A Satellite-Based Estimator of HIWC Probability

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OBJECTIVES & APPLICATIONS

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

- match satellite imagery with aircraft measurements of IWC
- develop statistics of satellite radiances/products as fn(IWC)
- 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 statistical probability predictor
- merge overshooting top data to diagnose “no fly” areas (P = 1)
- validate data using independent measurements
  - *in situ IWC*
  - *aircraft “events” (temperature anomalies, altitude loss, etc.)*
- predict location of HIWC in near term (later)

Data

- Langley satellite-derived cloud properties
  - T11, TWV-T11=BTD(WV), T11-TSW = BTD(SW), De, Teff, IWP
    - WV ~6.7 µm; SW ~ 12 µm; De – xtal effective diameter
    - T11 – obs 11-µm temperature; Teff – cloud effective temp ~ T11
  - automated overshooting top (OT) detection

In situ Data

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

- SAFIRE campaign (IKP-2)
  - Darwin 2014 (MTSAT-1R, MTSAT-2)

- IAGOS (In-service Aircraft for a Global Monitoring System)
  - 11 cases, 2012-2013 (Meteosat-9) cases with temperature anomalies

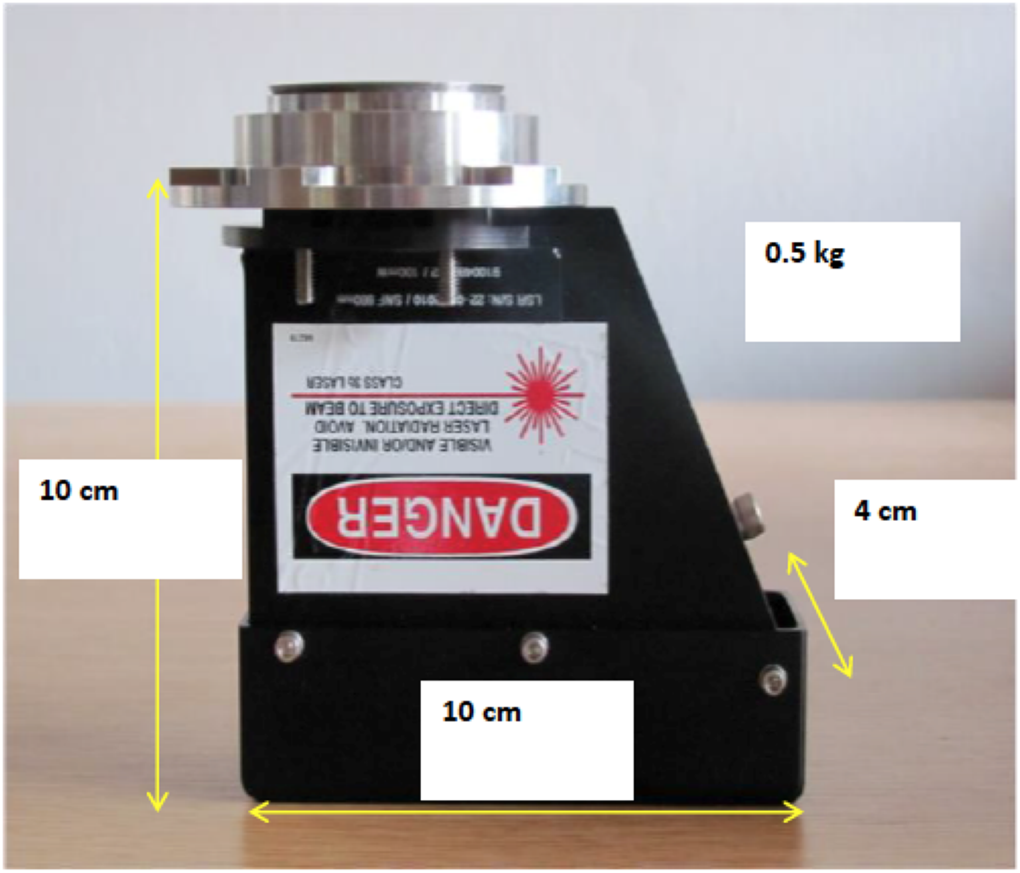
    BCP-100 measurements of T, TWC, N, De

Data Matching

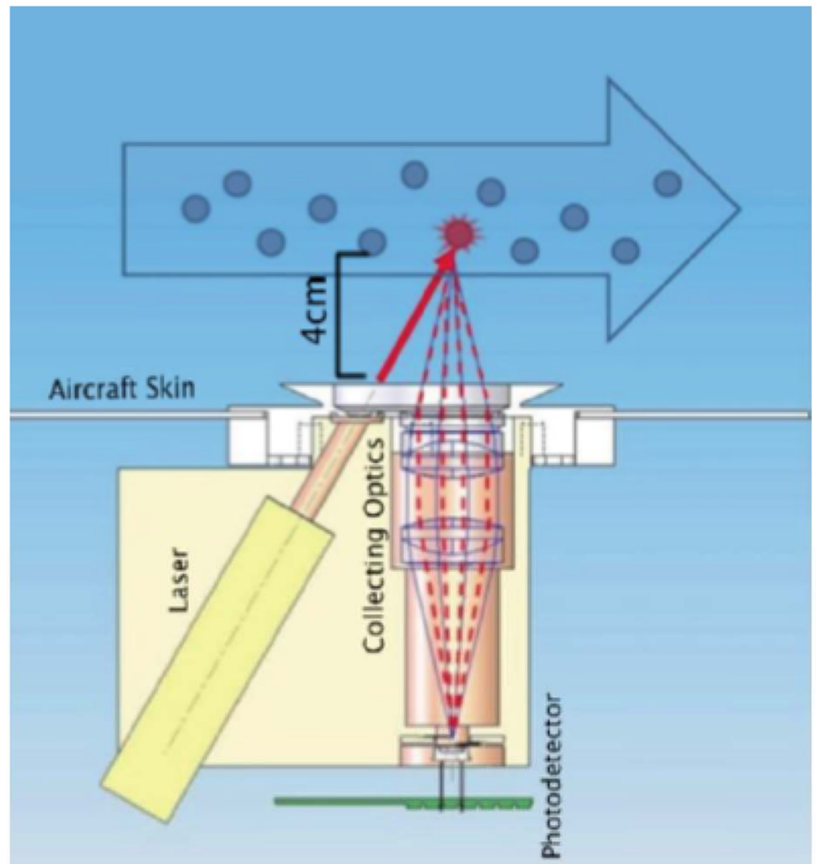
- Nearest pixel to flight location using closest time match (±15 min)

  1) daytime, SZA < 70°
  2) plane altitude > 5 km (many Santiago flights, Z < 8 km)
  3) plane instrument measured valid IWC (< 9999)
  4) satellite products indicate ice-phase cloud

The IAGOS Backscatter Cloud Probe (BCP-100)

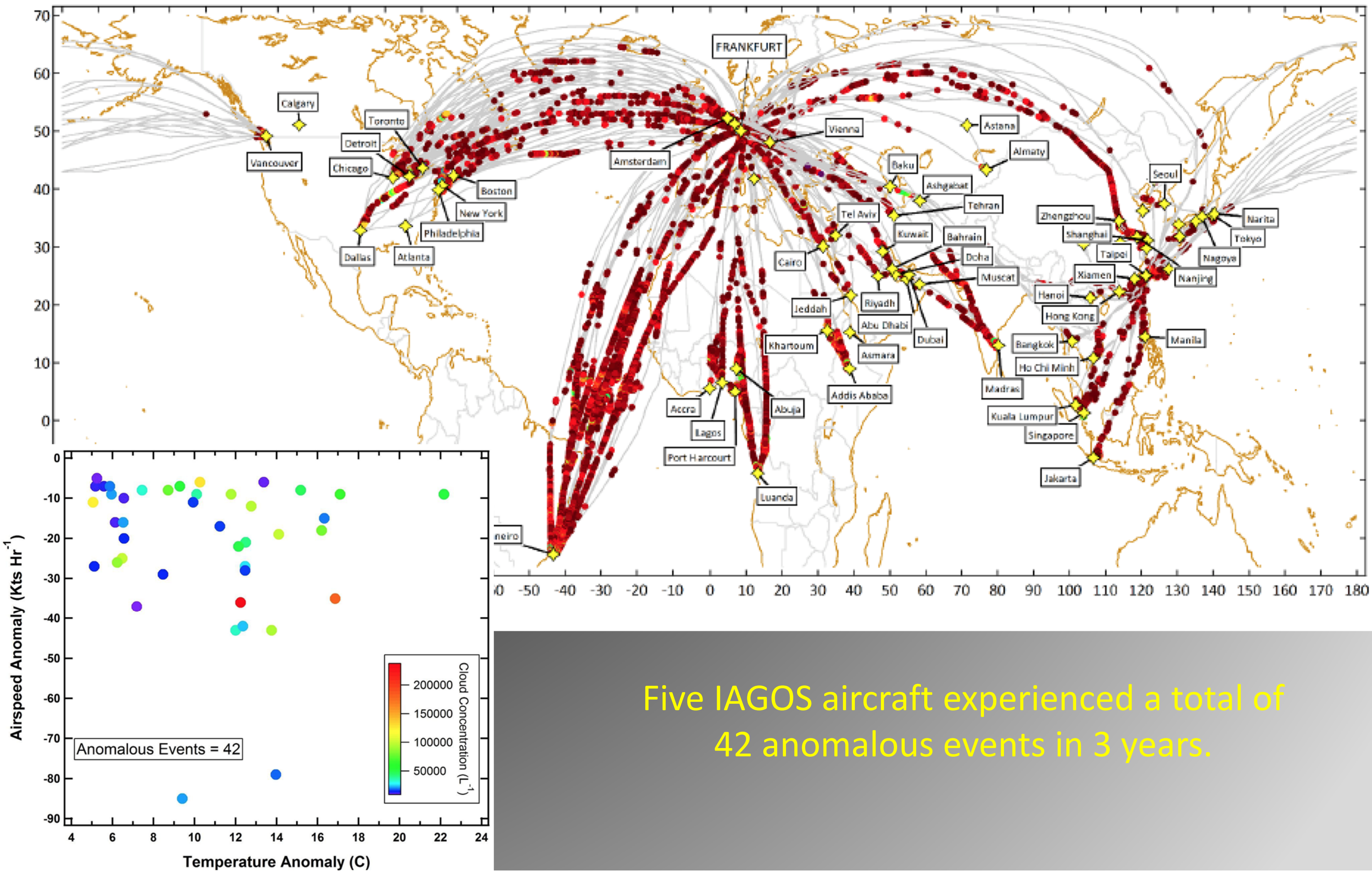


Max observed IWC: 0.01 – 0.08 gm^{-3}
?



Beswick et al., AMT, 2014

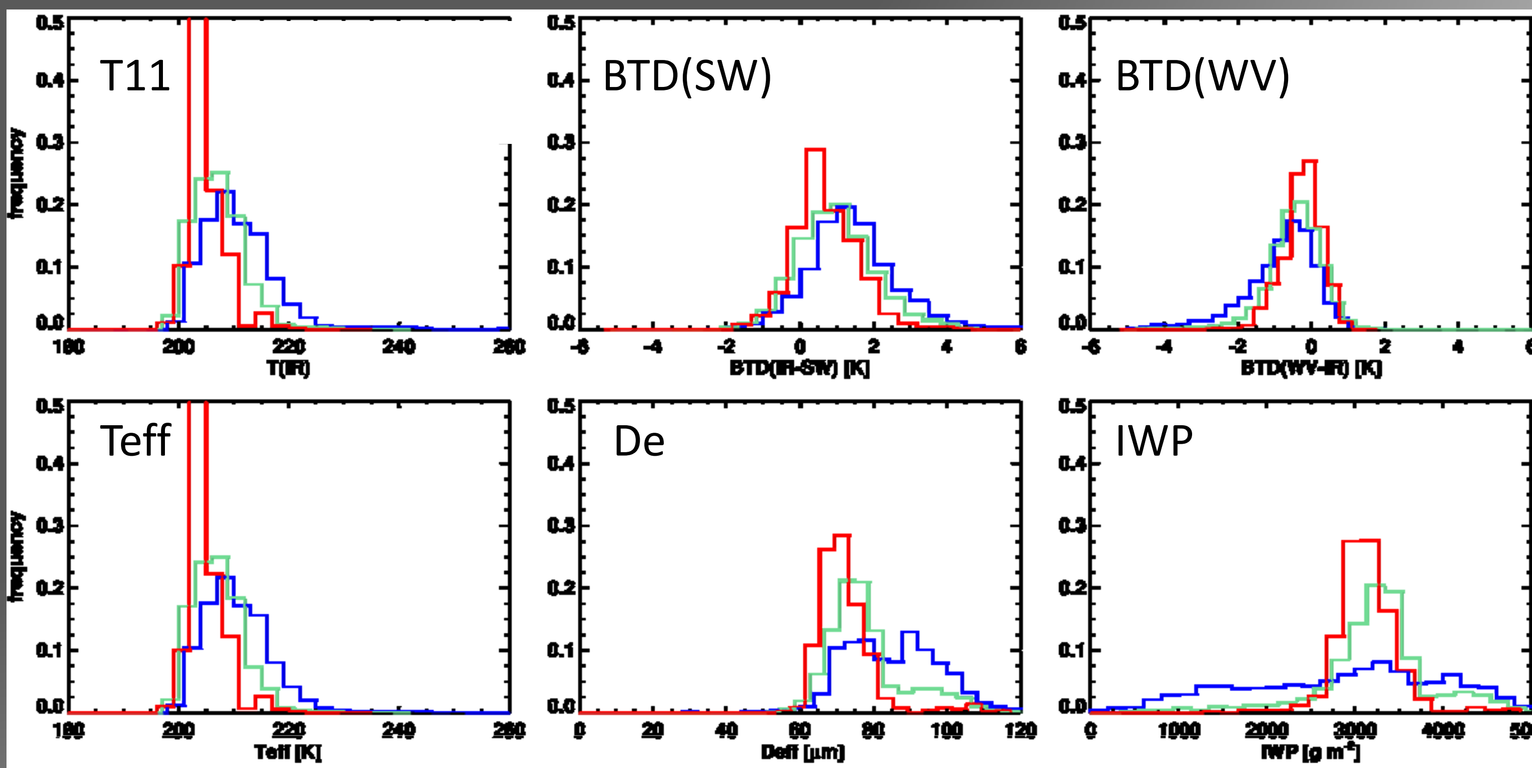
Flight Trajectories from 2012-2014
4399 Flights; 20557 flight hours; 665 hours in cloud



Five IAGOS aircraft experienced a total of 42 anomalous events in 3 years.

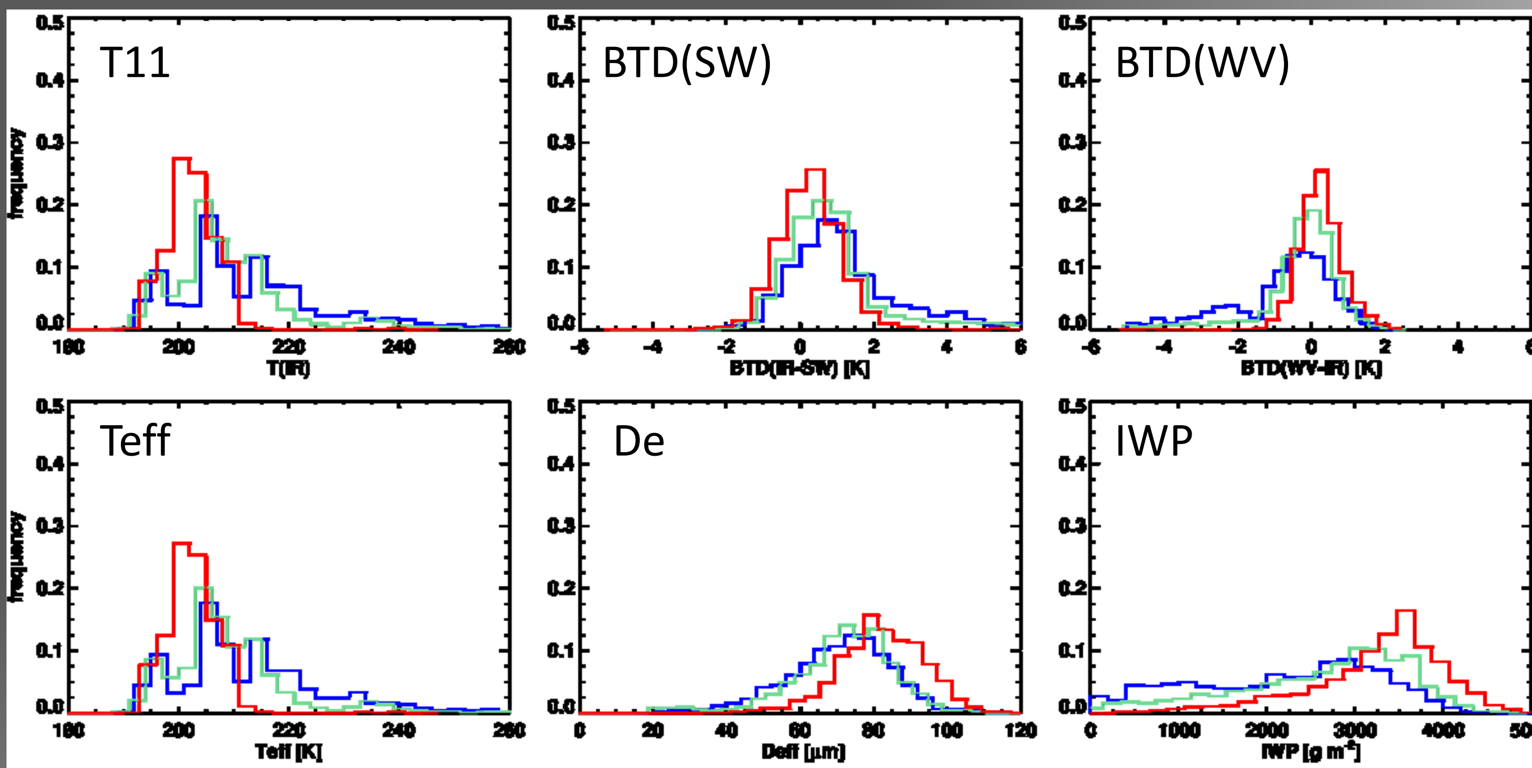
Cayenne 2010 data, G12 & G13

	0.5 < IWC < 1	1 < IWC < 3	IWC > 3
data points	14813	15749	2354
T_{11} [K]	210.79	207.13	204.98
BTD(IR-SW) [K]	1.48	1.00	0.70
BTD(WV-IR) [K]	-0.98	-0.45	-0.24
T_{eff} [K]	210.84	207.22	205.04
D_e [µm]	85.29	78.28	72.27
IWP [g m^{-2}]	2845.35	3226.58	3120.55



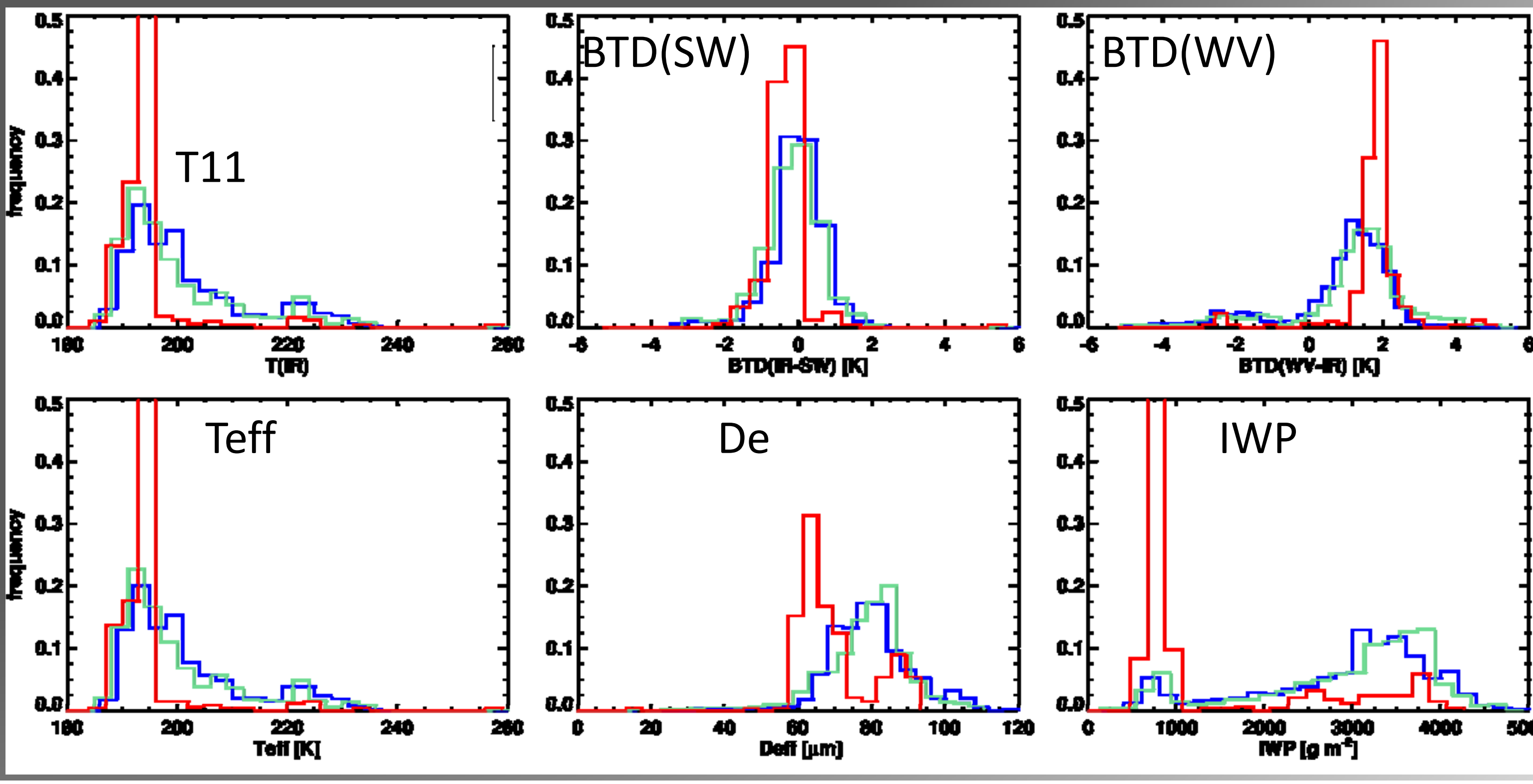
Santiago 2012 data, G12 & G13

	0.5 < IWC < 1	1 < IWC < 3	IWC > 3
data points	9263	31533	14808
T_{11} [K]	212.71	208.82	202.46
BTD(IR-SW) [K]	1.61	1.04	0.27
BTD(WV-IR) [K]	-1.44	-0.57	0.24
T_{eff} [K]	212.64	208.91	202.53
D_e [μm]	70.49	71.37	82.27
IWP [g m^{-2}]	2188.11	2624.55	3248.01



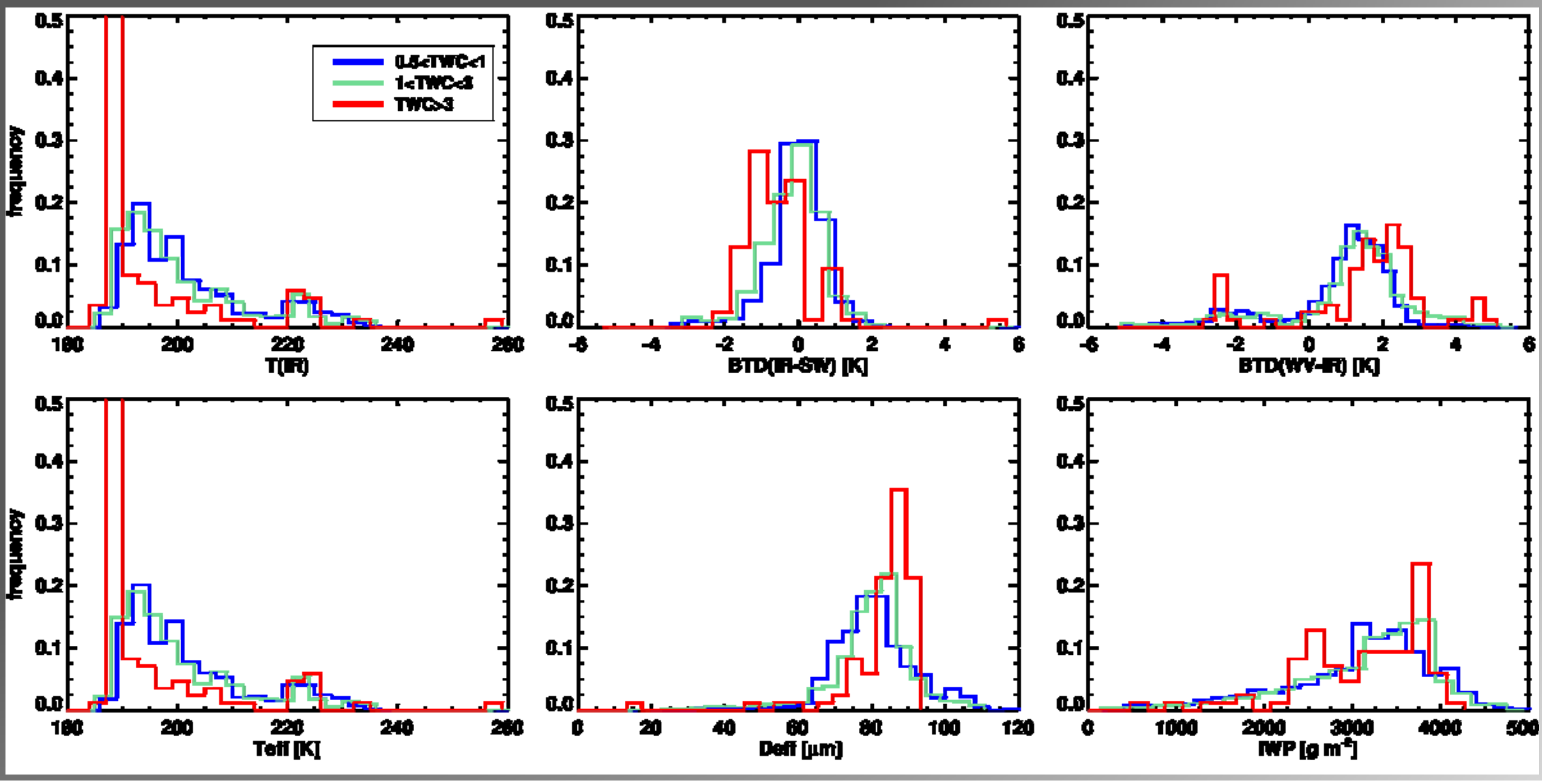
Darwin 2014 data, MTSAT-1R

	0.5 < IWC < 1	1 < IWC < 3	IWC > 3
data points	9418	9653	335
T_{11} [K]	201.50	199.95	194.36
BTD(IR-SW) [K]	-0.03	-0.17	-0.38
BTD(WV-IR) [K]	0.75	1.03	1.65
T_{eff} [K]	201.57	200.01	194.41
D_e [μm]	79.79	78.66	69.34
IWP [g m^{-2}]	2907.82	2930.85	1355.15



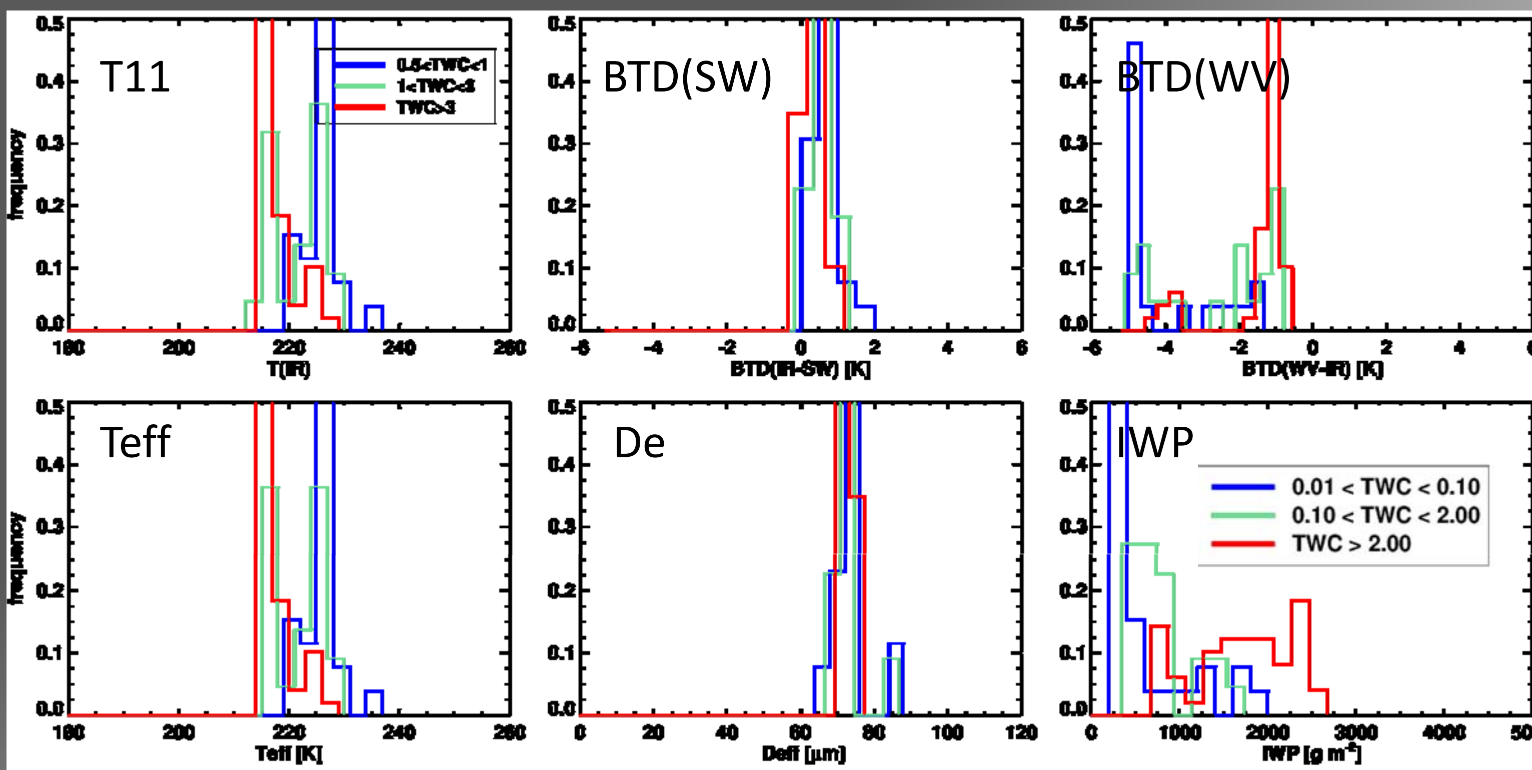
Darwin 2014 data, MTSAT-1R (no Feb 3)

	0.5 < IWC < 1	1 < IWC < 3	IWC > 3
data points	8750	8777	85
T_{11} [K]	201.82	200.52	196.45
BTD(IR-SW) [K]	-0.02	-0.16	-0.53
BTD(WV-IR) [K]	0.70	0.96	1.17
T_{eff} [K]	201.89	200.58	196.51
D_{eff} [microns]	80.55	79.92	83.28
IWP [g m^{-2}]	3073.78	3144.20	3096.64



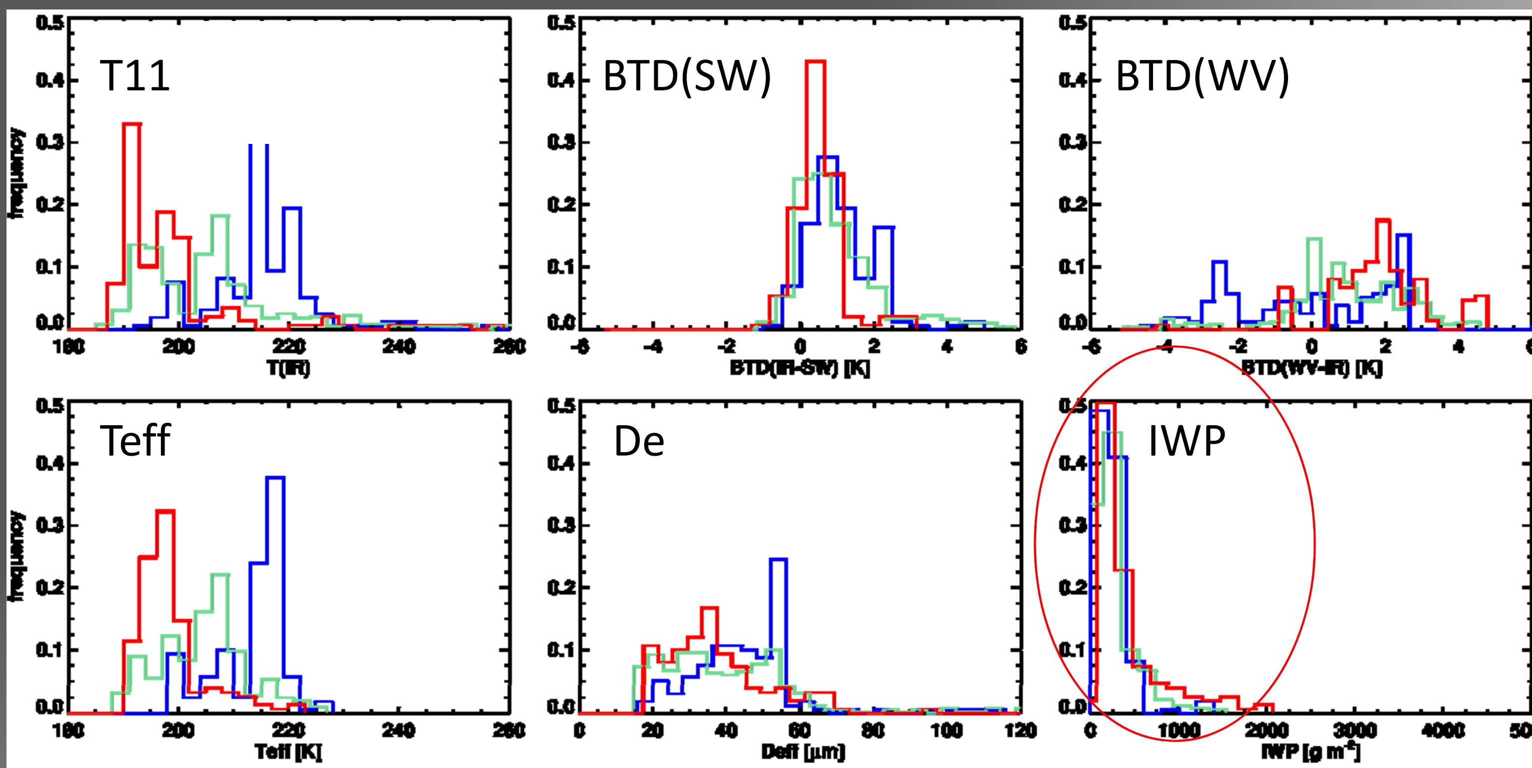
IAGOS data, Meteosat-9

	0.5 < IWC < 1	1 < IWC < 3	IWC > 3
data points	26	22	49
T_{11} [K]	225.99	221.61	217.39
BTD(IR-SW) [K]	0.67	0.58	0.31
BTD(WV-IR) [K]	-4.41	-2.58	-1.42
T_{eff} [K]	225.96	221.62	217.48
D_e [μm]	73.22	72.43	72.64
IWP [g m^{-2}]	660.22	782.64	1703.23



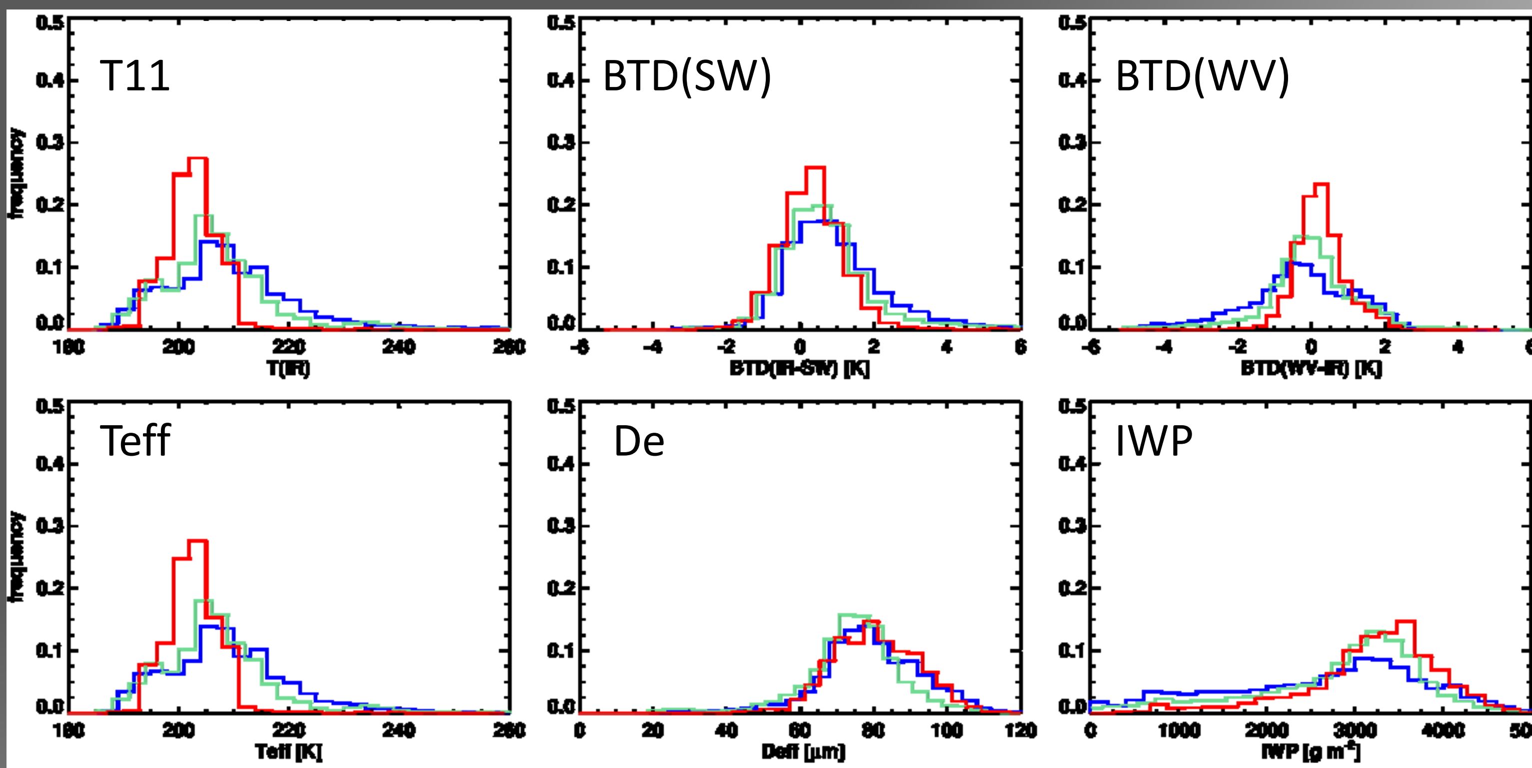
IAGOS data, Meteosat-9, nighttime

	0.5 < IWC < 1	1 < IWC < 3	IWC > 3
data points	159	398	149
T_{11} [K]	215.85	207.84	199.20
BTD(IR-SW) [K]	1.10	0.96	0.48
BTD(WV-IR) [K]	-1.54	-1.69	0.67
T_{eff} [K]	213.42	204.48	198.53
D_e [µm]	48.73	46.75	41.32
IWP [g m^{-2}]	237.03	259.13	416.99



Darwin 2010, Cayenne, Santiago, & Darwin 2014

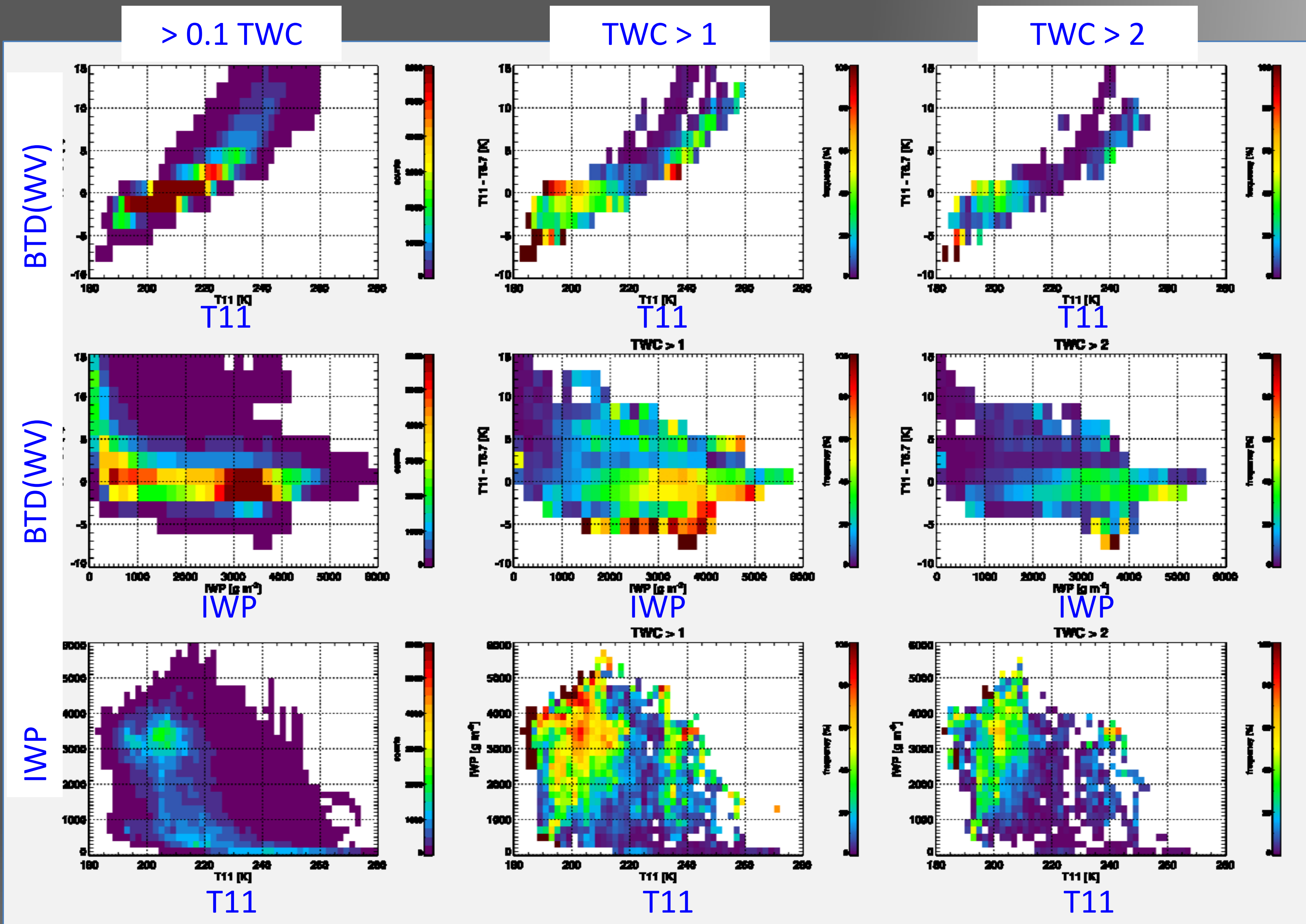
	0.5 < IWC < 1	1 < IWC < 3	IWC > 3
data points	35970	60378	17858
T_{11} [K]	209.06	207.02	202.61
BTD(IR-SW) [K]	1.07	0.82	0.32
BTD(WV-IR) [K]	-0.78	-0.36	0.22
T_{eff} [K]	209.02	207.06	202.68
D_e [µm]	79.13	74.31	80.49
IWP [g m^{-2}]	2634.42	2805.60	3185.63



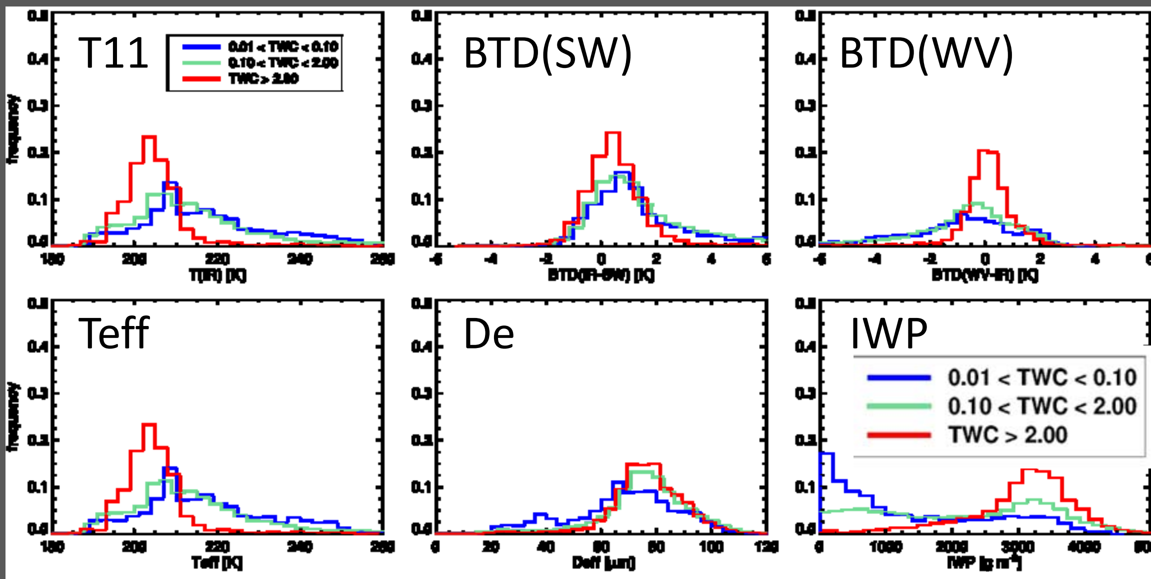
- T11, Teff, BTD(WV), IWP, & BTD(SW) show some sensitivity to IWC

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

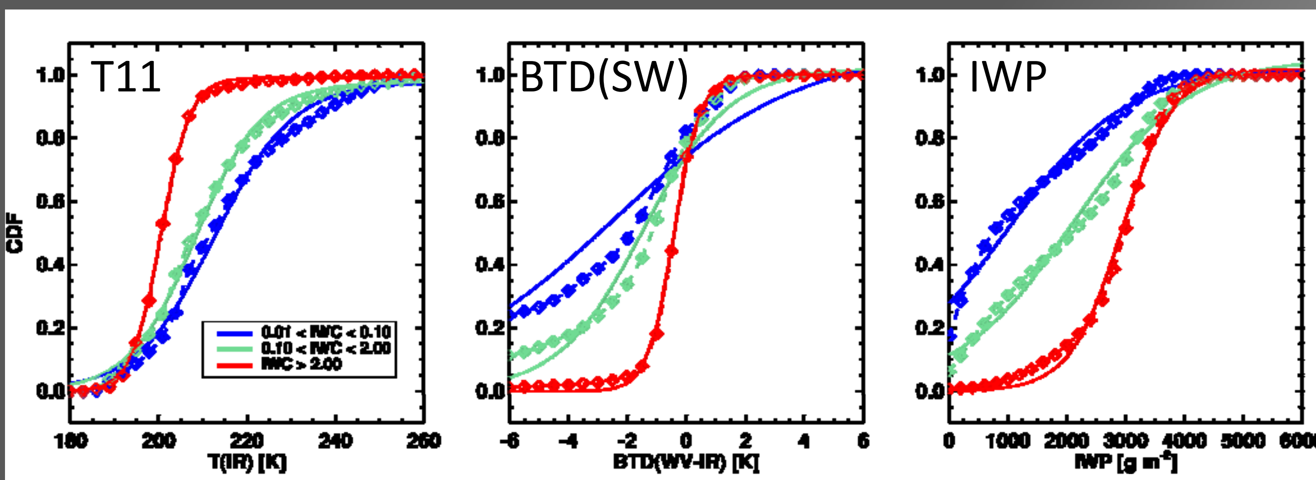
Joint Histograms - Darwin 2010, Cayenne, Santiago, & Darwin 2014



Cayenne 2010, Darwin 2010, Santiago 2012, Darwin 2014, IAGOS data



PDFs show lots of overlap, but HIWC stands out somewhat



Greater fraction of IWC > 2 cases had T(IR) < 200

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

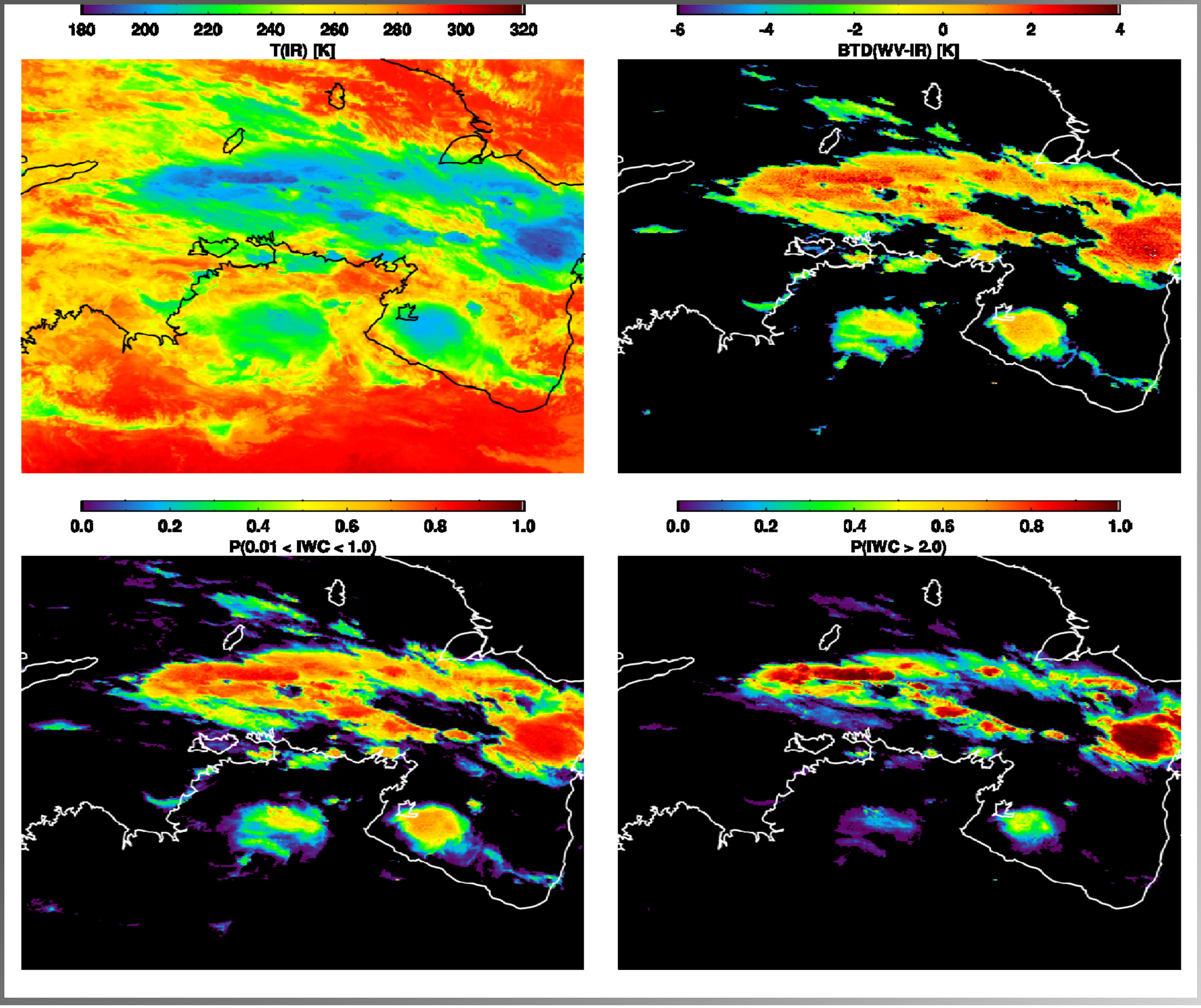
Dashed lines = actual CDF
Solid lines = fitted CDF

Use cumulative distribution functions (CDF) based on field experiment data to determine likelihood of HIWC based on T11, BTD(11-6.7), and IWP

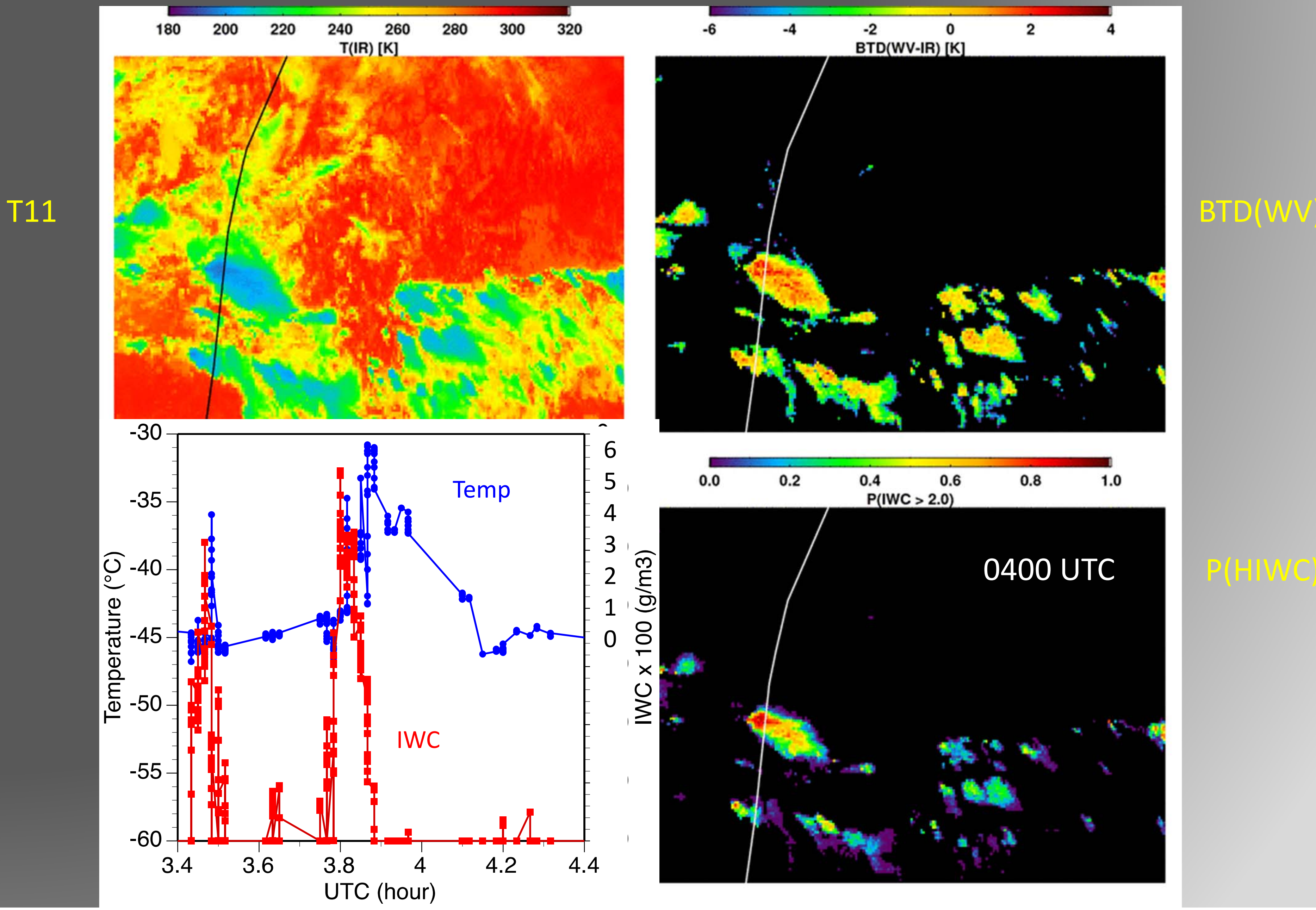
Long tails cause poorer fits. Can get better fits to BTD by constraining BTD values, i.e., don't consider BTD < -10 K to have any chance of HIWC

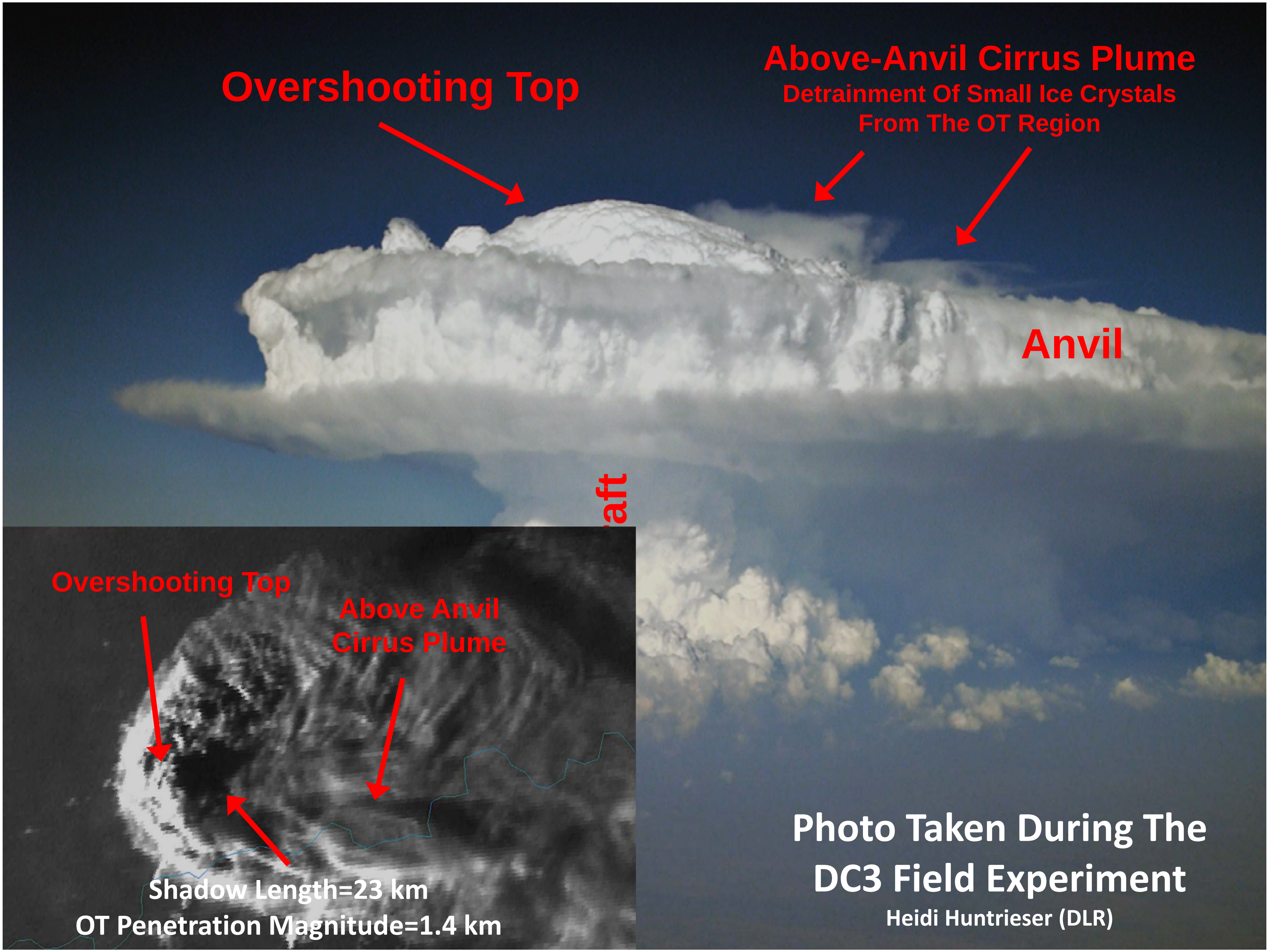
CDF-based P(HIWC) for Feb 17, 2014 near Darwin

P(HIWC) = f{CDF(T11), CDF[BTD(WV)]}

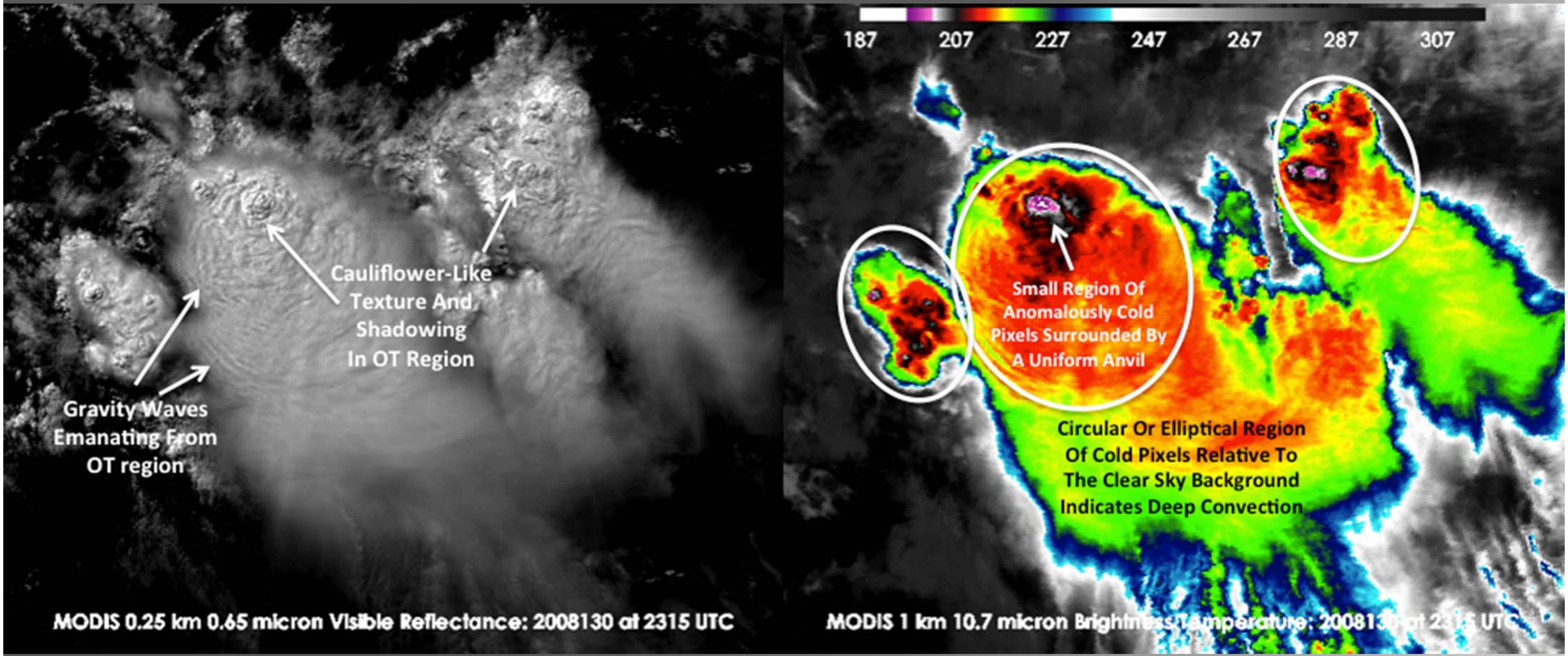


Temperature Anomaly and HIWC During Rio-to-Frankfurt Flight, 14 December 2012
IAGOS & Meteosat-9 Data




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***

Probabilistic Overshooting Cloud Top Detection

GOAL: Mimic the human process for overshooting top (OT) identification using visible & IR satellite imagery and numerical weather prediction (NWP) model data within an automated computer algorithm

Satellite IR and Visible OT Indicators Derived Via Image Pattern Recognition + NWP Derived Fields

↓

Large Training Database of Satellite + NWP Fields For <u>Both OT and Non-OT Anvil</u> Regions

↓

Logistic Regression Model Used To Discriminate Between The OT and Non-OT Anvil Populations

↓

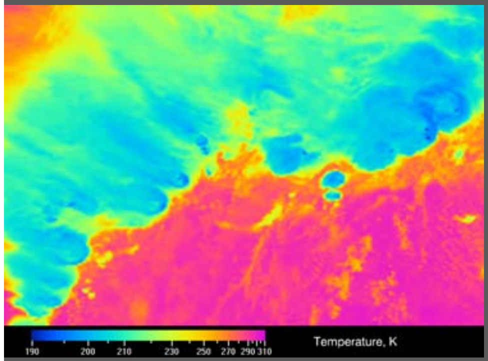
OT Probability Product

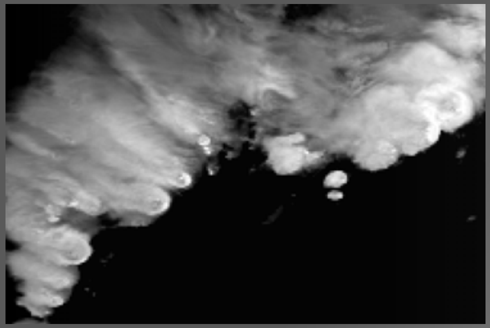
Infrared Channel Pattern Recognition

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

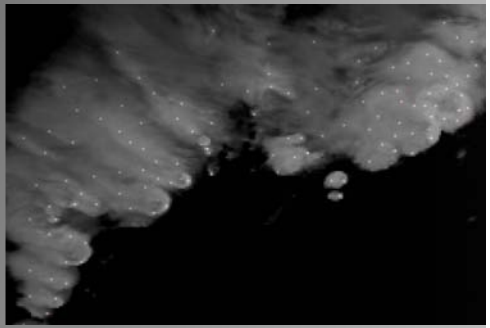
Automatically enhances deep convection without use of a fixed BT threshold and filters convective from non-convective clouds

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





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

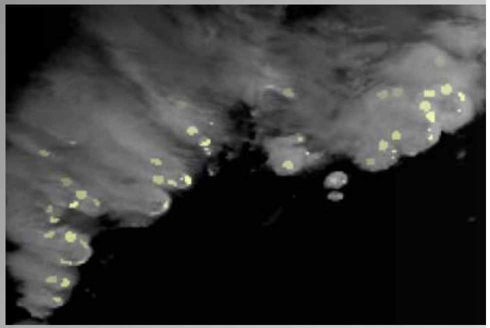
Pattern recognition is then used to ensure that the region being analyed is a deep convective cloud and with a shape and prominence typical of an OT

Pattern recognition uses

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

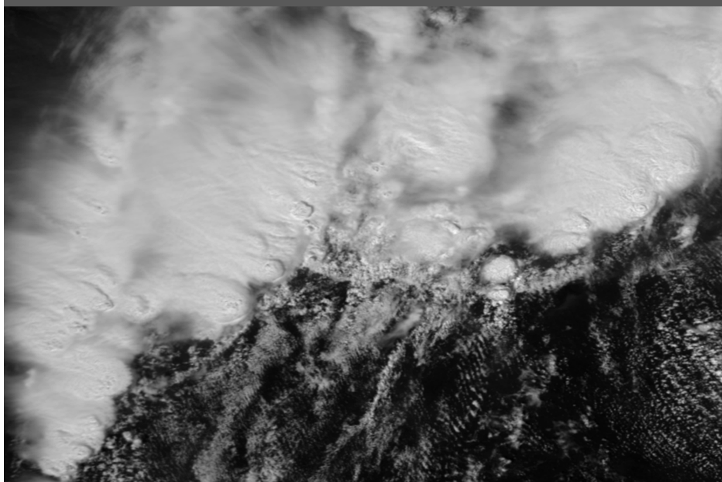
The net result is a cumulative rating obtained for each possible OT region. Pixels with a rating > 0 are considered final OT candidates

Final OT Candidate Regions Based on IR Analysis

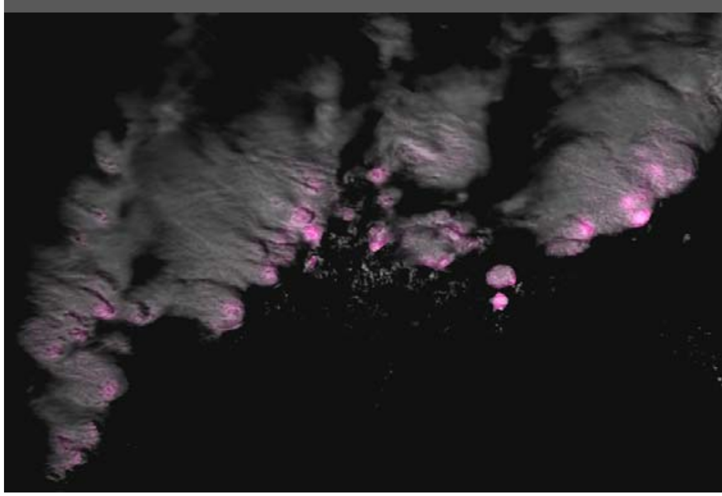


Visible Channel Pattern Recognition

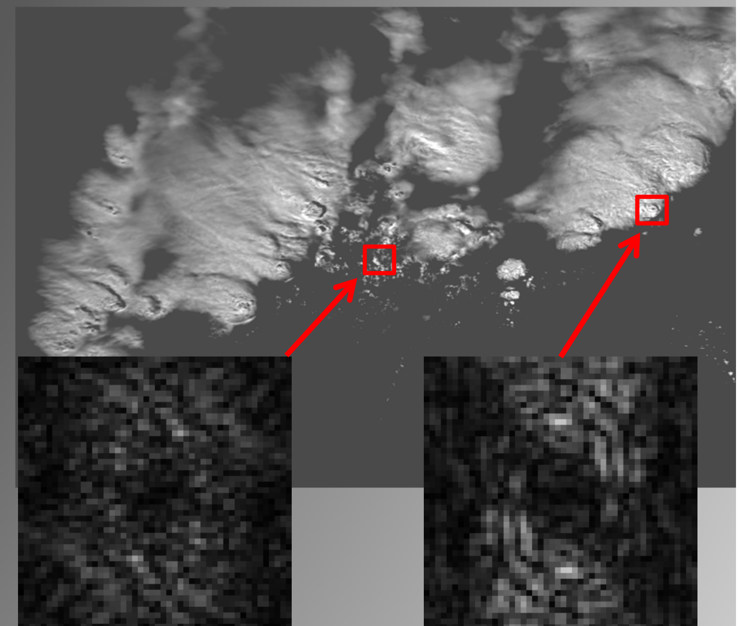
Input MODIS 1 km Visible Image



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.

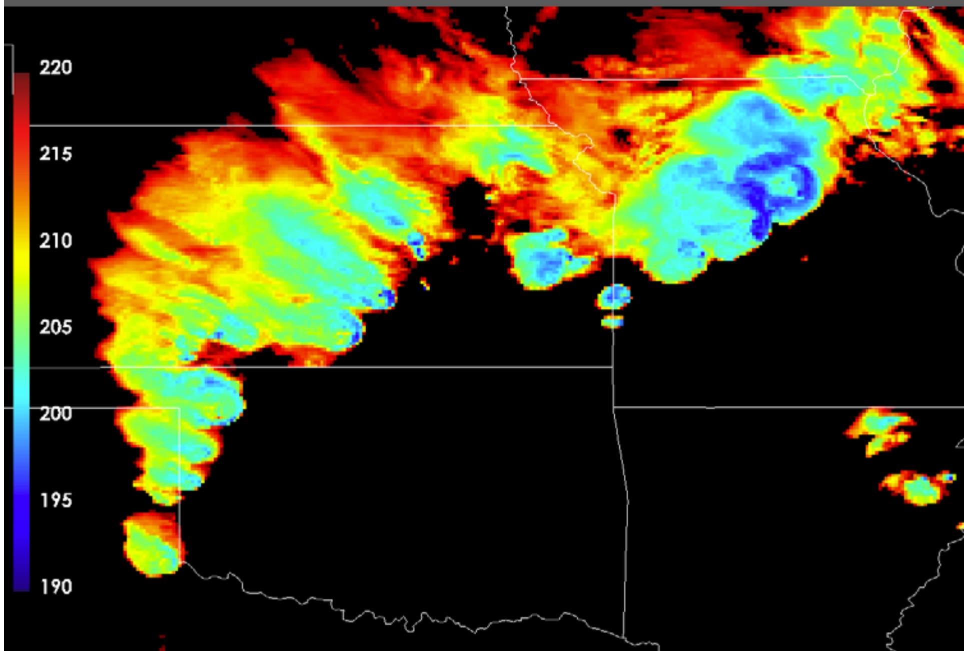
No ring pattern in the spectrum

Fourier frequency spectrum of a typical OT region

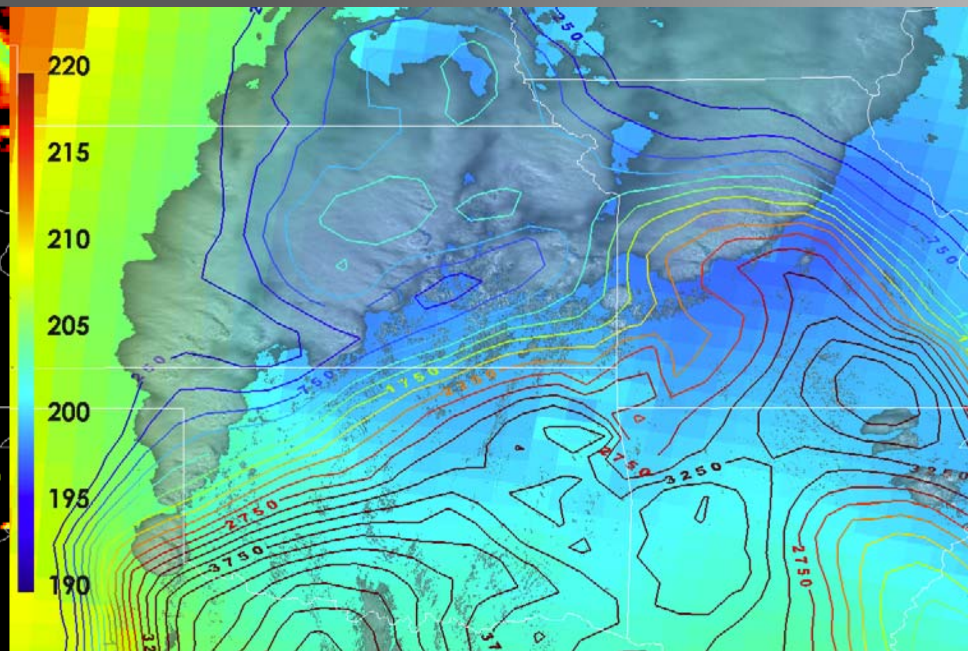
Ring fragments in the spectrum can be identified

Infrared Comparisons With NWP Model Fields

Input MODIS Infrared Image



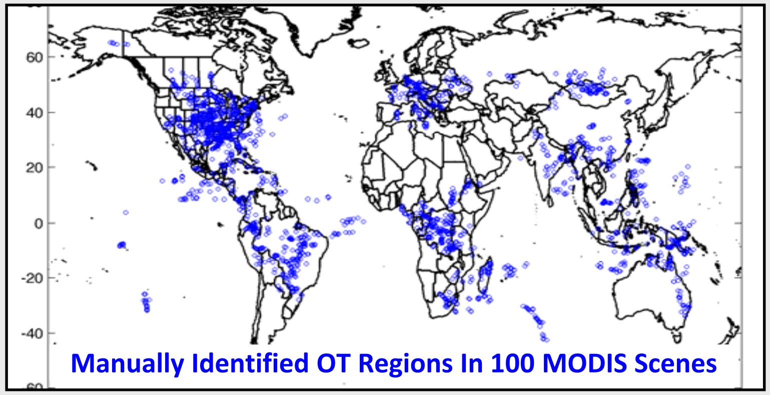
MODIS Visible Overlaid With
NWP Tropopause Temp and CAPE Contours



- A set of NWP-based parameters were evaluated for statistical significance in a logistic regression analysis
- The IR BT – Tropopause and IR BT – Most Unstable Equilibrium Level Temperature differences were 99+% significant for OT discrimination

Logistic Regression and Final OT Detection Product

A database of ~2000 OTs were manually identified in 100 daytime Aqua MODIS 250 m visible images. A similar number of non-OT anvil regions were also identified. This database is used to train and validate a logistic regression model to identify only OT-like features

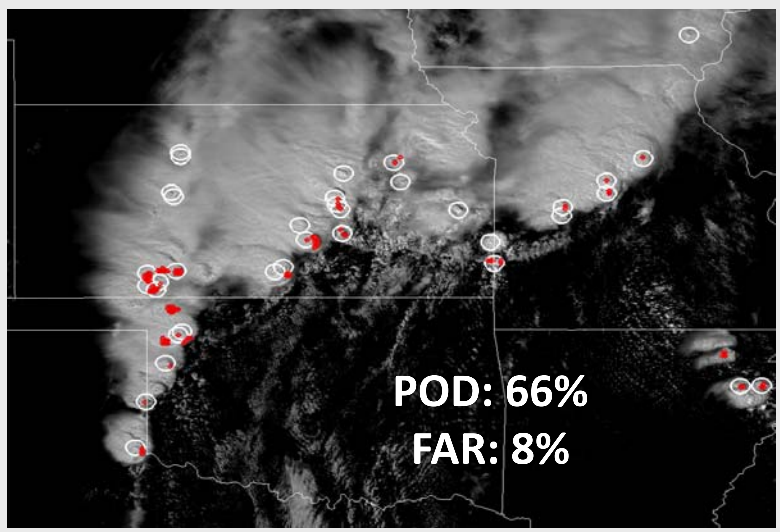


*Regression Result = $W_0 + W_1$*IR BT + W_2*(OT-Mean Anvil IR BT) + W_3*Visible Texture Rating + W_4*(IR BT –Tropopause Temp) + W_5*(IR BT – MU Equilibrium Level Temp)*

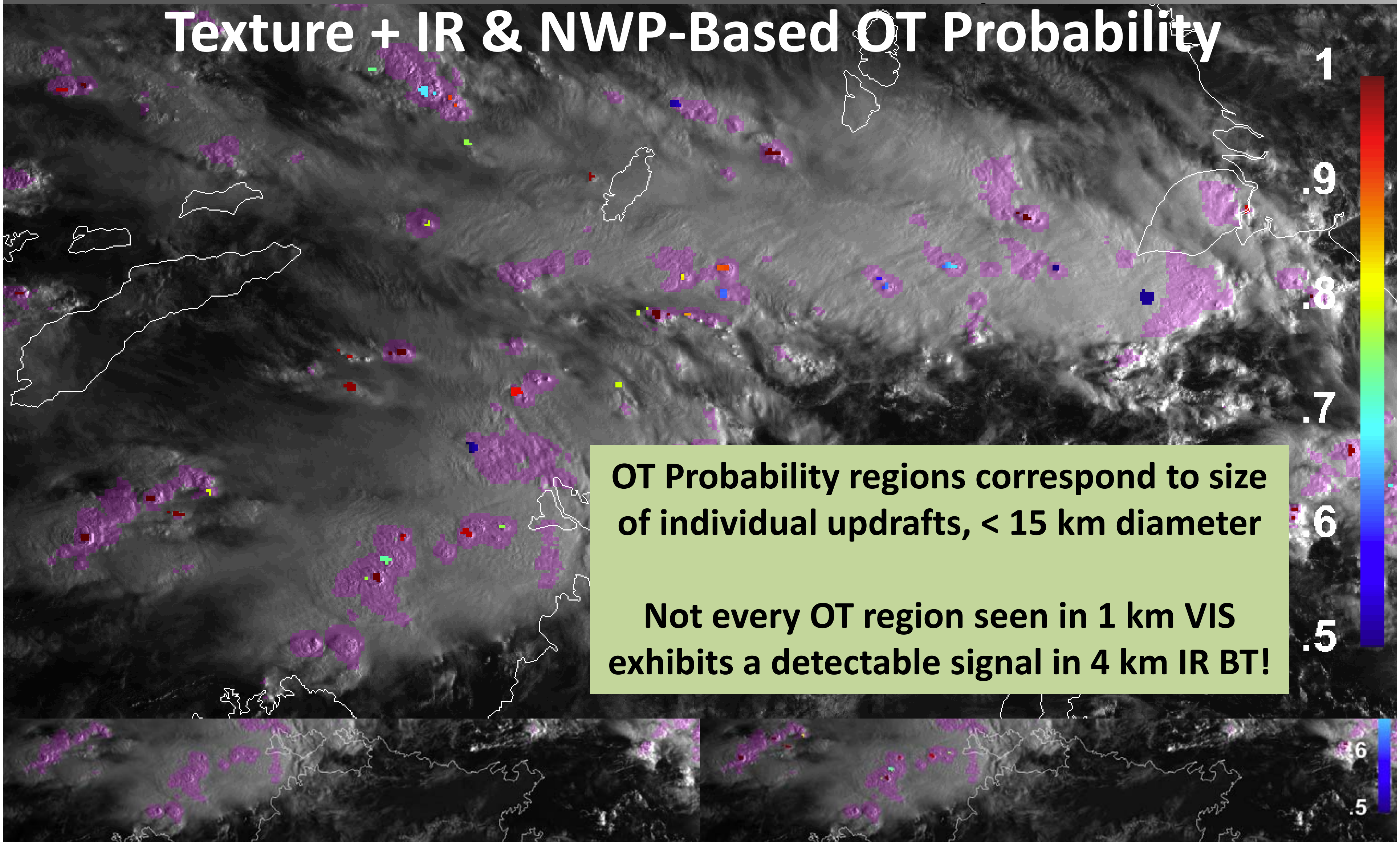
<u>OT Probability</u>

$$\text{OT Probability} = \frac{1}{1+\exp(-1*\text{Regression Result})}$$

OT Probability ≥ 0.5 (Red) Atop Human-Identified OTs (White Circles) and 250 m Visible Imagery

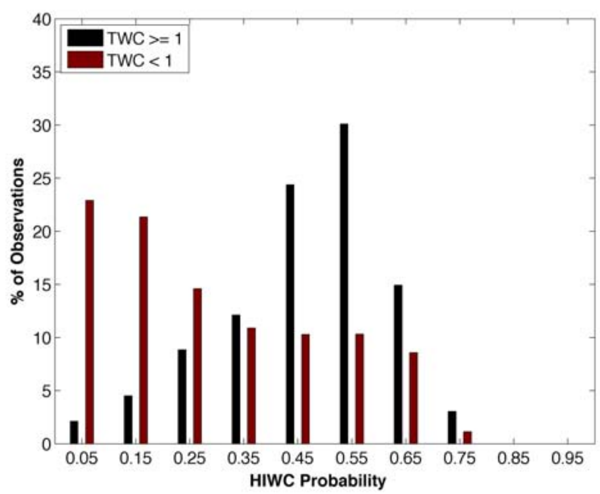


Automated Satellite-Based Overshooting Top Detection



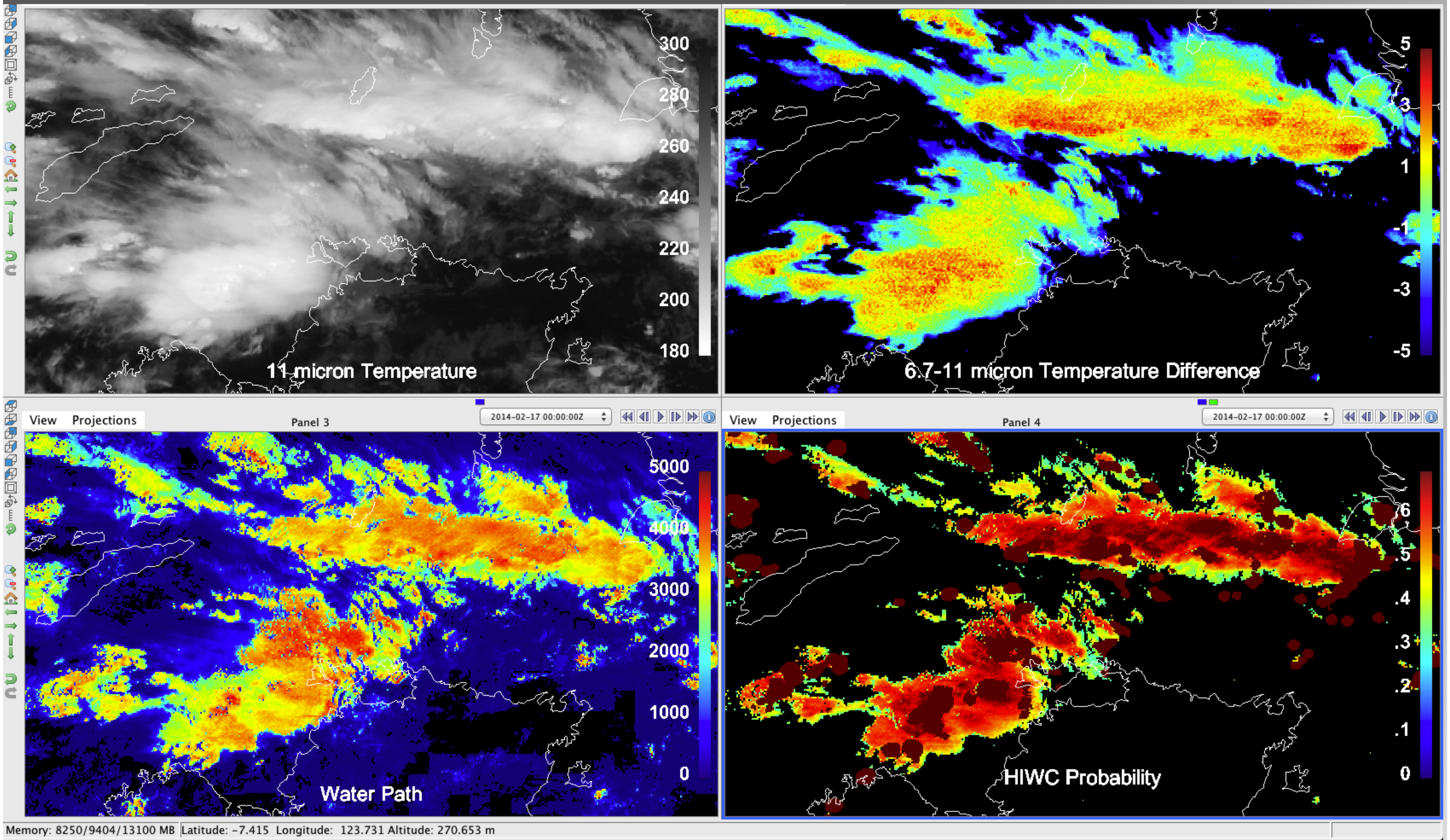
HIWC Probability Model Development

- **214,000+ time/space matched aircraft IKP TWC and satellite observations from the Darwin (2010 & 2014), Santiago (2012), and Cayenne (2010) campaigns**
- **Logistic regression analysis used to develop optimal satellite parameter weighting to identify TWC > 1**
  - IWC > 1 chosen instead of IWC > 2+ because the satellite-observed characteristics of IWC > 1 and > 2+ clouds are quite similar. Classifying HIWC < 2 "low IWC" is detrimental to the analysis
  - Net result is HIWC probability
- **BT11, BT67 – BT11, and Ice Water Path Retrieval were statistically significant predictors at the 99+% level**
- **Visible texture and IR-based overshooting top detections automatically assigned an OT probability rating = 1**

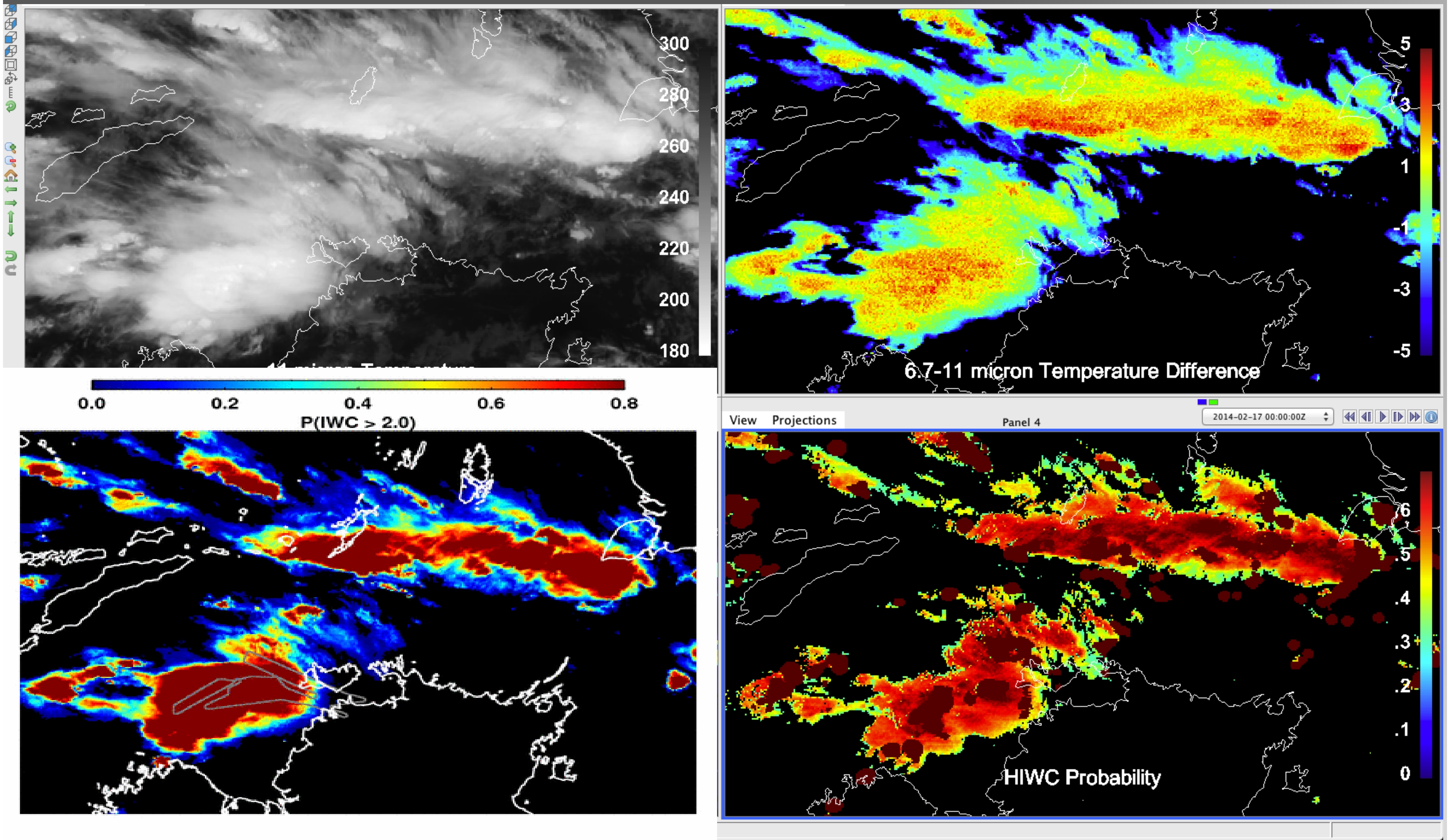


Prob > 0.4
TWC > 1 POD: 85%
TWC > 1 FAR: 30%

DAYTIME IWC > 1 PROBABILITY

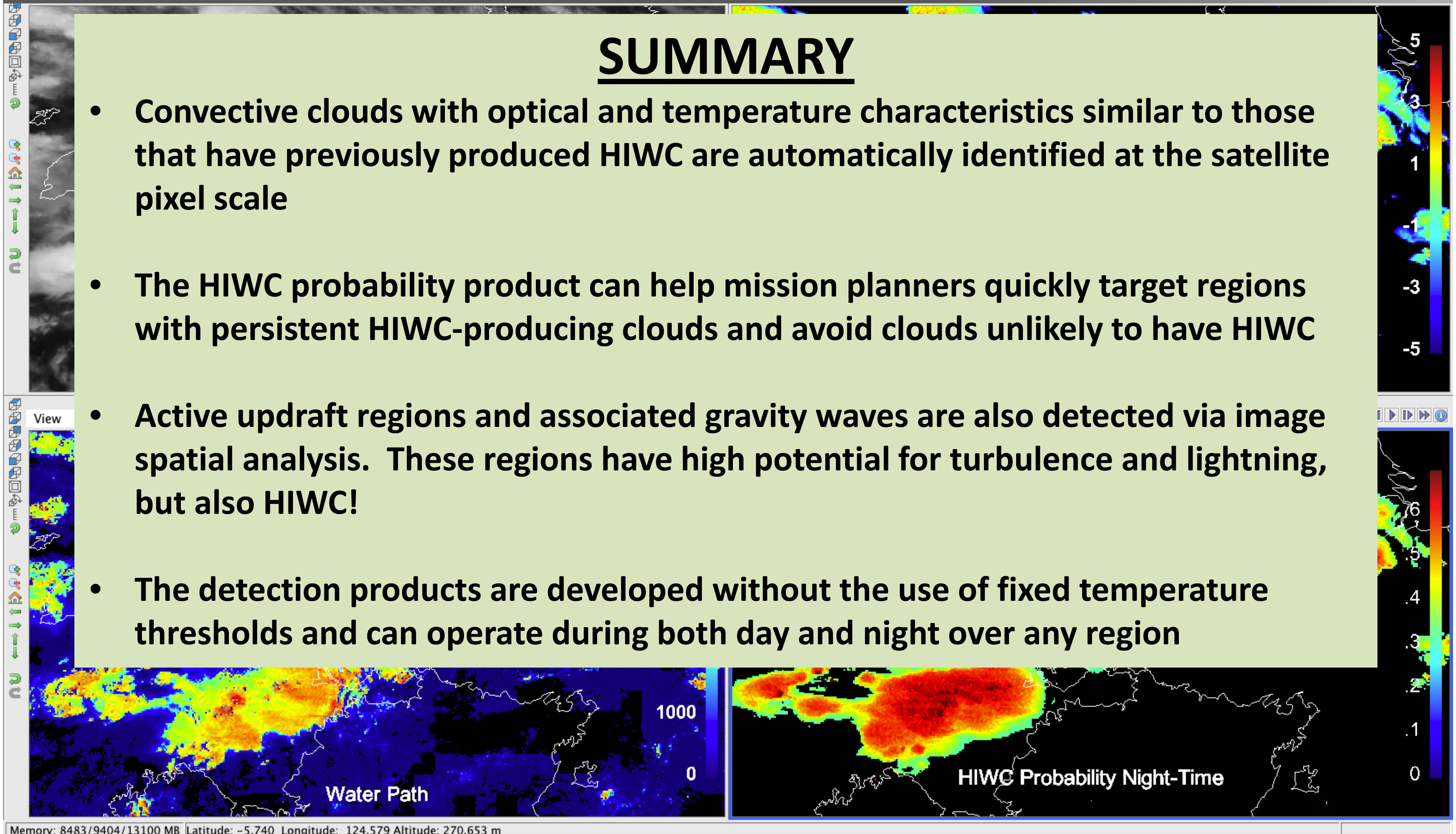


DAYTIME IWC > 1 vs. IWC > 2 PROBABILITIES



- More extensive high probability for HIWC > 2 from CDF approach
- Multiple parameter logistic regression method + OTs shows expanded areas of hazards

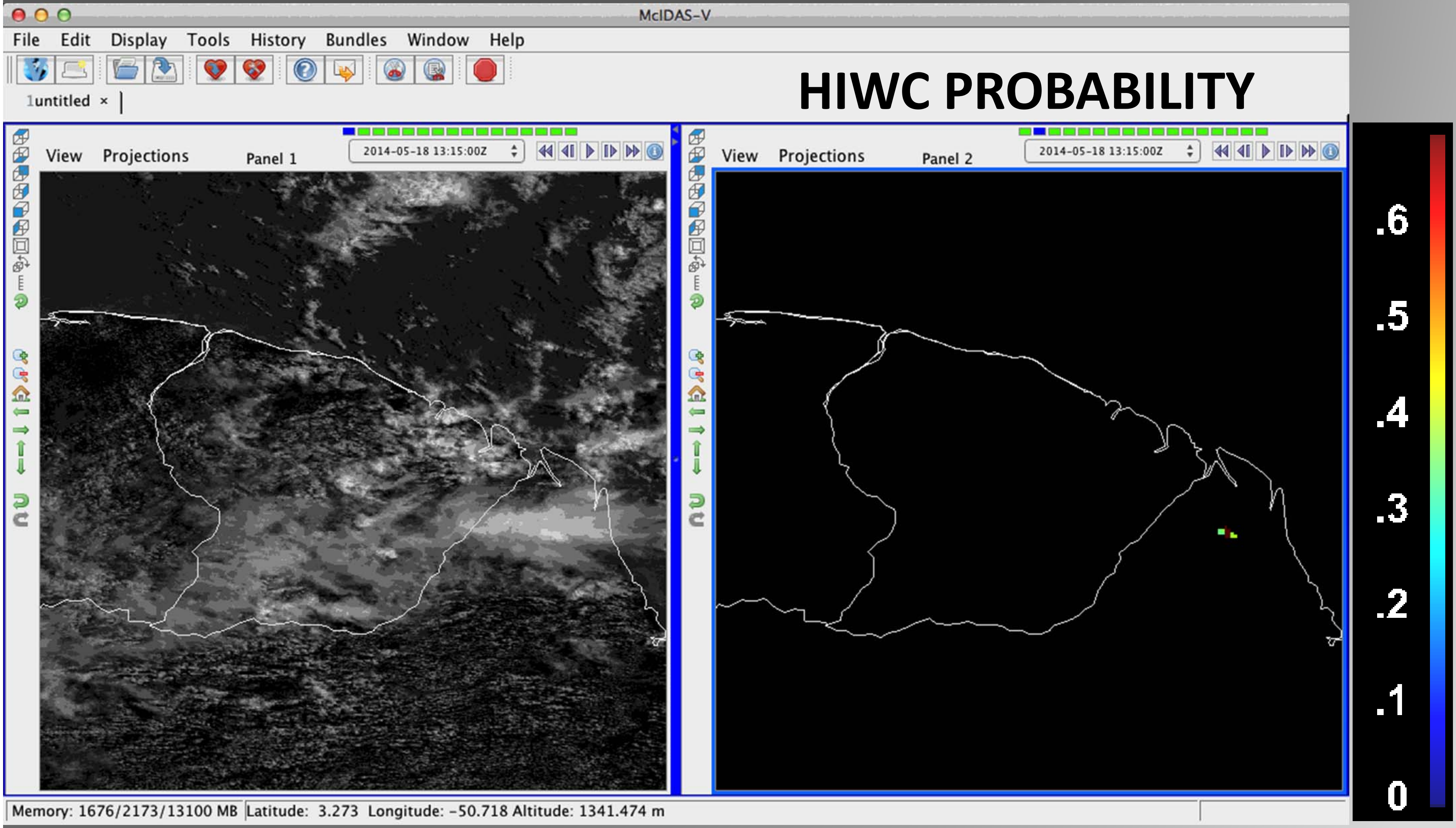
NIGHT IWC > 1 PROBABILITY



SUMMARY

- Convective clouds with optical and temperature characteristics similar to those that have previously produced HIWC are automatically identified at the satellite pixel scale
- The HIWC probability product can help mission planners quickly target regions with persistent HIWC-producing clouds and avoid clouds unlikely to have HIWC
- Active updraft regions and associated gravity waves are also detected via image spatial analysis. These regions have high potential for turbulence and lightning, but also HIWC!
- The detection products are developed without the use of fixed temperature thresholds and can operate during both day and night over any region

DAYTIME IWC > 1 PROBABILITY ANIMATION
GOES-13, French Guyana: May 18, 2014



Future

- Complete determination of best approach for HIWC probability nowcasting & merge with OT detection: => paper
  - need robust system day & night: does BTD(SW) help?
    do we need IWP? (new method for night IWP being developed)

- Validate with additional IAGOS and Cayenne 2015 data
  - resolve IWC magnitude differences

- 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?

- Participate in Cayenne 2015, Puerto Rico 2015