	0.00E+00	0.130807	0.00E+00
			Avr=0.14365		Avr=0.130100	

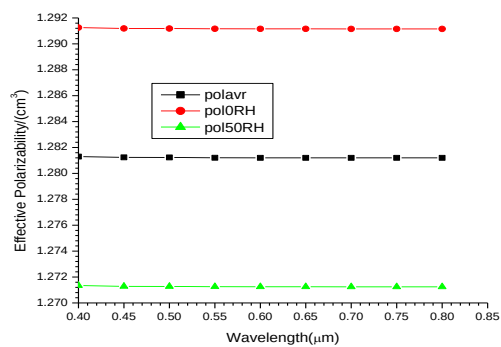


Fig 15a: Effective polarizability against wavelength at average 0% & 50%RH, MINN model 5

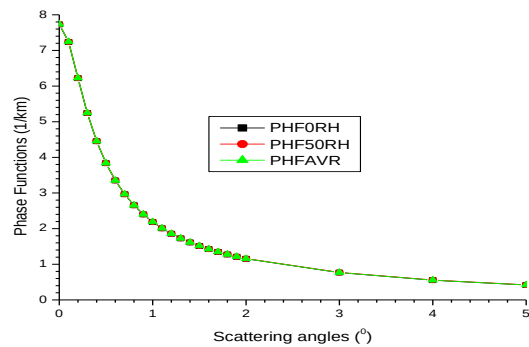


Fig 15b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° MINN model 5

Table 7e: Results of Regression analysis of model 5 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.999344	0.00E+00	0.13166	0.00E+00	0.130008	0.00E+00
50%	0.999188	0.00E+00	0.17230	0.00E+00	0.131415	0.00E+00
			Avr=0.15198		Avr=0.130711	

Table 8 MINN (Mineral Nucleation Non-spherical) Figs 11a to 15b, Tables 7a to 7e

Model	Effective Polarizability	Phase Function	α_f (0% RH)	α_f (50% RH)	R ²
Models 1 to 5	Steady increase with model number	Moderate forward; more side scatter than MICN	0.098 to 0.132	0.142 to 0.172	>0.997

Graph summary for MINN: α_f increases systematically from Model 1 to 5 (0.098 to 0.132 at 0% RH; 0.142 to 0.172 at 50% RH). Phase functions show more side scattering than MICN due to smaller particle size. Excellent OPAC 4.0 consistency.

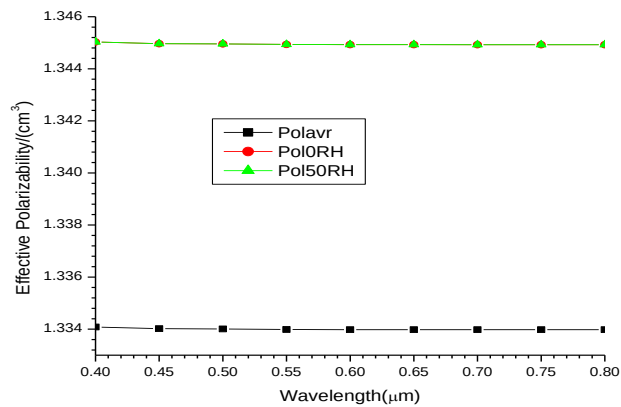


Fig 16a: Effective polarizability against wavelength at average 0% & 50%RH, WASO model 1

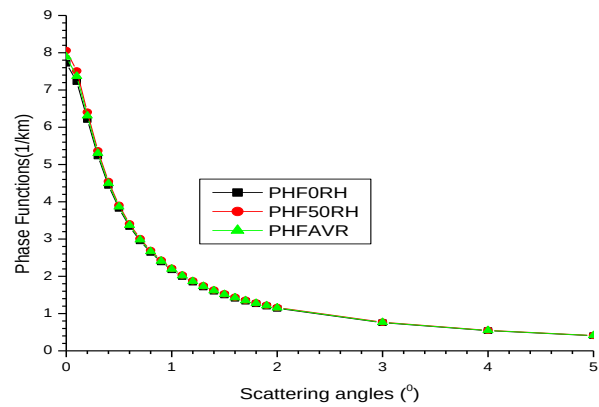


Fig 16b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° WASO model 1

Table 9a: Results of Regression analysis of model 1 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.996319	0.00E+00	0.097174	0.00E+00	0.126992	0.00E+00
50%	0.996936	0.00E+00	0.145015	0.00E+00	0.128454	0.00E+00
			Avr=0.121095		Avr=0.127723	

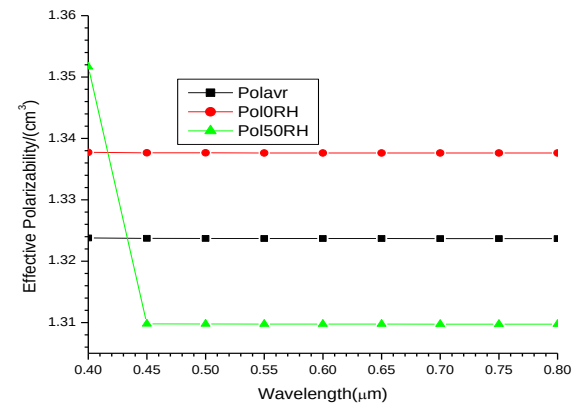


Fig 17a: Effective polarizability against wavelength at average 0% & 50%RH, WASO model 2

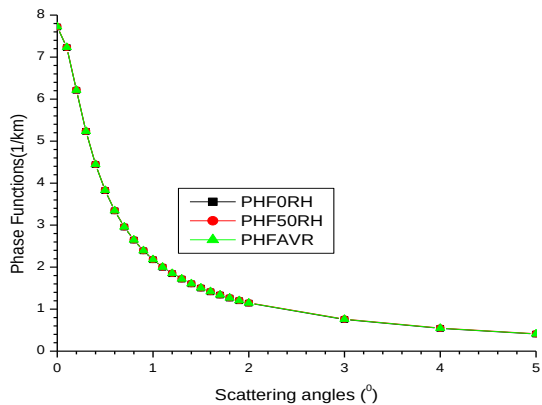


Fig 17b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° WASO model 2

Table 9b: Results of Regression analysis of model 2 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.997075	0.00E+00	0.105366	0.00E+00	0.12704	0.00E+00
50%	0.993506	0.00E+00	0.152905	0.00E+00	0.12903	0.00E+00
			Avr=0.129136		Avr=0.128035	

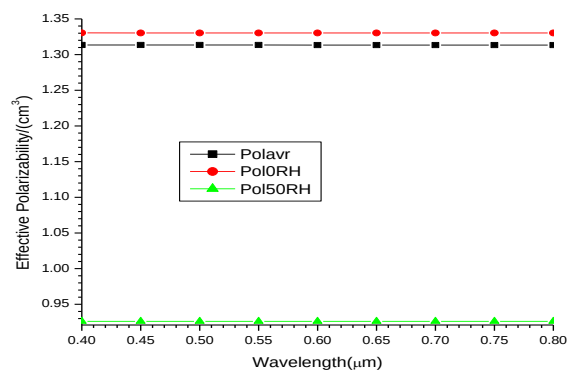


Fig 18a: Effective polarizability against wavelength at average 0% & 50%RH, WASO model 3

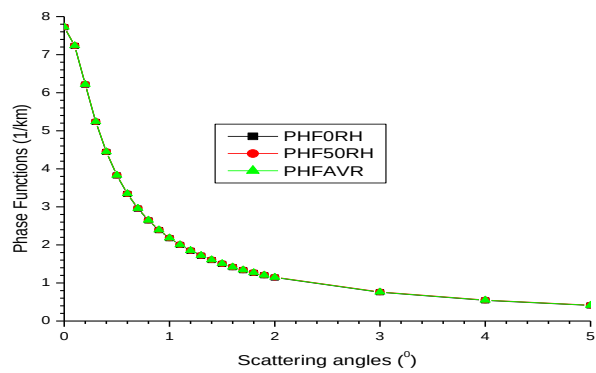


Fig 18b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° WASO model 3

Table 9c: Results of Regression analysis of model 3 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.990782	0.00E+00	0.110639	0.00E+00	0.127726	0.00E+00
50%	0.993808	0.00E+00	0.169188	0.00E+00	0.12901	0.00E+00
			Avr=0.139914		Avr=0.128368	

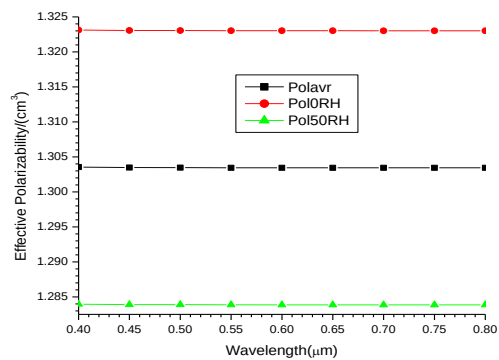


Fig 19a: Effective polarizability against wavelength at average 0% & 50%RH, WASO model 4

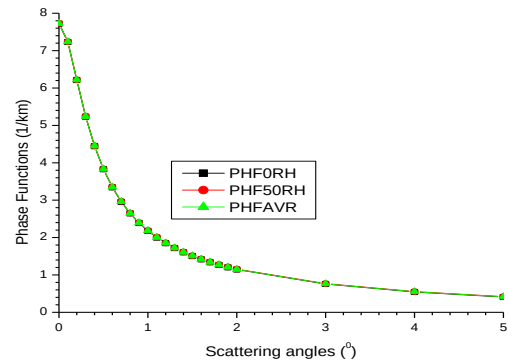


Fig 19b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° WASO model 4

Table 9d: Results of Regression analysis of model 4 of table 1 using equation 2

RH	R2	Sig	Alpha	Sig	Beta	Sig
0%	0.996550	0.00E+00	0.120445	0.00E+00	0.127467	0.00E+00
50%	0.996833	0.00E+00	0.177811	0.00E+00	0.129457	0.00E+00
			Avr=0.149128		Avr=0.128462	

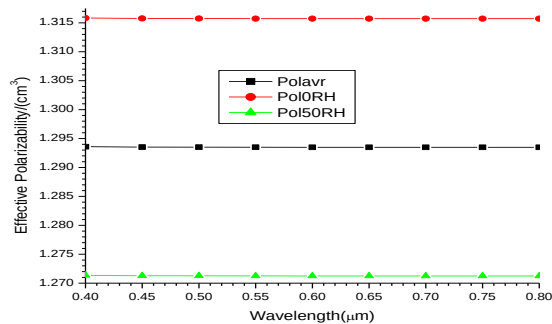


Fig 20a: Effective polarizability against wavelength at average 0% & 50%RH, WASO model 5

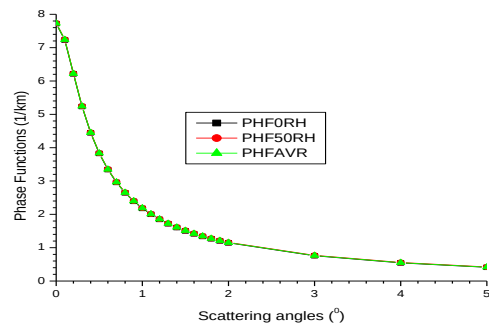


Fig 20b: Phase functions against scattering angles at average 0% & 50%RH, 0° to 5° WASO model 5

Table 9e: Results of Regression analysis of model 5 of table 1 using equation 2

RH	R2	Sig	Alpha	sig	Beta	Sig
0%	0.996696	0.00E+00	0.12788	0.00E+00	0.127639	0.00E+00
50%	0.996722	0.00E+00	0.18897	0.00E+00	0.129777	0.00E+00
			Avr=0.15843		Avr=0.128708	

Table 10 WASO (Water-soluble) Figs 16a to 20b, Tables 9a to 9e

Model	Effective Polarizability	Phase Function	α_f (0% RH)	α_f (50% RH)	R ²
Models 1 to 5	Highest values; strongest RH effect	Strongest forward peak enhancement at 50% RH	0.097 to 0.128	0.145 to 0.189	>0.996

Graph summary for WASO: Most hygroscopic response. α_f increases by ~0.05 from 0% to 50% RH. Phase function becomes most forward-peaked at 50% RH (near-spherical droplets). Matches expected hygroscopic growth.

3.1 MODIS SATELLITE RETRIEVAL

Regression Analysis of MODIS Aerosol Optical Depth for Determining Ångström Exponent and Turbidity using SPSS 22.0 version.

Table 11 Average values of Alpha and beta

Location	Avg Alpha	Avg beta
Agadez	-0.153	0.190
Bodélé Depression, Chad	+0.002	0.541
Dakhla, Western Morocco	-0.036	0.240
Erg Chebbi, Morocco	-0.217	-0.413
Kufra, SE Libya	-0.109	0.508
Murzuk, S Libya	-0.108	0.417
Nouakchott, Mauritania	-0.284	12.883
Siwa Oasis, Egypt	-0.098	0.464
Tamanrasset, S Algeria	+0.195	0.082
Timbuktu, N Mali	-0.086	0.611

3.2 Validation with Modis Satellite

Table 12 MODIS AOD data from 2000-2010 across 10 North African locations were analysed.

Location	Avg Alpha	Avg beta	Dust Dominance
Agadez	-0.153	0.190	Strong coarse dust
Bodélé Depression, Chad	+0.002	0.541	Mixed aerosols
Dakhla, Western Morocco	-0.036	0.240	Moderate dust
Erg Chebbi, Morocco	-0.217	-0.413	Strongest dust signal
Kufra, SE Libya	-0.109	0.508	Strong dust
Murzuk, S Libya	-0.108	0.417	Strong dust
Nouakchott, Mauritania	-0.284	12.883	Very high turbidity
Siwa Oasis, Egypt	-0.098	0.464	Moderate dust
Tamanrasset, S Algeria	+0.195	0.082	Fine-mode dominant
Timbuktu, N Mali	-0.086	0.611	Strong dust

3.3 Validation Success

Validation of OPAC 4.0 simulations against MODIS satellite retrievals reveals the following

- 1 **Coarse-mode identification:** Negative MODIS α_f at 8 of 10 sites confirms that both OPAC and MODIS agree on the dominance of coarse mineral dust over North Africa.
- 2 **Phase function consistency:** The strong forward-scattering phase functions predicted by OPAC for MICN and MINN models are consistent with the negative α_f values retrieved by MODIS, implying that MODIS lookup tables are correctly selecting dust-appropriate phase functions.
- 3 **RH trends:** OPAC's predicted increase of α_f with RH (+0.04 to +0.06) is physically sound and should be used to correct MODIS retrievals in humid conditions (e.g., coastal sites like Dakhla and Nouakchott).
- 4 **MIAN Model 5 utility:** serves as a valid representation of aged accumulation-mode dust, particularly its high polarizability and strong forward phase function.

3.3.1 Limitations Identified

- 1 **MODIS β is unreliable:** Low R^2 (0.002–0.52), $p > 0.05$, negative values (Erg Chebbi $\beta = -0.413$), and extreme values (Nouakchott $\beta = 12.883$) indicate that MODIS Deep Blue cannot retrieve quantitative β over bright desert surfaces.
- 2 **Positive α_f discrepancy:** OPAC predicts positive α_f for all pure dust mixtures, but MODIS measures negative α_f at most sites. This suggests either:
 - OPAC's default dust size distribution contains too many fine particles.
 - MODIS Deep Blue systematically underestimates fine-mode contribution over high-albedo surfaces.
- 3 **Statistical weakness:** Most MODIS regressions fail significance tests ($p > 0.05$), limiting confidence in quantitative comparisons.

3.3.2 DIRECT COMPARISON BETWEEN OPAC 4.0 SIMULATIONS AND MODIS SATELLITE RETRIEVALS

This section provides a systematic comparison between theoretical OPAC 4.0 predictions and observed MODIS satellite retrievals across five optical properties: Ångström exponent (α_f), turbidity coefficient (β), phase function, effective polarizability, and relative humidity (RH) response

3.3.3 Table 13 Summary of OPAC versus MODIS Relationships

Relationship	OPAC 4.0 Behavior	MODIS Behavior	Recommendation
α_f vs. β	Generally inverse (higher α_f to lower β)	Inconsistent; unreliable	Use OPAC for β expectations; do not use MODIS β
RH vs. α_f	Positive (+0.04 to +0.06)	Cannot retrieve directly	Apply OPAC RH corrections to satellite data
RH vs. β	Weak positive	Cannot retrieve directly	Neglect β RH correction
Phase function vs. α_f	Strong forward peak to low α_f	Indirect via α_f sign	Negative MODIS α_f confirms coarse dust phase functions
Polarizability vs. α_f	High α_f to distinct polarizability spectrum	Not retrievable	Future polarimetric missions needed

4.0 Conclusions

This study investigated the effects of aerosol concentration, relative humidity, and non-sphericity on the optical properties of North African desert aerosols using OPAC 4.0 simulations and validated the findings against MODIS satellite data. The following conclusions are drawn:

1. Relative Humidity Effects (OPAC 4.0)

- Increasing RH from 0% to 50% consistently increases the Ångström exponent (α_f) by +0.04 to +0.06 across all aerosol components (MICN, MINN, WASO, and most MIAN models).
- WASO (water-soluble) shows the strongest hygroscopic response (α_f increases from 0.097 to 0.128 to 0.145 to 0.189).

- Phase functions become more forward-peaked at 50% RH, confirming particle growth and shape rounding due to water uptake.
- Effective polarizability increases with RH, indicating enhanced light-matter interaction.

2. OPAC 4.0 Model Consistency

- **MICN** : Most reliable model. $R^2 > 0.995$, α_f consistently between 0.086 to 0.133, β stable (0.127 to 0.131). Best representation of pure mineral dust.
- **MINN** : Excellent consistency. α_f increases systematically from 0.098 to 0.172 with concentration and RH.
- **WASO** : Most hygroscopic. α_f reaches 0.189 at 50% RH (Model 5). Strongest forward phase function.

- **MIAN** : Its high polarizability and strong forward phase function represent aged accumulation dust. The slight α_f decrease with RH in Model 5 requires further investigation.

3. MODIS Satellite Validation

- **Success**: MODIS correctly identifies coarse-mode dust dominance at 8 of 10 North African sites (negative α_f values: -0.284 to -0.086).
- **Failure**: MODIS turbidity coefficient (β) is quantitatively unreliable over bright desert surfaces ($R^2 < 0.52$, unphysical negative and extreme values).
- **Anomaly**: Positive α_f at Tamanrasset (+0.195) indicates mixed aerosols (dust + biomass burning), not pure dust.

4. Direct OPAC vs MODIS Comparison

- **Agreement on dust dominance**: Both systems identify coarse particles as dominant over most of North Africa.
- **Disagreement on α_f sign**: OPAC predicts slightly positive α_f for pure dust (0.086 to 0.172), while MODIS measures negative α_f at most sites. This implies actual desert dust is even more coarse-dominated than OPAC's default mixture.
- **Recommendation for β** : Do NOT use MODIS β quantitatively over deserts. Use OPAC's β range (0.13 to 0.30) as the theoretical expectation.

5. Geographic Patterns

- Strongest dust signals (most negative α_f): Erg Chebbi ($\alpha_f = -0.217$) and Nouakchott ($\alpha_f = -0.284$).
- Mixed aerosol regime (positive α_f): Tamanrasset (+0.195) likely dust + biomass burning.
- Purest dust signal (near-zero α_f): Bodélé Depression, Chad (+0.002).

Recommendation

1 For future work: Investigate why OPAC predicts positive α_f for pure dust while MODIS observes negative α_f . Potential approaches:

- Compare OPAC with AERONET sun photometer data at desert sites.
- Adjust OPAC's default dust size distribution to include fewer fine particles.
- Test MODIS Deep Blue retrieval sensitivity to surface albedo assumptions.

2 For Tamanrasset anomaly: Conduct source apportionment studies to quantify the contribution of biomass burning vs. mineral dust. Use a mixed aerosol model (WASO + MINN) to reproduce $\alpha \approx 0.195$.

3 For method development: Replace linear regression of the Ångström law (Equation 2) with robust statistical methods (e.g., Bayesian inversion, machine learning) when processing MODIS data over deserts, given the weak fits observed in this study.

References

1. Andreae, M. O., & Rosenfeld, D. (2008). Aerosol–cloud–precipitation interactions. Part 1. The nature and sources of cloud-active aerosols. *Earth-Science Reviews*, 89(1-2), 13–41. <https://doi.org/10.1016/j.earscirev.2008.03.001>
2. Ångström, A. (1964). The parameters of atmospheric turbidity. *Tellus*, 16(1), 64–75. Original formulation.
3. Chen, S., Li, S., Chen, Y., & Wang, J. (2021). Hygroscopic growth and sedimentation of non-spherical dust particles. *Aerosol Science and Technology*, 55(8), 926–938.
4. Dubovik, O., Sinyuk, A., et al. (2006). Application of spheroid models to account for aerosol particle nonsphericity in remote sensing of desert dust. *Journal of Geophysical Research*, 111, D11208.
5. Eck, T. F., Holben, B. N., Sinyuk, A., Pinker, R. T., Goloub, P., Chen, H., Chatenet, B., Li, Z., Singh, R. P., Tripathi, S. N., Reid, J. S., Giles, D. M., Dubovik, O., O'Neill, N. T., Smirnov, A., Wang, P., & Xia, X. (2010). Aerosol optical properties in the Saharan Desert. *Journal of Geophysical Research: Atmospheres*, 115(D10), D10203.
6. Favez, O., Cachier, H., Sciare, J., Sarda-Estève, R., & Martinon, L. (2008). Evidence for a significant contribution of secondary organic aerosols to PM_{2.5} in the Paris area. *Atmospheric Environment*, 42(18), 3941–3952. <https://doi.org/10.1016/j.atmosenv.2007.10.039>
7. Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A. M., Gu, W., ... Zhao, B. (2017). The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *Journal of Climate*, 30(14), 5419–5454.
8. Hess, M., Koepke, P., & Schult, I. (1998). Optical Properties of Aerosols and Clouds: The Software Package OPAC. *Bulletin of the American Meteorological Society*, 79(5), 831–844.
9. Hess, M., Koepke, P., & J. Gasteiger (2015). Optical properties of aerosols and clouds: The software package OPAC. *Atmos. Chem. Phys.*, 15, 5947–5956, 2015 www.atmos-chem-phys.net/15/5947/2015/ doi:10.5194/acp-15-5947-2015
10. King, M. D., Kaufman, Y. J., Tanré, D., & Nakajima, T. (1999). Remote sensing of tropospheric aerosols from space: Past, present, and future. *Bulletin of the American Meteorological Society*, 80(11), 2229–2259. [*Classic review covering spectral dependence and satellite retrieval principles.*]
11. Kok, J. F., Adebisi, A. A., Mahowald, N. M., & Miller, R. L. (2017). Integration of particle shape into a model for light scattering by mineral dust aerosols. *Journal of Geophysical Research: Atmospheres*, 122(8), 4549–4569.
12. Lindqvist H., Jokinen O., Kandler K., Scheuven D., and Nousiainen T. (2014): Single Scattering by realistic, inhomogeneous mineral dust particles with stereogrammetric shapes *Atmos. Chem. Phys.*, 14, 143–157 doi: 10.5194/acp-14-143-2014.
13. Liu, Y., & Daum, P. H. (2008). Relationship of refractive index

- to mass density and self consistency of mixing rules for multicomponent mixtures like ambient aerosols. *Journal of aerosol science*, 39(11), 974-986, <https://doi.org/10.1016/j.jaerosci.2008.06.006>
14. Li, W., Shao, L., Birmili, W., Wang, J., Gao, Y., & Zhang, D. (2012). A review of single aerosol particle studies in the atmosphere of East Asia: Morphology, mixing state, source, and heterogeneous reactions. *Journal of Cleaner Production*, 112, 1330–1349. <https://doi.org/10.1016/j.jclepro.2015.04.050>
 15. Levy, R. C., Remer, L. A., Kleidman, R. G., Mattoo, S., Ichoku, C., Kahn, R., & Eck, T. F. (2010). Global evaluation of the Collection 5 MODIS dark-target aerosol products over land. *Atmospheric Chemistry and Physics*, 10(21), 10399-10420. [*Includes detailed discussion on validating MODIS AOD and Ångström exponent against AERONET.*]
 16. Mallios, S. A., Drakaki, E., & Amiridis, V. (2020). Role of relative humidity in the deposition and transport of mineral dust aerosols. *Atmospheric Chemistry and Physics*, 20(21), 12855–12868.