A PHYSICAL/OPTICAL MODEL FOR ATMOSPHERIC AEROSOLS WITH APPLICATION TO VISIBILITY PROBLEMS

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ABSTRACT

The objectives of this report are to describe a conceptually simple but accurate model for efficiently computing the optical properties of atmospheric aerosols. Aerosol characteristics such as size distribution, solubility, mixture and the atmospheric moisture effect are taken into account when computing its optical properties. The dependence of the latter on aerosol microstructure is also discussed. The optical properties of aerosols are computed by employing numerically stable algorithms for obtaining Mie solutions to coated spheres. Resulting bulk quantities such as the extinction/backscatter coefficient, the probability of scattering, and the scattering phase matrix can be incorporated into multiple scattering schemes of radiative transfer for visibility investigations and other types of studies.

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1. Introduction

Atmospheric aerosols affect not only visibility but also daily weather, the climate of the earth, and it has been speculated in some instances even the survival of certain organisms on earth. One of the most apparent influences of these aerosols is on the transfer of visible light in the terrestrial atmosphere which is especially important to problems of visibility and the perceived visual air quality. Difficulties posed in investigations of visibility are the best examples of the need for conducting this study.

Visibility modeling requires a proper description of the optical properties of these atmospheric aerosols and an accurate simulation of the physical processes of light propagation in the atmosphere. Specification of the composite optical properties of atmospheric aerosols under various conditions is in fact a complex problem. Many of the past investigations on this subject have focused on the relation of the extinction coefficients to the chemical specification of aerosol mass through empirical/statistical models employing multivariate linear regression (e.g. Barone *et al.*, 1978; Ouimette and Flagan, 1982), others have relied on more physical aerosol models (e.g. Sloane, 1984 and 1986; Pilinis, 1989 among others). Furthermore, most of these studies have limited their scope to Beer's law, in which the multiple scattering of light is neglected.

Visibility degradation is the result of two effects: the attenuation of image forming radiance (Beer's law) and the generation of path radiance by the atmospheric molecular and aerosol due to multiple scattering (angular redistribution). The difference in the path radiance between scattering dominated and absorption dominated aerosols can easily be as large as two orders of magnitude. Consequently, considerations of visibility reduction due only to the attenuation of light along the viewing path may produce large errors (e.g. Dave, 1981). Furthermore, the perceived visual air quality is often determined by the color of the sky which varies dramatically from clean and blue to turbid and yellowish or to brownish (e.g. Megaw, 1977; Dave, 1980; Groblicki *et al.*, 1981), depending in a complex way on the microstructure of the aerosol loading.

To account for the enhancement of path radiance by aerosol loading and multiple scattering under various conditions, accurate and efficient methods for computing the aerosol optical properties are required. In Section 2 we describe the utilization of unconditionally stable algorithms of Mie solutions for coated spheres and discuss the physical and chemical characteristics of atmospheric aerosol models used in this report. Based on their microstructures, the bulk optical properties of aerosols are determined in Section 3, in a way which allows these quantities to be easily incorporated into multiple scattering schemes of radiative transfer computations. In Section 4 examples illustrating use of this model and applications are given. A summary of this report is stated in Section 5. A well-documented and user-friendly computer code is given in Appendix A, together with a sample input/output in Appendix B.

2. Single Particle

The interaction of light with a single particle can be described within the framework of classical electromagnetic theory. In turn, the optical properties of the particle depends on its geometry, size and composition. However, the degree of complexity involved in obtaining rigorous solutions to Maxwell's equations is mainly determined by the geometry of the particle. For spherical particles, the exact solution to single scattering process is well known as Mie theory.

Aerosol particles that appear in the atmosphere are generally not spherical in shape. Although liquid aerosols or liquid-coated aerosols (e.g. coating of sulfuric acid solution; Bigg, 1980) are approximately spherical, dry particles tend to be irregular in shape. Pollack and Cuzzi (1980) suggested that for nonspherical particles with size parameter (the ratio of particle circumference to wavelength) less than ~ 5, the error caused by assuming sphericity is quite small. This is due to the light waves insensitivity to the particles' shape or variation in composition. Also, studies by Chýlek *et al.* (1976) and Holland and Gagne (1970) indicated that for particles of equal overall dimensions but different shapes the spherical particle exhibited the largest extinction. Therefore, Mie computations can still be applied to most non-spherical particles, provided that proper precautions are taken.

2.1 Mie theory and numerical solutions

The interaction of light with a scattering/absorbing homogeneous sphere is described by Mie theory and is adequately treated in a number of classic textbooks (e.g. van de Hulst, 1957; Deirmendjian, 1969). More recently, a number of improved Mie scattering algorithms have become available (e.g. Wiscombe, 1980; Bohren and Huffman, 1983). The physical parameters involved in Mie calculations are the complex refractive index of the sphere relative to the surrounding medium ($m = m_{real} - i m_{imaginary}$) and the size parameter ($x = \pi d/\lambda$; d for diameter and λ for wavelength). Indices of refraction for different types of aerosols used in this study are adopted from the literature such as the compilation of Shettle and Fenn (1979). The parameters required to completely describe single scattering are: extinction (Q_{ext}) and scattering (Q_{sca}) efficiency factors and the scattering phase matrix ($\mathbf{P}_{\cos\vartheta}$, the angular distribution and polarization of the scattered radiation related to scattering angle ϑ). These quantities can readily be computed from the expression outlined below (*cf.* Bohren and Huffman, 1983 for detailed derivations)

$$x^2 Q_{ext} = 2\sum_{\ell=1}^{\infty}(2\ell+1)\Re e(a_\ell + b_\ell), \tag{1}$$

$$x^2 Q_{sca} = 2\sum_{\ell=1}^{\infty}(2\ell+1)(a_\ell a_\ell^* + b_\ell b_\ell^*), \tag{2}$$

$$\mathrm{P}_{\cos\vartheta} = \begin{pmatrix} P_1 & 0 & 0 & 0 \\ 0 & P_2 & 0 & 0 \\ 0 & 0 & P_3 & P_4 \\ 0 & 0 & -P_4 & P_3 \end{pmatrix}, \tag{3}$$

where the complex quantities a_ℓ and b_ℓ are Mie coefficients and functions of x and m only. $\Re e(y)$ and y^* denote respectively the real part and the conjugate of complex variable y. The four matrix elements (P_j) are related to complex scattering amplitudes (S_1, S_2) for two orthogonal directions of incident polarization (Deirmendjian, 1969)

$$P_1 = \frac{4S_1S_1^*}{x^2Q_{sca}}, \quad P_2 = \frac{4S_2S_2^*}{x^2Q_{sca}}, \quad P_3 = \frac{4\Re e(S_1S_2^*)}{x^2Q_{sca}}, \quad P_4 = \frac{-4\Im m(S_1S_2^*)}{x^2Q_{sca}}, \tag{4}$$

where $\Im m(y)$ denotes the imaginary part of the complex variable y. Finally, if μ represents the cosine of the scattering angle (ϑ), the complex scattering amplitudes (S_1, S_2) have the following forms

$$S_1(\mu) = \sum_{\ell=1}^{\infty}\frac{2\ell+1}{\ell(\ell+1)}[a_\ell\phi_\ell(\mu) + b_\ell\tau_\ell(\mu)] \quad \text{and} \quad S_2(\mu) = \sum_{\ell=1}^{\infty}\frac{2\ell+1}{\ell(\ell+1)}[a_\ell\tau_\ell(\mu) + b_\ell\phi_\ell(\mu)], \tag{5}$$

where they are related to two angular eigenfunctions of ϕ and τ. Although ϕ and τ were originally defined in terms of the Legendre polynomials and their derivatives, they can be generated by their own recursion relationships

$$\begin{aligned} \phi_\ell(\mu) &= \mu\frac{2\ell-1}{\ell-1}\phi_{\ell-1}(\mu) - \frac{\ell}{\ell-1}\phi_{\ell-2}(\mu) \qquad \text{and} \\ \tau_\ell(\mu) &= \mu[\phi_\ell(\mu) - \phi_{\ell-2}(\mu)] - (2\ell-1)(1-\mu^2)\phi_{\ell-1}(\mu) + \tau_{\ell-2}(\mu) \end{aligned} \tag{6}$$

with the initialization of $\phi_0 = \tau_0 = 0, \phi_1 = 1$ and $\tau_1 = \mu$. Furthermore, $\phi_\ell(\mu)$ and $\tau_\ell(\mu)$ are alternately even and odd functions of μ since $\phi_\ell(-\mu) = (-1)^{\ell-1}\phi_\ell(\mu)$ and $\tau_\ell(-\mu) = (-1)^\ell\tau_\ell(\mu)$ and need only be computed for scattering angles between 0^o and 90^o. In some literature, the scattering phase matrix is defined slightly differently from that of Eq.(3) and is directly related to the Stokes parameters (e.g. I, Q, U, V). However, it is understood that the discrepancy can be eliminated by taking the average of the sum and difference between P_1 and P_2 (*cf.* subroutine LEGNDR and below for details).

Two other useful parameters are also computed: the backscatter efficiency factor (Q_{bks}) and the asymmetry factor (g). The backscatter efficiency factor can be obtained from

$$x^2Q_{bks} = \left|\sum_{\ell=1}^{\infty}(2\ell+1)(-1)^\ell(a_\ell - b_\ell)\right|^2, \tag{7}$$

which is an important parameter used in some active remote sensing techniques such as radar and lidar measurements. Also, the asymmetry factor is given by

$$g = \frac{4}{x^2Q_{sca}}\left[\sum_{\ell=1}^{\infty}\frac{\ell(\ell+2)}{(\ell+1)}\Re e(a_\ell a_{\ell+1}^* + b_\ell b_{\ell+1}^*) + \sum_{\ell=1}^{\infty}\frac{2\ell+1}{\ell(\ell+1)}\Re e(a_\ell b_\ell^*)\right], \tag{8}$$

which is the relative strength of forward scattering (1, complete forward; 0, isotropic; −1, complete backward scattering). The aforementioned Eqs.(1-8) are coded in subroutine COATMI of this model.

The angular dependence of the scattering phase matrix (i.e. $P_\jmath(\mu)$ as in Eq.[4]) is commonly represented as a weighted sum of Legendre polynomials ($\wp$) with a finite number of terms ($\aleph$)

$$P_\jmath(\mu) = \sum_{i=0}^{\aleph-1}\chi_i^\jmath\wp_i(\mu), \tag{9}$$

where the coefficients (χ_i^j) are the moments of P_j with respect to the Legendre polynomials

$$\chi_i^j = \frac{2i+1}{2}\int_{-1}^{1} P_j \wp_i(\mu)d\mu. \tag{10}$$

An appropriate and convenient way of performing integration required by Eq.(10) is provided by Gaussian Quadratures (Gauss-Legendre integration) in the range $(-1,1)$. The abscissae (q_i) and weights (w_i) are defined such that

$$\int_{-1}^{1} f(q)dq = \sum_{i=1}^{\aleph} w_i f(q_i) \tag{11}$$

and calculated using the Newton-Raphson method. Thus, q_i is found if the difference between q_i and its neighborhood $q_{i+\delta}$ converges to within a preferred machine precision (ϵ) or

$$q_{i+\delta} = q_i - \wp_{\aleph}(q_i)/\wp'_{\aleph}(q_i) \qquad \text{and} \qquad |q_i - \varsigma_{i+\delta}| \leq \epsilon, \tag{12}$$

where $\wp'$ denotes the derivatives of Legendre polynomials. Then, w_i can be determined by

$$w_i = \frac{2}{(1-q_i^2)[\wp'_{\aleph}(q_i)]^2}. \tag{13}$$

Here we use the standard recurrence relations for $\wp$ and $\wp'$

$$\begin{array}{lcr} \wp_{\aleph}(q_i) = [(2\aleph - 1)q_i\wp_{\aleph-1}(q_i) - (\aleph - 1)\wp_{\aleph-2}(q_i)]/\aleph, & & \wp_0(q_i) = 1, \\ & \text{with} & . \\ \wp'_{\aleph}(q_i) = \aleph[q_i\wp_{\aleph}(q_i) - \wp_{\aleph-1}(q_i)]/(q_i^2 - 1), & & \wp_{-1}(q_i) = 0 \end{array} \tag{14}$$

The aforementioned Eqs.(12-14) are contained in subroutine GAUSIN and Eqs.(10,11,14) in subroutine LEGNDR of this model. Also, if the coefficients (χ_i^j) have been calculated, Eq.(9) can be used to compute the angular dependence of scattering phase matrix, as in subroutine PMPLOT.

All that is left now for this section are the computations of the Mie coefficients a_ℓ and b_ℓ which depend on the size parameter and refractive index only. To account for the possibility of a sphere whose refractive index varies radially, the more general Aden and Kerker solution (Kerker, 1969) is used in place of the formal Mie solution. Unfortunately, many investigations have shown that several numerical problems are encountered in obtaining the Aden and Kerker solution (e.g., Kattawar and Hood, 1976; Toon and Ackerman, 1981 among others). To overcome

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these numerical instabilities, Toon and Ackerman (1981) reformulated Kerker's equations for a_ℓ and b_ℓ and their algorithms are adopted here. The keys to achieve numerical stability are: first replacing the Ricatti-Bessel functions with their logarithmic derivatives; if not applicable then, either forming ratios of the terms which have bounded values or eliminating them by using the fundamental relations. Thus, Toon and Ackerman (1981) derived a stable and efficient algorithm for a_ℓ and b_ℓ as

$$a_\ell = \frac{\psi_\ell(z_2)}{\zeta_\ell(z_2)} \left[\frac{U_1(k_1 + U_2U_3) - k_3U_2U_4}{U_5(k_1 + U_2U_3) - k_3U_2U_4} \right] \quad \text{and} \quad b_\ell = \frac{\psi_\ell(z_2)}{\zeta_\ell(z_2)} \left[\frac{U_6(k_2 + U_3U_7) - k_2U_4U_7}{U_8(k_2 + U_3U_7) - k_2U_4U_7} \right], \tag{15}$$

where $\psi_\ell(z) = zj_\ell(z), \zeta_\ell(z) = zh_\ell^2(z)$ and $j_\ell(z), h_\ell^2(z)$ denote respectively the spherical Bessel and Hankel functions. If the complex refractive indices of core (m_c), shell (m_s) and the radii of core (R_c), sphere (R_s) are specified, the variables U in Eq.(15) can be derived

$$\begin{aligned}
U_1 &= k_3\eta_\ell^1(z_1) - k_2\eta_\ell^1(z_2), & U_2 &= k_1\eta_\ell^1(z_4) - k_2\eta_\ell^1(z_3), \\
U_3 &= -i\left[\frac{\zeta_\ell(z_1)}{\psi_\ell(z_1)}\psi_\ell(z_4) - \zeta_\ell(z_4)\right]\psi_\ell(z_4), & U_4 &= [\psi_\ell(z_4)/\psi_\ell(z_1)]^2, \\
U_5 &= k_3\eta_\ell^1(z_1) - k_2\eta_\ell^3(z_2), & U_6 &= k_2\eta_\ell^1(z_1) - k_3\eta_\ell^1(z_2), \\
U_7 &= k_2\eta_\ell^1(z_4) - k_1\eta_\ell^1(z_3), & U_8 &= k_2\eta_\ell^1(z_1) - k_3\eta_\ell^3(z_2).
\end{aligned} \tag{16}$$

Here $\eta_\ell^1(z), \eta_\ell^3(z)$ denote respectively the logarithmic derivatives of $\psi_\ell(z), \zeta_\ell(z)$ and

$$z_1 = k_2R_s, \qquad z_2 = k_3R_s, \qquad z_3 = k_1R_c, \qquad z_4 = k_2R_c, \qquad \text{with}$$

$$k_1 = m_c 2\pi/\lambda, \qquad k_2 = m_s 2\pi/\lambda, \qquad k_3 = 2\pi/\lambda. \tag{17}$$

Before we start to discuss the algorithms for evaluating variables U, there are two practical issues that need to be clarified: first, the special case of a homogeneous sphere and second, the truncation and convergence criteria of the series. Although Kattawar and Hood (1976) demonstrated that a rapid loss of numerical significance occurs when the core no longer contributes to the series, this is not the case in Eqs.(15-16). Their algorithm is adopted for computational efficiency instead. Therefore, Mie theory for homogeneous spheres is applied when two conditions are met: (1) the order of the series is larger than the size parameter of the core ($\ell > 2\pi R_c/\lambda$; a typographical error has been found in Toon and Ackerman, 1981) and (2) the difference between the two series for coated and homogeneous spheres is less than a preferred machine precision (e.g., $|(a_{\ell,h}-a_\ell)/a_{\ell,h}| < 10^{-9}$ and $|(b_{\ell,h}-b_\ell)/b_{\ell,h}| < 10^{-9}$). Mie coefficients for the homogeneous sphere $(a_{\ell,h}, b_{\ell,h})$ are given by (e.g. Bohren and Huffman, 1983)

$$a_{\ell,h} = \frac{[D_\ell(z_1)/m_s + \frac{\ell}{z_2}]\psi_\ell(z_2) - \psi_{\ell-1}(z_2)}{[D_\ell(z_1)/m_s + \frac{\ell}{z_2}]\zeta_\ell(z_2) - \zeta_{\ell-1}(z_2)} \quad \text{and} \quad b_{\ell,h} = \frac{[m_s D_\ell(z_1) + \frac{\ell}{z_2}]\psi_\ell(z_2) - \psi_{\ell-1}(z_2)}{[m_s D_\ell(z_1) + \frac{\ell}{z_2}]\zeta_\ell(z_2) - \zeta_{\ell-1}(z_2)}, \tag{18}$$

where D_ℓ is the logarithmic derivative of ψ_ℓ. D_ℓ satisfies the recurrence relation

$$D_{\ell-1}(z_1) = \frac{\ell}{z_1} - \frac{1}{D_\ell + \ell/z_1} \qquad \text{with} \qquad D_\ell = 0 + i0. \tag{19}$$

Functions ψ_ℓ and ζ_ℓ also can be calculated recursively

$$\begin{aligned} \zeta_\ell(z_2) &= \frac{2\ell-1}{z_2}\zeta_{\ell-1}(z_2) - \zeta_{\ell-2}(z_2), & & \zeta_{-1}(z_2) = \cos z_2 - i\sin z_2, \\ & & \text{with} & \\ \psi_\ell(z_2) &= \Re e[\zeta_\ell(z_2)], & & \zeta_0(z_2) = \sin z_2 + i\cos z_2. \end{aligned} \tag{20}$$

The formal Mie solutions of Eqs.(1,2,5,7,8) are represented as a sum of an infinite series. It has been demonstrated (e.g. Wiscombe, 1980) that the series can be truncated when the order (L_{xx}) is slightly larger than the size parameter of the homogeneous sphere. Toon and Ackerman (1981) also considered the effect of coating material (L_{mx}) on the truncation of the series. By performing several experiments, therefore, we have justified that the order of series (L_{max}) should be sufficient if chosen from the maximum integer of L_{xx} and L_{mx}:

$$L_{xx} = x + 4x^{1/3} + 2 \qquad \text{and} \qquad L_{mx} = 1.1 \cdot x|m_s| + 1, \tag{21}$$

where $x = z_2$ is the size parameter of the entire sphere. If the value of $a_\ell a_\ell^* + b_\ell b_\ell^*$ converges at some preferred machine precisions (e.g. 10^{-14}), the calculation is terminated for computational economy.

The evaluation of U_1, U_2 and $U_5 \sim U_8$ involves the function η_ℓ^1, which is the logarithmic derivative of ψ_ℓ. It has been proven that a numerically stable way of obtaining $\eta_\ell^1(z)$ involves the use of downward recursion as in Eq.(19). In contrast, the function η_ℓ^3 is given by upward recursion (Kattawar and Plass, 1967; Toon and Ackerman, 1981)

$$\eta_\ell^3(z) = -\frac{\ell}{z} + \frac{1}{\ell/z - \eta_{\ell-1}^3(z)} \qquad \text{with} \qquad \eta_0^3(z) = -i. \tag{22}$$

Except for U_3 and U_4, the rest of the variables U (Eq.16) are readily obtained according to Eqs.(19,22). For a real argument such as z_2, the functions $\psi_\ell(z_2)$ and $\zeta_\ell(z_2)$ are bounded and can be calculated as in Eq.(20) by upward recursion. However, for complex arguments such as z_1, z_4 involved in U_4, the function ψ_ℓ is unbounded. However, Toon and Ackerman (1981) found that the ratio $\psi_\ell(z_4)/\psi_\ell(z_1)$ is bounded and is given by

$$\frac{\psi_\ell(z_4)}{\psi_\ell(z_1)} = \frac{\psi_{\ell-1}(z_4)}{\psi_{\ell-1}(z_1)} z_4 \left[\frac{\eta_\ell^1(z_1) + \ell/z_1}{z_4\eta_\ell^1(z_4) + \ell}\right] \quad \text{with} \quad \frac{\psi_0(z_4)}{\psi_0(z_1)} = \frac{A\sin x_4 + Bi\cos x_4}{C\sin x_1 + Di\cos x_1}, \tag{23}$$

where

$$\begin{aligned} z_1 &= x_1 + iy_1, & z_4 &= x_4 + iy_4, \\ A &= \exp(2y_4 + y_1) + \exp(y_1), & B &= \exp(2y_4 + y_1) - \exp(y_1), \\ C &= \exp(2y_1 + y_4) + \exp(y_4), & D &= \exp(2y_1 + y_4) - \exp(y_4). \end{aligned} \tag{24}$$

To evaluate U_3 completely, two additional terms $\zeta_\ell(z_1)\psi_\ell(z_4)$ and $\zeta_\ell(z_4)\psi_\ell(z_4)$ are required. They are

$$\zeta_\ell(z_1)\psi_\ell(z_4) = \frac{\zeta_{\ell-1}(z_1)\psi_{\ell-1}(z_4)z_4}{[\eta_\ell^3(z_1) + \ell/z_1][z_4\eta_\ell^1(z_4) + \ell]} \quad \text{and} \quad \zeta_\ell(z_4)\psi_\ell(z_4) = \frac{\zeta_{\ell-1}(z_4)\psi_{\ell-1}(z_4)z_4^2}{[z_4\eta_\ell^3(z_4) + \ell][z_4\eta_\ell^1(z_4) + \ell]}, \tag{25}$$

where the initial values are

$$\begin{aligned} \zeta_0(z_4)\psi_0(z_4) =& \frac{1}{2} + (\sin^2 x_4 - \frac{1}{2} + i\cos x_4 \sin x_4)\exp(2y_4), \\ \zeta_0(z_1)\psi_0(z_4) =& \frac{1}{2}[(\sin x_1 \sin x_4 - \cos x_1 \cos x_4) + i(\sin x_4 \cos x_1 + \cos x_4 \sin x_1)]\exp(y_1 + y_4) + \\ & \frac{1}{2}[(\sin x_1 \sin x_4 + \cos x_1 \cos x_4) + i(\sin x_4 \cos x_1 - \cos x_4 \sin x_1)]\exp(y_1 - y_4). \end{aligned} \tag{26}$$

These upward recursions have also been shown to be very stable by Toon and Ackerman (1981). Eqs.(15-26) are coded in subroutine COEFAB of this model.

2.2 Chemical species and solubility

The degree of interaction between light and aerosols is best described by the chemical characteristics of the aerosols. As seen from the formal Mie theory, the solutions depend only on the complex refractive indices (m) and optical size parameters (x) of the aerosols. Detailed specification of the refractive index for atmospheric aerosols is not available. In this report, six general categories of chemical species are considered. Shettle and Fenn (1979) compiled and tabulated the first five groups: water soluble (e.g. ammonium, organic compounds, etc.), dust-like (e.g. clay, quartz, etc.), soot (e.g. graphite, elemental carbon, etc.), sea salt (e.g. sodium, potassium chloride, etc.), and liquid water. Figure 1 shows the complex refractive indices of these five groups for wavelengths between $0.2\mu m$ and $40\mu m$. Due to the heavy use of fossil fuels on Earth, sulfuric acid particles have become the most abundant aerosols in the atmosphere. Therefore, Fig. 2 shows the complex refractive index for different concentrations of sulfuric acid solutions, adopted from Palmer and Williams (1975). The complex refractive indices of these six groups of aerosols are contained in the file AEROSL.IND and read by subroutine CRITAB. For general wavelength dependence, the real and imaginary part of the complex refractive index are obtained, respectively, by linear and logarithmic interpolations in subroutine REFIND of this model.

Besides the complex refractive index, the size parameter is the other factor that affects the efficiency of aerosols to absorb and scatter light at fixed wavelengths. Due to aerosol coating or solubility, the physical sizes of aerosols may grow. In a moist environment under supersatuation, water vapor is first absorbed by the soluble aerosol or insoluble core with soluble material coating. Consequently, the water activity not only changes the physical size of the aerosol but also its effective index of refraction. Therefore, the relationship between water uptake and water activity for aerosols is of paramount importance. Great efforts have been expended in this field over the past three decades (*cf.* Hänel, 1976 for a detailed review). Figure 3 depicts the observed water uptake of various aerosol types as a function of water activity. Curves of continental, maritime and urban types are adopted from Hänel (1976), ammonia sulfate from Hänel and Lehmann (1981), and pure sulfuric acid from Nair and Vohra (1975).

To deduce the wet aerosol sizes and effective indices of refraction, an iterative scheme developed by Shettle and Fenn (1979) and extended for coated spheres by Blanchet and List (1983) is adopted here. Under thermodynamic equilibrium with a moist environment at relative humidity RH, the

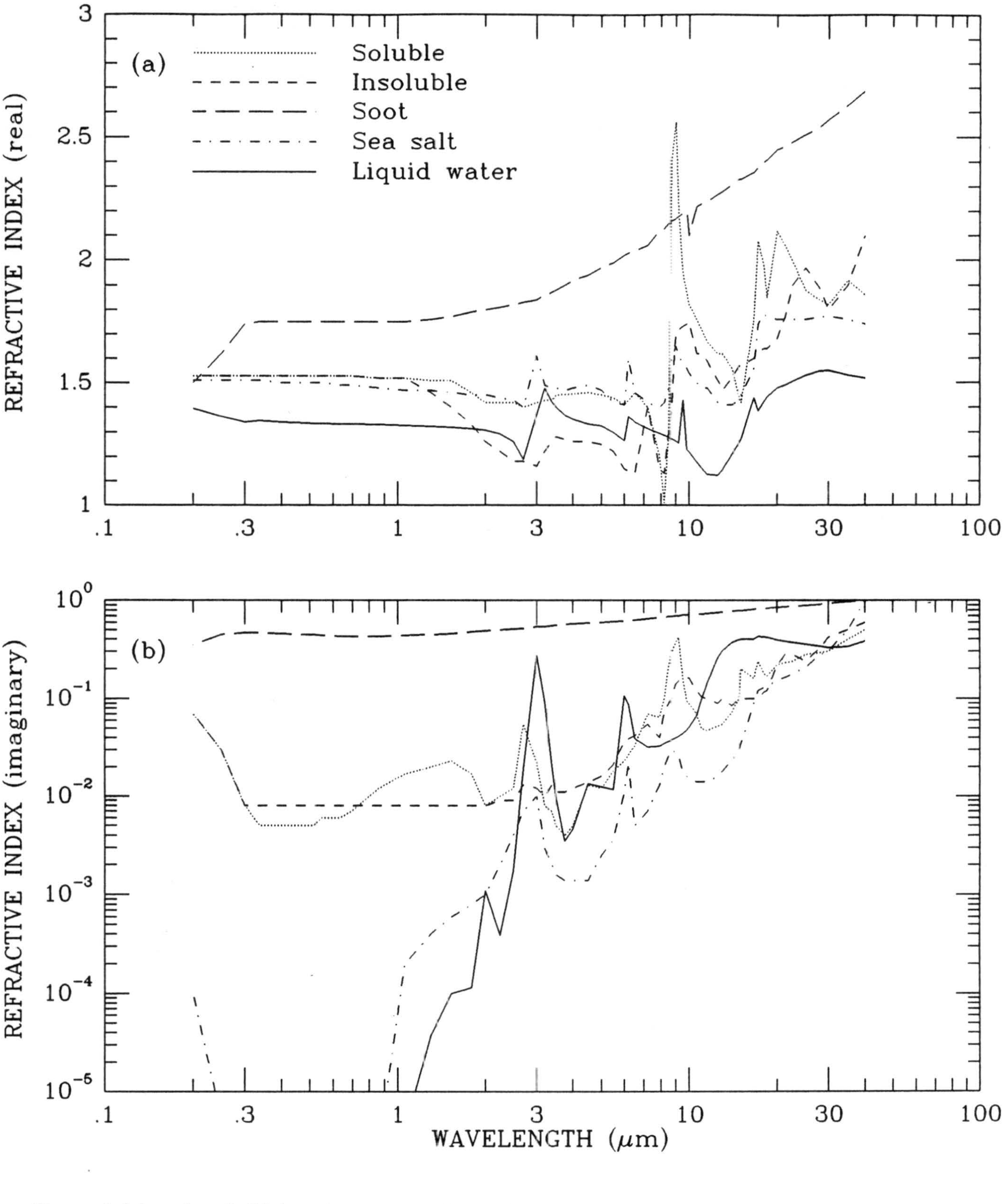


Figure 1 (a) real and (b) imaginary part of complex refractive indices for five general groups of aerosols (after Shettle and Fenn, 1979).

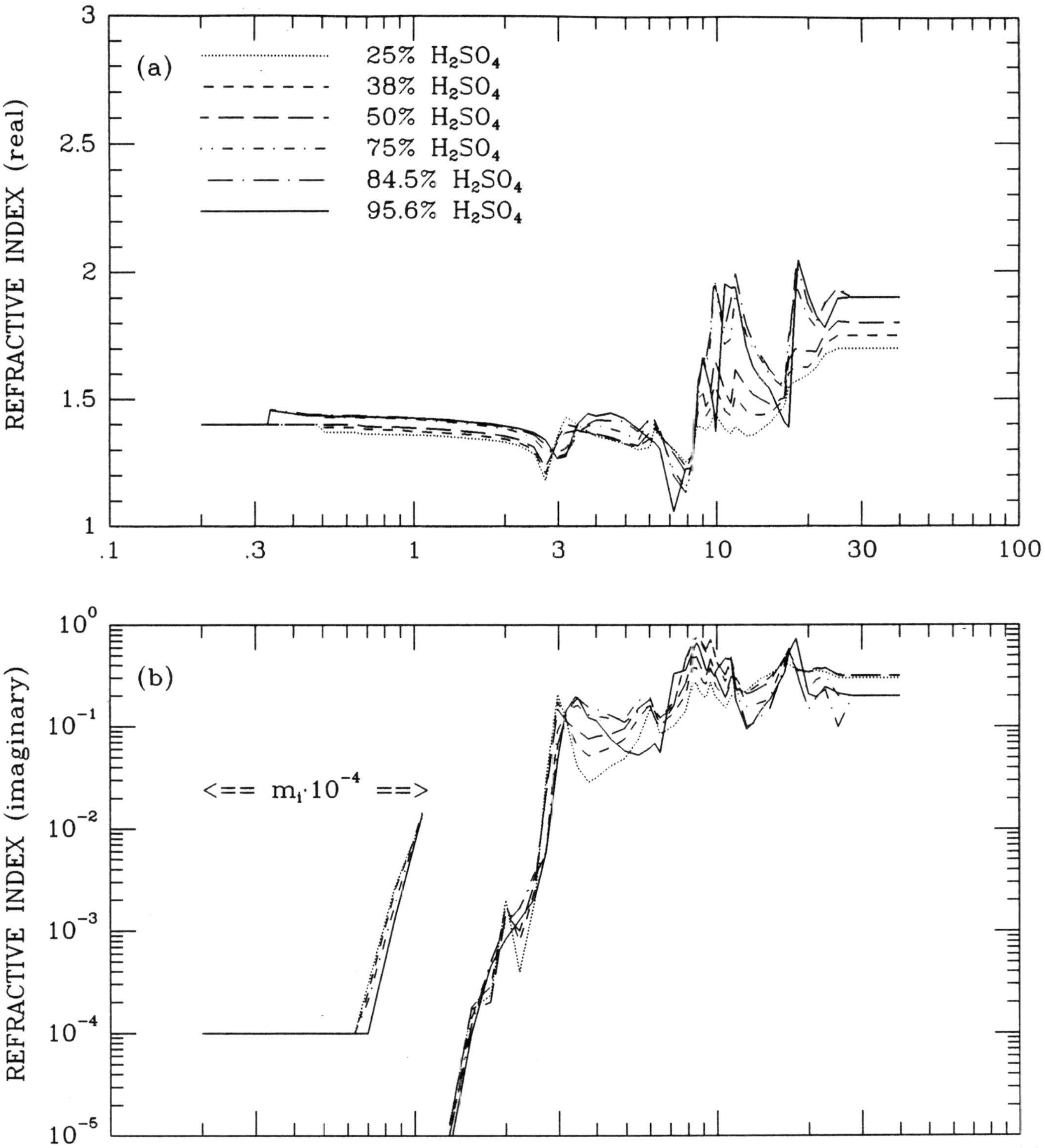


Figure 2 (a) real and (b) imaginary part of complex refractive indices for sulfuric acid solution at six different concentrations (after Palmer and Williams, 1975).

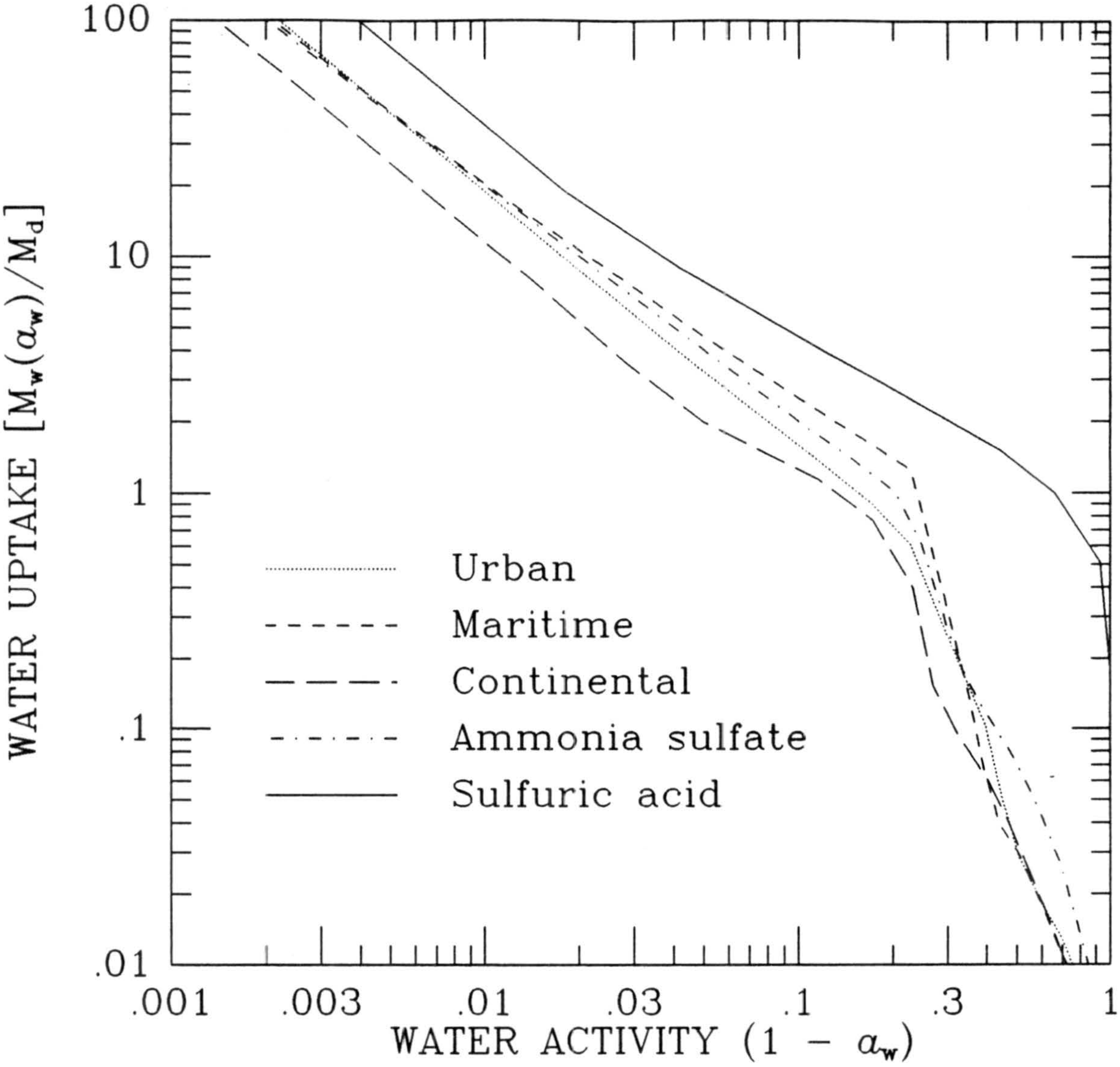


Figure 3 Water uptake of various aerosol types as a function of water activity (after Hänel, 1976; Hänel and Lehmann, 1981; Nair and Vohra, 1975).

water activity (a_w) of soluble aerosol at radius r (μm) can be expressed as

$$a_w(r) = RH \cdot \exp\left[-\left(\frac{2\sigma V_w}{R_w T}\right)\frac{1}{r(a_w)}\right], \tag{27}$$

where σ is the surface tension on the wet aerosol surface, V_w the specific volume of liquid water, R_w the gas constant for water vapor and T the absolute temperature (^oK). This is essentially a correction of RH by the Kelvin effect. However, as examined by Hãnel (1976), the surface tension can be replaced by that of liquid water only and this introduces errors of only a few percent. Therefore, Eq.(27) may be further simplified as

$$a_w(r) = RH \cdot \exp\left[\frac{-0.314688}{T\, r(a_w)}\right] \tag{28}$$

and is valid for the temperature range between 245^oK and 300^oK. The growth in aerosol size due to the condensation of water vapor is

$$r(a_w) = r_d\left[1 + \rho\frac{M_w(a_w)}{M_d}\right]^{1/3}, \tag{29}$$

where r_d denotes the radius of dry aerosol, ρ the density of aerosol relative to that of liquid water, and $M_w(a_w)/M_d$ the water uptake of aerosol (or the mass ratio of condensed water to dry aerosol).

Since the water activity exists in both sides of Eqs.(28-29), there is no analytic expression for aerosol size as a function of RH. Shettle and Fenn (1979) suggested that the most stable and economical scheme is to solve Eqs.(28-29) iteratively until a convergence is reached. Once the radius of wet aerosol is found, the effective index of refraction ($\bar{m}$) for the soluble aerosol which is homogeneously mixed with liquid water, is simply the volume weighted average of

$$\bar{m} = m_w + (m_h - m_w)\left[\frac{r_d}{r(a_w)}\right]^3, \tag{30}$$

where m_h and m_w represent the complex refractive indices of soluble aerosol and liquid water, respectively. When aerosol is composed of many soluble materials such as soluble core with acid-coating shell, the form of Eq.(30) is slightly modified. More discussion on mass/volume partition and the concept of effective-medium will be given in Section 3.2. The aforementioned Eqs.(28-29) are coded in subroutine COATIN and Eq.(30) in subroutine COATMI of this model.

3. Polydispersed Particles

Aerosols sampled *in situ* are generally not of a single-sized nor are aerosol distributions single-moded. Instead, aerosols often have sizes in ranges referred to as the nuclei mode, the accumulation mode and the coarse mode. In most cases the different modes are associated with varying aerosol species (Friedlander, 1970; Nilsson, 1979; Blanchet and List, 1983). For example, most of the sea salt aerosols are in the coarse mode. The aerosol size distribution of Los Angeles smog was well fitted by Davies (1974) using up to seven lognormal distributions, while Egan (1982) used generalized gamma distributions to simulate and examine a variety of aerosol measurements. Therefore, a wide range in composition of aerosol species can be modeled by changing the parameters of these analytic functions, and their bulk optical properties can also be examined extensively in terms of these distributions.

3.1 Size distribution

In practice, a volume of aerosols is a collection of discrete sized particles with a number concentration, which is commonly defined as particles per unit volume per unit radius $n(r)$, that varies with aerosol size. These grouped data are often presented in the form of a histogram. However, we may conveniently characterize such a polydispersion in terms of some type of analytical function. The lognormal and generalized gamma distribution functions are discussed here.

The lognormal distributions are frequently used in describing aerosol size and/or volume distributions (e.g. Davies, 1974), due to their unique properties discussed below. The lognormal size distribution has the form

$$n(r) = \frac{N_o}{r\sqrt{2\pi}\ln\sigma_g}\exp\left[-\frac{1}{2}\left(\frac{\ln r/r_m}{\ln\sigma_g}\right)^2\right], \tag{31}$$

where N_o is the total (volume) concentration of aerosols, r_m is the median (or geometric mean) radius and σ_g is the geometric standard deviation. By performing a mathematical transformation and algebraic manipulation, the p's moment of radius (r^p) with respect to the size distribution is readily obtained

$$\int_0^\infty \alpha r^p n(r)dr = \alpha r_m^p f_{\ln}(p) \int_0^\infty \frac{N_o}{r\sqrt{2\pi}\ln\sigma_g} \exp\left[-\frac{1}{2}\left(\frac{\ln r/r_{m,p}}{\ln\sigma_g}\right)^2\right] dr, \tag{32}$$

where

$$f_{\ln}(p) = \exp\left[\frac{p\ln\sigma_g}{\sqrt{2}}\right]^2 \qquad \text{and} \qquad r_{m,p} = r_m \exp[p(\ln\sigma_g)^2]. \tag{33}$$

These unique properties (e.g. Eqs.[32-33]), as shown in Fig. 4, are useful in characterizing the microphysics of aerosols. For example, when a particle number density is required (as in Mie computations), higher moments with known $r_{m,p}$ and fixed σ_g (e.g. $p = 3$ for mass/volume distributions as in Eq.[32]) can be easily transferred into a number density distribution by using the transformation of Eq.(33) to infer r_m. Moreover, the effective radius (r_{eff}), which is the ratio of third to second moment of the size distribution (Hansen and Travis, 1974), is an important parameter in characterizing single scattering properties and can be determined by

$$r_{eff} = r_m \exp\left[\frac{5}{2}(\ln\sigma_g)^2\right]. \tag{34}$$

The aerosol mass loading (M_h) and the cross sectional area per unit volume (A_h) are readily obtained as

$$M_h = \frac{4}{3}\pi\rho_{haze}N_o r_m^3 f_{\ln}(3) \qquad \text{and} \qquad A_h = \pi N_o r_m^2 f_{\ln}(2). \tag{35}$$

Another commonly used function is the generalized gamma distribution

$$n(r) = \frac{N_o}{\Gamma(\gamma)r_m}\left(\frac{r}{r_m}\right)^{\gamma-1} \exp\left(-\frac{r}{r_m}\right), \tag{36}$$

where Γ is the gamma function, r_m now represents a characteristic radius of the distribution and γ is a constant which is often an integer. The characteristic radius r_m and γ are closely related to the mode, mean and effective radii

$$\begin{cases} r_{mode} = (\gamma - 1)r_m \\ r_{mean} = \gamma r_m \\ r_{eff} = (\gamma + 2)r_m \end{cases} \qquad \text{or} \qquad \begin{cases} r_m = r_{mean} - r_{mode} \\ \gamma = r_{mean}/(r_{mean} - r_{mode}). \end{cases} \tag{37}$$

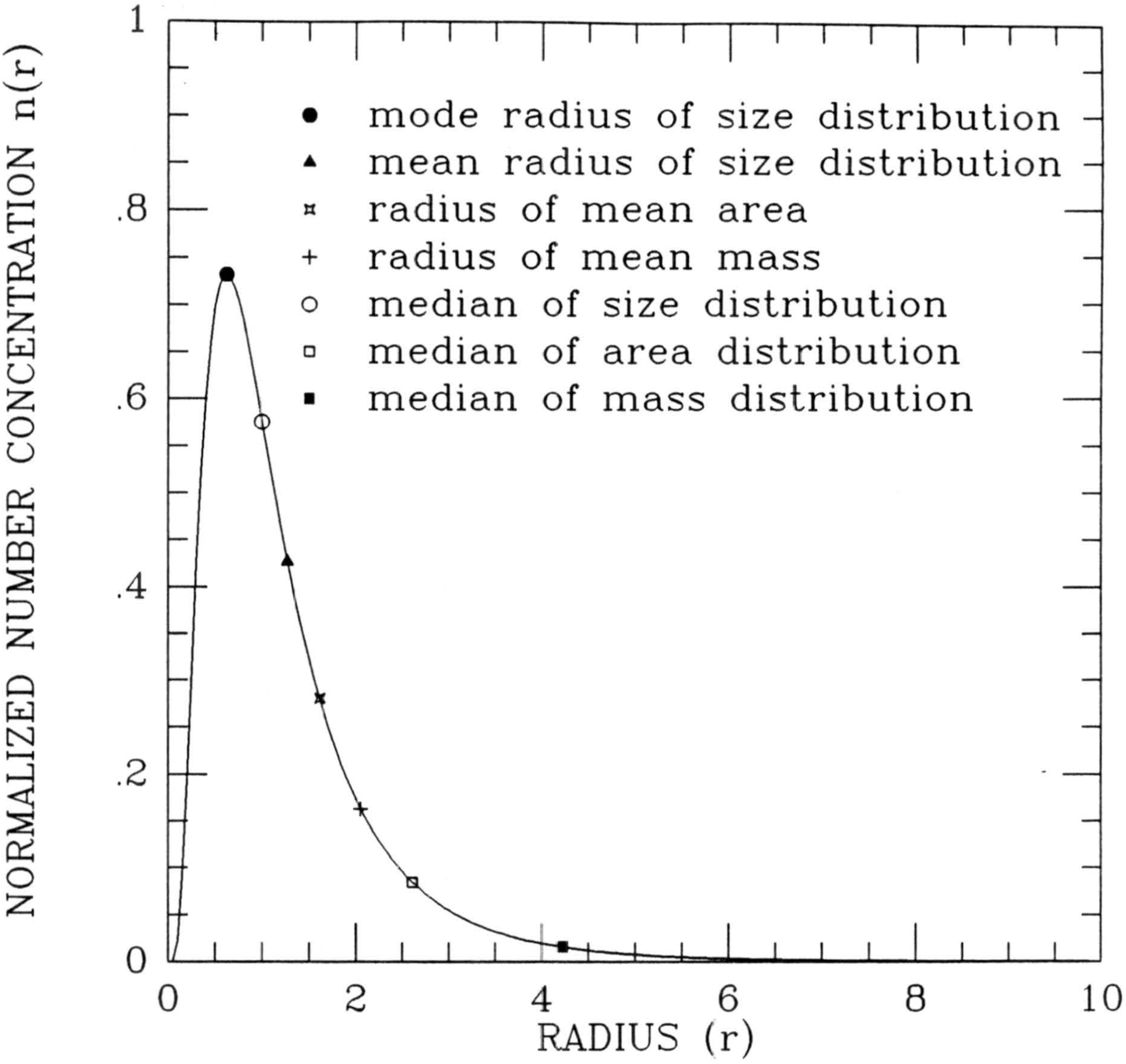


Figure 4 An example of the lognormal distribution in normalized linear form for $r_m = 1$ and $\sigma_g = 2$.

Parameter r_m represents the skewness of the distribution whereas γ defines the shape of the distribution such that large values of γ correspond to broad distributions. Typical examples, illustrated in Fig. 5, are C-type cloud and H-type haze particles of Deirmendjian (1969). Similarly, M_h and A_h associated with the generalized gamma distribution have the same forms as those of Eq.(35), except that $f_{\rm ln}$ is replaced by $f_{\rm gm}$ and $f_{\rm gm}(p) = \Gamma(p+\gamma)/\Gamma(\gamma)$. The aforementioned Eqs.(31-33,36-37) are coded in subroutine DLNDLR of this model.

3.2 Aerosol mixture and partition

Microscopic analyses of atmospheric constituents reveal that aerosols agglomerate in complex ways. As will be demonstrated in Section 4, different combinations of aerosol species produce changes of the effective optical characteristics of the aerosols which in turn influence the atmospheric visibility in important ways. In general, there are three types of mixture that can be readily approximated by physical models: external, internal, and volume mixture (e.g. Ackerman and Toon, 1981). Figure 6 shows these three types of aerosol mixtures. The properties of the individual chemical species that comprise the mixture are summed to represent the effective properties of an external mixing, in which aerosols are mixed as distinct particles without interaction. External mixing is the most frequent assumption used in the literature (Fig. 6a). Internal mixing, on the other hand, is defined such that aerosols exist as a core and/or a shell to form a coated particle. If the aerosol species are combined in fixed proportions, the combination is referred to as a volume mixture.

Chýlek *et al.* (1984) proposed and demonstrated another type of volume mixture, the random mixture illustrated in Fig. 6d. They used the so-called dynamic effective-medium approximation to evaluate the refractive index of a composite material. However, Bohren (1986) raised significant concerns regarding the applicability and validity of this type of volume mixture (e.g. concepts of effective-medium). In this report, we consider the volume mixture as if the aerosols are mixed homogeneously (Fig. 6c). For example, the effective indices of refraction are taken to be a combination by volume of the original dry soluble compound and the solution (e.g. water and/or

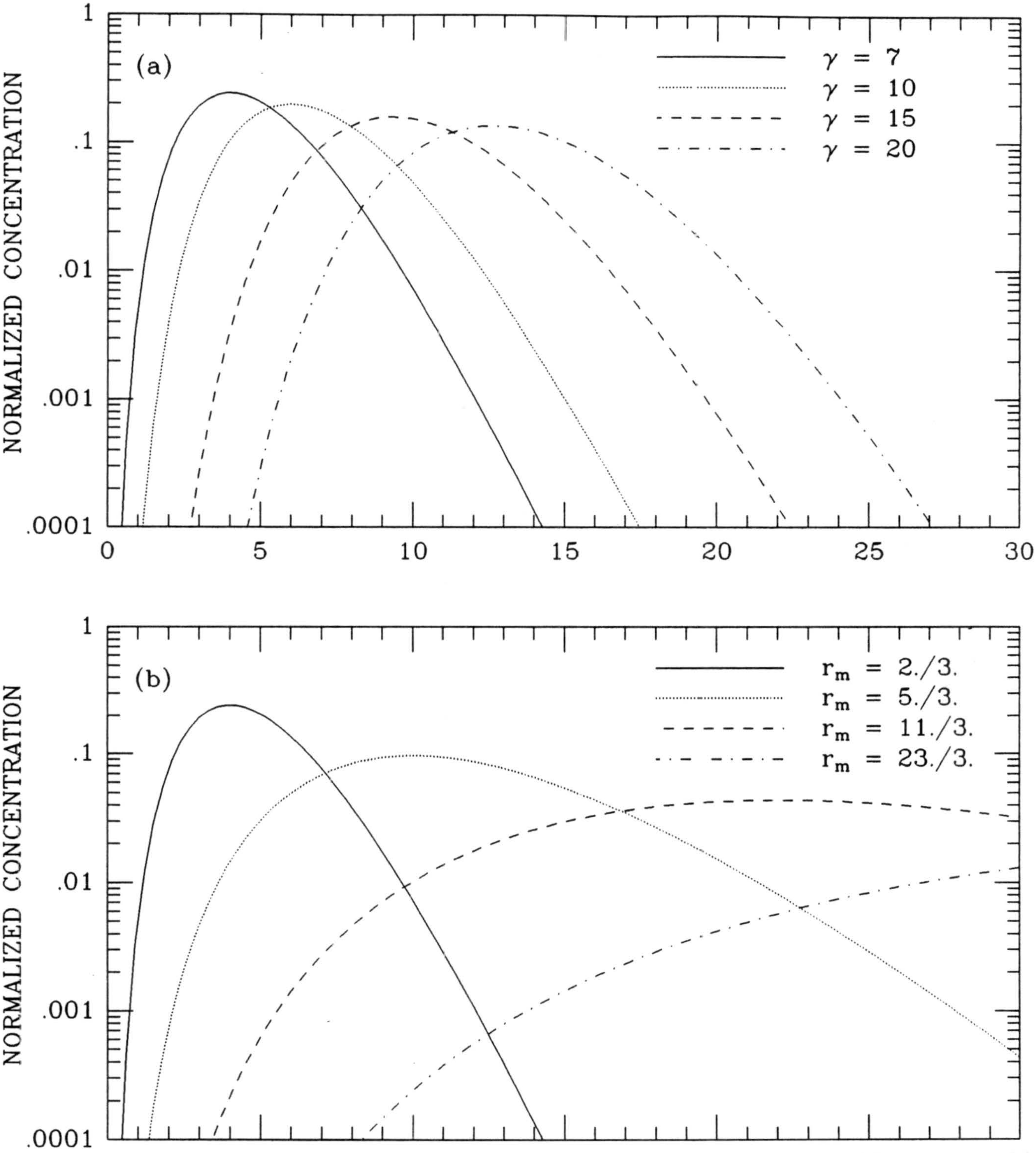
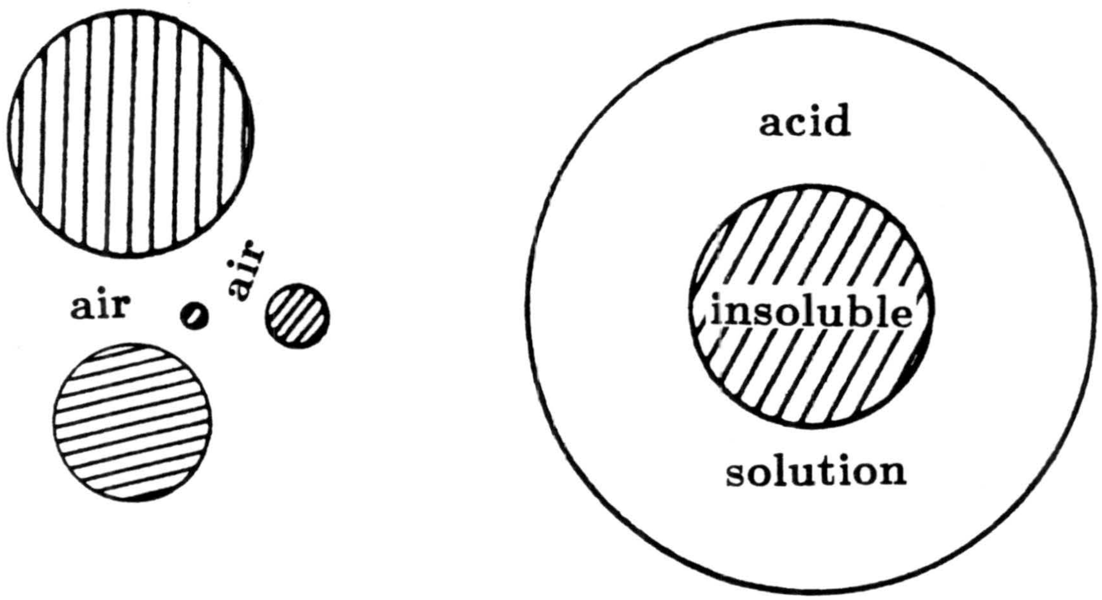
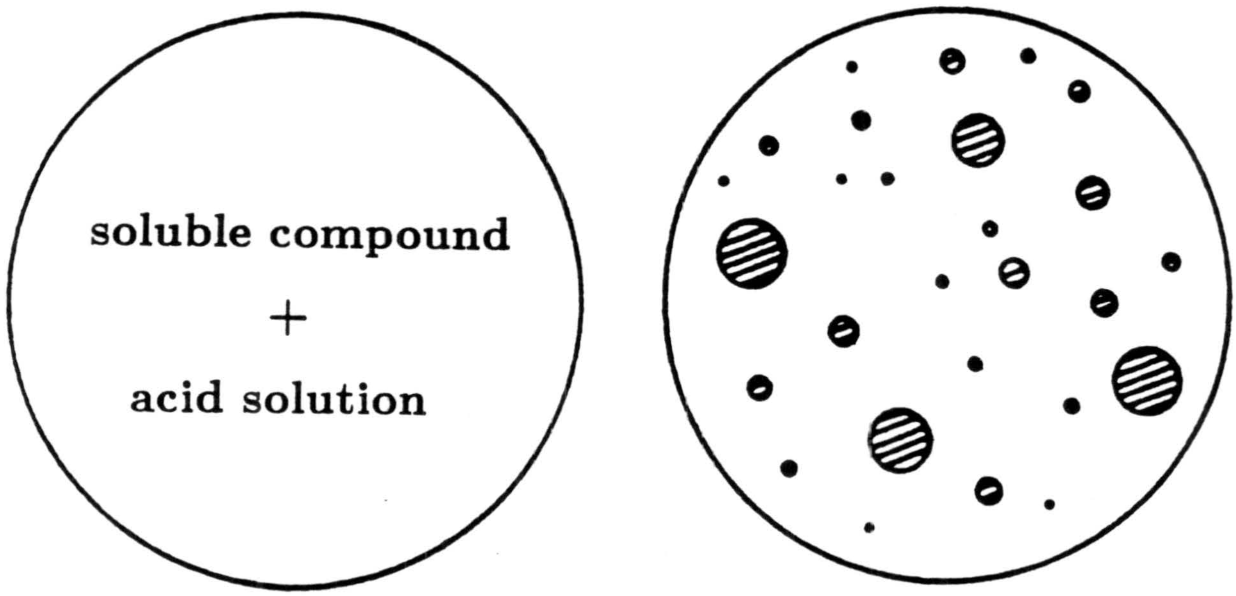


Figure 5 An example of the generalized gamma distribution for Deirmendjian C1-Cloud at $r_m = 2/3$ and $\gamma = 7$. Shown are (a) the broadness and (b) the skewness of the distribution.



(a) External mixture

(b) Internal mixture



(c) Volume mixture homogeneously

(d) Volume mixture randomly

Figure 6 Schematic representation of aerosol mixtures: (a) external mixture, (b) internal mixture with coating structure, and volume mixture for (c) homogeneously and (d) randomly.

sulfuric acid) when they are mixed. For the case of insoluble compounds, then the particle is considered to be an internal mixture with a coating structure (Fig. 6b).

According to Bigg (1980), aerosols sampled in the atmosphere are often composed of sulfate compounds. In the northern hemisphere some types of aerosol coating by sulfuric acid are commonly observed. Although the mixture of these aerosols is known qualitatively, it is not clear in a quantitative sense how the foreign material is distributed among all the host particles to form aerosol composites. In an effort to quantify the aerosol composite, we propose the term "aerosol partition" to represent the proportion of mass/volume between the foreign and host aerosols. From some observations (e.g. Hoff *et al.*, 1983), small particles of size less than $4\mu m$ appear to have a mass/volume proportional partition. Considering j's groups of non-acid aerosol mass ($\sum_j M_j$) coated by M_a sulfuric acid mass, then, according to the mass/volume partition, it is defined

$$f_h^j = \frac{M_j}{\sum_i M_i} \qquad \text{and} \qquad 1 = f_{haze} + f_{acid} = \sum_j \left[\frac{M_j}{\sum_i M_i + M_a}\right] + \frac{M_a}{\sum_i M_i + M_a}, \tag{38}$$

where f_h^j is the mass fraction of the jth non-acid aerosol over the total mass of non-acid aerosols. f_{haze} and f_{acid} denote the mass fractions of non-acid and acid aerosols to the total mass, respectively. After partitioning, the average density ($\bar{\rho}_j$), volume (V_h^j) and acid-coating volume (V_a^j) of the jth non-acid aerosol can be obtained via

$$\begin{aligned}
\bar{\rho}_j &= \frac{M_j + f_h^j M_a}{M_j/\rho_j + f_h^j M_a/\rho_a} = \frac{f_h^j[\sum_i M_i + M_a]}{f_h^j[\sum_i M_i/\rho_j + M_a/\rho_a]} = \left[\frac{f_{haze}}{\rho_j} + \frac{f_{acid}}{\rho_a}\right]^{-1}, \\
V_h^j &= \frac{M_j}{\rho_j} = \frac{M_j}{M_j + f_h^j M_a}\frac{V_j\bar{\rho}_j}{\rho_j} = f_{haze} V_j \frac{\bar{\rho}_j}{\rho_j}, \\
V_a^j &= \frac{f_h^j M_a}{\rho_a} = \frac{f_h^j M_a}{M_j + f_h^j M_a}\frac{V_j\bar{\rho}_j}{\rho_a} = f_{acid} V_j \frac{\bar{\rho}_j}{\rho_a},
\end{aligned} \tag{39}$$

where V_j is the total volume of the jth aerosol with acid coating. Eq.(38) is used in the main program AEROSL to determine the mass fractions and Eq.(39) is utilized in subroutine COATIN to compute the aerosol partition.

Noted here after aerosol partition (V), the effective index of refraction for soluble aerosol mixed with acid solution (i.e. $\bar{m}$ of Eq.[30]) should read

$$\bar{m} = \frac{m_h V_h + m_w V_w + m_a V_a}{V_h + V_w + V_a} = m_a + (m_h - m_a)\frac{V_h}{V} + (m_w - m_a)\frac{V_w}{V}, \tag{40}$$

where m_h and m_w represent the complex refractive indices of soluble aerosol and liquid water, respectively. To evaluate Eq.(40), the water uptake as in Eq.(29) is used twice to compute separately the amount of water vapor condensed on soluble aerosol (V_w) and on sulfuric acid for becoming acid solution (V_a). The concentration of acid solution (H_2SO_4, in %) is a function of the water uptake of sulfuric acid (*cf.* Eq.[29])

$$H_2SO_4 = \frac{M_a}{M_a + M_w} = [M_w/M_a + 1]^{-1} . \tag{41}$$

Thus, m_a is the complex refractive index of acid solution at this particular concentration. In practice, however, the last term in Eq.(40) does not contribute much to $\bar{m}$ (*cf.* Figs. 1-2) and can be neglected. Hence, Eq.(40) assumes the same form as that of Eq.(30), except that m_w is replaced by m_a. Eq.(41) is used in subroutine COATIN of this model.

3.3 Integrated optical properties

A volume of aerosols typically contains a mixture of particles of different sizes and species. The bulk optical properties of aerosols (e.g. extinction coefficient β_{ext}, probability of scattering $\tilde{\omega}$, and scattering phase matrix P_μ), which are ultimately used in multiple scattering radiation models, can be computed for each individual aerosol species (j) and the associated size distributions (n^i)

$$\begin{aligned} \beta^j_{sca} &= \frac{\pi}{k^3} \int_0^\infty x^2 Q_{sca}(x) n^i(x)\, dx, \\ \beta^j_{ext} &= \frac{\pi}{k^3} \int_0^\infty x^2 Q_{ext}(x) n^i(x)\, dx, \\ P^j(\mu) &= \frac{\pi}{k^3 \beta^j_{sca}} \int_0^\infty x^2 Q_{sca}(x) P(x,\mu) n^i(x)\, dx, \end{aligned} \tag{42}$$

where $k = k_3 = 2\pi/\lambda$ and $\tilde{\omega}^j = \beta^j_{sca}/\beta^j_{ext}$. The final optical properties of the combination of all aerosol species are then weighted properly according to their partitions in total volume (Blanchet and List, 1983). Therefore, it is assumed that each group of chemical species within each size distribution (n^i) has the same shape and the final optical properties (FOP) follow from

$$(\text{FOP}) = \sum_i \left[\frac{\sum_j (\text{FOP})^i_j f^j_h/\bar{\rho}_j}{\sum_j f^j_h/\bar{\rho}_j} \right] . \tag{43}$$

The final physical properties can be obtained in a similar form as that of Eq.(43), if each of them is derived in each size distribution for different water uptake. By defining the mass fraction of water vapor (M_w) condensed on the dry aerosol mass (M_h) as

$$f_m^j = \frac{M_w}{M_h} = \frac{V_{wet} - V_{dry}}{\bar{\rho}_j V_{dry}} \tag{44}$$

we yield, for instance, the averaged density of wet jth aerosols for a particular size distribution (n^i)

$$\rho_j^i = \frac{M_h + M_w}{V_{wet}} = \frac{1 + f_m^j}{1/\bar{\rho}_j + f_m^j}. \tag{45}$$

Equations (42-45) are coded in the main program AEROSL of this model. The rest of the physical properties, such as total mass, volume, and aerosol concentration, assume the same form as Eq.(43). Before ending this section, a flow chart is presented in Fig. 7 sketching the broad picture of this model.

4. Sample Results and Discussion

Published results of Mie computations abound in the literature. Of these, the most convenient for model comparison are the tabulated results of Deirmendjian (1969). We have arbitrarily chosen his C1-cloud for comparison. A typical input to the model (e.g. the case in page 205 of Deirmendjian, 1969) is given in Appendix B, together with the output results. As is evident from the model output, the extinction coefficient, probability of scattering and scattering phase matrix agree very well with those of Deirmendjian (1969).

Some other comparisons for model validation can be found in the work of Tsay *et al.* (1990). Here we concentrate on demonstrating and discussing the physical and optical properties of the aerosols from the model results. Figure 8 shows, for example, an aerosol size distribution commonly observed in the atmosphere (e.g. Bigg, 1980; Heintzenberg, 1980). Its corresponding characteristic parameters used in the lognormal functions are listed in Table 1 (Blanchet and List, 1983). If each mode of the size distribution is associated with one pure substance, which is assigned as soot, dust-like and sea salt aerosols, the bulk optical properties at 0.55μm wavelength can be obtained

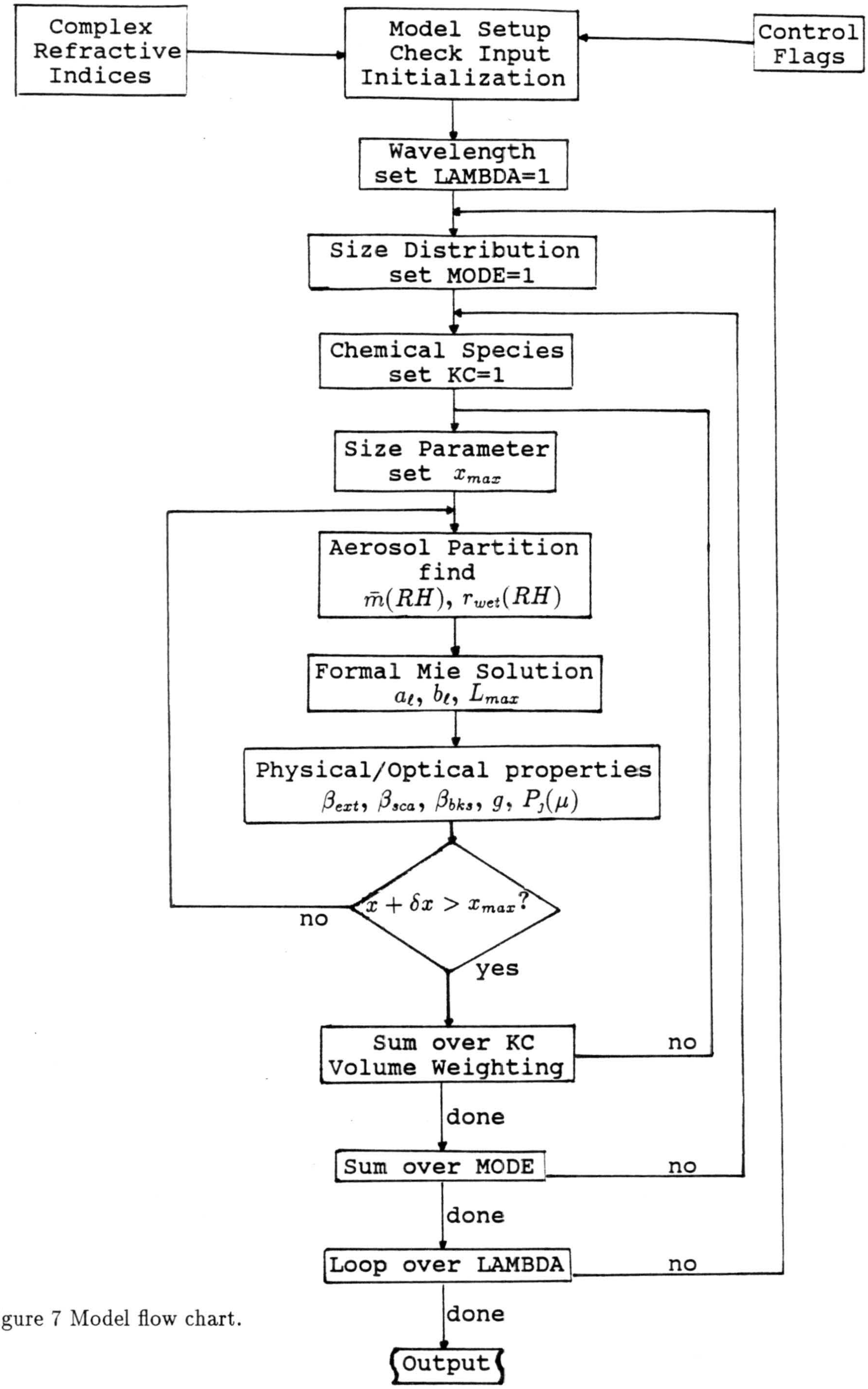


Figure 7 Model flow chart.

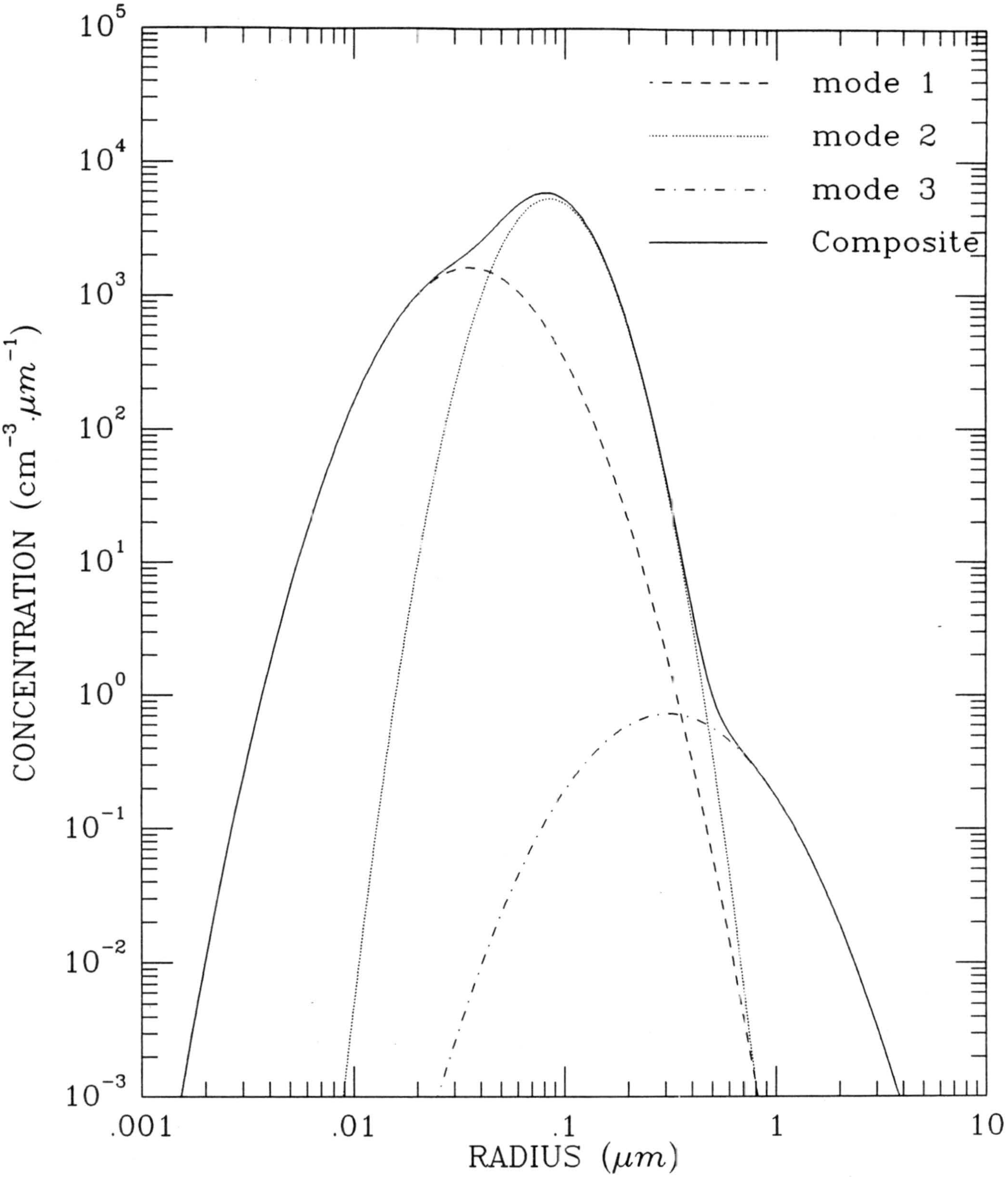


Figure 8 Size distribution of an aerosol model which is composed of three lognormal functions. The characteristic parameters of each mode are listed in Table 1.

Table 1. Size distribution parameters for an aerosol model having lognormal functions. r_m stands for the median radius (μm), σ_g for geometric standard deviation and N_o for total aerosol concentration (cm^{-3}).

Mode	r_m	σ_g	N_o
1	0.05	1.8	100
2	0.10	1.5	500
3	0.50	2.0	0.5

Table 2. Physical and optical properties for an aerosol model having the size distribution shown in Fig. 8. V_{dry} denotes the total volume of dry aerosols ($\mu m^3.cm^{-3}$); m, the index of refraction at $0.55\mu m$ wavelength; β_{ext}, the extinction coefficient (Km^{-1}); $\tilde{\omega}$, the single scattering albedo; and g, the asymmetry factor.

	physical properties				optical properties		
	mode	N_o	V_{dry}	m	β_{ext}	$\tilde{\omega}$	g
soot	1	100	0.248	1.75-0.440i	0.002781	0.39803	0.5442
dust-like	2	500	4.388	1.53-0.008i	0.030482	0.95865	0.6213
sea-salt	3	0.5	2.246	1.50-0.000i	0.002471	1.00000	0.7245
total	-	600.5	6.882	—	0.035734	0.91787	0.6265

from Eqs.(1-3,8,41). Results of such calculations are listed in Table 2 along with the corresponding physical properties of the aerosols. The calculated optical properties can be incorporated directly into most multiple scattering schemes of radiative transfer for other investigations. For visibility studies, the scattering phase matrix is of paramount importance for determining the path radiance. Figure 9 shows the intensity of scattering phase matrix for individual components as well as the total aerosol mixture. The scattering patterns for soot and dust-like aerosols are generally smooth in all directions, with a minimum near 130°. Since sea salt aerosols are relatively large and give rise to almost pure scattering, two extreme scattering features are displayed in the forward and backward directions. When all aerosols are mixed externally, the scattering pattern of the final composite aerosols is the weighted sum of the individual constituent scattering characteristics.

To explore the effect of relative humidity on aerosol physical and optical properties, a dry aerosol model is defined and tabulated in Table 3a. The aerosol compositions in each mode of the size distributions (same as in Table 1) are arbitrarily chosen to reflect their characteristic sizes. In a moist environment, soot and dust-like particles are not soluble. But with a coating of sulfuric acid they grow through the absorption of water vapor by the acid. In this case, bulk physical and optical properties for three relative humidities can be computed using a internal mixture and the results are listed in Table 3b. A nonlinear relation between the bulk optical properties and relative humidity is observed as expected. Figure 10 shows the intensity of scattering phase matrix for relative humidities of 0%, 50% and 90% at wavelength $0.55\mu m$. The most pronounced change in the scattering pattern is the dramatic increase in the forward peak when relative humidity is increased. This nonlinearity can be seen from the values listed in Table 3b in which the effective radius is doubled for an increase in relative humidity from 50% to 90% while only a 10% increase in particle size occurs for moisture changes from dry to 50% relative humidity. The sample input/output for this case can also be found in Appendix B. Also, the wavelength dependence of the intensity of scattering phase matrix is shown in Fig. 11 for the three primary colors of red ($0.63\mu m$), green ($0.55\mu m$) and blue ($0.45\mu m$). The major difference among these three scattering patterns is due

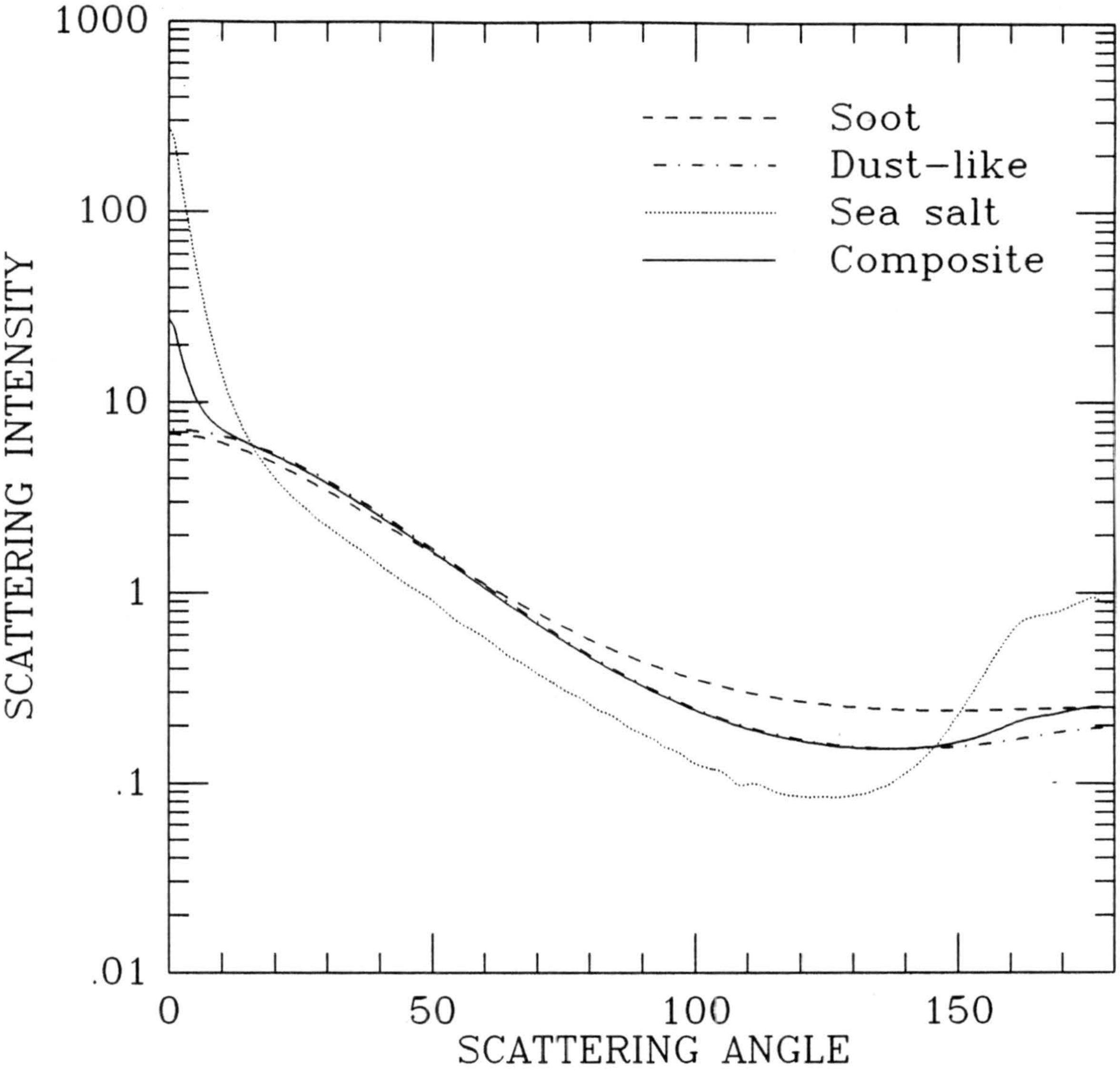


Figure 9 Scattering pattern for soot, dust-like, sea salt, and total aerosol composite at $0.55\mu m$ wavelength and dry environment (see text).

Table 3. As in Table 2, except for different aerosol compositions (%), relative humidities ($R.H.$, in %) and wavelengths. Notations are the same as in Table 2, except that V_{wet} and $r_{eff,wet}$ denote respectively the total volume and the effective radius of wet aerosols.

(a)

	soluble	dust-like	soot	sea-salt	H_2SO_4-acid
composition mode-1	15	10	60	0	15
composition mode-2	20	50	15	0	15
composition mode-3	10	10	5	60	15
aerosol density	1.85	1.85	2.0	2.45	1.835
type of activity	continental	–	–	maritime	H_2SO_4
solubility	soluble	insoluble	insoluble	soluble	soluble
refractive index $m_{0.45}$	1.53-0.005i	1.53-0.008i	1.75-0.454i	1.50-0.000i	1.40-0.000i
refractive index $m_{0.55}$	1.53-0.006i	1.53-0.008i	1.75-0.440i	1.50-0.000i	1.37-0.000i
refractive index $m_{0.63}$	1.53-0.006i	1.53-0.008i	1.75-0.430i	1.49-0.000i	1.37-0.000i

(b)

$R.H.$	$r_{eff,wet}$	V_{wet}	λ	β_{ext}	$\tilde{\omega}$	g
00%	0.211	6.882	0.45	0.048628	0.84874	0.6607
			0.55	0.037370	0.82368	0.6230
			0.63	0.030454	0.80384	0.5927
50%	0.241	9.737	0.45	0.062292	0.86905	0.6827
			0.55	0.048444	0.85026	0.6481
			0.63	0.039793	0.83517	0.6193
90%	0.407	26.11	0.45	0.109188	0.91377	0.7306
			0.55	0.085507	0.90391	0.7111
			0.63	0.071923	0.89703	0.6892

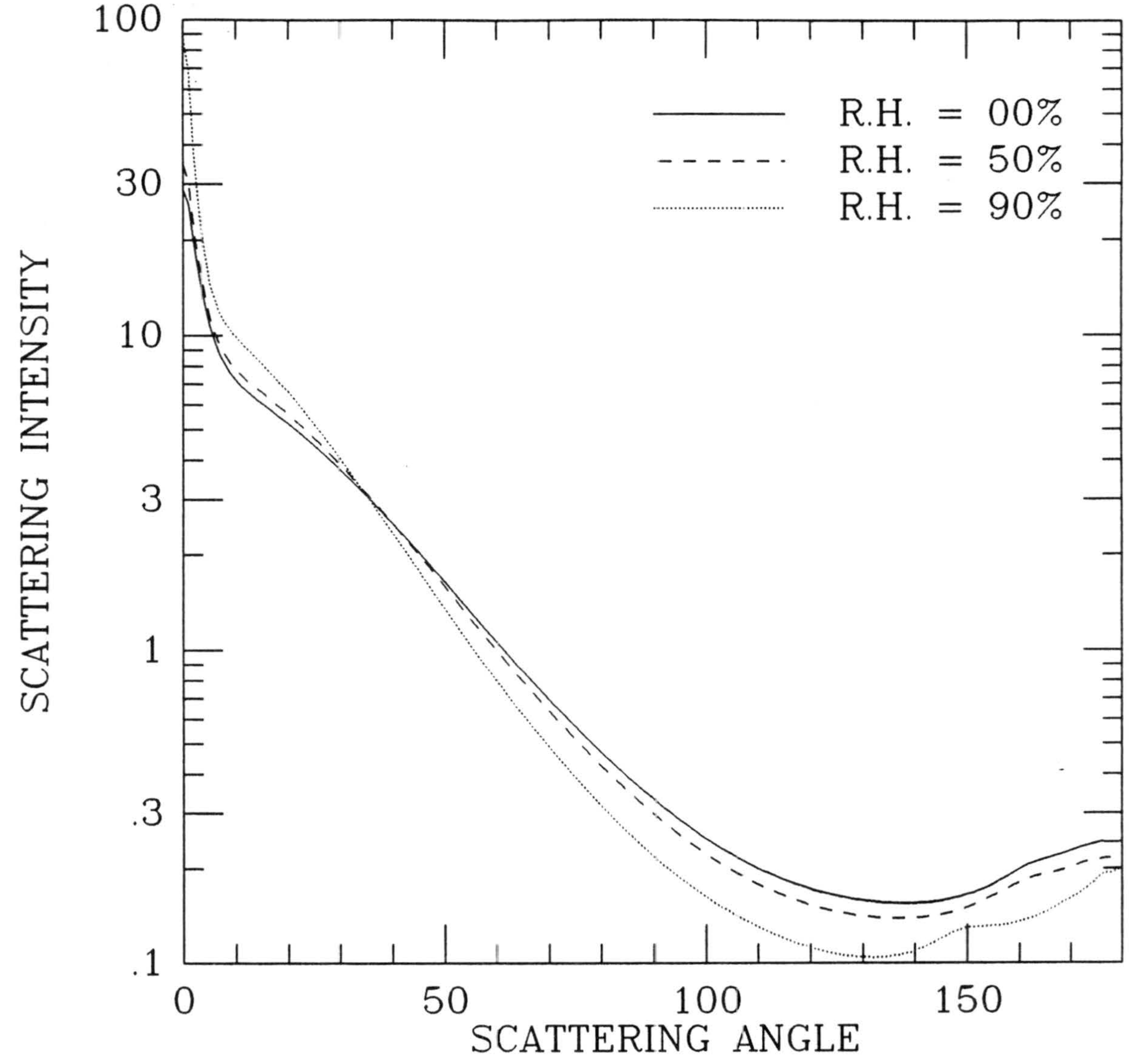


Figure 10 Scattering pattern of aerosol composite, defined as in Table 3a, for $0.55\mu m$ wavelength at 0%, 50%, and 90% relative humidity.

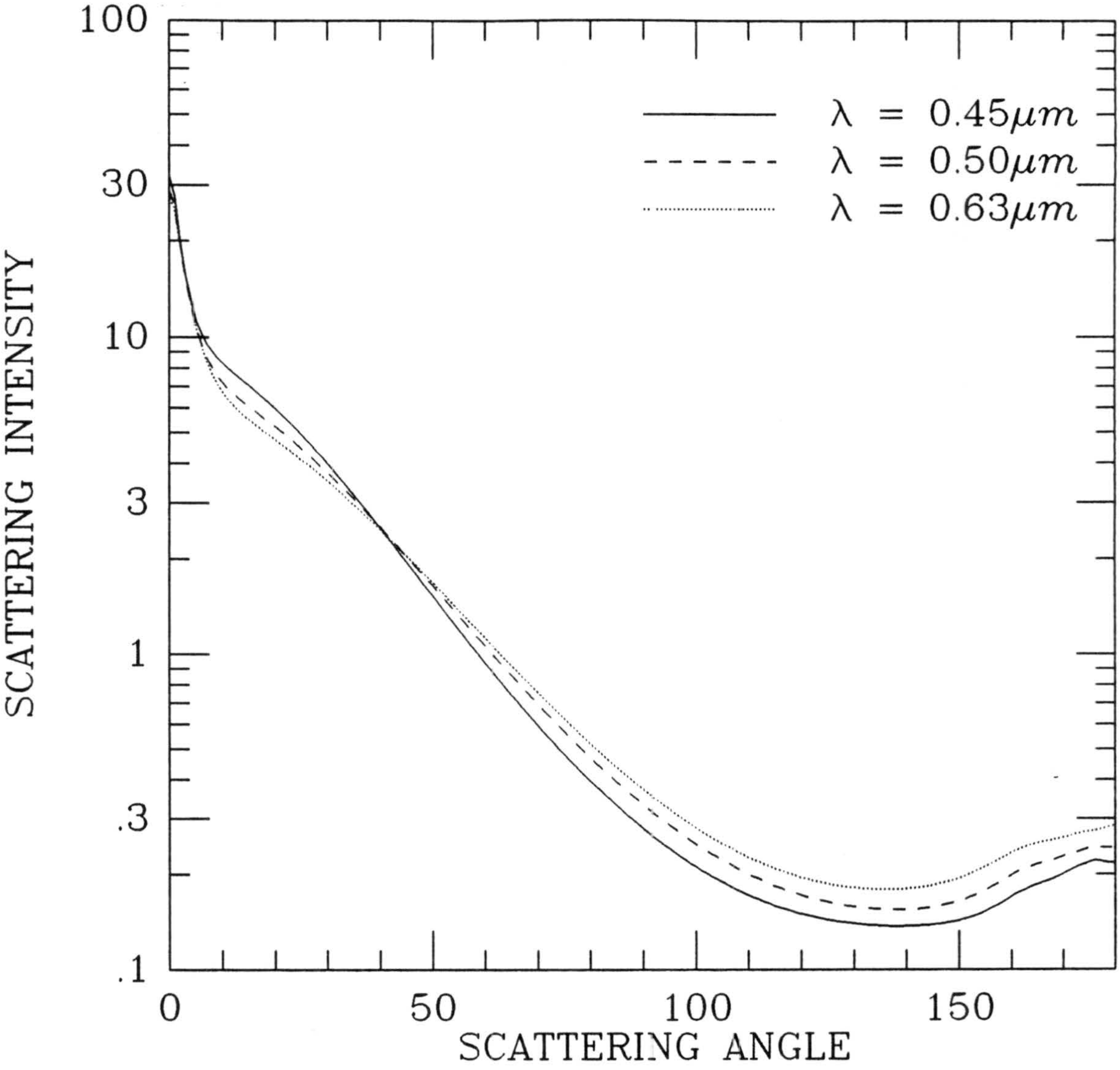


Figure 11 As in Fig. 10, except for a dry environment and at three wavelengths of $0.45 \mu m$, $0.55 \mu m$, and $0.63 \mu m$.

to the increase in backward scattering as the wavelength increases, caused mainly by the decrease of size parameters.

5. Summary and Future Studies

The objectives of this report are to describe a conceptually simple but accurate model for efficiently computing the physical and optical properties of atmospheric aerosols. The optical properties of atmospheric aerosols are closely related to their microstructure (e.g., size distribution, solubility, mixture) as well as the effect of atmospheric moisture. For the purpose of estimating these optical properties, the assumption that aerosol particles are spheres is invoked and numerically stable algorithms for obtaining Mie solutions to coated spheres is employed.

This model is capable of simulating the following aerosol characteristics: (1) six groups of chemical species with corresponding solubility, (2) two size distributions of lognormal and generalized gamma functions including their higher moments, (3) three types of aerosol mixture with their partition. The model contains a spectral range between 0.2 and $40\mu m$ and responds to a moist environment exhibiting a relative humidity up to 99.7%. Resulting bulk optical properties such as the extinction/backscatter coefficient, the probability of scattering, and the scattering phase matrix can be incorporated into multiple scattering schemes of radiative transfer for visibility investigations and other types of studies.

Tsay *et al.* (1990) have demonstrated the usefulness of this model, as a means of studying the sensitivity of the sky radiance to aerosol optical properties which are totally controlled by the aerosol microstructure. For instance, it is found that a thin aerosol layer can influence visibility by increasing the diffuse sky intensity, which in turn changes the contrast of an object viewed along a horizontal path. In other words, the background sky radiance viewed along a horizontal path is highly dependent on the aerosol scattering pattern. Because the model is very general and its program realization so user-friendly, it is very easy to modify the input data to accommodate any specified problems at hand.

Two immediate investigations are planned as a follow up to this study. The first concerns an extensive survey and understanding on the variablity of aerosol physical characteristics (e.g. size distribution, solubility, and mixture). During the life cycle of atmospheric aerosols, their physical and chemical properties change, following closely to the dynamical and environmental conditions. Therefore, a sensitivity study of the optical properties of aerosol for different aerosol microstructures is required.

Mie theory is a mathematically cumbersome and computationally tedious task, especially when performed at visible wavelengths for which the size parameters are relatively large. Thus, a parameterization scheme should be developed to minimize the time-consuming Mie computations. Finally, it is desirable that the optical properties of atmospheric aerosols can be parameterized in terms of a few bulk descriptors (e.g. mass loading and effective radius) and atmospheric conditions (e.g. relative humidity). This should prove useful for other investigators who are interested in accounting for the effects of aerosol optical properties on visual air quality but who do not have the models described in this report at their disposal.

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Appendix A. AEROSL Computer Codes

```
                            PROGRAM    AEROSL
C***********************************************************************
C
C            This is a model for computing the bulk physical and optical
C                properties of a given aerosol characteristics and under
C                 some environmental conditions (see report for detail).
C
C     Note:  This PROGRAM has been designed to be as much portable as
C            possible.  However, some part of Mie computations are
C            sensitive to machine precision.  For use in supercomputers,
C            the following statements need be changed:
C
C            1. IMPLICIT REAL*8 ==> IMPLICIT REAL (for single precision)
C            2. DLOG ==> ALOG (do not have a GENERIC FUNCTION name).
C
C
C     References:
C         Blanchet, J.P. and R. List, 1983, Estimation of optical
C              properties of arctic haze using a numerical model,
C              ATMOSPHERE-OCEAN, 21, 444-465.
C
C         Bohren, C. and D.R. Huffman, 1983, Absorption and Scattering
C              of Light by Small Particles, Chapter 4, Wiley & Sons,
C              New York, 530pp.
C
C         Deirmendjian, D., 1969, Electromagnetic Scattering on
C              Spherical Polydispersions, Chapter 3, Elsevier,
C              New York, 290pp.
C
C         Shettle, E.P. and R.W. Fenn, 1979, Models for the aerosols
C              of the lower atmosphere and the effects of humidity
C              variations on their optical properties, AFGL report 94pp.
C
C         Toon, O.B. and T.P. Ackerman, 1981, Algorithms for the
C              calculation of scattering by stratified spheres,
C              Appl. Optics, 20, 3657-3660.
C
C         van de Hulst, H.C., 1957, Light Scattering by Small Particles
C              Chapter 9, Dover, New York, 470pp.
C
C***********************************************************************
C
C    PARAMETER:
C           MHAZ:  maximum dimension of aerosol species
C           MLNM:  maximum dimension of aerosol size distribution
C           MTRM:  maximum dimension of Mie series
C            MWL:  maximum dimension of wavelength
C
C    INPUT:
C          PHASE:  .TRUE. for scattering phase matrix computation
C         STOKES:  .TRUE. for Stokes phase matrix;
```

```
C                  .FALSE., for Legendre coefficients
C           PLOT:  .TRUE. for summing up Legendre coefficients to get
C                         Stokes phase matrix
C         SOLUBL:  .TRUE. for soluble aerosols
C          TABLE:  .TRUE. print out aerosol and H2SO4 refractive indices
C        PRNT(1):  .TRUE. print out aerosol microphysics
C        PRNT(2):  .TRUE. print out aerosol optical properties in detail
C        PRNT(3):  .TRUE. print out aerosol phase matrix in detail
C
C             CM:  aerosol concentration (per cm3)
C           COMP:  aerosol mass fraction for each distribution (sum=1)
C          DENSH:  aerosol density (g/cm3)
C            GSD:  sigma_g or gamma for two size distributions below
C           ISIZ:  type of size distribution: 0, gamma; 1-3, log-normal
C          ITYPE:  aerosol water activity (see SUBROUTINE COATIN)
C          NMODE:  mumber of size distribution modes
C             RH:  relative humidity (1.0 for 100%)
C             RM:  median or characteristic radius of size distribution
C           RMAX:  maximum radius of size distribution
C           RMIN:  minimum radius of size distribution
C           TEMP:  temperature at degree K
C
C           CON0:  minimum aerosol concentration for consideration
C         LECOEF:  output number of Legendre coefficients
C         NANGLE:  odd number of angles in plotting phase matrix
C          NQUAD:  maximum even quadrature angles in Legendre expansion
C            NWL:  number of output wavelength considered
C          RENOM:  renormalization: <0, based on concentration;
C                                   >0, based on mass
C           RINC:  radius increment: <0, power law; 0, default;
C                                    >0, linear.
C             WA:  wavelength (micrometer)
C
C    OUTPUT:
C           COAT:  complex refractive index of wet aerosol/coating
C           CORE:  complex refractive index of dry aerosol
C          TCONC:  total concentration of aerosol distribution
C          TMASD:  total mass of dry aerosol
C          TMASW:  total mass of wet aerosol
C          TREFD:  total effective radius of dry aerosol
C          TREFW:  total effective radius of wet aerosol
C          TRDY2:  total surface of dry aerosol (without PI)
C          TRWT2:  total surface of wet aerosol (without PI)
C          TVOLD:  total volume of dry aerosol
C          TVOLW:  total volume of wet aerosol
C
C            BBK:  volume backscatter coefficient (Km-1)
C            BEX:  volume extinction  coefficient (Km-1)
C            BSC:  volume scattering  coefficient (Km-1)
C             OM:  probability of scattering (single scattering albedo)
C              G:  asymmetry factor
C            PMX:  scattering phase matrix
C
C    INTERNAL:
```

```
C
C     Note:  The internal variables used in this PROGRAM are well tied
C            with the variables of equations in the report.  Others like
C            Sxxxx and Txxxx denote the intermediate summation and total
C            of aforementioned xxxx variable, respectively.
C
C            GMU:  weights of Gauss-Legendre integration
C            GWT:  weights of Gauss-Legendre integration
C           P/PM:  scattering phase matrix
C           XMAX:  maximum size parameter of aerosol distribution
C           XMIN:  minimum size parameter of aerosol distribution
C                                                                  Input
      IMPLICIT    REAL*8 (A-H, O-Z)
      PARAMETER   ( MHAZ = 6, MLNM = 5, MTRM = 200, MWL = 55 )
      LOGICAL     PHASE, PLOT, PRNT( 3 ), SOLUBL( MHAZ ), STOKES, TABLE
      DIMENSION   CM( MLNM ), COMP( MHAZ,MLNM ), DENSH( MHAZ ),
     $            ITYPE( MHAZ ), GSD( MLNM ), RM( MLNM ), WA( MWL )
C                                                                 Output
      COMPLEX*16  COAT, CORE
      DIMENSION   BBK( MWL ), BEX( MWL ), BSC( MWL ), OM( MWL ), G( MWL )
      DIMENSION   FACT( MHAZ ), HMAS( MHAZ ), HRHO( MHAZ ), HVOL( MHAZ )
      DIMENSION   GMU( MTRM ), GWT( MTRM ), P( 4,MTRM ), PM( 4,MTRM ),
     $            SPM( 4,MTRM ), PMX( 4,MTRM )
C
      OPEN   (1, FILE='AEROSL.IND', STATUS='OLD')
      OPEN   (5, FILE='AEROSL.DAT', STATUS='OLD')
      OPEN   (6, FILE='AEROSL.PNT', STATUS='UNKNOWN')
      OPEN   (7, FILE='STOKES.DAT', STATUS='UNKNOWN')
C                                                          Input & check
      CALL   READIN( CM, COMP, CONO, DENSH, GSD, ISIZ, ITYPE, LECOEF,
     $               MHAZ, MTRM, NANGLE, NMODE, NQUAD, NWL, PHASE, PLOT,
     $               PRNT, RENOM, RH, RINC, RM, RMAX, RMIN, SOLUBL,
     $               STOKES, TABLE, TEMP, WA )
C
C                                                         Initialization
      PI = ACOS(-1.)
      TCONC = 0.
      TMASD = 0.
      TMASW = 0.
      TRDY2 = 0.
      TRDY3 = 0.
      TRWT2 = 0.
      TRWT3 = 0.
C                                                     Angular dependence
      IF ( PHASE )  THEN
         IF ( STOKES )  THEN
            NTERM = NANGLE
            DO 10 I = 1, (NTERM+1)/2
10          GMU(I) = COS( PI*(I-1)/(NANGLE-1) )
         ELSE
            NTERM = NQUAD
            CALL  GAUSIN( NTERM, PI, GMU, GWT )
         END IF
      END IF
```

```
C                                                 Main loop on wavelength
      DO 300 LAMBDA = 1, NWL
         BBK(LAMBDA) = 0.
         BEX(LAMBDA) = 0.
         BSC(LAMBDA) = 0.
         G(LAMBDA)   = 0.
         DO 20 I = 1, 4
            DO 20 J = 1, NTERM
            PMX(I,J) = 0.
20       CONTINUE
         XK   = 2.*PI/WA(LAMBDA)
         XMIN = XK*RMIN
         XMAX = XK*RMAX
         IF ( PRNT(2) ) WRITE (6,500) WA(LAMBDA), XMIN, XMAX
C
C                                         Loop on size distribution modes
C                                             Determine non-acid and acid
C                                              mass fractions by Eq.(38).
         DO 200 MODE = 1, NMODE
            FHAZE = 0.
            DO 30 J = 1, MHAZ-1
30          FHAZE = FHAZE + COMP(J,MODE)
            FACID = COMP(MHAZ,MODE)
            NF   = 0
            SMS = 0.
            SFV = 0.
            SVL = 0.
            SBBK= 0.
            SBEX= 0.
            SBSC= 0.
            SGSC= 0.
            SCONC = 0.
            SMASD = 0.
            SMASW = 0.
            SRDY2 = 0.
            SRDY3 = 0.
            SRWT2 = 0.
            SRWT3 = 0.
            DO 40 I = 1, 4
               DO 40 J = 1, NTERM
               SPM(I,J) = 0.
40          CONTINUE
C                                     Loop on aerosol species: 1) soluble,
C                                      2) dust-like, 3) soot, 4) sea salt,
C                                                    and 5) Liquid-Water
            IF ( PRNT(2) ) WRITE (6,510) MODE
            DO 100 KC = 1, MHAZ-1
               IF ( COMP(KC,MODE).NE.0. )  THEN
C
C                         Aerosol partition (e.g. acid distribution by mass)
C                             for current type(J).  Compute mass fraction of
C                                jth non-acid aerosol and average density by
C                                 Eqs.(38,39). Then, perform Mie computation
C                                        for each wavelength, mode and type.
```

```
                  FJH = COMP(KC,MODE)/FHAZE
                  DHAZE = DENSH(KC)
                  DACID = DENSH(MHAZ)
                  RHOAV = 1./(FHAZE/DHAZE+FACID/DACID)
                  CALL COATMI( CM(MODE), CONO, DACID, DHAZE, FACID,
     $                         FHAZE, GMU, GSD(MODE), GWT, ISIZ,
     $                         ITYPE(KC), LAMBDA, KC, NTERM, PHASE, RH,
     $                         RHOAV, RINC, RM(MODE), SOLUBL(KC),STOKES,
     $                         TEMP, XMIN, XMAX, WA(LAMBDA), BETABK,
     $                         BETAEX, BETASC, COAT, CONC, CORE, GSC,PM,
     $                         RDY2, RDY3, RLIN, RSC2, RSC3, RWT2, RWT3)
C
C                                    Dry volume weighting by Eqs.(39,43)
                  FV  = FJH/RHOAV
                  SFV = SFV + FV
                  SBEX = SBEX + BETAEX*FV
                  SBBK = SBBK + BETABK*FV
                  SBSC = SBSC + BETASC*FV
                  SGSC = SGSC + GSC*FV
                  IF ( PHASE )  THEN
                     DO 50 I = 1, 4
                        DO 50 J = 1, NTERM
                        SPM(I,J) = SPM(I,J) + PM(I,J)*FV
50                   CONTINUE
                  END IF
                  IF ( LAMBDA.EQ.1 )  THEN
                     SCONC = SCONC + CONC*FV
                     SRDY2 = SRDY2 + RDY2*FV
                     SRDY3 = SRDY3 + RDY3*FV
                     SRWT2 = SRWT2 + RWT2*FV
                     SRWT3 = SRWT3 + RWT3*FV
                     SMASD = SMASD + RHOAV*RDY3*FV
C                                                           Wet aerosol:
C                                                            Eqs.(44-45)
                     FJM    = 1.*(RWT3-RDY3) / (RHOAV*RDY3)
                     RHOJI = (1.+FM) / (1./RHOAV+FJM)
                     SMASW = SMASW + RHOJI*RWT3*FV
                     IF ( PRNT(1) )  THEN
                        NF = NF + 1
                        HRHO(NF) = RHOJI
                        HVOL(NF) = (4./3.)*PI*RWT3*FV
                        HMAS(NF) = HVOL(NF)*RHOJI
                        FACT(NF) = FV
                        SMS = SMS + FJH*(1.+FJM)
                        SVL = SVL + FJH*(1.+FJM)/RHOJI
                     END IF
                  END IF
C                             Print in detail for each mode and species:
C                                                     optical properties
                  IF ( PRNT(2) )  THEN
                     WRITE (6,520) KC
                     WRITE (6,530) CORE, COAT
                     WRITE (6,540) BETASC*PI/(1000.*XK**3),
     $                             BETABK*PI/(1000.*XK**3),
```

```
     $                              BETAEX*PI/(1000.*XK**3),
     $                              BETASC/BETAEX, GSC/BETASC
                  END IF
C                                                     physical properties
C
                  IF ( PRNT(1) .AND. (LAMBDA.EQ.1) )  THEN
                     IF ( .NOT.PRNT(2) ) WRITE (6,510) MODE
                     IF ( .NOT.PRNT(2) ) WRITE (6,520) KC
                     WRITE (6,550) CONC, RLIN/CONC, SQRT(RWT2/CONC),
     $                              RWT3/RWT2, PI*RWT2, (4./3.)*PI*RWT3,
     $                              RWT3/(3.*RWT2), RSC3/RSC2
                  END IF
C                                                 scattering phase matrix
C
                  IF ( PRNT(3).AND.PHASE )  THEN
                     IF ( STOKES )  THEN
                        WRITE (7,560) WA(LAMBDA)
                        DO 60 J = 1, NTERM
                        ANGLE = 180.*(J-1)/(NTERM-1)
60                      WRITE (7,570) ANGLE, (PM(I,J)/(PI*BETASC),I=1,4)
                     ELSE
                        CALL  LEGNDR( BETASC, GMU, GWT, NTERM, PM, P )
                        WRITE (6,560) WA(LAMBDA)
                        DO 70 J = 1, LECOEF
70                      WRITE (6,580) J-1, (P(I,J), I=1, 4)
                        IF ( PLOT )  THEN
                           CALL  PMPLOT( NANGLE, NTERM, P, PI, PM )
                           DO 80 J = 1, NANGLE
                           ANGLE = 180.*(J-1)/(NANGLE-1)
80                         WRITE (6,570) ANGLE, (PM(I,J), I=1, 4)
                        END IF
                     END IF
                  END IF
               END IF
100         CONTINUE
C                               End of integration over chemical species
C
            BEX(LAMBDA) = BEX(LAMBDA) + SBEX/SFV
            BBK(LAMBDA) = BBK(LAMBDA) + SBBK/SFV
            BSC(LAMBDA) = BSC(LAMBDA) + SBSC/SFV
            G(LAMBDA)   = G(LAMBDA)   + SGSC/SFV
            IF ( PHASE )  THEN
               DO 110 I = 1, 4
                  DO 110 J = 1, NTERM
                  PMX(I,J) = PMX(I,J) + SPM(I,J)/SFV
110            CONTINUE
            END IF
C                           Integrated physical properties for each mode
C
            IF ( LAMBDA.EQ.1 )  THEN
               TCONC = TCONC + SCONC/SFV
               TRDY2 = TRDY2 + SRDY2/SFV
               TRDY3 = TRDY3 + SRDY3/SFV
               TRWT2 = TRWT2 + SRWT2/SFV
```

```
               TRWT3 = TRWT3 + SRWT3/SFV
               TMASD = TMASD + (4.*PI/3.)*SMASD/SFV
               TMASW = TMASW + (4.*PI/3.)*SMASW/SFV
               IF ( PRNT(1) )  THEN
                  RHO = SMS/SVL
                  DO 120 N = 1, NF
                     FACT(N) = FACT(N)/SFV
                     HVOL(N) = HVOL(N)/SFV
                     HMAS(N) = HMAS(N)/SFV
120               CONTINUE
                  WRITE (6,590) (FACT(N),N=1,NF)
                  WRITE (6,600) RHO, (HRHO(N),N=1,NF)
                  WRITE (6,610) (HVOL(N),N=1,NF)
                  WRITE (6,620) (HMAS(N),N=1,NF)
               END IF
            END IF
200      CONTINUE
C                                          End of integration over modes
C                    Re-normalization: (1) RENOM <0, normalization based
C                       on dry mass (2) RENOM >0, based on concentration
C
         IF ( RENOM.LT.0. )  RATIO = ABS( RENOM )/TMASD
         IF ( RENOM.GT.0. )  RATIO = ABS( RENOM )/TCONC
         IF ( ABS(RENOM).GT.0. )  THEN
            BBK(LAMBDA) = BBK(LAMBDA)*RATIO
            BEX(LAMBDA) = BEX(LAMBDA)*RATIO
            BSC(LAMBDA) = BSC(LAMBDA)*RATIO
              G(LAMBDA) =   G(LAMBDA)*RATIO
            IF ( PHASE )  THEN
               DO 210 I = 1, 4
                  DO 210 J = 1, NTERM
                  PMX(I,J) = PMX(I,J)*RATIO
210            CONTINUE
            END IF
         END IF
C                                 Print phase matrix for each wavelength
         IF ( PHASE )  THEN
            IF ( STOKES )  THEN
               IF ( RENOM.LT.0. )  WRITE (7,630) RENOM
               IF ( RENOM.GT.0. )  WRITE (7,640) RENOM
               WRITE (7,560) WA(LAMBDA)
               DO 220 J = 1, NTERM
               ANGLE = 180.*(J-1)/(NTERM-1)
220            WRITE (7,570) ANGLE, (PMX(I,J)/(PI*BSC(LAMBDA)), I=1, 4)
            ELSE
               CALL  LEGNDR( BSC(LAMBDA), GMU, GWT, NTERM, PMX, P )
               IF ( RENOM.LT.0. )  WRITE (6,630) RENOM
               IF ( RENOM.GT.0. )  WRITE (6,640) RENOM
               WRITE (6,560) WA(LAMBDA)
               DO 230 J = 1, LECOEF
230            WRITE (6,580) J-1, (P(I,J), I=1, 4)
               IF ( PLOT )  THEN
                  CALL  PMPLOT( NANGLE, NTERM, P, PI, PMX )
                  DO 240 J = 1, NANGLE
```

```
                  ANGLE = 180.*(J-1)/(NANGLE-1)
240               WRITE (6,570) ANGLE, (PMX(I,J), I=1, 4)
               END IF
            END IF
         END IF
           G(LAMBDA) =   G(LAMBDA)/BSC(LAMBDA)
          OM(LAMBDA) = BSC(LAMBDA)/BEX(LAMBDA)
         BSC(LAMBDA) = BSC(LAMBDA)*PI/(1000.*XK**3)
         BEX(LAMBDA) = BEX(LAMBDA)*PI/(1000.*XK**3)
         BBK(LAMBDA) = BBK(LAMBDA)*PI/(1000.*XK**3)
300   CONTINUE
C                                              End loop over wavelengths
      TREFD = TRDY3/TRDY2
      TREFW = TRWT3/TRWT2
      TVOLD = (4./3.)*PI*TRDY3
      TVOLW = (4./3.)*PI*TRWT3
C+---------------------------------------------------------------------+
C!         Write out title, input and output data                      !
C+---------------------------------------------------------------------+
      WRITE (6,650)
      WRITE (6,660) NMODE, RMIN, RMAX, PHASE, RENOM, TABLE, PRNT(1),
     $              PRNT(2), PRNT(3)
      DO 400 J = 1, NMODE
400   WRITE (6,670) J, (COMP(I,J), I=1,MHAZ)
      WRITE (6,680) (DENSH(I),      I=1,MHAZ)
      WRITE (6,690) (ITYPE(I),    I=1,MHAZ-1)
      WRITE (6,700) (SOLUBL(I),   I=1,MHAZ-1)
      WRITE (6,710) TCONC, TREFD, TREFW, TMASD, TMASW, TVOLD, TVOLW
      WRITE (6,720) 100.*RH
      DO 450 I = 1, NWL
450   WRITE (6,730) I, WA(I), BEX(I), BSC(I), BBK(I), OM(I), G(I)
C
500   FORMAT(' LAMDA=',F6.3,'MICRONS', 5X,'XMIN =',F15.8,
     $       5X,'XMAX =',F15.8)
510   FORMAT(//, 4X, 'MODE = ',I2)
520   FORMAT(//, 7X, 'COMPONENT = ',I2)
530   FORMAT(9X, 'REFRACTIVE INDEX OF CORE =',2F15.11,
     $       5X, 'COAT =',2F15.11)
540   FORMAT(9X, 'BETASC=',E13.5,'/Km', 3X,'BETABK=',E13.5,'/Km', 3X,
     $       'BETAEX=',E13.5,'/Km', 3X,'OMEGA=',E13.5, 3X,'G=',E13.5//,
     $       9X,'SELECTED OUTPUT WERE NOT NORMALIZED.'//)
550   FORMAT(/,9X,'AEROSOL CONCENTRATION =',E20.5,' per cm3'/9X,
     $       'LINEAR MEAN RADIUS =',E23.5,' micron'/9X,'RMS RADIUS =',
     $       E31.5,' micron'/9X,'EFFECTIVE MEAN RADIUS =',E20.5,
     $       ' micron'/9X,'TOTAL CROSS-SECTIONAL AREA =',E15.5,
     $       ' micron2/cm3'/9X,'TOTAL VOLUME OF AEROSOL =',E18.5,
     $       ' micron3/cm3'/9X,'VOLUME/SURFACE RATIO =',E21.5,' micron',
     $       /9X,'MEAN RADIUS FOR SCATTERING =',E15.5,' micron')
560   FORMAT(//,45X, 'WAVELENGTH =',F7.2,'Micron', /, 12X,'Order',12X,
     $       'Coeff(P1)',8X,'Coeff(P2)',8X,'Coeff(P3)',8X,'Coeff(P4)')
570   FORMAT(5X, F6.1, 4F12.6)
580   FORMAT(12X,I5,5X,4E17.5)
590   FORMAT(///4X,'THE PARTICULATE CONCENTRATION FACTOR FOR EACH ',
     $       'NON-ACID COMPONANT IS = ', 5F8.4,//)
```

```
600   FORMAT(4X,'AVERAGE PARTICLES DENSITY (g/cm3) FOR THIS MODE =',
     $       F10.4,/,4X,'SPECIFIC DENSITY (g/cm3) OF EACH COMPONENT =',
     $       5F8.4,//)
610   FORMAT(4X,'PARTICULATE VOLUME (micron3/cm3) OF EACH COMPONENT =',
     $       5F10.4,//)
620   FORMAT(4X,'MASS (microgram/m3) OF EACH COMPONENT WITH ACID ',
     $       'COATING, IF ANY =', 5E12.4,//)
630   FORMAT(//,45X, 'OUTPUT WERE RENORMALIZED TO CONC. AT', E12.4,/)
640   FORMAT(//,45X, 'OUTPUT WERE RENORMALIZED TO MASS AT', E12.4,/)
650   FORMAT(1H1, T30,71('*'),/,T30,'*****',T96,'*****',/,T30,'*****',
     $       T55,'OUTPUT FROM PROGRAM ', T96,'*****',/,T30,'*****',T96,
     $      '*****',/,T30,'*****',T52,'ATMOSPHERIC AEROSOL MODEL',T96,
     $      '*****',/,T30,'*****',T96,'*****',/,T30,'*****',T96,'*****'
     $      ,/,T30,71('*'),/////,T30,'** PARAMETERS READ IN **',//)
660   FORMAT(T20,'NUMBER OF MODES IN ATMOSPHERIC AEROSOL =',I5,/,T20,
     $       'MINIMUM RADIUS USED',T54,'RMIN =',F9.3,' micron',/,T20,
     $       'MAXIMUM RADIUS USED',T54,'RMAX =',F9.3,' micron',//,T20,
     $       'THE FOLLOWING PROCESSES ARE INCLUDED IF',/,T20,
     $       'THE CODES ARE SET TO "TRUE";',/,T24,
     $       'PHASE MATRIX COMPUTATION ',T53,'PHASE =',L5,/,T24,
     $       'RE-NORMALIZE ON MASS OR CONC.,',T53,'RENOM :',F9.3,//,T20,
     $       'OUTPUT DATA CONTROL;',/,T20,
     $       ' TABLE =T --- REFRACTIVE INDICES,   TABLE  =',L5,/,T20,
     $       'PRNT(1)=T --- DETAIL MICRO. PARA., PRNT(1) =',L5,/,T20,
     $       'PRNT(2)=T --- DETAIL OPTIC. PARA., PRNT(2) =',L5,/,T20,
     $       'PRNT(3)=T --- DETAIL PHASE MATRIX, PRNT(3) =',L5,/,T28,
     $       'F --- OUTPUT DATA SUPPRESSED',//,26X,'(%)',11X,'Soluble',
     $      4X,'Insoluble',9X,'Soot',5X,'Sea Salt',' Liquid Water',
     $      3X,'H2SO4-Acid')
670   FORMAT(10X,'COMPOSITION OF MODE =', I3, 6F13.3)
680   FORMAT(10X,' DENSITY OF AEROSOL =', 3X, 6F13.3)
690   FORMAT(10X,'   TYPE OF ACTIVITY =', 3X, 5I13)
700   FORMAT(10X,'         SOLUBILITY =', 3X, 5L13)
710   FORMAT(////,T30,'** MICROPHYSICAL AND OPTICAL PROPERTIES **',//,
     $       10X,'TOTAL CONCENTRATION =', F16.3,' per cm3',/,
     $       9X,'DRY EFFECTIVE RADIUS =', F16.5,' micron',/,
     $       9X,'WET EFFECTIVE RADIUS =', F16.5,' micron',/,
     $       9X,'    DRY AEROSOL MASS =', F16.5,' microgram/m3',/,
     $       9X,'    WET AEROSOL MASS =', F16.5,' microgram/m3',/,
     $       9X,'  DRY AEROSOL VOLUME =', F16.5,' micron3/cm3',/,
     $       9X,'  WET AEROSOL VOLUME =', F16.5,' micron3/cm3',//)
720   FORMAT(50X, 'RELATIVE HUMIDITY = ', F6.2, '%', /, 10X, 'I',
     $       6X,'WAVELENGTH', 10X,'BETA_ext', 10X,'BETA_sca',
     $       10X,'BETA_bks', 12X,'OMEGA', 10X,'ASYM-FACT')
730   FORMAT(8X, I3, 6F18.10)
C
      STOP
      END
C***************************  END OF AEROSL  ***************************
C***********************************************************************
      SUBROUTINE  COATMI( CM, CONO, DACID, DHAZE, FACID, FHAZE, GMU,
     $                    GSD, GWT, ISIZ, ITYP, LAMBDA, KC, NTERM,
     $                    PHASE, RH, RHOAV, RINC, RM, SOLUBL, STOKES,
     $                    TEMP, XMIN, XMAX, WA, BETABK, BETAEX, BETASC,
```

```
     $                       COAT, CONC, CORE, GSC, PM, RDY2, RDY3, RLIN,
     $                       RSC2, RSC3, RWT2, RWT3 )
C                                   This routine provides a bookkeeping of
C                                       Mie computation and of integration
C                                          over a given size distribution.
C
      PARAMETER    ( MTRM = 200 )
      IMPLICIT     REAL*8 (A-H, O-Z)
      COMPLEX*16   COAT, CORE
      COMPLEX*16   A( MTRM ), B( MTRM ), BKS, BS1, BS2, FS1, FS2, S1CS2
      LOGICAL      PHASE, SOLUBL, STOKES
      DIMENSION    GMU( * ), GWT( * ), PHI( 3 ), PM( 4,* ), SRI( 2 ),
     $             TAU( 3 ), WK( 2,4,MTRM )
      EQUIVALENCE ( S1CS2,SRI(1) )
      DATA         DELX0/ 0.005 /
C                                                           Initialization
      CONC = 0.
      RLIN = 0.
      RDY2 = 0.
      RDY3 = 0.
      RWT2 = 0.
      RWT3 = 0.
      RSC3 = 0.
      RSC2 = 0.
      GSC  = 0.
      BETABK = 0.
      BETAEX = 0.
      BETASC = 0.
      DO 10 I = 1, 4
         DO 10 J = 1, NTERM
         PM(  I,J) = 0.
         WK(1,I,J) = 0.
         WK(2,I,J) = 0.
10    CONTINUE
      PI   = ACOS(-1.)
      XK   = 2.*PI/WA
      XR   = XMAX/XMIN
      DELX = DELX0
      DELR = DELX/XK
      XDRY = XMIN
C                                                          Start X do-loop
      I = 0
20    I = I + 1
      BKS  = (0.,0.)
      EXK  = 0.
      SCK  = 0.
      GP   = 0.
      RDRY = XDRY/XK
      H2SO4= 0.
C                                      Find aerosol water activity and compute
C                                         refractive indices of core and shell
C
      CALL  COATIN( DACID, DHAZE, FACID, FHAZE, ITYP, RDRY, RH, RHOAV,
     $              SOLUBL, TEMP, H2SO4, RHAZE, RWET )
```

```
      CALL  REFIND( H2SO4, KC, WA, COAT, CORE )
C
C                                           Calculate aerosol concentration and
C                                 weighted back to dry condition for later use
      IF ( I.GT.1 ) DELR = RWET - RWT1
      DRDRY = DELX/XK
      CALL  DLNDLR( CM, GSD, ISIZ, PI, RDRY, RM, COND )
      CONW = COND*DRDRY/DELR
      IF ( (RINC.GE.0.) .AND. (CONW.LE.CONO) )  THEN
         I = 0
         GO TO 70
      END IF
C                                         Determine effective index of refraction
C                                   by Eq.(30) for computing Mie coefficients
      RC = RHAZE
      IF ( SOLUBL )  THEN
         COAT = COAT + (CORE-COAT)*(RDRY/RWET)**3.
         RC   = 1.E-38
      END IF
      CALL  COEFAB( CORE, COAT, RC, RWET, XK, A, B, LMAX, X )
C                                                        Compute the bulk optical
C                                                    properties by Eqs.(1,2,7,8).
      SGNO = 1.
      DO 30 L = 1, LMAX
         SGNO= -SGNO
         BKS = BKS + (2*L+1)*SGNO*( A(L) - B(L) )
         EXK = EXK + 2*(2*L+1)*REAL( A(L)+B(L) )
         SCK = SCK + 2*(2*L+1)*( A(L)*CONJG(A(L))+B(L)*CONJG(B(L)))
         GP  = GP  + 4*( (L*(L+2))*REAL( A(L)*CONJG(A(L+1))+B(L)*
     $                  CONJG(B(L+1)) )/(L+1) + (2*L+1)*REAL( A(L)*
     $                  CONJG(B(L)) )/(L*(L+1)) )
30    CONTINUE
C                                      Calculate angular dependent phase matrix
C                                         from S1, S2, PHI and TAU by Eqs.(5,6).
      IF ( PHASE )  THEN
         IF ( STOKES )  THEN
            MTERM = (NTERM+1)/2
         ELSE
            MTERM = NTERM/2
            LMAX  = MIN0( LMAX, NTERM-1 )
         END IF
         DO 50 J = 1, MTERM
            JJ  = NTERM - J + 1
            FS1 = (0.,0.)
            FS2 = (0.,0.)
            BS1 = (0.,0.)
            BS2 = (0.,0.)
            PHI(1) = 0.
            PHI(2) = 1.
            TAU(1) = 0.
            TAU(2) = GMU(J)
            SGNO   = 1.
            DO 40 L = 1, LMAX
               IF ( L.EQ.1 )  THEN
```

```
                 PHI(3) = PHI(2)
                 TAU(3) = TAU(2)
              ELSE
                 PHI(3) = (2*L-1)*GMU(J)*PHI(2)/(L-1)-L*PHI(1)/(L-1)
                 TAU(3) = GMU(J)*(PHI(3)-PHI(1)) -
     $                    (2*L-1)*PHI(2)*(1.-GMU(J)**2) + TAU(1)
                 PHI(1) = PHI(2)
                 PHI(2) = PHI(3)
                 TAU(1) = TAU(2)
                 TAU(2) = TAU(3)
              END IF
C
              FS1 = FS1 + (2*L+1)*( A(L)*PHI(3)+B(L)*TAU(3) )/(L*(L+1))
              FS2 = FS2 + (2*L+1)*( B(L)*PHI(3)+A(L)*TAU(3) )/(L*(L+1))
              IF ( STOKES .AND. (J.EQ.JJ) )  GO TO 40
              BS1 = BS1 + (2*L+1)*( A(L)*PHI(3)*SGN0 +
     $                                  B(L)*TAU(3)*(-SGN0) )/(L*(L+1))
              BS2 = BS2 + (2*L+1)*( B(L)*PHI(3)*SGN0 +
     $                                  A(L)*TAU(3)*(-SGN0) )/(L*(L+1))
              SGN0 = -SGN0
40         CONTINUE
C                               Elements of phase matrix, part of Eq.(4)
C
           S1CS2 = FS1*CONJG(FS2)
           WK(1,1,J)  = CONW*( FS1*CONJG(FS1) )
           WK(1,2,J)  = CONW*( FS2*CONJG(FS2) )
           WK(1,3,J)  = CONW*SRI(1)
           WK(1,4,J)  =-CONW*SRI(2)
           IF ( STOKES .AND. (J.EQ.JJ) )  GO TO 50
           S1CS2 = BS1*CONJG(BS2)
           WK(1,1,JJ) = CONW*( BS1*CONJG(BS1) )
           WK(1,2,JJ) = CONW*( BS2*CONJG(BS2) )
           WK(1,3,JJ) = CONW*SRI(1)
           WK(1,4,JJ) =-CONW*SRI(2)
50      CONTINUE
     END IF
C                               Integrate bulk optical properties over X
     CEXK = CONW*EXK
     CSCK = CONW*SCK
     CNGP = CONW*GP
     CBKS = CONW*BKS*CONJG( BKS )
     IF ( I.GT.1 )  THEN
        DX  = X - X1
        GSC = GSC + 0.5*(CNG1+CNGP)*DX
        BETASC = BETASC + 0.5*(CSC1+CSCK)*DX
        BETAEX = BETAEX + 0.5*(CEX1+CEXK)*DX
        BETABK = BETABK + 0.5*(CBK1+CBKS)*DX
        IF ( PHASE )  THEN
           DO 60 J = 1, 4
              DO 60 L = 1, NTERM
              PM(J,L) = PM(J,L) + 0.5*(WK(1,J,L)+WK(2,J,L))*DX
60         CONTINUE
        END IF
C                              Integrate bulk physical properties over R
```

```
         IF ( LAMBDA.EQ.1 )  THEN
            DR   = RWET - RWT1
            CONC = CONC + 0.5*(CON1+CONW)*DR
            RLIN = RLIN + 0.5*(RWT1*CON1+RWET*CONW)*DR
            RDY2 = RDY2 + 0.5*(RDY1**2*CON1+RDRY**2*CONW)*DR
            RDY3 = RDY3 + 0.5*(RDY1**3*CON1+RDRY**3*CONW)*DR
            RWT2 = RWT2 + 0.5*(RWT1**2*CON1+RWET**2*CONW)*DR
            RWT3 = RWT3 + 0.5*(RWT1**3*CON1+RWET**3*CONW)*DR
            RSC3 = RSC3 + 0.5*(RWT1**3*CSC1/X1**2+RWET**3*CSCK/X**2)*DR
            RSC2 = RSC2 + 0.5*(RWT1**2*CSC1/X1**2+RWET**2*CSCK/X**2)*DR
         END IF
      END IF
C
70    CONTINUE
      CON1 = CONW
      RWT1 = RWET
      RDY1 = RDRY
      CNG1 = CNGP
      CSC1 = CSCK
      CEX1 = CEXK
      CBK1 = CBKS
      X1   = X
      IF ( PHASE )  THEN
         DO 80 J = 1, 4
            DO 80 L = 1, NTERM
            WK(2,J,L) = WK(1,J,L)
80       CONTINUE
      END IF
C                                               Choise of increment DELX
      IF ( RINC.LT.0. )  THEN
         DELX = XMIN*( XR**(-I/RINC) - XR**((1-I)/RINC) )
      ELSE IF ( RINC.EQ.0. )  THEN
         IF ( XDRY.GE.29.99 ) DELX = DELX0*200.
         IF ( XDRY.LT.29.99 ) DELX = DELX0*100.
         IF ( XDRY.LT.19.99 ) DELX = DELX0*40.
         IF ( XDRY.LT.9.99  ) DELX = DELX0*20.
         IF ( XDRY.LT.4.99  ) DELX = DELX0*10.
         IF ( XDRY.LT.0.99  ) DELX = DELX0* 1.
      ELSE
         DELX = RINC*XK
      END IF
      XDRY = XDRY + DELX
      IF ( XDRY.LE.XMAX )  GO TO 20
      IF ( CONC.LE.0. )  CALL  ERRMSG('FATAL RADIUS INCREMENT', .TRUE. )
C
      RETURN
      END
C***************************  END OF COATMI  ***************************
C***********************************************************************
      SUBROUTINE  COATIN( DACID, DHAZE, FACID, FHAZE, ITYP, RDRY, RH,
     $                    RHOAV, SOLUBL, TEMP, H2SO4, RHAZE, RWET )
C                             This routine computes the equilibrium size
C                                 of wet aerosol in a moist environment.
C
```

```
      IMPLICIT    REAL*8 (A-H, O-Z)
      LOGICAL     SOLUBL
      DIMENSION   AW( 18,5 ), HMWMD( 18,5 )
C
C                             Type of Activity: (1) Urban, (2) Maritime,
C                                   (3) Continental, (4) H2SO4, (5) H2O.
      DATA     AW/    1.E-10,.195,.304,.398,.493,.556,.605,.665,.704,
     $                  .772,.829,.886,.952,.975,.980,.986,.990,.9969,
     $                1.E-10,.204,.305,.399,.497,.557,.604,.653,.710,
     $                  .772,.834,.900,.950,.962,.975,.986,.990,.9969,
     $                1.E-10,.231,.301,.394,.485,.544,.590,.625,.677,
     $                  .731,.768,.827,.885,.950,.972,.986,.990,.9969,
     $                1.E-10,.001,.075,.340,.555,.823,.880,.958,.982,
     $                  .996,.998,1.00,.000,.000,.000,.000,.000,.0000,
     $                1.E-20,17*0.99/
      DATA     HMWMD/ 1.E-10,0.008,0.013,0.018,0.029,0.053,
     $                 0.104,0.174,0.259,0.607,0.907,1.400,
     $                 3.392,6.903,8.820,13.10,19.01,68.50,
     $                1.E-10,0.008,0.011,0.018,0.030,0.039,
     $                 0.064,0.145,0.379,1.249,1.648,2.520,
     $                 4.617,5.924,8.775,14.86,20.39,66.57,
     $                1.E-10,0.008,0.011,0.018,0.030,0.044,
     $                 0.058,0.070,0.094,0.152,0.397,0.765,
     $                 1.154,1.995,3.576,8.099,11.58,42.13,
     $                1.E-10,0.180,0.510,1.000,1.500,3.000,
     $                 4.000,9.000,19.00,99.00,199.0,9999.,
     $                 0.000,0.000,0.000,0.000,0.000,0.000,
     $                1.E-20,17*0.99/
C                                               Aerosol partition: Eq.(39)
      RWET  = RDRY
      RHAZE = RDRY
      IF ( FACID.GT.0. )  THEN
         VHAZE = FHAZE*RDRY**3*(RHOAV/DHAZE)
         VACID = FACID*RDRY**3*(RHOAV/DACID)
         RHAZE = VHAZE**(1./3.)
      END IF
C                                           Find water activity (AW) under
C                                     thermodynamic equilibrium by Eq.(28)
C                                   and corresponding water uptake (AWMDJ)
10    RINI = RWET
      AWR  = RH*EXP( -0.314688/(TEMP*RINI) )
      IF ( ITYP.EQ.5 ) AWR = 0.
      AWMDJ = 0.
      IF ( SOLUBL )  THEN
         DO 20 I = 2, 18
            IF ( AW(I,ITYP).GE.AWR )  THEN
            A0 = 1. - AWR
            A1 = 1. - AW(I-1,ITYP)
            A2 = 1. - AW(I,  ITYP)
            CALL  INTERP(2,A1,HMWMD(I-1,ITYP),A2,HMWMD(I,ITYP),A0,AWMDJ)
            GO TO 30
            END IF
20       CONTINUE
      END IF
```

```
C                                      Find the radius of wet aerosol at
C                                      relative humidity (RH) by Eq.(29)
30    IF ( FACID.LE.0. )  THEN
         RWET = RDRY*(1.+DHAZE*AWMDJ)**(1./3.)
      ELSE
C                                  Use Eqs.(28,29) again to evaluate the
C                                extra amount of water condensed on acid
         DO 40 J = 2, 12
            IF ( AW(J,4).GE.AWR )  THEN
               A0 = 1. - AWR
               A1 = 1. - AW(J-1,4)
               A2 = 1. - AW(J,  4)
               CALL  INTERP( 2,A1,HMWMD(J-1,4),A2,HMWMD(J,4),A0,AWMDA )
               RWET  = ( VHAZE*(1.+DHAZE*AWMDJ) +
     $                   VACID*(1.+DACID*AWMDA) )**(1./3.)
               GO TO 50
            END IF
40       CONTINUE
      END IF
C                             Iterate to get equilibrium size at current
C                           RH and compute acid concentration by Eq.(41)
C
50    IF ( ABS(RINI-RWET) .GT. 0.0001*RDRY )  GO TO 10
      IF ( FACID.GT.0. )  H2SO4 = 1./(AWMDA+1.)
      RETURN
      END
C**************************** END OF COATIN ****************************
C***********************************************************************
      SUBROUTINE  COEFAB( MC, MS, RC, RS, XK, A, B, LMAX, X )
C                       This routine computes Mie coefficients (al & bl)
C                              of a stratified and/or homogeneous sphere
C
      IMPLICIT    REAL*8 (A-H, O-Z)
      PARAMETER   ( MTRM = 200 )
      COMPLEX*16  A( * ), B( * ), D( 4,MTRM ), U( 8 ), ZETA( 3 ), Z( 4),
     $            ALH, BLH, CI, ETA31, ETA32, ETA34, K1, K2, K3,
     $            MC, MS, PSI41, ROBH, ZA1P4, ZA4P4
      LOGICAL     COATED
      COMMON      /EQ24/ X1, Y1, X2, Y2, X3, Y3, X4, Y4
      EQUIVALENCE ( Z(1),X1 )
      DATA        ZERO / 0. /
C                                                Initialization: Eq.(17)
      CI = (0.,1.)
      X  = RS*XK
      K1 = MC*XK
      K2 = MS*XK
      K3 = CMPLX( XK,ZERO )
      Z(1) = K2*RS
      Z(2) = K3*RS
      Z(3) = K1*RC
      Z(4) = K2*RC
C                          If the core is small, Mie series are computed
C                                for the shell only.  Eq.(21) is used to
C                                 determine the max. term of the series.
```

```
      COATED = .TRUE.
      IF ( RC/RS .LT. 0.000001 )  COATED = .FALSE.
      LMX  = 1.1 * X * ABS( MS ) + 1
      LXX  = X + 4.0 * X**0.3333 + 2
      LMAX = MAX0( LMX, LXX )
      MSIZ = XK * RC
      IF ( LMAX.GE.MTRM )  THEN
      CALL  ERRMSG('The upper limit of D(MTRM) is not enough', .FALSE. )
      CALL  ERRMSG('please search and increase PARAMETER MTRM', .TRUE. )
      END IF
C                         Downward recursion for logarithmic derivatives
C                                of Ricatti-Bessel function by Eq.(19).
      DO 10  J = 1, 4
10    D(J,LMAX) = (0.,0.)
      DO 30  M = 1, LMAX-1
         L = LMAX - M + 1
         D(1,L-1) = L/Z(1) - 1./( L/Z(1) + D(1,L) )
         IF ( COATED )  THEN
            DO 20 J = 2, 4
20          D(J,L-1) = L/Z(J) - 1./( L/Z(J) + D(J,L) )
         END IF
30    CONTINUE
C                                           Initialization: ZETA Eq.(20)
      ZETA(1) = CMPLX( COS(X),-SIN(X) )
      ZETA(2) = CMPLX( SIN(X), COS(X) )
      IF ( COATED )  THEN
C                                            Initialization: ETA Eq.(22)
         ETA31 = -CI
         ETA32 = -CI
         ETA34 = -CI
C                                        Initialization: PSI Eqs.(23-24)
         AA = EXP( 2.*Y4+Y1 ) + EXP( Y1 )
         BB = EXP( 2.*Y4+Y1 ) - EXP( Y1 )
         CC = EXP( 2.*Y1+Y4 ) + EXP( Y4 )
         DD = EXP( 2.*Y1+Y4 ) - EXP( Y4 )
         PSI41 = ( AA*SIN(X4) + CI*BB*COS(X4) ) /
     $           ( CC*SIN(X1) + CI*DD*COS(X1) )
C
C                                   Initialization: ZETA*PSI Eqs.(25-26)
         ZA4P4 = 0.5 + ( SIN(X4)*SIN(X4) - 0.5 + CI*COS(X4)*SIN(X4) )
     $                                                       *EXP(2.*Y4)
         ZA1P4 = 0.5*(   SIN(X1)*SIN(X4)-   COS(X1)*COS(X4) +
     $                CI*SIN(X4)*COS(X1)+CI*COS(X4)*SIN(X1) )*EXP(Y1+Y4)
     $         + 0.5*(   SIN(X1)*SIN(X4)+   COS(X1)*COS(X4) +
     $                CI*SIN(X4)*COS(X1)-CI*COS(X4)*SIN(X1) )*EXP(Y1-Y4)
      END IF
C                                          Set up for homogeneous sphere
      L = 1
60    CONTINUE
      ZETA(3) = (2*L-1)*ZETA(2)/X - ZETA(1)
C                                           Set up for stratified sphere
C               Compute Mie series for stratified sphere by Eqs.(15-16)
C             The ratio of spherical Bessel to Henkal function is ROBH.
C
```

```
      IF ( COATED )  THEN
         ETA31 = -L/Z(1) + 1./ ( L/Z(1) - ETA31 )
         ETA32 = -L/Z(2) + 1./ ( L/Z(2) - ETA32 )
         ETA34 = -L/Z(4) + 1./ ( L/Z(4) - ETA34 )
         PSI41 = PSI41*(  D(1,L) + L/Z(1) )/( D(4,L) + L/Z(4) )
         ZA1P4 = ZA1P4/( ( ETA31 + L/Z(1) )*( D(4,L) + L/Z(4) ) )
         ZA4P4 = ZA4P4/( ( ETA34 + L/Z(4) )*( D(4,L) + L/Z(4) ) )
C
         U(1) = K3*D(1,L) - K2*D(2,L)
         U(2) = K1*D(4,L) - K2*D(3,L)
         U(3) =-CI*( PSI41*ZA1P4 - ZA4P4 )
         U(4) = PSI41**2
         U(5) = K3*D(1,L) - K2*ETA32
         U(6) = K2*D(1,L) - K3*D(2,L)
         U(7) = K2*D(4,L) - K1*D(3,L)
         U(8) = K2*D(1,L) - K3*ETA32
         ROBH = REAL( ZETA(3) )/ZETA(3)
         A(L) = ROBH*( U(1)*K1 + U(1)*U(2)*U(3) - K3*U(2)*U(4) ) /
     $               ( U(5)*K1 + U(2)*U(3)*U(5) - K3*U(2)*U(4) )
         B(L) = ROBH*( U(6)*K2 + U(3)*U(6)*U(7) - K2*U(4)*U(7) ) /
     $               ( U(8)*K2 + U(3)*U(7)*U(8) - K2*U(4)*U(7) )
      END IF
C                  Compute Mie series for homogeneous sphere by Eq.(18)
C
      IF ( (.NOT.COATED) .OR. (L.GE.MSIZ) )  THEN
         ALH = ( ( D(1,L)/MS + L/X )*REAL( ZETA(3) ) - REAL(ZETA(2)) ) /
     $         ( ( D(1,L)/MS + L/X )*ZETA(3) - ZETA(2) )
         BLH = ( ( D(1,L)*MS + L/X )*REAL( ZETA(3) ) - REAL(ZETA(2)) ) /
     $         ( ( D(1,L)*MS + L/X )*ZETA(3) - ZETA(2) )
         IF ( .NOT.COATED )  THEN
            A(L) = ALH
            B(L) = BLH
         ELSE IF ( COATED )  THEN
            IF ( ABS( (ALH-A(L))/ALH ) .LT. 1.E-09  .AND.
     $           ABS( (BLH-B(L))/BLH ) .LT. 1.E-09 )  COATED = .FALSE.
         END IF
      END IF
C                                              Truncation of Mie series
      CONV = A(L)*CONJG( A(L) ) + B(L)*CONJG( B(L) )
      IF ( CONV .GE. 1.E-14 )  THEN
         ZETA(1) = ZETA(2)
         ZETA(2) = ZETA(3)
         L = L + 1
         IF ( L .LE. LMAX )  GO TO 60
         CALL  ERRMSG(’Mie series do not converge to 1.0E-14,’, .FALSE.)
         CALL  ERRMSG(’or LMAX (Eq.21) needs be modified.’, .TRUE. )
      END IF
      LMAX = L
      A(L+1) = (0.,0.)
      B(L+1) = (0.,0.)
C
      RETURN
      END
C***************************  END OF COEFAB  ***************************
```

```
C***********************************************************************
      SUBROUTINE  CRITAB
C                   This routine provides a tabulated complex refractive
C                        indices for five general groups of aerosols and
C                          sulfuric acid solution at six concentrations.
C
      IMPLICIT    REAL*8 (A-H, O-Z)
      COMMON      /REFIDX/  IWL,  WL( 61 ), CRE( 5,61 ), CIM( 5,61 ),
     $                  CH( 7 ), WLS( 61 ), CRS( 7,61 ), CIS( 7,61 )
C                                                           dry aerosols
      READ (1,*) IWL
      READ (1,60)
      DO 10 I = 1, IWL
         READ (1,*) WL(I), ( CRE(J,I), CIM(J,I), J=1,5 )
         DO 10 J = 1, 5
10       CIM(J,I) = - CIM(J,I)
20    CONTINUE
C                                                 sulfuric acid solution
      READ (1,*)  ( CH(I), I=1,7 )
      READ (1,60)
      DO 40 I = 1, IWL
        READ (1,*) WLS(I), ( CRS(J,I), CIS(J,I), J=2,5 )
        DO 30 J = 2, 5
30      CIS(J,I) = - CIS(J,I)
        IF ( I.EQ.IWL )  THEN
           CRS(1,IWL) = CRE(5,IWL)
           CIS(1,IWL) = CIM(5,IWL)
        ELSE
        CALL INTERP(1,WL(I),CRE(5,I),WL(I+1),CRE(5,I+1),WLS(I),CRS(1,I))
        CALL INTERP(2,WL(I),CIM(5,I),WL(I+1),CIM(5,I+1),WLS(I),CIS(1,I))
        END IF
40    CONTINUE
C
      READ (1,60)
      DO 50 I = 1, IWL
         READ (1,*) WLS1, ( CRS(J,I), CIS(J,I), J=6,7 )
         CIS(6,I) = - CIS(6,I)
         CIS(7,I) = - CIS(7,I)
50    CONTINUE
C
60    FORMAT( 1X )
      RETURN
      END
C****************************  END OF CRITAB  ***************************
C***********************************************************************
      SUBROUTINE  DLNDLR( CM, GSD, ISIZ, PI, RDRY, RM, COND )
C                        This routine provides the aerosol concentration
C                        from a given lognormal/gamma size distribution.
C
      IMPLICIT    REAL*8 (A-H, O-Z)
C                                                      Generalized gamma
      IF ( ISIZ.EQ.0 )  THEN
         N   = NINT( GSD )
         FAC = 1.
```

```
         DO 10 I = 1, N-1
10       FAC  = FAC*I
         COND = CM/(FAC*RM)*(RDRY/RM)**(N-1)*EXP( -(RDRY/RM) )
      ELSE
C                                                              Lognormal
         SIGMA= DLOG( GSD )
         RNM  = RM
         IF ( ISIZ.GT.1 ) RNM = RNM*EXP( -ISIZ*SIGMA**2 )
         COND = CM/( SQRT(2.*PI)*SIGMA*RDRY ) *
     $          EXP( -0.5*( DLOG(RDRY/RNM) / SIGMA )**2 )
      END IF
C
      RETURN
      END
C***************************  END OF DLNDLR  ***************************
C**********************************************************************
      SUBROUTINE  ERRMSG( MESSAG, FATAL )
C                          Print out an error message and stop if fatal.
      IMPLICIT      REAL*8 (A-H,O-Z)
      CHARACTER*(*) MESSAG
      LOGICAL       FATAL
C
      WRITE(6,100)  MESSAG
      IF ( FATAL )  STOP
C
100   FORMAT(' ===> ERROR : ', A, /)
      RETURN
      END
C***************************  END OF ERRMSG  ***************************
C**********************************************************************
      SUBROUTINE  GAUSIN( NTERM, PI, GMU, GWT )
C                                This routine computes the abscissas and
C                                weights for Gauss-Legendre integration.
C
      IMPLICIT     REAL*8 (A-H, O-Z)
      DIMENSION    GMU( * ), GWT( * )
      DATA         EPS/ 3.E-14 /
C                                  The abscissas are symmetric in (-1,1)
C                      Start with the desired root by Newton-Raphson method
C
      DO 30 I = 1, (NTERM+1)/2
         Q = COS( PI*(I-0.25)/(NTERM+0.5) )
C                                                                Eq.(14)
10       PL  = 1.
         PL1 = 0.
         DO 20 N = 1, NTERM
            PL0 = PL1
            PL1 = PL
            PL  = ( (2*N-1)*Q*PL1 - (N-1)*PL0 ) / N
20       CONTINUE
C                                                            Eqs.(12-14)
         PP = NTERM*(Q*PL-PL1)/(Q*Q-1.)
         Q1 = Q
         Q  = Q1 - PL/PP
```

```
            IF ( ABS(Q-Q1).GT.EPS )  GO TO 10
            GMU(I)         = Q
            GMU(NTERM+1-I) =-Q
            GWT(I)         = 2. / ((1.-Q*Q)*PP*PP)
            GWT(NTERM+1-I) = GWT(I)
30    CONTINUE
C
      RETURN
      END
C****************************  END OF GAUSIN  ****************************
C************************************************************************
      SUBROUTINE  INTERP( M, X1, Y1, X2, Y2, X, Y )
      IMPLICIT    REAL*8 (A-H, O-Z)
C                                                   Linear interpolation
      IF ( M.EQ.1 ) THEN
         SLOPE = (Y2-Y1) / (X2-X1)
         Y = Y1 + SLOPE*(X-X1)
C                                                Power law interpolation
      ELSE IF ( M.EQ.2 ) THEN
         SLOPE = DLOG(Y1/Y2) / DLOG(X1/X2)
         Y = Y2*(X/X2)**SLOPE
      END IF
C
      RETURN
      END
C****************************  END OF INTERP  ****************************
C************************************************************************
      SUBROUTINE  LEGNDR( BSC, GMU, GWT, NTERM, PM, P )
C               This routine expends the angular scattering phase matrix
C                     to Legendre polynomials and finds the coefficients
C
      IMPLICIT    REAL*8 (A-H, O-Z)
      DIMENSION   GMU( * ), GWT( * ), P( 4,* ), PM( 4,* )
C
C                            Convert scattering phase elements of Eq.(4)
C                                  into those corresponding to (I,Q,U,V)
      DO 20 I = 1, NTERM
         DO 10 J = 1, 4
10       P(J,I) = 0.
         SAVE = PM(1,I)
         PM(1,I)= (4./BSC)*0.5*(PM(1,I)+PM(2,I))
         PM(2,I)= (4./BSC)*0.5*(PM(2,I)-SAVE)
         PM(3,I)= (4./BSC)*PM(3,I)
         PM(4,I)= (4./BSC)*PM(4,I)
20    CONTINUE
C                                      Calculate coefficients of Legendre
C                                     polynomials by using Eqs.(10,11,14)
      DO 50 I = 1, NTERM
         PL0 = 0.
         PL1 = 1.
         PL  = 1.
         DO 40 N = 0, NTERM-1
            IF ( N.GT.0 )  PL = ( (2*N-1)*GMU(I)*PL1 - (N-1)*PL0 ) / N
            DO 30 J = 1, 4
```

```
30          P(J,N+1) = P(J,N+1) + 0.5*(2*N+1)*GWT(I)*PM(J,I)*PL
            PL0 = PL1
            PL1 = PL
40       CONTINUE
50    CONTINUE
C
      RETURN
      END
C***************************  END OF LEGNDR  ***************************
C**********************************************************************
      SUBROUTINE  PMPLOT( NANGLE, NTERM, P, PI, PM )
C                         This routine calculates the four elements of
C                              scattering phase matrix by summing up a
C                               given series of Legendre coefficients.
C
      IMPLICIT    REAL*8 (A-H, O-Z)
      DIMENSION   P( 4,* ), PM( 4,* )
C                                                       Initialization
      DELANG = 180./ (NANGLE-1)
      ANGLE  = 0.
C                                  Sum the Legendre series for each angle
C                                          by using Eqs.(9,14) in Loop-10
      DO 20 J = 1, NANGLE
         S1  = 0.
         S2  = 0.
         PM(3,J) = 0.
         PM(4,J) = 0.
         GMU = COS( ANGLE*PI/180. )
         PL0 = 0.
         PL1 = 1.
         PL  = 1.
         DO 10 N = 0, NTERM-1
            IF ( N.GT.0 )  PL = ( (2*N-1)*GMU*PL1 - (N-1)*PL0 ) / N
            S1  = S1 + P(1,N+1)*PL
            S2  = S2 + P(2,N+1)*PL
            PM(3,J) = PM(3,J) + P(3,N+1)*PL
            PM(4,J) = PM(4,J) + P(4,N+1)*PL
            PL0 = PL1
            PL1 = PL
10       CONTINUE
C                              Convert phase elements, which correspond
C                                   to (I,Q,U,V), into those of Eq.(4)
         PM(1,J) = (S1-S2) / (4*PI)
         PM(2,J) = (S1+S2) / (4*PI)
         PM(3,J) = PM(3,J) / (4*PI)
         PM(4,J) = PM(4,J) / (4*PI)
         ANGLE = ANGLE + DELANG
20    CONTINUE
C
      RETURN
      END
C***************************  END OF PMPLOT  ***************************
C**********************************************************************
      SUBROUTINE  READIN( CM, COMP, CONO, DENSH, GSD, ISIZ, ITYPE,
```

```
     $                    LECOEF, MHAZ, MTRM, NANGLE, NMODE, NQUAD, NWL,
     $                    PHASE, PLOT, PRNT, RENOM, RH, RINC, RM, RMAX,
     $                    RMIN, SOLUBL, STOKES, TABLE, TEMP, WA )
C                            This routine reads in all input parameters,
C                               control flags and checks their validity.
C
      IMPLICIT   REAL*8 (A-H, O-Z)
      DIMENSION  CM( * ), COMP( MHAZ,* ), DENSH( * ), ITYPE( * ),
     $           GSD( * ), RM( * ), WA( * )
      LOGICAL    FATAL, NEXT, PHASE, PLOT, PRNT( * ), SOLUBL( * ),
     $           STOKES, TABLE
      COMMON     /REFIDX/  IWL,  WL( 61 ), CRE( 5,61 ), CIM( 5,61 ),
     $                 CH( 7 ), WLS( 61 ), CRS( 7,61 ), CIS( 7,61 )
      DATA       FATAL /.FALSE./, NEXT /.FALSE./
C
      READ (5,70)
      READ (5,80) PHASE, STOKES, PLOT, TABLE, PRNT(1), PRNT(2), PRNT(3)
      READ (5,*)  RMIN
      READ (5,*)  RMAX
      READ (5,*)  RH
      READ (5,*)  RENOM
      READ (5,*)  NMODE
      READ (5,*)  CONO
      READ (5,*)  TEMP
      READ (5,*)  RINC
      READ (5,*)  ISIZ
      READ (5,*)  NWL
      READ (5,*)  (WA(I), I=1, NWL)
      READ (5,*)  NQUAD
      READ (5,*)  LECOEF
      READ (5,*)  NANGLE
      DO 10 J = 1, NMODE
10    READ (5,*)  CM(J), GSD(J), RM(J)
      DO 20 J=1,  NMODE
20    READ (5,*)  (COMP(I,J), I=1, MHAZ)
      READ (5,*)  (DENSH(I),  I=1, MHAZ)
      READ (5,*)  (ITYPE(I),  I=1, MHAZ-1)
      READ (5,*)  (SOLUBL(I), I=1, MHAZ-1)
C                                             Complex refractive indices
      CALL CRITAB
C                                                       Check input data
      IF ( MTRM.LT.NQUAD .OR. MTRM.LT.NANGLE )  THEN
         FATAL = .TRUE.
         CALL  ERRMSG('NQUAD/NANGLE exceeds dimension MTRM.', NEXT )
      END IF
      IF ( (WA(1).LT.WL(1)) .OR. (WA(NWL).GT.WL(IWL)) )  THEN
         FATAL = .TRUE.
         CALL  ERRMSG('WA-WL exceeds wavelength limitation.', NEXT )
      END IF
      IF ( (WA(1).LT.WLS(1)) .OR. (WA(NWL).GT.WLS(IWL)) )  THEN
         FATAL = .TRUE.
         CALL  ERRMSG('WA-WLS exceeds wavelength limitation.', NEXT )
      END IF
      IF ( RH.GT.0.996 )  THEN
```

```
         FATAL = .TRUE.
         CALL  ERRMSG('RH is larger than 99.6%.', NEXT )
      END IF
      SUM = 0.
      DO 30 J = 1, NMODE
         DO 30 I = 1, MHAZ
         SUM = SUM + COMP(I,J)
30    CONTINUE
      IF ( ABS(SUM-1.*NMODE) .GE. 0.00001 )  THEN
         FATAL = .TRUE.
         CALL  ERRMSG('Sum of all components is not unity.', NEXT )
      END IF
      IF ( FATAL )  CALL  ERRMSG('FATAL INPUT PROGRAM ABORTED.', FATAL )
C
      IF ( TABLE )  THEN
         WRITE (6,90)
         DO 40 I = 1, IWL
40       WRITE (6,100)  I, WL(I),  ( CRE(J,I), CIM(J,I), J=1,5 )
         WRITE (6,110)
         DO 50 I = 1, IWL
50       WRITE (6,120) I, WLS(I), ( CRS(J,I), CIS(J,I), J=1,5 )
         WRITE (6,130)
         DO 60 I = 1, IWL
60       WRITE (6,120) I, WLS(I), ( CRS(J,I), CIS(J,I), J=6,7 )
      END IF
C
70    FORMAT(1X)
80    FORMAT(L6)
90    FORMAT(10X,'I', 2X,'WAVELENGTH', 6X,'SOLUBLE', 11X, 'INSOLUBLE',
     $       11X,'SOOT', 15X,'SEA SALT', 13X,'WATER',//)
100   FORMAT(I11, F10.4, F9.3, E11.3, F8.3, E11.3, F8.3, F7.3,F12.3,
     $       E11.3, F8.3, E11.3)
110   FORMAT(1H1, 10X,'I', 2X,'WAVELENGTH', 5X,'.00 H2SO4', 10X,
     $       '.25 H2SO4', 10X,'.38 H2SO4', 10X,'.50 H2SO4', 10X,
     $       '.75 H2SO4',//)
120   FORMAT(I11, F10.4, 1X, 5(F8.3, E11.3))
130   FORMAT(1H1, 10X,'I', 2X,'WAVELENGTH', 4X,'.845 H2SO4', 9X,
     $       '.956 H2SO4',//)
      RETURN
      END
C****************************  END OF READIN  ****************************
C*************************************************************************
      SUBROUTINE  REFIND( H2SO4, KC, WA, COAT, CORE )
C                      This routine calculates the complex refractive index
C                           of the core and the shell (if any) of aerosols.
C
      IMPLICIT    REAL*8 (A-H, O-Z)
      COMPLEX*16  COAT, CORE
      COMMON      /REFIDX/ IWL, WL( 61 ), CRE( 5,61 ), CIM( 5,61 ),
     $                     WLS( 61 ), CRS( 7,61 ), CIS( 7,61 ), CH( 7 )
C
      DO 40 I = 2, IWL
         IF ( WL(I).GE.WA )  THEN
C                                          Refractive index of dry material
```

```
            CALL  INTERP(1,WL(I-1),CRE(KC,I-1),WL(I),CRE(KC,I),WA,CREAL)
            CALL  INTERP(2,WL(I-1),CIM(KC,I-1),WL(I),CIM(KC,I),WA,CIMAG)
            CORE = CMPLX( CREAL,CIMAG )
C                                              Refractive index of water
            IF ( H2SO4.EQ.0. )  THEN
               CALL INTERP(1,WL(I-1),CRE(5,I-1),WL(I),CRE(5,I),WA,CREAL)
               CALL INTERP(2,WL(I-1),CIM(5,I-1),WL(I),CIM(5,I),WA,CIMAG)
            ELSE
C                Refractive index of sulfuric acid at concentration H2SO4
               DO 20 L = 2, IWL
                  IF ( WLS(L).GE.WA )  THEN
                     DO 10 J = 2, 7
                        IF ( (CH(J).GE.H2SO4) .OR. (J.EQ.7) )  THEN
                           CALL INTERP( 1, CH(J-1), CRS(J-1,L-1),
     $                                  CH(J), CRS(J,L-1), H2SO4, CR1 )
                           CALL INTERP( 1, CH(J-1), CRS(J-1,L),
     $                                  CH(J), CRS(J,L),   H2SO4, CR2 )
                           CALL INTERP( 1, CH(J-1), CIS(J-1,L-1),
     $                                  CH(J), CIS(J,L-1), H2SO4, CI1 )
                           CALL INTERP( 1, CH(J-1), CIS(J-1,L),
     $                                  CH(J), CIS(J,L),   H2SO4, CI2 )
                           CALL INTERP( 1, WLS(L-1), CR1, WLS(L), CR2,
     $                                  WA, CREAL )
                           CALL INTERP( 1, WLS(L-1), CI1, WLS(L), CI2,
     $                                  WA, CIMAG )
                           GO TO 30
                        END IF
10                   CONTINUE
                  END IF
20             CONTINUE
            END IF
30          COAT = CMPLX( CREAL,CIMAG )
            RETURN
         END IF
40    CONTINUE
      END
C***************************  END OF REFIND  ***************************
C***********************************************************************
```

Appendix B. Sample Input/Output

(1) Input for the case of Table 2

```
                Test case of Deirmendjian C1-Cloud  (p.205)
    TRUE      !  PHASE   : Control flag of phase matrix computation
   FALSE      ! STOKES   : .TRUE. for Stokes phase matrix; .FALSE., Legendre
    TRUE      !  PLOT    : Sum up Legendre coeff. to get Stokes phase matrix
   FALSE      !  TABLE   : .TRUE. Print out aerosol and H2SO4 refractive indi
    TRUE      ! PRNT(1)  : .TRUE. Print out aerosol microphysics
   FALSE      ! PRNT(2)  : .TRUE. Print out aerosol optical properties in det
   FALSE      ! PRNT(3)  : .TRUE. Print out aerosol phase matrix in detail
   0.132      !  RMIN.   : Min. radius of size distribution
  15.852      !  RMAX.   : Max. radius of size distribution
   0.000      !    RH.   : Relative humidity (1.0 for 100%)
   0.000      ! RENOM.   : Renormalization flag
       1      ! NMODE.   : Number of size distribution modes
  1.E-20      !  CONO.   : Min. aerosol concentration
   288.0      !  TEMP.   : Temperature at degree K
  0.1321      !  RINC.   : Radius increment: 0, default; <0, power law; >0, l
       0      !  ISIZ.   : Size distribution: 0, Deirmendjian; 1-3, log-norma
       1      !   NWL.   : Number of output wavelengths below:
    16.6
      32      ! NQUAD    : Max. even quadrature angles in Legendre expansion
      17      ! LECOEF   : Output number of Legendre coefficients
      19      ! NANGLE   : Odd number of angles in plotting phase matrix
   100.0  7.000  0.66667
   0.000  0.000  0.000  0.000  1.000  0.000
   1.850  1.850  2.000  2.450  1.000  1.835
       3      3      1      2      5
    TRUE  FALSE  FALSE   TRUE   TRUE
```

(2) Input for a case similar to Table 3

```
             Test case of Arctic haze (Blanchet and List, 1983)
    TRUE      !  PHASE   : Control flag of phase matrix computation
   FALSE      ! STOKES   : .TRUE. for Stokes phase matrix; .FALSE., Legendre
    TRUE      !  PLOT    : Sum up Legendre coeff. to get Stokes phase matrix
   FALSE      !  TABLE   : .TRUE. Print out aerosol and H2SO4 refractive indi
    TRUE      ! PRNT(1)  : .TRUE. Print out aerosol microphysics
    TRUE      ! PRNT(2)  : .TRUE. Print out aerosol optical properties in det
    TRUE      ! PRNT(3)  : .TRUE. Print out aerosol phase matrix in detail
   0.001      !  RMIN.   : Min. radius of size distribution
  10.000      !  RMAX.   : Max. radius of size distribution
   0.000      !    RH.   : Relative humidity (1.0 for 100%)
   0.000      ! RENOM.   : Renormalization flag
       3      ! NMODE.   : Number of size distribution modes
  1.E-20      !  CONO.   : Min. aerosol concentration for consideration
   245.0      !  TEMP.   : Temperature at degree K
     0.0      !  RINC.   : Radius increment: 0, default; <0, power law; >0, l
       1      !  ISIZ.   : Size distribution: 0, Deirmendjian; 1-3, log-norma
       1      !   NWL.   : Number of output wavelengths below:
    40.0
      32      ! NQUAD    : Max. even quadrature angles in Legendre expansion
```

```
   17     ! LECOEF  : Output number of Legendre coefficients
  181     ! NANGLE  : Odd number of angles in plotting phase matrix
107.8  1.822  0.030
609.5  1.419  0.087
0.457  2.014  0.300
0.570  0.100  0.075  0.000  0.000  0.255
0.570  0.100  0.075  0.000  0.000  0.255
0.000  0.263  0.000  0.579  0.000  0.158
1.850  1.850  2.000  2.450  1.000  1.835
    3      3      1      2      5
 TRUE  FALSE  FALSE   TRUE   TRUE
```

I	WAVELENGTH	SOLUBLE	INSOLUBLE	SOOT	SEA SALT	WATER
1	0.2000	1.530 -0.700E-01	1.530 -0.700E-01	1.500 -0.350	1.510 -0.100E-03	1.396 -0.110E-06
2	0.2500	1.530 -0.300E-01	1.530 -0.300E-01	1.620 -0.450	1.510 -0.500E-05	1.362 -0.335E-07
3	0.3000	1.530 -0.800E-02	1.530 -0.800E-02	1.740 -0.470	1.510 -0.200E-05	1.340 -0.160E-07
4	0.3371	1.530 -0.500E-02	1.530 -0.800E-02	1.750 -0.470	1.510 -0.400E-06	1.345 -0.845E-08
5	0.4000	1.530 -0.500E-02	1.530 -0.800E-02	1.750 -0.460	1.500 -0.300E-07	1.339 -0.186E-08
6	0.4880	1.530 -0.500E-02	1.530 -0.800E-02	1.750 -0.450	1.500 -0.200E-07	1.335 -0.969E-09
7	0.5145	1.530 -0.500E-02	1.530 -0.800E-02	1.750 -0.450	1.500 -0.100E-07	1.334 -0.118E-08
8	0.5500	1.530 -0.600E-02	1.530 -0.800E-02	1.750 -0.440	1.500 -0.100E-07	1.333 -0.196E-08
9	0.6320	1.530 -0.600E-02	1.530 -0.800E-02	1.750 -0.430	1.490 -0.200E-07	1.332 -0.146E-07
10	0.6943	1.530 -0.700E-02	1.530 -0.800E-02	1.750 -0.430	1.490 -0.100E-06	1.331 -0.305E-07
11	0.8600	1.520 -0.120E-01	1.520 -0.800E-02	1.750 -0.430	1.480 -0.300E-05	1.329 -0.329E-06
12	1.0600	1.520 -0.170E-01	1.520 -0.800E-02	1.750 -0.440	1.470 -0.200E-03	1.326 -0.418E-05
13	1.3000	1.510 -0.200E-01	1.460 -0.800E-02	1.760 -0.450	1.470 -0.400E-03	1.323 -0.369E-04
14	1.5300	1.510 -0.230E-01	1.400 -0.800E-02	1.770 -0.460	1.460 -0.600E-03	1.318 -0.997E-04
15	1.8000	1.460 -0.170E-01	1.330 -0.800E-02	1.790 -0.480	1.450 -0.800E-03	1.312 -0.115E-03
16	2.0000	1.420 -0.800E-02	1.260 -0.800E-02	1.800 -0.490	1.450 -0.100E-02	1.306 -0.110E-02
17	2.2500	1.420 -0.100E-01	1.220 -0.900E-02	1.810 -0.500	1.440 -0.200E-02	1.292 -0.390E-03
18	2.5000	1.420 -0.120E-01	1.180 -0.900E-02	1.820 -0.510	1.430 -0.400E-02	1.261 -0.174E-02
19	2.7000	1.400 -0.550E-01	1.180 -0.130E-01	1.830 -0.520	1.400 -0.700E-02	1.188 -0.190E-01
20	3.0000	1.420 -0.220E-01	1.160 -0.120E-01	1.840 -0.540	1.610 -0.100E-01	1.371 -0.272E+00
21	3.2000	1.430 -0.800E-02	1.220 -0.100E-01	1.860 -0.540	1.490 -0.300E-02	1.478 -0.924E-01
22	3.3923	1.430 -0.700E-02	1.260 -0.130E-01	1.870 -0.550	1.480 -0.200E-02	1.422 -0.204E-01
23	3.5000	1.450 -0.500E-02	1.280 -0.110E-01	1.880 -0.560	1.480 -0.160E-02	1.400 -0.940E-02
24	3.7500	1.452 -0.400E-02	1.270 -0.110E-01	1.900 -0.570	1.470 -0.140E-02	1.369 -0.350E-02
25	4.0000	1.455 -0.500E-02	1.260 -0.120E-01	1.920 -0.580	1.480 -0.140E-02	1.351 -0.460E-02
26	4.5000	1.460 -0.130E-01	1.260 -0.140E-01	1.940 -0.590	1.490 -0.140E-02	1.332 -0.134E-01
27	5.0000	1.450 -0.120E-01	1.250 -0.160E-01	1.970 -0.600	1.470 -0.250E-02	1.325 -0.124E-01
28	5.5000	1.440 -0.180E-01	1.220 -0.210E-01	1.990 -0.610	1.420 -0.360E-02	1.298 -0.116E-01
29	6.0000	1.410 -0.230E-01	1.150 -0.370E-01	2.020 -0.620	1.410 -0.110E-01	1.265 -0.107E+00
30	6.2000	1.430 -0.270E-01	1.140 -0.390E-01	2.030 -0.625	1.600 -0.220E-01	1.363 -0.880E-01
31	6.5000	1.460 -0.330E-01	1.130 -0.420E-01	2.040 -0.630	1.460 -0.500E-02	1.339 -0.392E-01
32	7.2000	1.400 -0.700E-01	1.400 -0.550E-01	2.060 -0.650	1.420 -0.700E-02	1.312 -0.321E-01
33	7.9000	1.200 -0.650E-01	1.150 -0.400E-01	2.120 -0.670	1.400 -0.130E-01	1.294 -0.329E-01
34	8.2000	1.010 -0.100E+00	1.130 -0.740E-01	2.130 -0.680	1.420 -0.200E-01	1.286 -0.351E-01
35	8.5000	1.300 -0.215E+00	1.300 -0.900E-01	2.150 -0.690	1.480 -0.260E-01	1.278 -0.367E-01
36	8.7000	2.400 -0.290E+00	1.400 -0.100E+00	2.160 -0.690	1.600 -0.300E-01	1.272 -0.379E-01
37	9.0000	2.560 -0.370E+00	1.700 -0.140E+00	2.170 -0.700	1.650 -0.280E-01	1.262 -0.399E-01
38	9.2000	2.200 -0.420E+00	1.720 -0.150E+00	2.180 -0.700	1.610 -0.260E-01	1.255 -0.415E-01
39	9.5000	1.950 -0.160E+00	1.730 -0.162E+00	2.190 -0.710	1.580 -0.180E-01	1.430 -0.444E-01
40	9.8000	1.870 -0.950E-01	1.740 -0.162E+00	2.200 -0.715	1.560 -0.160E-01	1.229 -0.479E-01
41	10.0000	1.820 -0.900E-01	1.750 -0.162E+00	2.100 -0.720	1.540 -0.150E-01	1.218 -0.508E-01
42	10.5900	1.760 -0.700E-01	1.620 -0.120E+00	2.220 -0.730	1.500 -0.140E-01	1.179 -0.674E-01
43	11.0000	1.720 -0.500E-01	1.620 -0.105E+00	2.230 -0.730	1.480 -0.140E-01	1.153 -0.968E-01
44	11.5000	1.670 -0.470E-01	1.590 -0.100E+00	2.240 -0.740	1.480 -0.140E-01	1.126 -0.142E+00
45	12.5000	1.620 -0.530E-01	1.510 -0.900E-01	2.270 -0.750	1.420 -0.160E-01	1.123 -0.259E+00
46	13.0000	1.620 -0.550E-01	1.470 -0.100E+00	2.280 -0.760	1.410 -0.180E-01	1.146 -0.305E+00
47	14.0000	1.560 -0.730E-01	1.520 -0.850E-01	2.310 -0.775	1.410 -0.230E-01	1.210 -0.370E+00
48	14.8000	1.440 -0.100E+00	1.570 -0.100E+00	2.330 -0.790	1.430 -0.300E-01	1.258 -0.396E+00
49	15.0000	1.420 -0.200E+00	1.570 -0.100E+00	2.330 -0.790	1.450 -0.350E-01	1.270 -0.402E+00
50	16.4000	1.750 -0.160E+00	1.600 -0.100E+00	2.360 -0.810	1.560 -0.900E-01	1.346 -0.427E+00
51	17.2000	2.080 -0.240E+00	1.630 -0.100E+00	2.380 -0.820	1.740 -0.120E+00	1.386 -0.429E+00
52	18.0000	1.980 -0.180E+00	1.640 -0.115E+00	2.400 -0.825	1.780 -0.130E+00	1.423 -0.426E+00
53	18.5000	1.850 -0.170E+00	1.640 -0.120E+00	2.410 -0.830	1.770 -0.135E+00	1.443 -0.421E+00
54	20.0000	2.120 -0.220E+00	1.680 -0.220E+00	2.450 -0.850	1.760 -0.152E+00	1.480 -0.393E+00
55	21.3000	2.060 -0.230E+00	1.770 -0.280E+00	2.460 -0.860	1.760 -0.165E+00	1.491 -0.379E+00
56	22.5000	2.000 -0.240E+00	1.900 -0.280E+00	2.480 -0.870	1.760 -0.180E+00	1.506 -0.370E+00
57	25.0000	1.880 -0.280E+00	1.970 -0.240E+00	2.510 -0.890	1.760 -0.205E+00	1.531 -0.356E+00
58	27.9000	1.840 -0.290E+00	1.890 -0.320E+00	2.540 -0.910	1.770 -0.275E+00	1.549 -0.339E+00
59	30.0000	1.820 -0.300E+00	1.800 -0.420E+00	2.570 -0.930	1.770 -0.300E+00	1.551 -0.328E+00
60	35.0000	1.920 -0.400E+00	1.900 -0.500E+00	2.630 -0.970	1.760 -0.500E+00	1.532 -0.336E+00
61	40.0000	1.860 -0.500E+00	2.100 -0.600E+00	2.690 -1.000	1.740 -0.100E+01	1.519 -0.385E+00

I	WAVELENGTH	.00 H2SO4	.25 H2SO4	.38 H2SO4	.50 H2SO4	.75 H2SO4
1	0.2000	1.396 -0.110E-06	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07
2	0.2500	1.362 -0.335E-07	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07
3	0.3300	1.344 -0.949E-08	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07
4	0.3370	1.345 -0.847E-08	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07
5	0.4000	1.339 -0.186E-08	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07
6	0.4800	1.335 -0.911E-09	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07	1.400 -0.100E-07
7	0.5100	1.334 -0.110E-08	1.370 -0.100E-07	1.390 -0.100E-07	1.400 -0.100E-07	1.430 -0.100E-07
8	0.5500	1.333 -0.196E-08	1.370 -0.100E-07	1.390 -0.100E-07	1.400 -0.100E-07	1.430 -0.100E-07
9	0.6328	1.332 -0.147E-07	1.370 -0.100E-07	1.390 -0.100E-07	1.400 -0.100E-07	1.430 -0.100E-07
10	0.7020	1.331 -0.345E-07	1.363 -0.302E-07	1.382 -0.246E-07	1.394 -0.207E-07	1.428 -0.207E-07
11	0.8620	1.329 -0.338E-06	1.361 -0.272E-06	1.379 -0.250E-06	1.392 -0.207E-06	1.425 -0.183E-06
12	1.0640	1.326 -0.435E-05	1.358 -0.130E-05	1.373 -0.129E-05	1.387 -0.130E-05	1.420 -0.150E-05
13	1.2990	1.323 -0.367E-04	1.352 -0.133E-04	1.367 -0.129E-04	1.380 -0.126E-04	1.411 -0.105E-04
14	1.5380	1.318 -0.100E-03	1.346 -0.169E-03	1.360 -0.180E-03	1.373 -0.174E-03	1.403 -0.138E-03
15	1.7860	1.312 -0.973E-04	1.339 -0.237E-03	1.351 -0.287E-03	1.364 -0.200E-03	1.393 -0.486E-03
16	2.0000	1.306 -0.110E-02	1.331 -0.200E-02	1.343 -0.180E-02	1.355 -0.150E-02	1.384 -0.126E-02
17	2.2220	1.295 -0.326E-03	1.319 -0.400E-03	1.330 -0.800E-03	1.342 -0.100E-02	1.370 -0.167E-02
18	2.5000	1.261 -0.174E-02	1.286 -0.200E-02	1.300 -0.250E-02	1.311 -0.300E-02	1.344 -0.376E-02
19	2.7250	1.203 -0.240E-01	1.183 -0.310E-01	1.207 -0.250E-01	1.231 -0.220E-01	1.293 -0.600E-02
20	2.9850	1.363 -0.296E+00	1.354 -0.207E+00	1.342 -0.175E+00	1.330 -0.148E+00	1.292 -0.930E-01
21	3.1750	1.485 -0.113E+00	1.431 -0.118E+00	1.400 -0.117E+00	1.369 -0.113E+00	1.306 -0.131E+00
22	3.4130	1.418 -0.175E-01	1.408 -0.470E-01	1.393 -0.700E-01	1.375 -0.950E-01	1.357 -0.159E+00
23	3.4720	1.403 -0.105E-01	1.400 -0.400E-01	1.389 -0.640E-01	1.377 -0.920E-01	1.370 -0.161E+00
24	3.7590	1.368 -0.354E-02	1.372 -0.290E-01	1.370 -0.520E-01	1.369 -0.760E-01	1.396 -0.130E+00
25	4.0000	1.351 -0.460E-02	1.355 -0.320E-01	1.358 -0.560E-01	1.363 -0.800E-01	1.398 -0.126E+00
26	4.4640	1.333 -0.135E-01	1.340 -0.420E-01	1.343 -0.630E-01	1.350 -0.850E-01	1.384 -0.119E+00
27	4.9500	1.328 -0.125E-01	1.324 -0.490E-01	1.324 -0.760E-01	1.329 -0.960E-01	1.366 -0.118E+00
28	5.4950	1.298 -0.113E-01	1.301 -0.760E-01	1.310 -0.119E+00	1.316 -0.151E+00	1.337 -0.182E+00
29	6.0240	1.277 -0.104E+00	1.310 -0.148E+00	1.343 -0.165E+00	1.371 -0.185E+00	1.427 -0.191E+00
30	6.2110	1.362 -0.854E-01	1.379 -0.125E+00	1.387 -0.143E+00	1.403 -0.148E+00	1.422 -0.144E+00
31	6.4940	1.339 -0.393E-01	1.351 -0.850E-01	1.360 -0.105E+00	1.363 -0.120E+00	1.368 -0.123E+00
32	7.1940	1.312 -0.321E-01	1.304 -0.102E+00	1.297 -0.135E+00	1.285 -0.161E+00	1.222 -0.173E+00
33	7.8740	1.295 -0.327E-01	1.254 -0.143E+00	1.236 -0.206E+00	1.212 -0.268E+00	1.145 -0.445E+00
34	8.2640	1.284 -0.354E-01	1.277 -0.270E+00	1.282 -0.381E+00	1.280 -0.473E+00	1.241 -0.663E+00
35	8.5470	1.277 -0.370E-01	1.382 -0.268E+00	1.417 -0.376E+00	1.448 -0.485E+00	1.421 -0.758E+00
36	8.6960	1.272 -0.379E-01	1.395 -0.229E+00	1.451 -0.344E+00	1.507 -0.436E+00	1.545 -0.755E+00
37	9.0090	1.262 -0.400E-01	1.387 -0.201E+00	1.452 -0.269E+00	1.523 -0.335E+00	1.669 -0.590E+00
38	9.1740	1.240 -0.413E-01	1.377 -0.193E+00	1.434 -0.265E+00	1.471 -0.314E+00	1.626 -0.540E+00
39	9.5240	1.414 -0.447E-01	1.398 -0.273E+00	1.460 -0.376E+00	1.509 -0.462E+00	1.702 -0.711E+00
40	9.8040	1.229 -0.480E-01	1.442 -0.209E+00	1.556 -0.272E+00	1.649 -0.349E+00	1.944 -0.538E+00
41	9.9010	1.225 -0.484E-01	1.441 -0.195E+00	1.549 -0.247E+00	1.650 -0.314E+00	1.947 -0.453E+00
42	10.6380	1.176 -0.704E-01	1.382 -0.152E+00	1.454 -0.193E+00	1.535 -0.192E+00	1.717 -0.275E+00
43	11.1110	1.147 -0.106E+00	1.365 -0.200E+00	1.436 -0.269E+00	1.484 -0.311E+00	1.739 -0.463E+00
44	11.4940	1.126 -0.141E+00	1.393 -0.205E+00	1.512 -0.240E+00	1.617 -0.303E+00	1.916 -0.313E+00
45	12.5000	1.123 -0.259E+00	1.354 -0.224E+00	1.455 -0.211E+00	1.549 -0.210E+00	1.757 -0.158E+00
46	13.1580	1.156 -0.315E+00	1.358 -0.262E+00	1.440 -0.240E+00	1.520 -0.221E+00	1.701 -0.160E+00
47	13.8890	1.203 -0.366E+00	1.377 -0.294E+00	1.440 -0.266E+00	1.503 -0.242E+00	1.663 -0.171E+00
48	14.7060	1.252 -0.393E+00	1.400 -0.322E+00	1.443 -0.295E+00	1.488 -0.268E+00	1.613 -0.183E+00
49	14.9250	1.266 -0.401E+00	1.407 -0.329E+00	1.444 -0.304E+00	1.483 -0.277E+00	1.596 -0.191E+00
50	16.6670	1.359 -0.428E+00	1.473 -0.415E+00	1.498 -0.448E+00	1.506 -0.479E+00	1.542 -0.479E+00
51	17.2410	1.388 -0.429E+00	1.550 -0.412E+00	1.603 -0.443E+00	1.653 -0.496E+00	1.741 -0.594E+00
52	18.1820	1.430 -0.424E+00	1.572 -0.360E+00	1.629 -0.364E+00	1.700 -0.375E+00	1.946 -0.362E+00
53	18.5190	1.443 -0.421E+00	1.576 -0.355E+00	1.628 -0.354E+00	1.694 -0.360E+00	1.926 -0.299E+00
54	20.0000	1.480 -0.393E+00	1.596 -0.349E+00	1.627 -0.357E+00	1.690 -0.344E+00	1.823 -0.235E+00
55	21.2770	1.491 -0.379E+00	1.627 -0.354E+00	1.658 -0.374E+00	1.689 -0.361E+00	1.781 -0.290E+00
56	22.7270	1.508 -0.369E+00	1.676 -0.343E+00	1.719 -0.372E+00	1.758 -0.380E+00	1.881 -0.320E+00
57	25.0000	1.531 -0.356E+00	1.700 -0.303E+00	1.749 -0.327E+00	1.806 -0.319E+00	1.930 -0.200E+00
58	27.9000	1.549 -0.339E+00	1.700 -0.300E+00	1.750 -0.320E+00	1.800 -0.320E+00	1.900 -0.200E+00
59	30.0000	1.551 -0.328E+00	1.700 -0.300E+00	1.750 -0.320E+00	1.800 -0.320E+00	1.900 -0.200E+00
60	35.0000	1.532 -0.336E+00	1.700 -0.300E+00	1.750 -0.320E+00	1.800 -0.320E+00	1.900 -0.200E+00
61	40.0000	1.519 -0.385E+00	1.700 -0.300E+00	1.750 -0.320E+00	1.800 -0.320E+00	1.900 -0.200E+00

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 I  WAVELENGTH    .845 H2SO4          .956 H2SO4


 1    0.2000    1.400 -0.100E-07   1.400 -0.100E-07
 2    0.2500    1.400 -0.100E-07   1.400 -0.100E-07
 3    0.3300    1.400 -0.100E-07   1.400 -0.100E-07
 4    0.3370    1.460 -0.100E-07   1.459 -0.100E-07
 5    0.4000    1.448 -0.100E-07   1.443 -0.100E-07
 6    0.4800    1.442 -0.100E-07   1.438 -0.100E-07
 7    0.5100    1.442 -0.100E-07   1.438 -0.100E-07
 8    0.5500    1.438 -0.100E-07   1.434 -0.100E-07
 9    0.6328    1.438 -0.100E-07   1.434 -0.100E-07
10    0.7020    1.436 -0.100E-07   1.432 -0.100E-07
11    0.8620    1.431 -0.148E-06   1.429 -0.134E-06
12    1.0640    1.425 -0.152E-05   1.426 -0.140E-05
13    1.2990    1.416 -0.950E-05   1.420 -0.667E-05
14    1.5380    1.408 -0.122E-03   1.411 -0.988E-04
15    1.7860    1.400 -0.499E-03   1.404 -0.452E-03
16    2.0000    1.392 -0.119E-02   1.396 -0.837E-03
17    2.2220    1.382 -0.169E-02   1.385 -0.129E-02
18    2.5000    1.358 -0.338E-02   1.368 -0.211E-02
19    2.7250    1.320 -0.600E-02   1.339 -0.600E-02
20    2.9850    1.273 -0.670E-01   1.267 -0.480E-01
21    3.1750    1.283 -0.131E+00   1.274 -0.143E+00
22    3.4130    1.341 -0.181E+00   1.377 -0.197E+00
23    3.4720    1.361 -0.189E+00   1.403 -0.192E+00
24    3.7590    1.403 -0.156E+00   1.445 -0.122E+00
25    4.0000    1.418 -0.149E+00   1.435 -0.114E+00
26    4.4640    1.416 -0.127E+00   1.446 -0.750E-01
27    4.9500    1.414 -0.110E+00   1.426 -0.580E-01
28    5.4950    1.373 -0.140E+00   1.384 -0.530E-01
29    6.0240    1.425 -0.161E+00   1.341 -0.620E-01
30    6.2110    1.416 -0.120E+00   1.329 -0.690E-01
31    6.4940    1.378 -0.980E-01   1.305 -0.560E-01
32    7.1940    1.197 -0.161E+00   1.057 -0.334E+00
33    7.8740    1.132 -0.471E+00   1.225 -0.358E+00
34    8.2640    1.230 -0.666E+00   1.230 -0.532E+00
35    8.5470    1.403 -0.764E+00   1.447 -0.669E+00
36    8.6960    1.515 -0.777E+00   1.572 -0.615E+00
37    9.0090    1.682 -0.634E+00   1.654 -0.439E+00
38    9.1740    1.647 -0.574E+00   1.617 -0.360E+00
39    9.5240    1.749 -0.724E+00   1.548 -0.373E+00
40    9.8040    1.968 -0.528E+00   1.457 -0.311E+00
41    9.9010    1.954 -0.443E+00   1.372 -0.350E+00
42   10.6380    1.775 -0.323E+00   1.953 -0.468E+00
43   11.1110    1.884 -0.483E+00   1.937 -0.458E+00
44   11.4940    1.993 -0.247E+00   1.940 -0.181E+00
45   12.5000    1.793 -0.100E+00   1.710 -0.940E-01
46   13.1580    1.722 -0.108E+00   1.628 -0.110E+00
47   13.8890    1.677 -0.125E+00   1.584 -0.143E+00
48   14.7060    1.632 -0.144E+00   1.552 -0.176E+00
49   14.9250    1.617 -0.151E+00   1.543 -0.183E+00
50   16.6670    1.552 -0.400E+00   1.410 -0.340E+00
51   17.2410    1.671 -0.549E+00   1.389 -0.540E+00
52   18.1820    2.011 -0.391E+00   1.912 -0.740E+00
53   18.5190    2.011 -0.291E+00   2.045 -0.569E+00
54   20.0000    1.873 -0.146E+00   1.913 -0.209E+00
55   21.2770    1.807 -0.199E+00   1.826 -0.193E+00
56   22.7270    1.874 -0.231E+00   1.781 -0.248E+00
57   25.0000    1.938 -0.990E-01   1.896 -0.212E+00
58   27.9000    1.900 -0.200E+00   1.900 -0.200E+00
59   30.0000    1.900 -0.200E+00   1.900 -0.200E+00
60   35.0000    1.900 -0.200E+00   1.900 -0.200E+00
61   40.0000    1.900 -0.200E+00   1.900 -0.200E+00
```

```
MODE =  1


   COMPONENT =  5

     AEROSOL CONCENTRATION =          0.99998E+02 per cm3
     LINEAR MEAN RADIUS =             0.46665E+01 micron
     RMS RADIUS =                     0.49885E+01 micron
     EFFECTIVE MEAN RADIUS =          0.59981E+01 micron
     TOTAL CROSS-SECTIONAL AREA =     0.78178E+04 micron2/cm3
     TOTAL VOLUME OF AEROSOL =        0.62523E+05 micron3/cm3
     VOLUME/SURFACE RATIO =           0.19994E+01 micron
     MEAN RADIUS FOR SCATTERING =     0.65439E+01 micron


THE PARTICULATE CONCENTRATION FACTOR FOR EACH NON-ACID COMPONANT IS =    1.0000
AVERAGE PARTICLES DENSITY (g/cm3) FOR THIS MODE =      1.0000
SPECIFIC DENSITY (g/cm3) OF EACH COMPONENT =  1.0000
PARTICULATE VOLUME (micron3/cm3) OF EACH COMPONENT =62522.7933
MASS (microgram/m3) OF EACH COMPONENT WITH ACID COATING, IF ANY =  0.6252E+05


                                           WAVELENGTH =  16.60Micron
      Order               Coeff(P1)          Coeff(P2)          Coeff(P3)          Coeff(P4)
          0              0.10000E+01       -0.18537E+00        0.81196E+00       -0.18539E+00
          1              0.21450E+01       -0.27807E+00        0.21535E+01       -0.31026E+00
          2              0.23162E+01       -0.93567E-01        0.24002E+01       -0.11338E+00
          3              0.18570E+01        0.74564E-01        0.19528E+01        0.92814E-01
          4              0.12389E+01        0.15342E+00        0.12762E+01        0.17146E+00
          5              0.71074E+00        0.13876E+00        0.71313E+00        0.15251E+00
          6              0.36369E+00        0.95263E-01        0.35015E+00        0.98141E-01
          7              0.16641E+00        0.52185E-01        0.15441E+00        0.53032E-01
          8              0.70047E-01        0.25407E-01        0.62307E-01        0.24778E-01
          9              0.26873E-01        0.10873E-01        0.22993E-01        0.10455E-01
         10              0.95337E-02        0.43210E-02        0.77773E-02        0.39806E-02
         11              0.30514E-02        0.15468E-02        0.23525E-02        0.13493E-02
         12              0.87540E-03        0.49819E-03        0.62864E-03        0.39466E-03
         13              0.21789E-03        0.13721E-03        0.14503E-03        0.97195E-04
         14              0.46887E-04        0.32172E-04        0.28899E-04        0.20049E-04
         15              0.86567E-05        0.63624E-05        0.49617E-05        0.34701E-05
         16              0.13787E-05        0.10701E-05        0.73832E-06        0.50996E-06
                   0.0    0.788500     0.788500     0.788500     0.000000
                  10.0    0.729058     0.709633     0.719194    -0.010187
                  20.0    0.580323     0.520601     0.548550    -0.031570
                  30.0    0.405959     0.317606     0.355129    -0.047217
                  40.0    0.257893     0.167029     0.199555    -0.049057
                  50.0    0.155023     0.080089     0.099709    -0.040609
                  60.0    0.092100     0.037965     0.044978    -0.029001
                  70.0    0.056238     0.019594     0.017982    -0.018888
                  80.0    0.036286     0.011804     0.005441    -0.011697
                  90.0    0.025039     0.008354    -0.000295    -0.007098
                 100.0    0.018459     0.006716    -0.002989    -0.004285
                 110.0    0.014421     0.005912    -0.004352    -0.002566
                 120.0    0.011823     0.005542    -0.005141    -0.001484
                 130.0    0.010084     0.005439    -0.005699    -0.000783
                 140.0    0.008893     0.005560    -0.006166    -0.000338
                 150.0    0.008080     0.005911    -0.006574    -0.000093
                 160.0    0.007553     0.006441    -0.006896     0.000000
                 170.0    0.007259     0.006950    -0.007097     0.000008
                 180.0    0.007165     0.007165    -0.007165     0.000000
```

```
                    ************************************************************************
                    *****                                                              *****
                    *****                    OUTPUT FROM PROGRAM                       *****
                    *****                                                              *****
                    *****                 ATMOSPHERIC AEROSOL MODEL                    *****
                    *****                                                              *****
                    *****                                                              *****
                    ************************************************************************



                    ** PARAMETERS READ IN **


          NUMBER OF MODES IN ATMOSPHERIC AEROSOL =    1
          MINIMUM RADIUS USED               RMIN =    0.132 micron
          MAXIMUM RADIUS USED               RMAX =   15.852 micron

          THE FOLLOWING PROCESSES ARE INCLUDED IF
          THE CODES ARE SET TO "TRUE";
              PHASE MATRIX COMPUTATION     PHASE =    T
              RE-NORMALIZE ON MASS OR CONC.RENOM :    0.000

          OUTPUT DATA CONTROL;
           TABLE =T --- REFRACTIVE INDICES,   TABLE  =    T
          PRNT(1)=T --- DETAIL MICRO. PARA., PRNT(1) =    T
          PRNT(2)=T --- DETAIL OPTIC. PARA., PRNT(2) =    F
          PRNT(3)=T --- DETAIL PHASE MATRIX, PRNT(3) =    F
                  F --- OUTPUT DATA SUPPRESSED

                (%)           Soluble    Insoluble         Soot     Sea Salt Liquid Water    H2SO4-Acid
 COMPOSITION OF MODE =  1       0.000        0.000        0.000        0.000        1.000         0.000
  DENSITY OF AEROSOL =          1.850        1.850        2.000        2.450        1.000         1.835
    TYPE OF ACTIVITY =              3            3            1            2            5
          SOLUBILITY =              T            F            F            T            T


                    ** MICROPHYSICAL AND OPTICAL PROPERTIES **

 TOTAL CONCENTRATION =         99.998 per cm3
DRY EFFECTIVE RADIUS =        5.99813 micron
WET EFFECTIVE RADIUS =        5.99813 micron
    DRY AEROSOL MASS =    62522.79140 microgram/m3
    WET AEROSOL MASS =    62522.79140 microgram/m3
  DRY AEROSOL VOLUME =    62522.79326 micron3/cm3
  WET AEROSOL VOLUME =    62522.79326 micron3/cm3

                                                RELATIVE HUMIDITY =    0.00%
 I      WAVELENGTH            BETA_ext          BETA_sca          BETA_bks             OMEGA            ASYM-FACT
 1     16.6000000000      16.9695584880      6.7016362638      0.6033682162       0.3949210740       0.7149876591
```