

**NOAA NESDIS
CENTER for SATELLITE APPLICATIONS and
RESEARCH**

ALGORITHM THEORETICAL BASIS DOCUMENT

**AWG Cloud Cover Layer Algorithm
(CCL)**

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LIST OF ACRONYMS

ABI	Advanced Baseline Imager
ACHA	ABI Cloud Height Algorithm
ASSISTT	Algorithm Scientific Software Integration and System Transition Team
ARR	Algorithm Readiness Review
ATBD	Algorithm Theoretical Basis Document
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CCL	Cloud Cover Layer
CLAVR-x	Clouds from the Advanced Very High Resolution Radiometer (AVHRR) extended
CONUS	Continental US
FL	Flight Level
F&PS	Function and Performance Specification
GOES	Geostationary Operational Environmental Satellite
JPSS	Joint Polar Satellite System
NOAA	National Oceanic and Atmospheric Administration
NOAT	NWS Operational Advisory Team
VIIRS	Visible Infrared Imager Radiometer Suite

Abstract

The Cloud Cover Layer (CCL) retrieval algorithm derives cloud fraction at a predefined spatial resolution and between specified cloud layers. It also retrieves total cloud fraction from surface to top of the atmosphere at the same resolution. It mainly utilizes cloud mask and cloud top products from upstream cloud mask and height algorithms to derive CCL information. Consistent with the FP&S requirement, CCL products include 6 cloud fractions, including total fraction and 5 cloud layer fractions at predefined flight levels (SFC-FL050, FL050-FL100, FL100-FL180, FL180-FL240, and FL240-TOA). The horizontal resolutions for those fractions are 10km for full disk and CONUS, and 4km for mesoscale. The results are validated against CALIPSO/CALIOP.

1 INTRODUCTION

1.1 Purpose of This Document

The purpose of this Algorithm Theoretical Basis Document (ATBD) is to establish guidelines for producing and using the cloud cover layer (CCL) products for the Advanced Baseline Imager (ABI) sensor onboard the Geostationary Operational Environmental Satellite-16 (GOES-16) satellite. This document can also be used as a reference for the Joint Polar Satellite System (JPSS) Visible Infrared Imager Radiometer Suite (VIIRS) CCL products. However, note that JPSS CCL products use additional information such as cloud base and multilayer cloud flags, and will include additional products for supercooled water and convective clouds.

1.2 Who Should Use This Document

The intended users of this document are those interested in understanding the theoretical basis of the CCL algorithm and how to use the CCL products.

1.3 Inside Each Section

This document is broken down into the following main sections:

- System Overview: provides relevant details of the ABI sensor and provides a brief description of the products generated by the algorithm.
- Algorithm Description: provides a detailed description of the algorithm including its physical basis, its input and output.
- Assumptions and Limitations: provides an overview of the current limitations of the approach.

1.4 Related Documents

The CCL products are downstream products of the ABI Cloud Height Algorithm (ACHA). Its performance is also dependent on the cloud mask products. For the physical basis of these upstream cloud products, refer to their ATBDs.

1.5 Revision History

The initial version was created and delivered to the Center for Satellite Applications and Research (STAR) Algorithm Scientific Software Integration and System Transition Team (ASSISTT) in September 2018. It was created to accompany the delivery of the algorithm for the GOES-16 ABI sensor to the NWS Operational Advisory Team (NOAT).

2 OBSERVING SYSTEM OVERVIEW

The ABI sensor is the primary sensor onboard the National Oceanic and Atmospheric Administration's (NOAA) GOES-16 satellite. It observes the earth with 16 spectral bands and spatial resolutions of 0.5 to 2km. The ABI instrument has two scan modes and the default mode concurrently takes a full disk, the Continental US (CONUS), and mesoscale images at different temporal resolutions. This section describes the products generated by the ABI CCL algorithm.

2.1 Products Generated

The CCL algorithm provides an estimation of the cloud fraction between predefined cloud levels, as well as the total cloud fraction at a specified spatial resolution. The cloud levels can be flight levels (FLs) or pressure levels, and the number of levels vary (Figure 1). The original baseline requirement using a boundary of 680hPa and 440hPa is based on the International Satellite Cloud Climatology Project (ISCCP) classification of low, middle, and high clouds. The NOAT requirement increases the number of layers from 3 to 5. The 5 layers are from surface to FL at 5,000 ft (SFC-FL050), from FL at 5,000 ft to 10,000 ft (FL050-FL100), from FL at 10,000 ft to 18,000 ft (FL100-FL180), from FL at 18,000 ft to 24,000 ft (FL180-FL240), and from FL at 24,000 ft to top of the atmosphere (FL240-TOA). The horizontal spatial requirements are 10km for full disk and CONUS, and 4km for mesoscale. The output data are generated at 60-minute intervals for full disk and CONUS, and 5-minute for mesoscale. The algorithm also produces a cloudy/clear layer flag at pixel level for each layer. The layer flag is stored using bit structure in a one byte number. This algorithm is applicable to single layer clouds for the ABI products using cloud top only information. For JPSS, additional products will be available including convective and supercooled cloud fractions at each layer. Additionally, cloud base information is used.

NWS NOAT Guidance		NCEP Modification to Baseline		Original Baseline	
NOAT		NCEP		ISCCP	
TOA	_____	TOA	_____	TOA	_____
	Layer 5				
24 kft	_____				
	Layer 4	350 hPa	_____	440 hPa	_____
18 kft	_____				
	Layer 3				
10 kft	_____	700 hPa	_____	680 hPa	_____
	Layer 2				
5 kft	_____				
	Layer 1				
SFC	_____	SFC	_____	SFC	_____

Figure 1. Three varying definitions of cloud layers based on flight level (NOAT), and cloud top pressure (original baseline and NCEP modification).

The operational algorithm requirements for CCL products by NOAT are summarized in Table 1. It is important to note that the original accuracy requirement for the 3 layer baseline product is 80% correct classification. However, as the number of layers increase, more data tend to fall outside the correct classification bin. As flight level is derived from cloud top pressure (CTP) as will be discussed in 3.4.2.1, a simulation study is carried out using the ABI CTP specs requirements (Accuracy 50hPa, Precision 150hPa, for all clouds with emissivity > 0.8). The method employed is to generate a large number of data and add perturbation using CTP specs to the data. The correct classification ratio is then computed by dividing the number of data points within predefined levels after perturbation to the total number of points. The simulation study

reveals that the mean correct classification ratio decreases by 20% when the number of levels increase from 3 to 5. Therefore, the new specs requirement is reduced from 80% to 60% accordingly.

Table 1. CCL NOAT product requirement

Satellite Source (s)	GOES-16
Product Name	Cloud Cover Layers
Accuracy	60% Correct Classification for unobscured fraction in each layer
Latency	806 seconds (266 seconds for mesoscale)
Refresh	60 minutes (5 minutes for mesoscale)
Timeliness	See Latency
Coverage	Full Disk, CONUS, mesoscale
Horizontal Resolution	10 km (4 km for mesoscale)
Other attributes	6 Cloud Layers at predefined flight levels (total, SFC-FL050, FL050-FL100, FL100-FL180, FL180-FL240, FL240-TOA).

2.2 Instrument Characteristics

The CCL algorithm operates on a domain determined by the sensor resolution and coverage of data. It reads in cloudy and clear pixel flags produced by the Cloud Mask algorithm. It also relies on products from the ACHA algorithm. Since CCL is estimated from derived products and not from direct radiance measurements, there is no direct impact from the instrument design and channel characteristics.

2.3 Product Requirements

Because the estimation of CCL products requires cloud mask and height, the requirements for CCL are driven by upstream cloud mask and height algorithms, as shown in Table 2.

Table 2. CCL Product Input Requirements

Attribute	Threshold	Objective
Cloud Mask	Cloud mask ATBD Specs	Cloud mask ATBD Specs
Cloud Top Pressure	CTP ATBD Specs	CTP ATBD Specs

3 ALGORITHM DESCRIPTION

3.1 Algorithm Overview

The NOAT CCL algorithm provides information on the cloud fraction between predefined FLs. The cloud cover layer fraction is defined as the fraction of cloudy region at a horizontal resolution of 10km for full disk/CONUS and 4km for mesoscale. For total fraction, cloud mask flag, a cloud mask product, is used to compute the fraction occupied by clouds. Pixels classified as cloudy or probably cloudy are considered cloudy in CCL computation. For layer fractions, cloud top products from ACHA are used to determine the layer where clouds are present. CCL algorithm requires no further information than ACHA has. The NOAT CCL algorithm has no specific mode. However, the JPSS CCL algorithm provides options of different modes to support the use of cloud base and multilayer information. The algorithm derives the following products:

- Total cloud fraction

- Layer cloud fraction

- Cloud layer flag

3.2 Processing Outline

The processing outline of CCL computation is demonstrated in Figure 2. The NOAT ABI CCL algorithm is implemented within the ASSIST processing framework (FRAMEWORK) for GOES-16. FRAMEWORK routines are used to provide all of the observations and ancillary data.

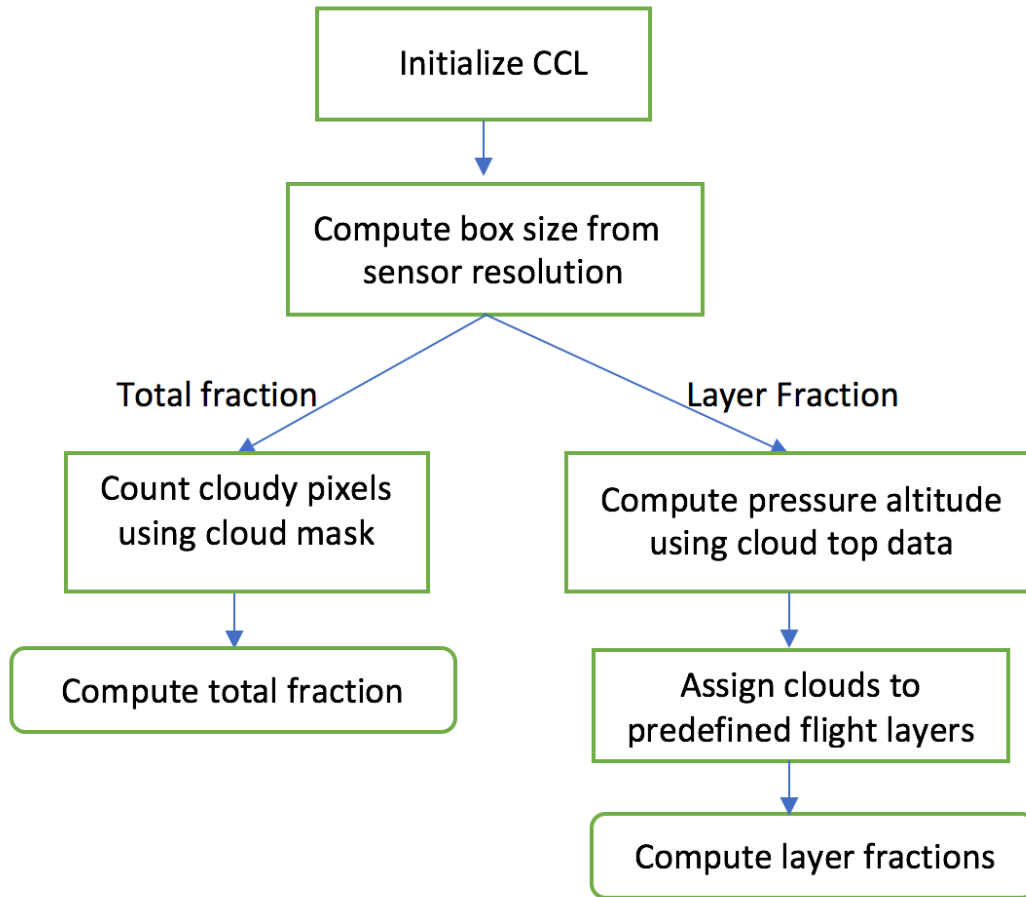


Figure 2. A flowchart of the CCL algorithm showing the computation of total and layer cloud fractions.

3.3 Algorithm Input

This section describes the required input data for the CCL algorithm.

3.3.1 Primary Sensor Data

The primary sensor input data includes sensor resolution and data quality flags.

3.3.2 Derived Data

- Cloud mask

A cloud mask is required to determine if a pixel is cloudy/clear to calculate total cloud fraction. This information is provided by the ABI baseline cloud mask algorithm.

- Cloud top pressure

Cloud top pressure, a product from the ACHA algorithm, is needed to estimate the cloud altitude to place the cloud in the appropriate layer. Cloud altitude has the same meaning as flight level in this document and will be used interchangeably.

- Cloud base pressure

Cloud base pressure is not needed for retrieving NOAT CCL but a required input for the JPSS CCL algorithm.

- Lower level cloud pressure

Similar as cloud base pressure, lower level cloud information is not required for the NOAT CCL product.

3.3.3 Dynamic Ancillary Data

Dynamic ancillary data such as NWP profiles and surface temperature are needed for the ACHA algorithm but not required in CCL.

3.4 Theoretical Description

This section describes the approach for estimating the CCL products.

3.4.1 Physics of the Problem

As discussed earlier, the computation of cloud cover layer fraction relies on preceding cloud mask and height algorithms. Provided cloud mask and ACHA data as inputs, computing CCL fractions is mainly a mathematical problem.

3.4.2 Algorithm Description

The logic of computing fractions is straightforward. The algorithm first computes the box size, determined by the sensor resolution and product resolution. The binary cloud/clear flag from the baseline cloud mask algorithm is used to compute the total cloud fraction. For layer cloud fraction, the cloud is placed between two FL levels based on ACHA inputs, and then layer cloud fraction is derived similarly by computing the fraction of clouds in the box. The steps for the computation of both total and layer cloud fractions are as follows:

- Compute box size based on sensor resolution and retrieval horizontal coverage;
- Convert cloud top pressure to flight level for each cloudy pixel;
- Classify each cloudy pixel into 1 of N layers, where N is 5 here; meanwhile, write layer information to the bit structure of the cloud layer flag;
- Iterate over all boxes, count the number of cloudy pixels for total and individual layers, and compute cloud fractions using the following formula

$$Fraction = N_{cloudy}/N_{total} \quad (1)$$

3.4.2.1 Converting cloud top pressure to flight level

In converting cloud top pressure to flight level, empirical coefficients are used (Table 3). Here, a comparison between the rigorous and empirical approaches are presented.

The hydrostatic equilibrium equation is

$$\frac{dp_c}{dz} = -\rho g \quad (2)$$

where P_c is pressure, z is height, ρ is air density, and g is acceleration of gravity. Assuming T_0 and P_0 , which are the atmospheric temperature and pressure at sea level with values of 288.15K

and 1013hPa, γ the atmospheric lapse rate (-6.5K/km), and R the specific gas constant of the air ($287 \text{ J} \cdot \text{kg}^{-1} \text{K}^{-1}$), the geopotential height of the cloud, Z, can be expressed as

$$Z = \frac{T_0}{\gamma} \left(\left(\frac{p_c}{p_0} \right)^{\frac{-\gamma R}{g}} - 1 \right) \quad (3)$$

The empirical formula currently adopted is Sarah Monette's approximation from NASA's HS3 campaign, where the coefficients are listed in Table 3:

$$Z = \begin{cases} \left(1 - \left(P_c / P_0 \right)^{LR_over_G} \right) * Z_0, & \text{if } P_c \geq PW1 \\ LN_1 * \log(P_c) + LN_2, & \text{if } P_c < PW1 \text{ and } P_c > PW2 \\ PN_4 * P_c^4 + PN_3 * P_c^3 + PN_2 * P_c^2 + PN_1 * P_c + PN_0, & \text{if } P_c < PW2 \text{ and } P_c > PW3 \\ missing & \text{if } P_c < PW3 \end{cases} \quad (4)$$

Table 3 Coefficients used to convert cloud top pressure to flight level

Coefficients	Values
PW1	227.9
PW2	56.89
PW3	11.01
P ₀	1013.25
LR_OVER_G	0.190263
Z ₀	145422.16
LN ₁	-20859.0
LN ₂	149255.0
PN ₄	0.000470034
PN ₃	-0.364267
PN ₂	47.5627
PN ₁	-2647.45
PN ₀	1238.42

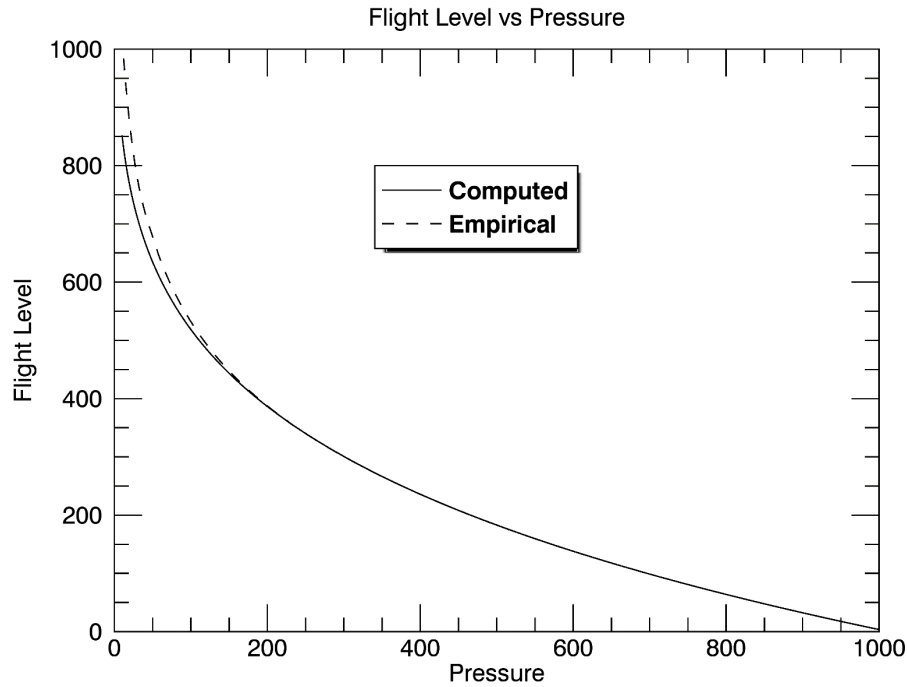


Figure 3. Computed flight level as a function of pressure. The solid line is based on the rigorous approach, and the dashed line shows the empirical method employed.

Figure 3 shows flight level as a function of atmospheric pressure, computed from both the rigorous approach (Eqn 3) and empirical approach (Eqn 4) with coefficients in Table 3. The figure shows that the two methods only diverge at heights above 200hPa and FL400, which is higher than the upper most FL required by the NOAT.

3.4.3 Algorithm Output

3.4.3.1 Output

The CCL algorithm creates the following products:

- Total cloud fraction
- Cloud fraction at each FL

All of these products are derived at predefined resolutions: 10km for full disk and CONUS, and 4km for mesoscale. Example images are provided in Section 4.

Additionally, cloud layer flag, which is an 8-bit integer used to indicate whether a pixel is cloudy or clear in each FL, is an intermediate product. Cloudy pixels are assigned a value of 1 whereas clear pixels are assigned a value of 0. The first bit corresponds to the lowest layer and the layer increases upward as bit position moves left. Figure 4 shows an example of a clear box as well as a situation where a single layer cloud is identified in layer 3.

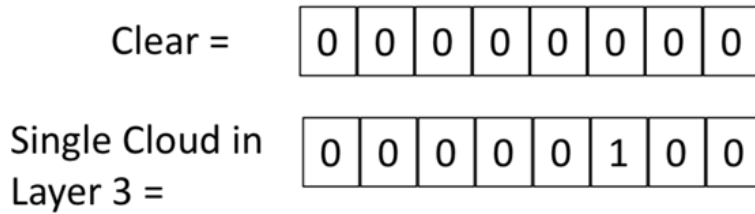


Figure 4. Illustration of cloud layer flag defined using a byte number. Cloudy and clear pixels are assigned 1 and 0, respectively. The first bit denotes the lowest layer and increases upwards as bit position moves left.

In the NOAT delivery, only unobscured single layer cloud top information is used to compute the cloud position. Therefore, a cloudy flag can only exist in one layer. In the JPSS CCL products, cloudy flags can occupy multilayers. For instance, if cloud base height is used to determine the vertical extent and the cloud base extends into other layers, all the layers in-between will be flagged as cloudy. If obscured clouds are used but not the cloud base, multi-discontinuous layers can be flagged as cloudy.

3.4.3.2 Product Quality Flag

There is currently no quality flag for CCL cloud fraction. However, cloud layer flag shares the same quality flag as ACHA products.

4 TEST DATASETS AND OUTPUT

4.1 Validation Overview

As CCL is computed using cloud mask and cloud top properties, validation of CCL products is essentially validation of cloud mask and ACHA products. Currently the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) products are adopted as validation datasets for CCL. As cloud mask is employed to compute the total fraction, and cloud mask validation is discussed in its own ATBD, the focus here is on layer cloud fraction.

4.1.1 ABI CCL Data

At the time of this document's preparation, the Algorithm Readiness Review (ARR) has been completed. CCL products are not yet operational. Therefore, one month of data from 03/17/2018 to 04/16/2018 were generated from FRAMEWORK and NOAA's Clouds from the Advanced Very High Resolution Radiometer extended (CLAVR-x) systems separately. The whole month of data was used for the validation.

Figure 5 shows an example of GOES-16 cloud top pressure and the derived cloud top altitude. In the cloud altitude image, the red and pink regions indicate clouds located in high altitudes and match well with the pressure image (high clouds in white). In Figure 6, total cloud fraction and layer fraction in 5 FLs are plotted. It provides a clear view of how clouds are distributed in different layers. Note that the sum of layer cloud fractions is not always equal to the total cloud fraction. This is because they are based on ACHA and cloud mask products separately. If a

cloudy mask is reported but ACHA fails to yield a valid retrieval, the sum of layer cloud fraction tends to be less. On the other hand, if cloud base and/or multilayer clouds are considered in estimating CCL, cloudy regions can be observed from different layer images over the same location.

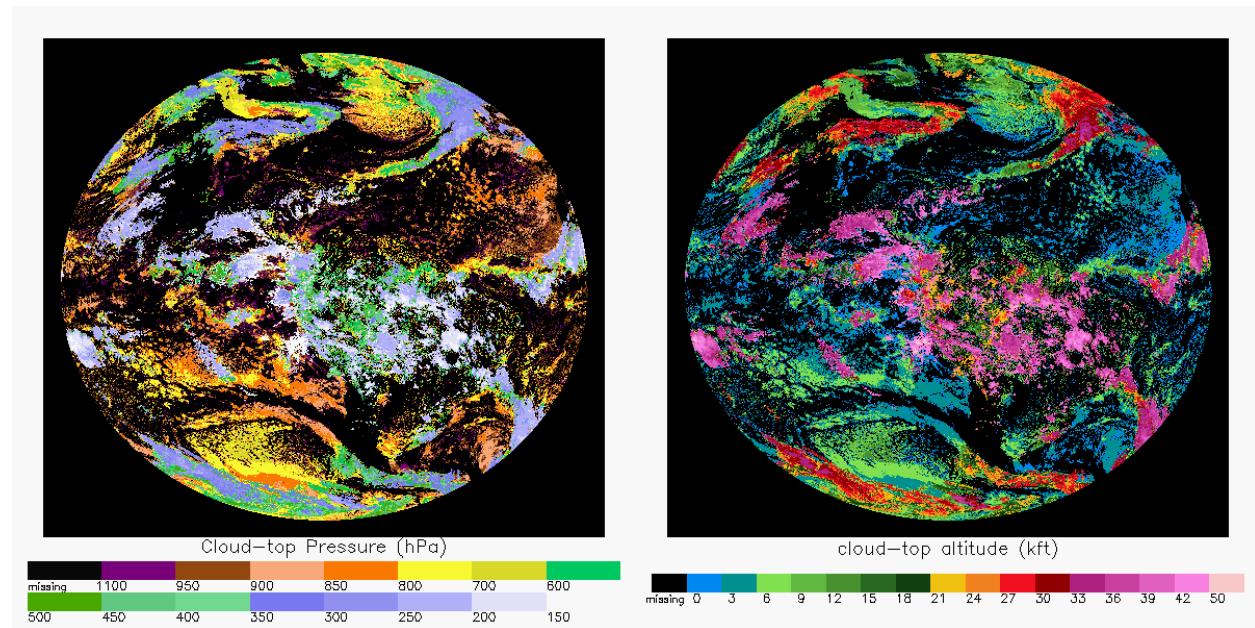


Figure 5. Retrieved GOES-16 ABI cloud top pressure (left) and cloud top altitude (right) for 1800 UTC on March 17, 2018.

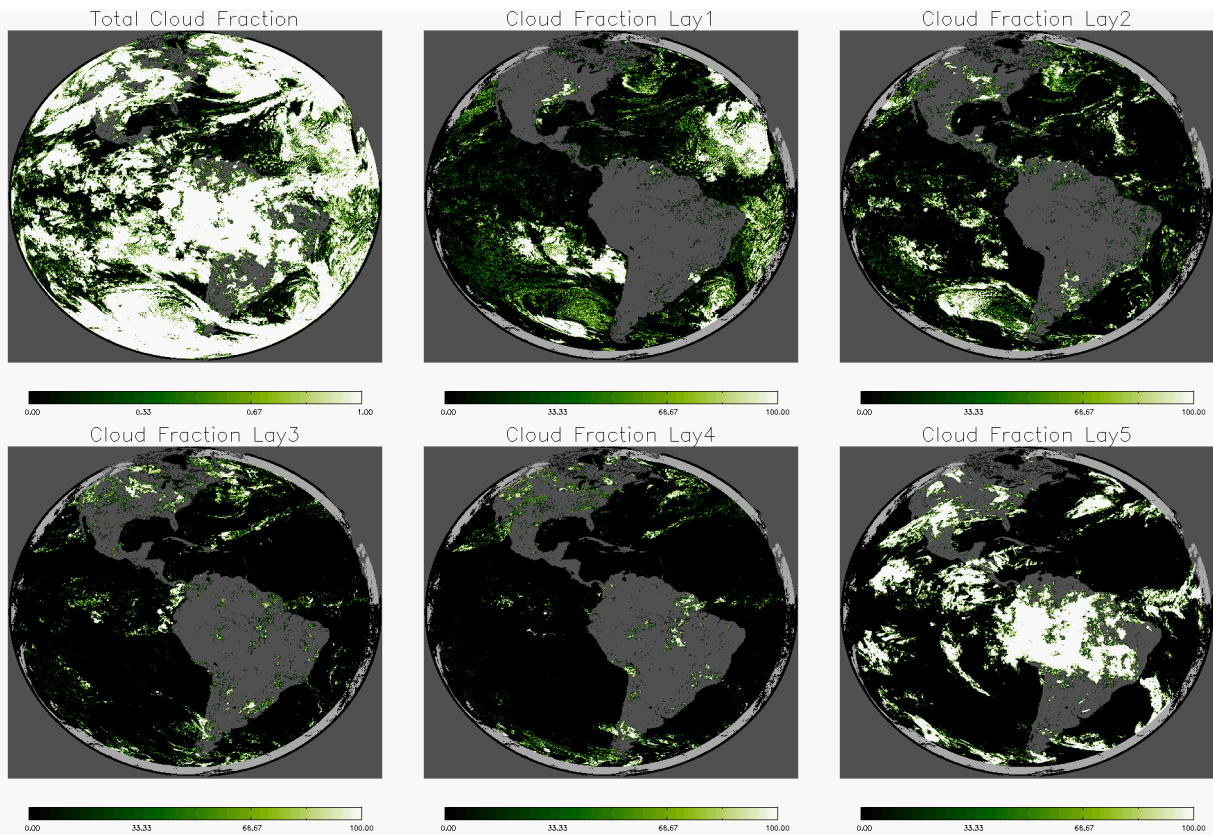


Figure 6. Illustration of cloud cover layer fraction using the same granule as in Figure 5. Top from left to right: total cloud fraction, cloud fraction at surface to FL50, FL50 to FL100; bottom from left to right: cloud fraction at FL100 to FL180, FL180 to FL240, FL240 to TOA. White region mean cloudy and green is for clear.

4.1.2 CALIPSO Data

The CALIPSO satellite was launched in 2006 and is still in operation. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor onboard CALIPSO is an active lidar system. The CALIOP observations provide vertical cross sections of the atmosphere and can accurately report the position of clouds. Currently, CALIPSO/CALIOP cloud layer products are used for CCL validation purposes.

4.2 Validation Procedures

CALIPSO/CALIOP only has data along its track, whereas CCL cloud fractions are statistical quantities over a region, so it is impossible to directly compare the two. However, since CCL fractions are derived from ACHA products, it is reasonable to validate the cloud top products and this can be done at the pixel level. Instead of directly comparing cloud top products, such as cloud top height/temperature/pressure, as described in the ACHA ATBD, the derived FLs are compared.

The goal of the validation is to find out the correct classification ratio and compare with the specs requirement. Percentages of correct classifications pixels within predefined FL are computed using the formula

$$Percentage = \frac{N_{corr}}{N_{all}} \times 100\% \quad (5)$$

where N_{corr} is the number of pixels with passive and active retrievals in agreement in the predefined FLs, and N_{all} is the total number of pixels.

4.2.1 Matching GOES-16 and CALIPSO

Both 1km and 5km CALIPSO/CALIOP cloud layer products were utilized in the analysis. This takes advantage of the high resolution of 1km data and better cirrus detection from the 5km data. GOES-16 and CALIPSO/CALIOP data are collocated along the CALIPSO track by limiting temporal difference to less than 12min and spatial separation to less than 500km. The collocations are done twice using both 1km and 5km data and the matchup files are then combined.

4.2.2 CALIPSO Analysis

Figure 7 presents the comparisons using ABI data from both FRAMEWORK and CLAVR-x. By definition, all pixels located in the five boxes along the diagonal line are correctly identified. It is clear that the majority of pixels meets the requirements. Due to mismatched cloud phases, specifically ice phase clouds reported as water cloud in ABI, a number of pixels underestimating CTP and hence FL, are observed. This is because the cloud phase algorithm is upstream of ACHA. Note that though FRAMEWORK and CLAVR-x are based on different phase algorithms, the two systems suffer from the same issue. When cloud phase matchings are applied, the validation performances improve significantly (Figure 8).

4.2.3 Error Budget

As discussed earlier, the original requirement for correct classification for unobscured clouds has been changed from 80% to 60%. The validation results presented here are based on the new requirement. Table 4 shows the correct classification rates. It is evident that CCL performance meets the specs when assessing 5 FLs combined, regardless of cloud phase matching. In Table 5, this percentage is computed for each individual FL. The performances tend to meet the specs requirement for lower and highest FLs. This is due to 1) tighter intervals for middle level clouds, and 2) outliers from both low and high FLs can affect the middle layer performance. However, since most data points are located at low and high FLs (Figures 7 and 8), the general CCL performance meets the NOAT requirement. It should also be emphasized that the ACHA algorithms used in FRAMEWORK and CLAVR-x are not the same (Baseline vs Enterprise), so the differences shown in the two systems are reasonable.

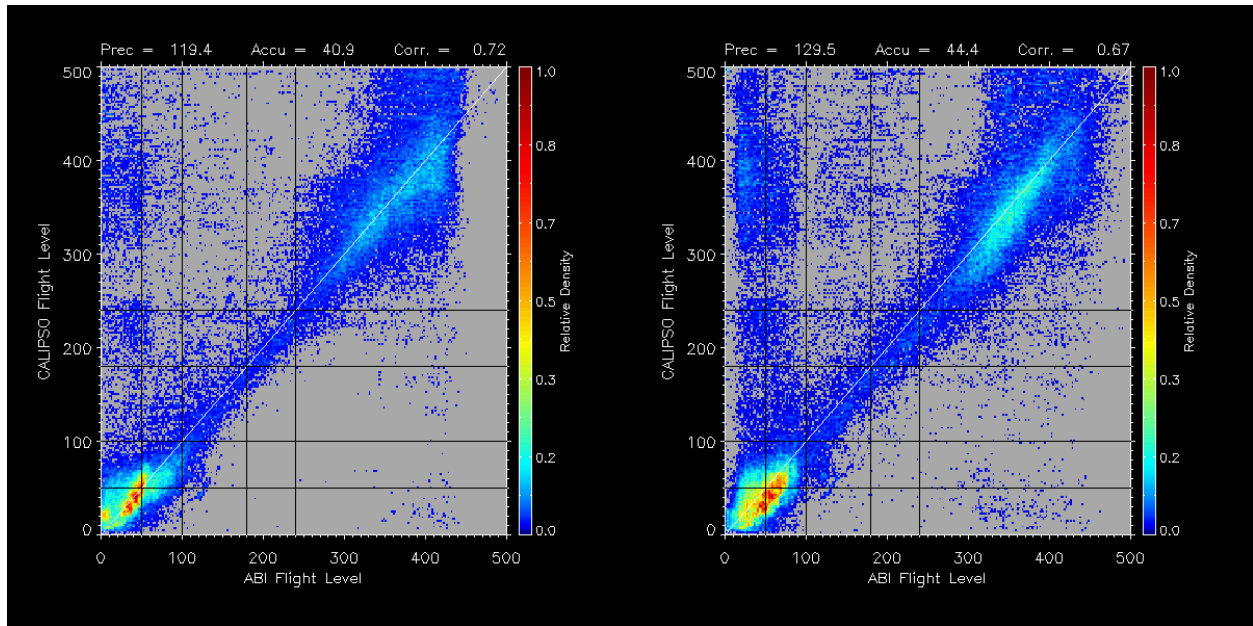


Figure 7. Comparisons of GOES-16 ABI and CALIPSO cloud top products converted to flight levels for FRAMEWORK(left) and CLAVR-x(right). Black solid lines show the FL boundary defined by NOAT requirement.

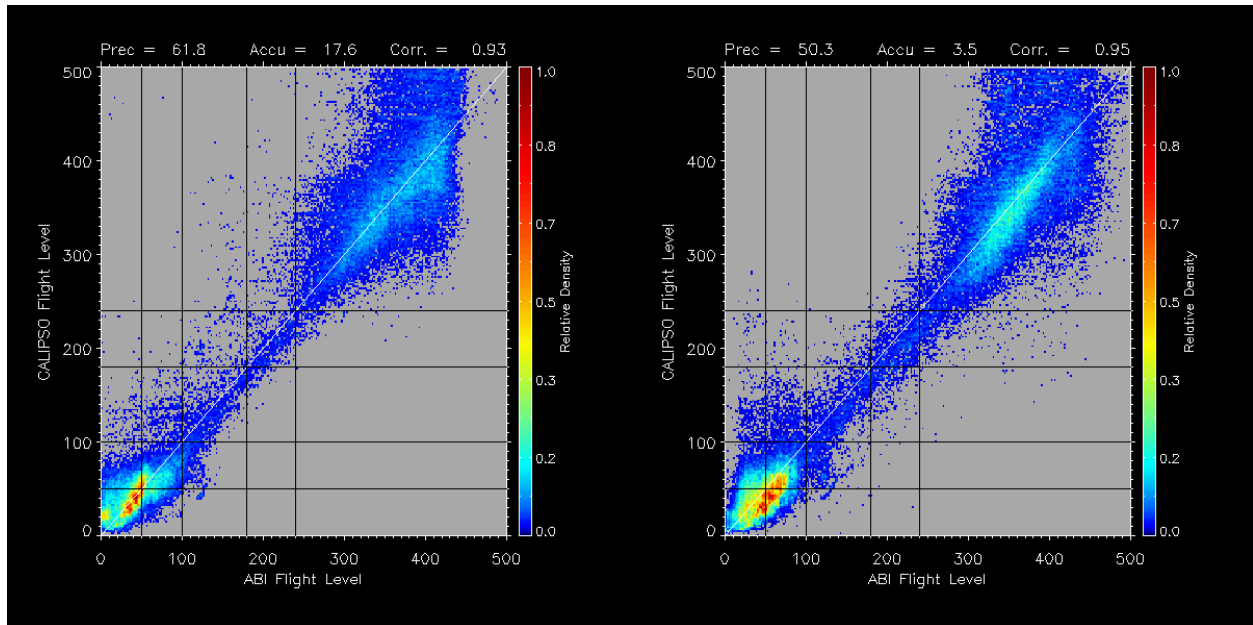


Figure 8. Similar as Figure 7 but with cloud phase matching between ABI and CALIPSO/CALIOP.

Table 4. Correct CCL classification ratios combining all 5 FLs. Original data and phase-matching filtered data are evaluated separately.

	No Filtering	Phase matched
ABI – FRAMEWORK	70.0%	82.6%
ABI – CLAVR-x	65.8%	81.4%

Table 5. Similar as Table 4 but results for each FL are presented.

		No Filtering	Phase matched
FRAMEWORK	Layer 1	80.0%	83.0%
	Layer 2	50.5%	53.5%
	Layer 3	44.5%	53.1%
	Layer 4	26.5%	44.5%
	Layer 5	78.9%	94.4%
CLAVR-x	Layer 1	64.6%	65.7%
	Layer 2	61.2%	64.0%
	Layer 3	40.6%	47.4%
	Layer 4	30.1%	49.8%
	Layer 5	74.1%	99.0%

5 PRACTICAL CONSIDERATIONS

5.1 Quality Assessment and Diagnostics

It is recommended that evaluation of the CCL product should be done in concert with upstream cloud mask and height input quality checks.

5.2 Exception handling

Quality control flags are checked and inherited from the input data for handling these exceptions:

- Bad sensor input data
- Missing sensor input data
- Missing ABI derived cloud mask, type, or ACHA cloud top data

A fill value will be assigned to any pixel with quality flags showing bad data or with any input values outside the acceptable range

5.3 Algorithm Validation

It is recommended CALIPSO analysis be adopted as the main validation method, for as long as they are available. If CALIPSO type data are not available, use of surface based lidar and radar measurements, such as those provided by the Atmospheric Radiation Measurement (ARM) program, is recommended.

6 ASSUMPTIONS and LIMITATIONS

6.1 Assumptions

For the CCL algorithm to perform properly, the following assumptions are made:

- ABI sensor meets its current specifications.
- All needed ABI and ancillary dynamic data are available.
- Columns comprise only one radiatively dominant cloud layer though cloud type and ACHA algorithms do allow for two layers if separately sufficiently. This applied to the NOAT CCL algorithm.

6.2 Limitations

- Clouds extending to lower level will only be considered for computing the upper level fraction.
- Cloud mask, type, and ACHA performances all impact CCL.

6.3 Improvement of CCL Product

The NOAT CCL algorithm assumes single layer clouds and does not require cloud base information. At the time of preparing the initial version of this document, use of both cloud base and multilayer clouds are supported and has been implemented in CLAVR-x. Meanwhile, the work to improve supercooled cloud detection and compute supercooled cloud fraction is ongoing.

7 REFERENCES

GOES-R Series Ground Segment (GS) Project Functional and Performance Specification (F&PS) [G417-R-FPS-0089]

GOES-R ABI Cloud Mask Algorithm Theoretical Basis Document

GOES-R ABI Cloud Type/Phase Algorithm Theoretical Basis Document

GOES-R Level 1 Requirements Document (L1RD)

GOES-R Series Mission Requirements Document (MRD) [P417-R-MRD-0070]

GOES-R Acronym and Glossary (P417-R-LIST-0142)