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CENTER for SATELLITE APPLICATIONS and RESEARCH

ALGORITHM THEORETICAL BASIS DOCUMENT

Enterprise AWG Cloud Base Algorithm (ACBA)

Version 2.3
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Yoo-Jeong Noh[1], Steven D. Miller[1], Curtis J. Seaman[1], John M. Haynes[1],
Yue Li[2], Andrew K. Heidinger[3], and Mark S. Kulie[3]

[1] Cooperative Institute for Research in the Atmosphere, Colorado State University, Ft. Collins, CO
[2] Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, Madison, WI
[3] NOAA/NESDIS/STAR, Madison, WI

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LIST OF ACRONYMS

AMSL	Above Mean Sea Level
ARM	Atmospheric Radiation Measurement program by the US Department of Energy
ACBA	Enterprise AWG Cloud Base Algorithm
ACHA	Enterprise AWG Cloud Height Algorithm
ASSISTT	Algorithm Scientific Software Integration and System Transition Team
AIADD	Algorithm Interface and Ancillary Data Description
ATBD	Algorithm Theoretical Basis Document
A-Train	Afternoon Train (Aqua, CALIPSO, CloudSat, etc.)
AVHRR	Advanced Very High Resolution Radiometer
AWG	Algorithm Working Group
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CBH	Cloud Base Height
CCL	Cloud Cover and Layers
CCL_NWP	Convective Condensation Level from the NWP
CGT	Cloud Geometric Thickness
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CIRA	Cooperative Institute for Research in the Atmosphere
CLAVR-x	Clouds from the AVHRR Extended
COT	Cloud Optical Thickness
CPR	Cloud Profiling Radar
CTH	Cloud Top Height
CTP	Cloud Top Pressure
CTT	Cloud Top Temperature
CWC	Cloud Water Content
CWP	Cloud Water Path
DCOMP	Daytime Cloud Optical and Microphysical Properties
ECMWF	European Center for Medium range Weather Forecasting
EPS	Effective Particle Size
GFS	Global Forecast System
IDPS	Interface Data Processing Segment
ISCCP	International Satellite Cloud Climatology Project
JPSS	Joint Polar Satellite System
L1RD	Level 1 Requirements Document
L1RDS	Level 1 Requirements Document SUPPLEMENT
LCL_NWP	Lifted Condensation Level from the NWP
LTM	Long Term Monitoring
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDE	NOAA NESDIS National Polar-orbiting Partnership Data Exploitation
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NCM	NDE Enterprise Cloud Mask
NLCOMP	Nighttime Lunar Cloud Optical and Microphysical Algorithm

NWP	Numerical Weather Prediction
S-NPP	Suomi National Polar-orbiting Partnership
STAR	Center for Satellite Applications and Research
VIIRS	Visible Infrared Imaging Radiometer Suite

ABSTRACT

This document describes a statistically-based algorithm for estimating Cloud Base Height (CBH), developed as part of Algorithm Working Group (AWG) for the Visible Infrared Imaging Radiometer Suite (VIIRS). The Enterprise AWG Cloud Base Algorithm, or ACBA, is predicated upon a statistical relationship drawn between the observed cloud geometric thickness (CGT), cloud top height (CTH), and cloud water path (CWP) using multi-sensor A-Train satellite data (CloudSat Cloud Profiling Radar (CPR), CALIPSO Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), and Aqua MODerate-resolution Imaging Spectroradiometer (MODIS)). Here, the active sensors provide the critical CGT information for training the algorithm. The relationship is then applied to current VIIRS retrievals CTH and CWP to estimate the CGT, which is subtracted from the CTH to obtain CBH. ACBA has been made flexible to run various sensors including VIIRS and GOES-16/17 ABI.

This Algorithm Theoretical Basis Document (ATBD) describes the required inputs, the theoretical foundation of the algorithm, the sources and magnitudes of the uncertainties, practical considerations for implementation, and the assumptions and limitations associated with the product. The results are validated against CloudSat CPR both statistically and for selected case studies are also shown. A comparison of performance against the original operational CBH algorithm is also provided.

1 INTRODUCTION

1.1 Purpose of This Document

The purpose of this Algorithm Theoretical Basis Document (ATBD) is to establish guidelines for producing the Algorithm Working Group (AWG) Cloud Base Height (CBH) product from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (S-NPP) mission, the 'risk reduction' satellite for the next generation polar-orbiting satellites in the Joint Polar Satellite System (JPSS) and JPSS satellite series including NOAA-20 and JPSS-2. This document describes the theoretical basis and required inputs of the algorithm as well as the sources and magnitudes of the uncertainties involved. The assumptions and limitations associated with the cloud base height (CBH) product and practical considerations for implementation are identified. Unless otherwise stated, the determination of CBH implies the estimated height above mean sea level (AMSL) of the base of the *uppermost cloud layer*, and requires the predetermination of cloud top height (CTH) and cloud water path (CWP) as input. An estimate of the cloud geometric thickness (CGT) is then subtracted from CTH to yield CBH. The CBH information is also made available to improve the Cloud Cover and Layers (CCL)—a downstream product.

1.2 Who Should Use This Document

The intended users of this document are those interested in understanding the theoretical basis of the CBH algorithm and how to use it for analysis and application to downstream quantitative products. This ATBD also provides information useful to anyone maintaining or modifying the original algorithm.

1.3 Inside Each Section

This document consists of the following main sections:

- **Observing System Overview**: provides relevant details of VIIRS and a brief description of the inputs and outputs associated with the CBH algorithm.

- **Algorithm Description**: provides a detailed description of the CBH algorithm including its physical basis, input, and output.

- **Assumptions and Limitations**: provides an overview of the current limitations of the approach and notes plans for overcoming these limitations with further algorithm development.

1.4 Related Documents

The CBH product leverages retrieval information from the Cloud Top Height (CTH) and Cloud Liquid/Ice Water Path (CWP) Level 2 environmental data records (EDRs). The

ATBDs for these ancillary products are available as part of the official JPSS Program release. This document does not relate to any other document except the Program Level 1 Requirements Document (L1RD), L1RD SUPPLEMENT (L1RDS), and JPSS Ground Segment Specifications Document, and to the references including ATBDs for CTH and cloud optical properties for deriving CWP (day and night) given throughout.

Motivation for this revision to the operational CBH algorithm is explained by Seaman et al. (2017), and a full technical description of the current CBH algorithm (the subject of this ATBD) is provided by Noh et al. (2017).

1.5 Revision History

The initial version 1.0 of the AWG CBH algorithm was created by the Cooperative Institute for Research in the Atmosphere team at Colorado State University, which includes the theoretical foundation of the statistical CBH algorithm and performance results. Its intent is to accompany the delivery of the latest version algorithm to the Center for Satellite Applications and Research (STAR) Algorithm Scientific Software Integration and System Transition Team (ASSISTT) as well as the algorithm readiness document. This updated version includes more clarified algorithm descriptions for deep convection and optically thin cirrus-type clouds, and recent evaluation results. The latest algorithm utilizes CWP input obtained from nighttime optical properties using VIIRS Day-Night Band (DNB) lunar reflectance data.

2 OBSERVING SYSTEM OVERVIEW

This section describes the output generated by the Enterprise CBH algorithm and its associated input requirements.

2.1 Products Generated

The output of the CBH product is an estimation of the AMSL base altitude of the *uppermost cloud layer* in each column of the atmosphere as viewed from above by VIIRS. The algorithm is applicable for single layer clouds. For multilayer cloud profiles, the CBH is predicated on the CTH of the uppermost cloud layer. While in the case of a single cloud layer the retrieved value is the lowest cloud base height (referred to in the aviation community as the 'ceiling'– the lowest cloud base of > 5/8 sky coverage), in a multilayer scene the attribution of the CBH to any specific cloud layer is dubious and it should not be regarded as the ceiling. The number of layers is not known in a typical scene, although in certain conditions the presence of a thin high cloud over thick low cloud can be ascertained. The current CBH product makes no special provisions for these situations and all cloudy pixels in VIIRS imagery are treated under the assumption of a single-layer cloud.

As such, the CBH product should not be interpreted to represent strictly what aviation users consider as cloud ceiling. The CBH algorithm is applied to pixels identified as "probably cloudy" or "confidently cloudy" by the VIIRS Enterprise Cloud Mask. It is currently generated for both daytime and nighttime scenes, with additional caveats at night due to lack of infrared band sensitivity to the CWP of optically thick clouds. To overcome this limitation, the latest algorithm version adopts nighttime optical properties utilizing VIIRS Day-Night Band (DNB) lunar reflectance data, which is effective to provide nighttime CWP when moonlight is sufficient. The estimate of CBH is used as input to the NESDIS NPP Data Exploitation (NDE) Enterprise Cloud Cover and Layers (CCL) product to improve cloud fractions of lower-level cloud layers. The cloud layer is classified by CTH first as being a high, middle, or low-level cloud. Additional vertical stratifications or partitioning by VIIRS-assigned cloud type (e.g., convective, supercooled) is also possible.

The operational algorithm requirements (threshold and objective performance) for VIIRS CTH and CBH are provided in Table 1. Owing to the understood physical limitations of CBH estimation, the thresholds and objectives for CBH are higher by a factor of 2, particularly for optically thick clouds.

Table 1. Requirements from VIIRS Cloud Top/Base Heights (Version 2.4).

Cloud Height (Top and Base) (VIIRS)		
EDR Attribute	**Threshold**	**Objective**
CTH/CBH Applicable Conditions: 1. Requirements apply whenever detectable clouds are present.		
a. Horizontal Cell Size	800 m	375 m

b. Vertical Reporting Interval	Top and Base of highest cloud in column	Top and Base of multiple cloud layers in the column
c. Mapping Uncertainty, 3 Sigma	4 km	1 km
d. Measurement Precision for CTH		
1. COT ≥ 1 (2)	1.0 km	0.15 km
2. COT < 1 (2)	2.0 km	0.15 km
e. Measurement Accuracy for CTH		
1. COT ≥ 1 (2)	1.0 km	0.3 km
2. COT < 1 (2)	2.0 km	0.3 km
d. Measurement Precision for CBH		
1. COT ≥ 1 (2)	2.0 km	0.3 km
2. COT < 1 (2)	3.0 km	0.3 km
f. Measurement Accuracy for CBH		
1. COT ≥ 1 (2)	2.0 km	0.3 km
2. COT < 1 (2)	3.0 km	0.3 km
g. Refresh	At least 90% coverage of the globe every 12 hours (monthly average)	4 hrs.
		v2.4, 12/13/12, CBH parts updated in 05/09/19 according to JERD-2476 &2477

Notes: Cloud height is defined for each cloud-covered earth location as the set of AMSL heights of the tops and bases of the cloud layers overlying that location.

2.2 Instrument Characteristics

The CBH algorithm operates on each pixel designated as cloudy or probably cloudy, as determined by the VIIRS Cloud Mask. Since CBH is estimated from derived products and not from direct radiance measurements, it is applicable to a variety of instrument designs and channel characteristics. This makes the algorithm portable to any observing system capable of supplying the required cloud property inputs. Because it operates on pixel-level EDRs, the CBH product maintains the native spatial resolution of the VIIRS measurements.

2.3 Product Requirements

The fidelity of CBH estimates is tied closely to the accuracy of upstream CTH and CWP retrievals and the representativeness of Numerical Weather Prediction (NWP) analyses (which are enlisted as ancillary data in some cases). The CBH product requires *a priori* information on cloud top height (CTH) and integrated cloud water path (CWP; liquid or ice). The CWP is derived using VIIRS retrievals of cloud optical thickness (COT) and cloud top effective particle size (EPS). It uses these parameters to interrogate cloud-height-dependent relationships derived from CloudSat/CALIPSO and MODIS (a sensor with similar capabilities to VIIRS).

The requirements for CBH are thus driven by the requirements of the upstream products feeding into it, as shown in Table 2.

Table 2. ACBA Product Input Requirements

Attribute	Threshold	Objective
Cloud Top Height	CTH ATBD Specs	CTH ATBD Specs
Cloud Water Path	CWP ATBD Specs	CWP ATBD Specs
*Cloud Optical Thickness	COT ATBD Specs	COT ATBD Specs
*Cloud Top Temperature	CTT ATBD Specs	CTT ATBD Specs
*NWP convective/lifted condensation levels		
*NWP Cloud Water Path		

***Note**: quantities required for alternative CBH estimates (COT and CTT for thin cirrus cloud base estimates; NWP lifting condensation and convective condensation levels (LCL_NWP/CCL_NWP) fields for deep convection, respectively). If VIIRS retrieval of CWP is not available, CWP derived from NWP can be utilized as supplementary data.

3 ALGORITHM DESCRIPTION

3.1 Algorithm Overview

The CBH algorithm provides information critical to estimating three-dimensional (3D) structures for clouds observed from VIIRS. The CBH product is derived at the pixel level for all cloudy/probably-cloudy pixels. In this document, CBH is defined as an estimation of the height AMSL of the base of the topmost cloud layer, which is calculated by subtracting an estimate of CGT from the retrieved CTH. CGT is predicated on the formation of statistical relationships between observed CGT and CWP expressed as a function of CTH. The algorithm derives the following products:

- Cloud Base Height
- Quality flags

3.2 Processing Outline

The processing outline of the CBH algorithm is summarized in Figure 1. The main algorithm retrieves CGT constrained by a relationship with CTH and CWP. To establish these relationships, MODIS-derived CWP for CTH within a certain geometric range were related to the CloudSat/CALIPSO-derived CGT via piecewise linear fitting. The VIIRS-derived CTH and CWP are used to select the appropriate relationship and derive a CGT value. The CGT is then subtracted from the retrieved CTH to yield an estimate of CBH. In limiting cases of optically thick deep convection, the CBH estimate is based on condensation levels derived from NWP data (local to the pixel), and in cases of thin cirrus, we employ an extinction model using COT and CALIPSO-based extinction coefficients.

The first version of the CBH algorithm was implemented in the Clouds from AVHRR Extended (CLAVR-x) processing system for demonstrations in the NOAA S-NPP Data Exploitation (NDE) system. The NDE system generates Level 2 data products using science algorithms developed by science teams comprised of NOAA and other agencies, and distributes the products to near real-time users on a subscription basis. The CBH algorithm is designed to run with CTH and CWP products and NWP supplementary data. Thus, the code is inserted downstream of the CTH and cloud optical property retrievals in the processing chain, as shown in Figure 1.

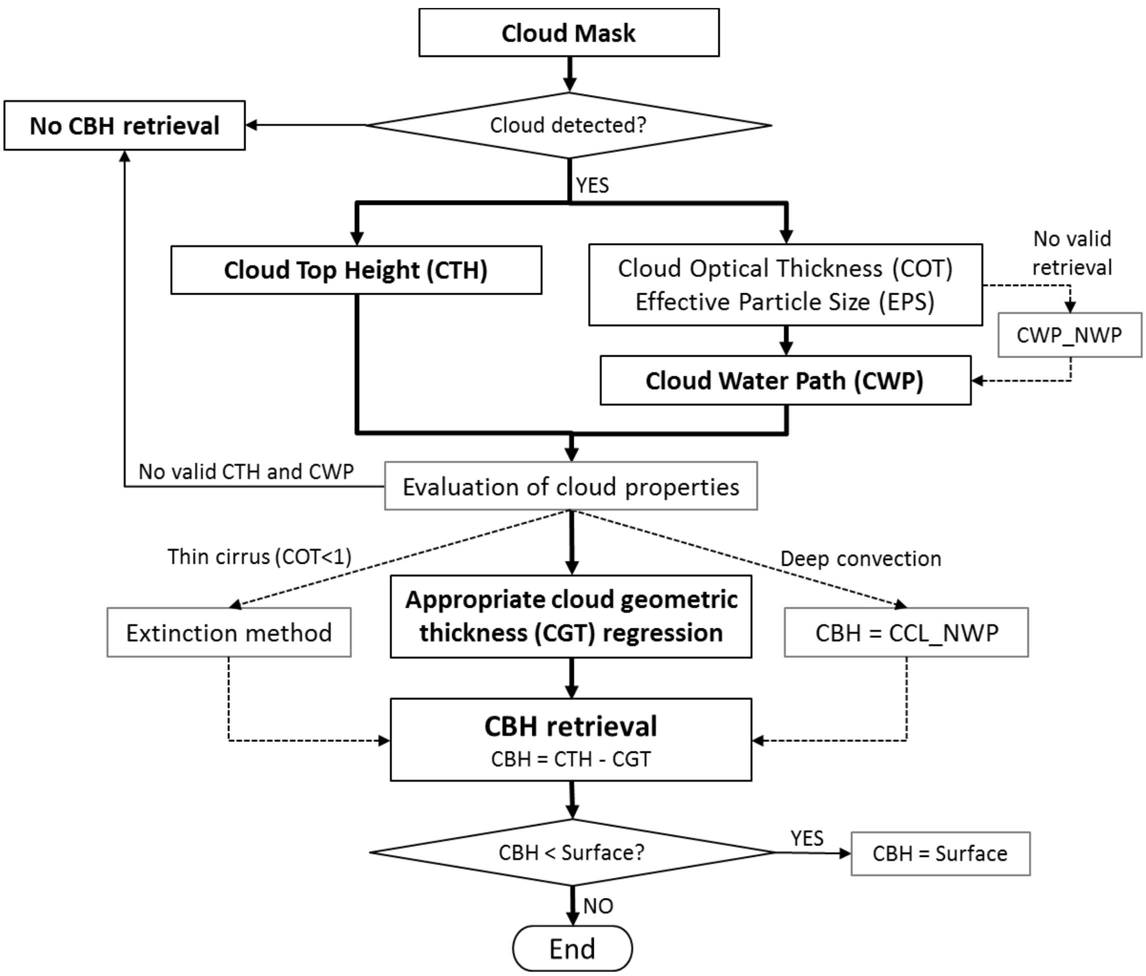

Figure 1 A schematic flowchart of the AWG CBH algorithm.

3.3 Algorithm Input

This section describes the required inputs for the CBH algorithm. The algorithm estimates CBH for all pixels identified as cloudy/probably-cloudy from the VIIRS Cloud Mask and maintains the spatial uniformity of the native VIIRS observations (i.e., pixel level output). Non-cloudy pixels are assigned missing fill values. The algorithm is run with the other cloud property retrieval algorithms, but is designed as a separate subroutine.

3.3.1 Primary Sensor Data

The CBH algorithm is operated downstream of the principal VIIRS cloud retrieval algorithms (Cloud Mask, CTH, and cloud optical properties used for deriving CWP). The same primary sensor data (calibrated radiances and brightness temperatures from specific VIIRS bands, and bad pixel mask data) are required throughout the cloud retrieval algorithms, including CBH. By 'primary sensor data', we mean the calibrated data (Level 1B) and geolocation information provided in the operational VIIRS Sensor Data Records (SDRs). Details on the information are provided in the AWG Cloud Height Algorithm (ACHA) and NPP Data Exploitation (NDE) Enterprise Cloud Mask ATBDs.

3.3.2 Derived Input Data

The following section lists and briefly describes the upstream products that are required by the CBH algorithm.

3.3.2.1 Main input

- **Cloud Mask**
  A cloud mask is required to determine which VIIRS pixels are likely to be cloudy and which are likely to be clear. Cloudy pixels are processed for CTH and CWP (liquid or ice) which serve as primary inputs for derivation of CGT, yielding the estimate of CBH. This information is provided by the NDE Enterprise Cloud Mask algorithm. Details on the Enterprise Cloud Mask are provided in a separate, dedicated ATBD.

- **Cloud Top Height (CTH)**
  CTH is required as *a priori* information to the CBH algorithm. The product is provided by the Enterprise Cloud Height Algorithm and information is provided in a separate, dedicated ACHA ATBD.

- **Cloud Water Path (CWP)**
  Cloud liquid/ice water path (CWP) is derived from cloud optical thickness (COT) and effective particle size (EPS), and is required to determine statistical regression coefficients for computing cloud geometric thickness (CGT) and ultimately estimating CBH. This information is provided by the cloud optical property retrieval algorithms. Details are provided in the respective ACHA and Cloud optical properties ATBDs.

3.3.2.2 Supplementary input

- **Cloud Optical Thickness (COT), Cloud Top Temperature (CTT), Cloud Type (CT)**
  For alternative CBH estimates, an extinction-based method for optically thin clouds such as thin cirrus has been adopted (Noh et al., 2017). COT and CT are used to identify thin cirrus clouds, and CTT is used to find a proper extinction coefficient to derive CGT for thin cirrus. The information of the products is provided in the ACHA ATBD.

3.3.3 Ancillary Data

The following ancillary datasets (i.e., data that are not native to the VIIRS SDRs or upstream cloud algorithms) are required to run the CBH algorithm:

- Surface elevation (to ensure that derived CBH do not fall below the surface)
- Convective/Lifted Condensation Levels from NWP model analysis (for limited deep convective cloud cases)
- Cloud Water Path from NWP model analysis (for pixels which do not have valid CWP retrieval values)

A more detailed description is provided in the VIIRS Algorithm Interface and Ancillary Data Description (AIADD) document.

3.4 Theoretical Description

This section describes a statistical approach for development of the AWG CBH algorithm from visible and infrared satellite measurements. The definition of CBH in this case applies to the uppermost layer of clouds. Our approach contains similarities to the VIIRS IDPS CBH algorithm (JPSS 2011) based on Hutchison et al. (2006), which retrieves CGT and subtracts this from cloud top height, but with important differences. Namely, the current method follows an alternative method to assigning CGT constrained by a CTH and CWP-dependent relationship that has been developed on actual observations of CGT from active spaceborne sensors. Details of the algorithm development are found in Noh et al. (2017). Here, we provide the physical basis for this statistical approach.

3.4.1 Physics of the Problem

Vertical cloud information, including CBH, is important in many weather and climate models and particularly to operational aviation. While satellite-borne sensors have provided a broad range of information on cloud properties over the globe, CBH from conventional satellites observations, based on infrared and visible radiances, is an inherently challenging problem. Cloud top radiances provide useful information on optical thickness, but very limited information on geometric thickness. The translation between the two forms of thickness is as variable as the morphologies of clouds found in nature.

The VIIRS Interface Data Processing Segment (IDPS) CBH retrieval algorithm is based on algorithm of Hutchison (2002) and Hutchison et al. (2006). This algorithm related COT and EPS to the liquid/ice CWP, and used the ratio of the CWP to an *a priori* estimate of liquid/ice cloud water content (CWC) to determine the CGT. As in the revised algorithm, this CGT is subtracted from the VIIRS-retrieved CTH to obtain CBH. It was determined in post-launch cal/val testing that this IDPS algorithm was not meeting performance requirements (Seaman et al. 2017), prompting development of a revised algorithm.

In the Enterprise AWG CBH algorithm (Noh et al. 2017), the CBH product is predicated on the notion that CGT can be related in a statistical sense to the retrieved CWP and the location of the cloud in the atmospheric column, represented by CTH. The CBH algorithm leverages statistical and semi-empirical techniques based on space-borne active sensor (cloud radar and 532 nm lidar) data for optimized CGT estimation, and is generally applicable to any observing system that offers estimates of CTH and CWP such as JPSS VIIRS and GOES-16/17 ABI. The CTH and CWP Level 2 information, as retrieved from the VIIRS visible and infrared observations, are used as main input for the algorithm.

3.4.1.1 Motivation for the statistical CBH estimate approach

As part of the JPSS Program's Cloud Calibration and Validation efforts, an evaluation of the VIIRS IDPS CBH algorithm has been conducted at the NOAA Cooperative Research Institute for Atmospheric Research (CIRA)/Colorado State University by comparing the IDPS CBH with observations of CBH from the Cloud Profiling Radar (CPR) onboard CloudSat (Seaman et al. 2017). The evaluation of the VIIRS IDPS CBH through matchups with daytime CloudSat data revealed that the IDPS CBH retrieval was not well correlated with CloudSat and error standard deviations for the individual granules exceeded the JPSS accuracy requirements for the VIIRS CBH product (± 2 km). Figure 2 shows an example of this performance. The results suggested that the strong dependency of the IDPS CBH algorithm on numerous upstream cloud retrieval products such as cloud phase and cloud type-dependent water content values add errors in estimating cloud base.

Based on these validation efforts, a new statistical approach for CBH retrievals was proposed and developed by using CGT stratified by CTH and expressed as a function of CWP. The relationships were derived from co-located NASA A-Train satellite data, and have been demonstrated to reduce errors resulting from incorrect cloud phase and type retrievals and related assumptions.

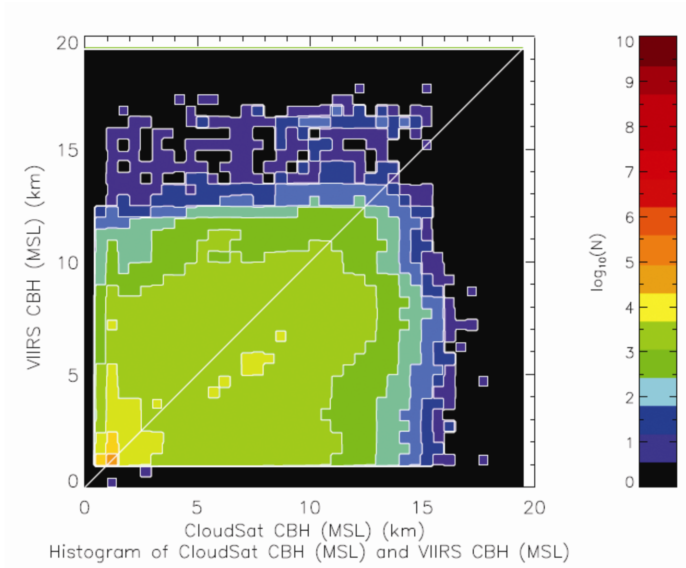

Figure 2 Two-dimensional histogram (scatter plot) of IDPS CBH retrievals from VIIRS vs. CloudSat observations of cloud base height, showing generally poor agreement. Colors represent the number of points in each 0.5 km height bin according to the logarithmic scaling indicated on the right. The white line represents the 1-to-1 line. From Seaman et al. (2017).

3.4.1.2 Cloud Microphysical Assumptions

All cloud microphysical assumptions included in the upstream CTH and CWP retrievals and cirrus cloud typing are inherited in the CBH algorithm. Otherwise, there are no specific microphysical assumptions made in the CBH retrieval.

3.4.2 Algorithm Description

The main approach employed for the Enterprise AWG Cloud Base Algorithm (ACBA) is piecewise linear regression. The benefits of this approach are that it is fast, flexible and allows for the easy addition of regression parameters. The section will describe the details of the methods and data adopted for the CBH algorithm.

3.4.2.1 Data used to derive the regressions between CTH and CWP

Our approach to estimate the CGT uses globally compiled statistics between CWP and COT by combining instantaneous passive and active sensor observations from multiple satellites of the NASA A-Train constellation (L'Ecuyer and Jiang 2010), so called for the early afternoon (13:30) local time of ascending node. The CWP information for the algorithm development is provided by Aqua MODIS (King et al. 1992). CloudSat radar data were used to obtain detailed cloud vertical structure (and hence CGT) along a curtain of MODIS data. Vertically resolved cloud geometric boundary information was derived from the combined products of CloudSat radar (Stephens et al. 2002) and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) lidar (Winker et al. 2003). The Cloud Profiling Radar (CPR, 94 GHz nadir-looking radar) on CloudSat can typically penetrate all non-precipitating clouds but has little sensitivity to optically thin cirrus and boundary layer clouds which the CALIPSO Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar is able to detect well, making the two sensors complementary for investigating the detailed vertical structures of clouds (Forsythe et al. 2012; Yao et al. 2013; Miller et al. 2014).

Several CloudSat standard data products provided by the CloudSat Data Processing Center (DPC; http://www.cloudsat.cira.colostate.edu) were employed in the analyses for the algorithm development and validation. Level 2B Cloud Geometrical Profile (2B-GEOPROF-LIDAR) data were used to qualitatively show the thickness of the clouds from the combination of the CloudSat CPR and the CALIPSO CALIOP profiles. The 2B-GEOPROF data (Marchand et al. 2008) offers cloud mask and radar reflectivity, which were used to assess the algorithm performance by comparing derived profiles against actual observations during periods when S-NPP and the A-Train were co-located (every 2-3 days).

The CloudSat CPR is also sensitive to precipitation-sized hydrometeors, which, when present, render ambiguous the true CBH and can introduce a low bias (lower CPR-reported CBH compared to the 'true' CBH that would be defined by the cloud droplet size distribution cut-off). Due to the strong dependency of radar reflectivity to the largest hydrometeors present in the range gate, there is no effective way to determine the cloud base height in the presence of precipitation. To minimize consideration of precipitating cloud profiles, precipitation flags in the 2C-PRECIP-COLUMN product were also utilized. The 2C-PRECIP-COLUMN product identifies precipitation using the path integrated attenuation algorithm of Haynes et al. (2009). Aqua MODIS Level-2 CWP values (MYD06) that overlaps and surrounds each CloudSat cloud profiling radar (CPR) footprint were used to build the relationship between CGT and CWP at a given range of CTH.

The CloudSat spacecraft began experiencing a battery anomaly condition in 2011. From that point onward, the CPR conducted operations only during daylight (ascending orbits). As such, the relationships derived for this algorithm are based on daytime cloud information. As daytime cloud optical property retrievals from VIIRS are more reliable than nighttime quantities, this CloudSat limitation does not adversely impact the overall performance of the ACBA.

3.4.2.2 Development of piecewise linear regression

The ACBA is defined as an estimate of the AMSL height of the base of the uppermost cloud layer, which is calculated by subtracting a derived CGT from CTH. The CTH is also derived from VIIRS upstream of the ACBA. CBH is retrieved only for pixels that are classified as cloudy (including 'probably cloudy') by the VIIRS cloud mask.

The retrieval of CBH in the ACBA is predicated on the notion that CGT can be related in a statistical sense to the retrieved liquid/ice CWP, with CTH providing a proxy for different cloud types found in the atmosphere. To first order, this assumption is similar to the original IDPS CBH algorithm, which first related COT and EPS to the CWP, and used the ratio of CWP to an *a priori* estimate of liquid/ice CWC to determine CGT (Hutchison et al. 2006). The IDPS algorithm assumed the liquid component of CWC was only a function of cloud type and not a function of a cloud's environmental characteristics (e.g., temperature, humidity, or location on the globe). Cloud type is a discretely defined quantity and the association of a characteristic CWC gives rise to large uncertainties and horizontal discontinuities in the CGT, as reflected in findings from the validation work of Seaman et al. (2017). The ice water component of CWC in the IDPS algorithm was temperature-dependent, but was also shown to result in large errors and spatial discontinuities. With the insight from the validation results and statistical analyses to obtain 3D cloud structures from CloudSat observations shown in Miller et al. (2014), a new method was proposed to improve CBH retrievals by using observed CGT, stratified by CTH and expressed as a function of CWP.

The basis of the new statistical CBH algorithm is illustrated in Figure 3. CGT of the uppermost layer from the combined CloudSat/CALIPSO cloud vertical profile product (2B-GEOPROF-LIDAR) is plotted versus MODIS Level-2 CWP values (MYD06) for a set of 100 orbits from July 2007. MODIS was used in this analysis because of the formation flight of Aqua with CloudSat/CALIPSO, and for its similarity in terms of retrieved cloud optical property (e.g., King et al. 1997) information to VIIRS. Similar relationships between CWP and CGT were calculated for CTHs residing in 2 km vertical bins from the surface to the top of the troposphere. All cases are from daytime, where CloudSat is operational and the MODIS CWP product (reliant on cloud optical thickness, COT and effective particle size, EPS) have inherently better performance. As discussed in Walther et al. (2013), retrieval of COT and EPS is difficult at night and leads to greatly reduced accuracy of these quantities. As seen in Figure 3, CGT rapidly increases in a nearly linear fashion for CWP values between 0 and 0.2 kg/m^2. Much more scatter occurs above 0.2 kg/m^2, reflecting the saturation of the infrared and visible radiance response to physically thicker clouds.

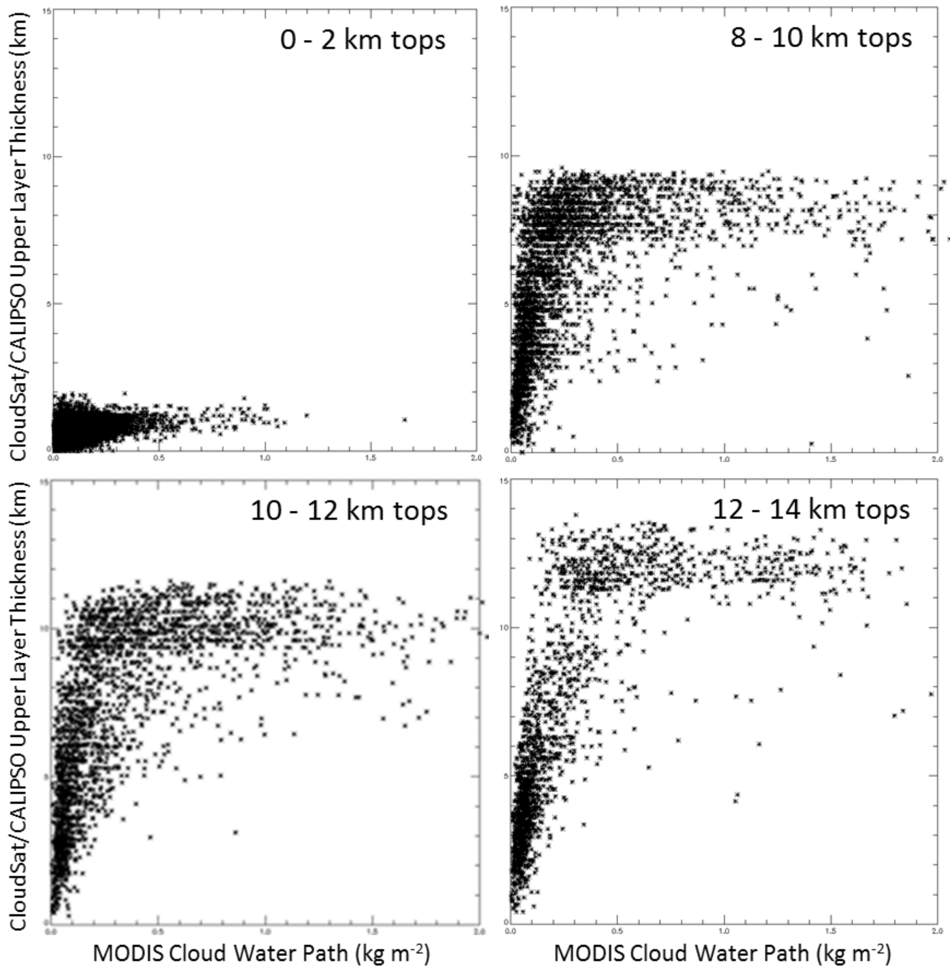

Figure 3 MODIS cloud water path versus CloudSat/CALIPSO cloud geometric thickness of the uppermost layer for tops between 0 – 14 km for matchups in July 2007.

Based on these findings, a piecewise linear regression was performed for four years of July data from 2007-2010, from a total of 1743 orbits of CloudSat/CALIPSO data (59,036 profiles). The regression fits were stratified by 2-km bins of CTH from the surface up to 20 km as derived from the MODIS Cloud Top Pressure (CTP) product. CTP was converted to CTH via coincident temperature profiles from the ECMWF model analysis. The median value of the MODIS CWP in each 2-km CTH bin was determined, and a linear regression above and below this threshold value was conducted. This approach preserved the linear response at low CWP in Figure 3, and provided the capability to estimate CGT for deeper clouds. The coefficients for the piecewise linear fits are summarized in Table 3. Although simple in construct, the piecewise linear method has been shown to out-perform the IDPS algorithm in head-to-head evaluations.

Table 3. Regression coefficients and median CWP binning by CTH (every 2 km) derived from CloudSat/CALIPSO and MODIS data (59,036 profile samples in July 2007-2010) which are used to compute CGT for CBH. The coefficient set (*a* and *b*) to be used is determined by inspection whether the pixel's CWP is above or below each CWP threshold for the corresponding CTH bin.

Cloud Top Height (km)	CWP thresholds (g/m^2)	Constant *a* (slope)	Constant *b* (y-int)
0 < CTH < 2	71	2.2581	0.4056
		0.9970	0.5170
2 ≤ CTH < 4	114	6.1098	0.6648
		0.9130	1.3570
4 ≤ CTH < 6	110	11.5574	1.2253
		1.3792	2.5866
6 ≤ CTH < 8	123	14.5382	1.7057
		1.6871	3.6228
8 ≤ CTH < 10	131	9.0986	2.1425
		2.4595	3.8696
10 ≤ CTH < 12	127	13.5772	1.8655
		4.8309	3.5314
12 ≤ CTH < 14	115	16.0793	1.6497
		5.0517	3.9861
14 ≤ CTH < 16	116	14.6030	2.0001
		6.0644	4.0330
16 ≤ CTH	99	9.2658	2.2964
		6.6043	3.2644

3.4.2.3 Implementation in the CLAVR-x system

The statistical CBH algorithm has been implemented in the Clouds from AVHRR Extended (CLAVR-x) processing system for demonstrations. A schematic diagram of the algorithm is shown in Figure 1. In our CBH algorithm, the CBH product requires *a priori* information on CTH and CWP. The CWP is derived using VIIRS retrievals of COT and EPS. These algorithms are embedded in the current CLAVR-x system. Currently, the daytime cloud optical and microphysical properties (DCOMP; Walther and Heidinger 2012) and nighttime lunar cloud optical and microphysical properties (NLCOMP; Walther et al. 2013) algorithms are operated in the CLAVR-x system. The CTH is produced from the NOAA AWG Cloud Height Algorithm (ACHA; Heidinger 2015) using IR channels, which is also part of the CLAVR-x.

In the case where both DCOMP and NLCOMP products are not available for a cloudy pixel, the cloud optical property output from ACHA is used for the CBH algorithm. The CBH algorithm uses these parameters to interrogate a height-dependent look-up-table (Table 3) which relates the integrated cloud water path to a geometric thickness. It finds where CTH is placed in the 2-km bins for each pixel and examines CWP against the CWP threshold to determine two regression constant sets in each CTH bin to cloud thickness. The CGT is then subtracted from the retrieved CTH to yield an estimate of CBH, according to:

$$CGT = (a \times CWP) + b \quad (3.1)$$

$$CBH = CTH - CGT \quad (3.2)$$

where two constants, a and b are selected from the lookup table (Table 3) depending on where the currently observed CTH falls within the 2 km vertical stratification.

Excessively large CGT values can occur for deep convective clouds. In limiting cases of optically thick deep convection (CWP $\geq$ 1.2 kg/m^2), the CBH estimate defaults to a height between convective condensation level (CCL) and lifted condensation level (LCL) as derived from NWP data that has been matched to the cloudy pixel's location and time of observation.

$$CBH = (CCL_{\_NWP} + LCL_{\_NWP}) \times 0.5 \text{ (pixels identified as deep convection)} \quad (3.3)$$

When CWP $\geq$ 1.0 kg/m^2, CBH changes linearly between the original CBH (Eq. 3.2) and NWP condensation levels (Eq. 3.3). For pixels where VIIRS does not provide a valid CWP, the corresponding NWP field values of CWP (currently, the full-column value) are used as supplementary data. If no NWP CWP exists, then an Error_Fill value is reported with description of 'no upstream input' reported. For the case results reported by Noh et al. (2017), NWP-supplied CWP values accounted for less than 1% of the total valid VIIRS retrievals, and that the average number of NWP-supplemented pixels is ~0.25%. Furthermore, NWP condensation level values were used less than 0.01 % of all pixels considered.

As a quality control filter, VIIRS pixels have been excluded when the CBH retrieval produces an out-of-range value (0 ~ 20 km) or has been assigned poor quality according to the granule's quality flags. Quality flags in the CBH retrieval product inherit the upstream quality flags as well as flags within the CBH algorithm itself. Specifically, the CBH product is a strong function of the CTH and integrated liquid/ice CWP derived from COT and EPS. If these upstream input data enter the CBH algorithm with out-of-range/poor-quality flags triggered, we assume that the CBH processing should inherit that information and not attempt a valid CBH estimate based on dubious information at that pixel. Cloud phase or type information is not utilized in the current CBH algorithm except for optically thin clouds such as 'thin cirrus', which will be described in the next section.

3.4.2.4 Extinction-based method for optically thin clouds

An extinction-based method developed by using CALIPSO data is employed for better CBH estimates of optically thin clouds such as thin cirrus. The extinction method, adopted from ongoing research at the University of Wisconsin-Madison's Cooperative Institute for Meteorological Satellite Studies (CIMSS), is an effective way of retrieving cloud base for upper-level thin cirrus cloud and has been validated against both ground based and space-based observations. Optically thin clouds such as Cirrus have COT less than 2 in general, and it is typically assumed that the satellite passive-sensor retrieved CTH is located at the vertical center of these clouds. Based on the assumption, CBH for these thin clouds can be derived by subtracting half of the CGT from the retrieved CTH. The CGT can be simply computed knowing the COT and extinction coefficient. The infrared-based COT retrieval is discussed in Heidinger et al. (2015). Since cirrus-like clouds are optically thin and therefore the observations are sensitive to the entire extinction profile through the clouds, it is also reasonable to assume a vertically invariant extinction coefficient for this approximation.

For computing the extinction coefficients, we take advantage of CALIPSO lidar data which provides the vertical profiles of cloud layers and is fairly accurate in determining COT and cloud upper/lower boundaries particularly for high thin clouds. The CALIPSO 5-km cloud layer product for September 2013 was used, and only single layer clouds with COT less than 2 were chosen for the analysis. Table 4 shows the extinction coefficients derived for five cloud top temperature (CTT) intervals. The method is applied to thin clouds with COT less than 1 in the current algorithm.

Table 4. Mean cirrus cloud extinction coefficients for five CTT intervals.

CTT interval (K)	< 200	200 ~ 220	220 ~ 240	240 ~ 260	> 260
Cirrus Extinction (km^{-1})	0.13	0.25	0.39	0.55	0.67

3.4.2.5 Treatment of Multi-layer Clouds

The CBH algorithm has been developed for optimal performance for single layer clouds. Given CTH and CWP, the CBH processing remains unchanged for pixels determined to be single or multi-layer clouds. When multiple layers of cloud exist, the algorithm reports the CBH based on the CTH of the upper-most cloud layer. An obvious caveat to the CBH retrieval in multi-layered cloud systems is that CWP retrievals represents a column-integrated quality, such that applying an augmented CWP will result in overestimation of CGT for the uppermost cloud layer, and commensurate underestimation (i.e., placing too low in the atmospheric column) of CBH for this uppermost cloud layer. Thus, users are advised to use the CBH product with caution when a multilayered cloud system is suspected (e.g., in cases where cloud overlap classification flag is specified in other VIIRS Cloud EDR products). Future developments of the ACBA are attempting to improve the description of two-layered cloud systems identified by VIIRS and to adopt machine learning approaches (e.g., Haynes et al. 2021).

3.4.2.6 Toward an Improved 'Cloud Cover and Layers' Product

The CBH information will be employed to enhance the Cloud Cover and Layers (CCL) product which is currently produced from the ACHA to determine the fractional area of clouds in various vertical layers of the atmosphere. The CBH algorithm provides additional lower-level cloud coverage information to the original CCL algorithm. Atmospheric layers in the CCL algorithm can be classified as High, Middle, and Low using the International

Satellite Cloud Climatology Project (ISCCP) standard definition with cloud top pressure (CTP) thresholds of 680 hPa and 440 hPa, or the NCEP definition of 631 hPa and 350 hPa. The layers can be defined based on flight levels of 5000, 10000, 18000, 24000 ft or above for aviation applications. For each cloudy pixel, the CBH is checked against these CTP thresholds and additional cloud fraction may be added to layers below the one in which the CTH resides. These lower layers would otherwise be missed by the original CCL algorithm since it uses no information on CGT. A conceptual illustration is shown in Figure 4. The CBH Team in collaboration with other Cloud Application Teams continue to improve the CCL product, deemed operationally useful by the aviation community.

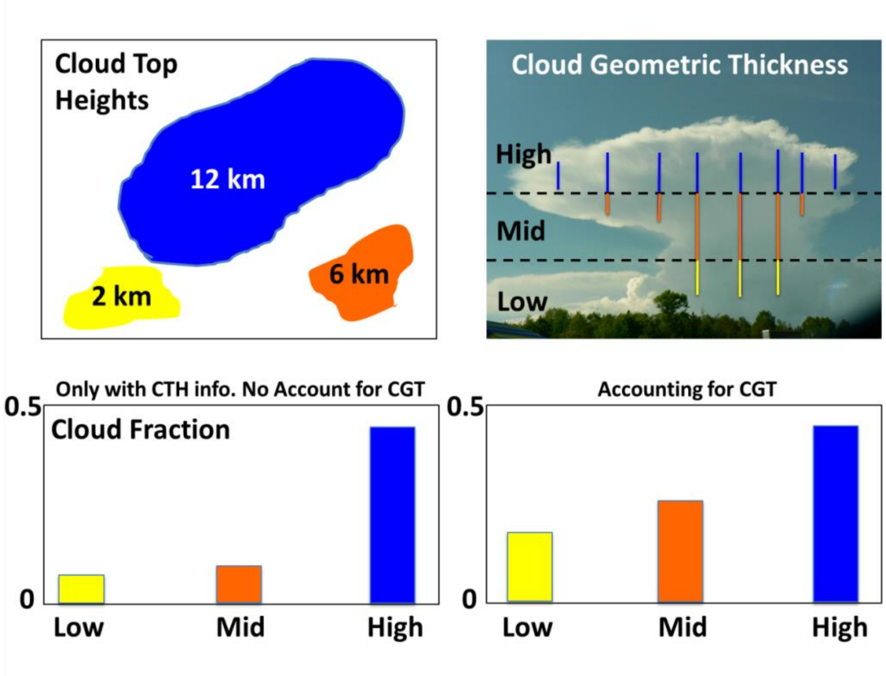

Figure 4 A conceptual figure of how cloud geometric thickness information can be used to modulate the layered cloud fraction (high/mid/low) by introducing additional cloud coverage at lower (unobserved via satellite) levels of the profile.

3.4.3 Algorithm Output

3.4.3.1 Output

The output of the AWG CBH algorithm provides the following product:

- Cloud base height

CBH of the uppermost layer of clouds is derived at the pixel level for all cloudy/probably cloudy pixels. It will have a native VIIRS M-Band horizontal resolution of 750 m. The algorithm should be run with the same refresh cycle for the other VIIRS Cloud Products.

3.4.3.2 Intermediate data

The CBH algorithm derives the intermediate products if they should be used in other algorithms, such as the Cloud Cover and Layers (CCL) algorithm. Please see the CCL ATBD for more information.

3.4.3.3 Product Quality Flag

In addition to the algorithm output, a pixel level product quality flag will be assigned. The possible values are shown in Table 5:

Table 5. Product quality flag values and descriptions for ACBA.

Flag Value	Description
0	Valid retrieval from the statistical method
1	Invalid due to the upstream input being invalid or clear
2	CBH = Terrain due to CBH lower than Terrain
3	Out of range due to CBH < minCbh (0 km) or CBH > maxCbh (20 km)
4	Invalid due to CBH >= CTH
5	Valid retrieval from the extinction method
6	Valid retrieval from NWP for deep convection

3.4.3.4 Processing Information Flag

In addition to the CBH algorithm output and quality flags, processing information will be subject to how the cloud algorithms are processed in the NDE system.

3.4.3.5 Metadata

In addition to the algorithm output, the following parameters will be output to the file as metadata for each file:

- Min and Max values of cloud base height
- Number of QA flag values
- Definition of QA flags

3.4.4 Algorithm Refinements

Since the CBH algorithm has a relatively short development history in comparison with other VIIRS Cloud EDRs which benefited from years of development, we anticipate that the CBH algorithm will undergo further refinements. The statistics will become more robust as additional data are introduced to the algorithm and additional quality control flags are included. Through further quality control, we will work toward higher-order piecewise fits to the current regression method. Algorithm refinements to be examined include improved performance in i) deep convective clouds using climatological data, ii) thin clouds using retrieved optical thickness and CloudSat/CALIPSO data, and iii) multilayer clouds using traditional statistics and machine learning approaches.

4 TEST DATASETS AND OUTPUTS

4.1 Validation Overview

Validation activities are aimed at characterizing uncertainties of the data products and the performance of the algorithm as well as identifying important algorithm refinements. We have assessed the performance of the ACBA using near simultaneous overpasses between VIIRS CBH retrievals and observations from CloudSat. The CBH retrieval algorithm was implemented in the CLAVR-x frame for preparation of demonstration in the NDE system. The initial results have been evaluated within the context of CLAVR-x against CloudSat observations, as reported in Noh et al. (2017), and are recapitulated here.

For validation of the ACBA we leveraged the satellite orbital prediction, parallax correction, and data extraction tools developed at CIRA for the VIIRS IDPS CBH evaluation using CloudSat data collocated with S-NPP VIIRS (Seaman et al. 2017). The rest of this section describes the validation datasets and methodologies employed in assessing the product of the CBH algorithm and results with evaluation of the accuracy and precision specifications.

4.1.1 Input Data

There were no proxy and simulated instrument data required for this validation, as the VIIRS instrument was already operating on S-NPP at the time of this algorithm development. Thus, we can use VIIRS data directly, and will leverage these measurements for the algorithm development/validation for JPSS-1, slated for launch in the Fall of 2017.

4.1.2 CloudSat Data

With the launch of CloudSat and CALIPSO into the NASA EOS A-Train in April 2006, the ability to perform global satellite cloud product validation increased significantly. Currently, CloudSat cloud products are being used to validate the ACBA product. CALIPSO data were used for specific validation of thin cirrus.

The CloudSat CPR is a near-nadir-looking (0.16° forward) W-band (94 GHz; 3 mm) cloud profiling radar with a field of view of ~1.3 km in the across-track dimension and ~1.7 km in the along-track dimension. Profiles are collected every 1.1 km, and the effective vertical resolution is ~240 m. Additional details of the CloudSat CPR are found in Stephens et al. (2002; 2008) and Tanelli et al. (2008). It is noted here again that a battery anomaly onboard the CloudSat satellite in April 2011 (prior to the launch of S-NPP) has limited operation of the CPR to the daytime side of the earth (Nayak et al. 2012). Therefore, validation using VIIRS-CloudSat matchups presented in the following section is for daytime passes only.

For validation, the following operational CloudSat Level 2 data are utilized.

- 2B-GEOPROF product for the CPR Cloud Mask
- 2C-PRECIP-COLUMN product for removing precipitation profiles

4.1.3 Ground-based Measurements

For nighttime CBH validation, we utilized surface-based ceilometer measurements from the US Department of Energy Atmospheric Radiation Measurement (ARM) Climate Research Facility (www.arm.gov) and continue to explore the possibility to use ARM radar/lidar data as an additional point-source validation. Since these are point observations, a considerably longer time series is required to build statistical robustness in the validations compared to the satellite-based simultaneous observation methods. The ground-based measurement validation should be regarded as provisional.

4.2 Validation Procedures

4.2.1 Matching CloudSat and VIIRS

The performance of the CBH retrieval was evaluated by comparing the VIIRS retrievals against observations from the CloudSat CPR. In this section, we describe the CloudSat CPR, define "matchup periods" where CloudSat and S-NPP observations are nearly co-located in space and time. We then describe the methodology by which VIIRS CBH retrievals were extracted and compared against CloudSat observations.

The 2B-GEOPROF and 2C-PRECIP-COLUMN operational CloudSat Level 2 data products were utilized for validation of ACBA. The 2B-GEOPROF product (Marchand et al. 2008) contains the calibrated radar reflectivity as well as the CPR Cloud Mask. The CPR Cloud Mask was used to identify CTH and CBH in the CloudSat observations, while the radar reflectivity was used as a sanity check against those estimates. For a CPR profile containing a single cloud layer, CBH is defined as the height AMSL of the lowest range gate in the CloudSat profile that is identified as cloudy according to the CPR Cloud Mask. In cases where multiple cloud layers exist in the profile, CBH is defined as the base of the uppermost cloud layer. CTH is defined as the height above AMSL of the highest range gate identified as cloudy in the CPR Cloud Mask. Since the CBH retrieval is only valid for clouds between 0 and 20 km AMSL, clouds with CTH exceeding 20 km AMSL were excluded. As CBH is difficult to define in precipitating clouds, CloudSat profiles likely containing precipitation were excluded from this analysis using precipitation flags from the 2C-PRECIP-COLUMN product (Haynes et al. 2009).

A battery anomaly onboard the CloudSat satellite in April 2011 (prior to the launch of S-NPP) has limited operation of the CPR to the daytime side of the earth (Nayak et al. 2012). The 2B-GEOPROF-LIDAR product which combines information from CloudSat and CALIPSO is often invalid or not available for the analysis due to the difficulty in maintaining tight formation flying since this battery anomaly occurred, and thus the distance between CloudSat and CALIPSO may exceed the requirements of the 2B-GEOPROF-LIDAR product. Another limitation of the CloudSat CPR is the presence of ground clutter which produces artifacts contaminating the first three range gates above the surface (up to ~750 m above ground level [AGL]). To ensure that cloud detection is not impacted by ground clutter, CloudSat profiles where the observed CBH and/or CTH are less than 1 km AGL were excluded from this analysis. Unfortunately, this precludes the analysis of many boundary layer clouds. However, uncertainties in the CBH of these low clouds (whose maximum uncertainty is of course confined to a maximum value of 1 km or less) may not be well characterized by the 250 m (oversampled from 500 m) vertical resolution of CloudSat in any case. The CloudSat Digital Elevation Map (DEM) in the 2B-GEOPROF product was used to determine height AGL.

The higher spatial resolution of VIIRS (~750 m) compared to the CloudSat CPR results in as many as 12 VIIRS pixels (at nadir) that can partially or fully overlap a single CloudSat footprint and as few as two (at VIIRS scan edge). For this work, we selected the VIIRS CBH retrieval for the overlapping pixel that is closest to the center of the CloudSat profile that did not contain any error fill values. The closest (non-error-filled pixel, if possible) VIIRS CBH retrieval that at least partially overlaps the CloudSat footprint, when paired with the CloudSat profile comprised the set of "matchup points."

Matchup points were excluded from the statistical analysis if any of the following conditions was true: i) either the VIIRS Cloud Mask or CPR Cloud Mask failed to detect cloud; ii) either the VIIRS or CloudSat CTH and/or CBH values were less than 1 km AGL or 20 km AMSL; iii) precipitation was identified in the CloudSat profile; iv) all VIIRS pixels that at least partially overlapped with the CloudSat profile were error-filled. Matchup points that were not excluded by this filter comprised "valid" matchup points.

4.2.2 Validation of CBH Retrievals

To estimate the precision and accuracy of the CBH retrievals, CloudSat data which provided information of the vertical cloud structures were used for daytime validation on a global scale, following the matchup methodology described in the previous section. This section describes the validation results of the performance of VIIRS CBHs generated from CLAVR-x for selective intensive matchup periods. GFS forecast data were used as the ancillary NWP data in the CLAVR-x run.

4.2.2.1 Matchup Periods

Matchup data from September-October 2013 and January-May 2015 were used to span the entire domain and encompass a full range of conditions. A "matchup period", as used here, defines the period of time during which CloudSat and VIIRS view the same locations on the Earth's surface within 15 minutes or less. Because VIIRS and CloudSat are located at different altitudes on the same orbital plane (i.e., sun-synchronous orbit with a 13:30 local time [LT] ascending-node equator crossing time), these matchup periods occur once every 2-3 days and last for approximately 4.5 hours, or 3 full orbits of the S-NPP satellite. Figure 5 shows sample CloudSat paths for an example matchup period.

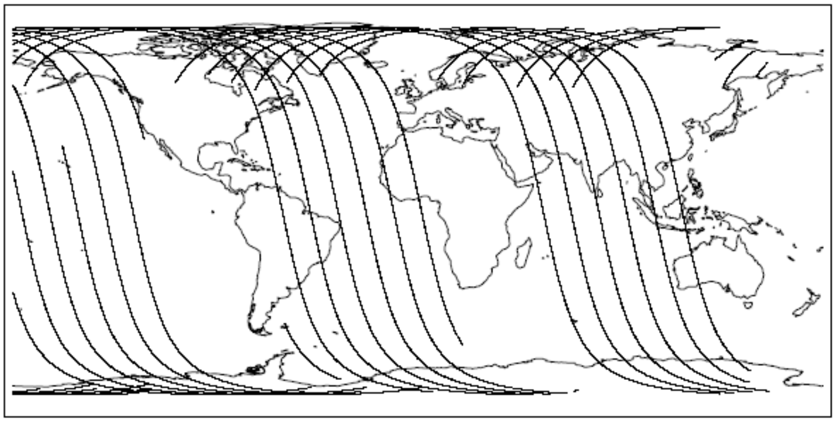

Figure 5 Locations of the matchup points for September – October 2013.

4.2.2.2 Comparisons of VIIRS CBH retrievals and CloudSat data

The CBH algorithm was applied to S-NPP VIIRS data, and the performance assessed through comparisons with CloudSat measurements matched in space/time to VIIRS. The retrievals were performed for two periods; September-October 2013 and January-May 2015. We assessed the accuracies of CBH and CTH using CloudSat data as truth, and the details for the VIIRS-CloudSat matchups can be found in Seaman et al. (2017). Since the CTH accuracy is critical to the CBH retrieval in the algorithm, the results shown here come from the subset of valid matchup points where the CTH retrieval is "within spec" with regard to CloudSat observations, per VIIRS performance requirements. "Within spec" means only cloudy pixels where the VIIRS CTH retrieval error (compared to CloudSat) is less than 1 km if the COT is greater than 1, or less than 2 km if the COT is less than 1, when compared to CloudSat observations. In examining the comparison results, it is noted that the VIIRS System Specification uncertainty requirement is 2 km for CBH. Matchup points where the error was less than 250 m were "correct," as this is approximately the vertical resolving capability of the CloudSat CPR.

Figure 6 shows examples of VIIRS-CloudSat matchups collected from the September-October 2013 matchup cases. The plots in Figure 6 show the vertical location of clouds as represented by the CloudSat Cloud Mask (gray-shading) along with the matching VIIRS vertical location of clouds as given by the CBH and CTH retrievals (colored according to the CLAVR-x cloud classification). Although cloud type retrieval information is not essentially involved in the statistical CBH estimation, the display is shown for information purposes. When CTH retrievals were accurate, the statistical CBH retrievals showed generally good performance for all cloud types compared against CloudSat. However, as shown in the middle left panel of Figure 6, when a large CWP value is retrieved in multi-layered cloud systems the CBH algorithm shows a tendency to identify the base of a lower cloud layer, as opposed to the base of the uppermost cloud layer. The CBH result will match most closely with the cloud base of the uppermost layer for single-layer clouds. Hence, CBH accuracy is tied to the accuracy of the CTH and CWP retrievals as well as to the validity of the single-layer cloud assumption.

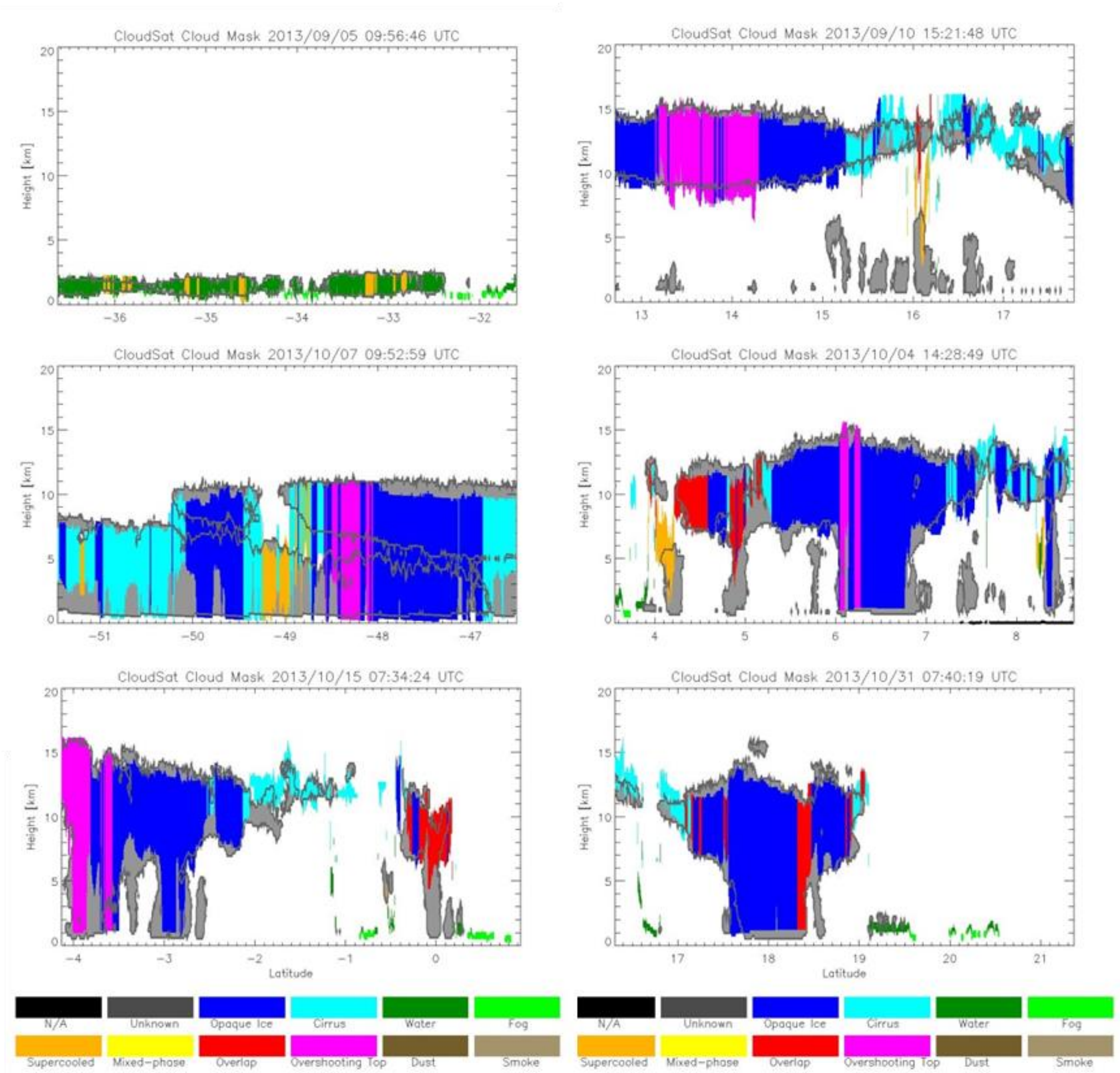

Figure 6 CBH retrievals from the statistical CBH retrieval algorithm for selected VIIRS granules during the January-May 2015 VIIRS-CloudSat matchups. The CloudSat cloud boundaries from 2B-GEOPROF data are in gray, and the VIIRS CTH and CBH retrievals are colored by each cloud type (obtained from CLAVR-x with VIIRS) for comparison purposes.

The original VIIRS IDPS CBH algorithm performance was also examined for these same cases. Figure 7 shows the comparison results with histograms of the number of matching points per bin on the logarithmic scale between the original IDPS and the new statistical regression ACBA when both were compared against CloudSat ‘truth’ observations for September – October 2013 matchups. Since the discrepancy related to the upstream IDPS products feeding into CBH may contribute to larger uncertainties in the algorithm comparison, we implemented a stand-alone code of the IDPS CBH algorithm as based on the original JPSS VIIRS CBH ATBD of JPSS (2011) and utilized the CLAVR-x supplied ancillary cloud property input data to provide a proxy to keep consistency in the comparison. For the matchup analysis, 1,051,243 matchup profiles for 2,077 VIIRS granules were examined, and 95,145 "within spec" matchup points were selected by removing ground clutter/precipitation contaminations and error-fill pixels. The statistical algorithm has more opportunities to retrieve valid CBH values compared to the IDPS algorithm that relies on more upstream cloud property products (i.e., more single points of failure). Initial results show the current statistical regression method outperforms the original IDPS CBH algorithm with CLAVR-x upstream input, with a tighter clustering of points along the 1:1 agreement line (Figure 7).

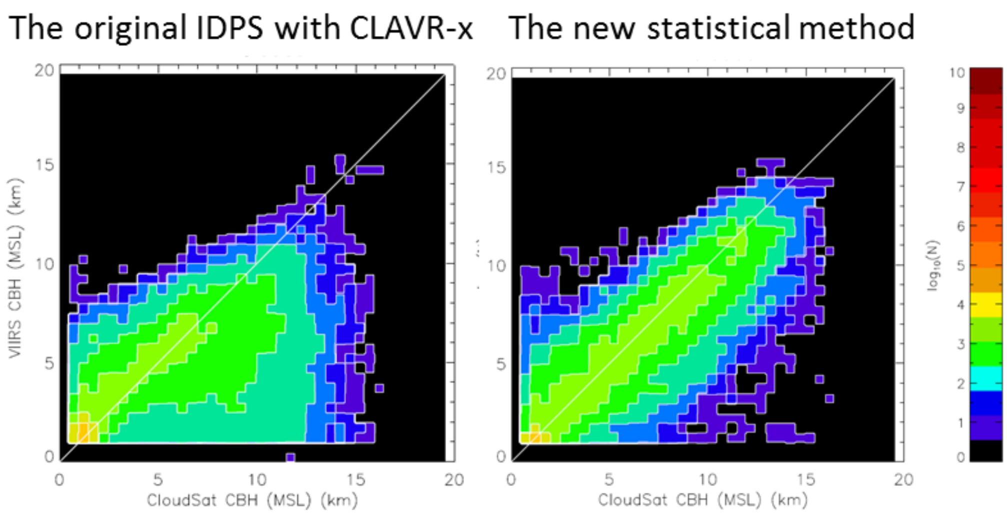

Figure 7 Two-dimensional histograms (scatterplots) of VIIRS-retrieved and CloudSat-observed CBH for the original IDPS CBH algorithm with CLAVR-x input (left) and the statistical algorithm (implemented within the CLAVR-x system) (right) for September – October 2013. Colors represent the number of valid matchup points (N) per bin on the logarithmic scale provided, and are valid for all cloud types globally where the cloud top height retrieval was accurate ("within spec").

The validation period is extended to the January-May 2015 matchups as shown in Figure 8. A total of 2,718,982 matchup profiles for 5,358 VIIRS granules was examined, and 216,745 "within spec" points are considered here. The general performance pattern is like the September-October 2013 matchups. In the histograms from the two period matchups for the statistical CBH algorithm, it is inferred that the largest errors occur when CloudSat observes the base height of the (likely optically thin) uppermost cloud layer of a multi-layer cloud system, while the CBH algorithm retrieves the base of a lower cloud layer, due to the sensitivity of VIIRS to CWP from both cloud layers. Another source of bias occurs when VIIRS CBH is high, but CloudSat CBH reaches almost to the surface. These cases might be caused by unflagged precipitation-contaminated CloudSat data. Although we are using precipitation flags from 2C-PRECIP-COLUMN to filter out those profiles in the comparisons, some unfiltered profiles may remain. In addition, there could exist optically thin high clouds that VIIRS detects but CloudSat does not. Further research is ongoing for the algorithm refinement.

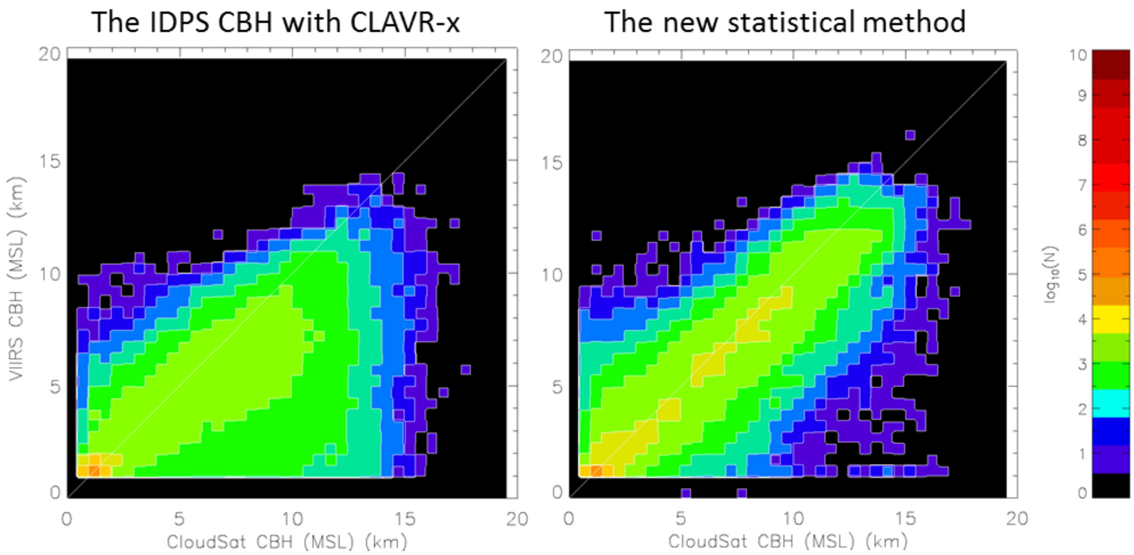

Figure 8 Two-dimensional histograms (scatterplots) of VIIRS-retrieved and CloudSat-observed CBH from the statistical CBH algorithm for January – May 2015 matchups. Colors represent the number of matching points (N) per bin on the logarithmic scale provided, and are valid for all cloud types globally where the cloud top height retrieval was accurate ("within spec").

Tables 6 and 7 show the CBH error statistics compared with CloudSat for each cloud type for September-October 2013 matchups and Jan-May 2015 matchups for "within spec" comparisons. Various statistical analyses are conducted to quantitatively investigate CBH algorithm performance for the selected matchup periods. It is noted that the statistics (error magnitudes) derived from CloudSat on cloud thickness as a function of cloud type are only shown to determine skill with respect to conventional climatology purposes, although the algorithm is not cloud-type-dependent except for thin cirrus. In the tables, matchup points where the error is less than 250 m (the minimum resolution of CloudSat) are "correct". In general, the statistical approach to retrieve CBH shows good agreement with CloudSat if the CTH accuracy is satisfied, and this satisfies the JPSS accuracy requirements for the VIIRS CBH product (± 2 km). The performance is best for water clouds and leaves room for further improvement in cases of overlap and overshooting cloud types (where multi-layer clouds might be involved) as well as opaque ice clouds. It should be noted that the sample numbers of opaque ice and overshooting cloud types are relatively small here.

To further improve the CBH algorithm, an extinction method described in the previous section was employed for optically thin clouds (typically cirrus) with COT less than 1. Figure 9a shows CBH comparisons between VIIRS (with the original regression algorithm) and CloudSat particularly for the thin 'cirrus-typed' clouds during September-October 2013 matchups. Note that the statistical results from the 'within spec' comparisons for these clouds were indicated in parentheses in Table 5. The original regression method showed a low bias in the CBH estimate for these clouds. The extinction-based method developed based on CALIPSO data has been implemented to improve CBH estimates of thin cirrus. The results shown in Figure 9b indicate improved performance. Compared to CloudSat ('within spec' analysis), the results with the extinction method provides statistically better CBH estimates that the error (bias) is improved from 1.4 km to -0.5 km, the root-mean-square error (RMSE) from 1.9 km to 1.3 km, and the standard deviation of the errors from 1.3 km to 1.2 km, with a higher correlation coefficient (R^2) of 0.78 (from the original 0.72). The extinction method has therefore been implemented in the current version of the CBH algorithm.

Table 6. Error statistics of cloud base heights (CBH) from VIIRS-CloudSat matchups for Sept-Oct 2013 (95,145 "within spec" matchup points).

CBH [km] within spec only	**Samples (%)**	**Avg error (bias)**	**Std of error**	**Median error**	**RMSE**	**r^2**	**CBH within 250 m of CloudSat (%)**
All	**100**	**0.3**	**1.7**	**0.2**	**1.7**	**0.791**	**19.9**
Cirrus (thin)	51 (6)	0.3 (-0.5)	1.7 (1.2)	0.2 (-0.5)	1.7 (1.3)	0.698 (0.775)	12.6 (15.4)
Opaque Ice	14	0.3	2.3	0.1	2.3	0.515	11.4
Water	9	0.2	0.5	0.2	0.5	0.688	53.6
Supercooled	21	0.3	1.1	0.1	1.1	0.688	30.5
Overlap	4	0.4	2.1	0.3	2.1	0.502	10.6
Overshooting	1	0.8	2.8	0.6	3.0	0.295	9.1

Table 7. Same as Table 6 but for Jan-May 2015 (216,745 "within spec" matchup points).

CBH [km] within spec only	**Samples (%)**	**Avg error (bias)**	**Std of error**	**Median error**	**RMSE**	**r^2**	**CBH within 250 m of CloudSat (%)**
All	**100**	**0.4**	**1.6**	**0.3**	**1.7**	**0.803**	**19.8**
Cirrus (thin)	49 (5)	0.5 (-0.4)	1.7 (1.3)	0.3 (-0.4)	1.7 (1.3)	0.729 (0.770)	12.2 (14.7)
Opaque Ice	12	0.5	2.3	0.3	2.3	0.486	11.3
Water	10	0.2	0.5	0.1	0.6	0.770	51.2
Supercooled	23	0.4	1.1	0.2	1.2	0.671	29.2
Overlap	5	0.4	2.2	0.3	2.2	0.447	10.8
Overshooting	1	0.6	3.4	0.2	3.5	0.196	7.5

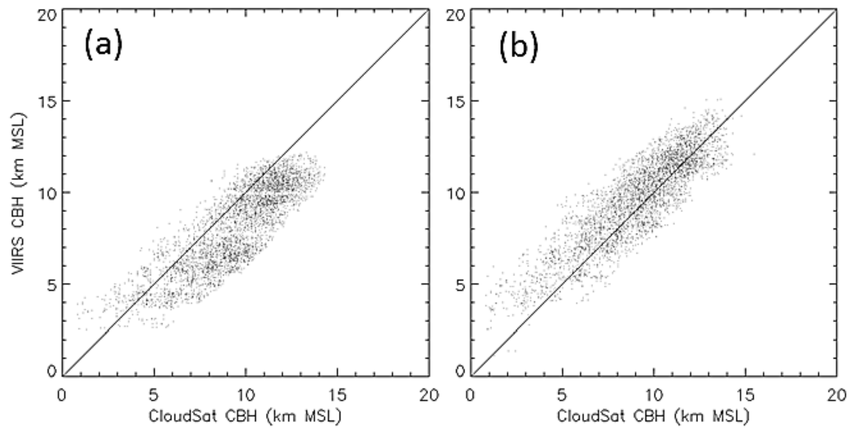

Figure 9 CBH comparisons between VIIRS and CloudSat for optically thin cirrus clouds during Sept-Oct 2013 matchups from (a) the original statistical regression method and (b) an extinction method using CALIPSO data. It is noted that the results are from "within spec" comparisons when CTH is in an accurate range compared to CloudSat data.

The initial results with the CBH algorithm applied to S-NPP VIIRS are very encouraging, even though there are some known limitations to this simple statistical approach. Comparison with CloudSat for the overpass periods show that the statistical retrieval approach used for VIIRS performs better than the original VIIRS IDPS CBH products particularly when CTH compares favorably with CloudSat observations, which are used as ground truth. This limited validation suggests the CBH product will meet JPSS system requirement for accuracy of the VIIRS CBH (± 2 km) if the CTH retrieval is accurate.

Although the dependency from upstream retrieval input is significantly reduced in the current algorithm, relative to the original IDPS algorithm, errors in CTH and CWP may directly affect the CBH product quality. Accurate CTH is the necessary condition for accurate retrieval of CBH. Multi-layered clouds ('overlap') are identified as an output from the CLAVR-x system (Pavolonis and Heidinger 2004). Please note that the current multilayer detection only performs well when there is large optical separation between layers. Since the ACBA is based on CTH and CWP retrieval values, CBH analyses are optimized for a single cloud layer. As the algorithm retrieves CBH for the uppermost cloud layer, the retrieved cloud base from the CBH algorithm may or may not be what is considered a 'ceiling' in the aviation community, depending on the presence or absence of multiple cloud layers. There could be a lower cloud layer below our retrieval base.

The VIIRS-CloudSat matchups show the performance is best for water clouds. Cirrus and multi-layered clouds need further improvement, and continued matchups with CALIPSO will be particularly useful for future investigation. CBH is currently retrieved for both daytime and nighttime if valid CTH and CWP values exist, although the regression method has been developed with daytime satellite data. Analyses with ground observations for nighttime performance are also currently being processed, a task which could not be accomplished using CloudSat due to a lack of nighttime data; furthermore, the algorithm performance might be degraded at night since nighttime cloud optical property retrievals (including CWP) are more challenging in this environment (Walther et al. 2013).

4.2.2.3 Nighttime CBH Analysis

Since CloudSat operates in daytime-only mode, ceilometer data from the ARM sites (Morris 2012) were utilized as a source of information for nighttime validation. Selected cases in 2015 were examined when S-NPP VIIRS overpasses near the North Slope of Alaska (NSA) site at Barrow and the Southern Great Plains (SGP) site in north-central Oklahoma. The laser ceilometer transmits near-infrared pulses of light and receives the light scattered back by clouds. It is capable of detecting up to three cloud layers with a maximum vertical range of about 8 km.

For nighttime retrievals, CBH was computed in CLAVR-x using cloud optical properties (in particular, the associated CWP) from NLCOMP (Walther et al. 2013, using moonlight measurements from the VIIRS Day/Night Band, with supplementary data from NWP CWP when the retrievals do not provide valid values for a given cloud pixel. Comparison results for 2019-2021 are shown in Figure 10. A matchup window of 1 km distance and 5-minute time lag is used between ARM and VIIRS data (2214 "within spec" matchups for NSA and 716 for SGP). Note that ARM NSA case can have multiple matchups per one day during wintertime. CBHs within the 2 km error range are found between red dotted lines. Overall, 89.2% of VIIRS CBHs against Ceil and 82.1% against MPL for NSA are present within 2 km error ranges, and they are 83.8% against Ceil and 67.5% against MPL for SGP. Although further investigation is in progress, the results show that the CBH algorithm often demonstrates limited skill at night and for multilayer cloud scenes (out of 2 km errors).

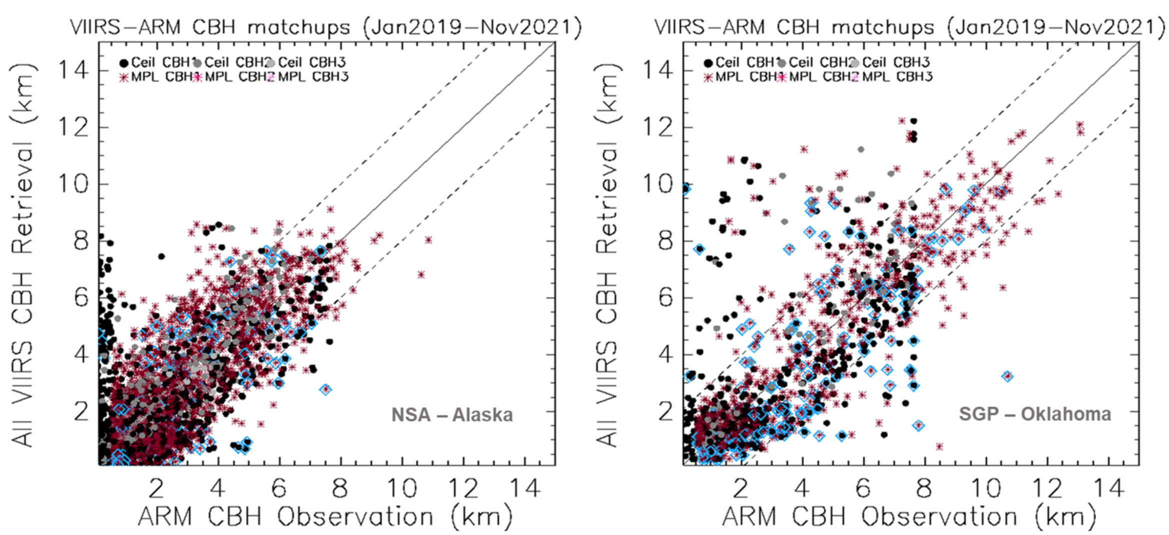

Figure 10 CBH comparisons between VIIRS and ground-based measurements (Ceilometer and Micro-Pulse Lidar) for ARM sites (NSA, Alaska and SGP, Oklahoma) when CTH from lidar (MPL) is within 2-km accuracy range compared with VIIRS CTH ("within spec" comparisons). Nighttime CBHs from NLCOMP using VIIRS DNB are colored in light blue.

4.2.2.4 Summary

A regression algorithm for estimating CGT and CBH of the uppermost cloud layer has been developed, which is constructed with a statistical method using multiple satellite data from the NASA A-Train constellation. CGT is predicated on the formation of relationships between observed CGT (from CloudSat/CALIPSO) and CWP (from Aqua MODIS) expressed as a function of CTH. For clouds not classified as thin cirrus or as deep convection, CBH is calculated by subtracting CGT from CTH. The accuracy of the CBH is directly proportional to the accuracy of CTH. The errors in CTH and CWP are inherited by the CBH retrieval. This statistical approach can minimize errors resulting from incorrect cloud type retrievals which caused errors in the original VIIRS IDPS CBH algorithm. CBH values for thick convective clouds are assigned the convective condensation level derived from NWP data. The current algorithm utilizes CWP input from nighttime optical properties (NLCOMP) using VIIRS DNB lunar reflectance data. The CBH algorithm has been integrated within the NOAA CLAVR-x frame and is being implemented in the NOAA JPSS operational cloud product system.

This ATBD describes the Enterprise AWG CBH algorithm which is currently operational. There are several areas of ongoing research to improve the regressions used to derive CWP. For example, separating the statistics by land and ocean is expected to lead to more robust results, considering the different cloud characteristics over each surface. Another possibility is using higher-order or additional piecewise fits to the water path vs. CGT relationships for the various CTH stratifications. For individual cloud scenes, additional research will be conducted to ensure the performance compared with other methods for specific cloud regimes (e.g., an adiabatic model for low marine clouds and an extinction method as a function of EPS and COT). The statistical CBH estimation method will be directly used to improve the VIIRS CCL EDRs, which calculates the cloud amount more accurately by extending the geometrically thick clouds into lower atmospheric layers.

4.2.3 Error Budget

CTH and CWP are key inputs which directly affect the accuracy of CBH retrievals. A sensitivity analysis is performed to assess the impact of errors in CTH and CWP. For the test, we assume three clouds as described below, and add 10%, 20%, and 50% errors in CTH and to the CWP, respectively.

- Cloud I: CTH = 1.5 km and CWP = 50 g/m^2 (Stratus type)
- Cloud II: CTH = 5.0 km and CWP = 193 g/m^2 (Altocumulus type)
- Cloud III: CTH = 10.0 km and CWP = 92 g/m^2 (Thick Cirrus type)

The results in Table 8 and Table 9 show that the relationships between errors in CTH and CWP and retrieved CGT and CBH are nonlinear and discrete due to the regression coefficients binned by 2-km CTH and CWP thresholds. Although the magnitudes of the induced errors in CGT and CBH retrievals highly vary depending on cloud scene, the impact of errors in CTH is most critical on CBH retrievals, with smaller errors due to CWP. Particularly, it is shown that errors in CTH may cause significant errors in CBH retrievals even in cases where CGT retrievals are unaffected.

Table 8. Sensitivity test of errors in CTH for three cloud scenarios.

	Added error (%)	Retrieved CGT (km)	Retrieved CBH (km)	Error in CGT (%)	Error in CBH (%)
Cloud I	0	0.52	0.98	0.0	0.0
	10	0.52	1.13	0.0	15.3
	20	0.52	1.28	0.0	30.5
	50	0.97	1.28	87.0	30.5
Cloud II	Added error (%)	Retrieved CGT (km)	Retrieved CBH (km)	Error in CGT (%)	Error in CBH (%)
	0	2.85	2.15	0.0	0.0
	10	2.85	2.65	0.0	23.3
	20	3.95	2.05	38.4	4.4
	50	3.95	3.55	38.4	65.4
Cloud III	Added error (%)	Retrieved CGT (km)	Retrieved CBH (km)	Error in CGT (%)	Error in CBH (%)
	0	3.11	6.89	0.0	0.0
	10	3.11	7.89	0.0	14.5
	20	3.12	8.88	0.4	28.8
	50	3.34	11.66	7.4	69.3

Table 9. Sensitivity test of errors in CWP for three cloud scenarios.

	Added error (%)	Retrieved CGT (km)	Retrieved CBH (km)	Error in CGT (%)	Error in CBH (%)
Cloud I	0	0.52	0.98	0.0	0.0
	10	0.53	0.97	2.2	1.1
	20	0.54	0.96	4.3	2.3
	50	0.59	0.91	14.2	7.5
Cloud II	Added error (%)	Retrieved CGT (km)	Retrieved CBH (km)	Error in CGT (%)	Error in CBH (%)
	0	2.85	2.15	0.0	0.0
	10	2.88	2.12	0.9	1.2
	20	2.91	2.09	1.9	2.5
	50	2.99	2.01	4.7	7.5
Cloud III	Added error (%)	Retrieved CGT (km)	Retrieved CBH (km)	Error in CGT (%)	Error in CBH (%)
	0	3.11	6.89	0.0	0.0
	10	3.23	6.77	4.0	1.8
	20	3.36	6.64	8.0	3.6
	50	4.2	5.8	34.9	15.8

From the validation results described in the previous section, Table 10 provides our preliminary estimate of an error budget obtained from 5-month matchup comparisons between VIIRS CBH and CloudSat observations. The "Bias Estimate" column values most closely match our interpretation of the F&PS accuracy specifications. It is noted that the error estimates are from the "within spec" analyses using cloudy pixels which CTH meets the VIIRS Accuracy and Precision Specification below (within 1 km for COT ≥ 1 or within 2 km for COT < 1 against CloudSat, considered as truth).

Table 10. Preliminary estimate of error budget for CBH when CTH is in an accurate range which meets the VIIRS accuracy and precision specification.

Product	Accuracy and Precision Specification (VIIRS)	Bias Estimate (mean)	Standard Deviation Estimate
Cloud Base Height	2 km (for both COT ≥ 1 and COT < 1)	**0.4 km**	**1.6 km**
***Cloud Top Height**	1 km when COT ≥ 1, 2 km when COT < 1	**0.41 km**	**0.75 km**

* **Note**: The error budget estimates for CTH (from the ACHA ATBD) are shown for reference only.

As Table 10 shows, the current CBH algorithm meets the VIIRS requirements for precision and accuracy. The main drivers of the CBH error budget are identified as follows:

1. *Accuracy of CTH retrievals*. As the performance of the CBH retrieval is highly dependent on the accuracy of the CTH retrieval, the inaccurate CTH may result in CBH failing to meet specification in terms of the standard deviation. The validation results for 5-month matchups between VIIRS CBH and CloudSat showed the standard deviation of the errors might exceed 2.7 km when erroneous CTH retrievals were involved in the analysis, although the mean bias was 0.8 km (median: 0.3 km).
2. *Accuracy of CWP retrievals*. The CBH algorithm relies on upstream cloud optical properties for CWP. It is well understood that CWP is difficult to retrieve at night, as the lack of visible band reflectance limits sensitivity. The operational VIIRS COT does not enlist Day/Night Band lunar information, and even if it did, not all nights provide sufficient moonlight for this to be a regularly available product. Therefore, it is very likely that the nighttime CBH retrieval performance would be degraded relative to the daytime retrievals. An evaluation of the nighttime CBHs is in progress.
3. *Precipitating clouds*. Since there is no effective way to determine the cloud base height in the presence of precipitation using CloudSat CPR data, errors in the CloudSat precipitation filter may add to the error budget. Further investigation will continue to identify the cases in detail.
4. *Multi-layer clouds*. Since the CBH algorithm has been developed optimal for single layer clouds or the uppermost layer of multi-layered clouds, the accuracy of the CBH product for multi-layer clouds may comprise the uncertainties of the upstream CTH and CWP retrievals from the AWG algorithm. We anticipate that in such systems the CBH for the uppermost layer will be underestimated (that is, placed too low in the column) owing to extra CWP contributions for the lower level cloud layers.

The CBH development team in collaboration with the ACHA development team will continue to be involved in developments that impact the error sources.

4.3 Long-Term Monitoring Plan

We will continue to support NOAA/NESDIS long-term monitoring and validation. As additional validation periods are determined, we will collect all available CloudSat and CALIPSO observations (and, possibly, EarthCARE, when it becomes available) for additional future Golden Days (intensive validation periods), if necessary.

5 PRACTICAL CONSIDERATIONS

5.1 Numerical Computation Considerations

The CBH algorithm is run in the NDE system and utilizes NDE supplied ancillary input data. Thus, the computational considerations for the CBH algorithm are subject to the NDE operational requirements.

5.2 Programming and Procedural Considerations

In the NDE system, the CBH algorithm run is currently the final step of the AWG Cloud Height Algorithm (ACHA which is responsible for the Cloud Top Pressure, Height, Temperature, and IR cloud optical property products) and Daytime and Nighttime Cloud Optical Properties Algorithm processing chain. The CBH algorithm follows the programming conventions and conditions for the upstream procedures. Implementations for improvement of the CCL algorithm using CBH information are in progress. The further procedure change is to be determined.

5.3 Quality Assessment and Diagnostics

It is recommended that evaluation of the CBH product should be done in concert with the upstream CTH and CWP input quality checks.

5.4 Exception Handling

The CBH algorithm checks for conditions where the algorithm cannot be performed. These conditions include no valid or missing upstream input values. In these cases, the appropriate flag is set to indicate that no cloud top height and cloud water path are produced for that pixel. In addition, a fill value is stored for the CBH at these locations.

5.5 Algorithm Validation

It is recommended that the CloudSat and CALIPSO analysis be adopted as the main validation tool, for as long as they are available. If these observations are not available, use of surface-based observation data from ceilometer, lidars and radars, such as provided by the Atmospheric Radiation Measurement (ARM) program, is recommended.

6 ASSUMPTIONS AND LIMITATIONS

The following sections describe the limitations and assumptions in the current version of the Enterprise ACBA.

6.1 Performance

Assumptions have been made in developing and estimating the performance of the CBH. The following list contains the current assumptions and proposed mitigation strategies.

- The CBH algorithm will operate on pixels determined to be cloudy or probably cloud by the VIIRS Cloud Mask. False cloud or missed cloud by Cloud Mask will be inherited by the CBH algorithm.
- Uncertainties in upstream retrievals of CTH and CWP will directly impact the accuracy of CBH retrievals.
- Multi-layered cloud systems present challenges to the VIIRS retrievals of cloud top height and optical properties. These errors will propagate down to affect CBH. The product should be used with caution in regions where overlapping clouds are present. An analysis of multilayered cloud system performance characteristics (including machine learning approaches) is forthcoming.
- Retrievals of cloud properties, and particularly CWP as inferred from cloud optical thickness and effective particle size, are limited at night. Thus, the CBH retrievals must be used with caution at night.
- The accuracy of NWP data, used as supplementary data in the CBH algorithm, may add uncertainties to a small fraction of retrievals.

6.2 Assumed Sensor Performance

It is assumed that the VIIRS sensor will meet its performance specifications. However, the CBH algorithm will be dependent on the following instrumental characteristic:

- Unknown spectral shifts in some channels will cause biases in the upstream cloud property retrievals that may in turn impact the performance of the CBH algorithm.

6.3 Pre-Planned Product Improvements

While development of the baseline CBH algorithm continues, we expect in the coming years to focus on the issues noted below.

6.3.1 Improvement of Cloud Cover and Layers Product

The CBH development team supports the ACHA development team in its development of an enhanced CCL product. The CBH algorithm will provide additional lower-level cloud coverage information to the current CCL algorithm for improved CCL products.

6.3.2 Improvement of Deep Convective and Thin Cirrus Clouds

We will continue the CBH algorithm improvement, emphasizing the following aspects.

- Improved performance in deep convective clouds using climatological data,
- Improved performance in optically thin cirrus-type clouds using retrieved optical thickness and CloudSat/CALIPSO data.

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