

Seasonal and spatial variations of global aerosol optical depth: multi-year modelling with GEOS-Chem-APM and comparisons with multiple-platform observations

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ABSTRACT

Recent AeroCom phase II experiments showed a large diversity in aerosol optical depth (AOD) among 16 detailed global aerosol models, which contributes to the large uncertainty in the predicted aerosol radiative forcing. The GEOS-Chem-APM, a global size-resolved aerosol model, can be considered as a representative AeroCom II model. In this study, multi-year AOD data (2004–2012) from ground-based Aerosol Robotic Network (AERONET) measurements and Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging SpectroRadiometer (MISR) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite retrievals are used to evaluate the performance of GEOS-Chem-APM in capturing observed seasonal and spatial AOD variations. Compared to the observations, the modelled AOD is overall good over land, but quite low over ocean possibly due to low sea salt emission in the model and/or higher AOD in satellite retrievals, specifically MODIS and MISR. We chose 72 AERONET sites having at least 36 months data available and representative of high spatial domain to compare with the model and satellite data. Comparisons in various representative regions show that the model overall agrees well in the major anthropogenic emission regions, such as Europe, East Asia and North America. Relative to the observations, the modelled AOD is systematically lower in biomass burning regions such as South Africa and South America possibly due to uncertainties in emission inventory, but slightly higher in North Africa likely associated with stronger dust emissions in the model. The model is able to capture the realistic seasonal cycle in all regions, including the peak of AOD in major dust events months and biomass burning seasons. The simulated inter-annual variability is overall consistent with the observations, which is distinctly shown in South Africa and South America with strong inter-annual variability compared to other regions.

Keywords: aerosol optical depth, GEOS-Chem-APM, MODIS, MISR, SeaWiFS, AERONET

1. Introduction

Aerosol particles not only affect Earth's energy budget by scattering and absorbing solar radiation and by altering cloud properties and lifetimes, but also influence weather, air quality and biogeochemical cycles. However, numerical predictions of aerosols still have large uncertainties. Recently, AeroCom phase II direct aerosol effect experiment reported a large diversity with respect to aerosol optical depth (AOD) among 16 detailed global aerosol models

(global mean total and anthropogenic AOD ranging from 0.072 to 0.174 and 0.010 to 0.053, respectively) (Myhre et al., 2013). Large diversity in the magnitude of AOD and their spatial distributions is one of key factors contributing to the large uncertainty of the model predicted aerosol radiative forcing (global mean ranging from -0.02 to -0.58 W m^{-2}) and its climatic effect. Therefore, evaluation of model performances with respect to AOD is a critical step to improve the model simulations and, thus, reduce the diversities. In the last decade, AOD has been measured by a number of satellite sensors, for example, TOMS, POLDER, MODIS (Moderate Resolution Imaging Spectroradiometer), MISR (Multi-angle Imaging SpectroRadiometer), SeaWiFS (Sea-viewing Wide

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Field-of-view Sensor), and CALIPSO. While satellites provide long-term uninterrupted observations of aerosol distribution and properties with global coverage, their retrievals are subject to some bias due to the retrieval schemes and various assumptions on surface conditions, aerosol properties, and so on. Furthermore, large diversities remain among various satellite observations (Ma et al., 2013). The ground-based observations from the world-wide Aerosol Robotic Network (AERONET, Holben et al., 1998, 2001) provide AOD data with relatively high accuracy, and could be used to evaluate satellite retrievals and model simulations.

The GEOS-Chem-APM (Yu and Luo, 2009; Ma et al., 2012; Yu et al., 2012) is one of the 16 global aerosol models participated in AeroCom phase II direct aerosol effect experiment (Myhre et al., 2013). The global annual mean total and anthropogenic AODs based on GEOS-Chem-APM (total 0.127 and anthropogenic 0.029) are close to the AeroCom II 16-model mean values (total 0.123 and anthropogenic 0.030) (Myhre et al., 2013) and, thus, can be considered as a representative model. In this study, multi-year AODs from multiple-platform observations including MODIS, MISR and SeaWiFS satellite retrievals and AERONET ground-based observations are employed to evaluate comprehensively the GEOS-Chem-APM model performance, focusing on seasonal and inter-annual variations in different regions around the globe.

This paper is organised as follows. In Section 2, descriptions of the GEOS-Chem-APM modelled AOD and observations from satellite data MODIS, MISR and SeaWiFS, and AERONET ground-based observations are outlined. In Section 3, the results of comparisons between the model and satellite as well as AERONET observations are presented, focusing on the seasonal and inter-annual variability in various regions. A summary and discussion is given in Section 4.

2. Global AOD: model and observations

2.1. GEOS-Chem-APM

The GEOS-Chem model is a global 3-D model of atmospheric composition driven by assimilated meteorological observations from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling Assimilation Office (GMAO). The model has been developed and used by many research groups and contains a number of state-of-the-art modules treating various chemical and aerosol processes (e.g., Bey et al., 2001; Martin et al., 2003; Park et al., 2004; Evans and Jacob, 2005; Liao et al., 2007; Fountoukis and Nenes, 2007) with up-to-date key emission inventories (e.g., Guenther et al., 2006; Bond et al., 2007). The APM (Advanced Particle Microphysics) model has

been incorporated into GEOS-Chem by Yu and Luo (2009). The basic microphysical processes in the model include nucleation, condensation/evaporation, coagulation, thermodynamic equilibrium with local humidity, and dry and wet deposition. Prognostic aerosol compositions include Secondary Particles (SP, containing sulphate, ammonia, nitrate and SOAs), black carbon (BC), primary organic carbon (POC), sea salt and mineral dust. The coating of secondary species on primary particles (sea salt, BC, POC and dust) is explicitly simulated.

A computationally efficient scheme, in terms of lookup tables, has been designed and developed to calculate online the aerosol optical properties that take advantage of important particle information (sizes, compositions, coating of primary particles by volatile species, hygroscopic growth, etc.) predicted by APM (Yu et al., 2012). The lookup tables are derived from the core-shell Mie scattering model of Ackerman and Toon (1981). The refractive indices for sulphate, ammonia, nitrate, SOA, primary organic aerosol (POA) and water are according to the corresponding values given in Aouizerats et al. (2010). The refractive indices for sea salt, BC and dust are based on values recommended by Krekov (1993), Bond and Bergstrom (2006) and Balkanski et al. (2007). More detailed information about the calculation of aerosol optical properties in GEOS-Chem-APM can be found in Yu et al. (2012) and Ma et al. (2012). The model results presented below are for AOD at 550 nm from a 9-yr simulation (2004–2012) using GEOS-Chem v8-03-02 + APM. The horizontal resolution is $2^\circ \times 2.5^\circ$, and there are 47 vertical layers in the model.

2.2. AERONET

The AERONET is a globally distributed remote sensing aerosol-monitoring network of ground-based sun photometers that measure sun and sky radiances (Holben et al., 1998). The automatic-tracking sun- and sky-scanning radiometers make direct sun measurements at least every 15 min at 340, 380, 440, 500, 675, 870, 940 and 1020 nm (nominal wavelengths) (Holben et al., 2001). The objective of this network is to assess aerosol optical properties and to validate satellite retrievals of aerosol optical properties. The network imposes standardisation of instruments, calibration and processing. Data from this collaboration provide globally distributed observations of spectral AODs, inversion products and precipitable water in geographically diverse aerosol regimes. AERONET data are also available at three levels: level 1.0 (unscreened), level 1.5 (cloud-screened) and level 2.0 (quality assured) (Holben et al., 1998). In the present study, we use the cloud-screened and quality-assured AERONET Level 2.0 data (Smirnov et al., 2000). The AOD at 550 nm obtained by spectral interpolation is used for comparisons.

2.3. MODIS, MISR and SeaWiFS satellite data

The MODIS on the Aqua satellite measures radiances at 36 wavelengths from 0.41 to 14 μm . A 2330-km viewing swath provides near-global coverage every day. MODIS/Aqua AOD data (Kaufman et al., 1997; Remer et al., 2005) is taken from the monthly level-3 product (MYD08_M3.051) with $1^\circ \times 1^\circ$ degree resolution, and combined with the separate deep blue product specifically for the AOD over desert regions. The annual averaged AOD at 550 nm is used for this study.

MISR (Martonchik et al., 1998) measurements are designed to improve our understanding of the Earth's environment and climate. Viewing the sunlit Earth simultaneously at nine widely-spaced angles, MISR provides radiometrically and geometrically calibrated images in four spectral bands at each of the angles. Spatial sampling of 275 and 1100 m is provided on a global basis. MISR level 3 monthly average globally gridded data product (MIL3MAE) has been obtained in $0.5^\circ \times 0.5^\circ$ resolution. The monthly mean AOD at 555 nm (green band) for the period 2004–2012 is applied for comparison.

SeaWiFS (Sayer et al., 2012a, 2012b) instrument was primarily designed to measure ocean colour. However, the unprecedented set of well-calibrated radiances measured in the wavelength range from the visible (412 nm) to the near infrared (865 nm) also make it well-suited to providing information about atmospheric aerosols (McClain et al., 1998). The aerosol retrieval system utilises a combination of the Deep Blue algorithm over land (Hsu et al., 2004, 2006) and the SeaWiFS Ocean Aerosol Retrieval (SOAR) algorithm over ocean (Sayer et al., 2012a). The level 3 monthly mean globally gridded data product in $1^\circ \times 1^\circ$ resolution at 550 nm for the time period 2004–2010 is used for comparison.

3. Results

For comparisons, the GEOS-Chem-APM simulations have been interpolated into the same spatial resolutions as MODIS ($1^\circ \times 1^\circ$), MISR ($0.5^\circ \times 0.5^\circ$) and SeaWiFS ($1^\circ \times 1^\circ$), using a simple linear interpolation method. The grid cells most close to the AERONET sites are chosen for comparisons between the model and AERONET.

3.1. Global

Figure 1a shows the time series of global mean of AOD from the GEOS-Chem-APM, and MODIS, MISR and SeaWiFS during the study period. Comparisons of the model with satellite data should be principally conducted under clear sky daytime from which satellite observes, our study shows that the modelled AOD in clear sky and clear

sky daytime is almost identical so only AOD in clear sky is presented in the study. However, definition of clear sky condition in satellite retrievals and in model could be different; for example, we define a clear sky condition once cloud cover (in a $2^\circ \times 2.5^\circ$ column) is less than 0.25. Overall, the modelled AOD shows a consistent temporal variation compared to satellite observations, with the maximum in spring and minimum in winter. For a global mean value computed from multi-year average (Table 1), AOD provided by MODIS (0.154) and MISR (0.168) is much higher than the model (0.102) and SeaWiFS (0.130). Large differences are found over ocean (Fig. 1b) among the satellite data with the highest AOD from MISR (0.157), second from MODIS (0.139) and lowest from SeaWiFS (0.110). Recent studies (e.g. Witek et al., 2013) found that overestimation of MISR over ocean is attributed to the false offset, and a new screening based on retrieval region characterisation is capable of substantially reducing MISR retrieval biases. In contrast, AODs over land (Fig. 1c) from satellite data are quite close. Comparisons of low (<0.1), median (0.1–0.3) and high (>0.3) AOD (Table 1) show that, compared to satellite retrievals, the modelled results are smaller for low and median AOD but larger for high AOD. The modelled AOD in all sky is shown in Fig. 1a as well for comparisons with other models, since AeroCom II global models (Myhre et al., 2013) provide AODs for all sky only. Figure 1a includes the results from 16 global models involved in AeroCom II (Myhre et al., 2013) for year 2006, giving a minimum of 0.07 from BCC and maximum of 0.17 from GISS-MATRIX, which presents quite large range among various models. The AODs from most models are lower than MISR and MODIS, considering they are obtained for all sky, which is $\sim 30\%$ higher than clear sky according to the GEOS-Chem-APM simulations, we conclude that AODs from most global models are lower than satellite retrievals including SeaWiFS. It should be noted that satellite data have some missing values over the polar regions which are not included into the global mean, while the modelled global mean include all the grid cells. This may cause some discrepancy. Additionally, the monthly mean modelled AOD are averaged from each day, and each time step, once cloud cover is less than 0.25, but the monthly mean of MODIS/MISR/SeaWiFS are averaged for clear sky conditions, and only once per day when the satellite overpass. This may also contribute to the discrepancy between the model and satellite retrievals. Time series of AOD from various aerosol component based on the simulation indicate that (Fig. 1d), from perspective of global mean, SP and mineral dust dominate the seasonal variation while other aerosol types, especially sea salt and BC, only have a minor impact on the seasonal variation.

Figure 2 shows the spatial distribution of AOD obtained from MODIS, MISR and SeaWiFS (a, b, and c).

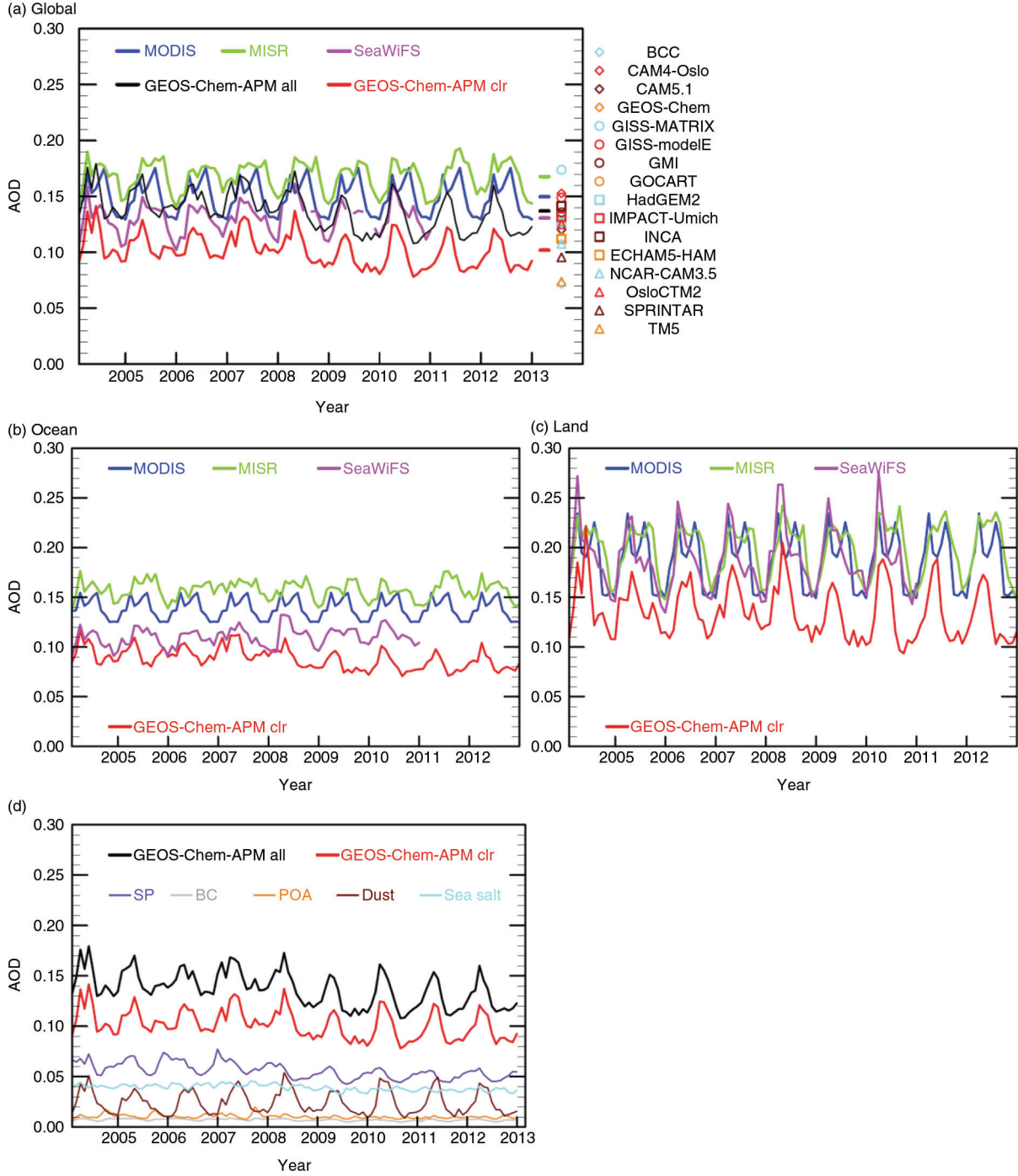


Fig. 1. (a) Time series of global mean AOD from the GEOS-Chem-APM, and MODIS, MISR and SeaWiFS from 2004 to 2012. The results from 16 AeroCom models are also marked in the figure; (b) time series of AOD over ocean; (c) over land; (d) time series of total AOD for clear sky and all sky, as well as the contributions of each aerosol components.

All satellite observations present high magnitudes over North Africa, Middle East, India and East Asia, but large discrepancies exist over ocean, especially Southern Ocean, where much higher AOD found from MODIS and MISR than SeaWiFS. Recent studies suggested that high

magnitudes in the MODIS and MISR may be caused by the contamination by stratocumulus and low broken cumulus clouds (Toth et al., 2013), while some studies (e.g. Witek et al., 2013) found that overestimation of MISR over ocean may be attributed to the false retrieval offset.

Table 1. Comparisons of AOD in clear sky from the GEOS-Chem-APM with satellite data MODIS, MISR and SeaWiFS, and comparisons in 72 AERONET sites having at least 36 months data available between the model and the observations. The AERONET sites with low quality and low spatial domain are also excluded

	GEOS-Chem-APM	MODIS	MISR	SeaWiFS	AERONET
Global	0.102	0.154	0.168	0.130	
Land	0.135	0.188	0.198	0.188	
Ocean	0.088	0.139	0.157	0.110	
Low AOD (<0.1)	0.055	0.069	0.075	0.066	
Median AOD (0.1,0.3)	0.148	0.156	0.162	0.158	
Large AOD (>0.3)	0.506	0.471	0.460	0.458	
72 AERONET sites	0.168	0.192	0.206	0.193	0.223

The band over the Southern Ocean is expected to be higher due to strong winds that induce higher sea salt emission, which is seen from MODIS and MISR, but somehow missing in SeaWiFS. The absolute differences of AOD (Fig. 2d, e, and f) between the model and satellite observations show that the modelled AOD is lower over oceanic regions, particularly in the tropical ocean, but higher over some continent regions, especially North Africa and East Asia. Overall, the global mean difference between the model and satellite data is -0.05 , -0.06 and -0.02 , for MODIS, MISR and SeaWiFS, respectively. It is seen from seasonal mean differences between the model and satellite data (Fig. 3) that maximum positive bias (up to 0.25) occurs over North Africa in MAM and DJF, while maximum negative bias (up to 0.25) over tropical ocean in JJA. Over most areas except North Africa, East Asia and tropical ocean, the absolute differences are roughly less than 0.1 in all seasons. In addition, large differences

are found over South America in SON during biomass burning season.

It is acknowledged that satellite retrievals are subject to the uncertainties due to cloud screening, aerosol models involved, surface conditions, and so on, so it is useful to compare the model with the relatively straightforward ground-based observations. Currently AERONET has more than 600 sites over the globe, with more over NH than SH, and more over land than ocean. As mentioned earlier, this study not only evaluates the annual mean and spatial distribution but also examines the seasonal and inter-annual variation. Therefore, we chose those sites with at least 36 months data available for our analysis, and we further eliminated the sites with a low spatial domain and with a low data quality according to the site assessment provided by Kinne et al. (2013). In total, 72 sites meet this criterion and are used in the study (show in Fig. 4). The statistical results for all sites (Table 1) show that mean

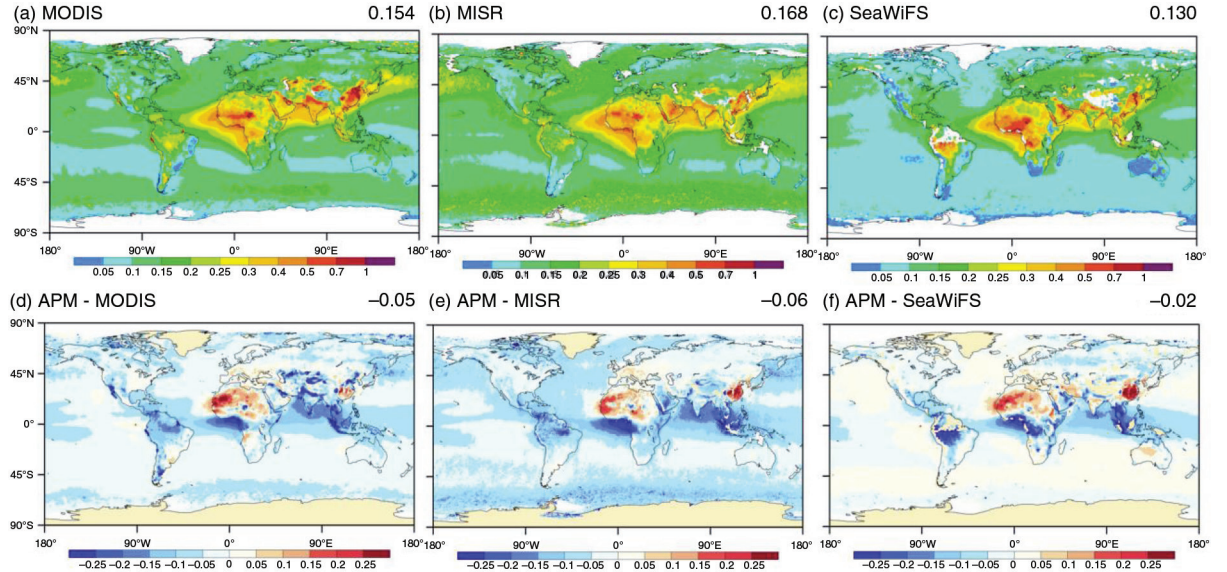


Fig. 2. Multi-year averaged AOD from MODIS, MISR, and SeaWiFS (a, b, c), and absolute differences between the GEOS-Chem-APM and MODIS, MISR and SeaWiFS in clear sky (d, e, f).

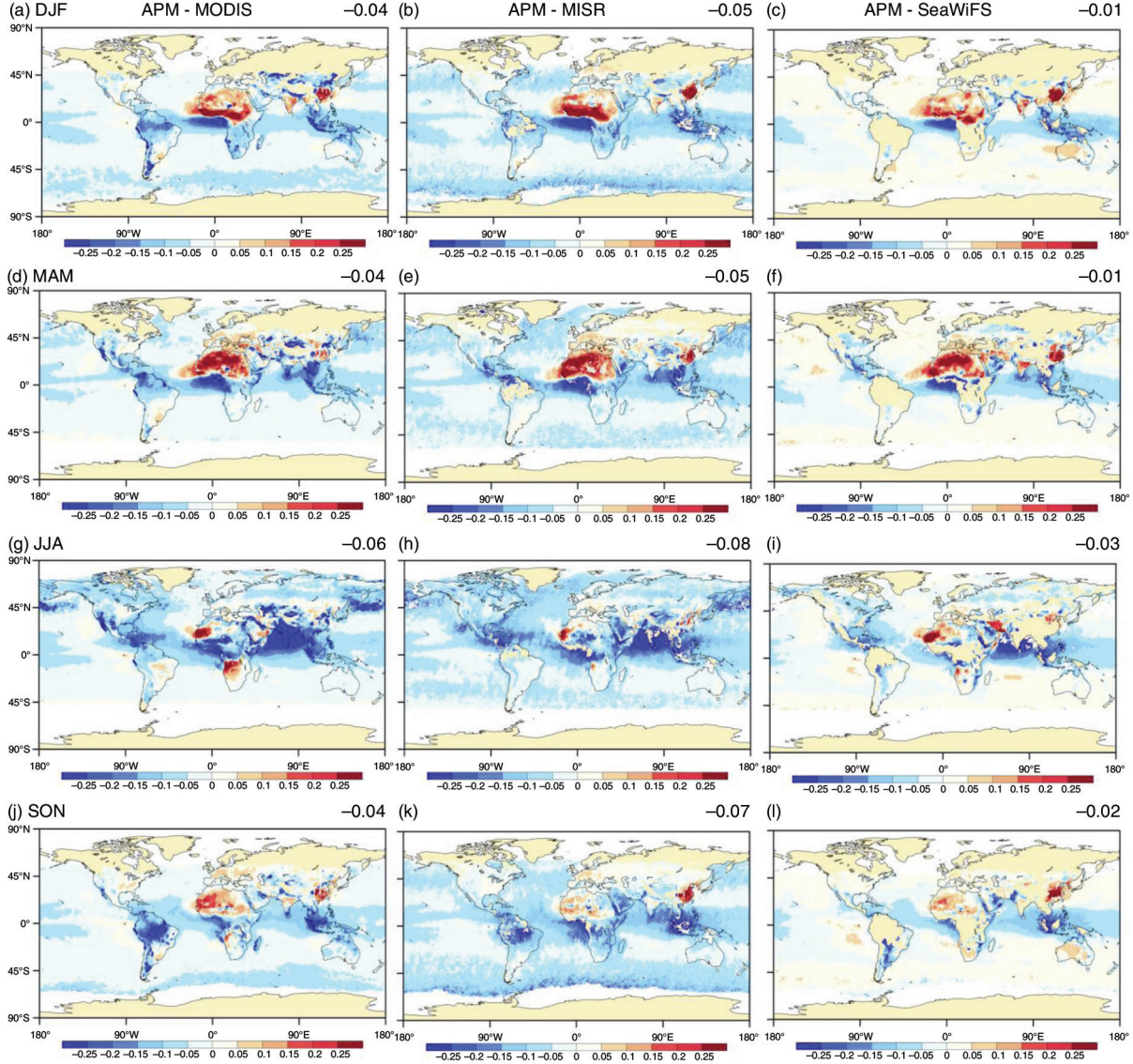


Fig. 3. Seasonal mean differences of AOD between the GEOS-Chem-APM and MODIS (a, d, g, j), MISR (b, e, h, k), and SeaWiFS (c, f, i, l) in DJF, MAM, JJA and SON.

value from the model is 0.168, which is lower than MODIS (0.192), MISR (0.206), SeaWiFS (0.193) and AERONET (0.223) observations.

3.2. Regions

AERONET sites locate in the different regions, with various aerosol emission sources and chemical components. In order to facilitate the analysis, we choose several regions representative of various dominant aerosol species, including North America, Europe, East Asia, North Africa, South Africa and South America. The selected regions include most of the AERONET sites which meets the

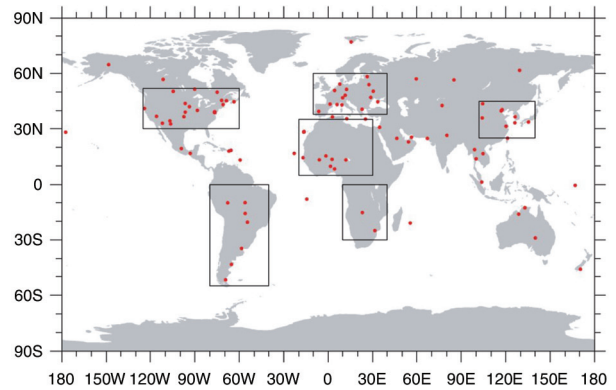


Fig. 4. Locations of 72 AERONET sites used in the study.

Table 2. Comparisons of aerosol optical depth (AOD) between the GEOS-Chem-APM (τ_1), and AERONET (τ_2), MODIS/MISR (τ_3), SeaWiFS (τ_4) in North America, where d is the absolute difference between the model and observations, and R correlation coefficient and s standard derivation. The negative differences are marked in blue, and the positive are marked in red. The R in black denotes that the correlation coefficient pass the Student's *t*-test ($\alpha=0.01$), otherwise in yellow. Mean values and standard deviation are also summarised in the bottom rows. The results are listed from low to high AOD observed from AERONET

	APM vs. AERONET					APM vs. MODIS/MISR					APM vs. SeaWiFS				
	τ_1	τ_2	d	R	s	τ_1	τ_3	D	R	s	τ_1	τ_4	d	R	s
1. Frenchman	0.05	0.07	−0.02	0.57	0.03	0.05	0.24	−0.19	0.88	0.05	0.05	0.18	−0.14	0.82	0.11
2. Sevilleta	0.04	0.07	−0.02	0.75	0.02	0.04	0.12	−0.08	0.76	0.03	0.04	0.05	0.00	0.44	0.04
3. White_San	0.05	0.07	−0.02	0.83	0.02	0.05	0.22	−0.17	0.86	0.05	0.05	0.05	0.00	0.45	0.03
4. Trinidad_H	0.08	0.09	−0.01	0.41	0.05	0.08	0.12	−0.04	0.38	0.04	0.08	0.08	0.00	0.68	0.03
5. Maricopa	0.06	0.09	−0.03	0.72	0.02	0.06	0.15	−0.10	0.71	0.04	0.06	0.10	−0.04	0.57	0.04
6. Halifax	0.08	0.10	−0.03	0.28	0.04	0.07	0.11	−0.04	0.25	0.07	0.08	0.09	−0.01	0.28	0.04
7. Bratts_Lake	0.09	0.10	−0.01	0.32	0.05	0.08	0.15	−0.07	0.72	0.05	0.09	0.12	−0.03	0.72	0.06
8. CARTEL	0.09	0.12	−0.03	0.52	0.05	0.09	0.10	−0.01	0.44	0.07	0.10	0.12	−0.02	0.48	0.07
9. Howland	0.09	0.12	−0.03	0.33	0.09	0.08	0.08	0.01	0.32	0.05	0.09	0.11	−0.02	0.29	0.07
10. KONZA_	0.11	0.13	−0.03	0.76	0.04	0.10	0.10	0.00	0.57	0.04	0.11	0.12	−0.01	0.80	0.05
11. Sioux_Fall	0.11	0.13	−0.03	0.69	0.05	0.11	0.11	0.00	0.44	0.05	0.11	0.11	0.00	0.59	0.06
12. Cart_Site	0.10	0.13	−0.03	0.64	0.05	0.10	0.10	0.00	0.76	0.03	0.11	0.09	0.02	0.69	0.04
13. Thompson	0.10	0.15	−0.05	0.47	0.07	0.10	0.11	−0.01	0.56	0.05	0.10	0.11	0.00	0.63	0.04
14. Ames	0.13	0.15	−0.02	0.75	0.05	0.12	0.11	0.01	0.44	0.04	0.13	0.14	−0.01	0.78	0.05
15. BONDVI	0.13	0.17	−0.04	0.82	0.06	0.13	0.13	−0.01	0.52	0.06	0.13	0.16	−0.03	0.67	0.07
16. GSFC	0.13	0.19	−0.07	0.84	0.09	0.12	0.15	−0.03	0.73	0.08	0.13	0.20	−0.07	0.82	0.05
17. SERC	0.12	0.19	−0.07	0.77	0.10	0.12	0.15	−0.03	0.79	0.06	0.13	0.20	−0.07	0.82	0.05
18. MD_Scien	0.13	0.20	−0.08	0.82	0.09	0.12	0.14	−0.02	0.75	0.06	0.13	0.19	−0.06	0.69	0.10
Mean	0.09	0.13	−0.03	0.63	0.05	0.09	0.13	−0.04	0.60	0.05	0.10	0.12	−0.03	0.62	0.06
Std	0.03	0.04	0.02	0.19	0.03	0.03	0.04	0.06	0.19	0.01	0.03	0.05	0.04	0.17	0.02

criterion mentioned above. Below, we analyse the statistics, seasonal variation and inter-annual variation for each region in detail.

3.2.1. North America. In total, 18 sites over North America meet the criterion, and the statistical results are listed in Table 2 from low to high AOD observed from AERONET. The modelled AOD in clear sky ranges from 0.04 to 0.13 with the mean value as of 0.09 and standard deviation 0.03, while AERONET AOD range from 0.07 to 0.20 with the mean value as of 0.13 and standard deviation 0.04. The absolute difference (d) between the model and AERONET is negative in all the sites, indicating that the modelled AOD is systematically lower than AERONET with a mean difference as of -0.03 . The statistical analysis indicates that the model has a good agreement with AERONET observations as the Student's *t*-test presents that the model and AERONET are statistically correlated, and standard deviation (s) for the time period in each site is generally low. Similar statistical analysis is performed for the model versus satellite observations over the corresponding AERONET site. As the AODs from MODIS and MISR are systematically higher and they have much similar

spatial distribution compared to SeaWiFS, we use the mean AOD from MODIS and MISR to save the space. The modelled AOD is overall lower than the observations, with the mean difference between the model and MODIS/MISR, and SeaWiFS as of -0.04 , and -0.03 . Almost all sites pass the statistically significance *t*-test except one. Considering the AERONET uncertainty of 0.01–0.02 (Holben et al., 2001), the expected error of MODIS AOD retrievals as $\pm(0.03+0.05\tau)$ over ocean and $\pm(0.05+0.20\tau)$ over land (Kaufman et al., 1997; Tanré et al., 1997), the error of MISR within 0.05 (Kahn et al., 2005, 2010) and error of SeaWiFS AOD as $0.03+15\%$ over ocean and $0.05+20\%$ over land at 550 nm (Sayer et al., 2012a, 2012b), it is concluded that the model can reasonably reproduce the observed magnitude of AOD.

Below we choose two sites with relatively large seasonal variability to evaluate the simulated seasonal and inter-annual variation of AOD, against AERONET, MODIS, MISR and SeaWiFS. The comparisons for the rest of the sites are not presented due to the limited paper space. Figure 5 shows the seasonal cycle in the site BONDVILLE (40.05N, 88.37W) and GSFC (38.99N, 76.83W). In BONDVILLE, the model captures the basic seasonal cycle obtained from AERONET and satellite observations, that is, minimum

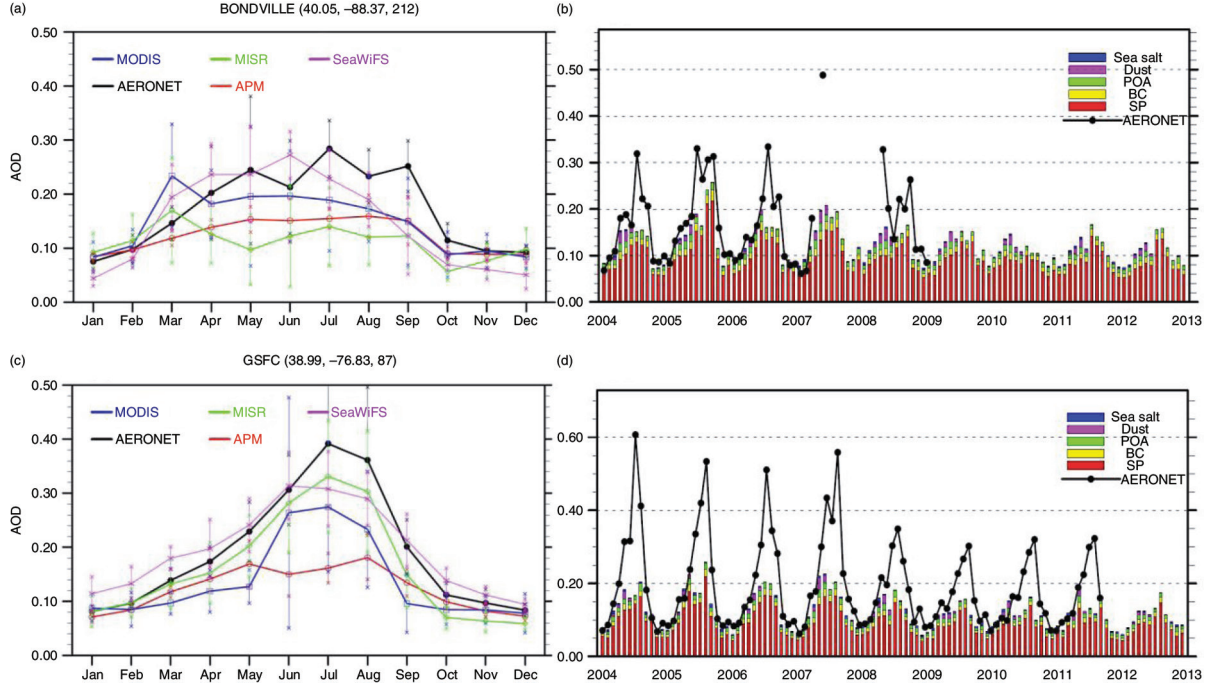


Fig. 5. Seasonal cycle (a and c) from the GEOS-Chem-APM, AERONET, MODIS and MISR in site BONDVILLE and GSFC over North America. The error bars over the curves denote the standard deviations. Time series of AOD contributed from each aerosol component and comparisons with AERONET from 2004 to 2012 (b and d).

in winter (Fig. 5a). The modelled AOD is generally lower than the observations in all seasons except winter. Larger standard deviation from the observations than the model shown as the error bars indicates that the observed large inter-annual variations of AOD are not reproduced by the model. Similar to the site BONDVILLE, in GSFC, both the magnitude and inter-annual variability of the modelled AOD are systematically smaller than the satellite and AERONET retrievals (Fig. 5c). As mentioned earlier, the GEOS-Chem-APM treats various aerosol components, including SP, BC, POA, mineral dust and sea salt. Figure 5b and d shows time series of contributions from each component to the total AOD, as well as the AERONET AOD. It is seen that the dominant aerosol species in BONDVILLE and GSFC is SP, while other species only contribute small amount of the total AOD. Therefore, it is possible that the model underestimates the magnitude of SP and/or the contributions of other components. It should be noted that the model grid covers large domain ($2^\circ \times 2.5^\circ$), so it is also possible that high AOD values might be smoothed.

3.2.2. Europe. In total, 12 sites in Europe meet the selection criterion. The statistical results summarised in Table 3 show that the modelled AOD range from 0.13 to 0.19 with the mean value as 0.16 and standard deviation as

0.02, while AERONET observed AOD range from 0.12 to 0.24 with the mean value as 0.18 and standard deviation as 0.04. The mean difference (d) between the model and AERONET is -0.01 , indicating that the magnitude of the modelled AOD agrees quite well with AERONET in Europe. The model is slightly higher than MODIS/MISR and SeaWiFS, with mean differences of 0.02 and 0.02, respectively. The good correlation coefficients in most sites with mean values as 0.50, 0.50 and 0.46 for the model versus AERONET, MODIS/MISR and SeaWiFS, respectively, implying that the model agrees well with the observations in the seasonal and inter-annual variations.

The comparisons in Erska (43.0N, 9.35E) and Toulou (43.13N, 6.0E) present that both magnitude and inter-annual variability of the modelled AOD is higher in spring compared to the observations (Fig. 6a and c). As shown in Fig. 6b and d, mineral dust is the dominant component in the spring, which implies that mineral dust transported from North Africa desert regions in the model is probably too high.

3.2.3. East Asia. Statistics from seven sites in East Asia (Table 4) show that the modelled AOD are slightly lower than the AERONET observation and MODIS/MISR while slightly higher than SeaWiFS, with the corresponding differences as of -0.13 , -0.02 and 0.04 . Large standard

Table 3. Same as Table 2, but for Europe

	APM vs. AERONET					APM vs. MODIS/MISR					APM vs. SeaWiFS				
	τ_1	τ_2	d	R	s	τ_1	τ_3	d	R	s	τ_1	τ_4	d	R	s
1. Caceres	0.13	0.12	0.01	0.53	0.06	0.13	0.09	0.04	0.52	0.06	0.14	0.11	0.02	0.33	0.07
2. Ersa	0.15	0.13	0.02	0.54	0.05	0.16	0.17	-0.01	0.51	0.06	0.17	0.13	0.03	0.57	0.05
3. Toulon	0.15	0.14	0.01	0.70	0.05	0.15	0.10	0.05	0.73	0.04	0.16	0.12	0.04	0.64	0.05
4. Le_Fauga	0.13	0.15	-0.02	0.56	0.05	0.13	0.12	0.01	0.58	0.05	0.13	0.15	-0.01	0.54	0.06
5. Minsk	0.16	0.16	0.00	0.41	0.07	0.16	0.16	0.00	0.40	0.07	0.16	0.18	-0.02	0.38	0.09
6. Munich_U	0.16	0.17	-0.01	0.47	0.06	0.17	0.14	0.03	0.57	0.05	0.19	0.13	0.06	0.51	0.05
7. Sevastopol	0.18	0.19	-0.01	0.43	0.07	0.18	0.15	0.03	0.47	0.06	0.19	0.17	0.01	0.59	0.06
8. IFT-Leipzi	0.19	0.19	0.00	0.64	0.05	0.20	0.17	0.03	0.52	0.06	0.22	0.19	0.03	0.29	0.08
9. Kyiv	0.17	0.20	-0.04	0.29	0.08	0.17	0.17	0.00	0.33	0.06	0.18	0.20	-0.02	0.28	0.08
10. Moldova	0.19	0.20	-0.01	0.59	0.05	0.19	0.13	0.06	0.46	0.06	0.21	0.16	0.04	0.36	0.06
11. Brussels	0.17	0.22	-0.04	0.54	0.08	0.19	0.18	0.02	0.37	0.10	0.21	0.19	0.01	0.47	0.07
12. Thessalon	0.17	0.24	-0.07	0.32	0.10	0.18	0.19	-0.01	0.57	0.07	0.19	0.18	0.00	0.57	0.08
Mean	0.16	0.18	-0.01	0.50	0.06	0.17	0.15	0.02	0.50	0.06	0.18	0.16	0.02	0.46	0.07
Std	0.02	0.04	0.03	0.12	0.02	0.02	0.03	0.02	0.11	0.01	0.03	0.03	0.03	0.13	0.01

deviation of the differences indicates that there exists significant spatial variability in East Asia. The correlation coefficients of the model versus AERONET in all sites pass the Student's *t*-test, which imply that the model agrees well with the observations in seasonal variation. The correlation is also generally good between the APM and MODIS/MISR, and between APM and SeaWiFS, implying time series of AOD provided by the model is consistent with the observations.

Two sites, Xianghe (39.75N, 116.96E) and Anmyon (36.53N, 126.33E), are chose as the examples to present

the seasonal and inter-annual variability in East Asia. The site Xianghe is a rural site and often covered by a thick layer of haze due primarily to anthropogenic emissions (Li et al., 2007). Both the model and the observations show the maximum in summer and minimum in winter (Fig. 7a). The peak AOD in spring caused by mineral dust can be found in both the model and AERONET. However, the AERONET observation presents a relatively large inter-annual variability (Fig. 7b), which is not successfully captured by the model. In Anmyon (Fig. 7c and d), the model

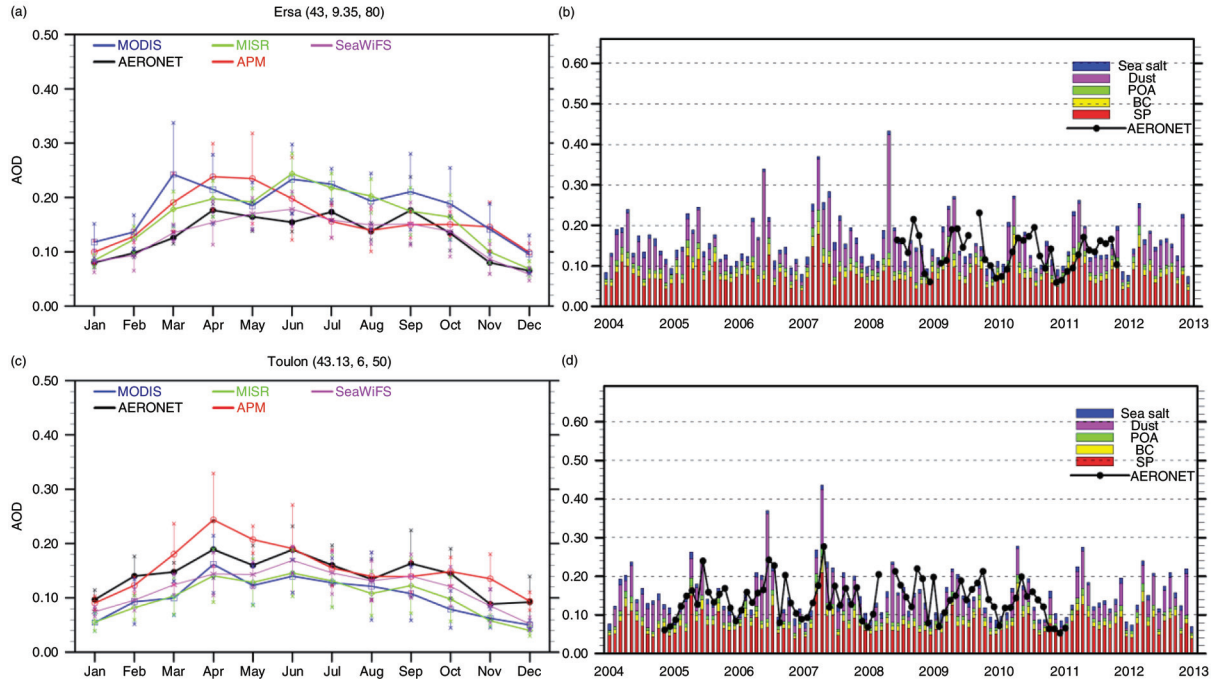


Fig. 6. Same as Fig. 5 but for AERONET site Ersa and Toulou over Europe.

Table 4. Same as Table 2, but for East Asia

	APM vs. AERONET					APM vs. MODIS/MISR					APM vs. SeaWiFS				
	τ_1	τ_2	d	R	s	τ_1	τ_3	d	R	s	τ_1	τ_4	d	R	s
1. Shirahama	0.20	0.29	-0.09	0.58	0.09	0.19	0.26	-0.07	0.59	0.08	0.20	0.21	-0.02	0.64	0.07
2. Xinglong	0.41	0.34	0.06	0.82	0.11	0.42	0.26	0.16	0.76	0.12	0.43	0.20	0.22	0.65	0.15
3. Gosan_SN	0.34	0.35	-0.01	0.31	0.15	0.32	0.33	-0.02	0.51	0.11	0.32	0.31	0.01	0.62	0.11
4. SACOL	0.08	0.38	-0.30	0.41	0.10	0.08	0.25	-0.17	0.59	0.06	0.08	0.12	-0.05	0.60	0.08
5. Anmyon	0.37	0.46	-0.09	0.32	0.22	0.35	0.37	-0.02	0.50	0.16	0.35	0.40	-0.06	0.66	0.13
6. XiangHe	0.58	0.79	-0.21	0.67	0.24	0.57	0.47	0.10	0.72	0.19	0.56	0.43	0.13	0.24	0.24
7. Taihu	0.55	0.84	-0.29	0.35	0.26	0.53	0.64	-0.10	0.31	0.22	0.57	0.50	0.06	0.32	0.17
Mean	0.36	0.49	-0.13	0.49	0.17	0.35	0.37	-0.02	0.57	0.13	0.36	0.31	0.04	0.53	0.14
Std	0.18	0.23	0.14	0.20	0.07	0.18	0.14	0.11	0.15	0.06	0.18	0.14	0.10	0.18	0.06

fails to capture the relatively high AOD in June and July observed by both satellite and AERONET observations. Large biases in summer indicate that the model might underestimates SP, POA and BC possibly due to incorrect emission inventory, and/or inaccurate representation of production and removal processes. Further studies are needed to improve the model.

3.2.4. North Africa. Nine AERONET sites in North Africa (Table 5) are used for comparisons. The model is overall slightly higher than AERONET, MODIS/MISR and SeaWiFS in the selected sites. The averaged difference is 0.01, 0.01 and 0.01, respectively, corresponding to the model versus AERONET, MODIS/MISR and SeaWiFS.

The standard deviation for the former is much larger (0.13) than the latter two (0.03 and 0.08), indicating large diversity between the model and AERONET. This may suggests that the localised AOD observed in AERONET is not reflected in coarser resolution results including the model and satellite data. The correlation coefficients between the model and the observations in all sites except one (DMN_Maine_Sorora) pass the statistically significant *t*-test, suggesting that temporal variation of AOD in the model is quite consistent with the observations.

Figure 8 shows the seasonal cycle and inter-annual variability in two sites, IER-Cinzana (13.27N, 5.93W) and Saada (31.62N, 8.15W), from the GEOS-Chem-APM simulation, as well as AERONET, MODIS, MISR and SeaWiFS observations. Figure 8a shows that the strongest

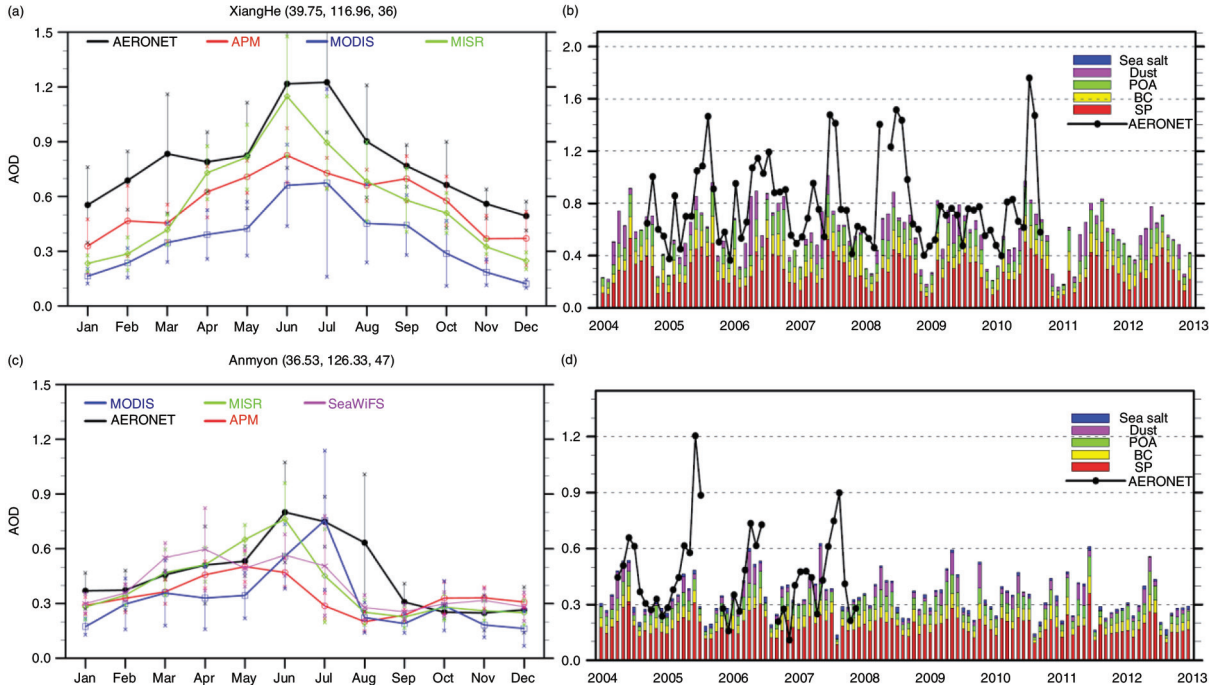


Fig. 7. Same as Fig. 5 but for AERONET site Xianghe and Anmyon over East Asia.

Table 5. Same as Table 2, but for North Africa

	APM vs. AERONET					APM vs. MODIS/MISR					APM vs. SeaWiFS				
	τ_1	τ_2	d	R	s	τ_1	τ_3	d	R	s	τ_1	τ_4	d	R	s
1. Izana	0.19	0.06	0.13	0.59	0.08	0.19	0.20	-0.01	0.69	0.08	0.18	0.16	0.02	0.75	0.07
2. La_Laguna	0.19	0.15	0.04	0.76	0.07	0.19	0.20	-0.02	0.69	0.08	0.18	0.16	0.02	0.75	0.07
3. Santa_Cruz	0.18	0.16	0.02	0.74	0.06	0.19	0.20	-0.02	0.69	0.08	0.18	0.16	0.02	0.75	0.07
4. Danker	0.57	0.44	0.12	0.53	0.27	0.55	0.48	0.07	0.51	0.29	0.57	0.44	0.13	0.56	0.25
5. DMN_Mai	0.57	0.49	0.08	0.11	0.39	0.53	0.52	0.01	0.16	0.34	0.57	0.54	0.03	0.26	0.35
6. IER_Cinza	0.45	0.49	-0.03	0.52	0.26	0.46	0.45	0.01	0.28	0.33	0.51	0.51	0.00	0.46	0.27
7. Agoufou	0.53	0.52	0.01	0.55	0.23	0.51	0.46	0.04	0.51	0.26	0.50	0.46	0.04	0.66	0.22
8. Banizoumb	0.56	0.57	-0.01	0.43	0.40	0.53	0.55	-0.02	0.21	0.45	0.55	0.53	0.02	0.41	0.40
9. Ilorin	0.36	0.66	-0.30	0.65	0.44	0.52	0.49	0.03	0.37	0.60	0.55	0.74	-0.19	0.38	0.56
Mean	0.40	0.39	0.01	0.54	0.24	0.41	0.39	0.01	0.46	0.28	0.42	0.41	0.01	0.55	0.25
Std	0.17	0.21	0.13	0.19	0.15	0.17	0.15	0.03	0.21	0.18	0.18	0.21	0.08	0.18	0.17

AOD occurs in spring while the lowest in summer, from both the model and observations. The dominant aerosol type is mineral dust (Fig. 8b), which is clearly shown in the model. The model appears to capture the high AOD in 2010 but fails to reproduce the high magnitude in 2009. In addition, the model has the maximum AOD in 2008, which is not observed from AERONET. The seasonal cycle in site Saada indicates the largest AOD occur in summer (Fig. 8c), while the model likely simulate two much mineral dust in spring (Fig. 8c and d). The inter-annual variability observed from AERONET is generally reproduced by the model.

3.2.5. South Africa. Since SeaWiFS observation has a quite large missing data over South Africa and South America, only AERONET, MODIS and MISR observations are employed for analysis. Statistics from two sites suggest that the modelled AOD is lower than the observations in South Africa (Table 6), with the averaged difference, that is, -0.09 and -0.02 for the APM versus AERONET and versus MODIS/MISR. This is possibly attributed to the low biomass burning emissions and/or SP formation. However, high correlation coefficients, that is, 0.80 and 0.60 , give the evidence that the model is able to capture the time series of AOD obtained from the

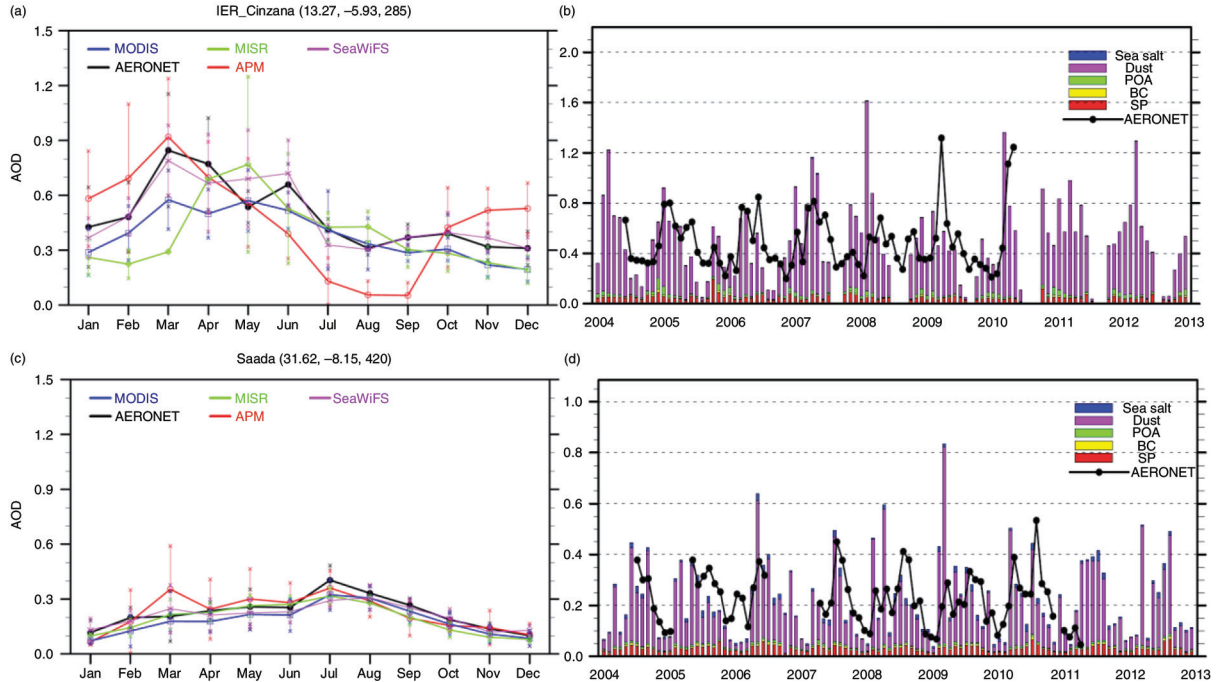


Fig. 8. Same as Fig. 4 but for AERONET site IER_Cinzana and Saada over North Africa.

Table 6. Same as Table 2, but for South Africa

	APM vs. AERONET					APM vs. MODIS/MISR				
	τ_1	τ_2	d	R	s	τ_1	τ_3	d	R	s
1. Skukuza	0.12	0.20	-0.08	0.74	0.06	0.13	0.13	0.00	0.48	0.06
2. Mongu	0.14	0.23	-0.09	0.85	0.10	0.15	0.18	-0.03	0.72	0.07
Mean	0.13	0.22	-0.09	0.80	0.08	0.14	0.16	-0.02	0.60	0.07
Std	0.01	0.02	0.01	0.08	0.03	0.01	0.04	0.02	0.17	0.01

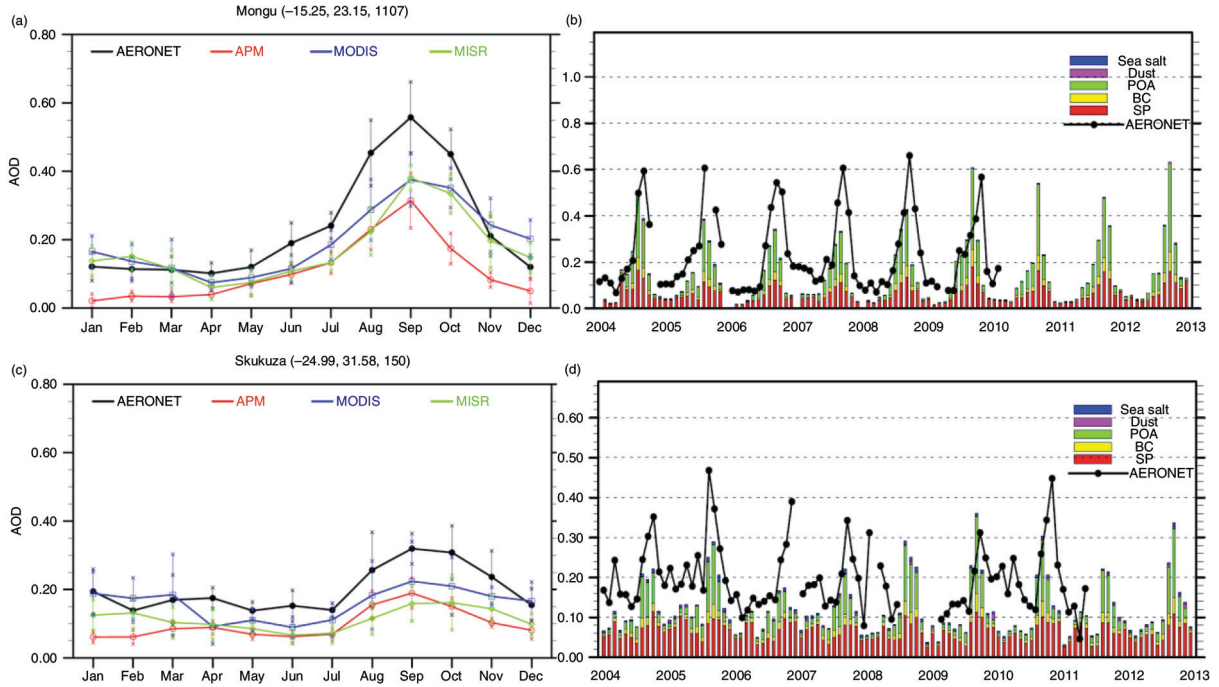


Fig. 9. Same as Fig. 4 but for AERONET site Mongu and Skukuza over South Africa.

Table 7. Same as Table 2, but for South America

	APM vs. AERONET					APM vs. MODIS/MISR				
	τ_1	τ_2	d	R	s	τ_1	τ_3	d	R	s
1. CEILAP-RG	0.05	0.02	0.03	0.54	0.01	0.05	0.04	0.01	0.21	0.02
2. Trelew	0.07	0.04	0.03	0.21	0.04	0.06	0.09	-0.03	0.65	0.04
3. CEILAP-BA	0.09	0.11	-0.03	-0.15	0.06	0.09	0.09	0.00	0.27	0.05
4. Campo_Grande_	0.11	0.17	-0.06	0.82	0.13	0.09	0.09	0.00	0.78	0.08
5. Rio_Branco	0.08	0.24	-0.16	0.70	0.25	0.13	0.26	-0.13	0.81	0.24
6. CUIABA-MIRA	0.15	0.27	-0.12	0.88	0.22	0.12	0.15	-0.03	0.85	0.12
7. Alta_Floresta	0.18	0.34	-0.16	0.85	0.29	0.19	0.27	-0.14	0.73	0.24
Mean	0.10	0.17	-0.07	0.55	0.14	0.10	0.14	-0.05	0.61	0.11
Std	0.05	0.12	0.08	0.39	0.11	0.05	0.09	0.06	0.26	0.09

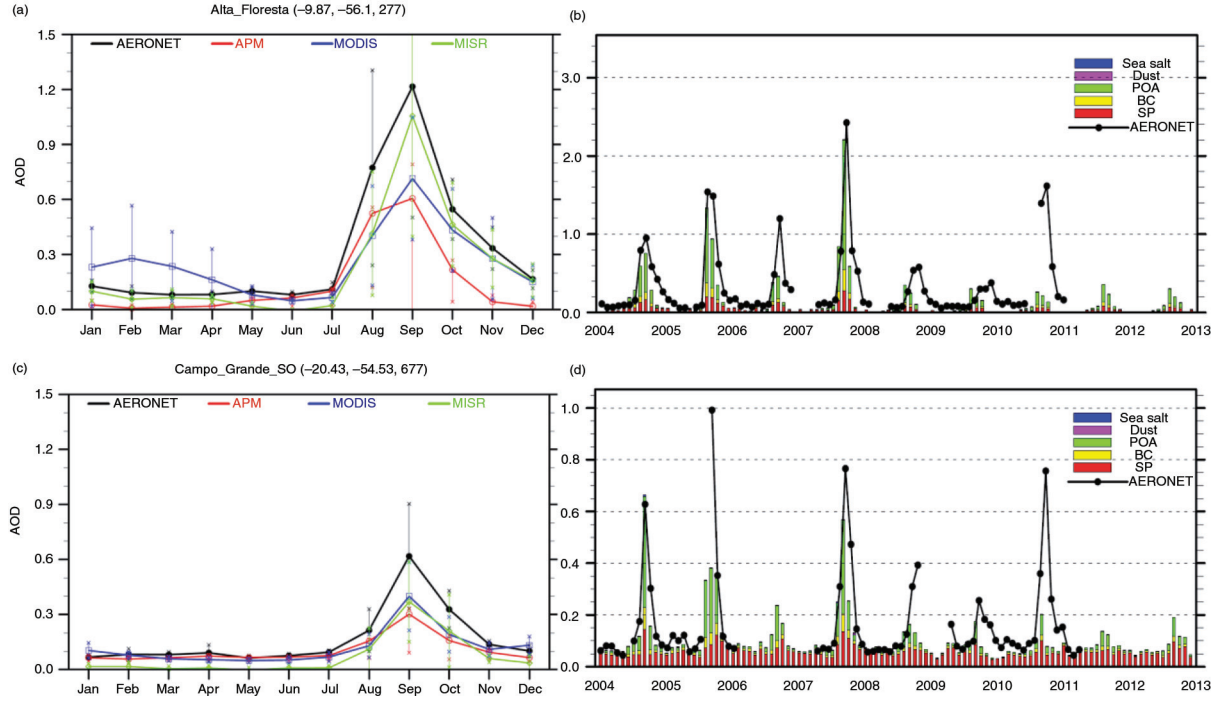


Fig. 10. Same as Fig. 4 but for AERONET site Alta_Floresta and Campo_Grande_SO over South America.

observations, which is also clearly shown in Fig. 9 for the two sites, Mongu (15.25S, 23.15E) and Skukuza (24.99S, 31.58E).

The site Mongu, located in a savannah region, is a mix of open woodland and grassland. The peak AOD occurs in autumn (Fig. 9a and c) during the dry season, and most of AOD is contributed from POA (Fig. 9b and d), which is the main aerosol type emitted from biomass burning. It is also shown that the model can reproduce the inter-annual variability observed in AERONET. The site Skukuza is a bit far away from the centre of savannah region, but affected by biomass burning. The seasonal cycle exhibit the similar feature as in Mongu but with much lower magnitude.

3.2.6. South America. Statistics from seven sites in South America (Table 7) show an overall low bias of the model compared to AERONET and MODIS/MISR in the sites with stronger biomass burning emission. Due to relatively small bias in the sites far away from biomass burning sources, the averaged modelled AOD for this region is slightly lower than AERONET and MODIS/MISR, with the differences as of -0.09 and -0.05 . The correlation coefficients in the site with high observed AOD between the model and AERONET and MODIS/MISR pass the statistically significance t -test.

Similar to South Africa, the peak AOD in site Alta_Floresta (9.87S, 56.20W) and Campo_Grande_SO (20.43S, 54.53W) occurs in autumn (Fig. 10a and c) during the biomass burning seasons. But the burning season in South America (Fig. 10b and d) is shorter compared to South Africa. The inter-annual variability, which is found mainly controlled by the magnitudes in autumn in South America, is overall captured very well by the model. The model tends to underestimate the AOD during biomass burning seasons. One possible reason could be due to coarse spatial resolution in the model. It also possibly implies that emission inventories of biomass burning need to be improved.

4. Summary and discussion

In this study, we use multi-year AOD data from the AERONET ground-based observations, and MODIS, MISR and SeaWiFS satellite retrievals, to evaluate the performance of a size-resolved global aerosol model GEOS-Chem-APM, with respect to the magnitudes, seasonal and inter-annual variability around the globe. The GEOS-Chem-APM is one of the 16 global aerosol models participated in AeroCom phase II direct aerosol effect experiment. The global annual mean total and anthropogenic AODs based on GEOS-Chem-APM are close to the 16-model mean values and, thus, can be considered as a representative AeroCom II model.

Time series of global mean of AOD from the model is overall consistent with MODIS, MISR and SeaWiFS, implying the regions with strong AOD, which dominate the global mean, are captured by the model. However, the global mean AOD from the model in clear sky conditions (cloud cover less than 0.25) is lower than satellite observations, particularly MODIS and MISR. There exists large bias in global mean AOD in all sky among 16 AeroCom II global aerosol models, ranging from 0.07 to 0.17. Considering the AOD in all sky is roughly 30% higher than clear sky, the corresponding AODs appear to be much lower than satellite observations. It is found that the low bias of global mean from the simulation is mostly due to the significant low bias over ocean, while the modelled AOD is generally good over land, particularly over the major anthropogenic emissions regions. The comparisons between the model and the observations over 72 sites which have at least 36 months data available and representative of high spatial domain (300km) from 618 AERONET sites show that the modelled AOD is overall lower relative to AERONET, MODIS, MISR and SeaWiFS.

To evaluate the model simulation in various regions, and identify the seasonal and inter-annual variation, we chose six representative regions for quantitative analysis, covering major anthropogenic emission regions, biomass burning regions and dust regions. The statistical analyses for these regions are performed, and seasonal and inter-annual variability in two example site of each region are explored. The main findings are summarised as follows:

- (1) Over major anthropogenic emission regions including North America, Europe and East Asia, the model overall agrees well with the observations, with a slightly lower AOD compared to the AERONET, MODIS/MISR and SeaWiFS observations. Over biomass burning regions, such as South Africa and South America, the modelled AOD is systematically lower than the observations. In contrast, over dust regions, for example, North Africa, the modelled AOD is slightly higher than observations. It may suggest that accurate emission inventory or parameterisation is critical to determine the modelled AOD since better agreements are achieved in industrial regions in which emission sources are relatively well understood and documented.
- (2) The GEOS-Chem-APM is able to reproduce the observed seasonal cycle over selected AERONET sites in various regions, implying the model captures the dominant aerosol species. Also, the model can overall capture the inter-annual variability, especially over South Africa and South America, where the largest inter-annual variability are found compared to the other regions. It appears that the simulated

inter-annual variability over the major industrial regions in NH is not so significant compared to AERONET.

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