Joint Polar Satellite System (JPSS) Cloud Products and Applications in Aviation

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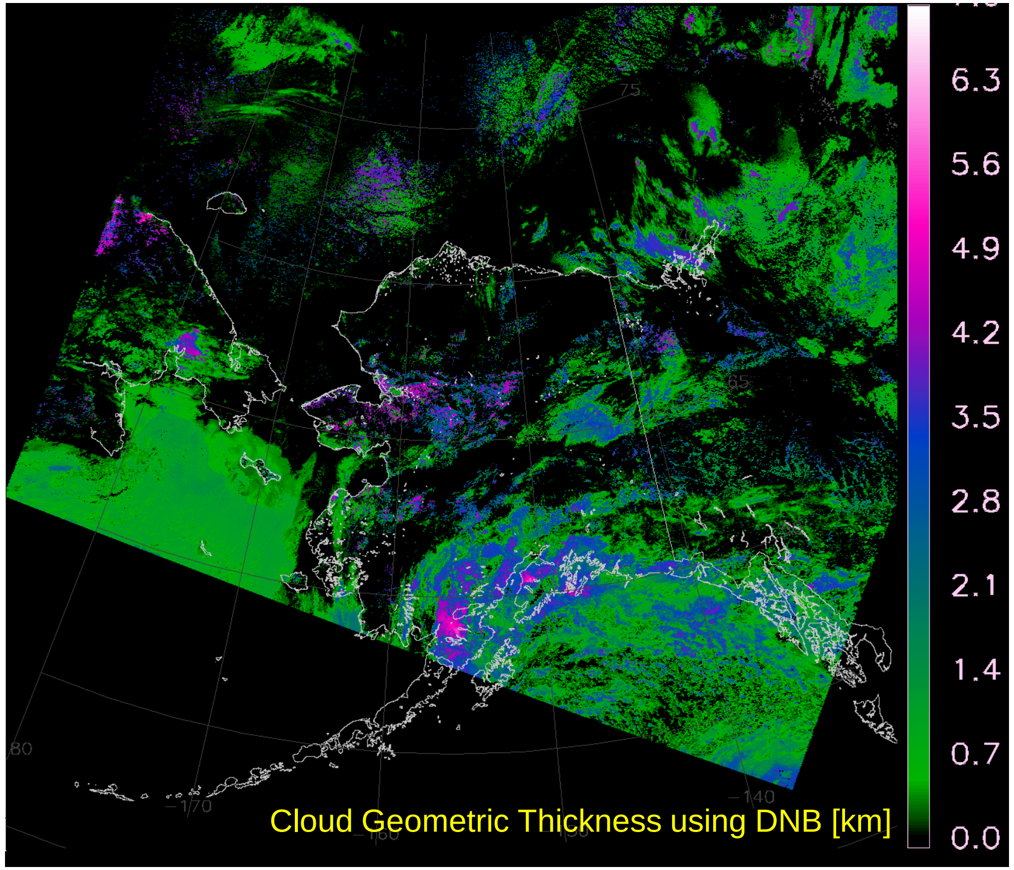
with NOAA and CIMSS collaborators

Thanks to our collaborators and Alaska users: **Mark Kulie** (NOAA), **William Straka, Yue Li**, **Steve Wanzong** (CIMSS), **Tom George** (Aircraft Owners & Pilots Association), **Adam White** (Alaska Airmen Assoc.), **Becca Mazur** (Arctic Testbed), **Carl Dierking, Jen Delamere, Jay Cable** (CICOES/GINA), **Amanda Terborg, Ty Higginbotham** (AWC/AWT), **Nadia Smith, Rebekah Esmaili** (STCNET), **Jenny Colavito** (FAA)

Nov 05, 2021 (SAWS 9 Workshop)

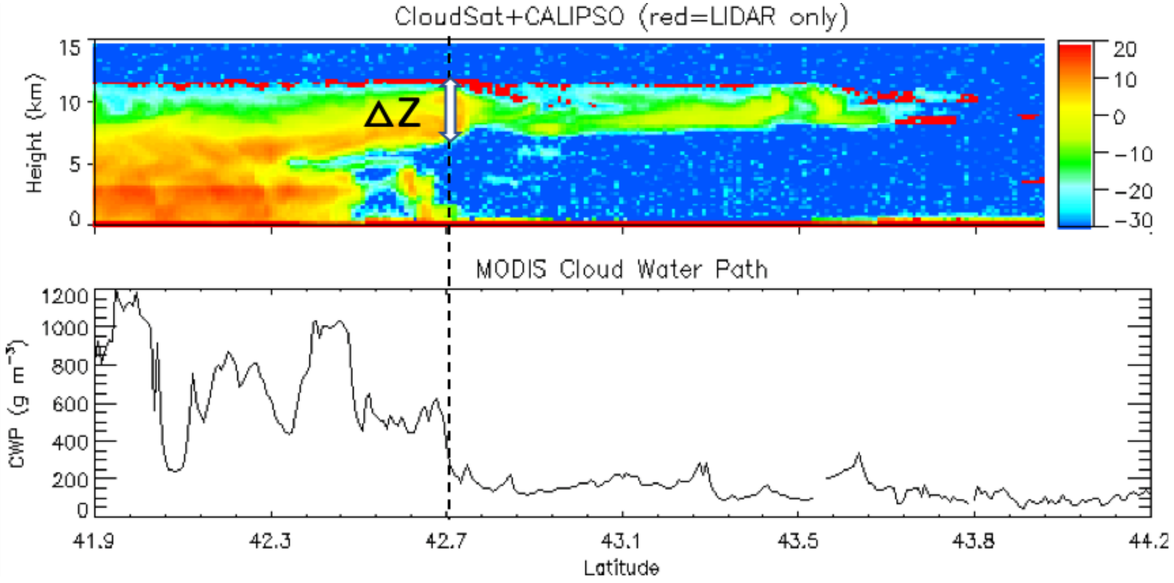
Cloud Vertical Structure from Satellite

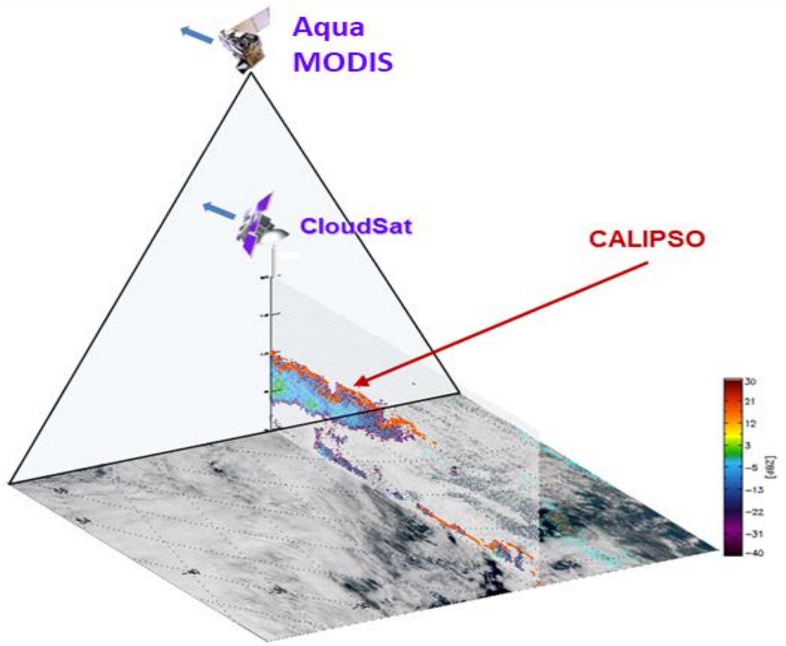
- **3-D cloud structure information** is significant to both aviation and model communities, but still challenging to conventional satellite observations using passive radiometers (e.g., VIIRS and ABI)



- Developed a statistical algorithm for Cloud Base Height (CBH) and Cloud Cover-Layers (CCL) using NASA A-Train satellite data, which is a key component to build the 3-D cloud field
- Product improvements based on user feedback to provide a comprehensive package of satellite cloud products in a more user-friendly way

Cloud Base Height Algorithm





- Developed a CBH/CGT algorithm constrained by Cloud Top Height (CTH) and Cloud Water Path (CWP) using a statistical analysis of A-Train satellite data (*Noh et al. and Seaman et al. 2017 JTECH*)

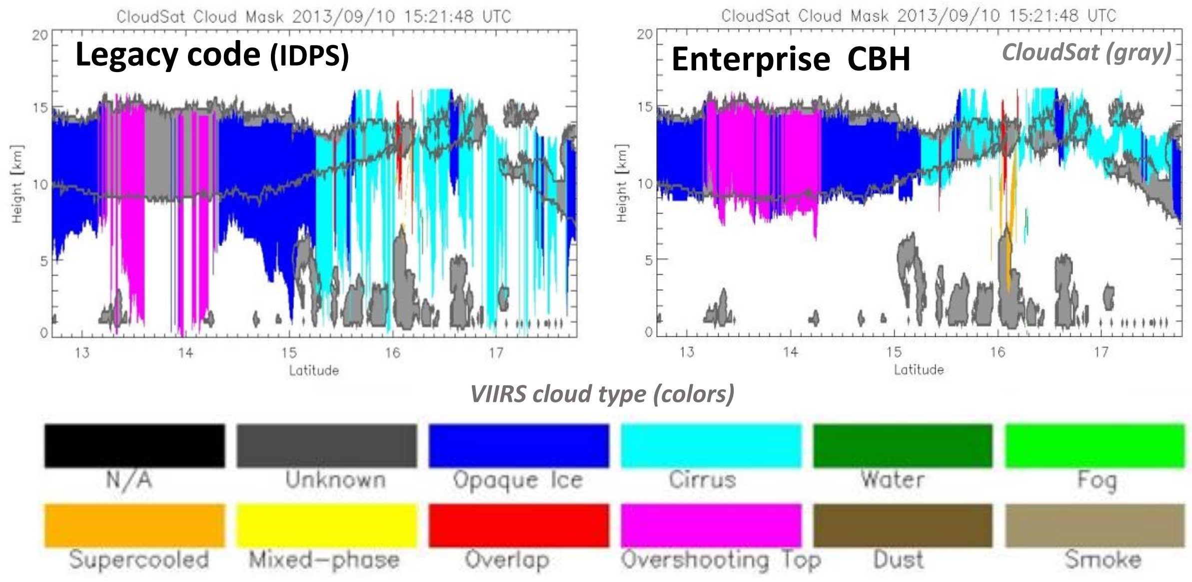
  CBH = CTH – ΔZ **(CGT; Cloud Geometric Thickness)**

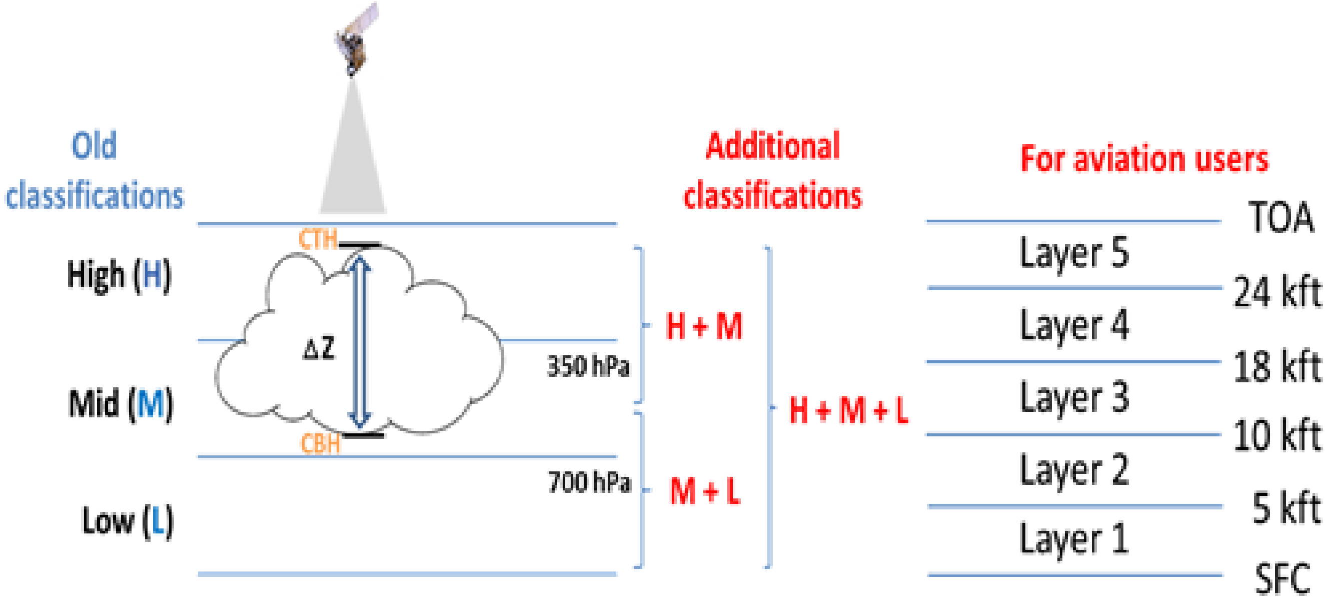
  where *CGT = a(CWP)+b* (*a, b* based on A-Train data)

- Key component for 3-D cloud structure information, used for improved Cloud Cover/Layers (CCL)

- Operational as part of the NOAA Enterprise Cloud Algorithm
  - ✔ Operational for JPSS VIIRS and under test for GOES ABI
  - ✔ Optimal for single layer clouds

Cloud Base Height Algorithm





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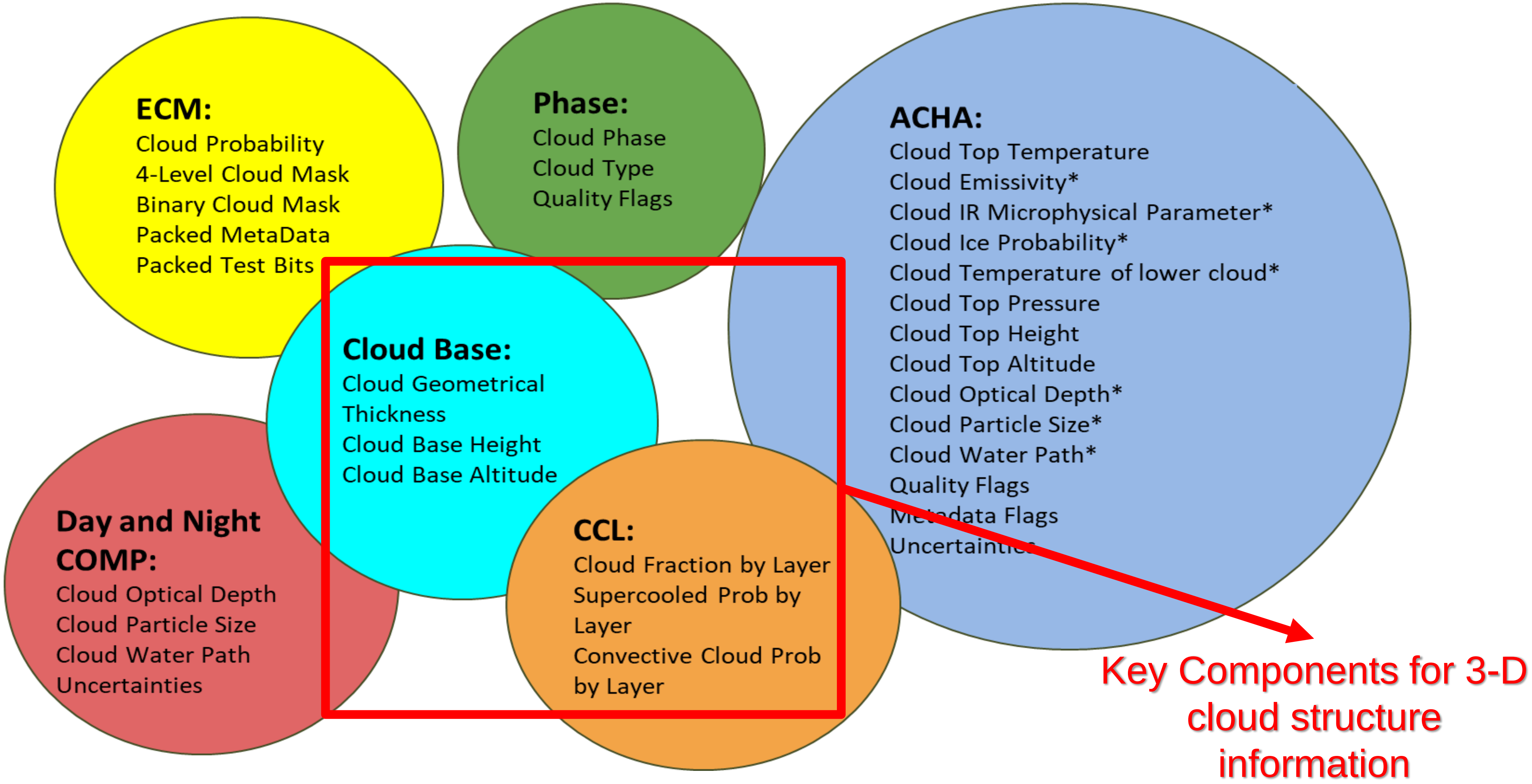
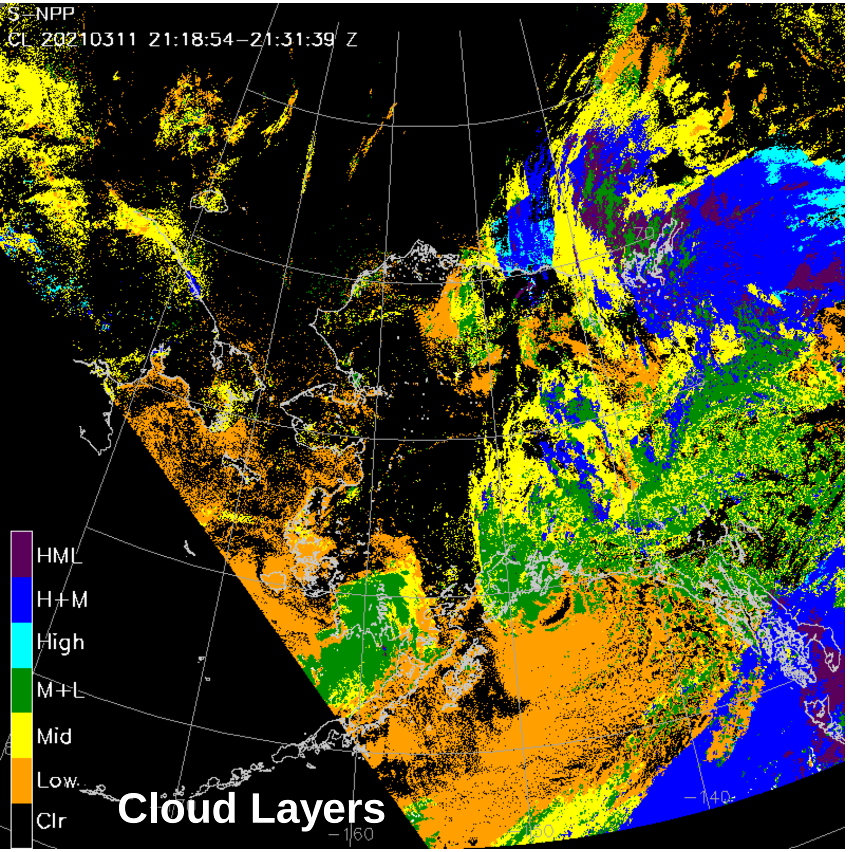
NOAA Enterprise Cloud Products

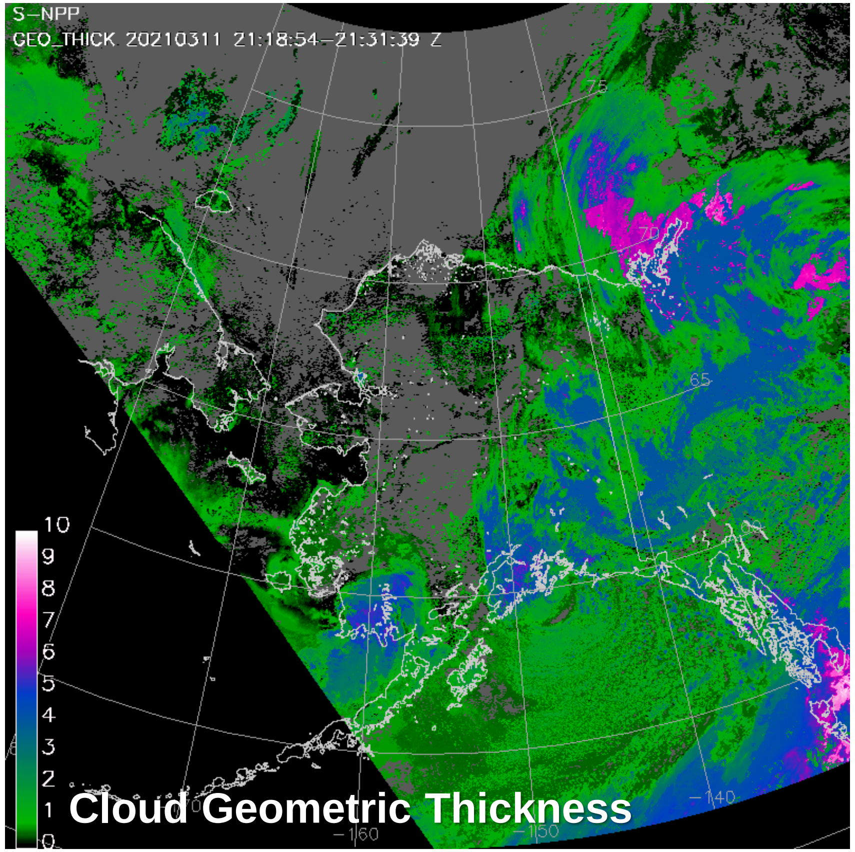


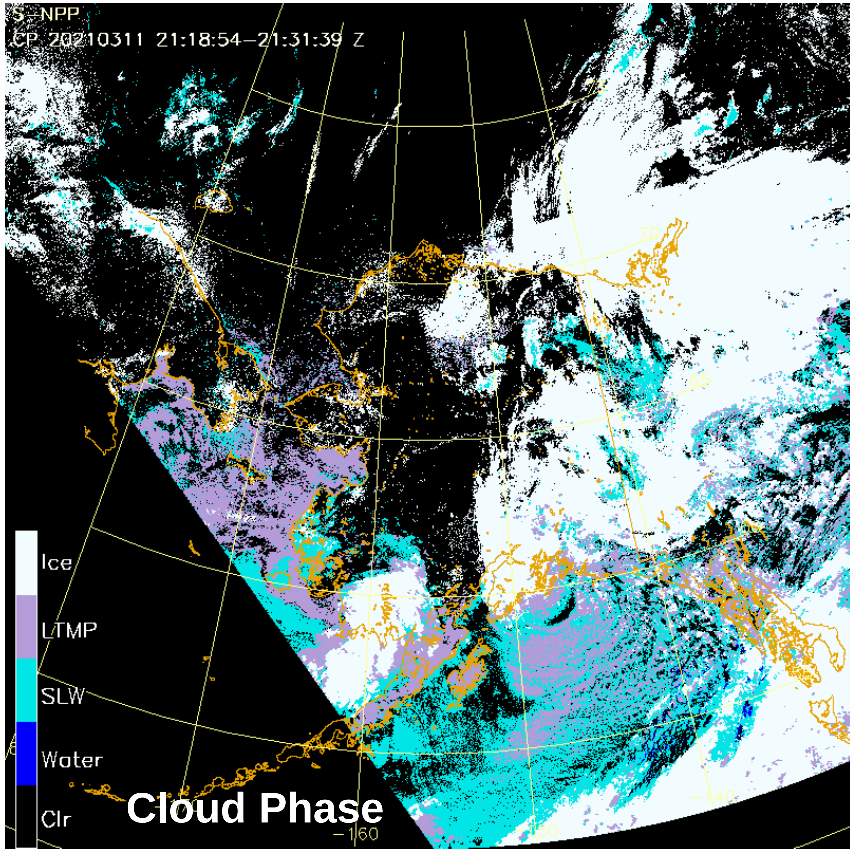
Enterprise Cloud Product Package

From 2020 EPS-SG STAR Product Requirements Review by A. Heidinger

VIIRS Arctic Cloud Products





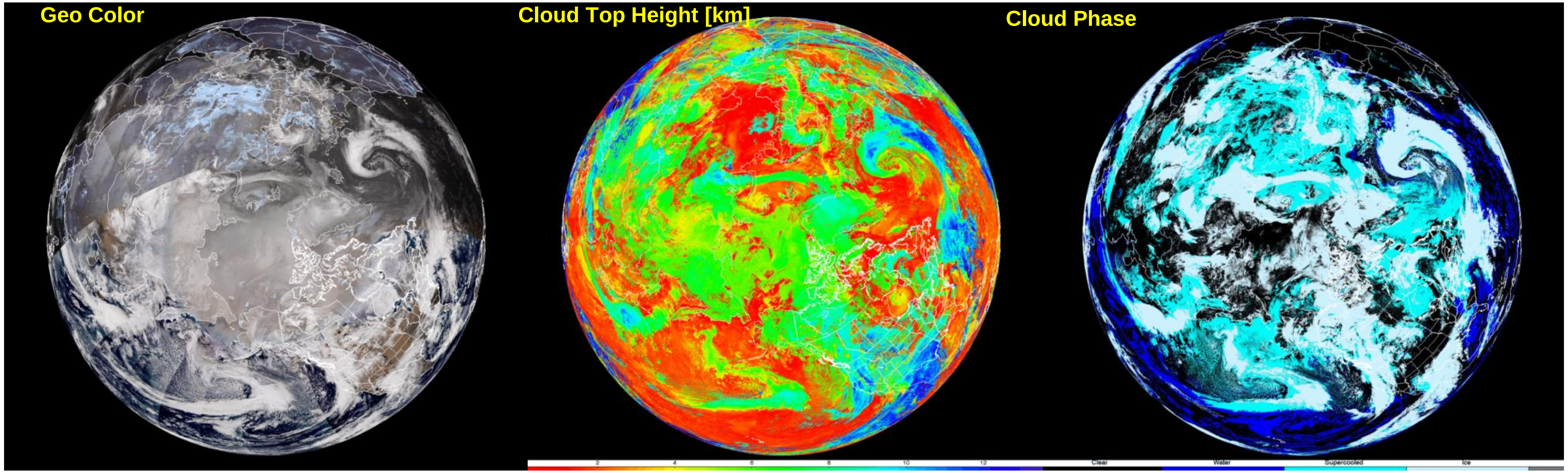


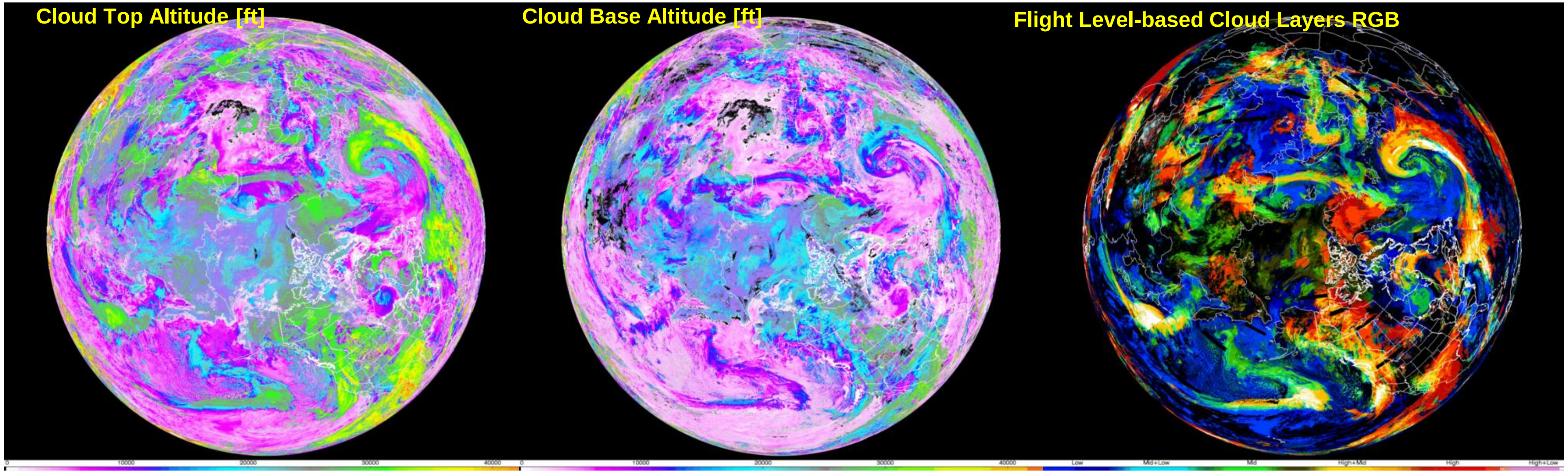
CIRA VIIRS Imagery and cloud products: https://rammb.cira.colostate.edu/ramsdis/online/npp_viirs_arctic.asp

Another VIIRS site by GINA/U. of Alaska-Fairbanks: http://hippy.gina.alaska.edu/distro/aviation/

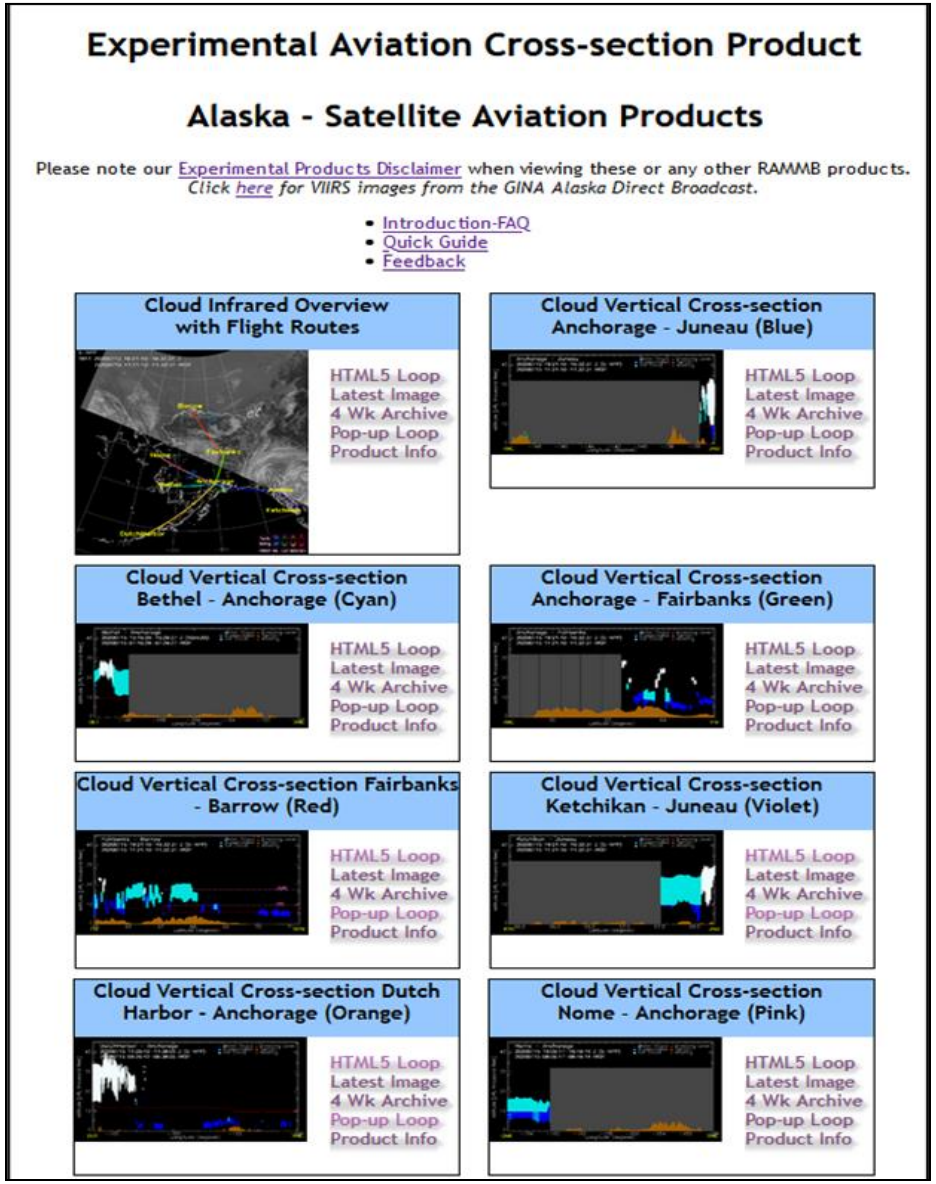
CIRA's Polar Slider (Northern/Southern Hemispheres)

- JPSS VIIRS Imagery and Cloud Products at http://rammb-slider.cira.colostate.edu (Satellite "*JPSS*")





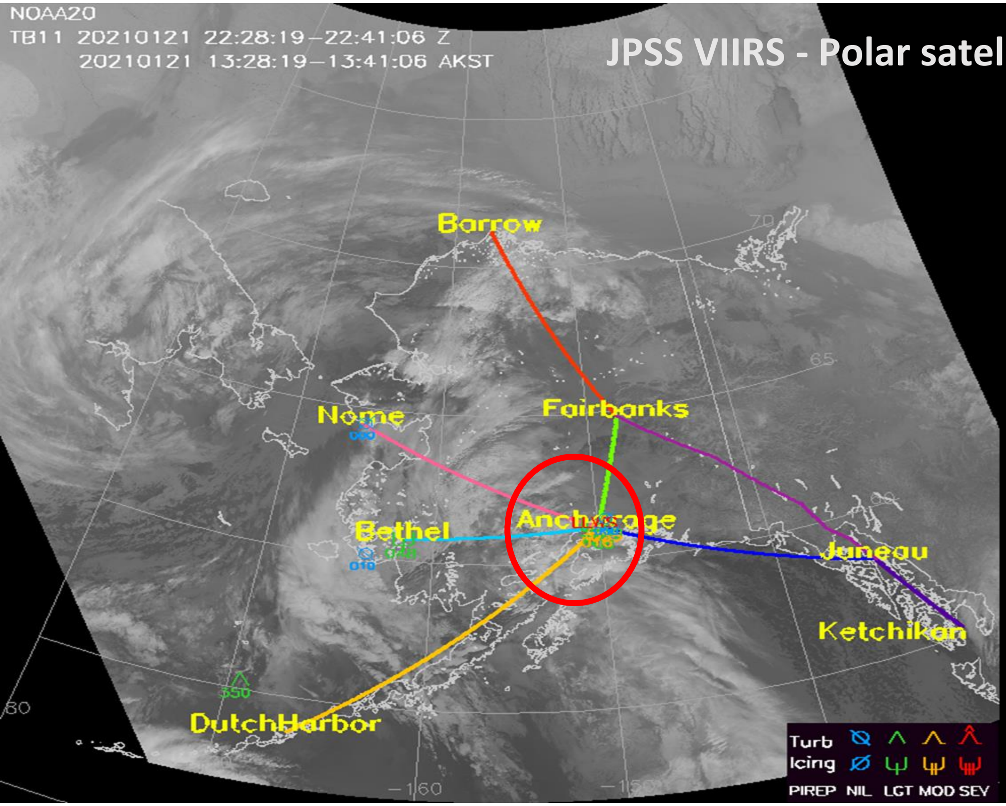
Satellite Cloud Vertical Cross-section products

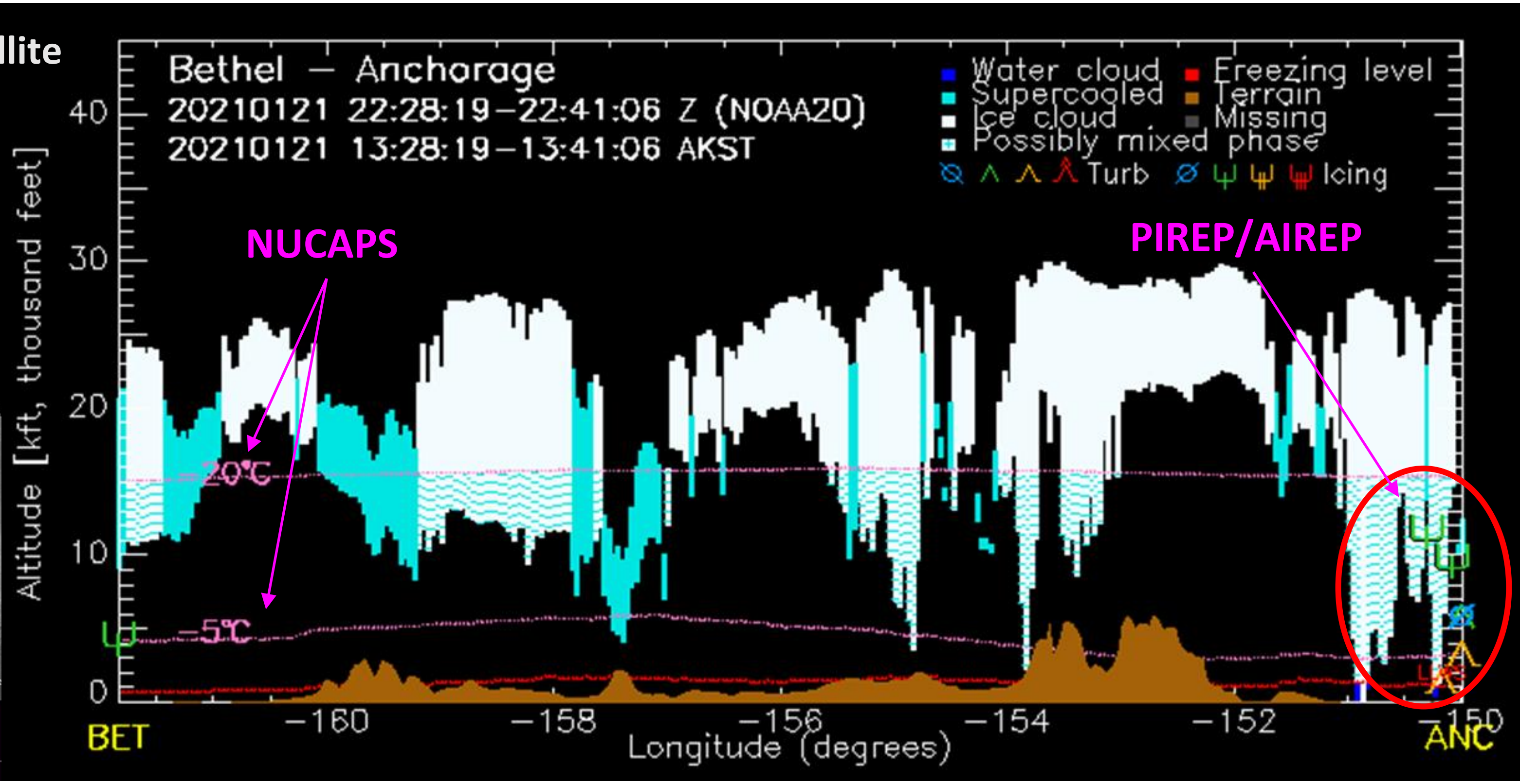


- **Experimental products for aviation users**
  - ✓ JPSS Cloud Product Alaska Demonstration as part of the NOAA JPSS Aviation Initiative
- **Cloud Vertical Cross-sections (CVC) along flight routes from NOAA Enterprise Cloud Products**
  - ✓ Satellite Cloud Top/Base Heights and Phase
  - ✓ NWP/NUCAPS temperatures data
  - ✓ PIREPs (icing and turbulence)
- **Training/display tools based on user feedback**
- **Thanks to Alaska users and collaborators!**
  - Tom George (AOPA), Adam White (AK Airmen Assoc.), Becca Mazur (Arctic Testbed), Jenny Colavito (FAA), and many users

Cloud Vertical Cross-sections along flight paths

- Experimental satellite cloud products for aviation users (**AK**, CONUS)
  - [**http://rammb.cira.colostate.edu/ramsdis/online/npp_viirs_arctic_aviation.asp**](http://rammb.cira.colostate.edu/ramsdis/online/npp_viirs_arctic_aviation.asp)
  - http://rammb.cira.colostate.edu/ramsdis/online/npp_viirs_conus_aviation.asp





Cloud Vertical Cross-sections along flight paths

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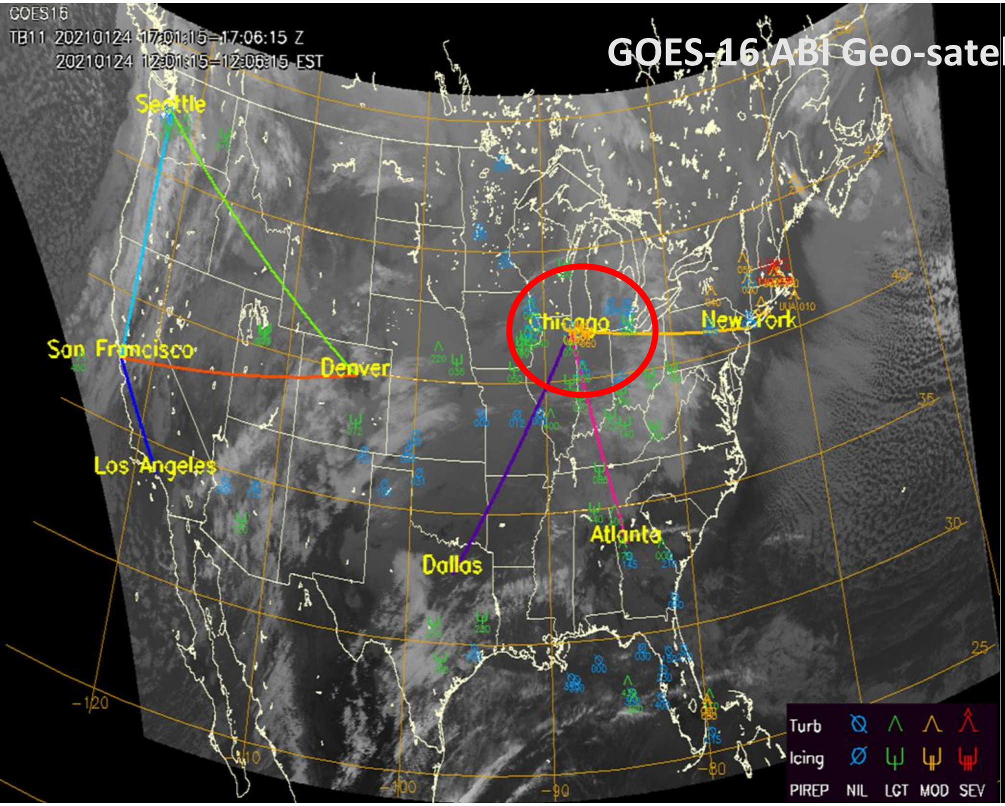
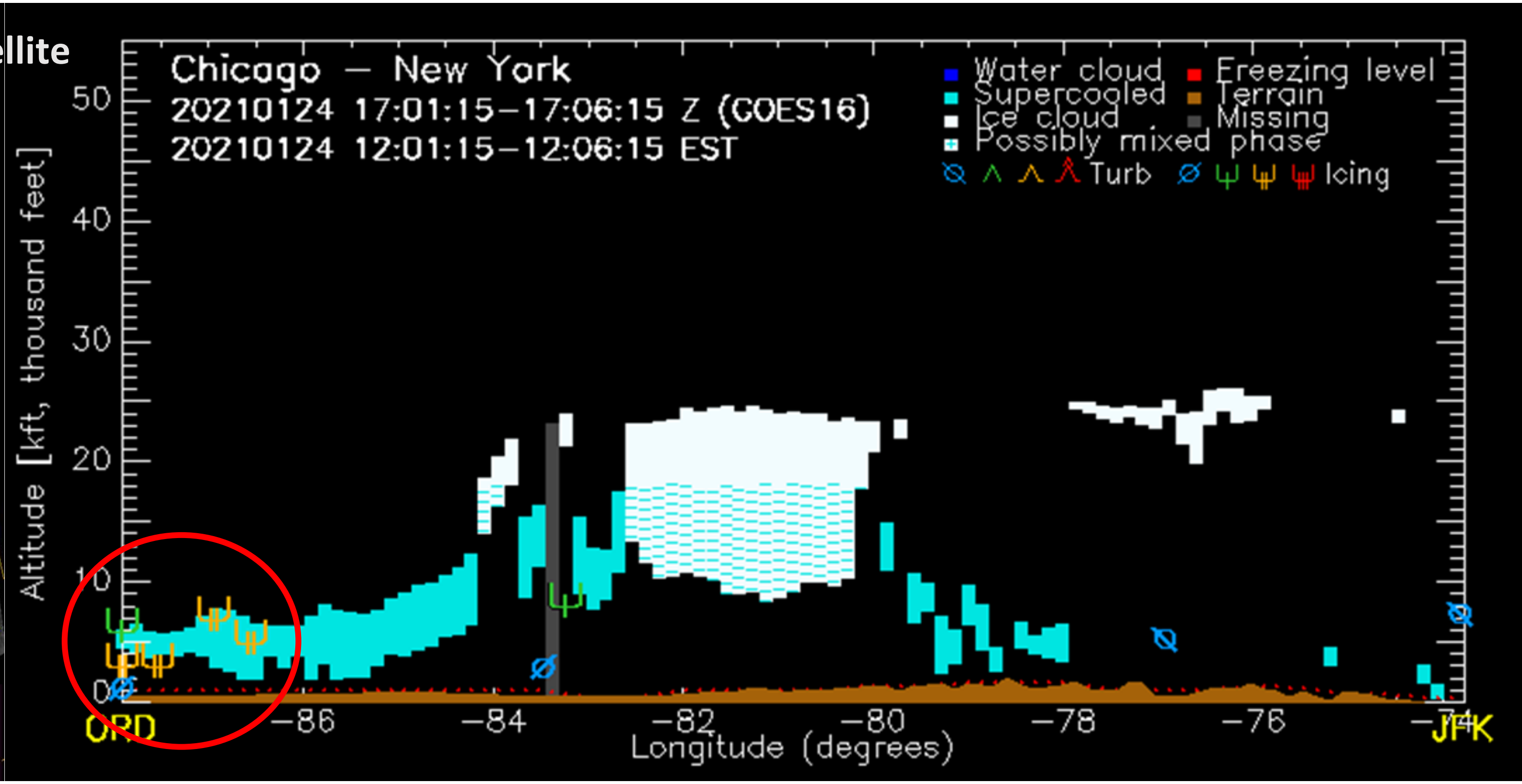
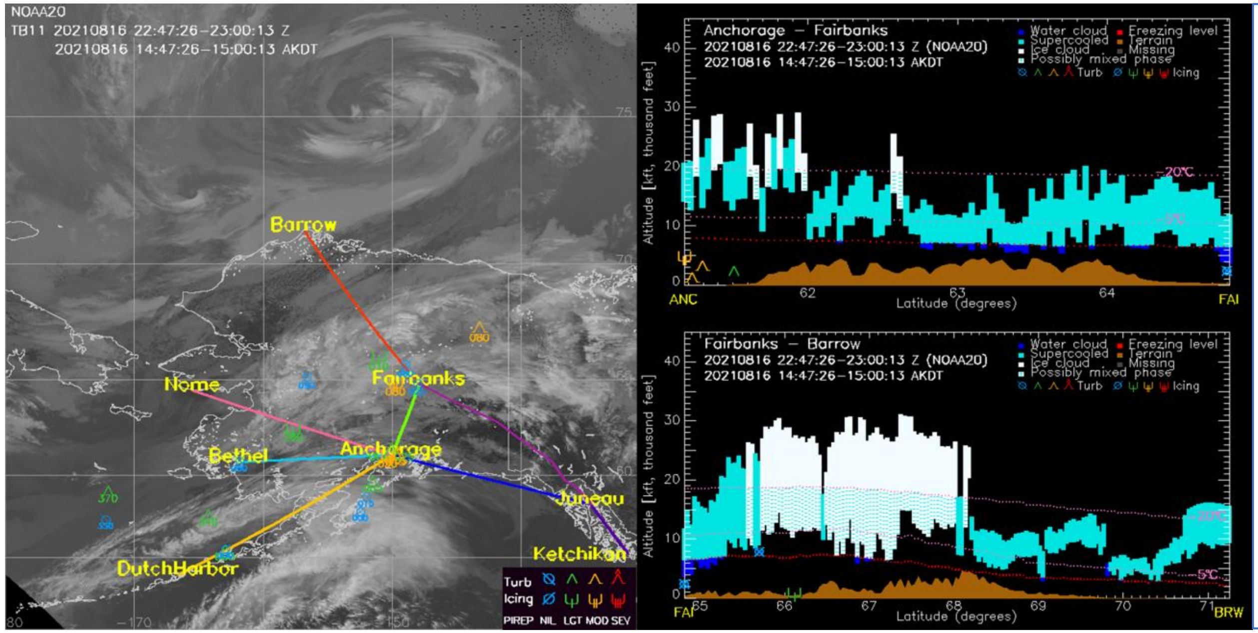




User engagement

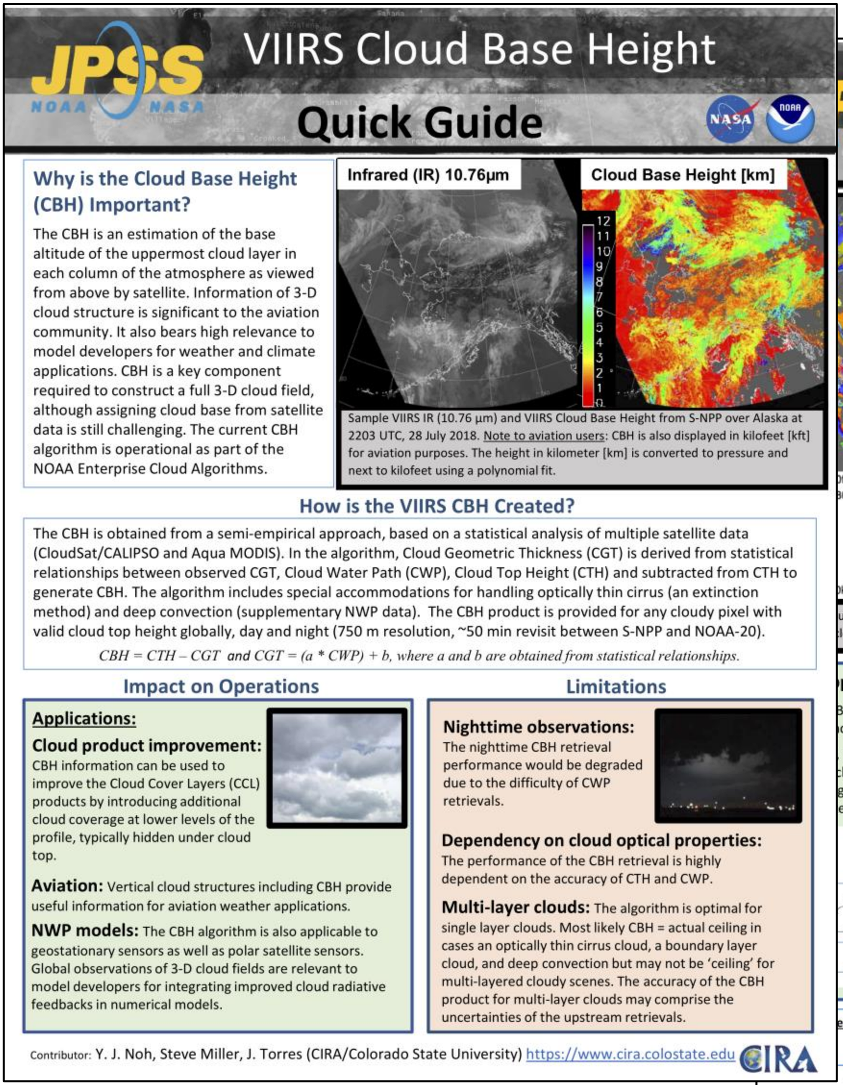
- JPSS Alaska Cloud Product Demonstration/JPSS Aviation Initiative
- CIRA Polar SLIDER and VIIRS Cloud Vertical Cross-sections were used during the official cloud product demonstration for user feedback

  - @NOAASatellites twitter to promote NOAA's new "Proving Ground Website“ , Alaska users’ blogs
  - NOAA/NASA online articles, Aircraft Owners & Pilots Association (AOPA) *ePilot* newsletter and weekly video program “AOPA Live” for Alaska pilots



NOAA-20 VIIRS IR image and cloud vertical cross-sections which were provided to the National Transportation Safety Board (NTSB) for an aircraft accident case investigation. The accident occurred around 2251 UTC on 16 August 2021 near Fairbanks, Alaska. A small airbus (Cessna 208B Grand Caravan) declared an emergency due to flight control issues from serious damage to the right aileron after encountering severe turbulence. Eight passengers and one pilot on board, and luckily no injuries were reported.

Quick Guide User Training Materials


VIIRS Cloud Base Height
Quick Guide

Why is the Cloud Base Height (CBH) Important?

The CBH is an estimation of the base altitude of the uppermost cloud layer in each column of the atmosphere as viewed from above by satellite. Information of 3-D cloud structure is significant to the aviation community. It also bears high relevance to model developers for weather and climate applications. CBH is a key component required to construct a full 3-D cloud field, although assigning cloud base from satellite data is still challenging. The current CBH algorithm is operational as part of the NOAA Enterprise Cloud Algorithms.

Sample VIIRS IR (10.76 µm) and VIIRS Cloud Base Height from S-NPP over Alaska at 2203 UTC, 28 July 2018. Note to aviation users: CBH is also displayed in kilofeet [kft] for aviation purposes. The height in kilometer [km] is converted to pressure and next to kilofeet using a polynomial fit.

How is the VIIRS CBH Created?

The CBH is obtained from a semi-empirical approach, based on a statistical analysis of multiple satellite data (CloudSat/CALIPSO and Aqua MODIS). In the algorithm, Cloud Geometric Thickness (CGT) is derived from statistical relationships between observed CGT, Cloud Water Path (CWP), Cloud Top Height (CTH) and subtracted from CTH to generate CBH. The algorithm includes special accommodations for handling optically thin cirrus (an extinction method) and deep convection (supplementary NWP data). The CBH product is provided for any cloudy pixel with valid cloud top height globally, day and night (750 m resolution, ~50 min revisit between S-NPP and NOAA-20).

$CBH = CTH - CGT$ and $CGT = (a * CWP) + b$, where a and b are obtained from statistical relationships.

Impact on Operations

Applications:

Cloud product improvement: CBH information can be used to improve the Cloud Cover Layers (CCL) products by introducing additional cloud coverage at lower levels of the profile, typically hidden under cloud top.

Aviation: Vertical cloud structures including CBH provide useful information for aviation weather applications.

NWP models: The CBH algorithm is also applicable to geostationary sensors as well as polar satellite sensors. Global observations of 3-D cloud fields are relevant to model developers for integrating improved cloud radiative feedbacks in numerical models.

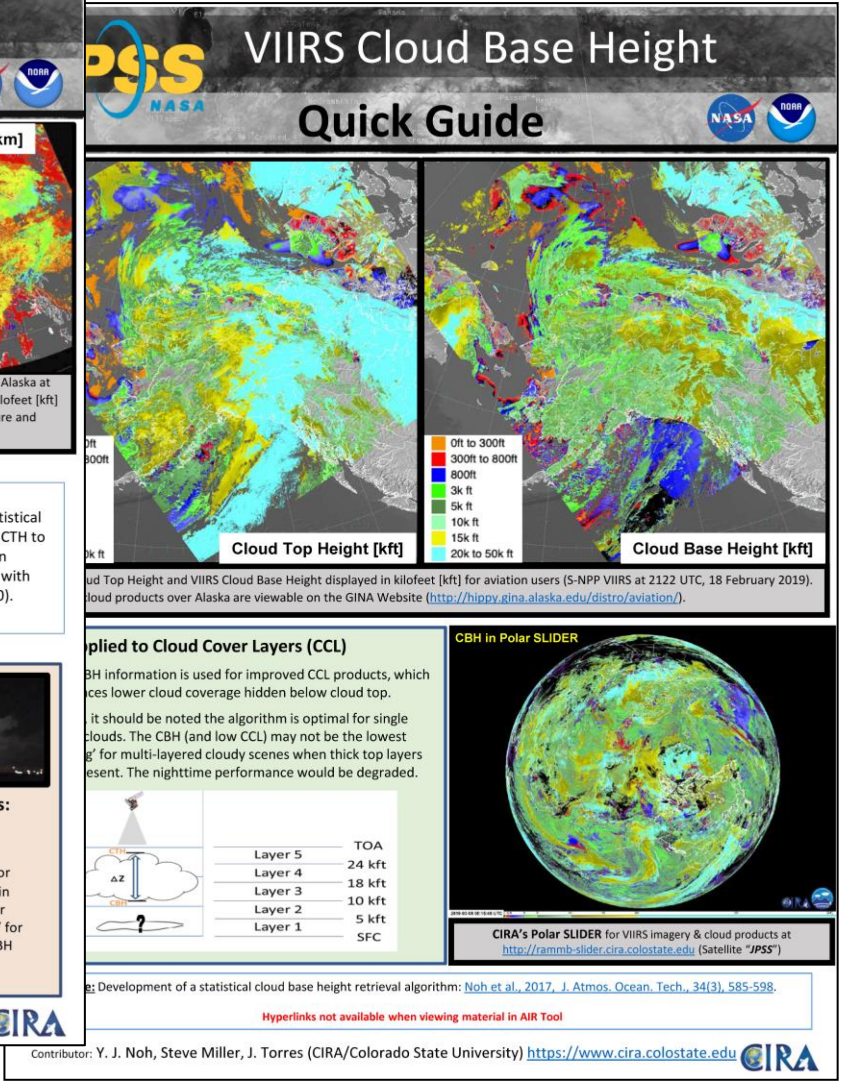
Limitations

Nighttime observations: The nighttime CBH retrieval performance would be degraded due to the difficulty of CWP retrievals.

Dependency on cloud optical properties: The performance of the CBH retrieval is highly dependent on the accuracy of CTH and CWP.

Multi-layer clouds: The algorithm is optimal for single layer clouds. Most likely CBH = actual ceiling in cases an optically thin cirrus cloud, a boundary layer cloud, and deep convection but may not be 'ceiling' for multi-layered cloudy scenes. The accuracy of the CBH product for multi-layer clouds may comprise the uncertainties of the upstream retrievals.

Contributor: Y. J. Noh, Steve Miller, J. Torres (CIRA/Colorado State University) https://www.cira.colostate.edu


VIIRS Cloud Base Height
Quick Guide

…ud Top Height and VIIRS Cloud Base Height displayed in kilofeet [kft] for aviation users (S-NPP VIIRS at 2122 UTC, 18 February 2019). …loud products over Alaska are viewable on the GINA Website (http://hippy.gina.alaska.edu/distro/aviation/).

…plied to Cloud Cover Layers (CCL)

…BH information is used for improved CCL products, which …ces lower cloud coverage hidden below cloud top.

… it should be noted the algorithm is optimal for single …clouds. The CBH (and low CCL) may not be the lowest …g' for multi-layered cloudy scenes when thick top layers …esent. The nighttime performance would be degraded.

CIRA's Polar SLIDER for VIIRS imagery & cloud products at http://rammb-slider.cira.colostate.edu (Satellite "JPSS")

…e: Development of a statistical cloud base height retrieval algorithm: Noh et al., 2017, J. Atmos. Ocean. Tech., 34(3), 585-598.

Hyperlinks not available when viewing material in AIR Tool

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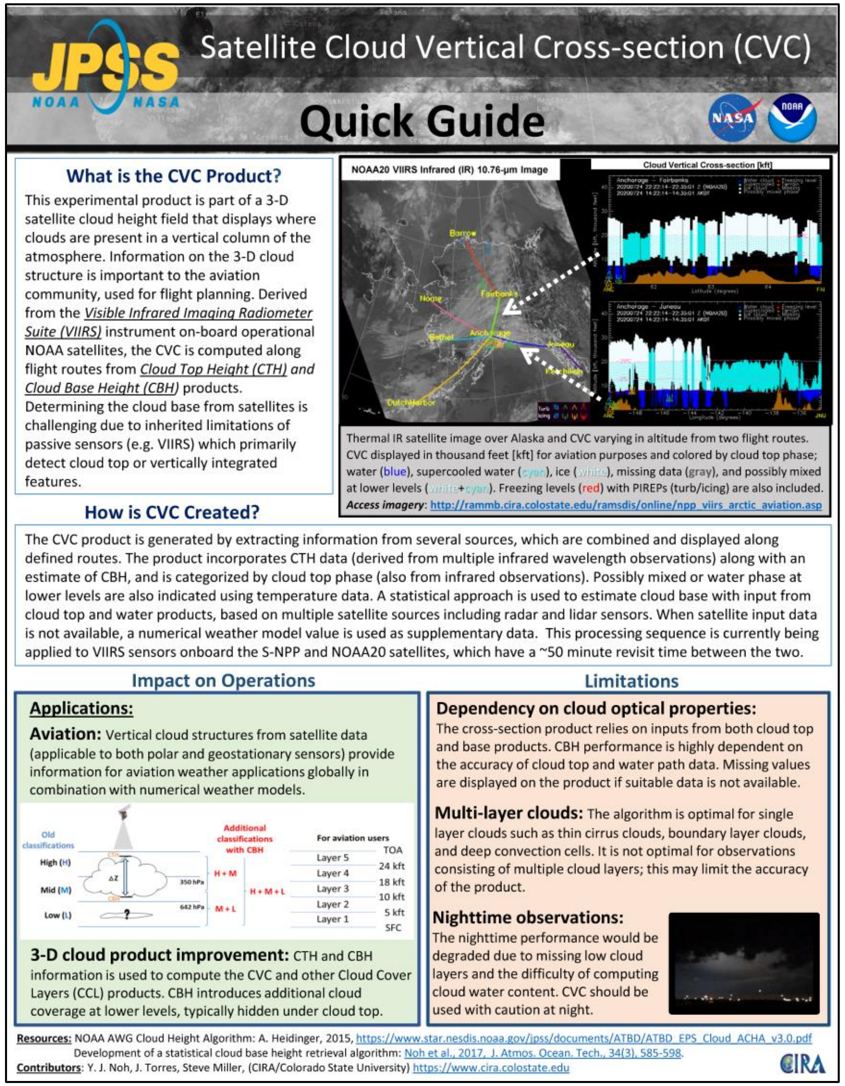
Satellite Cloud Vertical Cross-section (CVC)
Quick Guide

What is the CVC Product?

This experimental product is part of a 3-D satellite cloud height field that displays where clouds are present in a vertical column of the atmosphere. Information on the 3-D cloud structure is important to the aviation community, used for flight planning. Derived from the *Visible Infrared Imaging Radiometer Suite (VIIRS)* instrument on-board operational NOAA satellites, the CVC is computed along flight routes from *Cloud Top Height (CTH)* and *Cloud Base Height (CBH)* products. Determining the cloud base from satellites is challenging due to inherited limitations of passive sensors (e.g. VIIRS) which primarily detect cloud top or vertically integrated features.

Thermal IR satellite image over Alaska and CVC varying in altitude from two flight routes. CVC displayed in thousand feet [kft] for aviation purposes and colored by cloud top phase; water (blue), supercooled water (cyan), ice (white), missing data (gray), and possibly mixed at lower levels (white+cyan). Freezing levels (red) with PIREPs (turb/icing) are also included. *Access imagery*: http://rammb.cira.colostate.edu/ramsdis/online/npp_viirs_arctic_aviation.asp

How is CVC Created?

The CVC product is generated by extracting information from several sources, which are combined and displayed along defined routes. The product incorporates CTH data (derived from multiple infrared wavelength observations) along with an estimate of CBH, and is categorized by cloud top phase (also from infrared observations). Possibly mixed or water phase at lower levels are also indicated using temperature data. A statistical approach is used to estimate cloud base with input from cloud top and water products, based on multiple satellite sources including radar and lidar sensors. When satellite input data is not available, a numerical weather model value is used as supplementary data. This processing sequence is currently being applied to VIIRS sensors onboard the S-NPP and NOAA20 satellites, which have a ~50 minute revisit time between the two.

Impact on Operations

Applications:

Aviation: Vertical cloud structures from satellite data (applicable to both polar and geostationary sensors) provide information for aviation weather applications globally in combination with numerical weather models.

3-D cloud product improvement: CTH and CBH information is used to compute the CVC and other Cloud Cover Layers (CCL) products. CBH introduces additional cloud coverage at lower levels, typically hidden under cloud top.

Limitations

Dependency on cloud optical properties: The cross-section product relies on inputs from both cloud top and base products. CBH performance is highly dependent on the accuracy of cloud top and water path data. Missing values are displayed on the product if suitable data is not available.

Multi-layer clouds: The algorithm is optimal for single layer clouds such as thin cirrus clouds, boundary layer clouds, and deep convection cells. It is not optimal for observations consisting of multiple cloud layers; this may limit the accuracy of the product.

Nighttime observations: The nighttime performance would be degraded due to missing low cloud layers and the difficulty of computing cloud water content. CVC should be used with caution at night.

Resources: NOAA AWG Cloud Height Algorithm: A. Heidinger, 2015, https://www.star.nesdis.noaa.gov/jpss/documents/ATBD/ATBD_EPS_Cloud_ACHA_v3.0.pdf
Development of a statistical cloud base height retrieval algorithm: Noh et al., 2017, J. Atmos. Ocean. Tech., 34(3), 585-598.
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http://rammb.cira.colostate.edu/training/visit/quick_guides/QuickGuide_JPSS_VIIRS_CBH.pdf

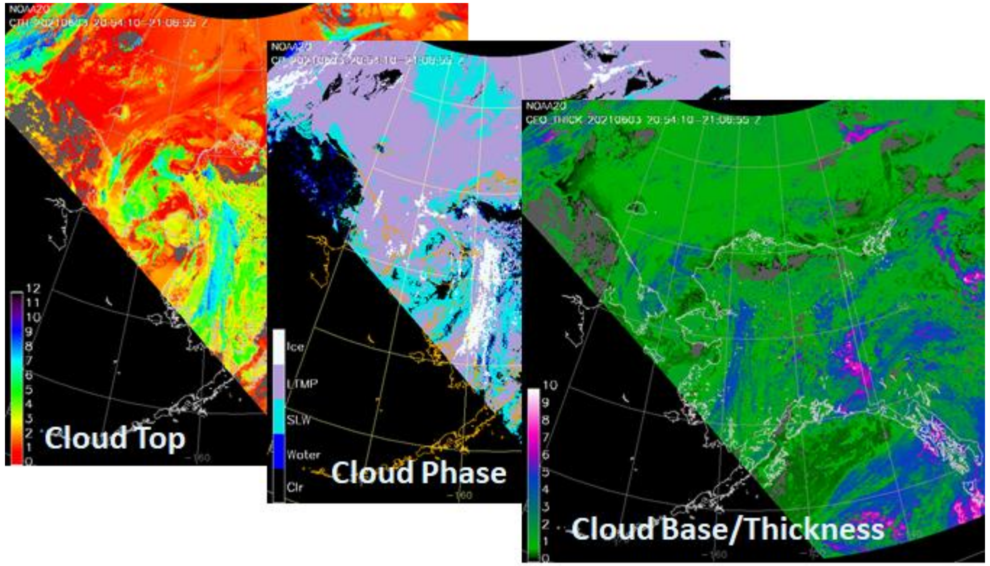
http://rammb.cira.colostate.edu/ramsdis/online/npp_viirs_arctic_aviation.asp

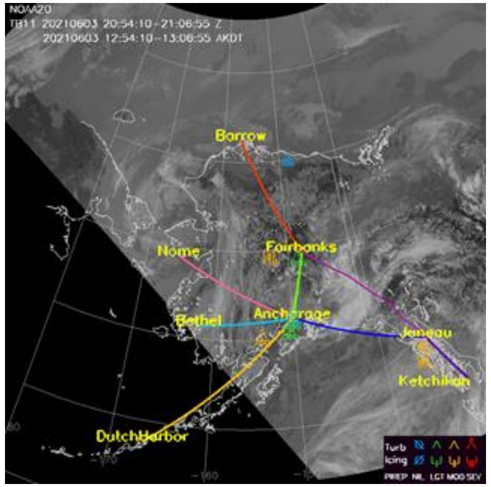
Improvement based on user feedback

Gridded 3-D Cloud Data

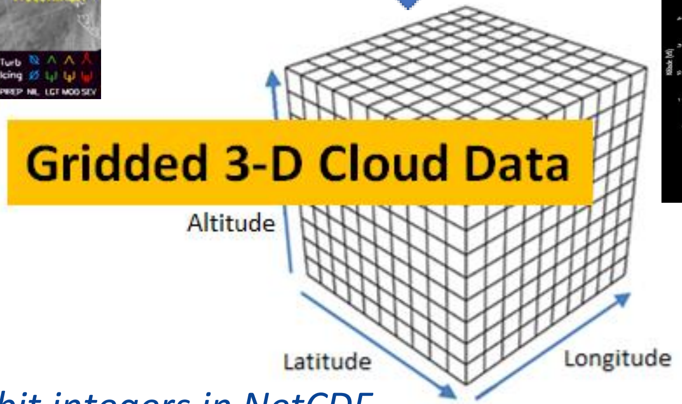
- A comprehensive package to extend the benefit of satellite data into the vertical dimension for aviation users -> ***Custom Cloud Cross-sections***
- Derived from multiple cloud products (cloud top/base and phase) with temperatures (NUCAPS/NWP model), PIREPs (icing/turbulence), and terrain data

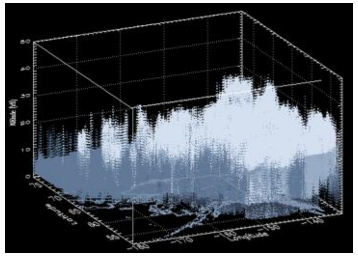
VIIRS individual 30-sec granules, pixel data





Temperatures (NUCAPS/NWP)
Terrain
PIREPs (Icing/Turb)

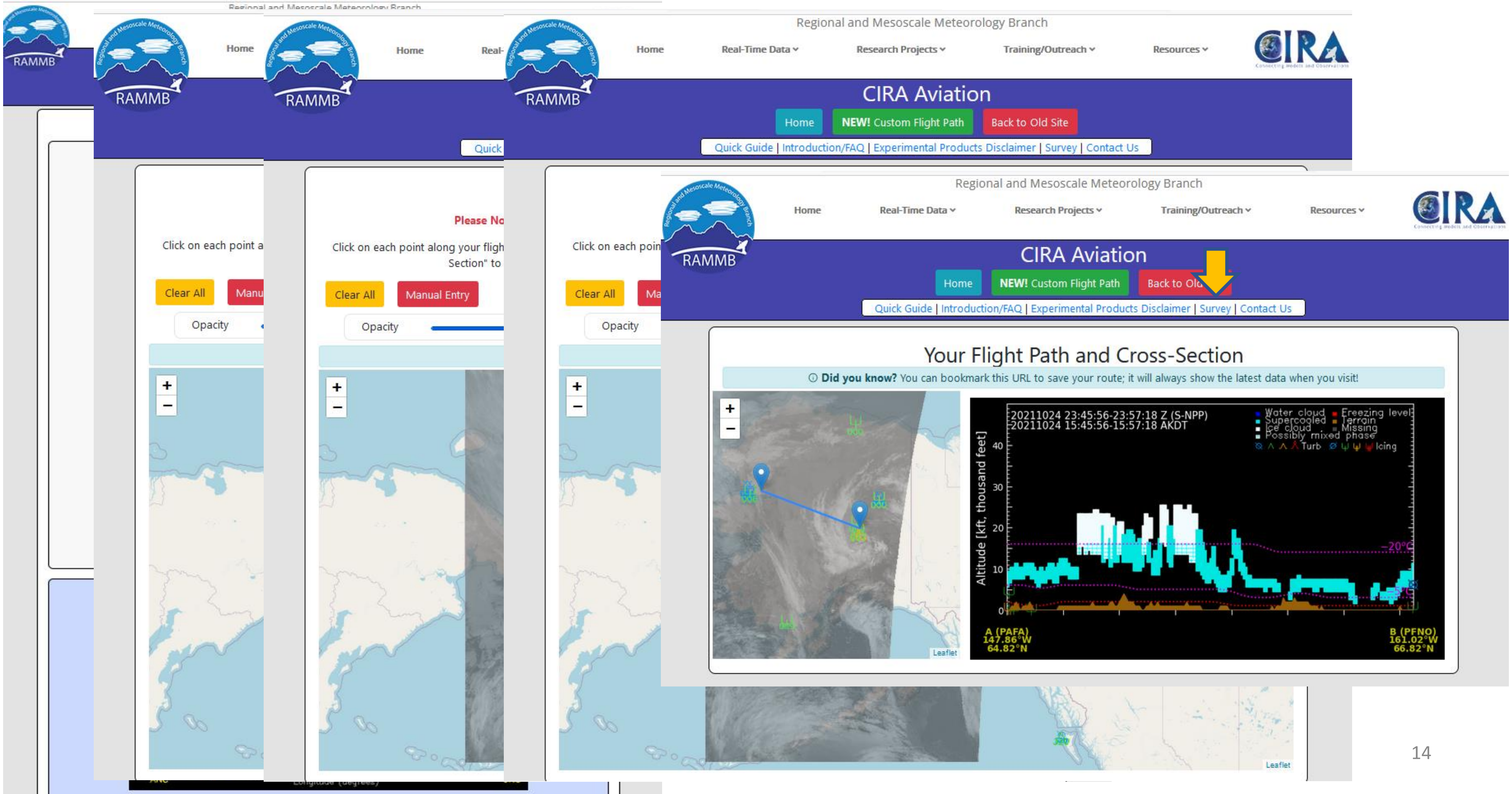




Compact 16-bit integers in NetCDF

New Aviation Website for custom cross-sections

https://aviation.cira.colostate.edu



Cloud Cover Layers with ML

- Aviation is particularly concerned with the location of **low clouds** (IFR conditions, icing, etc.) but still challenging in **multilayer scenes**
- Using Random Forest (RF) and Artificial Neural Network (ANN) - *All pixel-based*
- ABI multispectral information and NWP layer humidity trained using ‘truth’ from CloudSat radar and CALIPSO lidar
  - CloudSat/CALIPSO cloud boundaries, matched to parallax-corrected GOES-16 data from Oct 2018 – June 2019; total of 21.6 million radar profile
  - ***RF***: 125 trees, max depth of 30
  - ***ANN***: 3 layers fully connected layers, 37 to 71 hidden units per layer
- Allows addition of a **High + Low** classification

Variable	**Description and units**	**Notes**
REFL01 through REFL06	ABI Channel 01 through 06 visible reflectances	Normalized by cos(solar zenith angle)
TB07 through TB16	ABI Channel 07 through 16 brightness temperature (K)	
RH_{max}	Maximum RH between 650 and 1000 hPa (%)	
RH_{150}	RH at 150 hPa (%)	
Lat	Latitude in (degrees north)	
$Flag_{sfc}$	0 indicates land or mix, 1=water surface	Set to 1 where CLAVR-x *land_class* is 0,5,6,7
$Flag_{snow/ice}$	0 indicates snow/ice free land surface, 1=snow/ice present	Set to 1 if either GFS snow depth or ice fraction are > 0

5-fold cross validation was used for hyperparameter tuning of both models; details in Haynes et al. (2021)

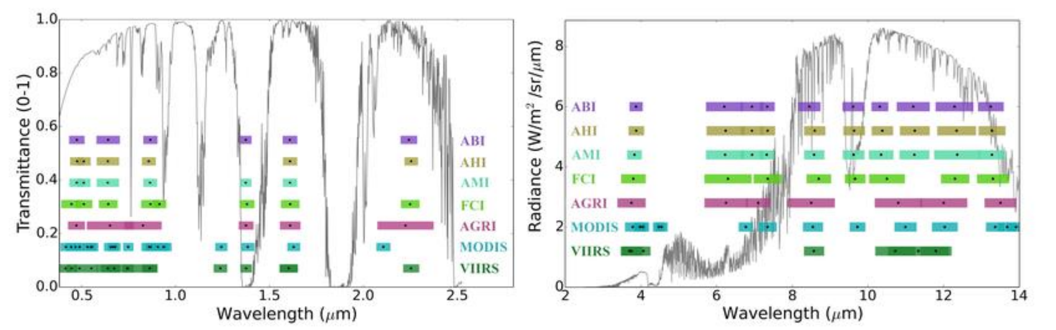
Extending the ML Algorithm

To nighttime

- Remove channels 1 through 7 (vis) from training
- PoD/FAR/CSI changes from (0.815 / 0.147 / 0.715) for the full algorithm to (0.770 / 0.184 / 0.656)
- Performance decrease, but still improvement over CCL

From ABI to VIIRS

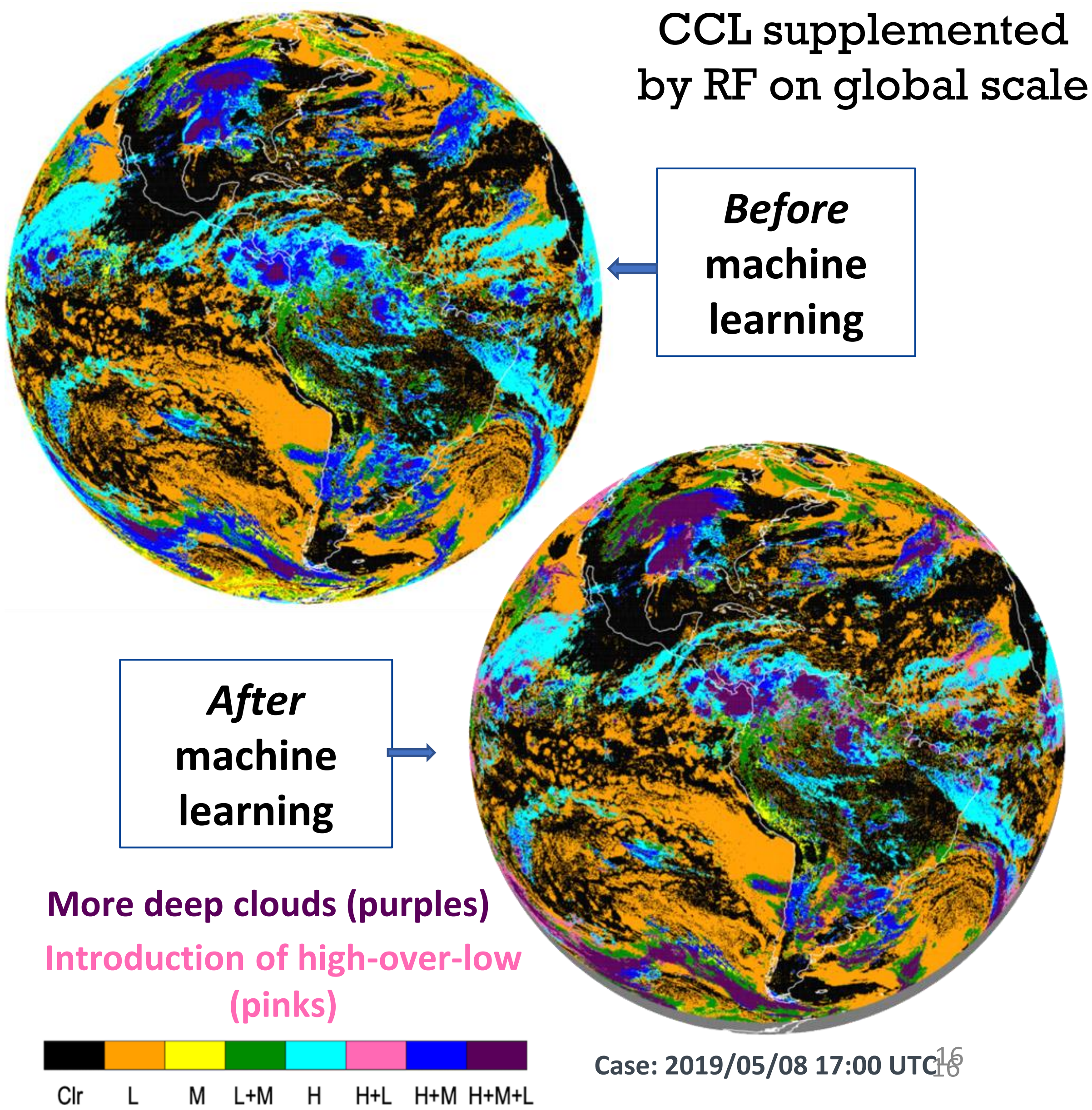
- Transfer learning: we are translating the algorithm to use VIIRS inputs at similar channels



Wang et al. 2020 (CC-BY 4,0, unmodified)

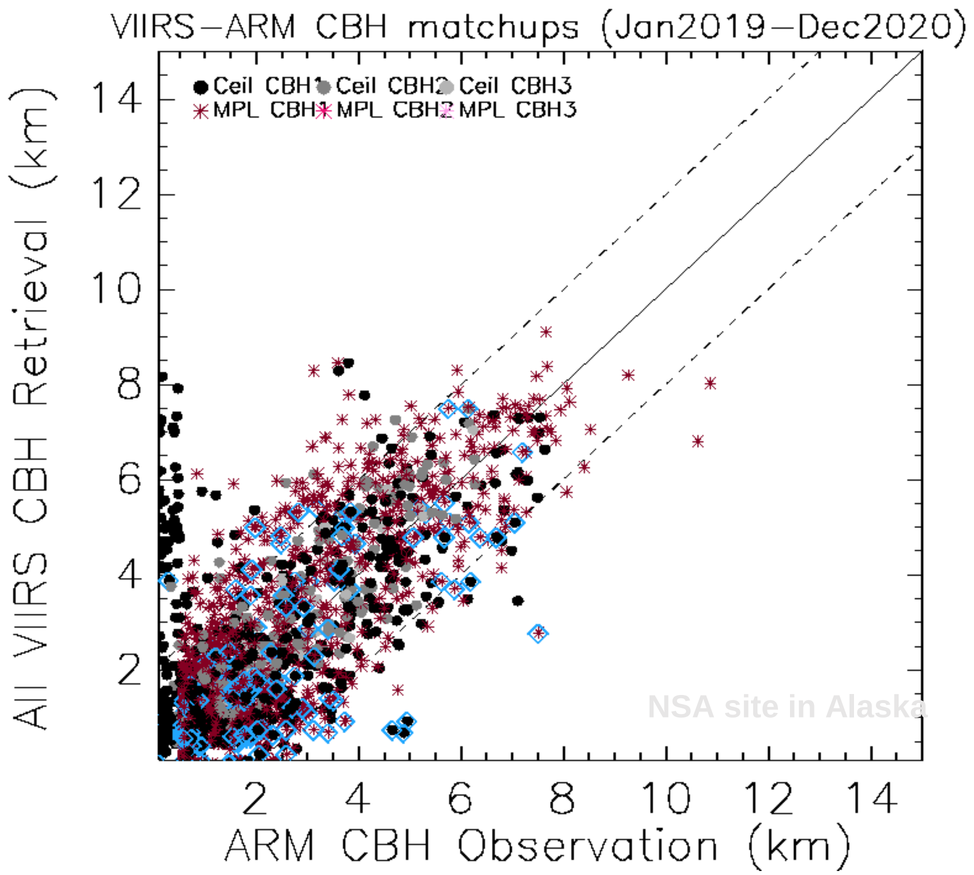
- CloudSat/CALIPSO/VIIRS matchups do occur, but the dataset is small given their orbits
- However, we can ABI/VIIRS matchups to adjust algorithm input histograms
- Future work to all vertical levels

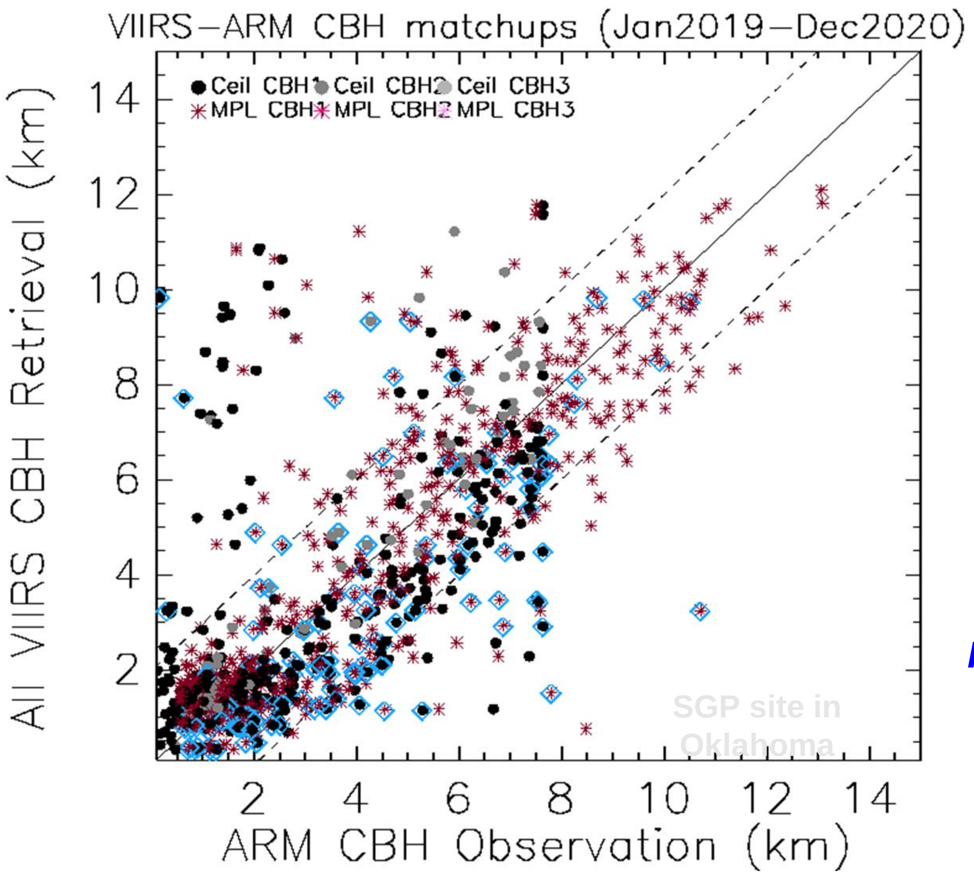
CCL supplemented by RF on global scale



Case: 2019/05/08 17:00 UTC

CBH comparisons with ARM measurements





In progress with METAR data

Comparisons of CBHs from VIIRS and ARM ground-based measurements for Jan 2019 - Dec 2020 (Micro-Pulse Liar in red-brown asterisk and Ceilometer in black-gray circles). Collocations between VIIRS pixel (parallax-corrected) and ARM site locations were conducted within 0.1 degree and 5-min window. Note that nighttime CBHs from NLCOMP using DNB are colored in blue.

("Within-spec" comparisons when VIIRS CTH is within 2 km against surface lidar CTH)

Summary

- **Develop a statistical CBH algorithm to provide 3-D cloud structure information using satellite observations**
  - Operational as part of the NOAA Enterprise Cloud Algorithms
- **Improve science algorithms**
  - Machine learning approach to improve multilayer cloud retrievals
  - Utilizing VIIRS DNB for nighttime retrievals (+ NWP, ATMS)
  - Validation against surface-based measurements and spaceborne active sensors
- **Introduce Cloud Vertical Cross-section products for aviation users**
- **Construct fully gridded 3-D Cloud data**
- **Product demonstration and training tools based on user feedback**

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