Theoretical Analysis of Retrieving Atmospheric Columnar Mie Optical Depth from Downward Total Solar Radiative Flux

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ABSTRACT

In this paper, the principle to determine the atmospheric columnar Mie optical depth from downward total solar radiative flux is theoretically studied, and the effect on Mie optical depth solution of the errors in surface albedo, single scattering albedo, asymmetrical factor of scattering phase function, instrumental constant and the approximate expression of diffusion flux is analyzed, and then a method for determining surface albedo in shorter wavelength range is presented.

I. INTRODUCTION

Atmospheric columnar aerosol and cloud optical depth is an important physical parameter of determining their radiative transfer characteristics, and aerosol atmospheric columnar optical depth is also a quantitative indication of atmospheric turbidity. The Langley method for determining atmospheric columnar optical depth is commonly used (Deirmendjian, 1980; Shaw, 1973), but it is not suitable to the case of cloudy days with larger optical depth. Considering some limitations in the Langley method, some scholars have paid great attention to the study of determining aerosol optical property from sky diffusion flux. Herman et al. (1975) studied the sensitivity of solar diffuse–to–direct ratio to the imaginary part of aerosol refractive index and surface albedo and then presented a method for retrieving the imaginary part from the ratio. This method is also suitable to the case of clear days. Up to now lidar is the main means to measure aerosol and cloud optical properties in the case of cloudy days (Platt et al., 1979; Kent et al., 1986; Dubinsky et al., 1985). But there is a limited capability in lidar measurement of cloud extinction coefficient distribution because the laser beam in visible wavelengths can not penetrate thicker cloud layer. This paper has studied the dependence of downward sky diffusion flux or total flux on aerosol and cloud optical properties and then presented a method of determining atmospheric columnar cloud or aerosol optical depth from the flux information detected with a semispherical radiometer.

II. PRINCIPLE AND NUMERICAL EXPERIMENTS

By neglecting atmospheric thermal emission in the visible region, radiative transfer equation at wavelength λ can be written as

$$\frac{\mu dI_\lambda(\tau,\mu,\varphi)}{d\tau} = I_\lambda(\tau,\mu,\varphi) - \frac{\tilde{\omega}}{4\pi}\int_0^{2\pi} d\varphi' \int_{-1}^{1} d\mu' p(\mu',\varphi',\mu',\varphi) I_\lambda(\tau,\mu',\varphi') - \frac{\tilde{\omega}F_0}{4} e^{-\tau/\mu_0} p(\mu,\varphi,-\mu_0,\varphi_0), \tag{1}$$

where $I_\lambda(\tau,\mu,\varphi)$ is the spectral radiative intensity, τ the optical depth, μ the cosine of zenith angle, φ the azimuth angle, $\tilde{\omega}$ the single scattering albedo, πF_0 the extraterrestrial solar spectral irradiance, P the scattering phase function, and μ_0 and φ_0 are respectively the cosine of solar zenith angle and its azimuth angle.

The downward total radiative flux at the ground level, $F_\lambda\downarrow$, equals solar direct flux F_{dir} plus downward diffusion flux $F_{dif}^\downarrow$, i.e.

$$F_\lambda^\downarrow = F_{dir} + F_{dif}^\downarrow, \tag{2}$$

$$F_{dir} = \pi F_0 \exp[-\tau_T(\lambda)/\mu_0]/\mu_0, \tag{3}$$

$$F_{dif}^\downarrow = \int_0^{2\pi} d\varphi \int_0^1 I_\lambda(\tau_T,\mu,\varphi)\mu d\mu, \tag{4}$$

$$\tau_T(\lambda) = \tau_R(\lambda) + \tau_M(\lambda), \tag{5}$$

where $\tau_T(\lambda)$ is the atmospheric columnar optical depth, τ_R the Rayleigh optical depth, and τ_M Mie optical depth, i.e. aerosol or cloud optical depth.

$F_\lambda^\downarrow$ and $F_{dif}^\downarrow$ can be determined through resolving radiative transfer equation (1). Define atmospheric diffusion transmissivity t_{dif}, direct transmissivity t_{dir} and total transmissivity t as follows:

$$t_{dif} = F_{dif}^\downarrow/(\pi F_0 \mu_0), \tag{6}$$

$$t_{dir} = F_{dir}/(\pi F_0 \mu_0) = \exp[-\tau_T(\lambda)/\mu_0], \tag{7}$$

$$t = F_\lambda^\downarrow/(\pi F_0 \mu_0) = t_{dif} + t_{dir}. \tag{8}$$

As far as the Langley method is concerned, the ratio between the solar direct intensity detected by a sunphotometer viewed against the sun and πF_0 is also equal to $\exp(-\tau_T(\lambda)/\mu_0)$, i.e. t_{dir}. Next, let us analyze the feasibility of determining cloud or aerosol optical depth from the above–defined transmissivity. For simplicity, the Eddington approximate formula derived by Shettle and Weinman(1970) is used in calculating downward diffusion flux $F_{dif}^\downarrow$, and its error effect will be discussed later. According to the formula, $F_{dif}^\downarrow$ depends on single scattering albedo $\tilde{\omega}$, asymmetry factor g, surface albedo A and atmospheric columnar optical depth.

Fig.1 shows the variations of diffusion transmissivity (curve 1), direct transmissivity (curve 2) and total transmissivity (curve 3) with Mie optical depth under different solar zenith angles and Rayleigh scattering optical depths, where the Mie optical depth varies from 0.01 to 100. In Fig.1(a), $\tau_R=0$ and $\mu_0=1$ (i.e. $\theta_0=0°$), and in Fig.1(b), $\tau_R=0$ and $\mu_0=0.1$ (i.e. $\theta_0=72.54°$), and in Fig.1(c), $\theta_0=0°$ and $\tau_R=0.2$. As shown in Fig.1, when Mie optical depth increases from 0.01, the diffusion transmissivity t_{dif} first increases and then decreases after reaching a maximum value at $\tau_M\approx 2$. Except for the vicinity of the maximum depth range of 2, the diffusion flux is sensitive to the variation of τ_M. Direct transmissivity usually decreases with the increase of τ_M, but as τ_M and θ_0 are smaller, t_{dir} is not sensitive to the variation of τ_M. In this case, τ_M retrieved from t_{dir} information can not give satisfactory accuracy. In addition, as τ_M is larger, for example $\tau_M > 10$, t_{dir} is much less than t_{dif}, and thus it is not suitable to use the Langley method for determining τ_M. Total transmissivity equals t_{dif} plus t_{dir}, as $\tau_T/\mu_0 < 1$, $t_{dir} > t_{dif}$, and as $\tau_T/\mu_0 > 1$, $t_{dir} < t_{dif}$. As shown in Fig.1(a) and (c), when $\theta_0=0°$ and τ_M varies between 0.01 and 0.6, t is almost constant, being approximately equal to the transmissivity in the case of

$\tau_T = \tau_R$. For the larger solar zenith angle case as shown in Fig.1(b), t is more sensitive to τ_M, but as τ_M is smaller, the sensitivity gets weaker. In a word, as $\tau_M / \mu_0 < 0.6$, τ_M solution retrieved from the total transmissivity t is sensitive to the error in t, and the method of determining τ_M from the direct transmissivity t_{dir} is more suitable. For cloud days with larger optical depth, to determine τ_M from the total transmissivity information is more suitable.

As τ_M is larger, it is proposed in this paper to use a hemispheric radiometer to measure the downward total radiation flux for determining τ_M, its difficulty is that diffusion flux component depends on not only θ_0 and τ_T but also $\tilde{\omega}$, A and g. The sensitivity of diffusion flux to g, A and $\tilde{\omega}$ can be seen from Figs.2—4, where g_M and $\tilde{\omega}_M$ are respectively Mie asymmetry factor and single scattering albedo with the following dependence on g and $\tilde{\omega}$

$$g = \tau_M g_M / (\tau_M + \tau_R),$$
$$\tilde{\omega} = (\tau_R + \tau_M \tilde{\omega}_M) / (\tau_M + \tau_R).$$

Here molecular absorption optical depth being zero is assumed.

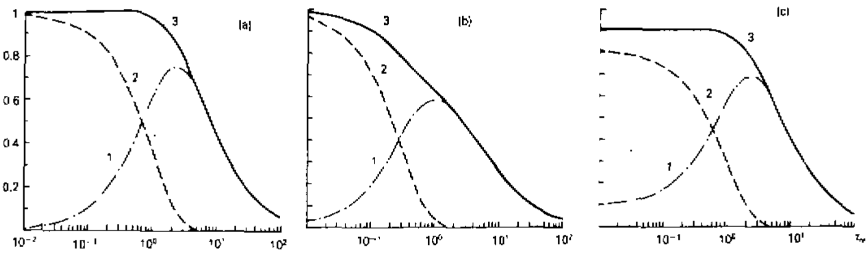

Fig. 1. Variations of t_{dir}, t_{dif} and t with τ_M. (a) $\tau_R=0$ and $\mu_0=1$; (b) $\tau_R=0$ and $\mu_0=0.3$, (c) $\tau_R=0.2$ and $\mu_0=1$.

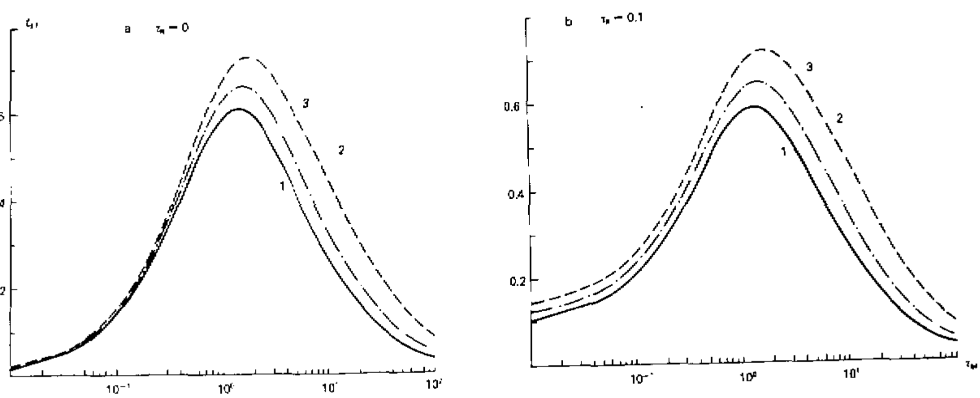

Fig. 2. Variation of diffusion transmissivity with Mie optical depth ($\mu_0=0.5$). 1. $A=0$; 2. $A=0.3$; 3. $A=0.6$.

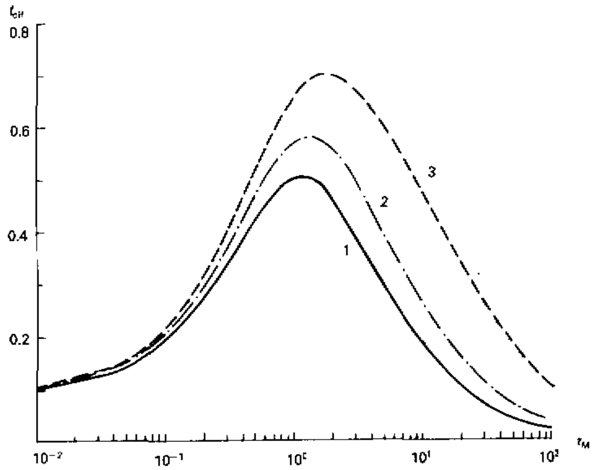

Fig. 3. Variation of t_{dif} with τ_M under different g_M ($\mu_0=0.5$ and $\tau_R=0.1$). 1. $g_M=0.5$; 2. $g_M=0.7$; 3. $g_M=0.9$.

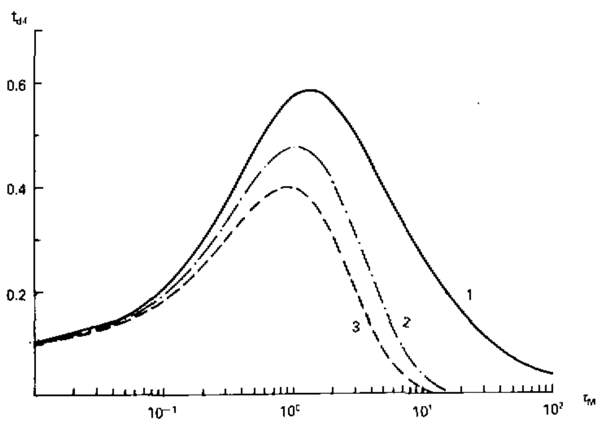

Fig. 4. Variation of t_{dif} with τ_M under different $\tilde{\omega}_M$ ($\mu_0=0.5$ and $\tau_R=0.1$). 1. $\tilde{\omega}_M=1$; 2. $\tilde{\omega}_M=0.9$; 3. $\tilde{\omega}_M=0.8$.

Curves 1, 2 and 3 in Fig. 2 correspond to $A=0$, 0.3 and 0.6, respectively. The larger A is, the larger t_{dif} is. For the case of $\tau_R=0$ (Fig.2a), as τ_M is smaller, the absolute variation of t_{dif} caused by surface albedo is very small, its relative variation tends to increasing with the increase of τ_M, and $\Delta t_{dif}/t_{dif}<15\%$ if $\Delta A<0.1$. The case of $\tau_R=0.1$ (Fig.2b) is considerably different from the case of $\tau_R=0$ with the conclusion that even as τ_M is very small, diffusion transmissivity is also quite sensitive to the variation of A because of a peak of molecular scattering phase function at $\theta\approx 180^{\circ}$. As τ_M is larger, the variation of diffusion transmissivity with surface albedo is hardly dependent on molecular scattering. As τ_M is smaller, the use of longer wavelength channel can decrease the error in the retrieved τ_M caused by uncertainty in A if τ_M is retrieved from t or t_{dif}.

The asymmetry factor of aerosol phase function usually varies from 0.5 to 0.75, and that of cloud from 0.75 to 0.9. Fig. 3 shows the variation of t_{dif} with τ_M under three cases of $g_M=0.5$, 0.7 and 0.9, with the result that the larger g_M is, the larger t_{dif} is. Therefore the value of τ_M retrieved from t will be smaller than the true value if g_M used in retrieving is larger than the true one, but the solution of τ_M retrieved from diffusion transmissivity has different characteristics. Let τ_M^* be Mie optical depth corresponding to the maximum value of t_{dif}. As $\tau_M<\tau_M^*$, τ_M determined from t_{dif} deviates less in the case of selected g_M larger than the true g_M, but as $\tau_M>\tau_M^*$, the solution deviates greatly.

Curves 1, 2 and 3 show the variations of t_{dif} with τ_M, corresponding to $\tilde{\omega}_M=1$, 0.9 and 0.8, respectively. As optical depth increases, multiple scattering component gets more dominant and the absorption of solar radiation by cloud or aerosol will intensify. Therefore, as τ_M is larger, t_{dif} is very sensitive to the variation of $\tilde{\omega}_M$. As shown in Fig.4, the downward diffusion flux at $\tilde{\omega}_M=1$ is larger than that at $\tilde{\omega}_M=0.9$ in the case of $\tau_M=20$ over one order of magnitude. Fortunately, as pointed out by Liou (1973), $\tilde{\omega}_M=1$ fits the possible values in the visible spectrum for clouds.

Further study was devoted to an analysis of the error in the retrieved τ_M caused by uncertainty in $\tilde{\omega}_M$, A, g_M and t from Tables 1—4, where $\tilde{\omega}_M^*$, A^*, g_M^* and τ_M^* are respectively exact values of single scattering albedo, surface albedo asymmetry factor and Mie optical depth and $\tilde{\omega}_M$, A and g_M their guesses in retrieving, and τ_M is Mie optical depth solution and $\Delta t/t$ is relative error in t. In Table 1, τ_M is the Mie optical depth solution retrieved from total transmissivity t under the condition of $\tau_R=0.1$ and $\mu_0=0.5$ by using the following cost function

$$S=ABS(1-t/t^*)\ , \tag{9}$$

where t^* stands for total transmissivity calculated from Shettle's and Weinman's approximate formula (1970) by using $\tilde{\omega}_M^*$, A^*, g_M^* and τ_M^*, which is regarded as the exact value, and t the value calculated from the same formula by using $\tilde{\omega}_M$, A and g_M. The effect of the error in the formula on retrieval result will be discussed in later section. The value of τ_M, which corresponds to the minimum value of cost function, is taken as Mie optical depth solution. The error of t is composed of measurement error of $F_\lambda\downarrow$ and determination error of πF_0. As shown in Table 1, the errors of g_M, A, $\tilde{\omega}_M$ and t have quite different effect on the solution in different optical depth ranges. As the error in g_M is the same, the larger τ_M^*, the larger the relative error of the solution. If Δg_M is within ± 0.05, as $0.01<\tau_M^*<1$, the relative error of τ_M is less than 25%, and as $1<\tau_M^*<100$, the error less than 35%. If the error of g_M is within ± 0.1, as $\tau_M^*>50$, the relative error of τ_M can be up to 100%. The effect of error in A on the solution is quite different from the former case. As τ_M^* is very small, the solution of τ_M is very sensitive to the error of A, for example, as $\tau_M^* = 0.01$ and $\Delta A = -0.1$, $\tau_M = 0.0025$, which is four times less than its exact value. As τ_M^* is larger, the sensitivity of the solution to the error in A is weaker with the result that as ΔA is within ± 0.1 and $\tau_M^* > 1$, the relative error of τ_M is less than 18%. The sensitivity of τ_M solution to the error in $\tilde{\omega}_M$ also gets stronger with the increase of τ_M^*. As τ_M^* is very large, much smaller error of $\tilde{\omega}_M$, can result in much larger error of τ_M solution. For example, as $\tau_M^* = 100$, if $\tilde{\omega}_M = 0.99$ is selected instead of its exact value of $\tilde{\omega}_M^* = 1$, the solution is 28.9, which is about three times less than its exact value. The contrary is the case of sensitivity of the solution to the error in t, i.e. the larger τ_M^*, the weaker the sensitivity. As $\Delta t / t = \pm 2\%$, solution error is less than 5% in the case of $\tau_M^* > 10$, but the error can be up to one order of magnitude in the case of $\tau_M^* = 0.01$. As τ_M^* is smaller, retrieving Mie optical depth from diffusion flux can be considered.

The relationship between the effect of errors in A, $\tilde{\omega}_M$, and g_M on the solution of τ_M and the solar zenith angle and Rayleigh optical depth can be seen from Tables 2—4. As τ_M^* is larger, the solution error is hardly dependent on the angle and τ_R, but as shown in Table 2, as τ_M^* is quite smaller and τ_R is larger, the error of τ_M caused by the same error in A tends to increasing and is closely dependent on the solar zenith angle, which is in relation with the characteristic of diffusion flux that as τ_M^* is smaller and τ_R larger, the flux is very sensitive to the variation of A. Furthermore, it can be seen from Tables 3–4 that as τ_M^* is smaller, the error of τ_M caused by the same error in $\tilde{\omega}_M$, and g_M has a slight variation with varying solar zenith angles and molecular optical depths, but the error by A has a considerable variation (see Table 2). The characteristic can be used in determining the shorter–wavelength surface albedo, and a retrieval example is given in Fig.5, where $\tau_R = 0.1$, $g_M^* = 0.75$, $A^* = 0.2$, $0.1 < \mu_0 < 0.3$, $\tau_M^* = 0.05$ and $\tilde{\omega}_M^* = 0.95$. Different surface albedos were used in retrieving Mie optical depth from two total transmissivity data at $\mu_0 = 0.1$ and 0.3 under the assumption of $\tilde{\omega}_M = 0.85$ and $g_M = 0.65$. According to the above–mentioned analysis, if τ_M^* is a constant, the value of A, which corresponds to the same solutions of τ_M retrieved from total transmissivity data with different solar zenith angles, can be taken as the solution of surface albedo. As shown in Fig.5, as $A = 0.208$, two A—τ_M curves, corresponding to $\mu_0 = 0.1$ and 0.3, coincide each other, and so it is taken as the albedo solution, which is very close to its exact value of 0.2 with a deviation of 0.008.

Clearly, in order to obtain more exact Mie optical depth information, proper selection of $\tilde{\omega}_M$, g_M and A is important. Many scholars have given surface albedo data with different ground–cover in the visible spectrum range (Paltridge and Platt.,1976; Chance et al., 1977). If $\Delta A < 0.05$ and $\tau_M^* > 0.5$, the error of τ_M less than 10% can be obtained. As τ_M^* is smaller and τ_R is larger, the above–mentioned method for determining surface albedo is suitable. It can be seen that the smaller τ_M^* is, the smaller the error of τ_M caused by uncertainty in g_M. For usual atmospheric aerosol size distribution, the value of fitted Junge distribution parameter, ν^*, varies from 2 to 4. According to our calculations, asymmetry factor of visible–wavelength aerosol phase in the distribution range is between 0.48 and 0.75 and has the following approximate expression

$$g_M = 0.92 - 0.1\nu^* . \tag{10}$$

According to Mie calculation data, if $2 < \nu^* < 4$, $0.05\ \mu m < r < 10\ \mu m$, the real part of aerosol refractive index varies between 1.4 and 1.65 and the imaginary part 0 and 0.05, the error of g_M determined from Formula (10) is within ± 0.05.

Table 1. Mie Optical Depth Retrieved from Total Transmissivity t for $g_M^* = 0.8$, $\tilde{\omega}_M^* = 1$, $\mu_0 = 0.5$, $\tau_R = 0.1$ and $A^* = 0.2$

g_M	$\tilde{\omega}_M$	A	$\Delta t/t$	τ_M								
0.75	1	0.2	0	0.00925	0.0900	0.435	0.85	4.02	8.17	16.3	40.0	80.9
0.7	1	0.2	0	0.0085	0.085	0.406	0.725	3.38	6.75	13.5	33.8	67.5
0.85	1	0.2	0	0.011	0.112	0.588	1.25	6.63	13.15	26.5	66.3	132
0.9	1	0.2	0	0.0123	0.125	0.725	1.50	10.4	16.2	37.6	100	198
0.8	1	0.1	0	0.0025	0.073	0.438	0.875	4.38	8.75	17.5	45.5	90.8
0.8	1	0.3	0	0.022	0.133	0.575	1.18	5.75	11.5	23.0	55.9	115
0.8	1	0.4	0	0.029	0.168	0.675	1.40	6.88	13.5	22.6	61.8	132
0.8	0.95	0.2	0	0.0083	0.078	0.338	0.604	2.25	5.18	6.43	10.7	12.5
0.8	0.99	0.2	0	0.0098	0.095	0.451	0.875	3.88	7.03	12.2	20.9	28.9
0.8	0.995	0.2	0	0.0099	0.099	0.475	0.925	4.38	8.25	14.5	26.3	37.5
0.8	0.999	0.2	0	0.010	0.100	0.500	0.975	4.88	9.53	18.0	38.8	60.7
0.8	0.9999	0.2	0	0.010	0.100	0.500	1.00	5.00	10.0	19.8	48.1	90.5
0.8	1	0.2	2%	0.0010	0.033	0.402	0.853	4.75	9.54	19.5	48.8	97.5
0.8	1	0.2	5%	0	0.011	0.263	0.650	4.25	9.00	18.5	47.6	95.0
0.8	1	0.2	−2%	0.026	0.173	0.613	1.15	5.25	10.5	20.5	51.3	103
				0.01	0.1	0.5	1	5	10	20	50	100

Table 2. Mie Optical Depth Solution Retrieved from Total Transmissivity for $g_M = g_M^* = 0.8$, $\tilde{\omega}_M^* = \tilde{\omega}_M = 0.98$, $\Delta t/t = 0$, $A^* = 0.2$ and $A = 0$

μ_0	τ_R	τ_M^*	τ_M	τ_M^*	τ_M
0.1	0.1	0.05	0.0413	50	48.7
1	0.1	0.05	0.0425	50	48.8
0.5	0.1	0.05	0.00875	50	48.8
0.5	0	0.05	0.0463	50	48.8
0.1	0	0.05	0.0498	50	48.8

Table 3. Mie Optical Depth Solution Retrieved from t for $A^* = A = 0.2$, $g_M^* = g_M = 0.8$, $\Delta t / t = 0$, $\tilde{\omega}_M^* = 0.98$ and $\tilde{\omega}_M = 0.9$

μ_0	τ_R	τ_M^*	τ_M	τ_M^*	τ_M
0.1	0.1	0.05	0.0401	50	20.0
1	0.1	0.05	0.0363	50	20.0
0.5	0.1	0.05	0.0375	50	20.1
0.5	0	0.05	0.0350	50	20.1
0.1	0	0.05	0.0438	50	20.0

Table 4. Mie Optical Depth Solution for $A^* = A = 0.2$, $\tilde{\omega}_M^* = \tilde{\omega}_M = 0.98$, $g_M^* = 0.8$, $\Delta t / t = 0$ and $g_M = 0.75$

μ_0	τ_R	τ_M^*	τ_M	τ_M^*	τ_M
0.1	0.1	0.05	0.0488	50	45
1	0.1	0.05	0.0664	50	45
0.5	0.1	0.05	0.0464	50	45
0.5	0	0.05	0.0463	50	45
0.1	0	0.05	0.0491	50	45

Table 5. Asymmetry Factor for $r_1 = 0.008$ and $\lambda = 0.55$ μm

r_2 (μm) / No	1.35	2.7	5.0	10	20	30	40	50	60
1	0.767	0.825	0.843	0.854	0.854	0.854	0.854	0.854	0.854
2	0.782	0.826	0.845	0.847	0.847	0.847	0.847	0.847	0.847

In clear days, τ_M^* is usually smaller, the sensitivity of τ_M to the error of g_M is weaker, but because the aerosol asymmetry factor varies in wider range, the proper choice of g_M is significant for improving the measurement accuracy of τ_M. For this reason, a method for simultaneous determination of τ_M and g_M from multi–wavelength measurement data is proposed. The method includes the following steps:

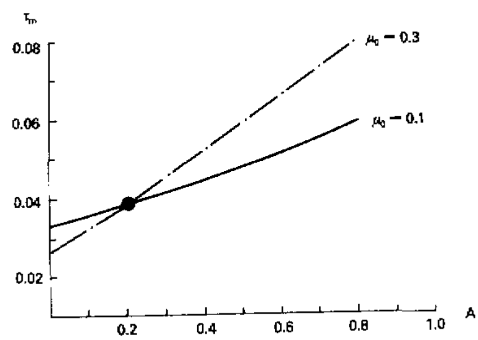

Fig.5. Mie optical depth solution for different A, $A^* = 0.2$, $g_M^* = 0.75$, $\tau_M^* = 0.05$, $\tilde{\omega}_M^* = 0.95$, $g_M = 0.65$ and $\tilde{\omega}_M = 0.85$.

(1) assume a guess of g_M and retrieve Mie optical depths from multi–wavelength total radiation flux data;

(2) fit Junge distribution from multi–wavelength Mie optical depths;

(3) determine a new g_M according to Formula (10);

(4) renewedly retrieve τ_M by using g_M determined in step (3).

Below, a numerical test is given, where two wavelengths of 0.55 μm and 0.85 μm are selected, the corresponding molecular optical depths are respectively 0.0926 and 0.0162, aerosol size distribution is the continent Diermendjian haze distribution ($n(r) = 4.97 \times 10^4 r^2 \exp(-15.1186 r^{0.5})$), aerosol refractive index is 1.5— 0 i, aerosol optical depth is 0.1 for 0.55 μm wavelength and 0.0899 for 0.85 μm wavelength, $0.05 < r < 5$ μm, and $A(0.55\ \mu m) = A(0.85\ \mu m) = 0.15$. First let $\tilde{\omega}_M = 1$; $A = 0.15$ and $g_M = 0.5$. Then optical depth solutions of 0.077 and 0.0719, respectively corresponding to 0.55 μm and 0.85 μm wavelengths, are obtained, and the Junge distribution parameter of $v^* = 2.069$ is determined according to $v^* = 2 + \ln[\tau_M(0.55\ \mu m) / \tau_M(0.85\ \mu m)]$, which is substituted into Formula (10) with the result that $g_M = 0.713$ (exact values of g_M are respectively 0.696 and 0.683 for wavelengths 0.55 μm and 0.85 μm). Then renewedly retrieved two–wavelength aerosol optical depths by using $g_M = 0.713$ are respectively 0.103 and 0.0930, which are very close to their exact values.

Next, let us analyze cloud asymmetry factor. Table 5 lists the value of cumulus C ($n(r) = 2.383 r^6 \exp(-3r/3)$) and corona cloud C ($n(r) = 1.085 \times 10^{-2} r^8 \exp(-r^3/24)$) modeled by Diermendjian (1969), marked as No.1 and No.2, respectively, where r_2 and r_1 are respectively maximum and minimum particle radius, $r_1 = 0.008$ μm, wavelength is 0.55 μm and refractive index 1.33– 0i. As shown in the table, as $r > 2.7$ μm, the variation of g_M is less than 0.03, as $5 < r_2 < 60$ μm, g_M of cumulus C has a variation less than 0.012 and corona cloud C 0.002, and the difference between them is less than 0.02 . As far as cumulus and stratus are concerned, if $g_M = 0.83$ in the visible spectrum range is selected, its error is generally not larger than 0.05.

The determination of $\tilde{\omega}_M$ is a more difficult question. The imaginary part of atmospheric columnar aerosol refractive index can vary from 0 to 0.079(Qiu,1986), and the corresponding value of $\tilde{\omega}_M$ from 0.6 to 1. If there is not additional information on $\tilde{\omega}_M$, there may be a larger error in aerosol optical depth solution retrieved from total transmissivity. A suitable method for this is simultaneously to measure total solar radiation flux and diffusion flux and then retrieved the imaginary part of aerosol refractive index by using the technique, similar to that presented by Herman(1975). As far as cloud is concerned, whether it is suitable to take $\tilde{\omega}_M = 1$ must be testified in the future experiment study.

Next, let us analyze the effect of the error due to the approximate expression of Shettle and Weinman to diffusion flux on the value of retrieved τ_M from Table 6. In numerical experiments, cost function is the same as Formula (9), but the value of t^* there is exactly calculated through solving radiative transfer equation (1) by using a method presented by Qiu (1986). In Table 6, the first 8 groups of data correspond to the condition of Junge size distribution of $v^* = 3$, aerosol refractive index of 1.5—0.01i, wavelength of 0.77 μm, $\tilde{\omega}_M = 0.9095$, $g_M = 0.68$ and $\tau_R = 0.03538$, and R is the ratio between the diffusion flux calculated from Shettle's and Weinman's expression and that exactly calculated from Eq.(1). The next three groups (9–11th) of data are obtained under the condition of continent Diermendjian's haze distribution(1969) ,aerosol refractive index of 1.5—0.05i, wavelength of 0.55 μm, $\tilde{\omega}_M = 0.745$, $g_M = 0.75$ and $\tau_R = 0.0926$. The last two groups of data are for the case of Hengey–Greenstein phase function with $g_M = 0.71$. As shown in Table 6, under different solar zenith angles, surface albedos, molecular optical depths and Mie optical depths varying from 0.1 to 20, the maximum error in downward diffusion flux calculated from Shettle's and Weinman's approximate expression is 7%, the maximum error in the solution caused by the error is 18%, and as τ^*_M is larger, the expression has higher accuracy and τ_M smaller error, for example, in the two cases of $\tau^*_M = 15$ and $\tau^*_M = 20$ (last two groups of data), the errors of τ_M are respectively less than 6% and 3%. Therefore, considering that the uncertainty in g_M, A and $\tilde{\omega}_M$ may result in the larger error of τ_M, the use of Shettle's and Weinman's approximate expression in our retrieving algorithm is suitable.

Table 6. Effect of Approximate Expression to Diffusion Flux on Optical Depth Solution

μ_0	τ^*_M	τ_R	A	m	$\tilde{\omega}_M$	g_M	R	τ_M
0.3131	0.1	0.03538	0	1.5–0.01i	0.9095	0.68	0.952	0.110
0.3131	0.3	0.03538	0	1.5–0.01i	0.9095	0.68	0.975	0.285
0.3131	0.6	0.03538	0	1.5–0.01i	0.9095	0.68	0.974	0.580
0.3131	0.1	0.03538	0.2	1.5–0.01i	0.9095	0.68	0.952	0.085
0.3131	0.3	0.03538	0.2	1.5–0.01i	0.9095	0.68	0.958	0.278
0.3131	0.6	0.03538	0.2	1.5–0.01i	0.9095	0.68	1.011	0.651
0.6869	0.1	0.03538	0.2	1.5–0.01i	0.9095	0.68	0.963	0.085
0.6869	0.3	0.03538	0.2	1.5–0.01i	0.9095	0.68	0.969	0.274
0.6869	0.1	0.0926	0.2	1.5–0.05i	0.745	0.758	1.07	0.118
0.6869	0.3	0.0926	0.2	1.5–0.05i	0.745	0.758	0.925	0.285
0.6869	0.6	0.0926	0.2	1.5–0.05i	0.745	0.758	0.938	0.550
0.4374	15	0.1	0		1	0.71	1.031	15.8
0.4374	20	0.1	0		1	0.71	1.026	20.5

III. CONCLUSIONS

As there is cloud in sky, the Langley method for determination of atmospheric columnar optical depth is generally unsuitable. This paper studies the suitability of retrieving Mie optical depth from total downward solar radiation flux (or diffusion flux) information. According to the study, retrieval accuracy depends on magnitude of errors in single scattering albedo, surface albedo, asymmetry factor and transmissivity t. As $\tau^*_M / \mu_0 < 0.05$, the effect of the error of t on the retrieval accuracy of τ_M is dominant; as τ_R is larger and τ^*_M is smaller, the solution of τ_M is considerably sensitive to the error in surface albedo; as τ^*_M is larger, the effect of the error in single scattering albedo is dominant and the error in t has weaker effect. In order to make the error of τ_M less than 30%, the error of the surface albedo would be less than 0.1, the asymmetry factor 0.05 and single scattering albedo 0.08 / $(1+\tau_M^*)$. It is much interested that as cloud optical depth is quite larger, the very small error of single scattering albedo may result in significant errors of the solution of τ_M.

As τ_M^* is smaller and τ_R larger, the effect of the error of A on the retrieval accuracy of τ_M is closely dependent on the solar zenith angle. The characteristic can be used in determining shorter-wavelength surface albedo.

In our study, horizontally homogeneous atmosphere and height-independent atmospheric scattering phase function are assumed. For thick or medium clouds, cloud optical depth is larger, its contribution to diffusion flux is usually dominant, and thus taking no account of variation of phase function with height may be suitable. However, for thin clouds, especially cirrus, it should be further studied in future experiments whether our method is suitable.

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