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Atmospheric Measurement Techniques

Intercomparison of column aerosol optical depths from CALIPSO and MODIS-Aqua

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Abstract. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) is carried on the CALIPSO satellite and has acquired global aerosol profiles since June 2006. CALIPSO is flown in formation with the Aqua satellite as part of the A-train satellite constellation, so that a large number of coincident aerosol observations are available from CALIOP and the MODIS-Aqua instrument. This study compares column aerosol optical depth at 0.532 µm derived from CALIOP aerosol profiles with MODIS-Aqua 0.55 µm aerosol optical depth over the period June 2006 through August 2008. The study is based on the CALIOP Version 2 Aerosol Layer Product and MODIS Collection 5. While CALIOP is first and foremost a profiling instrument, this comparison of column aerosol optical depth provides insight into quality of CALIOP aerosol data. It is found that daytime aerosol optical depth from the CALIOP Version 2 product has only a small global mean bias relative to MODIS Collection 5. Regional biases, of both signs, are larger and biases are seen to vary somewhat with season. Good agreement between the two sensors in ocean regions with low cloudiness suggests that the selection of lidar ratios used in the CALIOP aerosol retrieval is sufficient to provide a regional mean AOD consistent with that retrieved from MODIS. Although differences over land are observed to be larger than over ocean, the bias between CALIOP and MODIS AOD on a regional-seasonal basis is found to be roughly within the envelope of the MODIS expected uncertainty over land and ocean. This work forms a basis for further comparisons using the recently released CALIOP Version 3 data.

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1 Introduction

Aerosols have important effects on Earth's radiation budget through the scattering and absorption of sunlight, as well as through influences on cloud properties through a variety of different physical mechanisms. Aerosols have many different sources, both natural and anthropogenic, and can be transported on global scales. Limitations in our ability to observe and characterize aerosols globally are responsible in part for the current uncertainties in predicting global climate change (Yu et al., 2006). We have greatly advanced our understanding of aerosol horizontal distributions using satellite observations from sensors such as AVHRR, TOMS, MODIS, and MISR. However, the vertical profile of aerosol still remains uncertain. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission was developed to provide a global profiling capability to complement current capabilities to observe aerosol and cloud from space.

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument, onboard the CALIPSO satellite, provides detection and characterization of aerosols and clouds using profiles of laser depolarization and 2-wavelength laser backscatter. The active laser technique provides high vertical resolution and allows retrieval of aerosol profiles above lower-lying clouds and below optically thin clouds, as well as in cloud-free conditions. CALIOP has been operating since June 2006 and has produced the first multi-year global record of the 3-dimensional distribution of aerosol (Winker et al., 2010). CALIPSO flies as part of the A-Train constellation along with the PARASOL, Aqua, Aura, and CloudSat satellites (Stephens et al., 2002). The A-train orbit is sun-synchronous, with an equator crossing time of about 01:30 p.m. and a 98° orbit inclination.

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While the strength of CALIOP is aerosol profile measurements, global validation of CALIOP profiles is difficult. Relatively dense networks of groundbased lidars in Europe and Japan provide opportunities for regional validation, but there are almost no suitable lidar systems in the southern hemisphere or over the oceans. Further, the nadir-only measurement geometry limits the usefulness of ground sites which are located far from the CALIPSO ground track. Field campaigns involving airborne lidars are useful, but provide very limited spatial and temporal coverage. Aerosol optical depth (AOD) data from MODIS-Aqua provides a column constraint, however, and can be compared with AOD derived from CALIOP daytime profiles of aerosol extinction. While this is less than ideal, the MODIS Collection 5 AOD product has undergone extensive validation (e.g. Remer et al., 2005; Kahn et al., 2007) and data quality is well understood. Flying the CALIPSO and Aqua satellites in formation provides a large number of near-simultaneous, coincident aerosol observations with global coverage. Comparisons of AOD from MODIS and CALIOP characterize the CALIOP AOD product and also provide valuable insights into the performance of the CALIOP profile retrievals.

CALIOP Version 2 data products (Winker et al., 2009) reported the optical depths of aerosol layers, but column AOD was not reported until Version 3 (released in mid-2010). For this study, AOD at 0.532 µm was derived by vertically summing the aerosol layer optical depths in the CALIOP Version 2.01 5-km Aerosol Layer Product. These column AODs were then compared with AOD at 0.55 µm from MODIS-Aqua Collection 5. This paper presents an initial, statistical comparison, which illuminates characteristics of the CALIOP Version 2.01 aerosol product and also serves as a benchmark against which to compare the CALIOP Version 3 product. Other validation studies are underway, utilizing AOD measurements from AERONET and direct aerosol extinction profile measurements from airborne HSRL operated by NASA Langley Research Center (Hair et al., 2008). These studies will provide additional perspectives on CALIOP AOD data quality.

2 Measurements

Since the launch of the MODIS and MISR instruments in 1999, advanced satellite measurements have greatly increased our knowledge of the global distribution and properties of aerosols (Kaufman et al., 2002). MODIS provides daily near-global coverage and retrievals of AOD at several wavelengths over both ocean and land. Relative to previous satellite sensors used to retrieve aerosol, MODIS has provided improved spatial resolution, better spectral coverage, and improved calibration. Development of the AERONET network of groundbased sunphotometers has allowed an unprecedented degree of validation of aerosol retrievals from MODIS.

CALIOP, acquiring global aerosol observations since 2006, is complementary to MODIS in several ways. While CALIOP has a swath with essentially zero width, observing only along the sub-satellite point it acquires vertical profiles at two wavelengths (0.532 µm and 1.064 µm) and two orthogonal polarizations, with a vertical resolution of 30–60 m (Hunt et al., 2009). Analysis of the spectral and polarization diversity of the return signals, as a function of altitude, provides some skill in identifying aerosol type and also allows identification of columns which are inhomogeneous in terms of aerosol type (Omar et al., 2009). While the MODIS and CALIOP AOD retrievals rely on a number of assumptions and are subject to several sources of error, the retrieval methods are completely different and the CALIOP assumptions and sources of error are independent of those of MODIS. Thus, a comparison of the two AOD datasets can lead to insights into the strengths and limitations of both datasets.

2.1 MODIS

The Moderate Resolution Imaging Spectroradiometer (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. Different algorithms are used to retrieve AOD over ocean and over land. Over ocean, seven wavelengths (0.47, 0.55, 0.66, 0.86, 1.2, 1.6, and 2.12 µm) are used to retrieve aerosol optical depth and other aerosol properties (Tanré et al., 1997). These channels have spatial resolutions of 250 m or 500 m and calibration of the radiances is believed to be accurate to 2% or better. Radiances are grouped into nominal 10-km cells containing 20×20 pixels at 500-m resolution. All 400 pixels must be identified as ocean pixels for the ocean algorithm to be applied. If any land is contained within the cell the land algorithm is applied (Remer et al., 2005). After screening for clouds and marine sediments, the brightest 25% and darkest 25% of the remaining 500-m pixels are discarded. Retrievals are performed on the remaining pixels. To avoid errors due to sunglint, retrievals are performed only for pixels where the glint angle is greater than 40°. Outside the glint regions the water-leaving radiance is assumed to be negligible except at 0.55 µm where it is assumed to be 0.005. Wind speed is assumed to be 6 m s^{-1} everywhere.

Over land, AOD is retrieved at 0.47, 0.55, and 0.66 µm (Kaufman et al., 1997). As described above, the land algorithm is also used in coastal areas. The land algorithm only retrieves AOD over dark surfaces. Pixels containing snow/ice and cloudy pixels are masked out. Cloud mask quality flags (cf_land, cf_ocean) are included in the data product to indicate the fraction of cloudy pixels within the $10 \times 10\,km^2$ grid cells. $cf\_x = 3$ indicates greater than 90% cloudy pixels, while $cf\_x = 0$ indicates fewer than 30% cloud pixels. After masking, dark pixels are selected based on their reflectance at 2.12 µm. Surface reflectance must fall within the range 0.01 to 0.25 to be selected. Pixels are then sorted according to their reflectance at 0.66 µm and the darkest 20% and brightest 50% within each 10-km cell are discarded. Retrievals are performed on the remaining 30% of pixels.

The primary sources of uncertainty in MODIS AOD are instrument calibration errors, cloud-masking errors, incorrect assumptions on surface reflectance, and aerosol model selection (Remer et al., 2005; Levy et al., 2010). Retrievals are sensitive to assumptions on surface reflectance, especially over land where reflectance is higher and more variable than over ocean and near sunglint over ocean, and these effects become more important as AOD decreases. The AOD retrieval also depends on the fine and coarse mode aerosol models which are used. Selection of an inappropriate model can result in systematic AOD errors.

A number of validation studies have characterized uncertainties of the MODIS AOD product. Relative to AERONET AOD measurements, Remer et al. (2005) found that one standard deviation of MODIS-Terra AOD fell within the expected uncertainties of $\Delta\tau = \pm 0.03 \pm 0.05\tau$ over ocean and $\Delta\tau = \pm 0.05 \pm 0.15\tau$ over land. Ichoku et al. (2002) compared AOD from MODIS-Terra and MODIS-Aqua averaged over $50 \times 50\,\mathrm{km}^2$ boxes with Aeronet AOD. Redemann et al. (2006) compared MODIS AOD at the $10 \times 10\,\mathrm{km}^2$ scale of the Level 2 product with AERONET. Kahn et al. (2007) look at AOD retrievals over the ocean from the MODIS and MISR instruments on the Terra satellite to identify sources of systematic bias.

2.2 CALIOP

CALIOP measures elastic laser backscatter at 1.064 µm and the parallel and cross-polarized components of the 0.532 µm return signal, from which the linear depolarization is derived (Hunt et al., 2009). At the Earth's surface, the diameter of the laser footprint is 70 m, with successive footprints spaced by 333 m along the orbit track. The instrument has a fixed near-nadir view angle, so the measurements map a vertical curtain along the orbital path. The 0.532 µm backscatter signal is sampled every 30 m vertically from −0.5 km to 8.2 km. Between 8.2 km and 20.2 km altitude profiles are averaged to 60 m in the vertical and every three successive shots are averaged together to give a horizontal resolution of 1 km. The geolocated and altitude-registered Level 1 data are calibrated before being processed for Level 2 data products. Daytime measurements have a lower signal-to-noise ratio than at night owing to the noise added by the solar background illumination. Subtle diurnal differences in aerosol retrievals are caused by the use of different calibration algorithms for day and for night.

Briefly, extinction coefficients are retrieved in three steps: (1) backscatter profiles are searched for layers, with horizontal averaging varying from 1/3 km to 80 km; (2) identified layers are classified as cloud or aerosol; and (3) aerosol and cloud extinction profiles are retrieved, starting with the highest layers detected and working down to the Earth's surface (Winker et al., 2009 and references therein). Aerosol retrievals are performed on layers which have been horizontally averaged over 5 km, 20 km, or 80 km. Retrieval results are reported at 5-km horizontal scale in the 5-km Aerosol Layer Product. Retrieval results from 20-km or 80-km layers are repeated 4 times or 16 times in the 5-km product.

Extinction retrieval from an elastic backscatter lidar such as CALIOP is under-determined and an additional constraint is required. In the case of an elevated aerosol layer with clean (aerosol-free) air above and below the layer, the transmittance through the layer can be derived from the clear-air signals on either side of a layer. If the SNR of these clear-air signals is high enough, the measured transmittance can be used as the necessary constraint on the extinction retrieval (Young, 1995). For CALIOP, the SNR of the clear-air returns is rarely high enough during daytime (due to the solar background) to apply this technique. Therefore, for the daytime retrievals of interest here, an algorithm is used to estimate the "lidar ratio" (the ratio of particle extinction to 180-degree backscatter) from the 0.532 µm backscatter and depolarization signals (Omar et al., 2009), which provides the necessary constraint for the retrieval. Aerosol extinction is retrieved above clouds and below optically thin clouds, as well as in cloudfree columns, but only within identified aerosol layers (Young and Vaughan, 2009).

Significant sources of uncertainty in the CALIOP AOD retrieval are instrument calibration errors, errors in discriminating cloud from aerosol, and the failure to properly detect aerosol layers (Winker et al., 2009). Retrieval errors will also be produced by selection of an inappropriate aerosol model. For CALIOP, this amounts to selecting the appropriate lidar ratio. These errors may act to either increase or decrease AOD. The Version 2 CALIOP algorithms only retrieve extinction and optical depth within detected layers. Thus, tenuous aerosol which is not detected will not be retrieved, which always decreases the retrieved AOD.

The primary products compared in this paper are the 0.55 µm Optical_Depth_Land_and_Ocean from the MODIS-Aqua Level 2 aerosol data product (MYD04_L2), and the 0.532 µm aerosol layer optical depth from the CALIOP Level 2 5-km Aerosol Layer Product. The layer optical depth is summed over each aerosol layer in a 5-km the column to obtain the 0.532 µm column AOD. Corrections for the spectral dependence of AOD have not been applied. The difference in AOD between 0.55 µm and 0.532 µm is expected to be small (2–4% for typical Ångstrom exponents of 0.5 to 1), and much smaller than the differences observed in this study.

Figure 1 shows seasonally-averaged AOD from MODIS and from CALIOP observations, plotted on the same $5^\circ \times 5^\circ$ equal-angle grid. Daytime and nighttime AOD distributions from CALIOP are generally similar. Differences are due to a combination of differences between day and night sensitivity, differences in systematic calibration errors for day and night, differences in spatial sampling, and diurnal changes in the aerosol. Even though the MODIS and daytime

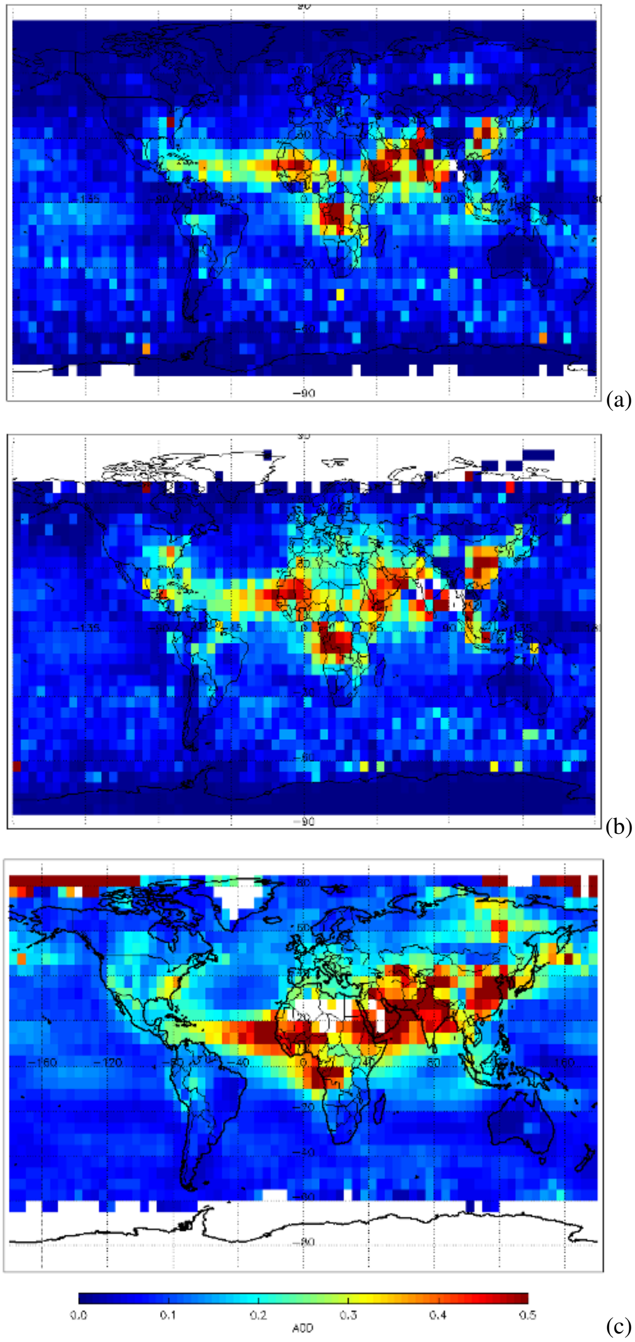

Fig. 1. Seasonal-mean AOD distributions for JJA 2006 from **(a)** CALIOP daytime retrievals; **(b)** CALIOP nighttime retrievals; and **(c)** MODIS retrievals.

CALIOP observations are simultaneous, a number of differences can be seen, due in part to differences in spatial sampling of the two instruments. CALIOP retrieves AOD over the Sahara desert and other bright surfaces where the MODIS product does not have any values. Daytime CALIOP measurements extend to higher southern latitudes than MODIS. Because CALIOP measurements are at nadir only, many fewer samples are acquired than from MODIS and many grid cells are sampled only about once per week, causing CALIOP AOD to appear to be noisier than MODIS AOD. Intense but intermittent aerosol events – such as dust storms or forest fires – may be missed by CALIOP, resulting in smaller grid-cell averages than MODIS AOD which better represents the seasonal-mean AOD at smaller spatial scales due to its daily coverage.

3 Method

Because of the large differences in spatial sampling, the remainder of the comparisons in this paper are based on simultaneous, co-located daytime CALIOP and MODIS observations. The comparison of matched observations reduces uncertainties from spatial and temporal differences of the observations, but greatly reduces the number of observations and so may compromise the geophysical representivity. First, MODIS 10-km cells coincident with CALIOP 5-km pixels are identified. After applying quality screening to the CALIOP aerosol data, layer optical depths are summed to derive 0.532 µm column AOD. Coincident CALIOP and MODIS AOD are then stored, along with cloud masking information.

3.1 Sampling geometry and co-location

CALIOP laser footprints have a diameter of 70 m with a center-center separation of about 330 m. Thus there are about 30 footprints within a $10 \times 10\,\text{km}^2$ MODIS grid cell. The orbits of the CALIPSO and Aqua satellites are controlled to keep the along-track separation at about 2 min and the relative cross-track error of the two satellite groundtracks is held to about 10 km. MODIS AOD is not retrieved for pixels over water where the sunglint angle is less than 40°. Therefore the plane of the CALIPSO orbit is shifted relative to the plane of the Aqua orbit to move the CALIOP footprint out of the sunglint region seen by MODIS. At the equator, the CALIPSO subsatellite point falls 215 km to the east of the Aqua subsatellite point. The cross-track bias between the two satellites decreases with increasing latitude, until the orbit planes intersect at the orbit turning points (82° N and 82° S). Thus the CALIOP footprint is continually moving cross-track with respect to the MODIS $10 \times 10\,\text{km}^2$ grid (Fig. 2). Spatially coincident CALIOP and MODIS AOD observations are identified when the distance between the center of a CALIPSO 5-km "pixel" and that of a MODIS pixel is less than 10 km. This criterion automatically selects time-coincident measurements (within 2 min). At the equator, the MODIS view angle to the CALIOP footprint is about 17°. During June-July-August (the worst case), the number of co-located AOD samples is limited in the northern mid-latitudes and subtropics because the CALIOP footprint falls

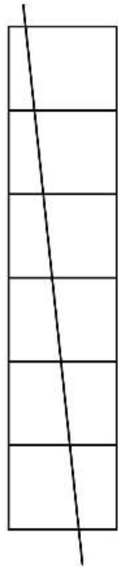

Fig. 2. Geometry of the MODIS 10-km cell vs. the CALIOP ground track.

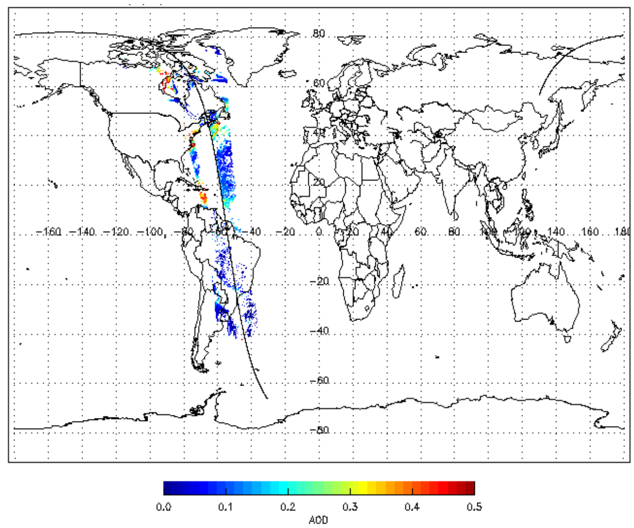

Fig. 3. CALIPSO ground-track superimposed on color-coded MODIS AOD retrievals, 1 July 2006. In northern mid-latitudes, the CALIPSO groundtrack falls within the eastern edge of the MODIS sunglint region, so MODIS AOD is not retrieved to the west of the CALIPSO ground-track.

just within the eastern edge of the MODIS sunglint region (Fig. 3), where MODIS AOD is not available.

3.2 Data screening

Additional quality screening is applied to CALIOP Level 2 aerosol data before aggregating into grid-cell averages. The algorithm used for CALIOP extinction retrievals becomes unstable at high optical depths. If the lidar ratio selected for the retrieval is too large, the solution can diverge and become infinite. When this happens, the selected lidar ratio is automatically reduced to avoid a diverging solution (Young and Vaughan, 2009). Although this happens rarely in aerosol layers, it has been found that these retrievals are not reliable, so columns containing aerosol layers where the final lidar ratio is different from the initial lidar ratio are screened out. Also, in Version 2 data, a small number of aerosol layers are found to have anomalously large layer-integrated attenuated backscatter values, most often due to overcorrection of the attenuation of overlying layers. Therefore, columns containing aerosol layers with integrated attenuated backscatter greater than 0.01 sr^{-1} are also screened out.

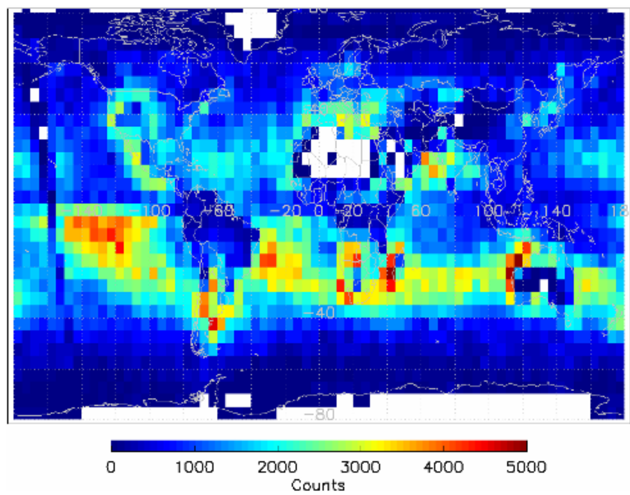

Fig. 4. Map showing the number of the CALIPSO and MODIS coincidences with valid AOD data from both instruments from 15 June 2006 to 31 August 2008.

Figure 4 shows the number of 5-km CALIOP columns with valid data from both instruments between 15 June 2006 and 31 August 2008. For MODIS this represents all of the pixels except for those filled with a missing value due to cloud cover, high reflectance surface, or sunglint, while the CALIPSO pixels with valid data are those remaining after the screening described above. Over this time period there are about 1.8 million coincident AOD retrievals. Over ocean, about 12% of the CALIPSO daytime footprints have a coincident MODIS AOD value. The co-located measurements are heavily weighted toward the Southern Hemisphere due to a combination of cloud cover, reflective land surfaces, and sunglint. Even with the 215 km offset, the CALIPSO ground track falls just within the edge of the MODIS sun glint areas at northern mid-latitudes from May through July and this contributes to fewer coincident samples over the ocean in the Northern Hemisphere spring and summer. The standard MODIS algorithms do not retrieve AOD over highly reflective land surfaces such as deserts, ice, and snow, which reduces the number of coincidences over land at mid and high

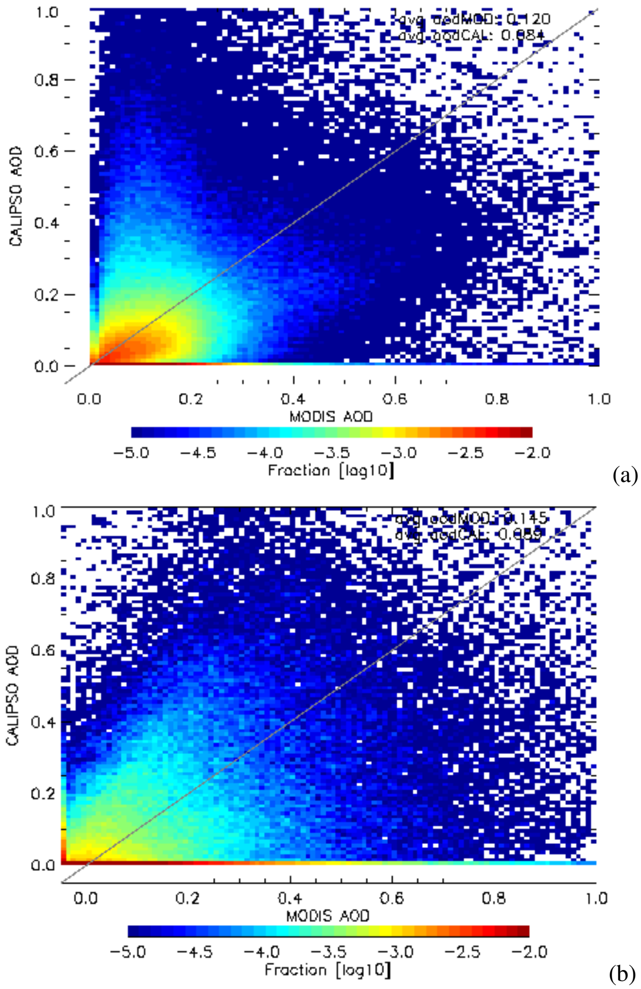

Fig. 5. Frequency distributions of AOD values for JJA (between 15 June 2006 and 31 August 2008) over the global ocean **(a)** and land **(b)** using all coincident CALIOP and MODIS AOD data.

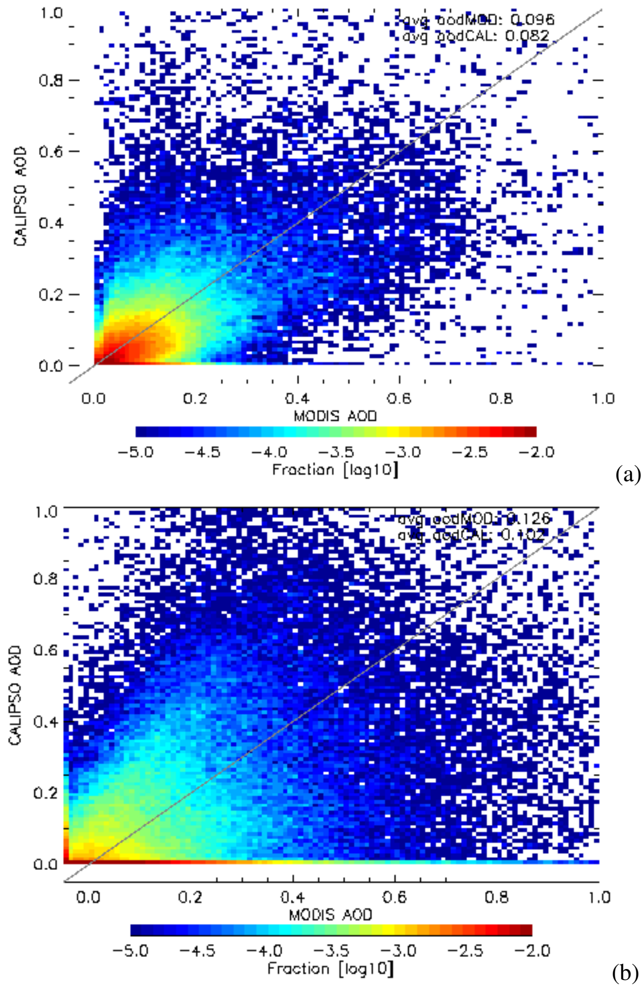

Fig. 6. Frequency distributions of AOD values for JJA (between 15 June 2006 and 31 August 2008) over the global ocean **(a)** and land **(b)** using the most stringent MODIS cloud screening.

latitudes. Polar night further reduces the number of MODIS observations at high latitudes and there are relatively few coincident samples in the tropics due to frequent cloud cover.

4 Effects of cloud screening

The next few figures show the frequency distributions of AOD values from the two instruments. These distributions are used to help identify general characteristics of the two data sets and determine the effects of additional screening. Figure 5 shows the two-dimensional frequency distributions of the coincident CALIOP and MODIS AOD values over ocean (a) and over land (b) for the time period from 15 June 2006 to 31 August 2008. The samples going into these histograms are instantaneous, co-located MODIS and CALIOP AOD values. The CALIOP AOD data are screened using the method described in the Sect. 3.2, while MODIS AOD is used regardless of cloud fraction within the 10-km cell.

Several features of these plots give insight into data quality. MODIS and CALIOP AOD over ocean exhibit a degree of correlation, although the scatter is large. There is little correlation over land however. CALIOP uses the same retrieval algorithm over land and ocean, while MODIS uses different algorithms. Differences between Fig. 5a and b may be due to larger instantaneous uncertainties in the MODIS land algorithm, or may just reflect the higher spatial variability of aerosol over land. Looking at AOD values smaller than 0.2, CALIOP AOD is biased somewhat low relative to MODIS for both land and ocean. A prominent feature seen in both scatter plots is a high population in the MODIS AOD bins between zero and 0.6 for zero CALIOP AOD. This feature extends to −0.05 in the MODIS bins for land. A similar feature is seen over land for zero MODIS AOD and CALIOP AOD less than 0.1. A noticeable feature in the

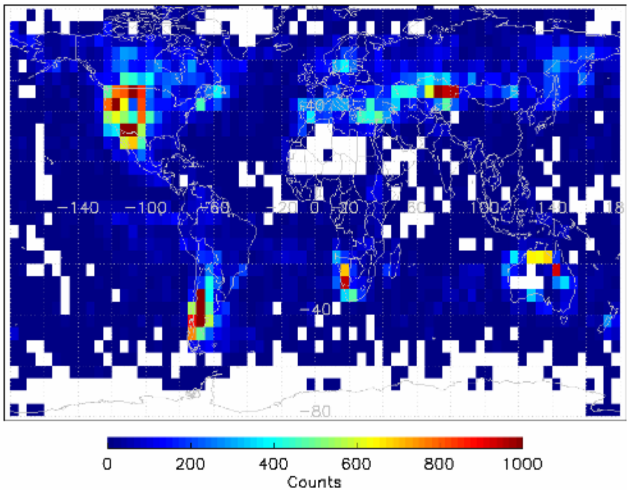

Fig. 7. Number of cloudfree 5-km pixels where CALIOP AOD = 0 and MODIS AOD > 0.05 for instantaneous, co-located retrievals, 15 June 2006–31 August 2008.

ocean plot is an enhanced population in the CALIOP AOD range between 0.4 and 0.8 for MODIS AOD smaller than 0.2.

The scatter plots in Fig. 6 are produced in the same way as those in Fig. 5 except for more stringent cloud screening, using only coincident AOD from grid cells where less than 30% of the MODIS pixels are cloudy ($cf\_x = 0$). The area of enhanced CALIOP AOD between 0.4 and 0.8 corresponding to MODIS AOD less than 0.2, seen in Fig. 5a, has disappeared. When the locations of this population are mapped, they are seen to predominantly come from relatively clean ocean regions dominated by trade cumulus, and analysis of CALIOP cloud height data shows the population is associated with clouds having tops below 2 km. Therefore, this population may be an artifact due to a known error in the CALIOP Version 2 production software where small-scale boundary layer clouds are not properly cleared from 5-km average profiles. These cloud contaminated profiles are most often classified as cloud, but if classified as aerosol they would contribute to a high bias in AOD. Figure 6a also shows substantial effects of the additional cloud screening on the population of MODIS bins for zero CALIOP AOD over ocean. The frequency of large MODIS AOD values is greatly reduced, indicating these may be due to cloud contamination or possibly side-scattering from clouds. The distribution for land, however, exhibits little change in the general pattern with the exception of the high MODIS AOD range.

One additional level of cloud-screening was applied. CALIOP identifies clouds in roughly 20–30% of MODIS $10 \times 10\,km^2$ grid cells with less than 30% cloudy pixels. The histograms of Fig. 6 do not change significantly if these cloudy columns are screened out, but the mean AOD decreases somewhat. Table 1 summarizes changes in mean AOD for the three different levels of cloud screening.

Table 1. Global-mean AOD for different cloud-screening criteria. Averaging period is JJA between 15 June 2006 and 31 August 2008.

	Ocean		Land	
	MODIS	CALIOP	MODIS	CALIOP
All MODIS AOD	0.120	0.084	0.145	0.089
MODIS < 30% cloudy	0.096	0.082	0.126	0.102
CALIOP cloud-free	0.083	0.076	0.082	0.094

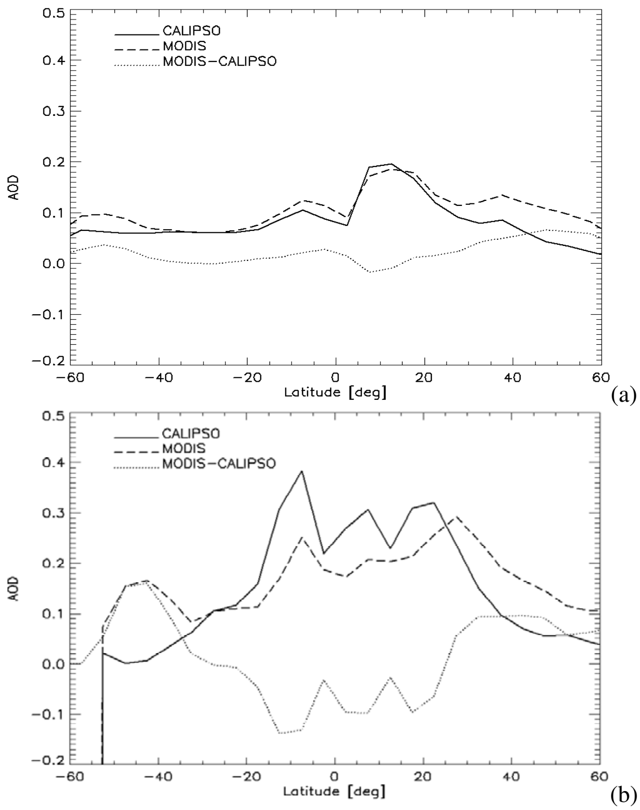

Fig. 8. Zonal mean AOD from CALIPSO and from MODIS, and zonal mean MODIS-CALIPSO differences for cloud-free columns for the period 15 June 2006 to 31 August 2008. **(a)** Over ocean; **(b)** over land.

The large MODIS AOD values corresponding to near-zero CALIOP AOD – seen along the x-axis of Figs. 5b and 6b – are not significantly affected by more stringent cloud screening. If we map the location of these observations, many are associated with arid regions having 2.12 µm surface reflectance greater than 15% (Fig. 7). While there are a number of possible explanations for high MODIS AOD and near-zero CALIOP AOD, it is likely that use of incorrect surface reflectivity values in the MODIS retrievals is one source.

5 Comparison of spatial averages

The following analyses are based on fully cloud-screened data, where fewer than 30% of MODIS pixels are cloudy and CALIOP detects no clouds in the column. Figure 8 compares MODIS and CALIOP zonal mean AOD distributions for ocean and for land, averaged over the entire 27-month period. Over ocean, zonal mean AOD differences (MODIS – CALIPSO) range from −0.02 to +0.06. The agreement is reasonably good, except that MODIS AOD is significantly larger than CALIOP north of 30° N and about 0.03 larger than CALIOP between 40°–60° S. The range of the AOD difference over land is much larger, from −0.14 to +0.18, which may be due in part to the much smaller number of co-located samples over land. Referring back to Fig. 4, it can be seen that many land regions have few co-located samples relative to much of the ocean. CALIOP AOD is lower than MODIS at high northern and southern mid-latitudes, as over ocean, but is also higher than MODIS between 20° S–20° N, a region where smoke from biomass fires is the most commonly found aerosol type. There is a known Northern Hemisphere bias in the Version 2 daytime CALIOP 0.532 µm calibration. The calibration bias causes the attenuated backscatter signal to be low in northern mid-latitudes and may contribute to the generally smaller CALIOP AOD values seen in the Northern Hemisphere in Fig. 8.

To provide more insight into these zonal patterns, Fig. 9 illustrates the geographical distribution of seasonally-averaged differences in co-located MODIS and CALIOP AOD. A $5° \times 5°$ grid is used to provide sufficient statistics for the nadir-only CALIPSO retrievals without losing regional patterns of the AOD distribution. Only CALIOP AOD from cloud-free 5-km columns and MODIS AOD from grid cells with less than 30% cloud pixels are used. Grid cells with few co-located AOD samples sometimes exhibit large differences. Therefore, grid cells containing fewer than 50 co-located AOD pairs are colored gray. Retrievals over surfaces flagged as snow/ice are also screened out. Some of the striking differences in Fig. 9 result from the plotting of absolute, rather than relative, differences. The MODIS declarations of expected retrieval uncertainty contain both absolute and relative components, and both are needed. A significant hemispheric pattern is seen, with MODIS AOD tending to be higher than CALIOP AOD in the Northern Hemisphere and somewhat lower in the Southern Hemisphere, except for 40°–60° S during Austral spring and summer when MODIS AOD is somewhat higher. Some of this difference is due to the generally higher aerosol loading in the Northern Hemisphere, particularly over China and Africa during some seasons, where absolute differences should naturally increase.

Numerous regional biases can also be seen, some which are counter to the overall north-south pattern. MODIS AOD is consistently lower than CALIOP over India, except in arid northwest India and Pakistan where MODIS is consistently higher. In this comparison, CALIOP tends to be higher than MODIS over the Eastern US and lower over Western US. CALIOP AOD is generally larger than MODIS over tropical Africa, except during DJF where MODIS AOD is larger over Niger/Nigeria. In the Southern Hemisphere, CALIOP AOD is consistently higher over central and southern Africa, while MODIS is consistently higher in the Gulf of Guinea – both regions typically dominated by smoke. MODIS AOD is consistently higher in southeast Argentina. The seasonal cycle over Brazil is not well sampled, probably because of persistent cloud cover. During the dry season (SON) CALIOP AOD is higher in eastern Brazil, while MODIS AOD is significantly higher in western Brazil and Bolivia. The bias in the southern oceans tends to be negative during Northern Hemisphere spring and summer, and positive during fall and winter. There is a degree of consistency in these regional differences, pointing to the likelihood of underlying causes in algorithms and calibration.

6 Discussion

As outlined above, errors in the AOD retrievals from CALIOP and from MODIS arise from a number of different sources. One or another of these sources of error may be dominant in different situations. Attribution of the differences seen here between CALIOP and MODIS AOD to specific sources of error requires detailed case studies, such as have been performed for comparisons of MODIS and MISR AOD (Kahn et al., 2007). Nevertheless, we can draw a number of conclusions regarding the strengths and weaknesses of the two sensor's abilities to retrieve mid-visible total column AOD. On a regional-seasonal basis, over the vast majority of the world's oceans having sufficient number of collocations in conditions with less than 30% cloudiness, the difference in AOD between the two sensors is within the expected uncertainty of the MODIS over-ocean product, $\pm 0.03 \pm 5\%$. This is despite the proximity of the CALIPSO track to the edge of the MODIS sun glint shield during late spring and summer. The agreement between the two sensors in this situation suggests that the selection of lidar ratios used in the CALIOP retrieval of aerosol over the oceans is sufficient to provide a regional mean AOD which is consistent with that retrieved from MODIS.

Differences between CALIOP and MODIS AOD increase as the ocean environment becomes cloudier, with the MODIS AOD becoming higher relative to CALIOP. Because discriminating aerosol and cloud in the lidar return should be more reliable than from a passive imager, and because the active sensor will not be affected by cloud side scattering, we suspect the discrepancy between CALIOP and MODIS in cloudy situations to be largely a result of cloud effects in the MODIS retrieval. The fact that MODIS acquires a high bias in cloudy collocations, reinforces this conclusion. Other studies have also noted cloud effects in the MODIS ocean aerosol product (Zhang and Reid, 2006). The

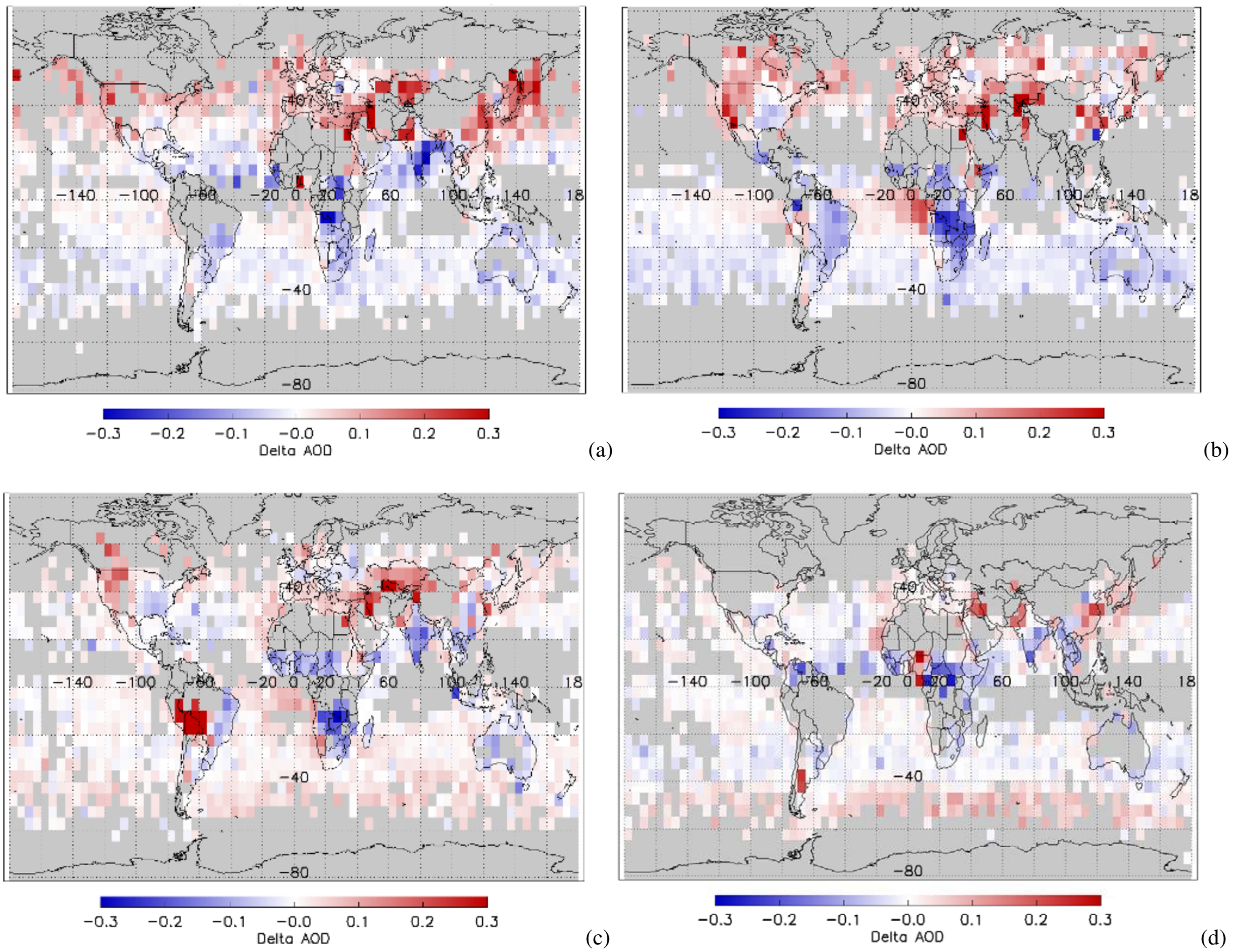

Fig. 9. Seasonal-mean differences of MODIS and CALIOP AOD (MODIS–CALIOP), averaged for seasons over the period of 15 June 2006 to 31 August 2008. Grey indicates grid cells with insufficient number of samples. **(a)** March-April-May; **(b)** June-July-August; **(c)** September-October-November; **(d)** December-January-February.

seasonally-varying bias in the southern oceans may be driven in part by high surface winds, producing a surface reflectance higher than that assumed in the MODIS retrieval. However, the CALIOP aerosol-cloud discrimination in the Version 2 product is not perfect, which introduces sufficient uncertainty in this conclusion to warrant further investigation of CALIOP-MODIS AOD comparisons in cloudy environments using Version 3 data.

Over land the situation becomes more complex for both sensors. CALIOP faces a wider variety of aerosol types, introducing greater uncertainty in the choice of aerosol model and lidar ratio used in the retrieval. The brighter land surfaces (relative to ocean scenes) increase the noise in daytime CALIOP signals, contributing to AOD retrieval errors in several different ways. One impact is to make detection of aerosol layer base height more difficult. Mis-estimated bases are usually biased high, leading to an underestimate of AOD. This may contribute to the low bias of CALIOP AOD relative to MODIS in eastern China. Meanwhile, the variable land surface introduces greater uncertainty into the MODIS retrieval, as well. These factors result in larger differences between the two sensors regionally and seasonally over land. In some locations, such as eastern North America, when there are sufficient samples, CALIOP and MODIS AOD agree to within MODIS' expected error over land of $\pm 0.05 \pm 15\%$. However, most land areas exhibit larger differences than this. In some specific areas where MODIS error is known to be large (the intermountain west of North America and south-central Argentina, for example) (Levy et al., 2010), the large difference between CALIOP and MODIS is attributed to MODIS error for the most part. In other regions, MODIS validates very well with ground-based sunphotometers (for example: India – Jethva et al., 2010; China outside of major cities – Mi et al., 2007; southern Africa – Levy et al., 2010). In these situations the discrepancy between CALIOP and MODIS is likely to be primarily due to limitations of the CALIOP retrieval. Even though the land exhibits relatively larger discrepancies between the two sensors, on a regional-seasonal basis, the bias between the two on a global and zonal mean basis is roughly within the envelope of the MODIS expected uncertainty over land and ocean.

7 Summary

A methodology has been developed for screening CALIOP AOD data and comparing with MODIS AOD. Initial AOD comparisons have been performed based on CALIOP Version 2 and MODIS Collection 5 data. The results are encouraging in terms of using CALIOP quantitatively to measure aerosol extinction on the climate scale, and in many circumstances on local scales as well. While CALIOP AOD has larger uncertainty than MODIS in some (but not all) situations, it gains in its ability to observe aerosol where MODIS cannot: above and near clouds, over unfavorable surfaces and at night.

This work forms a basis for further comparisons using the recently released CALIOP Version 3 data. Apparent systematic regional differences identified here, such as between southern Africa and the Gulf of Guinea, or between eastern and Western US, provide motivation for more detailed case studies to diagnose the source of these differences at the algorithm level.

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