



How NASA's Spaceborne Active Sensors Have Contributed to Operational NOAA 3D Cloud Products for Aviation

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- Most cloud information from passive remote sensing instruments is limited to the tops of clouds, or the top of the topmost cloud layers.
- But information on what's happening closer to the surface is valuable for aviation and other real-time applications
- Using CloudSat/CALIPSO data, CIRA has been developing cloud products to estimate the *vertical distribution of clouds* from operational, passive satellite observations



I. Cloud Vertical Structure

- Why is this important to operational users, and how do we measure it?

II. Cloud Base / Vertical Structure from Passive Sensors

- An improved cloud base algorithm
- Applications to ABI and VIIRS, including customizable cloud vertical cross sections

III. A machine learning application to improve detection of difficult-to-retrieve clouds

IV. Towards the future



I. Cloud Vertical Structure

Why is this important, and how do we measure it?

- Cloud base / ceiling is particularly important for aviation, especially for *general aviation*
 - Instrument Flight Rules (IFR)
 - Mountain obscuration
 - Aerodrome forecasting
- How can we *operationally* measure/infer cloud base?



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Aviation Weather Center



abdallah (CC BY-SA 2.0)

- We can get cloud bases from ceilometers, where available

FAA/NWS Ceilometer Network



Alaska



Hawaii



Pros: High vertical and temporal resolution, automated obs

Con: Limited distribution and representativeness



JK047

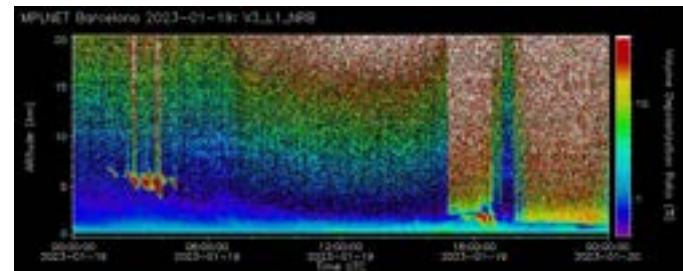
- Ground-based millimeter wavelength radars; lidars – ARM Sites, MPLNET



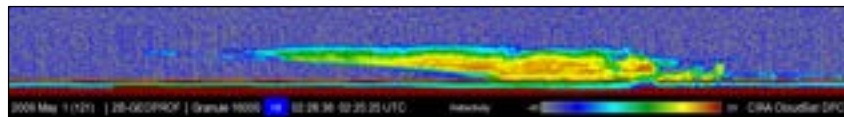
KAZR: Ka band radar (ARM)



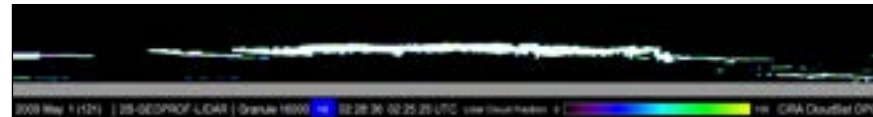
MMCR: Ka band radar (ARM)



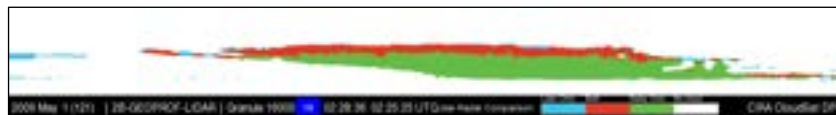
- CloudSat and CALIPSO (future AOS / EarthCARE)



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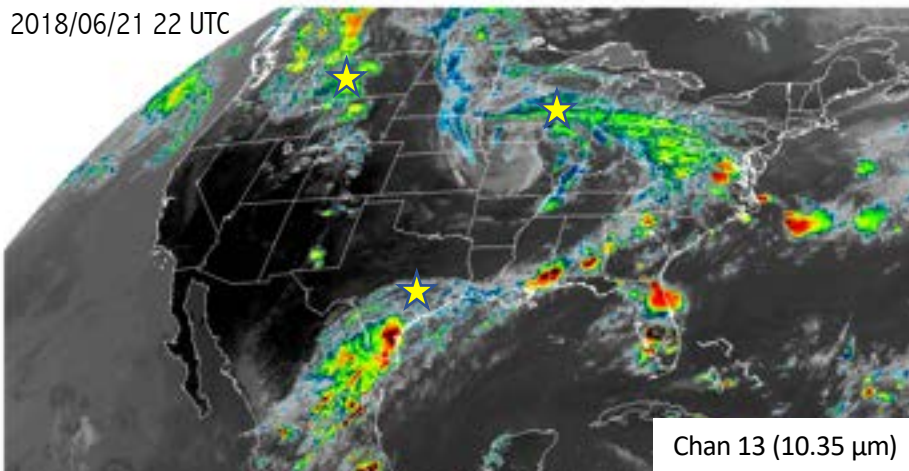
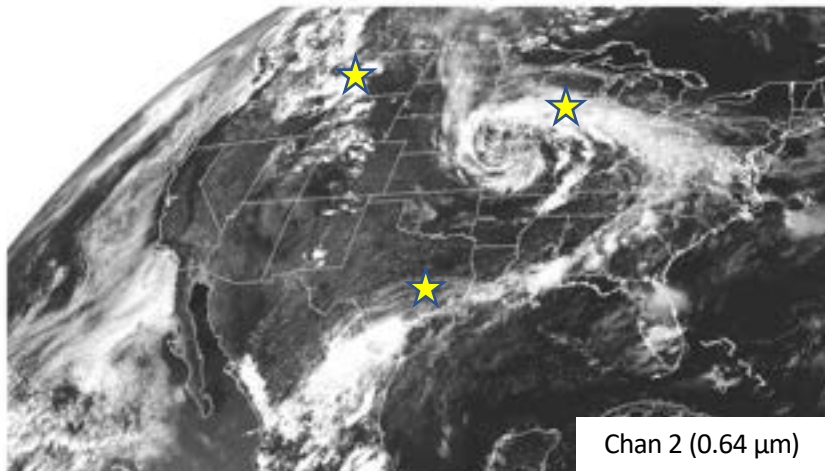


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Pros: High vertical resolution, high temporal resolution (ground sites)
Con: Low temporal resolution (C/C), lack of global applicability; costly

We are all familiar with using passive satellite imagery to locate clouds in time and space... but by *space* we usually mean *horizontal space*.

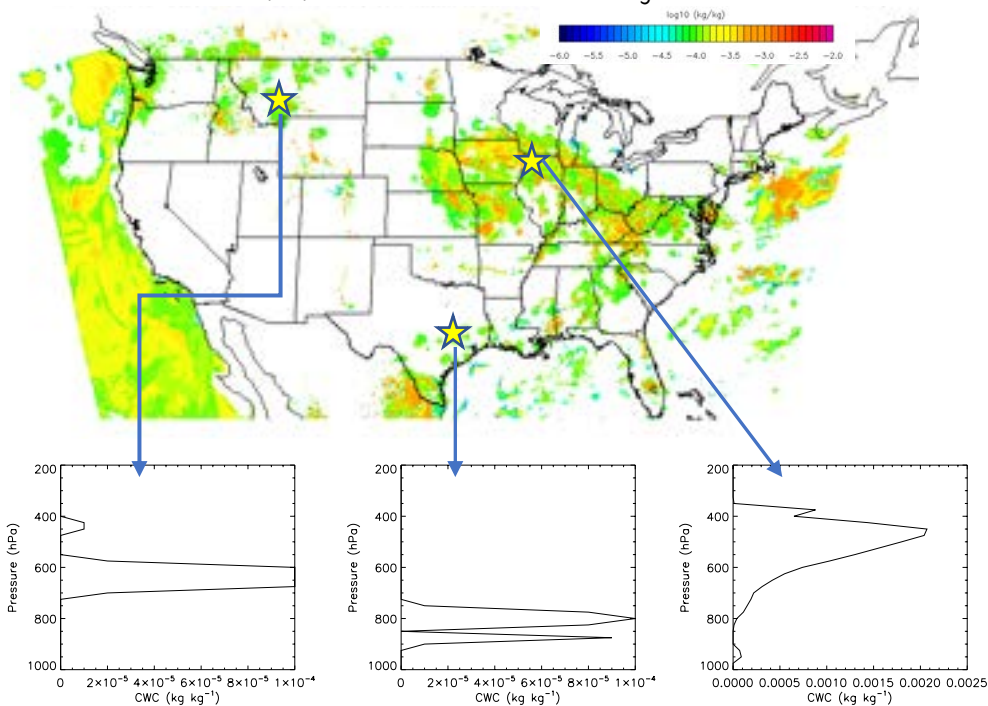


What does the vertical profile of cloudiness look like at the ★ locations?

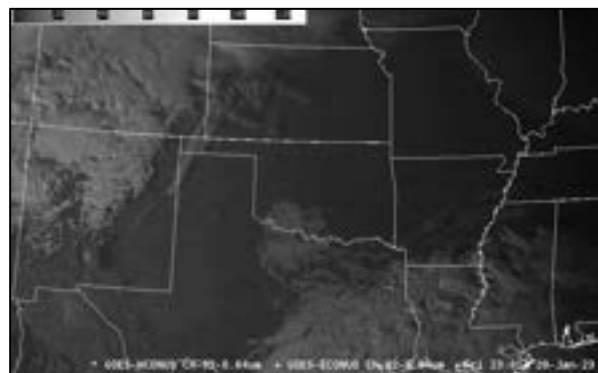
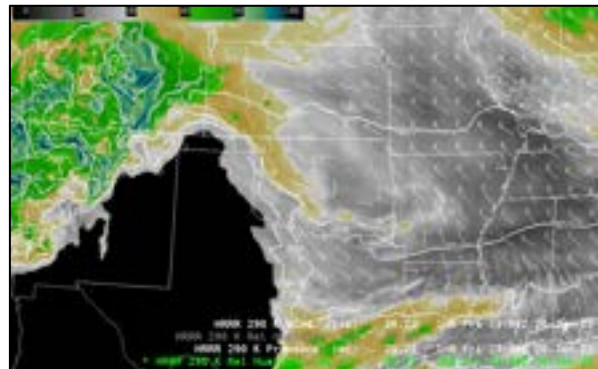
By using a combination of different channels, combined with surface observations, we might make some guesses – but can we do this operationally?

Another option is to appeal to high resolution forecast models (NWP)...

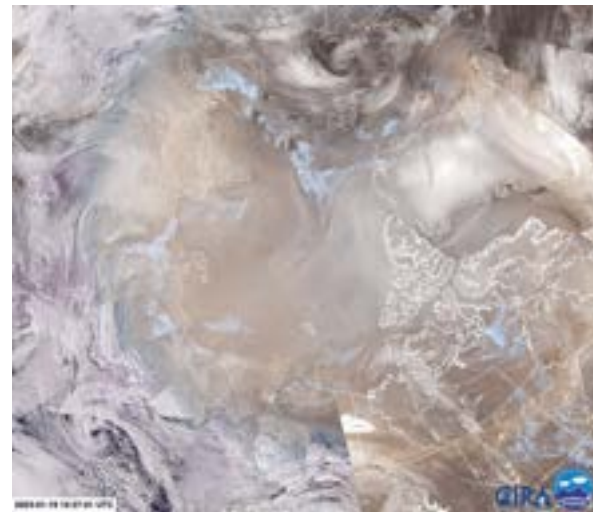
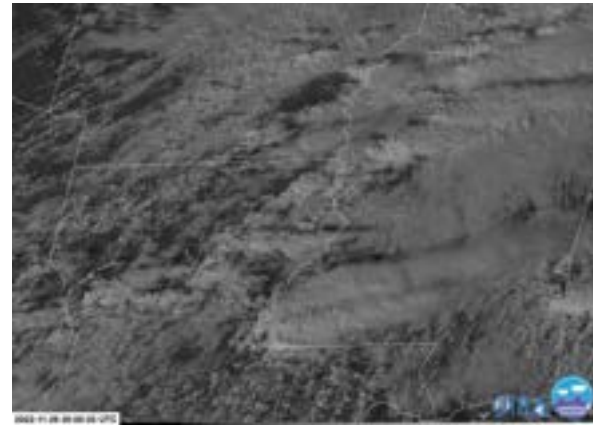
2018/06/21 22 UTC F00 HRRR cloud mixing ratio



In practice, forecasters often use relative humidity (RH) from NWP as a proxy for cloud cover...

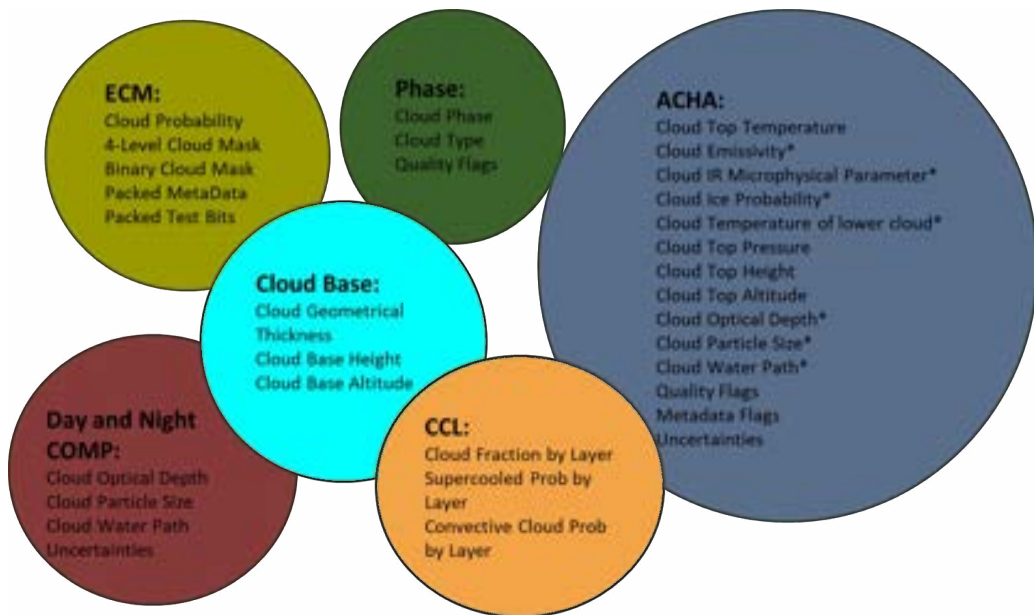


- Satellites sensors like the GOES Advanced Baseline Imager (ABI) or JPSS Visible Infrared Imaging Radiometer Suite (VIIRS) have some **distinct advantages**...
 - ABI: 10 minute CONUS refresh rate; 1 minute (or 30 seconds) for meso sectors
 - VIIRS: Frequent monitoring for high latitude regions
- BUT these are **passive sensors**...
 - Most information content is near cloud top
 - Multilayer clouds obscure information about low levels
- Can we use them to say something useful about cloud vertical structure?



II. Cloud Base / Vertical Structure from Passive Sensors





Enterprise Cloud Product Package

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

- **Cloud top height** is a key operational product produced by the NOAA Enterprise Cloud product suite.
- Our focus has been on the two circles at left feature **cloud base height (CBH)** and **cloud geometric thickness (CGT)**...
- ... and this is where CloudSat/CALIPSO have been instrumental

- Originally, VIIRS utilized a cloud base height (CBH) algorithm for liquid clouds as follows:

$$CBH = CTH - \left(\frac{LWP}{LWC} \right) \quad LWP = \frac{2\tau\rho r_e}{3}$$

Red variables from upstream retrievals

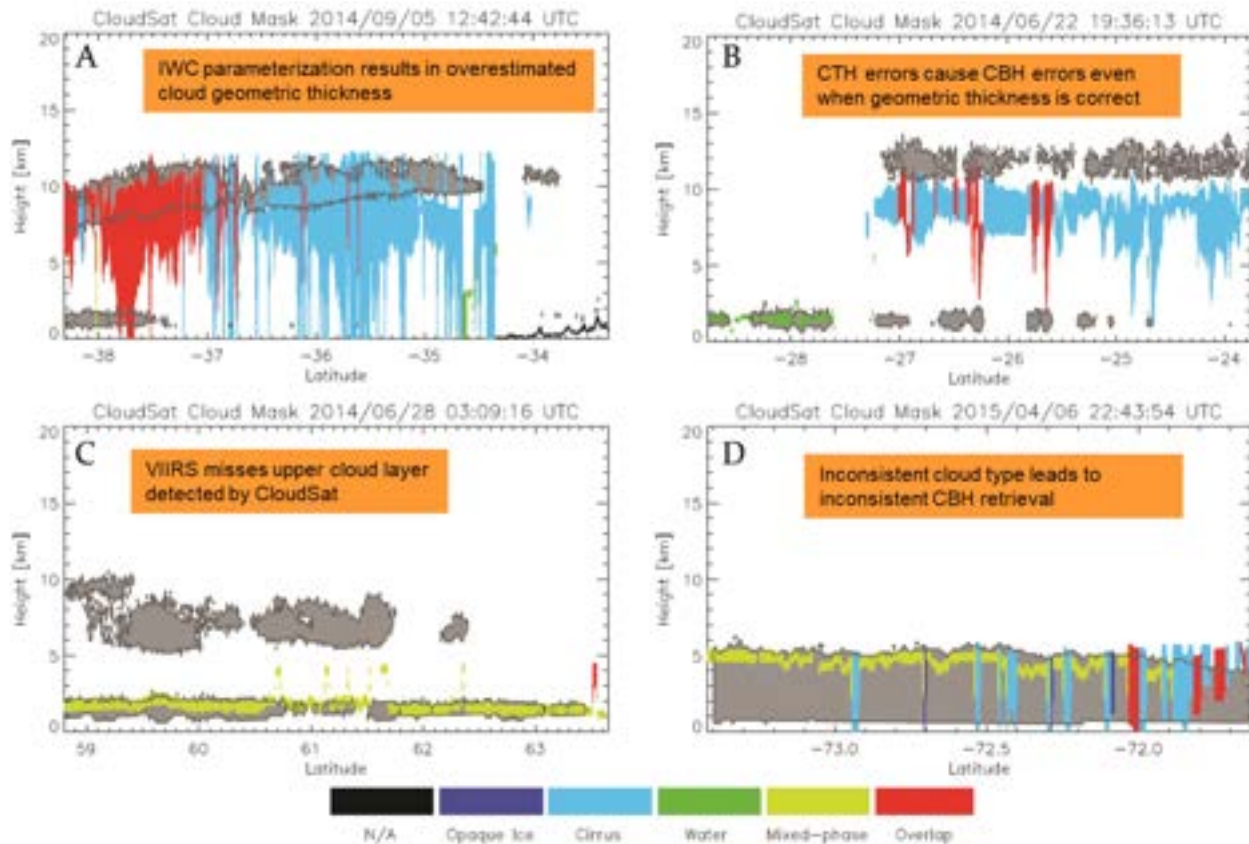
LWC is pre-defined average value based on cloud type; cloud type comes from upstream retrieval

(*) Ice retrieval is similar, but assumes IWC is function of temperature

- The fact that LWC was a mean dependent on cloud type was extremely problematic
- Seaman et al. (2017) used matchups between JPSS and CloudSat (overlap ~4.5 hours every 2-3 days, resulting in 11-12 overlap periods per month) to evaluate the performance of the algorithm described above
 - Daytime only
 - Excluding precipitation
 - Require CBH,CTH above 1 km

CloudSat (gray)
VIIRS cloud bounds (colors)

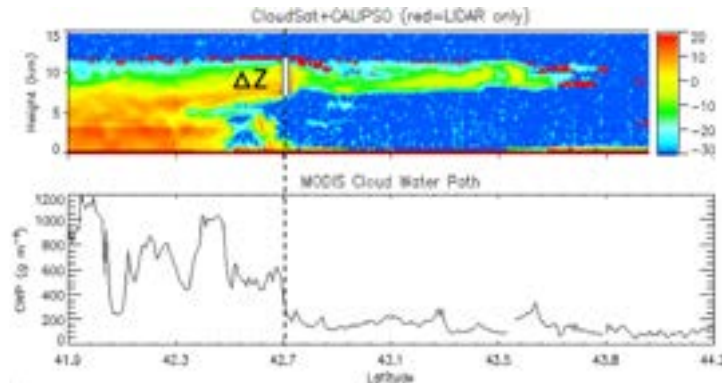
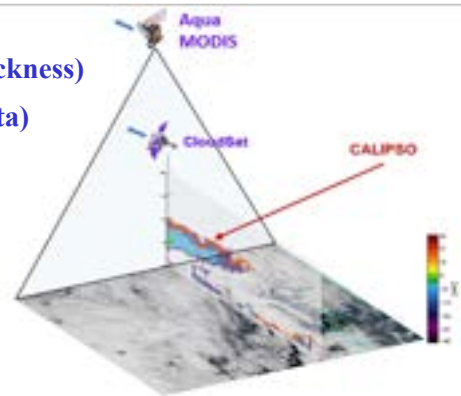
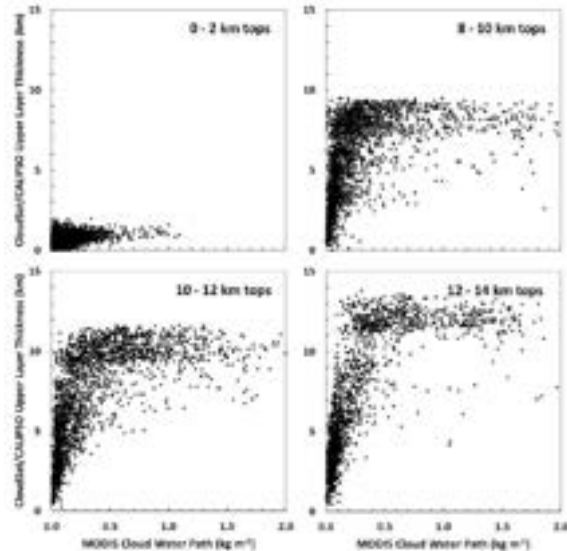
Credit: Curtis Seaman
Seaman et al. (2017)



RMSE ~ 2.7 km
 $r^2 = 0.452$

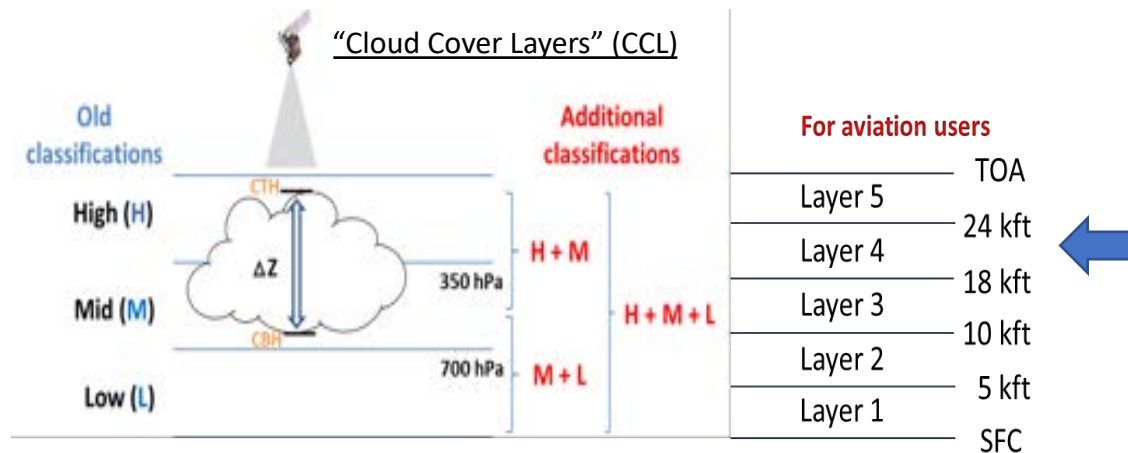
- We developed a cloud base height / cloud geometric thickness algorithm using NASA A-Train satellite data, and then applied it to VIIRS and then ABI (Noh et al. 2017, JTECH)

$CBH (*) = CTH - \Delta Z$ (CGT; Cloud Geometric Thickness)
 where $\Delta Z = a(CWP) + b$ (a, b based on A-Train data)



(*) Special considerations for optically thin clouds and optically thick clouds
No more cloud type dependency!

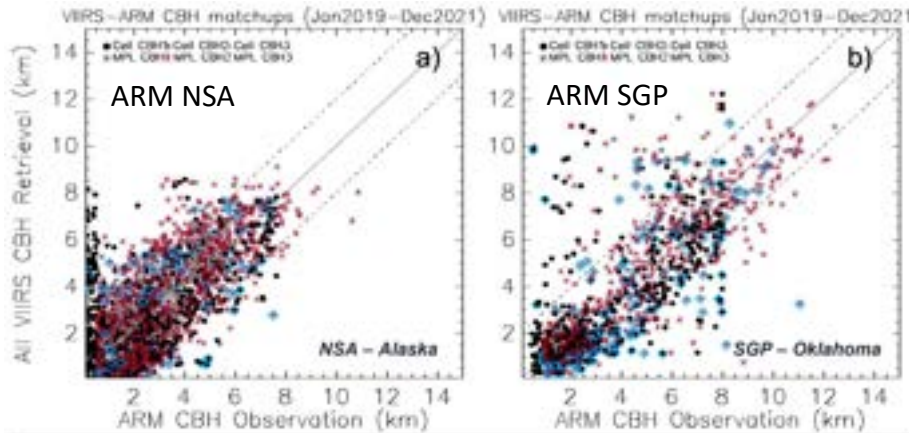
- Having developed these coefficients, we can now apply them to *any data* source that provides CTH and CWP
- Optimal for single layers – more on this later
- Retrieving geometric thickness means a better Cloud Cover Layers product:



Cloud Base Height:

ARM Ceilometer / MPL

vs.
VIIRS



Samples where VIIRS cloud base heights are within 2 km of..

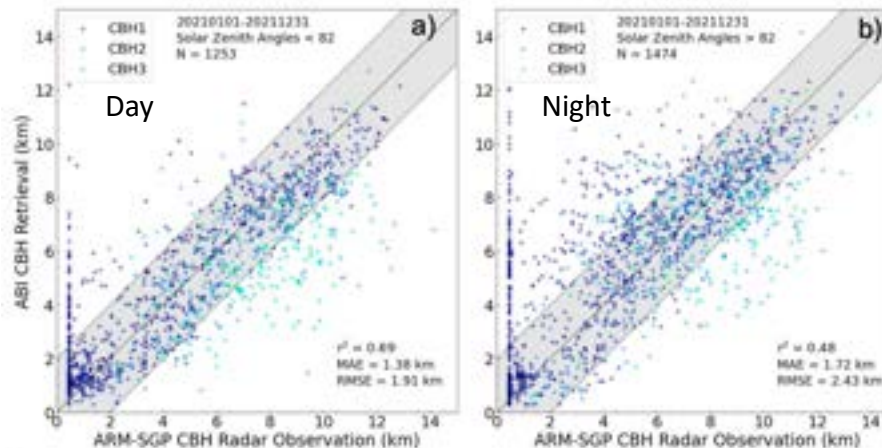
Ceilometer / MPL:

- 89% / 82% (NSA)
- 85% / 68% (SGP)

Cloud Base Height:

ARM SGP KAZR radar

vs.
ABI



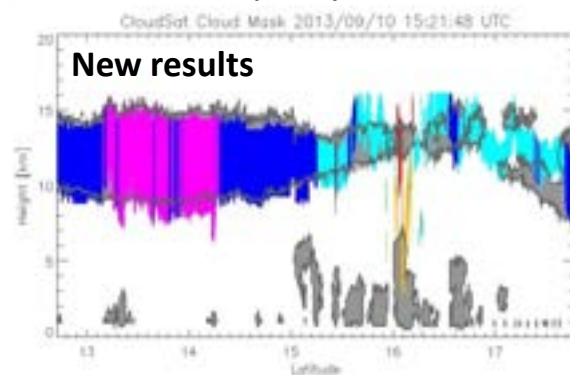
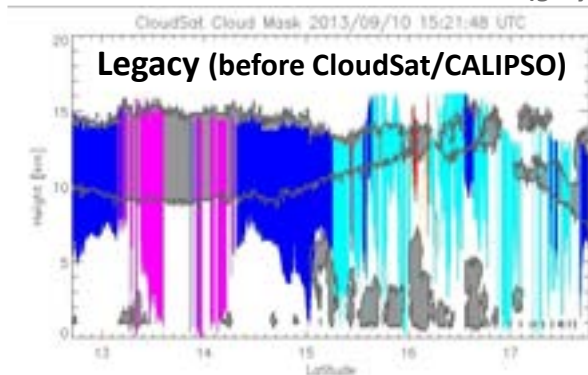
KAZR radar:

- 80% (day) / 70% (night)

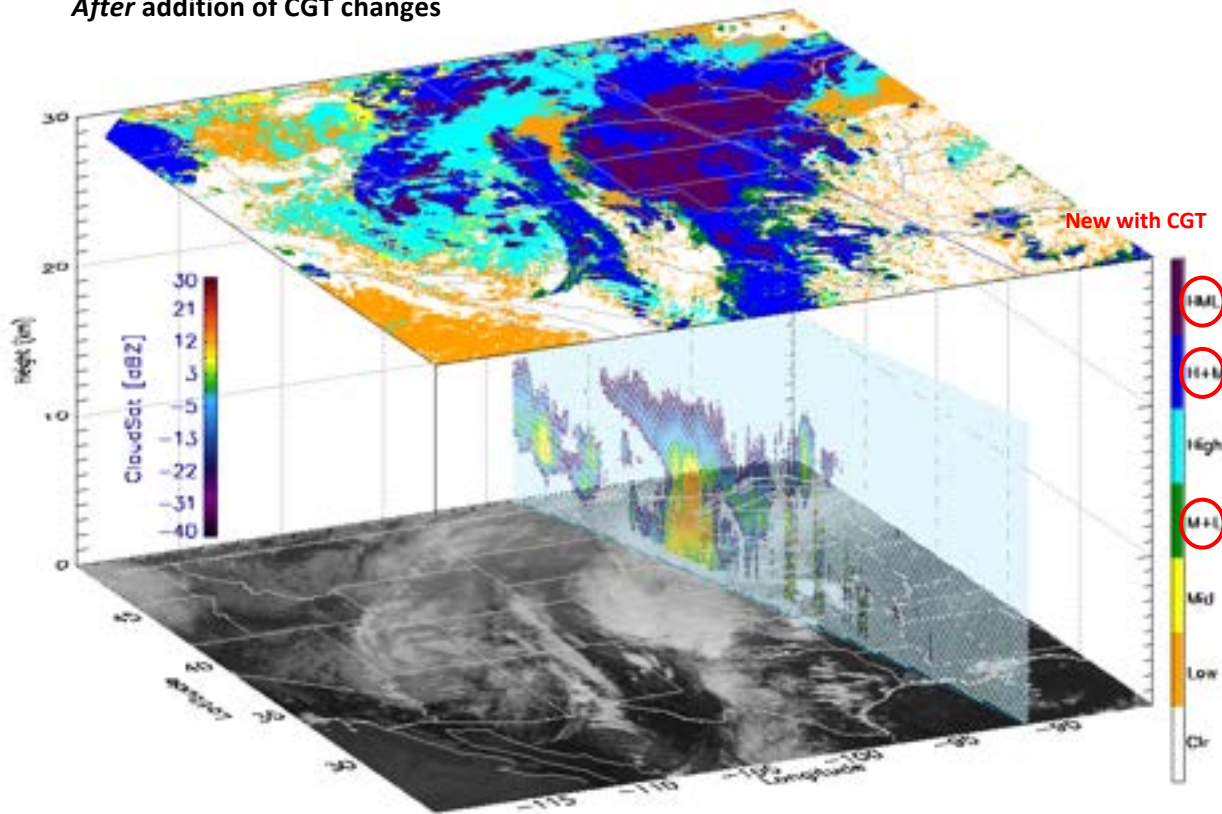
CBH comparison: “in-spec” results for VIIRS
relative to CloudSat/CALIPSO

| | RMSE | r^2 |
|------------------|--------|-------|
| Legacy algorithm | 2.7 km | 0.452 |
| New algorithm | 1.7 km | 0.791 |

CloudSat (gray) *VIIRS cloud bounds (colors)*



GOES-16 ABI
 After addition of CGT changes



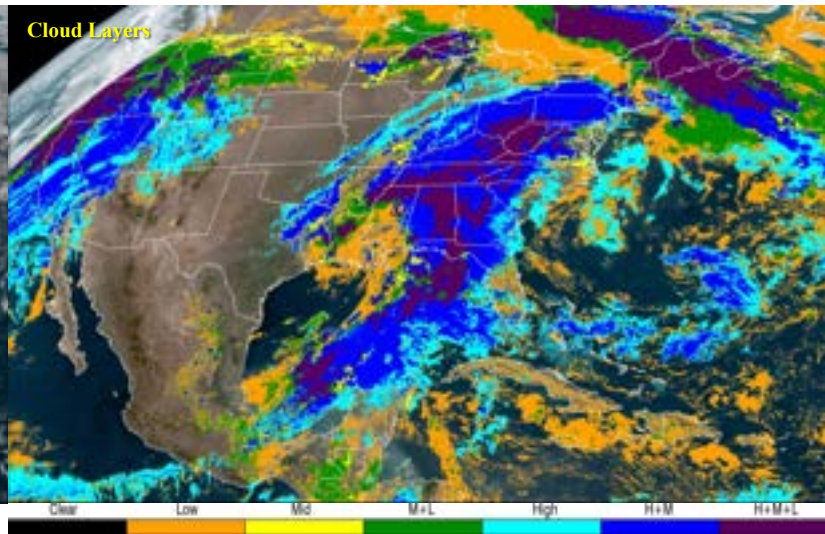
- Now applicable to polar and geostationary satellite sensors (JPSS VIIRS and GOES ABI, AHI, ...)
- Real-time display for the products available in CIRA's SLIDER - <http://rammb-slider.cira.colostate.edu>
- May be particularly useful for oceanic flight routing when combined with GLM

GOES-16 ABI GeoColor
with GLM overlay (L2 group energy)

Cloud Cover Layers



1806 – 2106 UTC (per 15 min) 08 April 2019



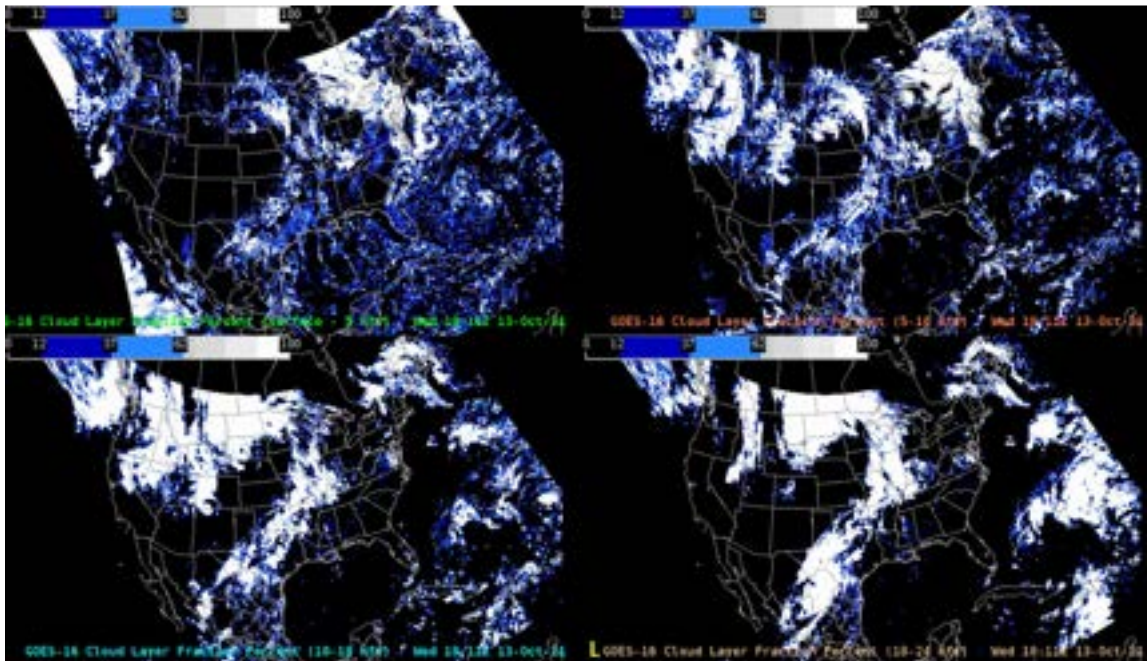
GOES-16 ABI CONUS

< 5 kft

5-10 kft

10-18 kft

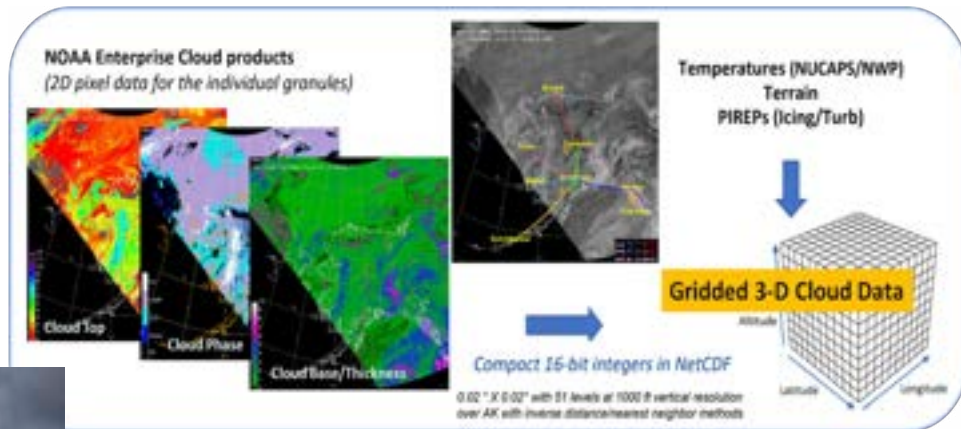
18-24 kft



Debra Molnar
Ty Higginbotham
Amanda Terborg

- Layer cloud fractions improved with Cloud Base in AWIPS II at the Aviation Weather Center
- Provisional review this Spring
- Current work: Development of volume browser display

- Working with the [JPSS Aviation Initiative](#), we have developed real-time VIIRS-based cloud vertical cross sections for Alaska
- Goal is to enable production of an “[active sensor-like](#)” cloud mask between arbitrary locations



- Aviation is critical for health and safety in remote regions of Alaska, and to economy
- Large number of aircraft based in AK!

Gillfoto (CC BY-SA 2.0)



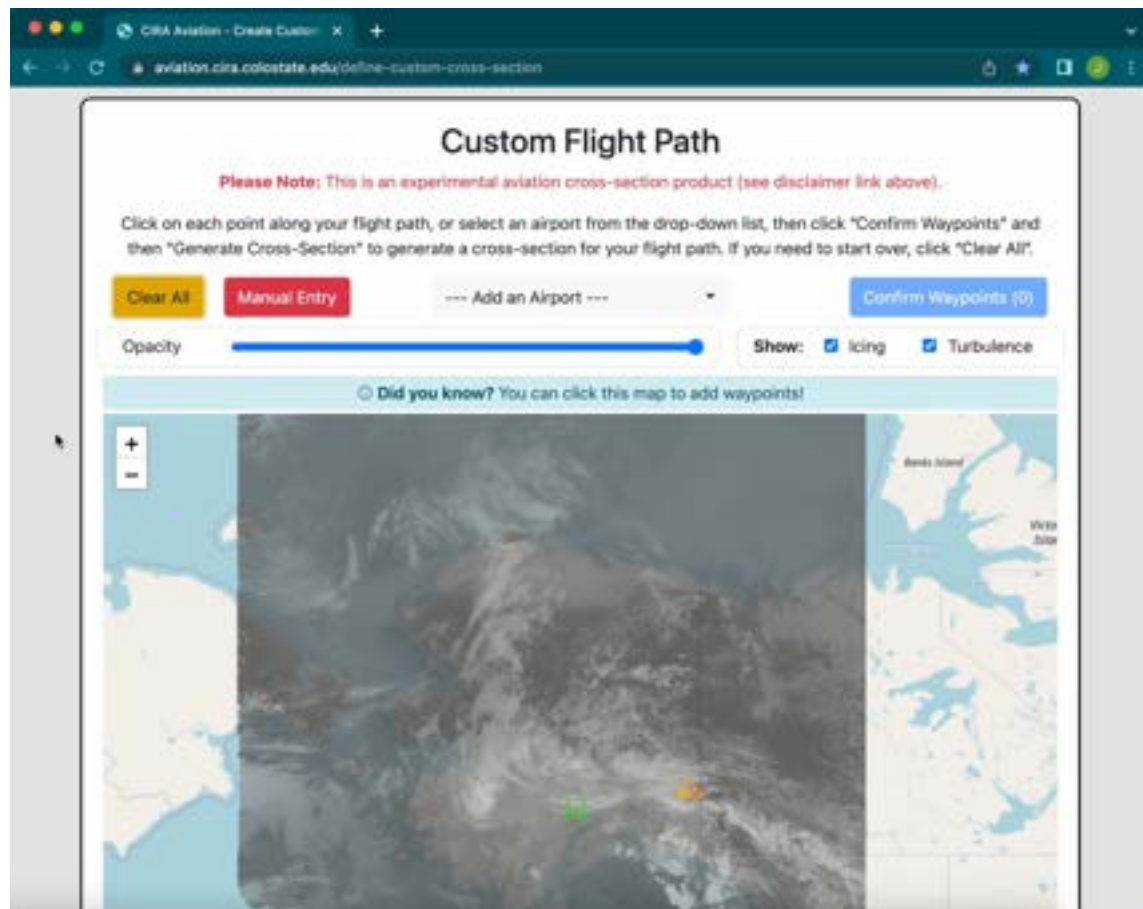
Zachary Perras

<https://aviation.cira.colostate.edu>

(Click at right for demo)

- "Active sensor-like" cloud vertical cross sections...
- ... without the active sensors! (*)
- (*) but impossible w/o them!
- Let's take a tour...

Leigh Cheatwood-Harris
Mattie Niznik



- Building on the success of our Alaska (VIIRS) product, and supporting user requests from West Coast WFOs, we are now testing a **CONUS, ABI-based cross section product**





Hurricane Fiona (*)

(*) Not a flight path we would recommend...

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Custom Flight Path

Please Note: This is an experimental aviation cross-section product (see disclaimer link above).

Click on each point along your flight path, or select an airport from the drop-down list, then click "Confirm Waypoint" and then "Generate Cross Section" to generate a cross-section for your flight path. If you need to start over, click "Clear All".

Clear All Manual Entry Add an Airport Confirm Waypoint

20220922 17:01:17-17:06:17 Z (GOES16 ABI) 20220922 13:01:17-20220922 13:06:17 EDT

- Blue: Other cloud
- Green: Freezing level
- Red: Precipitated
- Purple: IFR cloud
- Orange: Precip
- Yellow: Visibility mixed phase
- Light Blue: Turb
- Dark Blue: Wing

Altitude [kft, thousands feet]

20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430 440 450 460 470 480 490 500 510 520 530 540 550 560 570 580 590 600 610 620 630 640 650 660 670 680 690 700 710 720 730 740 750 760 770 780 790 800 810 820 830 840 850 860 870 880 890 900 910 920 930 940 950 960 970 980 990 1000 1010 1020 1030 1040 1050 1060 1070 1080 1090 1100 1110 1120 1130 1140 1150 1160 1170 1180 1190 1200 1210 1220 1230 1240 1250 1260 1270 1280 1290 1300 1310 1320 1330 1340 1350 1360 1370 1380 1390 1400 1410 1420 1430 1440 1450 1460 1470 1480 1490 1500 1510 1520 1530 1540 1550 1560 1570 1580 1590 1600 1610 1620 1630 1640 1650 1660 1670 1680 1690 1700 1710 1720 1730 1740 1750 1760 1770 1780 1790 1800 1810 1820 1830 1840 1850 1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100 2110 2120 2130 2140 2150 2160 2170 2180 2190 2200 2210 2220 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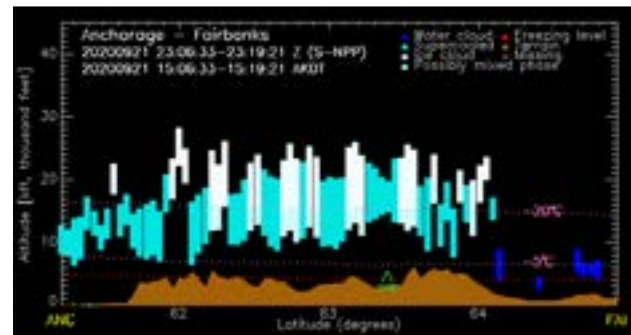
- We have regular interactions with pilots (JPSS Aviation Initiative), many opportunities for feedback

Feedback for This Image



- Partner with Aviation Weather Center for product evaluation and forecaster interaction
- Featured in Aircraft Owners & Pilots Association *ePilot* newsletter and weekly program, as well as the annual survey, receiving generally favorable marks

“I took off from FAI at 2300Z Sept 21 and landed at MRI (Merrill Field Anchorage) at 0100Z Sept 22 (3 pm to 5 pm AKDT). I observed no ceiling from FAI to the Alaska Range foothills, which is basically in agreement with the cross sections. By the time I was over Totatlanika River strip (9AK) I was under scattered to broken clouds with bases around 5,500 ft MSL. Basically, I flew under a broken to overcast ceiling that was at about 5,500 to 6,000 ft nearly all the way from McKinley Park (PAIN) to about Willow (PAOU). These bases were considerably lower than shown on the cross sections for most of the route...” (AK local pilot)

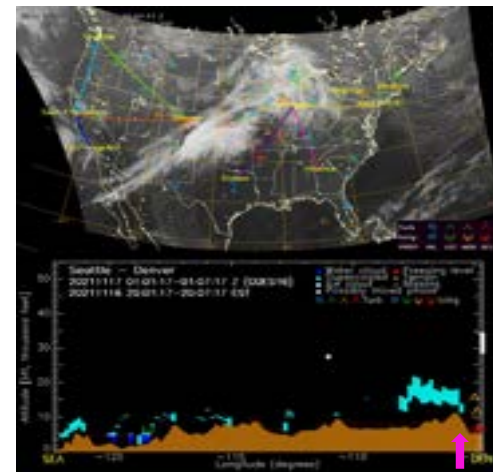


- We have regular interactions with pilots (JPSS Aviation Initiative), many opportunities for feedback



- Partner with Aviation Weather Center for product evaluation and forecaster interaction
- Featured in Aircraft Owners & Pilots Association *ePilot* newsletter and weekly program, as well as the annual survey, receiving generally favorable marks
- We have provided data for multiple NTSB investigations

Feedback for This Image



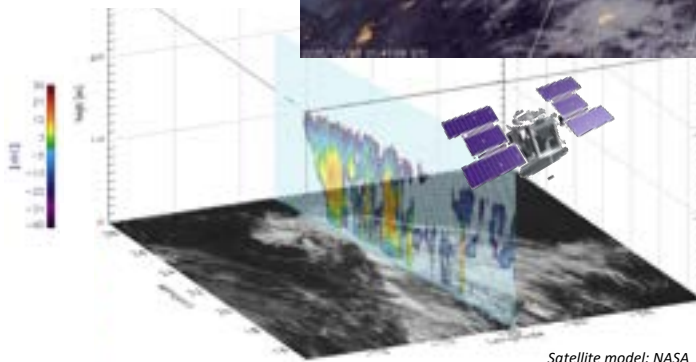
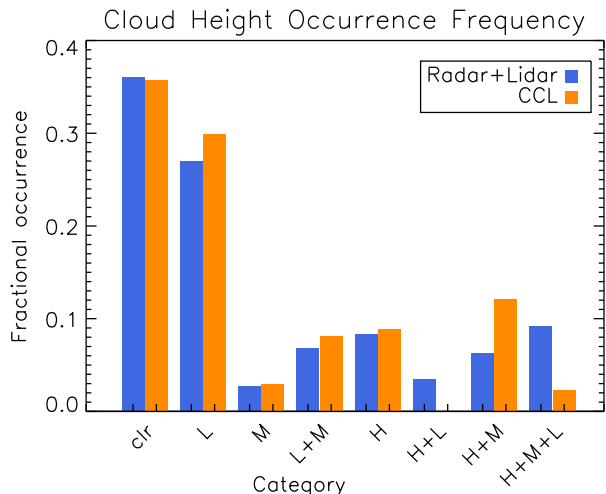
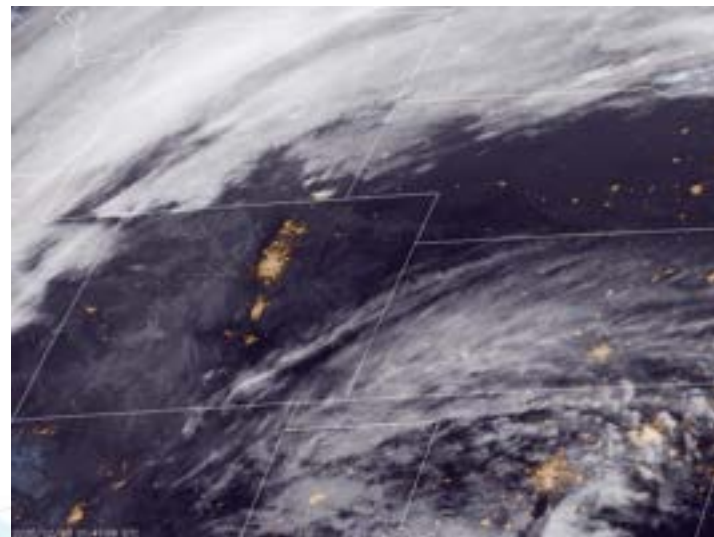
Small plane crash in Front Range Colorado mountains

III. Machine Learning for Difficult to Retrieve Clouds



- Multi-layer clouds are a problem for our current scheme, which is expected to perform best for single-layer clouds
- We are addressing this with machine learning, using CloudSat/CALIPSO (matched to GOES-16 ABI) as “truth”

Multilayer cloud example (CIRA GeoColor)

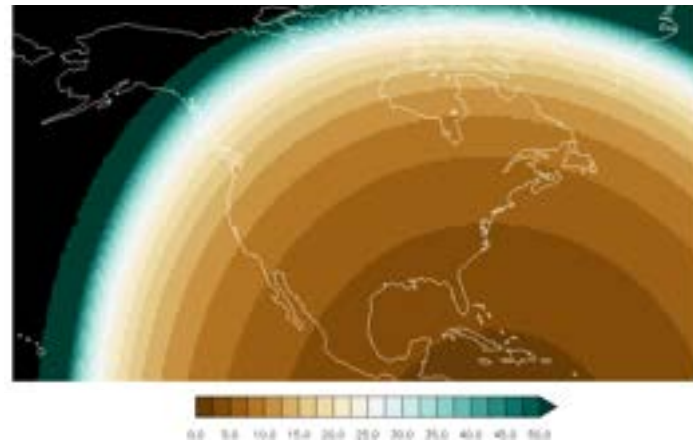


Start with a matchup dataset between GOES 16 ABI and CloudSat/CALIPSO

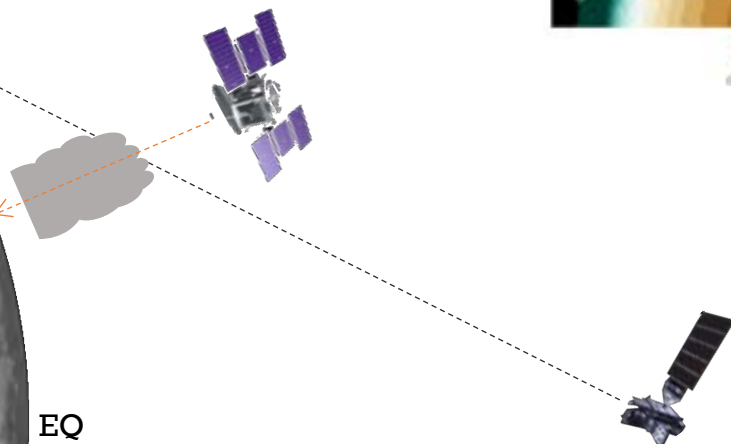
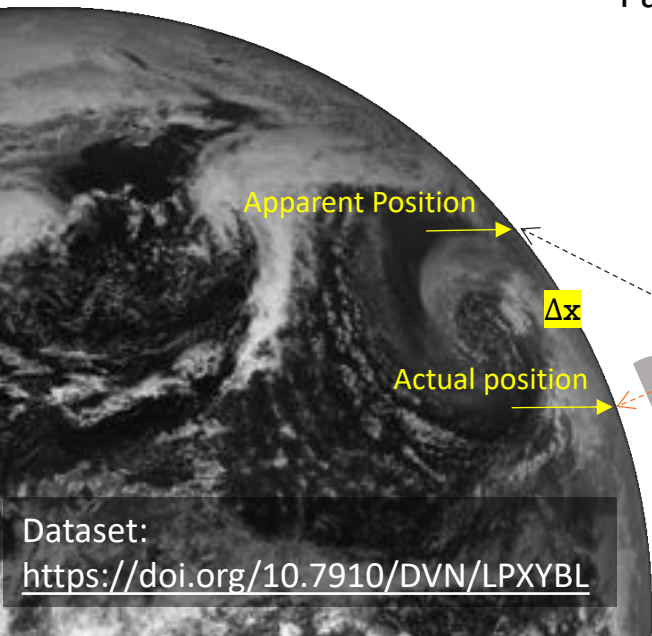
Matchup characteristics:

- Oct 2018 – Jun 2019
- Parallax correction applied

Parallax Error Δx (km) for 5 km High Cloud



NP



Dataset:
<https://doi.org/10.7910/DVN/LPXYBL>

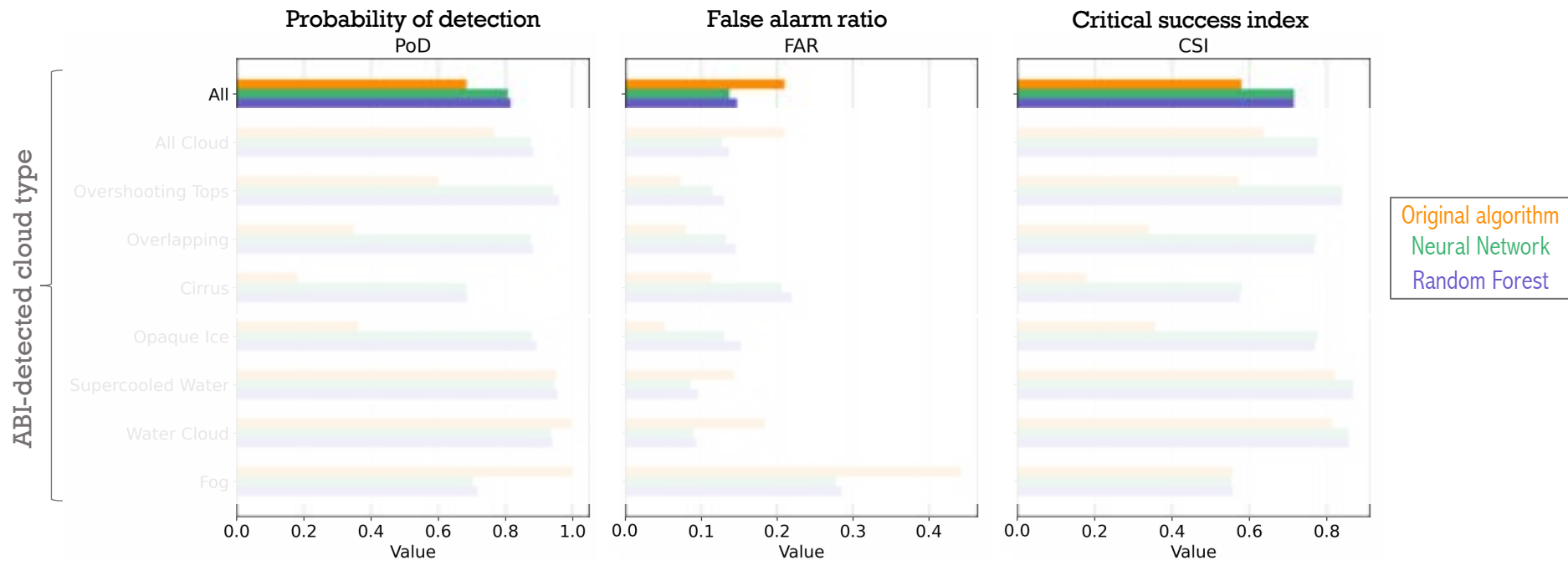
EQ

- Dataset:
 - ~ 22 million radar profiles matched to parallax-corrected GOES-16 ABI Refl / T_b
- Inputs:
 - ABI channels (all channels; common ratios and channel differences also tested)
 - Low-level relative humidity (serves as a low cloud proxy) from NWP model
 - Surface information
- “Truth”:
 - Was a low cloud present ($p > 631$ hPa) present? 0 or 1 ... classification problem
- Models (All **pixel-based**)
 - Random forest
 - 125 trees, max depth of 30
 - Artificial neural network
 - 3 fully connected layers
 - 37 / 77 / 71 hidden units per layer

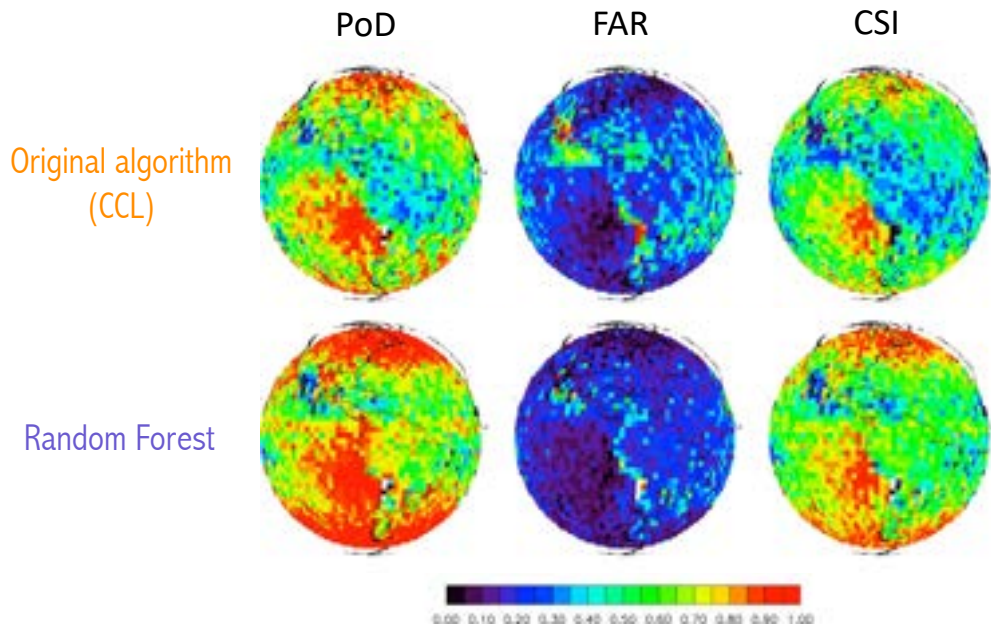
| Variable | Description and units | Notes |
|--------------------------|--|---|
| REFL01 through REFL06 | ABI Channel 01 through 06 visible reflectances | Normalized by $\cos(\text{solar zenith angle})$ |
| TB07 through TB16 | ABI Channel 07 through 16 brightness temperature (K) | |
| RH _{max} | Maximum RH between 650 and 1000 hPa (%) | |
| RH ₁₅₀ | RH at 150 hPa (%) | |
| Lat | Latitude in (degrees north) | |
| Flag _{land} | 0 indicates land or mix, 1=water surface | Set to 1 where CLAVR-x <i>land_class</i> 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 |

See Haynes et al. (2022), JTECH

Statistics for **low cloud** detection on ABI testing dataset



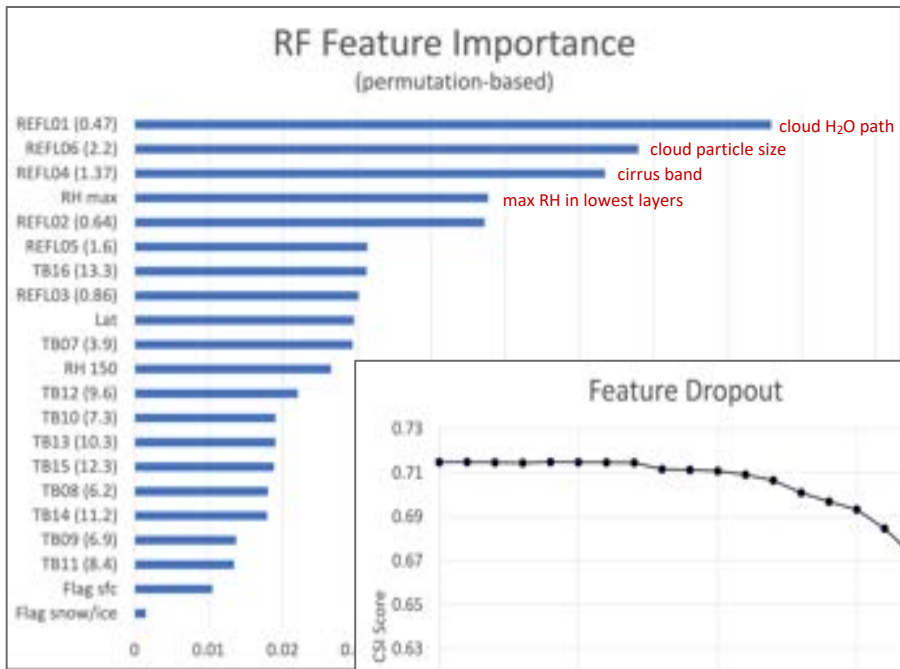
- Machine learning models outperform original algorithm, especially for mixed “Cirrus”/”Overlapping”
- ANN and RF are remarkably similar in performance!



- Machine learning produces greatest performance enhancements relative to original algorithm...
 - ... in higher latitudes
 - ... in cases where Enterprise/ABI identifies "Cirrus" (hidden low cloud / multilayer)

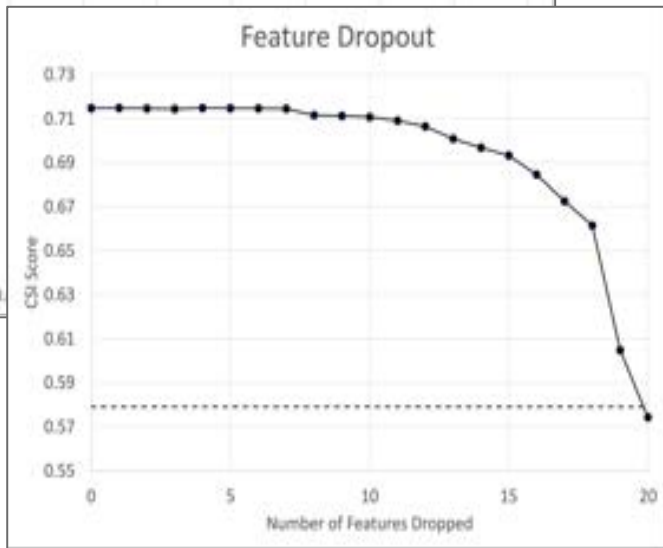
| | Low Cloud Detection Algorithm | Prob of Detection | False Alarm Ratio |
|------------|-------------------------------|-------------------|-------------------|
| All cases | Original statistical (CCL) | 0.685 | 0.210 |
| | Random Forest / ANN | 0.815 / 0.807 | 0.147 / 0.137 |
| ABI Cirrus | Original statistical (CCL) | 0.183 | 0.114 |
| | Random Forest / ANN | 0.686 / 0.684 | 0.219 / 0.206 |

Feature Importance



RF permutation-based feature importance highlights importance of **visible channels** and **RH**, which is used as a cloud proxy

- The top 3 channels (0.47, 2.2, 1.37 μm) contain information that is useful for differentiating cirrus with and without underlying low cloud



The “Feature Dropout” plot demonstrates how the CSI score changes as features are cumulatively dropped as predictors, from least to most important.

- The curve is flat for up to ~ 10 features dropped!
- Very little influence by surface-type flags
- Demonstrates **correlation** between ABI channels.
- Also suggests a **simplified model** will have similar performance!

CCL supplemented by RF on full disk

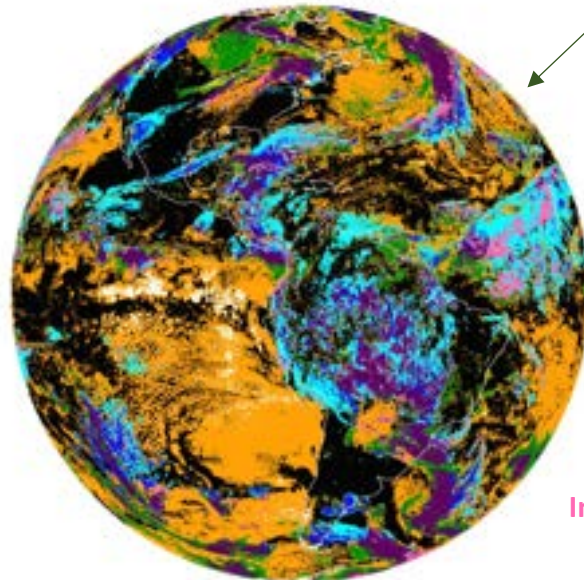
CCL-only Cloud Height
2021/321 20:00



Before machine learning



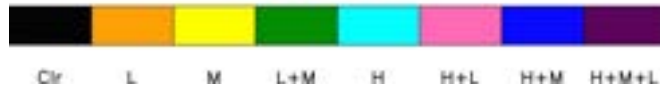
CCL + RF Cloud Height
2021/321 20:00



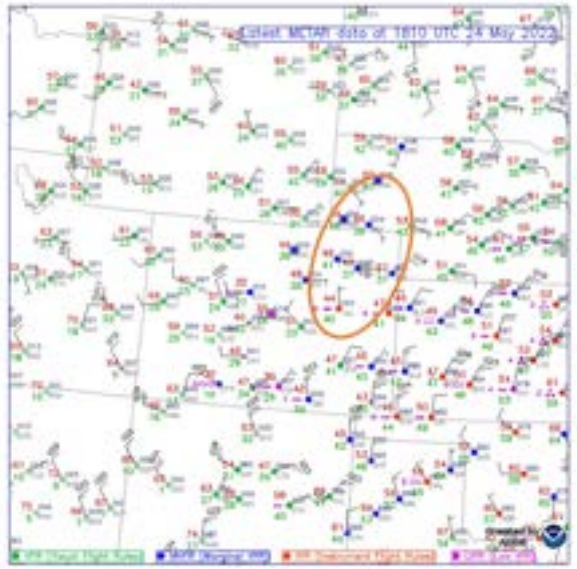
Includes a "nighttime version" 🌙 that excludes channels 1 through 7 (vis) from training

After machine learning

More deep clouds (purples)
Introduction of high-over-low (pinks)



Case studies suggest the machine learning augmentation to CCL produces a much more accurate representation of low cloud presence

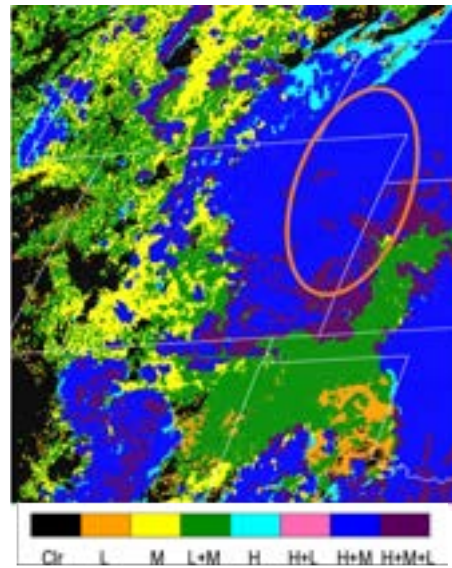


Example case study: upper-level low exits Rockies

Marginal VFR conditions with 1-3kft ceilings in northeast Colorado and Neb. Panhandle

These ceilings are better represented with machine learning addition

KDGA 241755Z AUTO 11003KT 10SM SCT027 SCT032 OVC038 12/06 A3006 RMK AO2 T01170061 10120 20070
 KSTK 241735Z AUTO 04004KT 10SM OVC021 09/05 A3004 RMK AO2

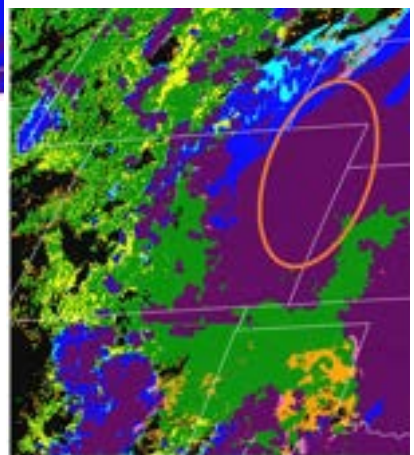


CCL supplemented by RF

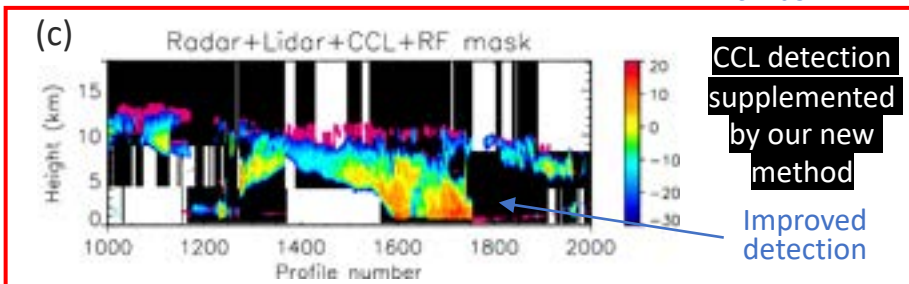
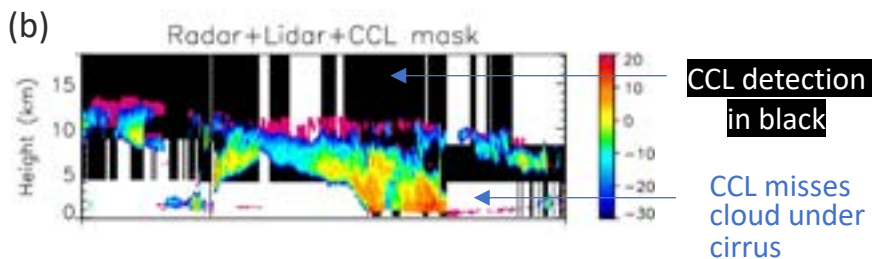
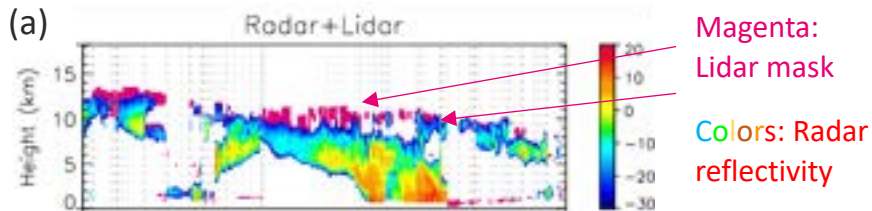
Before machine learning

After machine learning

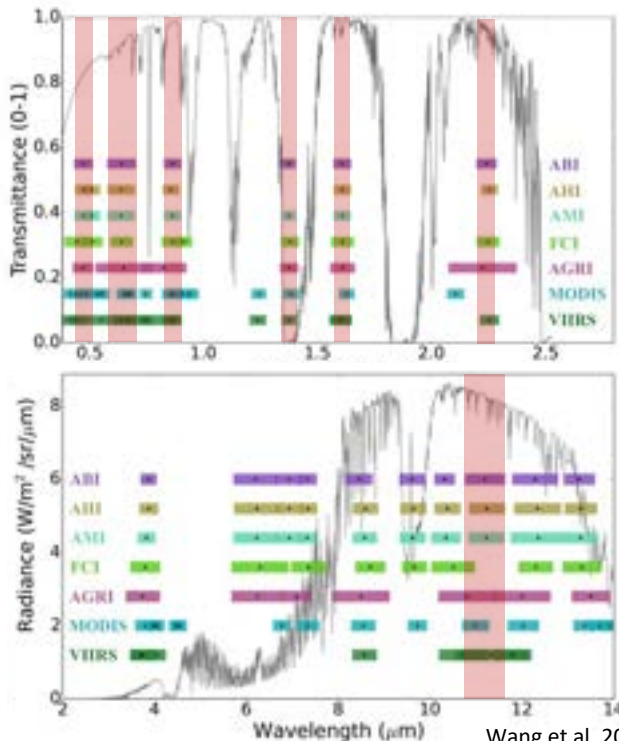
More deep clouds (purples)
 NEW high-over-low (pinks)



Example cross sections through ABI "Cirrus"

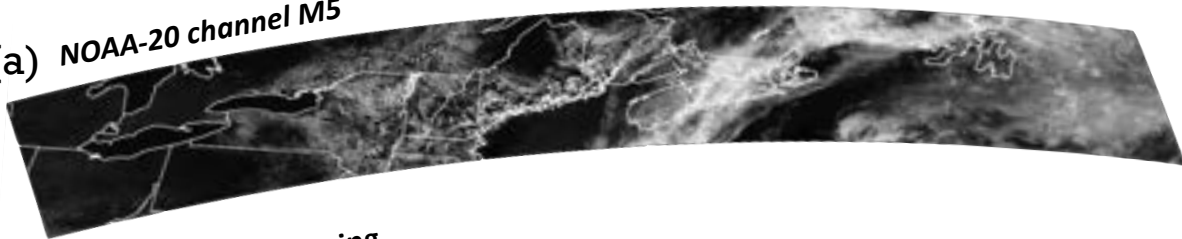


- Simplified “7 channel model” for VIIRS

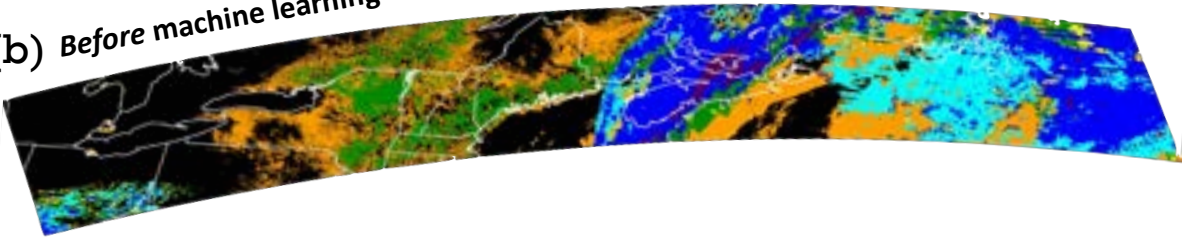


Wang et al. 2020, Remote Sens.

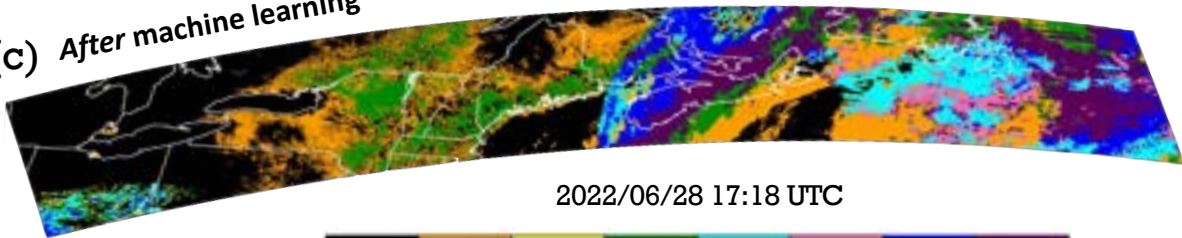
(a) NOAA-20 channel M5



(b) Before machine learning



(c) After machine learning



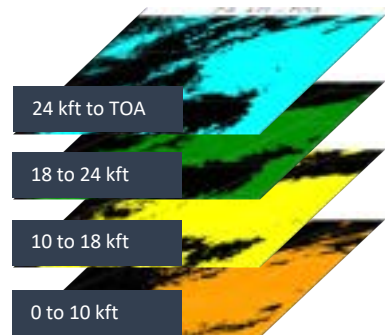
2022/06/28 17:18 UTC



Clr L M L+M H H+L H+M H+M+L

Preliminary example - uncalibrated

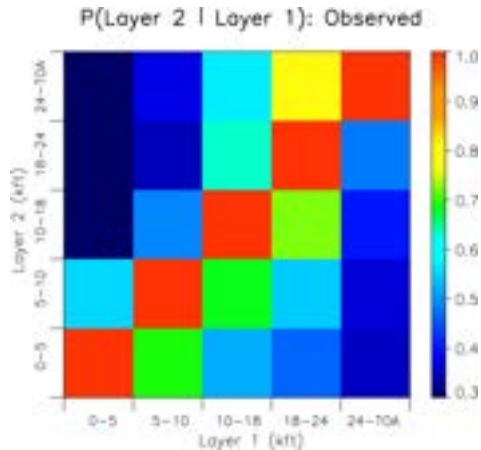
- Using multi-output prediction, we can use the same inputs to predict not only low cloud, but cloud in **any layer of our choosing**.
- This should ideally (and to a large extent does) preserve the observed correlation between cloud layers.



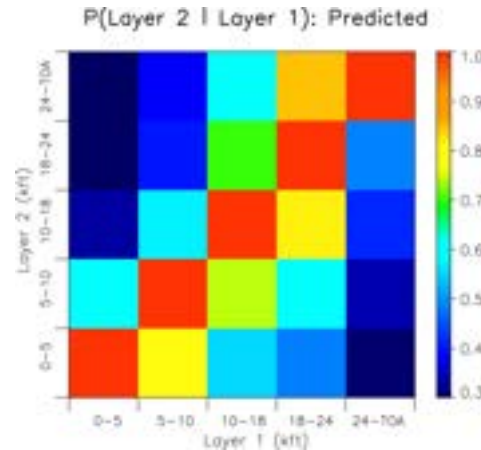
Global Evaluation of multilayer cloud mask

| | PoD | Success ratio | Accuracy |
|---|------|---------------|----------|
| Topmost layer | 0.86 | 0.89 | 0.93 |
| (... intermediate layers not shown ...) | | | |
| Bottommost layer | 0.72 | 0.80 | 0.84 |

Observed correlation between cloud layers



Predicted correlation between cloud layers



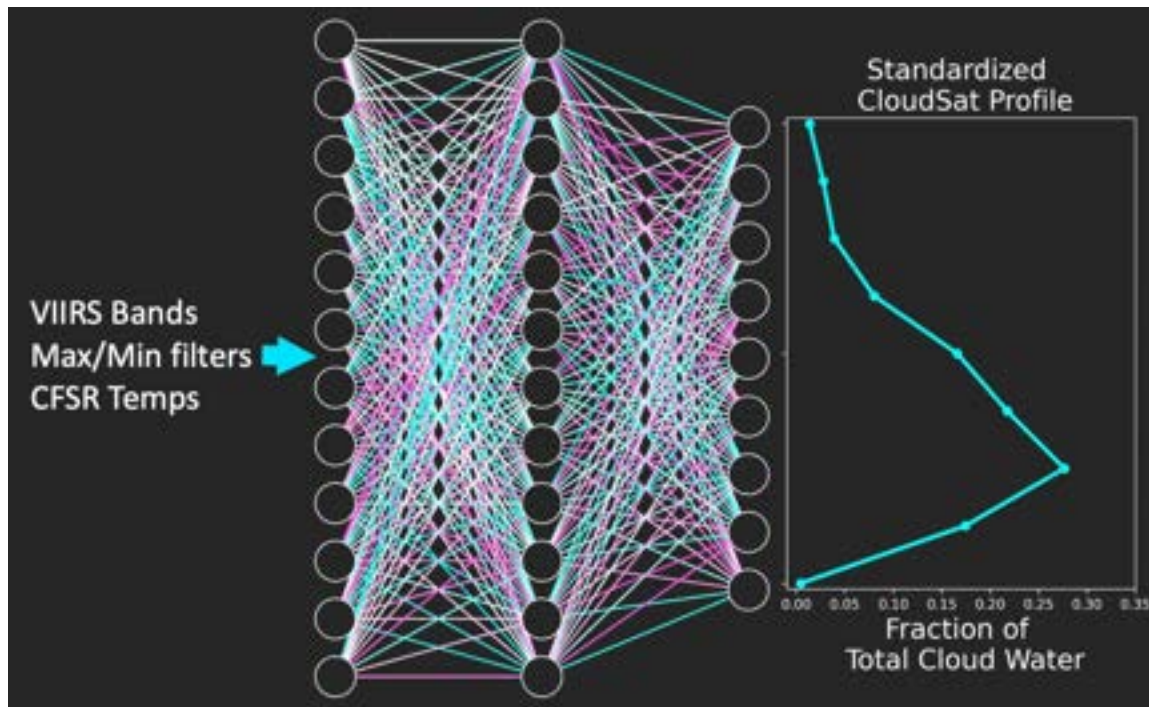
IV. Towards the Future



In progress: Can we predict vertical profiles of cloud water content from passive sensors?

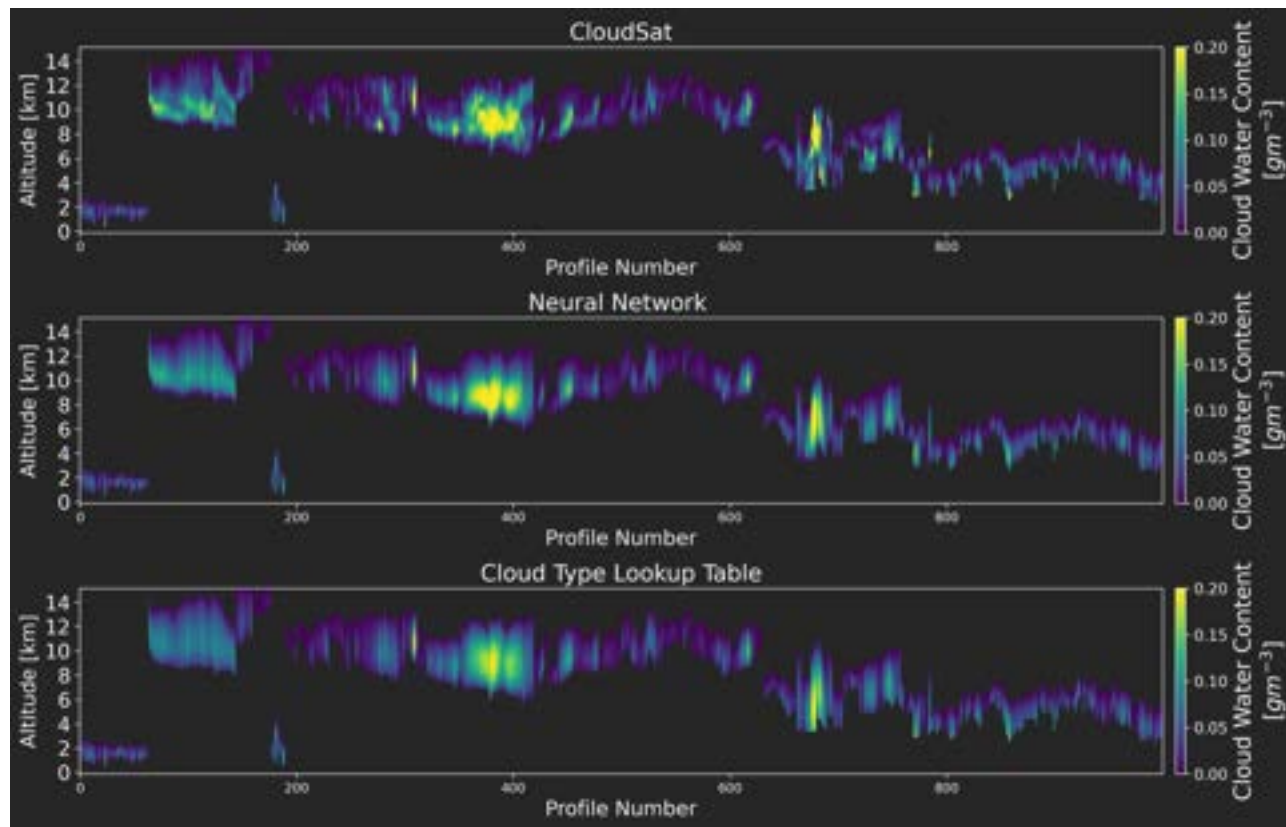
Again, we appeal to active sensors!

- Multi-layer perceptron
 - 4 fully-connected layers with 64 units each
 - Leaky ReLU
- Output
 - 9-valued standardized profile
 - Softmax



Credit: Chuck White et al.

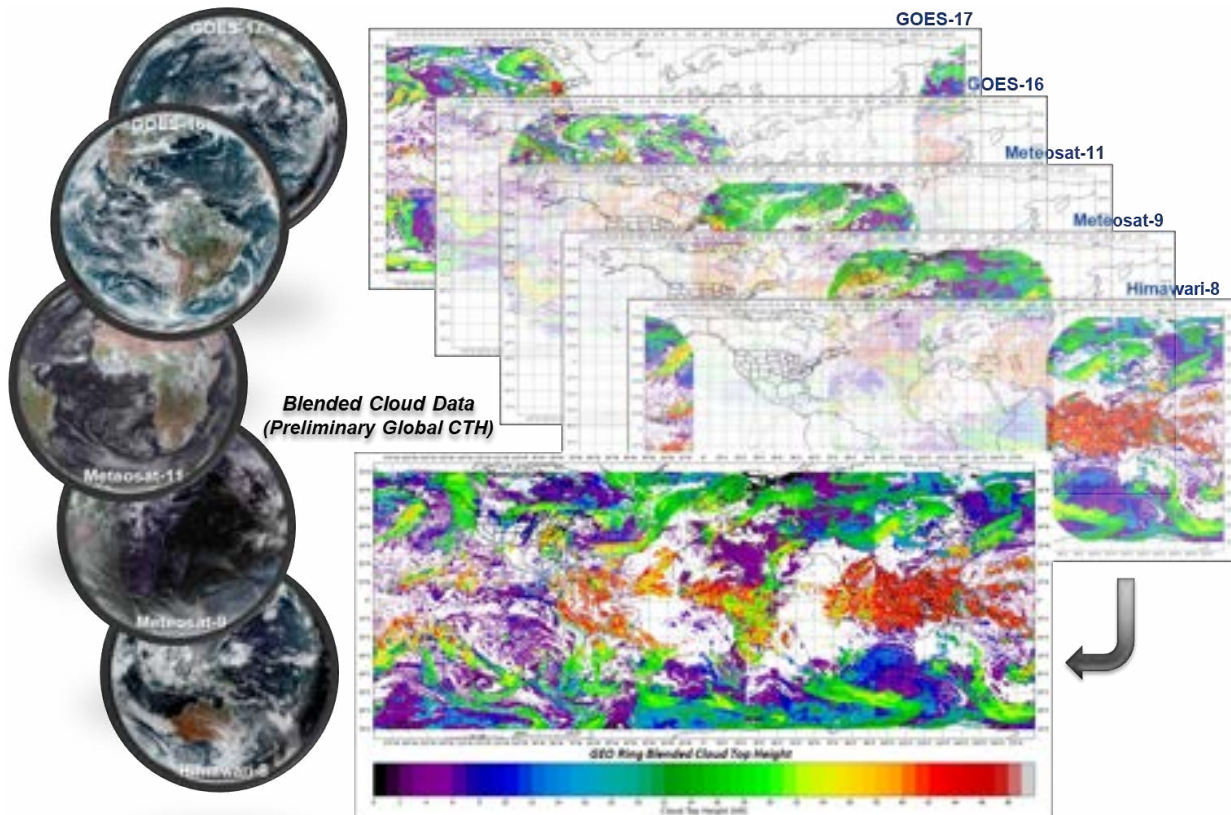
- Example preliminary result
- For demonstration purposes, we assume we know the actual cloud thickness for these single-layer cases
- Demonstrates a future capability that may be useful for aircraft icing



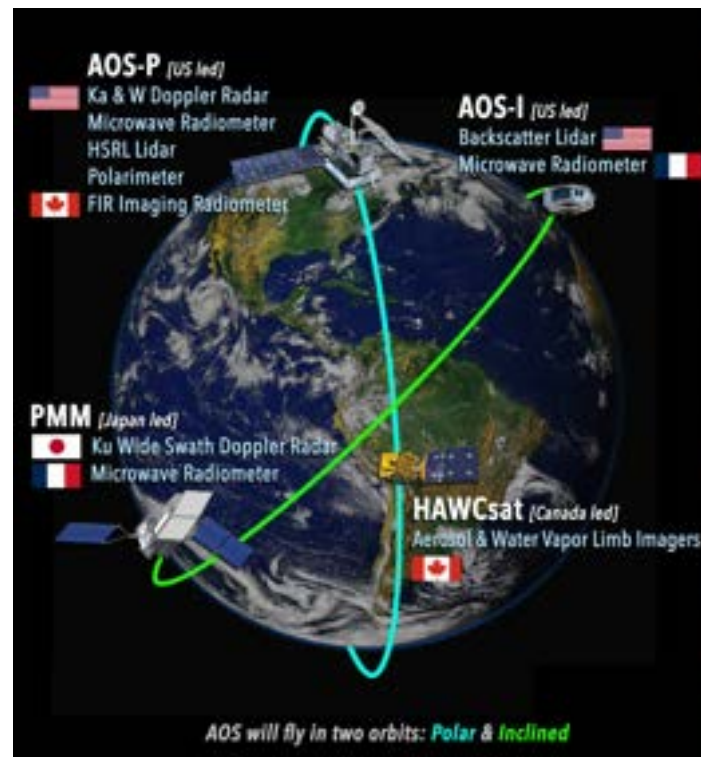
Work in progress



- Working towards creation of a global, 3D gridded real-time cloud product
- Combine GEO and LEO sensors
- Compliments ISCCP-NG

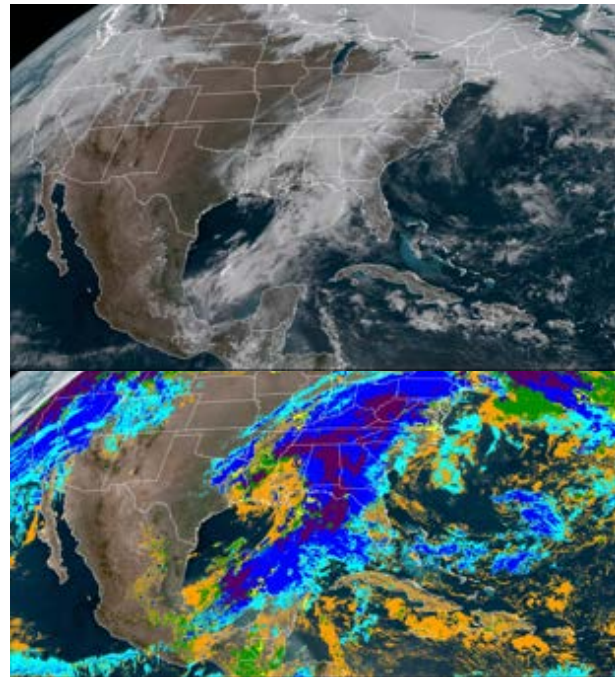


- We need more measurements to do more science!
- Machine learning is data-hungry. So is validation.
- CloudSat and CALIPSO have made this work possible. [AOS](#), [EarthCARE](#), [INCUS](#), and other missions of this type are needed to continue it.

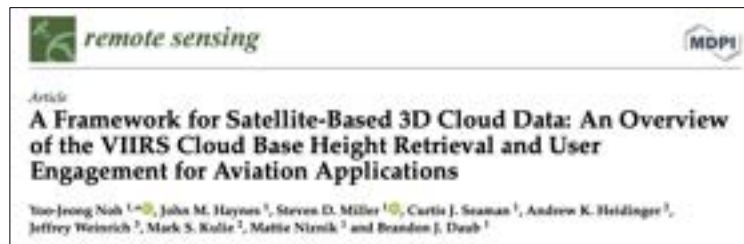


NASA

- Active sensors have been instrumental in our work to derive 3D cloud profiles from passive sensors
- 3D cloud products are now being produced in near real-time to benefit NOAA operational users, particularly in aviation
 - Cloud cross-sections available from: <https://aviation.cira.colostate.edu> for Alaska and CONUS
 - Machine-learning is used to augment our statistical based cloud cover layer product (CONUS), accessible via <https://rammb-slider.cira.colostate.edu>
 - Testing with operational users at the Aviation Weather Center



- CIRA is now working toward production of a **global, real-time gridded 3D cloud product** combining geostationary and polar orbiter sensors
- We're interested in more than just cloud masks... currently working on vertical **cloud water content** profiles as well.



Thank you!

- Haynes, J. M., Y.-J. Noh, S. D. Miller, K. D. Haynes, I. Ebert-Uphoff, and A. Heidinger, 2022: Low cloud detection in multilayer scenes using satellite imagery with machine learning methods. *J. Atmos. Ocean. Technol.*, **39**, <https://doi.org/10.1175/JTECH-D-21-0084.1>.
- Noh, Y.-J., and Coauthors, 2017: Cloud-base height estimation from VIIRS. Part II: A statistical algorithm based on A-Train satellite data. *J. Atmos. Oceanic Technol.*, **34**, 585–598, <https://doi.org/10.1175/JTECH-D-16-0110.1>.
- Noh, Y.-J., and Coauthors, 2022: A framework for satellite-based 3D cloud data: an overview of the VIIRS cloud base height retrieval and user engagement for aviation applications. *Remote Sensing*, **14**, 5524, <https://doi.org/10.3390/rs14215524>.
- Seaman, C. J., Y.-J. Noh, S. D. Miller, A. K. Heidinger, and D. T. Lindsey, 2017: Cloud-base height estimation from VIIRS. Part I: operational algorithm validation against CloudSat. *J. Atmos. Oceanic Technol.*, **34**, 567–583, <https://doi.org/10.1175/JTECH-D-16-0109.1>.