New Parameterizations to Improve Ice Overlapping Liquid Cloud Water Content And Path Estimates from Passive Satellite Imager Data

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Background

The global distribution of cloud ice and liquid water is not very well known *(e.g. Waliser et al. 2009, Lebsock and Su, 2014)*

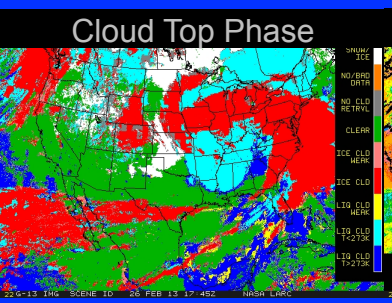
- CMIP5 models show large differences (factor of 2-10) in LWP and IWP
- No global consensus from satellite observations. Different sensors have different sensitivities, attenuation limits, retrieval errors

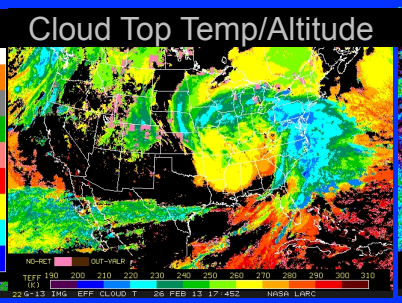
Despite uncertainties, satellite cloud retrievals are widely used in weather and climate applications

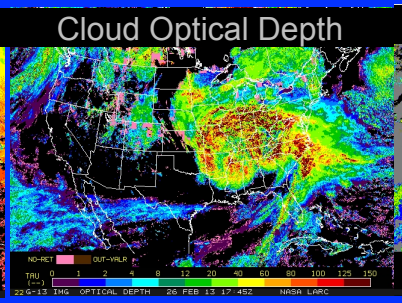
- Required to compute Earth's energy budget
- Model Evaluation
- Nowcasting aviation weather hazards (aircraft icing)
- Model Assimilation (e.g. CTH operational at NCEP, CWP experiments at NSSL and NCAR, COD experiments in GEOS-5)

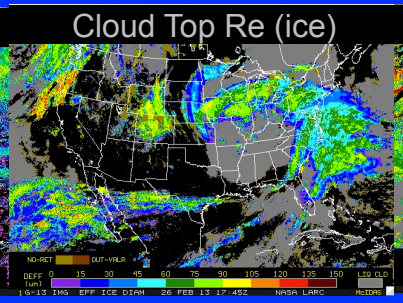
Satellite Imager cloud properties advantageous (spatial and temporal resolution)

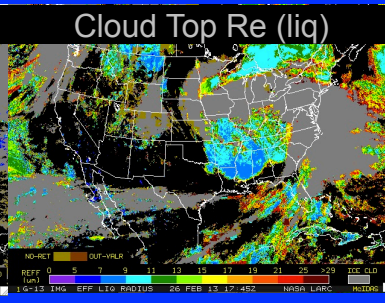
Imager radiances contain cloud top and vertical integral information but limited information on vertical structure

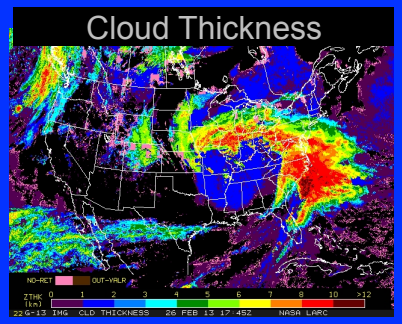


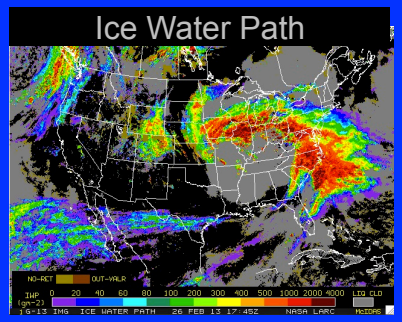


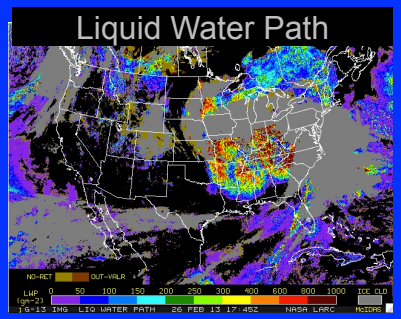












Retrieval methods assume vertical homogeneity in cloud phase (either all ice or all liquid) and PSD.

- Violated in nature, particularly deep ice and ice over water cloud systems (synoptic storms, convection)
- Large errors in IWP possible but have been difficult to ascertain
- Embedded liquid not retrieved or accounted for (CWP climatology biased)

Cloud Water Content Profiling Method

- Developed for application to passive satellite imager cloud retrievals
- Incorporates best information on cloud vertical structure from multiple sensors and models and constrains with COD, Tc, other radiance info from satellite imagers
- Vertical structure info assessed climatologically (often not available at imager resolution)
- Applicable to all cloud types
- Focus on single-layer continuous ice over water clouds
  - *Ice phase tops*
  - *COD > 10*
- Goal is to retrieve ice and liquid water content/path simultaneously and with improved accuracy from passive (coincident radar data not needed for application)
- Validate and refine method based based on comparisons with CloudSat/ CALIPSO, ground-based radar/radiometer, and aircraft data

Profiling Algorithm

IWC(z), LWC(z) from satellite imager data

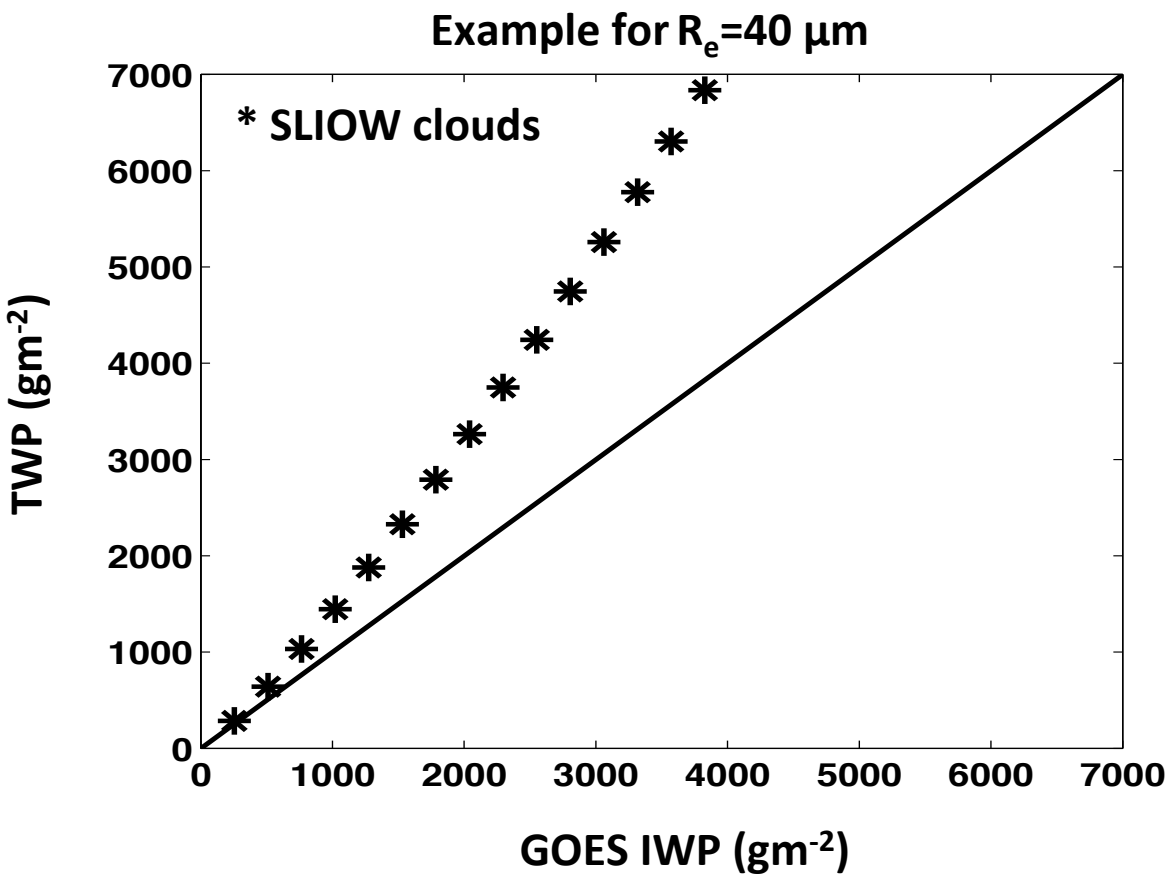
Key elements needed

- TWP
- Cloud water content vertical distribution functions
- Cloud boundaries ($\Delta Z = f\,(COD, Tc)$)
- Guidance on cloud phase partitioning for mixed phase levels

Parameterization for Total Water Path (TWP)

Initial parameterization uses DOE ARM data (i.e. TWP from ground-based cloud radar, lidar and microwave radiometer data) correlated with GOES COD.

5-year dataset at ARM SGP site

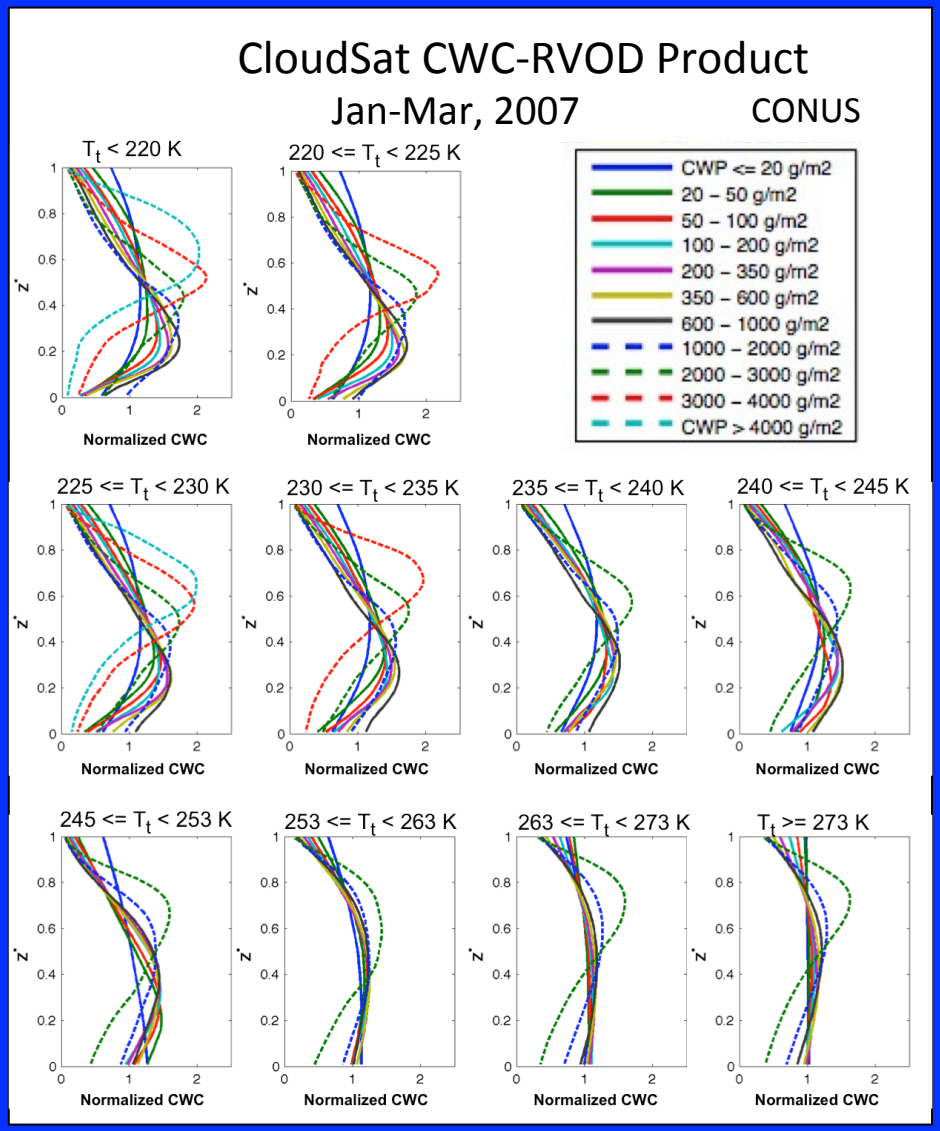


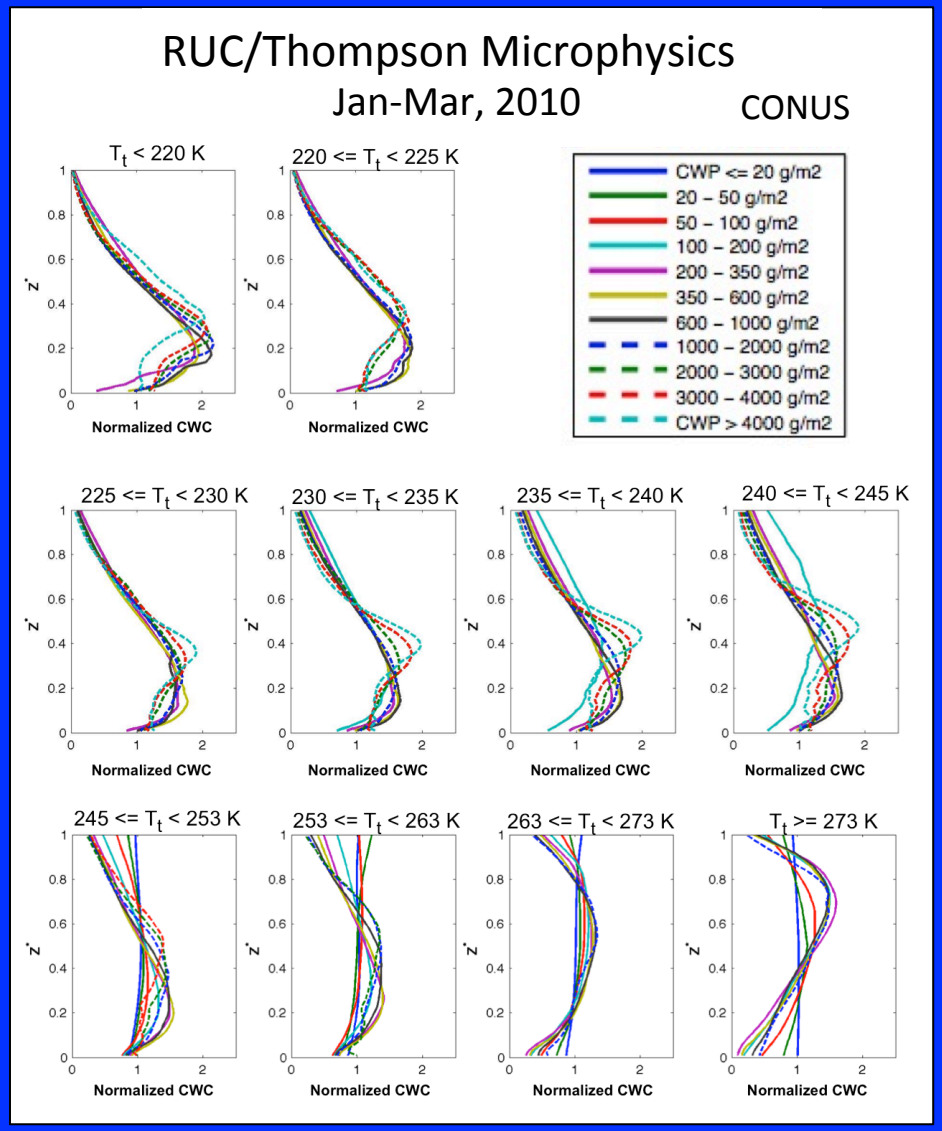
TWP nearly twice as large as the standard satellite retrieval of IWP for optically thick ice over water clouds

Typical Vertical Distribution of Total Water Content (TWC)

Normalized profiles averaged for wide range of cloud types (TWC(z) = TWP * CWCn(z))

Combination of CloudSat/CALIOP + NWP yields best results





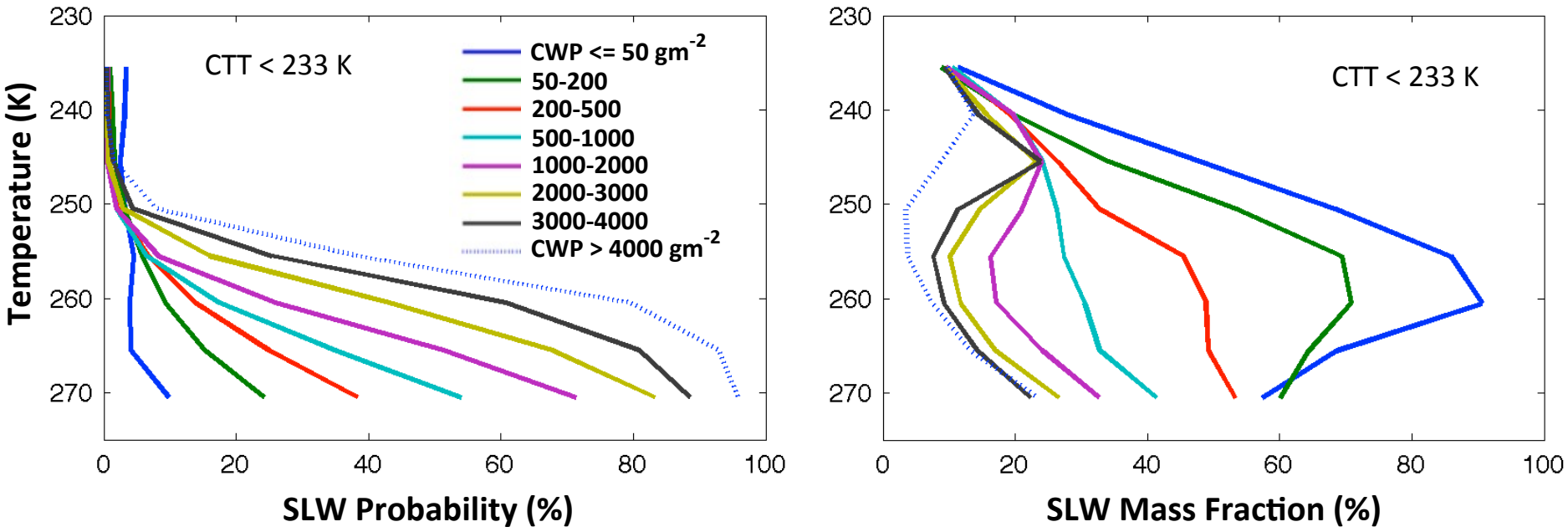
Cloud Phase Partitioning in Vertical

- Guidance from NWP cloud analyses
- SLW mass fraction needed to partition IWC(z) and LWC(z) from TWC(z)
- SLW probabilities provide guidance on SLW top temperatures (scheme tuned to icing PIREPS)

Thompson/NCAR Cloud Microphysics
In RUC/Rapid Refresh models
liquid: $q_{liq} + q_{rain}$
ice: $q_{ice} + q_{snow} + q_{graupel}$

SLW Probability and Mass Fraction

Climatological approach as a function of T for lots of cloud types (~50)



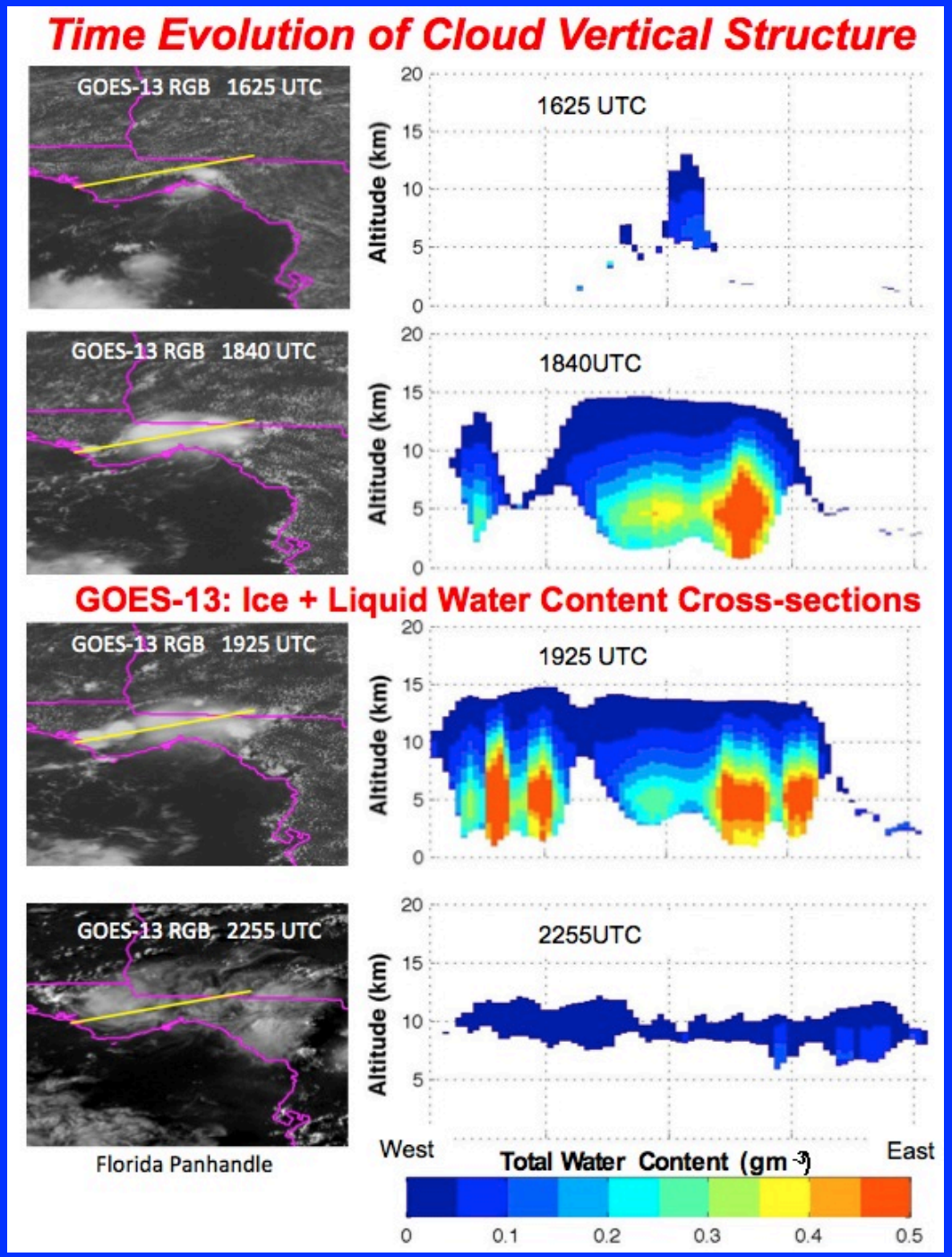
Jan-Mar, 2010

Profiling Method

All of this information parameterized, stored in LUT's, and utilized in a profiling algorithm to estimate IWC(z) & LWC(z) profiles at the resolution of the satellite imager

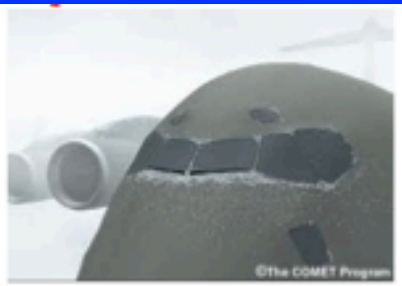
4-D Cloud properties from GEO

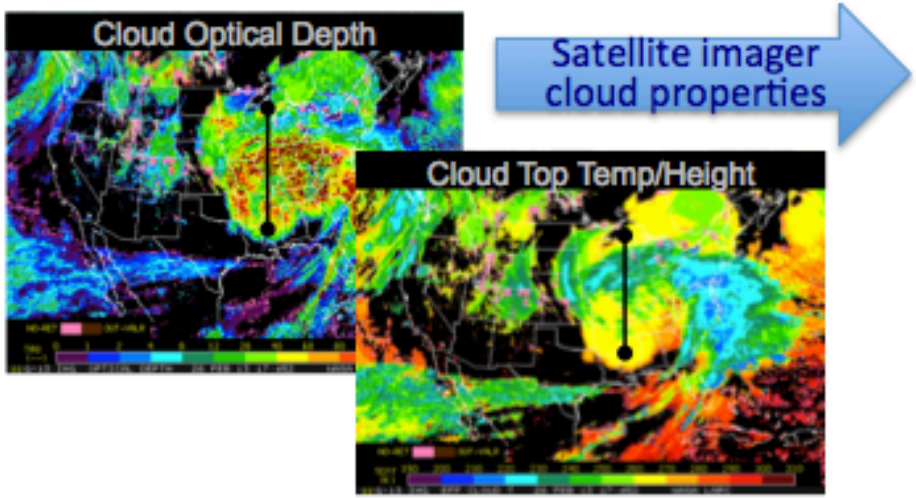
Time evolution of cloud ice and liquid water content derived from GOES during a thunderstorm outbreak over the Florida panhandle

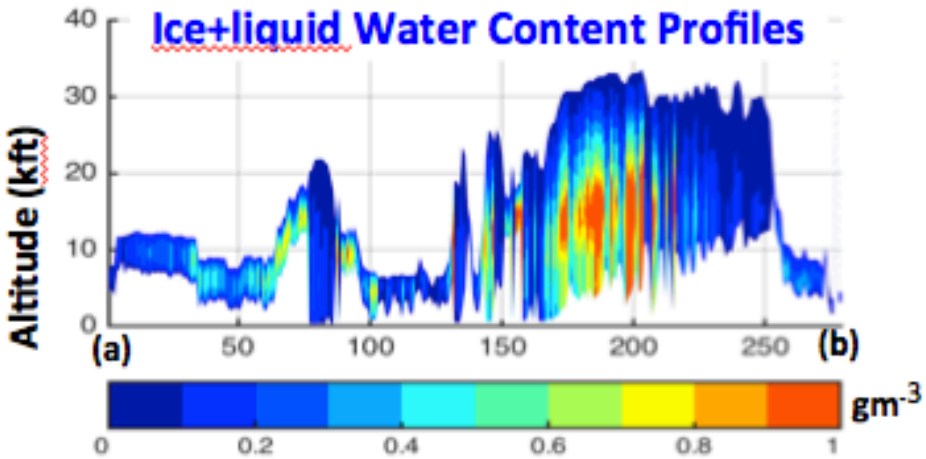


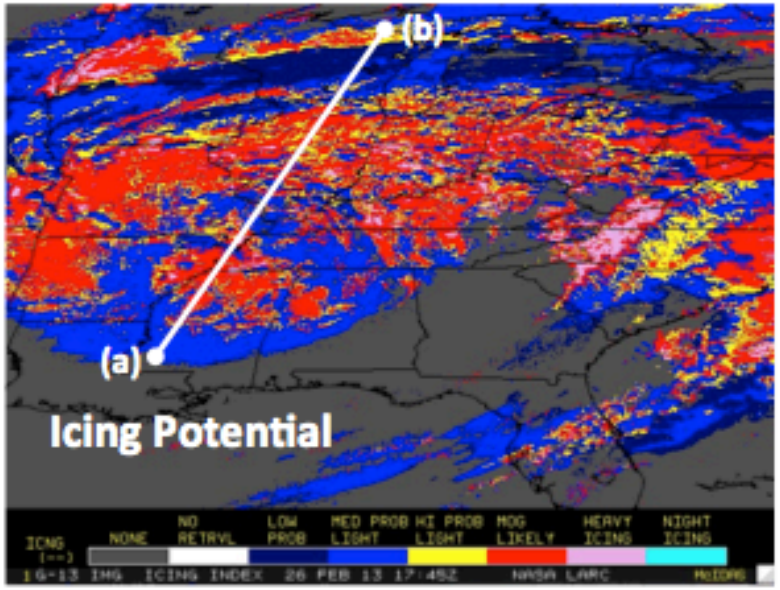
CWC Profiles used to infer aircraft icing conditions

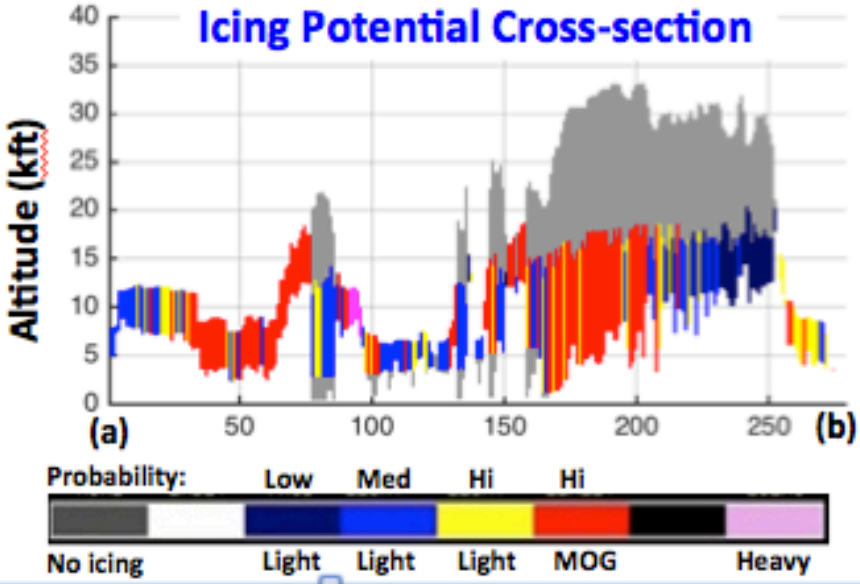
Verified with Pilot Reports over the U.S.
Being evaluated in NWS aviation weather forecast offices





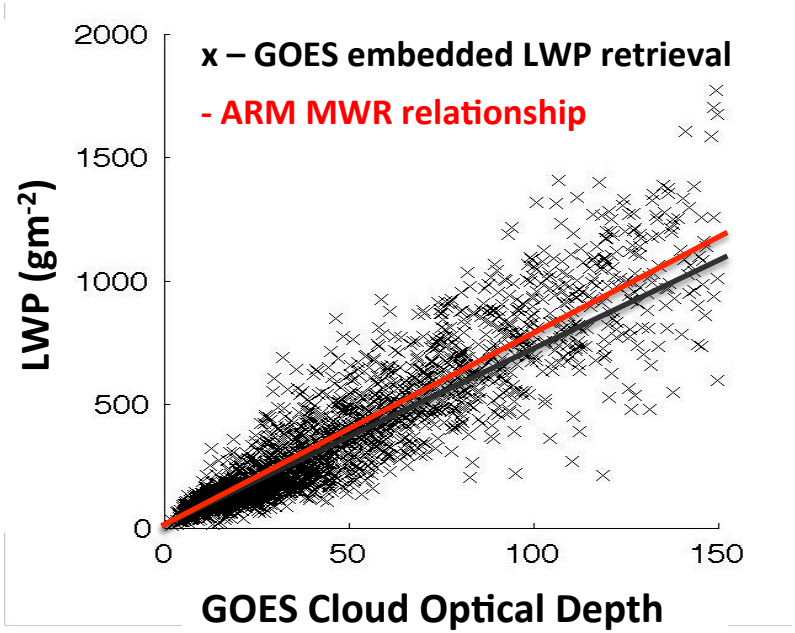


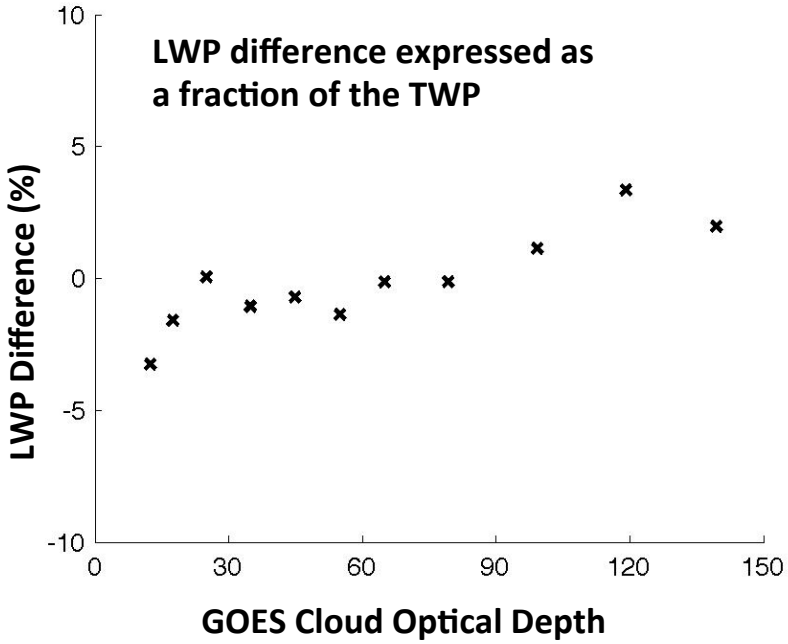




LWP Validation

Single-layer ice over water clouds (known icing conditions)
CONUS, Jan-Mar, 2013



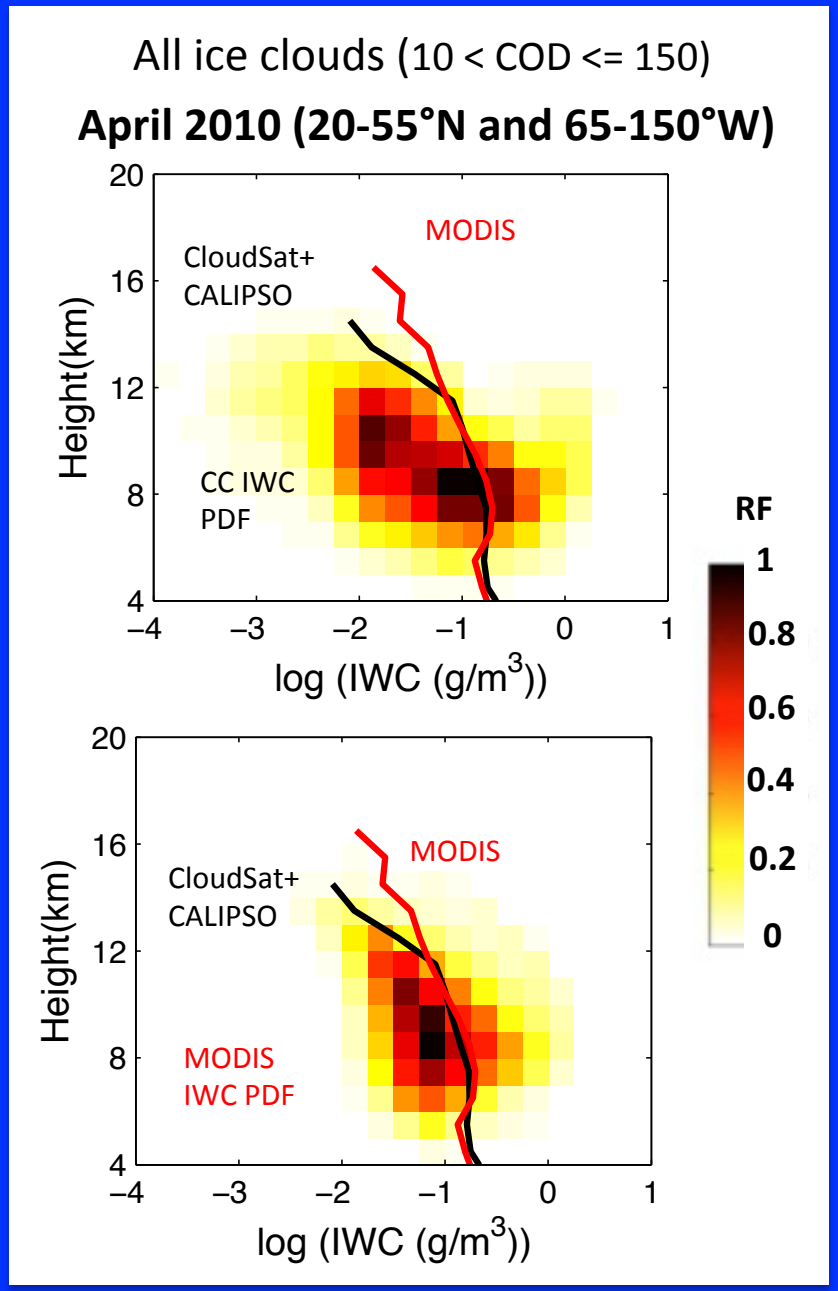


- **GOES LWP-COD relationship matches ARM MWR relationship with COD**
  - **Suggests NWP cloud phase partitioning works well**
- **Pilot reports verify satellite icing intensity/altitude estimates**
  - **Skill in overlapping cloud conditions matches that for unobscured SLW clouds**

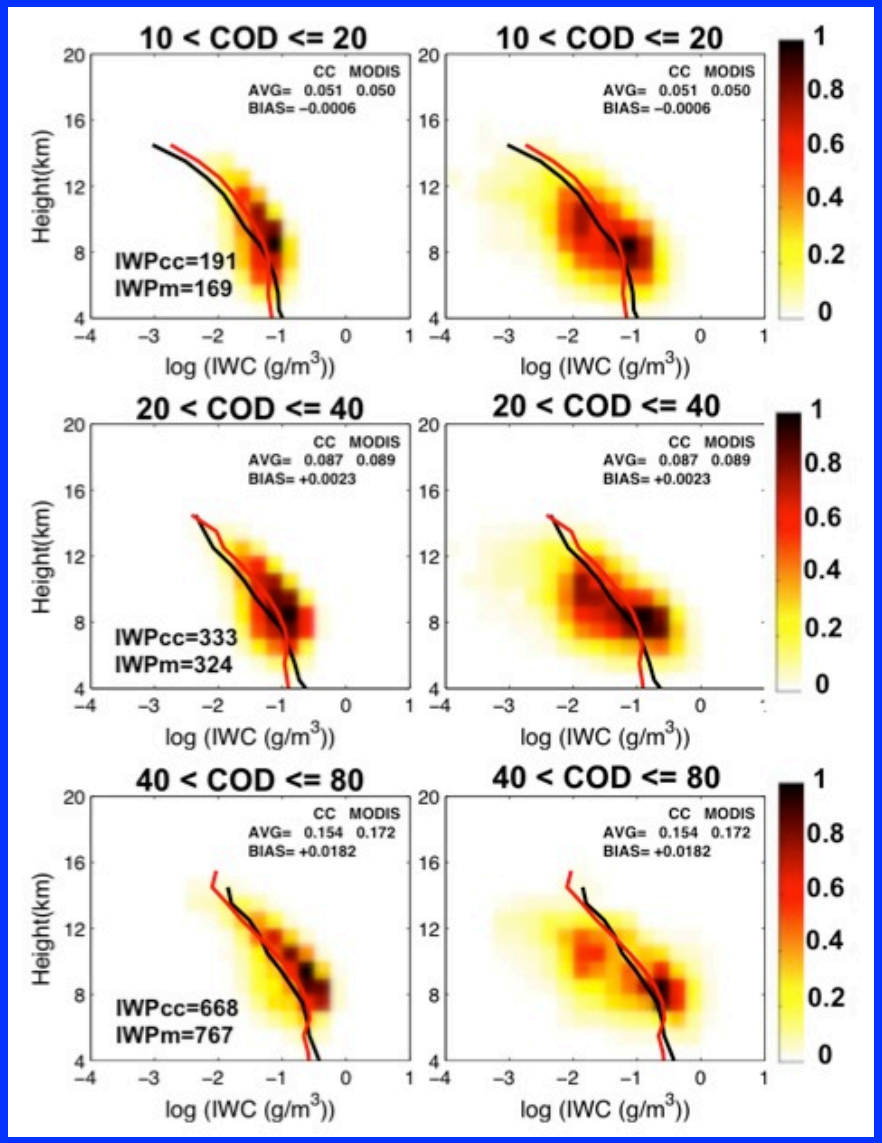
MODIS IWC/IWP Validation using CERES C3M Product

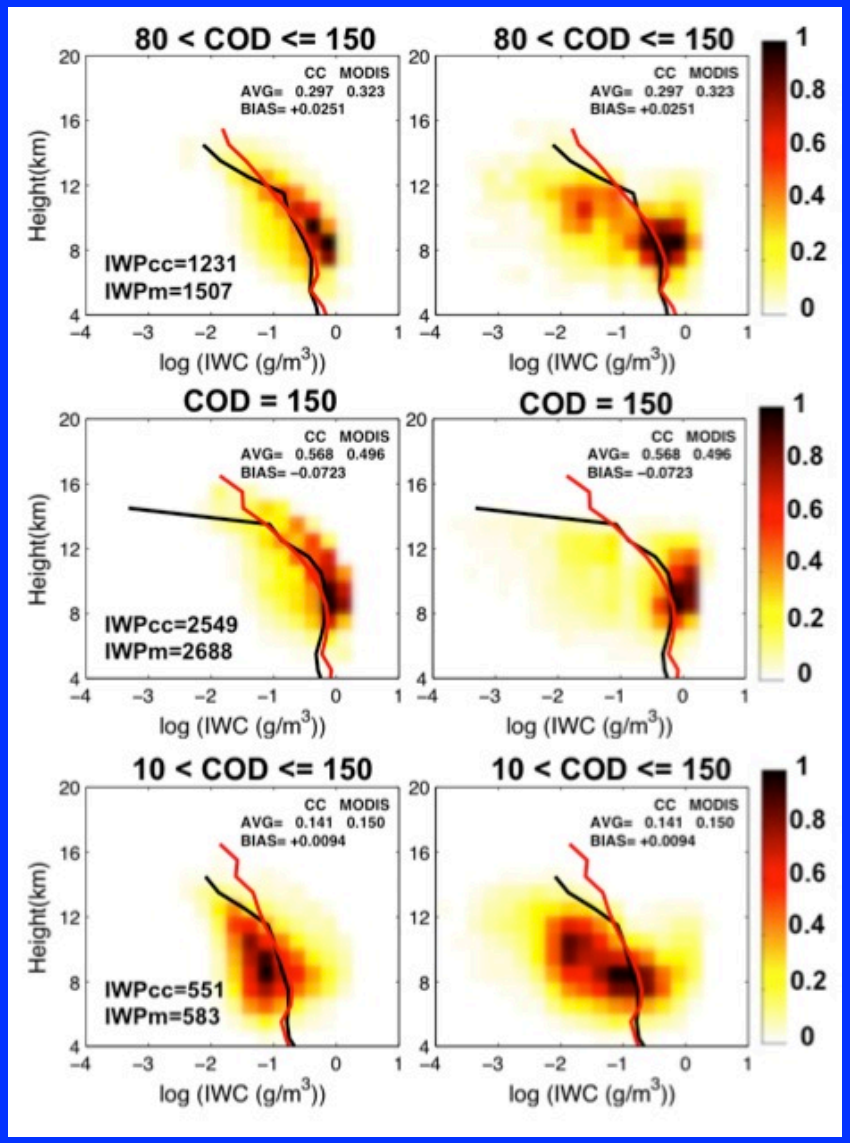
- C3M - matched CALIPSO IWC (version3), CloudSat CWC-RO, CERES MODIS Ed4 cloud properties at 1km resolution *-Kato et al. (JGR, 2011)*
- Other active sensor datasets (2CICE, DARDAR) not yet used in evaluations
- Comparisons made for all ice-phase topped clouds and stratified by COD
- Comparisons only use data above 253K level - avoids most areas with mixed phase & CPR attenuation

- High sensitivity of CALIOP responsible for large differences at high altitude
- MODIS PDF narrower (climatological approach doesn't capture extremes)
- MODIS CTH, CBH errors also contribute to differences



MODIS IWC/IWP Validation using CERES C3M Product





Overall, good agreement in monthly means as a function of altitude and over a wide range of COD

Validation of IWC/IWP using ATRAIN Data

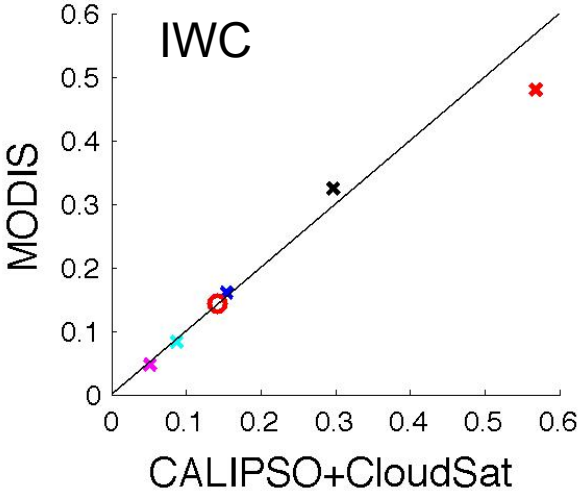
Profiling Method applied to MODIS Cloud Properties

April 2010 (CONUS), Optically thick clouds (ice phase tops, tau>10)

Monthly Means stratified by MODIS COD

IWC (g/m^3)

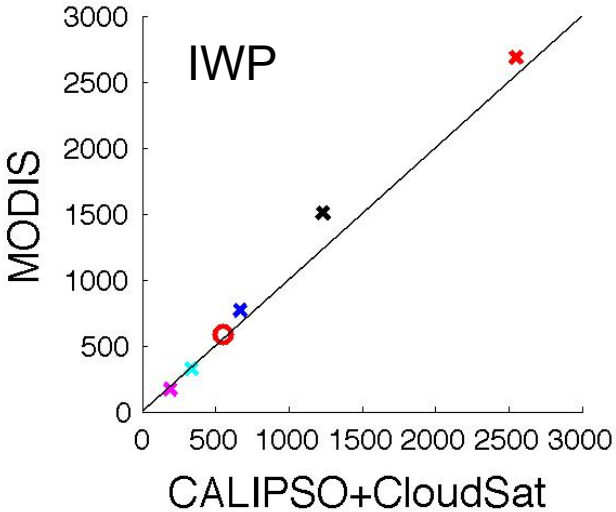
COD BIN	CALIPSO +CloudSat	MODIS	BIAS	N
10-20	0.051	0.047	-8%	5083
20-40	0.087	0.083	-5%	4149
40-80	0.154	0.161	5%	2635
80-150	0.297	0.325	9%	730
150	0.568	0.480	-15%	965
ALL	0.141	0.143	1%	13562



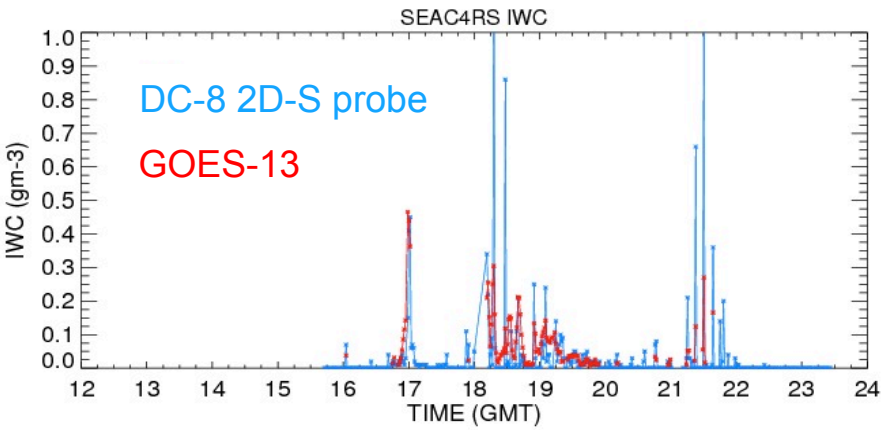
Assessed at altitudes above -20C level

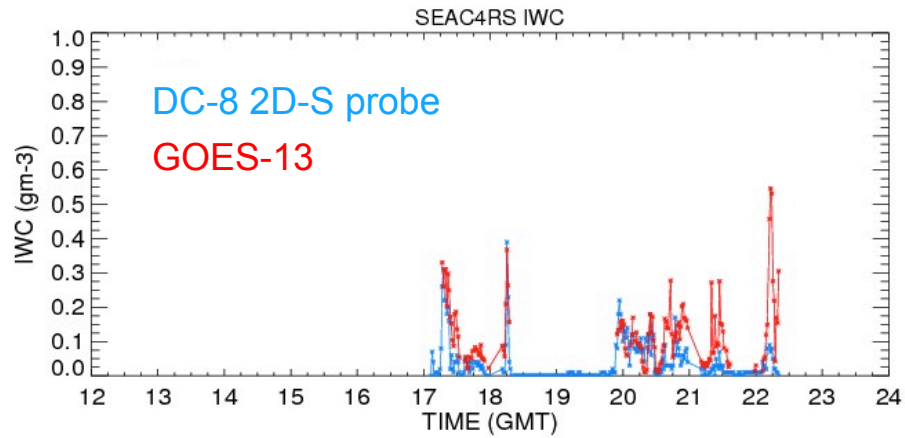
IWP (g/m^2)

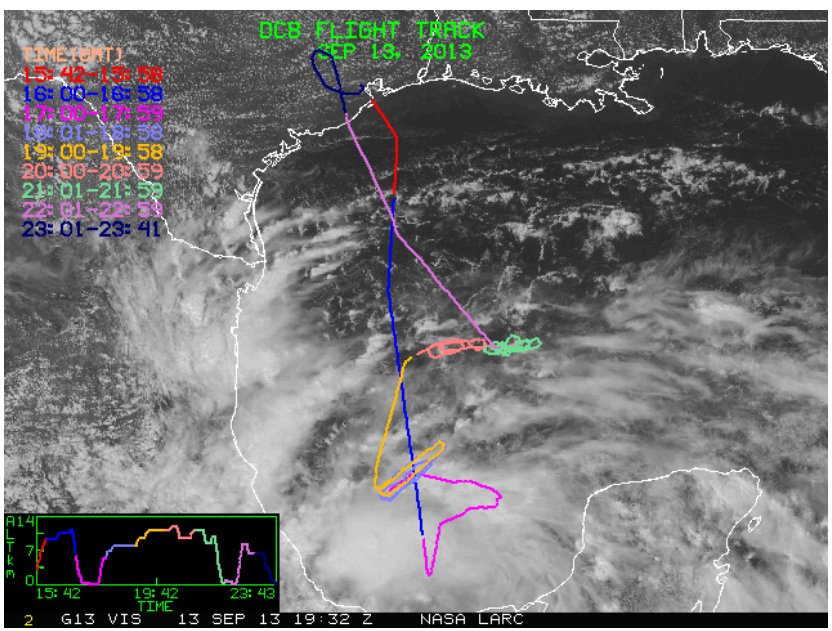
COD BIN	CALIPSO +CloudSat	MODIS	BIAS	N
10-20	191	169	-12%	5083
20-40	333	324	-3%	4149
40-80	668	767	15%	2635
80-150	1231	1507	22%	730
150	2549	2688	5%	965
ALL	551	583	6%	13562

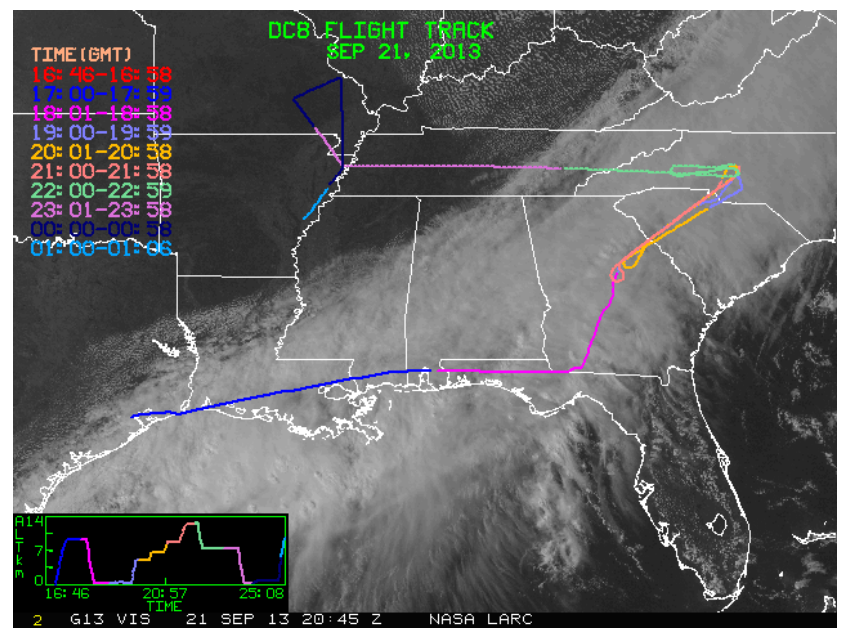


Imager IWC retrievals using profiling method agree well with in-situ aircraft data



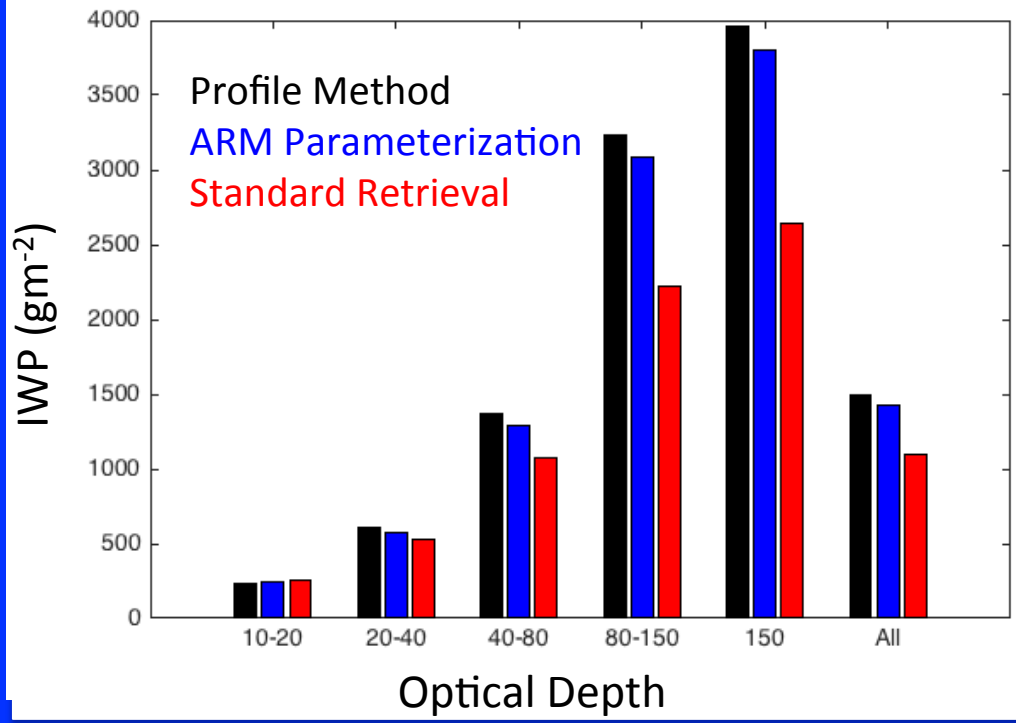






Profiling Method Total Column IWP used to Test and Refine IWP Parameterizations

Jan-Mar, 2013 (Known icing conditions, Ice Phase tops)



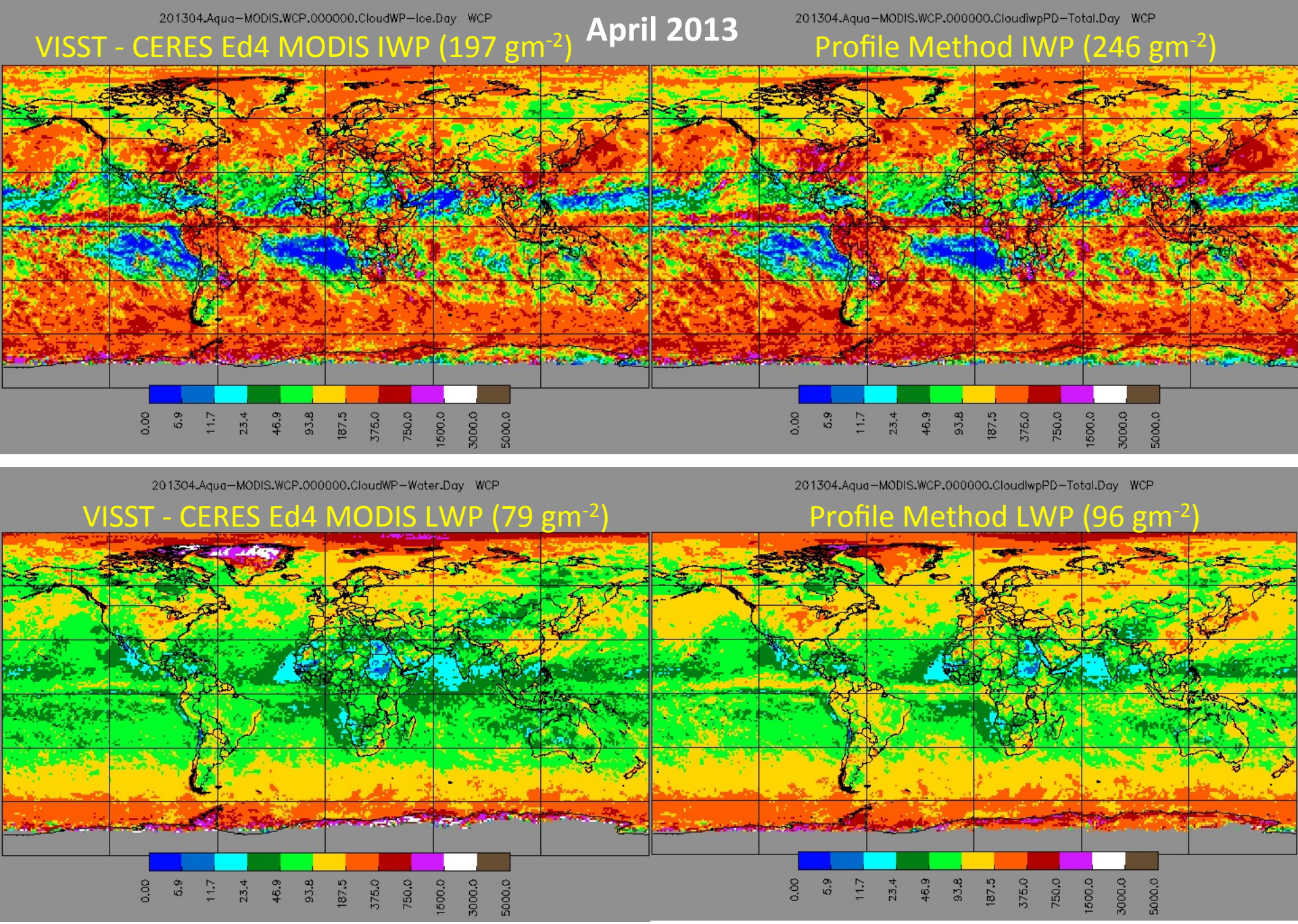
BIAS (%) vs Profile Method

COD BIN	Profile method (IWP)	ARM Param	Sat-CoRPS (VISST)	N
10-20	234	3%	11%	62515
20-40	604	-5%	-11%	74047
40-80	1368	-5%	-22%	47192
80-150	3228	-4%	-38%	25905
150	3960	-4%	-33%	42893
ALL	1494	-4%	-27%	252552

Model vertical structure/phase partitioning works well

Standard method (e.g CERES CWG) underestimates IWP by up to 40%

April 2013



Non-polar means (shown parentheses) increase up to 40% (~25% overall) using Profile method

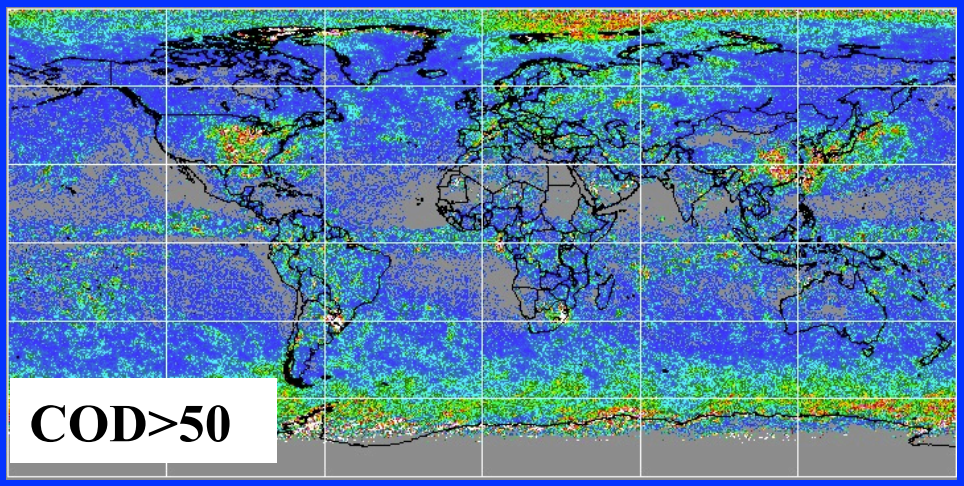
Summary

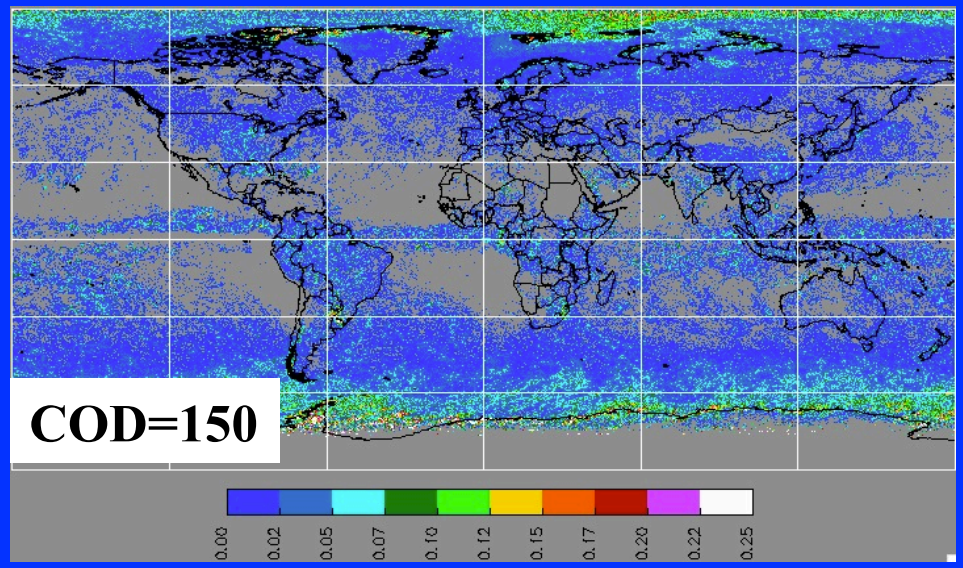
- Profiling technique is a passive satellite sensor approach fully constrained with imager cloud properties (don't need a cloud radar)
- Incorporates best available information on cloud vertical structure/phase from other sensors and models (climatological approach)
- Works over land and ocean and can be applied to all cloud types providing high spatial and temporal resolution (4D cloud properties)
- Simultaneous retrievals of ice and liquid water path in SL overlapping clouds agree reasonably well with those from other sensors and in situ data over U.S.
- More work needed to expand the method for global application and evaluation.
- IWC estimates in mature deep convective clouds too low by a factor of 2-3 (using airborne radar & in-situ data in HIWC conditions to refine method).
- Improved knowledge of ML clouds (e.g. previous talk) will enhance the accuracy and utility of the method
- Eventually, the imager profiles will be used to develop new, more accurate IWP parameterizations that could be applied in other satellite retrieval systems.

Backups and Spares

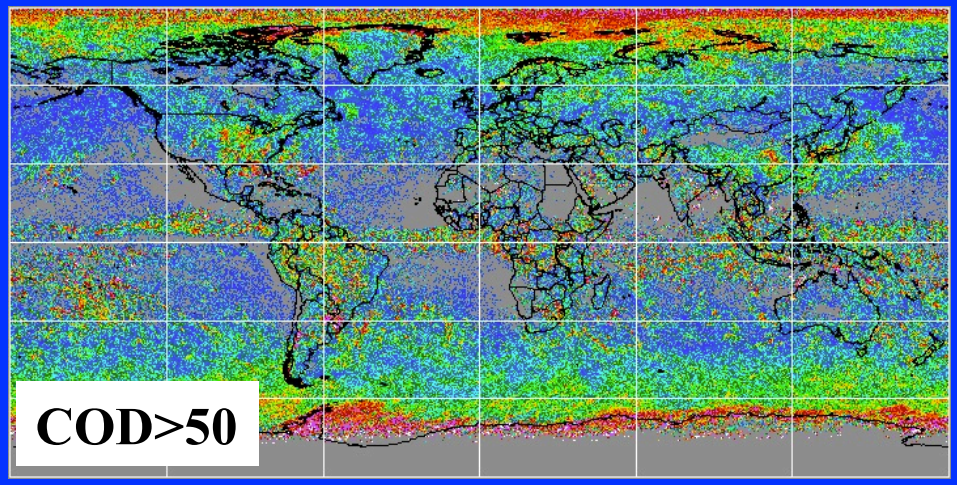
OPTICALLY THICK ICE OVER WATER CLOUDS MATTER

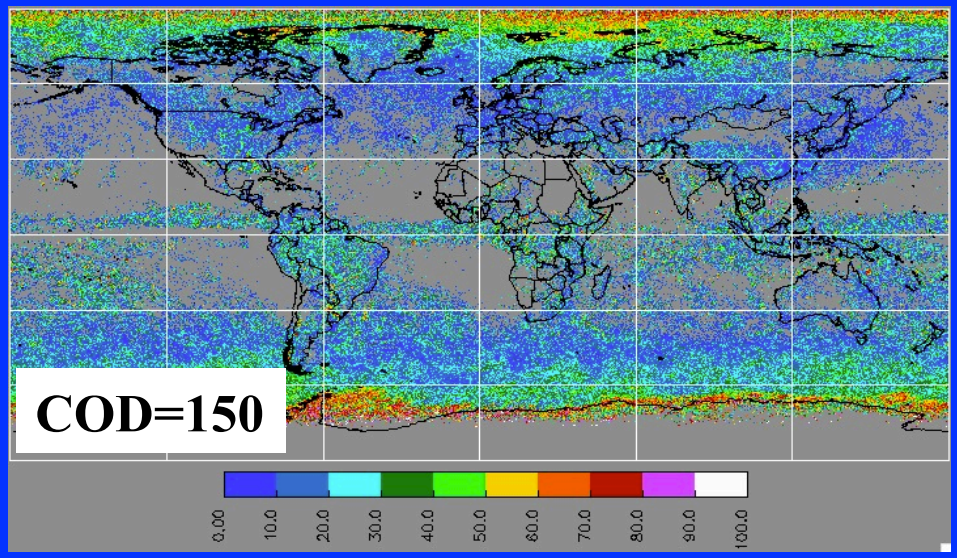
Ice Cloud Fraction (not many)



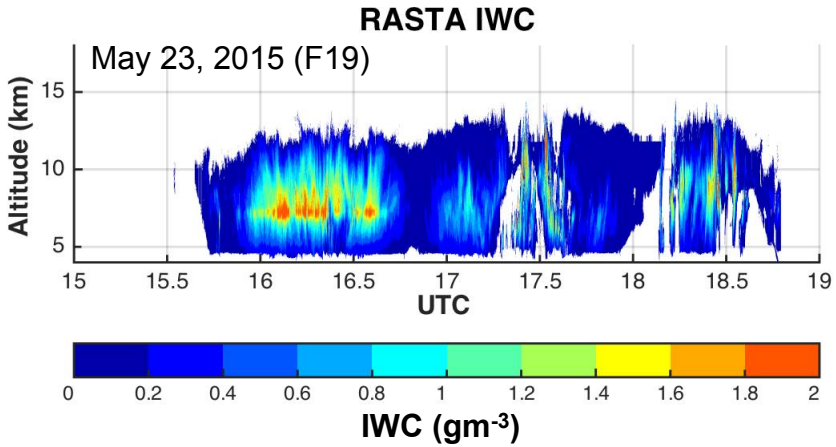


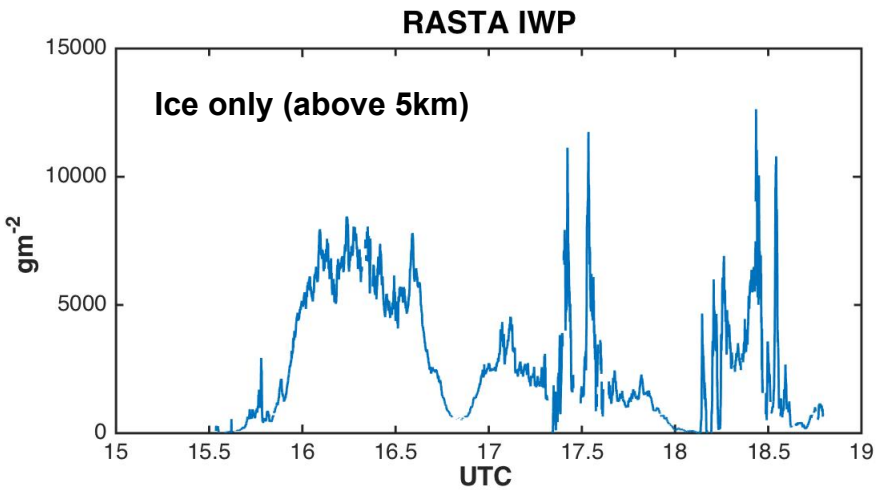
Relative contribution to mean IWP (Large!)

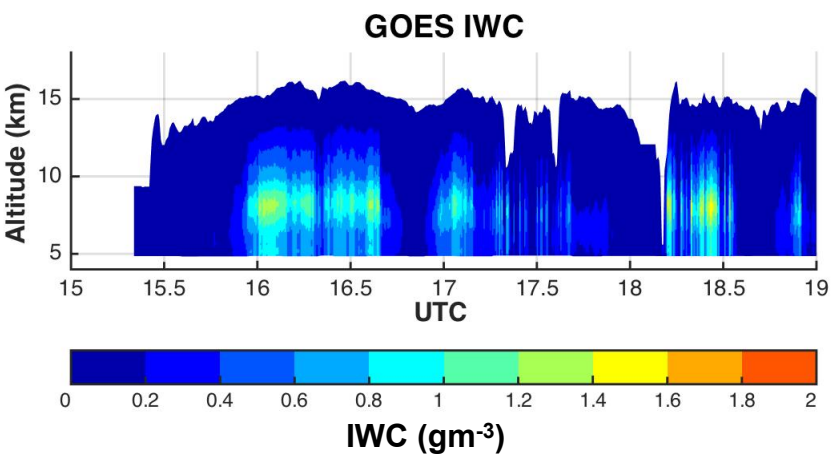


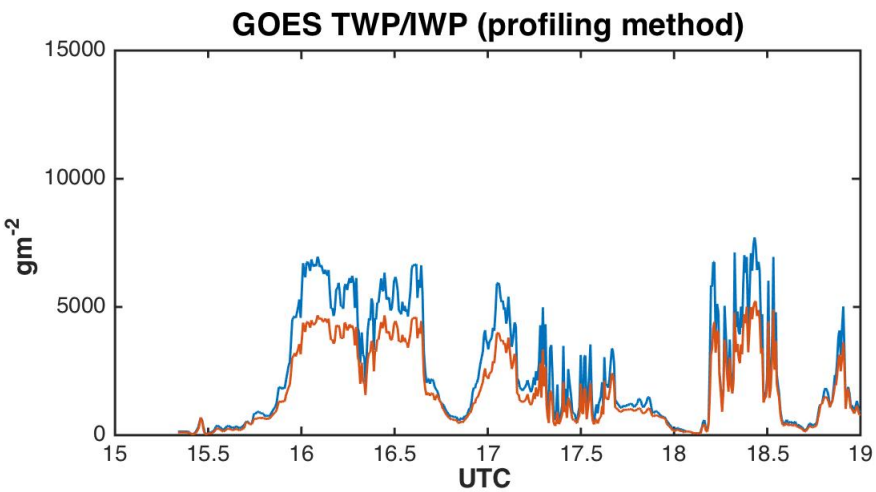


IWC retrievals from airborne radar in deep convection
- being used to refine TWP estimates





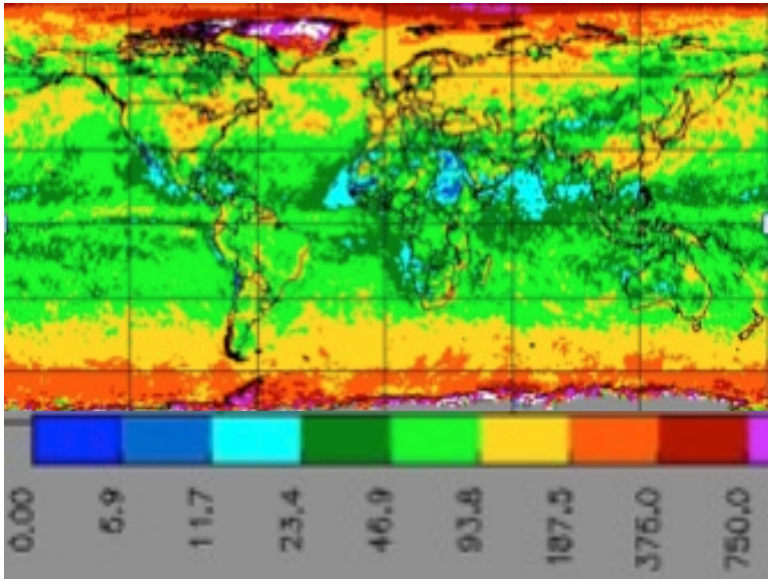




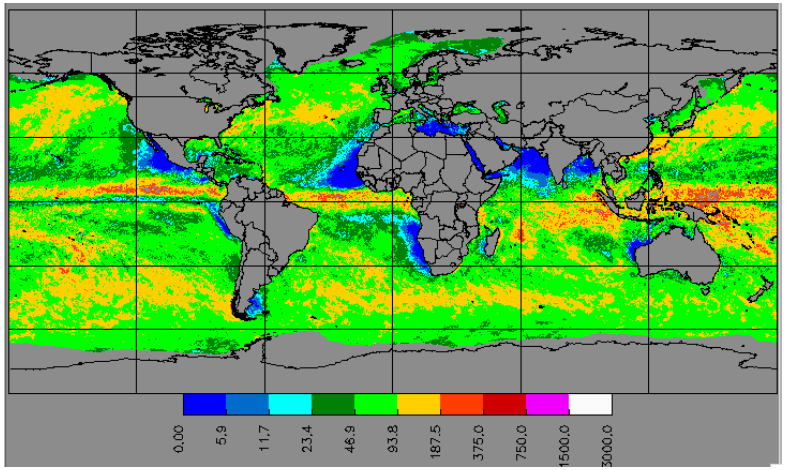
RASTA : RAdar SysTem Airborne (95 ghz) in HAIC/HIWC Field Programs

Delanoë et al. 2015

CERES Ed4 MODIS LWP (April 2013)

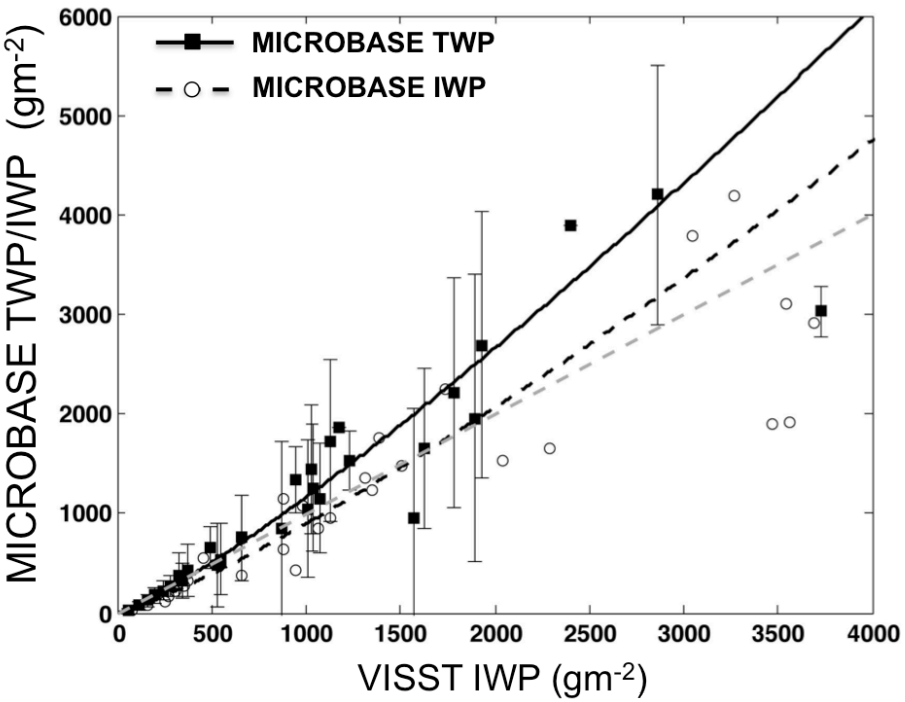


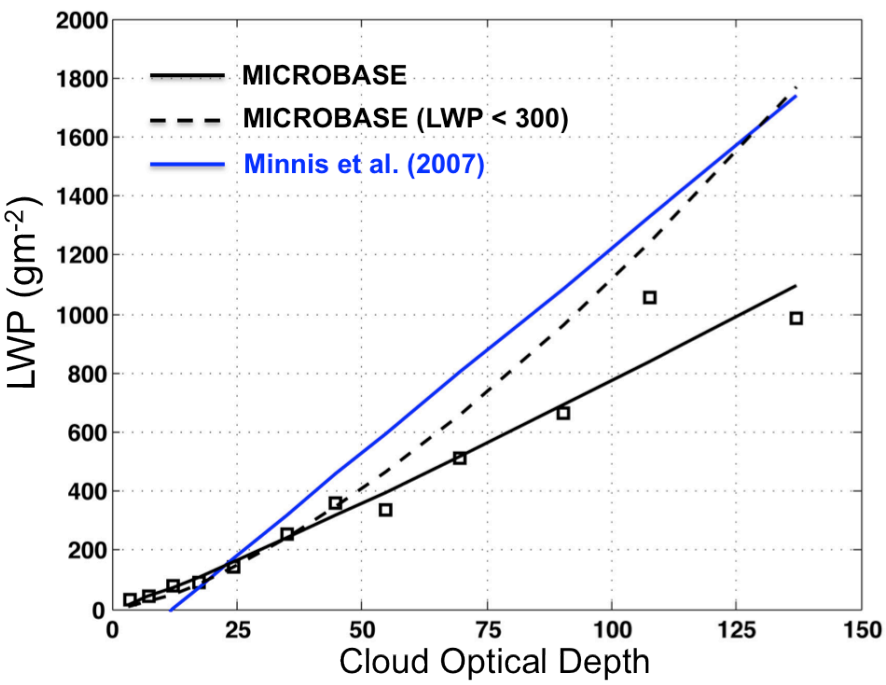
AMSR-2 LWP (April 2013)



Parameterization for Total Water Path (TWP)

Based on co-located satellite retrievals (i.e. COT, Re) from GOES and DOE ARM data (i.e. IWP + LWP from ground-based cloud radar, lidar and microwave radiometer data). 5-year ARM MICROBASE dataset at ARM SGP site



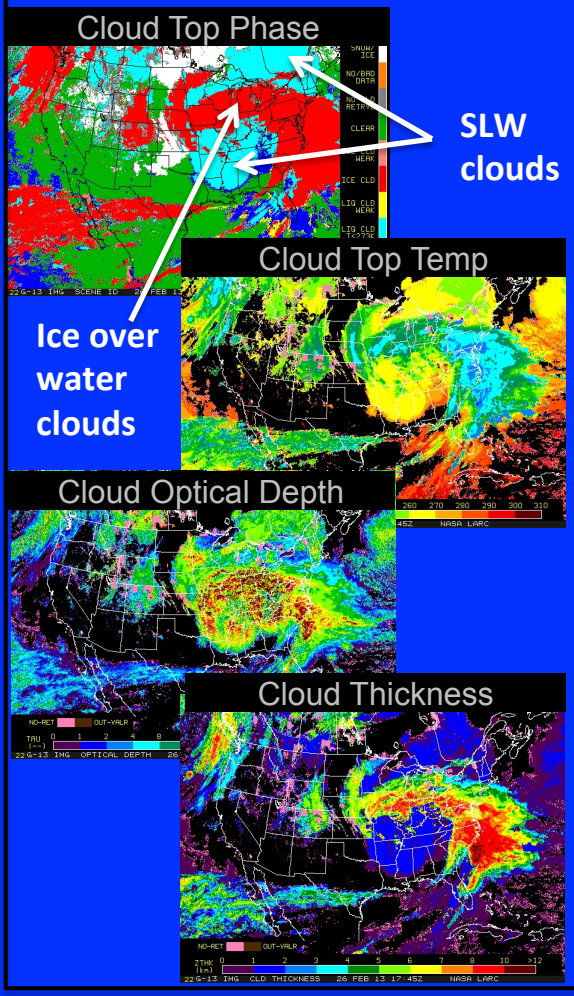


Some tuning needed to get closer to the right answer: TWP = TWP (MMCR)+ LWP (MWR)

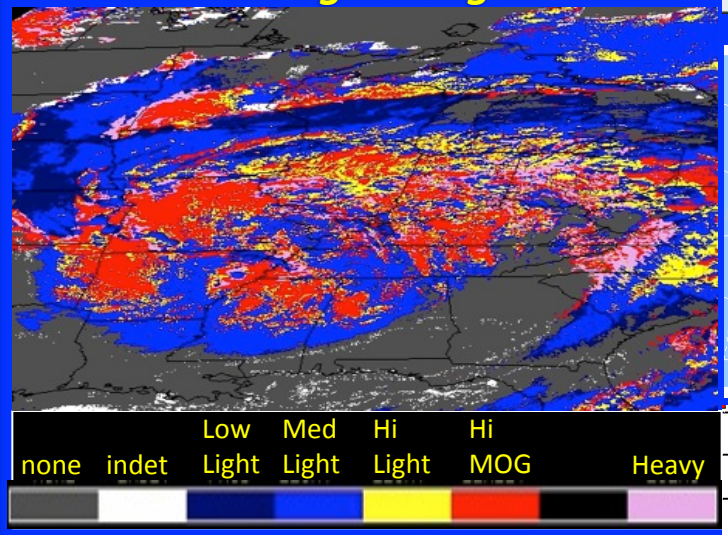
AIRCRAFT ICING

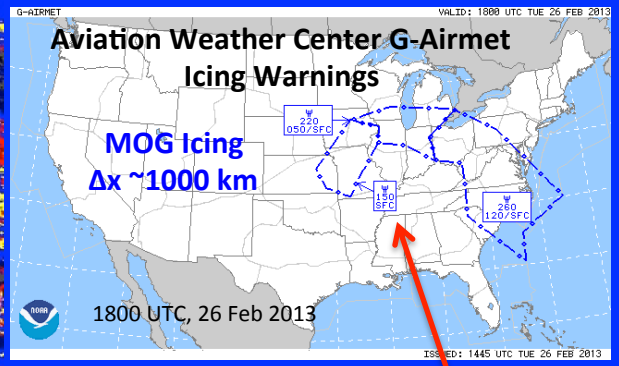
Profiling method used to infer SLW and icing intensity embedded in deep clouds

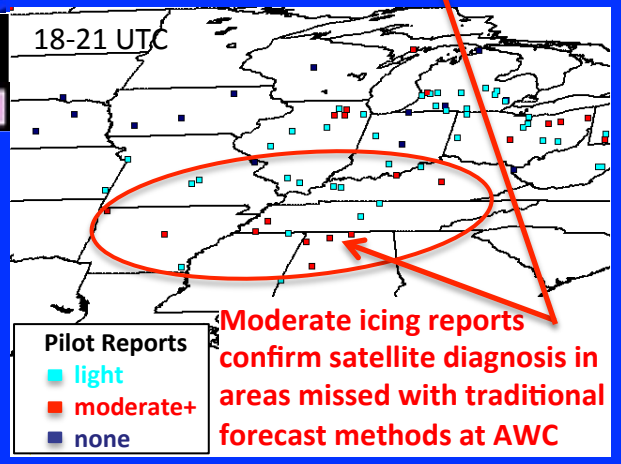
GOES Cloud Properties



Satellite Flight Icing Threat



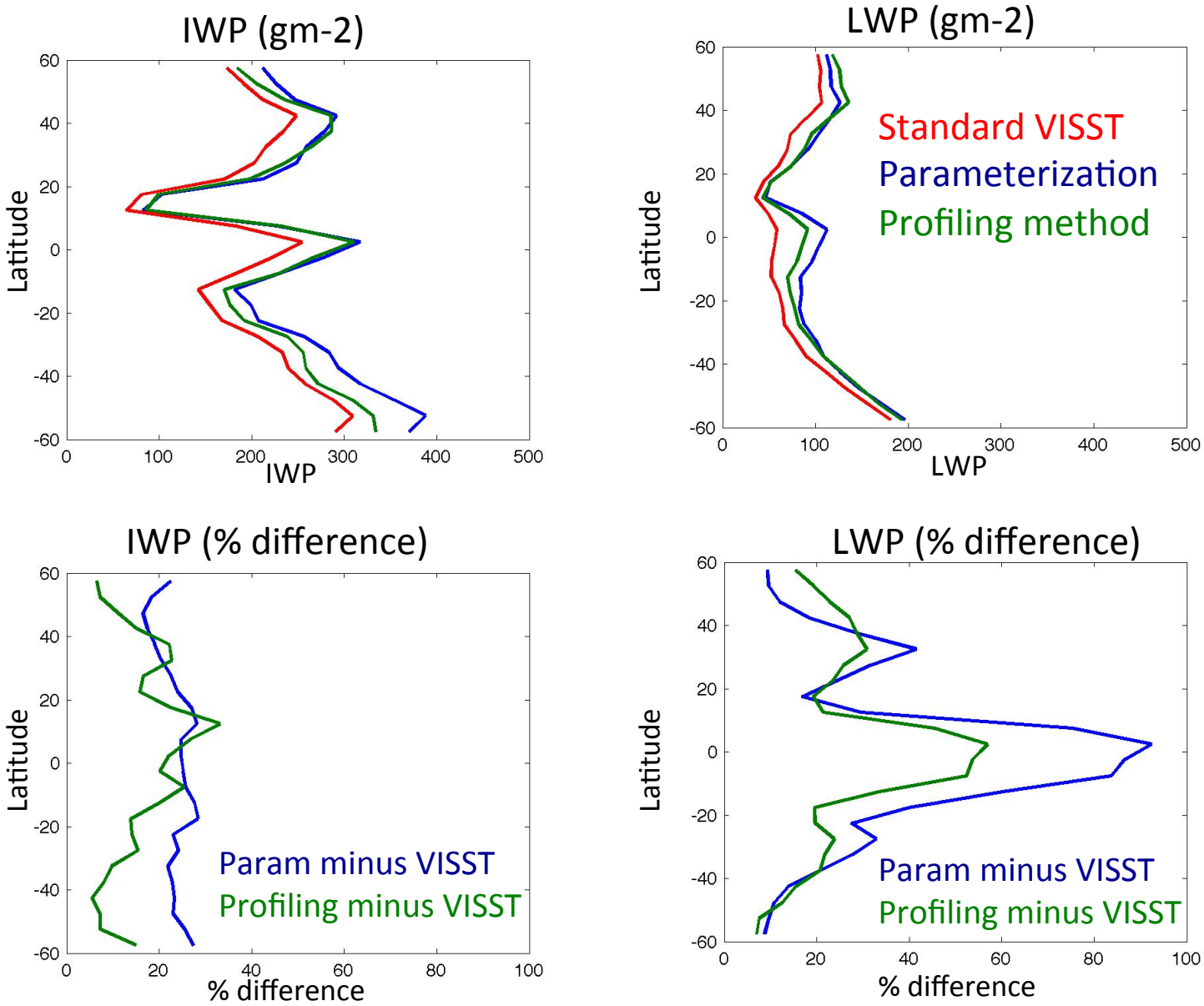




Icing products being demonstrated in GOES-R Proving ground with support from Risk Reduction program

Satellite method equally skillful in detecting icing conditions in glaciated and SLW-topped clouds

ZONAL MEANS


IWP (gm-2)
Latitude
IWP
LWP (gm-2)
Latitude
LWP
Standard VISST
Parameterization
Profiling method
IWP (% difference)
Latitude
% difference
Param minus VISST
Profiling minus VISST
LWP (% difference)
Latitude
% difference
Param minus VISST
Profiling minus VISST