Satellite Identification/Nowcasting of HIWC North American Work

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PROBLEM

• Aircraft events occurring in flight, usually at cruise altitude, have been attributed to occurrence of high ice water contents and possibly large concentrations of small ice crystals

- not sure of exact characteristics causing the "events"
  - *What is the level of IWC that causes engine failure?*
  - *Is magnitude or time of exposure a larger factor?*
  - *Is it related to particle size?*
  - must assume some IWC threshold to cause "events"
- typically occurs well below cloud top and in convective situations
  - satellite imagery "sees" mostly cloud top
  - *Is there a relationship between what satellite sees and the IWC within the cloud interior?*
- *can we use satellites to provide avoidance warnings to pilots?*
  - must develop some measure of expected occurrence of HIWC

OBJECTIVES & APPLICATIONS

• Objectively determine if HIWC can be associated with any parameter or set of parameter values derived from current passive geostationary satellite data

- match satellite imagery with aircraft measurements of TWC
- develop statistics of satellite radiances/products as fn(TWC)
- revise as state of the art advances
- use satellites needed to cover variety of domains
    - current: GOES, Meteosat, MTSAT
    - future: INSAT, Himawari-8 & GOES-R

• Develop technique to nowcast HIWC conditions using satellite data

- convert observations to statistical probability predictor
- merge overshooting top data to diagnose "no fly" areas (P = 1)
- validate data using independent measurements
    - *in situ TWC measurements*
    - *aircraft "events" (temperature anomalies, altitude loss, etc.)*
- predict location of HIWC in near term (later)

Using Single-Satellite 2-D Products

Relating column values to IWC

DATA

• Satellite imager radiances & satellite-derived cloud properties*
  - T11, TWV-T11=BTD(WV), T11-TSW = BTD(SW), Teff, optical depth (COD), De, IWP
    - WV ~6.7 *μ*m; SW ~12 *μ*m; De – xtal effective diameter
    - T11 – obs 11-*μ*m temperature; Teff – cloud effective temp ~ T11
  - automated overshooting top (OT) detection & texture field
    - *Bedka and Khlopenkov (submitted JAMC, 2015)*

In situ Data

• Airbus campaigns (Robust-probe)
  - Darwin 2010, MTSAT
  - Cayenne 2010, GOES-12/13, Meteosat-9
  - Santiago 2012, GOES-13

• SAFIRE campaign (IKP-2)
  - Darwin 2014 (MTSAT-1R, MTSAT-2)
  - Cayenne 2015 (GOES-13, Meteosat-10)

* Properties derived using Satellite ClOud & Radiation Property retrieval System (SatCORPS)
  - *Minnis et al. (SPIE, 2008; TGRS, 2011)*

Data Matching & Analysis

• Nearest 4-pixel average to flight location using closest time match ($\pm$15 min)

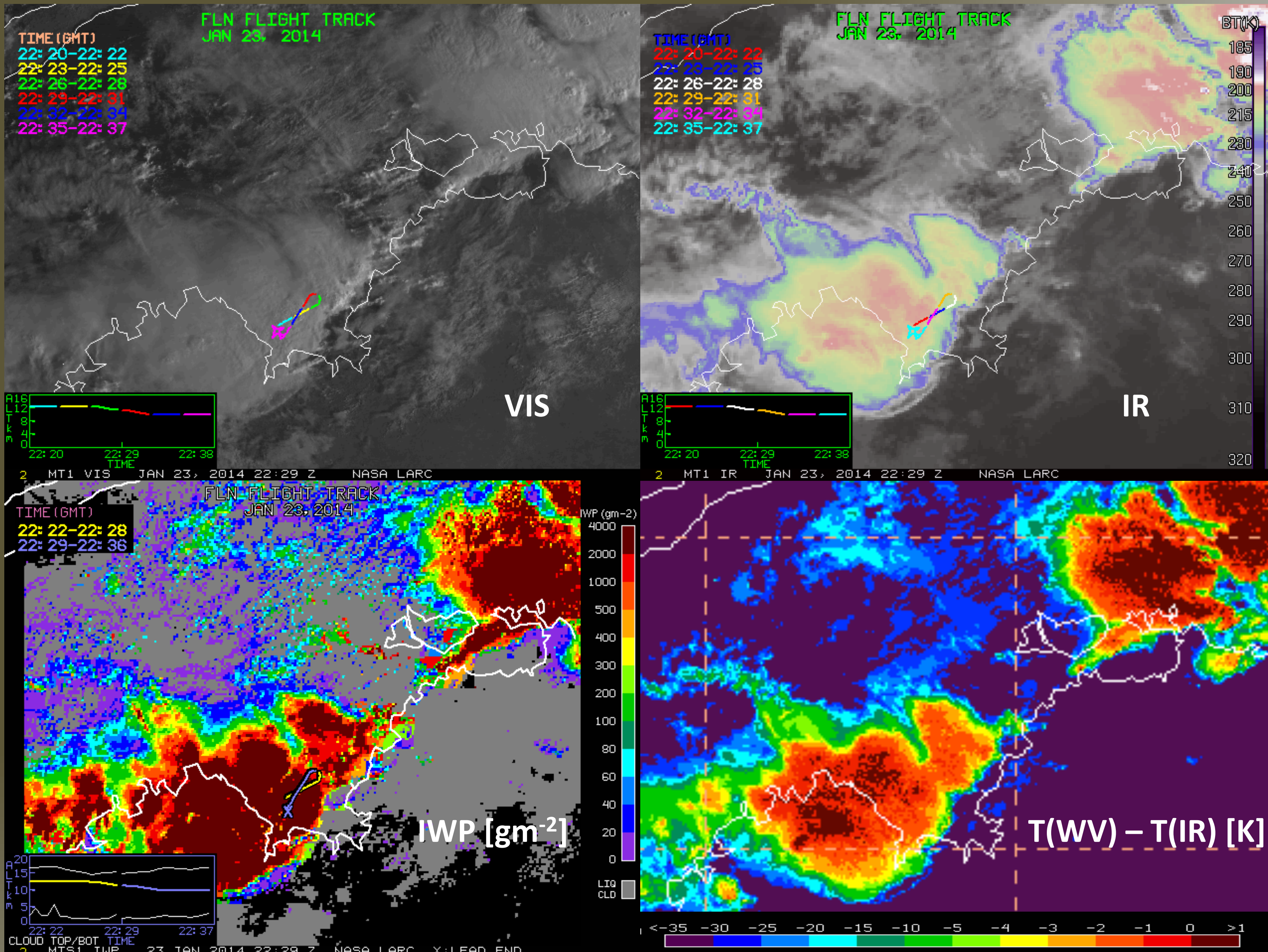
1) daytime, SZA < 75°
2) static air temperature SAT < 0*C
3) plane instrument measured valid IWC
4) satellite products indicate ice-phase cloud
5) satellite data corrected for parallax

• Create histograms of parameter values as function of in situ TWC

• Develop probability estimator from histograms

* SAT is Static Air Temperature from probe

Satellite Products during HIWC Darwin 2014, MTSAT-1R, 22:29 UTC, 23 January



Products Along Falcon Flight Track

21 – 23 UTC, 23 Jan 2014

- 4 pixel average closest to flight location (±5 min), 10 min MTSAT-1R data

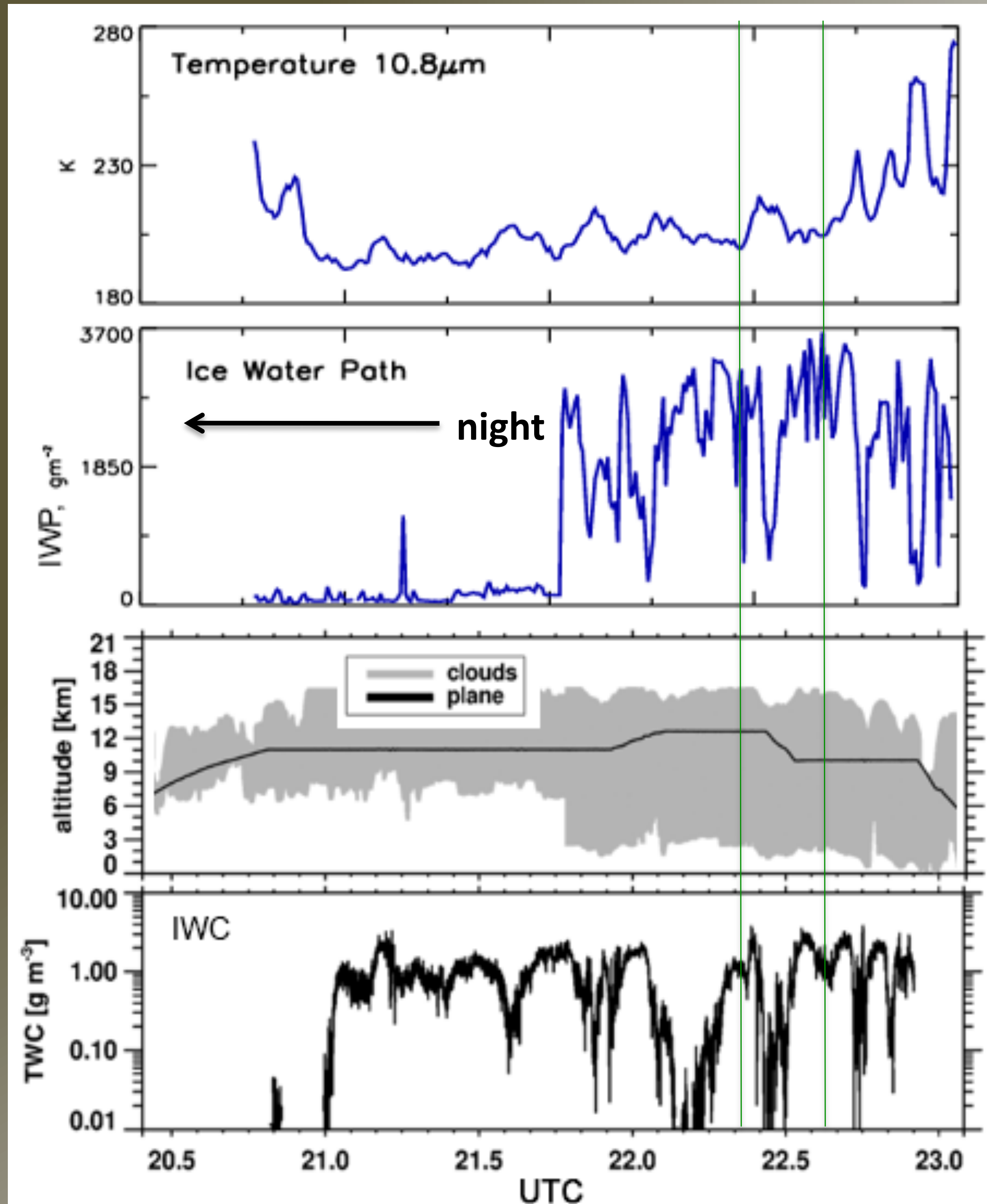
1) averages matched to Falcon IKP-2 TWC data

2) Results combined from all flights & analyzed

3) Highest IWP correspond to highest IWC, except at beginning of run

Data accessible at

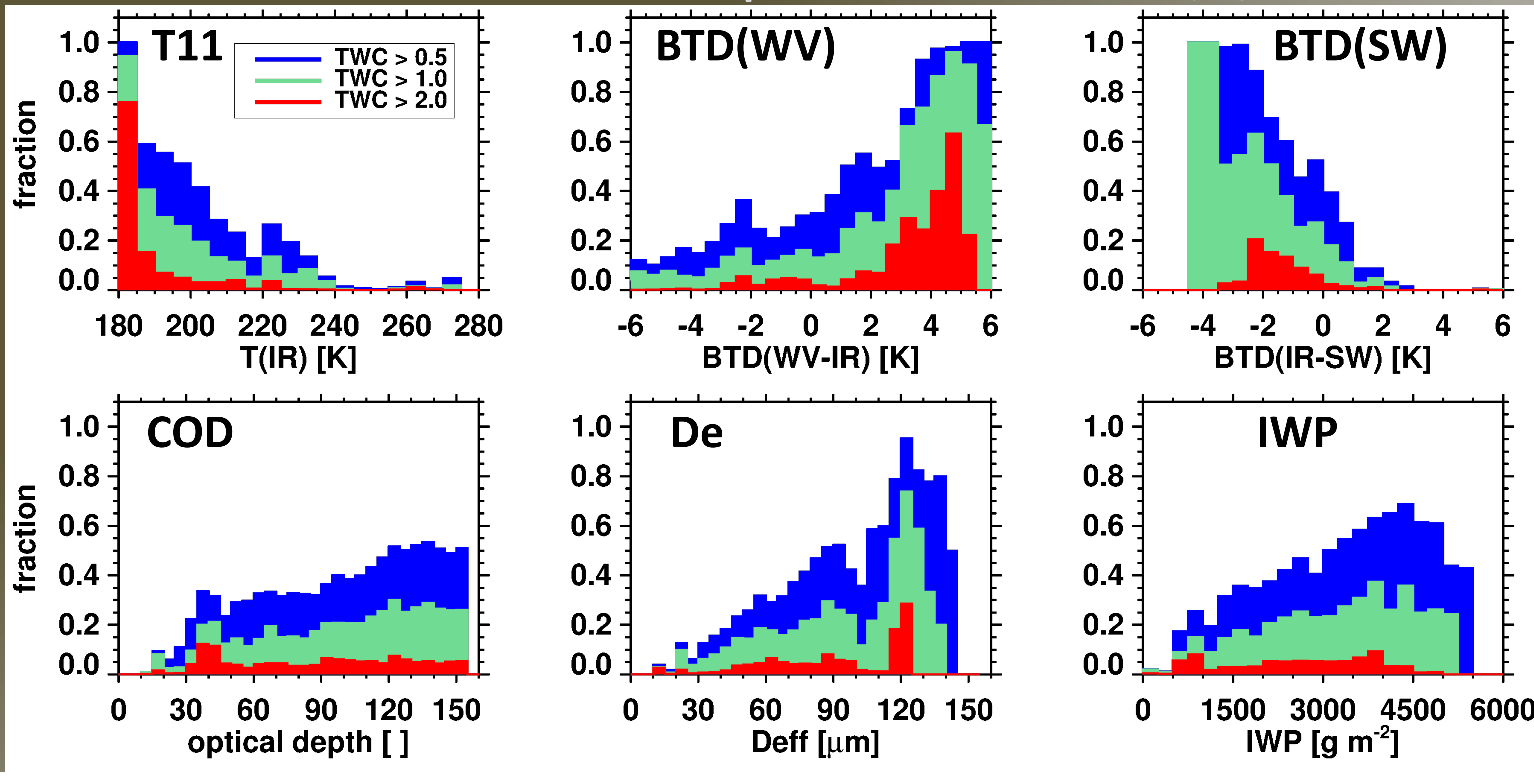
www-pm.larc.nasa.gov



Darwin 2014 data, MTSAT-1R

	TWC > 0.5	TWC > 1	TWC > 2
data points	29035	14649	3852
T_{11} [K]	200.20	199.81	198.92
BTD(IR-SW) [K]	-0.18	-0.26	-0.45
BTD(WV-IR) [K]	0.88	0.98	1.13
optical depth (COD)	124.74	124.97	111.63
D_e [μm]	78.25	77.82	75.13
IWP [g m^{-2}]	2953.68	2959.90	2575.12

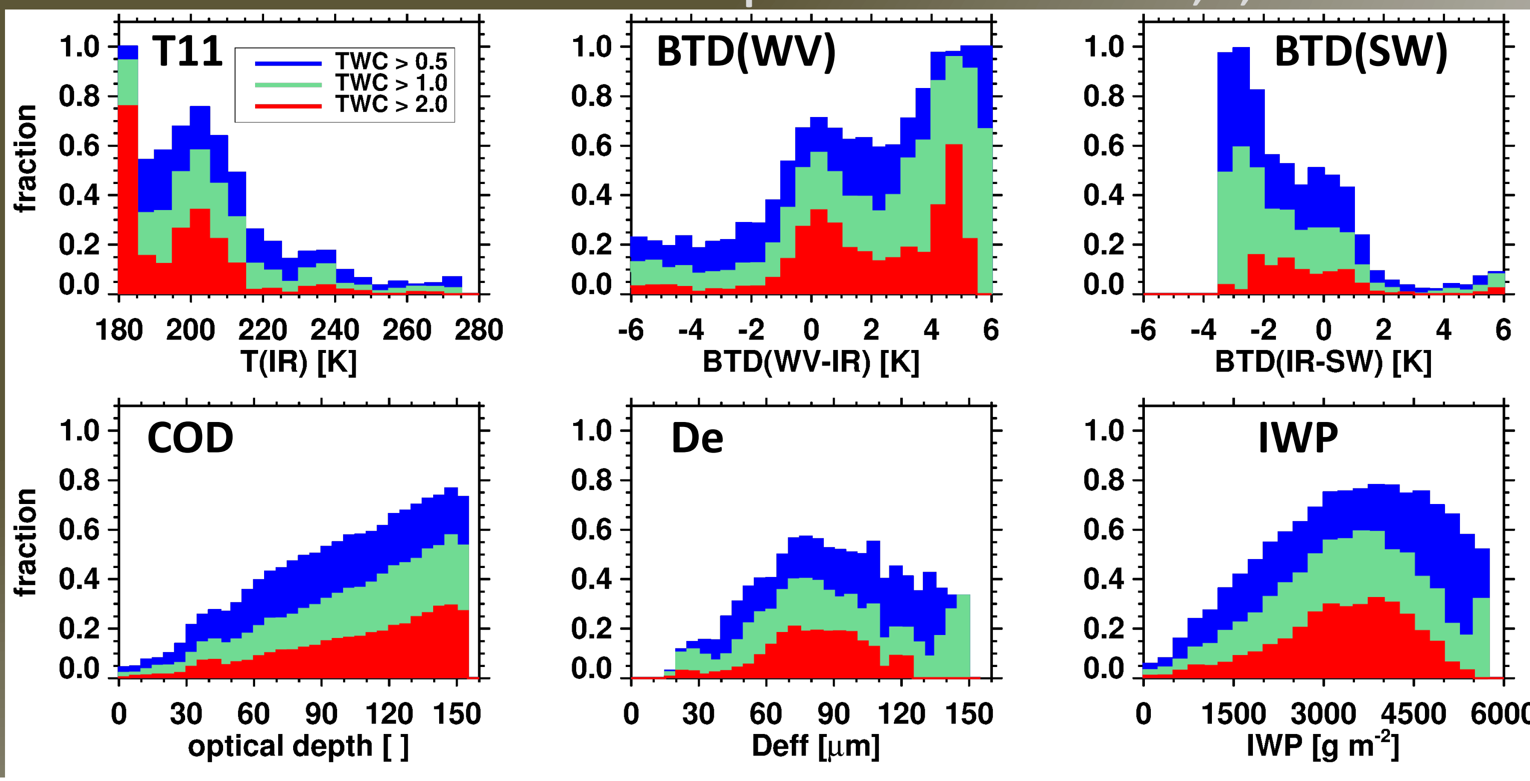
Fraction of Binned Cloud Properties with TWC > 0.5, 1, and 2



Darwin 2010, Cayenne 2010, Santiago, & Darwin 2014

	TWC > 0.5	TWC > 1	TWC > 2
data points	168374	114214	55201
T_{11} [K]	206.44	205.70	204.51
BTD(IR-SW) [K]	0.27	0.25	0.29
BTD(WV-IR) [K]	-0.09	0.06	0.23
optical depth (COD)	122.36	126.94	130.16
D_e [μm]	75.48	75.45	76.78
IWP [g m^{-2}]	2818.01	2921.79	3035.98

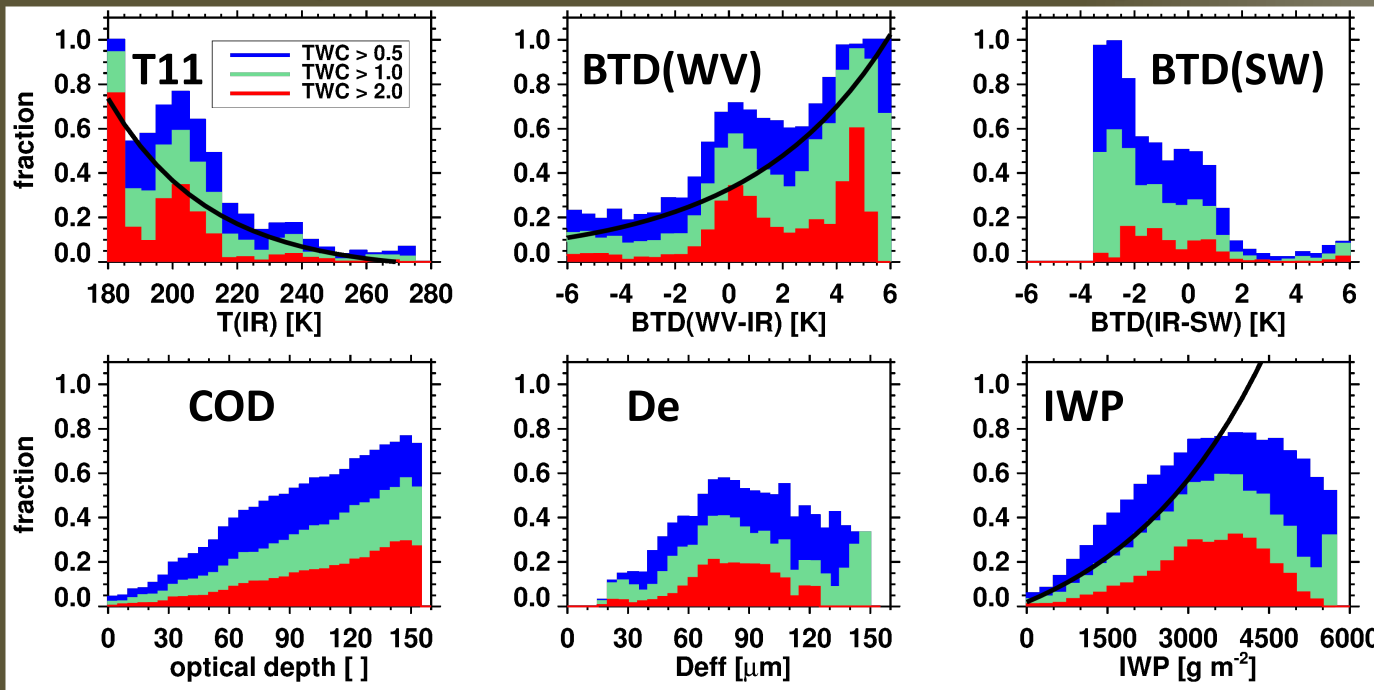
Fraction of Binned Cloud Properties with TWC > 0.5, 1, and 2



- T11, Teff, BTD(WV), optical depth, & IWP show some sensitivity to IWC

- Further analysis using T11, BTD(WV), COD, and IWP
  - Teff ~ T11
  - BTD(SW) small signal, missing on current GOES

Cayenne 2010, Darwin 2010, Santiago 2012, Darwin 2014



Most HIWC occurred for T11 < 240 K

BTD < -1 is fairly common for low IWC, but less common for HIWC. Most HIWC cases have BTD > -1

IWP < 2000 is fairly common for low IWC, but less common for HIWC. Most HIWC cases have IWP > 2000

Histograms show lots of overlap, but HIWC stands out somewhat

Define HIWC as TWC > 1 and fit exponential functions of form $y = a_0 a_1^x + a_2$ to the histograms

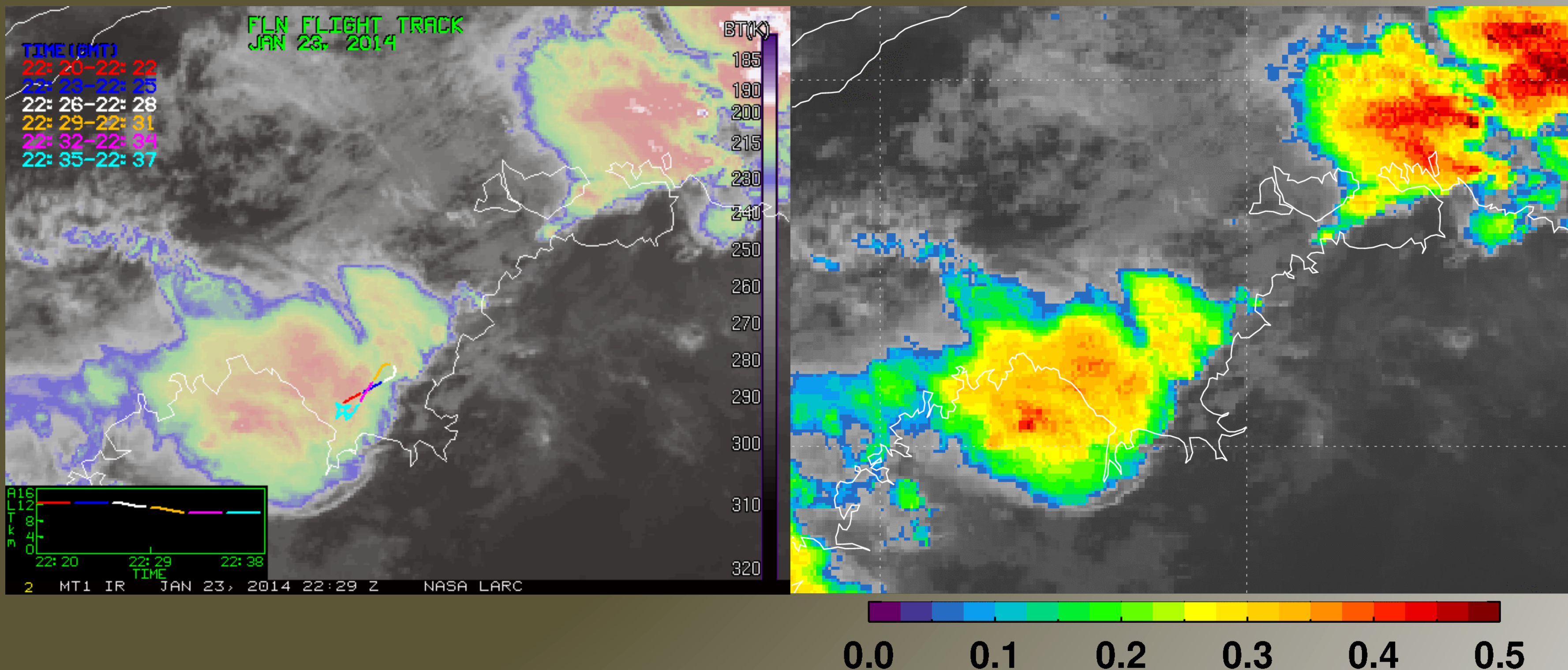
Treat each as independent test, although they are not truly independent. TIR and BTD(WV) are correlated.

Use product of TIR and BTD(WV) score to compute PHIWC

$$P = \sqrt[n]{\prod_{i=1}^{n} p_i}$$

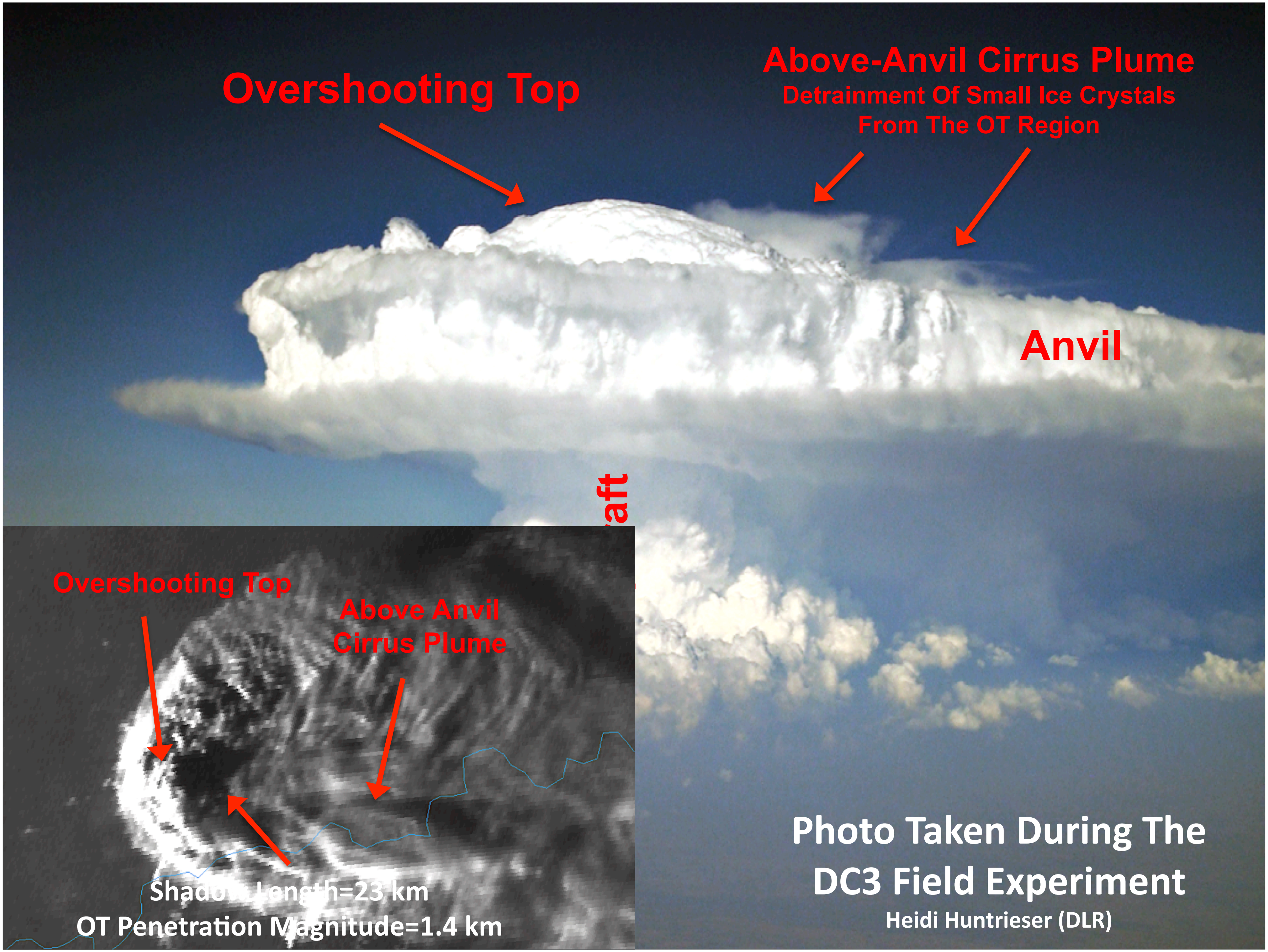
Optical depth and IWP may also be useful but require cloud products (lag time). COD & IWP limited at nighttime because thick clouds radiate as blackbody (emis = 1 for COD ~8)

Applying HIWC Probability Index

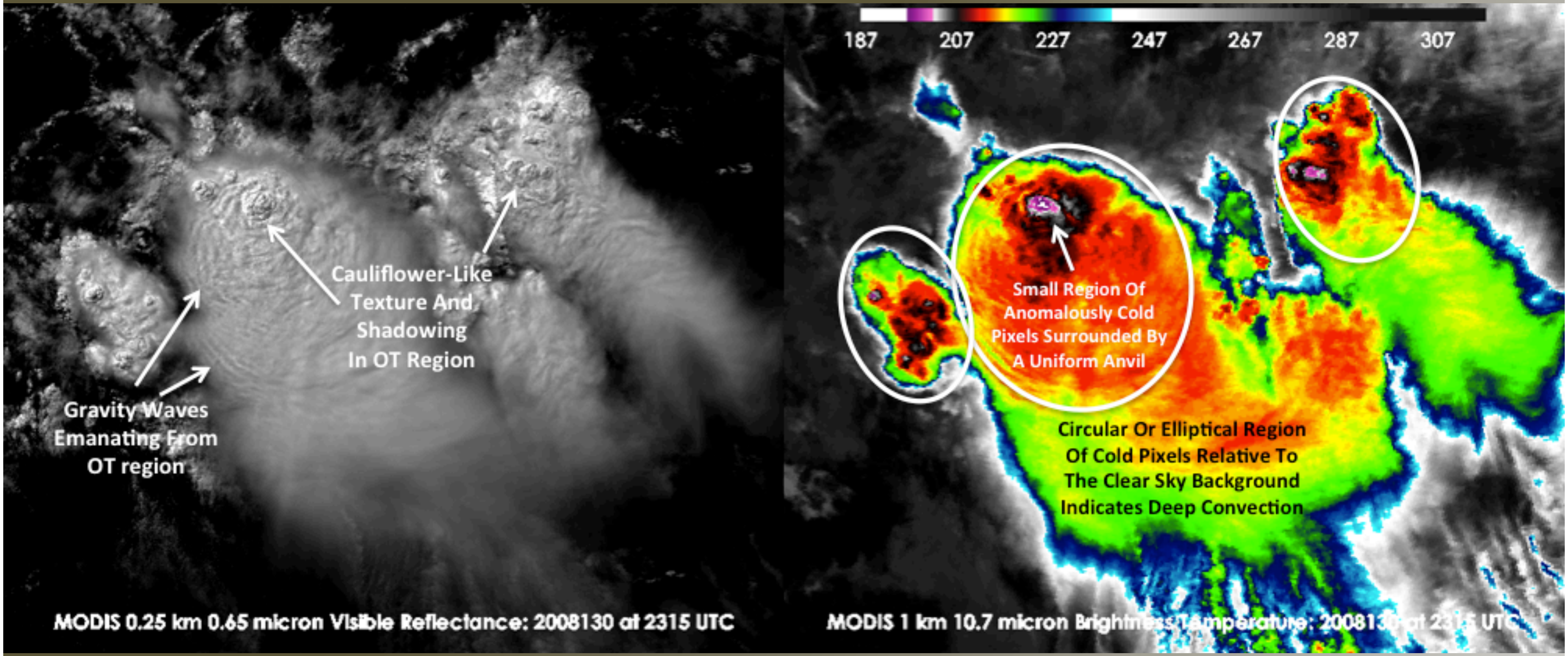


- Low PHIWC around cloud edges, higher near convective core
- Increases with decreasing T11 and increasing BTD(WV)

Overshooting Tops


Overshooting Top
Above-Anvil Cirrus Plume
Detrainment Of Small Ice Crystals
From The OT Region
Anvil
Overshooting Top
Above Anvil
Cirrus Plume
Shadow Length=23 km
OT Penetration Magnitude=1.4 km
Photo Taken During The
DC3 Field Experiment
Heidi Huntrieser (DLR)

How Does the Human Mind Identify an Overshooting Top in Satellite Imagery?

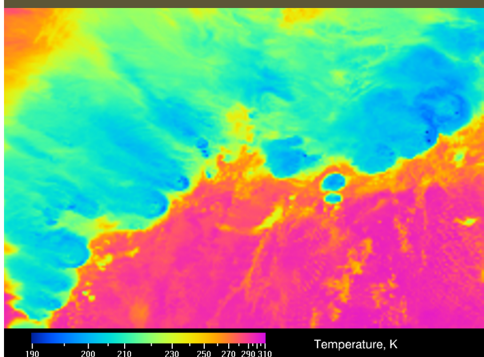


How Can A Computer Algorithm Emulate The Human Mind?

- Satellite data are simply a 2-D array of numbers
- What is an "anvil" cloud? Based on reflectance or temperature value? Something more complex?
- How does one quantify "texture"?
- ***We need to transform what we take for granted in our minds into computer code that can reliably detect overshooting top features anywhere at any time***

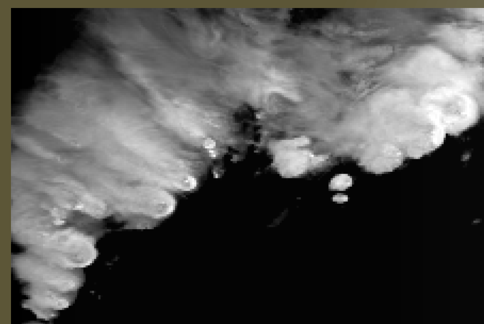
Infrared Channel Pattern Recognition

Input MODIS IR Temperature (BT) Image, Remapped To 4 km/Pixel

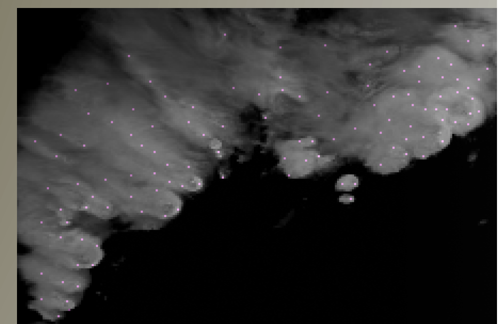


BT Score: $\text{BTscore} = \left(T_{avg} - T\right)^{0.7}\left(255 - T\right)^{1.3}/16 + 2 \cdot \sigma(T)$

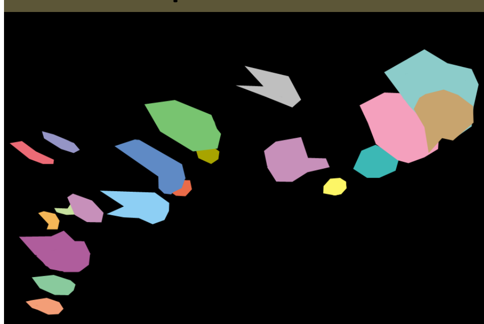
Automatically enhances deep convection without use of a fixed BT threshold and filters convective from non-convective clouds



Identify Local BT Score Maxima As Initial OT Candidates



Perform Spatial Analysis Of The BT Score Field Around Initial OT Candidates To Map Convective Anvils



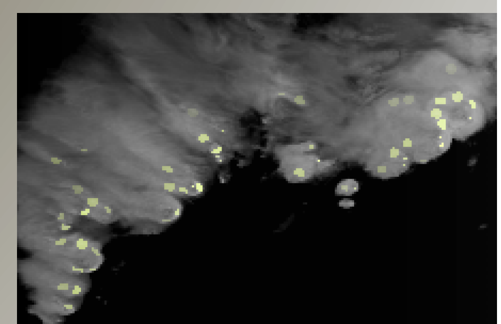
Pattern recognition is then used to ensure that the region being analyed is a deep convective cloud and with a shape and prominence typical of an OT

Pattern recognition uses

- OT shape correlation
- OT prominence relative to surrounding anvil
- Anvil flatness, roundness, and edge sharpness

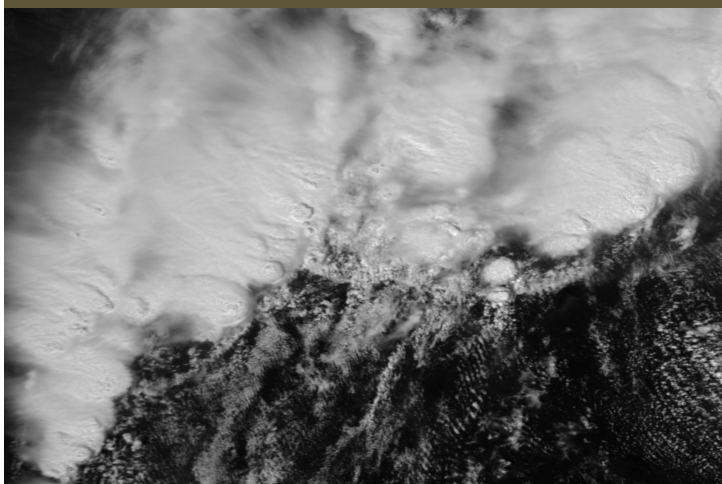
The net result is a cumulative rating obtained for each possible OT region. Pixels with a rating > 0 are considered final OT candidates

Final OT Candidate Regions Based on IR Analysis

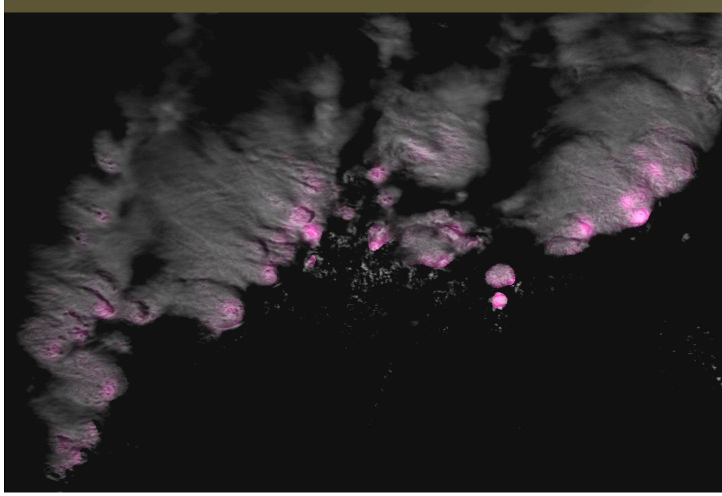


Visible Channel Pattern Recognition

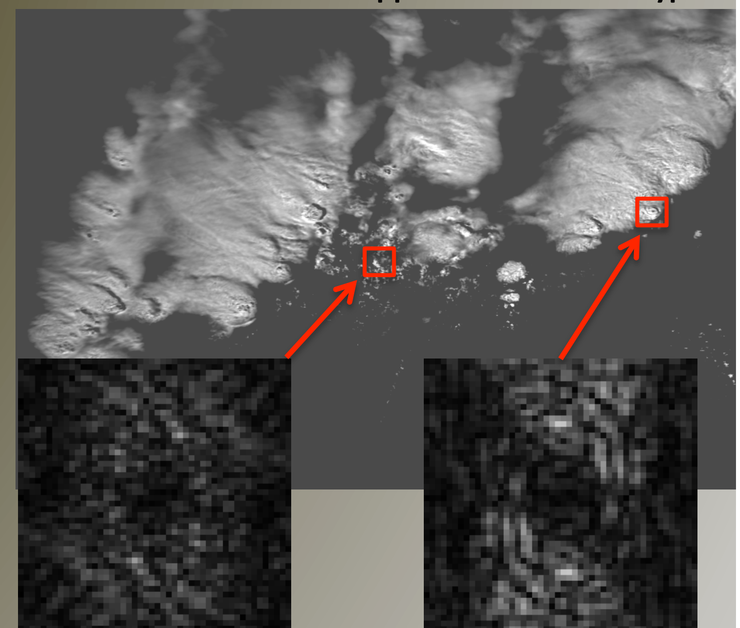
Input MODIS 1 km Visible Image



Final OT Candidate Regions
Based on Visible Analysis



Non-linear Brightness Correction to Highlight Convective Clouds and Suppress Other Cloud Types



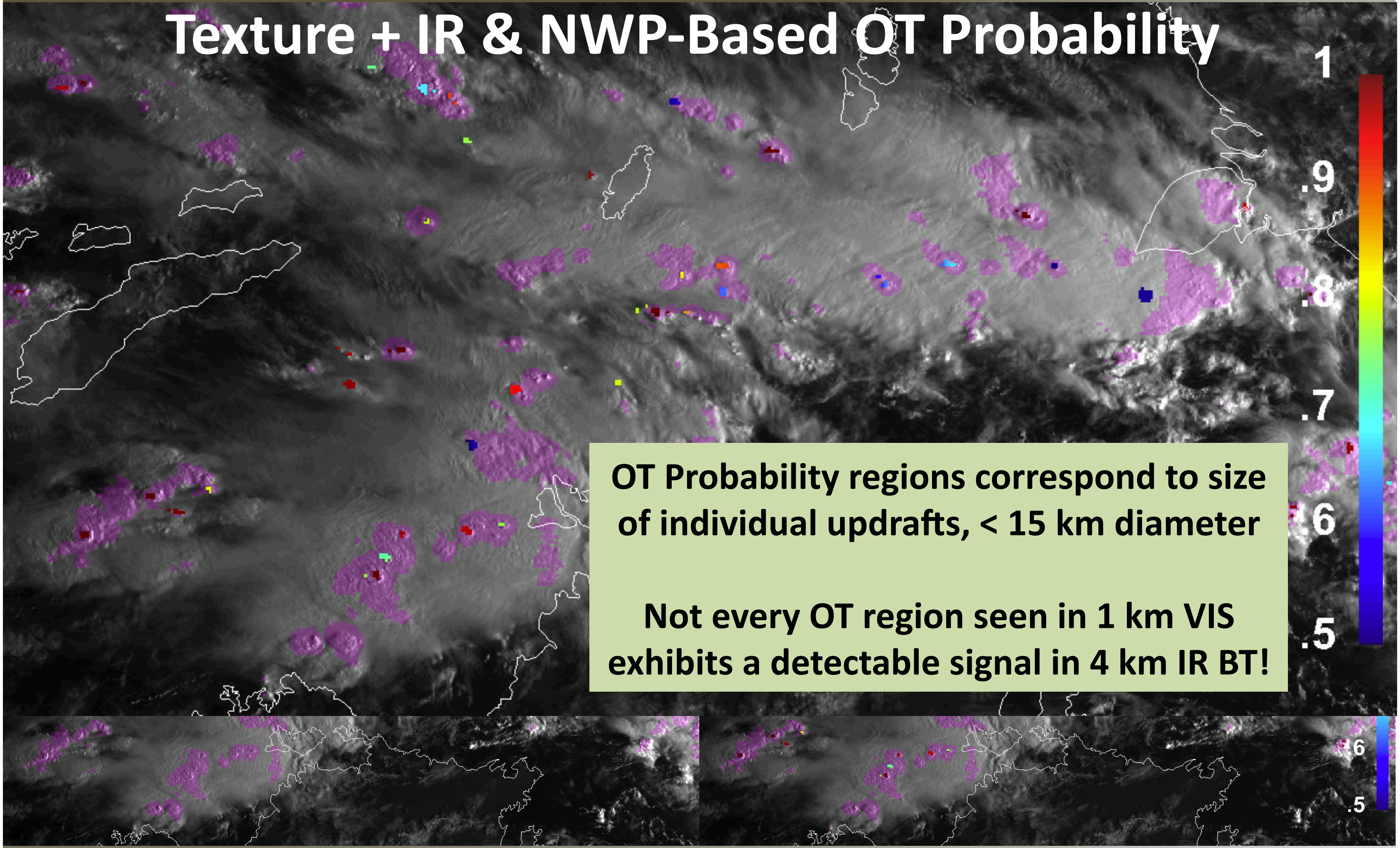
Fourier frequency spectrum of an area with random spatial variability.

No ring pattern in the spectrum

Fourier frequency spectrum of a typical OT region

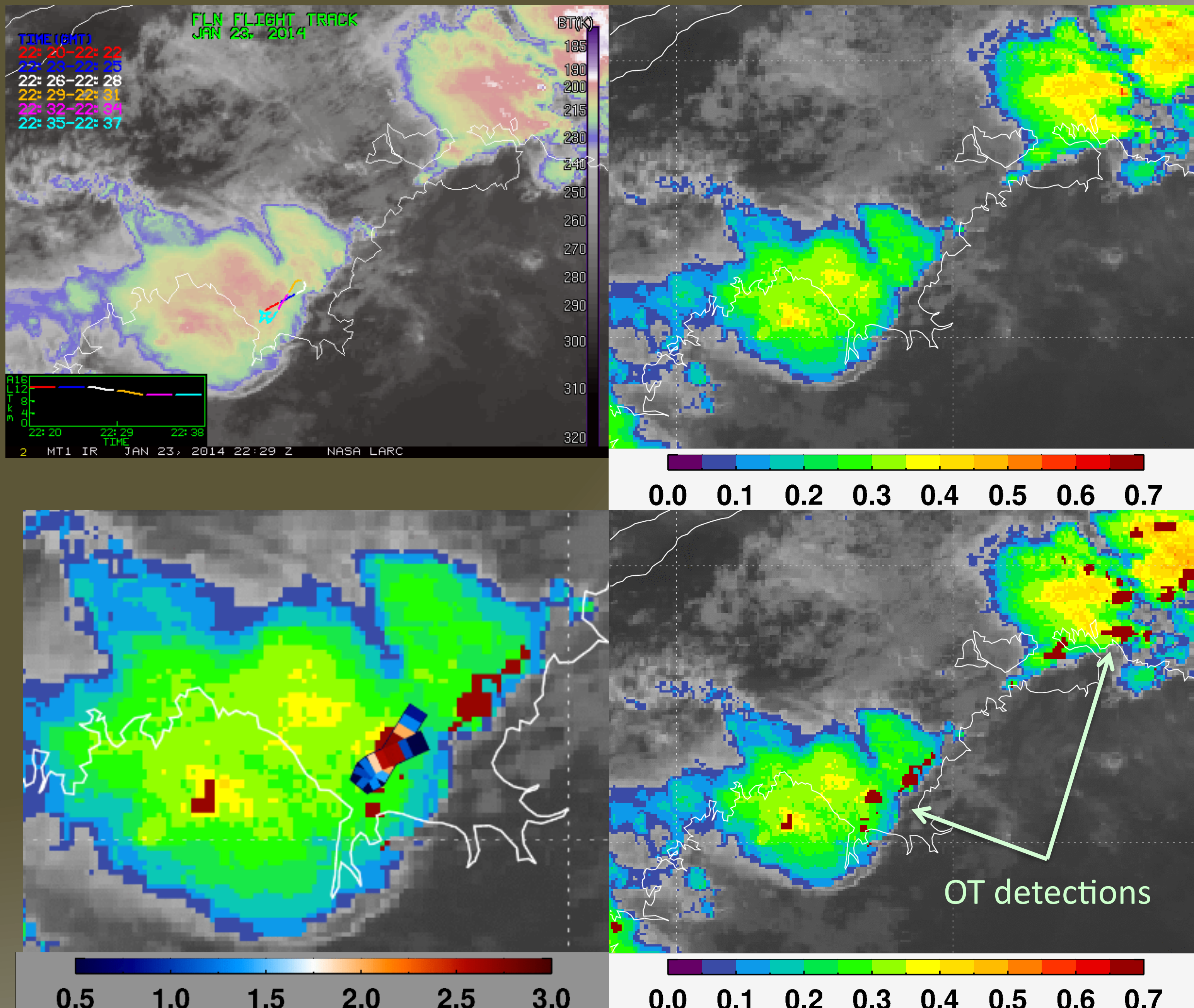
Ring fragments in the spectrum can be identified

Automated Satellite-Based Overshooting Top Detection

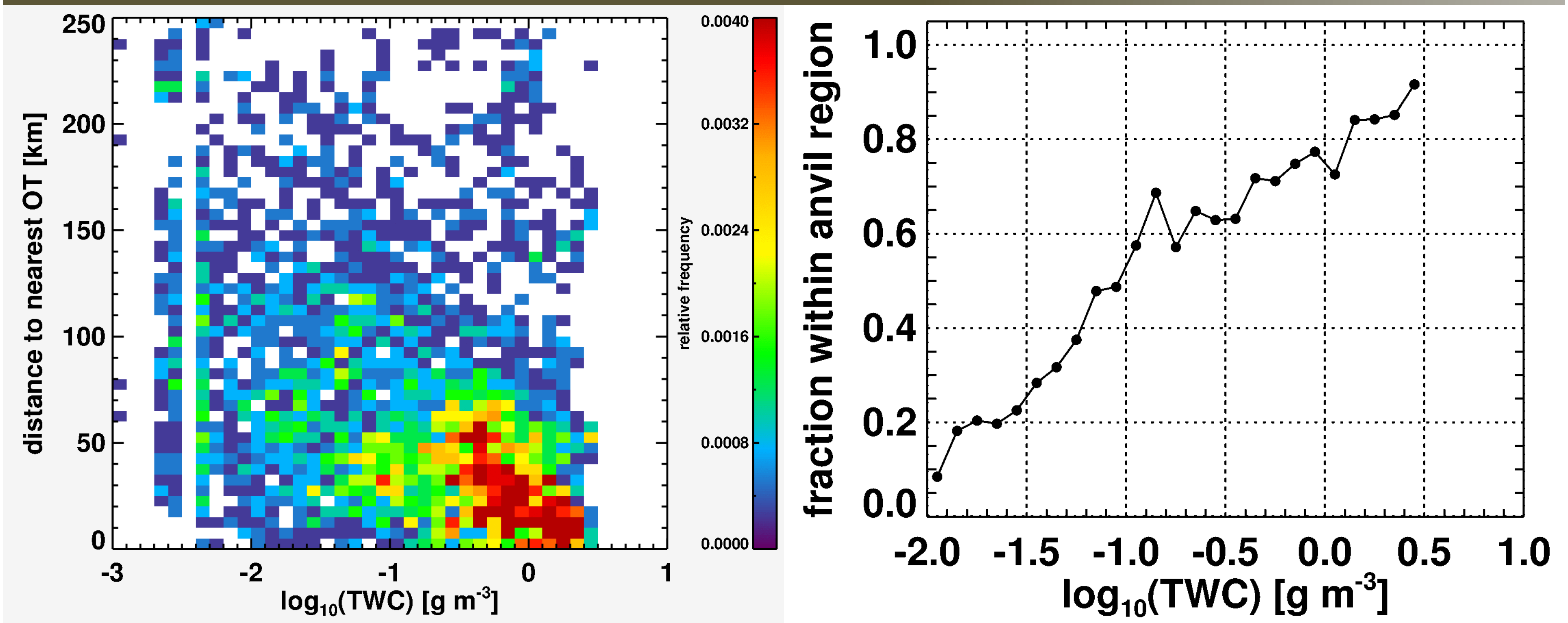


Bedka & Khlopenkov, JAMC, 2015

HIWC Product Enhanced by OT Product



Relating HIWC to Convective Cores



- MTSAT-1R, 10-min imagery for HAIC-HIWC Darwin
- Computed distance to nearest OT for all TWC > 0, SAT < 0*C
- 76% of TWC > 1 occurred within 50-60 km (25-30 nmi) of OT detections
- ~80%+ of TWC > 1 measurements occurred within anvil cloud
- Darwin had coldest T11
- Use distance factor to improve probability and smooth transition around OTs
- Future generation imagers will routinely have 10-min or less imagery

Using 3-D Products

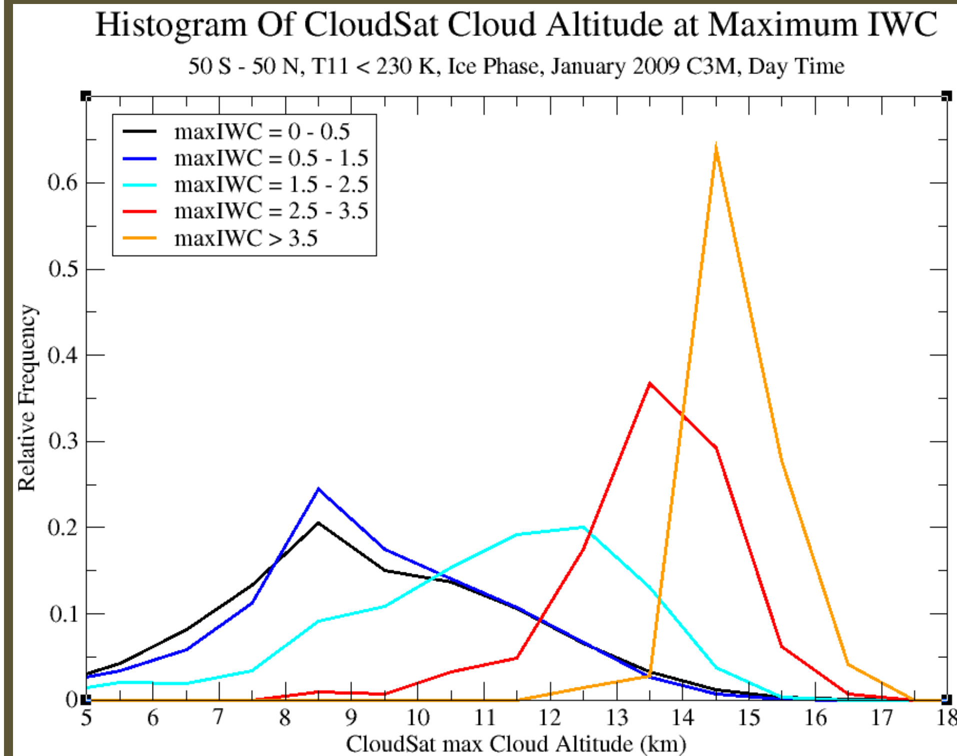
Other tools assess HIWC occurrence

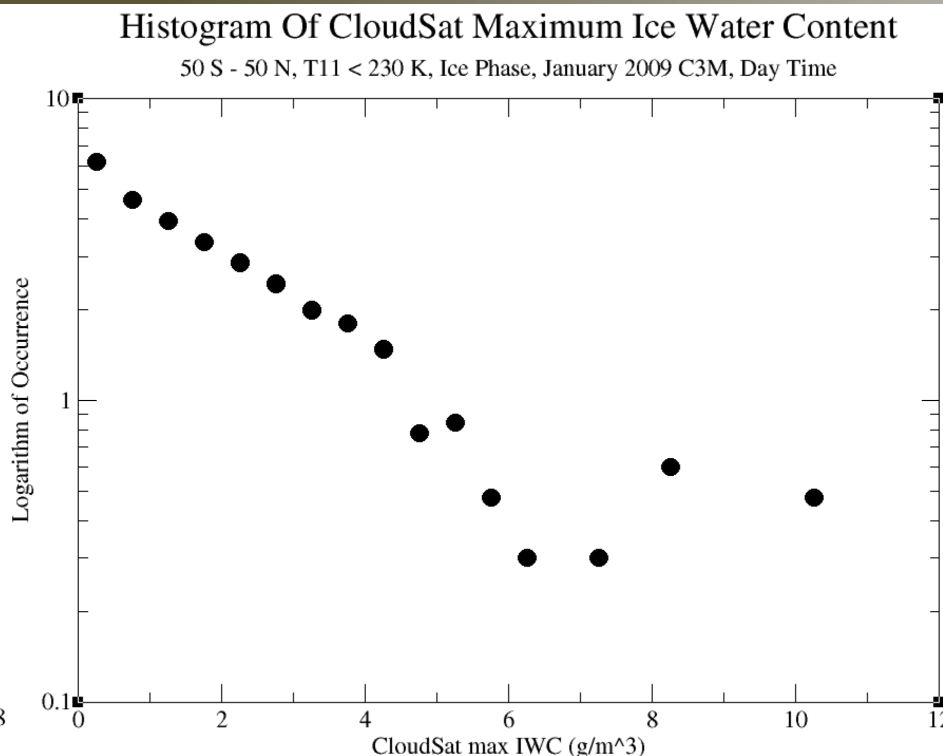
- *CloudSat*
- *RASTA*
- *Dual-angle satellite retrieval of cloud-top IWC*

Relating column values to IWC

- *Parameterization based on CloudSat & MODIS*

CloudSat CALIPSO (CC), max IWC Statistics
January 2009





- Zmax for *maxIWC* > 2 gm^{-3} typically occurs above 12 km
  - CC profile may be attenuated, hiding larger values at lower levels
  - IWC may overestimated in some cases; uncertainty in CloudSat IWC => how does it affect results
- *maxIWC* > 2 gm^{-3} accounts for ~0.7% of all clouds with T11 < 230 K
  - *maxIWC* > 2.5 gm^{-3} for ~0.2%=> infrequent event

Cloud Profiling from Passive Imager Data

Based on results of W. L. Smith, Jr., *Phd Diss*. 2014

- developed normalized profiles of cloud water content (CWC) from matched CERES MODIS retrievals & blended CALIPSO-CloudSat and NWP profiles

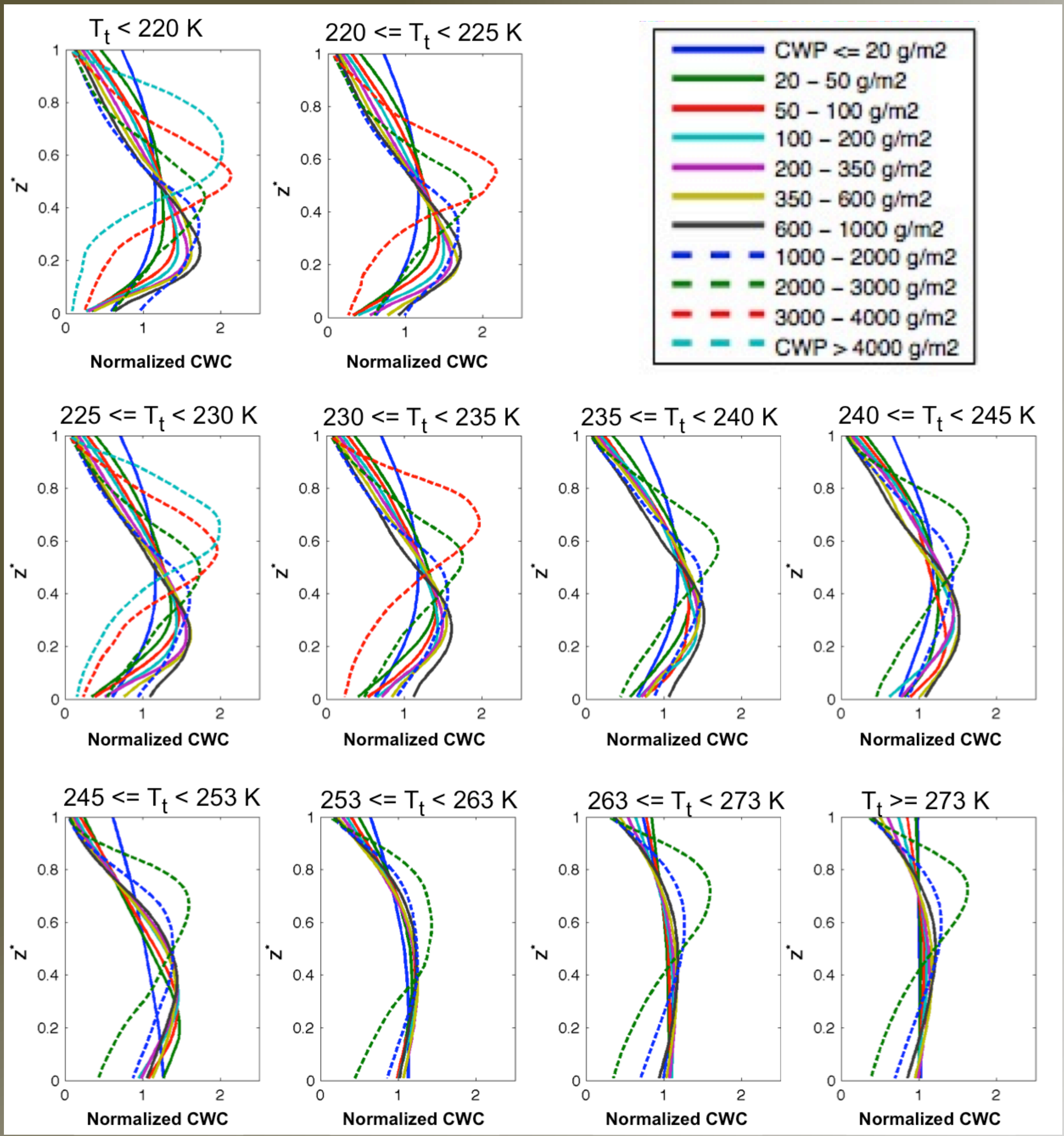
- given a passive retrieval, determines CWC profiles & estimates height of ice-water boundary

- increases retrieval utility, 3-D expansion, & greatly improved aircraft icing diagnoses

- Can it be used for HIWC applications?

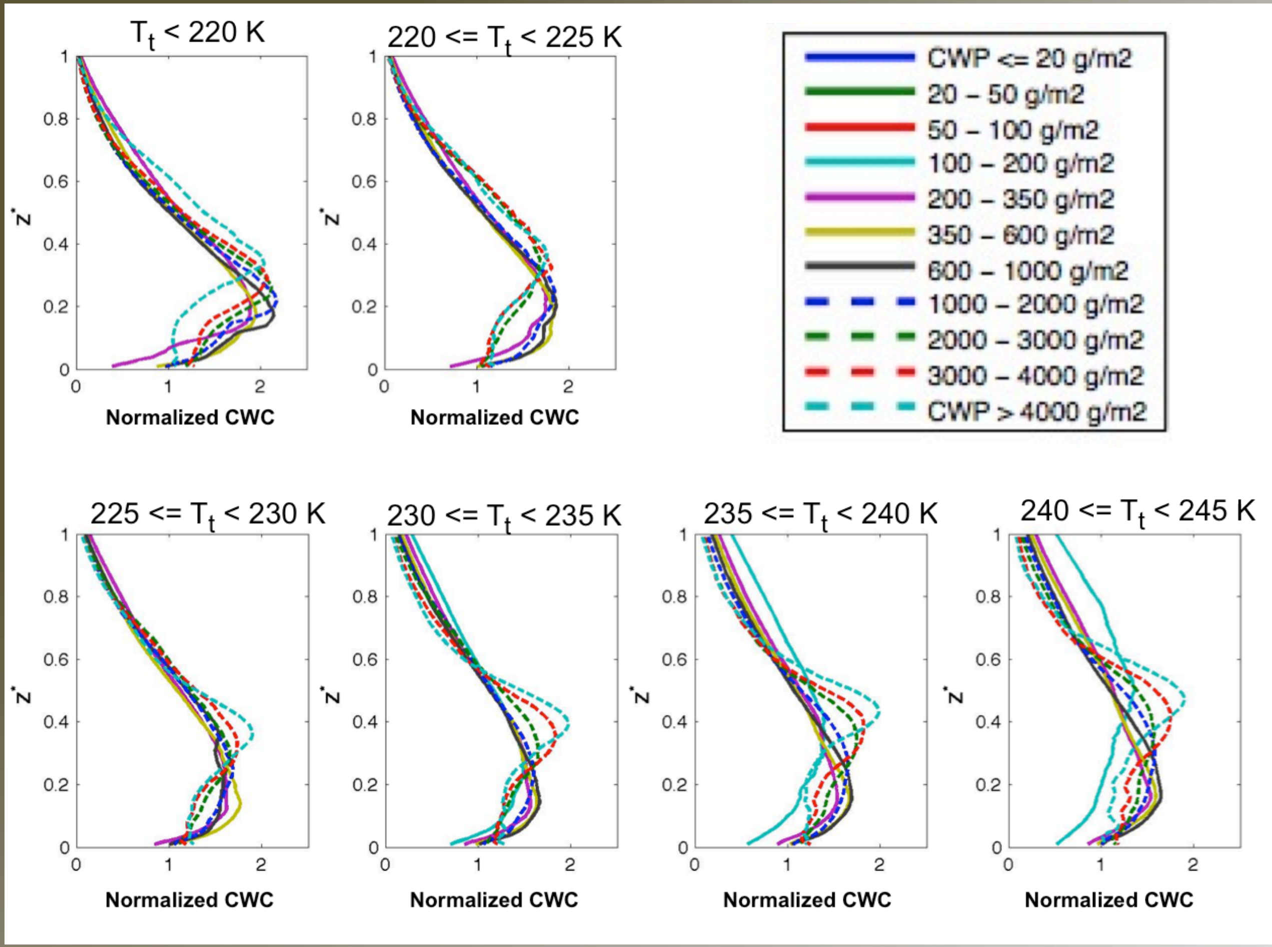
Normalized CWC(z) from CloudSat RVOD Product over CONUS Jan – March 2007

- zmax rises with CWP
  - attenuation?
- suggests CWP- *maxIWC* link
- How do these curves look from RASTA?



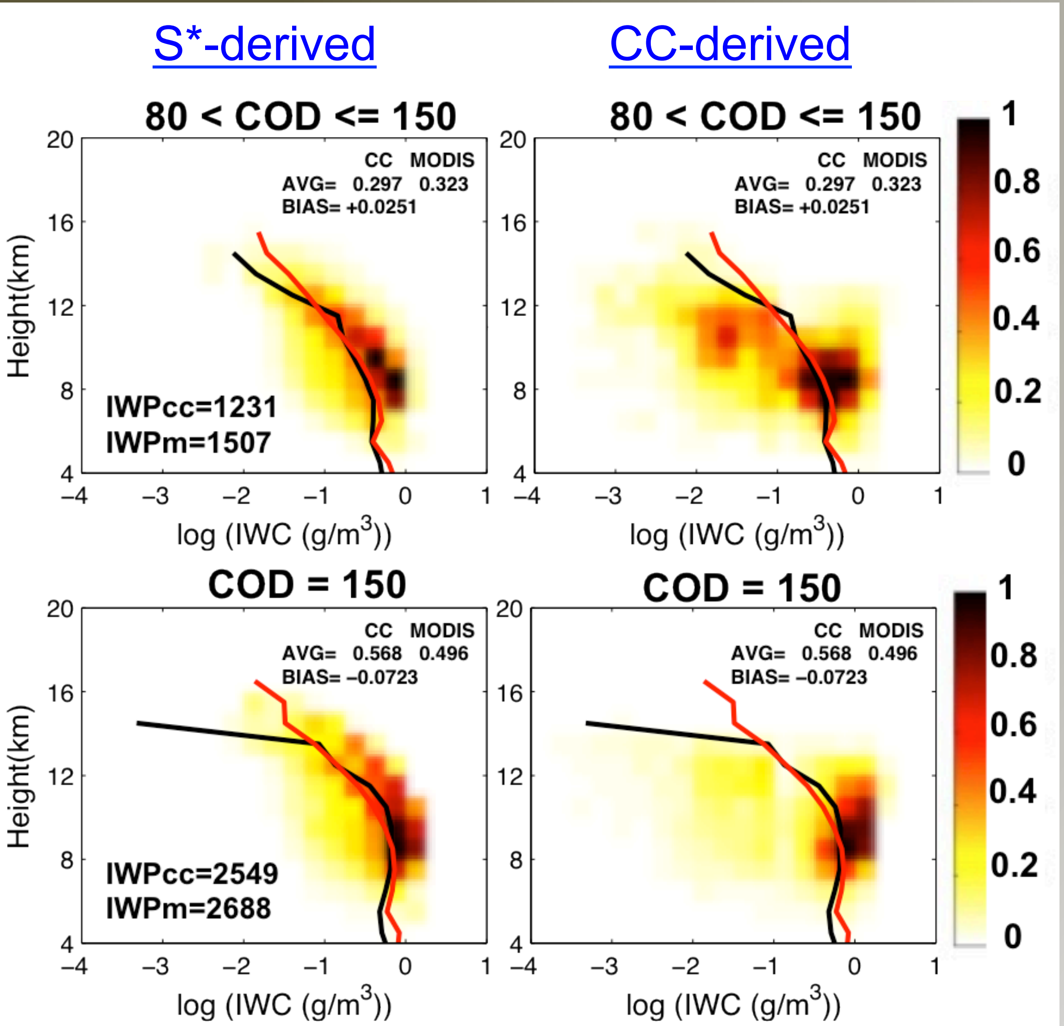
S*(z) = Normalized CWC(z) from CloudSat RVOD Product Adjusted to RAP profile for T > -20°C
CONUS, Jan – March 2007

- accounts for attenuation
- *zmax* lower, but still rises with CWP
- How do these curves look from RASTA?
- Given Ttop, Ztop, COD, CWP from satellite imager, => **estimate IWC(z)**



Retrieved IWC(z)Distributions from S*-MODIS & CALIPSO-CloudSat RVOD Product over CONUS April 2010

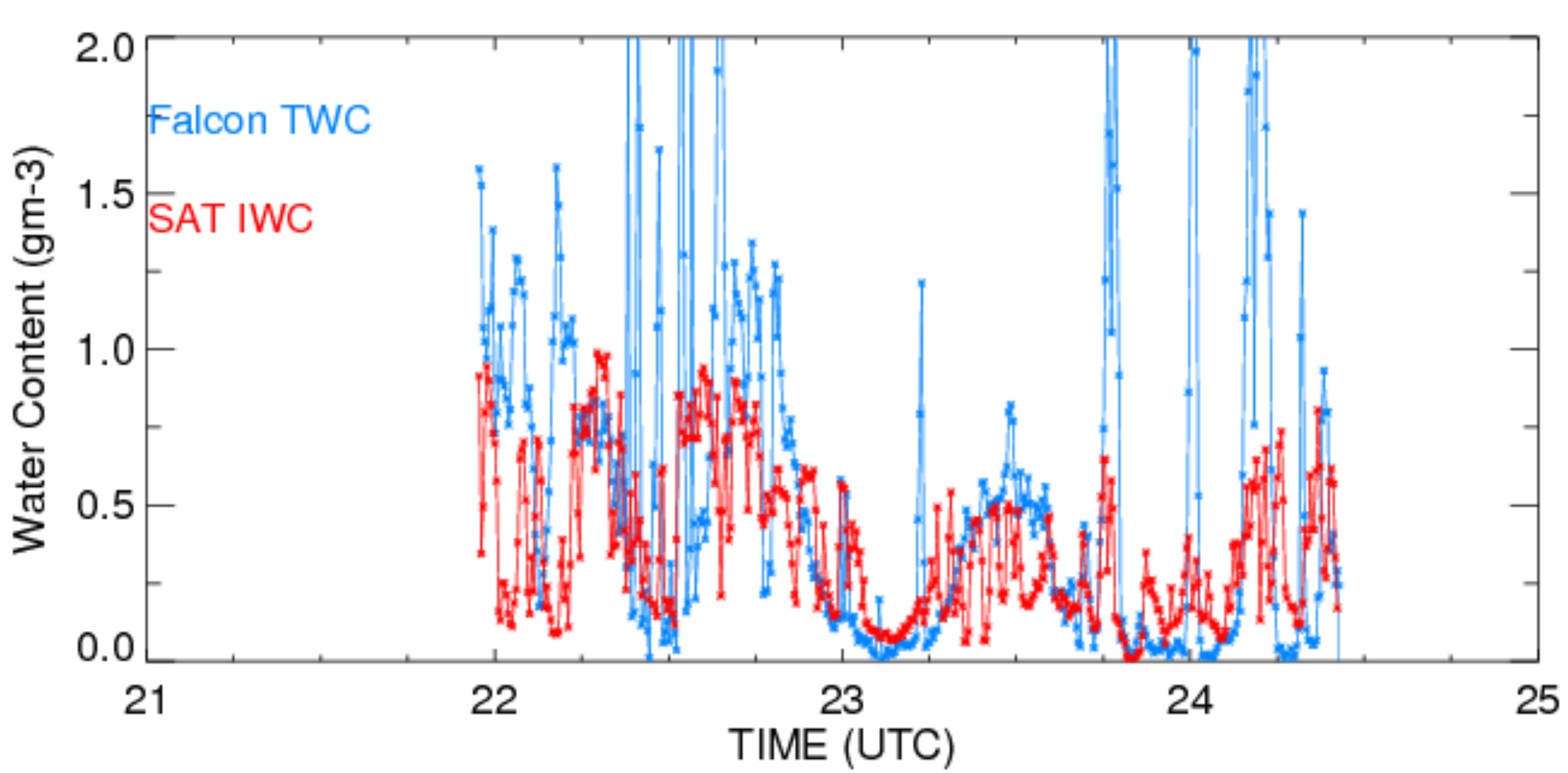
- *maxIWC* > 1 only for COD > 80
  - attenuation?
- *zmax* between 8 and 12 km
- S*
- Confirm/revise with RASTA



- Unless large anomaly, no HIWC for COD < 80

- Smoothed curve misses high values

Initial IWC Comparison,18 February Flight



- Satellite approach captures gist of variability, but too smooth
- Using average profiles, especially this case, will not produce anomalies
- Refined categories may be useful for improving the correspondence
  - develop HIWC curves

Dual-satellite IWC Retrieval

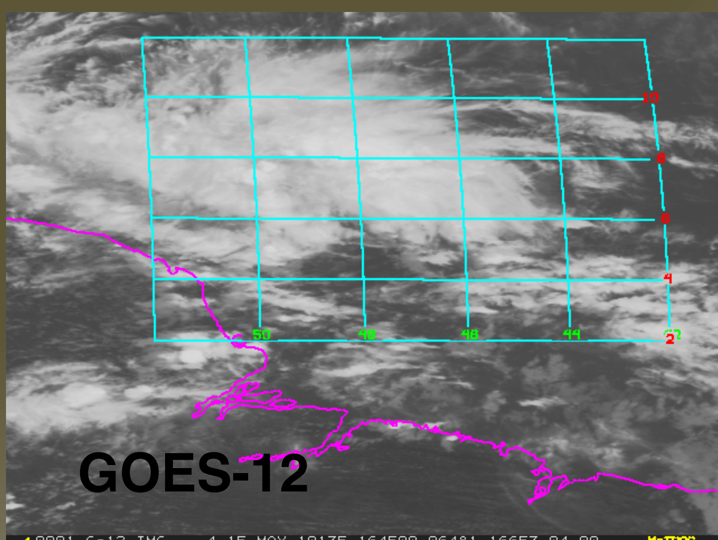
- IWC can be estimated for top ~1.1 optical depth of a given cloud using simultaneous T11 measurements of a cloud from two different viewing zenith angles

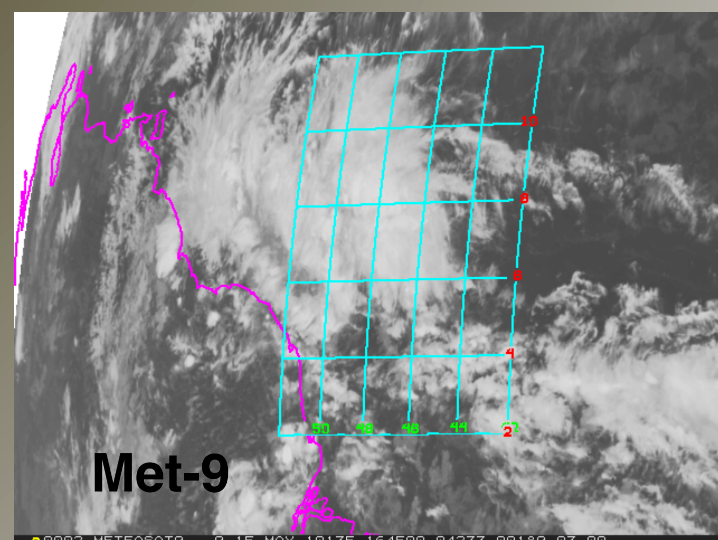
- Yost et al. (JGR, 2010)

- Can these retrievals be related to maximum IWC within cloud interior?

$$IWC = \lambda D_e \frac{2\rho_i}{3Q_e} \frac{\mu_2 - \mu_1}{Z_{eff1} - Z_{eff2}}$$

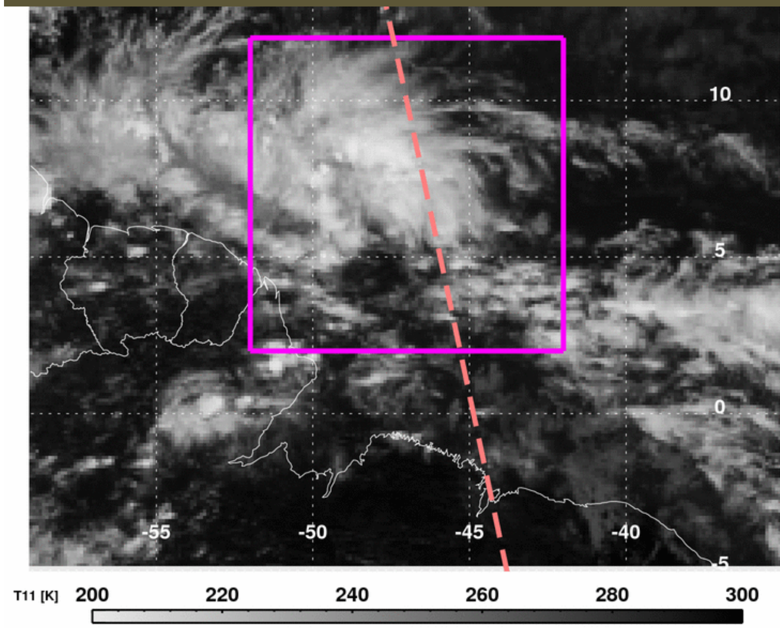
- $\lambda \approx 1.2$
- D_e = crystal effective diameter
- ρ_i = ice density
- Q_e = extinction efficiency at 11 µm
- μ_1, μ_2 = cosine of viewing zenith angle for satellite 1, 2
- Z_{eff1}, Z_{eff2} = effective cloud height**

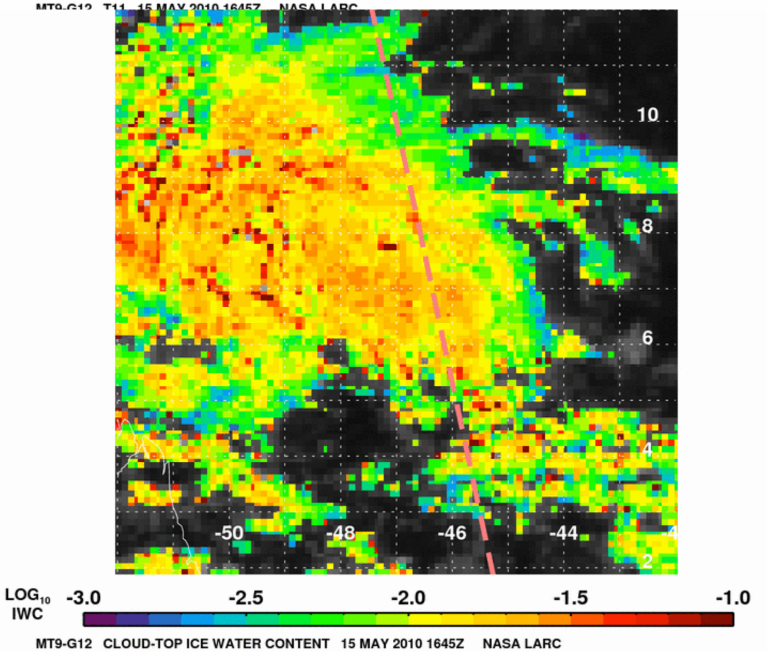




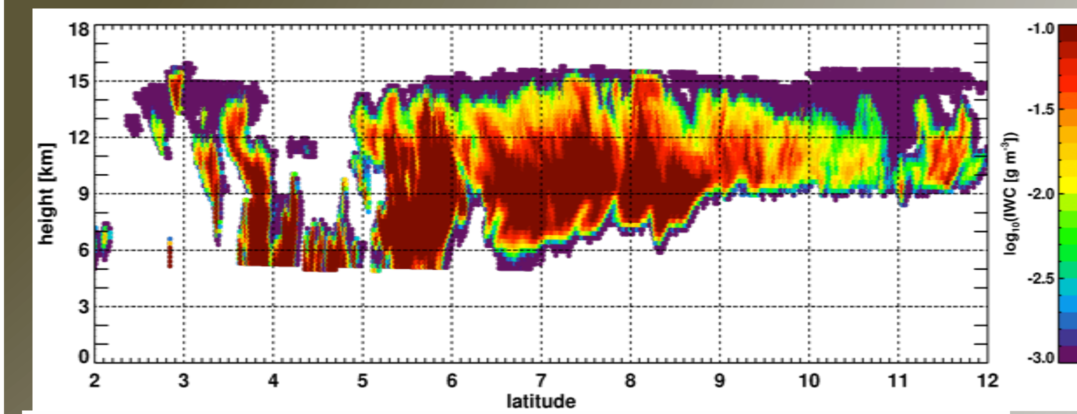
**corresponds to effective radiating temperature

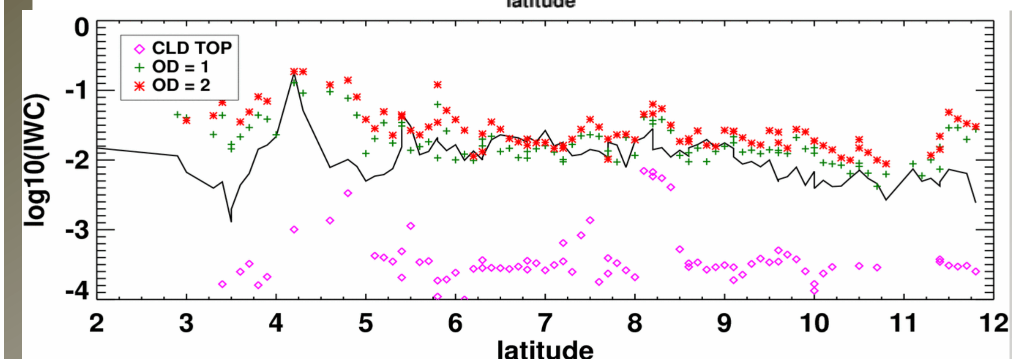
Dual-Angle IWC vs. CloudSat
French Guiana: 15 May 2010





- Lat/lons are parallax corrected
- Put into 0.10x0.10-degree grid
- CloudSat overpass @ 16:47 UTC
- Retrieved IWC resembles CloudSat IWC (2C-ICE product) corresponding to 1-2 optical depth units beneath cloud top





FUTURE

- Complete determination of best approach for HIWC probability nowcasting & merge with OT detection
  - need robust system day & night (BTs only?)
  - Do COD/IWP add value? (new method for night IWP being developed)
- Continue validation with Florida and Cayenne 2015 data
  - Resolve TWC & BT magnitude differences
  - normalize across different regions/campaigns using tropopause temperature or mean anvil T11 from OT product
- Determine short-term forecast using NWP advection & cell growth rates from identified OT and high-probability pixels
- Refine CloudSat IWC profiles for deep convective systems
  - identify anomalous profiles in sets dependent on T11, BTD, IWP
  - comparisons with RASTA?
- Analyze Cayenne 2015, Florida 2015 datasets