



The Effects of variation of water soluble aerosols concentration, relative humidity, effective polarizability with wavelength, phase functions and scattering angles of desert aerosols

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Abstract: This paper investigates the effects of variation of Water soluble concentrations (WASO), relative humidity, phase functions and scattering angles with wavelength, effective polarizability of desert aerosols. OPAC 4.0 (Optical Properties of Aerosols and Clouds) software package using FORTRAN program to model the effect of Water soluble concentrations at the visible spectral range of (0.4-0.80 μ m) and at eight relative humidities (0%,50%,70%,80%,90%,95%,98% & 99%) was used. Water soluble concentrations (WASO) were varied while that of Mineral accumulation, Mineral nucleation and Mineral coarse was kept constant. From the results obtained it was observed that the phase functions decreases as the scattering angle increased. Comparing phase functions at 0%RH to 99%RH, at each model there is more scattering at shorter wavelength due to smaller particles it signifies more absorption at larger scattering angle. The results have shown the clear increase in concentration and decrease in volume mix ratio as the relative humidity (RH) increases. The concentrations were varied to obtain five different models. Stokes parameter was use to obtain the phase functions and Lorentz- Lorentz relation for refractive index to determine the polarizability for single and effective polarizability aerosol, present in the desert atmosphere.

Keywords: Relative Humidity (RH), Water soluble concentrations (WASO), phase functions, scattering angles and effective polarizability.

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1. Introduction

Aerosols are tiny solid or liquid particles suspended in the atmosphere and play a significant role in the earth's climate system. Water-soluble aerosols (WASO) are an important component of atmospheric aerosols, particularly in desert regions where mineral dust and other aerosol particles are abundant. These aerosols can interact with solar radiation, influencing the Earth's energy balance and climate.

Phase functions describe the angular distribution of scattered light by aerosol particles. Water-soluble aerosols can modify the phase function of desert aerosols, leading to changes in the scattering

pattern and can increase the scattering at smaller angles, affecting the aerosol's optical properties (Li *et al.*, 2017).

The scattering angle is a critical parameter in determining the phase function of aerosols. In desert regions, the scattering angle can vary significantly due to the presence of mineral dust and other aerosol particles. Water-soluble aerosols can alter the scattering angle, influencing the amount of radiation scattered in different directions (Kim *et al.*, 2018).

Polarizability is a measure of how easily an aerosol particle can be polarized by an electric field. Water-soluble aerosols can affect the polarizability of desert aerosols, modifying their optical properties. Increase in polarizability of aerosol particle leads to changes in their scattering behavior (Zhang *et al.*, 2020).



in this work, volume mix ratios, dry and wet mode radii were extracted from OPAC (4.0) at spectral wavelength of (0.4 to 0.8 μm) at eight relative humidities (00%, 50%, 70%, 80%, 90%, 95%, 98%, and 99%). The three mineral components and water-soluble of desert aerosols were varied. The parameters were analyzed using excel, origin60 and some standard formulae to determine relative humidity, phase functions, scattering angles and effective polarizability of desert aerosols.

2. Theoretical Framework

lorentz lorentz relation for the refractive index (n) was used to obtain the polarizability for single aerosol particle α is given by (Liu & Daum, 2008)

$$\alpha = \frac{3(n^2-1)}{\rho(n^2+2)} \quad (1)$$

where α , is the polarizability of one type of aerosol n , is the refractive index, ρ is the number density (cm^{-3}). As desert aerosols are mixtures of different components (water soluble and insoluble) and different chemical constitutes the use of the effective medium theory is necessary. To determine the effective polarizability of the mixture the following addition relation is used by, (Liu & Daum, 2008) as

$$\alpha_{\text{eff}} = \sum_{i=1}^n V_i \alpha_i \quad (2)$$

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.

2.1 Phase Function

The phase functions exhibit distinct features, such as forward and backward scattering peaks, which varied depending on the aerosol shape, size and refractive index. Function F_{11} in equation (3) is called the phase functions and is normalized 1 such that Lindqvist *et al*, (2014)

$$\frac{1}{2} \int_0^\pi \sin(\theta) F_{11}(\theta) d\theta = 1 \quad (3)$$

3. Methodology

The analysis was made using OPAC 4.0 Software Package in obtaining the variation.

3.1 OPAC 4.0 Software Package

OPAC 4.0 serves as a tool to scientists who need to describe the optical properties of the atmosphere for climate-modeling purposes. It consists of datasets of optical properties of cloud and aerosol components that describe average conditions in combination, which allows calculation of any mixtures of these components. Since real aerosol in the atmosphere always is a mixture of different components, OPAC 4.0 is made possible to get optical properties of any mixtures of the basic components and to calculate optical depths on the base of exponential aerosol height profiles. OPAC 4.0 consists of two parts.

The first part is a dataset of microphysical properties and the resulting optical properties of cloud and aerosol components at different wavelengths and for different humidity conditions. The other part is a FORTRAN program that allows the user to extract data from this dataset, to calculate additional optical properties, optical properties of mixtures of the stored clouds and aerosol components Hess *et al.*, (1998).

The extinction coefficient, scattering coefficient, absorption coefficient, single scattering albedo and asymmetric parameters were extracted from OPAC at all relative humidities (00%, 50%, 70%, 80%, 90%, 95%, 98%, 99%) and at (0.4 – 0.8 μm) visible spectral wavelengths. The results were then analyzed using regression analysis.

The OPAC desert aerosol type is a mixture of water soluble (50% relative humidity is assumed) and mineral particles of nucleation, accumulation and coarse modes with a volume mixing ratio of, respectively, 0.02, 0.03, 0.74, and 0.20 (Hess *et al.*, 1998). As mentioned earlier, we alter component mixing ratios within an aerosol type by a scaling factor ranging from 0.001 to 1,000. The overall size distribution of mineral particles is modified by scaling the mixing ratio of the nucleation, accumulation, and coarse modes. In addition, the volume fraction of mineral and water soluble particle are changed by changing their composition densities each by 30% from the actual value given.

3.2 The Model's Components of the Compositions of the Desert Aerosols

The compositions used in this work are summarized in the tables below. Table 1 presents the composition of the desert aerosols, Table 2 details on the size distribution and shape of the aerosol particles used in determining the variation of the mixture in desert aerosol.

Table1 The models used in the simulation of the desert aerosols at 0% (WASO)

	Model 1	Model 2	Model 3	Model 4	Model 5
Comp	No. Den(cm^{-3})	No. Den(cm^{-3})	No. Den(cm^{-3})	No. Den(cm^{-3})	No. Den(cm^{-3})
WASO	2000	2600	3200	3800	4400
MIAN	30.50	30.50	30.50	30.50	30.50
MICN	0.142	0.142	0.142	0.142	0.142
MINN	269.5	269.5	269.5	269.5	269.5

Table2 The microphysical properties of the desert aerosols (Hess *et al.*, 2015)

Components	R _{min} (μm)	R _{max} (μm)	Sigma	R _{dry} (μm)
WASO	0.005	20	2.24	0.0212
MIAN	0.005	20	2.00	0.3900
MICN	0.005	20	2.15	1.9000
MINN	0.005	20	1.95	0.0700

4. Results and Discussions

This section presents the graphs of phase functions with scattering angles at visible spectral range of (0.4 to 0.80μm) for eight relative humidities (RHs) (00%,50%,70%,80%,90%,95%,98%,99%), figures (1a to 40a) shows phase functions against scattering angles

from 0⁰ to 180⁰ which are too close, for clarity figures (1b to 40b) from 0⁰ to 5⁰ which show the increase of phase functions with RH. Figures (41-45), show the effective polarizability were plotted in water-soluble non spherical (**WASO**) present in desert atmosphere.

4.1 WASO MODEL 1

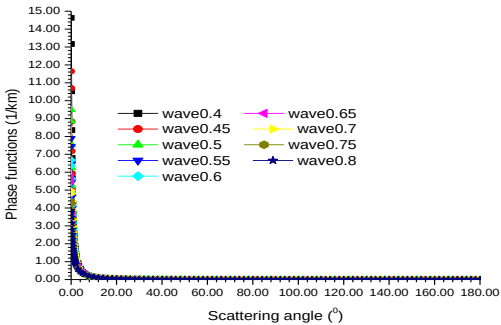


Figure 1 (a) graphs of Phase functions against scattering angles at 0%RH at WASO model 1.

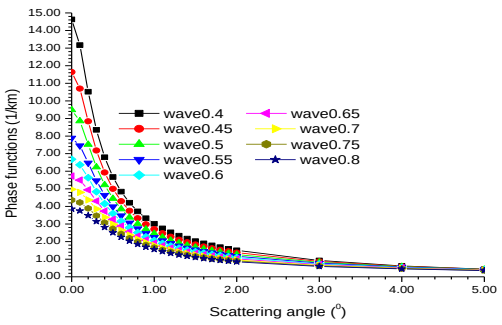


Figure 1 (b) graphs of Phase functions against scattering angles at 0%RH at WASO model 1.

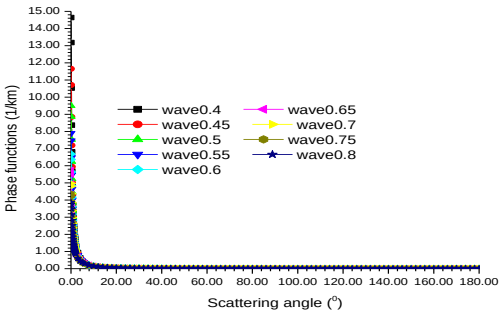


Figure 2 (a) graphs of Phase functions against scattering angles at 50%RH at WASO model 1.

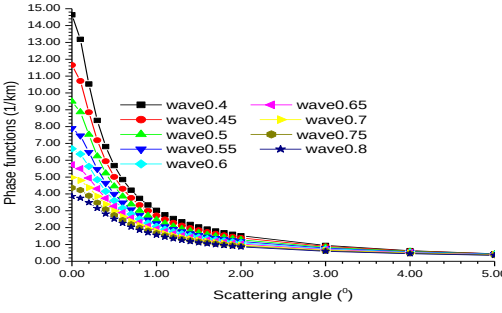


Figure 2 (b) graphs of Phase functions against scattering angles at 50%RH at WASO model 1.

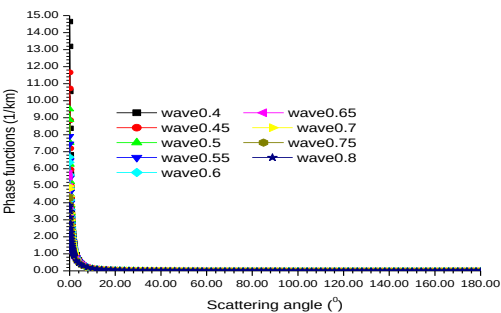


Figure 3 (a) graphs of Phase functions against scattering angles at 70%RH at WASO model 1.

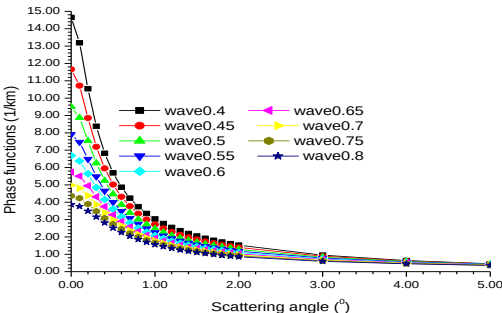


Figure 3 (b) graphs of Phase functions against scattering angles at 70%RH at WASO model 1.

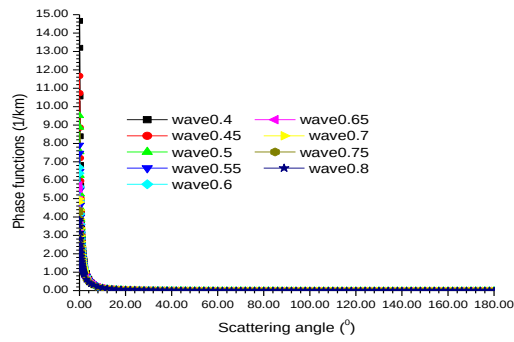


Figure 4 (a) graphs of Phase functions against scattering angles at 80%RH at WASO model 1.

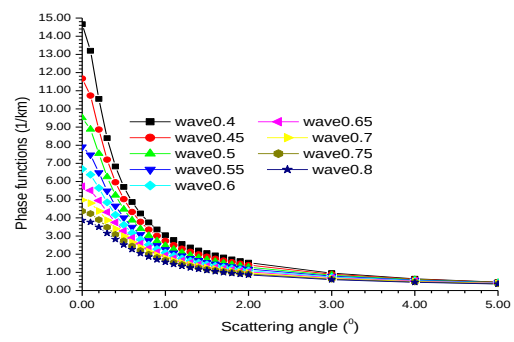


Figure 4 (b) graphs of Phase functions against scattering angles at 80%RH at WASO model 1.

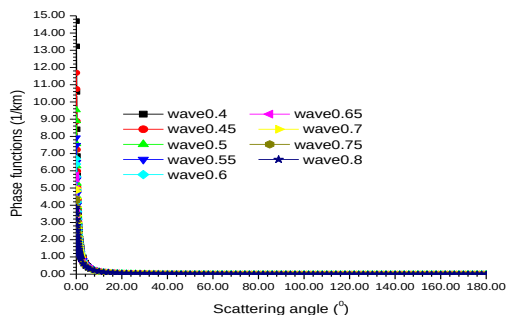


Figure 5 (a) graphs of Phase functions against scattering angles at 90%RH at WASO model 1.

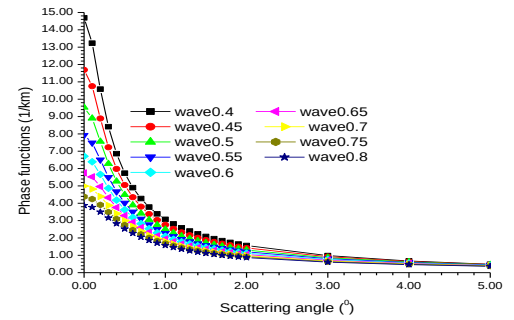


Figure 5 (b) graphs of Phase functions against scattering angles at 90%RH at WASO model 1.

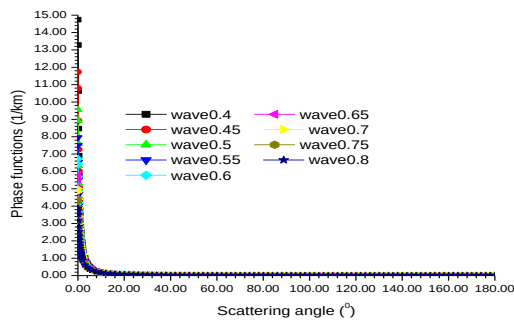


Figure 6 (a) graphs of Phase functions against scattering angles at 95%RH at WASO model 1.

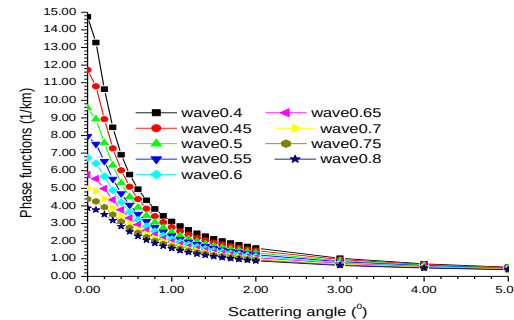


Figure 6 (b) graphs of Phase functions against scattering angles at 95%RH at WASO model 1.

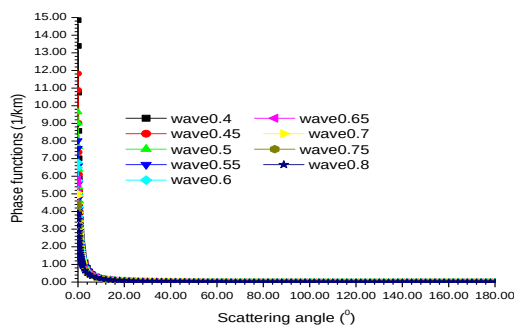


Figure 7 (a) graphs of Phase functions against scattering angles at 98%RH at WASO model 1.

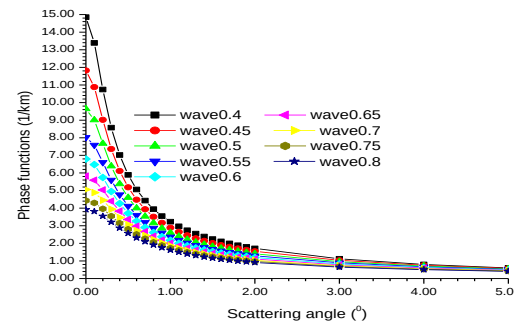


Figure 7 (b) graphs of Phase functions against scattering angles at 98%RH at WASO model 1.

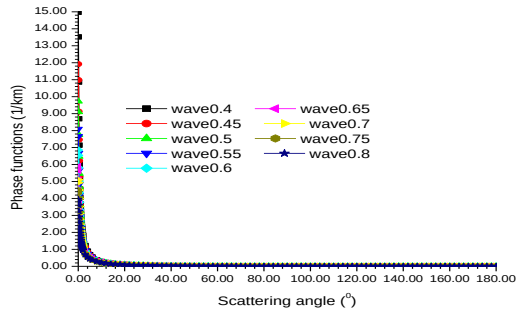


Figure 8 (a) graphs of Phase functions against scattering angles at 99%RH at WASO model 1.

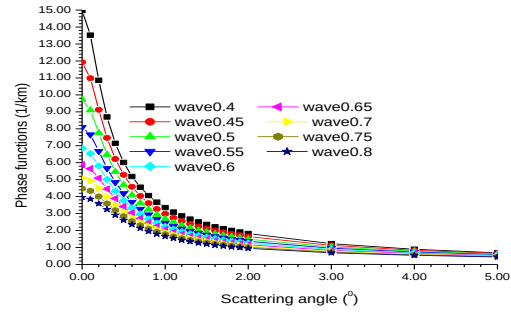


Figure 8 (b) graphs of Phase functions against scattering angles at 99%RH at WASO model 1.

From figures (1a to 8a), it can be observed that phase functions decrease with scattering angles. The phase functions are higher at shorter wavelength but can be seen more clearly at figures (1b to 8b).

It's almost constant from 0%RH to 98%RH due presence of fine particles but deliquescence at 99%RH due presence of

coarse particles, because aerosols absorb more water and enhances strong forward scattering, leading to increased particle size and changes in their optical properties which obeys inverse power law distribution, increase in scattering at smaller angles is due to presence of larger particles while decreased at large angle is due smaller particles.

4.2 WASO MODEL 2.

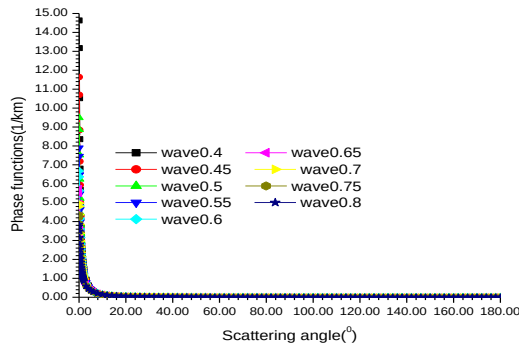


Figure 9 (a) graphs of Phase functions against scattering angles at 0%RH at WASO model 2.

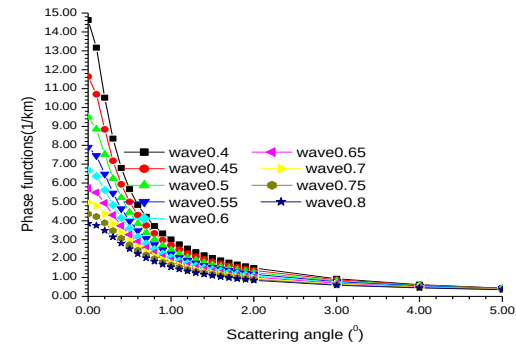


Figure 9 (b) graphs of Phase functions against scattering angles at 0%RH at WASO model 2.

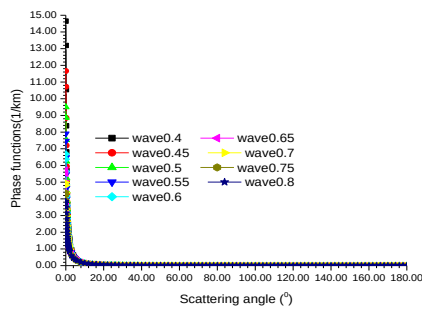


Figure 10 (a) graphs of Phase functions against scattering angles at 50%RH at WASO model 2.

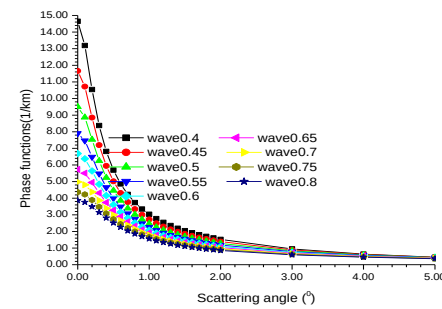


Figure 10 (b) graphs of Phase functions against scattering angles at 50%RH at WASO model 2.

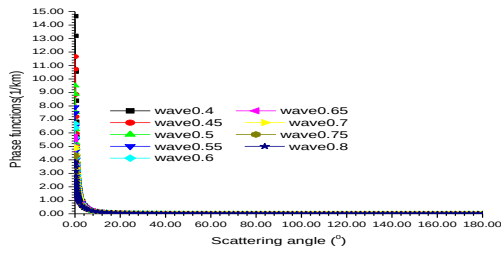


Figure 11 (a) graphs of Phase functions against scattering angles at 70%RH at WASO model 2.

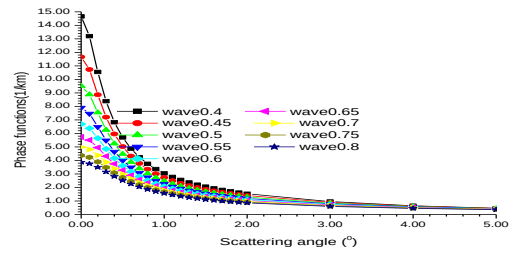


Figure 11 (b) graphs of Phase functions against scattering angles at 70%RH at WASO model 2.

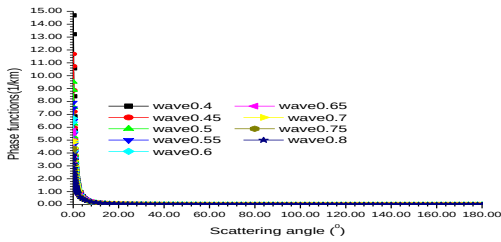


Figure 12 (a) graphs of Phase functions against scattering angles at 80%RH at WASO model 2.

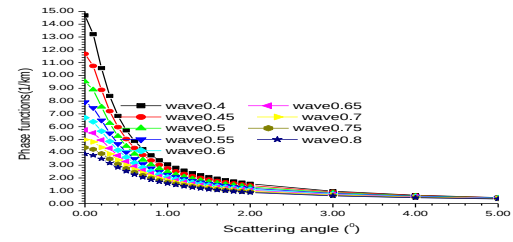


Figure 12 (b) graphs of Phase functions against scattering angles at 80%RH at WASO model 2.

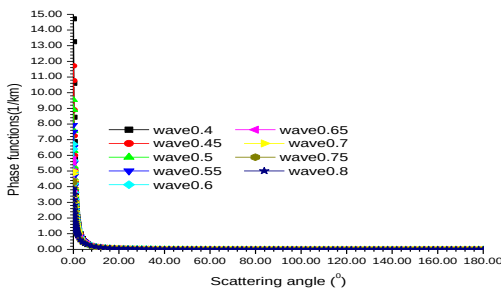


Figure 13 (a) graphs of Phase functions against scattering angles at 90%RH at WASO model 2.

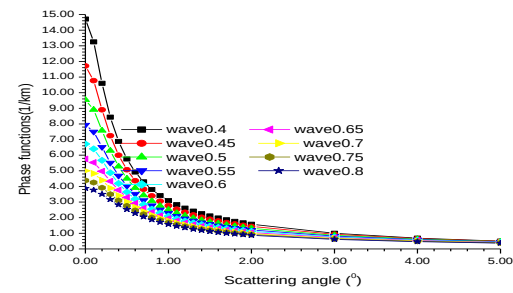


Figure 13 (b) graphs of Phase functions against scattering angles at 90%RH at WASO model 2.

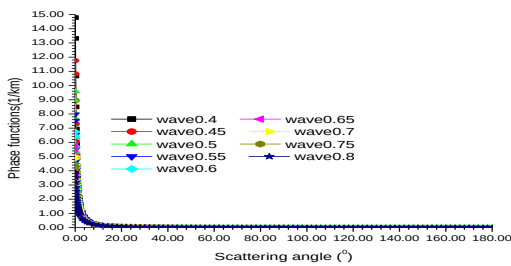


Figure 14 (a) graphs of Phase functions against scattering angles at 95%RH at WASO model 2.

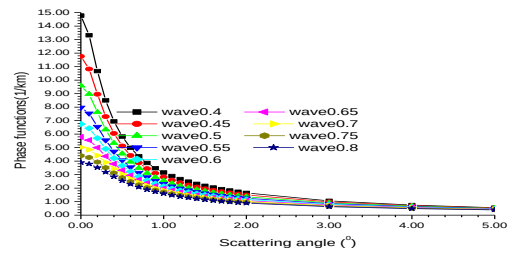


Figure 14 (b) graphs of Phase functions against scattering angles at 95%RH at WASO model 2.

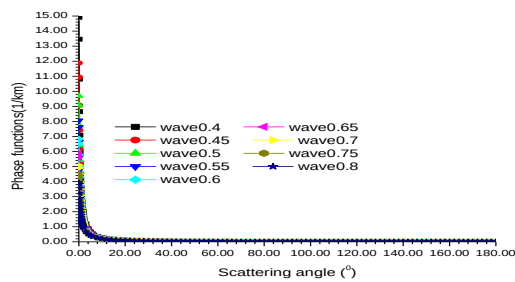


Figure 15 (a) graphs of Phase functions against scattering angles at 98%RH at WASO model 2.

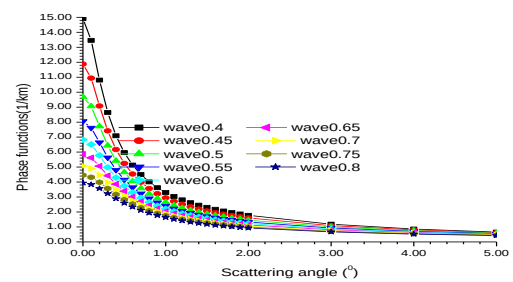


Figure 15 (b) graphs of Phase functions against scattering angles at 98%RH at WASO model 2.

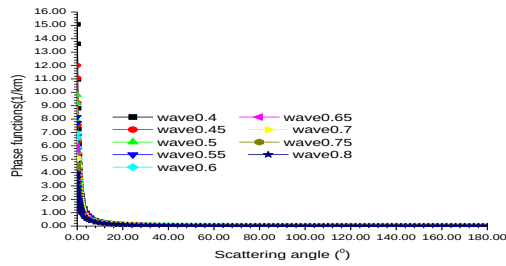


Figure 16 (a) graphs of Phase functions against scattering angles at 99%RH at WASO model 2.

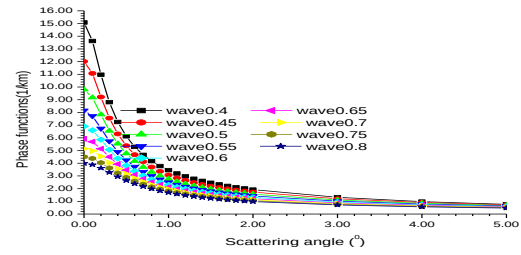


Figure 16 (b) graphs of Phase functions against scattering angles at 99%RH at WASO model 2.

From figures (9a to 16a), it can be observed that phase functions decrease with scattering angles. The phase functions are higher at shorter wavelength but can be seen clearly at figures (9b to 16b).

It's almost constant from 0%RH to 98%RH due presence of fine particles but deliquescence at 99%RH due presence of

coarse particles, because aerosols absorb more water and enhances strong forward scattering, leading to increased particle size and changes in their optical properties which obeys inverse power law distribution, increase in scattering at smaller angles is due to presence of larger particles while decreased at large angle is due smaller particles.

4.3 WASO MODEL 3

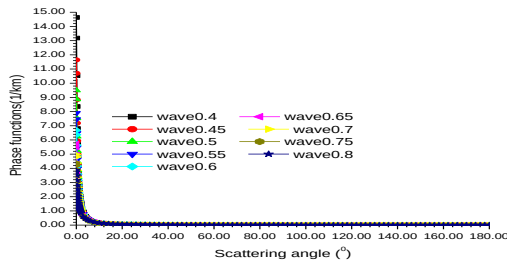


Figure 17 (a) graphs of Phase functions against scattering angles at 0%RH at WASO model 3.

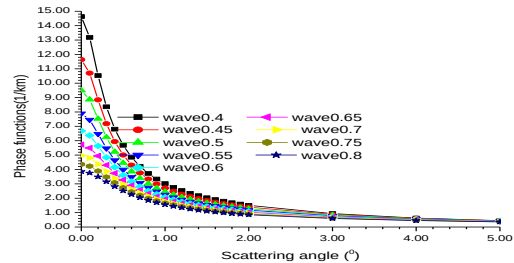


Figure 17 (b) graphs of Phase functions against scattering angles at 0%RH at WASO model 3.

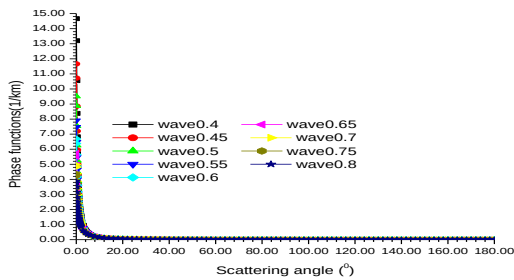


Figure 18 (a) graphs of Phase functions against scattering angles at 50%RH at WASO model 3.

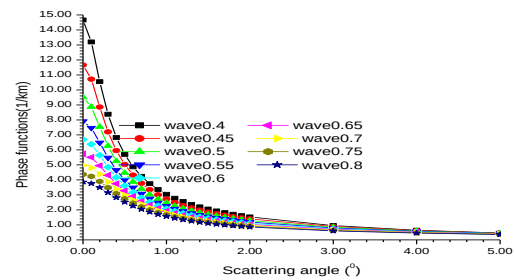


Figure 18 (b) graphs of Phase functions against scattering angles at 50%RH at WASO model 3.

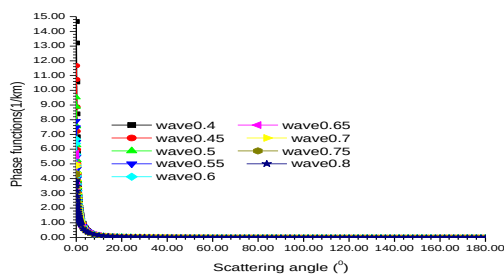


Figure 19 (a) graphs of Phase functions against scattering angles at 70%RH at WASO model 3.

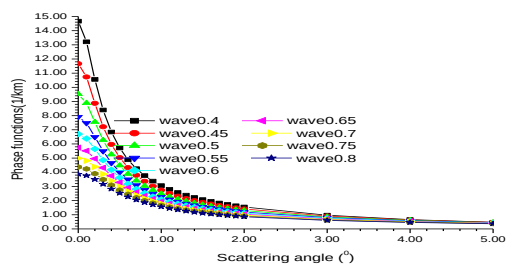


Figure 19 (b) graphs of Phase functions against scattering angles at 70%RH at WASO model 3.

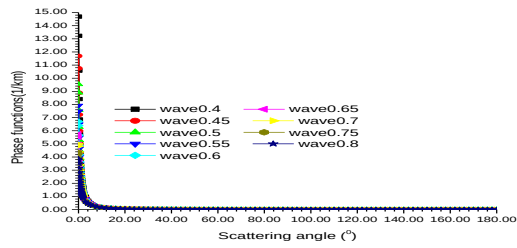


Figure 20 (a) graphs of Phase functions against scattering angles at 80%RH at WASO model 3.

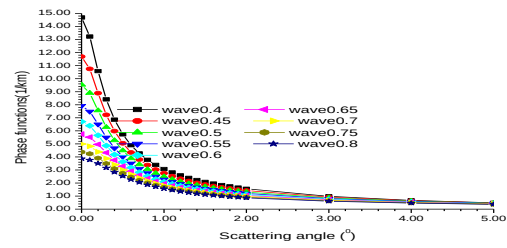


Figure 20 (b) graphs of Phase functions against scattering angles at 80%RH at WASO model 3.

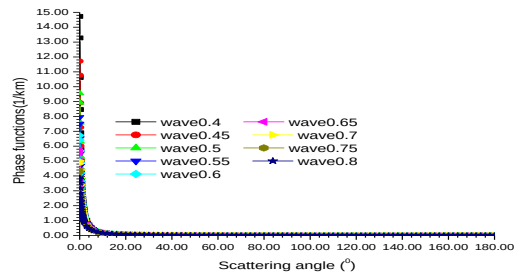


Figure 21 (a) graphs of Phase functions against scattering angles at 90%RH at WASO model 3.

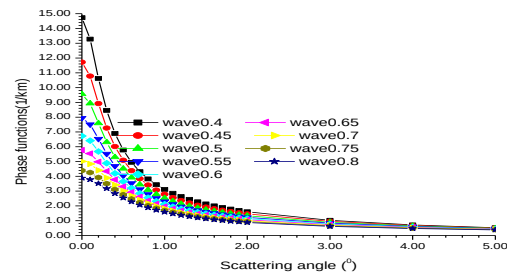


Figure 21 (b) graphs of Phase functions against scattering angles at 90%RH at WASO model 3.

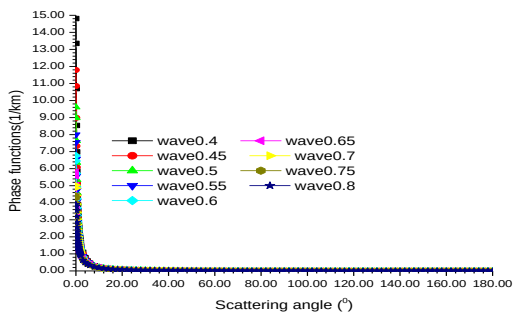


Figure 22 (a) graphs of Phase functions against scattering angles at 95%RH at WASO model 3.

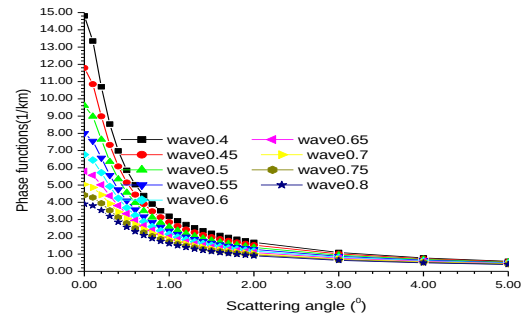


Figure 22 (b) graphs of Phase functions against scattering angles at 95%RH at WASO model 3.

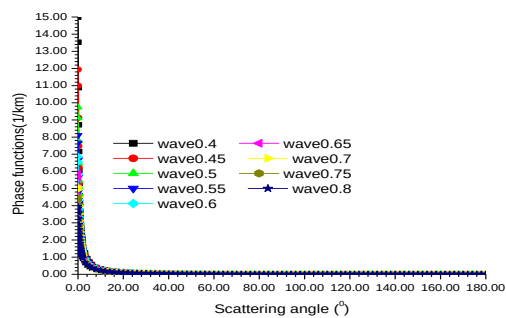


Figure 23 (a) graphs of Phase functions against scattering angles at 98%RH at WASO model 3.

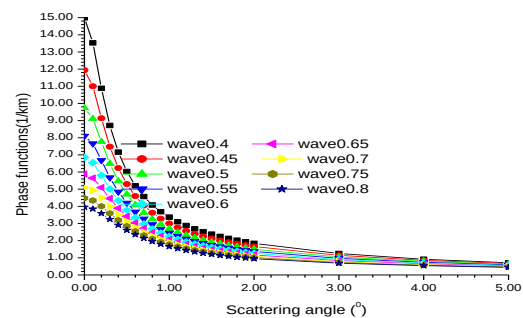


Figure 23 (b) graphs of Phase functions against scattering angles at 98%RH at WASO model 3.

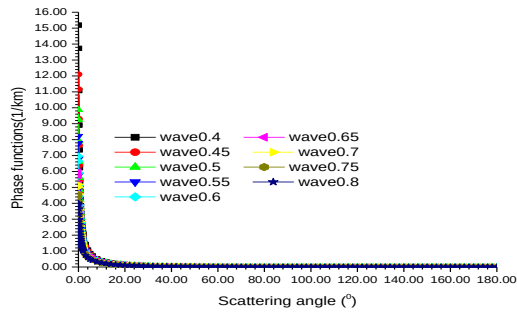


Figure 24 (a) graphs of Phase functions against scattering angles at 99%RH at WASO model 3.

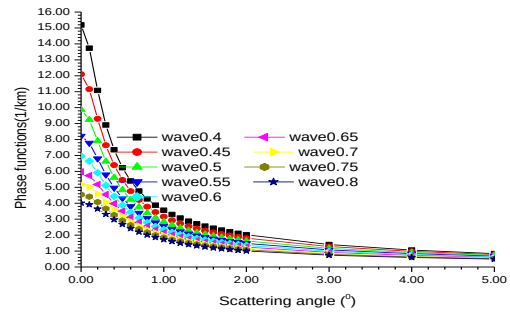


Figure 24 (b) graphs of Phase functions against scattering angles at 99%RH at WASO model 3.

From figures (17a to 24a), it can be observed that phase functions decrease with scattering angles. The phase functions are higher at shorter wavelength but can be seen clearly at figures (17b to 24b).

It's almost constant from 0%RH to 98%RH due presence of fine particles but deliquescence at 99%RH due presence of

coarse particles, because aerosols absorb more water and enhances strong forward scattering, leading to increased particle size and changes in their optical properties which obeys inverse power law distribution, increase in scattering at smaller angles is due to presence of larger particles while decreased at large angle is due smaller particles.

4.4 WASO MODEL 4

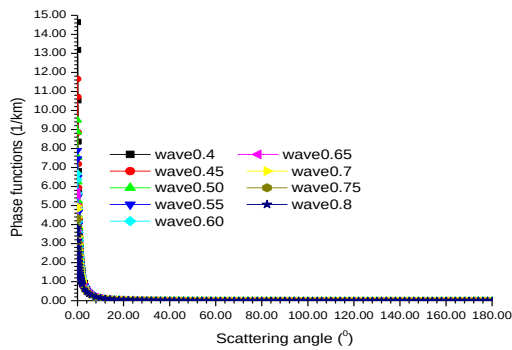


Figure 25 (a) graphs of Phase functions against scattering angles at 0%RH at WASO model 4.

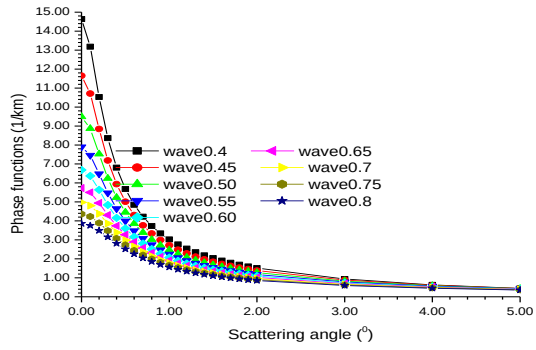


Figure 25 (b) graphs of Phase functions against scattering angles at 0%RH at WASO model 4.

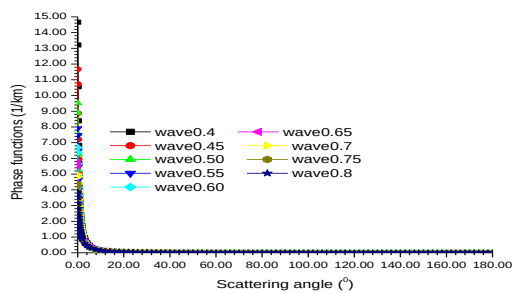


Figure 26 (a) graphs of Phase functions against scattering angles at 50%RH at WASO model 4.

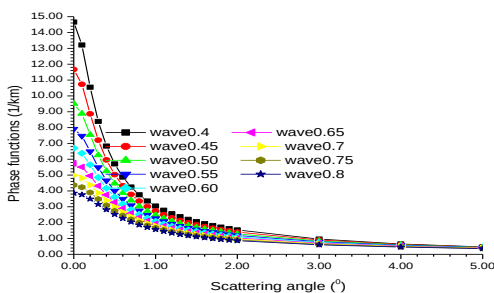


Figure 26 (b) graphs of Phase functions against scattering angles at 50%RH at WASO model 4.

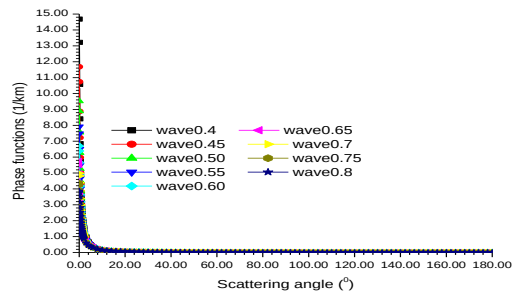


Figure 27 (a) graphs of Phase functions against scattering angles at 70%RH at WASO model 4.

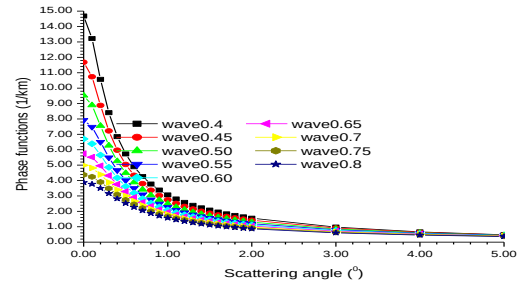


Figure 27 (b) graphs of Phase functions against scattering angles at 70%RH at WASO model 4.

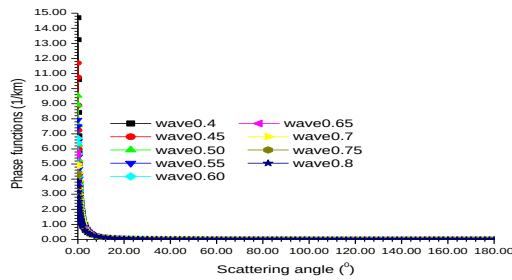


Figure 28 (a) graphs of Phase functions against scattering angles at 80%RH at WASO model 4.

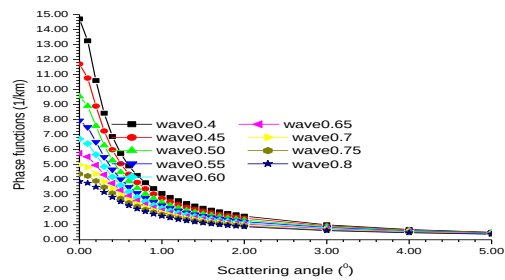


Figure 28 (b) graphs of Phase functions against scattering angles at 80%RH at WASO model 4.

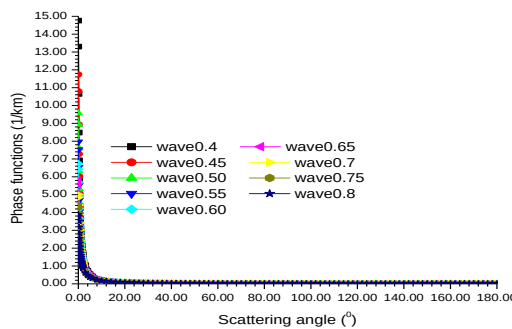


Figure 29 (a) graphs of Phase functions against scattering angles at 90%RH at WASO model 4.

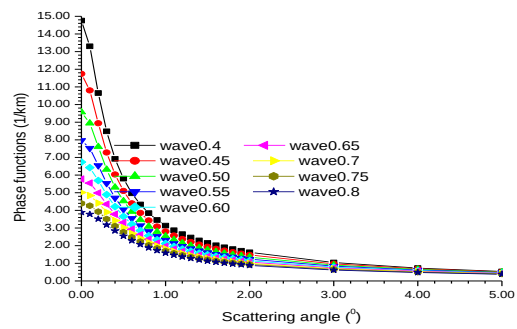


Figure 29 (b) graphs of Phase functions against scattering angles at 90%RH at WASO model 4.

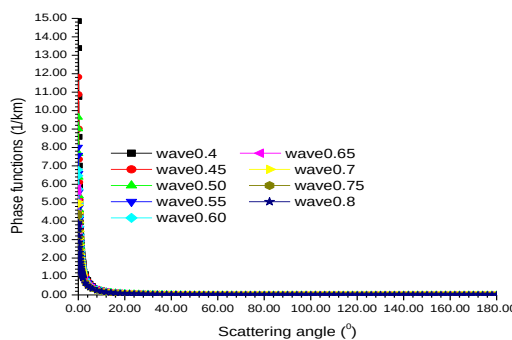


Figure 30 (a) graphs of Phase functions against scattering angles at 95%RH at WASO model 4.

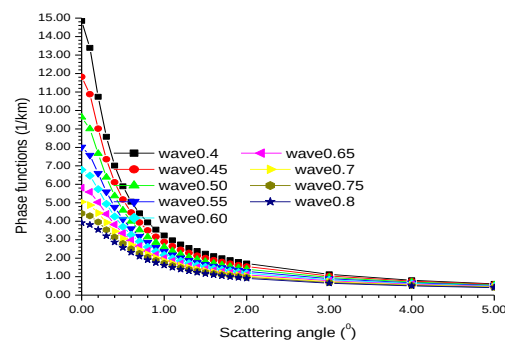


Figure 30 (b) graphs of Phase functions against scattering angles at 95%RH at WASO model 4.

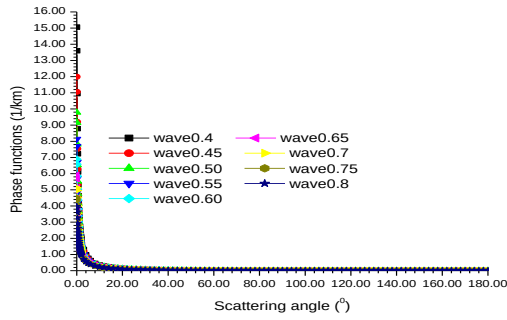


Figure 31 (a) graphs of Phase functions against scattering angles at 98%RH at WASO model 4.

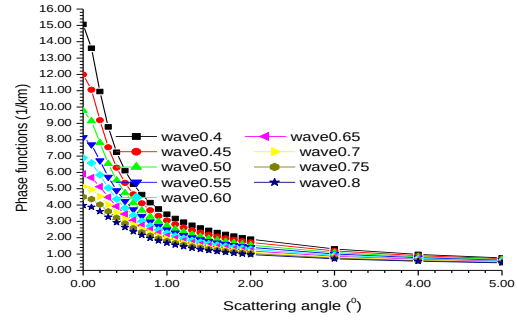


Figure 31 (b) graphs of Phase functions against scattering angles at 98%RH at WASO model 4.

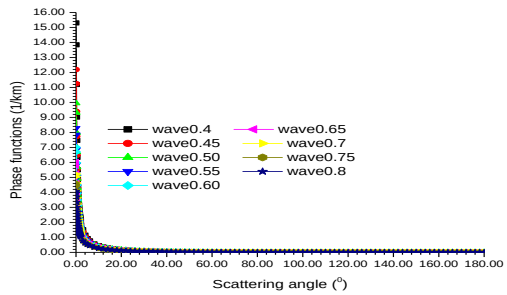


Figure 32 (a) graphs of Phase functions against scattering angles at 99%RH at WASO model 4.

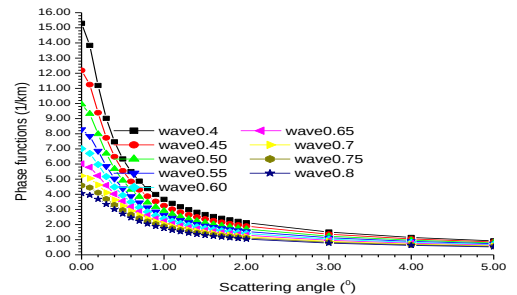


Figure 32 (b) graphs of Phase functions against scattering angles at 99%RH at WASO model 4.

From figures (25a to 32a), it can be observed that phase functions decrease with scattering angles. The phase functions are higher at shorter wavelength but can be seen clearly at figures (25b to 32b).

It's almost constant from 0%RH to 95%RH due presence of fine particles but deliquescence at 98RH% & 99%RH due

presence of coarse particles, because aerosols absorb more water and enhances strong forward scattering, leading to increased particle size and changes in their optical properties which obeys inverse power law distribution, increase in scattering at smaller angles is due to presence of larger particles while decreased at large angle is due smaller particles.

4.5 WASO MODEL 5

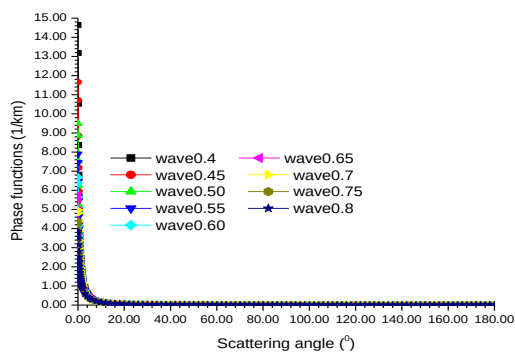


Figure 33 (a) graphs of Phase functions against scattering angles at 0%RH at WASO model 5.

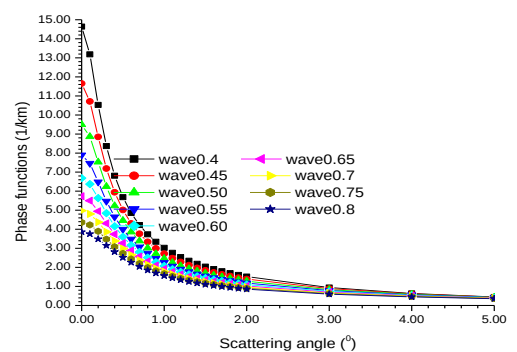


Figure 33 (b) graphs of Phase functions against scattering angles at 0%RH at WASO model 5.

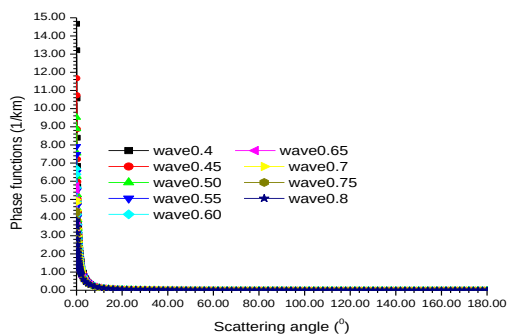


Figure 34 (a) graphs of Phase functions against scattering angles at 50%RH at WASO model 5.

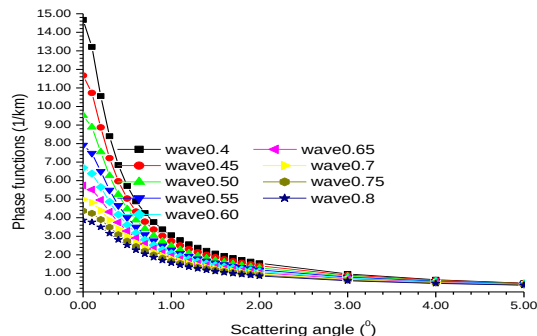


Figure 34 (b) graphs of Phase functions against scattering angles at 50%RH at WASO model 5.

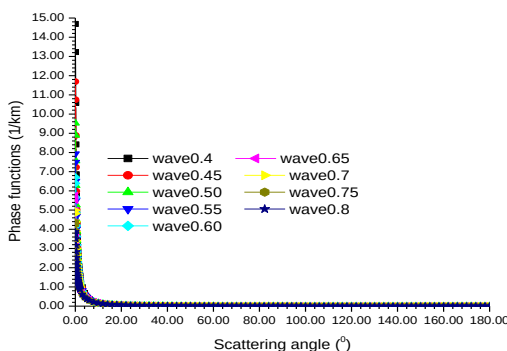


Figure 35 (a) graphs of Phase functions against scattering angles at 70%RH at WASO model 5.

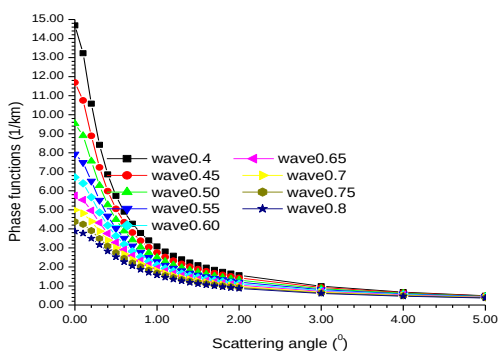


Figure 35 (b) graphs of Phase functions against scattering angles at 70%RH at WASO model 5.

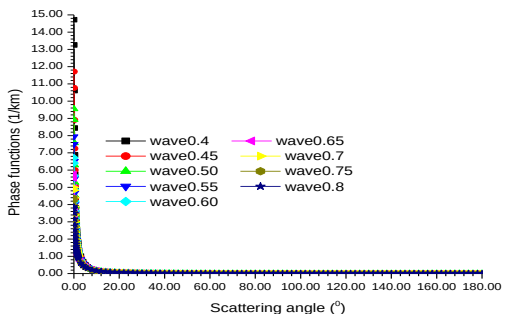


Figure 36 (a) graphs of Phase functions against scattering angles at 80%RH at WASO model 5.

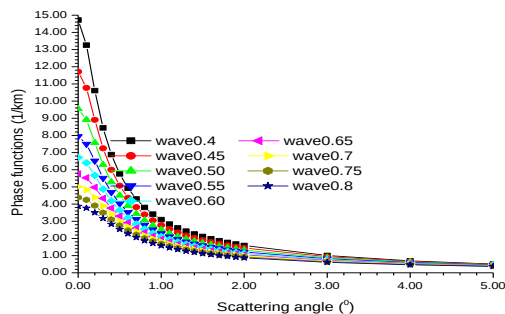


Figure 36 (b) graphs of Phase functions against scattering angles at 80%RH at WASO model 5.

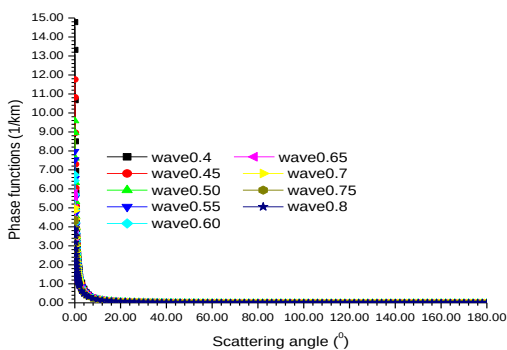


Figure 37 (a) graphs of Phase functions against scattering angles at 90%RH at WASO model 5.

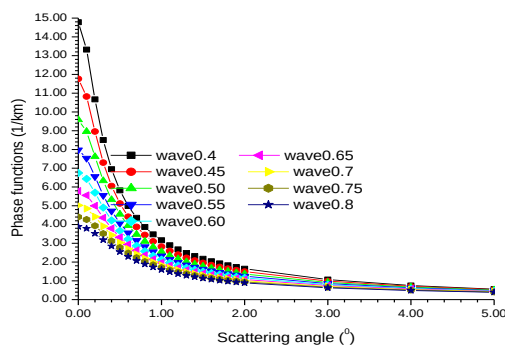


Figure 37 (b) graphs of Phase functions against scattering angles at 90%RH at WASO model 5.

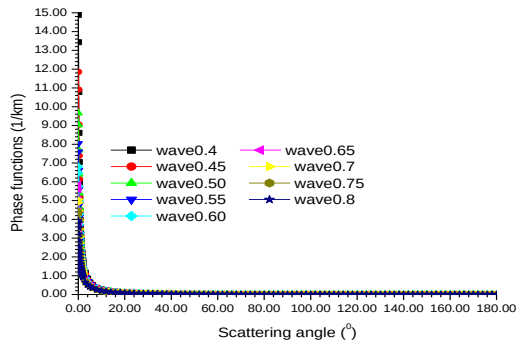


Figure 38 (a) graphs of Phase functions against scattering angles at 95%RH at WASO model 5.

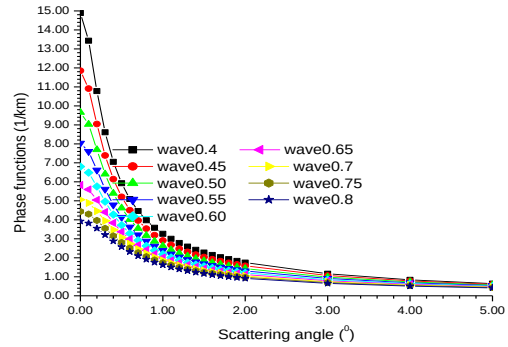


Figure 38 (b) graphs of Phase functions against scattering angles at 95%RH at WASO model 5.

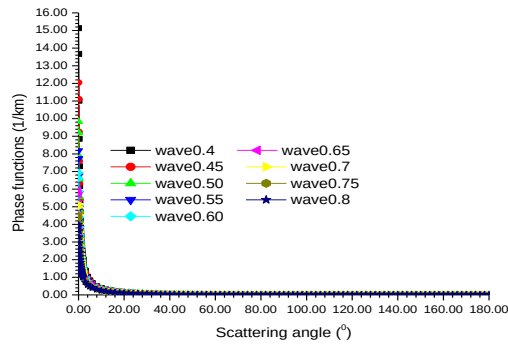


Figure 39 (a) graphs of Phase functions against scattering angles at 98%RH at WASO model 5.

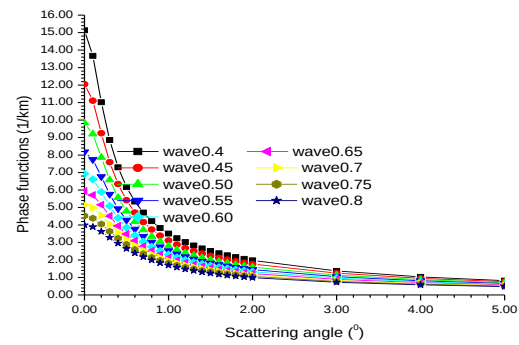


Figure 39 (b) graphs of Phase functions against scattering angles at 98%RH at WASO model 5.

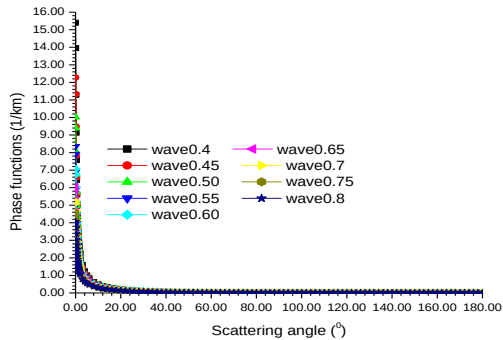


Figure 40 (a) graphs of Phase functions against scattering angles at 99%RH at WASO model 5.

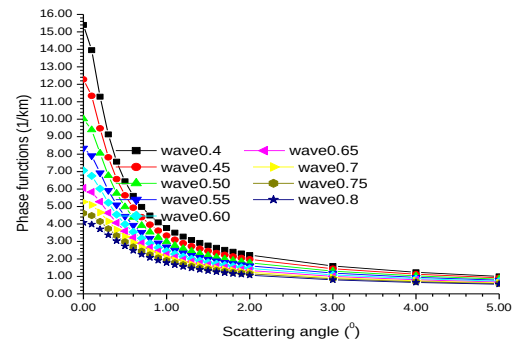


Figure 40 (b) graphs of Phase functions against scattering angles at 99%RH at WASO model 5.

From figures (33a to 40a), it can be observed that phase functions decrease with scattering angles. The phase functions are higher at shorter wavelength but can be seen clearly at figures (33b to 40b).

It's almost constant from 0%RH to 95%RH due presence of fine particles but deliquescence at 98RH% & 99%RH due presence of coarse particles, because aerosols absorb more water and enhances strong forward scattering, leading to increased

particle size and changes in their optical properties which obeys inverse power law distribution, increase in scattering at smaller angles is due to presence of larger particles while decreased at large angle is due smaller particles.

4.6 Effective Polarizability Graph

This section presents the graphs of effective polarizability with wavelength based on the models presented in tables 1 & 2 above.

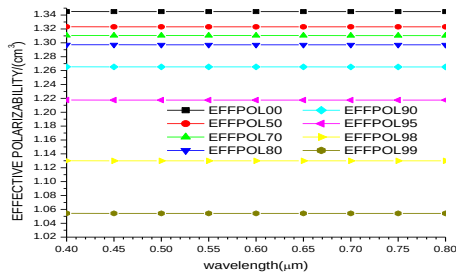


Figure 41: A graph of Effective polarizability against wavelength WASO model 1

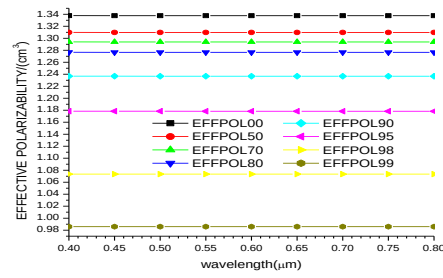


Figure 42: A graph of Effective polarizability against wavelength WASO model 2

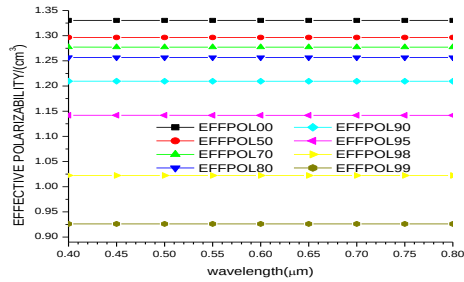


Figure 43: A graph of Effective polarizability against wavelength WASO model 3

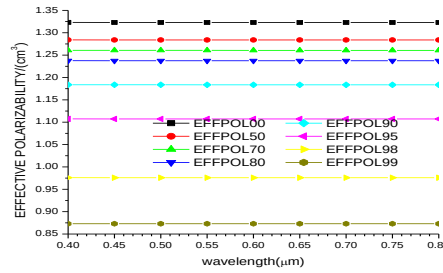


Figure 44: A graph of Effective polarizability against wavelength WASO model 4

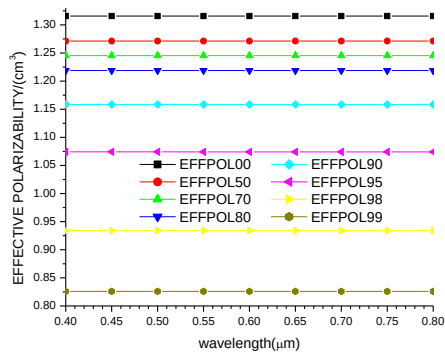


Figure 45: A graph of Effective polarizability against wavelength WASO model5

Figures (41-45), show that the effective polarizability decreases with the increase in RH, but almost constant with the increase wavelength. The decrease is attributed to high concentration of water soluble which leads to increase in scattering and water uptake, resulting in a shielding effects that reduces the effective polarizability. The study finds that in desert regions, a measure of non-spherical aerosols is generally between 20%RH and 40%RH. This suggests a significant presence of non-spherical dust particles in desert environments, influencing the scattering and polarization of light. due to particle size distribution and aerosol composition.

5. Conclusions

The analysis of the phase functions of water-soluble components in desert aerosols (WASO), as presented in Figures 1-40 (a & b), provides new insights into the optical properties of these aerosols. The results demonstrate that the phase functions of mixture components is highly sensitive to particle size and relative

humidity (RH), with larger particles dominating scattering at smaller angles and smaller particles driving absorption at larger angles as suggested by Mishchenko *et al* (2002), Reid *et al* (2003) and Yang *et al* (2015).

Notably, the increase in RH leads to an increase in particle size, resulting in enhanced strong forward scattering. The comparison of phase functions from model 1 model 3 at 0% RH to 98% RH reveals a consistent decrease in phase functions with increasing wavelength, attributed to the increased influence of fine particles also consistent with the findings of Mishchenko *et al* (2002).

Furthermore, the phase functions obey inverse power-law distribution due to the decrease in scattering angle as observed by Liu *et al* (2018).

While the effective polarizability decreases with increasing RH due to particle size distribution and aerosol composition. The decrease is attributed to high concentration of water soluble which leads to

increase in scattering and water uptake, resulting in shielding effects that reduces the effective polarizability as suggested by Seinfeld *et al* (2016). These findings have significant implications for understanding the impact of mixture components in desert aerosols on the Earth's climate system, particularly in arid and semi-arid regions. The results of this study can be used to improve the accuracy of radiative transfer models, remote sensing retrievals, and climate predictions.

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