CALIPSO Lidar Level 3 Ice Cloud Data Description Document
Version 2.00

Last Updated: 17 November 2025

Data Version:	2.00
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Data Date Range:	June 13, 2006 to June 30, 2023

Introduction

The lidar level 3 (L3) ice cloud product reports global distributions of ice cloud extinction coefficient and ice water content histograms at monthly time scales on a uniform spatial grid (2.5° longitude × 2.0° latitude × 120 m altitude). It also includes background meteorological data, cloud sample counts and surface information. All level 3 parameters are derived from the CALIPSO version 5.00 level 2 5 km cloud profile products, with a temporal aggregation over one month.

Three level 3 data files are generated each month according to lighting conditions: daytime only, nighttime only, and both day and night.

There are no major changes from Version 1.00 to Version 2.00, other than being based on the latest version of level 2 products (V5). The production code was modified for Version 2.00 to read level 2 information left by the LEM algorithm and this is used to exclude data from the level 3 product which is negatively impacted by low energy shots.

Resolution and Coverage

The level 3 ice cloud product reports monthly aggregations of ice cloud occurrences. Granules straddling two consecutive months have been examined carefully to make sure each portion has been included in the correct month.

Table 1 lists the spatial coverage and resolution of this product. They are designed to be compatible with other level 3 cloud and aerosol products. The spatial resolution for the level 3 ice cloud product, it is 2.5° longitude by 2.0° latitude and 120 m altitude. For the level 3 cloud occurrence product, it is 2.5° longitude by 2.0° latitude and 60 m altitude while for the level 3 aerosol product, it is 5.0° longitude by 2.0° latitude and 60 m altitude. All products start counting from the same lower altitude boundary. The level 3 cloud occurrence product and the ice cloud product have the same altitude coverage. All level 3 ice cloud products have a higher upper altitude boundary than that of the L3 aerosol product, i.e., 20.2 km vs. 12.0 km.

Table 1: The spatial coverage and resolution of L3 ice cloud product.

Spatial Coverage	Spatial Resolution
360° longitude (180° W to 180° E)	2.5° longitude
170° latitude (85° S to 85° N)	2.0° latitude
-0.5 km to 20.2 km altitude	120 m vertical

Besides reporting cloud occurrence in counts as a function of cloud phase and opacity, the ice cloud count is also reported as a histogram of the layer optical depth in each three-dimensional (3D) grid cell. Accordingly, this parameter is described as four-dimensional (4D) array.

Table 2 summarizes the dimensions of the science data sets which are described as two-dimensional (2D), 3D or 4D arrays, depending on their purpose.

Table 2: Number of dimensions and dimension lengths of science data sets of L3 cloud occurrence product.

Number of Dimensions	Spatial Resolution
2-D	number of latitudes bins × number of longitude bins = 85 × 144
3-D	number of latitudes bins × number of longitude bins × number of altitude bins = 85 × 144 × 344
4-D	number of latitudes bins × number of longitude bins × number of altitude bins × number of optical depth histogram bins = 85 × 144 × 344 × 7

Table 3 defines the optical depth ranges spanned by each of the 7 bins in the ice cloud optical depth histograms. In Version 1.00, bin 7 was 'reserved' due to a question whether opaque cloud layers were counted correctly. That question was resolved for Version 2.00 and bin 7 now reports sample counts for opaque layers, as intended.

Table 3: Optical depth bins and intervals used when creating ice cloud optical depth histograms

Bin	Optical Depth Range
1	Optical Depth < 0.01
2	0.01 ≤ Optical Depth < 0.03
3	0.03 ≤ Optical Depth < 0.10
4	0.10 ≤ Optical Depth < 0.30
5	0.30 ≤ Optical Depth < 1.00
6	Optical Depth ≥ 1.00 & Transparent
7	Opaque

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Additional Documentation

Project Documentation

- CALIPSO Data Management Team: CALIPSO Data Products Catalog, PC-SCI-503, Release 5.00.
- Winker, D. M., C. A. Hostetler, M. A. Vaughan, and A. H. Omar, 2006: CALIOP Algorithm Theoretical Basis Document: Part 1 : CALIOP Instrument, and Algorithms Overview, PC-SCI-202 Part 1 Release 2.0, https://ntrs.nasa.gov/citations/20250006626.
- Vaughan, M. A., D. M. Winker, and K. A. Powell, 2005: CALIOP Algorithm Theoretical Basis Document Part 2: Feature Detection and Layer Properties Algorithms, PC-SCI-202 Part 2 Release 1.01, https://ntrs.nasa.gov/citations/20250006627.
- Liu, Z., A. H. Omar, Y. Hu, M. A. Vaughan, and D. M. Winker, 2005: CALIOP Algorithm Theoretical Basis Document: Part 3: Scene Classification Algorithms, PC-SCI-202 Part 3 Release 1.0, https://ntrs.nasa.gov/citations/20250006628.

Peer-Reviewed Algorithm Papers

- Tackett, J. L., R. A. Ryan, A. E. Garnier, J. Kar, B. Getzewich, X. Cai, M. A. Vaughan, C. R. Trepte, R. Verhappen, D. M. Winker and K.-P. A. Lee, 2025: Mitigating Impacts of Low Energy Laser Pulses on CALIOP Data Products, *EGUsphere* [AMTD], https://doi.org/10.5194/egusphere-2025-2376.
- Winker, D., X. Cai, M. Vaughan, A. Garnier, B. McGill, M. Avery and B. Getzewich, 2024: A Level 3 monthly gridded ice cloud dataset derived from 12 years of CALIOP measurements, *Earth Syst. Sci. Data*, **16**, 2831–2855, https://doi.org/10.5194/essd-16-2831-2024.

Glossary and Acronym Dictionary

Term	Meaning
AMSL	above mean sea level
AOD	aerosol optical depth
ATBD	algorithm theoretical basis document
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
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
HOI	horizontally oriented ice
IAB	integrated attenuated backscatter
IWC	ice water content
IWP	ice water path
L1B	level 1B
LEM	low energy mitigation
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2
N/A	not applicable
PSC	polar stratospheric cloud
QA	quality assurance/quality control
QC	quality control/quality assurance
ROI	randomly oriented ice
SNR	signal-to-noise ratio
SDS	scientific data set
TAI	International Atomic Time
UTC	Coordinated Universal Time
WRS	Worldwide Reference System
YAML	Yet Another Markup Language / YAML Ain't Markup Language

Scientific Data Sets: Altitude and Position

Longitude_Midpoint

Units: degrees_east

Format: Float_32

Valid Range: -180, 180.0

Description: Longitude at the grid cell midpoint.

Latitude_Midpoint

Units: degrees_north

Format: Float_32

Valid Range: -85.0, 85.0

Description: Latitude at the grid cell midpoint.

Altitude_Midpoint

Units: km

Format: Float_32

Valid Range: -0.5, 20.2

Description: Altitude at the grid cell midpoint.

Scientific Data Sets: Meteorological Parameters

Pressure_Mean

Units: hPa

Format: Float_32

Valid Range: 1.0, 1086.0

Description: Mean of all pressures reported within the monthly latitude-longitude-altitude grid cell derived from the Modern Era Retrospective-Analysis for Research (MERRA-2) reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System.

Pressure_Standard_Deviation

Units: hPa

Format: Float_32

Valid Range: 0.0, 50.0

Description: Standard deviation of all pressures reported within the monthly latitude-longitude-altitude grid cell derived from the Modern Era Retrospective-Analysis for Research (MERRA-2) reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System.

Temperature_Mean

Units: degC

Format: Float_32

Valid Range: -120.0, 60.0

Description: Mean of all temperature reported within the monthly latitude-longitude-altitude grid cell derived from reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System.the Modern Era Retrospective-Analysis for Research (MERRA-2) reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System.

Temperature_Standard_Deviation

Units: degC

Format: Float_32

Valid Range: 0.0, 30.0

Description: Standard deviation of all temperature reported within the monthly latitude-longitude-altitude grid cell derived from reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System.

The Modern Era Retrospective-Analysis for Research (MERRA-2) reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System.

Relative_Humidity_Mean

Units: NoUnits

Format: Float_32

Valid Range: 0.0, 1.5

Description: Mean of all relative humidity reported within the monthly latitude-longitude-altitude grid cell derived from reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System. The Modern Era Retrospective-Analysis for Research (MERRA-2) reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System.

Relative_Humidity_Standard_Deviation

Units: NoUnuts

Format: Float_32

Valid Range: 0.0, 0.8

Description: Standard deviation of all relative humidity reported within the monthly latitude-longitude-altitude grid cell derived from reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System. The Modern Era Retrospective-Analysis for Research (MERRA-2) reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System.

Tropopause_Height_Mean

Units: km

Format: Float_32

Valid Range: 4.0, 22.0

Description: Mean of all tropopause height reported within the monthly latitude/longitude grid cell derived from reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System. The Modern Era Retrospective-Analysis for Research (MERRA-2) reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System.

Tropopause_Height_Standard_Deviation

Units: km

Format: Float_32

Valid Range: 0.0, 5.0

Description: Standard deviation of all tropopause height reported within the monthly latitude/longitude grid cell, in kilometers; derived from reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System. The Modern Era Retrospective-Analysis for Research (MERRA-2) reanalysis product provided to the CALIPSO project by the GMAO Data Assimilation System.

Scientific Data Sets: Surface and Over-flight Parameters

DEM_Surface_Elevation_Minimum

Units: km

Format: Float_32

Valid Range: -1.0, 9.0

Description: Minimum of surface elevation for all columns reported in the latitude/longitude grid cell, in kilometers, above local mean sea level obtained from the CloudSat Digital Elevation Map (DEM).

DEM_Surface_Elevation_Maximum

Units: km

Format: Float_32

Valid Range: -1.0, 9.0

Description: Maximum of surface elevation for all columns reported in the latitude/longitude grid cell, in kilometers, above local mean sea level obtained from the CloudSat Digital Elevation Map (DEM).

DEM_Surface_Elevation_Median

Units: km

Format: Float_32

Valid Range: -1.0, 9.0

Description: Median of surface elevation for all columns reported in the latitude/longitude grid cell, in kilometers, above local mean sea level obtained from the CloudSat Digital Elevation Map (DEM).

Land_Surface_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of 5 km columns within the latitude/longitude grid cell having surface type at the middle-point lidar footprint classified as land (all surface types other than water) by the International Geosphere-Biosphere Programme (IGBP). The IGBP surface types reported by CALIPSO are the same as those used in the CERES/SARB surface map.

Water_Surface_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of 5 km columns within the latitude/longitude grid cell having surface type at the middle-point lidar footprint classified as water by the International Geosphere/Biosphere Programme (IGBP). The IGBP surface types reported by CALIPSO are the same as those used in the CERES/SARB surface map.

Days_Of_Month_Observed

Units: NoUnits

Format: UInt_32

Valid Range: 0…4,294,967,295

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 1. 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.

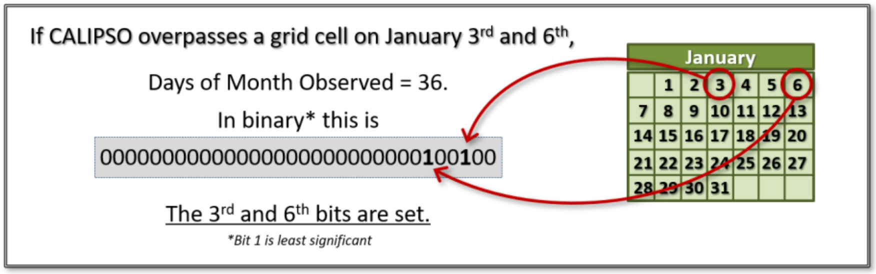

Figure 1: Illustration of the mapping between calendar days and the Days_Of_Month_Observed parameter.

Scientific Data Sets: Histogram Bin Boundaries

Extinction_Coefficient_532_Bin_Boundaries

Units: 1/km

Format: Float_32

Valid Range: -0.1, 10.0

Description: Bin boundaries used for ice cloud total extinction coefficient (channel 532 nm) histogram. Three boundaries are reported at each bin: lower boundary, middle boundary and upper boundary.

Ice_Water_Content_Bin_Boundaries

Units: g/m^3

Format: Float_32

Valid Range: -0.01, 1.0

Description: Bin boundaries used for ice water content histogram. Three boundaries are reported at each bin: lower boundary, middle boundary and upper boundary.

Scientific Data Sets: Extinction Coefficient and Ice Water Content

Extinction_Coefficient_532_Histogram

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Histogram of ice cloud extinction coefficients derived from the 532 nm channel in the monthly latitude-longitude-altitude grid cell. Extinction coefficient sample counts are aggregated only for ice clouds that have passed all quality filters. In Figure 2, the histogram contains the numbers of ice cloud samples in a specific extinction coefficient bin range in a specific 3D spatial grid cell.

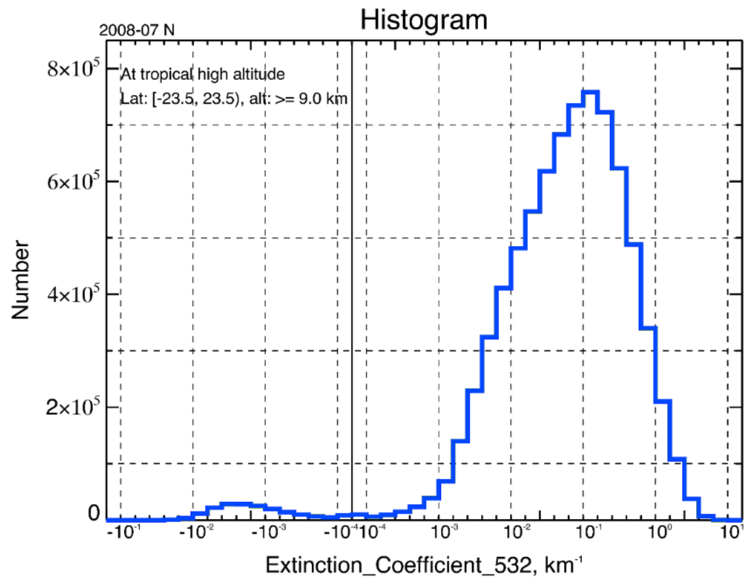

Figure 2: Histogram of night-time extinction coefficient derived from the 532 nm channel above 9 km altitude in the tropics (23.5°S to 23.5°N) in July 2008. w The X-Axis scale is logarithmic. The dashed vertical line separates negative and positive coefficients. The Y-Axis is linear and shows the number of ice clouds observed in each coefficient bin range.

Ice_Water_Content_Histogram

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Histogram of cloud ice water content (IWC) in the monthly latitude-longitude-altitude grid cell. IWC sample counts are aggregated only from ice clouds that have passed all quality filters. As illustrated in Figure 2, the histogram contains the numbers of ice cloud samples in a specific IWC bin range in a specific 3D spatial grid cell.

Extinction_Coefficient_532_Median

Units: 1/km

Format: Float_32

Valid Range: -0.1, 1.0

Description: Median in-cloud ice cloud extinction coefficient in the monthly latitude-longitude-altitude grid cell. It is derived from samples passing all quality filters and within the range of valid extinction coefficient (-0.1 km^{-1} - 10.0 km^{-1}).

Ice_Water_Content_Median

Units: g/m^3

Format: Float_32

Valid Range: -0.01, 1.0

Description: Median in-cloud IWC in the monthly latitude-longitude-altitude grid cell. It is derived from samples passing all quality filters and within the range of valid IWC range (-0.01 $g{\cdot}m^{-3}$ - 1.0 $g{\cdot}m^{-3}$) only.

Scientific Data Sets: Sampling

Lidar_Surface_Subsurface_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of lidar-detected surface or subsurface samples in the monthly latitude-longitude-altitude grid cell. If a lidar surface is detected, the subsurface extends down to the bottom of the vertical range which is around -0.5 km

Totally_Attenuated_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of totally attenuated samples, in counts, in the monthly latitude-longitude-altitude grid cell. If a lidar surface is not detected due to optically thick clouds, the region between the base of the bottom cloud layer and the bottom of the vertical range (~ -0.5 km) are all considered as totally attenuated samples.

Cloud_Free_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of cloud free samples in the monthly latitude-longitude-altitude grid cell, including clear sky and aerosol features.

Cloud_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of cloud samples in the monthly latitude-longitude-altitude grid cell.

Water_Cloud_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of water (liquid) cloud samples in the monthly latitude-longitude-altitude grid cell.

Unknown_Cloud_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of cloud samples of unknown phase and undetermined cloud samples, in counts, in the latitude-longitude-altitude grid cell.

Ice_Cloud_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of ice cloud samples, before extinction quality filtering, in the monthly latitude-longitude-altitude grid cell.

Ice_Cloud_Rejected_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of ice cloud samples in the monthly latitude/longitude/latitude grid cell failing to pass the extinction retrieval quality control filters.

Ice_Cloud_Accepted_Samples

Units: NoUnits

Format: Int_16

Valid Range: 0…32,767

Description: Number of ice cloud samples in the monthly latitude/longitude/latitude grid cell passing all quality control filters.

Number_of_5km_Profiles_Evaluated

Units: NoUnits

Format: Int_32

Valid Range: 0…4,294,967,295

Description: Number of 5 km horizontal resolution columns evaluated.

Number_of_5km_Profiles_Excluded

Units: NoUnits

Format: Int_32

Valid Range: 0…4,294,967,295

Description: Number of 5 km horizontal resolution columns excluded.

Metadata Descriptions

Product_ID

Units: no unit (NoUnits)

Format: Char

Valid range: CAL_LID_L3_Ice_Cloud

Definition: A character string (80-byte maximum) specifying the data product name. For all CALIPSO Lidar Level 3 Ice Cloud products, this string will always be “CAL_LID_L3_Ice_Cloud”.

Date_Time_of_Production

Units: no unit (NoUnits)

Format: Char

Valid range: 4/2006 - 9/2025

Definition: A 27-byte character string that specifies the UTC date and time at which the data was generated. The format is yyyy-mm-ddThh:nn:ss.ffffffZ, where yyyy is the year, mm is the month, dd is the day, hh is the hour, nn is the minute, ss is the second, and ffffff is the fractional second. Date and time are separated by the character 'T'. The 'Z' indicates that time is given in UTC.

Nominal_Year_Month

Units: no unit (NoUnits)

Format: Char

Valid range: 200606 - 202306

Definition: A six-digit integer indicating the data acquisition year and month of the original CALIPSO measurements aggregated to create the level 3 file; data format is yyyymm.

Program_Configuration

Units: no unit (NoUnits)

Format: Char

Valid range: N/A

Definition: Contains the complete contents of the YAML runtime program configuration file. The parameters in this file control the sizes of the array dimensions used by the program, dictate the configuration of the cloud quality assessment filter, and specify the minimum allowable input file size.

Number_of_Level2_Files_Analyzed

Units: no unit (NoUnits)

Format: UInt_16

Valid range: 0...900

Definition: Number of level 2 granules analyzed to generate this level 3 ice cloud file. Filenames for these granules are given in the List_of_Input_Files field.

Number_of_Bad_Profiles

Units: no unit (NoUnits)

Format: UInt_16

Valid range: 0...65,535

Definition: Number of 5 km profiles excluded from aggregation due to anomalous failure to detect the surface (see **Error! Reference source not found.** in the Data Quality Statement for the release of the CALIPSO Lidar Level 3 Ice Cloud Version 2.00)

List_of_Input_Files

Units: no unit (NoUnits)

Format: Char

Valid range: N/A

Definition: List of Level 2 5 km cloud profile product files/granules used to generate this Level 3 ice cloud file. The Number_of_Level2_Files_Analyzed field reports the number of granules in this list.

Data Release Information

Table 4: Release date, version number, data date range, production strategy, and versions of the lidar level 2 source files used to create all CALIPSO lidar level 3 ice cloud products

Release Date	Version	Data Date Range	Production Strategy	Input Products and Versions
October 2025	2.00	June 2006 to June 2023	Standard	V5.00 Level 2 5km CPro
September 2024	1.00	January 2017 to January 2022	Standard	V4.20 Level 2 5km CPro
May 2018	1.00	June 2006 to Dec 2016	Standard	V4.10 Level 2 5km CPro

Data Quality Information

Data Quality Statement for the release of the CALIPSO Lidar Level 3 Ice Cloud Version 2.00

The version 2.00 level 3 ice cloud product is processed from the V5.0 level 2 5 km cloud profile product. The major change in the version 2.00 product, other than benefiting from the improved V5.0 level 1 and level products, is the addition of the low energy mitigation (LEM) algorithm (Tackett et al. 2025) to remove impacts of the low energy shots which occurred with occurring frequency in the last years of the mission. From the beginning of the CALIPSO mission through 2018 the mean local time (MLT) of the equator crossing was held constant. The CALIPSO orbit began to drift in 2019 and the MLT of the orbit changed significantly by the end of the mission, which risks aliasing the diurnal cycle into the long-term record. This is discussed below.

Low Laser Energy Mitigation

CALIOP began experiencing a significant number of intermittent low energy laser pulses starting in mid-2017, primarily over the South Atlantic Anomaly (SAA) region (Tackett et al. 2025). These low energy pulses degraded data quality in affected profiles and also impacted retrievals in 5-km columns containing low energy shots. In the V1.00 release of L3-ICE, low energy laser shots were rare and the V1.00 level 3 algorithm was not aware whether low energy shots were present or not. In the later years of the mission, however, low energy shots became more frequent, especially in the SAA, and impacts of low energy shots could no longer be ignored. The major difference between V2.00 and V1.00 level 3 cloud products is that the V2.00 algorithms are now aware of the application of a low energy mitigation (LEM) algorithm that was used in the production of all V5.0 level 2 products (Tackett et al., 2025). The LEM algorithm removes level 1 data affected by low energy from L2 processing in small, targeted segments to minimize data loss. The remaining data not excluded from L2 processing yields cloud (and aerosol) retrievals with similar quality as data in regions 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 a new LEM column QC flag. All L3 cloud products benefit from the L2 LEM algorithm and L2 profiles that are rejected by LEM are now excluded from L3 monthly aggregation.

Figure 3 compares daytime monthly zonal-mean extinction of the V1.00 and V2.00 products for January 2008. It can be seen that there are no major differences between the two versions. The largest differences are seen above 15 km altitude at high latitudes, regions which are dominated by polar stratospheric clouds (PSCs). **Error! Reference source not found.** shows the ratio (V2.00/V1.00) of annual mean ice cloud extinction in 2008 and 2021. It can be seen that mean differences are small and, in some places, are of different sign for night and day. In 2021, larger differences are seen near 30°S at latitudes where the SAA occurs.

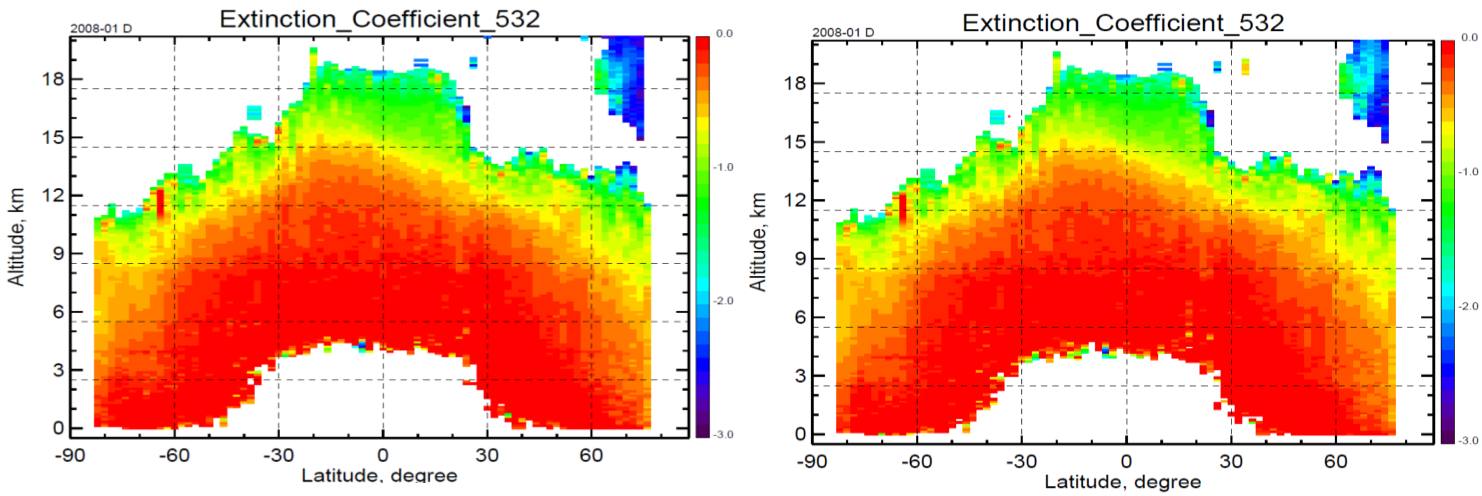

Figure 3: Comparison of V2.00 (left) and V1.00 (right) daytime zonal mean extinction for January 2008. Color bar indicates logarithm of the mean ice cloud extinction (/km).

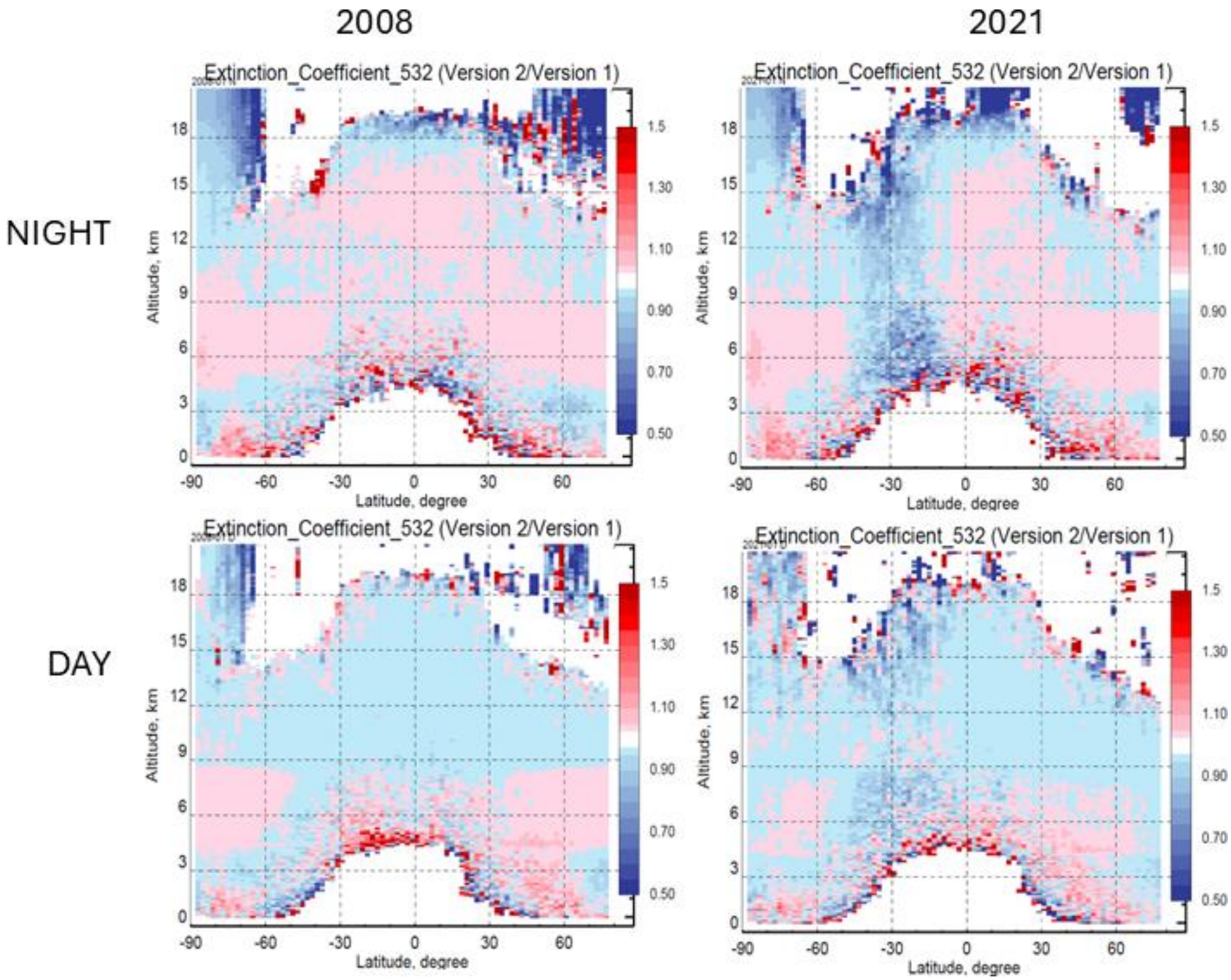

Figure 4: Comparison of V1.00 and V2.00 zonal mean ice cloud extinction for January 2008 and January 2021.

Figure 5 compares column IWP for January 2008 and January 2021 from V1.00 and V2.00 which more clearly shows the impact of low energy shots within the SAA. V2.00 is very similar to V1.00 in 2008. White areas indicating either no ice clouds detected or very few ice clouds are seen in the subtropics and are similar in both versions. But in 2008 there were very few low energy laser shots, while in 2021 there were orders of magnitude more. On average, 40% of the shots within the SAA in 2021 were low energy. Data in the V1.00 product was not screened for low energy shots and the 'no cloud' regions in 2008 and 2021 are similar. The large white region in 2021 V2.00 centered at 45°W is the result of the LEM algorithm screening out the low quality retrievals due to low energy shots.

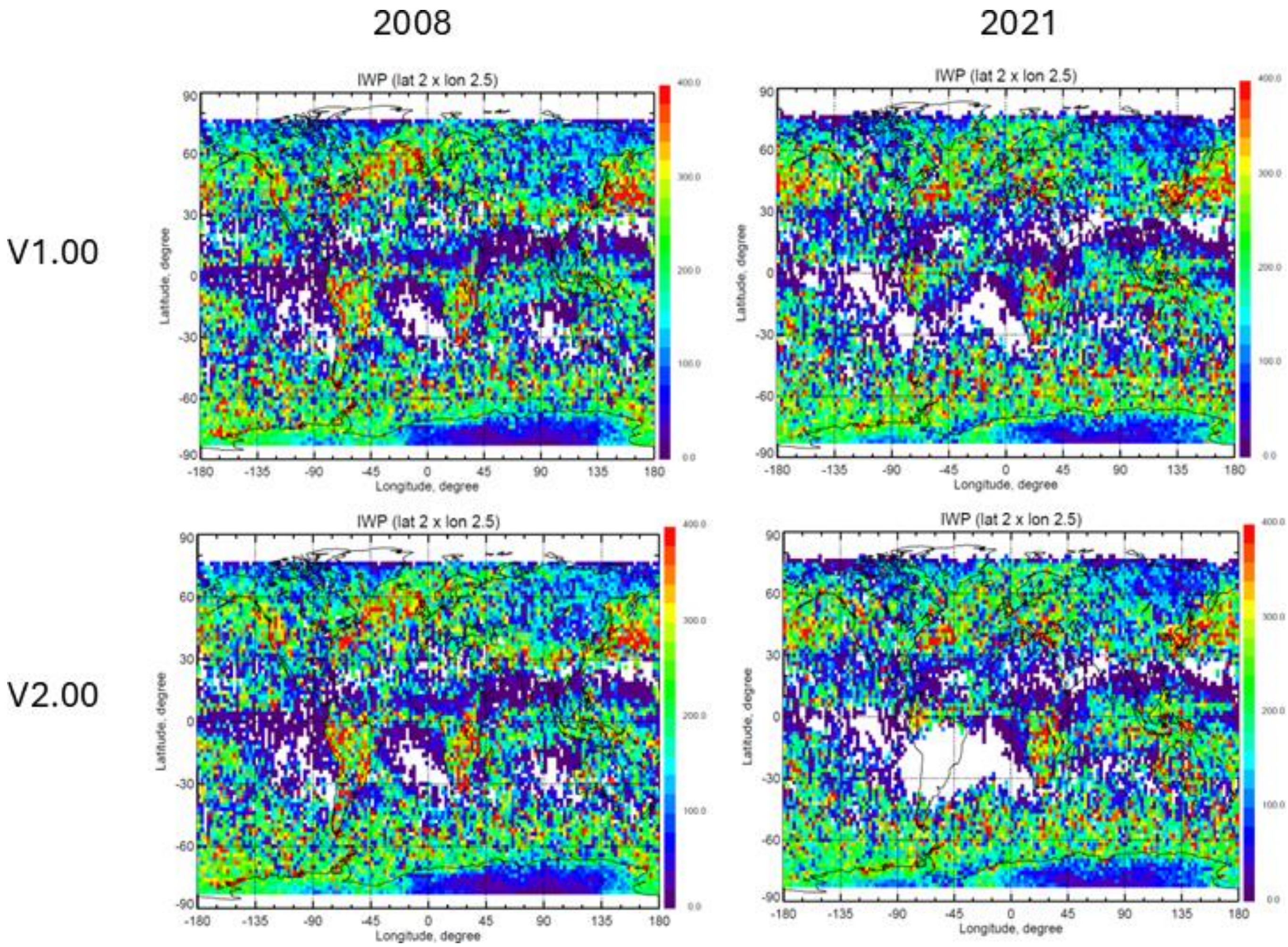

Figure 5: Comparison of V1.00 and V2.00 column IWP for January 2008 and January 2021.

<u>In-cloud IWC and Grid-averaged IWC</u>

In the lidar level ice cloud product, the median ice cloud extinction coefficient and median IWC in each monthly 3D spatial grid cell are reported as Extinction_Coefficient_532_Median and Ice_Water_Content_Median. Further discussion on the derivation of the IWC is summarized in V1.00 data quality summary section later in this document.

Figure 6 shows the time series of de-seasonalized monthly (day + night) global mean cloud occurrence and IWC profiles. The discontinuity near the end of 2007 between 6 km and 12 km is due to a change in the CALIOP view angle from 0.3° to 3.0°. Intermittent anomalies above 18 km are primarily due to the seasonal occurrence of PSCs in the polar regions.

Figure 7 shows the time series of monthly global mean ice water path (IWP), computed as the integral over latitude of monthly mean IWC shown in Figure 6. There is no significant non-zero trend throughout most of the mission. But there appears to be a slight increase in IWP starting around month 144, corresponding to the time when CALIPSO left the A-train and the CALIPSO orbit began to drift. Any upward trend here could, therefore, potentially be due to the orbit drift rather than an actual change in global IWP.

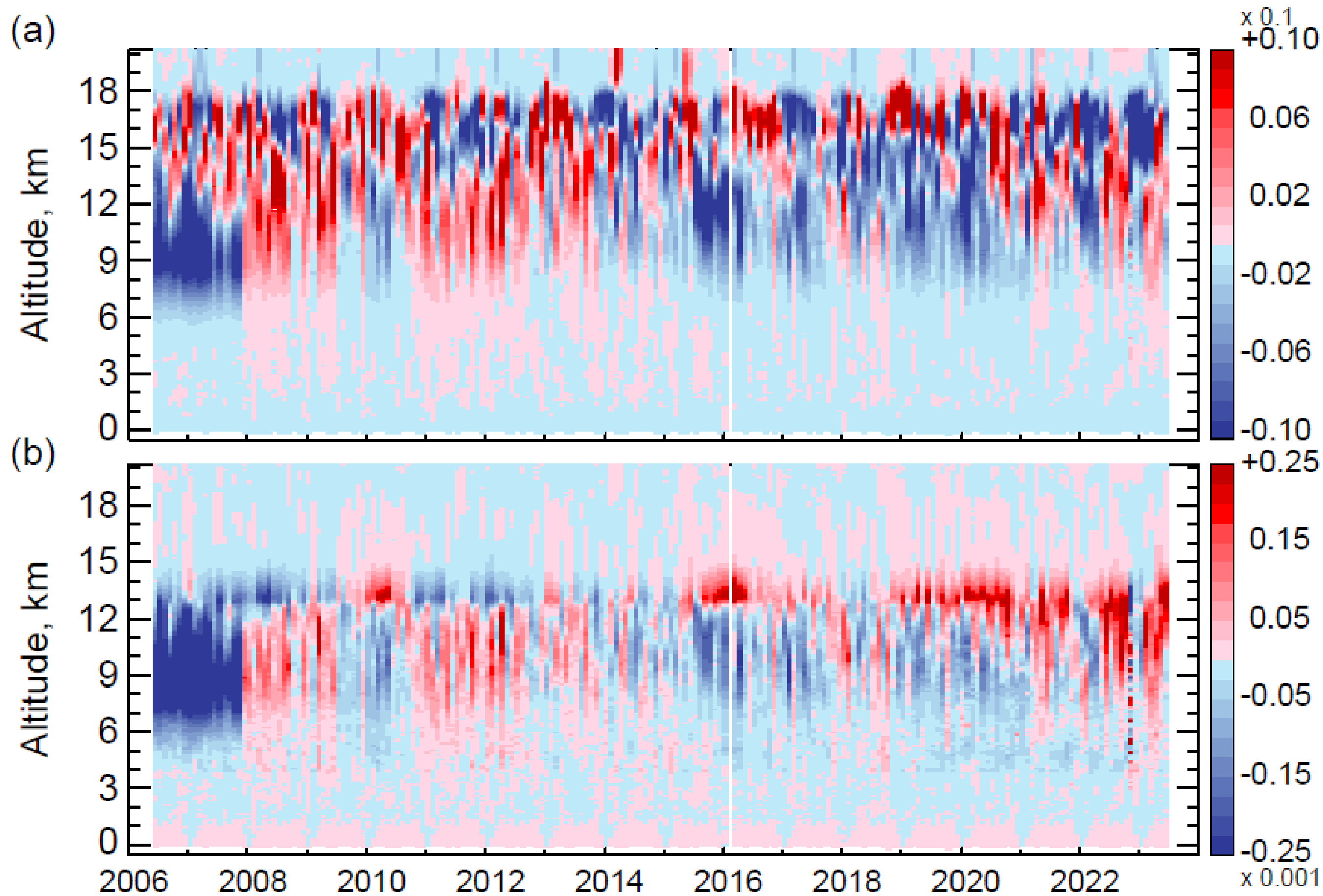

Figure 6: De-seasonalized time series of monthly global anomalies of a) ice cloud occurrence and b) IWC from June 2006 to June 2023. Color coding indicates relative variation from the mean with a range of ±2% for ice cloud occurrence and ±0.25 x 10-3 g/m3 for IWC. The blue regions below 12 km and prior to December 2007 show the impact of the different sensitivities of CALIOP to HOI at view angles of 0.3° (prior to December 2007) and at 3.0°.

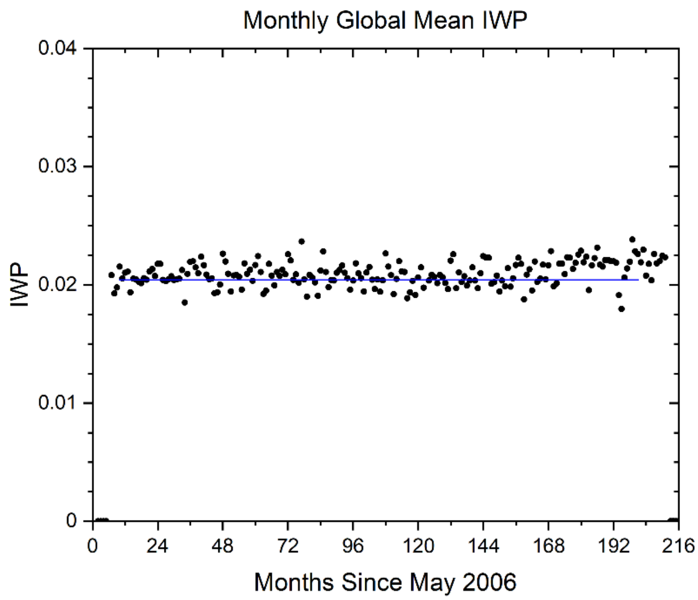

Figure 7: Time series of monthly global mean IWP over the length of the mission.

<u>Orbit Drift</u>

The CALIPSO orbit began to drift in 2019 after the orbit was lowered and the satellite ran out of fuel to perform orbit control maneuvers. As shown 8 and Table 5, mean local time (MLT) of the ascending node was tightly controlled to 13:45 from 2006 until the orbit lowering in September 2018 and began to drift after that. By the end of the mission, the MLT had drifted to about 15:30. As discussed in Noël et al. (ACP, 2018) studies of trends in the long-term cloud record should consider potential biases due the orbit drift aliasing the diurnal cycle into the long-term record.

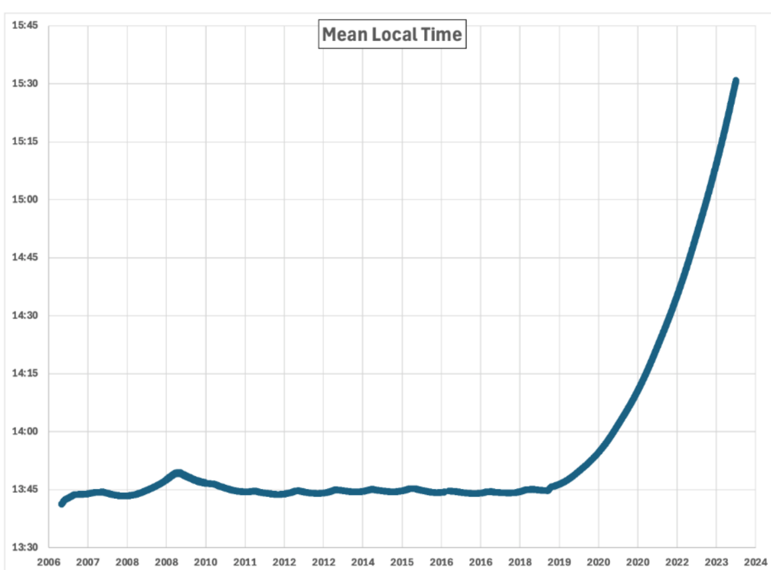

Figure 8: Mean local time of the equatorial crossing time (ascending node) over the CALIPSO mission.

Table 5: Mean local time of the equatorial crossing time (ascending node) over the CALIPSO mission.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006	-	-	-	-	-	13:42	13:43	13:43	13:43	13:43	13:43	13:44
2007	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:43	13:43	13:43	13:43	13:43
2008	13:43	13:43	13:43	13:44	13:44	13:44	13:45	13:45	13:45	13:46	13:46	13:47
2009	13:47	13:48	13:49	13:49	13:49	13:48	13:48	13:47	13:47	13:47	13:46	13:46
2010	13:46	13:46	13:46	13:46	13:45	13:45	13:45	13:45	13:44	13:44	13:44	13:44
2011	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:43	13:43	13:43	13:43
2012	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44
2013	13:44	13:44	13:44	13:45	13:45	13:44	13:44	13:44	13:44	13:44	13:44	13:44
2014	13:44	13:44	13:45	13:45	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44
2015	13:44	13:45	13:45	13:45	13:45	13:45	13:44	13:44	13:44	13:44	13:44	13:44
2016	13:44	-	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44
2017	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44	13:44
2018	13:44	13:45	13:45	13:45	13:45	13:44	13:44	13:44	13:44	13:45	13:46	13:46
2019	13:46	13:47	13:47	13:48	13:48	13:49	13:50	13:50	13:51	13:52	13:53	13:54
2020	13:55	13:56	13:57	13:58	13:59	14:01	14:02	14:04	14:05	14:06	14:08	14:10
2021	14:11	14:13	14:15	14:17	14:19	14:21	14:23	14:25	14:27	14:29	14:31	14:34
2022	14:36	14:39	14:41	14:44	14:47	14:49	14:52	14:55	14:58	15:01	15:04	15:08
2023	15:11	15:14	15:17	15:21	15:25	15:28	-	-	-	-	-	-

Data Quality Statement for the release of the CALIPSO Lidar Level 3 Ice Cloud Version 1 .00

The version 1.00 level 3 ice cloud product is processed from the V4.10 level 2 5 km cloud profile product.

In order to properly aggregate the statistics from the level 2 cloud profile product one must consider four different conditions within each 5 km column; cloud free, cloud, totally attenuated and lidar detected surface and/or subsurface. These different conditions are identified using the Atmospheric_Volume_Description parameter contained in the lidar level 2 product.

A “cloud free” region includes either clear sky or aerosol. A “cloud” region contains features classified as clouds prior to the application of any quality filters. Depending on the opacity of a 5 km column, i.e., feature type 7 (no signal, totally attenuated) present or not, the column can either have a “totally attenuated region” or “lidar detected surface/subsurface region”. If the column is opaque, the “totally attenuated region” spans altitudes from where the backscatter signal becomes totally attenuated to the low boundary of the vertical range, which is around - 0.5 km. Typically the start of the totally attenuated region is the apparent base of the lowest detected cloud layer. In this case, there is no lidar detected surface or subsurface region. On the other hand, if the column is transparent the lidar detected surface and subsurface region is from the surface, as detected by the lidar, to the low boundary of vertical range which is around -0.5 km.

For instances when clouds are detected in the column, the algorithm aggregates the cloud ice/water phase decoded from Atmospheric_Volume_Description parameter. The level 3 ice cloud product reports the number of clouds with phase classified as water, ice, or unknown/not determined prior to quality filtering. The number of ice cloud samples, Nice, includes both randomly orientated ice (ROI) and horizontally orientated ice (HOI).

If there are clouds in the column classified as ice, the algorithm then applies quality filters and rejects or accepts ice cloud samples depending on whether they pass the filters. Only the extinction coefficients and IWC of “accepted” ice clouds are used to compute the histograms and medians.

<u>Quality Filter Information</u>

A set of quality filters is used to select high confidence ice clouds with confident extinction retrievals. There are two types of filters: quality assurance (QA) filters and quality control (QC) filters. The QA filters are chosen to select ice clouds with high confidence in feature type and ice/water phase. The QC filters make sure only ’confident’ extinction retrievals are used.

<u>QA Filter Acceptance Criteria</u>

CAD Score Filter: accepted feature type confidence is low, medium, or high (featureQA = 1, 2, 3). This is equivalent to choosing clouds with CAD score between 20 and 100.

Cloud Phase Filter: Only ROI clouds with high phase confidence are accepted. The level 2 5 km cloud profile product reports cloud phase and confidence in 30 m bins, while extinction and IWC are reported at 60 m resolution. To account for these different bin sizes the algorithm requires that each of the two 30 m bins contained in the parent 60 m bin must be high confidence ROI, otherwise the entire 60 m bin is filtered out.

<u>QC Filter Acceptance Criteria:</u>

Extinction QC Flag Filter: Only extinction QC flag = 0, 1, 2, 16 or 18 are accepted. These representconstrained and unconstrained retrievals for both transparent and opaque clouds. Extinction QC flag values other than these are ignored since they indicate a greater likelihood of erroneously large or negative values, or that no solution was possible within allowable lidar ratio bounds. More information about this flag can be found on the Level 2 Cloud Profile Product Data Summary.

Extinction QC Uncertainty Filter: The extinction QC uncertainty must be less than 99.9 km^{-1} to ensure a convergent solution. An uncertainty of 99.9 km^{-1} is assigned by the retrieval algorithm when the extinction uncertainty estimate begins to diverge to infinity while iterating downward through the profile (i.e. high to low altitude). In this case the retrieval results become unreliable. Therefore, the filter excludes ice cloud samples having extinction uncertainty equal to 99.9 km^{-1}, as well as all samples below because the untrustworthy extinction solution is propagated to lower altitudes. All excluded ice clouds are counted as rejected ice cloud samples.

Overlying Optical Depth Filter: The overlying optical depth (OD) must be less than or equal to 2. As the signal propagates into the cloud from high to low (i.e. the altitude decreases), the signal gradually attenuates due to both the background atmosphere and any embedded features. The overlying optical depth increases as does the retrieval uncertainty. To reject highly uncertain portions of the extinction retrieval an overlying OD threshold 2 is set (see Winker et al. 2024). The overlying OD is derived by summing the 532 nm extinction coefficient over the defined vertical grid. The algorithm continually calculates the OD as it progresses downward. At the point at which the OD reaches the threshold value of 2, all ice cloud samples in the profile at that altitude and below are ignored and counted as rejected ice cloud samples.

Overlying Feature Filter: If an invalid feature (feature type = 0) or water cloud (feature type = 2 and ice/water phase = 2) is detected, based on feature information decoded from the Atmospheric_Volume_Description, then any ice cloud samples identified beneath the water cloud or invalid feature are considered suspicious and are rejected.

Figure 9 shows the impact of the quality filters on ice cloud occurrence. While the zonal patterns with/without filters look similar, the quality filters tend to reject many of the few ice clouds observed at low altitudes in the tropics and mid-latitudes.

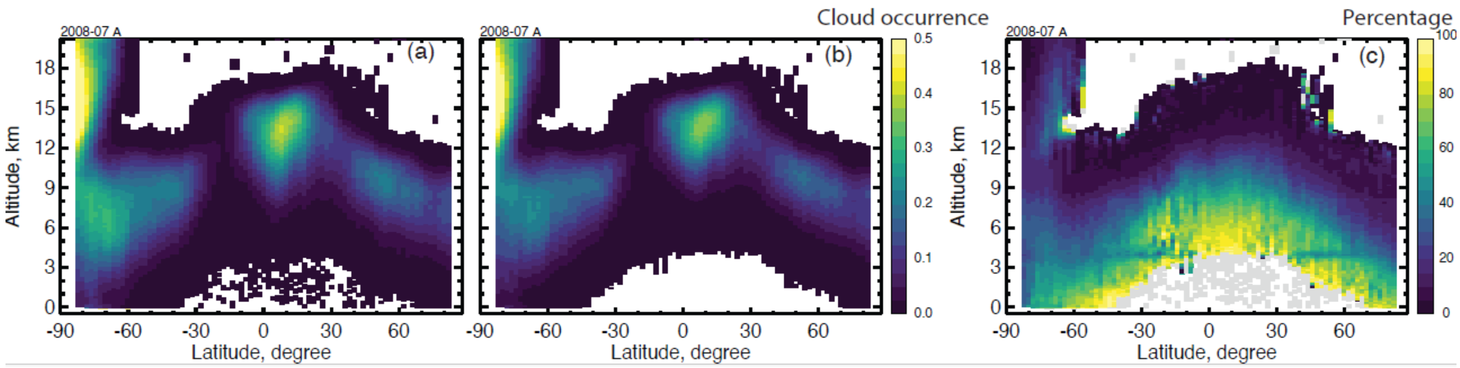

Figure 9: Zonal patterns of ice cloud occurrence frequency for July 2008 (night) before (a) and after (b) filtering. Cloud occurrence from 0 to 0.5 is coded in color. Panel (c) plots the percentage of samples removed by filtering, with gray representing 100% removal.

<u>Cirrus Fringe</u>

The tenuous edges of cirrus clouds were frequently misclassified as aerosol by the CALIPSO Cloud Aerosol Discrimination (CAD) algorithm in previous versions of the level 2 products. In the V4.10 level 2 algorithm, those misclassified aerosols are changed to ROI clouds with low feature confidence , “no confidence” phase, and a special CAD score of 106.

For the lidar level 3 ice cloud product these ice clouds with a CAD of 106 have been counted but are rejected and do not contribute to the cloud extinction and IWC statistics.

<u>Spatial Grids of Level 3 Tropospheric Aerosol and Level 3 Ice Cloud Products</u>

The spatial grid of level 3 ice cloud product is designed to be compatible with the level 3 tropospheric aerosol product. The spatial resolution for level 3 ice cloud product is 2.5° longitude by 2.0° latitude and 120 m altitude. For level 3 aerosol product, it is 5.0° longitude by 2.0° latitude and 60 m altitude. Both products use the same lower altitude boundary.

Figure 10 illustrates the vertical grid resolution and vertical range of the lidar level 2 aerosol/cloud profile product, the lidar level 3 tropospheric aerosol product, and the lidar level 3 ice cloud product. If a user is interested in combining the lidar level 3 tropospheric and ice cloud products, they can define a grid resolution, e.g, longitude

5.0° by latitude 2.0° by altitude 120 m, and then aggregate ice cloud information and aerosol information from their default grid resolutions to the new grid resolution.

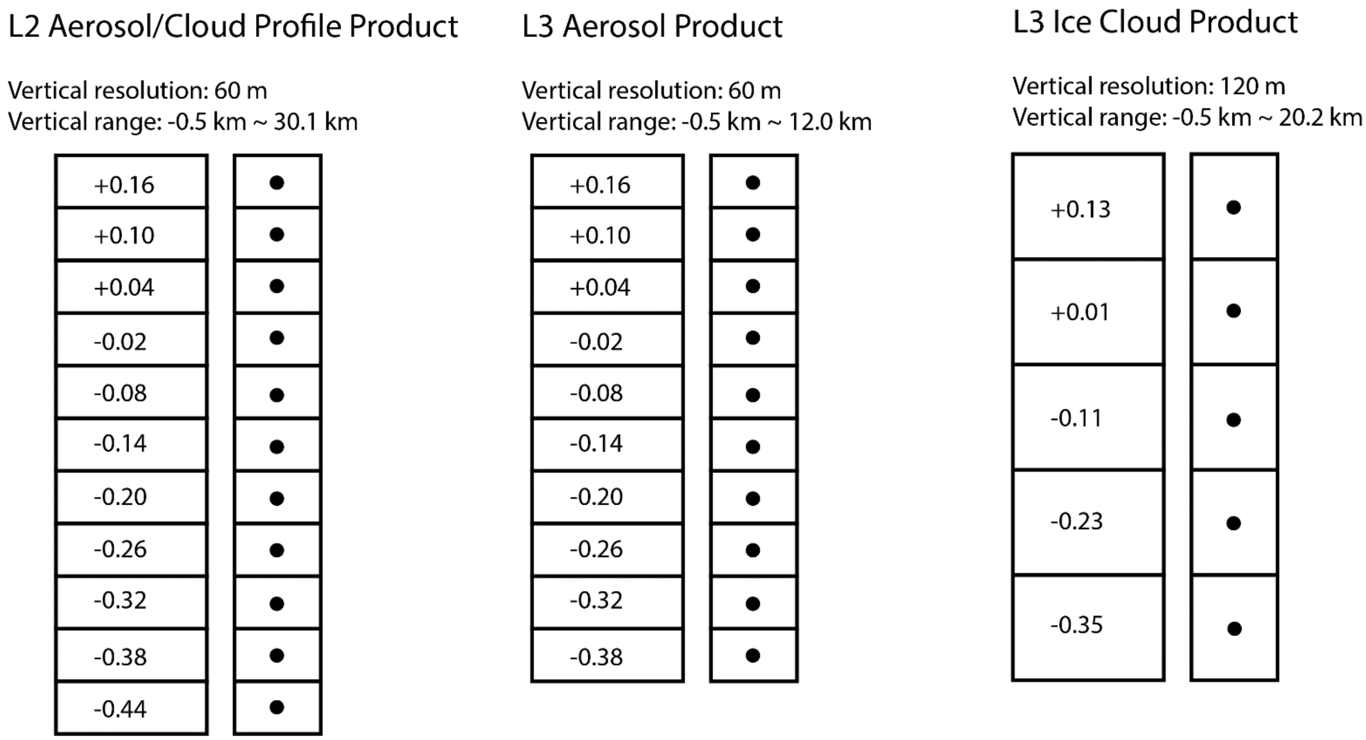

Figure 10: Vertical grid resolution and vertical range of level 2 aerosol/cloud profile product, level 3 tropospheric aerosol product and level 3 ice cloud product. The numbers on the left column of level 2 aerosol/cloud profile product are the lidar altitudes which are the centers of vertical bins. The dots on the right column show the center point. Similarly, the numbers on the left columns of level 3 product are the lidar altitude at the center points as shown as black dots on the right columns. Note the center of level 3 ice cloud product vertical grid is the center of every two neighboring vertical grids of level 3 tropospheric aerosol product.

<u>Histogram Bins</u>

In the level 3 ice cloud product, the ice cloud extinction coefficients retrieved from 532 nm channel and ice water content are described by two full histograms with 44 bins.

The histogram bin structure is specially designed to accommodate retrieved extinction coefficient and ice water content which spans several orders of magnitude. As shown in Table 6, among those 44 bins, 42 bins contain the nominal range of expected values from bin 2 to 43. Expected values for extinction coefficients are -0.1 km^{-1} to 10.0 km^{-1} and those for ice water content are between -0.01 g·m^{-3} and 1.0 g·m^{-3}. Negative and positive outliers are recorded in histogram bins 1 and 44, respectively. Small magnitude values with less confidence are stored in bin 17 and 18. The 40 bins (bins 2-16 and bins 19-43) are uniform in common logarithm space with base 10. Each bin size is 0.2, thus five bins represent 1 order of magnitude. Note the bin boundaries reported here are in linear scale thus they are not uniformly spaced. Negative extinction coefficients and ice water contents are expected within the distribution of level 2 retrieved solutions and are thereby included in the level 3 product to accurately represent the retrieved population in the level 2 data product.

Table 6: Histogram Bin Structures

bin number	extinction coefficient range (km^{-1})	IWC range ($g \cdot m^{-3}$)
1	$(-3.402 \times 10^{38}, -1.0 \times 10^{-1})$	$(-3.402 \times 10^{38}, -1.0 \times 10^{-2})$
2-16	$[-1.0 \times 10^{-1}, -1.0 \times 10^{-4})$	$[-1.0 \times 10^{-2}, -1.0 \times 10^{-5})$
17	$[-1.0 \times 10^{-4}, 0)$	$[-1.0 \times 10^{-5}, 0)$
18	$[0, 1.0 \times 10^{-4})$	$[0, 1.0 \times 10^{-5})$
19-43	$[1.0 \times 10^{-4}, 1.0 \times 10^{+1})$	$[1.0 \times 10^{-5}, 1.0 \times 10^{0})$
44	$[1.0 \times 10^{+1}, 3.402 \times 10^{38})$	$[1.0 \times 10^{0}, 3.402 \times 10^{38})$

Figure 11 shows the ice cloud extinction coefficient and IWC histograms at three altitude bins in the tropics, at night, in July 2008. The tropics are defined as a region between latitude 23.5° S to 23.5° N. The peak of the distribution at the highest altitude has a smaller extinction coefficient and ice water content. This suggests that the in-cloud extinction coefficient and IWC increase as the altitude decreases. The area of each distribution gives the number of observed ice clouds at that altitude range. Note that there are many more ice clouds observed between 13 km and 14 km than between 9 km and 10 km.

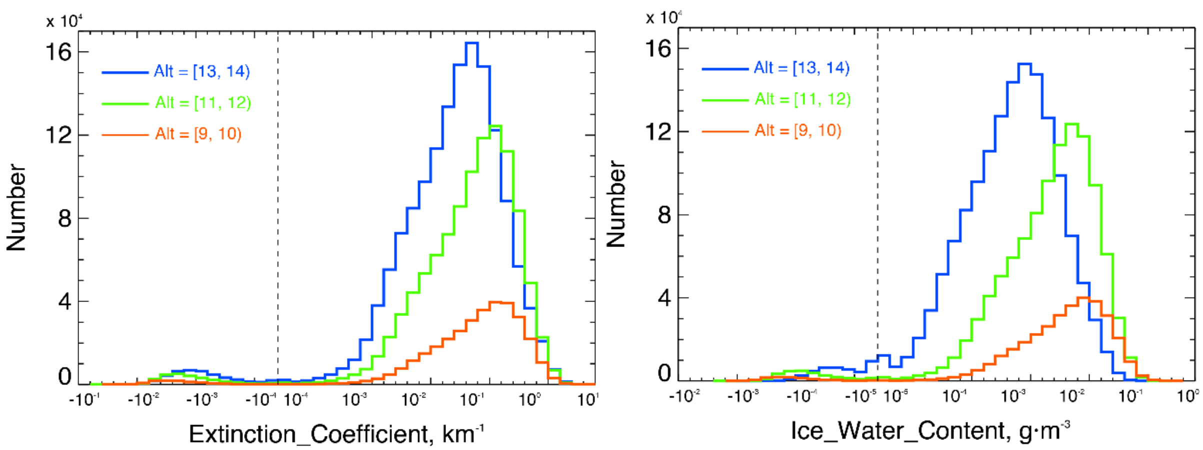

Figure 11: Histograms of ice cloud extinction coefficients and ice water content observed at three altitude ranges in the tropics. The X-axis is logarithmic. The Y-axis is linear. The vertical dashed line separates negative and positive values.

In-cloud IWC and Grid-averaged IWC

In the lidar level ice cloud product, the median ice cloud extinction coefficient and median IWC in each monthly 3D spatial grid cell are reported as Extinction_Coefficient_532_Median and Ice_Water_Content_Median. As explained above, there are 44 bins describing the full distribution of IWC. The valid range of IWC is from -0.01 $g \cdot m^{-3}$ to 1.0$\cdot$g m^{-3}. The first bin (bin 0) and the last bin (bin 43) are for IWC less than -0.01 $g \cdot m^{-3}$ and larger than 1.0 $g \cdot m^{-3}$. There are also two bins, 16 and 17, for IWC values whose absolute magnitudes are less than 10^{-5}, and are therefore typically less confident than larger values. These extreme small values are included when computing the median IWC. Note these two parameters report the median extinction coefficient and IWC within ice clouds, in other words, the in-cloud median values.

If a user is interested in calculating the mean in-cloud ice water content, it is recommended using this set of equations, with parameters Ice_Water_Content_Histogram, Ice_Water_Content_Bin_Boundary (middle boundary for example). Here the number of the accepted ice clouds is not exactly equal to Ice_Cloud_Accepted_Samples since we do not include small values or outliers in bin 0, 16, 17 and 43.

$$\overline{IWC_{in\_cloud}} = \frac{\sum Ice\_Water\_Content\_Bin\_Boundary \times Ice\_Water\_Content\_Histogram}{\text{Number of accepted ice clouds}}$$

$$= \frac{(\sum_{bin1}^{bin15} + \sum_{bin18}^{bin42})(Ice\_Water\_Content\_Bin\_Boundary \times Ice\_Water\_Content\_Histogram)}{(\sum_{bin1}^{bin15} + \sum_{bin18}^{bin42})Ice\_Water\_Content\_Histogram}$$

It may be necessary to consider ice cloud occurrence when deriving the grid-averaged ice water content. In this case, the occurrence of ice cloud in each monthly 3D grid cell is estimated as the ratio between number of accepted ice clouds (excluding outliers) with the sum of cloud and cloud free samples. The following set of equations can derive grid-averaged (ie: all-sky) IWC using the parameters Ice_Water_Content_Histogram, Ice_Water_Content_Bin_Boundary, Cloud_Samples and Cloud_Free_Samples:

$$\overline{IWC_{grid\_averaged}} = \frac{\sum Ice\_Water\_Content\_Bin\_Boundary \times Ice\_Water\_Content\_Histogram}{Cloud\_Samples + Cloud\_Free\_Samples}$$

$$= \frac{(\sum_{bin1}^{bin15} + \sum_{bin18}^{bin42})(Ice\_Water\_Content\_Bin\_Boundary \times Ice\_Water\_Content\_Histogram)}{Cloud\_Samples + Cloud\_Free\_Samples}$$

Figure 12 shows the in-cloud averaged IWC and grid-averaged (all-sky) IWC. As shown on the left, the in-cloud IWC increases as the altitude decreases and temperature increases. The grid-average IWC shows the influence of the changes in ice cloud occurrence. As altitude decreases, the grid-averaged IWC increases at first and then decreases with altitude as shown on the right of **Error! Reference source not found.**.

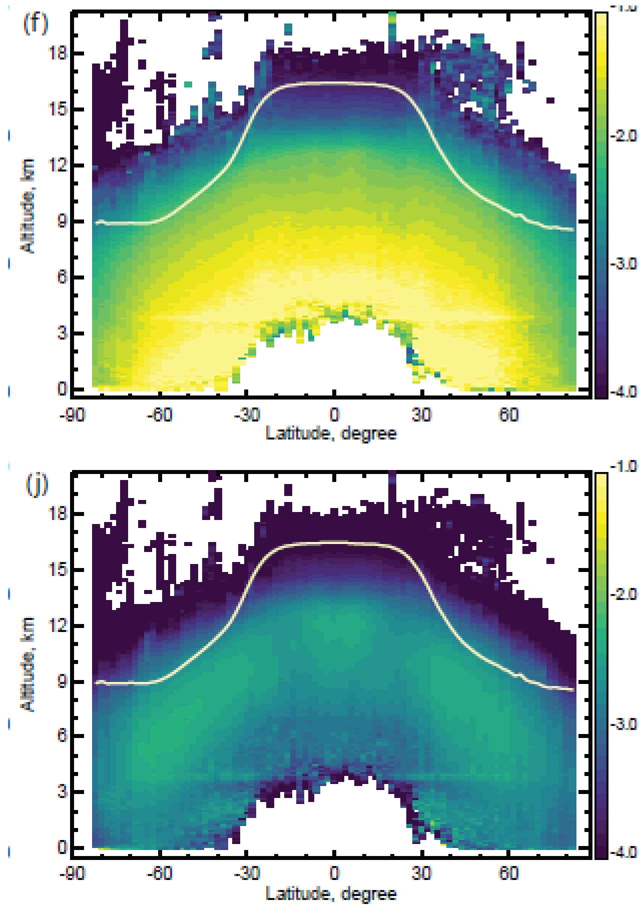

Figure 12: Nighttime annual zonal mean pattern of in-cloud averaged IWC (above) and grid-averaged IWC (below) for 2008. The latitude bin is 2° and the altitude bin is 120 m. The color bars are logarithmic, units are g·m-3. White lines indicate annual mean height of the tropopause.

<u>Excluded Profiles</u>

For a given 5 km profile (the fundamental resolution used by the level 2 data) there can be instances when there is clear-air throughout the entire column without a valid lidar detected surface (and no feature type 5 either). This occurs when the lowest cloud or aerosol layer in a 5 km profile touches the surface but fails to pass the surface thickness threshold test applied in the lidar level 2 algorithm. For these cases, the entire 5 km profile is excluded. These removed columns are added to the Number_of_Bad_Profiles parameter contained in the file. In July 2008 the occurrences of these bad profiles were about 0.08% during day and 0.007% at night.

<u>Processed Level 2 5 km Cloud Profile Product files</u>

Information on the number of Level 2 5 km Cloud Profile Product files aggregated into a monthly level 3 file is reported in the metadata as Number_of_Level2_Files_Analyzed. The list of those files is also provided in List_of_Input_Files. As shown in Figure 13, the number of processed day granules typically equals that of night granules in each month. Occasionally there would be one count off due to the possibility including the last granule from the previous month for processing either day or night granules. This granule has records for two consecutive days where some belonging to the previous month and some to the current month.

It can be noticed that there are no level 3 ice cloud product files in February 2016. During that month, the CALIPSO satellite was turned off due to a GPS clock problem.

In the metadata, a user can also find detailed information on the grid and on the filters in the Program_Configuration.

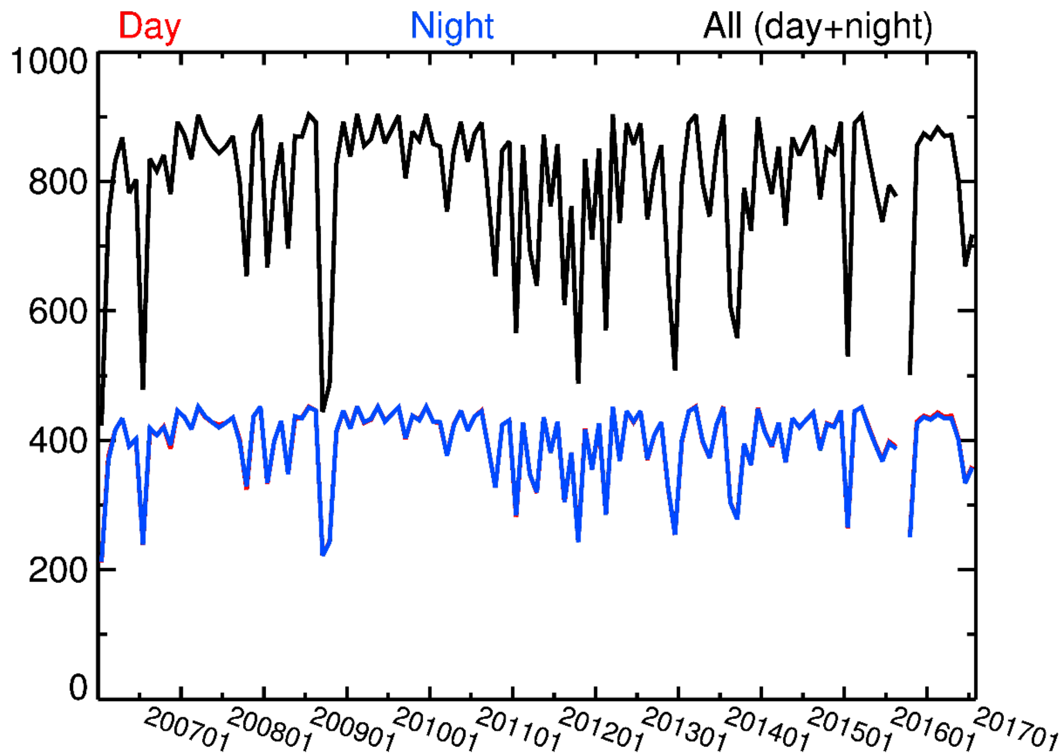

Figure 13: The number of processed level 2 5 km cloud profile product files for the standard V1.00 level 3 ice cloud product.

References

Tackett, J. L., R. A. Ryan, A. E. Garnier, J. Kar, B. Getzewich, X. Cai, M. A. Vaughan, C. R. Trepte, R. Verhappen, D. M. Winker and K.-P. A. Lee, 2025: Mitigating Impacts of Low Energy Laser Pulses on CALIOP Data Products, *EGUsphere* [AMTD], https://doi.org/10.5194/egusphere-2025-2376.

Winker, D., X. Cai, M. Vaughan, A. Garnier, B. McGill, M. Avery and B. Getzewich, 2024: “A Level 3 monthly gridded ice cloud dataset derived from 12 years of CALIOP measurements”, *Earth Syst. Sci. Data*, **16**, 2831–2855, https://doi.org/10.5194/essd-16-2831-2024.