Estimation of the Aerosol Phase Function in Backscatter from Simultaneous Satellite and Sun-Photometer Measurements

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ABSTRACT

The backscatter part of the aerosol phase function $P^A(\chi)$, where χ is the scattering angle, is difficult to measure from the ground. Experimental data for $\chi > 120°$ are not reported in the literature. Customarily, $P^A(\chi)$ is calculated from Mie theory using an aerosol size distribution either prescribed or estimated by inversion of spectral or almucantar/aureole measurements. These results clearly require validation using direct measurements. In this paper, an empirical phase function of atmospheric aerosol over the ocean is estimated in backscatter ($\chi > 130°$) from coincident measurements of upward radiance in channel 1 (0.63 μm) of the Advanced Very High Resolution Radiometer (AVHRR) on board National Oceanic and Atmospheric Administration satellites and sun-photometer aerosol optical thickness, δ^A_{SP}. This study uses 31 sun-photometer measurements, collected during two oceanic cruises over the North Atlantic in 1989 and 1991. The accuracies of both satellite radiances and sun-photometer δ^A_{SP} are well documented. The linearized form of the single-scattering approximation for the radiative transfer equation is used, with some adjustments to account approximately for multiple scattering effects. The newly estimated empirical phase function shows variability from one point to another, but on the average, is close to that expected for maritime aerosols as found in the literature. The results of the present study may be used to constrain the range of variability of the aerosol phase function in real marine atmospheres, which is important for aerosol retrieval from historical Coastal Zone Color Scanner (CZCS), present (AVHRR), and future satellite sensors Moderate-Resolution Imaging Spectroradiometer (MODIS), Multiangle Imaging Spectroradiometer (MISR), and Sea-Viewing-Wide-Field-of-View-Sensor (SeaWiFS).

1. Introduction

As a usual practice, aerosol phase function in backscatter is calculated from Mie theory using an aerosol size distribution, either prescribed or estimated by inversion of spectral or almucantar/aureole measurements (e.g., Nakajima et al. 1989; Kaufman et al. 1994). These results clearly require validation using direct measurements. However, experimental data for backscatter are difficult to obtain from ground measurements, especially over the oceans. For scattering angles $\chi > 90°$, only experimental data by Kaufman et al. (1994) are available; for $\chi > 120°$, no data have been reported in the literature.

The open ocean has very low reflectance in the near-infrared, and the marine aerosol is almost purely scattering (albedo of single scattering $\omega \to 1$) when not mixed with continental sources (dust, smoke, soot) (e.g., Viollier et al. 1980; Gordon and Morel 1983; World Climate Program-55 1983; World Climate Program-112 1986; D'Almeida et al. 1991). In this case, the upward radiance depends mainly on the aerosol optical thickness δ^A and the aerosol single scattering phase function $P^A(\chi)$, χ being scattering angle. Retrieval of δ^A_{SAT} from satellite over oceans was proposed by Griggs (1983). In this case, $P^A(\chi)$ has to be prescribed, as was realized, for example, in the algorithm of Rao et al. (1989), which uses measurements in channel 1 (0.63 μm) of the Advanced Very High Resolution Radiometer (AVHRR) onboard National Oceanic and Atmospheric Administration (NOAA) polar orbiters. In this paper, the problem of δ^A_{SAT} retrieval using a prescribed $P^A(\chi)$ is inverted so that an empirical phase function $P^A_{emp,i}(\chi_i)$ is retrieved at each match-up point i for a particular scattering geometry χ_i having the $\delta^A_{SP,i}$ determined from the collocated sun-photometer measurement. The linearized form of the single-scattering approximation for the radiative transfer equation is used, with some adjustments to account approximately for multiple scattering effects. The procedure is applied to 31 match-ups with sun-photometer measurements collected during two cruises to the North Atlantic. Uncertainties in $P^A_{emp,i}(\chi_i)$, resulting from the simplified approach, and from errors in satellite and sun-photometer data, are estimated.

Plotting all the results of $P^A_{emp,i}(\chi_i)$ together versus scattering angles χ_i shows variability of the phase function from one point to another, even for the same scattering geometry. Part of this variability is attributed to imperfections of the satellite–sun-photometer data and/or the

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procedure used for estimating the phase function. Some variability, however, is due to real changes in aerosol microphysical characteristics. On the average, the newly estimated $P^A_{\rm emp}$ is fairly close to the phase functions of maritime aerosol theoretically proposed by Quenzel and Kaestner (1980), Sturm (1981), and D'Almeida et al. (1991).

The result of the present study can be used to constrain the range of variability in the aerosol phase function to be expected from a real atmosphere over the oceans for backscatter. The empirical phase function is systematically lower than that used in the algorithm of Rao et al. (1989), and is a candidate for its replacement, after possible adjustments and fine tuning. An example of actual retrievals with a new phase function is given, and it shows significant improvement. This information is also needed in the design of aerosol retrieval algorithms from historical and future sensors such as CZCS (e.g., Mukai et al. 1992), MODIS (King et al. 1992), SeaWiFS (EOS 1993), and MISR (Diner et al. 1994).

2. Overview of the approach to estimating $P^A_{emp,i}(\chi_i)$ from match-up data

In the multiple-scattering regime, the upward radiance is a complicated integral over the full range of scattering angles, that is, different parts of the phase function contribute to the scalar value of upward radiance. To retrieve $P^A_{\rm emp}(\chi)$, one has to solve a functional equation. This problem is poorly conditioned (i.e., the same value of radiance may result from different phase functions) and requires additional constraints on the phase function under retrieval.

One solution is to assume that the phase function belongs to a known class of functions with few parameters—for example, two-term Henyey-Greenstein (see, e.g., Sturm 1981)

$$P^A_{\rm 2HG}(\chi) = f\frac{1 - g_1^2}{(1 + g_1^2 - 2g_1\cos\chi)^{3/2}} + (1 - f)\frac{1 - g_2^2}{(1 + g_2^2 - 2g_2\cos\chi)^{3/2}}, \quad (1)$$

and estimate the parameters (f_i, $g_{1,i}$, and $g_{2,i}$) in each individual match-up point i by method of trial and error, substituting different combinations along with $\delta^A_{{\rm SP},i}$ into a numerical multiple-scattering radiative transfer code and minimizing the difference between the calculated radiance and the satellite measurement. Another solution is to impose constraints with a microphysical aerosol model (e.g., Wang and Gordon 1994), which is somewhat equivalent to the previous one as long as the Mie theory is used to translate the microphysical model into a phase function, thus reducing the procedure to that described above. In both cases, the solution might appear nonunique and sensitive to measurement errors in $\delta^A_{\rm SP}$ and satellite radiances if more than one parameter is used to describe the phase function/microphysical model. A version of the second approach has been used by Ignatov et al. (1995a,b) and found too cumbersome, time consuming, and inconclusive. Here, we instead have tried a semianalytical procedure described below, which uses a linearized form of the single-scattering approximation of the radiative transfer equation, corrected for multiple-scattering effects in a simplified fashion.

The linearized single-scattering approximation of the radiative transfer equation gives (Viollier et al. 1980; Gordon and Morel 1983; Bréon 1993)

$$\omega[P^A(\chi) + \Delta P^A(\mu_s, \mu_v, \phi)]\delta^A = 4\mu_s\mu_v\left[\frac{\rho(\mu_s, \mu_v, \phi)}{t^{\rm oz}(\mu_s, \mu_v)} - \rho^{\rm R}(\mu_s, \mu_v, \phi) - \rho^S T(\mu_s, \mu_v)\right]. \quad (2)$$

Here, $\mu_s = \cos\Theta_s$, $\mu_v = \cos\Theta_v$, Θ_s and Θ_v are the solar and satellite zenith angles, and ϕ the relative azimuth angle. An apparent reflectance at the top of the atmosphere, $\rho = (\pi L)\,(\mu_s F_\lambda)^{-1}$, is defined by normalization of the measured satellite radiance L [W (m^2 μm sr)$^{-1}$], to solar spectral irradiance F_λ [W (m^2 μm)$^{-1}$], and "overhead" illumination geometry; $T^{\rm oz}$ is the round-trip ozone transmission; $\rho^{\rm R}$ is Rayleigh scattered contribution to ρ; ρ^S is oceanic diffuse reflectance; T is Rayleigh–aerosol atmospheric transmittance; ω is single-scattering albedo; δ^A is aerosol optical thickness; P^A is aerosol phase function, normalized to 4π. A "diffuse glint" correction to the phase function, ΔP^A, is given as (e.g., Viollier et al. 1980; Gordon and Morel 1983; Bréon 1993)

$$\Delta P^A = [\rho_{\rm F}(\mu_s) + \rho_{\rm F}(\mu_v)]P^A(\chi^+). \quad (3)$$

Here, $\rho_{\rm F}$ is Fresnel's reflection coefficient from a flat surface, and the angle χ^+ is measured between the vector of specularly reflected light and the viewed pixel-to-satellite vector. For the typical observation-illumination conditions, the diffuse glint correction, ΔP^A, is small as compared to P^A—that is, $\Delta P^A/P^A \ll 1$—since $\rho_{\rm F} \sim (2–5) \times 10^{-2}$, and $P^A(\chi^+) \sim P^A(\chi)$. For the rough ocean, the assumption of a flat surface still provides a good approximation if one stays away from the specular reflection (Bréon 1993).

The factors on the right-hand side of Eq. (2) are either measured values (ρ, μ_s, μ_v) or well-constrained functions. Neglecting ΔP^A, and assuming the aerosol to be nonabsorbing with $\omega \approx 1$, the value of $P^A(\chi_i)$ can be estimated from combined satellite and sun-photometer measurements in each match-up point i through Eq. (2). Note that this formulation does not require any a priori information of the shape of $P^A(\chi)$. However, the accuracy of this procedure is contingent upon proper treatment of the multiple scattering effects, disregarded in Eq. (2), and handling the diffuse glint correction, ΔP^A, which depends upon P^A (χ_i^+).

3. Data

Two combined satellite–sun-photometer datasets used in the present study are described in detail by Ignatov

et al. (1995a,b). Sun-photometer data, δ^A_{SP}, have been collected during two oceanic cruises of the research vessel *Akademik Vernadsky* (hereafter, *AV-89* and *AV-91*, respectively). The 58 match-ups (20 obtained for *AV-89* and 38 for *AV-91*) cover large areas in the North Atlantic in years 1989 and 1991. The 1991 data have been collected during early post–Mount Pinatubo period. However, the ship was sailing in an area north of the Tropics, which, according to Long and Stowe (1994), was not greatly affected by volcanic dust at this time. Therefore, the two datasets may both be considered representative of tropospheric aerosol over the ocean under a variety of conditions. Satellite data were obtained from the *NOAA-11* satellite. Uniformity of aerosol optical thickness both in space (using satellite retrievals) and time (using sun-photometer data) was carefully checked in each match-up to ensure consistency of satellite and ship measurements under comparison, and local averaging in space and time was applied to depress residual noise that remained in both datasets. The latter procedure minimizes the match-up errors and is described in detail by Ignatov et al. (1995a). Both sun-photometer and AVHRR data have been carefully calibrated. Accuracy of δ^A_{SP} is about 0.02 (Korotaev et al. 1993), and satellite radiances about 2% (Rao and Chen 1995; Mitchell et al. 1997).

This dataset was devoted to the validation of δ^A_{SAT} retrievals over global oceans, routinely made at the National Oceanic and Atmospheric Administration since 1990 (Stowe 1991). The algorithm of Rao et al. (1989) uses $P^A_{3.5}(\chi)$ derived from Mie calculations with a modified Junge aerosol size distribution: $dN/dr = 0$ ($r < r_{min}$ and $r > r_{max}$); $dN/dr = A$ ($r_{min} \le r \le r_m$); $dN/dr = A(r/r_m)^{-(\nu+1)}$ ($r_m \le r \le r_{max}$). Parameters r_{min} and r_m, r_{max} are equal to 0.03, 0.1, and 10 μm, respectively; size parameter $\nu = 3.5$ (corresponds to an equivalent Ångström exponent $\alpha \approx 1.5$), and a complex index of refraction $n = 1.5 - 0.0i$ ($\omega = 1$). The latter model was adopted from Griggs (1983). Retrievals of $\delta^A_{3.5}$ from AVHRR channel 1 data are made using multiple-scattering look-up table precalculated with Dave's (1973) code, taking into account Lambertian oceanic reflectance $\rho^S = 0.002$ and diffuse glint, using only those pixels that are viewed at least 40° apart from the specular reflection point.

The correlation between $\delta^A_{3.5}$ and δ^A_{SP} from these data is shown in Fig. 1. Ignatov et al. (1995a,b) have shown that the discrepancy between $\delta^A_{3.5}$ and δ^A_{SP}, in particular a systematic underestimation of about 40%, can be attributed only to the assumption of an incorrect aerosol model, since all other sources of errors in $\delta^A_{3.5}$ have been carefully removed. Equation (2) shows that the microphysical model influences the results of δ^A_{SAT} retrieval through two mechanisms—the albedo of single scattering and the phase function. Ignatov et al. (1995a,b) attempted to reconcile δ^A_{SAT} and δ^A_{SP} by inferring a microphysical model from the wavelength dependence of the δ^A_{SP} and showed that introducing aerosol absorption can

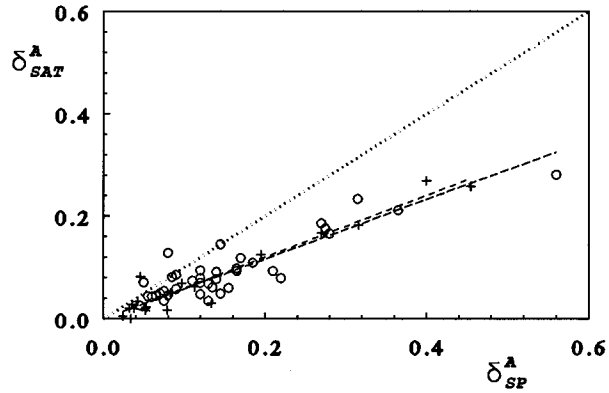

FIG. 1. Comparison of the satellite aerosol optical thickness retrievals, δ^A_{SAT}, with sun-photometer measurements, δ^A_{SP}, for *AV-89* (+) and *AV-91* (○) at the wavelength of $\lambda = 0.63$ μm. Here, δ^A_{SAT} is retrieved from AVHRR channel 1 (0.63 μm) radiances calibrated according to Rao and Chen (1995) using corrected oceanic reflectance model as described in Ignatov et al. (1995a,b). The atmospheric radiative transfer numerical model is from Rao et al. (1989) (aerosol phase function $P^A_{3.5}$). Perfect agreement line is also shown.

remove systematic discrepancy between δ^A_{SAT} and δ^A_{SP}. Additional analysis has shown that a nonzero imaginary part of the refractive index influences the results of δ^A_{SAT} retrieval mainly through decreasing the phase function in the backscatter (about 30%) rather than through the albedo of single scattering (only 10%; $\omega \approx 0.9$). Therefore, we neglect any deviation of the albedo of single scattering from unity in the present study, since it may result in error in the retrieved $P^A_{emp,i}(\chi_i)$ of less than 10%. In fact, the probable error is even less, since for many types of aerosol that one can encounter over the ocean under typical humidity conditions, the albedo of single scattering is $\omega \ge 0.95$ at 0.63 μm (e.g., D'Almeida et al. 1991). The result shown in Fig. 1 is a starting point of the further analysis, in which departure of the aerosol single-scattering albedo from unity is neglected.

4. Procedure

To estimate $P^A_{emp,i}(\chi_i)$ at each matchup point i, the following scaling relation is used:

$$[P^A_{3.5}(\chi_i) + \Delta P^A_{3.5,i}]\,\delta^A_{3.5,j} = [P^A_{emp,i}(\chi_i) + \Delta P^A_{emp,j}]\,\delta^A_{SP,i}, \quad (4)$$

where $\delta^A_{3.5,i}$ is a result of the exact numerical retrieval (see Fig. 1) with $P^A_{3.5}$ used as input to Dave's radiative transfer code (Dave 1973). Equation (4) does not rely on the simplified radiative transfer Eq. (2) anymore; rather, it uses only an assumption of linearity of the upward radiance with respect to the product $[P^A(\chi) + \Delta P^A]\delta^A$. Provided Eq. (4) is valid, the problem of estimating $P^A_{emp,i}(\chi_i)$ is thus reduced to assigning ΔP^A_{emp}, which, according to Eq. (2), depends upon another scattering angle, χ^+.

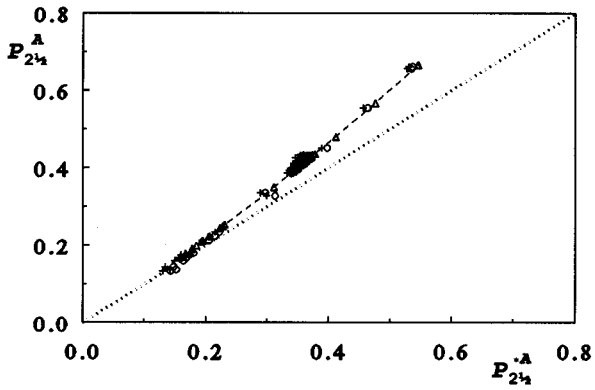

FIG. 2. The true phase function $P^A_{2.5}$ vs the estimated one $P^{*A}_{2.5}$ from Eq. (4), for the three different $P^A_{\rm ref}$: $P^A_{3.5}$ (Δ), $P^A_{2.5}$ (+), and $P^A_{\rm 2HG}$ (○). Dashed line: fit equation $P^A_{2.5} = P^{*A}_{2.5} + 0.4\,(P^{*A}_{2.5})^2$.

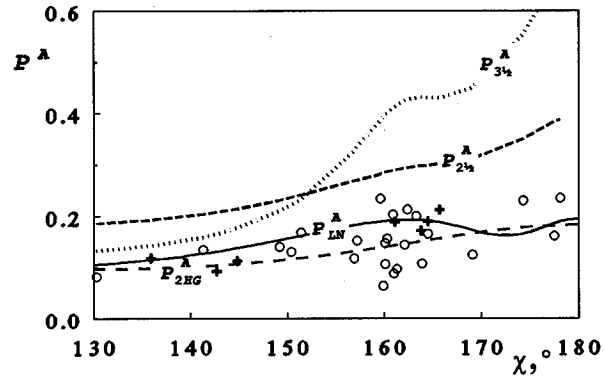

FIG. 3. Four model phase functions: $P^A_{3.5}$, $P^A_{2.5}$, $P^A_{\rm 2HG}$ [according to Sturm (1981) and Gordon and Castaño (1987), $f = 0.983$, $g_1 = 0.82$, and $g_2 = -0.55$ approximating the maritime aerosol phase function given by Quenzel and Kaestner (1980)], $P^A_{\rm LN}$ [$r_m = 0.1$, $\sigma = 2.03$ μm, $n = 1.4 - 0i$, according to D'Almeida et al. (1991) corresponding to the clean maritime aerosol], and results of the empirical phase function $P^A_{\rm emp}$ estimation for *AV-89* (+) and *AV-91* (○). All phase functions are normalized to 4π. Special analysis does not show any statistically significant correlation between ($P^A_{\rm emp} - P^A_{\rm 2HG}$) and $\delta^A_{\rm SP}$.

Equation (4) contains two unknown values of the phase function at scattering angles χ_i and χ_i^+. To remove this uncertainty, we assume that $\Delta P^A_{\rm emp} \approx \Delta P^A_{\rm ref}$, where $P^A_{\rm ref}$ is a prescribed reference phase function. Small errors in ΔP^A should not result in large errors in P^A retrieval, since $\Delta P^A/P^A \ll 1$. As a result, one obtains the following equation for $P^A_{{\rm emp},i}$ (χ_i) retrieval:

$$P^{*A}_{{\rm emp},i}(\chi_i) = [P^A_{3.5}(\chi_i) + \Delta P^A_{3.5,i}]\frac{\delta^A_{3.5,i}}{\delta^A_{{\rm SP},i}} - \Delta P^A_{{\rm ref},i}. \quad (5)$$

Either $P^A_{3.5}$, or any other phase function, like $P^A_{\rm 2HG}$, can be used as a reference.

In case of small aerosol loadings, derivation of $P^A_{{\rm emp},i}$ (χ_i) is unreliable. Mathematically, one has an indeterminant of the type "zero-over-zero" in Eq. (5) since both $\delta^A_{3.5,i}$ and $\delta^A_{{\rm SP},i}$ are small, and are therefore subject to the influence of measurement errors and the uncertainties of their respective retrieval algorithms. To minimize the influence of those errors, only data with $\delta^A_{\rm SP} > 0.1$ are used. This reduces the number of points from 58 to 31, 7 of these from *AV-89* and 24 from *AV-91*.

To test the accuracy of Eq. (5), the following numerical experiment was done. The radiative transfer model was run with the phase function $P^A_{2.5}$, corresponding to another size parameter, $v = 2.5$, and $\delta^A_{{\rm SAT},i} = \delta^A_{2.5,i}$ was retrieved. The estimated phase functions, $P^{*A}_{2.5,i} = (P^A_{3.5,i} + \Delta P^A_{3.5,i})(\delta^A_{3.5,i}/\delta^A_{2.5,i}) - \Delta P^A_{{\rm ref},i}$, were compared with the true values, $P^A_{2.5,i}$, for the specific observation–illumination geometries (Fig. 2). To assess the sensitivity of the $P^{*A}_{2.5,i}$ to the $\Delta P^A_{\rm ref}$, three different reference phase functions have been tested: $P^A_{\rm ref}(\chi) = P^A_{3.5}(\chi)$; $P^A_{2.5}(\chi)$; and $P^A_{\rm 2HG}(\chi)$ with $f = 0.983$, $g_1 = 0.82$, and $g_2 = -0.55$, all of which are shown in Fig. 3. The latter, according to Gordon and Castaño (1987), approximates the maritime aerosol phase function described by Quenzel and Kaestner (1980). The backscatter part of the phase function $P^A_{\rm 2HG}(\chi)$ recommended by Sturm (1981) ($f = 0.985$, $g_1 = 0.80$, and $g_2 = -0.50$, not shown) reproduces that of Gordon and Castaño (1987) within a few percent.

Figure 2 shows that the relationship between the $P^{*A}_{2.5}(\chi_i)$ estimated from Eq. (5), and the exact one, $P^A_{2.5}$ (χ_i), can be approximated by the following equation:

$$P^A_{2.5}(\chi_i) = P^{*A}_{2.5}(\chi_i) + 0.4[P^{*A}_{2.5}(\chi_i)]^2. \quad (6)$$

The quadratic term in Eq. (6) may be viewed as a multiple-scattering correction to the linear Eq. (5). Indeed, $P^A \to P^{*A}$ while $P^{*A} \to 0$ [quasi–single-scattering regime, Eq. (5) works almost perfectly], and the correction to P^{*A}, derived from linear Eq. (5), increases with P^{*A}. The scatter around the regression line gradually decreases as the model used for $P^A_{\rm ref}$ approaches the model under retrieval, ranging from −8% to +10% for $P^A_{\rm ref}(\chi) = P^A_{3.5}(\chi)$, and from −5% to 30% for $P^A_{\rm ref}(\chi) = P^A_{\rm 2HG}(\chi)$. Larger relative errors are associated with smaller absolute values of $P^{*A}_{2.5}$.

5. Results and discussion

The results of $P^A_{{\rm emp},i}(\chi_i)$ retrieval using Eq. (5), with $P^A_{\rm ref}(\chi) = P^A_{3.5}(\chi)$, are shown in Fig. 3 versus scattering angle χ_i, each point corresponding to one match-up. Note that Eq. (6) was used to account approximately for the multiple-scattering effects.

There is no significant difference in the retrieved $P^A_{{\rm emp},i}(\chi_i)$ for the two datasets used in the analysis, which independently confirms that the effect of volcanic dust in the *AV-91* data is undetectable. On the average, the two-term Henyey-Greenstein phase function, $P^A_{\rm 2HG}$, representative of maritime aerosol (Sturm 1981; Gordon and Castaño 1987) shows the best agreement with $P^A_{\rm emp}$. Also, the phase function, $P^A_{\rm LN}$, corresponding to a lognormal size distribution representative of clean maritime aerosol is shown. According to D'Almeida et al.

(1991), aerosol over oceans is composed of four lognormal modes, two of which provide main contributions: accumulation of sea salt and sulfate. Both these modes have a refractive index close to $1.4 - 0i$ and modal radius of $r_m \approx 0.1$ μm for the relative humidity of 80%, which is typical of the open ocean and the mode's width of $\sigma = 2.03$ μm. Therefore, the single-mode lognormal size distribution is used to represent approximately these two modes. The $P^A_{\rm LN}$ shows a good agreement, on the average, with both $P^A_{\rm emp}$ and $P^A_{\rm 2HG}$.

a. Error balance in $P^A_{emp}(\chi)$

The scatter of experimental points around $P^A_{\rm 2HG}$ is about $\pm 50\%$. Part of this scatter results probably from methodological and measurement errors. Substituting $P^A_{\rm ref}(\chi) = P^A_{2.5}(\chi)$ and $P^A_{\rm ref}(\chi) = P^A_{\rm 2HG}(\chi)$ has shown that typical errors in the retrieved $P^A_{{\rm emp},i}$ (χ_i), resulting from uncertainties in $P^A_{\rm ref}$ (χ), are about 10%–20%, reaching at maximum 40% for $\chi_i < 150°$. Another source of error is the uncertainty in sun-photometer data of $\Delta\delta^A_{\rm SP} \approx 0.02$. Since typical values of $\delta^A_{\rm SP} \approx 0.2$ (see Fig. 1), the resulting error in $P^A_{{\rm emp},i}(\chi_i)$ is about 10%. Possible errors in satellite calibration of about 2% translate to 5%–10% error in $P^A_{{\rm emp},i}(\chi_i)$ for typical aerosol loadings $\delta^A_{\rm SP} \approx 0.2$. Possible absorption of aerosol, implicitly treated in the present study, results in $\omega < 1$. Since typical values of the albedo of single scattering are $\omega \approx 0.90$–0.95, this translates to at most 5%–10% error in the retrieved phase function. Uncertainties resulting from lack of exact matching of satellite and sun-photometer data are expected to be small, as compared to other sources of error. This is because only cases with uniform $\delta^A_{\rm SAT}$ in space, and with stable $\delta^A_{\rm SP}$ in time, were retained. Further, residual noise is reduced by averaging in space and time. Summing up, one obtains that the typical error in the retrieved $P^A_{{\rm emp},i}(\chi_i)$ is about 30%–40% but may reach 50%–60% for smaller-scattering angles.

b. Practical use of $P^A_{emp}(\chi)$ for AVHRR retrievals

The algorithm of Rao et al. (1989) assumes $P^A_{3.5}(\chi)$ to be a ''universal'' function, ascribing all variability in the satellite-measured radiance, for a given observation–illumination geometry, to δ^A. If $P^A_{3.5}(\chi)$ is representative of an average aerosol over the ocean, then retrievals $\delta^A_{\rm SAT}$ should cluster around the true aerosol optical thicknesses without bias, with random errors resulting from variability of $P^A(\chi)$ around $P^A_{3.5}(\chi)$. Figure 1 shows, however, that in addition to pronounced random difference, there is also a systematic disagreement between $\delta^A_{\rm SAT}$ and $\delta^A_{\rm SP}$ consistent for both datasets. This implies that the $P^A_{3.5}(\chi)$ used in the operational retrievals is not representative of the average Atlantic aerosol. Figure 3 shows that all the experimental points fall well below $P^A_{3.5}$, which explains the systematic underestimation in satellite retrievals traced in Fig. 1. Here, $P^A_{2.5}$ [the size parameter $\nu = 2.5$ corresponds to an equivalent Ångström exponent $\alpha \approx 0.5$, which is more consistent with the sun-photometer measurements used by Ignatov et al. (1995a,b)] is even farther from most experimental points. Therefore, if one has no choice but to prescribe the phase function nonvariable, the two-term Henyey-Greenstein phase functions proposed by Sturm (1981) and Gordon and Castaño (1987), or that derived from the lognormal size distribution (D'Almeida et al. 1991), can be recommended. Note that the scatter in $P^A_{\rm emp}(\chi)$ may indicate that the phase function for aerosol over the ocean varies within $\pm 50\%$, which according to Eq. (4) translate to 50% errors in $\delta^A_{\rm SAT}$. This is confirmed by Fig. 4, which shows results of $\delta^A_{\rm SAT}$ retrievals using the $P^A_{\rm LN}(\chi)$ phase function. The systematic disagreement between $\delta^A_{\rm SAT}$ and $\delta^A_{\rm SP}$ is almost alleviated (cf. Fig. 1). Note that increased scatter in Fig. 4 suggests that one could achieve better precision in practical retrievals if $\delta^A_{\rm SAT}$ from Fig. 1 are empirically adjusted—say, multiplied by a constant of approximately 1.7. However, the scatter around the regression line also increases in this case 1.7 times. Therefore, there is no statistical gain as compared to the empirical phase function approach, which additionally is more consistent with the physics of the phenomenon.

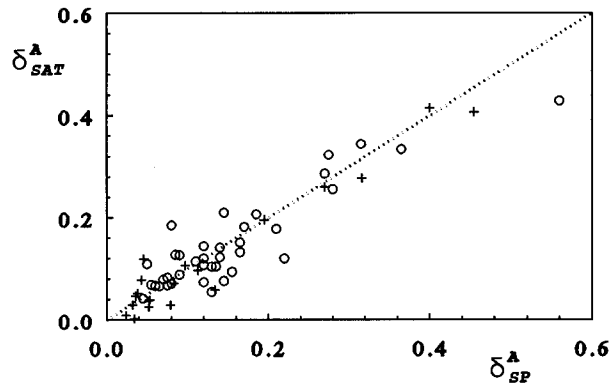

FIG. 4. Same as Fig. 1 but using $P^A_{\rm LN}$ instead of $P^A_{3.5}$.

For single-channel retrievals, the only alternative to a ''universal'' empirical phase function would involve its parameterization versus δ^A: $P^A = f(\delta^A)$, which allows one to keep one unknown under retrieval—δ^A. Special analysis has been carried out to check this hypothesis, which has not revealed any statistically significant correlation between $(P^A_{\rm emp} - P^A_{\rm 2HG})$ and $\delta^A_{\rm SP}$ in the datasets under analysis.

Running radiative transfer model with an empirical phase function, one can establish a unique scattering-geometry-specific relationship between δ^A and upward atmospheric radiance, and use it further for the $\delta^A_{\rm SAT}$ retrievals from satellite. This approach is somewhat equivalent to that proposed by Kaufman (1993), who has established such a relationship empirically from coincident ground-based sun-photometer measurements of aerosol optical thickness and path radiance at the scattering angle $\chi = 120°$.

Some studies suggest using measurements in AVHRR channel 2 (0.83 μm) to estimate P^A, which is then used in the retrieval of δ^A (e.g., Durkee et al. 1991). This procedure is not straightforward, however. Kaufman (1993) shows from his experimental studies that ''atmospheric corrections of satellite data acquired over land should be based on an average aerosol model rather than on a derived wavelength dependence of the optical thickness.'' Also, derivation of the wavelength (Ångström) exponent from AVHRR channels 1 and 2 is not an easy task even over the oceans (e.g., Kaufman et al. 1990; Ignatov 1997). And in any case, a more complicated two-channel procedure should be introduced only after the potential of the one-channel algorithm is fully realized, its advantages and deficiencies understood, and the necessity and sufficiency of additional measurements convincingly proved. To that end, using the empirically derived phase function instead of the one in use by NOAA (Rao et al. 1989) is the logical next step in that direction, providing a bridgehead between the present and future generation of aerosol retrieval algorithms. Its use may lead to errors in δ^A_{SAT} up to 50%. The remaining random uncertainty if confirmed by further validation of the improved one-channel algorithm may be potentially reduced using measurements from additional channels.

c. *Possible implications of using only large aerosol loadings*

The present study includes only match-ups with large aerosol loadings ($\delta^A_{\mathrm{SP}} \geq 0.1$), which are not typical for clean maritime conditions (e.g., Tomasi and Prodi 1982; Yershov et al. 1990; Smirnov et al. 1995). As a result, the derived empirical phase function may not be representative of clean maritime aerosol since many match-ups, collected near the coasts of Africa and North America, can be contaminated by desert dust and industrial plumes.[1] This has two practical implications. First, the validity of the derived phase function in other highly turbid situations over the ocean (caused, say, by volcanic eruptions, biomass burning, or yellow sand events over the Pacific), must be checked. Also, application of the derived phase function in the case of small aerosol loadings may be questionable. However, for practical retrievals from AVHRR, error in P^A is of more concern for large aerosol loadings, since absolute error, $\Delta\delta^A_{\mathrm{SAT}}$, is proportional to δ^A_{SAT} for the same relative error in P^A [see Eq. (2)]. For small aerosol loadings, the accuracy of δ^A_{SAT} is mainly controlled by factors such as uncertainties in oceanic reflectance and in satellite radometer calibration, rather than by an inadequate aerosol model (Ignatov 1997). Note that reducing the absolute uncertainty, $\Delta\delta^A_{\mathrm{SAT}}$, is important for climate modeling (e.g., Charlson et al. 1992). In this regard, the derived empirical phase function apparently is superior to the $P^A_{3.5}(\chi)$ in aerosol retrievals from AVHRR.

[1] The majority of match-ups (24 out of 31) analyzed in this paper were collected in July–September 1991 shortly after the Mount Pinatubo eruption and thus may suffer from some volcanic aerosol contamination, although the bulk of the stratospheric aerosol was in the Tropics during this period (Long and Stowe 1994). Also, the Mount Pinatubo effect in our data if present should create clustering of points in Figs. 1, 3, and 4 due to the different physical properties. This is clearly not the case, which leads to the conclusion that volcanic aerosol has a negligible effect on the results in the present analysis.

6. Conclusions

The empirical aerosol phase function in backscatter P^A_{emp} has been estimated, with an accuracy of about 30%–40%, from simultaneous satellite radiances in channel 1 of AVHRR, and ship sun-photometer measurements collected during two oceanic experiments. For the first time it was shown that the combination of ground-based and satellite radiation measurements provides a new tool to measure the backscatter of atmospheric aerosol—information hardly accessible from ground-based observations alone. The results look promising, and the methodology should be further refined and improved.

The newly derived $P^A_{\mathrm{emp}}(\chi)$ shows variability of up to $\pm 50\%$ from one matchup point to another, even for the same scattering geometry. On the average, it is close to that of the aerosol maritime model of Quenzel and Kaestner (1980), used by Sturm (1981) and Gordon and Castaño (1987), and to that of D'Almeida et al. (1991). This phenomenological similarity is not to be confused with geophysical interpretation of the empirical phase function since the latter, derived for $\delta^A > 0.1$, is hardly expected to represent typical clean maritime aerosol.

The derivation of a phase function in the present study was primarily motivated by practical applications for remote sensing of aerosol from space, in particular, from AVHRR. The single-mode lognormal model from D'Almeida et al. (1991) has been tested and is recommended as a first guess for future practical use (Stowe et al. 1997). However, the uncertainty of up to about $\pm 50\%$ in the retrieved δ^A_{SAT} still remains. Additionally, narrow testing of the empirical phase function may require its further fine tuning to better fit the experimental data, using more match-ups, for different scattering geometries and in different regions of the ocean. We consider a reliable single-channel retrieval model as a temporary trade-off rather than a final destination while in transition to a future multispectral retrieval scheme. It provides a standard that is to be further improved by taking into account the effects of a variable phase function using measurements in additional spectral intervals [e.g., SeaWiFS, MODIS, AVHRR channels 2 (0.83 μm) and 3A (1.6 μm) and at additional view angles (e.g., MISR)].

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