National Aeronautics and Space Administration

Langley Research Center

Hampton, Virginia 23681-2199

Cloud – Aerosol LIDAR and Infrared Pathfinder Satellite Observations (CALIPSO)

Data Description and Quality Summary

Lidar Level 3 Tropospheric Aerosol Data

DOI: https://doi.org/10.5067/CALIOP/CALIPSO/CAL_LID_L3_Tropospheric_Aerosol_Data_Description_Document_V5

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January 16, 2026

CALIPSO Lidar Level 3 Tropospheric Aerosol Data Description Document

Version 5.00

Final Data Version:	5.00
Final Data Release Date:	October 1, 2025
Final Data Date Range:	June 2006 to June 2023

Introduction

The CALIPSO lidar level 3 tropospheric aerosol profile product reports monthly mean profiles of 532 nm aerosol optical properties on a uniform spatial grid, with each grid cell spanning 2° of latitude, 5° of longitude, and 60 m in altitude (Tackett et al., 2018). All level 3 parameters in the version 5.0 release are derived from the version 5.0 CALIOP level 2 aerosol profile product and are quality screened prior to averaging. Eight level 3 data files are generated each month. Nighttime and daytime data are reported separately for four different sky conditions. The "cloud-free" version is constructed using only those L2 profiles in which no clouds were detected at 5 km, 20 km, or 80 km averaging intervals. Clouds detected at single shot resolution in the boundary layer are assumed to be removed entirely by the level 2 boundary layer cloud clearing algorithm. The "cloudy skies transparent" version aggregates all (and only) those 5 km L2 profiles in which the Earth's surface was detected, whereas the "cloudy skies opaque" version reports monthly mean aerosol properties harvested exclusively from 5 km L2 profiles in which an opaque cloud was detected. The comprehensive "all sky" L3TAP includes all tropospheric aerosols detected in all of the aforementioned sky conditions.

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Glossary and Acronym Dictionary

Term	Meaning
AOD	Aerosol optical depth
AMSL	above mean sea level
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
DEM	digital elevation model
GMAO	Global Modeling and Assimilation Office
granule	continuous data segment in which all measurements were acquired while the lidar was configured for daytime data acquisition only or nighttime data acquisition only; each granule spans approximately one half of a full orbit, with daytime granules being slightly larger/longer than nighttime granules
HDF	Hierarchical Data Format
IGBP	International Geosphere–Biosphere Programme
LEM	low energy mitigation
MAC	Maps of Aerosol lidar ratios for CALIPSO
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2
NSA	negative signal anomaly
SAA	South Atlantic Anomaly
SNR	signal-to-noise ratio
SDS	scientific data set
sr	steradian

File Organization

Eight level 3 files are produced for eight unique combinations of sky conditions and lighting conditions (i.e., day vs. night).

Table 1: Level 3 data files produced.

Sky Condition	Lighting Condition
All sky	Night, day (separate)
Cloud-free	Night, day (separate)
Cloudy-sky, transparent	Night, day (separate)
Cloudy-sky opaque	Night, day (separate)

Statistics are reported in separate files corresponding to the relevant sky condition and lighting condition. Sky conditions describe the cloud occurrence frequency and location within the level 2 columns that are aggregated by level 3. There are four varieties of sky condition:

Table 2: Description of the four sky conditions.

Sky Condition	Lighting Condition
All Sky	All level 2 columns are averaged, regardless of cloud occurrence
Cloud-Free	Only cloud-free level 2 columns are averaged
Cloudy-Sky, Transparent	Only level 2 columns containing transparent clouds are averaged
Cloudy-Sky Opaque	Only level 2 columns containing opaque clouds are averaged

For the purposes of the level 3 tropospheric aerosol product, clouds detected at 5 km horizontal resolution or greater are used for screening; i.e., cloud-free columns do not contain clouds found at 5 km or coarser resolution, but they may contain clouds found at 1/3 km horizontal resolution. These higher resolution clouds have been removed by the level 2 planetary boundary layer cloud-clearing algorithm prior to computing aerosol layer properties. Note that aerosol properties are never reported within clouds in any CALIPSO data product.

Temporal and spatial resolution

Statistics are aggregated with a temporal resolution of one month and are reported on an equal-angle grid with the following specifications.

Table 3: Coverage and spatial resolution of level 3 tropospheric aerosol products.

Spatial Coverage	Spatial Resolution	Number
360° longitude (180°W to 180°E)	5° longitude	72
170° latitude (85°N to 85°S)	2° latitude	85
−0.5 km to 12 km altitude	60 m vertical	208

Based on the resolution of the grid defined in Table 3, level 3 quantities are reported in arrays having two, three, or four dimensions. Table 4 below lists the sizes of all arrays of 2 dimensions or greater, excluding aerosol type distribution and aerosol spatial distribution arrays. Those arrays have similar dimensionality as the 3-D and 4-D arrays below, except the final dimension length depends on the purpose of the array. The product descriptions of those arrays provide more details on sizes and content.

Table 4: Coverage and spatial resolution of level 3 tropospheric aerosol products. The number of percentiles is 11, containing the minimum, maximum, and the 10th, 20th, …, 90th percentiles.

Dimensions	Dimension Length
2-D	num. latitudes × num. longitudes (85 × 72)
3-D	num. latitudes × num. longitudes × num. altitudes (85 × 72 × 208)
4-D	num. latitudes × num. longitudes × num. altitudes × num. percentiles (85 × 72 × 208 × 11)

Level 2 input data

Version 5.0 level 2 data is used as input for the version 5.0 level 3 tropospheric aerosol product.

Quality screening strategy in version 5.0

Prior to generating level 3 statistics, all level 2 aerosol profile extinction samples are quality screened using filters designed to eliminate samples and layers that were detected or classified with very low confidence or that have untrustworthy extinction retrievals. Quality filters are described below. An in-depth description of many of these filters and their impacts on version 3 level 3 statistics is given in Tackett et al., 2018. Since this publication, filter 2 has been modified and filters 8-12 have been implemented.

1) **CAD score filter.** Only aerosol layers having cloud-aerosol discrimination (CAD) scores in the range [−100, −20] are used. Level 2 CAD scores range from −100 to 100 where aerosol feature type classifications are negative and cloud classifications are positive (Liu et al., 2019). The magnitude of the CAD score indicates the confidence in the classification: |CAD score| = 100 is maximum confidence while |CAD score| = 0 indicates no confidence. Layers with CAD scores between −20 and 20 are often the result of erroneous layer detection triggered by noise. The lower confidence boundary of −20 was selected empirically by assessing the dependence of the number of layers rejected, the average extinction, and the propagated extinction uncertainties on the CAD score limit. This analysis revealed that varying the CAD threshold between −60 and −20 does little to remove large or negative extinction outliers or to reduce the propagated uncertainty. However, allowing aerosol layers with CAD scores closer to 0 does allow large and negative outliers into the extinction averages and increases the uncertainty.

2) **Extinction QC flag filter.** Aerosol samples having any of the following extinction QC flag bits set are rejected: 3, 5, 7, 8, 9, 10, 11, 12, or 14. Bit 2 is also conditionally rejected if the aerosol layer integrated attenuated backscatter is > 98 % of that expected for an opaque layer or if the lidar ratio has been reduced excessively (*see Sidebar 1: Conditions required for accepting suspicious solutions based on extinction QC bit 2*). These bits indicate failures in the level 2 extinction retrieval and are considered untrustworthy. Aerosol samples are also rejected if they are beneath cloud layers having any of the following extinction QC flag bits set: 2, 3, 5, 7, 8, 9, 10, 11, 12, or 14. Because the extinction retrieval operates from the highest altitude downward, errors are propagated into lower layers. For this reason, aerosol samples are also rejected beneath any layer failing the extinction QC flag filter.

3) **Extinction uncertainty filter.** Only samples where aerosol extinction uncertainty is less than 99.9 km^{-1} are allowed. Uncertainty of 99.9 is a flag value assigned by the retrieval algorithm when the extinction uncertainty estimate has begun to diverge to infinity while iterating down the profile (Young et al., 2018). In this case the retrieval results become unreliable, and we exclude aerosol samples having extinction uncertainty equal to 99.9 and all aerosol samples at lower altitudes in the same profile since the untrustworthy extinction solution is propagated to lower altitudes as the retrieval proceeds downward.

4) **Isolated 80 km aerosol layer filter.** Aerosol layers detected at 80 km horizontal resolution that are not adjacent (either vertically or horizontally) to another aerosol layer and do not contain an embedded aerosol layer are excluded from quality screened level 3 statistics. Requiring that another aerosol layer is adjacent improves the confidence that a real aerosol layer exists in the region. Isolated 80 km layers tend to occur at higher altitudes and have very low extinction values. Therefore, excluding them has little impact on the column AOD.

5) **Misclassified cirrus fringe filter.** Occasionally, the tenuous edges of cirrus clouds are misclassified as aerosol by the cloud aerosol discrimination algorithm as shown in Figure 1 below. This happens most often for optically thin layers detected at 20 and 80 km horizontal resolutions. Because these misclassified cirrus fringes can mis-represent the vertical distribution of aerosol , aerosol layers adjacent to ice clouds are assumed to be misclassified clouds and are rejected. Specifically, aerosol layers above 4 km in altitude that are adjacent to an ice cloud (with ice/water phase either randomly oriented or horizontally oriented) having cloud top temperature less than 0°C are rejected prior to computing level 3 statistics.

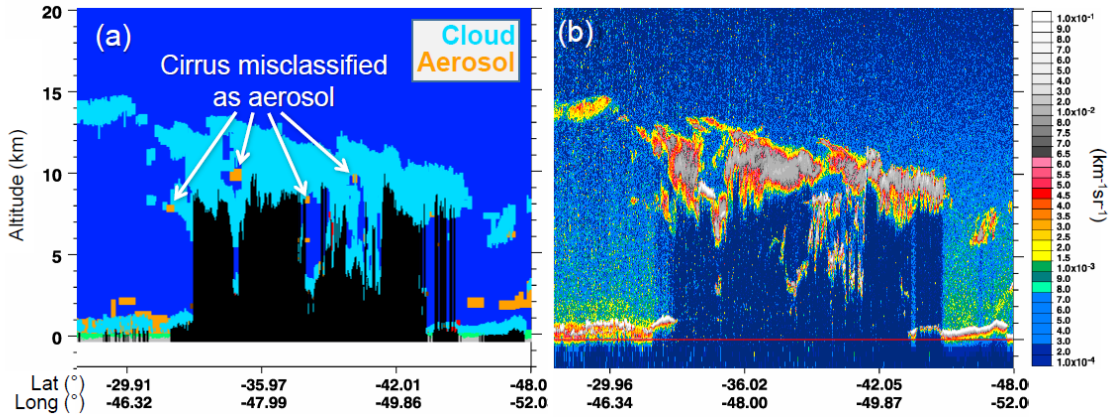

Figure 1: (a) Version 3.0 level 2 vertical feature mask showing where the fringes of cirrus clouds are misclassified as aerosol, and (b) total attenuated backscatter at 532 nm observed on 10-Nov-2011 at approximately 04:30Z (Tackett et al., 2018 © Authors 2018, CC BY 4.0).

6) **Undetected near-surface aerosol filter.** At times the level 2 feature detection algorithm may not detect the entire vertical extent of aerosol layers that extend to the surface. Often aerosol bases are assigned at 30 - 90 meters above the local surface due to overlying attenuation. If the aerosol base extension algorithm is invoked (Vaughan et al., 2010), the base is assigned to 90 meters above the local surface by default. This results in a low bias in the mean extinction profiles near the surface since "clear air" extinction is assumed to be 0.0 km^{-1} and undetected aerosol with non-zero extinction likely exists beneath these assigned bases.

In order to avoid a low bias in level 3 mean aerosol extinction, for each level 2 profile, samples classified as "clear air" lying beneath the lowest quality screened aerosol layer whose base is below 250 meters are excluded from level 3 statistics; i.e., these values are not assumed to have clear air extinction of 0.0 km^{-1}; instead, they are ignored.

7) **Surface contamination filter.** On rare occasions, the surface return signal is not completely removed from an atmospheric feature in contact with the planetary surface. This can happen over highly variable terrain or under substantial attenuation. Level 2 aerosol extinction coefficients experiencing surface contamination are biased high in the range bin nearest to the surface. To avoid this bias, all level 2 aerosol extinction within 60 meters of the planet surface are excluded from level 3 calculations.

Note: This filter was initially implemented in early level 3 versions to mitigate the impact of the “negative signal anomaly” which occurs when the level 1B attenuated backscatter becomes anomalously negative at the onset of an abrupt target such as the surface or a dense cloud. In level 2 releases prior to version 4.1, the aerosol extinction would also become anomalously negative at the range bin adjacent to the abrupt target. Level 2 processing has been modified from V4.1 onward to correct the malign effects of the negative signal anomaly, so this level 3 filter is only implemented to avoid surface contamination.

8) **Cloud layer fraction filter.** Aerosol extinction samples having a Cloud Fraction > 0.94 are rejected to avoid cloud contamination. In the lower troposphere, level 2 extinction range bins are reported at 60 m vertical x 5 km horizontal resolution and are comprised 30 single-shot attenuated backscatter measurements. Single-shot cloud detections are removed from these range bins in level 2, leaving only measurements classified as aerosol. The “aerosol-only” attenuated backscatters are averaged together and contribute to the extinction retrieval. The retrieved aerosol extinction can be spuriously large due to cloud contamination if most of the level 2 range bin was dominated by cloud attenuated backscatter. The level 2 Cloud Layer Fraction SDS, with scaled values ranging between 0.0 and 1.0, is thereby used to determine the number of single shot values classified as cloud within an aerosol extinction sample. All aerosol samples having scaled Cloud Layer Fraction values exceeding the threshold are rejected, along with all aerosol extinction samples at lower altitudes within the same profile.

9) **Misclassified opaque cloud filter.** Occasionally opaque clouds can be misclassified as opaque aerosol layers. This occurs most often underneath optically thick overlying cloud cover, which degrades the fidelity of the

cloud-aerosol discrimination algorithm for lower layers. Because cloud contamination caused by an opaque cloud can significantly impact monthly mean aerosol extinction, opaque aerosol layers that are adjacent to opaque cloud layers are rejected.

10) **Overlying two-way transmittance filter.** The ability to accurately detect, classify, and retrieve extinction for aerosol layers from space is degraded when overlying attenuation becomes substantial. Aerosol layers are especially vulnerable because they can be weakly backscattering and exist beneath dense clouds. To avoid erroneous retrievals due to excessive attenuation, level 3 rejects aerosol layers where the overlying two-way transmittance at 532 nm is less than 0.005 (optical depth > ~2.65). This threshold indicates that the signal has been reduced to approximately 0.5 % of its starting magnitude. Level 3 evaluates the overlying 532 nm particulate optical depth reported in the aerosol layer product to identify layers that should be rejected. Because this level 2 parameter is reported at a fixed 5 km horizontal resolution, layers detected at 20 km and 80 km resolutions are evaluated based on their mean overlying optical depths.

11) **Low laser energy mitigation.** CALIOP experienced an increasing number of intermittent low energy laser pulses from mid-2016 through the end of the mission, primarily over the South Atlantic Anomaly (SAA) region and elsewhere at lower rates. This behavior significantly degraded data quality of affected profiles. A low energy mitigation (LEM) algorithm was implemented in the version 5.0 level 2 data release that identifies and rejects LEM-affected data (Tackett et al., 2025). Rejected data are replaced by a special flag value (−444) and a new LEM column QC flag was added to the level 2 products. Level 3 algorithms use this information to exclude the following rejected level 2 data from the monthly aggregation: (1) extinction coefficients containing the special flag value −444 and (2) profiles where LEM column QC flag indicates rejection (any of bits 1-3 are set; see Appendix B of Tackett et al., 2025).

12) **Minimum columns searched filter.** Level 3 latitude × longitude grid cells having fewer than 80 columns searched during the month are set to fill values (-9999). This is to avoid reporting monthly statistics in grid cells that are grossly under-sampled compared to CALIOP's nominal sampling capabilities (~250 columns per month on average near the equator). The threshold of 80 columns searched affects less than 0.1 % of level 3 grid cells at low latitudes prior to the onset of low energy pulses in mid-2016. Data rejection due to level 2 low energy mitigation in subsequent years causes most grid cells within the South Atlantic Anomaly region to be fill values. Level 3 grid cells along the day-night terminator are also impacted by this filter because they are often sparsely sampled due to the latitude limits of CALIPSO's orbit geometry.

Scientific Data Sets: Spatial Coordinates

Longitude_Midpoint

Units: degrees east

Format: Float_32

Valid Range: -180.0, 180.0

Size: 72 x 1

Description: Longitude at the latitude/longitude/altitude grid cell midpoint.

Latitude_Midpoint

Units: degrees north

Format: Float_32

Valid Range: -90.0, 90.0

Size: 85 x 1

Description: Latitude at the latitude/longitude/altitude grid cell midpoint.

Altitude_Midpoint

Units: km

Format: Float_32

Valid Range: -0.5, 12.1

Size: 208 x 1

Description: Altitude (AMSL) at the latitude/longitude/altitude grid cell midpoint.

Scientific Data Sets: Meteorological Context

Pressure_Mean

Units: hPa

Format: Float_32

Valid Range: 1.0, 1086.0

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Mean of all pressures reported within the latitude/longitude/altitude grid cell; derived from the MERRA-2 data product provided by the GMAO Data Assimilation System.

Pressure_Standard_Deviation

Units: hPa

Format: Float_32

Valid Range: 0.0, 15.0

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Standard deviation of all pressures reported within the latitude/longitude/altitude grid cell; derived from the MERRA-2 data product provided by the GMAO Data Assimilation System.

Temperature_Mean

Units: °C

Format: Float_32

Valid Range: -120.0, 60.0

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Mean of all temperatures reported within the latitude/longitude/altitude grid cell; derived from the MERRA-2 data product provided by the GMAO Data Assimilation System.

Temperature_Standard_Deviation

Units: °C

Format: Float_32

Valid Range: 0.0, 10.0

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Standard deviation of all temperatures reported within the latitude/longitude/altitude grid cell; derived from the MERRA-2 data product provided by the GMAO Data Assimilation System.

Relative_Humidity_Mean

Units: NoUnits

Format: Float_32

Valid Range: 0.0, 1.5

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Mean of all relative humidities reported within the latitude/longitude/altitude grid cell; derived from the MERRA-2 data product provided by the GMAO Data Assimilation System.

Relative_Humidity_Standard_Deviation

Units: NoUnits

Format: Float_32

Valid Range: 0.0, 0.4

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Standard deviation of all relative humidities reported within the latitude/longitude/altitude grid cell; derived from the MERRA-2 data product provided by the GMAO Data Assimilation System.

Tropopause_Height_Minimum

Tropopause_Height_Maximum

Tropopause_Height_Mean

Units: km

Format: Float_32

Valid Range: 4.0, 22.0

Fill Value: -9999.0

Size: 85 x 72

Description: Minimum, maximum, and mean of all tropopause heights (AMSL) reported within the latitude/longitude/altitude grid cell; derived from the MERRA-2 data product provided by the GMAO Data Assimilation System.

Tropopause_Height_Standard_Deviation

Units: km

Format: Float_32

Valid Range: 0.0, 5.0

Fill Value: -9999.0

Size: 85 x 72

Description: Standard deviation of all tropopause heights (AMSL) reported within the latitude/longitude/altitude grid cell; derived from the MERRA-2 data product provided by the GMAO Data Assimilation System.

Meteorological_Samples_Averaged

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72

Description: Number of 5 km horizontal resolution MERRA-2 meteorological profiles averaged within the latitude/longitude grid cell.

Scientific Data Sets: Surface Information

Surface_Elevation_Minimum

Surface_Elevation_Maximum

Surface_Elevation_Median

Units: km

Format: Float_32

Valid Range: 1.0, 9.0

Fill Value: -9999.0

Size: 85 x 72

Description: Minimum, maximum, and median surface elevation (AMSL) of all columns reported in the latitude/longitude grid cell; obtained from the CloudSat science team digital elevation model (DEM).

Land_Samples

Units: No Units

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72

Description: Number of 5 km horizontal resolution columns having surface type classified as land (i.e., not water) at the lidar footprint within the latitude/longitude grid cell; obtained by the International Geosphere/Biosphere Programme (IGBP).

Water_Samples

Units: No Units

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72

Description: Number of 5 km horizontal resolution columns having surface type classified as water at the lidar footprint within the latitude/longitude grid cell; obtained by the International Geosphere/Biosphere Programme (IGBP).

Scientific Data Sets: Overflight Information

Days_Of_Month_Observed

Units: No Units

Format: UInt_32

Valid Range: 0...4,294,967,295

Size: 85 x 72

Description: Bit-mapped 32-bit unsigned integers indicating the calendar days of each month on which CALIPSO made observations within a given latitude/longitude grid cell. Bits are set to true (1) in each grid cell containing a valid CALIPSO observation on that calendar day. For example, if CALIPSO made observations within a grid cell on the 1st day of the month, then the least significant bit (i.e., bit 1) would be set to true. Similarly, if CALIPSO made observations on the 2nd day of the month, then bit 2 would be set to true and so on. An additional example is shown in Figure 2. Based on CALIPSO's orbit, a grid cell at the equator would have many fewer days set to true than a grid cell near the poles.

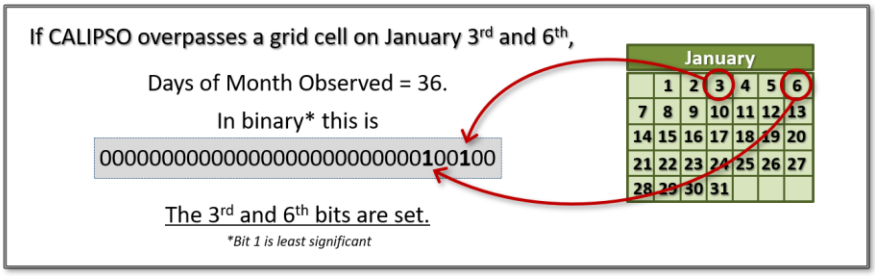

Figure 2: Illustration of the mapping between calendar days and the Days_Of_Month_Observed parameter

Scientific Data Sets: Static Parameters

Initial_Aerosol_Lidar_Ratio_532

Units: sr

Format: Float_32

Valid Range: 20.0, 70.0

Fill Value: -9999.0

Size: 7 x 1

Description: Initial aerosol lidar ratios at 532 nm used for unconstrained extinction retrievals of marine, dust, polluted continental/smoke, clean continental, polluted dust, elevated smoke, and dusty marine subtypes (not including MAC Table Interpolation).

Table 5: Initial lidar ratios and initial lidar ratio uncertainties at 532 nm reported in the level 3 tropospheric aerosol product.

Aerosol	Initial lidar ratio 532 nm (sr)	Initial lidar ratio uncertainty 532 nm (sr)
Marine	23.0	5.06
Dust	44.0	8.8
Polluted Continental/Smoke	70.0	24.5
Clean Continental	53.0	23.85
Polluted Dust	55.0	22.0
Elevated Smoke	70.0	16.1
Dusty Marine	37.0	14.8

Initial_Aerosol_Lidar_Ratio_Uncertainty_532

Units: sr

Format: Float_32

Valid Range: 2.0, 30.0

Fill Value: -9999.0

Size: 7 x 1

Description: Initial aerosol lidar ratios uncertainties at 532 nm used for unconstrained extinction retrievals of marine, dust, polluted continental/smoke, clean continental, polluted dust, elevated smoke, and dusty marine subtypes (not including MAC Table Interpolation). See Table 1 for values.

Scientific Data Sets: Aerosol Optical Properties

Extinction_Coefficient_532_Mean

Units: 1/km

Format: Float_32

Valid Range: 0.0, 4.0

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Mean of all quality-screened level 2 aerosol extinction coefficients within the latitude/longitude/altitude grid cell. Level 2 atmospheric range bins classified as clear air are assumed to have aerosol extinction = 0.0 /km and range bins containing features classified as cloud or stratospheric aerosol are ignored.

Extinction_Coefficient_532_Standard_Deviation

Units: 1/km

Format: Float_32

Valid Range: 0.0, 0.15

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Standard deviation of all quality-screened level 2 aerosol extinction coefficients within the latitude/longitude/altitude grid cell. Level 2 atmospheric range bins classified as clear air are assumed to have aerosol extinction = 0.0 /km and range bins containing features classified as cloud or stratospheric aerosol are ignored.

Extinction_Coefficient_532_Percentiles

Units: 1/km

Format: Float_32

Valid Range: 0.0, 4.0

Fill Value: -9999.0

Size: 85 x 72 x 208 x 11

Description: An 11-element array with the first value containing the minimum of all quality-screened aerosol extinction coefficients and the last containing the maximum within the latitude/longitude/altitude grid cell. Intermediate elements specify aerosol extinction coefficients corresponding to percentiles between 10% (element 2) and 90% (element 10). Level 2 atmospheric range bins classified as clear air are assumed to have aerosol extinction = 0.0 /km.

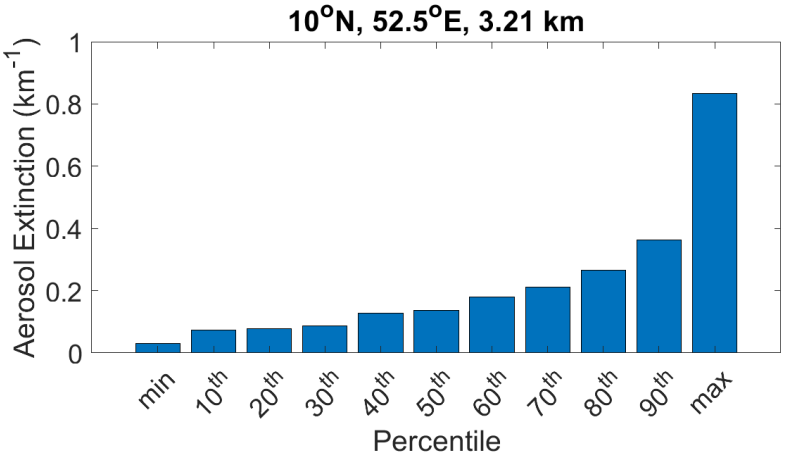

Figure 3: Minimum, maximum, and percentiles of all level 2 aerosol extinction coefficients contributing to a single level 3 latitude/longitude/altitude grid cell in June 2016 daytime, all-sky.

AOD_Mean

Units: NoUnits

Format: Float_32

Valid Range: 0.0, 5.0

Fill Value: -9999.0

Size: 85 x 72

Description: Mean 532 nm aerosol optical depth (AOD), calculated as the vertical integral of the level 3 mean aerosol extinction coefficients in the latitude/longitude grid cell.

AOD_63_Percent_Below

Units: km

Format: Float_32

Valid Range: 0.0, 12.0

Fill Value: -9999.0

Size: 85 x 72

Description: Altitude at which the vertical integral of the column mean extinction coefficients from the Earth's surface upward first reaches 63% of the total column AOD.

AOD_90_Percent_Below

Units: km

Format: Float_32

Valid Range: 0.0, 12.0

Fill Value: -9999.0

Size: 85 x 72

Description: Altitude at which the vertical integral of the column mean extinction coefficients from the Earth's surface upward first reaches 90% of the total column AOD.

Scientific Data Sets: Sample Counting Statistics

Samples_Searched

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Total number of level 2 atmospheric measurements examined for each latitude/longitude/altitude grid cell at 5 km horizontal x 30 m vertical resolution, regardless of whether they were accepted, rejected, or ignored by level 3 processing. Represents the number of opportunities for CALIOP to observe the atmosphere.

Samples_Averaged

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Number of level 2 samples contributing to the mean, standard deviation, and percentiles of extinction in each latitude/longitude/altitude grid cell at 5 km horizontal x 30 m vertical resolution. Includes the number of aerosol samples detected and accepted, and the number of clear-air range bins which are assumed to have aerosol extinction = 0.0 /km.

Samples_Aerosol_Detected_Accepted

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Number of level 2 aerosol samples detected and accepted by level 3 quality assurance filtering criteria in each latitude/longitude/altitude grid cell at 5 km horizontal x 30 m vertical resolution.

Samples_Aerosol_Detected_Rejected

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Number of level 2 aerosol samples detected and rejected by level 3 quality assurance filtering criteria in each latitude/longitude/altitude grid cell at 5 km horizontal x 30 m vertical resolution.

Samples_Cloud_Detected

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Number of level 2 cloud samples detected in each latitude/longitude/altitude grid cell at 5 km horizontal x 30 m vertical resolution.

Scientific Data Sets: Aerosol Type Distribution

Aerosol_Type

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 208 x 7

Description: Histogram of sample counts for all level 2 aerosol subtypes detected and accepted in each latitude/longitude/altitude grid cell. There are seven CALIPSO aerosol subtypes: marine, dust, polluted continental/smoke, clean continental, polluted dust, elevated smoke, and dusty marine, respectively. Therefore, the dimensions of this array are the number of latitudes x the number of longitudes x the number of altitudes x the number of aerosol subtypes.

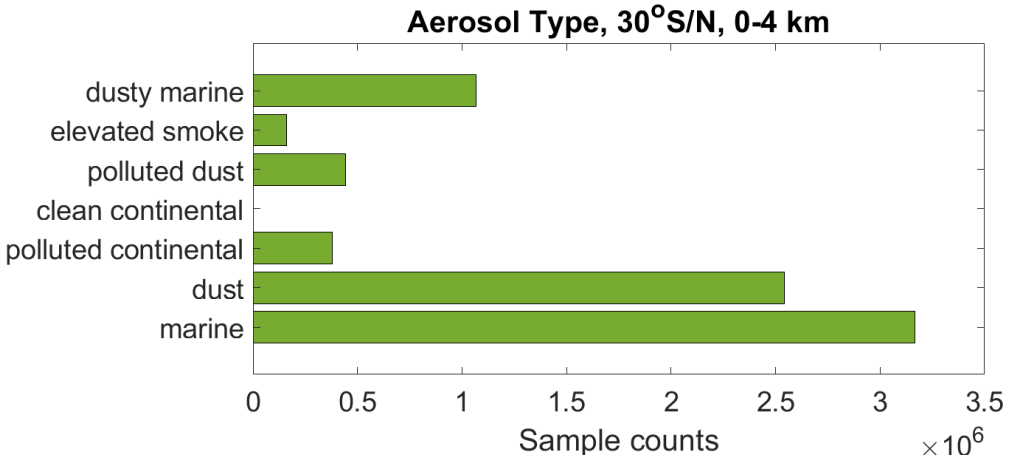

Figure 4: Aerosol type histogram for 30°S to 30°N and from 0 to 4 km altitude in June 2016 daytime, all-sky.

Multiple_Aerosol_Type_Count

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 8

Description: Histogram documenting occurrence of multiple aerosol subtypes in each latitude/longitude grid cell. Each element of this 8-element array records the number of instances for which N different aerosol types were detected in the individual level 2 aerosol profiles within each latitude/longitude grid cell. N ranges from 0 (no aerosol detected in a column) to 7 (seven CALIPSO aerosol types were detected in a single column). Therefore, the dimensions of this array are the number of latitudes x the number of longitudes x the number of aerosol types detected.

Number_Layers_Per_Column

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 9

Description: Histogram of the number of level 2 aerosol layers detected in each latitude/longitude grid cell. The first element of this 9-element array records the number of columns having zero aerosol layers. Similarly, the second element records the number of columns having one aerosol layer, and so on. The ninth array element records the number of columns having eight or more aerosol layers detected. Therefore, the dimensions of this array are the number of latitudes x the number of longitudes x the number of aerosol layers detected.

Highest_Aerosol_Layer_Detected

Units: km

Format: Float_32

Valid Range: 0.0, 20.0

Fill Value: -9999.0

Size: 85 x 72 x 11

Description: Distribution of highest level 2 aerosol layer top altitudes (AMSL) detected within each latitude/longitude grid cell, reported as percentile arrays. Percentiles are 11-element arrays with the first value containing the minimum layer top altitude within the grid cell and the last containing the maximum. Intermediate elements specify layer top altitudes corresponding to percentiles between 10% (element 2) and 90% (element 10). Therefore, the dimensions of this array are the number of latitudes x the number of longitudes x the number of percentiles.

Lowest_Aerosol_Layer_Detected

Units: km

Format: Float_32

Valid Range: 0.0, 20.0

Fill Value: -9999.0

Size: 85 x 72 x 11

Description: Distribution of lowest aerosol layer base altitudes (AMSL) detected within each latitude/longitude grid cell, reported as percentile arrays. Percentiles are 11-element arrays with the first value containing the minimum layer base altitude within the grid cell and the last containing the maximum. Intermediate elements specify layer base altitudes corresponding to percentiles between 10% (element 2) and 90% (element 10). Therefore, the dimensions of this array are the number of latitudes x the number of longitudes x the number of percentiles.

Scientific Data Sets: Aerosol Spatial Distribution

Layer_Separation_Minimum

Layer_Separation_Maximum

Layer_Separation_Median

Layer_Separation_Mean

Units: km

Format: Float_32

Valid Range: 0.0, 20.0

Fill Value: -9999.0

Size: 85 x 72 x 7

Description: Minimum, maximum, median, and mean vertical separation between all detected aerosol layers in all columns within each latitude/longitude grid cell. Layer separation is defined as the vertical distance between two aerosol layers that are separated by either clear air or cloud. Since there can be more than two aerosol layers in a column, layer separation statistics are reported using 7-element arrays where the first element reports the separation statistics for columns where two aerosol layers are detected, the second element reports separation statistics for columns where three aerosol layers are detected, and so on. The last element reports separation statistics for columns where eight or more layers aerosol layers are detected. Therefore, the dimensions of this array are the number of latitudes x the number of longitudes x the number of layers.

Layer_Separation_Standard_Deviation

Units: km

Format: Float_32

Valid Range: 0.0, 5.0

Fill Value: -9999.0

Size: 85 x 72 x 7

Description: Standard deviation of vertical separations between all detected aerosol layers in all columns within each latitude/longitude grid cell. Layer separation is defined as the vertical distance between two aerosol layers that are separated by either clear air or cloud. Since there can be more than two aerosol layers in a column, layer separation statistics are reported using 7-element arrays where the first element reports the separation statistics for columns where two aerosol layers are detected, the second element reports separation statistics for columns where three aerosol layers are detected, and so on. The last element reports separation statistics for columns where eight or more layers aerosol layers are detected. Therefore, the dimensions of this array are the number of latitudes x the number of longitudes x the number of layers.

Single Aerosol Subtype Vgroups

Single aerosol subtype statistics are reported in individual Vgroups each named according to the subtype: Dust, Elevated Smoke, Polluted Dust, Polluted Continental, Marine, Dusty Marine, and Clean Continental. The aerosol subtype is also appended to the SDS name for each of the single-subtype parameters.

Extinction_Coefficient_532_Mean_[Subtype]

Units: 1/km

Format: Float_32

Valid Range: 0.0, 4.0

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Mean of quality-screened level 2 aerosol extinction coefficients for the aerosol subtype indicated in the SDS name within the latitude/longitude/altitude grid cell. Level 2 atmospheric range bins classified as clear air are assumed to have aerosol extinction = 0.0 /km and range bins containing features classified as cloud, stratospheric aerosol, or other aerosol subtypes are ignored.

Extinction_Coefficient_532_Standard_Deviation_[Subtype]

Units: 1/km

Format: Float_32

Valid Range: 0.0, 0.15

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Standard deviation of quality-screened level 2 aerosol extinction coefficients for the aerosol subtype indicated in the SDS name within the latitude/longitude/altitude grid cell. Level 2 atmospheric range bins classified as clear air are assumed to have aerosol extinction = 0.0 /km and range bins containing features classified as cloud, stratospheric aerosol, or other aerosol subtypes are ignored.

Samples_Averaged_[Subtype]

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 208

Number of level 2 samples contributing to the mean, standard deviation, and percentiles of extinction for the aerosol subtype indicated in the SDS name in each latitude/longitude/altitude grid cell at 5 km horizontal x 30 m vertical resolution. Includes the number of dust aerosol samples detected and accepted and the number of clear-air range bins which are assumed to have aerosol extinction = 0.0 /km.

Samples_Aerosol_Detected_Accepted_[Subtype]

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Number of level 2 aerosol samples detected and accepted by level 3 quality assurance filtering criteria for the aerosol subtype indicated in the SDS name in each latitude/longitude/altitude grid cell at 5 km horizontal x 30 m vertical resolution.

Samples_Aerosol_Detected_Rejected_[Subtype]

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 208

Description: Number of level 2 aerosol samples detected and rejected by level 3 quality assurance filtering criteria for the aerosol subtype indicated in the SDS name in each latitude/longitude/altitude grid cell at 5 km horizontal x 30 m vertical resolution.

AOD_Mean_[Subtype]

Units: NoUnits

Format: Float_32

Valid Range: 0.0, 5.0

Fill Value: -9999.0

Size: 85 x 72

Description: Mean 532 nm aerosol optical depth (AOD) for the aerosol subtype indicated in the SDS name, calculated as the vertical integral of the level 3 mean dust aerosol extinction coefficients in the latitude/longitude grid cell.

Number_Layers_Per_Column_[Subtype]

Units: NoUnits

Format: Int_16

Valid Range: 0...32,767

Fill Value: -9999.0

Size: 85 x 72 x 9

Description: Histogram of the number of level 2 aerosol layers detected for the aerosol subtype indicated in the SDS name in each latitude/longitude grid cell. The first element of this 9-element array records the number of columns having zero aerosol layers. Similarly, the second element records the number of columns having one aerosol layer, and so on. The ninth array element records the number of columns having eight or more aerosol layers detected. Therefore, this array has size number of latitudes x number of longitudes x number of aerosol layers detected.

Highest_Aerosol_Layer_Detected_[Subtype]

Units: km

Format: Float_32

Valid Range: 0.0, 20.0

Fill Value: -9999.0

Size: 85 x 72 x 11

Description: Distribution of highest level 2 aerosol layer top altitudes (AMSL) detected for the aerosol subtype indicated in the SDS name within each latitude/longitude grid cell, reported as percentile arrays. Percentiles are 11-element arrays with the first value containing the minimum layer top altitude within the grid cell and the last containing the maximum. Intermediate elements specify layer top altitudes corresponding to percentiles between 10% (element 2) and 90% (element 10). Therefore, this array has size number of latitudes x number of longitudes x number of percentiles.

Lowest_Aerosol_Layer_Detected_[Subtype]

Units: km

Format: Float_32

Valid Range: 0.0, 20.0

Fill Value: -9999.0

Size: 85 x 72 x 11

Description: Distribution of lowest aerosol layer base altitudes (AMSL) detected for the aerosol subtype indicated in the SDS name within each latitude/longitude grid cell, reported as percentile arrays. Percentiles are 11-element arrays with the first value containing the minimum layer base altitude within the grid cell and the last containing the maximum. Intermediate elements specify layer base altitudes corresponding to percentiles between 10% (element 2) and 90% (element 10). Therefore, this array has size number of latitudes x number of longitudes x number of percentiles.

Layer_Separation_Minimum_[Subtype]

Layer_Separation_Maximum_[Subtype]

Layer_Separation_Median_[Subtype]

Layer_Separation_Mean_[Subtype]

Units: km

Format: Float_32

Valid Range: 0.0, 20.0

Fill Value: -9999.0

Size: 85 x 72 x 7

Description: Minimum, maximum, median, and mean vertical separation between all detected aerosol layers in all columns for the aerosol subtype indicated in the SDS name within each latitude/longitude grid cell. Layer separation is defined as the vertical distance between two aerosol layers that are separated by either clear air or cloud. Since there can be more than two aerosol layers in a column, layer separation statistics are reported using 7-element arrays where the first element reports the separation statistics for columns where two aerosol layers are detected, the second element reports separation statistics for columns where three aerosol layers are detected, and so on. The last element reports separation statistics for columns where eight or more layers aerosol layers are detected. Therefore, this array has size number of latitudes x number of longitudes x number of layers.

Layer_Separation_Standard_Deviation_[Subtype]

Units: km

Format: Float_32

Valid Range: 0.0, 5.0

Fill Value: -9999.0

Size: 85 x 72 x 7

Description: Standard deviation of vertical separations between all detected aerosol layers in all columns for the aerosol subtype indicated in the SDS name within each latitude/longitude grid cell. Layer separation is defined as the vertical distance between two aerosol layers that are separated by either clear air or cloud. Since there can be more than two aerosol layers in a column, layer separation statistics are reported using 7-element arrays where the first element reports the separation statistics for columns where two aerosol layers are detected, the second element reports separation statistics for columns where three aerosol layers are detected, and so on. The last element reports separation statistics for columns where eight or more layers aerosol layers are detected. Therefore, this array has size number of latitudes x number of longitudes x number of layers.

Metadata Parameters

Product_ID

An 80-byte (max) character string specifying the data product name. The first portion of this string will be "CAL_LID_L3_Tropospheric_APro_" and the final portion will indicate the sky condition, "AllSky", "CloudFree", "CloudySkyTransparent", or "CloudySkyOpaque".

Nominal_Year_Month

A six-digit integer indicating the year and month when data within the level 3 file was measured by CALIPSO in the format yyyymm.

Number_of_Level2_Files_Analyzed

Integer indicating the number of level 2 granules analyzed to generate the level 3 file.

Earliest_Input_Filename

A 160-byte (max) character string specifying the filename of the first (by calendar day and time) level 2 aerosol profile granule analyzed within the month of the level 3 file.

Latest_Input_Filename

A 160-byte (max) character string specifying the filename of the last (by calendar day and time) level 2 aerosol profile granule analyzed within the month of the level 3 file.

Data_Screening_Script_Filename

A 160-byte (max) character string specifying the filename of the script containing configuration information and command sequences that were executed during the processing of the CALIPSO lidar level 3 data product.

List_of_Input_Files

A 30,000-byte (max) character string containing the list of level 2 aerosol profile granules used to construct the level 3 file.

Data Release Information

Over the course of the mission, the CALIPSO project released four major versions of the lidar level 3 tropospheric aerosol product and three minor updates. Table 6 lists all major and minor releases.

Table 6: Release date, version number, date range, and production strategy for all CALIOP level 3 tropospheric aerosol products.

Lidar Level 3 Tropospheric Aerosol Products			
Release Data	Version	Data Date Range	Production Strategy
October 2025	5.00	June 2006 to June 2023	Standard
October 2020	4.21	July 2020 to December 2021	Standard
September 2019	4.20	June 2006 to June 2020	Standard
December 2016	3.10	December 2016 to December 2016	Standard
October 2015	3.00	June 2006 to November 2016	Standard
April 2013	1.30	March 2013 to September 2015	Beta
December 2011	1.00	June 2006 to February 2013	Beta

Data Quality Information

Data Quality Statement for the Version 5.00 Lidar Level 3 Tropospheric Aerosol Product

The sections below highlight the most significant changes made in the CALIOP version 5.00 level 3 tropospheric aerosol data products.

Input data for version 5.0

The version 5.0 (V5.0) level 3 tropospheric aerosol product (L3 TAP) uses the version 5.0 level 2 (V5.0 L2) data products as input. It thereby benefits from the improvements of the L2 updates. Most notably, (1) a new low energy mitigation algorithm identifies and excludes data with degraded quality (Tackett et al., 2025) and (2) new regionally/seasonally dependent lidar ratios for aerosol classified as marine and dusty marine improve extinction retrieval accuracy for aerosol mixtures over ocean (Toth et al., 2025). The CALIPSO V5.0 L2 data quality summary provides full details of level 2 modifications.

Low laser energy mitigation

CALIOP began experiencing a significant number of intermittent low energy laser pulses starting in mid-2016, primarily over the South Atlantic Anomaly (SAA) region. Their frequency increased during the latter years of the mission, with low energy pulses eventually also appearing outside the SAA, though at low rates. These low energy

pulses degraded data quality in affected profiles. In the previous V4.20 release of the L3 TAP, data within the SAA region was set to fill values for all months from September 2016 onward to mask data affected by low energies. This approach was insufficient because low energy pulses significantly impacted data outside the SAA in the final years of the mission. The new approach for L3 relies on the low energy mitigation (LEM) algorithm that was introduced in L2 processing for the V5.0 release (Tackett et al., 2025). This algorithm removes level 1 data affected by low energy from L2 processing in small, targeted segments to minimize data loss. The remaining data processed by L2 yields aerosol and cloud retrievals having similar quality as data unaffected by low energy pulses. Despite efforts to minimize data loss, some L2 data is totally rejected by LEM, particularly over the SAA. The V5.0 L2 product identifies LEM-rejected data using a special flag value (−444) and with the new LEM column QC flag. The L3 TAP code now uses this information to exclude profiles that are rejected by LEM from contributing to the monthly aggregation. Specifically, L2 extinction coefficients set to the special flag value −444 and profiles where LEM column QC flag indicates rejection (any of bits 1-3 are set) are excluded. Figure 5 demonstrates the reduction in number of samples averaged in the L3 TAP due to LEM in a month that is substantially impacted by low energy laser pulses. Globally, application of LEM reduces the mean samples averaged by 3.6%. However, the largest reduction in samples averaged is over the SAA where grid cells exhibit reductions of −80 to −100%. This level of data loss motivated the new L3 minimum columns searched filter, discussed next.

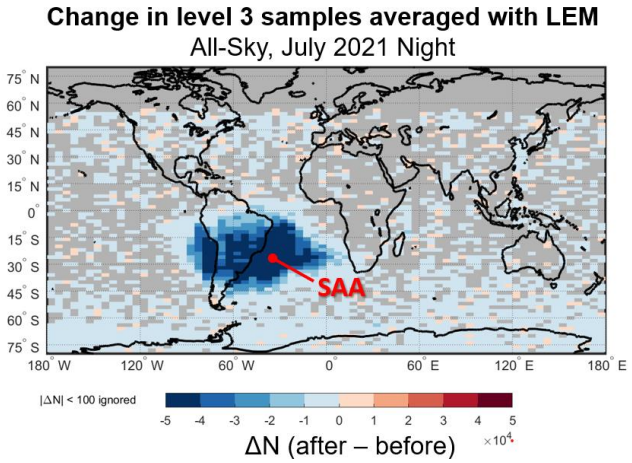

Figure 5: Change number of samples averaged in the L3 TAP, after LEM implemented minus before LEM for July 2021 at night, all-sky. Gray indicates the change in samples averaged is less than 100.

New minimum columns searched filter

A new filter added to the V5.0 L3 TAP now replaces sampling statistics with fill values in all grid cells reporting an insufficient number of columns searched over the course of the month. Doing this avoids reporting (possibly statistically insignificant) monthly statistics in grid cells that are grossly under sampled compared to CALIOP's nominal sampling capabilities. For context, the L3 TAP process searched ~325 columns per month in 95 % of grid cells near the equator prior to the low laser energy issue (2007-2015). In only 5 % of grid cells were fewer than 120 columns searched per month. These low numbers occurred due to data downlink issues and time periods when the CALIPSO payload was turned off. From mid-2016 onward, complete sampling loss occurred with increasing frequency in the SAA region because of rejection by the low energy mitigation (LEM) algorithm. A minimum columns searched threshold is set at 80 columns per month in the V5.0 L3 TAP for each latitude × longitude grid cell. This represents the lowest 0.1 % of columns searched for typical sampling conditions. Level 3 grid cells not meeting this minimum sampling requirement are populated with fill values in V5.0. Figure 6 demonstrates the impact of the new filter. Several granules are missing during this month due to downlink issues, reducing the columns searched over east Africa and western Asia (left). The gray grid cells over the SAA are caused by the minimum samples searched filter, indicating that no data is reported in the L3 TAP due to LEM rejection. These grid cells contain fill values for the mean AOD (right), mean extinction, and other L3 SDSs. The minimum columns searched filter also impacts grid cells along the day/night terminator due to low columns searched counts.

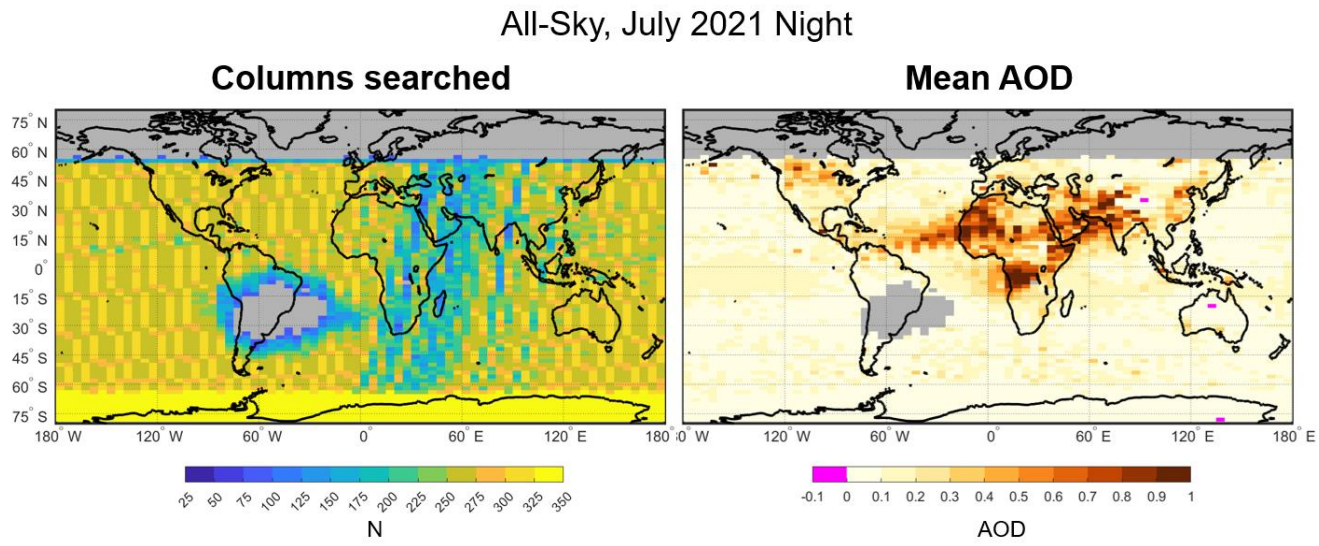

Figure 6: Number of columns searched (left) and mean aerosol optical depth (right) for July 2021 at night, all-sky. Gray indicates no data reported.

Extinction QC flag filter updated

The "extinction QC flag filter" is perhaps the most influential quality screening mechanism used in L3 TAP processing. The CALIOP L2 extinction retrieval process reports diagnostic information in the bit-mapped SDS Extinction_QC_Flag_532 (Young et al., 2018). This information is critical for distinguishing between successful and failed retrievals. In the previous V4.2 L3 data release, this filter required aerosol layers to have extinction QC values of 0, 1, 16, or 18 and cloud layers above aerosols were required to have extinction QC values of 0, 1, or 2. These values indicate:

- 0 (bit 0) – unconstrained solution; default lidar ratio is used
- 1 (bit 0) – constrained solution; initial lidar ratio is calculated based on a measured constraint
- 2 (bit 1) – initial lidar ratio reduced to achieve a solution
- 16 (bit 4) – unconstrained solution; layer is opaque
- 18 (bits 2, 4) – initial lidar ratio reduced; layer is opaque

This list represented the highest quality extinction retrievals for the V4.1 L2 data release. However, it is too restrictive in L3 TAP quality filtering for several reasons. First, it rejects aerosol layers where the initial lidar ratio was reduced to achieve a solution (extinction QC = 2; bit 1 set). Lidar ratio reductions in aerosol typically occur when the layer is optically thick, and small deviations from the true lidar ratio can cause large errors in retrieved extinction. The motivation for rejecting these layers was rooted in analysis of retrievals in the V3.0 L2 data products, circa 2013, where lidar ratios were reduced excessively due to normalization errors subsequently causing biased solutions. Since then, a new set of quality checks was added in the version 4.2 L2 extinction retrieval algorithm to identify layers having suspicious solutions after the lidar ratio has been reduced. These quality checks ensure three things: 1) the overlying integrated attenuated backscatter (IAB) is not excessive, which may trigger suspicious lidar ratio reductions; 2) the layer IAB is not excessive, suggesting errors in overlying attenuation correction; and 3) the lidar ratio has not been reduced excessively (Young et al. 2018). Layers failing these quality control checks have bit 2 set in the extinction QC flag (yielding extinction QC = 6) and are deemed "suspicious solutions". Because the extinction QC flag provides a means to identify and reject retrievals where the lidar ratio reduction results in a suspicious solution, the V5.0 L3 TAP process now accepts aerosol extinction retrievals where the lidar ratio is reduced (extinction QC = 2).

Second, some aerosol retrievals are falsely flagged as suspicious because the L2 quality check uses a static threshold to identify excessive layer IAB which does not account for the natural variability of lidar ratios. This makes aerosol layers with true lidar ratios less than the default CALIOP values more likely to be flagged as suspicious. To avoid this, the V5.0 L3 TAP process now accepts aerosol layers with extinction QC = 6 after reevaluating the layer IAB threshold and the excessive lidar ratio reduction threshold to account for natural variability using the tests in Sidebar 1.

Sidebar 1: Conditions required for accepting suspicious solutions based on extinction QC bit 2

Accept aerosol layers having extinction QC = 6, 70, 8191, or 8262 (bits 1 and 2 are set and possibly bits 6 or 13) if neither of these conditions are met.

1. Layer integrated attenuated backscatter (γ') is greater than 98 % of that expected for an opaque layer (γ'_{opaque}), where γ'_{opaque} is calculated as:

$$\gamma'_{\text{opaque}} = \frac{1}{2S_i(1 - \Delta S_i)}$$

   Aerosol lidar ratio S_i is the level 2 initial 532 nm lidar ratio SDS. Natural variability is captured by the lidar ratio relative uncertainty ΔS_i, defined in the table below.

2. Lidar ratio reduction yields a final 532 nm lidar ratio (S_f) value less than the minimums given in the following table. These values capture the greater of (a) two standard deviations from the mean or (b) a 35 % reduction from the mean.

Aerosol subtype	ΔS_i	$S_{f,\text{minimum}}$ (sr)
Marine	0.22	12.88
Dust	0.20	26.4
Polluted continental/smoke	0.35	24.5
Clean continental	0.45	18.55
Polluted dust	0.40	19.25
Elevated smoke	0.23	37.8
Dusty marine	0.40	22.2

Lastly, two informational bits in the extinction QC flag that do not address the success or failure of a retrieval can cause extinction QC values outside the list of values that were accepted in previous L3 versions. A new bit was enabled with the V4.5 L2 release for range bins in the L2 profile products that contain two different subtypes, and therefore, two different lidar ratios (bit 13). Likewise, informational bit 6 flags layers where the negative signal anomaly (NSA) was detected and mitigated in the upper-most or lower-most range bin of the layer. Retrievals for these two situations are not necessarily erroneous and should be considered for acceptance. Allowing for these bits to be accepted, and allowing extinction QC = 2 and 6, yields a long list of accepted extinction QC values when all possible combinations of accepted bits are considered. For this reason, the extinction QC flag filter is being restated for the V5.0 L3 TAP release to identify *rejected bits* in the extinction QC flag rather than *accepted values*. Table 7 indicates extinction QC flag bits that are rejected during quality filtering for the V5.0 L3 TAP. The same list is applied to clouds and aerosol layers, except for suspicious solution – clouds are always rejected if bit 2 is set whereas aerosol layers with bit 2 set are rejected if they fail the adjusted IAB and lidar ratio reduction threshold tests described above.

Table 7: Zero-based bits in the L2 extinction QC flag rejected in V5.0 L3 TAP processing. Rows shaded in red indicate bits that are rejected.

Bit	Reject sample?	Interpretation
0		unconstrained retrieval; initial lidar ratio
0		constrained retrieval
1		Initial lidar ratio reduced to achieve solution
2	Yes for clouds, conditionally for aerosol	Suspicious retrieval; excessive layer or overlying IAB, or excessive lidar ratio reductions.
3	Yes	Lidar ratio reduced and converged; backscatter uncertainty solution does not exist
4		Layer is opaque
5	Yes	Estimated optical depth error exceeds the maximum allowable value
6		Negative signal anomaly detected
7	Yes	Retrieval terminated at maximum iterations for a constrained retrieval
8	Yes	No solution possible within allowable lidar ratio bounds
9	Yes	Two-way particulate transmittance converged ; constrained retrieval not achieved
10	Yes	Backscatter coefficients not converging; maximum lidar ratio correction reached
11	Yes	Uncertainties not converging and maximum lidar ratio correction iterations achieved
12	Yes	Lidar ratio converged but retrieval still not converging
13		Range bin contains two different feature types that may have different lidar ratios
14	Yes	Complex retrieval failure
15	-	Fill value or no solution attempted

The example in Figure 7 below demonstrates aerosol that is recovered because of updates to the extinction QC flag filter. This is a dense dust plume over the Arabian Peninsula beneath cirrus, a situation where the aerosol lidar ratios likely need to be adjusted due to small errors in overlying transmittance estimates. The lower two panels show the L2 aerosol extinction coefficients that are rejected during L3 TAP processing in light red. Whereas the previous list of acceptable extinction QC flag values from the V4.2 L3 rejects a substantial portion of the dense dust plume (middle panel), the updates list of acceptable extinction QC values in V5.0 L3 allows significantly more aerosol to be accepted.

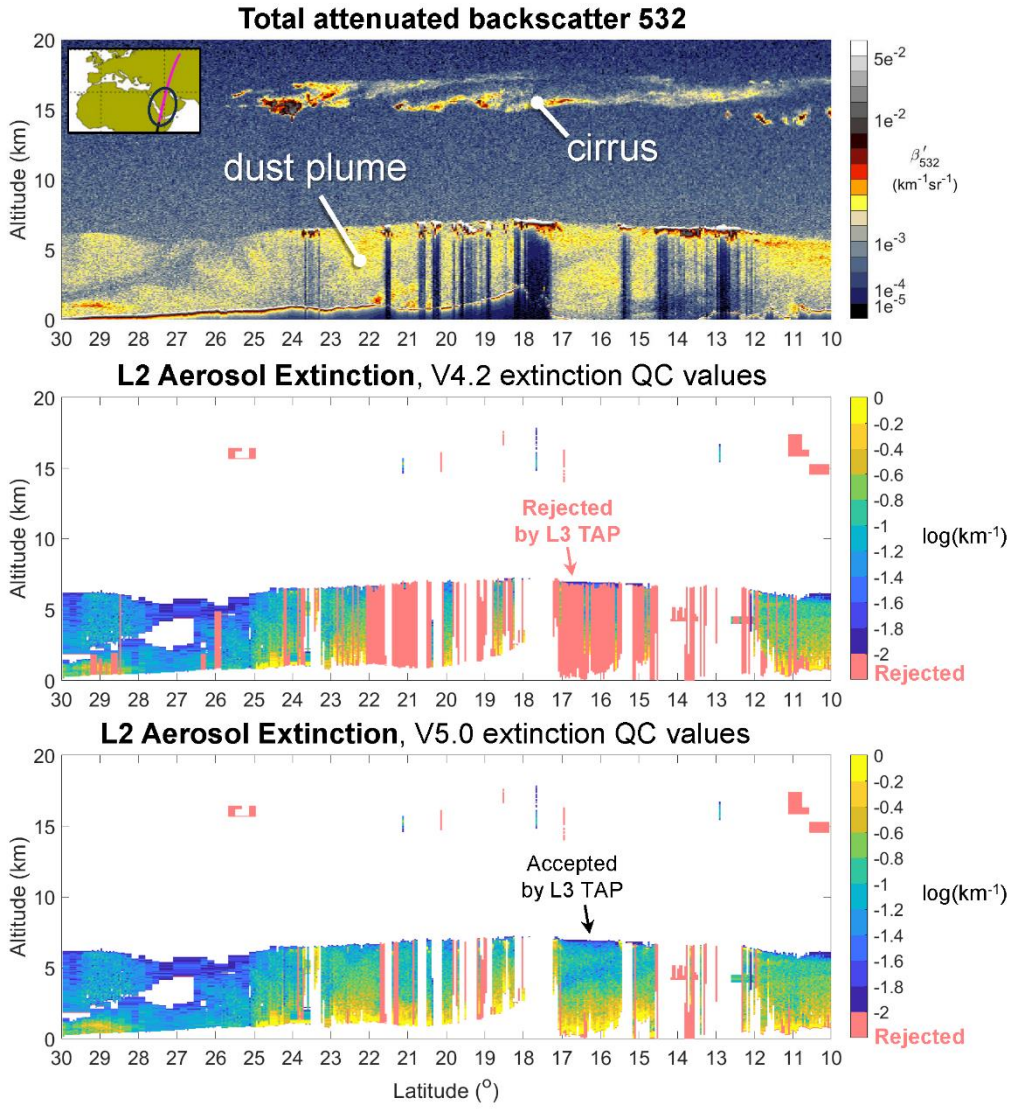

Figure 7: Observation of a dense dust plume beneath cirrus on 10-Jul-2015 at 23:00 UTC, (top panel) total attenuated backscatter at 532 nm, (middle panel) L2 aerosol extinction coefficients filtered using the previous V4.2 L3 list of valid extinction QC values, and (bottom panel) L2 aerosol extinction coefficients filtered using the V5.0 L3 list of valid extinction QC flag values. The light-red color indicates range bins that are rejected during L3 TAP processing.

Figure 8 shows the relative change in number of samples averaged for June-August 2015 when the new extinction QC values are allowed. The largest increases in aerosol samples occur in regions where dust and smoke aerosol loadings are highest and where overlying cirrus is common: for this season, tropical/northern Africa and southwest Asia. The subsequent changes in seasonal mean AOD are illustrated by Figure 9 and Table 8. Because these previously rejected aerosol layers are now included, the all-sky aerosol optical depth increases in these regions by ~30 %. The bottom row of Figure 10 shows the change in mean AOD for the cloud-free sky condition. Compared to all-sky, the increase in mean AOD is smaller, particularly over regions where frequent cirrus exists due to the intertropical convergence zone during this season. There remain regions over northern Africa and southwest Asia where the mean cloud-free AOD increases are similar to all-sky increases due to the presence of dense dust, urban pollution, and smoke aerosol. Lidar ratio reductions for dense aerosol in cloud-free sky conditions are more likely to occur because the initial lidar ratio selected is too large, necessitating its reduction. This also happens in the all-sky condition, with the added possibility of errors in overlying transmittance corrections that trigger lidar ratio

reductions. As a result, the global mean AOD increases by 17 % for all-sky and 12 % for the cloud-free sky condition (Table 8). A larger increase occurs for daytime global mean AOD of 23 % for all sky and 17 % for cloud-free.

The increases in mean AOD in the V5.0 L3 TAP are an improvement relative to previous L3 versions because the densest aerosol plumes on the planet are now allowed to contribute to the monthly aggregation. These strongly backscattering aerosol events were systematically undersampled due to the L3 extinction QC flag filter, biasing the averaged aerosol extinction low in regions where they are common. By revising the extinction QC flag filter in V5.0 so that they can contribute, the low bias is removed, enabling the L3 TAP to more accurately represent the distribution of aerosol extinction in these important regions.

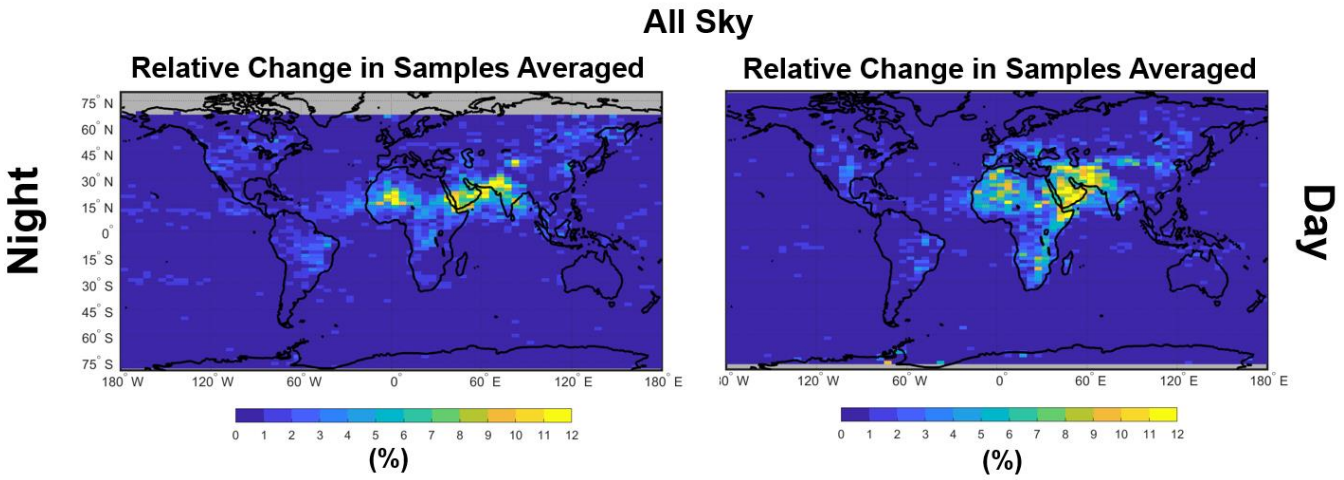

Figure 8: Relative change in all-sky samples averaged for June, July, August 2015: V5.0 minus V4.2 valid extinction QC flag values; night (left column), day (right column).

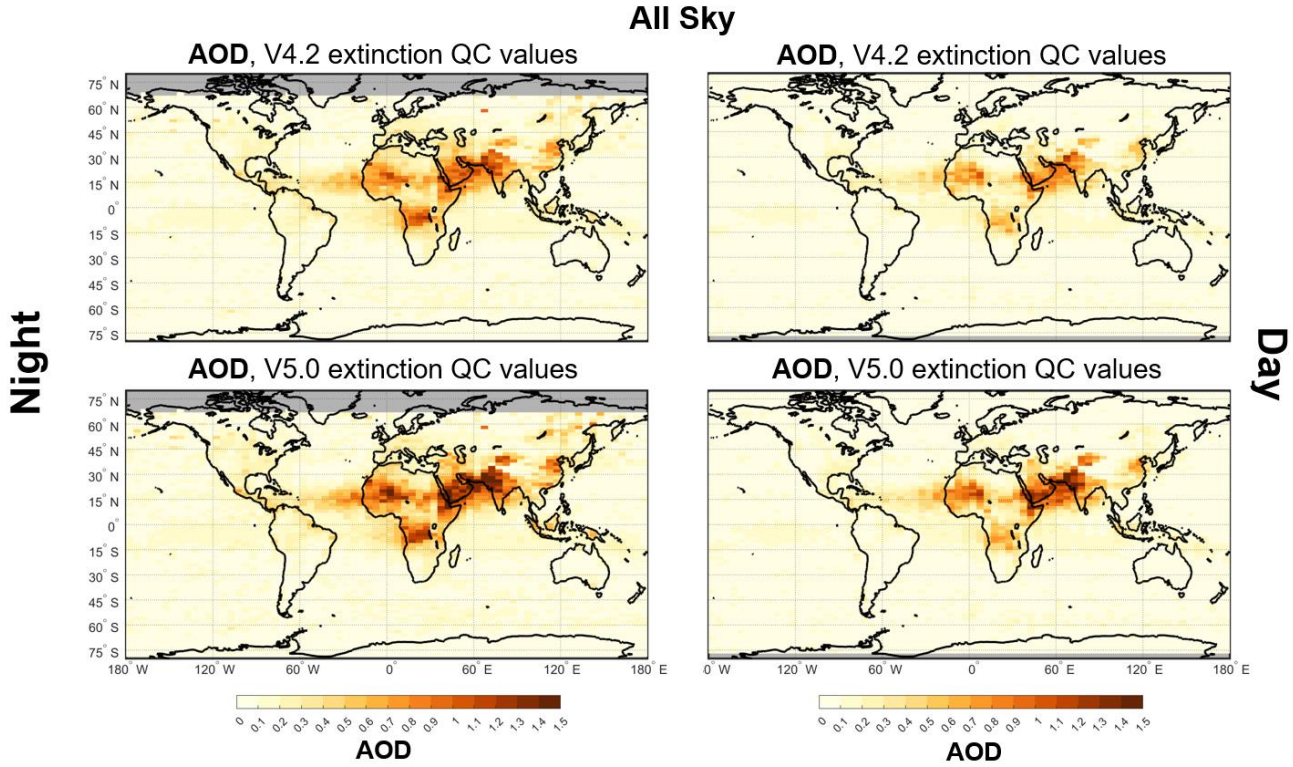

Figure 9: Level 3 all-sky mean AOD for June, July, August 2015 using the valid extinction QC flag values in V4.2 (top row) and the new valid extinction QC flag values (bottom row); night (left column), day (right column).

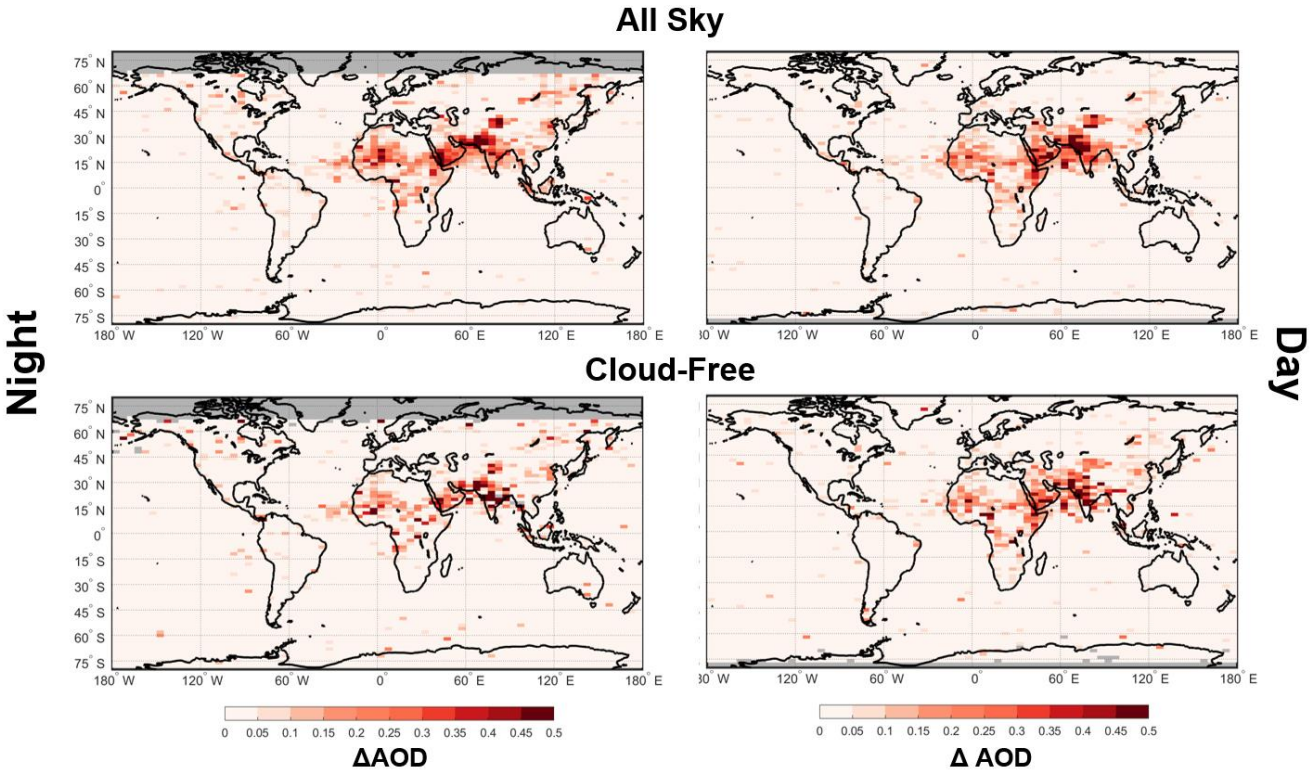

Figure 10: Difference in level 3 mean AOD in June, July, August 2015 for all sky (top row) and cloud-free (bottom row): AOD calculated using V5.0 accepted extinction QC values minus the AOD calculated using V4.2 accepted extinction QC values; night (left column), day (right column).

Table 8: Global level 3 mean AOD for June, July, August 2015 with the valid extinction QC flag values for V4.2, V5.0, and the relative difference.

	All-Sky		Cloud-Free	
	Day	Night	Day	Night
V4.2 extQC flags	0.1064	0.1632	0.1178	0.1606
V5.0 extQC flags	0.1306	0.1908	0.1380	0.1794
Relative difference	22.7 %	16.9 %	17.7 %	11.7 %

New minimum overlying two-way transmittance filter

Though CALIOP can observe beneath semi-transparent features, excessive signal attenuation can eventually degrade feature detection fidelity and increase the uncertainty of retrieved extinction coefficients. Retrievals in strongly attenuating layers are also more sensitive to lidar ratio selection errors which also amplify retrieval errors in features at lower altitudes, such as PBL aerosol. For these reasons, L3 V5.0 adopts a new minimum overlying two-way transmittance (T_p^2) filter that rejects aerosol layers having a mean overlying $T_p^2 < 0.005$. In other words, these are retrievals operating on signals that are at 0.5 % of their original, unattenuated strength, corresponding to an overlying optical depth of > 2.64916. Figure 11 shows the cumulative frequency of overlying T_p^2 for all aerosol layers in 2015. Around 45 % of suspicious solutions (extinction QC = 6) have overlying $T_p^2 < 0.005$ which is expected since strongly attenuating scenes are likely to trigger suspicious solutions. Note that suspicious solutions exceeding the overlying T_p^2 threshold are still adjudicated by the adjusted IAB and lidar ratio reduction threshold tests described in the previous section. Very few (~3 %) of unsuspicious solutions have overlying T_p^2 below this threshold.

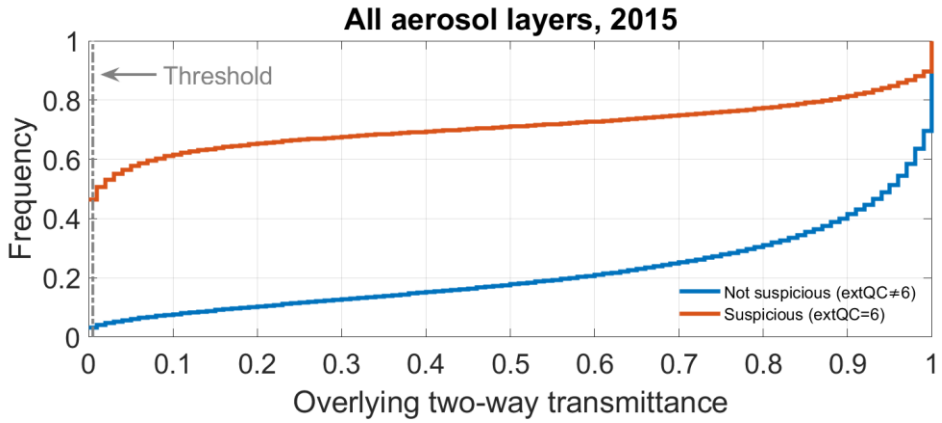

Figure 11: Cumulative distribution of overlying 532 nm two-way transmittance for all aerosol layers detected in 2015, separated by suspicious solutions (extQC = 6; red) and unsuspicious solutions (extQC ≠ 6; blue). The vertical grey dashed line indicates the threshold below which overlying two-way transmittance filter will reject aerosol layers in the V5.0 level 3 data product ($T_p^2 < 0.005$; OD > 2.64916).

Changes in number of aerosol samples rejected and accepted for the all-sky condition due solely to the minimum two-way transmittance filter are shown in Figure 12 for September 2015. Relatively speaking, these changes in sample counts are small. The number of rejected aerosol samples increased by 0.5 % and the number accepted decreased by −0.1 %. Among the latitude-longitude grid cells that changed, the interquartile range (25th, 75th) of relative AOD differences in the all-sky data set is −1.7 to 3.0 %, with a global mean AOD decrease of −1.3 %. The changes in sample counts and AOD is negligible for the cloud-free sky condition.

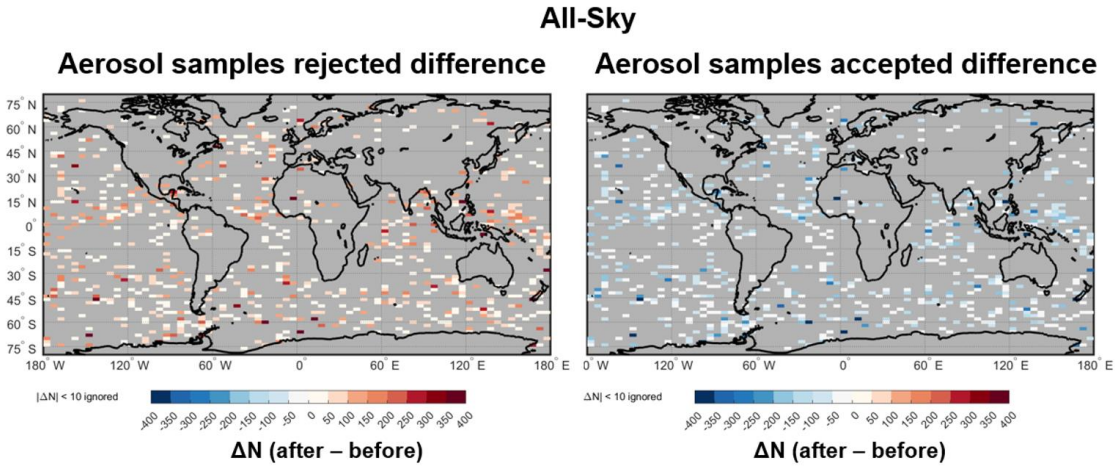

Figure 12: Absolute difference in number of aerosol samples rejected (left) and accepted (right) in the V5.0 L3 TAP due solely to the new minimum two-way transmittance filter for September 2015 at night, all-sky.

Single-subtype statistics provided for all CALIOP tropospheric aerosol subtypes

Aerosol layers are each assigned a subtype by the L2 aerosol classification algorithm corresponding to either marine, dust, polluted dust, dusty marine, elevated smoke, polluted continental/smoke or clean continental (Omar et al., 2009; Kim et al., 2018). The primary aerosol statistics in the L3 TAP are for retrievals containing all aerosol subtypes. Previous L3 TAP releases also included separate science data sets (SDSs) for statistics of a few individual aerosol subtypes, namely: dust, polluted dust, and elevated smoke. The V5.0 L3 TAP release now also include statistics for the remaining CALIOP aerosol subtypes. To improve the organization of the data files, all single-subtype SDSs are now in Vgroups named according to the aerosol subtype (Table 9). The single-subtype SDSs in previous L3 releases have also been moved to eponymously named Vgroups.

Table 9: Names of new Vgroups in the V5.0 L3 TAP and their SDS contents. The name of each aerosol subtype is appended to SDS names where indicated by "[Subtype]".

New Vgroups in V5.0	SDS contents of each Vgroup
Dust	Extinction_Coefficient_532_Mean_[Subtype]
Elevated_Smoke	Extinction_Coefficient_532_Standard_Deviation_[Subtype]
Polluted_Dust	Samples_Aerosol_Detected_Accepted_[Subtype]
Polluted_Continental	Samples_Aerosol_Detected_Rejected_[Subtype]
Marine	Samples_Averaged_[Subtype]
Dusty Marine	AOD_Mean_[Subtype]
Clean Continental	Number_Layers_Per_Column_[Subtype]
	Highest_Aerosol_Layer_Detected_[Subtype]
	Lowest_Aerosol_Layer_Detected_[Subtype]
	Layer_Separation_Minimum_[Subtype]
	Layer_Separation_Maximum_[Subtype]
	Layer_Separation_Median_[Subtype]
	Layer_Separation_Mean_[Subtype]
	Layer_Separation_Standard_Deviation_[Subtype]

Correction to quality filtering for layers detected at different resolutions in the same profile

A correction was made to the L3 TAP quality filtering procedure for rejecting layers that fail the extinction QC flag filter. Level 2 processing detects layers at multiple resolutions (finest to coarsest), yielding profiles with layers detected at different resolutions (Vaughan et al., 2009). Because the CALIOP L2 extinction retrieval operates from the highest altitude downward, errors in higher layers can propagate into lower layers depending on their relative positions and averaging required for detection (Young and Vaughan, 2009). In previous L3 releases, data rejection caused by the extinction QC flag did not properly account for layers reported at different horizontal resolutions in the same profile. In some cases, higher resolution layers passing the extinction QC flag filter were incorrectly rejected when they intrude into coarser resolution layers that failed the filter. In other cases, higher resolution features embedded within coarser resolution features that failed the extinction QC flag filter were incorrectly accepted. The quality filtering procedure has been corrected in the V5.0 L3 TAP to account for layers detected at different horizontal resolutions within the same profile. Layers are now properly rejected when they are affected by propagated extinction retrieval failures captured by the extinction QC flag filter. Figure 13 demonstrates the change in number of aerosol samples rejected and its impact on mean AOD in February 2021 at night. Globally, 5.6 % more aerosol samples are rejected, increasing global mean AOD by 1.0 %. For individual latitude-longitude grid cells, the interquartile range (25^{th}, 75^{th}) of changes in AOD are −1.3 % to 3.4 %.

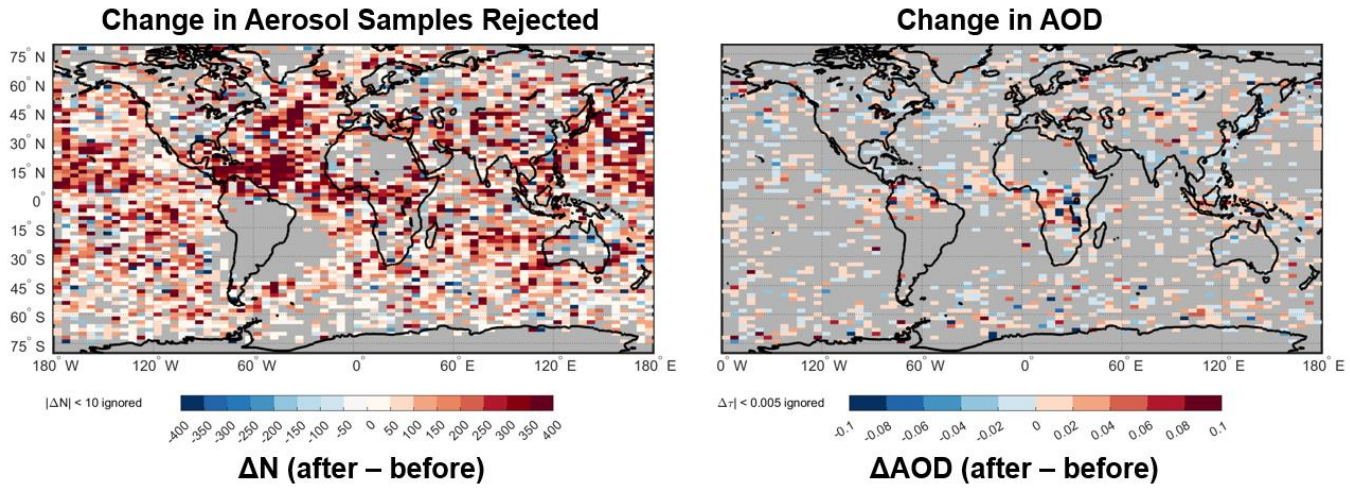

Figure 13: Absolute changes in number of aerosol samples rejected (left) and mean AOD (right) for February 2021 at night, all-sky after correction to quality filtering to account for layers detected at different horizontal resolutions within the same profile.

HDF File Changes

The V5.0 CALIPSO data products are distributed as Hierarchical Data Format Version 4 (HDF4) files, consistent with the EOS requirement in effect when CALIPSO launched in 2006. Since launch, there have been substantial technological advances in data discoverability and access resources. To make CALIPSO data more readily accessible to the scientific community beyond the life of the mission and take advantage of newer data access capabilities, several modifications were made to the format and content of the CALIOP HDF files. These include:

- Updating all units to conform to NetCDF Climate and Forecast (CF) metadata conventions.
- Ensuring that all dimensions are named, to allow HDF to NCDF conversions using commercial off the shelf (COTS) tools that currently exist.
- Creating/expanding SDS attributes and comments to make the data products more self-documenting.

Data Quality Statement for the Version 4.21 Lidar Level 3 Tropospheric Aerosol Product

Data Version: 4.21
Data Release Date: October 12, 2020
Data Date Range: June 2006 to December 2021

Version 4.21 reflects a change in the data products due to a required upgrade to the operating system on the CALIPSO production cluster. All algorithms were re-compiled to process in this new environment with no change to the underlying science algorithms or inputs.

Data Quality Statement for the Version 4.20 Lidar Level 3 Tropospheric Aerosol Product

Data Version: 4.20
Data Release Date: September 11, 2019
Data Date Range: June 2006 to December 2020

The version 4.20 release of the CALIPSO lidar level 3 tropospheric aerosol profile product marks several improvements over the prior version 3 release. Most importantly, the new level 3 product is constructed from version 4 level 2 input data which are the highest quality and most sophisticated of all CALIOP level 2 data products. New level 3 quality screening procedures have been implemented to improve the quality of statistics reported by the product. Minor changes to science data set names and bug fixes are also included in this release. These improvements are detailed below.

Product Name Change

With the version 4.20 release, this product has been renamed to the CALIPSO lidar level 3 *tropospheric* aerosol profile product. The "tropospheric" descriptor was added to differentiate this product from the recently released CALIPSO lidar level 3 stratospheric aerosol profile product which only reports data above the tropopause. This is not to say however that the level 3 tropospheric aerosol product covers the entire troposphere or is bound solely within the troposphere. Because it has a fixed top altitude of 12 km, (a) some tropospheric aerosols (e.g., in tropical latitudes) will not be reported in the tropospheric aerosol profile product, and (b) some level 3 range bins will reside above the tropopause (e.g., in polar regions). However, because the focus of this product is on tropospheric aerosol, only aerosol extinction for layers detected below the tropopause contributes to the statistics. Aerosol layers detected above the tropopause are ignored (i.e., all level 2 stratospheric aerosol layers).

Input Data Change

Version 4 level 2 data is used as the input data for V4.20 release of the level 3 tropospheric aerosol product. This takes advantage of the improved calibration, cloud-aerosol discrimination, aerosol subtyping, and extinction retrievals embodied in the version 4 data products (see the Atmospheric Measurement Techniques special issue: CALIPSO version 4 algorithms and data products).

Algorithm Changes

Several changes in data quality screening have been made in version 4 level 3 in order to further avoid extinction retrieval errors, reduce the occurrence of cloud contamination, and mitigate the influence of low-energy laser shots in the South Atlantic Anomaly region. These changes are described below. Otherwise, the gridding and averaging methods are the same as in the previous release.

Extinction QC flag filter now evaluates all detected layers and removes aerosol extinction

In previous versions, the extinction QC flag was only evaluated for layers classified as aerosol, but not for layers classified as cloud or for stratospheric features. In version 4, the extinction QC flag is evaluated for all detected layers, regardless of feature type, and aerosol extinction samples beneath layers having suspicious extinction QC flags are now rejected. This is important because errors in the top-down level 2 extinction retrieval are propagated to layers at lower altitudes. These changes will reduce the impact of suspicious extinction retrievals on level 3 statistics.

In version 4 level 2, the generic stratospheric feature type has been eliminated. Tropospheric and stratospheric aerosol layers are required to have extinction QC = 0, 1, 16, or 18. Cloud layers are required to have extinction QC = 0, 1, or 2. The extinction QC value of 2 indicates that the initial lidar ratio is reduced to achieve a successful solution. This value is allowed for clouds but excluded for aerosols for two reasons. First, for layers with relatively large optical depths, even small overestimates of the lidar ratio can cause the extinction solutions to fail before the full vertical extent of a layer has been retrieved. Obtaining a successful solution thus requires reducing the layer lidar ratio, and assigning a QC flag of 2. Within the global CALIPSO data set, the median cloud optical depth is substantially higher than the median aerosol optical depth, and hence the occurrence frequency of QC = 2 is much higher for clouds than for aerosols (e.g., only ~0.7% of all unique aerosol layers detected during 2012 had extinction QC flags of 2, whereas for clouds the fraction rises to ~5.2%). Second, for the uppermost layer in a column, QC = 2 almost certainly indicates an overestimate of the layer lidar ratio. However, for layers lying beneath other layers, the interpretation of QC = 2 is ambiguous, as it is much more likely to result from overestimates of the optical depths in overlying layers. Once again, within the global CALIPSO data set, clouds are the uppermost layer in a column far more often than aerosols. Readers looking for more detail on this topic are referred to section 5.3.1 in Tackett et al., 2018 and section 3.5 in Young et al., 2018. Modifications to the extinction QC flag filter increases the rejection frequency from about 5% to 20% of version 4 aerosol extinction samples. Global mean AOD is reduced by approximately 15%.

New cloud layer fraction filter

A new filter has been implemented to reduce the possibility of cloud contamination in the level 3 tropospheric aerosol product. It evaluates the fraction of each aerosol extinction sample containing clouds (i.e., the cloud layer fraction) and rejects those samples where the fraction exceeds a threshold. In the lower troposphere, level 2 extinction samples are comprised of at most 30 single shot attenuated backscatter measurements. Only those measurements classified as aerosol are averaged together and ultimately contribute to the retrieved aerosol extinction within the 60 m vertical x 5 km horizontal resolution sample. The level 2 Cloud Layer Fraction science data set (SDS), ranging from 0 to 30, is used to determine the number of single shot values classified as cloud within an aerosol extinction sample.

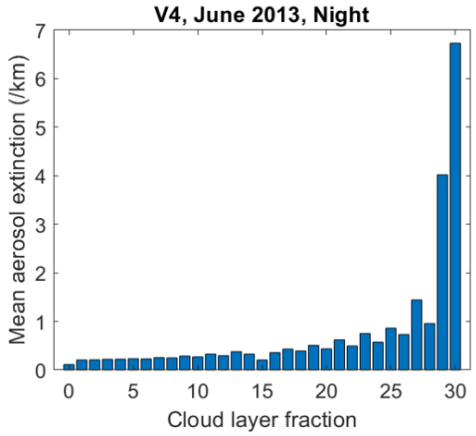

Figure 1: Mean level 2 aerosol extinction as a function of cloud layer fraction (30 = 100%) for June 2013 at night.

As illustrated in Figure 1, the retrieved aerosol extinction can be spuriously large when most of the level 2 range bin is dominated by cloud attenuated backscatter. Questionably large aerosol extinction is reported when the cloud layer fraction is 29 or 30. In fact, the cloud layer fraction = 30 case is especially dubious because this indicates that the sample is 100% cloudy, yet an aerosol extinction is reported. This rare special case, affecting < 0.01% of all aerosol extinction samples in level 2 version 4.20, is being investigated and will be remedied in a forthcoming level 2 data release.

In accordance with the new level 3 tropospheric aerosol product filter, all aerosol samples having Cloud Layer Fraction > 28 (corresponding to 97% cloudy) are rejected, along with all aerosol extinction samples at lower altitudes within the same profile. For two test months in 2011, this filter rejected less than 0.06% of aerosol extinction samples and decreased global all-sky AOD by less than 0.04 during daytime and 0.75% at night.

New misclassified opaque cloud filter

Another new cloud contamination filter has been added to level 3 to reject opaque clouds that have been misclassified as opaque aerosol. This occurs mostly beneath optically thick cloud overlying cover, which degrades the fidelity of the cloud-aerosol discrimination algorithm for lower layers. Though opaque aerosol layers are rare, and those that are misclassified clouds are even more rare, their retrieved extinction is substantial. In order to avoid overestimating the level 3 mean aerosol extinction, opaque aerosol layers that are horizontally adjacent to opaque cloud layers are rejected as misclassified clouds. For two test months in 2011, this filter rejected less than 0.6% of aerosol extinction samples and decreased global mean AOD by roughly 5%, demonstrating the importance of rejecting these misclassified features.

Low laser energy mitigation

Since September 2016, CALIOP has been experiencing low energy laser shots, primarily over the South Atlantic Anomaly (SAA) region. This behavior has significantly degraded the quality of affected profiles. In order to avoid

impacting level 3 data quality, all level 2 profiles within the SAA region are excluded for data months September 2016 onward. Figure 2 below illustrates the excluded region.

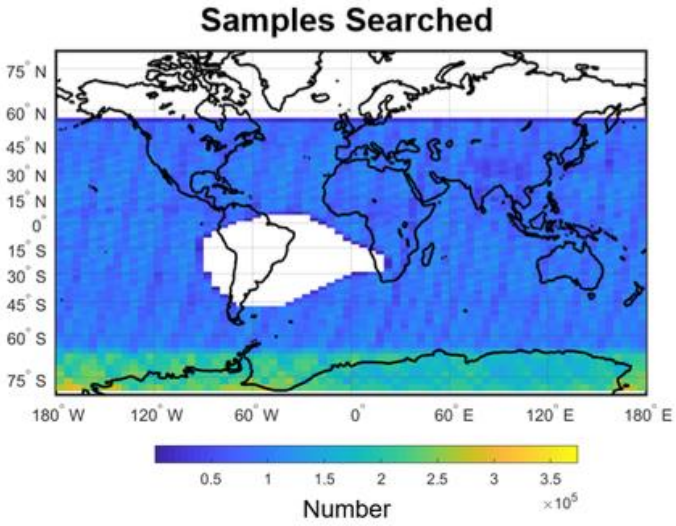

Figure 2: Samples searched by level 3 algorithm for June 2018 at night. No samples are searched in white regions.

Changes in aerosol optical depth, extinction, and sampling

The primary changes in level 3 mean aerosol optical depth and extinction as compared to the previous version are caused by differences in the input level 2 data. Specifically, changes to the aerosol subtyping algorithm and to default aerosol lidar ratios in version 4 level 2 (Kim et al., 2018) are most influential. The impacts of these changes are readily apparent in Figure 3 below. AOD decreases occur over the western Atlantic and over the Arabian Sea due to the reclassification of polluted dust to dusty marine. Decreases occur below 60° S because aerosols over snow, ice, and tundra are no longer constrained to the clean continental or polluted continental types. AOD increases occur over northern Africa and over the ocean due to lidar ratio increases for dust and clean marine. These AOD changes are consistent with version 4 level 2 changes documented by Kim et al., 2018.

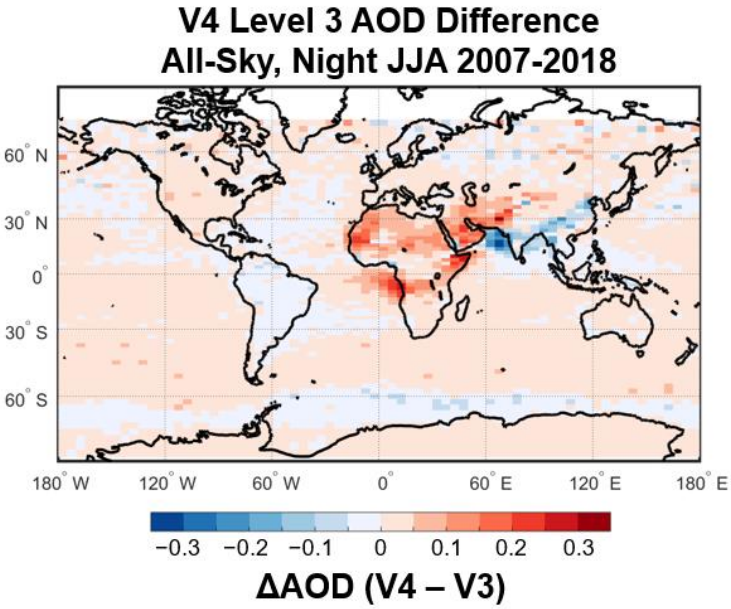

Figure 3: Difference in level 3 mean AOD (V4-V3) for June-August, 2007-2018, all-sky at night.

Globally, the version 4 level 2 changes alone cause the level 3 cloud-free mean AOD to increase by 25% at night and increase by 15% at day relative to the previous version. The new level 3 quality screening procedures (excluding the SAA mitigation filter) decrease the global mean level 3 AOD, yielding a net AOD increase of 16% at night and 6% at day between the previous and the current version of the level 3 product. This is because the new quality screening procedures double the rejection frequency of aerosol extinction samples. Globally, the all-sky rejection frequency has increased to 30% (similar for night and day), and the cloud-free rejection frequency has increased to 16% at night and 22% at day. We believe the new quality screening procedures are effective at only retaining the highest quality aerosol extinction retrievals and the consequent decrease in samples contributing to the level 3 product is justified.

Science Data Set (SDS) Changes

- Histogram SDS sizes have been increased to accommodate the level 2 version 4 dusty marine aerosol type.
- All SDS names containing "Extinction_532" are now "Extinction_Coefficient_532" to conform with level 2 nomenclature.
- All SDS names containing "Smoke" are now "Elevated_Smoke" to conform with version 4 level 2 aerosol subtyping nomenclature (Kim et al., 2018).
- The list of input level 2 aerosol profile granules contributing to the monthly level 3 file are now included in the file metadata as "List_of_Input_Files".

Bug Fixes

- Relative humidity now reported as ratio rather than percent.
- Excluded profiles no longer contribute to meteorological or surface SDS calculations.
- Corrected an error where some aerosol samples within layers that should have been rejected by the misclassified cirrus cloud filter were occasionally not rejected.
- Sample statistics now contain fill values (-9999) rather than zeros in grid cells where no observations are made during the month.

Data Quality Statement for the Version 3.10 Lidar Level 3 Tropospheric Aerosol Product

Data Version: 3.10
Data Release Date: December 16, 2016
Data Date Range: December 2016

Version 3.10 reflects a change in the data products due to a required upgrade to the operating system on the CALIPSO production cluster. All algorithms were re-compiled to process in this new environment with no change to the underlying science algorithms or inputs.

Data Quality Statement for the Version 3.00 Lidar Level 3 Tropospheric Aerosol Product

Data Version: 3.00
Data Release Date: October 14, 2015
Data Date Range: June 2006 to November 2016

The version 3.00 release of the lidar level 3 aerosol profile product contains several improvements to the original version 1 release. New definitions for sky condition now partition the atmosphere into a consistent set of monthly mean aerosol extinction profiles which yield more useful representations of vertical aerosol loading compared to sky conditions in version 1 which were difficult to interpret. Single-species averages for polluted dust and smoke have been added using an improved averaging strategy which generates level 3 aerosol extinction profiles with shapes that more faithfully represent the input level 2 extinction profiles. A revised aerosol optical depth (AOD) calculation removes low-biases that existed in level 3 monthly mean AOD. Mean aerosol extinction near the

planetary surface has been improved by (a) mitigating the impact of negative signal anomalies, which cause negative spikes in aerosol extinction at the onset of the surface, and (b) correctly compensating for high biases (i.e., premature base determination) in the level 2 layer base detection algorithm. Two new extinction scale height data sets have been added to identify altitudes below which 63% and 90% of the total mean AOD is found. Several rarely used statistics have also been removed. The major version number for this release (version 3) reflects that version 3 level 2 data products have been used as input for the level 3 product. These improvements are described in greater detail below.

Level 2 Input Data

The following table lists the version numbers of level 2 data used as input for the V3.00 level 3 product. Note that the major version number (3) matches between level 2 and level 3. Minor version number changes to the level 2 products occur at boundaries between months, so a given level 3 file will only contain input for a single version of the level 2 product.

Lidar Level 2 Input Data for Level 3 Aerosol Profile Product, V3.00	
Level 2 Version	Data Date Range
3.30	March 2013 - present
3.02	November 2011 - February 2013
3.01	June 2006 - October 2011

Sky Descriptions

Level 3 averages are reported for four different sky conditions. “Sky condition” refers to occurrence and location of clouds within the level 2 profiles which are included in the level 3 average. As seen in Table 10, the definitions for sky conditions have changed in V3.00:

Table 10: Revised sky condition definitions for the V3.00 release of CALIOP’s tropospheric aerosol product

Sky Condition (V3)	Description of Level 2 Data Usage
All Sky	All level 2 columns are averaged, regardless of cloud occurrence
Cloud-Free	Only cloud-free level 2 columns are averaged
Cloudy-Sky Transparent	Only level 2 columns containing transparent clouds are averaged
Cloudy-Sky, Opaque	Only level 2 columns containing opaque clouds are averaged

An example of how an individual level 2 granule is parsed into the four sky conditions is shown in Figure 1. Note that it is possible to derive mean extinction for all sky from the cloud-free, cloudy-sky transparent and cloudy-sky opaque sky conditions by weighting the mean extinction values by the “Samples Averaged” statistic for each sky condition.

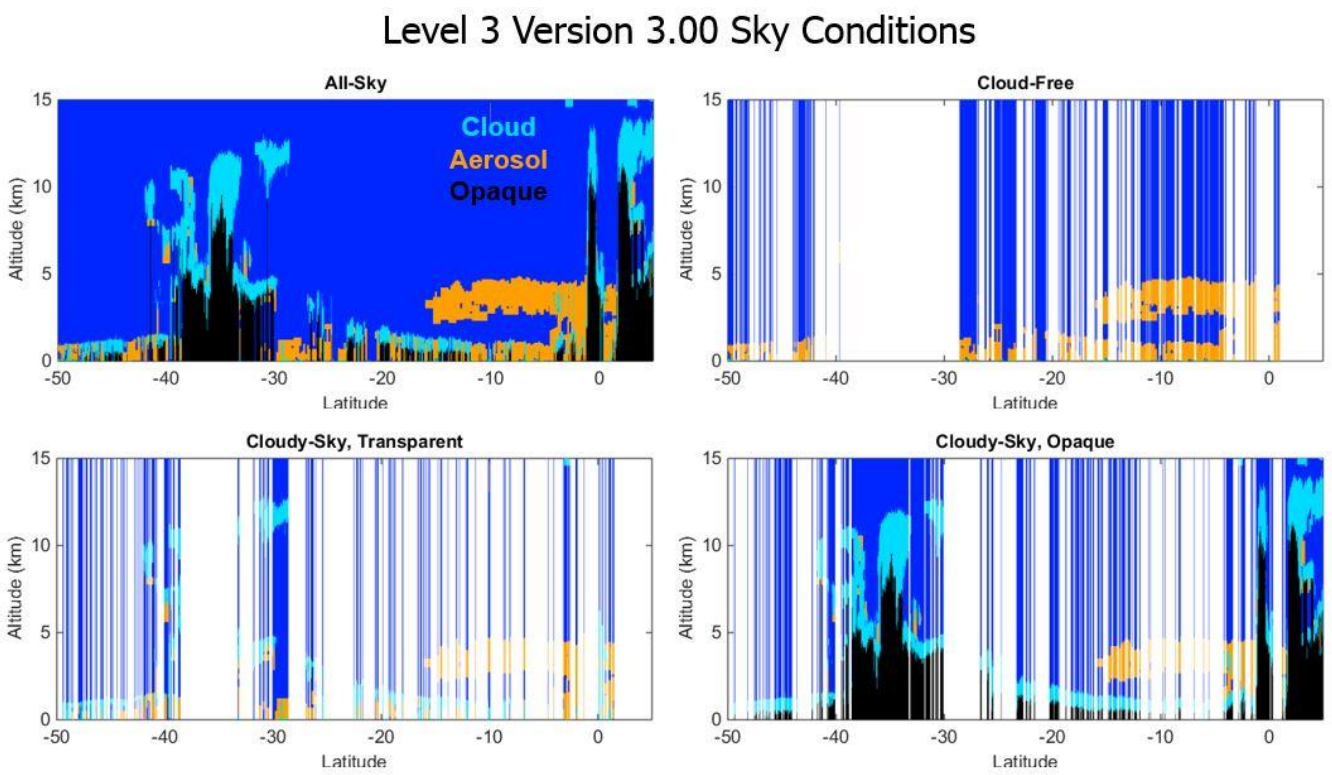

Figure 1: Level 3 Version 3 sky conditions applied to a single level 2 granule. White indicates columns which are excluded from the particular sky condition.

New Single Aerosol Species Averages

Extinction, AOD and sampling statistics are now included for polluted dust-only and smoke-only in addition to dust-only which was reported in version 1.

Revised Averaging Methods for Single Aerosol Species Averages

When averaging level 2 extinction for single aerosol species (for example dust-only), the aerosol extinction for all other aerosol species are now assigned extinction = 0.0 km^{-1} prior to calculating the average. In version 1 of the level 3 product, extinction for those other aerosol species were ignored in the average, which introduced a high bias into the mean extinction at altitudes dominated by other aerosol species (Amiridis et al., 2013).

Figure 2 below demonstrates this effect. Saharan dust transporting westward during Boreal summer initially remains elevated and then descends gradually into the marine boundary layer (MBL) towards the Caribbean (Liu et al, 2008). Dust-only extinction should therefore peak above the MBL just west of the North Africa coast. In level 3 version 1, the dust-only extinction profile in this region shows two peaks - one at 4 km and a second, larger peak in the MBL. The lower peak occurs because the fraction of dust samples decreases rapidly near the ocean surface where marine aerosol is the dominant species (Figure 1, right panel). Since the marine aerosol extinction was ignored during the averaging process, the mean dust-only extinction near the surface is magnified because numerous "dust-free" extinction values of 0.0 km^{-1} (i.e., where the aerosol is marine, not dust) are not included in the averages. Crucially, the profile shape for dust-only extinction becomes badly deformed solely because a small amount of dust existed at the same altitude as marine aerosol. This deformation is not an accurate portrayal of the profile shapes reported by the CALIOP level 2 aerosol profile product, but is instead an artifact of the single aerosol species averaging procedure used in the version 1 analyses. In the version 3 product, all non-dust aerosol extinction is set to 0.0 km^{-1} during the averaging process which yields a dust-only extinction profile with a single peak near 4 km that is more representative of dust-only extinction in this region. A similar methodology is implemented for polluted dust-only and smoke-only averages in level 3 version 3.

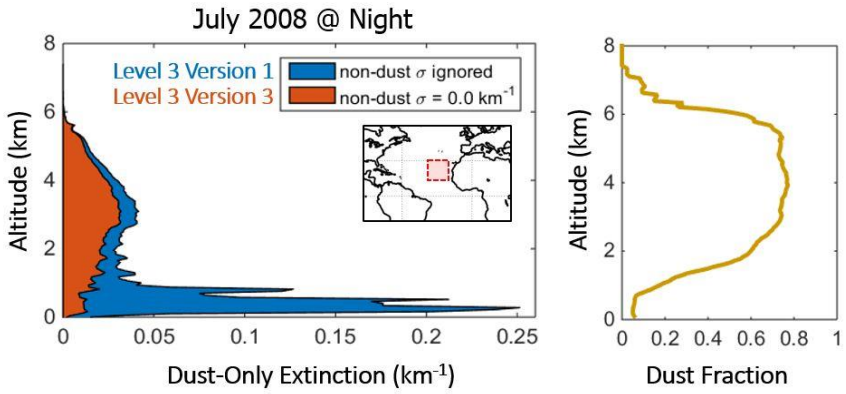

Figure 2: Level 3 mean dust-only extinction averaged according to level 3 version 1 and version 3 methodologies (left panel) and the fraction of dust samples out of all possible aerosol subtypes (right panel) for July 2008 at night. Inset map indicates region examined (red box).

Revised AOD Mean Computation

Mean aerosol optical depth (AOD) reported in version 3 of the level 3 product is computed as the vertical integral of the mean level 3 extinction profile. In contrast, version 1 mean aerosol optical depth was computed as the average of level 2 column AODs. The version 1 method caused a low-biased mean AOD because the columns being averaged together have unequal geometric depths due to cloud cover, opacity or data quality filtering (Figure 3). A simple example demonstrates this. Imagine two level 2 aerosol extinction profiles - one profile having valid aerosol extinction all the way down to the surface and the other profile having an opaque cloud with a small amount of aerosol extinction above. Computing the vertical integral for these two profiles would yield one relatively large AOD and one small AOD since there is less aerosol above cloud. Averaging these AODs together would give a rather small AOD. Conversely, averaging these two extinction profiles together and then integrating the mean extinction would yield a larger AOD that is representative of the aerosol loading at all altitudes. This is the version 3 method. It also has the benefit that the mean AOD is consistent with the mean extinction profiles reported.

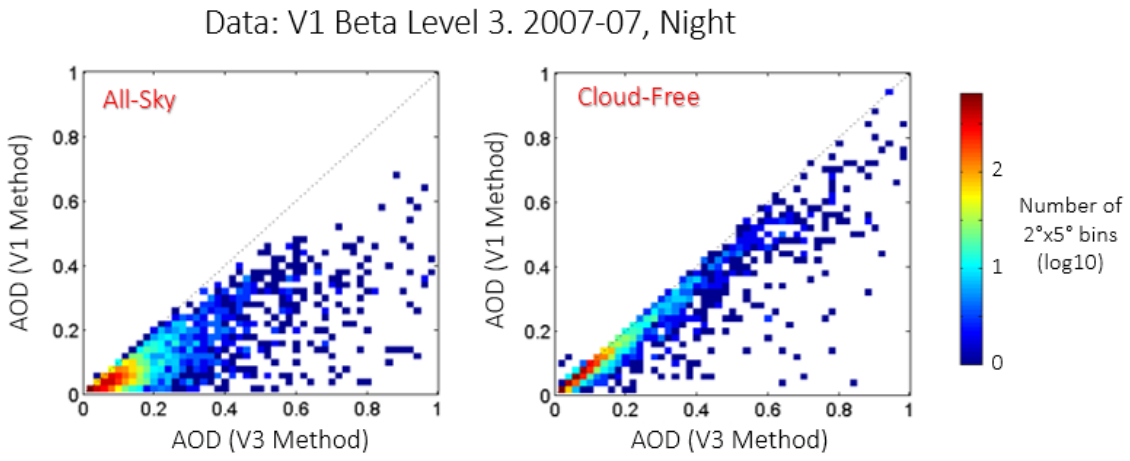

Figure 3: Version 1 Level 3 AOD for one month calculated according to the version 1 method (average of column AODs) and the version 3 method (integral of mean extinction).

New Extinction Scale Heights

New science data sets, “AOD 63% Below” and “AOD 90% Below” indicate the altitude which contains 63% and 90% of the total mean aerosol optical depth below.

Revised Low-Bias Filter for Undetected Surface-Attached Aerosols

When the CALIPSO feature detection algorithm does not detect the entire vertical extent of an aerosol layer and/or the aerosol base extension algorithm is invoked, a gap of "clear-air" can exist beneath the layer base and the surface. If left as "clear-air", level 3 mean extinction would exhibit a low bias in range bins near the surface. To guard against this in version 1 of the level 3 product, "clear-air" was ignored below the lowest layer in a column whose base was below 2.5 km. However, setting this threshold altitude at 2.5 km proved to be overly aggressive, and would occasionally introduce high biases into the level 3 profiles. With version 3, the lowest layer base altitude threshold is lowered to 250 meters, which is much more consistent with the "clear-air" gap of 90-120 meters from the surface that is seen in the level 2 products. This revision focuses the filter application more precisely where it is needed rather than at higher altitudes which, as mentioned, can otherwise yield a high bias in level 3 mean extinction.

New Negative Signal Anomaly Mitigation Strategy

A recently discovered phenomenon, dubbed a "negative signal anomaly" sometimes occurs when the level 1B attenuated backscatter becomes anomalously negative at the abrupt onset of a strongly scattering target such as the planetary surface or a dense cloud. Aerosol extinction can also become anomalously negative when attenuated backscatter affected by the anomaly is included in the extinction retrieval. Subsequent level 3 mean extinction would therefore exhibit a low bias near the surface where the negative signal anomaly is present. To mitigate the impact of this anomaly, all level 2 aerosol extinction coefficients within 60 meters of the planetary surface are excluded from level 3 calculations. Globally, this yields a 2-5% decrease in AOD, but increases AOD in regions strongly affected by the negative signal anomaly. Crucially, anomalously low spikes in level 3 extinction in lowest altitude range bins have been removed.

Removed Statistics

The following statistics have been removed from the level 3 aerosol profile product compared to V1.x.

- Extinction 532 median, skew, RMS
- Extinction 532 dust median, skew, RMS, percentiles
- AOD median, skew, RMS, percentiles
- AOD dust median, skew, RMS, percentiles
- AOD and AOD dust statistics were previously reported for all four sky conditions in every level 3 file. In V3.00, AOD is only reported for the sky condition of the level 3 file.

Known Issues

The following sections describe issues with the level 3 product known at the time of its release in October 2015.

Undetected Aerosol Influence on the Level 3 Aerosol Extinction Statistics

Regions classified as "clear air" by the CALIPSO feature detection algorithms are assumed to have aerosol extinction = 0.0 km^{-1} when calculating level 3 averages of aerosol extinction. CALIOP has a limited detection sensitivity however, and weakly scattering layers go undetected, resulting in a low bias. This occurs most often in the upper troposphere where aerosol layers tend to be optically weak, in the daytime since the SNR is smaller than at nighttime resulting in more layer misdetection, and beneath optically thick clouds due to significant signal attenuation. More details of why some aerosol features may go undetected can be found in the level 2 aerosol layer data quality summary. Biases due to missed detections are believed to be small at night in most regions, though potential biases have not yet been comprehensively quantified by validation intercomparisons. Biases can be more pronounced in the daytime when strongly scattering layers are not detected due to enhanced solar noise over bright surfaces. The impact of this effect has not been quantified at this time.

Meteorological Context Statistics not Calculated for each Sky Conditions

Currently, each meteorological context parameter is generated for every grid cell by averaging together all profiles of the parameter that exist within the grid cell together, regardless of cloud cover or aerosol quality screening. As a consequence, there is not a one-to-one correspondence between the region of sky used to generate aerosol extinction statistics and the region of sky used to generate the meteorological context statistics. For example, the aerosol extinction reported for the "Cloud-Free" sky condition will not include extinction samples in cloudy columns, but the Temperature statistics (for example), and all other meteorological parameters would still contain those samples in cloudy columns.

Samples Searched Statistics Does Not Include Cloudy Samples

The "Samples Searched" statistic is intended to represent the number of atmospheric samples searched by the level 3 algorithm regardless of whether they were accepted, rejected, or ignored in the averaging process. This statistic should include cloudy samples, but it does not in the V3.00 release. This will be corrected in a forthcoming release.

Data Quality Statement for the Version 1.30 Lidar Level 3 Tropospheric Aerosol Product

Data Version: 1.30
Data Release Date: April 2013
Data Date Range: March 2013 to September 2015

Level 2 input data for level 3 product changed to version 3.30.

Excerpt from the version 3.30 lidar level 2 data quality summary:

The Version 3.30 CALIOP Lidar Level 1, Level 2, and Level 3 data products incorporate the updated GMAO Forward Processing – Instrument Teams (FP-IT) meteorological data, and the enhanced Air Force Weather Authority (AFWA) Snow and Ice Data Set as ancillary inputs to the production of these data sets, beginning with data date March 1, 2013.

GEOS-5 Changes and CALIOP Impact Summary

Level 3 aerosol extinction and aerosol optical depth:

GEOS-5 molecular number densities increased by small amounts in the CALIPSO calibration regions and by smaller amounts at other altitudes, slightly increasing the number of aerosol layers detected and increasing their attenuated backscatter. Consequent small increases in aerosol extinction and aerosol optical depth are much smaller than uncertainties in these parameters.

Data Quality Statement for the Version 1.00 Lidar Level 3 Tropospheric Aerosol Product

Data Version: 1.00
Data Release Date: December 2011
Data Date Range: June 2006 to February 2013

The lidar level 3 aerosol product is a quality screened aggregation of level 2 aerosol profile data. As such, its data quality is inherited in part from the level 2 aerosol profile data inputs and in part from the quality screening and re-gridding algorithms used to produce level 3 outputs. Users are advised to consult the lidar level 2 aerosol profile product data quality statement in conjunction with this statement to acquire a comprehensive understanding of level 3 data quality.

Data in this beta release has not been validated. Several known data quality issues are addressed below. These issues are currently under investigation by the CALIPSO Lidar Science Working Group.

Near-surface aerosol extinction

Extinction values reported in the lowest few range bins near the surface can be impacted by several types of retrieval errors. These surface related issues manifest themselves in level 3 aerosol extinction profiles as rapid decreases in extinction in near-surface range bins and occasionally spikes where surface contamination occurs. Two quality assurance filters have been implemented to remove some of the surface contamination errors which cause extinction spikes. Causes of the anomalous decrease in extinction in the lowest range bins are still under investigation.

Aerosol extinction coefficients within 180 meters of the surface in this beta release are untrustworthy and should be ignored. Users should consult the level 3 parameter Surface Elevation Maximum in each grid cell to determine which samples exist within 180 m of the maximum surface elevation and then ignore those samples and all that exist at lower altitudes in that grid cell.

Undetected aerosol influence on level 3 aerosol extinction statistics

Regions classified as "clear air" by the CALIPSO feature detection algorithms are assumed to have aerosol extinction = 0.0 km^{-1} when calculating level 3 averages of aerosol extinction. CALIOP has a limited detection sensitivity however, and weakly scattering layers go undetected, resulting in a low bias. This occurs most often in the upper troposphere where aerosol layers tend to be optically weak, in the daytime since the SNR is smaller than at nighttime resulting in more layer misdetection, and beneath optically thick clouds due to significant signal attenuation. More details of why some aerosol features may go undetected can be found in the level 2 aerosol layer data quality summary. Biases due to missed detections are believed to be small in most regions, though potential biases have not yet been quantified by validation intercomparisons.

Though regions of "clear air" are assumed to have aerosol extinction = 0.0 km^{-1}, the same assumption cannot be made about the aerosol extinction uncertainty - there is no such thing as no uncertainty. Thus, level 3 aerosol extinction RMS uncertainties are calculated by only propagating the level 2 aerosol extinction uncertainties of detected aerosol layers that have passed quality screening criteria. Uncertainties due to undetected layers are not included in the propagated level 3 uncertainty.

Overlying cloud influence on level 3 aerosol extinction averages

Level 3 aerosol extinction statistics are reported for two sky conditions, "All Sky" and "Combined". While the former includes all quality screened aerosol extinction in deriving statistics, the latter excludes aerosol detected beneath clouds. Statistics are broken up in this manner because overlying clouds attenuate the lidar signal and decrease SNR, making faint layers more difficult to detect and increasing uncertainty in a variety of ways. The distribution of level 2 aerosol extinction tends to broaden with overlying cloud cover with more increasing occurrence of extreme outliers, shown in Figure 4. Quality filters implemented for level 3 are successful at removing many of these extreme outliers; namely, the extinction QC flag and extinction uncertainty filters.

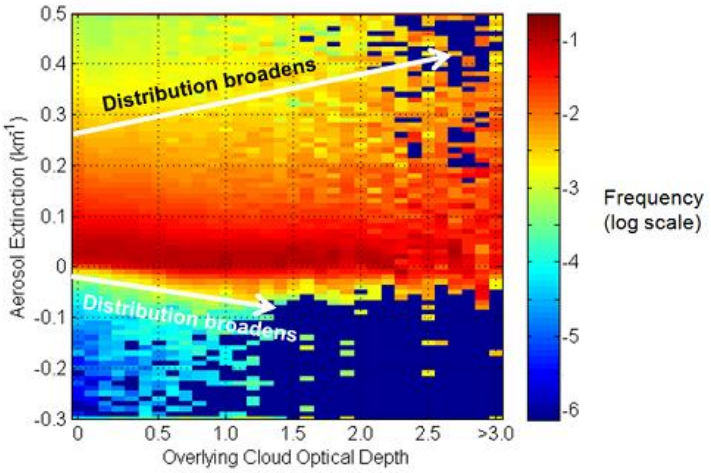

Figure 4. Frequency distribution of quality screened level 2 aerosol extinction samples as a function of overlying *ice* cloud optical depth in August 2007 in a region of frequent cirrus cloud cover (0°E, 120°E; 25°S, 25°N).

In spite of the increased uncertainties of aerosol retrieved below cloud, regional monthly mean all-sky and clear-sky profiles appear to be consistent. Comparison of level 3 aerosol extinction between the "All Sky" and "Combined" sky conditions reveals that the mean level 3 aerosol extinction is slightly lower in magnitude for the "All Sky" case even though more aerosol samples are included. This is shown by the cumulative distribution of level 3 aerosol extinction for one month in Figure 5 (left panel). This may be due to more clear air samples being averaged in with the aerosol beneath cloud, causing the mean extinction to be smaller for "All Sky" compared to "Combined". Also, the RMS uncertainty tends to be slightly larger for the "All Sky" case even though the RMS uncertainty decreases with the inverse of number of aerosol samples accepted (Figure 5, right panel).

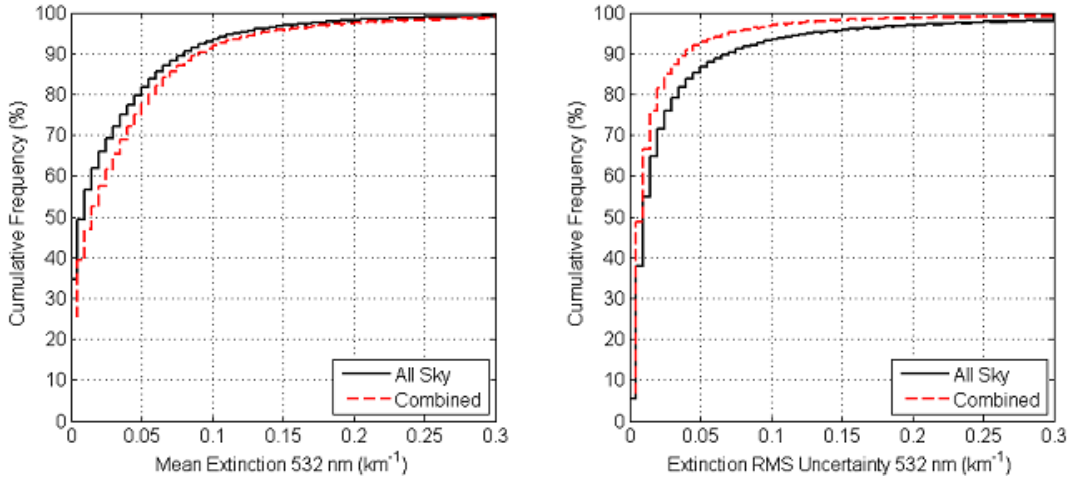

Figure 5. Cumulative frequency distributions of level 3 mean aerosol extinction (left) and level 3 aerosol extinction RMS uncertainty (right) for "All Sky" (black) and "Combined" (red dashed) sky conditions. Data is from a pre-beta level 3 aerosol file, June 2006 at night. Mean level 3 aerosol extinction values where aerosol is not detected are ignored.

Until validation studies are completed, users should treat "All Sky" level 3 optical properties carefully in regions with significant overlying cloud cover (in southeast Asia during the Indian monsoon, for instance). It is also advisable to check the statistic Samples Aerosol Detected Accepted to ensure a sufficient number of aerosol samples are available.

Known issue with meteorological context statistics

Currently, each meteorological context parameter is generated for every grid cell by averaging together all profiles of the parameter that exist within the grid cell together, regardless of cloud cover or aerosol quality screening. As a consequence, there is not a one-to-one correspondence between the region of sky used to generate aerosol extinction statistics and the region of sky used to generate the meteorological context statistics. For example, the aerosol extinction reported for the "Combined" sky condition will not include samples beneath clouds, but the Temperature statistics (for example), and all other meteorological parameters would still contain those samples beneath clouds. This issue will be addressed in a forthcoming release.

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