Optical Properties of Aerosols and Clouds: The Software Package OPAC

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ABSTRACT

The software package OPAC (Optical Properties of Aerosols and Clouds) is described. It easily provides optical properties in the solar and terrestrial spectral range of atmospheric particulate matter. Microphysical and optical properties of six water clouds, three ice clouds, and 10 aerosol components, which are considered as typical cases, are stored as ASCII files. The optical properties are the extinction, scattering, and absorption coefficients, the single scattering albedo, the asymmetry parameter, and the phase function. They are calculated on the basis of the microphysical data (size distribution and spectral refractive index) under the assumption of spherical particles in case of aerosols and cloud droplets and assuming hexagonal columns in case of cirrus clouds. Data are given for up to 61 wavelengths between 0.25 and 40 μm and up to eight values of the relative humidity. The software package also allows calculation of derived optical properties like mass extinction coefficients and Ångström coefficients.

Real aerosol in the atmosphere always is a mixture of different components. Thus, in OPAC it is made possible to get optical properties of any mixtures of the basic components and to calculate optical depths on the base of exponential aerosol height profiles. Typical mixtures of aerosol components as well as typical height profiles are proposed as default values, but mixtures and profiles for the description of individual cases may also be achieved simply.

1. Introduction

Optical properties of particulate atmospheric constituents, that is, water and ice clouds and aerosol particles, affect local radiative forcing, the radiation balance of the earth, and thus climate. Moreover, these properties are essential for remote sensing, both of the constituents themselves and with respect to the masking effect against other quantities. The effects of aerosol particles dominate in the solar spectral range but are not negligible at other wavelengths and the effects of clouds are similar both in the solar and in the terrestrial spectral range. To make such optical properties available and easy to handle, the software package OPAC (Optical Properties of Aerosols and Clouds) was put together, which on the one hand provides the optical properties of water droplets, ice crystals, and aerosol particles, both in the solar and terrestrial spectral range, and on the other hand includes software to handle the data.

The properties of clouds and aerosol particles are highly variable, both in time and space. This is valid for the number density, that is, the amount of particles per volume, for the microphysical properties like size distribution, refractive index and shape, and for the height distribution. Moreover, in most cases the actual properties are not known. For this reason, it is impossible to model aerosols and clouds in detail. It is necessary to reduce the variability of naturally occurring aerosols and clouds to typical cases, but without neglecting possible fluctuations. In OPAC, this goal is achieved by the use of a dataset of typical clouds and internally mixed aerosol components. The aerosol components can be externally mixed to a wide range of tropospheric aerosols. The properties of the clouds and aerosol components are given together with a FORTRAN program, which allows the calculation of optical parameters for any mixture of clouds and aerosols components. This gives the possibility to model climate-relevant optical properties of atmospheric particulate constituents for individual cases. The optical proper-

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ties of cloud droplets and aerosol particles are modeled under the assumption of sphericity, those of ice crystals under the assumption of hexagonal columns.

This concept of separation of components of microphysical and optical properties easily enables future extensions and improvements. It is possible to add new cloud or aerosol components or to replace existing data with improved data with changed microphysical input data or to use properties of nonspherical particles, without affecting the remaining parts of OPAC.

Section 2 describes the structure of the software package OPAC, and section 3 the microphysical properties of all aerosol components and clouds in OPAC. Section 4 shows which optical properties can be extracted from the dataset or calculated within OPAC, and in section 5 proposed mixtures of aerosol components are presented. With respect to global distribution, mixtures of aerosol are presented in the Global Aerosol Data Set (GADS; Koepke et al. 1997). This uses the same aerosol components as OPAC but is compiled to give a basis for calculating global aerosol radiative forcing.

2. The software package

OPAC consists of two parts. The first part is a dataset of microphysical properties and the resulting optical properties of cloud and aerosol components at different wavelengths and for different humidity conditions. The other part is a FORTRAN program that allows the user to extract data from this dataset, to calculate additional optical properties, and to calculate optical properties of mixtures of the stored clouds and aerosol components.

The dataset gives the microphysical and optical properties for six types of water clouds, three ice clouds, and 10 aerosol components. Data are available at 61 wavelengths between 0.25 and 40 μm for aerosols and water clouds, and at 67 wavelengths between 0.28 and 40 μm for ice clouds. The data are given in each case for 1 particle cm^{-3}, which describes the effective properties of the mixture of all particles in the size distribution. For practical use, the values must be multiplied by the total number density. In the case of those aerosol components that are able to take up water, data for eight values of relative humidity (0%, 50%, 70%, 80%, 90%, 95%, 98%, 99%) are given. The data are stored as ASCII files, one file for each cloud or aerosol component and each relative humidity. The total amount of stored data is about 3.2 MB.

The computer code serves two purposes. First, single cloud or aerosol components can be selected, and all or some of their optical properties can be extracted or calculated from the dataset. Second, it is possible to select one of those mixtures of aerosol components, which are proposed as default values in OPAC (cf. section 5), or to define an additional mixture and to calculate its optical properties. Height distribution of aerosol particles is given but may also be changed with data given by the user.

For the sake of portability, the program is distributed as FORTRAN source code. All necessary input to the program must be entered as an ASCII text file. The details are explained in an example of such a file that is distributed with OPAC. A further file contains a complete list of files belonging to the software package and a description on how to install and use OPAC. To run the program, details to five topics must be given in the input file. The first topic deals with the desired mixture of cloud or aerosol components. Here, it is possible to select one of the default clouds or aerosol types (cf. section 5a) or to define a new mixture of the given components. The second topic deals with the height profile (cf. section 5b). For the default mixtures the default profiles may as well be used as new user-defined profiles. For new mixtures, however, new profiles have to be introduced. The third topic is the selection of the wavelengths for which optical parameters shall be calculated from those stored in the database. The fourth topic concerns the selection of the classes of relative humidity for which the calculations shall be performed. Finally, the desired optical parameters (cf. section 4) have to be selected. The resulting optical properties of the cloud or aerosol type are written to an ASCII output file.

3. Dataset of the microphysical properties of aerosols and clouds

The radiative properties in OPAC are modeled on the basis of components of aerosols and clouds, from which weighted sums of these data are used to describe radiative properties of the total amount of aerosol particles, water droplets, and ice crystals in the atmosphere. Each component is described by an individual particle size distribution and spectral refractive index. Its radiative properties are modeled with Mie theory in the case of cloud droplets and aerosol particles and with geometric optics in the case of ice crystals, which are assumed to be hexagonal columns for calculations

in the solar spectral range (Hess and Wiegner 1994). In the terrestrial spectral range, ice crystals are also considered to be spheres because the geometric optics assumption is only valid for particles, which are considerably larger than the wavelength of the incident radiation. The components are described in the following sections. Default values of aerosol mixtures are given in section 5.

a. Water clouds

Water clouds are described by the modified Gamma distribution after Deirmendjian (1969):

$$\frac{dN}{dr} = Nar^{\alpha} \exp\left[-\frac{\alpha}{\gamma}\left(\frac{r}{r_{\mathrm{mod}}}\right)^{\gamma}\right] = Nar^{\alpha} \exp(-Br^{\gamma})$$

(3a)

with

$$B = \frac{\alpha}{\gamma r_{\mathrm{mod}}^{\gamma}},$$

where N is the total number density in particles per cubic centimeter and r_{mod} the mode radius in micrometers. The constants α and γ describe the slope of the size distribution, while a is a normalization constant ensuring that the integral of the size distribution over all radii yields N. From this size distribution, as from any size distribution, an effective radius r_{eff} may be derived, which often is used in cloud research:

$$r_{\mathrm{eff}} = \frac{\int r^3 \frac{dN}{dr} dr}{\int r^2 \frac{dN}{dr} dr}.$$

(3b)

The parameters of the size distributions together with r_{eff} with particle number density N and the liquid water content L belonging to this number density are listed in Table 1a. For all models used, droplets outside the size range between 0.02 and 50 μm would not significantly contribute to either the optical properties or the liquid water content of the clouds, and thus they are not taken into account. The total particle number density given in Table 1a is a typical value, which is used as a seperate figure to make it possible to vary the liquid water content without changing the droplet size distribution.

The parameters of the normalized size distributions are selected out of those that Tampieri and Tomasi (1976) fitted to published measurements with respect to r_{mod} and the relative course of the size spectrum. From this collection, distributions have been selected that fit published measurements with respect to the liquid water content L for typical values of the number density N.

Five water-cloud models and one fog model are considered in OPAC. They are as well chosen to be representative for average conditions as to reflect

TABLE 1a. Microphysical properties of the water-cloud and fog models. For explanation see section 3a.

Component	File name	r_{mod} (μm)	α	γ	a	B	r_{eff} (μm)	N (cm^{-3})	L (g m^{-3})
Stratus (continental)	STCO	4.7	5	1.05	9.792E–3	0.938	7.33	250	0.28
Stratus (maritime)	STMA	6.75	3	1.30	3.818E–3	0.193	11.30	80	0.30
Cumulus (cont., clean)	CUCC	4.8	5	2.16	1.105E–3	0.0782	5.77	400	0.26
Cumulus (cont., polluted)	CUCP	3.53	8	2.15	8.119E–4	0.247	4.00	1300	0.30
Cumulus (maritime)	CUMA	10.4	4	2.34	5.674E–5	0.00713	12.68	65	0.44
Fog	FOGR	8.06	4	1.77	3.041E–4	0.0562	10.70	15	0.058

cloud-formation processes (Pruppacher and Klett 1978): the size distribution of stratus clouds is usually broader than that of cumuli but they contain fewer drops per volume than cumulus clouds. Clouds over the oceans tend to have broader distributions than clouds over the continents, and polluted clouds contain more but smaller drops than clean ones. The following clouds have been chosen.

- *Stratus (continental)* is described according to measurements published by Diem (1948) and Hoffmann and Roth (1989). A size distribution fitted to measurements at the base of a stratus cloud has been selected from Tampieri and Tomasi (1976).
- *Stratus (maritime)* contains fewer but larger drops than the continental stratus, and its size distribution is broader. A size distribution fitted to measurements at the top of a stratus cloud after Tampieri and Tomasi (1976) has been selected because this distribution showed the best fit with regard to N, r_{mod}, and L, measured by Squires (1958), Stephens et al. (1978), Tsay and Jayaweera (1984), and King et al. (1993), and the appropriate distinction to the continental stratus and the cumulus clouds described below.
- *Cumulus (continental, clean)* is described by the distribution parameters for the cumulus model 4 in Tampieri and Tomasi (1976). They satisfactorily fit measurements published by Squires (1958), Leaitch et al. (1992), and Fitzgerald and Spyers-Duran (1973). The distribution is smaller than that of the stratus clouds and it contains more drops.
- *Cumulus (continental, polluted)* is described by the distribution parameters for the cumulus model 3 in Tampieri and Tomasi (1976). It contains more and smaller droplets than a clean cumulus cloud. The values for N, r_{mod}, and L are within the range reported from Diem (1948) and Fitzgerald and Spyers-Duran (1973). This should be considered as an example of a cloud developed in a strongly polluted atmosphere. The same size distribution, but with a number density $N = 400$ particles cm^{-3}, is also suited to represent a stratocumulus cloud. In this case the liquid water content is $L = 0.092$ g m^{-3}.
- *Cumulus (maritime)* contains less and larger drops than the continental cumulus clouds and the size distribution is broader. As size distribution parameters, those of the cumulus model 11 in Tampieri and Tomasi (1976) have been selected.

The selected *fog* size distribution is radiation fog 3 of Tampieri and Tomasi (1976) with a number density of 15 particles cm^{-3}, yielding a liquid water content of 0.058. This is a very broad distribution with large droplets, thus representing a mature fog with moderately low visibility. In all cases, the refractive index of pure water after Hale and Querry (1973) is used for the calculations of optical properties. The additional absorption in cloud droplets, which is caused by the cloud condensation nuclei, should not be neglected, but appropriate refractive index data are not available yet.

b. Cirrus clouds

The size distribution functions used are analytical functions after Heymsfield and Platt (1984), calculated with help of the parametrization after Liou (1992), which relates the parameters $a_{1,2}$, $b_{1,2}$, and I to the temperature in the cloud:

$$\frac{dN}{dx} = N f a_1 x^{b_1} I \quad \text{for} \quad x < x_0$$

$$\frac{dN}{dx} = N f a_2 x^{b_2} I \quad \text{for} \quad x > x_0,$$

(3c)

with x the maximum dimension of the ice crystals, that is, the length of the columnar crystals used for calculating the optical properties; N the number density; and I the ice water content. Here f is an additional factor that had to be introduced because integration of the size distributions does not yield in all cases the experimentally derived ice water content I, if single hexagonal columns are assumed as particle shape (Strauss et al. 1997). The size distributions are mixtures of eight columnar ice crystals of different size and correspondingly different aspect ratio that are randomly oriented in space (Hess and Wiegner 1994). Properties of three cirrus clouds are provided, valid for clouds at different temperatures.

Cirrus 1 is valid for a temperature of −25°C. The slope of this size distribution shows a considerably slower decrease toward large particles than that of the model cirrus 2.

Cirrus 2 is valid for −50°C. In this case, the value of $f = 3.48$ suggests the presence of rosette-like crystals, which consist of several arms of columnar crystals. Since such particles are more likely to have larger sizes, f is only applied to particles larger than 90 μm.

The models cirrus 1 and cirrus 2 may be regarded

TABLE 1b. Microphysical properties of ice cloud models. For explanation of the size distribution parameters see Section 3b. cirrus 3 is the same distribution as cirrus 2 between 20 and 2000 μm. Additionally, there are 0.169 particles m^{-3} between 2 and 6 μm and 0.387 particles m^{-3} between 6 and 20 μm.

Component	File name	a_1	b_1	a_2	b_2	x_0	f	r_{eff} (μm)	N (cm^{-3})	I (g m^{-3})
Cirrus 1: −25°C	CIR1	4.486E+08	−2.417	1.545E+14	−4.376	670	0.909	91.7	0.107	0.0260
Cirrus 2: −50°C	CIR2	5.352E+10	−3.545	—	—	—	3.48	57.4	0.0225	0.00193
Cirrus 3: −50°C (+ small particles)	CIR3	5.352E+10	−3.545	—	—	—	3.48	34.3	0.578	0.00208

as limiting cases for what can be expected in the presence of cirrus clouds with respect to the relative amount of large particles. These size distributions are only valid for ice crystals larger than 20 μm. Smaller particles are neglected. This will not lead to large errors, as long as the cloud's optical depth is prescribed and only phasefunctions in the visible spectral range are considered. If the optical depth, however, shall be calculated from the particle number density and the cloud boundaries, the small particles may not be neglected. In this case, cirrus 3 should be applied, which is the same as cirrus 2 but extended with particles in the size range 2–20 μm based on aircraft measurements with help of an ice crystal replicator. This size distribution is taken after Strauss et al. (1997).

The parameters of the distributions together with total particle number density N and ice water content I are listed in Table 1b.

The sizes of the smallest and the largest ice crystal used correspond to surface equivalent spheres with radii of 1.8 and 271 μm, respectively. Since the size distributions do not decrease to larger radii as fast as the gamma distributions used for water clouds, even the larger ice crystals contribute significantly to the optical properties and the ice water content of the cloud.

c. Aerosol components

Aerosol particles result from different sources and processes. At any place in the atmosphere there exists a mixture of particles of different origin. To describe the wide range of possible compositions, the aerosol particles are modeled as components (Deepak and Gerber 1983), each of them meant to be representative for a certain origin, that is, an internal mixture of all chemical substances that have a similar origin. These components may be externally mixed to form aerosol types. External mixture means that there is no physical or chemical interaction between particles of different components. Useful examples of aerosol types, as typical external mixtures of the components, are described in section 5.

As size distributions, lognormal distributions [cf., e.g., Deepak and Gerber (1983)] are applied for each component i:

$$\frac{dN_i(r)}{dr} = \frac{N_i}{\sqrt{2\pi}\, r \log \sigma_i \ln 10} \exp\left[\frac{1}{2} \left(\frac{\log r - \log r_{\text{mod}N,i}}{\log \sigma_i} \right)^2 \right],$$
(3d)

where $r_{\text{mod}N,i}$ is the mode radius, σ_i measures the width of the distribution, and N_i is the total particle number density of the component i in particles per cubic centimeter. The microphysical properties of aerosol components are listed in Table 1c. The upper and lower limits of the particle sizes taken into account for Mie calculations are r_{min} and r_{max}. Here ρ is the density of the particles in grams per cubic centimeter. The mass concentration M^* in micrograms per cubic meter is valid for $N_i = 1$ particle cm^{-3} and is calculated with a cutoff radius of 7.5 μm to give results, which describe usual impactor measurements. The term $r_{\text{mod}V}$ is the mode radius of the volume distribution, which can be calculated from Eq. (3d) using V_i instead of N_i and $r_{\text{mod}V,i}$ instead of $r_{\text{mod}N,i}$. The mode radius is calculated from $r_{\text{mod}N,i}$ with

$$r_{\text{mod}V} = r_{\text{mod}N} 10^{\left(3 \log^2 (\sigma_i) \ln 10 \right)}.$$
(3e)

The following paragraphs describe the aerosol components. They are based on older descriptions (e.g.,

TABLE 1c. Microphysical properties of aerosol components in dry state. Here, σ, r_{modN}, r_{modV}, r_{min}, and r_{max} are parameters of the lognormal size distributions (see section 3c). The term ρ is the density of the aerosol particles and M^* is the aerosol mass per cubic meter air, integrated over the size distribution and normalized to 1 particle per cubic centimeter of air. The term M^* [(μg m^{-3}) (particles cm^{-3})$^{-1}$] is calculated with a cutoff radius of 7.5 μm.

Component	File name	σ	r_{modN} (μm)	r_{modV} (μm)	r_{min} (μm)	r_{max} (μm)	ρ (g cm^{-3})	M^* (μg m^{-3})/ (part. cm^{-3})
Insoluble	INSO	2.51	0.471	6.00	0.005	20.0	2.0	2.37E1
Water-soluble	WASO	2.24	0.0212	0.15	0.005	20.0	1.8	1.34E−3
Soot	SOOT	2.00	0.0118	0.05	0.005	20.0	1.0	5.99E−5
Sea salt (acc. mode)	SSAM	2.03	0.209	0.94	0.005	20.0	2.2	8.02E−1
Sea salt (coa. mode)	SSCM	2.03	1.75	7.90	0.005	60.0	2.2	2.24E2
Mineral (nuc. mode)	MINM	1.95	0.07	0.27	0.005	20.0	2.6	2.78E−2
Mineral (acc. mode)	MIAM	2.00	0.39	1.60	0.005	20.0	2.6	5.53E0
Mineral (coa. mode)	MICM	2.15	1.90	11.00	0.005	60.0	2.6	3.24E2
Mineral-transported	MITR	2.20	0.50	3.00	0.02	5.0	2.6	1.59E1
Sulfate droplets	SUSO	2.03	0.0695	0.31	0.005	20.0	1.7	2.28E−2

Shettle and Fenn 1979; Deepak and Gerber 1983; d'Almeida et al. 1991) with slight modifications that can be found in GADS (Koepke et al. 1997), where the same aerosol components are used as in OPAC. It must be mentioned that the given aerosol components are adapted to average conditions, and therefore their size distributions and refractive indices are not necessarily valid for actual conditions.

The *water-insoluble* part of aerosol particles consists mostly of soil particles with a certain amount of organic material.

The *water-soluble* part of aerosol particles originates from gas to particle conversion and consists of various kinds of sulfates, nitrates, and other, also organic, water-soluble substances. Thus it contains more than only the sulfate aerosol that is often used to describe anthropogenic aerosol. The mass density of sulfate is only about half that of the water-soluble component. This component is also used to model the dimethyl sulfide–related aerosol produced over the oceans.

The *soot* component is used to represent absorbing black carbon. Carbon is not soluble in water and therefore the particles are assumed not to grow with increasing relative humidity. The density of soot is given as

1 g cm^{-3} because the soot particles sampled on filters and used to determine aerosol weight per volume of air are fluffy particles with space inside. The optical properties, however, neglect the chainlike character of these particles and are calculated assuming the size distribution with many very small particles (which would have the density 2.3 g cm^{-3}). Moreover, no coagulation of soluble aerosol and soot is assumed.

Sea-salt particles consist of the various kinds of salt contained in seawater. Two sea-salt modes are given to allow for a different wind-speed-dependent increase of particle number for particles of different size (Koepke et al. 1997).

Mineral aerosol or desert dust is produced in arid regions. It consists of a mixture of quartz and clay minerals and is modeled with three modes to allow to consider increasing relative amount of large particles for increasing turbidity. *Mineral transported* is used to describe desert dust that is transported over long distances with a reduced amount of large particles. Mineral aerosol particles are assumed not to enlarge with increasing relative humidity.

The *sulfate* component (75% H_2SO_4) is used to describe the amount of sulfate found in the Antarctic aerosol. It is also used as the stratospheric background

aerosol, which is considered only for calculating the aerosol optical depth (cf. section 5b). It is not suited to describe anthropogenic sulfate aerosols that are included in the water-soluble component.

For those aerosols that are able to take up water, the mode radius as well as the limiting radii are increased with increasing relative humidity, while σ_i is assumed to remain unchanged. Eight values of relative humidity have been applied for the calculations: 0%, 50%, 70%, 80%, 90%, 95%, 98%, and 99%. The radii for the eight relative humidities are calculated with a program after Hänel and Zankl (1979). The assumption of a single function relationship between relative humidity and size of aerosol particles, without considering the hysteresis effect (whereby drying particles at the same relative humidity may have different sizes than moistening particles), is made with respect to natural conditions. Particles have in most cases passed through conditions with high relative humidity and therefore act on the upper branch of the hysteresis curve.

The refractive index of humid aerosols changes as the dry particulate matter is mixed with water. This change has been calculated by a simple volume weighting formula after Shettle and Fenn (1979) using the mode radii of the dry and wet particles for calculating an average particle volume. Water refractive indices, after Hale and Querry (1973), are used.

The refractive indices of the aerosol components dominantly are from d'Almeida et al. (1991), which partly refer to Shettle and Fenn (1979), in a few cases corrected with respect to different sources (Koepke et al. 1997). They are available in the OPAC files of optical properties of aerosol and cloud components together with the refractive indices of water and ice, but are not given here as a table.

4. Modeled optical properties

OPAC allows the calculation of the optical properties of aerosols and water clouds at 61 wavelengths between 0.25 and 40 μm and of cirrus clouds at 67 wavelengths between 0.28 and 40 μm. The real and imaginary parts of the refractive indices are given for these wavelengths. The optical properties are calculated with Mie theory (Quenzel and Müller 1978) for water droplets, aerosol particles, and ice crystals in the terrestrial spectral range and with ray tracing for ice crystals in the solar spectral range (Hess and Wiegner 1994).

To avoid repeated Mie- or ray-tracing calculations, optical properties of basic aerosol components and clouds are stored in OPAC in separate files for each component and relative humidity. These are

- the extinction coefficient σ_e^1 (km^{-1}),
- the scattering coefficient σ_s^1 (km^{-1}),
- the absorption coefficient σ_a^1 (km^{-1}),
- the volume phase function $p^1(\Theta)$ (km^{-1} sr^{-1}),
- the single scattering albedo ϖ_0, and
- the asymmetry parameter g.

Here, σ_e^1, σ_s^1, σ_a^1, and p^1 are normalized to a number density of 1 particle cm^{-3}. To get the absolute values of σ_e, σ_s, σ_a, and $p(\Theta)$, the stored data have to be multiplied by the total particle number density.

The following quantities may easily be taken from OPAC, where they are calculated from the stored data by use of the equations given below.

The normalized extinction coefficient $\sigma_{e,n}$ is normalized to the value at the wavelength 0.55 μm,

$$\sigma_{e,n} = \frac{\sigma_e}{\sigma_e(0.55\mu m)}. \tag{4a}$$

The lidar ratio L(sr) is defined by

$$L = \frac{\sigma_e}{p(180)}. \tag{4b}$$

The aerosol optical depth τ is calculated from the extinction coefficient of the chosen aerosol type (cf. section 5a) in combination with the height profile $N(h)$ (cf. section 5b), which is predefined in OPAC or given by the user for four discrete layers:

$$\tau = \sum_j \int_{H_{j,\min}}^{H_{j,\max}} \sigma_{e,j}(h)\,dh = \sum_j \sigma_{e,j}^1 N_j(0) \int_{H_{j,\min}}^{H_{j,\max}} e^{-\frac{h}{Z_j}}\,dh, \tag{4c}$$

where $\sigma_{e,i}^1$ is the extinction coefficient of the aerosol or cloud in layer j, normalized to 1 particle cm^{-3}. The parameters of the height profile are explained in section 5b.

The optical depth of clouds is calculated assuming one homogeneous layer with cloud droplet density independent of height ($Z = \infty$). Thus, the formula is reduced to

$$\tau = \sigma_e^1 N(0) \Delta h, \qquad (4d)$$

where Δh is the geometrical thickness of the cloud. The default value of $\Delta h = 1$ km may be changed by the user. In both cases, for aerosols and clouds, the optical depth of air molecules is not included.

The spectral turbidity factor T_L is given as

$$T_L = \frac{\tau + \tau_M}{\tau_M}, \qquad (4e)$$

where τ_M is the spectral optical depth of the air molecules, calculated with a formula after Hansen and Travis (1974).

The visibility (km) is

$$vis = \frac{3.0}{\sigma_e(0.55\mu m) + \sigma_M(0.55\mu m)}, \qquad (4f)$$

with the constant set to 3.0 to represent real observer visibility (Gordon 1970). The term σ_M is the extinction coefficient due to air molecules at 0.55 μm. In OPAC the value valid for $p_o = 1013$ hPa (sea level) is used:

$$\sigma_M(0.55\mu m) = 0.01159(km^{-1}). \qquad (4g)$$

For other altitudes, described by pressure p, it must be adapted by multiplication with p/p_o.

The mass extinction cross section (specific extinction coefficient) σ_e^* (m² g⁻¹) is the ratio of extinction coefficient σ_e (km⁻¹) to the aerosol mass M (μg m⁻³):

$$\sigma_e^* = \frac{\sigma_e}{M}. \qquad (4h)$$

It should be mentioned again that, for compatibility with measurements, the extinction coefficient is calculated for the airborne particles, that is, for radii up to the value r_{max}, while the mass is determined under assumption of an impactor cutoff radius of 7.5 μm.

The mass absorption cross section (specific absorption coefficient) σ_α^* (m² g⁻¹) is defined similar to the extinction ratio but using σ_a:

$$\sigma_a^* = \frac{\sigma_a}{M}. \qquad (4i)$$

The Ångström coefficient α describes the relative spectral course of the extinction coefficient in

$$\sigma_e(\lambda) = \beta \, \lambda^{-\alpha}, \qquad (4j)$$

where β is the extinction coefficient at 1 μm. This formula is valid for all wavelengths only if the particle size distribution fits a Junge power law function. For lognormal size distributions as used in OPAC and for most of natural conditions, α is not constant, but its value depends on the wavelength range that is used for its determination. Thus, OPAC gives the possibility to calculate α and β for two pairs of wavelengths, namely, 0.35–0.5 μm and 0.5–0.8 μm, which cover the range often used in the description of measured spectral aerosol extinction:

$$\alpha = \frac{\log[\sigma_e(\lambda_2)] - \log[\sigma_e(\lambda_1)]}{\log(\lambda_1) - \log(\lambda_2)}, \text{ and} \qquad (4k)$$

$$\beta = \frac{\sigma_e(\lambda_1)}{\lambda_1^\alpha}.$$

With respect to practical use, in addition to the spectral optical properties, spectrally weighted optical properties may be calculated. In case of the solar spectral range, the spectral optical properties are weighted with the solar spectrum E_o between 0.3 and 3.3 μm:

$$\overline{\sigma}_{e,a,\text{sol}} = \frac{\displaystyle\int_{0.3}^{3.3} \sigma_{e,a}(\lambda) E_o(\lambda) d\lambda}{\displaystyle\int_{0.3}^{3.3} E_o(\lambda) d\lambda} \left(km^{-1}\right), \qquad (4l)$$

the single scattering albedo is

$$\overline{\omega}_o = \frac{\displaystyle\int_{0.3}^{3.3} \omega_o(\lambda) \sigma_e(\lambda) E_o(\lambda) d\lambda}{\displaystyle\int_{0.3}^{3.3} \sigma_e(\lambda) E_o(\lambda) d\lambda}, \qquad (4m)$$

and the asymmetry parameter

$$\overline{g} = \frac{\displaystyle\int_{0.3}^{3.3} g(\lambda) \sigma_s(\lambda) E_o(\lambda) d\lambda}{\displaystyle\int_{0.3}^{3.3} \sigma_s(\lambda) E_o(\lambda) d\lambda}. \qquad (4n)$$

In case of the terrestrial spectral range, the terrestrial emission at 300 K between 8 and 15 μm B_{300} is used for the weighted absorption coefficient:

$$\overline{\sigma}_{a,\text{ter}} = \frac{\int_8^{15} \sigma_a(\lambda) B_{300}(\lambda) d\lambda}{\int_8^{15} B_{300}(\lambda) d\lambda} \left(\text{km}^{-1}\right). \quad (4o)$$

As already mentioned, optical properties of cloud and aerosol components are stored in OPAC as separate ASCII files, one for each component and relative humidity. They easily can be accessed with any text-viewing program and thus are not shown here in detail as tables. Only as examples, radiative properties at 0.5 μm for the cloud types are given in Table 2 and a few examples of optical properties of typical aerosol mixtures as proposed in the next chapter are shown in Table 3. Basic optical properties of the aerosol components are, however, published in Koepke et al. (1997).

5. Mixing of atmospheric particles

Optical properties of aerosol components are not of direct practical use, since aerosol particles in the atmosphere always exist as mixtures of several components. In OPAC, they are handled in that way with the possibility to combine them as much as you like. First, the components can be mixed and thus the optical properties for an atmospheric layer can be calculated. Second, up to four atmospheric layers can be used for calculating the aerosol optical depth.

a. Mixtures of different components

The capability of OPAC to mix optical properties of components is most interesting with respect to aerosol because aerosol usually is a combination of particles of different origin. Nevertheless, it is also possible to define external mixtures of clouds and aerosols, thus modeling the effect of interstitial aerosol particles in clouds.

OPAC allows handling of mixtures of the given components, freely defined by the user. Moreover, default values of 10 aerosol types are proposed to span the range of climatologically important aerosols. They are given both to represent average conditions and also to consider extreme conditions for sensitivity studies, and therefore users should be careful with respect to use for actual situations. The aerosol types and the components that compose them are specified in Table 4. Number densities N (particles cm^{-3}) and mass densities M (μg m^{-3}) both belonging to the components i and to the total aerosol type are given, as well as the mixing ratios again both for number (n_i) and mass (m_i). Mixing in OPAC is based, however, in any case on the particle number densities N_i, which are independent of relative humidity. They sum up to the number density

$$N = \sum_i N_i = N \sum_i n_i. \quad (5a)$$

The mass, however, depends on relative humidity h:

$$M(h) = \sum_i M_i(h) = \sum_i N_i M_i^*(h)$$
$$= N \sum_i n_i M_i^*(h) = N M^*(h) \sum_i m_i(h), \quad (5b)$$

where M^* is the mass normalized to one particle—that is, an average value, where the integral over the number size distribution is 1. The mass values given in

TABLE 2. Selected optical properties of all clouds at a wavelength of 0.55 μm.

Cloud	$\sigma_e(0.55\,\mu\text{m})$ (km^{-1})	Vis (km)	$\omega_o(0.55\,\mu\text{m})$	$g(0.55\,\mu\text{m})$
Stratus (continental)	59.500	0.05	1.0	0.865
Stratus (maritime)	41.800	0.07	1.0	0.867
Cumulus (cont.,clean)	72.200	0.04	1.0	0.866
Cumulus (cont., polluted)	121.800	0.02	1.0	0.850
Cumulus (maritime)	53.900	0.06	1.0	0.868
Fog	8.400	0.36	1.0	0.866
Cirrus 1	0.662	4.00	1.0	0.783
Cirrus 2	0.072	36.00	1.0	0.769
Cirrus 3	0.130	21.00	1.0	0.757

TABLE 3. Selected optical properties of all tropospheric aerosol types at a relative humidity of 80% and of the background aerosols. The optical depths of boundary layer aerosols include the free troposphere and the stratosphere. Height profiles are given in Table 5.

Aerosol type	σ_e (0.55 μm) (km^{-1})	σ_e^* (0.55 μm) (m^2 g^{-1})	τ (0.55 μm)	Vis (km)	ω_o (0.55 μm)	g (0.55 μm)	α (0.35–0.5)	α (0.5–0.8)
Continental clean	0.026	2.39	0.064	79	0.972	0.709	1.10	1.42
Continental average	0.075	2.51	0.151	35	0.925	0.703	1.11	1.42
Continental polluted	0.175	2.86	0.327	16	0.892	0.698	1.13	1.45
Urban	0.353	2.87	0.643	8	0.817	0.689	1.14	1.43
Desert	0.145	0.64	0.286	19	0.888	0.729	0.20	0.17
Maritime clean	0.090	1.29	0.096	30	0.997	0.772	0.12	0.08
Maritime polluted	0.115	1.50	0.117	24	0.975	0.756	0.41	0.35
Maritime tropical	0.043	1.26	0.056	55	0.998	0.774	0.07	0.04
Arctic	0.023	2.17	0.063	88	0.887	0.721	0.85	0.89
Antarctic	0.011	3.33	0.072	130	1.000	0.784	0.34	0.73
Mineral transported (2–3.5 km)	0.064	0.37	0.097	—	0.837	0.775	−0.10	−0.13
Free troposphere (2–12 km)	—	—	0.013	—	0.934	—	1.21	1.58
Stratosphere (12–35 km)	—	—	0.005	—	1.000	—	0.74	1.14

Table 4 as examples and discussed later represent a relative humidity of 50%.

It must be emphasized that the number mixing ratios given to describe aerosol types may be used only in combination with the size distributions given for the components. Mass mixing ratios of the components, which usually are expected to describe the fractions of the components, result from the combination of a given of number mixing ratios and size distributions of the components, together with the physical density ρ used for the particles. As to be seen in Table 4, the very low values in number mixing ratio of the insoluble component must not be neglected, and the rather high number mixing ratio of soot is realistic with respect to the size distributions used.

The extinction coefficient is calculated by

$$\sigma_e = \sum_i \sigma_{e,i}^1 N_i. \qquad (5c)$$

The other optical parameters are calculated according to the same principle.

In the following paragraphs, short descriptions of the aerosol types proposed in OPAC are given.

Continental aerosol types are distinguished between desert and nondesert types, and the nondesert types again are separated with respect to the amount of soot.

- *Continental clean* aerosol represents remote continental areas without or with very low anthropogenic influences and consequently less than 0.1 μg m^{-3} soot. The composition that is given in Table 4 contains no soot at all and thus is a lower benchmark with respect to absorption in the solar spectral range.
- *Continental average* aerosol is used to describe anthropogenically influenced continental areas. Therefore it contains soot and an increased amount of the insoluble and water-soluble components.

- *Continental polluted* aerosol is for areas highly polluted by man-made activities. The mass density of soot is 2 μg m^{-3}, and the mass density of water-soluble substances is more than double that in continental average aerosol.
- *Urban* aerosol represents strong pollution in urban areas. The mass density of soot is 7.8 μg m^{-3}, and the mass densities of both water-soluble substance and insoluble substance are about twice those of the continental polluted aerosol as found in center areas of large cities.
- *Desert* aerosol is used to describe aerosol over all deserts of the world, and no distinction with respect to the local properties is made. It consists of the mineral aerosol components in a combination that is representative for average turbidity, together with a certain part of the water-soluble component.

Maritime aerosol types contain sea salt particles whose amount depends on the wind speed. Here, an amount of 20 particles m^{-3} sea salt is assumed. This corresponds to a wind speed of 8.9 m s^{-1} as a result of an empirical relation (Koepke et al. 1997), which was developed using data of number and mass concentrations and also fits size distribution measurements.

- *Maritime clean* is given to represent undisturbed remote maritime conditions with no soot, but with a certain amount of water-soluble aerosol, which is used to represent the non–sea salt sulfate.

TABLE 4. Composition of aerosol types. Mass values are given for a relative humidity of 50% and for a cutoff radius of 7.5 μm.

Aerosol types	Components	N_i (cm^{-3})	M_i (μg m^{-3})	Number mixing ratios (n_j)	Mass mixing ratios (m_j)
Continental clean	total	2600	8.8		
	water soluble	2600	5.2	1.0	0.591
	insoluble	0.15	3.6	0.577E–4	0.409
Continental average	total	15 300	24.0		
	water soluble	7000	14.0	0.458	0.583
	insoluble	0.4	9.5	0.261E–4	0.396
	soot	8300	0.5	0.542	0.021
Continental polluted	total	50 000	47.7		
	water soluble	15 700	31.4	0.314	0.658
	insoluble	0.6	14.2	0.12E–4	0.298
	soot	34 300	2.1	0.686	0.044
Urban	total	158 000	99.4		
	water soluble	28 000	56.0	0.177	0.563
	insoluble	1.5	35.6	0.949e–05	0.358
	soot	130 000	7.8	0.823	0.079
Desert	total	2300	225.8		
	water soluble	2000	4.0	0.87	0.018
	mineral (nuc.)	269.5	7.5	0.117	0.033
	mineral (acc.)	30.5	168.7	0.133E–1	0.747
	mineral (coa.)	0.142	45.6	0.617–4	0.202
Maritime clean	total	1520	42.5		
	water soluble	1500	3.0	0.987	0.071
	sea salt (acc.)	20	38.6	0.132E–1	0.908
	sea salt (coa.)	3.2E–3	0.9	0.211E–5	0.021
Maritime polluted	total	9000	47.4		
	water soluble	3800	7.6	0.422	0.160
	sea salt (acc.)	20	38.6	0.222E–2	0.814
	sea salt (coa.)	3.2E–3	0.9	0.356E–6	0.019
	soot	5180	0.3	0.576	0.006
Maritime tropical	total	600	20.8		
	water soluble	590	1.2	0.983	0.058
	sea salt (acc.)	10	19.3	0.167E–1	0.928
	sea salt (coa.)	1.3E–3	0.3	0.217E–5	0.014
Arctic	total	6600	6.8		
	water soluble	1300	2.6	0.197	0.382
	insoluble	0.01	0.2	0.152E–5	0.029
	sea salt (acc.)	1.9	3.7	0.288E–3	0.544
	soot	5300	0.3	0.803	0.044
Antarctic	total	43	2.2		
	sulfate	42.9	2.0	0.998	0.910
	sea salt (acc.)	0.47E–1	0.1	0.109e–2	0.045
	mineral (tra.)	0.53E–2	0.1	0.123E–3	0.045

- *Maritime polluted* refers to a maritime environment under anthropogenic influence with highly variable amounts of soot and also of anthropogenic water-soluble particles. Here 0.3 and 7.6 μg m^{-3} are assumed, respectively. The sea salt components are kept unchanged compared to clean maritime.
- *Maritime tropical* aerosol has a low density of water-soluble substance. We also assume a lower wind speed (5 m s^{-1}) and hence a correspondingly lower number density of sea salt.
- *Arctic* aerosol can be found in the whole Arctic region north of 70°N. The type modeled here describes conditions with a large amount of soot particles transported from the midlatitude continental areas to the Arctic. Since these conditions are valid mainly during springtime, one should be careful with the application of this aerosol type for other seasons.
- *Antarctic* aerosol can be found over the Antarctic continent. It consists mostly of sulfate droplets but also of mineral and sea salt particles. The composition provided here is valid for summer conditions.

All aerosol types defined here may have additional components with varying number densities according to the actual location for which they are assumed to be valid. In coastal areas, for example, they all may have an additional sea salt component. Near deserts, urban aerosol may be influenced by mineral aerosols. As long as one is interested only in average conditions at a certain place or on aerosol variability, the predefined aerosol types will be sufficient. In other cases the user himself should define appropriate mixtures of aerosol types.

The aerosol types described above are valid for the mixing layer—that is, the first atmospheric layer above the ground that is assumed to be well mixed. Above this layer up to three additional layers of background aerosols may be placed for calculations of the optical depth.

A possible second aerosol layer above the boundary layer aerosol types is *mineral transported.* This is present if mineral aerosol is lifted by convection to heights where it can be transported over long distances, for instance, from the Sahara over the Atlantic or from the Gobi to China. In the Saharan dust layer over the Atlantic, the particle number density of mineral aerosol varies from about 100 particles cm^{-3} near the African coast to less than 1 particle cm^{-3} near the American coast. For the aerosol type mineral transported, the component mineral transported is used with 175 μg m^{-3} corresponding to 11 particles cm^{-3}.

To allow calculation of total optical depth, data are included to describe aerosol extinction in the free troposphere and the stratosphere.

The aerosol in the *free troposphere* is modeled by the continental components at a relative humidity of 50%, with a dominant part of the water-soluble component ($n_i = 0.6$ and $m_i = 0.949$), a certain part of soot ($n_i = 0.4$ and $m_i = 0.0189$), and some insoluble particles ($n_i = 0.00017$ and $m_i = 0.032$), which can be assumed for the Northern Hemisphere. A hypothetical number density of 730 particles cm^{-3} at sea level is assumed, allowing the use of (5d) for the description of height distributions, resulting, for example, in a number density of 390 particles cm^{-3} ($M = 0.49$ μg m^{-3}) at a height of 5 km.

The aerosol in the *stratosphere* is given only for background conditions with 3 particles cm^{-3}, which yields an optical depth of about 0.005. The treatment of stratospheric aerosol is not comprehensive, but only used to infer spectral optical depths.

As mentioned, the goal of OPAC is an easy provision of optical properties between 0.3 and 40 μm wavelengths for as many combinations of the components as you like. Thus, only an example can be given here. In Table 3, the most relevant optical properties at 550 nm are shown for all aerosol types proposed above. They are valid for a relative humidity of 80% in the case of the boundary aerosols and of 50% for the free troposphere. The optical depth of the boundary layer aerosols is calculated with the height profiles described below—that is, including the free troposphere and the stratospheric layer but without mineral transported aerosol. The optical depth of the background layers is given separately in Table 3 using the indicated layer boundaries and the scale heights given in Table 5.

b. Vertical distribution

To provide optical depths of aerosols or of cloud layers in OPAC [cf. Eqs. (4c) and (4d)], height profiles of the particle number density are given.

For all clouds, a uniform height distribution within the cloud is assumed and a thickness of 1 km is given as a default value, which may be changed by the user.

The distribution of aerosol particles with height is described by means of exponential profiles given by

$$N(h) = N(0)e^{-\frac{h}{Z}}, \tag{5d}$$

with h the altitude above ground in kilometers and Z

TABLE 5. Height profiles of all aerosol types.

Aerosol type	H (km)	Z (km)	H_{ft} (km)
Continental clean	2	8	10
Continental average	2	8	10
Continental polluted	2	8	10
Urban	2	8	10
Desert	6	2	6
Maritime clean	2	1	10
Maritime polluted	2	1	10
Maritime tropical	2	1	10
Arctic	2	99	10
Antarctic	10	8	2
Mineral transported (2–3.5 km)	1.5	99	—
Free troposphere (H_{ft} variable)	—	8	—
Stratosphere (12–35 km)	23	99	—

the scale height in kilometers, which describes the slope of the profile. With $Z = 8$ km, the value valid for air molecules, a constant mixing of air and aerosol is described. Here $Z = 99$ km represents a homogeneous layer without dependence on height; $N(0)$ is the number density of the aerosol type at sea level (N_i in Table 4).

The atmosphere is comprised of up to four discrete layers. For each layer j the thickness $H = (H_{j,max} - H_{j,min})$ of the aerosol layer and the scale height Z are shown in Table 5. The layer boundaries $H_{j,min}$ and $H_{j,max}$ of all layers may be changed by the user.

In the first layer, aerosol is assumed with the mixtures described in section 5a. The scale height Z for the proposed aerosol types is given in Table 5, but it may also be changed by the user.

On top of this first layer a desert dust layer may be placed, consisting of the type of mineral transported. The default value for the thickness of this layer is 0. Here ($H_{2,min} = H_{2,max}$), that is, no dust is assumed, but it may be changed by the user. A layer thickness of 1.5

km and a particle number density of 11 particles cm^{-3} (default) yield an additional optical thickness of 0.1. The term N may be changed by the user and is assumed to be independent of height ($Z = 99$ km).

The third and fourth layers represent the free troposphere and the stratosphere. The aerosol in the free troposphere is assumed for the region above the aerosol near ground or above the layer with mineral-transported aerosol if present. For the proposed aerosol types, the upper boundary of this layer is always situated at 12 km. Therefore, its thickness depends on the thickness of the first layer and the presence of the mineral-transported layer. The resulting values are given as H_{ft} in Table 5. The composition of the background aerosol types [i.e., $\sigma_{e,j}^1$ and $N_j(0)$ in Eq. (4c)] cannot be changed by the user, but the background optical depth can be varied by changing the layer boundaries and the scale heights. The stratospheric aerosol always is assumed between 12 and 35 km with no variations with respect to volcanic activity.

6. Conclusions

The software package OPAC is intended to serve as a tool to scientists who need to describe the optical properties of the atmosphere for climate-modeling purposes. It therefore consists of datasets of optical properties of cloud and aerosol components that describe average conditions in combination with easy-to-use software, which allows calculation of any mixtures of these components. Various user-defined aerosol mixtures are possible, and a set of typical mixtures is also provided. Combination of different individual radiative datasets in OPAC has the advantage of convenient use and also easy improvements. This can be done by simply changing or adding single components or their properties. For example, it will be possible to include optical properties of nonspherical aerosol particles instead of the results of Mie calculations, which are used now even for the insoluble and mineral aerosol components.

The software package OPAC is freely available on the World Wide Web at http://www.meteo.physik.uni-muenchen.de/strahlung/aerosol/aerosol.html.

References

d'Almeida, G. A., P. Koepke, and E. P. Shettle, 1991: *Atmospheric Aerosols: Global Climatology and Radiative Characteristics.* A. Deepak Publishing, 561 pp.

Deepak, A., and H. E. Gerber, Eds., 1983: Report of the experts meeting on aerosols and their climatic effects. WCP-55, 107 pp. [Available from World Meteorological Organization, Case Postale No. 5, CH-1211 Geneva, Switzerland.]

Deirmendjian, D., 1969: *Electromagnetic Scattering on Spherical Polydispersions.* Elsevier, 290 pp.

Diem, M., 1948: Messungen der größe von wolkenelementen II. *Meteor. Rundsch.,* **1,** 261–273.

Fitzgerald, J. W., and P. A. Spyers-Duran, 1973: Changes in cloud nucleus concentration and cloud droplet size distribution associated with pollution from St. Louis. *J. Appl. Meteor.,* **12,** 511–516.

Gordon, J. F., 1970: Daytime visibility. A conceptual review. AFGL-TR-79-0257.

Hale, G. M., and M. R. Querry, 1973: Optical constants of water in the 200-nm to 200-mm wavelength region. *Appl. Opt.,* **12,** 555–563.

Hänel, G., and B. Zankl, 1979: Aerosol size and relative humidity: Water uptake by mixtures of salts. *Tellus,* **31,** 478–486.

Hansen, J. E., and I. D. Travis, 1974: Light scattering in planetary atmospheres. *Space Sci. Rev.,* **16,** 527–610.

Hess, M., and M. Wiegner, 1994: COP: A data library of optical properties of hexagonal ice crystals. *Appl. Opt.,* **33,** 7740–7746.

Heymsfield, A. J., and C. M. R. Platt, 1984: A parameterization of the particle size spectrum of ice clouds in terms of the ambient temperature and the ice water content. *J. Atmos. Sci.,* **41,** 846–855.

Hoffmann, H.-E., and R. Roth, 1989: Cloud physical parameters in dependence on height above cloud base in different clouds. *Meteor. Atmos. Phys.,* **41,** 247–254.

King, M. D., L. F. Radke, and P. V. Hobbs, 1993: Optical properties of marine stratocumulus clouds modified by ships. *J. Geophys. Res.,* **98** (D2), 2729–2739.

Koepke, P., M. Hess, I. Schult, and E. P. Shettle, 1997: Global Aerosol Data Set. MPI Meteorologie Hamburg Report No. 243, 44 pp.

Leaitch, W. R., G. A. Isaac, J. W. Strapp, C. M. Banie, and H. A. Wiebe, 1992: The relationship between cloud droplet number concentrations and anthropogenic pollution: Observations and climatic implications. *J. Geophys. Res.,* **97** (D2)**,** 2463–2474.

Liou, K. N., 1992: *Radiation and Cloud Processes in the Atmosphere.* Oxford University Press, 473 pp.

Pruppacher, H. R., and J. D. Klett, 1978: *Microphysics of Clouds and Precipitation.* D. Reidel Publishing Company, 714 pp.

Quenzel, H., and H. Müller, 1978: Optical properties of single Mie particles: Diagrams of intensity-, extinction-, scattering-, and absorption efficiencies. Universität München, Meteorologisches Institut, Wiss. Mit. Nr. 34, 59 pp. [Available from Meteorologisches Institut, Theresienstraße 37, D-80333 München, Germany.]

Shettle, E. P., and R. W. Fenn, 1979: Models for the aerosols of the lower atmosphere and the effects of humidity variations on their optical properties. AFGL-TR-79-0214, 94 pp. [Available from AFCRL, Hanscom Field, Bedford, MA 01731.]

Squires, P., 1958: The microstructure and colloidal stability of warm clouds. *Tellus,* **10,** 256–261.

Stephens, G. L., C. W. Paltridge, and C. M. R. Platt, 1978: Radiation profiles in extended water clouds III: Observations. *J. Atmos. Sci.,* **35,** 2133–2141.

Strauss, B., R. Meerkoetter, B. Wissinger, P. Wendling, and M. Hess, 1997: On the regional climatic impact of contrails: Microphysical and radiative properties of contrails and natural cirrus clouds. *Ann. Geophys.,* **15,** 1457–1467.

Tampieri, F., and C. Tomasi, 1976: Size distribution models of fog and cloud droplets in terms of the modified gamma function. *Tellus,* **28,** 333–347.

Tsay, S., and K. Jayaweera, 1984: Physical characteristics of Arctic stratus clouds. *J. Climate Appl. Meteor.,* **23,** 584–596.