# THE GLOBAL 3D DISTRIBUTION OF TROPOSPHERIC AEROSOLS AS CHARACTERIZED BY CALIOP

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## ABSTRACT

The CALIOP lidar, carried on the CALIPSO satellite, has been acquiring global atmospheric profiles since June 2006. A monthly-mean, global gridded aerosol profile product constructed from CALIOP data has been developed and is now available. Averaged aerosol profiles for cloud-free and all-sky conditions are reported separately. This 6-year dataset characterizes the global 3-dimensional distribution of tropospheric aerosol. Vertical distributions are seen to vary with season, as both source strengths and convective activity vary. Aerosol is found at significantly higher altitudes over land than over ocean, except in regions of continental outflow from Africa and Asia. In most regions, clear-sky and all-sky mean aerosol profiles are found to be quite similar, implying a lack of correlation between high semi-transparent cloud and boundary layer aerosol. Data screening and issues of detection and diurnal biases will also be discussed. The work described here forms an initial global 3D aerosol climatology which hopefully will be continued for several more years and eventually be extended by ATLID on the EarthCare satellite.

## 1. INTRODUCTION

Aerosols have a variety of effects on Earth's climate, including effects on cloud formation and properties as well as direct radiative influences. The nature of these effects depends strongly on the vertical distribution of the aerosol. Warming effects of absorbing aerosol are amplified when they are located above bright clouds, and the atmospheric lifetime of aerosol is much greater in the free troposphere than in the planetary boundary layer. Longer lifetime allows aerosol to be transported further from its sources, affecting the geographic pattern of aerosol impacts.

Models are relied on to estimate the effects of aerosols on Earth's climate but there is a wide diversity in the vertical distribution of aerosol between models, leading to differences in predicted geographic distribution and climate effects [1, 2]. Until recently, however, the global 3D measurements needed to evaluate model performance have been lacking. The CALIOP lidar, carried on the CALIPSO satellite, has been acquiring global aerosol and cloud profile data since 2006 [3]. This dataset now offers the opportunity to characterize the global 3D distribution of aerosol as well as seasonal and interannual variations, and confront aerosol models with observations in a way that has not been possible before. With that goal in mind, a monthly global gridded dataset of aerosol extinction profiles has been constructed. This dataset is now being characterized and validated.

## 2. LEVEL 2 AND LEVEL 3 AEROSOL DATA

CALIOP acquires lidar backscatter profiles at 532 nm and 1064 nm, including profiles of depolarization at 532 nm. After calibration and range registration, cloud and aerosol layers are identified and aerosol extinction is retrieved at 532 nm and 1064 nm, using estimated lidar ratios [4, and references therein]. Results from the retrievals are stored in the Level 2 aerosol and cloud profile products.

Aerosol retrievals are only performed within detected layers, as the CALIOP SNR does not permit retrievals in clear air at the spatial resolution of the Level 2 products. Detection thresholds are defined in terms of 532 nm scattering ratio and are adjusted according to altitude, solar background illumination, and averaging resolution [5]. Detection thresholds, in terms of aerosol extinction are shown in Figure 1. The sudden change at 8 km is to account for the change in vertical resolution, from 30 m to 60 m, above 8 km. Because the lidar ratio of smoke is much larger than that of marine aerosol, lower levels of aerosol extinction can be detected for marine aerosol than for smoke.

To construct the Level 3 product, Level 2 aerosol extinction data are averaged onto a global 3D grid with 60 meter vertical resolution, from the surface to 12 km altitude, and 2° x 5° lat-long resolution. Currently, only 532 nm extinction profiles are included. Data files contain separate extinction profiles for dust only and for all aerosol species. CALIOP retrieves aerosol below optically thin cloud as well as in clear skies and above clouds. Separate files report all-sky and cloud-free aerosol profiles. Gridded average column AOD for several different conditions (cloud-sky, all-sky, etc) is also included.

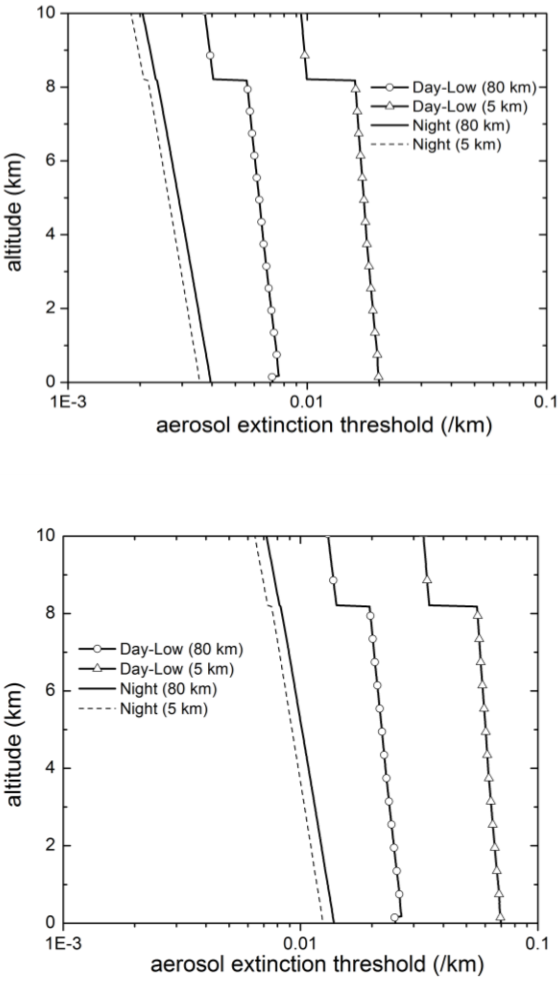

Fig. 1. Detection thresholds used in Level 2 data processing, in terms of 532 nm aerosol extinction. Upper panel: marine (best case, S = 20 sr); Lower panel: smoke (worst case, S = 70 sr).

## 2.1 Data Screening

Several quality control flags contained in the Level 2 files are used to screen the data before averaging:

To avoid aerosol layers which might be the result of detection artifacts, only layers with Cloud Aerosol Discrimination scores (CAD_score) of less than -20 are used. The Extinction QC flag (Ext_QC) indicates the type of retrieval performed on each layer and conditions on the outcomes. Only aerosol layers with Ext_QC values of 0, 1, 18 and 16 are accepted, although Ext_QC=1 (indicating constrained retrievals) are very rare for aerosol retrievals. Ext_QC values of 0 and 16 correspond to retrievals of semi-transparent and opaque layers (respectively) where the initial lidar ratio remains unchanged. Ext_QC=18 indicates an opaque layer where the retrieval diverges and the initial lidar ratio is changed to allow a solution [6]. Layers with Ext_QC=2, indicating a semi-transparent layer where the initial lidar ratio is changed, are rejected.

Each aerosol extinction value in the Level 2 products has an associated extinction uncertainty. An extinction uncertainty (Unc_532) of 99.9 $\text{km}^{-1}$ indicates a retrieval failure at that point. Therefore, range bins with Unc_532 = 99.9 $\text{km}^{-1}$ and all extinction values at lower altitudes in the profile are rejected.

In addition to screening based on quality flags, several other screening steps are also applied. The most important of these is a test for misclassified cloud. Weakly scattering edges of ice clouds are sometimes misclassified as aerosol by the cloud-aerosol discrimination algorithm, producing anomalous enhancements of aerosol loading in the upper troposphere. Therefore, single aerosol layers occurring in isolation but adjacent to ice clouds are assumed to be misclassified cloud and are ignored. This test is applied only to aerosol layers above 4 km altitude.

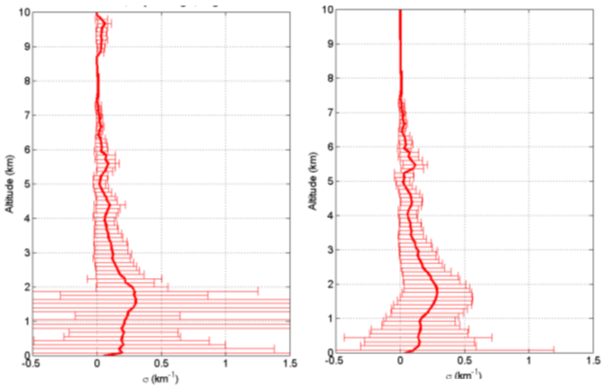

Fig. 2. Average 532 nm extinction profiles, August 2007, 35N - 40N, 75W - 80W. Left panel: unscreened cloud-free profile; Right panel: after screening applied.

Fig. 2 compares a mean clear-sky profile before and after screening. Horizontal bars indicate estimated RMS errors. Note there are small changes in the mean profile at some altitudes, but large decreases in the error bars. The aerosol layer between 9-10 km in the left panel is due to cirrus misclassified as aerosol, and is removed by the test for isolated aerosol layers adjacent to ice cloud. Because retrieval errors propagate downward, the lower parts of the profile always have higher uncertainty and contain more retrieval artifacts. Changes in the lowest 2 km of the profile are due primarily to the Ext_QC and Unc_532 tests, which tend to remove data with retrieval artifacts.

## 2.2 Averaging

The current CALIOP algorithms only retrieve aerosol within detected layers and range bins outside detected layers are assigned fill values. When profiles are averaged, fill values representing clear air are assigned an extinction value of zero km$^{-1}$. This results in an underestimate of mean extinction. We believe the low bias is small in most cases (see discussion below) and this is being addressed in initial validation studies.

Range bins within cloud or where the signal is completely attenuated, such as below opaque layers, are ignored when averaging. Regions within cloud are identified using cloud mask information contained in the CALIOP Level 2 products. Detection of aerosol layer bases can be difficult and the layer detection algorithm sometimes places the aerosol layer base well above the local surface. To avoid underestimating the lowest part of the aerosol profile, regions of clear air between the surface and the base of an aerosol layer within 2.46 km of the local surface are ignored when averaging.

## 3. RESULTS

Figure 3 shows a comparison of mid-summer cloud-free and all-sky extinction profiles for the eastern United States (31-41N and 95-75W). The clouds in the columns with cloudy-sky aerosol retrievals tend to be semi-transparent cirrus. All-sky and cloud-free profiles are seen to be very similar, with AOD of 0.216 and 0.218, respectively, even though about 30% of the all-sky aerosol retrievals come from below clouds. Regional mean all-sky and cloud-free profiles tend to be quite similar, implying that high clouds and aerosol loading within the planetary boundary, where most of the aerosol is located, are largely uncorrelated. This does not always hold, however. In southeast Asia, where cloud cover is 90% or more, clear-sky regions represent a biased sample of both geography and meteorology. In this case, systematic differences are seen between all-sky and clear-sky profiles.

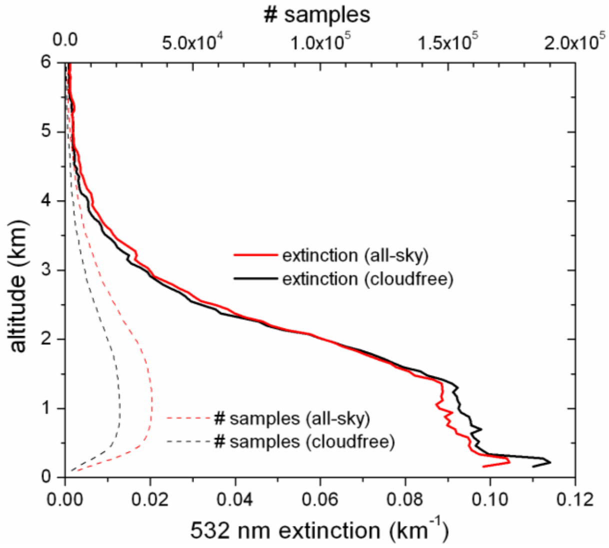

Fig. 3. Mean night profiles over eastern US (95W-75W, 30N-40N) during July 2006-2011. Solid lines: 532 nm aerosol extinction; dashed lines: number of aerosol samples.

Fig. 4 shows the annual zonal mean distribution of aerosol extinction. Dotted lines show altitudes where 63% and 90% of the AOD lies below. A maximum in near-surface extinction is seen between 40S-60S, representing marine aerosol in the southern ocean. Saharan dust is responsible for another near-surface maximum between 0-40N, and also the strongest vertical transport. At mid and high latitudes, aerosol is largely confined to the lowest kilometer of the atmosphere. Data such as this can provide much stronger tests of model transport and aerosol removal processes than have been available before [2].

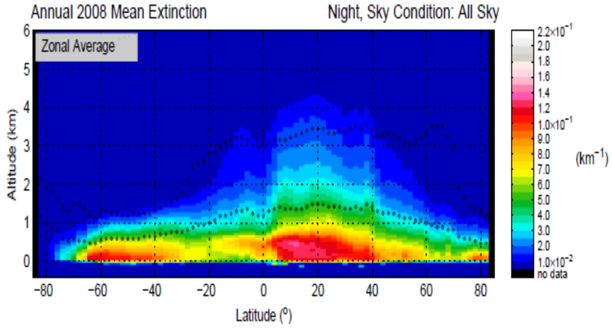

Fig. 4. Annual zonal mean 532 nm aerosol extinction for 2008. Nighttime, all-sky.

To get a global picture of the variation in vertical distribution of aerosol we plot an extinction scale height, $H_{63}$, the altitude which is above 63% of the column AOD. Shown in Fig. 5 for two seasons, these maps indicate regional variations in the strength of vertical transport and the transport of elevated aerosol layers. Strong contrasts in height are seen between land and ocean. $H_{63}$ is referenced to sea level, so high values are seen over the Tibetan plateau, where surface elevations range from 3-4 km. High values seen over Antarctica and Greenland are spurious, as very little aerosol is seen above the ice sheets. Differences in $H_{63}$ between JJA and SON reflect seasonal differences in regional source strengths and transport patterns.

Looking at Fig. 5, during summer we see strong high altitude outflow of Sahara dust and African smoke westward into the Atlantic Ocean, outflow into the Arabian Sea, and high altitude outflow in the summer from East Asia into the northwest Pacific. Significant seasonal changes are seen, comparing JJA and SON. High altitude continental outflow is generally much weaker in SON, except for African smoke, where the region of outflow has shifted southward in response to seasonal southward movement of the burning region.

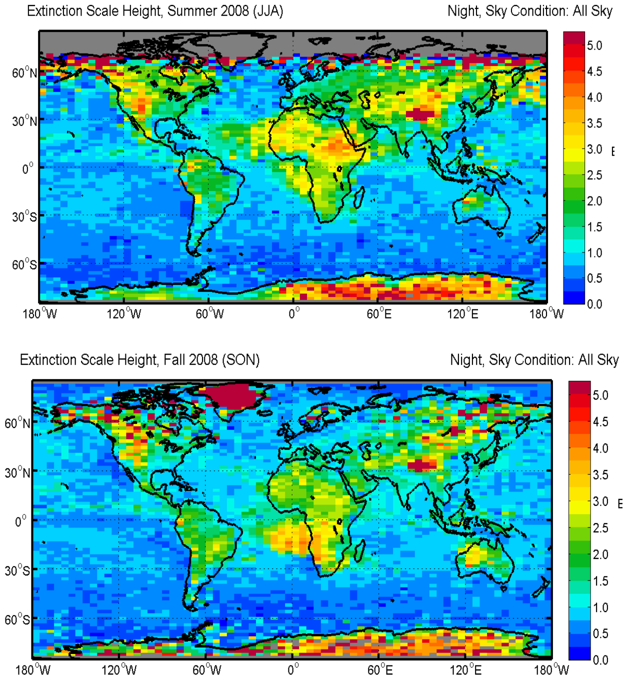

Fig. 5. Global variation of the $H_{63}$ height metric. Upper panel: JJA 2008; Lower panel: SON 2008.

Aerosol profiles exhibit diurnal biases due to improved detection sensitivity at night vs. daytime. Fig. 6 shows the ratio of daytime to nighttime zonal mean extinction for JJA. Diurnal biases are small below 1 km, where aerosol loading is relatively high. Daytime zonal mean extinction is biased low by as much as 50% above 2 km, although zonal mean biases between 10N-30N are small at most altitudes.

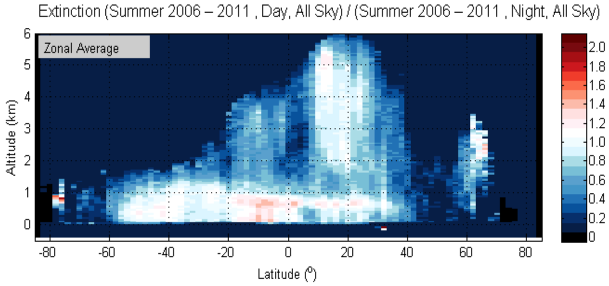

Fig. 6. Diurnal bias in zonal mean 532 nm aerosol extinction (ratio of day to night extinction) for JJA, 2006-2011.

While the standard CALIOP Level 2 processing detects enhanced aerosol loading in the upper troposphere (UT) – such as elevated smoke or dust - typical aerosol loading in the UT falls below the detection limits shown in Figure 1. As mentioned above, regions of ‘clear air’ where no aerosol is detected are assigned an extinction of zero km$^{-1}$ so the Level 3 mean profiles represent a lower limit on the aerosol loading.

Kent et al. [7] investigated aerosols in the upper troposphere using data from LITE and SAGE II. LITE showed aerosol layers with 532 nm extinction typically ranging from 0.01 - 0.02 km$^{-1}$, believed to be primarily smoke, in the otherwise very clean southern hemisphere upper troposphere. Outside these enhanced layers, the average lower limit on aerosol extinction between 6-9 km altitude was found to be about 0.001 km$^{-1}$.

Although validation of this global gridded product is just beginning, we believe the overall shape of the profiles is accurate and representative. However, due to detection limits of the CALIOP Level 2 algorithm, magnitudes in the upper troposphere represent lower limits on the true aerosol loading. We plan to investigate SAGE data more fully to better characterize the variability of aerosol in the UT. We also plan to investigate CALIOP retrievals of the full atmospheric column to provide a more accurate picture of aerosol loading in the upper troposphere. The primary uncertainty in these retrievals is due to calibration errors, so this activity involves improvements to the CALIOP 532 nm calibration as well.

## 4. REFERENCES

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