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Key Points:

- Current CALIOP data products are shown to provide only an upper bound on modeled aerosol concentrations in the free troposphere
- The practice of *filling in* missing retrievals has a disproportionate effect in the free troposphere where most aerosol is undetected

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On the Limits of CALIOP for Constraining Modeled Free Tropospheric Aerosol

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Abstract The spaceborne Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument provides valuable information on the vertical distribution of global aerosol and is often used to evaluate vertical aerosol distributions in general circulation models (GCMs). Here we show, however, that the detection limit of the CALIOP retrievals mean background aerosol is not detected, leading to substantially skewed statistics that moreover differ significantly by product. In the CALIOP Level 2 product this missing low-backscatter aerosol results in the retrieved aerosol distribution significantly overrepresenting aerosol backscatter and extinction in the middle and upper troposphere if taken to be representative of the undetected aerosol. The CALIOP Level 3 product assumes no aerosol where none is detected, which then leads to an underestimation in the aerosol extinction profile in the upper troposphere. Using the ECHAM-HAM GCM, we estimate that the mean fraction of aerosol undetected by CALIOP daytime (nighttime) retrievals is 41% (44%) globally.

Plain Language Summary The spaceborne Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument provides valuable information on the vertical distribution of global aerosol and is often used to evaluate vertical aerosol distributions in general circulation models (GCMs). Here we show, however, that the detection limit of the CALIOP retrievals mean background aerosol is not detected, leading to substantially skewed statistics that depend on assumptions about the missing aerosol. Using the ECHAM-HAM GCM, we estimate that the mean fraction of aerosol undetected by CALIOP daytime (nighttime) retrievals is 41% (44%) globally.

1. Introduction

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument has provided a unique insight into the vertical distribution of cloud and aerosol globally since its launch in 2006. Given the sparsity and limited global representativeness of in situ aircraft campaigns and ground-based lidar networks, CALIOP backscatter and extinction measurements have been relied upon to constrain the vertical aerosol distribution in GCMs (Koffi et al., 2016, 2012; Yu et al., 2010). Recent work has shown, however, that undetected aerosol extinction values can contribute to a low bias in the aerosol optical depth (AOD) as compared to Moderate Resolution Imaging Spectroradiometer (Kim et al., 2017; Thorsen et al., 2017; Toth et al., 2018).

While these recent studies (Kim et al., 2017; Thorsen et al., 2017; Toth et al., 2018) have focused on the issue of retrieval fill values, where the retrieval algorithm was unable to discern an unambiguous aerosol signal and its consequences for AOD, this work focuses on the backscatter and extinction values which *are* reported, and how representative those are in the middle to upper troposphere.

By taking all valid CALIOP L2 aerosol (at 532 nm) measurements over 2008 we find that the CALIOP reported aerosol backscatter and extinction above 5 km approaches the detection thresholds of the retrieval (as estimated from Winker et al., 2009, which gives a detailed description of these thresholds). Collocating high temporal resolution backscatter fields from the aerosol-climate model ECHAM-HAM shows that this bias leads to an overestimation in the global mean attenuated backscatter of 1–2 orders of magnitude above 5 km. We independently demonstrate this by comparing the CALIOP backscatter with airborne measurements using a High Spectral Resolution Lidar (HSRL), conducted during the ORACLES campaign. We estimate that this lack of sensitivity leads to a global mean fraction of aerosol undetected by CALIOP of 41% (44%) during nighttime (daytime).

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2. Data and Methods

We use the CALIOP Level 2 version 4 aerosol profile data for all of 2008 and use the supplied cloud-aerosol discrimination (CAD) score to include only the L2 columns which include at least one aerosol retrieval (CAD score < -20). We also exclude any columns with cloud retrievals (CAD score > 0) and any special CAD scores ($>|100|$)—which might indicate a bad shot. This follows the method used in Winker et al. (2013). For extinction fields we only consider those retrievals with Extinction_QC < 2, signifying constrained retrievals for which the lidar ratio was directly determined by the attenuated backscatter data or an unconstrained retrieval for which the initial lidar ratio was unchanged during solution process. We have also used CALIOP Level 1 version 4 attenuated backscatter data. This is only screened using the associated Level 2 vertical feature mask to remove any columns including detected cloud layers. We then linearly interpolate high temporal resolution model output onto these data points using the community intercomparison suite (CIS) (Watson-Parris et al., 2016) in order to minimize temporal sampling biases (Schutgens et al., 2016) and average each of the points into 300-m vertical bins. For the CALIOP Level 3 comparisons we use the standard cloud-free aerosol profile monthly mean product, for which the latest version available is version 3.0.

In order to supplement the comparison of CALIOP extinction profiles, which introduce large uncertainties due to the need for the CALIOP retrieval to estimate a lidar ratio for the aerosol (Vaughan et al., 2009), we have implemented an online backscatter calculation within ECHAM-HAM allowing both backscatter and extinction comparisons. We use the lidar equation to simulate total (aerosol + gas) attenuated backscatter observed from space, averaged over each model level:

$$\beta_{\text{att}}(z) = \beta e^{-2\int_z^\infty \alpha dz} \quad (1)$$

where β and α are total (aerosol + gas) backscatter and extinction across a level, respectively. The extinction and backscatter of aerosol are calculated from look-up tables (created for Mie-scattering spherical particles) as per the standard ECHAM-HAM calculation of clear-sky aerosol optical properties (Stier et al., 2005, 2007), which produces global mean AODs in good agreement with observation (Zhang et al., 2012). The extinction and backscatter of gas molecules is calculated as per Bodhaine et al. (1999), which is estimated to allow errors of less than 1% for visual wavelengths.

Otherwise, the model is the latest ECHAM6.3-HAM2.3 version (Tegen et al., 2018, version ECHAM6.1-HAM2.0 is described by Zhang et al., 2012) run at T63L31 with Atmospheric Chemistry and Climate Model Intercomparison Project interpolated (Lamarque et al., 2010), and Global Fire Assimilation System wildfire emissions nudged to the 2008 meteorology using ERA-Interim reanalysis data (Dee et al., 2011).

3. Results

In the following discussion we use the ECHAM-HAM model as a useful baseline against which we compare the CALIOP retrievals under different assumptions. The model will of course have its own biases; however, these are likely small compared to the CALIOP biases in the middle and upper troposphere—as will be shown at the end of the section and do not impact the conclusions.

In order to improve the signal-to-noise ratio when retrieving optically thin aerosol layers, the CALIOP Level 2 retrieval algorithm performs horizontal averaging over progressively longer horizontal scales. The best sensitivity is therefore achieved when averaging over 80 km (the largest horizontal distance used). In Figure 1 we show the global median CALIOP L2 aerosol backscatter profiles and interquartile range for daytime and nighttime data based on different horizontal averaging scales, and the theoretical detection limit in each case (estimated from Winker et al., 2009) along with collocated ECHAM-HAM backscatter profiles. While the model aerosol backscatter remains similar at day and night and under the different averaging regimes of CALIOP, we see that the CALIOP profiles above 5 km show significant differences and lie on the theoretical detection limits in each case. While the longer horizontal averaging is only required for optically thinner aerosol, and so would be expected have smaller backscatter values, the fact that the profiles are so close to the theoretical detection limit in each case suggests that CALIOP is only sampling the upper edge of the real aerosol backscatter distribution in the free troposphere. This is also demonstrated by the sharp cutoff in the joint histogram of CALIOP L2 backscatter with altitude (not shown).

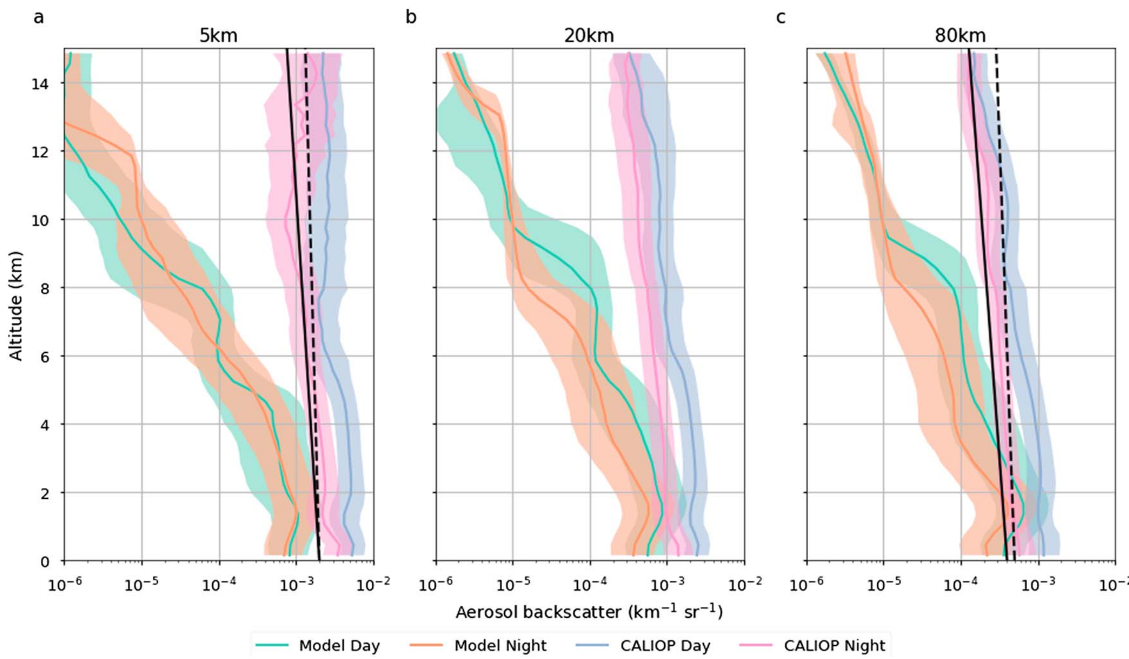

Figure 1. Global median CALIOP L2 aerosol backscatter profiles for the year of 2008 from (a) 5- (b) 20-, and (c) 80-km horizontal averages at both daytime and nighttime. Temporally and spatially collocated median ECHAM-HAM backscatter profiles are also shown in each case, along with the theoretical detection limit of CALIOP estimated for 5 and 80 km from Winker et al., 2009 (no 20-km estimate was available). CALIOP = Cloud-Aerosol Lidar with Orthogonal Polarization.

This bias is present in both the backscatter and extinction products and manifests itself differently in the L2 and L3 products. In Figure 2a we show the CALIOP L2 and collocated model global mean aerosol extinction profiles as a function of altitude. It is clear that while the model predicts extinction values approaching 10^{-4} km^{-1}, the CALIOP extinction remains above 10^{-2} km^{-1}, corresponding to its

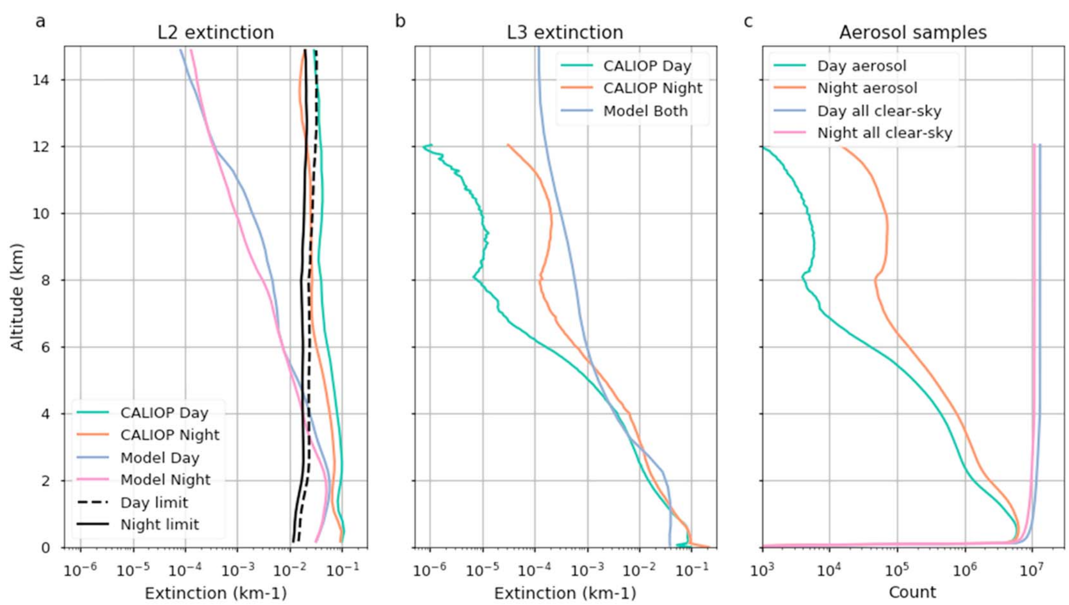

Figure 2. Global extinction profiles for the year of 2008 from CALIOP and ECHAM-HAM. (a) Globally averaged CALIOP L2 and temporally and spatially collocated model profiles and the theoretical detection limits (in black) for day and nighttime retrievals. (b) Mean CALIOP L3 (day and night) and model (combined) extinction profiles. (c) The number of CALIOP L3 samples included in each altitude bin and the number of corresponding samples positively identified as aerosol during day and night. CALIOP = Cloud-Aerosol Lidar with Orthogonal Polarization.

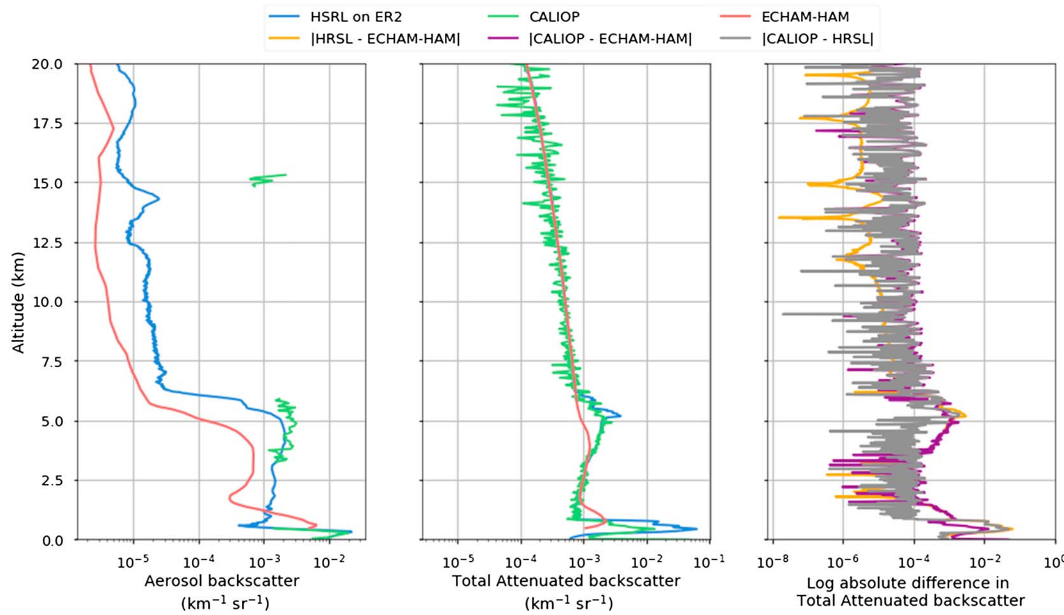

Figure 3. Mean backscatter profiles from CALIOP and the ER2 mounted HRSL during a deliberate satellite underpass in the ORACLES campaign and collocated ECHAM-HAM profiles. (a) Aerosol backscatter profiles, (b) attenuated total backscatter, and (c) the log difference in attenuated backscatter. HSRL = High Spectral Resolution Lidar; CALIOP = Cloud-Aerosol Lidar with Orthogonal Polarization.

reported lower detection limit, also shown (converted from the backscatter limit reported by Winker et al., 2009, using the mean CALIOP lidar ratio).

Neglecting the effect of collocation for now, we also consider the gridded, monthly mean Level 3 product. Figure 2b shows the global mean CALIOP L3 extinction profiles for daytime and nighttime and the mean ECHAM-HAM extinction profiles (with no distinction between day/night). The CALIOP L3 profiles have a very different form, and the nighttime retrieval shows reasonable agreement with the model. The daytime profile, however, is now *smaller* than the model. This is because, in contrast to the L2 example, the L3 averages are constructed assuming aerosol extinction is 0 in clear-air L2 samples where no aerosol is detected. Assuming that the CALIOP aerosol retrieval samples most of the true distribution and only a small number of missing values are present, this is a good approximation; however, this is not the case in the middle-to-upper troposphere. Figure 2c shows the number of clear-air samples (where aerosol could potentially be detected) and the number of samples where aerosol is detected (from L3, though this is the same as L2). Assuming that there is always some aerosol present at each point, the CALIOP aerosol retrieval detects it only around 1% of the time above 6 km. Figures 1 and 2 make it clear that the large differences in the CALIOP L3 day and night profiles above 6 km can be attributed, almost entirely, to the different number of missing values. It is likely that the apparent model underestimation below 6 km in Figure 2a can also be partly attributed to CALIOP detection limitations, although model biases cannot be ruled out. However, CALIOP L3 extinction profiles in Figure 2b (which fill missing extinction values with 0/km) are seen to agree with ECHAM-HAM better than L2 extinction profiles (which average only the reported extinction values).

An extensive evaluation of the CALIOP L1 attenuated backscatter using the airborne HSRL over the continental United States has shown good agreement (Rogers et al., 2011). Here we consider a (much smaller) comparison of the total attenuated and aerosol backscatter using the HSRL on a National Aeronautics and Space Administration ER-2 flight during the recent ORACLES campaign (ORACLES Science Team, 2017). The ER2 performed a dedicated CALIOP underpass around 1,000 km long during the campaign, providing an ideal opportunity to compare with CALIOP and the model. While the comparison is limited to only one flight, we are not attempting to perform a full statistical evaluation and only wish to demonstrate the issues highlighted above.

Figure 3a shows the mean aerosol backscatter along the HSRL track, CALIOP, and collocated ECHAM-HAM. The model does underestimate the aerosol backscatter compared to HSRL, but it is important to note that

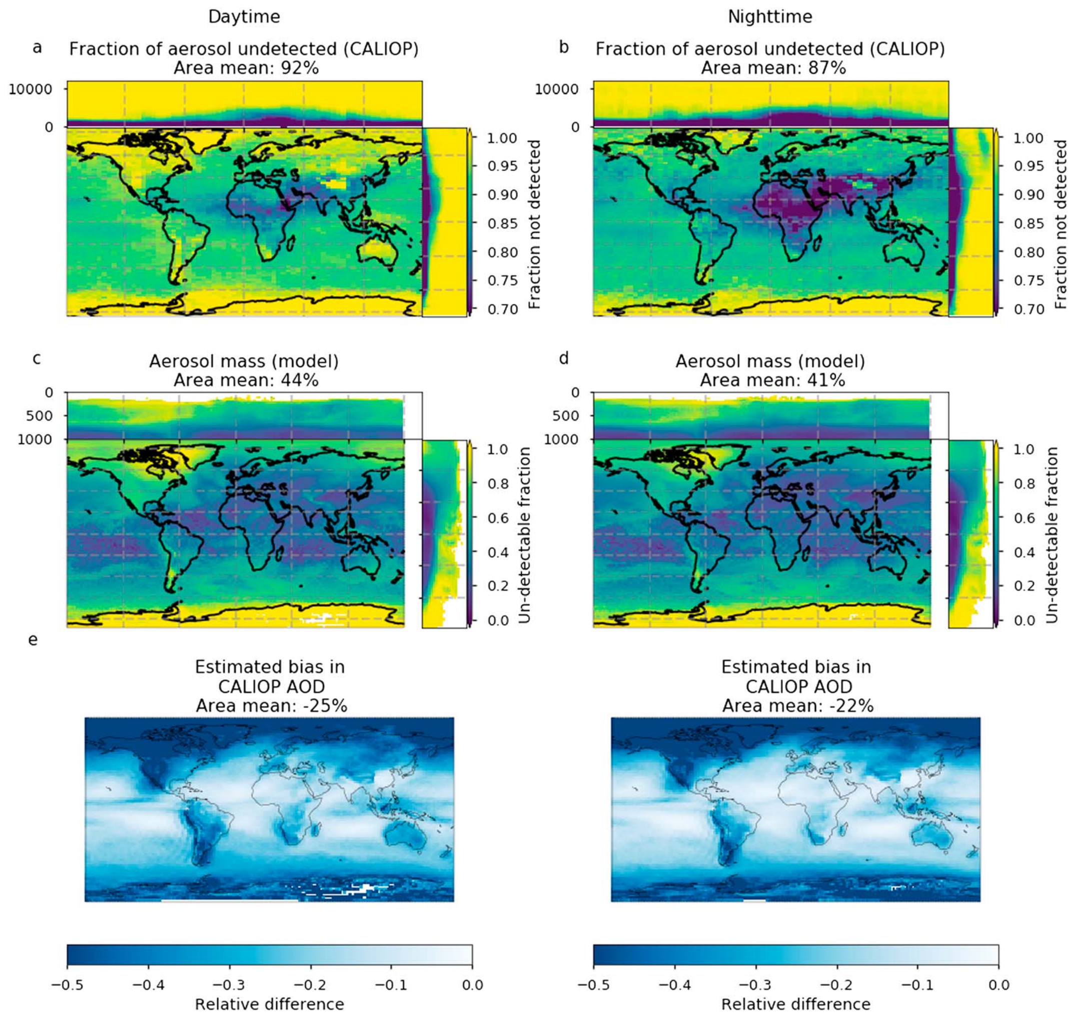

Figure 4. (a and b) The fraction of aerosol to clear-sky samples from the CALIOP L3 data set for all of 2008. The central panel of each plot shows the vertical mean over the globe, while the top and side panels show the meridional and zonal means respectively. The area weighted global mean values are included in the titles. The vertical axes range from 0 to 12,000 m for the CALIOP profiles and 1,000–20 hpa for the model profiles. Detection is good in the boundary layer globally but falls to nearly 0 in the free troposphere and struggles over continental regions. (c and d) The proportion of aerosol Mass in ECHAM-HAM, which would be missed (undetected) assuming backscatter detection sensitivities of 3×10^{-4} and 2×10^{-4} km^{-1}/sr, corresponding to the CALIOP daytime and nighttime sensitivity respectively. (e and f) The relative bias in CALIOP AOD estimated from the model assuming the same backscatter detection sensitivities. CALIOP = Cloud-Aerosol Lidar with Orthogonal Polarization; AOD = aerosol optical depth.

the model bias is roughly constant with altitude, and much smaller than the bias in global CALIOP L2 or L3 data seen in the above comparisons. While CALIOP agrees extremely well with HSRL up to 5 km, above this, where the model and HSRL show a sharp drop in backscatter, CALIOP detects no aerosol and so performs no aerosol retrieval, apart from the one detection at 15 km.

To try and determine the impact of the requirement for positive aerosol detection by CALIOP for aerosol backscatter to be included in the L2 product, we also compare the cloud-screened total attenuated backscatter. This is shown for all three data sets in Figure 3b. A comparison between CALIOP and HSRL reproduces the good agreement found by (Rogers et al., 2011). The collocated model attenuated backscatter shows the same underestimation in the layer where biomass burning smoke is expected (Zuidema et al., 2016) but very good agreement in the free troposphere. The signal in this region above around 5 km, however, is dominated by molecular scattering, which is expected to be accurate in the model. The log of the absolute differences between the data sets is shown in Figure 3c. Apart from the smoke layer at 5 km, the CALIOP-model differences are no larger than the CALIOP-HSRL differences. This suggests insufficient signal in the CALIOP L1 attenuated backscatter (averaged over 1,000 km during the daytime) to constrain the model at these altitudes even without the need for a positive aerosol detection. Significantly more horizontal averaging would need to be performed for CALIOP to retrieve the upper tropospheric aerosol backscatter observed by HSRL on the ER2 (which is around 700 km closer to the aerosol than CALIOP).

Due to temporal and regional differences in aerosol loading and composition the effect of this bias is not globally uniform. Figures 4a and 4b show the fraction of clear-sky samples detected as aerosol globally from the CALIOP L3 data set for all of 2008 during daytime and nighttime, respectively. In order to estimate the impact of the CALIOP sensitivity limits on model aerosol evaluation, we can also mask the model aerosol fields where the model reported backscatter falls below a given threshold and calculate the fraction of that aerosol field, which is then detectable. For example, the fraction of aerosol mass (F_M) is determined by the following:

$$F_M = \frac{\sum_t M}{\sum_t M_a} \text{ where } M_a = \begin{cases} 0, & \beta < C \\ M, & \beta \geq C \end{cases}$$

The threshold C is assumed to be 3×10^{-4} and 2×10^{-4} km^{-1}/sr for daytime and nighttime retrievals, respectively. This corresponds to the theoretical threshold at 10-km altitude with 80-km averaging from Winker et al. (2009), which is a lower threshold (higher sensitivity) than used in Thorsen et al. (2017) (1.5×10^{-3} and 7.7×10^{-4} km^{-1}/sr for daytime and nighttime, respectively). Figures 4c and 4d show the fraction of undetectable aerosol mass in ECHAM-HAM assuming the CALIOP backscatter detectability. While the Saharan dust outflows can be detected more than 80% of the time, the aerosol over continental United States, particularly above 750 hPa is very rarely detectable (<20% of the time). The area weighted global mean fraction of undetected aerosol is 44% for daytime and 41% for nighttime. While this estimate relies on the aerosol distribution, composition, and optical properties used in the model, it provides a plausible estimate to complement other observational constraints, which have their own limitations. Figures 4e and 4f show the relative bias in CALIOP AOD estimated from the model by including and removing all layers with undetectable aerosol using the same detection limits. There is a strong negative relative bias at the poles, where the AOD is small, and also over the West Coasts of North and South America. Elsewhere, the bias is smaller but consistently around 10%. Interestingly, the pattern of the bias closely matches the regions with the highest frequency of zero AOD reported in Thorsen et al. (2017).

4. Conclusions

CALIOP provides invaluable observations of the vertical distribution of clouds and aerosol globally, provided that the uncertainties are well characterized and accounted for. Recent work has highlighted the issue of missing values in the CALIOP aerosol extinction profile and the consequences for AOD measurements. Here we show that because so many of the aerosol retrievals are below the detection limit and classified as missing in the upper troposphere, and only the occurrences of enhanced aerosol are reported, the globally averaged (backscatter, and hence extinction) profiles above 5 km show a high bias if constructed by averaging only the layers reported in the L2 product. Previous work describing the generation and evaluation of a Level 3 monthly CALIOP aerosol product (Winker et al., 2013) addressed this problem by assigning each of the missing values a zero-extinction value. A detailed model evaluation (Koffi et al., 2012) found large overestimates in model extinction above 6 km using this approach but could not attribute this to model or observational bias. Fortunately, this and later work (Koffi et al., 2016) limited their evaluation to the lowest 6 km of the atmosphere specifically in order to avoid this problem. It seems clear from Figure 2, however, that the arbitrary zero-fill-value value does not give a sufficiently representative estimate of the aerosol present, and it is this that leads to the apparent model overestimation of the extinction in the upper troposphere seen in these evaluations.

We have shown the effects of missing optically thin aerosol for evaluating model vertical aerosol distributions, and aerosol above cloud can be significant. This also affects integrated radiative properties (such as AOD) and shows large regional differences. While the exact fraction will depend on the detection threshold chosen and the model used, we have shown that a significant proportion of model simulated aerosol mass in the free troposphere globally is not detected by CALIOP. Thus, great care should be taken in using

CALIOP L2 or L3 aerosol profile data to evaluate the vertical distribution of aerosol in GCMs, particularly above 5 km. The availability of a CALIOP simulator for models, replicating the detection limits of the retrieval, would greatly help in this regard. Nevertheless, it is hoped that cloud-screened and heavily horizontally averaged CALIOP L1 total attenuated backscatter profiles may be able to overcome some of these limitations.

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