Regional comparison and assimilation of GOCART and MODIS aerosol optical depth across the eastern U.S.

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[1] This study compares aerosol optical depths (AOD) products from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model and their integrated products with ground measurements across the eastern U.S. from March 1, 2000 to December 31, 2001. The Terra MODIS Level-3 (collection 4) AOD at 0.55 μm has better correlation, but consistently overestimates the values of the Aerosol Robotic Network (AERONET) measurements. GOCART has small biases for a 22-month integration, and slight positive biases appeared for the cold season. These results are also supported by the comparison with the IMPROVE (Interagency Monitoring of Protected Visual Environments) light extinction index. The optimal interpolation improves the daily-scale RMSE from either MODIS or GOCART alone. However, the regional biases in the aerosol products constitute a major constraint to the optimal estimate of AOD. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 1640 Global Change: Remote sensing; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 5704 Planetology: Fluid Planets: Atmospheres—composition and chemistry. **Citation:** Matsui, T., S. M. Kreidenweis, R. A. Pielke Sr., B. Schichtel, H. Yu, M. Chin, D. A. Chu, and D. Niyogi (2004), Regional comparison and assimilation of GOCART and MODIS aerosol optical depth across the eastern U.S., *Geophys. Res. Lett.*, *31*, L21101, doi:10.1029/2004GL021017.

1. Introduction

[2] Recent developments of satellite remote sensing and chemical-transport models improve the characterization of regional/global distributions of aerosol concentrations [*Kaufman et al.*, 1997; *Chin et al.*, 2002]. Assimilation technique is also developed to maximize the utility of the existing aerosol products [*Yu et al.*, 2003]. These developments have significantly improved our understanding of the global aerosol radiative forcing.

[3] This work compares the AOD from current versions of the Terra Moderate-Resolution Imaging Spectroradiometer (MODIS) retrievals, the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model, and the MODIS-GOCART assimilated products across the eastern U.S. This region features high concentrations of anthropogenic hygroscopic aerosols accompanied by high relative humidity (RH) [*Malm et al.*, 2004], the existence of an extensive ground-based aerosol monitoring network [*Malm et al.*, 2004; *Holben et al.*, 1998], and the reported positive bias of the MODIS AOD during the ACE-Asia field experiment in April 2001 (M. Chin et al., Aerosol distribution in the Northern Hemisphere during ACE-Asia: Results from global model, satellite observations, and Sun photometer measurements, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as Chin et al., submitted manuscript, 2004). Therefore, the regional intercomparison is critical for further evaluation and improvement of existing products.

2. Data

2.1. Ground-Based Measurements

[4] The following ground-based *column AOD* and near-surface light extinction index (*Bext*) are used to evaluate the aerosol products in this study.

[5] Aerosol Robotic Network (AERONET) is the ground-based remotely sensed aerosol measurement network equipped with well-calibrated CIMEL Sun photometers [*Holben et al.*, 1998]. The 10 rural sites in the eastern U.S. (including Cartel, GSFC, Cove, Egbert, Chequamegon, Bondville, Walker Branch, Stennis, CART site, and Konza EDC) were carefully chosen to assure adequate data coverage and homogeneous spatial distribution. This study uses the Angstrom exponent coefficient derived from the *Level-2 quality assured daily mean* (*during daytime*) column AOD at 0.5 μm and 0.67 μm for deriving the AOD at 0.55 μm.

[6] The IMPROVE (Interagency Monitoring of Protected Visual Environments) monitoring network measures fine and coarse aerosols in mostly rural areas throughout the United States [*Malm et al.*, 2004]. The network collects *24-hour* PM2.5 and PM10 samples every third day. The PM2.5 samples are analyzed for mass, elemental composition, ions, and organic and elemental carbon, while the PM10 filters are analyzed for mass. The data are sufficient to reconstruct the major aerosol components ammonium sulfate and nitrate, organics, light absorbing carbon and soil, which account for most of the measure fine mass. A near-surface *Bext* (visible broad band) is also calculated from

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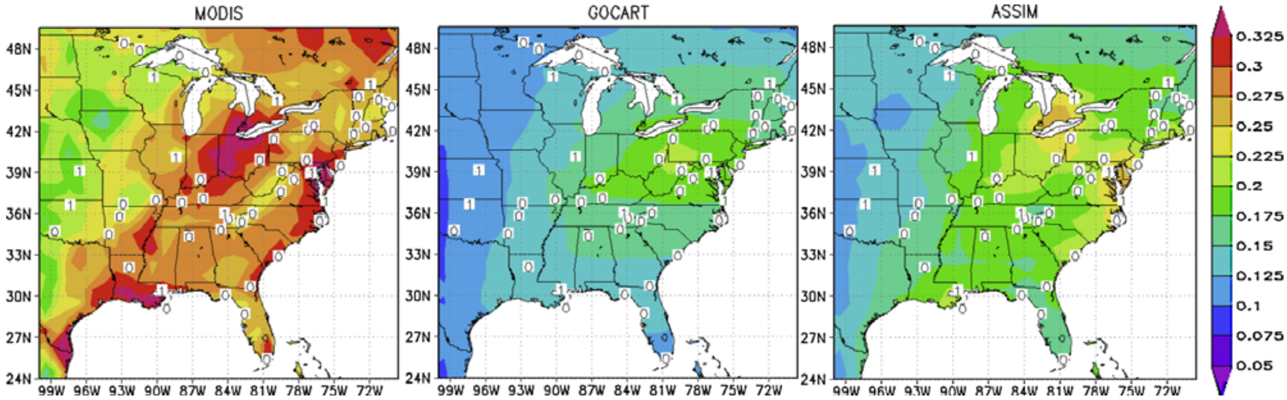

Figure 1. 22-month (Mar 1, 2000–Dec 31, 2001) averaged AOD at 0.55 μm from the MODIS retrievals, the GOCART simulation, and the MODIS-GOCART assimilation (ASSIM). AERONET and IMPROVE sites are represented as 1 and 0, respectively.

these data using the aerosol components, assumed component mass extinction efficiencies, and component water growth estimates based on climatological values of RH [*US EPA*, 2003].

2.2. Aerosol Products: MODIS, GOCART, and Assimilation

[7] The MODIS instrument aboard the EOS Terra satellite has been providing *instantaneous aerosol measurements* over land and ocean since March 2000 with local overpass time around 10:30 A.M. (see details in *Kaufman et al.* [1997]). AOD is determined by fitting lookup tables of assumed aerosol optical properties to the observed radiance. Validation with AERONET measurements showed that averaged errors of MODIS Level-2 products are generally within the estimated uncertainties, $\pm 0.05 \pm 0.20\tau$ over land [*Chu et al.*, 2002]. This study uses the Terra MODIS Level-3 (collection 4) column AOD at 0.55 μm, which are archived on a global $1^\circ \times 1^\circ$ latitude-longitude grid.

[8] GOCART is a global chemical-aerosol-transport model, driven by the Goddard Earth Observing System Data Assimilation System (GEOS DAS) global analysis ($2^\circ \times 2.5^\circ$ grid space), including RH fields. It prognoses a global distribution of sulfate and its precursors, organic carbon, black carbon, mineral dusts and sea salt. AOD is determined from the dry mass concentrations and the mass extinction coefficients, which are functions of the size distributions, refractive indices, and RH-dependent hygroscopic growth of individual aerosol types [see details in *Chin et al.*, 2002]. Note that the aerosol optical properties could be different between the GOCART and MODIS retrievals. This study uses daily column AOD from Chin et al., submitted manuscript (2004), which updated the emission inventory of aerosols and their precursors from the earlier version.

[9] MODIS-GOCART has been integrated (denoted as ASSIM) through the optimal interpolation (OI) following the method in *Yu et al.* [2003]. The absolute errors, derived from the comparisons with the daily AERONET measurements over a 22-month period across the eastern U.S. (see section 3.1), are used to derive the fractional error (f) and the minimum root-mean square (RMS) uncertainties (ε) for GOCART and MODIS that determine the weight of interpolation ($f_{MODIS} = 0.41$, $\varepsilon_{MODIS} = 0.01$, $f_{GOCART} = 0.35$, $\varepsilon_{GOCART} = 0.05$). The errors in the satellite retrievals are assumed to be uncorrelated at the horizontal length scale ($L = 0$ km), while the errors in the model are assumed to be horizontally correlated ($L = 200$ km) (see discussions in *Yu et al.* [2003]).

3. Regional Intercomparison

[10] The regional comparison extends from March 1, 2000 to December 31, 2001 at AERONET and IMPROVE sites, located apart from the emission source. This comprises 22-month daily values promising enough data for a robust statistical analysis. The sampling is conducted only when the MODIS, GOCART, and AERONET/IMPROVE are simultaneously available. The focused area is the eastern U.S. (24°N–49°N, 100°W–70°W), which is approximately the same region with smoke/urban/dust aerosols defined in the MODIS retrievals [*Kaufman et al.*, 1997].

3.1. Daily and Long-Term Analysis

[11] Figure 1 shows the 22-month averaged AOD from the three products. All three AOD data reproduce a gradient from highest values in the mid-east to lowest values the western edge of the domain, but they also have considerably different distributions of AOD across the eastern part of the domain. The MODIS retrievals and ASSIM are spatially heterogeneous, and high AOD peaks exist along the coastal zones and over the Ohio River valley. The GOCART simulations appear to be more homogeneous and lower AOD than those in the MODIS retrievals.

[12] Figure 2a compares the three AOD products with the ground-based measurements at 10 AERONET sites for a daily (black) and 22-month averaged case (red). For a daily case, the GOCART contains large scatters due to a combination of errors in the model simulation and the sampling volume difference (point versus grid), with a severe underestimation (more than factor of 2) at many high AOD. The temporal averaging most likely removed the point-versus-grid errors, and GOCART AOD (red) becomes comparable to the AERONET measurements (RMSE = 0.028). The characteristics of the errors were consistent with those of *Chin et al.* [2002]. The MODIS retrievals have high

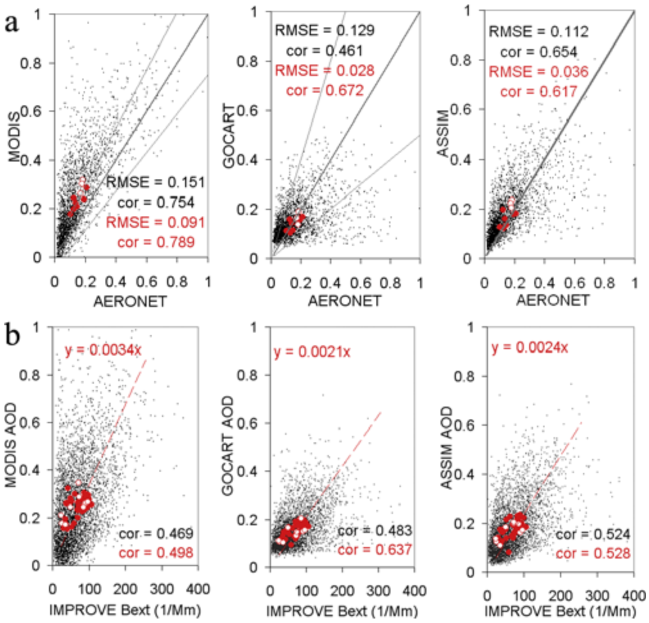

Figure 2. (a) Daily (black dots) and 22-month averaged (red dots) comparison between corresponding gridded AOD and AERONET measurements. (# of sample = 2627, # of site = 10) (b) Daily (black dots) and 22-month averaged (red dots) comparison between corresponding gridded AOD and IMPROVE measurements. (# of sample = 4328, # of site = 48) Note that red open circles represent the sites in the coastal zone; the thick gray line represents a 1:1 ratio; and thin gray line represents estimated errors of the corresponding aerosol products [*Chu et al.*, 2002; *Chin et al.*, 2002].

correlation, but overestimate the AOD for both a daily (RMSE = 0.152) and 22-month averaged case (RMSE = 0.091). These high biases are consistent to the results as shown by Chin et al., submitted manuscript (2004). The ASSIM generate the best daily-scale RMSE (0.112). However, correlation and a 22-month averaged RMSE are values between those in GOCART and MODIS.

[13] The IMPROVE data is utilized to evaluate the comparison furthermore, since the distribution of the AERONET network would be coarse for a regional evaluation (Figure 1). Regardless the intrinsic difference between the IMPROVE-measured near-surface *Bext* and the AERONET-measured column AOD, the scatters of the daily values in Figure 2b appear quite similar to those in Figure 2a. This indicates that the vertical distribution of AOD is not a dominant factor during the study period (22-month), although the AOD in the free troposphere would be important in the biomass burning events. Therefore, only the 22-month averaged case is discussed here. Under the assumption of the uniform aerosol mixing in the boundary layer (i.e., zero intercept) for long-term integration, the regressed slopes approximately represent the mixing depth (Figure 2b). Direct conversion from the IMPROVE *Bext* to the corresponding column AOD products result in the mean depths of the aerosol mixing layers: 3.4, 2.1, and 2.4 (km) for MODIS, GOCART and ASSIM, respectively. The observed typical mixing depths across the eastern U.S. (~2 km) [*Holzworth*, 1967] also indicate the overestimation of the MODIS retrievals and good agreement of the GOCART simulation found in the Figure 2a.

3.2. Warm and Cold Season Analysis

[14] We separate the analysis into warm (April–September) and cold (October–March) seasons (Figure 3a). The MODIS retrievals capture the strong seasonality in warm and cold seasons with consistent positive biases, while the GOCART simulation shows a weak overestimation (underestimation) of the AOD in the cold (warm) season. Because of the overestimated AOD of the MODIS retrievals and underestimated AOD of the GOCART simulations in the warm season, the ASSIM becomes less biased with the best RMSE (0.040). Yet, the cold-season positive biases in both the GOCART simulation and the MODIS retrievals result in an overestimation in the ASSIM.

[15] The IMPROVE *Bext* is also utilized to evaluate seasonality of the estimated AOD (Figure 3b). Slopes obtained from the MODIS and the ASSIM versus IMPROVE are larger in the warm season (converted mixing depth 3.8 km and 2.5 km, respectively) than those in the cold season (converted mixing depth 2.7 km and 2.1 km, respectively), although both mixing depths are overestimated than the typical values in the warm (~2 km) and cold season (~1.5 km) [*Holzworth*, 1967]. The converted mixing depth of the GOCART for the cold season (2 km) is higher than the typical observed depth (less than 1.5 km) [*Holzworth*, 1967]. This supports the weak overestimation

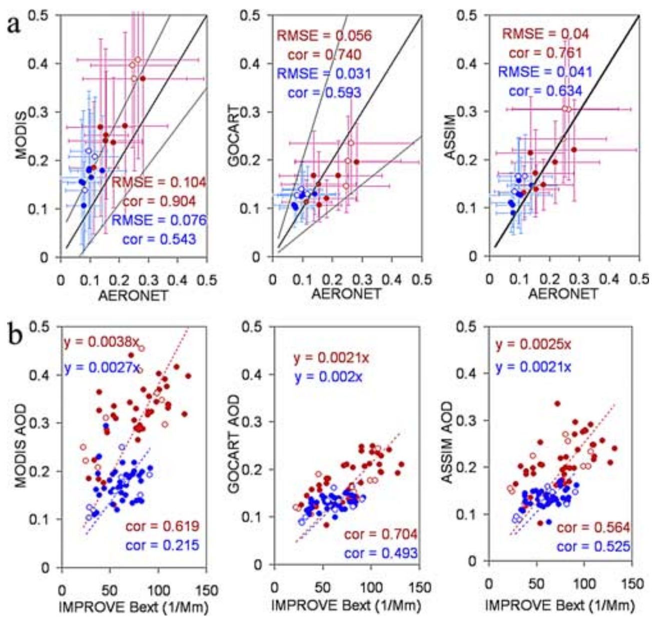

Figure 3. (a) Same as 2a, but integrated for warm and cold season. Warm Season (Red, April–September, # of sample = 1609, # of site = 10). Cold Season (Blue, October–March, # of sample = 1018, # of site = 10). Vertical and horizontal bars represent the standard deviation at each site. (b) Same as 2b, but integrated for warm and cold season. Warm Season (Red, April–September, # of sample = 2322, # of site = 47). Cold Season (Blue, October–March, # of sample = 2006, # of site = 48). Dotted line is the regression with zero intercept.

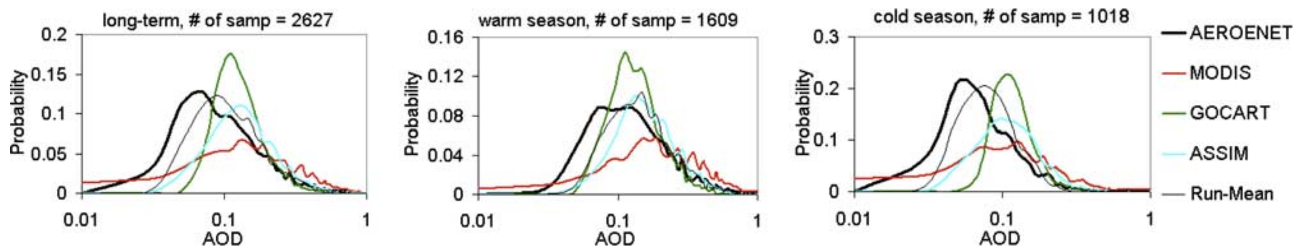

Figure 4. Probability distribution functions of MODIS, GOCART, ASSIM, and the AERONET measurements. 3-day running means (Run-Mean) are performed for the AERONET measurements to represent the approximate grid-volume transformation.

of the GOCART simulation in the cold season found in Figure 3a.

4. Probability Distribution

[16] To illustrate the overall characteristics of the ground-based versus three AOD products, we made the probability distribution function (PDF) in Figure 4. The PDF of the AERONET AOD is lognormally distributed. With respect to the central limit theorem, the PDF of the horizontally or temporally integrated values befalls narrower distribution with a peak at higher AOD. We performed the running mean average of the AERONET measurements in order to approximate a scale transformation from a point to the grid scale, since the direct horizontal average of the AERONET measurements cannot be conducted. Three-day running mean (± one day) was conducted for representing the horizontal average with respect to the similar values of spatial autocorrelation (0.4∼0.6) at hundreds-km horizontal scale (100∼250 km) to the one-day temporal autocorrelation based on the result of *Anderson et al.* [2003]. The PDF resulted from the corrected AERONET measurements are shifted toward the higher AOD. A comparison with the shifted AERONET PDF suggests that the slight underestimation of the GOCART in the warm season is due to its narrower PDF associated with its large grid size, whereas slight overestimation of the GOCART in the cold season is due to the model bias. Those support the discussion in Figure 3b. The PDF of the MODIS retrievals is more broadly distributed, overestimating the frequency of large AOD. For the warm season, a combination of the high and low biases results in the appropriate PDF for the ASSIM. For the cold season, the ASSIM poorly represent the PDF due to a combination of the high biases of the MODIS and GOCART. These confirm the results; the quality of the ASSIM depends on the biases of the original products, which must be removed as much as possible before the assimilation.

5. Summary and Discussion

[17] This study compared the spatio-temporal AOD of the instantaneous satellite (MODIS) retrievals, daily mean of chemical-transport model (GOCART) simulation, and assimilated (MODIS-GOCART) products with daily mean ground measurements at AERONET and IMPROVE sites across the eastern U.S. at a daily, seasonal, and 22-month average scale. The three AOD products exhibit significantly different distribution of AOD in the study area, and would result in the considerably different estimation of the aerosol effect on regional climate.

[18] Overestimations of the MODIS Level-3 (collection 4) AOD at 0.55 μm are confirmed in comparison with the daily and time-integrated values in the AERONET measurements and IMPROVE *Bext* across the eastern U.S., although it has high correlations with AERONET measurements. The overestimation could be due to a) the erroneous estimation of the surface reflectance related to unresolved surface water contamination [*Chu et al.*, 2002], b) the incorrect choice of the aerosol dynamic model and assumptions of aerosol optical properties [*Kaufman et al.*, 1997], or c) a comparison between the instantaneous MODIS retrievals and the daily AERONET data. Those issues should be included in future MODIS aerosol retrievals over land.

[19] For a 22-month averaged case, the GOCART AOD are in the best agreement with AERONET measurements, whereas this agreement was deteriorated when the long-term integration was replaced by integration over a seasonal and daily scale. The coarse grid size and temporally smooth emission rate result in the characteristics of the histogram and scatter plots of the GOCART. Careful examination revealed that GOCART has slight positive biases for the cold season. Biases could be corrected by improving the model processes for boundary layer depth estimates, including realistic seasonal variation of anthropogenic emission, incorporating precipitation-assimilated meteorological fields for wet deposition, or better handling the aerosol microphysics.

[20] The optimal interpolation reduced the temporal RMSE of both the MODIS retrievals and the GOCART simulations. Because of the different systematic biases in the MODIS retrievals and the GOCART simulation, the assimilation (optimal interpolation) does not necessarily provide the best estimation. Developments of unbiased products are critical for better assimilation of regional AOD. These results can be utilized for future improvement of the aerosol estimation and assimilation from the GOCART and the MODIS.

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