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Atmospheric correction: Computing atmospheric diffuse transmittance

Jinji Ma [a,b,*], Shizhi Yang [a], Xianbing Wang [a], Yanli Qiao [a]

[a] Remote Sensing Laboratory, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, HeFei 230031, China
[b] College of Physics and Electronic Information, Anhui Normal University, WuHu 241000, China

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Abstract

If we can accurately compute the leaving-water radiance and atmospheric diffuse transmittance, we will accurately retrieve the atmosphere optical properties over the case II water by MODIS image. According to the paper by Wang [Wang, Menghua, 1999. Atmospheric correction of ocean color sensors: computing atmospheric diffuse transmittance. Appl. Opt. 38, 451–455] to using the reciprocal equation derived by Yang and Gordon [Yang, H., Gordon, H.R., 1997. Remote sensing of ocean color: assesment of water-leaving radiance bidirectional effects on atmospheric diffuse transmittance. Appl. Opt. 36, 7887–7897] for atmospheric diffuse transmittance of the ocean–atmosphere system, we examined the accuracy of an analytical equation proposed by Gordon et al. [Gordon, H.R., Clark, D.K., Brown, J.W., Brown, O.B., Evans, R.H., Broenkow, W.W., 1983. Phytoplankton pigment concentrations in the Middle Atlantic Bight: comparison of ship determinations and CZCS estimates. Appl. Opt. 22, 20–36] in computing the atmospheric diffuse transmittance for wavelengths from MODIS band 1 central wavelength to MODIS band 7 for central wavelength both a pure Rayleigh and a two-layer Rayleigh-aerosol atmosphere overlying a rough ocean surface. It was found that for viewing angles up to approximately 40°, the analytical formula produces errors between 3% and 4% for nonabsorbing and weakly absorbing aerosols and for aerosol optical thicknesses $\tau_a \leq 0.4$. The error increases with an increase in aerosol absorption, aerosol optical thicknesses, and viewing angle, and with the decrease of wavelength. By a simple numerical fit to modify the analytical formula, the atmospheric diffuse transmittance can be accurately computed usually to within ~1% for a variety of aerosol models,

* Corresponding author. Remote Sensing Laboratory, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, HeFei 230031, China. Tel.: +86 551 5593048; fax: +86 551 5591010.
E-mail address: jinji_ma@yahoo.com.cn (J. Ma).

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aerosol optical thicknesses $\tau_a \leq 0.6$, viewing angles $\theta \leq 60°$, different aerosol vertical structure distribution, and for wavelengths from MODIS band 1 central wavelength to MODIS band 7 central wavelength.

Keywords: Radiative transfer; Diffuse transmittance; Optical thickness; Rough ocean surface

1. Introduction

In ocean-color remote sensing, the sensor-measured radiance at the top of the ocean–atmosphere system, measured at wavelength λ, can be written as

$$L_t(\lambda) = L_r(\lambda) + L_a(\lambda) + L_{ra}(\lambda) + t(\lambda)L_{wc}(\lambda) + t(\lambda)L_w(\lambda) \tag{1}$$

where $L_r(\lambda)$, $L_a(\lambda)$ and $L_{ra}(\lambda)$ are contributions, respectively, from the multiple scattering of air molecules (Rayleigh scattering with no aerosols), aerosols (no air molecules), and Rayleigh-aerosol interactions (Gordon and Wang, 1994a). The $L_{wc}(\lambda)$ is the radiance at the sea surface that arises from sunlight and skylight reflecting from whitecaps on the surface (Gordon and Wang, 1994b; Frouin et al., 1996; Moore et al., 2000). The $L_w(\lambda)$ is the water-leaving radiance that is the desired quantity in ocean-color remote sensing to relate the ocean near surface physical and bio-optical properties and $t(\lambda)$ is the atmospheric diffuse transmittance that accounts for the effects of propagating $L_w(\lambda)$ and $L_{wc}(\lambda)$ from the sea surface to the top of the atmosphere. Note that the surface sun glitter term in Eq. (1) has been ignored because there are usually no meaningful retrievals in regions significantly contaminated by sun glint. The goal of the atmospheric correction is to retrieve the water-leaving radiance $L_w(\lambda)$ accurately from spectral and angular measurements of radiance $L_t(\lambda)$ at the satellite. The atmosphere correction algorithm (Gordon and Wang, 1994a) of the ocean color sensors (SeaWiFS, MODIS, et al.) uses the two near-infrared bands (Hooker et al., 1992). To obtain the $L_w(\lambda)$ from $t(\lambda)L_w(\lambda)$, however, the diffuse transmittance of the ocean–atmosphere system $t(\lambda)$ is needed. The $t(\lambda)$ value usually depends not only on the optical properties of the atmosphere, wavelength, and viewing geometry, but also on the angular distribution of the water-leaving radiance $L_w(\lambda)$. To compute $t(\lambda)$, however, one can usually assume that $L_w(\lambda)$ is independent of the viewing angle, i.e., the water-leaving radiance is uniformly distributed (Wang et al., 2001). Any angular dependence of $L_w(\lambda)$ can be incorporated as a function of the ocean water optical properties and the solar illumination geometry (Morel and Gentili, 1996). Inasmuch as the optical properties of both ozone and water vapor are purely absorbing (no scattering) and the effects of the diffuse transmittance from both ozone and water vapor can be easily calculated, here it is assumed that the diffuse transmittance $t(\lambda)$ is composed only of contributions from air molecules and atmospheric aerosols.

Assuming that the water-leaving radiance $L_w(\lambda)$ is uniform, the atmospheric diffuse transmittance $t(\lambda)$ in Eq. (1) can be computed through a reciprocal procedure by solving the radiative transfer equation for the ocean–atmosphere system (Yang and Gordon, 1997). Gordon et al. (1983), however, has proposed a simple approximation to compute the atmospheric diffuse transmittance. This analytical formula was used in the atmospheric correction of imagery data

Table 1
Values of coefficients to fit the diffuse transmittance computations for a pure Rayleigh atmosphere bounded by a rough ocean

j	a_{0j}	a_{1j}	a_{2j}	a_{3j}	a_{4j}
1	0.95167	−0.06246	0.09567	−0.01982	−0.00142
2	−0.08929	2.45235e−4	0.03475	−0.00724	5.07723e−4
3	−0.01797	−5.90683e−4	0.00561	−0.00128	9.60525e−5

processing for the CZCS on Nimbus-7 during its 8-year mission from 1978 to 1986 (Gordon et al., 1980).

2. Rayleigh atmosphere

For a pure Rayleigh bounded rough ocean surface, the atmospheric diffuse transmittance can be approximated by (Gordon et al., 1983)

$$t_r(\lambda,\theta) = \exp[-\tau_r(\lambda)/2\cos\theta] \quad (2)$$

where $\tau_r(\lambda)$ is the Rayleigh optical thickness and θ is the viewing angle. We have examined the accuracy of Eq. (2) for wavelengths from MODIS band 1 central wavelength to MODIS band 4 central wavelength and viewing angles from 0° to 80°. It was found that by using Eq. (2), the error in computing $t_r(\lambda,\theta)$ ranged from 0.23% to 13.5% for viewing angles from 0° to 80° at the MODIS band 3 central wavelength, whereas errors are usually within 1% at the MODIS band 1

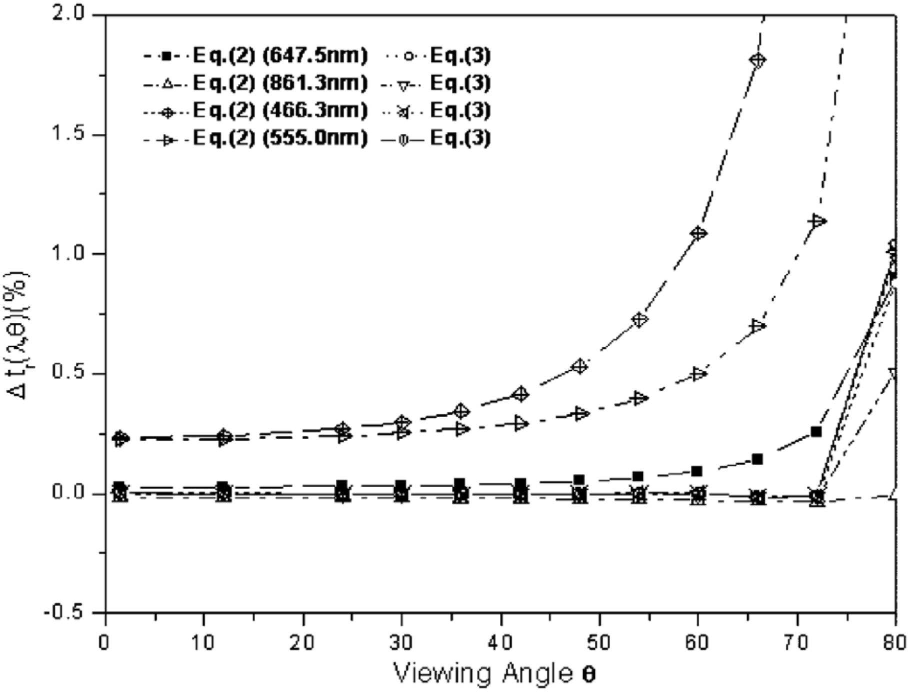

Fig. 1. Errors (%) in computing diffuse transmittance using Eqs. (2) and (3) for a pure Rayleigh atmosphere for wavelengths 466.3, 555.0, 647.5, and 861.3 nm and for viewing angles from 0° to 80°.

central wavelength and MODIS band 2 central wavelength. To improve the accuracy of computing $t_r(\lambda,\theta)$, we found that it is efficient to modify Eq. (2) with a fitting method such as

$$t_r^{(C)}(\lambda,\theta) = \exp[-C_r(\lambda,\theta)\tau_r(\lambda)/2\cos\theta] \quad (3)$$

where $C_r(\lambda,\theta)$ is parameter to fit the value of diffuse transmittance for a Rayleigh-ocean system. From simulations, $C_r(\lambda,\theta)$ can be approximated with a polynomial fit to the Rayleigh optical thickness as

$$C_r(\lambda,\theta) = a_1(\theta) + a_2(\theta)\ln[\tau_r(\lambda)] + a_3(\theta)\ln^2[\tau_r(\lambda)] \quad (4)$$

and coefficients $a_1(\theta)$, $a_2(\theta)$, $a_3(\theta)$ and $a_4(\theta)$ can be fitted with $1/\cos\theta$ as

$$a_j(\theta) = a_{0j} + a_{1j}/\cos\theta + a_{2j}/\cos^2\theta + a_{3j}/\cos^3\theta + a_{4j}/\cos^4\theta \quad (5)$$

where a_{0j}, a_{1j}, a_{2j}, a_{3j} and a_{4j} (j=1–4) can be found with a polynomial fit to Eq. (4) for a given view angle θ. The first, we can obtain the value of diffuse transmittance at each angle from 1.5° to 80° by 6° at different wavelengths through the reciprocity principle (Yang and Gordon, 1997) by solving the radiative transfer equation for a Rayleigh atmosphere bounded by a rough ocean surface (Cox and Munk, 1954). For solving the RTE, we selected the surface wind of 6.0 m/s. The second, using this value and Eq. (3), obtained the value of parameter $C_r(\lambda,\theta)$ at different angles and wavelengths. At last, we can obtain the values of coefficients $a_j(\theta)$ according to Eq. (4) and the value of parameter $C_r(\lambda,\theta)$ such as Table 1 provides the values. Assuming that $t_r^{(m)}(\lambda,\theta)$ is the true value of diffuse transmittance that was obtained through the reciprocity principle (Yang and Gordon, 1997) by solving the radiative transfer equation for a Rayleigh atmosphere bounded by a rough ocean surface (Cox and Munk, 1954), the error

$$\Delta t_r(\lambda,\theta) = t_r(\lambda,\theta) - t_r^{(m)}(\lambda,\theta) \quad (6)$$

can be computed. Fig. 1 shows a comparison of the results of error $\Delta t_r(\lambda,\theta)$ using Eqs. (2) and (3) for wavelengths 466.3, 555.0, 647.5, and 861.3 nm and for viewing angles from 0° to 80°. It is obvious that errors $\Delta t_r(\lambda,\theta)$ are much less when Eq. (3) is used. It was found that, for $\theta \leq 60°$, errors $\Delta t_r(\lambda,\theta)$ obtained with Eq. (3) are within 0.092% for wavelengths from the MODIS band 1 central wavelength to MODIS band 4 central wavelength.

3. Two-layer Rayleigh-aerosol atmosphere

For an atmosphere composed of both air molecules and aerosols bounded by a rough ocean surface, the diffuse transmittance can be approximated by (Gordon et al., 1983)

$$t(\lambda,\theta) = t_r(\lambda,\theta)t_a(\lambda,\theta)$$

$$t_a(\lambda,\theta) = \exp\{-[1-\omega_a(\lambda)F_a(\lambda)]\tau_a(\lambda)/\cos\theta\} \quad (7)$$

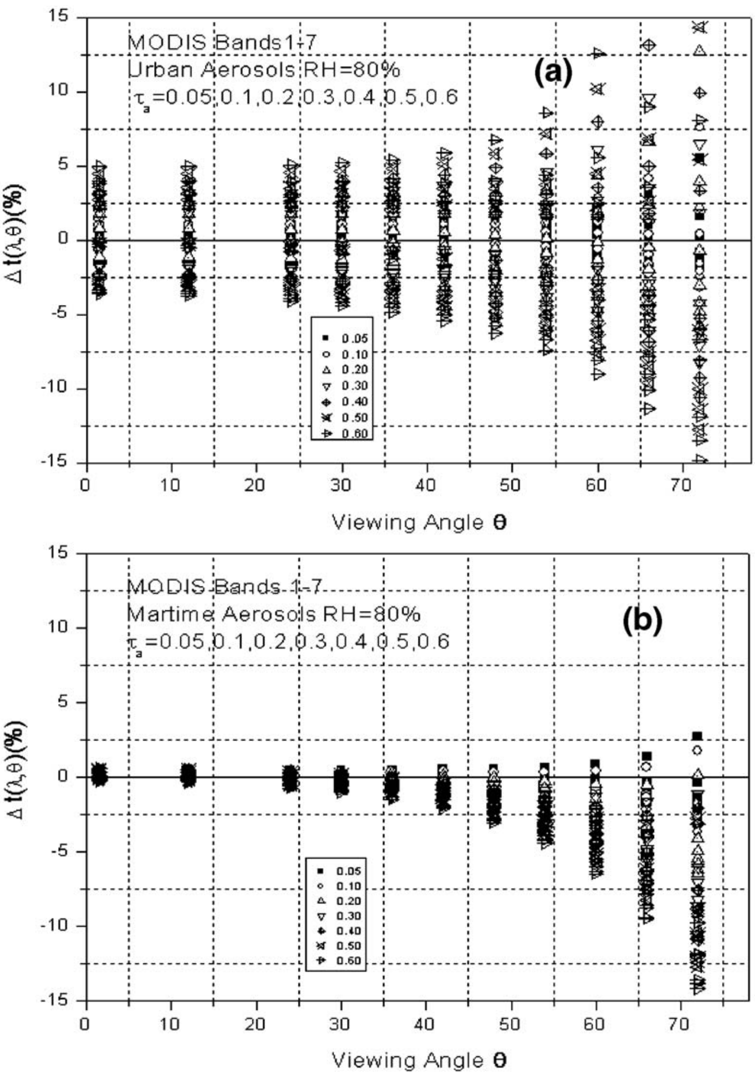

Fig. 2. Errors (%) in computing diffuse transmittance using Eqs. (7) for a two-layer Rayleigh-aerosol atmosphere bounded by a rough ocean surface for aerosol optical thicknesses of 0.05–0.6, viewing angles from 1.5° to 72°, at seven spectral wavelengths from 466.3 to 2120 nm and for (a) Urban and (b) Maritime aerosol models with RH values of 80%.

where ω_a is the aerosol single-scattering albedo and τ_a is the aerosol optical thickness. The $F_a(\lambda)$ is defined as

$$F_a(\lambda) = 1/2\int_0^1 P_a(\Theta, \lambda)\mathrm{d}\cos\Theta \qquad (8)$$

where $P_a(\lambda)$ is the aerosol scattering phase function normalized to 4π. Since photons scattered by aerosols are characteristically strongly packed in the forward direction, the term

Table 2
Values of coefficients to fit the diffuse transmittance computations for a two-layer Rayleigh-aerosol atmosphere bounded by a rough ocean

λ (nm)	j	b_{0j}	b_{1j}	b_{2j}	b_{3j}	b_{4j}
466.3	1	0.75659	−1.68642	1.26319	−0.31429	0.02818
	2	−0.25976	−0.33619	0.49546	−0.13662	0.01168
	3	−0.16059	0.02967	0.07238	−0.02143	0.00144
	4	−0.03691	0.03398	−0.01254	0.00369	−5.16071e−4
555.0	1	0.87750	−1.74148	1.18370	−0.28341	0.02564
	2	−0.04705	−0.57054	0.57359	−0.14700	0.01313
	3	−0.04256	−0.08600	0.11275	−0.02775	0.00215
	4	−0.00690	0.00161	0.00279	4.30211e−5	−1.28185e−4
647.5	1	0.75554	−1.53005	0.98915	−0.22445	0.01962
	2	−0.03590	−0.59747	0.57581	−0.14959	0.01416
	3	−0.04266	−0.08307	0.10477	−0.02625	0.00227
	4	−0.00766	0.00194	0.00242	−9.3008e−5	−6.71028e−5
861.3	1	0.57256	−1.63156	1.01975	−0.24226	0.02269
	2	0.01278	−0.59073	0.52024	−0.13437	0.01310
	3	−0.02496	−0.08150	0.08709	−0.02133	0.00193
	4	−0.00518	3.78189e−4	0.00199	−7.12462e−5	−4.16179e−5
1242.5	1	0.58917	−1.94203	1.15764	−0.27381	0.02550
	2	0.72499	−0.88875	0.63565	−0.15963	0.01528
	3	0.24273	−0.18817	0.12682	−0.03011	0.02710
	4	0.03294	−0.01584	0.00873	−0.00171	1.16216e−4
1632.5	1	0.30766	−1.84822	0.95230	−0.21281	0.01873
	2	0.85158	−0.99939	0.56420	−0.13150	0.01173
	3	0.26575	−0.24493	0.12462	−0.02699	0.00220
	4	0.03190	−0.02426	0.01072	−0.00207	1.4169e−4
2120.0	1	0.35653	−2.07499	0.96005	−0.20387	0.01701
	2	1.48866	−1.27443	0.61900	−0.13632	0.01153
	3	0.43800	−0.32329	0.14463	−0.03012	0.00237
	4	0.04712	−0.03092	0.01253	0.00238	1.62799e−4

of $[1-\omega_a\lambda F_a\lambda]$ is generally small. Therefore, the Rayleigh-scattering effects usually dominate in $t(\lambda)$, in particular, at short wavelengths.

The Eq. (7) have testified by Wang with lots of aerosol models which have nonabsorbing model and very strongly absorbing model (Wang, 1999). So we only used Maritime, Urban, used-defined1 aerosol models with a relative humidity(RH) of 80% to test the accuracy of Eq. (7). We have evaluated the accuracy of the atmospheric diffuse transmittance using Eq. (7) for wavelengths from MODIS band1 of central wavelengths to MODIS band 7 of central wavelengths, view angles from 1.5° to 72°, and three aerosol models with aerosol optical thickness τ_a=0.05, 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6. The true values of the diffuse transmittance for a two-layer atmosphere bounded by a roughness of ocean surface were obtained from the result computed in Eq. (1) by use of the reciprocity principle (Yang and Gordon, 1997). The error $\Delta t(\lambda,\theta)=t(\lambda,\theta)-t^{(m)}(\lambda,\theta)$ can then be calculated. Fig. 2a and b provides examples of $\Delta t(\lambda,\theta)$ (%) for, respectively, the Urban and Maritime aerosol models with 80% RH. Each figure includes the seven MODIS central wavelengths from MODIS band 1 to band 7 central wavelength, seven aerosol optical thicknesses from 0.05 to 0.6, and eleven viewing angles from 1.5° to 72°. Fig. 2a and b shows that Eq. (7) are reasonably accurate for nonabsorbing and weakly absorbing aerosols and for a not too large aerosol optical thickness with $\theta \leq 40°$. It is truly remarkable that simple formulas as in Eq. (7) performed reasonably well for the various

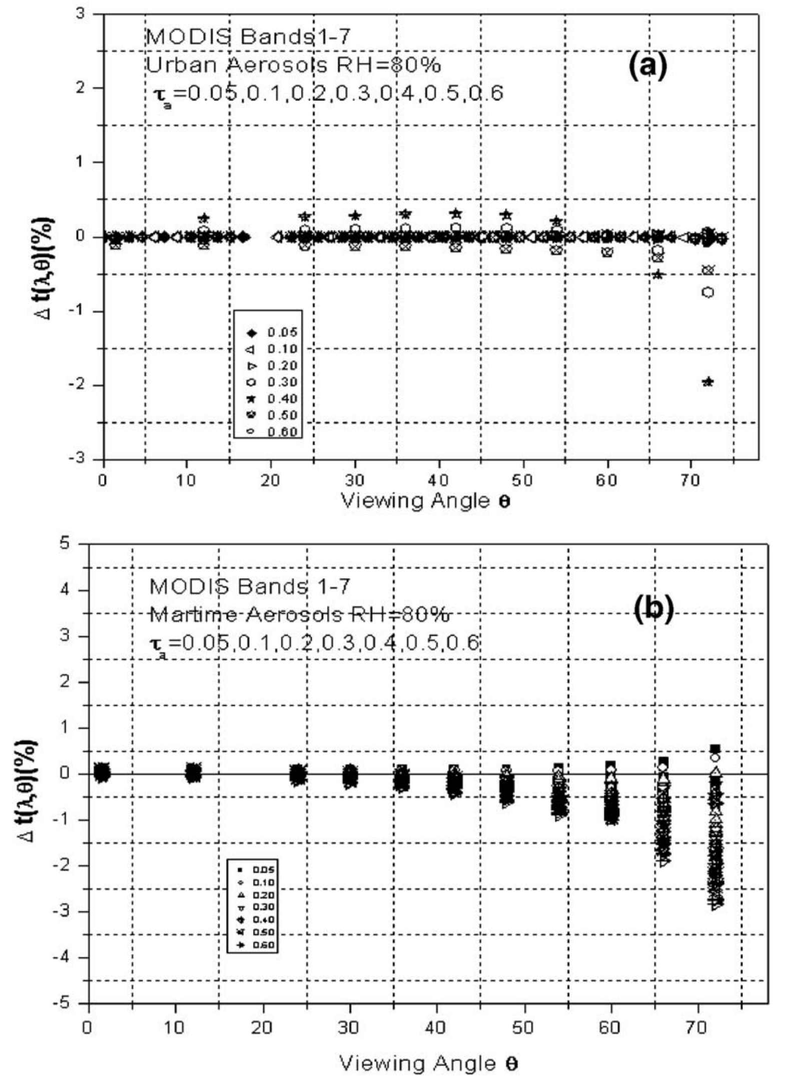

Fig. 3. Same as in Fig. 2 except Eqs. (9) were used to compute the diffuse transmittance.

cases. The errors in computing $t(\lambda,\theta)$ with Eq. (7) are within 4–5% (most cases within 1–3%) for aerosol optical thickness $\tau_a \leq 0.4$ and $\theta \leq 40^\circ$.

4. Modification of Eq. (7)

To improve the accuracy of computing the $t(\lambda,\theta)$ value, we explored many different ways of modifying Eq. (7) and found, through trial and error, that it works reasonably well when Eq. (7) were modified as follow:

$$t^{(c)}(\lambda,\theta) = t_r^{(c)}(\lambda,\theta)\, t_a^{(c)}(\lambda,\theta)$$

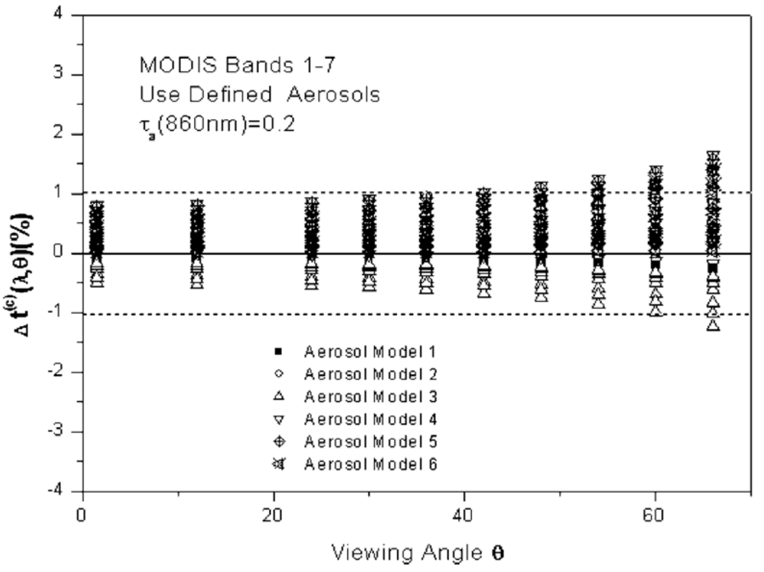

Fig. 4. Errors (%) in computing diffuse transmittance using Eq. (9) for cases of a two-layer Rayleigh-aerosol atmosphere for the Used-define aerosol models, optical thickness, viewing angles 1.5° to 66°, and for the MODIS 1–7 channel center wavelengths.

$$t_a^{(c)}(\lambda,\theta) = \exp\{-a_0(\lambda)[1+\omega_a(\lambda)C_a(\lambda,\theta)]/\cos\theta\} \tag{9}$$

where $t_r^{(c)}(\lambda,\theta)$ is given by Eqs. (3)–(5), $a_0(\lambda)=[1-\omega_a(\lambda)F_a(\lambda)]\tau_a(\lambda)$ is the aerosol optical parameter, and $C_a(\lambda)$ is a coefficient that best fits atmospheric diffuse transmittance for the ocean–atmosphere system. Form simulations, $C_a(\lambda,\theta)$, can be approximated with a polynomial fit to a quantity of $\ln[a_0(\lambda)]$ as

$$C_a(\lambda,\theta) = b_1(\lambda,\theta) + b_2(\lambda,\theta)\ln[a_0(\lambda)] + b_3(\lambda,\theta)\ln^2[a_0(\lambda)] + b_4(\lambda,\theta)\ln^3[a_0(\lambda)] \tag{10}$$

and coefficients $b_1(\lambda,\theta)$, $b_2(\lambda,\theta)$, $b_3(\lambda,\theta)$, and $b_4(\lambda,\theta)$ can be fitted with $1/\cos\theta$ as

$$b_j(\lambda,\theta) = b_{0j}(\lambda) + b_{1j}(\lambda)/\cos\theta + b_{2j}(\lambda)/\cos^2\theta + b_{3j}(\lambda)/\cos^3\theta + b_{4j}(\lambda)/\cos^4\theta \tag{11}$$

where $b_{ij}(\lambda)$ ($i=0$–4 and $j=1$–4) can be found with a polynomial fit to Eq. (9) at a given wavelength. We computed coefficients $b_{ij}(\lambda)$ at seven wavelengths from MODIS band 1 to MODIS band 7 central wavelengths. Table 2 provides coefficients $b_{ij}(\lambda)$ at these seven wavelengths. The coefficients $b_{ij}(\lambda)$ were obtained by a best fit with Eq. (9) for Urban and Maritime aerosol models with 80% RH, optical thickness to much as 0.6, and viewing angles θ up to 72°. The detail process is defined in the Appendix. Again, the errors in computing atmospheric diffuse transmittance using Eq. (9), $\Delta t^{(c)}(\lambda,\theta)=t^{(c)}(\lambda,\theta)-t^{(m)}(\lambda,\theta)$, were calculated. Example results are presented in Fig. 3a and b. The test cases in Fig. 3a and b are the same as those in Fig. 2a and b. The results show that Eq. (9) works quite well for various aerosol optical properties, different viewing angles, and for wavelengths from MODIS band 1 to MODIS band 7 central wavelengths. With the exception of some cases having large aerosol optical thickness,

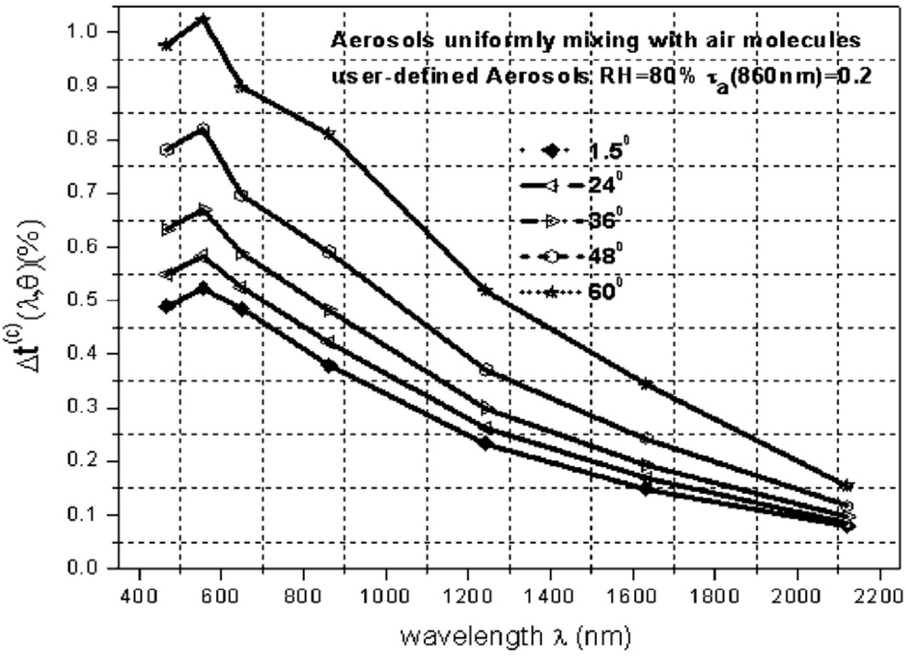

Fig. 5. Errors (%) in computing diffuse transmittance using Eqs. (9) for cases of a one-layer atmosphere, in which the aerosols and air molecules are uniformly mixed, bounded by a rough ocean surface for the Used-define aerosol model 1, optical thickness, viewing angles 1.5°, 24°, 36°, 48°, and 66° and for seven wavelengths at 466.3, 550, 647.5, 861.3, 1242.5, 1632.5, and 2120 nm.

i.e., τ_a=0.6, errors $\Delta t^{(c)}(\lambda,\theta)$ are usually within 1% for $\theta \leq 60°$. In most cases, the errors are within 0.5%.

5. Test of Eq. (9) with other cases

To test the efficacy of Eq. (9), we applied to cases of aerosol models that differ from seven aerosol models that were used to derive coefficients $C_a(\lambda,\theta)$. We tested six Used-define aerosol

Table 3
Values of parameters Ca(λ,θ) to compute Eqs. (5) and (9) and RTE for a two-layer Rayleigh-aerosol atmosphere in the above conditions

Angle	λ (nm)						
	466.3	555.0	647.5	861.3	1242.5	1632.5	2120.0
1.5°	0.41888	0.28093	0.28775	0.02636	−1.0893	−1.2989	−2.1586
12°	0.41028	0.27491	0.2811	0.02002	−1.0930	−1.3000	−2.1578
24°	0.38509	0.25646	0.26021	−4.2508E−4	−1.1053	−1.3040	−2.1548
30°	0.36732	0.24253	0.24393	−0.01671	−1.1153	−1.3077	−2.1533
36°	0.34701	0.22541	0.22327	−0.03781	−1.1285	−1.3127	−2.1515
42°	0.32526	0.20511	0.19782	−0.06441	−1.1455	−1.3198	−2.1502
48°	0.30368	0.18176	0.16714	−0.09749	−1.1674	−1.3296	−2.1498
54°	0.2848	0.15564	0.13069	−0.13826	−1.1949	−1.3429	−2.1509
60°	0.27303	0.12755	0.08793	−0.18841	−1.2298	−1.3608	−2.1544
66°	0.27857	0.10056	0.03901	−0.25011	−1.2722	−1.3837	−2.1601
72°	0.34249	0.10055	5.20258E−4	−0.31461	−1.3124	−1.4010	−2.1556

Table 4
Values of parameters $b_i(\lambda,\theta)$ to compute Eq. (10) for a two-layer Rayleigh-aerosol atmosphere in the above conditions

Angle	λ (nm)														
	466.3				555.0				647.5				861.3	
	b_1	b_2	b_3	b_4	b_1	b_2	b_3	b_4	b_1	b_2	b_3	b_4	b_1	b_2
1.5°	0.04758	−0.22516	−0.07845	−0.01229	0.06236	−0.17741	−0.04128	−0.00257	0.01397	−0.19239	−0.04475	−0.00344	−0.25837	−0.17836
12°	0.0478	−0.21882	−0.07594	−0.0119	0.05963	−0.17344	−0.03991	−0.00243	0.00101	−0.18914	−0.04361	−0.00332	−0.26377	−0.17676
24°	0.0521	−0.19662	−0.06742	−0.01062	0.05428	−0.15858	−0.035	−0.00193	0.00106	−0.17631	−0.03935	−0.00287	−0.27702	−0.16827
30°	0.0594	−0.17705	−0.06025	−0.0096	0.05365	−0.14448	−0.03056	−0.00149	−0.0026	−0.16374	−0.03542	−0.00247	−0.28486	−0.15976
36°	0.074	−0.1492	−0.05045	−0.00829	0.05778	−0.12311	−0.02405	−8.67611E−4	−0.00262	−0.14434	−0.02958	−0.0019	−0.2908	−0.14579
42°	0.10124	−0.10956	−0.03708	−0.00659	0.07114	−0.09116	−0.01464	8.9326E−6	0.00492	−0.1151	−0.02116	−0.00111	−0.29224	−0.12442
48°	0.14949	−0.0531	−0.01887	−0.00439	0.10115	−0.04331	−0.00102	0.00125	0.02687	−0.07081	−0.00889	1.07709E−5	−0.28329	−0.0909
54°	0.23236	0.02758	0.00596	−0.00155	0.16049	0.02894	0.01894	0.00306	0.07482	−0.00338	0.00915	0.00163	−0.25412	−0.03796
60°	0.37244	0.14344	0.03991	0.00219	0.27167	0.13973	0.04873	0.00576	0.17011	0.10161	0.03652	0.00406	−0.18729	0.04638
66°	0.60478	0.30519	0.08413	0.00683	0.47634	0.31271	0.09387	0.00988	0.35408	0.27038	0.07952	0.0079	−0.04593	0.18715
72°	0.9665	0.49228	0.12537	0.01022	0.84568	0.57165	0.15561	0.01492	0.70777	0.54444	0.14566	0.01343	0.24976	0.43257

Angle	λ (nm)													
	861.3		1242.5				1632.5				2120.0			
	b_3	b_4	b_1	b_2	b_3	b_4	b_1	b_2	b_3	b_4	b_1	b_2	b_3	b_4
1.5°	−0.03859	−0.00291	−0.44308	0.32809	0.15413	0.02425	−0.78225	0.29683	0.12068	0.01643	−0.94687	0.70718	0.23121	0.02647
12°	−0.038	−0.00284	−0.45107	0.32678	0.15364	0.02417	−0.79361	0.29176	0.11913	0.01624	−0.9577	0.70215	0.22973	0.02629
24°	−0.03512	−0.00254	−0.47245	0.32596	0.15302	0.02398	−0.8268	0.27781	0.11467	0.01567	−1.01036	0.67063	0.22066	0.02534
30°	−0.03249	−0.00229	−0.48641	0.3273	0.15292	0.02386	−0.85097	0.26836	0.1115	0.01525	−1.04099	0.65467	0.21583	0.02478
36°	−0.02841	−0.0019	−0.50017	0.33186	0.1534	0.02375	−0.88051	0.25697	0.10747	0.0147	−1.08893	0.62686	0.20756	0.02388
42°	−0.02254	−0.00138	−0.51174	0.34093	0.15457	0.02364	−0.91195	0.24665	0.10331	0.01409	−1.13663	0.60153	0.19955	0.02294
48°	−0.01374	−6.13615E−4	−0.51359	0.3606	0.15796	0.02366	−0.94416	0.23807	0.09899	0.01339	−1.1954	0.5695	0.18924	0.02175
54°	−2.9665E−4	5.28085E−4	−0.4985	0.39499	0.16412	0.02382	−0.97154	0.23501	0.09522	0.01264	−1.25716	0.53677	0.17794	0.02038
60°	0.02054	0.00228	−0.44746	0.45701	0.17598	0.02436	−0.98255	0.24529	0.09365	0.01197	−1.31179	0.50989	0.16692	0.01892
66°	0.05479	0.00519	−0.32522	0.56849	0.19815	0.02562	−0.95841	0.27948	0.09613	0.01147	−1.35009	0.49247	0.15629	0.01733
72°	0.11255	0.00988	−0.05507	0.77192	0.23829	0.02794	−0.85884	0.35651	0.10481	0.01105	−1.34786	0.49174	0.14534	0.01529

models which have four basic components of dust-like, oceanic, water-soluble and soot (WCP55, 1983). The used-define aerosol model 1 is composed of 25% dust-like, 25% oceanic, 25% water-soluble and 25% soot; model 2 is composed of 45% dust-like, 15% oceanic, 15% water-soluble and 25% soot; model 3 is composed of 5% dust-like, 45% oceanic, 45% water-soluble and 5% soot; model 4 is composed of 35% dust-like, 35% oceanic, 15% water-soluble and 15% soot; model 5 is composed of 10% dust-like,10% oceanic, 40% water-soluble and 40% soot; and model 6 is composed of 10% dust-like, 10% oceanic, 10% water-soluble and 70% soot. These used-define aerosols have nonabsorbing and strongly absorbing models. Fig. 4 provides examples of errors $\Delta t^{(c)}(\lambda,\theta)$ (%) for the six used-define aerosol models, the MODIS channel centers at 466.3, 550, 647.5, 861.3, 1242.5, 1632.5, and 2120 nm, and for viewing angles $\theta = 1.5°–66°$. To see the variety of effects that aerosol models have on the computations, the results of $\Delta t^{(c)}(\lambda,\theta)$ in Fig. 4 for the six Used-define aerosol models are shown. The aerosol optical thickness $\tau_a(860) = 0.2$ was used in Fig. 4. Note that the Used-define model 3 has a strong spectral variation with optical thickness. The $\tau_a(\lambda)$ value at 466.3 nm is larger than 0.6 in both cases. Nevertheless, Fig. 4 shows that Eq. (9) is quite accurate in their computation of the atmospheric diffuse transmittance. Errors $\Delta t^{(c)}(\lambda,\theta)$ are usually within ~1% for most cases for $\theta \leq 60°–66°$ $\tau_a(\lambda) \leq 0.6°$.

We also tested the efficacy of Eq. (9) in the computation of the atmospheric diffuse transmittance for different aerosol vertical structure distributions for a strongly absorbing aerosol. We used the used-defined model 6 with 80% RH for the aerosol that is uniformly mixed with air molecules. This is an extreme case in which aerosol vertical distribution is completely different from a two-layer model. Fig. 5 presents the results $\Delta t^{(c)}(\lambda,\theta)$ of this computation for the used-define model six with aerosol optical thickness $\tau_a(860) = 0.2$, viewing angles 1.5°, 24°, 36°, 48°, and 66°, and at the seven MODIS central wavelengths. When the figure was generated, the true values of the diffuse transmittance $t^{(m)}(\lambda,\theta)$ were obtained using the reciprocity principle by solving the radiative transfer equation for a one-layer atmosphere in which aerosols and air molecules were uniformly mixed, bounded by a rough ocean surface and the wind speed is 6 m/s. The $\Delta t^{(c)}(\lambda,\theta)$ values were computed using Eq. (9), and the error was then calculated. The values of aerosol optical thicknesses $\tau_a(\lambda)$ vary from 0.2 at 550 nm to 0.56 at 466 nm. Fig. 5 shows that Eq. (9) works quite well for a completely different aerosol vertical structure. Errors are all within ~1%. The results show that the atmospheric diffuse transmittance is almost of the aerosol vertical structure distribution.

6. Conclusions

We have evaluated the accuracy of an analytical formula from Gordon et al. (1983) by computing the atmospheric diffuse transmittance for wavelengths from center of MODIS band 1 to MODIS band 7 for both a pure Rayleigh and a two-layer Rayleigh-aerosol atmosphere bounded by a rough ocean surface. It was found that the analytical equation is reasonably accurate for nonabsorbing and weakly absorbing aerosols and for not too large aerosol optical thickness ($\tau_a \leq 0.4$) for viewing angles of $\theta \leq 40°$. The computational errors in the atmospheric diffuse transmittance by use of the analytic formula were usually within 2–3% for these cases. To improve the accuracy of computing the atmospheric diffuse transmittance, we modified the analytical formula using the numerical fitting. The modified formula in computing atmospheric transmittance has been tested extensively with various aerosol models, aerosol optical thicknesses, viewing geometries, different aerosol vertical structure distributions, and at wavelengths from center of MODIS band 1 to MODIS band 7. Results show that the modified formula can usually calculate the atmospheric diffuse transmittance to within an accuracy of ~1% for $\tau_a \leq 0.6$ and $\theta \leq 60°$. In most cases, the predicted values are within an accuracy of 0.6%.

Appendix A

The process of deriving the coefficients in Table 2 using Eq. (11). Let us use an example to detail the process. To be brief, we only use a aerosol model (Urban aerosol model) and an aerosol optical thickness. In the urban aerosol model, the single-scattering albedo is 0.8686, 0.8684, 0.8666, 0.8658, 0.8658, 0.8722, and 0.8654, the aerosol optical thickness is 0.740, 0.050, 0.040, 0.327, 0.196, 0.1319, and 0.084, at the 466.3, 550, 647.5, 861.3, 1242.5, 1632.5, and 2120 nm, respectively. According to the Urban scattering phase function and Eq. (8), we can compute $\boldsymbol{F}_a(\boldsymbol{\lambda})$; the values are 0.6548, 0.6460, 0.6382, 0.5881, 0.4989, 0.4340, and 0.3552, at 466.3, 550, 647.5, 861.3, 1242.5, 1632.5, and 2120 nm, respectively.

First, we can obtain the value of diffuse transmittance at each angle from 1.5° to 72° by 6° at different wavelengths through the reciprocity principle (Yang and Gordon, 1997) by solving the radiative transfer equation for two-layer Rayleigh-aerosol atmosphere bounded by a rough ocean surface (Cox and Munk, 1954). In solving the RTE, we selected the surface wind of 6.0 m/s. Second, we use these above values and Eqs. (5) and (9) to obtain the value of parameter $\boldsymbol{C}_a(\boldsymbol{\lambda},\boldsymbol{\theta})$ at different angles and wavelengths. Table 3 provides parameters $\boldsymbol{C}_a(\boldsymbol{\lambda},\boldsymbol{\theta})$ at these seven wavelengths and 11 angles in these conditions. The process has been described in Section 2. We can obtain seven tabulations as Table 3 just by changing the aerosol optical thickness from 0.05 to 0.6 at 550 nm, but the single-scattering albedo and the parameter $\boldsymbol{F}_a(\boldsymbol{\lambda})$ are not changed. For simplification, we did not provide the other six tables in the article. Using all the seven tables such as Table 3, the coefficients $\boldsymbol{b}_{ij}(\boldsymbol{\lambda})$ can be computed. The advantage of the process is that we can compute the coefficients $\boldsymbol{b}_i(\boldsymbol{\lambda},\boldsymbol{\theta})$ ($\boldsymbol{i}=1,4$. such as Table 4) with a polynomial fit to Eq. (10) and the seven tables of data, and then we use Table 4 to compute the coefficients $\boldsymbol{b}_{ij}(\boldsymbol{\lambda})$ (such as the Table 2) with the polynomial fit to Eq. (11).

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