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Atmospheric Measurement Techniques Discussions

Comparison of AOD between CALIPSO and MODIS: significant differences over major dust and biomass burning regions

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Abstract

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) provide, for the first time, global vertical profiles of aerosol optical properties, but further research is needed to evaluate the CALIPSO products. In this study, we employed about 6 yr (2006–2011) of CALIPSO level-3 monthly mean gridded aerosol optical depth (AOD) products (daytime and nighttime), for cloud free conditions, to compare with the MODIS Terra/Aqua level-3 monthly mean AOD dataset for the same time period. While the spatial distribution and seasonal variability of CALIPSO AOD is generally consistent with that of MODIS, CALIPSO is overall lower than MODIS as much more of the CALIPSO data is smaller than 0.1, while more of the MODIS data is greater than 0.1. We will focus on four regions that have large systematic differences: two over dust regions (the Sahara and Northwest China) and two over biomass burning regions (South Africa and South America). It is found that CALIPSO AOD is significantly lower than MODIS AOD over dust regions during the whole time period, with a maximum low bias of 0.3 over the Saharan region, and 0.25 over Northwest China. For biomass burning regions, CALIPSO AOD is significantly higher than MODIS AOD over South Africa, with a maximum high bias of 0.25. Additionally CALIPSO AOD is slightly higher than MODIS AOD over South America for most of the time period, with a few exceptions in 2006, 2007, and 2010, when biomass burning is significantly stronger than during other years. The results in this study indicate that systematic biases of CALIPSO relative to MODIS are closely associated with aerosol types, which vary by location and season. Large differences over dust and biomass burning regions may suggest that assumptions made in satellite retrievals, such as the assumed lidar ratios for CALIPSO retrievals over dust and biomass burning regions, or the surface reflectance information and/or the aerosol model utilized by MODIS algorithm, are not appropriate. Further research is needed to narrow down the exact source of bias in order to improve the satellite retrievals.

1 Introduction

Aerosols play an important role in global climate change by scattering and/or absorbing radiation and altering cloud properties. However, estimation of the radiative forcing by aerosols is very uncertain due to a lack of knowledge of the microphysical and optical properties of aerosol particles and their non-homogeneous spatial distribution. In the last few decades, aerosol properties have been studied by conducting intensive field campaigns. However, field observations are generally limited in temporal and spatial coverage. In contrast, satellite observations provide long term, uninterrupted spatial coverage, an effective tool for monitoring the global aerosol distribution and properties. Aerosol optical depth (AOD) has been provided by various satellite sensors such as AVHRR, TOMS, MODIS, and MISR. Due to these products being passive sensor measurements, they mainly provide total column values with little information on the vertical distributions of aerosols, which are crucial for the radiative effect of aerosols.

The launch of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) provides a global profile that complements passive sensors when observing aerosols and clouds from space. Currently there are only limited validations of CALIPSO aerosol profiles against ground-based lidar measurements (Kim et al., 2008; Mamouri et al., 2009; Wu et al., 2011), thus it is difficult to validate the vertical profiles with the global coverage. However, it is feasible to compare the vertically integrated extinction, i.e. aerosol optical depth (AOD), with observations from other satellite sensors, such as MODIS, MISR as well as the ground-based AERONET. Such comparisons will provide valuable insights into the performance of CALIPSO profile retrievals. Yu et al. (2010) employed CALIPSO observations from June 2006 to November 2007 to compare with GOCART model simulations and MODIS retrievals. Their comparison indicated that CALIPSO AOD is generally lower than MODIS AOD in most regions. Kittaka et al. (2011) compared AOD at 532 nm, derived from CALIPSO version 2 data, with MODIS-Aqua AOD at 550 nm from June 2006 through August 2008. They found that AOD from CALIPSO has a small global mean bias relative to MODIS Collection

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5. Redemann et al. (2012) assessed the consistency between instantaneously collocated level-2 AOD from MODIS-Aqua and CALIPSO version 2 and 3, and found that CALIPSO V3 (by comparison to V2) is generally in better agreement with MODIS AOD. Schuster et al. (2012) compared Level 2 version 3 CALIPSO AOD with measurements at 147 AERONET sites and found a CALIPSO bias of −13 % relative to AERONET for the 3-yr period from June 2006 to May 2009.

The studies above are all based on CALIPSO level-2 products. The CALIPSO team recently released the level 3 monthly mean gridded dataset, which provides the total AOD and vertical profile of aerosol extinction in a global grid box to facilitate comparison with model validation. In this study, we compare nearly 6 yr of CALIPSO AOD data (June 2006 through 2011) with AOD from MODIS. In contrast to the previous studies, we not only compare global scale CALIPSO and MODIS AOD, but we also analyze the large systematic AOD differences over two dust and two biomass burning regions. Combined with the GEOS-Chem-APM model simulated optical depth for each aerosol component, we investigate the differences between CALIPSO and MODIS by examining seasonal variability and inter-annual variation.

This paper is organized as follows. In Sect. 2, descriptions of AOD data from CALIPSO and MODIS are outlined. In Sect. 3, the results of comparisons between CALIPSO and MODIS AOD are described, with a focus on the comparisons over major dust and biomass burning regions. A summary is given in Sect. 4.

2 Satellite AOD measurements

2.1 CALIPSO

CALIPSO was launched on 28 April 2006 with an equator-crossing time of about 01:30 p.m. and 01:30 a.m. and a 16-day repeating cycle (Winker et al., 2010). The main objective of the CALIPSO mission is to provide a global, multi-year data set of cloud and aerosol spatial and optical properties from which to assess uncertainties of

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aerosol direct and indirect effects on climate forcing and cloud-climate feedback. The Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument, on CALIPSO, is a two-wavelength (532 and 1064 nm), polarization lidar. CALIOP provides substantial and unique information on vertical and geographical distributions of clouds and aerosols. CALIOP conducts nearly continuous observations of height-resolved attenuated backscatter over the globe (Sassen, 2000; Winker et al., 2003). In this study, we use level 3 monthly mean gridded ($2^{\circ} \times 5^{\circ}$) products which provide the aerosol extinction coefficient at 532 nm, column aerosol optical depth, and aerosol layer properties in the global grid cell derived from the CALIPSO lidar level 2 aerosol profile product. AOD statistics are reported for four sky conditions: all sky, cloud-free, above cloud and combined. For this study we use the dataset for cloud-free condition and both the daytime and nighttime.

2.2 MODIS

The Moderate Resolution Imaging Spectroradiometer (MODIS) measures radiances at 36 wavelengths from 0.41 to 14 µm. A 2330-km viewing swath provides near-global coverage every day. There are two MODIS sensors (King et al., 2003) observing Earth from polar orbit aboard NASA's Terra (since February 2000) and Aqua (since June 2002) satellites. The different equatorial crossing times of the two satellites, with Terra crossing at 10:30 LT and Aqua at 13:30 LT, may introduce differences in the retrieved aerosol products due to different viewing geometries returning different distributions of scattering angles. Therefore, we use the retrieved AOD products from both Terra and Aqua in this study. The MODIS AOD data (Kaufman et al., 1997; Remer et al., 2005) is taken from the monthly mean level-3 products from Terra (MOD08_M3.051) and Aqua (MYD08_M3.051) with a $1^{\circ} \times 1^{\circ}$degree resolution, and combined with the deep blue product, specifically retrieved for the AOD over desert regions.

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3 Comparisons of AOD between CALIPSO and MODIS

For the comparisons, MODIS monthly mean AOD data ($1^\circ \times 1^\circ$) have been interpolated into the same grid cell as CALIPSO ($2^\circ \times 5^\circ$) using a simple linear interpolation method. The results are presented below.

3.1 CALIPSO and MODIS AOD

Figure 1 shows 6-yr (2006 to 2011) averaged CALIPSO daytime AOD at 532 nm (left column), MODIS Terra AOD at 550 nm (middle column) and their differences (right column) in January, April, July, and October. Overall, both CALIPSO and MODIS show similar spatial distributions, e.g. the maximum AOD occurs over North and West Africa due to Saharan dust events, the maximums over East Asia, India, Europe and North America are mainly due to industrial based fossil fuel emissions, and the South Africa and South American peaks are due to biomass burning. The seasonal variability from CALIPSO is also consistent with MODIS. For instance, both satellite datasets show high magnitudes over Central-West Africa in January due to biomass burning, and then shift northward in April and July due to increasing dust events, and relatively low values over North Africa in October. The seasonality of biomass burning in South Africa and South America is also evident from both CALIPSO and MODIS. However, CALIPSO is systematically lower than MODIS over ocean, especially over the Southern Ocean, which is clearly shown in the right column of Fig. 1.

Figure 2 presents the results from CALIPSO nighttime AOD at 532 nm and MODIS Aqua AOD at 550 nm. Although there are some minor differences between CALIPSO daytime and nighttime and between Terra and Aqua, no significant differences were found when looking at 6-yr averaged monthly mean data. Therefore the differences of AOD between CALIPSO nighttime and MODIS Aqua are similar to the ones shown in Fig. 1. We also compare the CALIPSO nighttime AOD to MODIS Terra, and CALIPSO daytime to MODIS Aqua, and found similar features (figure omitted).

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The averaged results based on the monthly mean AOD data starting from 2006 to 2011 (Table 1) show that the CALIPSO AOD during the study period at daytime (0.103 over land, 0.087 over ocean) is much lower than MODIS AOD (0.190 over land, 0.144 over ocean). The CALIPSO AOD at nighttime (0.150 over land, 0.139 over ocean) is 46 % and 60 % higher than daytime over land and ocean respectively, which is 30 % lower than MODIS over land but very close to MODIS over ocean. The overall low CALIPSO AOD is possibly because the CALIPSO algorithms only retrieve extinction and optical depth within detected layers (Winker et al., 2009). Thus, tenuous aerosol, which is not detected, will not be retrieved. This always decreases the retrieved AOD.

Figures 3 and 4 present the linear regression analysis based on the monthly mean AOD data from 2006 to 2011 for CALIPSO daytime and CAIPSO nighttime versus MODIS Terra and Aqua respectively. The total sample number (N), linear regression equation, and correlation coefficient (R) are included in the scatter plots. The inserted plots within each scatter plot summarize the frequencies of AOD in the specific ranges. It is shown that there are less sample numbers at nighttime than daytime because of missing data for the nighttime product. The correlation coefficients in all cases range from 0.55 to 0.60, with no significant differences. The inserted plots indicate that the highest frequency of CALIPSO AOD lies in the range less than 0.1, while the highest frequency of MODIS AOD falls within the 0.1–0.2 range. For all the ranges with AOD larger than 0.2, the frequency of MODIS is always higher than that of CALIPSO, thus, CALIPSO AOD is consistently lower than MODIS for both daytime and nighttime cases over land and ocean. Comparing Figs. 3 and 4 also shows that, over land, more of the CALIPSO, but less of the MODIS, data lies in the 0.1–0.2 range at nighttime than daytime, leading to better a consistency between CALIPSO and MODIS AOD at nighttime. Over ocean, more than 90 % of the data are smaller than 0.2 for both CALIPSO and MODIS. However, most CALIPSO data are smaller than 0.1, while most MODIS data are greater than 0.1, highlighting the low bias of CALIPSO relative to MODIS.

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3.2 Significant difference over major dust and biomass burning regions

Although CALIPSO AOD is generally lower than MODIS AOD, it is interesting to see that it is higher in some regions (positive values in the right column of Figs. 1 and 2), specifically over regions with stronger biomass burning (e.g. South Africa). It is also shown that CALIPSO AOD is substantially lower than MODIS AOD over major dust regions (negative values in the right column of Figs. 1 and 2), especially over the Sahara dust regions and Northwest China. Next, we analyze in detail the large systematic difference over these regions (marked in the red rectangles in Figs. 1 and 2). The GEOS-Chem-APM model simulations are also employed to assist the analysis.

3.2.1 GEOS-Chem-APM model

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) (e.g. Bey et al., 2001). 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 with up-to-date key emission inventories (e.g. Guenther et al., 2006; Bond et al., 2007).

The APM model, incorporated into GEOS-Chem by Yu and Luo (2009), is an advanced multi-type, multi-component, size-resolved microphysics model. 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 sulfate, ammonia, nitrate and SOAs), black carbon (BC), primary organic carbon (OC), sea salt (SS), and mineral dust (DS). The current GEOS-Chem-APM employs 40 bins for SP to cover the dry diameter size range of 0.0012 µm to 12 µm, 20 bins for SS to cover the dry diameter size range of 0.012 µm to 12 µm, and 15 bins for DS particles to cover size range of 0.03 µm to 50 µm. In addition, two log-normal modes with one for fossil fuel (median diameter of 60 nm) and another for biomass burning (median diameter of 150 nm) are employed to represent hydrophobic BC, while another two log-normal modes are used for hydrophilic BC. Similarly, 4 log-normal modes are used to represent hydrophobic and hydrophilic OC. The formation of new particles is calculated with the ion-mediated nucleation mechanism (Yu, 2010). The contributions of nitrate, ammonium, and SOAs to secondary particle growth are considered. The coating of secondary species on primary particles (sea salt, BC, OC, and dust) is explicitly simulated. The model has been validated with a large number of relevant aerosol measurements (Yu and Luo, 2009; Yu et al., 2010, 2012; Ma et al., 2012).

3.2.2 Significant difference over major dust and biomass burning regions

Figure 5 shows the time series of monthly mean AOD from CALIPSO daytime/nighttime and MODIS Terra/Aqua during the period from 2006 to 2011 over the Sahara, Northwest China (NW China), South Africa, and South America. Over the Sahara, it is clearly shown that MODIS AODs (both Terra and Aqua) are always higher than CALIPSO AODs (daytime and nighttime). In addition, MODIS/Aqua is generally higher than MODIS/Terra while CALIPSO/nighttime is usually higher than CALIPS/daytime, with the largest bias during the summer. Over NW China, although AOD is much lower compared to the Sahara, similar behavior can be found except the largest bias of CALIPSO relative to MODIS occurs in spring. Over South Africa, CALIPSO AOD is systematically higher than MODIS AOD for each year, especially during the months from July to September. Over South America, the differences between CALIPSO and MODIS are not as significant and systematic as shown in other regions. The AOD over this region shows significant inter-annual variability compared to the other regions, i.e. there are much larger magnitudes in the years 2006, 2007 and 2010 than the other years. It is interesting to note that the largest bias over South America occurs during the months July through September in years 2006, 2007 and 2010 when AOD is substantially higher.

As discussed above, it appears that the largest bias of CALIPSO relative to MODIS occurs during the active dust seasons over the major dust regions, i.e. summer over the Sahara, and spring over NW China. The pattern also applies to the active biomass

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burning seasons over major biomass burning regions, i.e. July through September. Below, we combine GEOS-Chem-APM simulated AOD for each aerosol component to examine the results shown above. It should be pointed out that GEOS-Chem-APM derived AODs of primary particles include the contribution of the secondary species coated on them, which are explicitly tracked in the model (Yu et al., 2012).

The GEOS-Chem-APM simulated aerosol concentrations have been compared with observations, while optical properties have been validated against ground observations (AERONET, Holben et al., 1998) and satellite retrievals (MODIS and MISR). The model can reasonably reproduce the spatial distribution and seasonal variations of aerosol concentrations and optical depth (Ma et al., 2012; Yu et al., 2012). Figures 6–9 show the time series of GEOS-Chem-APM simulated aerosol AOD for SP, SS, DS, BC, and OC, together with the time series of differences of AOD (ΔAOD) between CALIPSO daytime/nighttime (represented by CALD/CALN) and MODIS Terra/Aqua (represented by MODT/MODA). It is shown in Fig. 6 that total AOD is dominated by DS over the Sahara, while other aerosol components, such as SP, SS, OC, and BC, contribute only a small amount to the total AOD. The large bias of CALIPSO relative to MODIS is consistent with the peak of DS AOD, with the largest bias at around −0.3 during the summer seasons. Compared to the Saharan region, DS contributes a relatively small fraction of AOD over NW China (Fig. 7), but a large fraction from SP and some contributions from OC and BC. Therefore, while the largest ΔAOD is roughly consistent with the peak of DS AOD, the magnitude is generally less than −0.25. The results over the Sahara and NW China indicate that satellite retrievals appear to have a large bias over the dust regions. This has been supported by the study of Schuster et al. (2012), in which they compared CALIPSO AOD with AERONET ground observations and found that the relative and absolute bias are reduced if the data containing dust is omitted. One possible reason for the difference is the uncertainty of the assumed lidar ratio over dust regions for CALIPSO retrievals.

The results over South Africa (Fig. 8) show that secondary particles (SP) contribute the most to total AOD over this region, and that OC and BC are the second

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greatest contributors to this total. The consistent inter-annual cycle between SP AOD and OC/BC AOD implies that they all come from similar sources (biomass burning). Therefore the largest ΔAOD between CALIPSO and MODIS corresponds to the peak of OC/BC AOD, which occurs during the biomass burning season from July to September. In contrast to South Africa, over South America (Fig. 9) SP contributes to a much greater fraction of total AOD, while OC/BC contributes much less. The magnitude of ΔAOD is systematically low compared with the magnitudes over South Africa, with a slightly positive bias during most of the time period. A few exceptions occur in the biomass burning seasons during the years 2006, 2007, and 2010, where the corresponding ΔAOD is over −0.20. It is noticed that they are consistent with the highest OC/BC AOD fractions of the total AOD for the years 2006, 2007, and 2010. The results indicate that there exist significant differences between CALIPSO and MODIS retrievals for the strong biomass burning seasons and years, suggesting that the satellite retrieval algorithms need to be improved in the case of strong biomass burning events.

4 Summary and discussion

In this study, we compared CALIPSO daytime/nighttime AOD at 532 nm and MODIS Terra/Aqua AOD at 550 nm by using nearly 6 yr satellite retrieval data starting from June 2006 through the end of 2011. It is found that CALIPSO AOD is generally lower than MODIS AOD, whether day or nighttime, Terra or Aqua products are used. The low bias of CALIPSO relative to MODIS is caused by low frequencies of CALIPSO in the larger AOD ranges, and a much high frequency of values smaller than 0.1.

It is interesting to find that CALIPSO AOD is substantially higher than MODIS AOD over major biomass burning regions (e.g. South Africa) during the biomass burning season (July to September), but lower than MODIS over major mineral dust regions (e.g. the Sahara) and during the active dust season (summer over Sahara). We employed about 6 yr of CALIPSO and MODIS AOD data, combined with the GEOS-Chem-APM simulated aerosol AOD for each aerosol component during the same time period,

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to investigate the time series over the four regions including the Sahara, NW China, South Africa, and South America. Our analysis shows that CALIPSO AOD is systematically lower than MODIS AOD over the Sahara and NW China, with the maximum differences occurring during the active dust seasons, i.e. summer over the Sahara, and spring over NW China. Since dust particles contribute less to the total AOD over NW China than the Sahara for each year, the bias of CALIPSO relative to MODIS is smaller over NW China. While the contribution from SP is quite large for both South Africa and South America, the OC/BC contribution is much larger over South Africa than South America, which leads to a larger bias for CALIPSO relative to MODIS. The differences between CALIPSO and MODIS over South America are generally small, except during the biomass burning seasons with exceptionally high OC/BC contributions in 2006, 2007, and 2010.

Our study indicates that satellite retrieval algorithms, e.g. lidar ratios used in CALIPSO retrievals, or assumptions made in MODIS algorithms, such as single scattering albedo or other aspects utilized by the aerosol models, may not work well over the strong dust and biomass burning regions and/or during their active seasons. Further research is needed to identify the reasons for this bias and to improve the satellite AOD retrievals.

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Table 1. Global averaged AOD from Level 3 CALIPSO daytime/nighttime and MODIS Terra/Aqua over land and ocean for the data starting from June 2006 until 2011.

	land	ocean
CALIPSO		
day	0.103	0.087
night	0.150	0.139
MODIS		
Terra	0.187	0.148
Aqua	0.193	0.140

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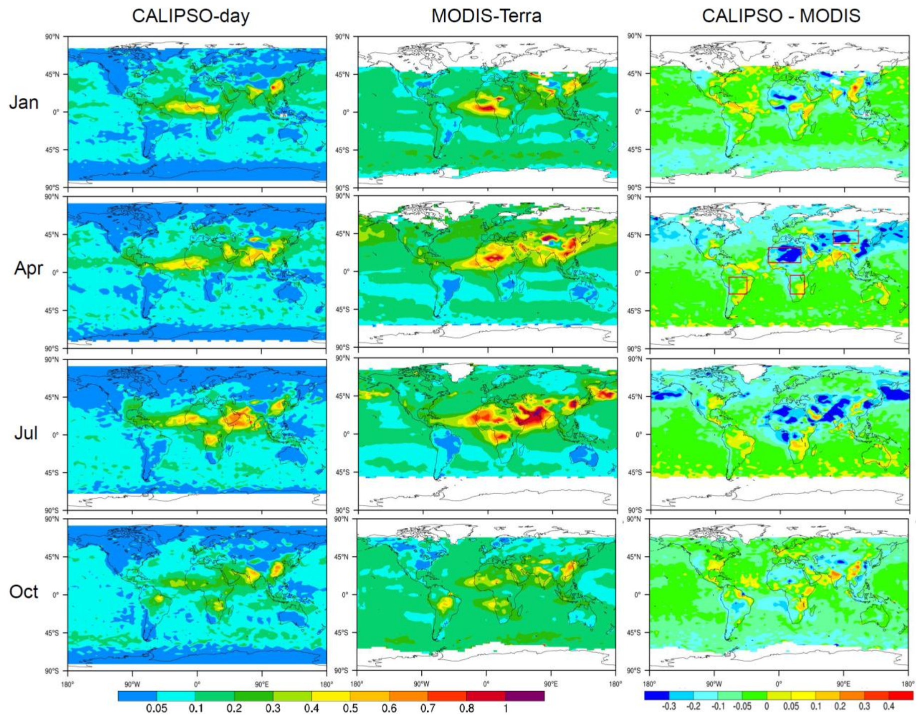

Fig. 1. Multi-year averaged (2006–2011) aerosol optical depth (AOD) from CALIPSO daytime, MODIS Terra, and their differences in January, April, July, and October. The red rectangles shown in the right column plot mark the regions for the Sahara, Northwest China, South Africa, and South America.

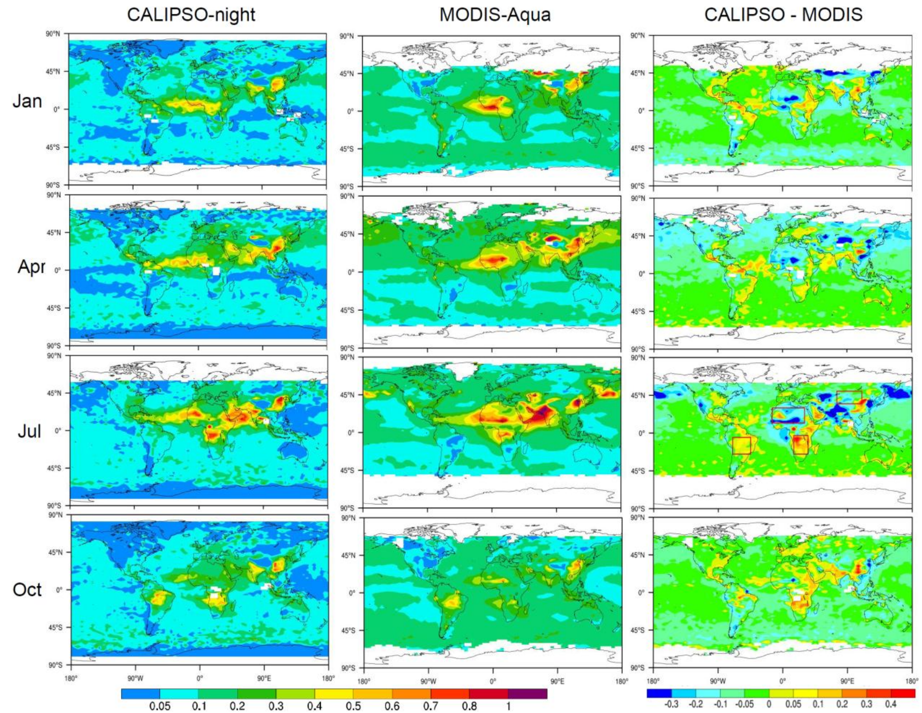

Fig. 2. Same as Fig. 1 but for the data from CALIPSO nighttime and MODIS Aqua.

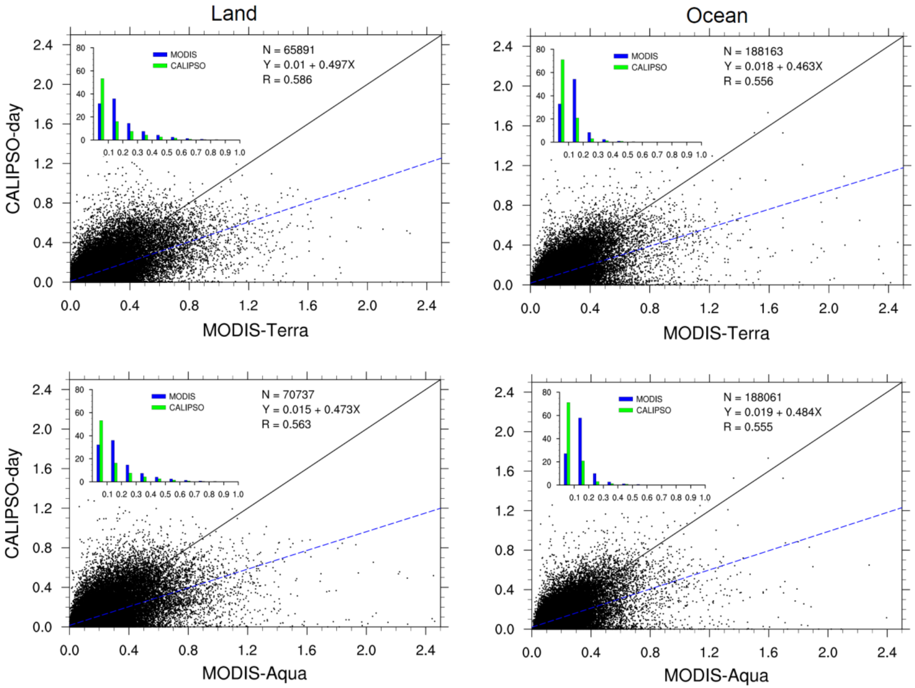

Fig. 3. CALIPSO daytime AOD at 532 nm compared with MODIS Terra/Aqua AOD at 550 nm for the whole time period starting from June 2006 to 2011. Data are separated according to the land or ocean. The solid line and the dashed lies are the 1 : 1 and the linear regression lines respectively. Text at the top describes the number of samples (*N*), the regression curve, and correlation coefficient (*R*). The inserted plots show the frequency (%) of CALIPSO and MODIS AOD occurring in the specific ranges in 0.1 intervals.

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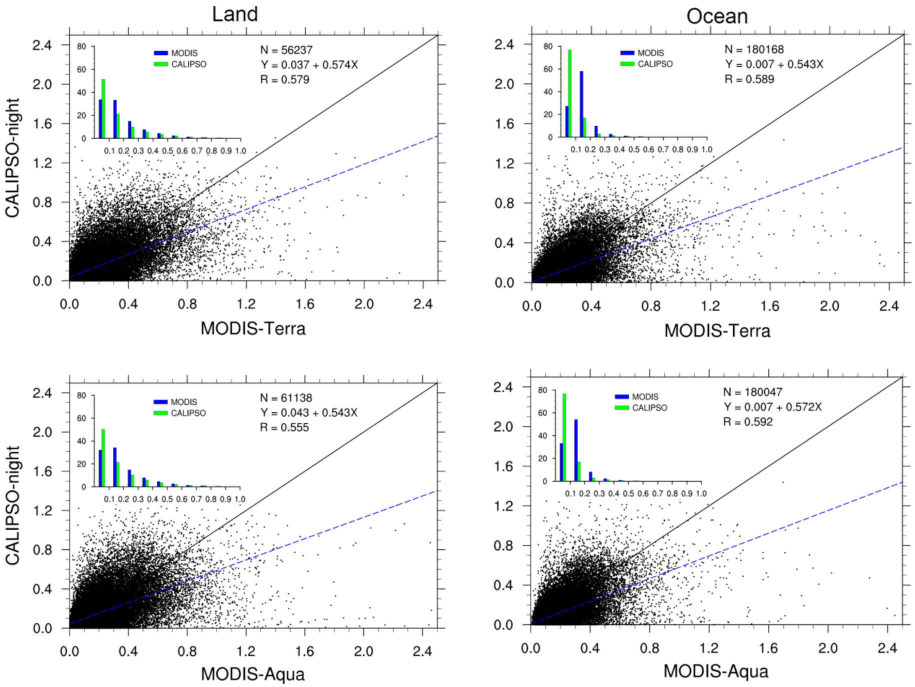

Fig. 4. Same as Fig. 3 but for CALIPSO nighttime data.

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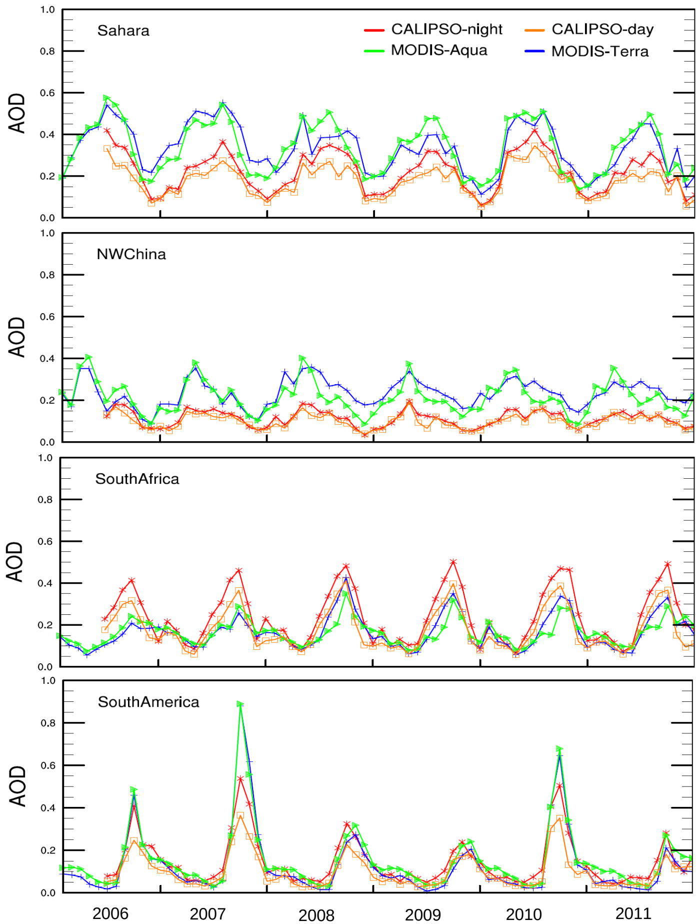

Fig. 5. Time series of AOD from CALIPSO daytime/nighttime and MODIS Terra/Aqua during the year from 2006 to 2011 over the Sahara, Northwest China, South Africa, and South America.

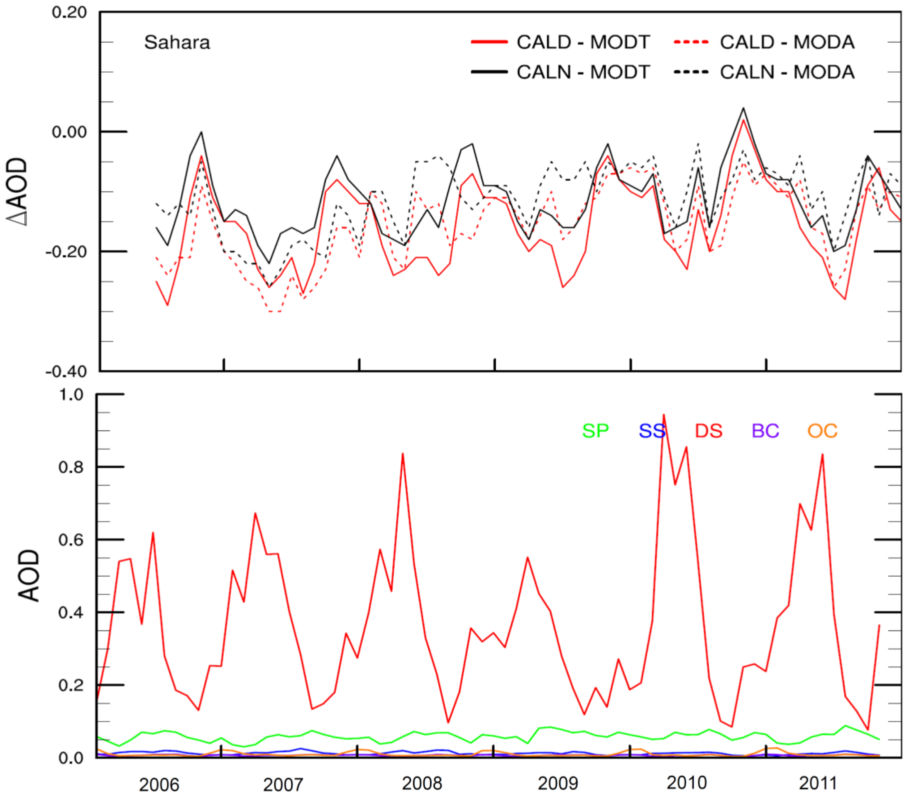

Fig. 6. Top plot shows the differences of AOD (ΔAOD) between CALIPSO daytime (CALD), nighttime (CALN), and MODIS Terra (MODT), Aqua (MODA). Bottom plot shows the GEOS-Chem-APM simulated AOD for SP (secondary particle), SS (sea salt), DS (mineral dust), BC (black carbon), and OC (organic carbon). The results shown here are for the Sahara.

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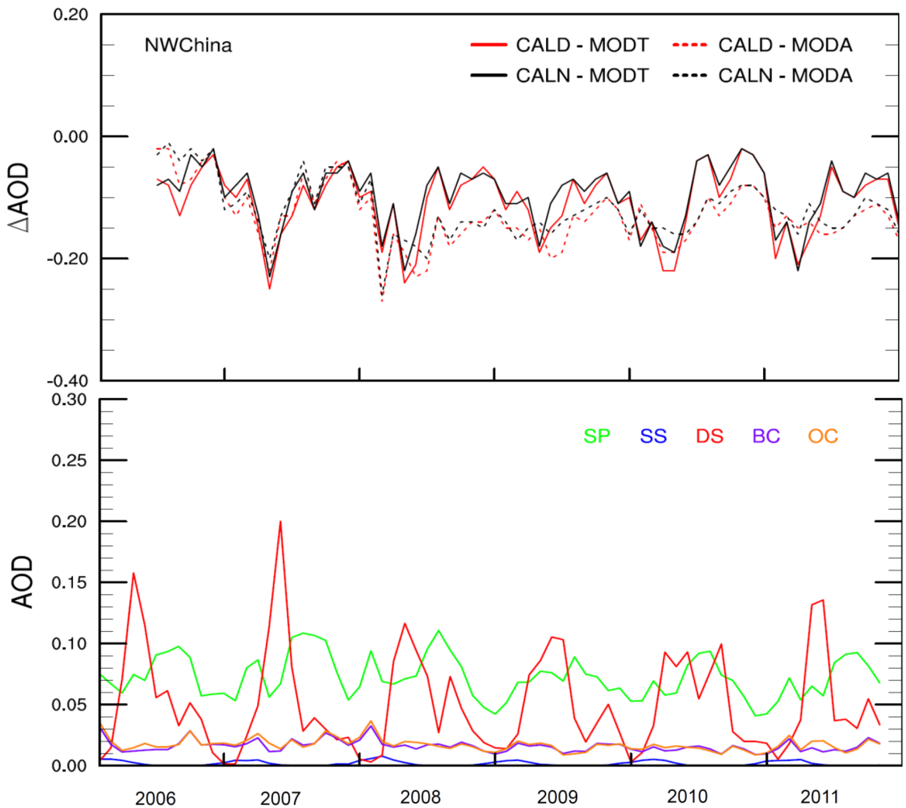

Fig. 7. Same as Fig. 6 but for Northwest China.

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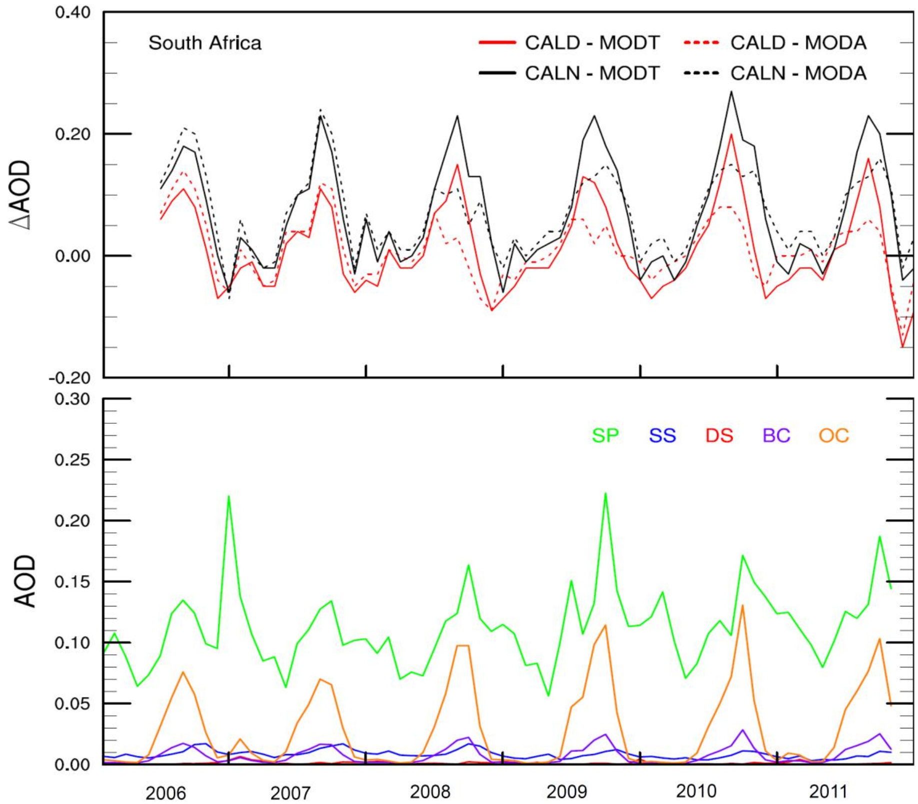

Fig. 8. Same as Fig. 6 but for South Africa.

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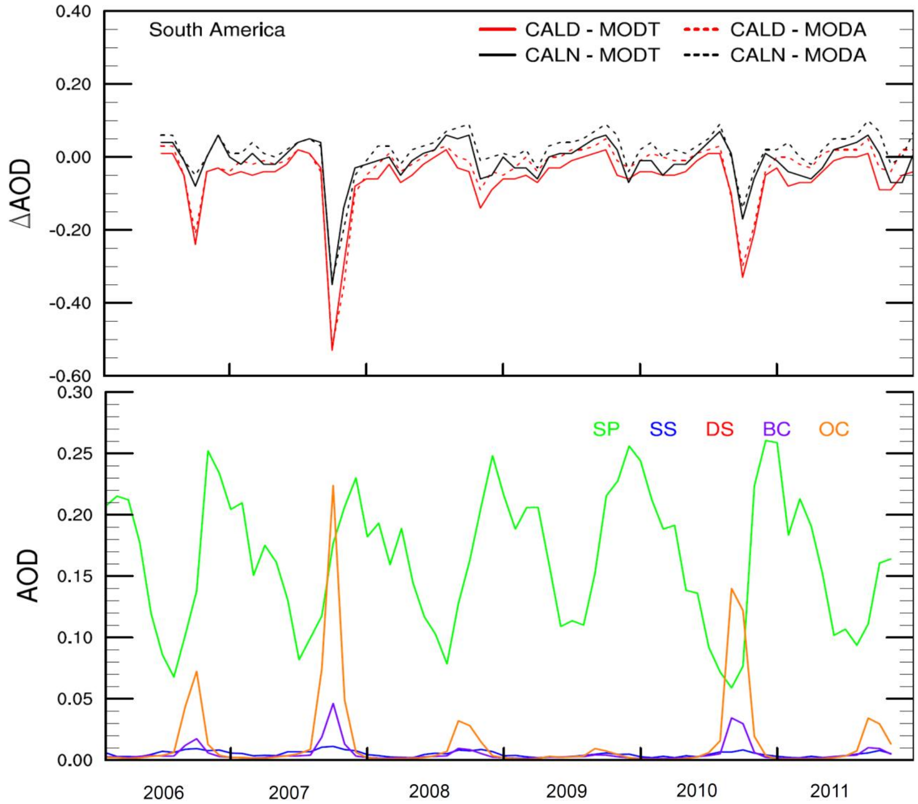

Fig. 9. Same as Fig. 6 but for South America.

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