

**Evaluating nighttime  
CALIOP 0.532  $\mu\text{m}$   
aerosol optical depth**

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**Evaluating nighttime CALIOP 0.532  $\mu\text{m}$   
aerosol optical depth and extinction  
coefficient retrievals**

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## Abstract

NASA Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) Version 3.01 5-km nighttime 0.532  $\mu\text{m}$  aerosol optical depth (AOD) datasets from 2007 are screened, averaged and evaluated at  $1^\circ \times 1^\circ$  resolution versus corresponding/co-incident 0.550  $\mu\text{m}$  AOD derived using the US Navy Aerosol Analysis and Prediction System (NAAPS), featuring two-dimensional variational assimilation of quality-assured NASA Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging Spectroradiometer (MISR) AOD. Daytime datasets are investigated similarly for context. Regional-mean CALIOP vertical profiles of night/day 0.532  $\mu\text{m}$  extinction coefficient are compared with 0.523/0.532  $\mu\text{m}$  ground-based lidar measurements to investigate representativeness and diurnal variability. In this analysis, mean nighttime CALIOP AOD are mostly lower than daytime (0.121 vs. 0.126 for all aggregated data points, and 0.099 vs. 0.102 when averaged globally per normalized  $1^\circ \times 1^\circ$  bin), though the relationship is reversed over land and coastal regions when the data are averaged per normalized bin (0.134/0.108 vs. 0.140/0.112, respectively). Offsets assessed within single bins alone approach  $\pm 20\%$ . CALIOP AOD, both day and night, are higher than NAAPS over land (0.137 vs. 0.124) and equal over water (0.082 vs. 0.083) when averaged globally per normalized bin. However, for all data points inclusive, NAAPS exceeds CALIOP over land, coast and ocean, both day and night. Again, differences assessed within single bins approach 50% in extreme cases. Correlation between CALIOP and NAAPS AOD is comparable during both day and night. Higher correlation is found nearest the equator, both as a function of sample size and relative signal magnitudes inherent at these latitudes. Root mean square deviation between CALIOP and NAAPS varies between 0.1 and 0.3 globally during both day/night. Averaging of CALIOP along-track AOD data points within a single NAAPS grid bin improves correlation and RMSD, though day/night and land/ocean biases persist and are believed systematic. Vertical profiles of extinction coefficient derived in the Caribbean compare well with ground-based lidar observations, though potentially anomalous selection of a-priori lidar ratios for

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CALIOP retrievals is likely inducing some discrepancies. Mean effective aerosol layer top heights are stable between day and night, indicating consistent layer-identification diurnally, which is noteworthy considering the potential limiting effects of ambient solar noise during day.

## 1 Introduction

Launched into orbit in 2006, the three-channel Cloud Aerosol Lidar with Orthogonal Polarization instrument (0.532  $\mu\text{m}$  with linear polarization diversity, and 1.064  $\mu\text{m}$ ; CALIOP) flown aboard the National Aeronautics and Space Administration (NASA) and Centre National d'Études Spatiales (CNES) Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite has collected the first global, inter-seasonal and multi-annual profiles of aerosol particle and optically-thin cloud structure from space (Winker et al., 2010). The vertical profile for aerosol particle electro-optical scattering, in particular, is a unique and highly synergistic satellite measurement, since passive aerosol-focused remote sensors alone are limited at best in observing vertically-resolved information with reasonably high resolution. CALIOP profiling has thus benefitted a number of aerosol research initiatives, including global particle transport studies (e.g., Uno et al., 2009), surface emission estimates and injection scenario characterization (e.g., Bessagnet et al., 2008; Amiridis et al., 2010), pyrocumulonimbus plume identification and dispersion (Fromm et al., 2010), volcanic plume monitoring (e.g., Carn et al., 2009; Campbell et al., 2012), coupled two/three-dimensional variational (2-D/3-DVAR) data assimilation for global mass transport forecasting (e.g., Campbell et al., 2010; Zhang et al., 2011), four-dimensional ensemble Kalman filter data assimilation (e.g., Sekiyama et al., 2010), and transport model validation (e.g., Uno et al., 2008; Yumimoto et al., 2008).

Calibration of CALIOP signals (e.g., Powell et al., 2009; Rogers et al., 2011) and verification/validation of value-added (i.e., Level 2.0 and higher) NASA data products (e.g., Liu et al., 2009; Kacenelenbogen et al., 2011) ensure that high-accuracy data are

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available for researchers, and that the archive is consistent for legacy study long after the mission is completed. Kittaka et al. (2011) recently compare 0.532  $\mu\text{m}$  aerosol optical depth (AOD) retrievals reported in the NASA Version 2.01 CALIOP 5-km Aerosol Layer product versus 0.550  $\mu\text{m}$  AOD retrievals based on measurements made by the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua satellite, and thus collected in formation and approximately 5 min before CALIOP as part of the NASA “A-Train” constellation (e.g., Stephens et al., 2002). Naturally, this work relates only to half of all available CALIOP AOD data, since MODIS retrievals are based on scattered solar radiances. Given that the lidar is duly capable of nighttime measurements, additional validation is necessary to fully evaluate CALIOP aerosol retrieval performance. Furthermore, given that particle layer identification and the accuracy of the CALIOP-derived 0.532  $\mu\text{m}$  extinction coefficient, and thus its column-integrated sum AOD, are each a function of the amount of ambient solar background light measured in any given scattering profile (i.e., noise; Hunt et al., 2009; Liu et al., 2009; Vaughan et al., 2009; Young and Vaughan, 2009), nighttime AOD retrievals should exhibit relative accuracies and skill that differ from, and nominally exceed, those from daytime.

In this paper, quality-assured (QA) Version 3.01 CALIOP Level 2 5-km 0.532  $\mu\text{m}$  nighttime AOD are evaluated from 2007 at  $1^\circ \times 1^\circ$  resolution versus an aerosol forecast model equipped with a 2-DVAR ( $x, y$ ) assimilation scheme for QA AOD datasets from Terra and Aqua MODIS and the NASA Multi-angle Imaging Spectroradiometer (MISR). The study includes all 2007 QA CALIOP 5-km aerosol profiles available where column-integrated AOD  $\neq 0$ , no cloud was present within the along-track average and an aerosol particle layer was resolved to within 250 m of the surface, thus limiting undersampling and sample bias caused by transmission loss and/or scattering ambiguities through the profile. The US Navy Aerosol Analysis and Prediction System (NAAPS) is a  $1^\circ \times 1^\circ$  global aerosol mass transport model used for computing 6-day forecasts of smoke, dust, sulfate, sea salt and  $\text{SO}_2$  mass concentration every 6 h. Global and regional mean CALIOP AOD, correlation coefficients and root mean square

deviation are derived relative to corresponding 0.550  $\mu\text{m}$  NAAPS AOD to qualitatively assess day/night retrieval skill and accuracies and quantitatively estimate relative offsets. Profiles of CALIOP-derived 0.532  $\mu\text{m}$  extinction coefficient are further compared versus ground-based lidar measurements to investigate representativeness, potential bias, and identify any diurnal variability present.

## 2 CALIOP/NAAPS AOD datasets and model skill versus MODIS and AERONET

### 2.1 2007 CALIOP and NAAPS AOD datasets

The Version 3.01 CALIOP Level 2 Aerosol Profile product (L2-AProf) includes 0.532  $\mu\text{m}$  extinction coefficient profiles with corresponding retrieval uncertainties derived in 5-km along-track segments at 60 m vertical resolution, separated into contiguous daytime and nighttime granule files. As CALIOP is an elastic-backscatter lidar instrument, the extinction coefficient is derived using the Hybrid Extinction Retrieval Algorithm (HERA; Young and Vaughan, 2009), based on a-priori selection of a multiple-scattering correction factor (nominally set to unity for aerosols) and the ratio for extinction and backscatter coefficients. The latter term, the so-called “lidar ratio”, is assumed constant vertically within detected layers (Omar et al., 2009), and is used for solving the single elastic-scattering lidar equation that contains these two separate and unknown quantities (Young and Vaughan, 2009; Oo and Holz, 2011). Retrieval uncertainties begin with an estimate of the signal noise scale factor, and are computed at each range bin reported in the Level 1B attenuated backscatter product at 20.16 Hz pulse repetition frequency and 30/60 m vertical resolutions, for 0.0 to 8.2 and 8.2 to 20.1 km a.m.s.l. (above mean sea level), respectively (Liu et al., 2006). Since the CALIPSO 98.2° retrograde satellite orbit limits the poleward extent of the polar-orbiting ground track, only data between 80° N/S are analyzed (referred to as “global” for simplicity).

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The 2007 dataset was chosen for this analysis for its lack of significant data gaps, and singular use of the primary instrument laser system throughout that year (Hunt et al., 2009). To ensure that only QA measurements are included, each L2-AProf 5-km extinction profile solved for 2007 was screened and low-confidence data points excluded before integrating and solving column AOD. Based on specific parameter profiles defined for and included in L2-AProf, and described elsewhere (NASA, 2010), for a given 5-km profile an extinction coefficient value is considered QA and included in the column-integrated sum (i.e., AOD), when at the corresponding range either

1. Extinction\_QC\_532( $r$ ) is equal to 0, 1, 2, 16 or 18,
2.  $-20 \geq \text{CAD\_Score}(r) \geq -100$ ,
3. Extinction\_Coefficient\_Uncertainty\_532( $r$ )  $\leq 10 \text{ km}^{-1}$ ,
4. Atmospheric\_Volume\_Description( $r^*$ , bits 1–3) is equal to 3, or
5. Atmospheric\_Volume\_Description( $r^*$ , bits 10–12) is not equal to 0,

where ( $r$ ) relates each value as a function of range.

Extinction\_QC\_532 reports on the type of retrieval used for solving extinction (constrained versus unconstrained), whether or not the subject layer was opaque, and the result of the process (convergent, divergent or oscillating). Should the initial lidar ratio chosen deviate significantly from reality, the solution diverges. The algorithm then adjusts the a-priori value in order to reiterate and reevaluate. If a stable result is not derived, and/or if the solution does not fall within a range of acceptable values for AOD and/or magnitudes of extinction coefficient, the Extinction\_QC\_532( $r$ ) parameter setting reflects the instability. CAD\_Score reflects confidence of the classification of a layer as aerosol or cloud within a bin. Extinction\_Coefficient\_Uncertainty values exceeding  $10 \text{ km}^{-1}$  reflect increasingly unrepresentative values, though this setting is conservative, as the parameter is set to  $99 \text{ km}^{-1}$  for retrievals deemed unstable. Atmospheric\_Volume\_Description at bits 1–3 describes the type of scattering target identified, where a value of ‘3’ indicates aerosol particle presence. Bits 10–12 denote the type

of aerosol particle identified. Here, “0” represents “not determined” cases, which are rejected. Aerosol particle extinction profiles that contain only fill values after screening (i.e., AOD = 0) indicate regions of the atmosphere where the mass loading lies below the instrument detection limits. These profiles are removed from the sub-sample.

5 Tackett (2012) describe a similar rubric for filtering L2-AProf retrievals and achieving what they designate as Level 3 QA status. They further discuss the ramifications of tuning each metric. The study here is thus unique to this five-step screening process, though differences from that used by Tackett (2012) are considered slight. For example, they reject values for Extinction\_QC\_532(*r*) set equal to 2, and only reject values for  
10 Extinction\_Coefficient\_Uncertainty\_532(*r*) equal to 99. Cases of Extinction\_QC\_532(*r*) equal to 2 represent less than 2% of all 2010 nighttime, for example. Other screening metrics are used that remove misclassified cirrus clouds, aerosol layers attributable to noise and surface contamination. The consequences of these latter steps are believed mostly negligible for their impact on mean AOD composites studied here, though future  
15 work is necessary to ensure this.

Since L2-AProf includes data reported at 60 m vertical resolution, measurements below 8.2 km a.m.s.l. reflect two-bin averages of raw 30 m resolution data. Consecutive 30 m bins reflecting either cloud or aerosol scattering are never averaged together to yield a single 60 m bin in the L2-AProf file. Therefore with (4) and (5),  $r^*$  relates to  
20 the possibility that one of the two bins used for creating the average value may not correspond with an Atmospheric\_Volume\_Description value equal to 3, though the other must. Since such a bin cannot represent cloud, and must instead be either “Clear Air”, or “Surface Return”, and the extinction coefficient is not reported for these bin types, we include these 60 m data points in the analysis, for they reflect the corresponding aerosol-related value specifically. Only those bins between the surface and  
25 10.0 km a.m.s.l. are analyzed.

Two additional screening metrics are applied to the sample. First, profiles where cloud was present at any range (Atmospheric\_Volume\_Description equal to 2) within the 5-km along-track average are removed. Cloud scattering can negatively influence

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the aerosol particle scattering profile and subsequent retrievals of corresponding extinction and backscatter coefficients, since transmission losses must be corrected for. Further, when clouds are present below or embedded within aerosol particle layers, full source pulse attenuation for most lidar instruments occurs at visible optical depths approaching 3.0 (Sassen and Cho, 1992). Source pulse attenuation is thus a common limitation for nadir-aligned profiling of aerosol particle scattering. Accordingly, as a second screening metric, profiles are removed if aerosol particle scattering is not detected to within 250 m of the surface in the 5-km along-track average. Like clouds, dense aerosol layers can exhibit visible optical depths approaching 3.0, thus limiting CALIOP profiling to the surface (Hunt et al., 2009; Vaughan et al., 2009; Liu et al., 2011). This metric also screens profiles limited by simple undersampling of diffuse/optically-thin layers below layer-detection thresholds.

Each QA 5-km CALIOP L2-AProf profile and AOD data point is sorted into a global  $1^\circ \times 1^\circ$  grid matching the NAAPS model domain based on the center of the 5-km along-track data average. The data are then paired with the corresponding  $0.550 \mu\text{m}$  AOD retrieved from the closest six-hourly NAAPS 00-hr model analysis derived after assimilation. 2DVAR NAAPS assimilation is conducted using the Navy Atmospheric Variational Data Assimilation System (NAVDAS) for Aerosol Optical Depth (NAVDAS-AOD; Zhang et al., 2005; Zhang and Reid, 2006, 2009). QA MODIS over-ocean (Zhang and Reid, 2006; Shi et al., 2011a) and over-land AOD (Hyer et al., 2011) products and Version 1 of an assimilation-grade MISR AOD product (Shi, 2009) are system inputs. Descriptions of NAVDAS-AOD and its impact on NAAPS performance are given by Zhang et al. (2008) and Reid et al. (2009). Global AOD derived with NAAPS after 2DVAR MODIS and MISR assimilation are validated using quality-assured Level 2 NASA Aerosol Robotic Network measurements (AERONET; Holben et al., 1998). With 2DVAR assimilation, the model exhibits accuracies comparable to that of satellite retrievals (e.g., Zhang et al., 2008; Zhang and Reid, 2010; Hyer et al., 2011), and forecasts are improved by 20–40 % (Zhang et al., 2008, 2010, 2011).

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Given that NAAPS assimilates MODIS and MISR AOD, model errors co-vary closely with those inherent to the satellite datasets. Skill, uncertainty and retrieval bias for both MODIS and MISR AOD have been evaluated and reported (e.g., Hsu et al., 2004; Martonchik et al., 2004; Remer et al., 2005; Redemann et al., 2006; Zhang and Reid, 2006; Kahn et al., 2007, 2009; Hyer et al., 2011; Shi et al., 2011a,b). NAAPS exhibits similar tendencies (e.g., Zhang and Reid, 2009). However, QA screening limits error propagation into the model. For example, empirical corrections compensate for MODIS retrievals involving dust particles, which can be high by as much as 10–20%, and for fine-mode fractional AOD that can be low by a similar amount (Hyer et al., 2011). Though MISR biases are relatively less intrusive (Shi et al., 2011b), the instrument operates with a relatively limited viewing swath compared with MODIS and global coverage is achieved only once every eight days (e.g., Diner et al., 2002).

### 2.2 NAAPS Skill versus MODIS/MISR and AERONET

NAAPS AOD analyses reflect the influence of the free-running model forecast, as well as AOD assimilation (i.e., MODIS and MISR) in sunlit sectors at 0-h. NAAPS AOD in the nighttime (i.e., dark) sector at 0-h, used here, thus reflect the influence of at least 12 h of model integration since AOD was last assimilated. Zhang et al. (2011) report mean global 0.550  $\mu\text{m}$  AOD error at 12-h relative to AERONET near 0.075. However, this considers only the sunlit sector of the model at 12-h, where validation data are available, but with no assimilation having occurred at initialization. NAAPS skill within the dark sector of the forecast at 12-h is undetermined. Therefore, uncertainties of the NAAPS 0.550  $\mu\text{m}$  AOD used here must be inferred from interpolating between the two surrounding time steps, 0 and 24-h. The magnitude of the global mean error is very likely less than  $\sim 0.075$ , though, given potential assimilation within the sunlit sector at model initialization, in contrast to Zhang et al. (2011).

Shown in Fig. 1 are mean NAAPS 0-h analysis and co-incident integrated 0.550  $\mu\text{m}$  QA MODIS and 0.557  $\mu\text{m}$  MISR AOD during 2007, correlation and root mean square deviation (RMSD) between the two, number of data points and the ratio of NAAPS to

MODIS/MISR AOD (differences between MODIS and MISR wavelengths are presumed negligible, given the relative uncertainty necessary for interpolating MISR to 0.550  $\mu\text{m}$ ). NAAPS resolves areas of persistently high AOD well compared to MODIS/MISR (Fig. 1a and b). Globally, correlation coefficients exceed 0.8 (Fig. 1c) and RMSD ranges between 0.02–0.10 (Fig. 1d), though select regions peak over 0.20 (east-central Asia, being most notable). Relative AOD ratios between the two are near unity (Fig. 1f). Some bias is present, predominantly over land, where fewer suitable AOD retrievals are available (e.g., Hyer et al., 2011) and model source functions exert stronger influence. For instance, NAAPS is relatively high over Sahara, southern Africa and western Australia, and low over the western United States and east-central Asia.

Corresponding findings for the 24-h NAAPS forecast are shown in Fig. 2. Skill degradation is apparent. The model retains most of the regional structure depicted in the MODIS/MISR composite (Fig. 2a vs. b). However, correlation drops, with only a few regions maintaining a value above 0.8 (Fig. 2c). RMSD increases (Fig. 2d) over corresponding high-biased regions, which are greatly enhanced, over western Sahara, central and southern Africa, and eastern/south-central Asia (Fig. 2f). As a whole, the model is biased slightly high globally, on average, nearing 20% compared with the satellites. This is somewhat deceptive, however, since many of these regions, including the oceans, typically exhibit relatively low mean AOD on the order of 0.10 or lower at 0.550  $\mu\text{m}$ , such that a 10% offset (0.01) can create relatively large apparent differences.

When evaluating 2007 NAAPS AOD with coincident AERONET ground-based observations, many of the interpretations of Figs. 1 and 2 are reinforced (Fig. 3). For the 0-h model analysis, AOD correlation varies from 0.82 to 0.83 at over land and coastal sites, respectively, with absolute errors from 0.063 to 0.077. For the 24-h forecast, AOD correlation drops to 0.69 and 0.77, respectively, and absolute error rises accordingly to 0.077 and 0.092. These results are similar to those recently reported by Zhang et al. (2011).

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In summary, whereas a comprehensive quantitative assessment of CALIOP AOD retrievals based on NAAPS is undeterminable, interpretation of the differences between day/night performance, and thus the identification of potential bias, are qualitatively feasible. Each dataset exhibits characteristic uncertainties that exceed even the slight offset expected between the two due to the difference in wavelength (3% for an Angstrom Exponent of 1.0). However, since CALIOP AOD retrievals are algorithm/retrieval dependent (i.e., not direct measurements), it is relevant that the nighttime global database be investigated and compared with those for daytime in a relative sense in order to underscore performance strengths and/or identify issues requiring technical improvements. Both steps will lead to a more consolidated mission archive, advancing our understanding of global elastic-scattering lidar instrument observations and providing a logical framework for future projects. The results depicted in Figs. 1–3 indicate that nighttime NAAPS AOD represent a stable estimate of AOD for this purpose.

### 3 CALIOP AOD retrievals versus NAAPS: nighttime and daytime assessment

#### 3.1 Global aerosol optical depths

This section begins with an assessment of mean day/night 2007 CALIOP QA 0.532  $\mu\text{m}$  AOD derived at  $1^\circ \times 1^\circ$  global resolution, comparing with NAAPS as a reference dataset. Not every  $1^\circ \times 1^\circ$  grid bin contains CALIOP data. This is a result of the CALIPSO polar-orbiting ground track, and causes striping of null data points in the global composite images shown. Anderson et al. (2003) show that the horizontal covariance of aerosol physical properties exhibits a mean e-folding distance of only a few hundred kilometers, which was subsequently verified solely from satellite observations by Zhang et al. (2008). Since a CALIOP QA observation is assigned to the closest NAAPS grid bin based on the center of its 5-km along-track data average, which can result in a nearly 80 km offset at the equator, the bulk of the points making up each bin average will fall within a range where autocorrelation nominally exceeds 0.8.

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Shown in Table 1 are mean AOD for both day, night, day/night ratio and total from the 2007 QA CALIOP and corresponding NAAPS sub-sample, derived both for all data points inclusive and where each bin value is treated as a single normalized point. The analysis is broken out relative to the surface type attributed to the NAAPS model domain (over land, coast and ocean). For all data points, global mean CALIOP AOD is 0.126 during day, 0.121 at night (+4.4 % day/night offset) and 0.123 total, compared with NAAPS at 0.132, 0.136 (−2.8 % day/night offset) and 0.134, respectively. When normalized per bin, thus compensating for differences in sample size within the aggregate mean, CALIOP values are 0.102, 0.099 (+2.5 % day/night offset) and 0.101, compared with 0.097, 0.097 (0.0 % day/night offset) and 0.097 from NAAPS. Note that over-ocean mean CALIOP and NAAPS AOD in each scenario from Table 1 is at least 10 % lower than the 0.120 0.550  $\mu\text{m}$  AOD threshold approximated from Zhang and Reid (2010) and their 2007 QA MODIS global dataset. This likely reflects more accurate cloud screening available from CALIOP relative to the passive datasets assimilated by NAAPS, and the offset may approximate a lingering passive AOD bias present in these carefully-screened datasets due to optically-thin clouds. This finding requires further study and analysis.

Mean nighttime 2007 QA CALIOP AOD are shown at  $1^\circ \times 1^\circ$  resolution in Fig. 4a, depicting the prominent aerosol features found in the corresponding NAAPS composite (Fig. 4b). Correlation between the two datasets (Fig. 4c) ranges mostly between 0.30 and 0.70 per bin, increasing near the equator. The relationship is very low at higher latitudes. Regions of relatively high correlation are found near the west African coast, including the Caribbean, Brazil, tropical Atlantic, central Sahara, southern Africa and southwest Asia. Aside from southern Africa, which is subject to spring and summer anthropogenic burning and absorbing smoke aerosols (e.g., Campbell et al., 2002), these regions are most commonly impacted by Saharan desert dusts, where a-priori assignment of the lidar ratio for extinction retrieval is relatively stable (e.g., Liu et al., 2008). Central Sahara and southern Africa are also regions where NAAPS is known to be biased high (Reid et al., 2009), so these results are encouraging. Low correlation

over oceans and at higher latitudes is understandable, given that the dynamic range of AOD is much lower there than over land and nearest the equator (Figs. 3a–b and 4a–b).

Globally, RMSD (Fig. 4d) exceeds 0.1 over water and peaks over 0.25 over land per bin, which is a factor of at least two higher than that found between NAAPS and MODIS/MISR (Figs. 1c and 2c). As alluded to above, numbers of available data points per bin (Fig. 4e) are highest near the equator, despite an orbiting ground-track that is more favorable to high-latitude coverage (points lacking data in these composites are depicted as white, and thus not reflected in the color bars given). A similar pattern is found by Kittaka et al. (2011) when comparing CALIOP versus MODIS, thus indicating that cloud cover is largely driving this relationship. However, compromised layer-identification and retrievals in low AOD scenarios at higher latitudes (i.e., relatively low particle backscatter coefficients within the column profile, wherein algorithm sensitivity is low) at higher latitudes, also potentially contributes.

CALIOP-to-NAAPS AOD ratios (Fig. 4f) indicate that the satellite retrievals are higher than the model across the southern oceans, in the Caribbean, Brazil, east Africa and Australia, but are generally lower elsewhere, though sample noise is again high at increasingly higher latitudes. From the per bin global averages in Table 1, CALIOP values are slightly higher within the global mean (0.099 vs. 0.097). Values are higher over land and coastal regions, but slightly lower over oceans. For all data points, however, NAAPS exceeds CALIOP globally (0.134 vs. 0.123), being higher over each surface regime.

Mean daytime 2007 QA CALIOP AOD retrievals (Fig. 5) depict the same major features as those derived during night, and are again consistent with corresponding daytime NAAPS data (Fig. 5b). These results are also consistent with both sets of global averages reported in Table 1. This finding is notable. The effects of ambient solar noise on CALIOP AOD retrievals are limited. Unlike the nighttime comparison above, NAAPS includes data from the sunlit sector of the model here, thus consistent with the 0-h model analysis that benefits from concurrent MODIS/MISR assimilation.

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Correlation between CALIOP and NAAPS, however, remains relatively low (Fig. 5c). The highest relative correlation is found the tropical Atlantic and eastern Caribbean. RMSD exhibits little variability (Fig. 5d) compared with results derived at night, though over-ocean values trend slightly higher. Numbers of available data points per grid bin again are highest near the equator (Fig. 5e).

Ratios of daytime CALIOP-to-NAAPS AOD (Fig. 5f) are slightly higher than night over the southern oceans, Caribbean and west/central Tropical Atlantic and most of the Pacific. However, the relationship is very difficult to characterize at high latitudes, from relatively low sample sizes. For the global per bin averages in Table 1, CALIOP AOD exceeds NAAPS (0.102 vs. 0.097), and the relationship holds for all three surface regimes. For all data points, however, NAAPS is again higher than CALIOP (0.132 vs. 0.126) in the global mean. This again holds for land, coast and ocean.

Shown in Fig. 6a are global composites of CALIOP day/night AOD ratio per bin, with corresponding results for NAAPS shown in Fig. 6b. As discussed above from Table 1, CALIOP day/night ratios exceed unity globally both for all data points and the per-bin normalized analysis (4.4 and 2.5%, respectively). The relationship is reversed, however, when averaged globally per bin over land and coastal sites (0.134/0.108 vs. 0.140/0.112, respectively), which is seen most prominently in the composite image over the sub-tropical Atlantic Ocean and Europe. Maximum offsets per bin are  $\pm 20\%$  from these data, though this relationship is again sensitive to the dynamic range globally of AOD, discussed above, which complicates the analysis in regions where mean values are relatively low. The NAAPS day/night ratio, on the other hand, is less than unity when averaged globally for all data points (2.8%) and very near 1.0 when averaged per bin (Table 1). Notable deviations from this latter standard are found in the composite image over the southern oceans and the southeastern Pacific, in general.

## 3.2 Sub-regional AOD assessments

Eight regions were selected for a comprehensive quantitative comparison of the 2007 QA CALIOP and NAAPS AOD datasets. Depicted on a global map in Fig. 7, these regions and their equivalent longitude/latitude start/end points are: North Atlantic (NA; 70° W/35° N–60° W/45° N), Caribbean (C; 65° W/10° N–55° W/20° N), Tropical Atlantic (TA; 35° W/15° N–25° W/25° N), Europe (E; 5° E/50° N–25° E/5° N), Arabian Sea (AS; 60° E/10° N–70° E/20° N), Southeast Asia (SEA; 100° E/10° N–110° E/20° N), South China Sea (SCS; 110° E/5° N–120° E/15° N) and Sea of Japan (SoJ; 130° E/35° N–140° E/45° N). Regional assignments and latitude/longitude points are also detailed in Tables 2–4, which include summaries of related AOD statistics derived for each domain, and are described in more specific detail below. Three regions are strictly over water (NA, TA, AS), three include some land and coastline, but are primarily over water (C, SCS, SoJ), and two are mostly over land (E and SEA).

Table 2 includes results derived within each sub-region for averaged 2007 5-km CALIOP QA sub-sample and corresponding NAAPS AOD from both night and day, retrieval uncertainty, RMSD, correlation coefficient, slope and coordinate of y-intercept for the linear regression between the two, median AOD, sample size and total available retrieval sample size. The ratio of the latter two parameters is considered a first-order proxy for regional cloud frequency. The primary findings from this analysis are:

1. Mean nighttime CALIOP AOD are lower than daytime values in five of the sub-regions (NA, C, AS, SEA and SCS) by as much as 20%. In NA and C, NAAPS exhibits a day/night offset, though of not the same magnitude (approaching 10%). In the others, NAAPS exhibits relative stability diurnally. This day/night offset from both datasets is generally consistent with the global averages of all data points and as normalized per bin, as described from Table 1.
2. CALIOP AOD retrieval uncertainties exhibit little day/night variance. Sample sizes, however, are very high regionally, thus driving values low. No offset is found

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from further investigation of monthly and seasonal mean values (not shown), however. This is unusual considering the propagation of signal noise induced by solar background rates during daytime.

- 3. Mean CALIOP AOD are lower than that derived from NAAPS over water, except along the Saharan Dust Belt (C, TA, AS night), and high compared with the model over land. ... 4. RMSD between CALIOP and NAAPS varies between 0.10 and 0.35 amongst the sub-regions, with no apparent difference between night and day. ... 5. Correlation between CALIOP and NAAPS varies between 0.20 and 0.75 within the sub-regions. ... 6. QA sample size relative to the complete Level 2 5-km NASA aerosol data product archive reflect rejection rates varying from 40–80%.

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CALIOP averages including two or more contiguous data points (Fig. 8b), averages of six or more consecutive points (Fig. 8c), eleven or more (Fig. 8d) and sixteen or more (Fig. 8e). Given the 98.2° inclination angle of the CALIPSO near-polar orbit, its ground-track at the equator intersecting a single NAAPS grid-bin can include as many as twenty-two consecutive 5-km L2-AProf profiles, based on assignment of a 5-km CALIOP QA profile to NAAPS bin at the mid-point of the along-track average and 112.47 km per degree of latitude (e.g., Campbell et al., 2010).

Little change is found between Tables 2 and 3. Mean nighttime CALIOP AOD remain lower than the daytime mean in the same five sectors as above. AOD retrieval uncertainties show little difference between night and day, except in NA, SEA and SCS. Mean CALIOP AOD relative to NAAPS exhibit the same land/ocean offsets, including over the Saharan Dust Belt sub-region. Correlation and the slope of the linear regression between the two datasets exhibit no statistically-significant changes. RMSD drops slightly to between 0.10 and 0.30. At increasingly longer data averages in the C sub-region (Fig. 8), correlation coefficient increases and the slope of the linear regression mostly decreases up to the inclusion of eleven or more data points (Fig. 8d). When sixteen or more points are included, daytime correlation recedes slightly, nighttime increases very slightly and both slopes increase, which likely reflects the growing influence of aerosol autocorrelation lengths and representativeness bias for averages of 80 km or more (Anderson et al., 2003; Zhang et al., 2008). In this instance, the overestimate of AOD in the C sub-region by CALIOP compared with NAAPS appears, again, systemic.

Results of a third and final analysis are shown in Table 4. Here, only contiguous along-track data averages coinciding with the same NAAPS grid bin and containing at least six data points are used. However, the lowest and highest 25 % of those CALIOP data points making up the average are rejected. The purpose of this screening is to isolate the mode within the data distribution that best represents algorithm performance, excludes noise and potentially unfiltered cloud bias, and is less subject to random error. Notably, CALIOP AOD increase relative to NAAPS, compared with Tables 2 and 3, exceeding the model in C, TA, E, AS day and SEA. Correlation mostly increases, varying

now between 0.30 and 0.85, though relative decreases occur in some sub-regions (i.e., SEA night). Linear regression slopes trend slightly closer to unity, and RMSD improves in all sub-sectors except SEA. Some performance criteria improve with averaging and careful sample selection. Systematic retrieval offsets, however, persist.

### 3.3 How representative is the day/night CALIOP vertical extinction coefficient profile?

Mean CALIOP 0.532  $\mu\text{m}$  aerosol particle extinction coefficient profiles with corresponding error bars, solved by interpolating the 60 m 2007 QA sub-sample to a 100 m vertical grid, are shown annually for the C sub-region in Fig. 9 for day, night and the aggregate mean (Fig. 9a), the March–May seasonal average (MMA; Fig. 9b), June–August (JJA; Fig. 9c), September–November (SON; Fig. 9d) and December–February (DJF; Fig. 9e). For comparison, corresponding mean Level 2.0 aerosol extinction coefficient profiles with uncertainties derived from the Micropulse Lidar Network (MPLNET; Welton et al., 2001) 0.532  $\mu\text{m}$  instrument at Barbados (13.17° N, 59.43° W, 30 m a.m.s.l.) for data collected from August 2008 through June 2011. Additionally, for the JJA composite, the mean Level 2.0 0.523  $\mu\text{m}$  extinction coefficient profile with corresponding error bars is shown from an MPLNET instrument deployed for the June–July 2000 Puerto Rican Dust Experiment at Roosevelt Roads Naval Station, Puerto Rico (18.22° N, 65.60° W, 6 m a.m.s.l.; Reid et al., 2003).

MPLNET extinction retrievals are based on a single-channel elastic-scattering measurement, like CALIOP. However, inversion of the processed signal is constrained by AOD measurements made with a co-located AERONET sun photometer, and a layer-mean lidar ratio is solved as an intermediate processing step (e.g., Welton et al., 2002). Mean 2007 total annual CALIOP 0.532  $\mu\text{m}$  AOD at C is 0.188, whereas NAAPS 0.550  $\mu\text{m}$  AOD is 0.164. At Barbados, the corresponding AERONET-integrated mean annual 0.532  $\mu\text{m}$  AOD for the MPLNET Level 2.0 data period is 0.174, and 0.211 during JJA. The Roosevelt Roads mean for June–July 2000 is 0.208. The Puerto Rican MPLNET dataset has been studied previously (e.g., Livingston et al., 2003; Reid et

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al., 2003). As some representativeness bias is present in these comparisons (e.g., Kovacs, 2006), they are presented strictly for qualitative interpretation.

CALIOP and MPLNET mean annual profiles depict a common layer depth, and are mostly similar in vertical distributions. Below 1.0 km a.m.s.l., CALIOP is higher, and MPLNET is higher between 1.0 and 2.5 km a.m.s.l. CALIOP indicates slightly more extinction present above 2.5 km a.m.s.l., as well. Below 1.0 km a.m.s.l., calibration for optical overlapping in the MPL receiver system is sensitive at heights nearest the instrument (Campbell et al., 2002). MPLNET retrievals of extinction have been shown effective and robust, however, throughout the aerosol particle profile when compared with other lidars, including Raman-based instruments, and airborne measurement techniques (Schmid et al., 2006). Greater disparity is present within the seasonal profiles. MPLNET resolves a greater elevated layer component at Barbados above 1.0 km a.m.s.l. during MAM, less extinction above 2.5 km a.m.s.l. during JJA and lower values below 1.0 km a.m.s.l. during JJA, SON and DJF. The 2000 Roosevelt Roads mean profile matches very well with that from Barbados during JJA.

In Fig. 10, fractional partitioning of extinction as a function of the seven discrete aerosol species used in HERA for parameterizing the a-priori lidar ratio value in the CALIOP retrieval is shown for the mean 2007 annual and JJA profiles. This analysis indicates that “polluted dust” contributes most at C below 1.0 km a.m.s.l. During JJA (Fig. 10b), when near-surface magnitudes are highest annually, the fractional contribution of “polluted dust” dominates CALIOP extinction at these heights. The a-priori lidar ratio used for “polluted dust” is 55 sr, versus 40 sr for “dust” and 20 sr for “clean marine” (Omar et al., 2009). This relatively absorptive aerosol particle type may bias values high relative to the selection of these two other less-absorptive aerosol particle types, which are common to the regional C marine boundary layer (Li-Jones and Prospero, 1998). As context, the layer-mean lidar ratio solved in MPLNET Lever 2.0 retrievals at Barbados was 31.4 annually and 31.0 during JJA. At Roosevelt Roads, it was 53.1.

The daytime CALIOP aerosol particle extinction coefficient profile exhibits higher values during daytime at C than night, which is consistent with generally higher daytime

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AOD found globally discussed above. In spite of this, as seen from Fig. 9, the mean particle layer top height solved during night matches well with that from day. This is surprising given both the AOD difference combined with the effects of solar background noise, which might be expected to limit daytime identification of diffuse/optically-thin aerosol particles common near and above the top of the surface-detached aerosol layer.

In Table 5, the height of the 0.01, 0.001 and 0.0001  $\text{km}^{-1}$  isopleth found from each sub-regional mean 0.532  $\mu\text{m}$  CALIOP extinction coefficient profile for both day and night is reported. At C, heights are 3.8, 4.8 and 5.1 km a.m.s.l., respectively during daytime, compared with 3.4, 4.6 and 5.3 km a.m.s.l. at night. In the other sub-regions at the 0.01 and 0.001  $\text{km}^{-1}$  thresholds, mean heights are relatively consistent except for SCS and SoJ. At 0.0001  $\text{km}^{-1}$  resolution, however, significant offsets are found, which are believed consistent with optimized nighttime sensitivities. Therefore, to within a few hundred meters, CALIOP layer-identification and mean layer top height is relatively stable diurnally, save for the most optically-thin (i.e., negligible) segments of the particle profile.

The sum total of particle layers identified in CALIOP retrievals at night exceeds that found during daytime by more than 50 % despite lower mean AOD (not shown). Somewhat paradoxically then, and in closing, higher AOD are found during daytime in spite of fewer total layers, but with a common mean effective layer top height. Future study is necessary to reconcile this finding. One plausible cause relates to the sensitivity of layer-identification thresholds between day/night for resolving clear sky gaps within diffuse/optically-thin layers (e.g., Campbell et al., 2008). At night, improved sensitivity and algorithm/logical compliance identifying clear-sky gaps can yield lower AOD compared with daytime, where apparent gaps and inherent noise are integrated within the column solution. However, note that in the annual mean at C (Fig. 9a), the bulk of the AOD offset is induced nearest the surface within a segment of highest values for extinction coefficient. This suggests that in this case another mechanism may be occurring, including day/night differences in layer base identification by the algorithms or simple

physical decoupling in the boundary layer from surface source forcing (e.g., Osborne et al., 2000).

#### 4 Conclusions and impact

NASA Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) Version 3.01 5-km quality-assured (QA) retrievals of 0.532  $\mu\text{m}$  aerosol optical depth (AOD) from 2007 are evaluated during nighttime at  $1^\circ \times 1^\circ$  resolution relative to 0.550  $\mu\text{m}$  analyses made by a global aerosol transport model equipped with two-dimensional variational assimilation of quality-assured NASA Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging Spectroradiometer (MISR) AOD. The US Navy Aerosol Analysis and Prediction System (NAAPS) generates global forecasts for aerosol visibility every six hours out to six days. NAAPS AOD analyses used to validate CALIOP retrievals reflect a nominal 12-h model forecast due to lack of MODIS/MISR data for assimilation within the dark sector of the model at initialization. The model is shown to exhibit reasonable stability, however, between the 0-h analysis and 24-h forecast when compared with MODIS/MISR, thus ensuring representativeness for this study. Daytime comparisons of CALIOP and NAAPS are described as supplemental context for the nighttime study. Global composites of CALIOP and NAAPS AOD are shown, as well as statistical analyses for eight regional domains. Averaged vertical profiles of 0.532  $\mu\text{m}$  CALIOP extinction coefficient versus ground-based elastic-scattering lidar retrievals are shown, as well as fractional contribution to total AOD for each of the seven distinct aerosol models used for assigning the a-priori lidar ratio used in solving CALIOP extinction.

The primary findings of this study are:

1. Mean nighttime CALIOP AOD are in nearly all cases lower than daytime values (0.121 vs. 0.126 for all aggregated data points, and 0.099 vs. 0.102 when averaged per grid bin, both globally), though the relationship is reversed

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- when analyzed in a per-bin average over land and coastal regions (0.134/0.108 vs. 0.140/0.112, respectively). Though the magnitude of the offset varies regionally, maximums per bin approach 20 %. Prominent regions where nighttime AOD exceeds daytime include the sub-tropical Atlantic Ocean and Europe. AOD uncertainties exhibit day/night variability in only a limited number of global regions, and only when along-track averaging and sample-filtering of high-variance data points are applied.
2. When globally averaged per  $1^\circ \times 1^\circ$  grid bin, CALIOP AOD are higher over land versus NAAPS (0.137 vs. 0.124). Over water, the two datasets are nearly equal (0.082 vs. 0.083). For all data points inclusive, NAAPS exceeds CALIOP over all surface types (land, coastal and ocean). When analyzed for eight distinct sub-regions, CALIOP exceeds NAAPS over land, though the relationship does not hold over open waters near the Sahara region that are frequently subject to dust transport. Differences exceed that expected for the slight wavelength difference between the two datasets, approaching 50 % in extreme cases. Regional land/ocean offsets in CALIOP AOD are consistent with those identified in previous studies (Campbell et al., 2011; Kittaka et al., 2011).
3. Correlation between 5-km CALIOP AOD and corresponding NAAPS data points is relatively low globally during both day and night except for Saharan dust transport zones over the Tropical Atlantic and Caribbean, where correlation approaches 0.8. Along-track averaging and sample filtering, described above, improve this and other statistical methods described for assessing CALIOP retrieval skill (i.e., root mean square deviation and the slope of the linear regression). However, whereas further averaging and data screening improve these statistical metrics, systemic biases, such as high/low land/water and high day versus night AOD relative to NAAPS persist.

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4. Annual and seasonal mean vertical profiles 0.532  $\mu\text{m}$  for aerosol particle extinction coefficient compare well with ground-based 0.523  $\mu\text{m}$  and 0.532  $\mu\text{m}$  elastic-scattering lidar retrievals collected at two sites. Offsets and their variability regionally are likely due to irregularities in the a-priori selection of the lidar extinction-to-backscatter ratio necessary for conducting iterative elastic-scattering CALIOP retrievals of 0.532  $\mu\text{m}$  aerosol particle extinction coefficient. An example of such irregularity is shown from the Caribbean, where selection of a relatively absorptive aerosol particle model type is likely inducing a higher mean extinction coefficient near the surface than is present. It is undetermined how this effect is manifested with the global averages.

5. Although daytime AOD are generally higher than nighttime values, effective CALIOP-derived layer top heights are comparable (significant variance found for only the most optically-thin/diffuse segments of mean extinction coefficient profiles), despite more total particle layers being identified during night. Further study is necessary to reconcile this scenario.

Overall, the results of this study demonstrate that nighttime CALIOP datasets are reasonably consistent with daytime retrievals. This finding is impressive given the negative influence of ambient solar noise on lidar retrievals at visible wavelengths, particularly for single-channel elastic-scattering instruments, for which extinction is retrieved indirectly (e.g., Young and Vaughan, 2009). Kittaka et al. (2011) note that differences are to be expected between night and daytime datasets due to variability in systematic calibration errors, instrument sensitivities in day and nighttime sky conditions, and diurnal changes to the aerosol. The systematic offset between day and nighttime AOD is a topic that requires further study in order to reconcile previous versions, and motivate future iterations, of the Level 2 data archive. Still, whereas many important characteristics of the CALIOP datasets have been identified and reported relative to NAAPS datasets, and are summarized above, perhaps the more important conclusion from this study is that CALIOP Version 3.01 retrieval performance is stable throughout the

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diurnal cycle, which is a notable achievement for the mission science team, and an important performance metric for investigators tasked with applying these data for climate study.

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**Table 2.** For 2007 and each sub-region defined, mean annual nighttime (NGT) and daytime (DAY) CALIOP aerosol optical depth (AOD), instrument/retrieval uncertainty (UNC.), corresponding mean annual NAAPS AOD, root-mean square deviation between CALIOP and NAAPS, correlation coefficient between the two (CORL.), slope of the linear regression between the two (SLOPE), coordinate value of y-intercept solved from regression (COORD.), median of CALIOP AOD (MEDIAN) and sample size (SAMPLE) and total number of available data files regardless of cloud-screening protocols described (TOTAL).

	N. Atlantic 70° W/35° N– 60° W/40° N		Caribbean 65° W/10° N– 55° W/20° N		T. Atlantic 35° W/15° N– 25° W/25° N		Europe 5° E/50° N– 25° E/55° N		Arabian Sea 60° E/10° N– 70° E/20° N		SE Asia 100° E/10° N– 110° E/20° N		S. China Sea 110° E/5° N– 120° E/15° N		Sea of Japan 130° E/35° N– 140° E/45° N	
	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY
CALIOP	0.077	0.102	0.177	0.207	0.234	0.214	0.208	0.178	0.236	0.277	0.341	0.385	0.087	0.099	0.153	0.147
UNC.	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001
NAAPS	0.128	0.136	0.158	0.171	0.191	0.192	0.163	0.162	0.252	0.251	0.338	0.323	0.155	0.147	0.190	0.205
RMSD	0.123	0.143	0.177	0.177	0.223	0.159	0.229	0.184	0.186	0.181	0.328	0.327	0.122	0.107	0.183	0.188
CORL.	0.183	0.236	0.721	0.687	0.631	0.661	0.323	0.271	0.476	0.534	0.511	0.571	0.238	0.427	0.385	0.429
SLOPE	0.201	0.283	1.506	1.442	1.246	1.211	0.827	0.525	1.070	0.994	0.669	0.988	0.341	0.525	0.615	0.530
COORD.	0.051	0.064	−0.06	−0.04	−0.00	−0.02	0.073	0.093	−0.03	0.028	0.114	0.066	0.034	0.021	0.037	0.039
MEDIAN	0.057	0.069	0.088	0.118	0.130	0.147	0.129	0.129	0.178	0.233	0.209	0.263	0.067	0.072	0.091	0.095
SAMPLE	3703	2736	11 039	8179	9691	10 174	5138	3798	11 248	8338	4729	2161	4999	2201	6308	4988
TOTAL	6389	5398	19 049	17 810	15 737	18 614	10 494	7041	17 986	17 557	12 572	10 095	14 990	10 776	11 952	10 058

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**Table 3.** As in Table 1, for all contiguous averages of CALIOP data segments occurring within the same NAAPS  $1^\circ \times 1^\circ$  grid bin.

	N. Atlantic 70° W/35° N– 60° W/40° N		Caribbean 65° W/10° N– 55° W/20° N		T. Atlantic 35° W/15° N– 25° W/25° N		Europe 5° E/50° N– 25° E/55° N		Arabian Sea 60° E/10° N– 70° E/20° N		SE Asia 100° E/10° N– 110° E/20° N		S. China Sea 110° E/5° N– 120° E/15° N		Sea of Japan 130° E/35° N– 140° E/45° N	
	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY
CALIOP	0.084	0.111	0.188	0.204	0.246	0.235	0.226	0.194	0.248	0.292	0.347	0.385	0.089	0.101	0.166	0.162
UNC.	0.004	0.006	0.004	0.004	0.004	0.004	0.006	0.007	0.004	0.005	0.007	0.011	0.004	0.007	0.004	0.005
NAAPS	0.135	0.136	0.161	0.170	0.195	0.203	0.164	0.160	0.256	0.258	0.336	0.330	0.156	0.151	0.198	0.213
RMSD	0.113	0.144	0.152	0.136	0.194	0.135	0.211	0.193	0.159	0.153	0.282	0.290	0.107	0.101	0.160	0.176
CORL	0.239	0.221	0.825	0.794	0.724	0.792	0.382	0.205	0.622	0.623	0.623	0.625	0.311	0.490	0.462	0.461
SLOPE	0.180	0.274	1.616	1.439	1.278	1.287	0.898	0.384	1.247	0.990	0.784	0.899	0.344	0.539	0.619	0.529
COORD.	0.060	0.074	−0.07	−0.04	−0.00	−0.03	0.078	0.133	−0.07	0.036	0.084	0.088	0.035	0.026	0.044	0.049
MEDIAN	0.066	0.079	0.097	0.121	0.132	0.169	0.151	0.147	0.193	0.245	0.236	0.267	0.072	0.087	0.106	0.111
SAMPLE	436	342	1040	871	1035	1068	669	519	937	799	531	267	509	291	732	597

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**Table 4.** As in Tables 1 and 2, for those contiguous averages of CALIOP data segments containing at least 6 AOD values, where the highest and lowest 25 % of the data are rejected and the median 50 % analyzed.

	N. Atlantic 70° W/35° N– 60° W/40° N		Caribbean 65° W/10° N– 55° W/20° N		T. Atlantic 35° W/15° N– 25° W/25° N		Europe 5° E/50° N– 25° E/55° N		Arabian Sea 60° E/10° N– 70° E/20° N		SE Asia 100° E/10° N– 110° E/20° N		S. China Sea 110° E/5° N– 120° E/15° N		Sea of Japan 130° E/35° N– 140° E/45° N	
	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY	NGT	DAY
CALIOP	0.075	0.100	0.174	0.210	0.234	0.210	0.193	0.165	0.242	0.274	0.339	0.402	0.086	0.094	0.148	0.139
UNC.	0.005	0.007	0.004	0.005	0.005	0.005	0.007	0.008	0.005	0.006	0.008	0.015	0.004	0.008	0.005	0.006
NAAPS	0.127	0.136	0.158	0.172	0.193	0.191	0.163	0.160	0.254	0.251	0.334	0.328	0.152	0.145	0.189	0.204
RMSD	0.100	0.120	0.131	0.143	0.178	0.107	0.172	0.123	0.159	0.139	0.294	0.287	0.101	0.077	0.141	0.155
CORL	0.295	0.341	0.826	0.788	0.716	0.773	0.376	0.417	0.559	0.639	0.571	0.695	0.320	0.660	0.507	0.558
SLOPE	0.234	0.341	1.484	1.468	1.210	1.132	0.746	0.573	1.119	0.989	0.728	1.206	0.346	0.554	0.687	0.556
COORD.	0.046	0.054	−0.06	−0.04	0.001	−0.01	0.071	0.073	−0.04	0.027	0.096	0.007	0.033	0.014	0.018	0.026
MEDIAN	0.063	0.070	0.089	0.126	0.131	0.155	0.131	0.132	0.191	0.236	0.225	0.281	0.069	0.077	0.094	0.098
SAMPLE	272	204	812	610	731	757	384	281	767	598	367	161	361	162	472	385

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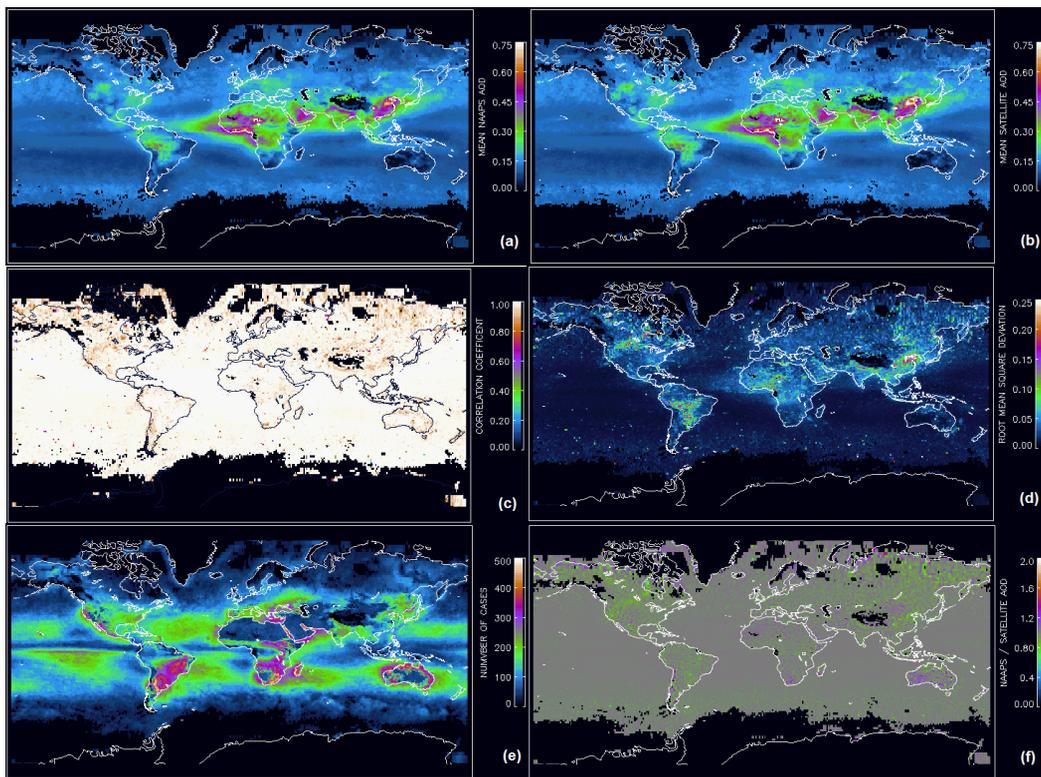
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**Table 5.** For each sub-region defined beginning in Table 1, the mean height for both day and night corresponding with the 0.01, 0.001 and 0.0001  $\text{km}^{-1}$  isopleth for CALIOP-derived 0.532  $\mu\text{m}$  extinction coefficient.

	DAY			NIGHT		
	0.01 $\text{km}^{-1}$	0.001 $\text{km}^{-1}$	0.0001 $\text{km}^{-1}$	0.01 $\text{km}^{-1}$	0.001 $\text{km}^{-1}$	0.0001 $\text{km}^{-1}$
N. Atlantic 70° W/35° N–60° W/40° N	1.8	3.7	4.2*	2.0	4.0*	N/A
Caribbean 65° W/10° N–55° W/20° N	3.8	4.8	5.1	3.4	4.6	5.3
T. Atlantic 35° W/15° N–25° W/25° N	4.2	5.4	6.2	4.5	5.6	6.3
Europe 5° E/50° N–25° E/55° N	2.5	3.7	4.6*	2.5	4.1	6.2
Arabian Sea 60° E/10° N–70° E/20° N	4.1	5.1	5.5	3.9	5.2	5.8*
SE Asia 100° E/10° N–110° E/20° N	3.4	4.5	4.8	3.4	4.3	5.0
South China Sea 110° E/5° N–120° E/15° N	1.9	2.5	3.6	1.8	4.0	4.2*
Sea of Japan 130° E/35° N–140° E/45° N	2.9	5.0	9.9	3.4	7.3	N/A

\* denotes the presence of multiple layers, and hence the corresponding mean height for the lowest such layer. Cases where the isopleth height exceeded 10.0 km a.m.s.l. are denoted with “N/A”.



**Fig. 1.** For 2007 at  $1^\circ \times 1^\circ$  global resolution, **(a)** mean  $0.550 \mu\text{m}$  NAAPS 0-h analysis aerosol optical depth (AOD) for data points with co-incident  $0.550 \mu\text{m}$  MODIS and/or  $0.557 \mu\text{m}$  MISR AOD retrieval (i.e., daytime), **(b)** corresponding MODIS/MISR mean AOD, **(c)** correlation coefficient between the two datasets for all points inclusive, **(d)** root mean square deviation between the two, **(e)** number of cases per grid bin and **(f)** the corresponding ratio of mean NAAPS to MODIS/MISR AOD.

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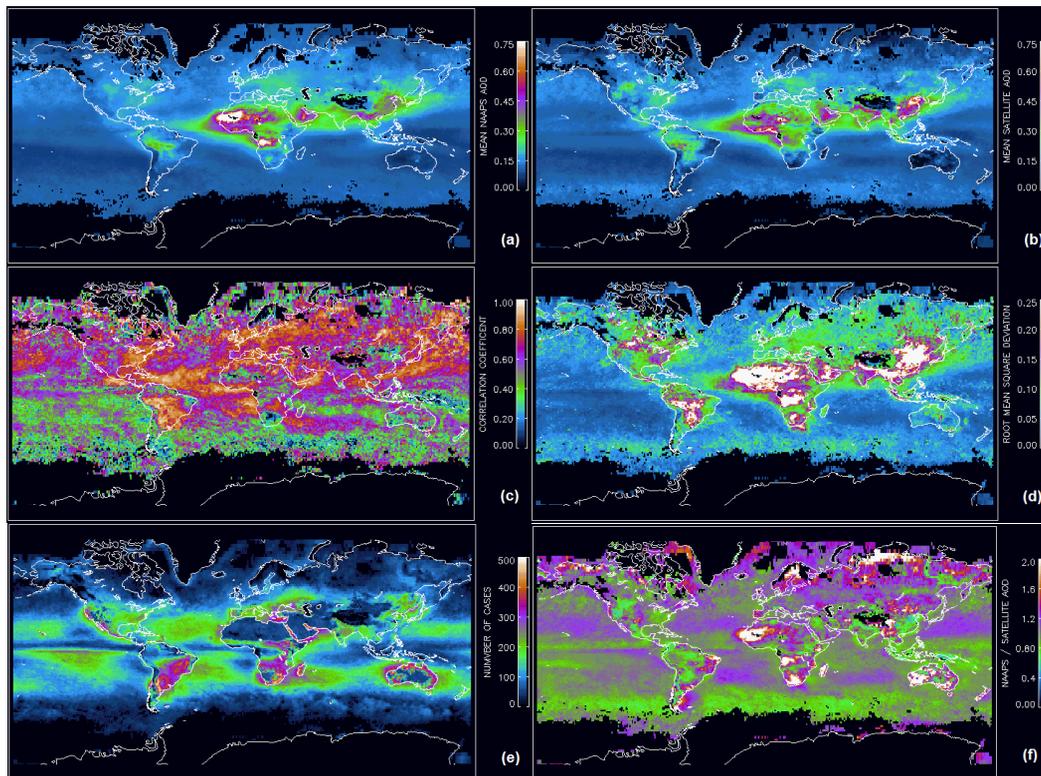
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**Fig. 2.** For 2007 at  $1^\circ \times 1^\circ$  global resolution, **(a)** mean NAAPS 24-h forecast AOD for data points with co-incident  $0.550 \mu\text{m}$  MODIS and/or  $0.557 \mu\text{m}$  MISR AOD retrieval (i.e., daytime), **(b)** corresponding MODIS/MISR mean AOD, **(c)** correlation coefficient between the two datasets for all points inclusive, **(d)** root mean square deviation between the two, **(e)** number of cases per grid bin and **(f)** the corresponding ratio of mean NAAPS to MODIS/MISR AOD.

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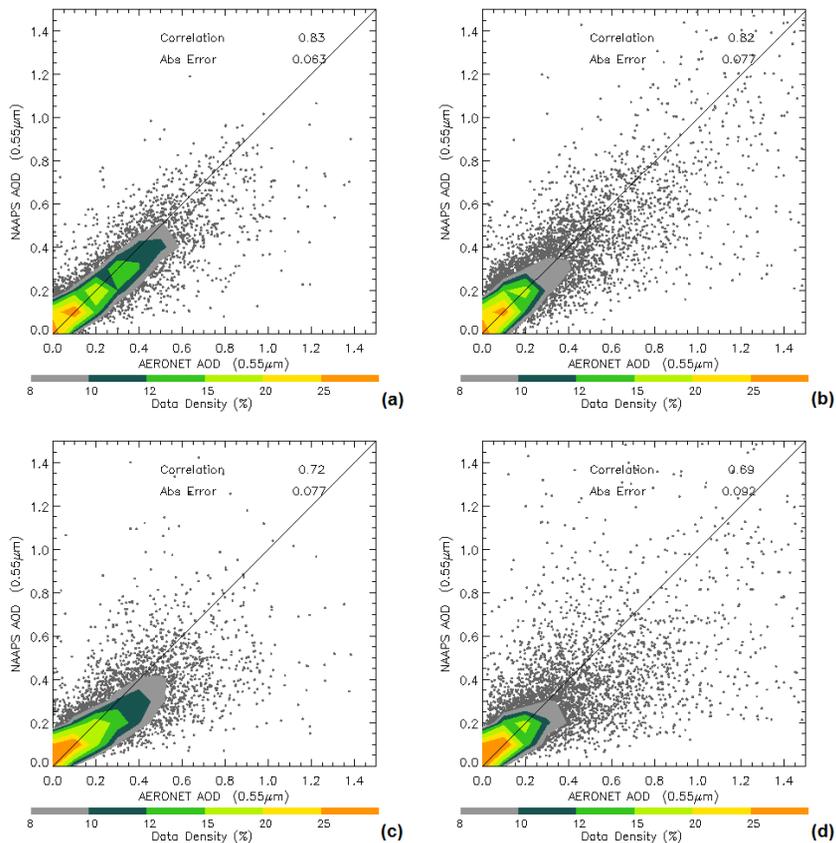
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**Fig. 3.** For 2007, comparisons of NAAPS and co-incident AERONET 0.550  $\mu\text{m}$  AOD measurements for the 0-h model analysis at (a) over-ocean and (b) over-land sites, and the 24-h forecast model analysis at (c) over-ocean and (d) over-land sites. Corresponding correlation and absolute error for each profile are given in the inset. One-to-one ratio lines are superimposed.

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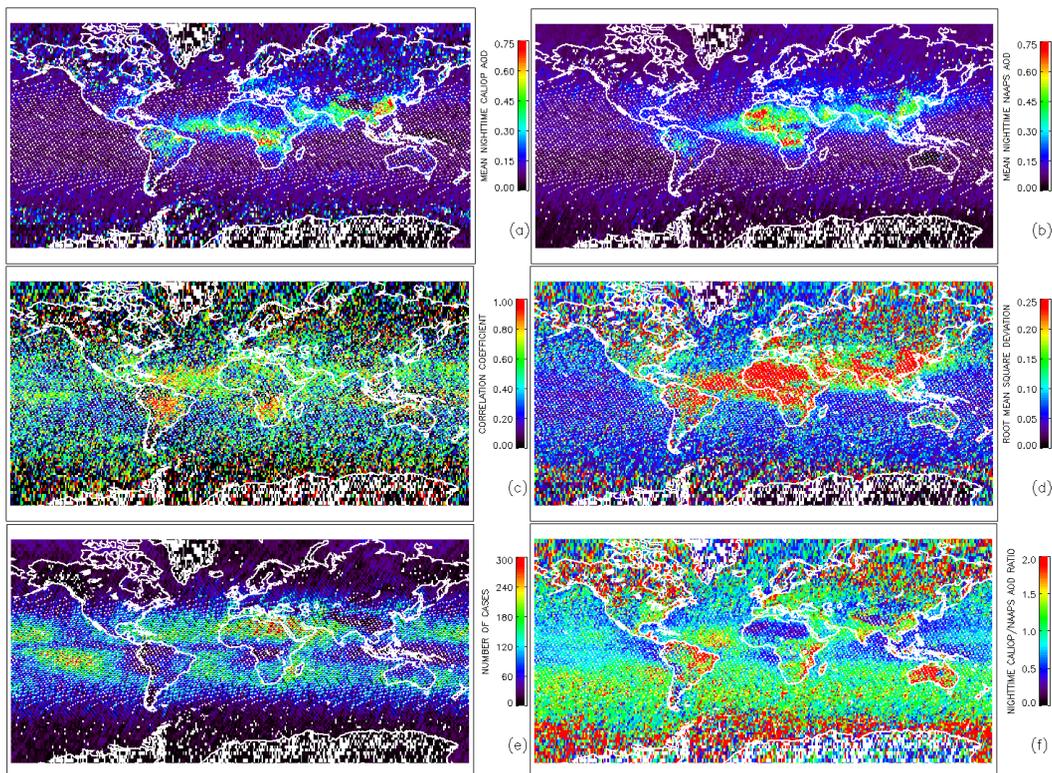
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**Fig. 4.** For 2007 at  $1^\circ \times 1^\circ$  global resolution, **(a)** mean nighttime CALIOP 0.532  $\mu\text{m}$  AOD, **(b)** corresponding mean nighttime NAAPS 0.550  $\mu\text{m}$  AOD (see text), **(c)** correlation coefficient between the two datasets for all points inclusive, **(d)** root mean square deviation between the two, **(e)** number of corresponding cases per grid bin and **(f)** the ratio of corresponding mean nighttime CALIOP/NAAPS AOD. Points with no data coincide with a white pixel color that is not represented on the color bar.

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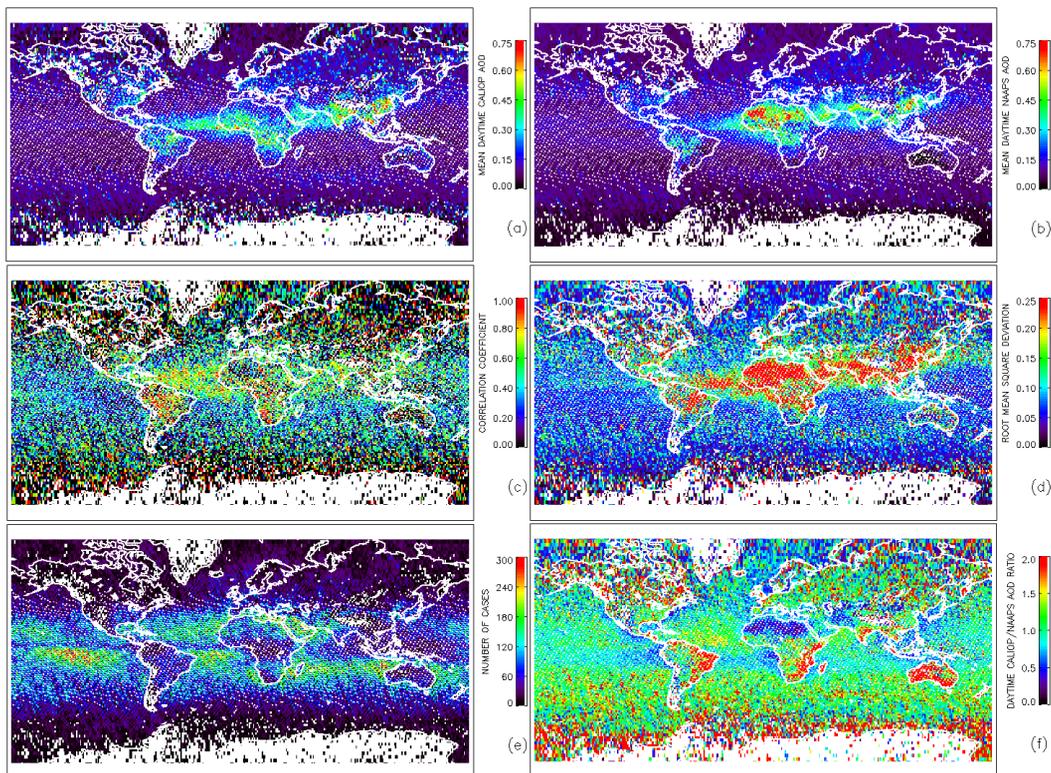
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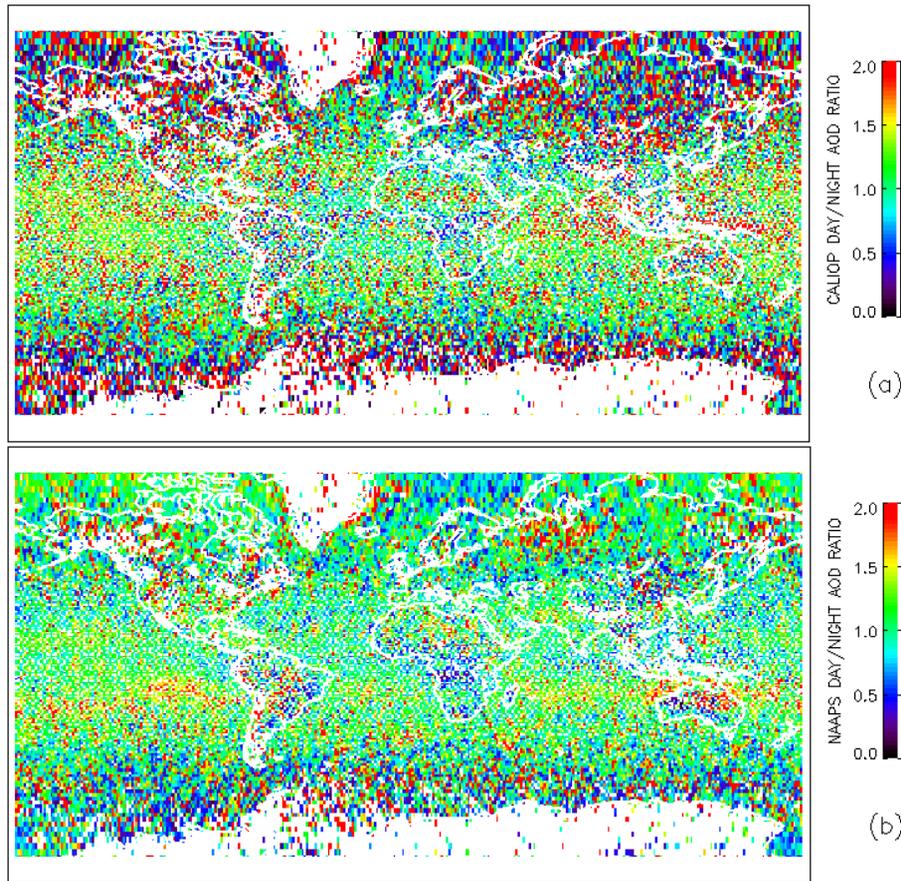


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**Fig. 5.** For 2007 at  $1^\circ \times 1^\circ$  global resolution, **(a)** mean daytime CALIOP 0.532  $\mu\text{m}$  AOD, **(b)** corresponding mean daytime NAAPS 0.550  $\mu\text{m}$  AOD (see text), **(c)** correlation coefficient between the two datasets for all points inclusive, **(d)** root mean square deviation between the two, **(e)** number of corresponding cases per grid bin and **(f)** the corresponding ratio of mean daytime CALIOP and NAAPS AOD. Points with no data coincide with a white pixel color that is not represented on the color bar.



**Fig. 6.** Ratio of daytime versus nighttime AOD from 2007 for **(a)** CALIOP ( $0.532\ \mu\text{m}$ ) and **(b)** NAAPS ( $0.550\ \mu\text{m}$ ) for co-incident data points (see text). Points with no data coincide with a white pixel color that is not represented on the color bar.

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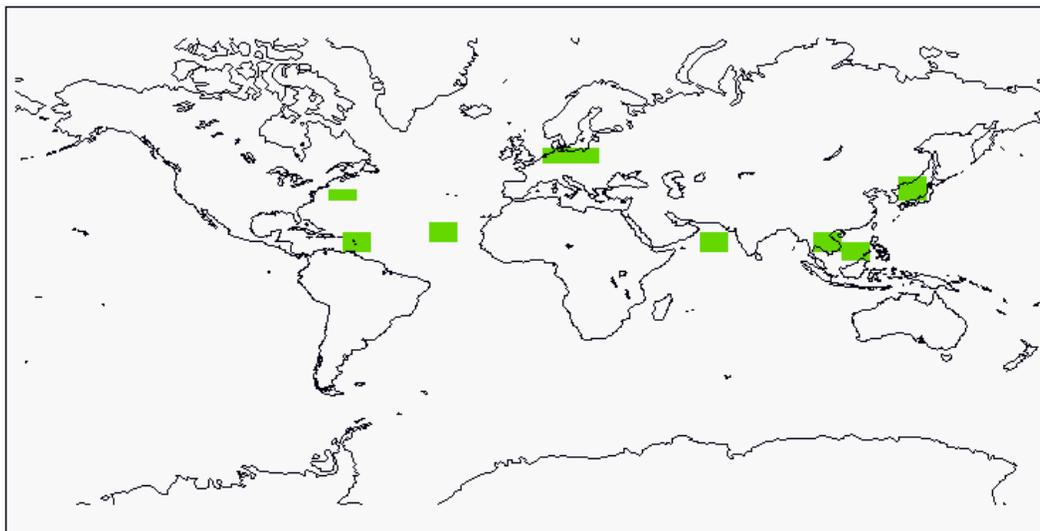
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**Fig. 7.** Depiction of the eight regions (North Atlantic, Caribbean, Tropical Atlantic, Europe, Arabian Sea, Southeast Asia, South China Sea and Sea of Japan) investigated for CALIOP versus NAAPS AOD comparisons.

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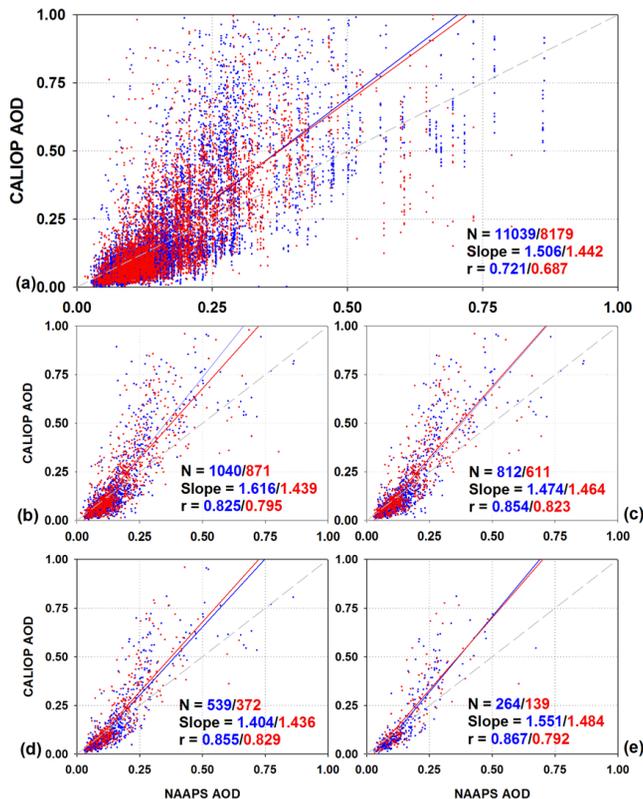
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**Fig. 8.** In 2007 for Caribbean sector ( $65^{\circ}\text{W}/10^{\circ}\text{N}$  to  $55^{\circ}\text{W}/20^{\circ}\text{N}$ ), **(a)** all CALIOP 0.532  $\mu\text{m}$  AOD versus corresponding  $1^{\circ} \times 1^{\circ}$  0.550  $\mu\text{m}$  NAAPS AOD during night (blue) and day (red), with number of data points, linear regression slope and correlation coefficient,  $r$ , given in the inset; **(b)** same but for averages of CALIOP along-track 0.532  $\mu\text{m}$  AOD in segments of 2–5 data points occurring within the same NAAPS grid bin; **(c)** same for averages of 6–10 such consecutive data points; **(d)** 11–15 data points; **(e)**  $\geq 16$  data points.

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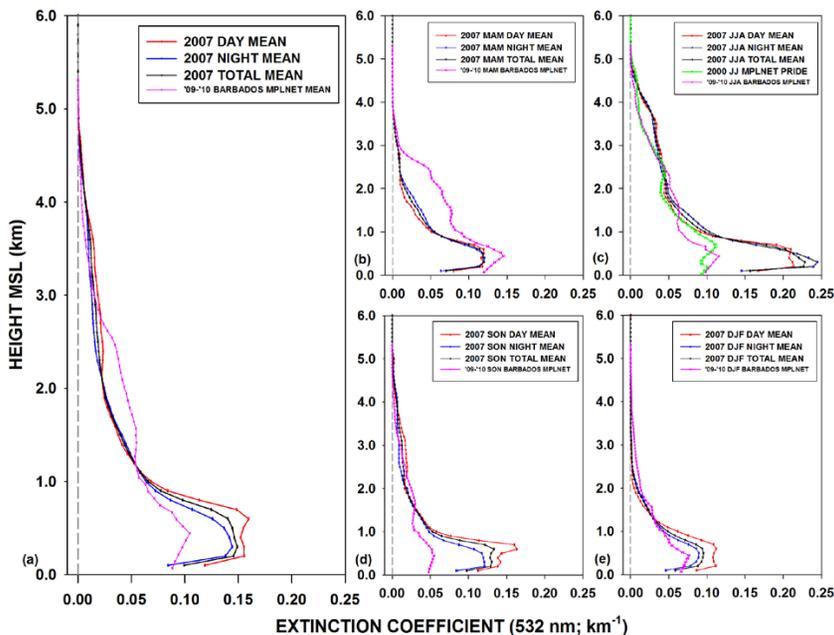
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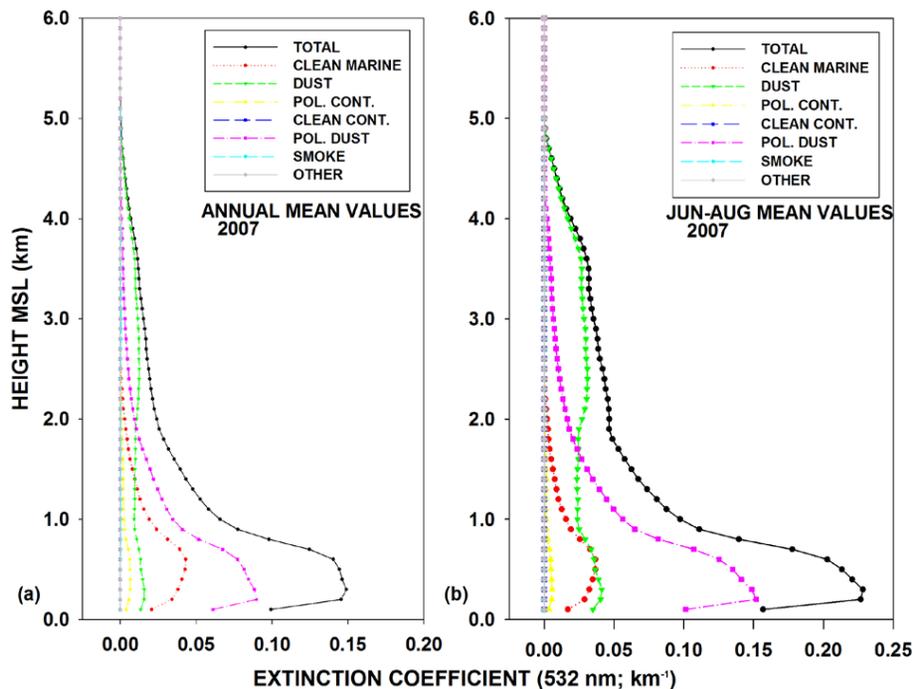
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**Fig. 9.** In 2007 for Caribbean sector (65° W/10° N to 55° W/20° N), **(a)** mean daytime, nighttime and total 0.532  $\mu\text{m}$  CALIOP extinction coefficient profiles (see inset) and mean Micropulse Lidar Network (MPLNET) Level 2.00.532  $\mu\text{m}$  extinction coefficient profile collected at Barbados (13.17° N, 59.43° W, 30 m a.m.s.l.) for August 2008–June 2011; **(b)** March-to-May three-monthly average of 2007 CALIOP mean day, night and total 0.532  $\mu\text{m}$  extinction coefficient profile versus corresponding three-monthly average of Barbados MPLNET data from 2009–2011; **(c)** June–August three-monthly average of 2007 CALIOP mean day, night and total 0.532  $\mu\text{m}$  extinction coefficient profile versus mean Level 2.0 0.523  $\mu\text{m}$  extinction coefficient profile derived for June–July 2000 at MPLNET/Roosevelt Roads Naval Station, Puerto Rico site (18.22° N, 65.60° W, 6 m a.m.s.l.) and for Barbados from 2009–2011; **(d)** same as **(b)** now for September-to-November; **(e)** same as **(b)** and **(d)** now for December-to-February.

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**Fig. 10.** Corresponding with both the (a) 2007 total mean annual profile in Fig. 9a and (b) June–August 2007 three-monthly averaged one in Fig. 9c, the fractional contribution to total extinction coefficient for each of the seven possible species identified, and thus parameterized for lidar extinction-to-backscatter ratio, in CALIOP aerosol retrievals (see inset).

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