Empirical Methods to Improve Cloud Water Budget Estimates From Passive Satellite Measurements

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Background

Weather and climate applications require accurate characterizations of the vertical distribution of clouds

- Climate: needed for accurate radiative fluxes, to understand cloud effects (CERES), validate climate models
  - CERES SARB (Kato et al.) combining MODIS/imager cloud properties with CloudSat/CALIPSO
- Weather: 3-d cloud information also needed for accurate forecasting
  - Clouds wreak havoc on temperature forecasts
  - Needed by the energy and transportation sectors
  - Associated with hazardous weather (e.g. severe weather, fog, aircraft icing, etc)
  - NWP clouds not in the right place at the right time – only useful on synoptic scales, problems with mass, phase
  - Active sensor coverage insufficient

Satellite imagers observe clouds on time/space scales required

Pioneering work by CERES Cloud Team for Weather Applications

Cloud retrieval algorithm adapted for application to weather satellite data

- Started in late '90's for ARM program
- Expanded for global application to GEOsats (R. Palikonda talk on Tuesday)
- Products available for operational use at NCEP and elsewhere
- Assimilated in NWP by NOAA and NASA (GMAO)
- GEO cloud products fed back to CERES for TISA

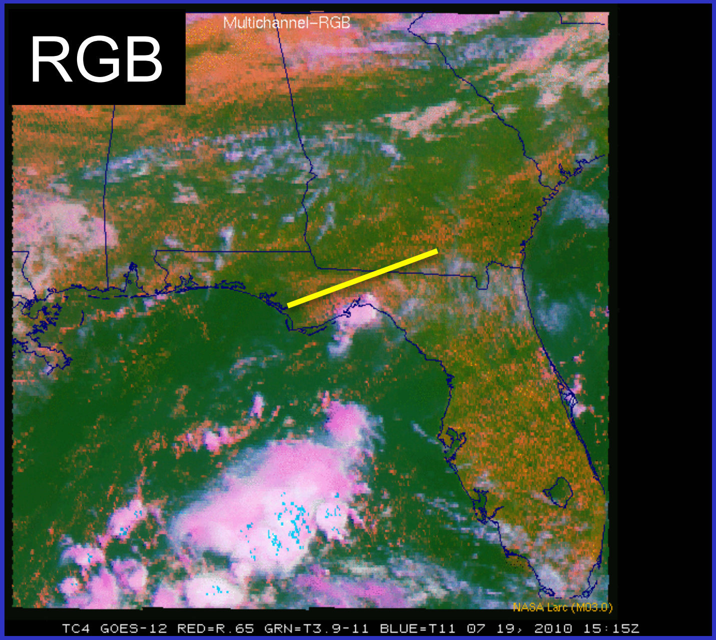
Innovative cloud retrieval development (led by P. Minnis)

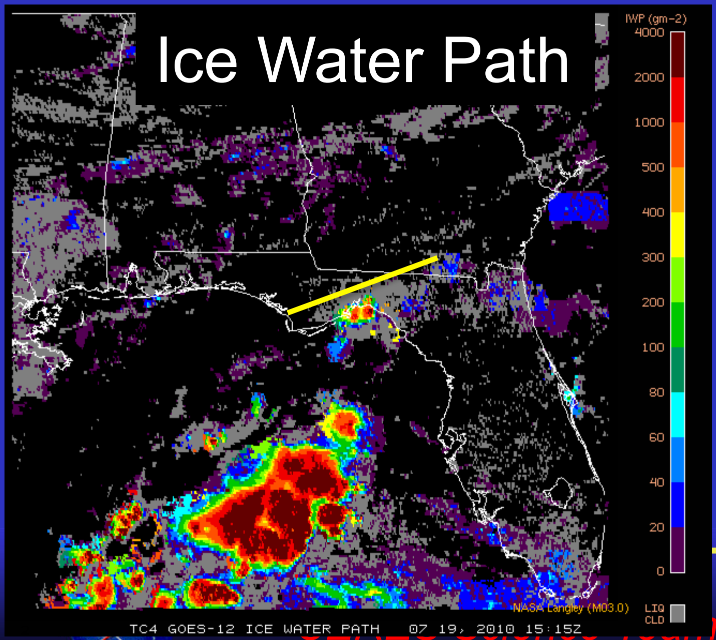
- State of the art advances for ice clouds
- Accurate geometric cloud boundaries: physical tops, lapse rate approach for BL clouds, cloud thickness provides 3D potential (needed for weather)
- ML technique to ID overlapping clouds and improve retrievals

Next step, cloud impacts (how to make use of COT, IWP/LWP, R_e)

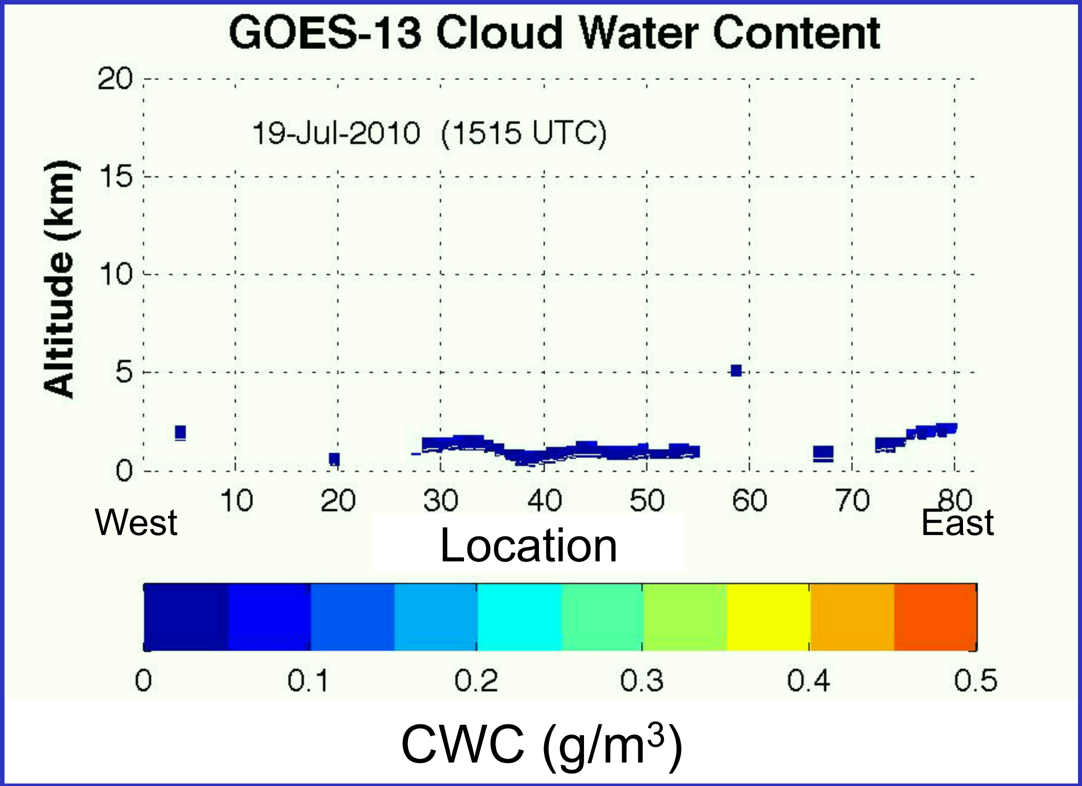
- Some model assimilation work using integral parameters in progress (NSSL, GMAO)
- Profiling technique (4-D clouds) and application for nowcasting aircraft icing conditions

GOES-13 Rapid Scan July 19, 2010





Smith et al (A-train mtg 2010)



Objectives

Describe recent progress in developing a profiling technique designed to improve the instantaneous vertical resolution of clouds from satellite imager cloud retrievals

- Exploit climatological information on cloud vertical structure derived from active sensor data and cloud models (need both to get the best answer)
- Focus on optically thick ice over water cloud systems (challenging for inferring accurate cloud properties and icing conditions)
- Demonstrate the accuracy and utility with comparisons to coincident active sensor retrievals and validation with icing PIREPS

Aircraft Icing

- Icing can overwhelm aircraft ice protection systems (if they exist)
- Icing the primary cause of 80 accidents (263 fatalities) worldwide in the last 10 years, and was a contributing factor in many more events (EASA)
- General aviation most susceptible, but impact to commercial operations also significant (NTSB)
- Pilots and aviation managers need to know where and when icing can occur
  - PIREPS are first order over USA: but *relatively sparse, aircraft dependent, location uncertain, very few over Europe*
  - Numerical analyses and forecasts: *freezing levels, cloud expectations* (synoptic scale guidance)
  - Clouds resolved explicitly in NWP only capture about 40% of icing PIREPS
- Improved resolution of icing conditions a high priority for NWS and FAA

Aircraft Icing

In-flight aircraft icing depends on:

- Meteorological factors
  - Presence of super-cooled liquid water, SLW
  - Liquid water content, LWC
  - Droplet size distribution, N(r)
  - Temperature, T(z)
- Airframe and flight parameters (not accounted for)
  - One size fits all approach difficult

Ice accretion on wing leading edge

(a) while in cloud

(b) after ascending above cloud

Photo credits: NASA Glenn Research Center

Aircraft Icing

Information contained in satellite cloud retrievals

- Low (liquid) cloud retrievals (SLW observed directly)
  - Cloud Top Temperature, Phase, SLW
  - Liquid Water Path: LWP = f(LWC)
  - Effective Droplet Size: $r_e = f(N(r))$

- Ice over water clouds (need to infer SLW properties)
  - Exploit multilayer techniques for Ci over St
  - For deep ice over water clouds, the situation is more complex. Need information on cloud vertical structure and phase partitioning (unobserved). Satellite cloud retrievals can be used to constrain the problem.

Ice accretion on wing leading edge

(a) while in cloud

(b) after ascending above cloud

Photo credits: NASA Glenn Research Center

NASA LaRC Icing Algorithms

Satellite cloud retrievals are the primary inputs

Goals: Likelihood for SLW, potential icing intensity, expected altitude range

1. Low cloud algorithm (SLW clouds)
   - Map LWP, R_e to icing threat for SLW pixels
2. Multi-layer algorithm (cirrus over stratus)
   - Derive lower level Tcld, LWP (F.-L. Chang technique) and apply low cloud icing algorithm
3. **Optically thick ice cloud algorithm (deep, ice over water clouds)**
   - Use imager cloud retrievals (cloud boundaries, T_t, COT, and IWP) to constrain climatological cloud vertical structure information derived as a function of cloud type from ARM data, CloudSat/CALIPSO, and cloud models

→ goal to estimate icing probability and intensity profile, altitude boundaries and use to infer the icing threat for the layer

Thick Ice Over Water Cloud Algorithm

Quick overview of primary elements:

(1) Need TWP for thick clouds (IWP ≠ TWP for these clouds?)

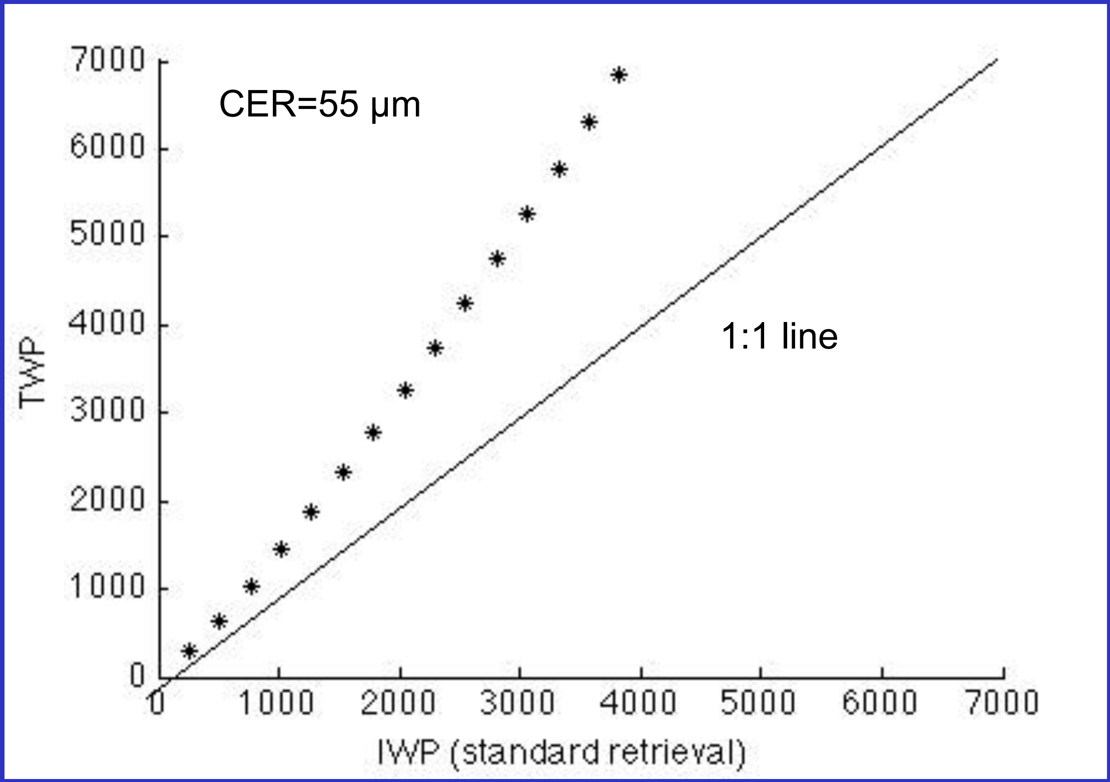
- Optically thick clouds matter for weather and climate (small % of clouds but significant fraction of total cloud water
- IWP retrieval assumptions violated (not all ice, not VH)
- Reflectance saturation problem (max COT=150)

(2) Want to distribute TWP in vertical (i.e. derive CWC(z)) and estimate the potential for liquid and SLWC(z)

Thick Ice Over Water Cloud Algorithm

TWP parameterization:

- Based on correlations between GOES cloud retrievals and ARM Microbase product (Radar/MWR retrievals) at SGP



Cloud Water Content Profiling Technique

GOAL: Develop normalized climatological CWC profiles [S(z)] from observations and models and constrain with imager cloud properties to estimate profiles with high space/time resolution over wide areas

Cirrus clouds (COT < 10, T_{base} < -20C)

- Compute from CloudSat and CALIPSO (CC) IWC retrievals

All other clouds

- Combine explicit cloud analyses from models (better in lower trop) + CC (upper trop)

$$S(z^*) = \frac{CWC(z^*)}{\overline{CWC}}$$

Normalized vertical coordinate

$$z^* = (z - z_b)/(z_t - z_b) \qquad z^* = 1\ (z_t) \quad z^* = 0\ (z_b)$$

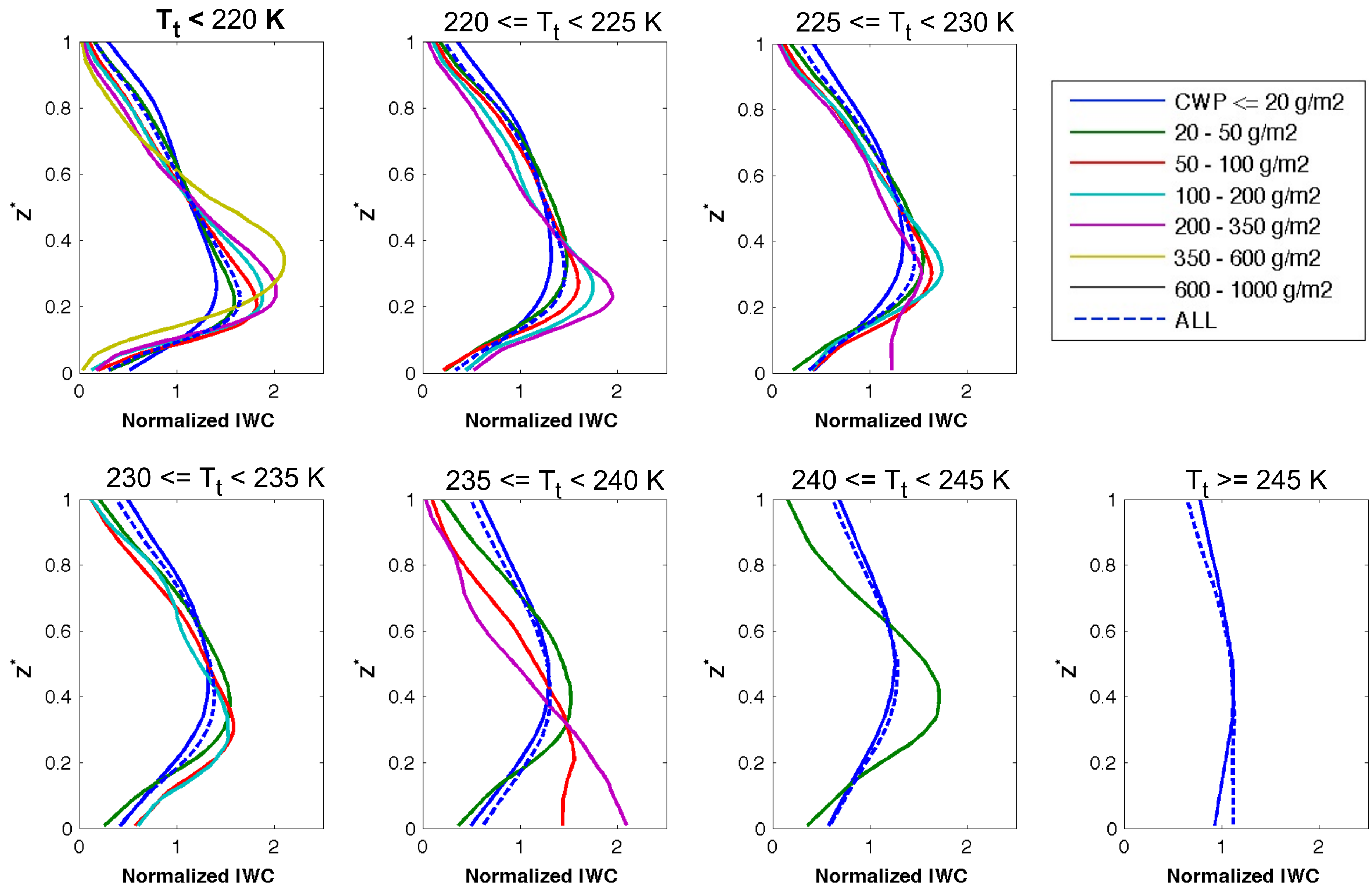
where $$\overline{CWC} = \frac{CWP}{\Delta Z}$$

(1) Develop S from CC and models
- 50 cloud types (T_{top}, CWP)

(2) Retrieve CWC(z) by multiplying S by CWP/ΔZ retrieved from imager data

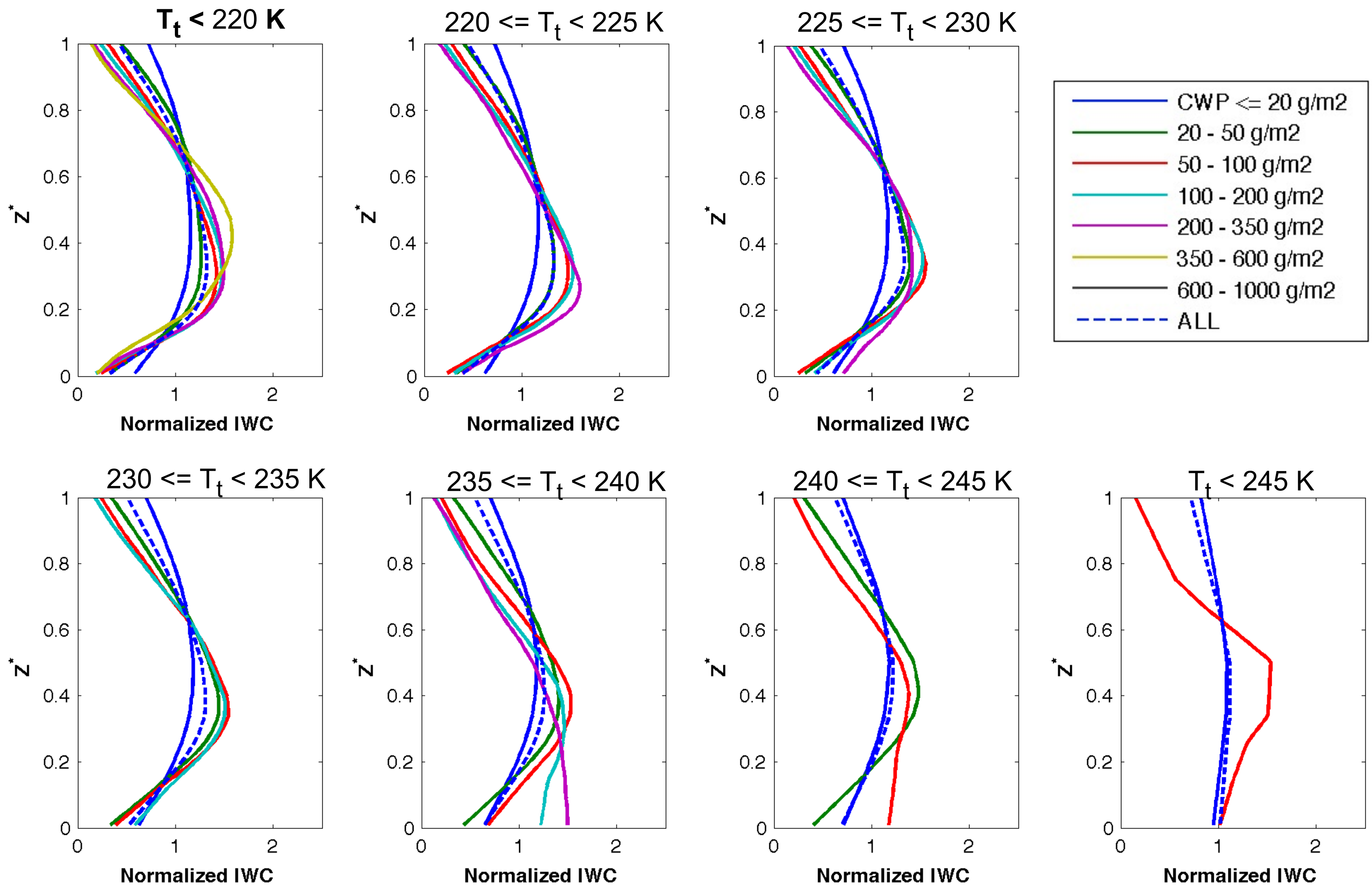
Normalized CWC Profiles (Cirrus) Cloudsat 2C-ICE

(CONUS, Jan-Mar, 2007)

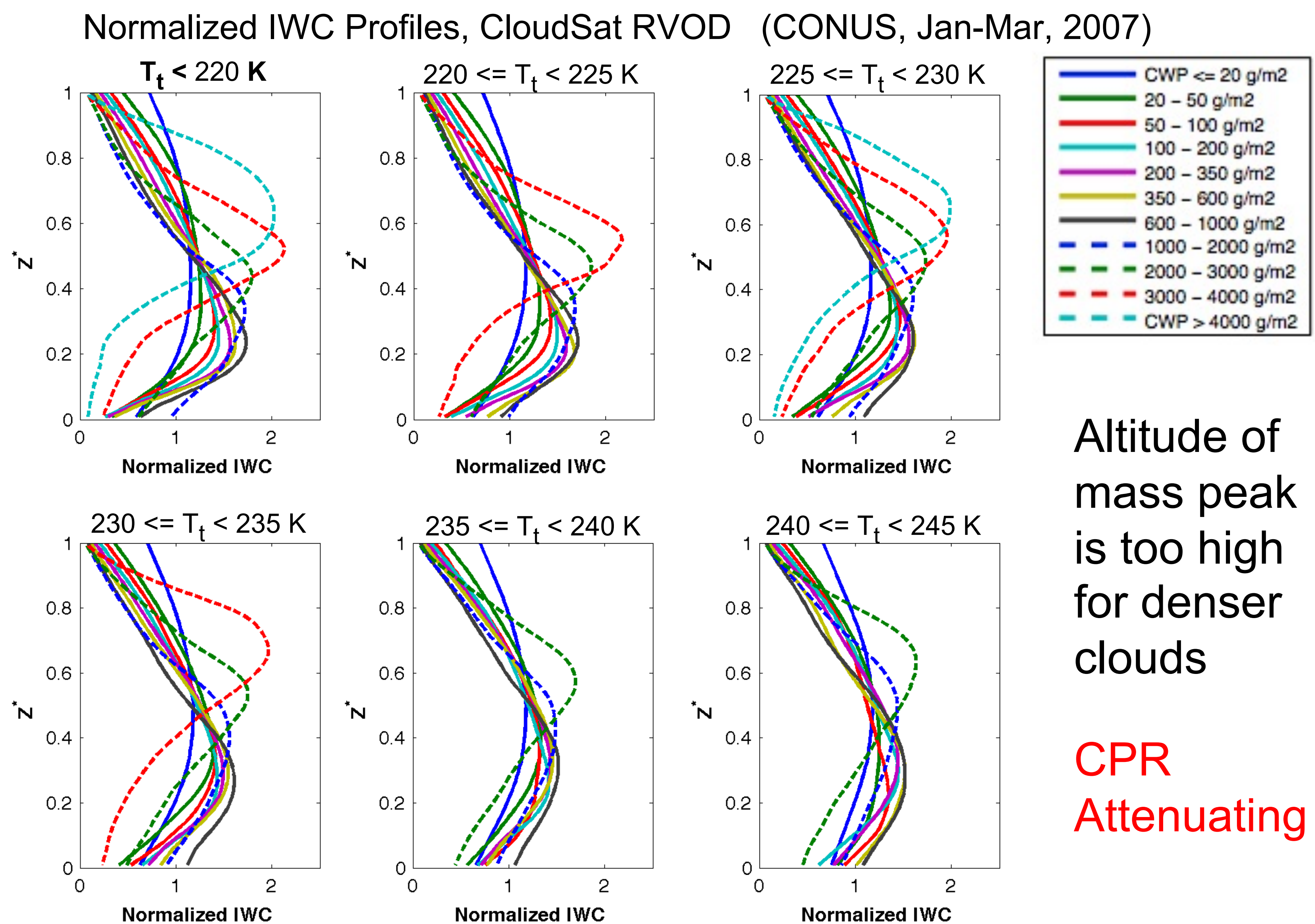


Normalized CWC Profiles (Cirrus) Cloudsat RVOD

(CONUS, Jan-Mar, 2007)



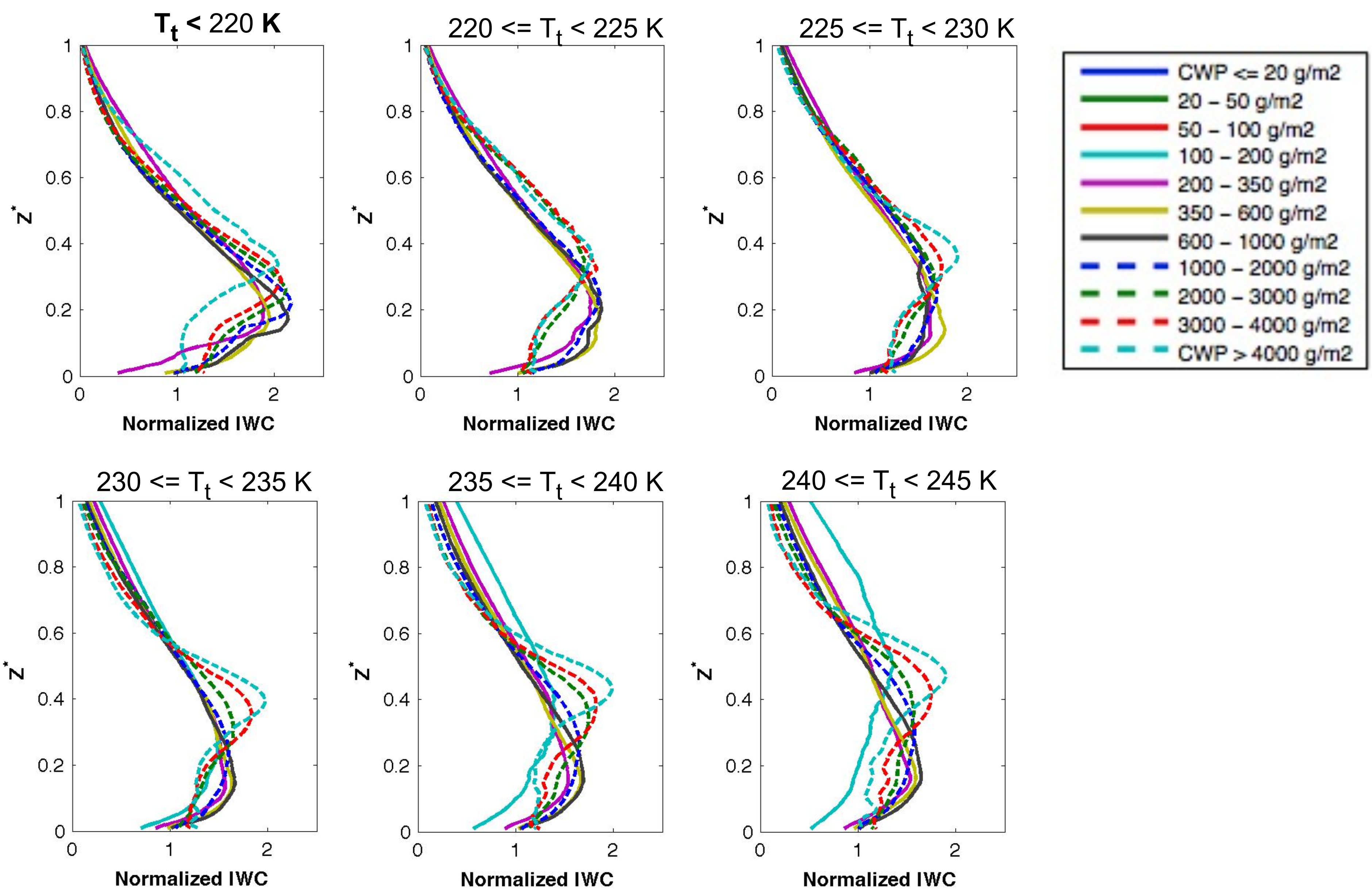
Normalized CWC Profiles (All Clouds) Cloudsat RVOD



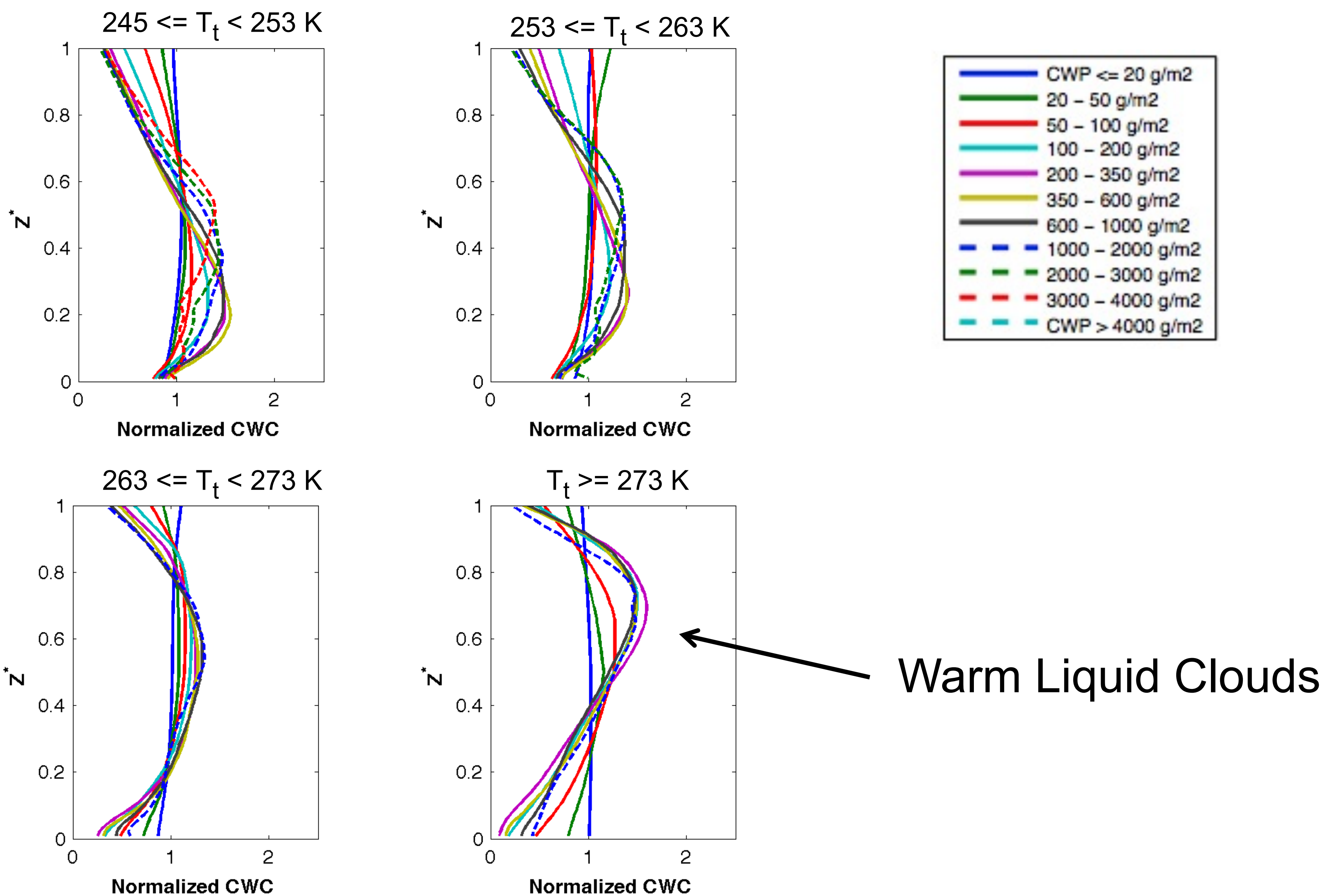
Altitude of mass peak is too high for denser clouds

CPR Attenuating

Normalized CWC Profiles (All Clouds) NWP + RVOD



Normalized CWC Profiles (All Clouds) NWP + RVOD

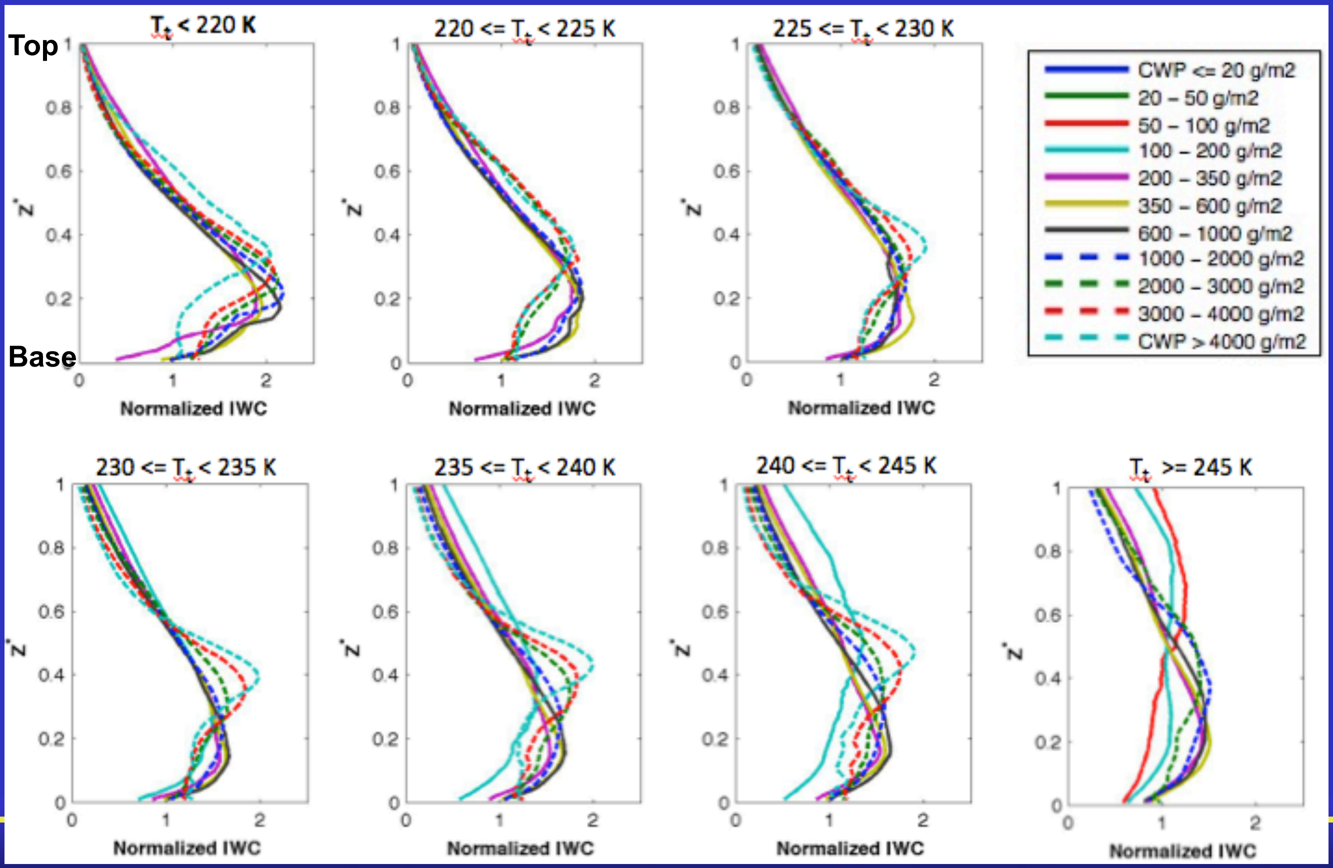


Thick Ice Over Water Cloud Algorithm

Normalized CWC Profiles, Hybrid (NWP + CloudSat/CALIPSO)

50+ cloud types defined by CWP, T_t ; Ice-topped clouds with COT > 10

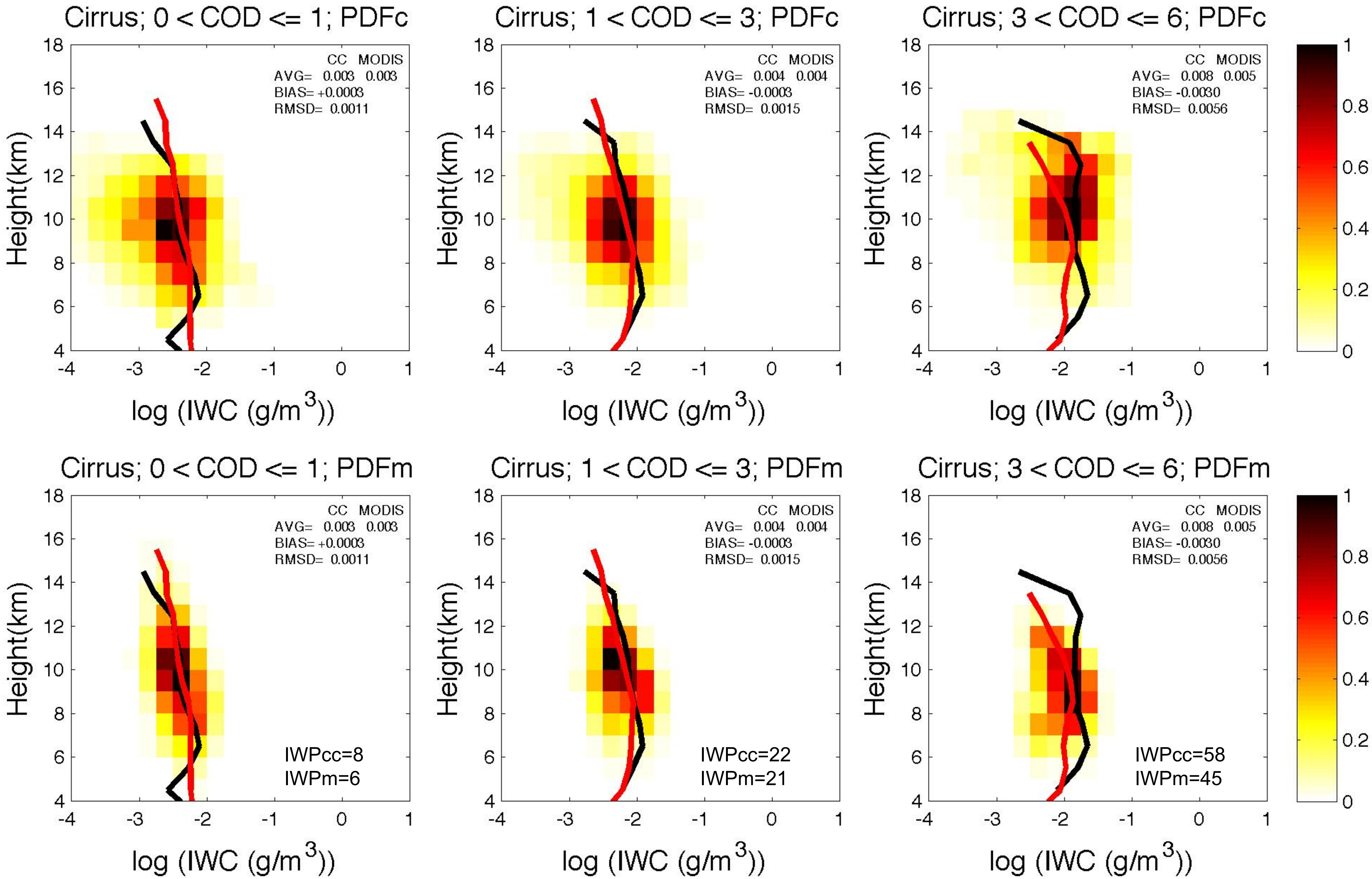
Multiply by retrieved CWP / ΔZ to estimate CWC(z)



Cirrus IWC Profiles from MODIS: Validation

CALIPSO+CloudSat vs. CERES MODIS

w/RVOD+RAP VDF's
IOLAP=4



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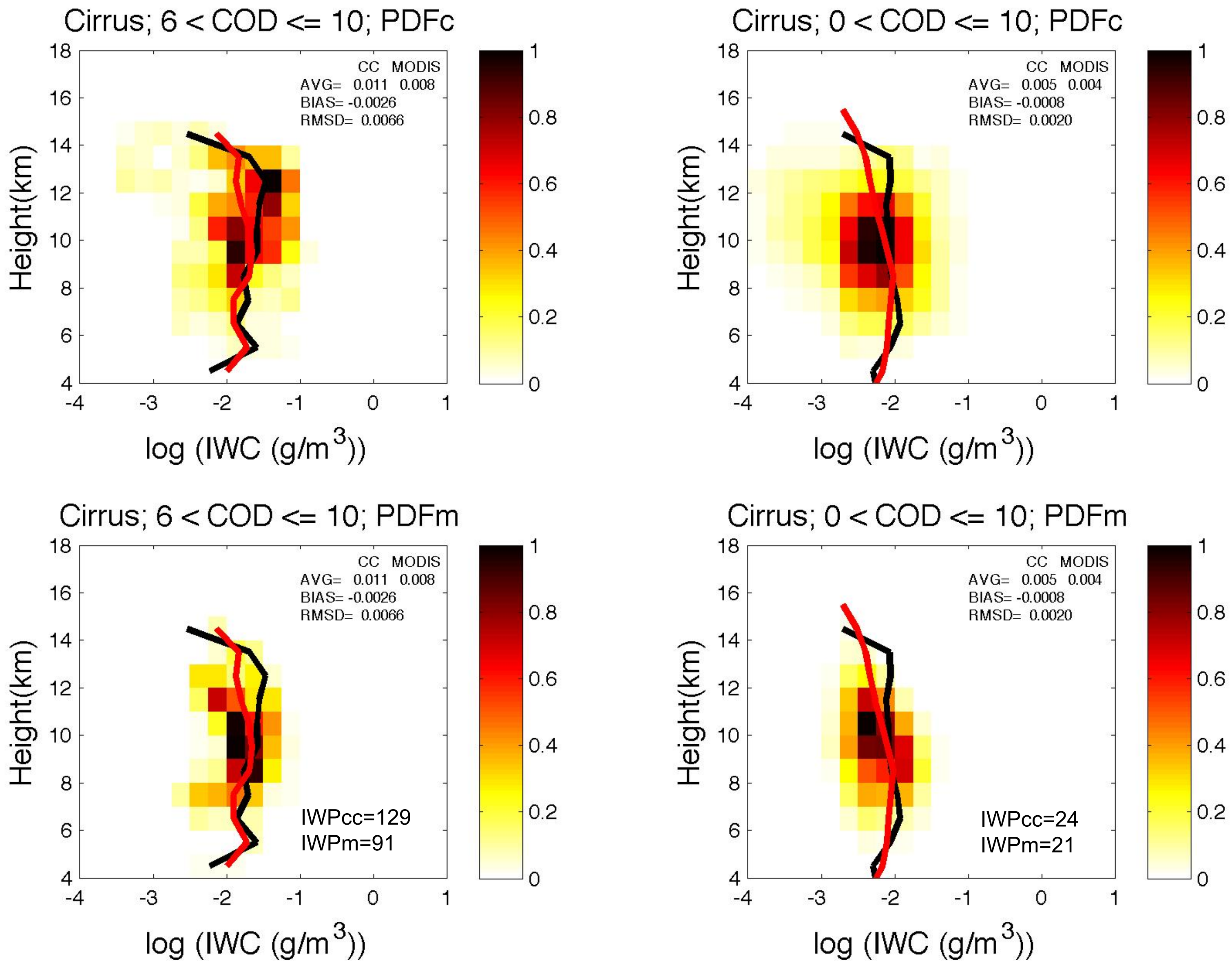
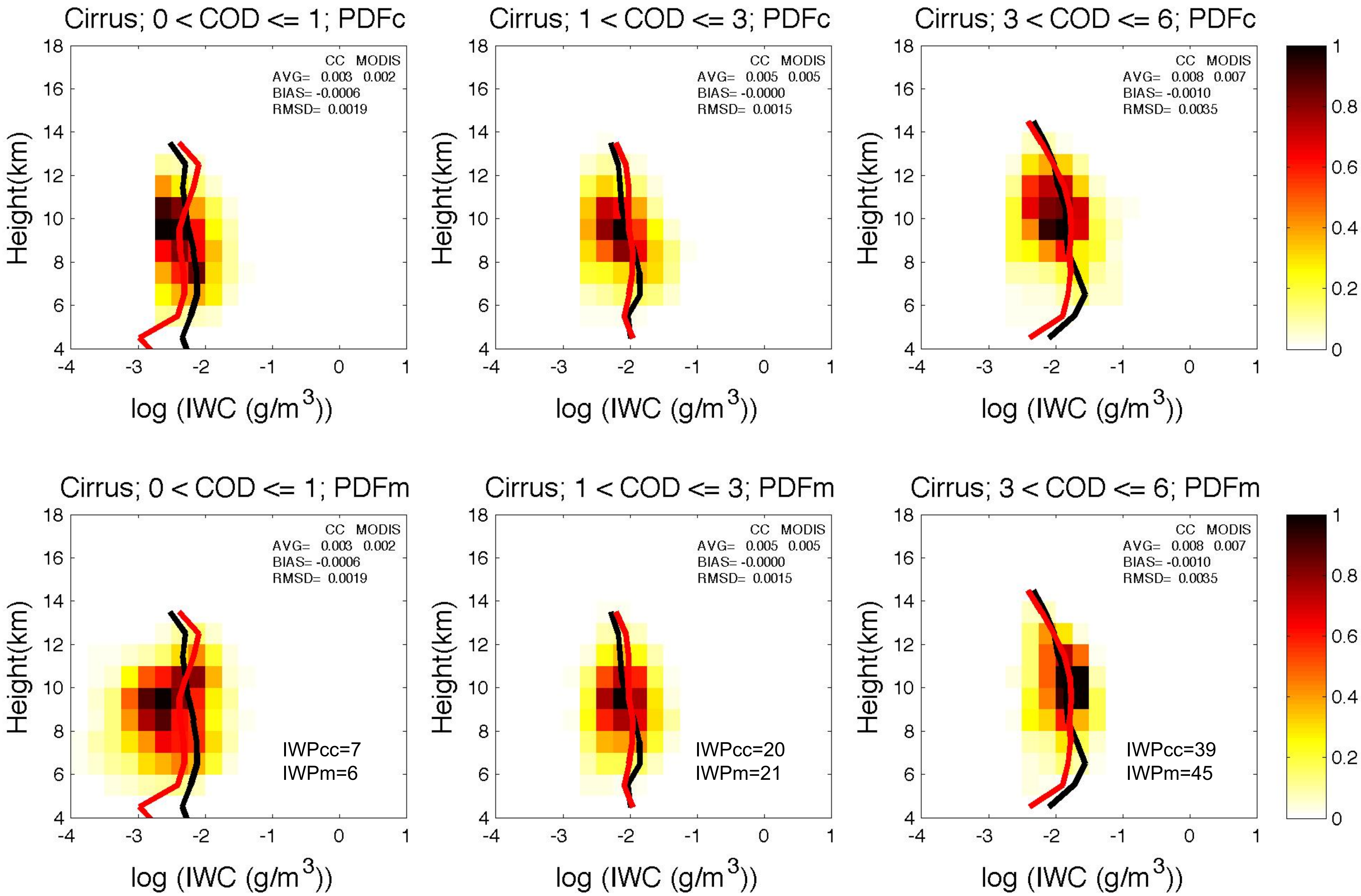


Cirrus IWC Profiles from MODIS: Validation

CloudSat vs. CERES MODIS w/CloudSat Top and Base

w/RVOD VDF's



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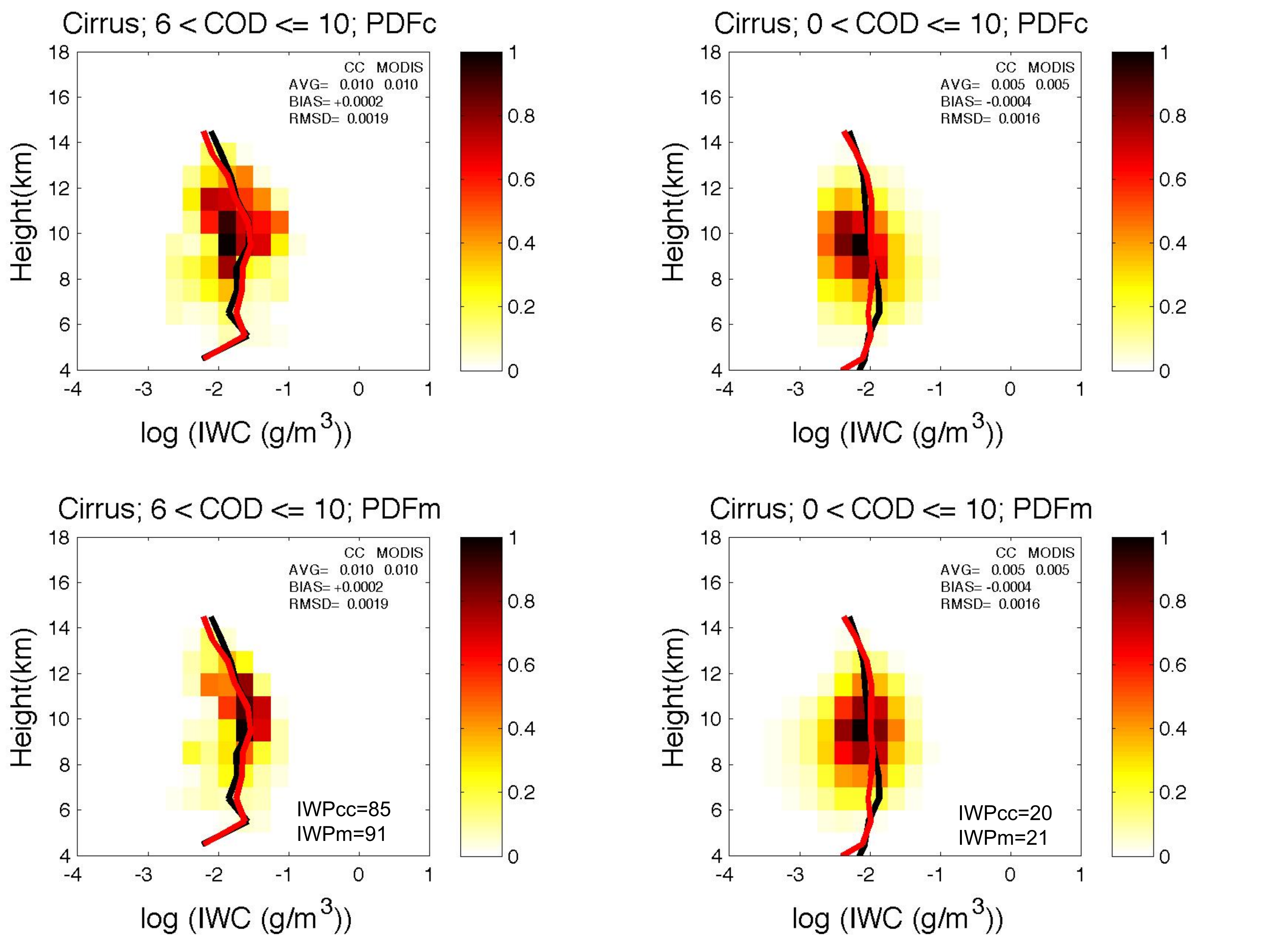

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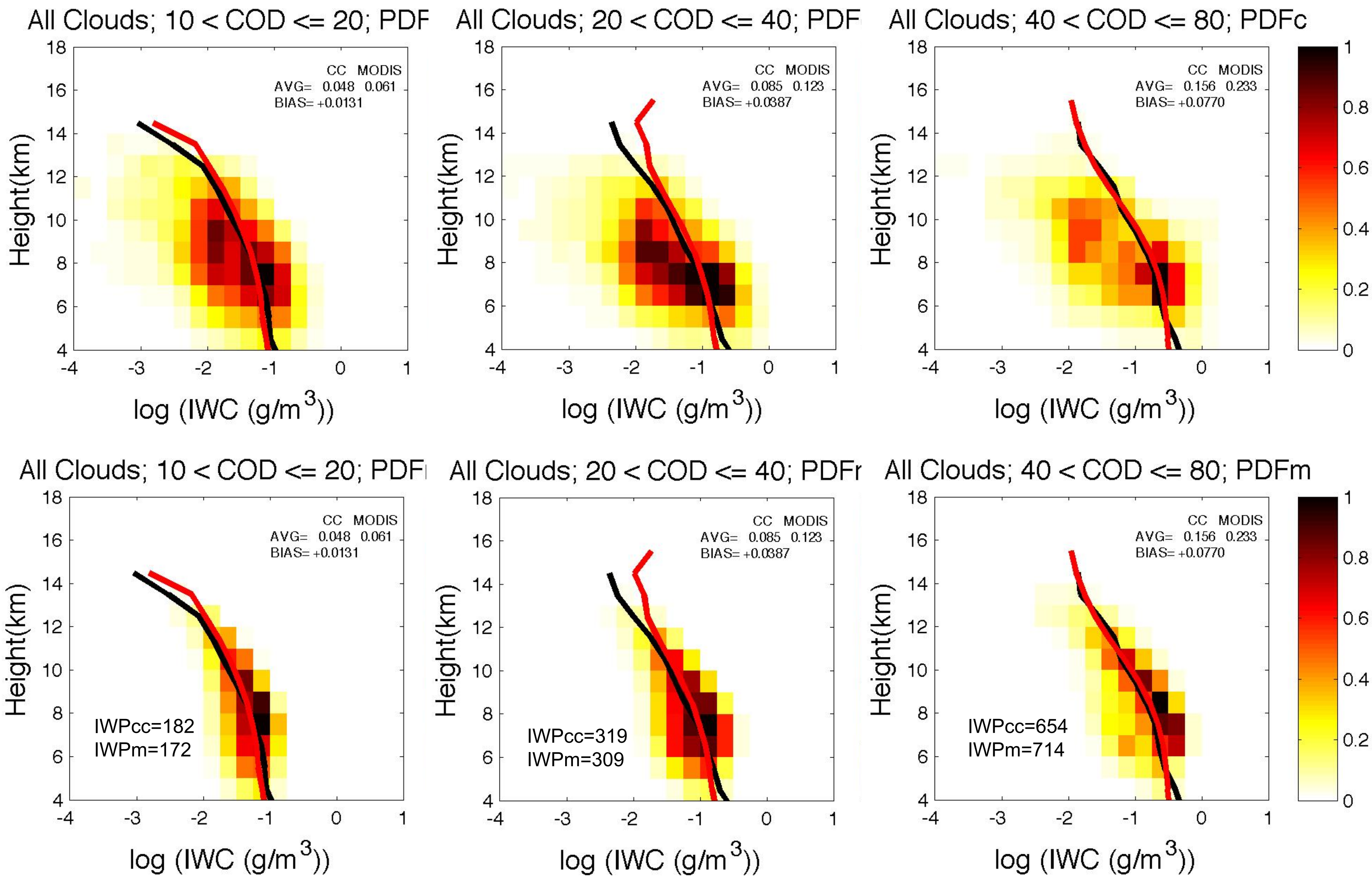

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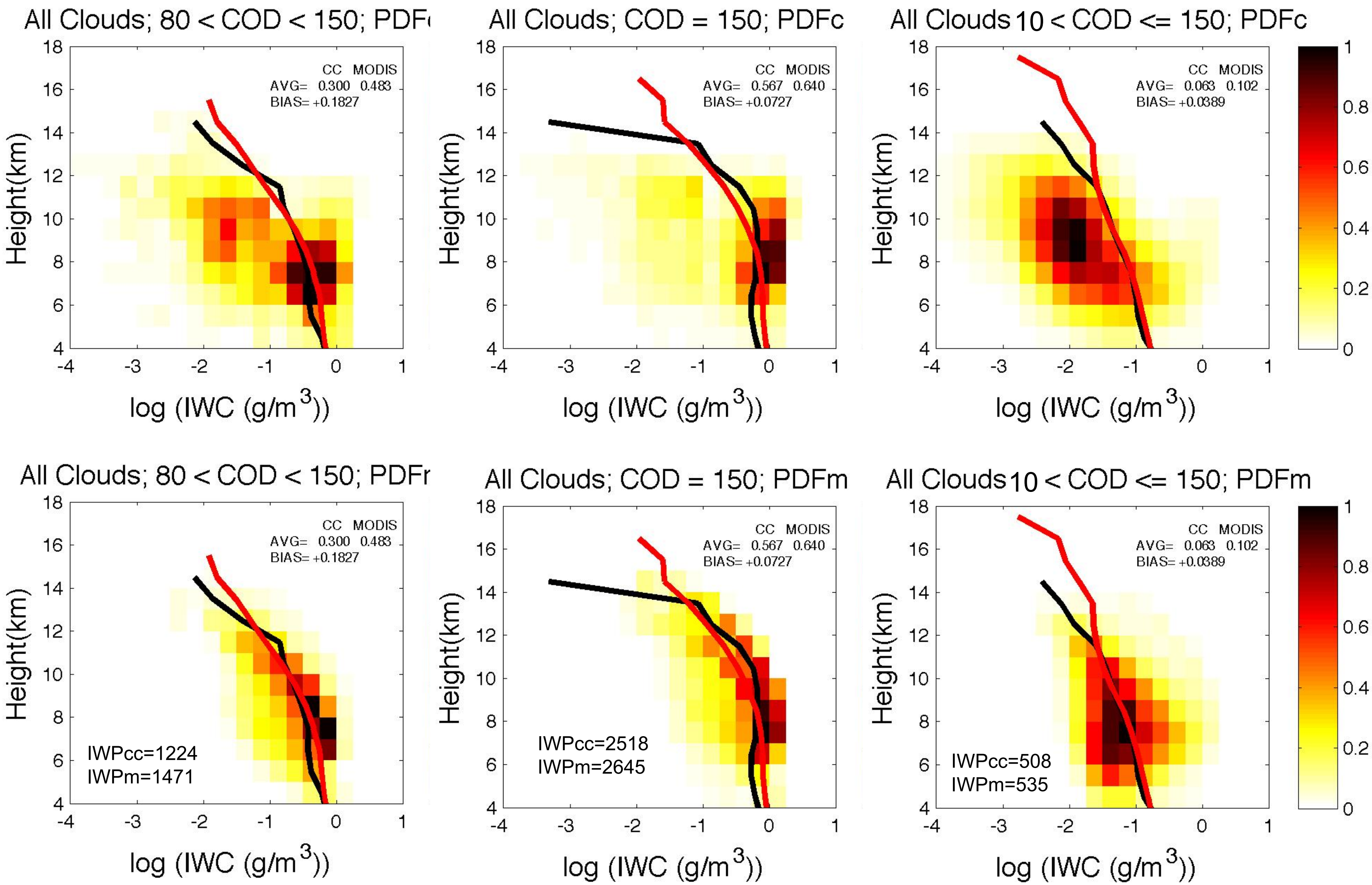


Thick Ice Over Water Cloud Algorithm

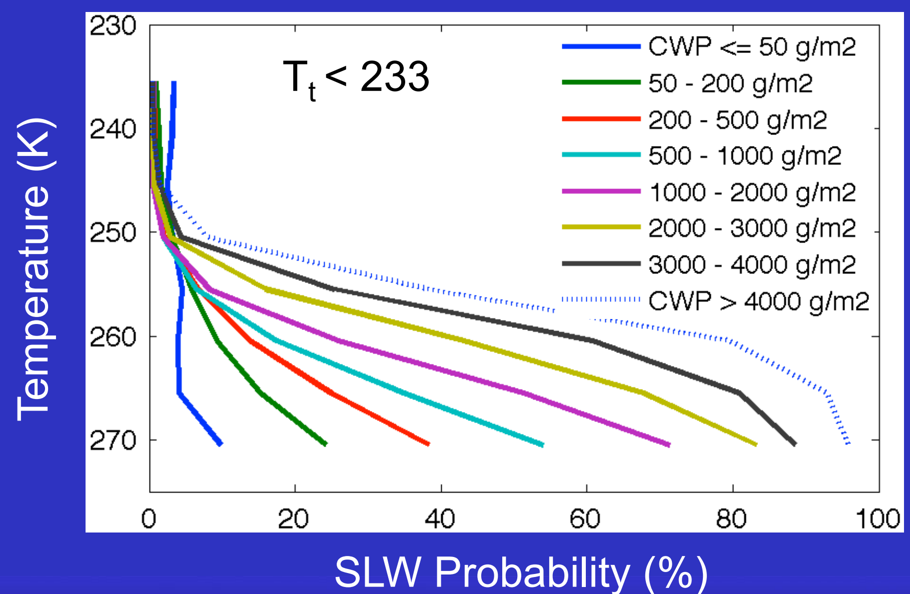
- Have CWC(z), need SLWC(z) for icing

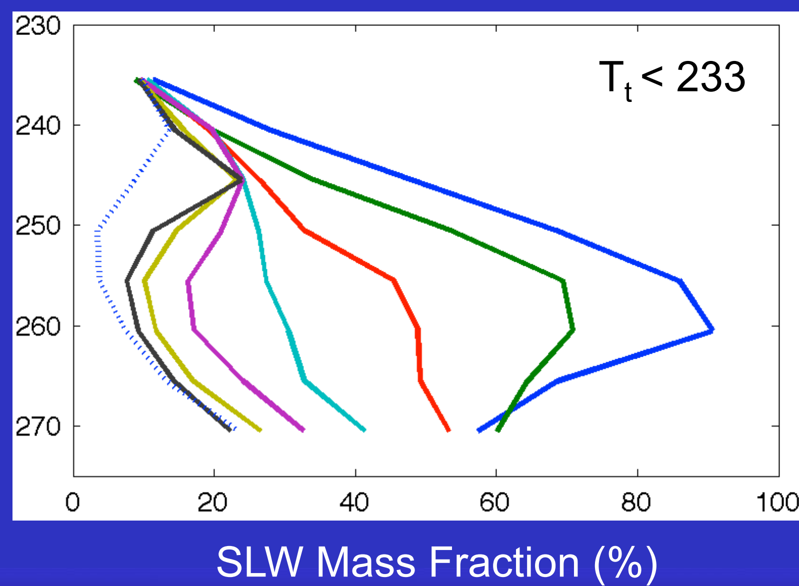
Thompson/NCAR Cloud Microphysics
liquid: $q_{liq} + q_{rain}$
ice: $q_{ice} + q_{snow} + q_{graupel}$

- NWP cloud analyses (e.g. NOAA RUC/RAP) have what we want, are SLW friendly but we can't use directly (clouds not in right place/time)

SLW probability and mass fraction

Climatological approach as a function of T for lots of cloud types





How do we pull this all together to estimate the Flight Icing Threat embedded in deep ice over water clouds

- Cloud water content, cloud probability, SLW probability and SLW mass fraction VDF's stored in lookup tables
- Derive standard cloud retrievals from favorite imager and estimate TWP
- For each cloudy pixel, determine the cloud type based on the retrieved T_{top}, Tau, IWP, and ΔZ
- For that cloud type extract the appropriate VDF's and apply to the appropriate satellite derived cloud products to determine:
  1. The probability for cloud as a function of altitude
  2. The probability for SLW as a function of altitude
  3. The S-LWC profile
- Combine (1) and (2) to estimate probability for icing
- Map (3) to the potential intensity (airfoil model)

Icing Intensity Mapping

LWC (gm^{-3})	Icing category
<0.01	No icing
0.01 to 0.017	Trace
0.017 to 0.03	Trace-light
0.03 to 0.066	Light
0.066 to 0.12	Light-moderate
0.12 to 0.2	Moderate
0.2 to 0.37	Moderate-heavy
>0.37	Heavy

From Politovitch (2003)

Consolidate for users:

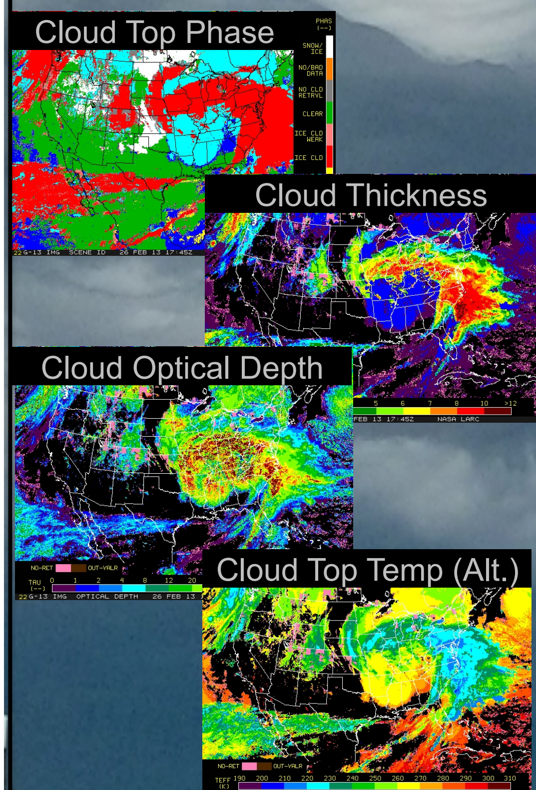
- Define icing threat for layer (max Picing, intensity)
- Determine icing altitude boundaries

  - Variable PSLW threshold used to estimate top
  - Icing base determined from retrieved Z_{base}, and Z_{273k}

Aircraft Icing

Satellite cloud retrievals can resolve aircraft icing conditions and improve forecasts

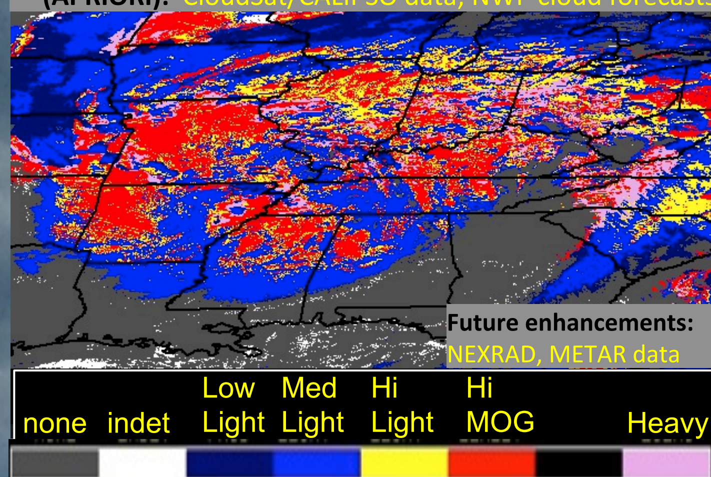
CERES GOES Cloud Properties

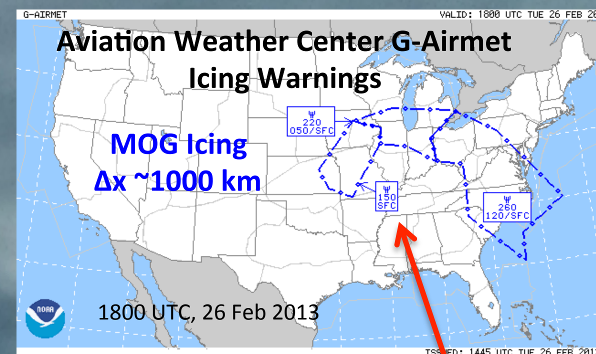


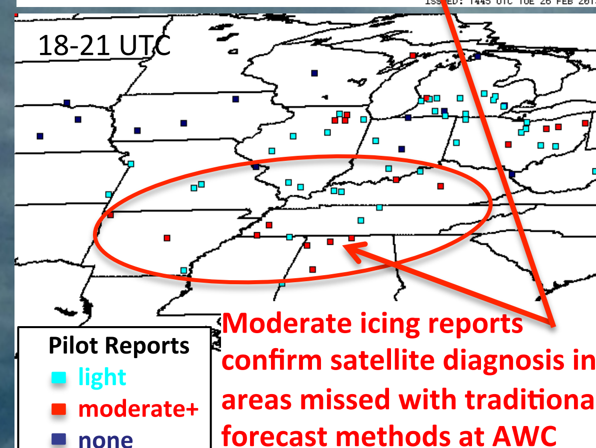
Satellite Flight Icing Threat

INPUTS (R/T): GOES cloud properties; NWP T(z), RH(z)

(APRIORI): CloudSat/CALIPSO data; NWP cloud forecasts

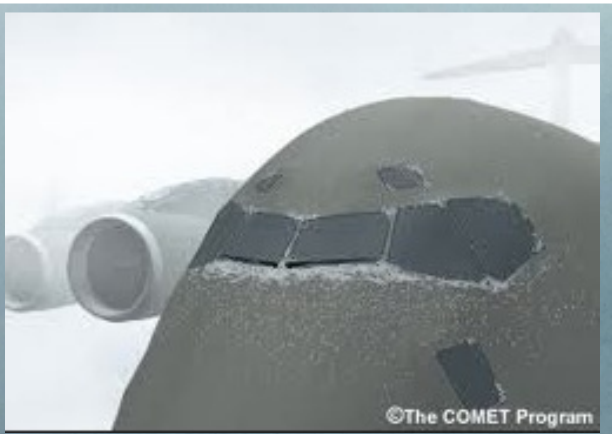






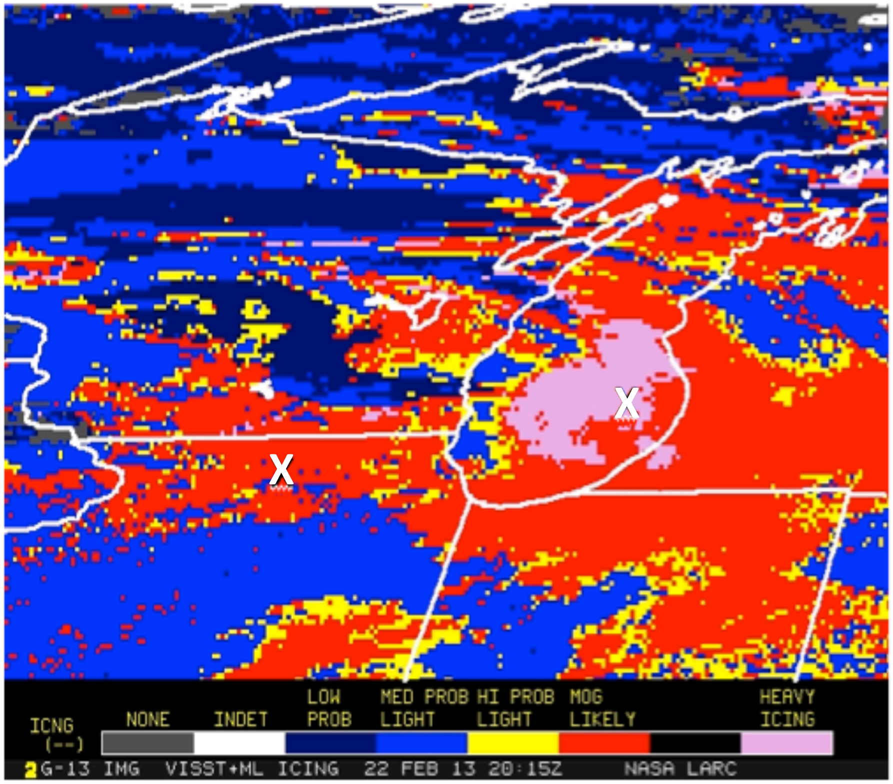
"Satellite method can provide early warning and improved resolution of icing threat not captured in current forecasting techniques, and reduces over-warning."

Aircraft Icing

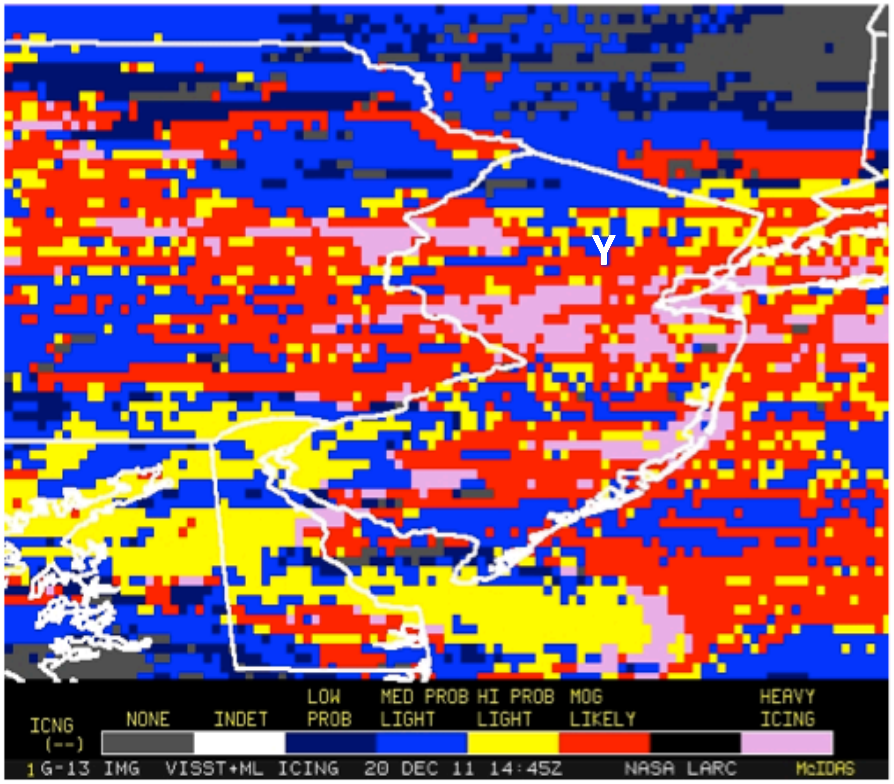


Satellite retrievals can resolve heavy to severe icing conditions

22 Feb 2013 (2015 UTC)



20 Dec 2011 (2015 UTC)



X – denotes severe icing PIREPs

AWC issued SIGMET 2-3 hours later

Y – denotes location of TBM-700 crash

Aircraft Icing

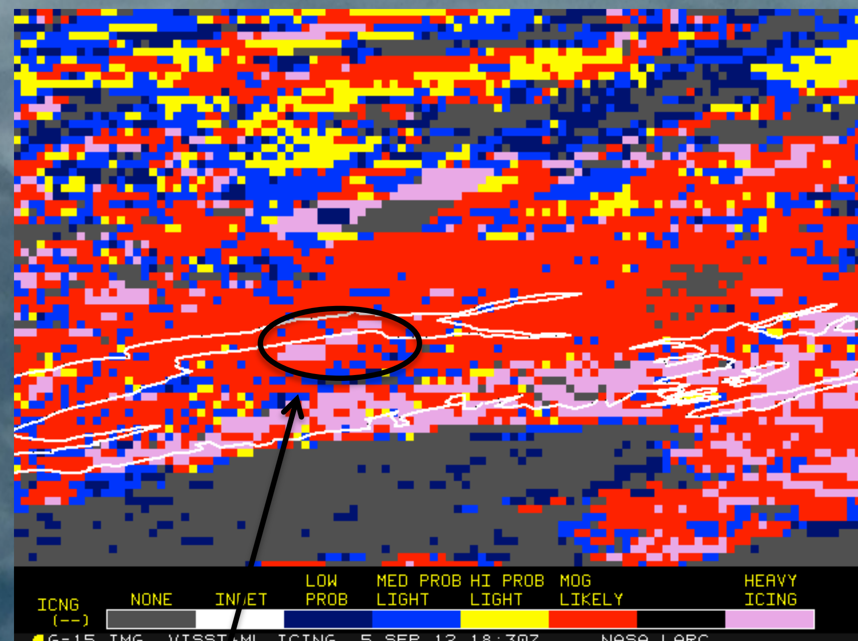
Satellite retrievals can resolve heavy to severe icing conditions

9/5/2012 Era Flight 847
Anchorage To Homer
5000 feet altitude loss due to icing

- Flight reportedly reached 12K ft and then lost 5000 feet altitude and returned to Anchorage
- 15 on board, including 12 passengers, a pilot, co-pilot, and flight attendant

Bombardier DHC-8-103, registration N886EA

GOES Flight Icing Threat
5 Sep 2012 (18:30 UTC)



Heavy icing detected from GOES in vicinity of aircraft incident

Verification: Icing Detection vs. PIREPS

Jan – Mar, 2013 (USA)

Satellite icing assessed in 20-km radius region at PIREP

Satellite Method	N	PODY	Accuracy
OVC Liquid Clouds	5201	99%	91%
OVC Ice Clouds	2408	99%	86%
All OVC Regions	11712	99%	90%

- Icing detection accuracy beneath ice clouds almost as accurate as that for unobscured liquid clouds

- False alarms difficult to quantify since icing PIREPS biased (few 'no icing' reports). PODN, POFD, TSS not meaningful

Verification: Icing Intensity vs. PIREPS

Icing intensity from satellite also has skill

Dominant intensity in 20-km satellite region

Source	N	PODL	PODM	Accuracy
Liquid Clouds	5013	60%	61%	60%
Ice Clouds	2236	61%	45%	57%

Dominant intensity (ambiguous satellite regions count as hit)

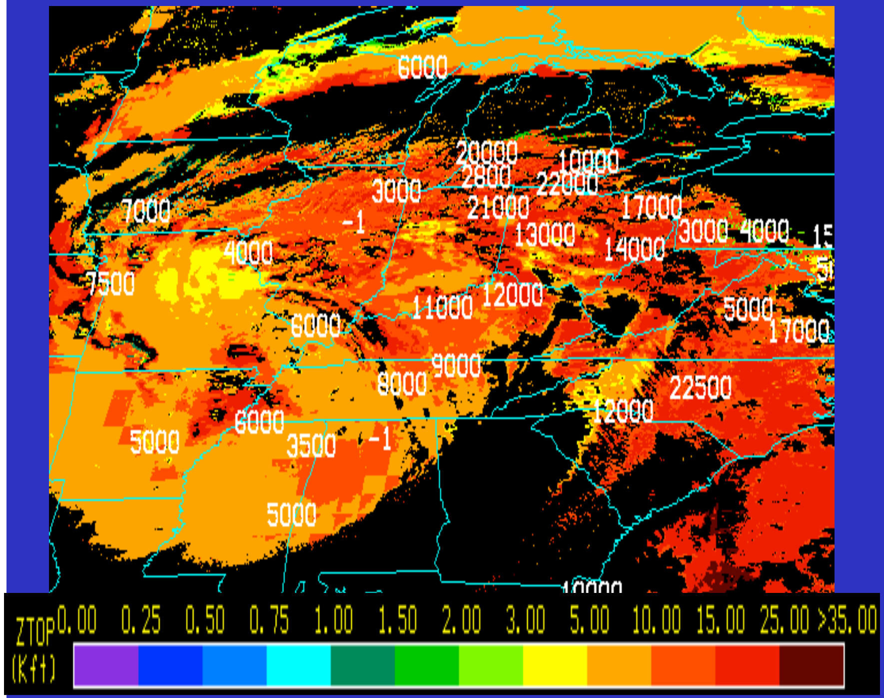
Source	N	PODL	PODM	Accuracy
Liquid Clouds	5013	76%	66%	73%
Ice Clouds	2236	80%	47%	72%

Satellite method produces the right fraction of MOG icing (~25%, agrees with PIREPS)

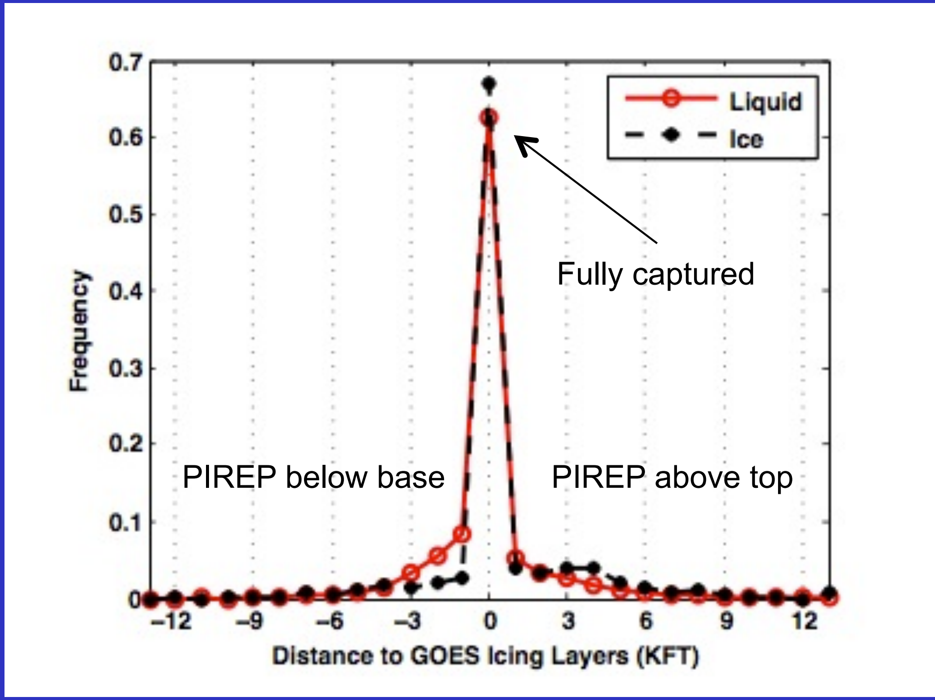
Verification: Icing Layer Top and Base Altitude

Note: unique solution for ice over water clouds (depends on cloud type)

GOES Icing Layer Top Altitude



Frequency of icing PIREPS relative to satellite icing layer altitude boundaries



Derived icing altitude boundaries capture most icing PIREPS found in ice and liquid topped clouds

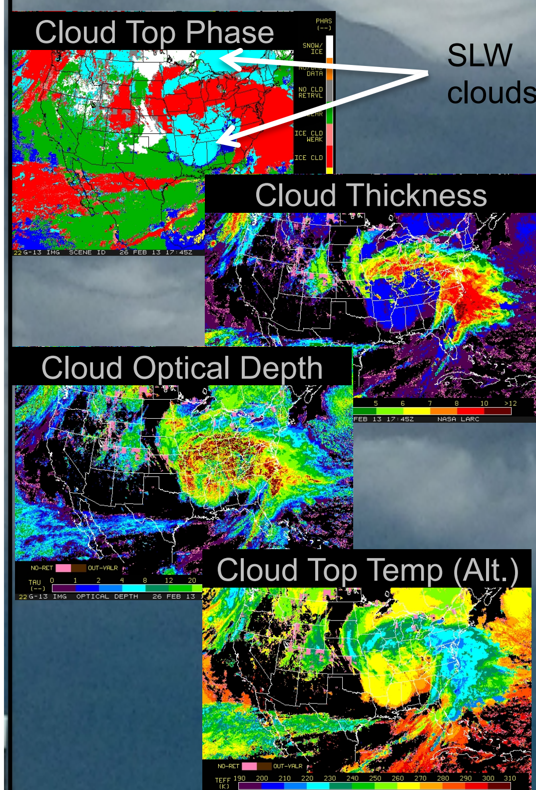
Summary

- Cloud water content profiling technique producing good results and the potential for more realistic global estimates of IWP/LWP, and atmospheric heating rates
  - ***SLWC inferred in thick ice over water clouds corresponds well with icing PIREPS***
  - ***LWP also agrees reasonably well with MWR data***
  - ***MODIS and CloudSat IWP in upper troposphere (< 253K) agree to 5%on average for all clouds***
  - ***MODIS and Calipso+Cloudsat IWC agreement also about 5% for Cirrus clouds but MODIS IWC about 40% higher in deep ice over water clouds (attributed to MODIS IWP/DZ correlation)***
- Future work includes global application to CERES MODIS and comparisons with CCCM profiles
- Satellite cloud retrievals improve the spatial and temporal resolution of icing conditions compared to traditional forecasting methods
  - ***Icing detection accuracy is ~ 90%.***
  - ***Icing severity accuracy vs PIREPS ~60-75% (daytime only)***
  - ***Icing altitude boundaries well captured***
- 3.9 μm CER retrievals can identify dangerous icing conditions associated with SLD.
- Future work needed to reduce false alarms (difficult to assess). Some known problem areas (e.g. large SLW CER around ice cloud edges)

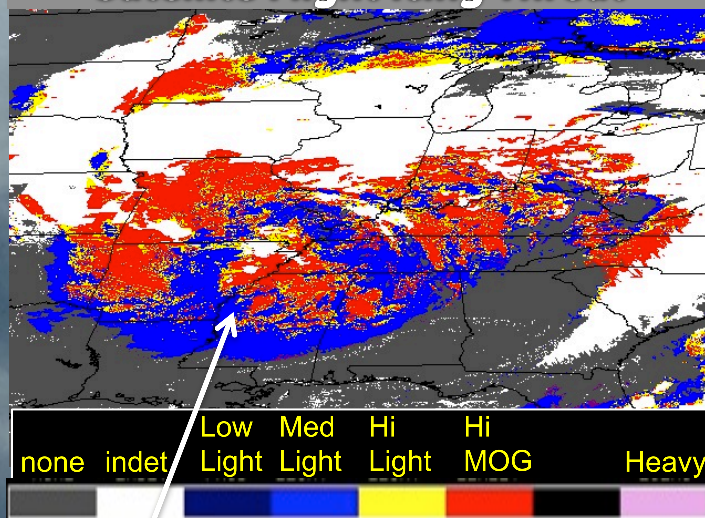
Aircraft Icing

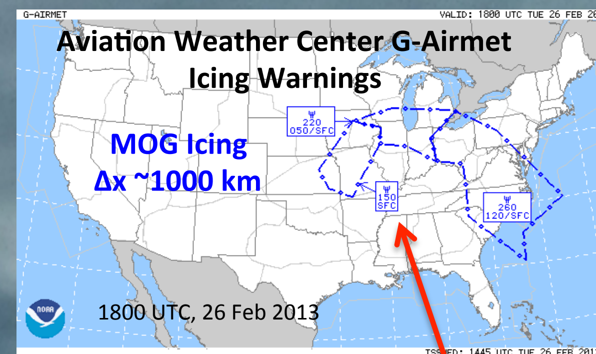
Low cloud algorithm maps retrieved LWP, R_e for to icing threat (SLW clouds)

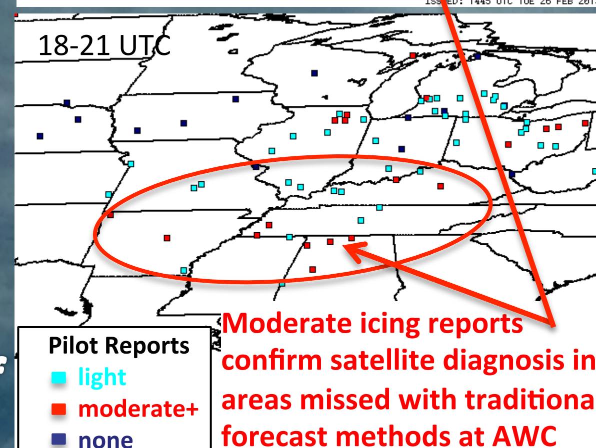
CERES GOES Cloud Properties



Satellite Flight Icing Threat







Moderate icing reports confirm satellite diagnosis in areas missed with traditional forecast methods at AWC

"Satellite method provides early warning and improved resolution of icing threat not captured in current forecasting techniques (for low clouds). Model approach used at AWC captures the icing threat in deep ice over water clouds.