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
CDO	Convection Diagnosis Oceanic
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, including supercooled and convective clouds, at a predefined spatial resolution and between specified atmospheric levels. It also retrieves the 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. Convective CCL are compared against rainfall and Convection Diagnosis Oceanic products.

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. The algorithm discussed here can also be applied to other satellite sensors.

1.

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.

2.

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).

Updates were made in February 2021 to describe new algorithms and products. The new products are the supercooled and convective cloud products.

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 atmospheric levels, as well as the total cloud fraction at a specified spatial resolution. The atmospheric 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-miunte 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. The retrievals can be conducted using three combinations: 1) using cloud top only; 2) using both cloud top and base; 3) using cloud top, base and lower level cloud top, if available. Other than cloud fraction, this algorithm also retrieves supercooled cloud fraction and convective cloud fraction as each layer.

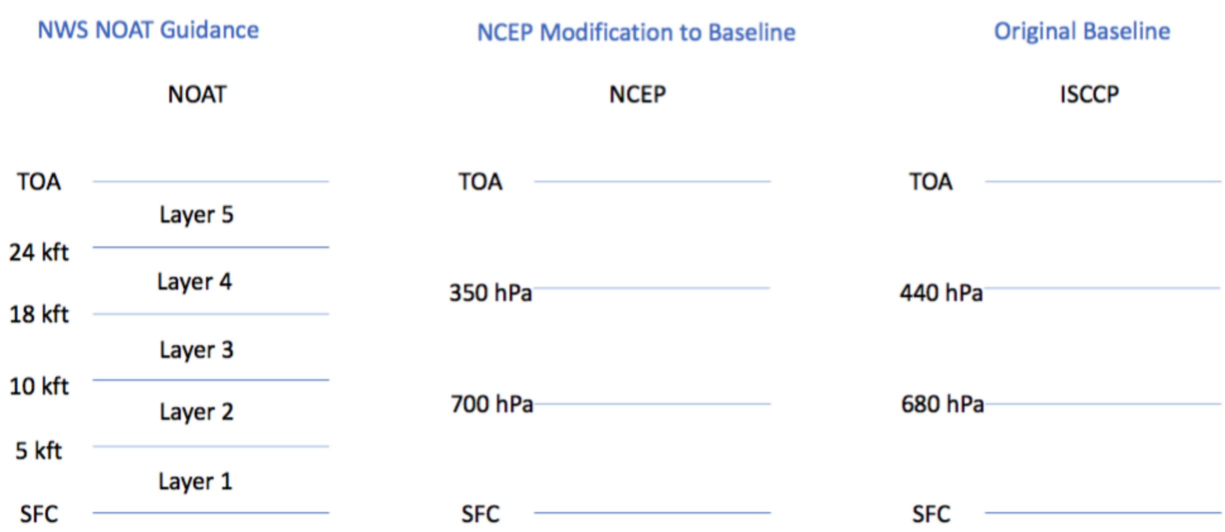

Figure 1. Three varying definitions of cloud layers based on flight level (NOAT), and cloud top pressure (original baseline and NCEP modification).

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 increases, 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 CCL algorithm provides options of different modes to support the use of cloud base and multilayer information. There are three modes available: 2) using cloud top only; 2) using cloud top and cloud base; and 3) using cloud top, cloud base, and lower level clouds when available.

The algorithm derives the following products:

Total cloud fraction, including all, supercooled and convective clouds
Layer cloud fraction, including all, supercooled and convective clouds
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.

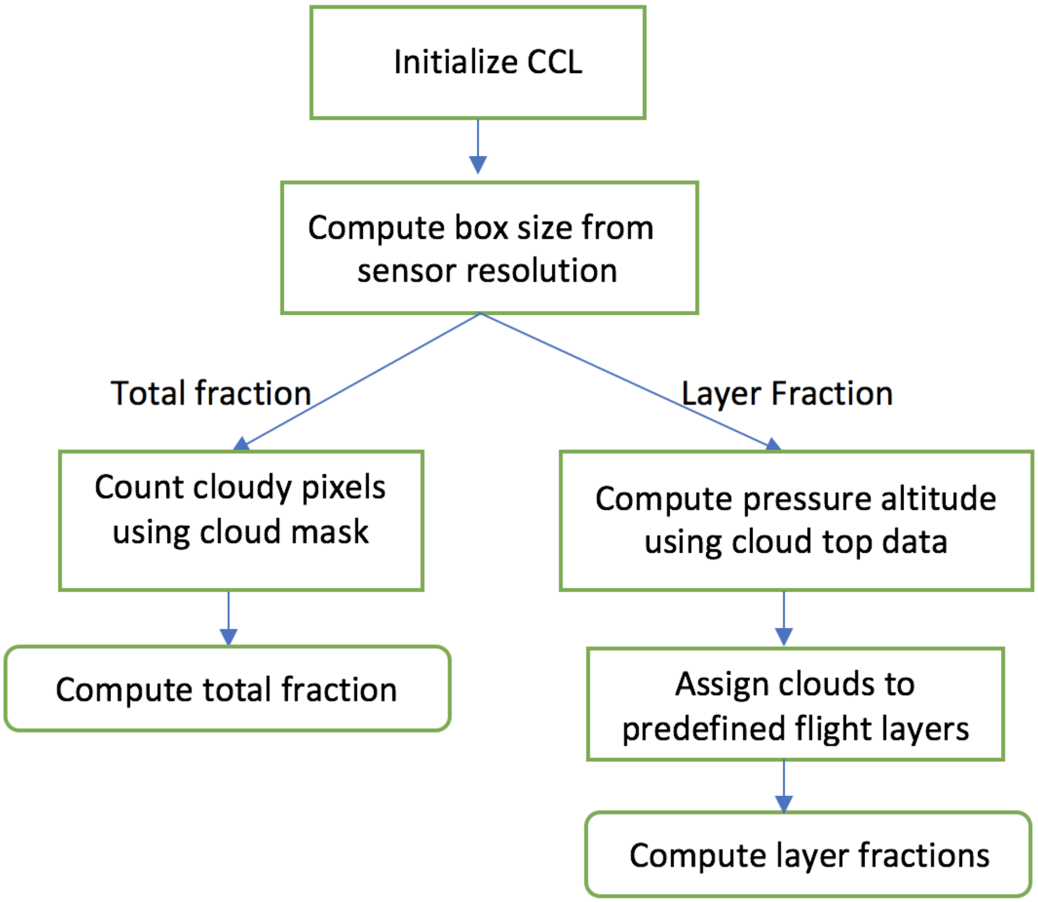

Figure 2. A flowchart of the CCL algorithm showing the computation of total and layer cloud fractions.

3.3 Algorithm Input

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

3.3.1 Primary Sensor Data

- Sensor resolution
- Brightness temperature at 11µm
- Brightness temperature at 6.7µm, if available
- 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
- Lower-level cloud top pressure

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

- Lower-level cloud base pressure
- Cloud altitude
- Cloud base altitude
- Lower-level cloud top altitude
- Lower-level cloud base altitude
- Freezing level pressure
- Cloud top temperature
- Cloud base temperature
- Lower-level cloud top temperature
- Cloud top height
- Level of free convection height
- Tropopause emissivity at 11µm

3.3.3 Dynamic Ancillary Data

- NWP profiles
- Surface temperature

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.

Supercooled clouds are clouds in liquid phase with temperature below the freezing temperature (273.15K). The supercooled cloud probability is computed based on its relationship with cloud temperature, which is derived using the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) cloud phase products. Figure 3 shows the statistical relationship trained with CALIPSO data. The values of probability range between 0 and roughly 0.9. It can be noted that supercooled clouds can exist when the temperature is as low as around 235K.

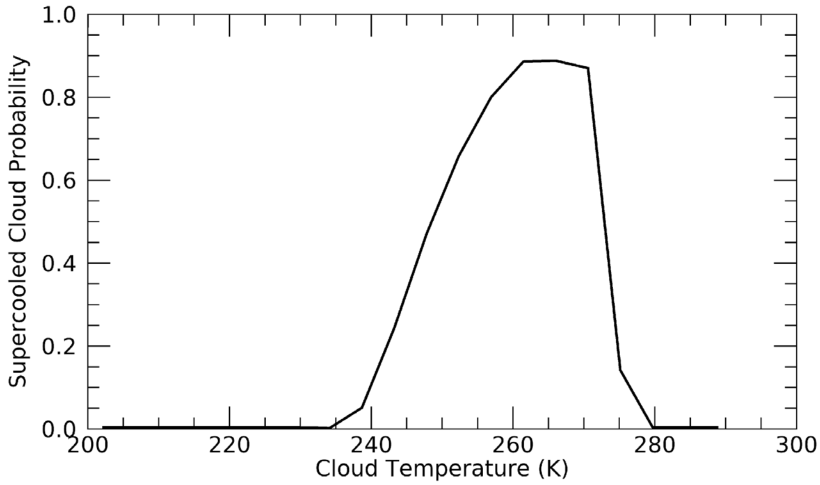

Figure 3. Probability of supercooled clouds as a function of cloud temperature.

Here, the concept of level of free convection (LFC) is used to compare to the ACHA cloud top height retrievals to detect if a cloudy pixel is convective. The LFC is defined as the level where an air parcel is warmer than its environment, after first going up with the dry adiabatic lapse until the lifting condensation level, then continuing to rise with the moist adiabatic lapse rate. Due to the air parcel being warmer than the environment, it will continue to rise, and convection may develop. Therefore, convection is likely when the cloud top is higher than the LFC.

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:

a. Compute box size based on sensor resolution and retrieval horizontal coverage;
b. Convert cloud top pressure to flight level for each cloudy pixel;
c. 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;
d. Iterate over all boxes, count the number of cloudy pixels for total and individual layers, and compute cloud fractions using the following formula

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

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

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

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 temperate 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 ($287\ J \cdot kg^{-1}K^{-1}$), the geopotential height of the cloud, Z, can be expressed as

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

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

$$Z = \begin{cases} \left(1 - \left({P_c}/{P_0}\right)^{LR\_over\_G}\right) * Z_0, & if\ P_c\ gt\ Pw1 \\ LN_1 * log(P_c) + LN_2\ , & if\ P_c < PW1\ and\ P_c > PW2 \\ PN_4 * {P_c}^4 + PN_3 * {P_c}^3 + PN_2 * {P_c}^2 + PN_1 * P_c + PN_0, & if\ P_c < PW2\ and\ P_c > PW3 \\ missing & if\ P_c < Pw3 \end{cases}$$

(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

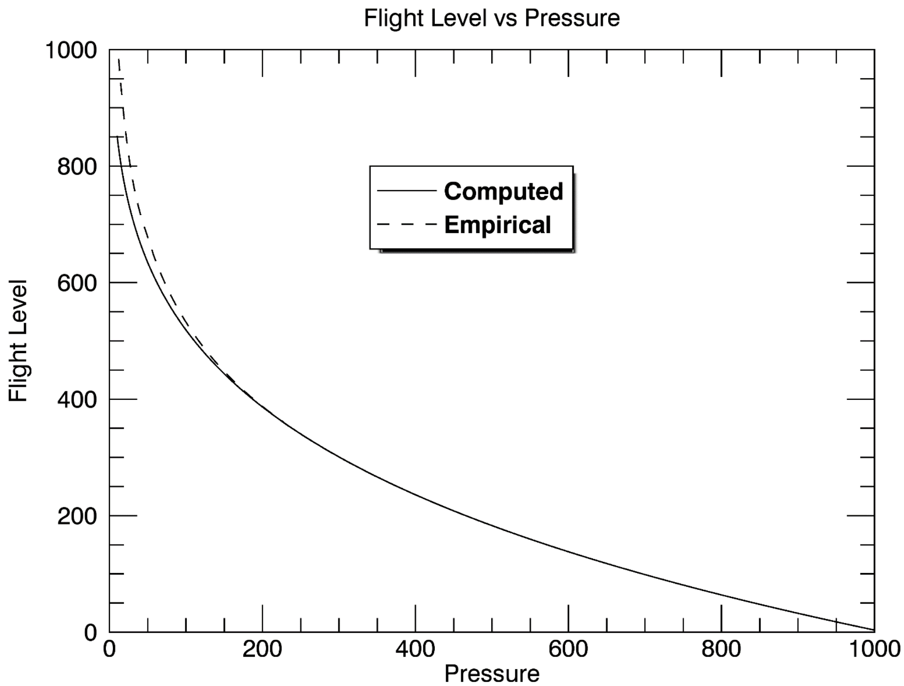

Figure 4. Computed flight level as a function of pressure. The solid line is based on the rigorous approach, and the dashed line shows the empirical method employed.

Figure 4 shows flight level as a function of atmospheric pressure, computed from both the rigorous approach (Eqn 3) and the 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.

3.4.2.2 Supercooled cloud probability/fraction

The computation of supercooled probability for each pixel is based on a look-up-table computed from CALIPSO data, as shown in Figure 3. The cloud temperature retrieved in ACHA is used. When cloud base is used, a linear temperature lapse rate is assumed inside the cloud and temperature at each layer top is computed. Therefore, supercooled cloud probability at each layer can be computed. The total supercooled fraction is assigned the highest from each layer. It should be noted that using cloud base information can often detect higher supercooled probability compared to using the cloud top only, due the variation of probability with temperature, as Figure 3 shows. This also means that using cloud base will likely show a larger total supercooled cloud fraction.

When the lower-level cloud mode is used, it is only computed when the lower level cloud top is located at least one layer below where the upper level cloud base is. The supercooled probability is then computed using the lower-level cloud top temperature.

1. 3.4.2.3 Convective cloud probability/fraction

ACHA retrieved cloud top height is compared to computed LFC height to detect convective activity. ACHA cloud top height is set to be at least 1km higher than the height of LFC for the detection of convection to reduce erroneous detections. To filter thin cirrus clouds that are misidentified as convective clouds, a minimum cloud emissivity of 1.0 is required. Additionally, a method of deep convection detection is applied. A pixel is identified as deep convection if the following conditions is met: 1) Brightness temperature at 11μm is less than 210K; or 2) Tropopause emissivity at 11μm is greater than 0.95; or 3) Tropopause emissivity at 11μm is greater than 0.9 and brightness temperature difference between 6.7μm and 11μm is greater than 0.9. Lastly, if difference between surface temperature and brightness temperature at 11μm is less than 30K, the pixel is considered non-convective to limit false alarm over elevated terrains. Unlike supercooled clouds, the convective probability for each cloudy pixel is assigned as either 0 (non-convective) or 1 (convective).

When cloud base is used, the convective layer is extended to the layer where cloud base is located. It is unlikely that multilayer clouds are present when convection is detected. However, if lower-level cloud is present, the layer is assigned to be convective as well.

3.4.3 Algorithm Output

3.4.3.1 Output

The CCL algorithm creates the following products:

- Total cloud fraction
- Total cloud fraction uncertainty
- Cloud fraction at each FL
- Cloud layer flag
- Total supercooled cloud fraction
- Supercooled cloud layer flag
- Total convective cloud fraction
- Convective cloud layer flag

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, the 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. For supercooled and convective clouds, the layer flag is set to 1 if the fraction at the pixel level is greater than 0.5. Otherwise, it is set to be 0. The first bit corresponds to the lowest layer and the layer increases upward as bit position moves left. Figure 5 shows an example of a clear box as well as a situation where a single layer cloud is identified in layer 3.

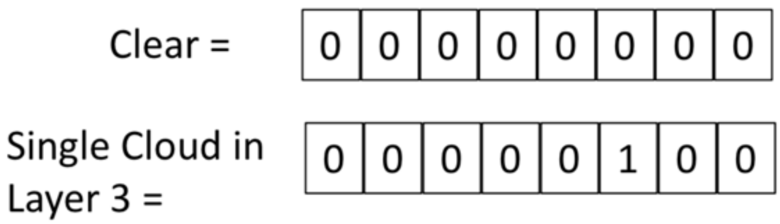

Figure 5. Illustration of cloud layer flag defined using a byte number. Cloudy and clear pixels are assigned 1 and 0, respectively. The first bit denotes the lowest layer and increases upwards as bit position moves left.

If using unobscured single layer cloud top information only, a cloudy flag can only exist in one layer. If the cloud base and/or multilayer flag is used, 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 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.

For convective cloud validation, due to the lack of reliable and objective information on convective clouds, especially on pixel level, at this stage, the validation primarily relies on qualitative visual comparisons with other products. For this purpose, the GOES-16 operational cloud phase and rainfall rate products, and the Convection Diagnosis Oceanic (CDO) product developed by the University Corporation for Atmospheric Research (UCAR) and Research Applications Laboratory (RAL) using geostationary satellite data, are used.

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 6 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 7, 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.

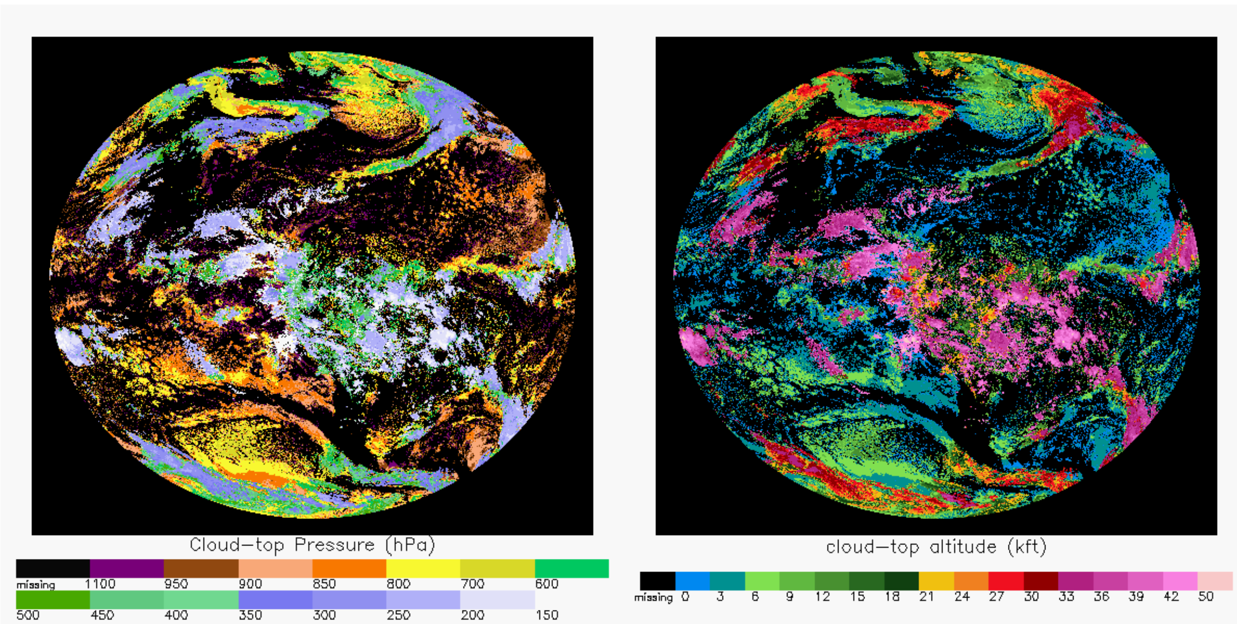

Figure 6. Retrieved GOES-16 ABI cloud top pressure (left) and cloud top altitude (right) for 1800 UTC on March 17, 2018.

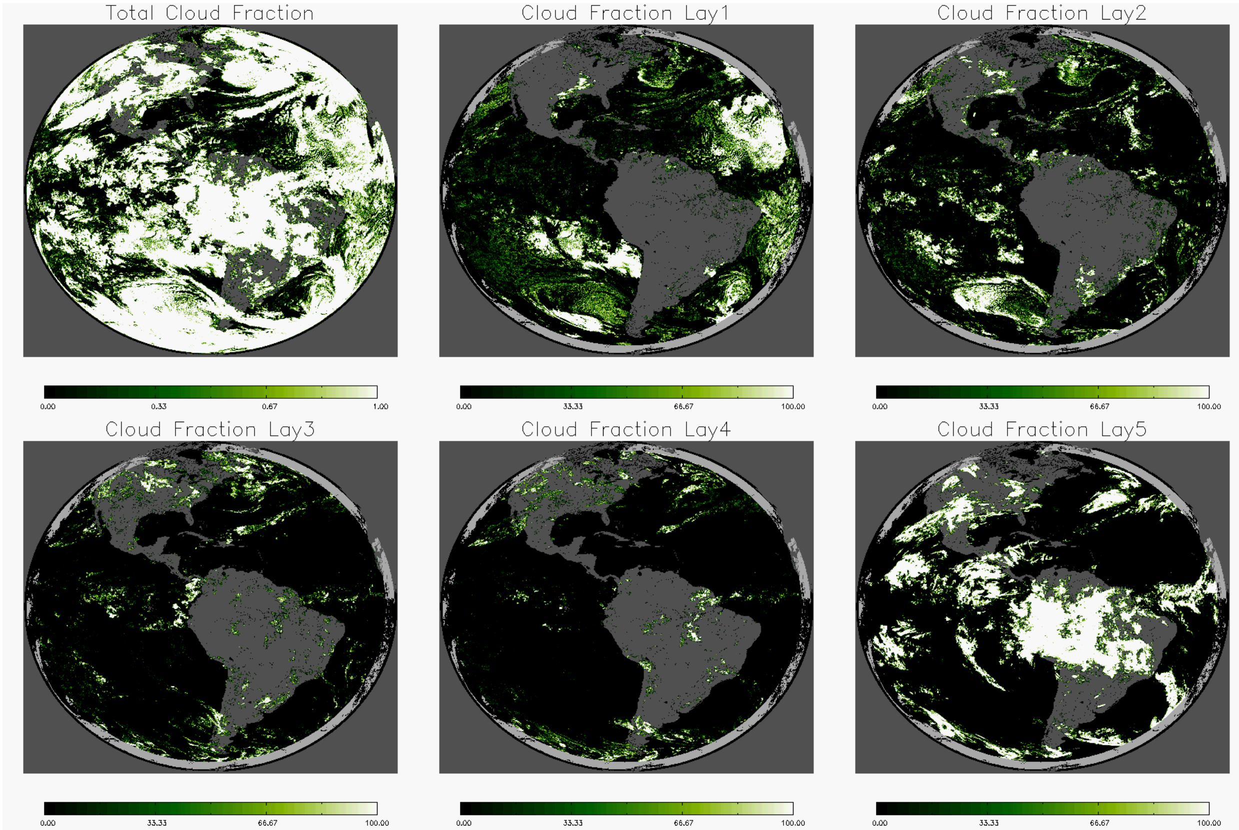

Figure 7. Illustration of cloud cover layer fraction using the same granule as in Figure 5. Top from left to right: total cloud fraction, cloud fraction at surface to FL50, FL50 to FL100; bottom from left to right: cloud fraction at FL100 to FL180, FL180 to FL240, FL240 to TOA. White regions mean cloudy 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.

4.1.3 ABI Rain Rate Data

The ABI operational Rain Rate product is generated using infrared channel observations and calibrated against microwave derived rain rates. It is recognized that not all rain is produced by convection, and vice versa. However, it is reasonable to attribute medium to heavy rainfall to convection.

4.1.4 CDO Data

The CDO is a weighted product of cloud height and convection diagnosis product derived from brightness temperature, as well as the lightning product. The lightning product has a higher weight than the others. The values of CDO product corresponding to convection ranges between

2 for likely to 6 for extreme. This product is produced in near-real-time by the University Corporation for Atmospheric Research (UCAR), Research Applications Laboratory (RAL) and made available via the Local Data Manager (LDM).

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.

For supercooled cloud validation, similar as above, the correct classification is defined as the ratio of number of pixels meeting the agreed FL requirement, as well as both passive and active products indicating the presence of supercooled clouds, to the number of pixels meeting the agreed FL requirement and active products indicating the presence of supercooled clouds.

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.

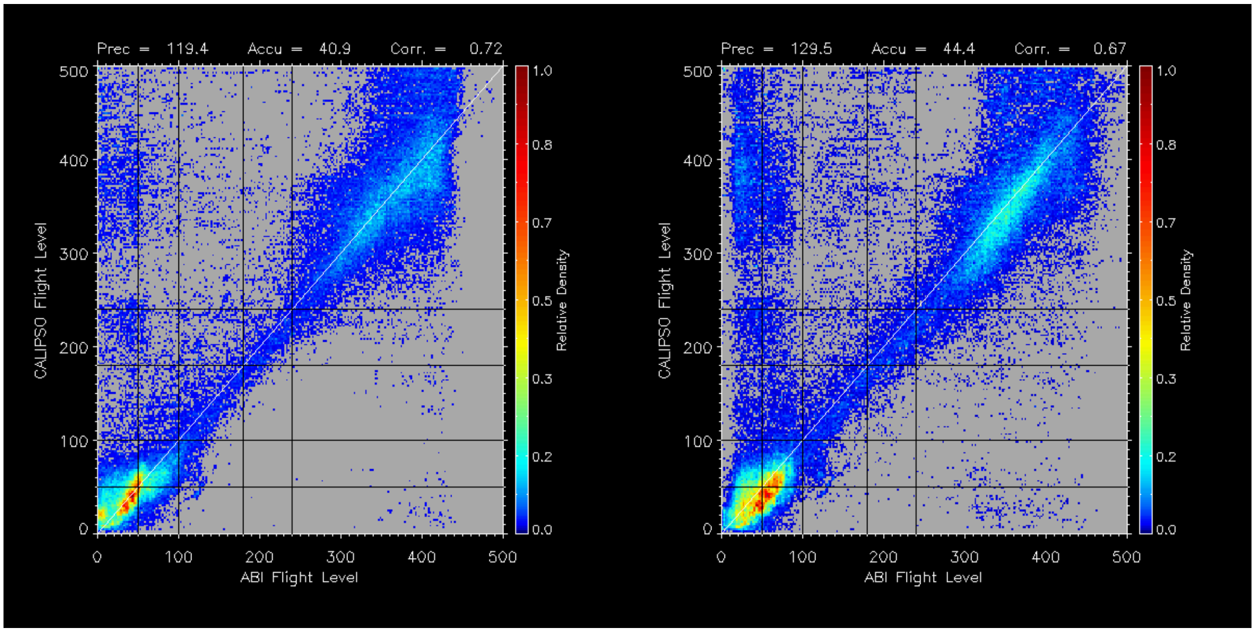

Figure 8. Comparisons of GOES-16 ABI and CALIPSO cloud top products converted to flight levels for FRAMEWORK(left) and CLAVR-x(right). Black solid lines show the FL boundary defined by NOAT requirement.

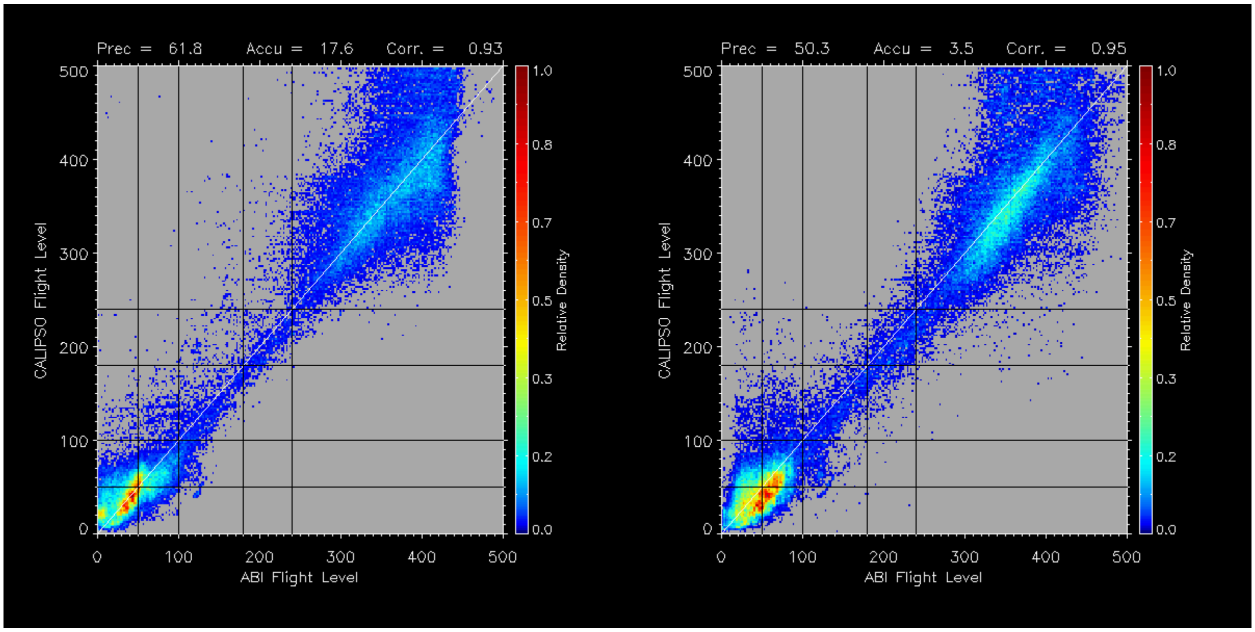

Figure 9. Similar as Figure 8 but with cloud phase matching between ABI and CALIPSO/CALIOP.

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%

In the validation of supercooled CCL products, one single day of NOAA-20 VIIRS data on 04/08/2020 were conducted and collocated to the CALIPSO product. Here validation is conducted against CALIPSO top layer product, so only cloud top information is used for the retrieval. Figure 10 shows retrieved total supercooled and convective convections over the Antarctic and Arctic regions. Cloud type generated from CLAVR-x is also shown for comparison purposes. Satellite retrievals over the polar regions are more challenging than tropical and midlatitude regions. However, it can be observed that the performances of two CCL products are reasonably well. In the validation against CALIPSO, the correct identification ratio defined requires the flight level agreement between passive and active sensors. Without cloud phase matching, the computed ratio shows a value of 58.7%; and when cloud phase matching is applied, a significant improvement is observed with a value of 90.0%. This again emphasizes the importance of correct phase identification on downstream products. Note that due to the limited amount of data used here, the correct classification ratio may fluctuate. However, numbers presented here show the robustness of the algorithm.

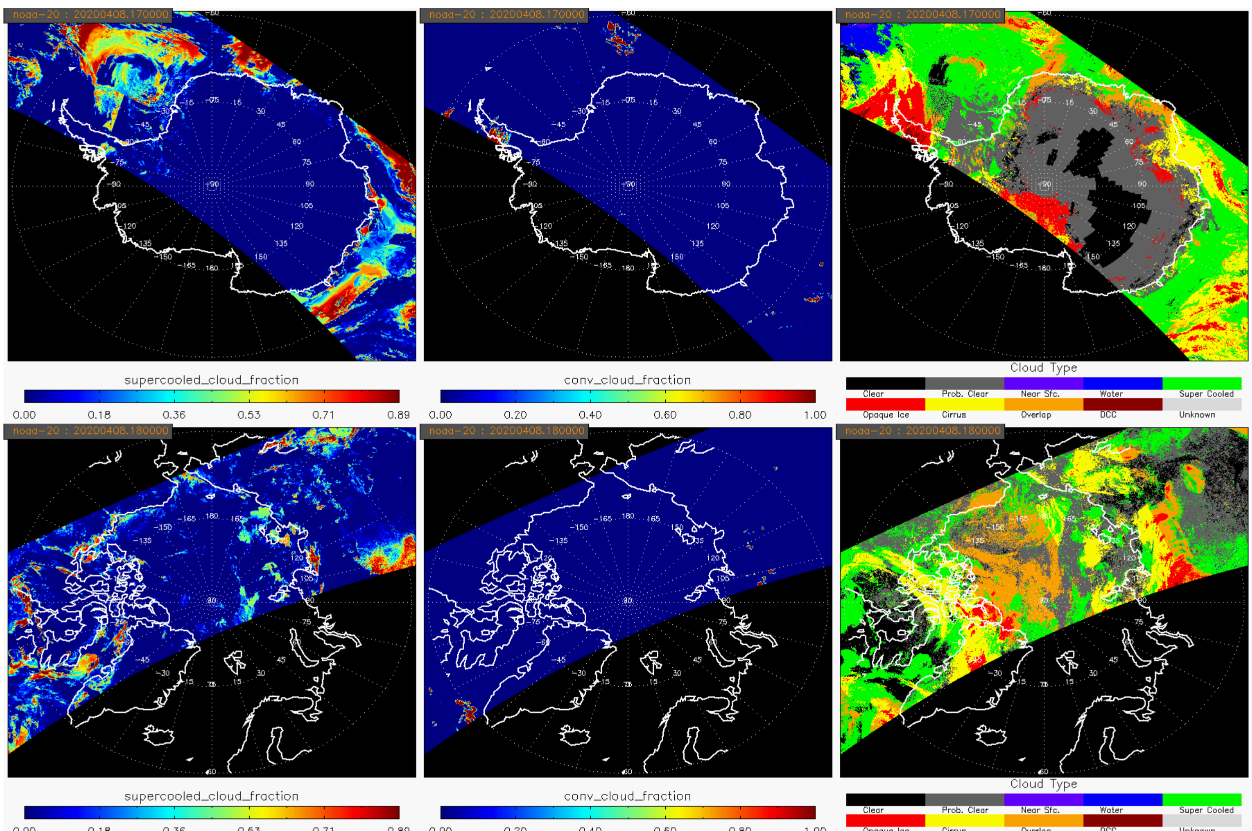

Figure 10. An example of supercooled and convection cloud fraction over the Antarctic (top) and Arctic (down) retrieved from NOAA-20 VIIRS data on 04/08/2020. Cloud type retrieved from CLAVR-x (right column) is also shown for comparison.

As discussed previously, quantitative validation of convective clouds is difficult due to lack of reliable information at the pixel level. Hence, qualitative comparisons are presented here. Figures 11 and 12 show the computed total convective cloud fraction compared to rainfall and CDO products for the GOES-16 sensor over tropical regions (Figure 11) as well as the midlatitudes (Figure 12). It is clear that the convective CCL retrieval tends to capture the missed fraction from either rainfall or CDO product. For instance, the non-precipitating weak convection is shown in both CCl and CDO (Figure 11); over the eastern Canada, convection is hardly seen from CDO, but is shown in CCL as well as precipitation (Figure 12). Figures 13 and 14 show the animations for a single day during boreal winter. Since precipitation does not necessarily come with convection, such as shallow convection, which can be also visually identified by looking at the variation of brightness temperature at 11um, apparently, convective CCL shows a better coverage where convection occurs. Note that while qualitative comparisons are presented at the writing of this document, there will be efforts to quantify the accuracy of convective CCL products making use of various sources of data.

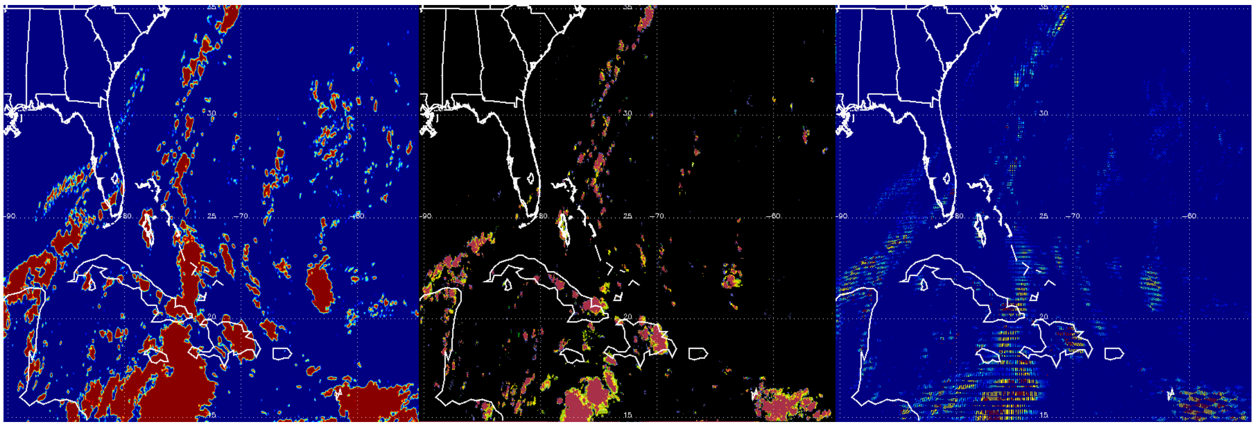

Figure 11. GOES-16 total convective cloud fraction (left), rainfall amount (middle) and CDO (right) on 09/30/2020 at 1900UTC over southeastern United States and the tropical ocean. Note that CDO values are integers between 2 and 6, and large values indicate a larger possibility of convection.

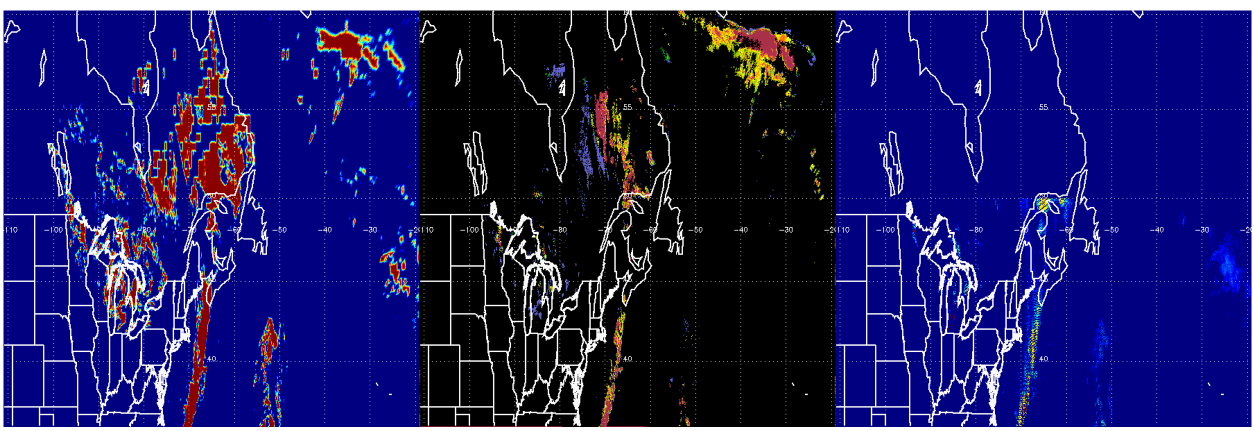

Figure 12. GOES-16 total convective cloud fraction (left), rainfall amount (middle) and CDO (right) on 09/30/2020 at 1900UTC over northeastern United States and eastern Canada.

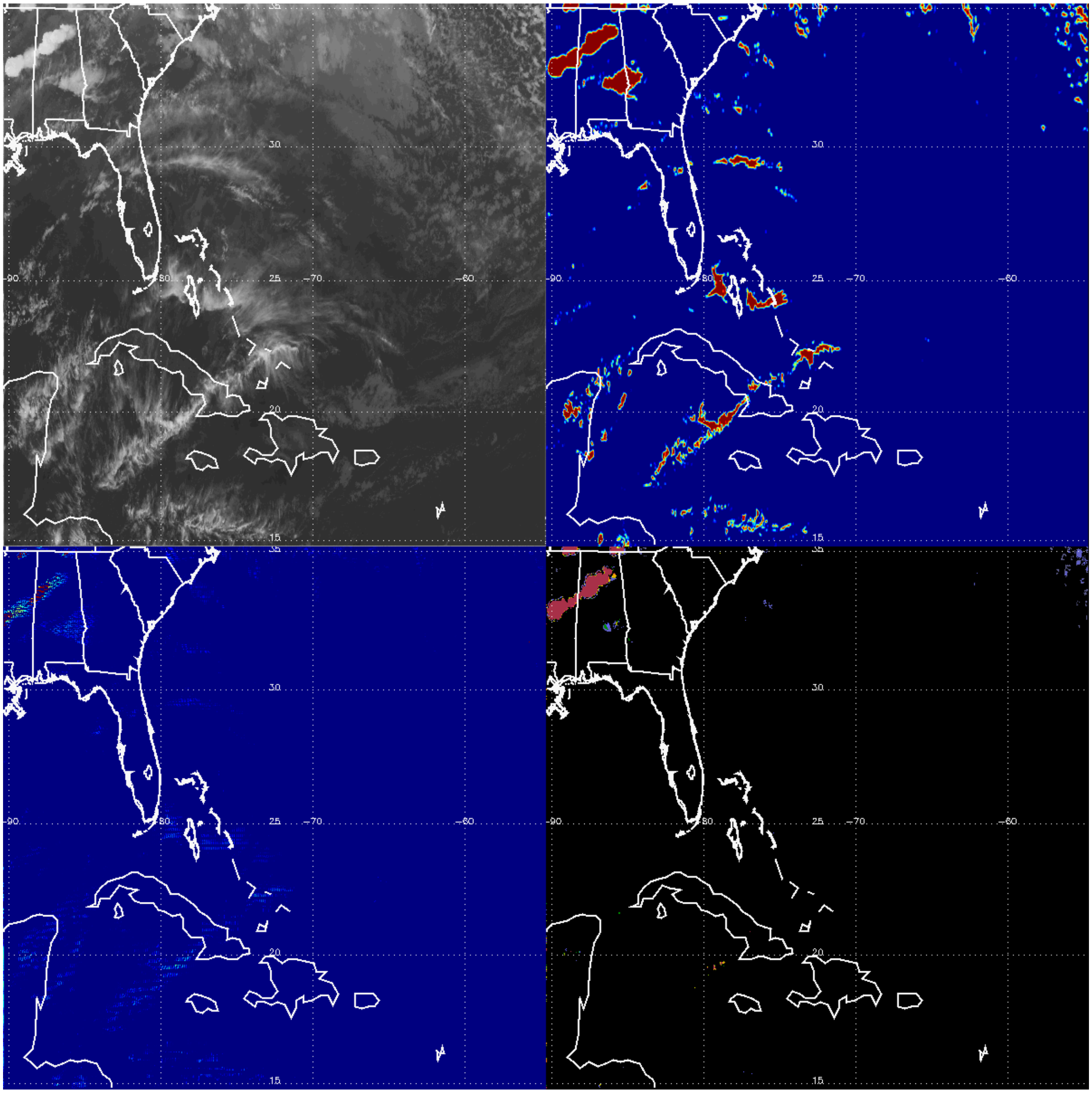

Figure 13. Animation of GOES-16 brightness temperature at 11um (top left), total convective cloud fraction (top right), CDO (bottom left), and rainfall amount (bottom right) on 01/26/2021 over southeastern United States and the tropical ocean.

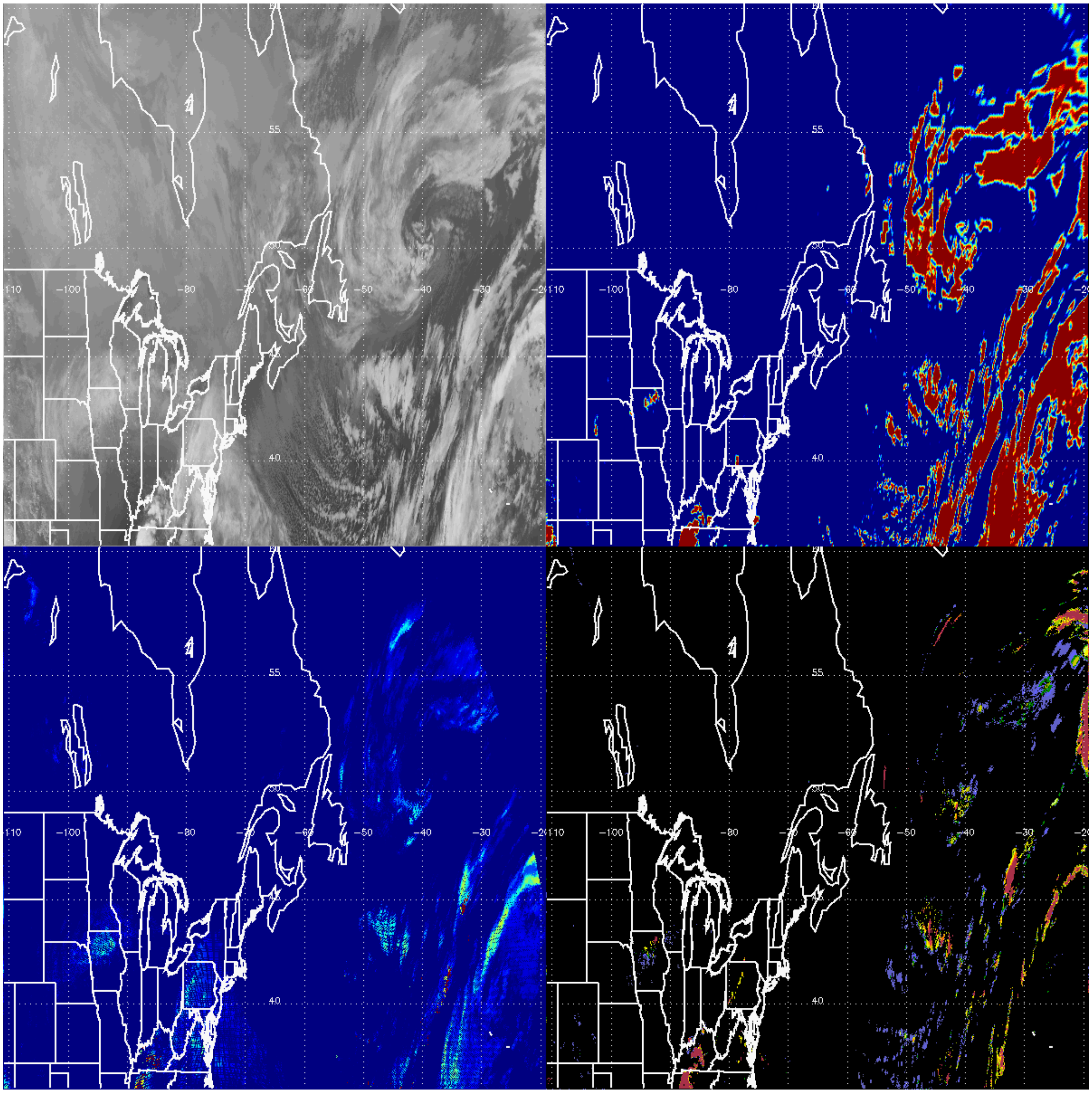

Figure 14. Animation of GOES-16 brightness temperature at 11um (top left), total convective cloud fraction (top right), CDO (bottom left), and rainfall amount (bottom right) on 01/26/2021 over northeastern United States and eastern Canada.

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. The work to further improve supercooled cloud detection and convective cloud fraction will continue.

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)