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Key Points:

- Aerosols in China are heavy and absorbing
- Strong absorbing aerosols affect retrieval of cloud properties
- The effects have opposite biases from satellite and surface

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Opposite effects of absorbing aerosols on the retrievals of cloud optical depth from spaceborne and ground-based measurements

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Abstract Absorbing aerosols above or within cloud layers have drawn much attention in recent years due to substantially enhanced absorption of solar radiation that may affect reflection at the top of the atmosphere. The retrieval of cloud properties is usually conducted without any regard to aerosols. This study illustrates that retrievals of cloud optical depth (τ_c) from spaceborne and ground-based sensors are both affected by such aerosols and lead to opposite biases. A ground-based retrieval algorithm is developed for the simultaneous retrieval of τ_c and cloud droplet effective radius using spectral irradiance measurements from a multifilter rotating spectroradiometer and liquid water path (LWP) data from a microwave radiometer deployed in China. The algorithm is applied to data acquired from 17 May 2008 to 12 May 2009 at a heavily polluted site in the heart of the Yangtze delta region in China. The ground-based retrieval of cloud droplet effective radius increases with increasing LWP. Moderate Resolution Imaging Spectroradiometer retrievals tend to overestimate (underestimate) LWP when cloud LWP is less (greater) than about 200 g/m^2. Model tests show strong sensitivities to the retrieval of τ_c from ground and spaceborne sensors under varying absorption, loading, and vertical distribution conditions. For absorbing aerosol mixed with cloud, τ_c tends to be underestimated from space, but overestimated from the ground, leading to very poor agreement between ground-based and Moderate Resolution Imaging Spectroradiometer retrievals. Their differences increase with increasing τ_c. This finding suggests that in a turbid atmosphere with absorbing aerosols, the aerosol effect should be considered, or it would mislead any validation using satellite and ground-based retrievals.

1. Introduction

To improve cloud parameterization schemes, a better knowledge of temporal and spatial variations of cloud properties is needed. Cloud optical thickness (τ_c), the effective radius of cloud droplets (r_e), and liquid water path (LWP) are the most important parameters for warm clouds. In recent decades, many efforts have been devoted to retrieving these parameters from satellite measurements [e.g., *King et al.*, 1992; *Han et al.*, 1994; *Nakajima and Nakajima*, 1995; *Chang and Li*, 2002, 2003; *Zhao et al.*, 2002; *Platnick et al.*, 2003]. To validate satellite remote sensing, several studies have compared satellite retrievals with in situ measurements made from aircraft [e.g., *Platnick and Valero*, 1995; *Dong et al.*, 2002]. However, there are few such airborne data sets available to evaluate satellite remote sensing algorithms. Errors in satellite-retrieved τ_c, r_e, and LWP arise from several sources, such as instrument calibration, uncertainties in water vapor concentration, the presence of undetected thin cirrus, and the assumption of plane-parallel clouds. Because clouds are highly variable, satellite retrievals must be validated for different cloud types in different regions of the world. Aerosol absorption above a cloud layer can significantly affect the accuracy of satellite-retrieved τ_c and r_e [*Haywood et al.*, 2004; *Wilcox et al.*, 2009; *Coddington et al.*, 2010]. Methods have been proposed to detect such aerosol from satellite and to estimate changes in aerosol radiative forcing [*Chand et al.*, 2008, 2009; *Yu et al.*, 2012; *Yu and Zhang*, 2013]. It is worth noting that aerosol is most often found below or within clouds, especially low boundary layer clouds. Aerosol effects on the retrieval of low cloud parameters have been seldom studied.

In addition to satellite retrievals, surface observations of τ_c, r_e, and LWP are also very important not only for improving our understanding of cloud processes and for improving cloud parameterization schemes but also for validating satellite retrievals. Downwelling shortwave narrowband and broadband irradiances are useful for retrieving τ_c [*Francis et al.*, 1991; *Leontyeva et al.*, 1994; *Leontyeva and Stamnes*, 1994; *Dong et al.*, 1997; *Lubin and Simpson*, 1997; *Pinto et al.*, 1997; *Barker et al.*, 1998]. Among these, *Dong et al.* [1997] proposed a method to retrieve τ_c and r_e from LWP, cloud geometric thickness, and downwelling shortwave flux. Stratus cloud properties at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site were deduced and compared to those retrieved from satellite measurements [*Dong et al.*, 2002, 2008]. A good agreement between surface and Clouds and the Earth's Radiant Energy System/Moderate Resolution Imaging Spectroradiometer- (MODIS) retrieved cloud properties was found. For a vegetated land surface, reflectances at wavelengths (λ) > 700 nm are much larger than those at λ < 700 nm. Based on this fact, *Marshak et al.* [2004] and *Chiu et al.* [2006] presented a method for deducing τ_c and effective cloud fraction from zenith radiances at 670 nm and 870 nm measured by a Cimel Sun photometer. *Chiu et al.* [2010] improved the method by using radiance observations at 440 nm instead of at 670 nm. They compared the Aerosol Robotic Network (AERONET) and MODIS-retrieved τ_c at the ARM SGP site and showed that large differences between the two retrievals for some Terra and Aqua overpass. The multifilter rotating shadowband radiometer (MFRSR) measures solar irradiances at six wavelengths (415, 500, 615, 670, 870, and 940 nm) simultaneously. *Min and Harrison* [1996] presented a method for the retrieval of τ_c and r_e from transmittances observed at 415 nm and LWP deduced from a microwave radiometer. They used the Langley method to calibrate the MFRSR. Retrieved τ_c at the ARM SGP site was compared to those deduced from the Geostationary Operational Environmental Satellites (GOES) measurements, and results showed that the ground-based and GOES retrievals of τ_c agreed well when τ_c < 10, but differed more when clouds were thicker. *Liu et al.* [2013] retrieved cloud parameters following a similar method applied to data acquired by a large suite of instruments consisting the ARM Mobile Facility that was deployed in China in 2008. They found generally larger disagreements with satellite retrievals than the previous studies.

The degradation in agreement likely stems from the influence of absorbing aerosols, which can also impinge on the retrieval of cloud properties. To the knowledge of the authors, the impact of aerosols on the comparison of cloud retrievals from ground-based and spaceborne sensors has not been explored. Previous studies have inferred the impact from comparisons between airborne and spaceborne sensors [*Haywood et al.*, 2004] and between different types of spaceborne sensors [*Wilcox et al.*, 2009]. This issue must be dealt with, especially in many fast-developing regions such as China, where aerosol loading is heavy with high concentrations of soot associated with biomass burning and the burning of coal [e.g., *Li et al.*, 2007, 2011; *Lee et al.*, 2007].

Surface-measured and MODIS-retrieved cloud properties over a heavily polluted site in southeast China near Shanghai are compared. An iterative algorithm is developed to retrieve τ_c and r_e from downwelling radiative fluxes at 415 nm measured by a MFRSR and LWP derived from a multichannel microwave radiometer profiler (MWRP). The MFRSR is carefully calibrated by matching direct solar irradiances measured simultaneously by the MFRSR and a CE-318 Sun photometer calibrated by the AERONET group. The differences between MODIS cloud products (MOD06) and our retrievals are presented and discussed. The effect of aerosols on both surface and satellite retrievals will be stressed.

The following section describes the instruments and data used. A description of retrieval algorithms applied to the data is given in section 3. Error analysis of the retrievals is presented in section 4. Section 5 compares the retrieval results and explains their discrepancies. The study is summarized in section 6.

2. Observational Data and Instrument Calibration

Data used in this study were acquired during the East Asian Studies of Tropospheric Aerosols and Their Impact on Regional Climate field experiment [*Li et al.*, 2011]. The experiment was conducted at multiple locations in China, and the measurements were made by an extensive set of instruments provided by the Department of Energy's Atmospheric Radiation Measurement Mobile Facility and participating Chinese institutions.

This study makes use of data collected at the Taihu Lake ecosystem research station (31.421°N, 120.215°E). Instruments include a MFRSR, a MWRP, a Sunphotometer, a micropulse lidar, and pyranometers/pyrheliometers. The sampling frequency of the MFRSR and the MWR is 0.017 Hz. Data used in this study were collected from 17 May 2008 to 12 May 2009.

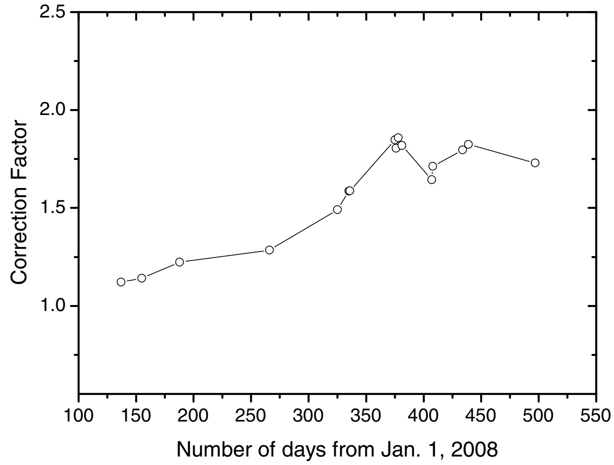

Figure 1. Time series of the correction factor.

The station is located in the heart of the Yangtze delta region and is surrounded by three megacities: Shanghai (150 km to the east of the station), Nanjing (200 km to the west of the station), and Hangzhou (150 km to the south of the station). As a result, aerosol loading is very high in this region; the annual average aerosol optical thickness (τ_a) at the site was 0.87 ± 0.54 [*Lee et al.*, 2010]. Air quality in the region is susceptible to intensive industrial activities (the region contains one of the most dense concentrations of factories in the world), coal-based power plants, vehicle exhaust, and mineral dust transported from remote desert regions in the spring season [*Liu et al.*, 2011]. The region is also occasionally blanketed with thick layers of biomass-burning aerosols presumably from the local burning of agriculture waste [*Fan et al.*, 2010]. MFRSR instrument calibration is essential to obtain accurate retrievals of cloud properties. *Min and Harrison* [1996] used the traditional Langley method to calibrate their MFRSR, which is an approach widely used in observations of direct solar radiation [*Shaw et al.*, 1973; *Shaw*, 1976; *Harrison and Michalsky*, 1994; *Michalsky et al.*, 2001; *Augustine et al.*, 2003]. The Langley method is limited to cases when the atmosphere is very clear and stable. At Taihu, such atmospheric conditions are seldom met. *Alexandrov et al.* [2002] proposed a method using direct-to-diffuse ratios to correct the daily variation in aerosol optical depth. *Lee et al.* [2010] modified the Langley method so that the highest irradiance value at a given air mass during a given period is used. The MFRSR at Taihu is calibrated by comparing MFRSR-measured direct irradiances to those that are used to generate AERONET aerosol products, which are based on data from a frequently calibrated Sun photometer.

The measurements at 415 nm are used to derive τ_c. The τ_a at 415 nm is obtained from those at 380, 440, 500, and 670 nm using a spline interpolation algorithm. The MFRSR-measured direct irradiances at 415 nm are averaged over 12 min, centered at the AERONET sampling time. The calibrated irradiance can be written as

$$I_{415} \quad = \quad C I^0_{417}, \tag{1}$$

where I^0_{415} is the direct solar irradiance measured during the original calibration. I_{415} can be calculated from AERONET-derived τ_a, as described above. The correction factor, C, is calculated by taking the ratio of I_{415} to I^0_{415}. Figure 1 shows how C increases dramatically during 2008 then stabilizes from February 2009 onward. The increase happened because the optical inlet of the MFRSR was soiled from aerosol particle deposition. The value of C on any given day during the data sampling period is obtained by interpolation.

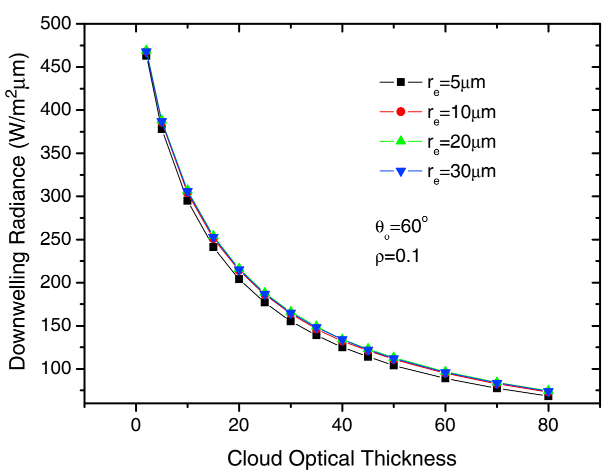

Figure 2. Downwelling surface radiative fluxes at 415 nm as a function of τ_c for different r_e.

3. Retrieval Algorithm

To gain insight into the sensitivity of downwelling shortwave fluxes at 415 nm to changes in τ_c and r_e, radiative transfer calculations were performed using the code described by *Zhao and Li* [2007] and developed originally by *Nakajima and Tanaka* [1988]. Figure 2 shows simulated downwelling solar fluxes at 415 nm as a function of τ_c for different r_e. In the calculation, the solar zenith angle is 60° and the

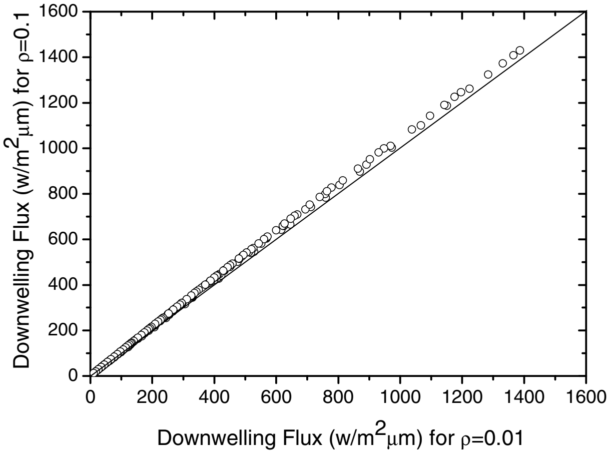

Figure 3. Downwelling surface radiative fluxes at 415 nm when $\rho = 0.1$ as a function of downwelling surface radiative fluxes at 415 nm and when $\rho = 0.01$ for varying cloud optical depth.

surface albedo (ρ) is 0.1. Downwelling surface radiative fluxes decrease with increasing τ_c, suggesting that τ_c can be derived from downwelling flux measurements. When r_e is larger than 10 μm, changes in r_e have little effect on downwelling radiative fluxes. However, when r_e is less than 10 μm, changes in r_e can significantly affect downwelling radiative fluxes. For example, as r_e changes from 5 μm to 10 μm, the downwelling radiative flux increases from about 1% (at $\tau_c = 2$) to 7% (at $\tau_c = 80$), which, in turn, can cause errors of about 0.2 to 6 in the retrieved τ_c. So to get an accurate retrieval of τ_c, r_e must be retrieved simultaneously. An iterative algorithm for the simultaneous retrieval of τ_c and r_e based on downwelling radiative fluxes at 415 nm, and LWP has been developed.

The cloud droplet size distribution used in the algorithm is lognormal:

$$n(r) = \frac{N}{\sqrt{2\pi}\sigma r} \exp^{-\frac{(1n(r) - 1n(r_o))^2}{2\sigma^2}}, \tag{2}$$

where r is the droplet radius, $n(r)$ is the number of droplets with radii between (r, $r + dr$) per unit volume, N is the number of droplets per unit volume, and r_o is the mode radius. The r_e and mode radius for a lognormal distribution are related in the following way:

$$r_e = r_0 e^{\frac{5}{2}\sigma^2}. \tag{3}$$

In this study, the value of σ is 0.39 [*Frisch et al.*, 1995; *Dong et al.*, 1997].

The parameters τ_c and r_e can be obtained by minimizing the difference, δ, between measured and calculated downwelling radiative fluxes at 415 nm, i.e.,

$$\delta = ABS(F^m - F^c(r_e, \tau_c, \theta_0, \rho, \tau_a, \varpi_\alpha)), \tag{4}$$

$$\mathrm{LWD} = \frac{2}{3}\tau_c \times r_e, \tag{5}$$

where F^m and $F^c(r_e,\tau_c,\theta_0,\rho,\tau_a,\omega_a)$ represent measured and calculated downwelling radiative fluxes, respectively, θ_0 is the solar zenith angle, $\rho = 0.05$, and ω_a is the aerosol single scattering albedo. This value of ρ is close to the annual mean albedo (0.054) at Taihu, based upon the MODIS retrievals. Equation (5) is derived under the assumption that liquid water content is a constant vertically [*Stephens*, 1978]. The Golden section search method [*Curtis and Wheatley*, 2004] is used to minimize δ.

4. Error Analysis

Errors in τ_c and r_e retrieved using the algorithm described above arise from uncertainties in surface albedo and aerosol properties, errors in MWR-derived LWP and MFRSR-derived τ_c, and the assumption that the cloud layer is horizontally homogenous. Figure 3 shows downwelling radiative fluxes at 415 nm when $\rho = 0.1$ as a function of downwelling radiative fluxes at 415 nm and when $\rho = 0.01$ for varying cloud thickness. Downwelling radiative fluxes can increase by about 3.9% when ρ changes from 0.01 to 0.1, so a suitable value for ρ must be selected to obtain an accurate retrieval of cloud properties. The values of ρ in the algorithm are obtained from the MODIS bidirectional reflectance distribution function /albedo (MOD43B) products. *Wang et al.* [2010] illustrated that the accuracy of ρ derived from MODIS measurements is about 0.015. This guarantees that retrieval errors resulting from the effect of ρ are not significant. A 5% uncertainty in radiance measurements by MFRSR leads to a 5–10% error in τ_c retrievals [*Liu et al.*, 2013].

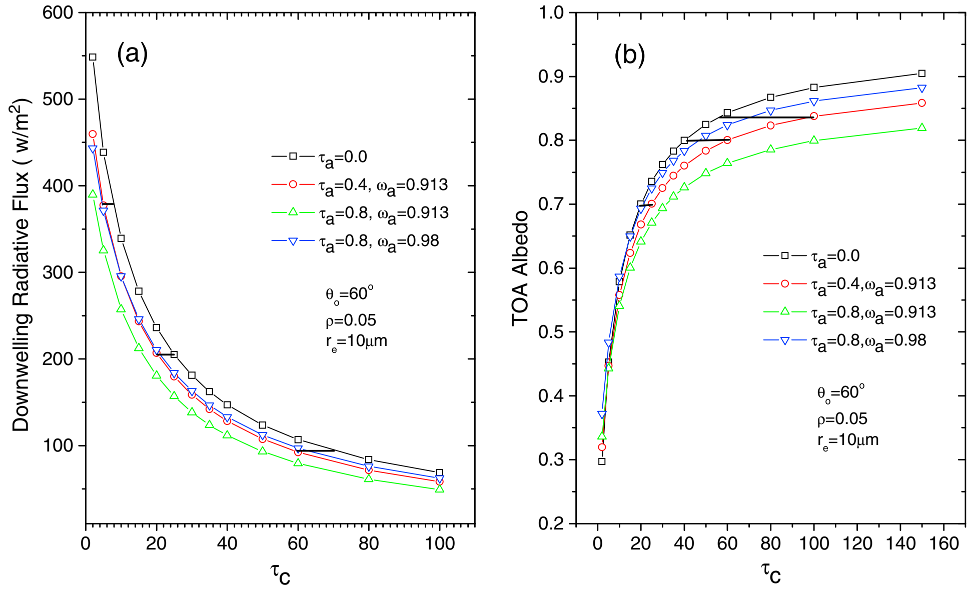

Figure 4. (a) Downwelling surface radiative fluxes at 415 nm and (b) TOA albedo as functions of τ_c for different combinations of τ_a (0.0, 0.4, and 0.8) and ω_a (0.913 and 0.98).

The effect of aerosols on downwelling radiative fluxes at the surface for different combinations of τ_a and ω_a is shown in Figure 4a. The curves for no aerosol ($\tau_a = 0$) and absorbing aerosols are different. Downwelling surface radiative fluxes decrease with increasing τ_a for absorbing aerosols. When $\omega_a = 0.913$, a representative value for the Taihu station [*Lee et al*., 2007], and τ_a increases from 0.0 to 0.4, downwelling surface radiative fluxes decrease by about 12–14%. If τ_a in an actual atmosphere is 0.4 and the effect of aerosols is not considered in cloud property retrievals, errors in retrieved τ_c are about 2.3 for $\tau_c = 2$ and about 18 for $\tau_c = 80$. Errors (horizontal lines in the figure) increase with increasing τ_c. Errors resulting from the aerosol effect increase with increasing aerosol loading. From Figure 4a, if τ_a in an actual atmosphere is 0.8, downwelling surface radiative fluxes decrease by about 23–29%. Such differences in radiative fluxes can result in serious overestimations in the retrievals of τ_c. Changes in ω_a will also result in changes in downwelling surface radiative fluxes. For example, for $\tau_a = 0.8$, increasing ω_a from 0.913 to 0.98 can result in significant increases in downwelling surface radiative fluxes. The magnitudes of downwelling surface radiative fluxes calculated with $\tau_a = 0.8$ and $\omega_a = 0.98$ are comparable to that calculated with $\tau_a = 0.4$ and $\omega_a = 0.913$.

A similar impact is expected on reflected fluxes inferred from satellite measurements. Figure 4b shows the albedo at the top of the atmosphere (TOA) as a function of τ_c for the same combinations of τ_a and ω_a as in Figure 4a. The TOA albedo is defined as the ratio of outgoing to incoming solar radiative fluxes, representing reflectances averaged over all viewing directions. At a fixed τ_c, the TOA albedo changes with varying aerosol properties. This clearly illustrates that uncertainties in aerosol properties can influence τ_c retrieved from satellite measurements. For moderately absorbing aerosols ($\omega_a = 0.913$), the aerosol effect increases with increasing τ_a. For thicker clouds, aerosols can significantly decrease the TOA albedo in overcast cases, therefore leading to underestimations of τ_c. Horizontal lines shown in Figure 4b denote the retrieval errors. For $\tau_c = 5$, an increase in τ_a from 0 to 0.4 results in a change in TOA albedo of about -0.0057, which, in turn, causes a τ_c retrieval error of about -0.1. For the same moderately absorbing aerosols when $\tau_a = 0.8$, which is close to the mean value at Taihu, neglecting the aerosol effect can result in an error of -60 in retrieved τ_c for $\tau_c = 100$. This is consistent with the analysis of aircraft measurements done by *Haywood et al*. [2004] and with the comparisons made between MODIS and Advanced Microwave Scanning Radiometer–Earth Observing System LWP retrievals over biomass burning regions by *Wilcox et al*. [2009]. As ω_a increases, the retrieval error decreases. For $\omega_a = 0.98$, the retrieval errors are smaller than those for $\tau_a = 0.4$ and $\omega_a = 0.913$.

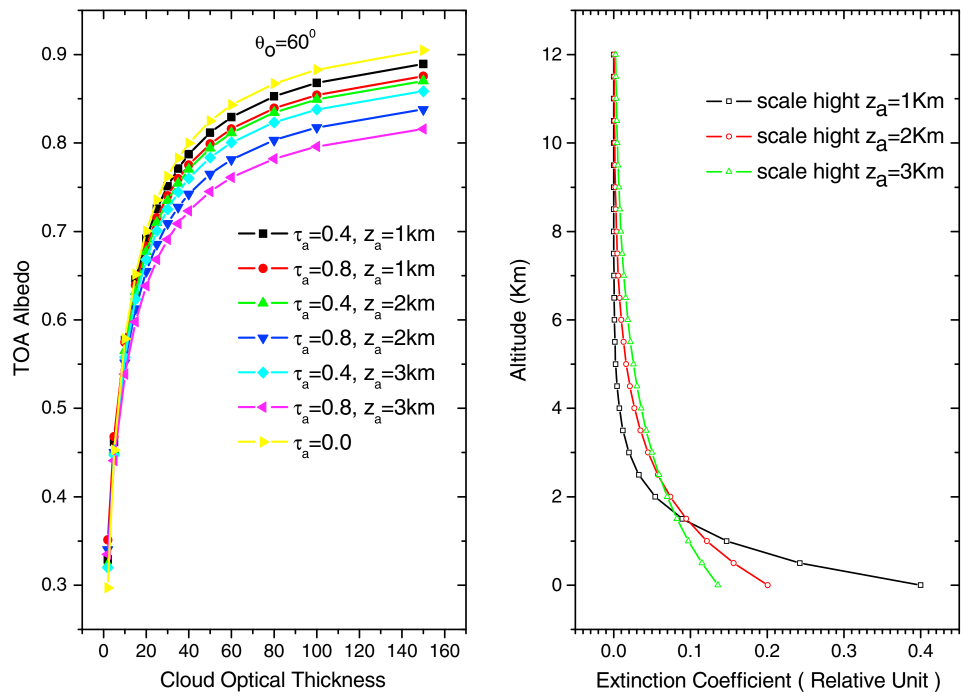

Figure 5. (a) TOA albedo as a function of τ_c for different combinations of τ_a and (b) aerosol vertical profiles (at different scale heights, z_a). In the calculation, the aerosol single scattering albedo is fixed at 0.913.

Such errors depend on the distribution of aerosols relative to a cloud layer. Figure 5a shows TOA albedo as a function of τ_c for different combinations of τ_a and aerosol vertical profiles, and Figure 5b shows aerosol vertical profiles for the three scale heights (z_a). Aerosols can significantly decrease TOA albedo. The impact of aerosols on TOA albedo becomes stronger with increasing τ_a and z_a.

The effect of aerosols on the retrieval of τ_c from satellite measurements is opposite to that from surface measurements. In a turbid atmosphere, neglecting aerosol effects results in large differences between the two retrievals. This is illustrated in Figure 6, which shows the results from radiative transfer simulations, $\omega_a = 0.913$ in the calculations. The diagonal line shown in the figure represents cases where the aerosol effect is taken into consideration in the retrievals. Red ($\tau_a = 0.4$) and black ($\tau_a = 0.8$) curves show simulated retrievals without considering the aerosol effect. The surface-retrieved τ_c is systematically larger than that retrieved from satellite measurements. The difference between the surface and satellite retrievals increases with increasing τ_c.

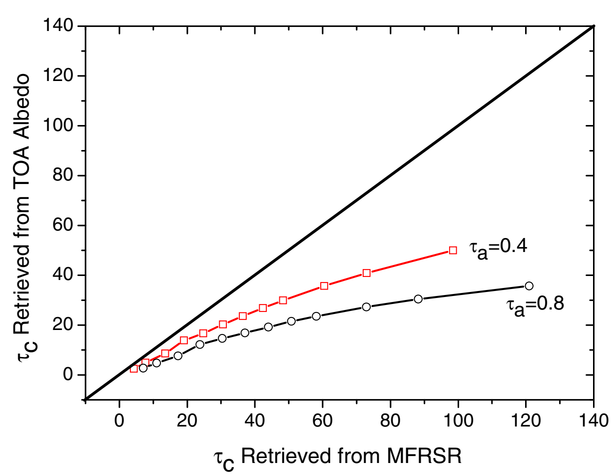

Figure 6. Comparison between simulated surface and satellite retrievals where ω_a is 0.913, $\theta_0 = 60°$, $\rho = 0.05$, and $r_e = 10\ \mu$m. The diagonal line represents retrievals taking into account the aerosol effect. Red ($\tau_a = 0.4$) and black ($\tau_a = 0.8$) curves show simulations that ignore the aerosol effect.

These modeling-based findings suggest that the aerosol effect must be considered in cloud retrievals in a turbid atmosphere containing a significant fraction of soot. *Lee et al.* [2010] showed that under clear-sky conditions, the annual mean τ_a at Taihu is 0.87 ± 0.54. Aerosol loading may be lower under overcast conditions because some aerosol particles can act as cloud condensation nuclei and be mixed internally with liquid water. In light of this, τ_a and ω_a were set to 0.4 and 0.913, respectively

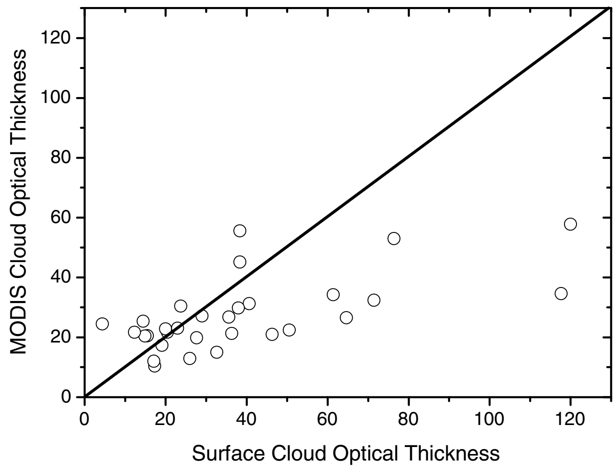

Figure 7. MODIS-retrieved τ_c as a function of surface-retrieved τ_c.

(half the clear-sky value). Note that these are ad hoc values, due to a lack of observations under cloudy conditions.

Errors in LWP derived from a MWR depend mainly on the accuracy of instrument measurements and the retrieval algorithm. Several studies concerning the accuracy of LWP retrievals have been carried out [e.g., *Gaussiat et al.*, 2007; *Wang*, 2007; *Marchand et al.*, 2003; *Dong et al.*, 1997; *Liljegren et al.*, 2001]. Among these, *Dong et al.* [1997] and *Liljegren et al.* [2001] have shown that errors in LWP derived from MWR measurements are about 20 g/m^2 when LWP $<$ 200 g/m^2 and 10% when LWP $>$ 200 g/m^2. Because τ_c is derived mainly from measurements of downwelling surface radiative flux, the uncertainties in LWP have negligible effects on the τ_c retrieval. The uncertainties in LWP can affect retrievals of r_e. As per equation (5), the error in ground-based retrieval of r_e depends on the combination of LWP and τ_c and their retrieval errors that are further linked to aerosol absorbing properties.

The plane-parallel assumption in radiative transfer calculations can also incur errors in the retrievals of τ_c and r_e. These errors depend on cloud geometry (i.e., roughness), cloud microphysical structure, and Sun-Earth-satellite viewing geometries. The three-dimensional (3-D) effect on downwelling and upwelling fluxes is not just random but systematically biased, which has been demonstrated via Monte Carlo simulations [*Barker and Li*, 1997]. *Boers et al.* [2000] and *Rozwadowska* [2004] analyzed 3-D radiative effects on τ_c deduced from surface pyranometer measurements. Ignorance of cloud inhomogeneity generally leads to underestimation of τ_c. *Boers et al.* [2000], for example, found that a mean bias of -1 was induced by 3-D radiative effects even for overcast but not homogeneous clouds. *Rozwadowska* [2004] showed that the plane-parallel assumption also resulted in negative errors in retrieved τ_c; the maximum error in that study reached -20%.

5. Comparison Between Surface and MODIS-Retrieved Cloud Properties

To put the above theories and/or postulations to test, cloud parameters retrieved from surface and satellite measurements were compared. To this end, MODIS data were matched with ground data in terms of temporal and spatial domains. Cloud quantities inferred from surface measurements were averaged within +/$-$30 min of the satellite overpass time. Those from the MOD06 products were averaged over a 30 km × 30 km area centered on Taihu. Only water clouds under overcast conditions with LWP $<$ 700 g/m^2 were selected for the comparison, based on the MODIS cloud cover and thermodynamic phase products. The constraint in the magnitude of LWP was imposed to avoid the effects of precipitation on the cloud property retrieval.

Figure 7 shows the comparison between MODIS and surface retrieved τ ($\tau_{c,modis}$ and $\tau_{c,surf}$). The linear correlation coefficient is equal to 0.67. For $\tau_{c,surf}$ less than about 20, $\tau_{c,surf}$ and $\tau_{c,modis}$ are comparable; $\tau_{c,modis}$ is systematically less than $\tau_{c,surf}$ for $\tau_{c,surf} > 20$. The difference between $\tau_{c,surf}$ and $\tau_{c,modis}$ increases with increasing τ_c. Surface-based and MODIS retrievals may be influenced by 3-D radiative effects on cloud reflectance and transmittance. However, 3-D effects may not explain the trend seen in differences between $\tau_{c,surf}$ and $\tau_{c,modis}$ because (1) these effects can result in simultaneous decreases or increases in surface and satellite-retrieved τ_c and (2) the average horizontal scale for surface retrievals is much larger than that for MODIS retrievals and thus is less susceptible to the 3-D effect.

In the previous section, it is noted that absorbing aerosols could seriously affect cloud retrievals from both surface and satellite measurements. Figure 8 shows simulated surface and satellite-retrieved τ_c ($\tau_a = 0.4$ in both simulations), where the aerosol effect is included in the surface retrieval, but not in the retrieval from satellite measurements. Although the magnitudes of the differences are not exactly the

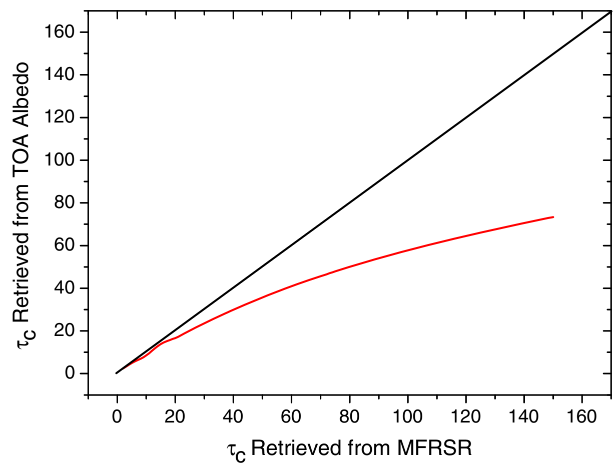

Figure 8. As in Figure 6, but for simulations with $\tau_a = 0.4$ and where the aerosol effect is included in the surface retrieval (red line).

same, the pattern is similar to that seen in Figure 6. This close resemblance suggests that the aerosol effect is the primary reason for the bias between $\tau_{c,surf}$ and $\tau_{c,modis}$.

In addition to the artifact caused by absorbing aerosols, MODIS retrievals are also subject to some inherent errors, as analyzed in detail by *King et al*. [1997, 2004] and *Platnick et al*. [2003]. Retrieval errors may arise from uncertainties in instrument calibration, surface albedo, atmospheric correction, and the plane-parallel cloud assumption. However, these types of errors do not necessarily lead to the systematic bias (relative to surface retrievals) in τ_c as shown in Figure 6.

Figure 9 shows the MODIS-retrieved LWP as a function of surface-based LWP retrievals. As previously stated, errors in LWP derived from MWR measurements are about 20 g/m^2 for LWP $<$ 200 g/m^2 and 10% for LWP $>$ 200 g/m^2. Satellite retrievals of LWP are significantly larger than surface LWP retrievals below 200 g/m^2, but are smaller for larger LWP. Errors in the MODIS LWP could result from biases in the retrievals of τ_c and r_e according to equation (5). As the negative biases in τ_c increase with the magnitude of τ_c, the MODIS LWP is more likely to be underestimated for thicker clouds than for thinner clouds due to the effect of absorbing aerosols alone, whereas LWP may be systematically overestimated by a likely positive bias in r_e stemming from its vertical variation. Overall, the mean values of LWP from MODIS and ground retrievals are 184.99 and 168.56 g/m^2, respectively. The mean difference is 16.43, and the standard deviation is 152.8 g/m^2. The positive bias in the MODIS-based retrieval is at odds with its negative bias in τ_c, which may be explained by an opposite bias in the retrieval of cloud particle size.

Note that satellite retrievals of r_e are representative of values near cloud tops only [*Chang and Li*, 2002, 2003]. For the majority of nonprecipitating clouds, cloud particle size increases with height due to condensational growth [*Miles et al*., 2000; *Chen et al*., 2007, 2008]. As such, the retrieved r_e tends to be larger than the mean cloud layer r_e. Precipitating clouds are excluded in this study because MWR retrievals of LWP are not reliable under rainy conditions. The combined effects of the predominant positive bias of r_e and the changing negative bias of τ_c (larger for thicker clouds) from MODIS retrievals appear to agree qualitatively with the comparison of r_e from MODIS and from ground sensors for different LWP, as shown in Figure 10. MODIS-retrieved r_e is larger (smaller) than ground-based r_e for small (large) LWP. Surface-retrieved r_e increases with increasing LWP, which holds in the case of nonprecipitating clouds. For LWP less than about 200 g/m^2, MODIS-retrieved r_e is considerably larger than surface retrievals of r_e, but the difference decreases as LWP increases. Other causes may also help explain this. For example, the reflectance at 2.13 μm may be underestimated due to a cloud 3-D effect. The cloud shadow effect can result in a decrease in cloud reflectance and an overestimation in r_e [e.g., *Davis and Marshak*, 2010]. However, it is beyond the scope of this study to either prove or disprove this supposition.

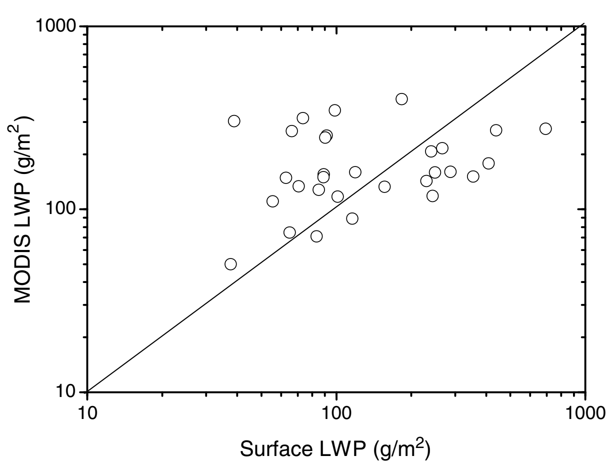

Figure 9. MODIS retrievals of LWP as a function of surface retrievals of LWP.

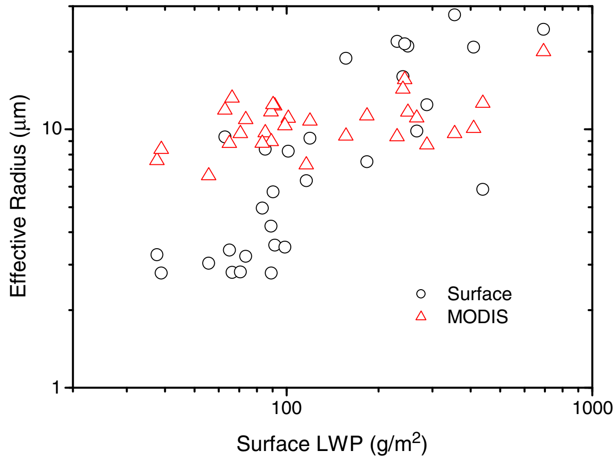

Figure 10. Scatterplot of r_e as a function of LWP retrieved from the surface. Circles represent surface retrievals of r_e, and triangles represent MODIS retrievals of r_e.

6. Summary and Conclusions

Surface-based and satellite remote sensing techniques have proven indispensable for gaining knowledge about cloud temporal and spatial variations. Comparisons between cloud properties retrieved from surface-based and spaceborne observations have been widely pursued as a means of validating satellite retrievals. It is essential to understand and reconcile any systematic differences before we attribute any discrepancies to satellite retrieval errors. Indeed, both retrievals suffer from retrieval uncertainties, although the latter was often treated as the "ground-truth" with respect to satellite retrievals. This study identifies a common cause of the retrieval errors in a set of cloud parameters in a heavily polluted region in China whose effect is opposite to the retrievals of cloud optical depth (τ_c) from ground and satellite, leading to exceptionally large discrepancies in τ_c. The common cause is heavy loading of strongly absorbing aerosols endemic to the region.

An iterative algorithm for the simultaneous retrieval of τ_c and r_e was first developed, which combines MFRSR-measured downwelling radiative fluxes and LWP retrievals from a MWR. The algorithm was then applied to the data collected from 17 May 2008 to 12 May 2009 at the Taihu Lake station located in the center of the Yangtze delta region. Aerosol optical depth (AOD) is exceptionally high and single scattering albedo is moderately low over the site. Comparisons between surface-retrieved and satellite-retrieved cloud properties were performed. The impacts of aerosols on both surface and satellite retrievals were analyzed in detail, which lead to the following conclusions.

The effect of absorbing aerosols on downwelling surface solar fluxes at 415 nm can result in significant errors in the retrieved τ_c. These errors increase with increasing τ_c and AOD in a turbid atmosphere containing absorbing aerosols. These aerosols also have a significant impact on the TOA albedo and thus lead to serious errors in the retrieved τ_c from satellite as well. Both errors increase with τ_c in opposite directions: positive biases for surface retrievals and negative biases for satellite retrievals. The simulation-based finding agrees with the observation-based finding that MODIS τ_c retrievals are systematically less than surface τ_c retrievals and that their differences increase with increasing τ_c. MODIS retrievals of r_e are larger (smaller) than ground retrievals for low (high) LWP. Overall, satellite retrievals show significantly less variability than ground-based retrievals. Such systematic discrepancies were attributed to two factors. Satellite retrievals represent cloud top values that are larger than cloud layer mean values, while τ_c from MODIS is underestimated due to absorbing aerosols. Another likely reason is the cloud shadow effect, which can result in a decrease in cloud reflectance and an overestimation of r_e. Biases in the retrieval of τ_c and r_e lead to biases in LWP. For LWP less than about 200 g/m^2, MODIS systematically overestimates LWP relative to ground-based MWR retrievals.

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