New Advances in Automated Overshooting Top Detection and Analysis of Storms in Super Rapid Scan Imagery

Kristopher Bedka

Science Directorate, Climate Science Branch
NASA Langley Research Center

With Many Contributions From
Konstantin Khlopenkov, Cecilia Wang, Benjamin Scarino, Jake Smith, Cameron Homeyer, and John Mecikalski

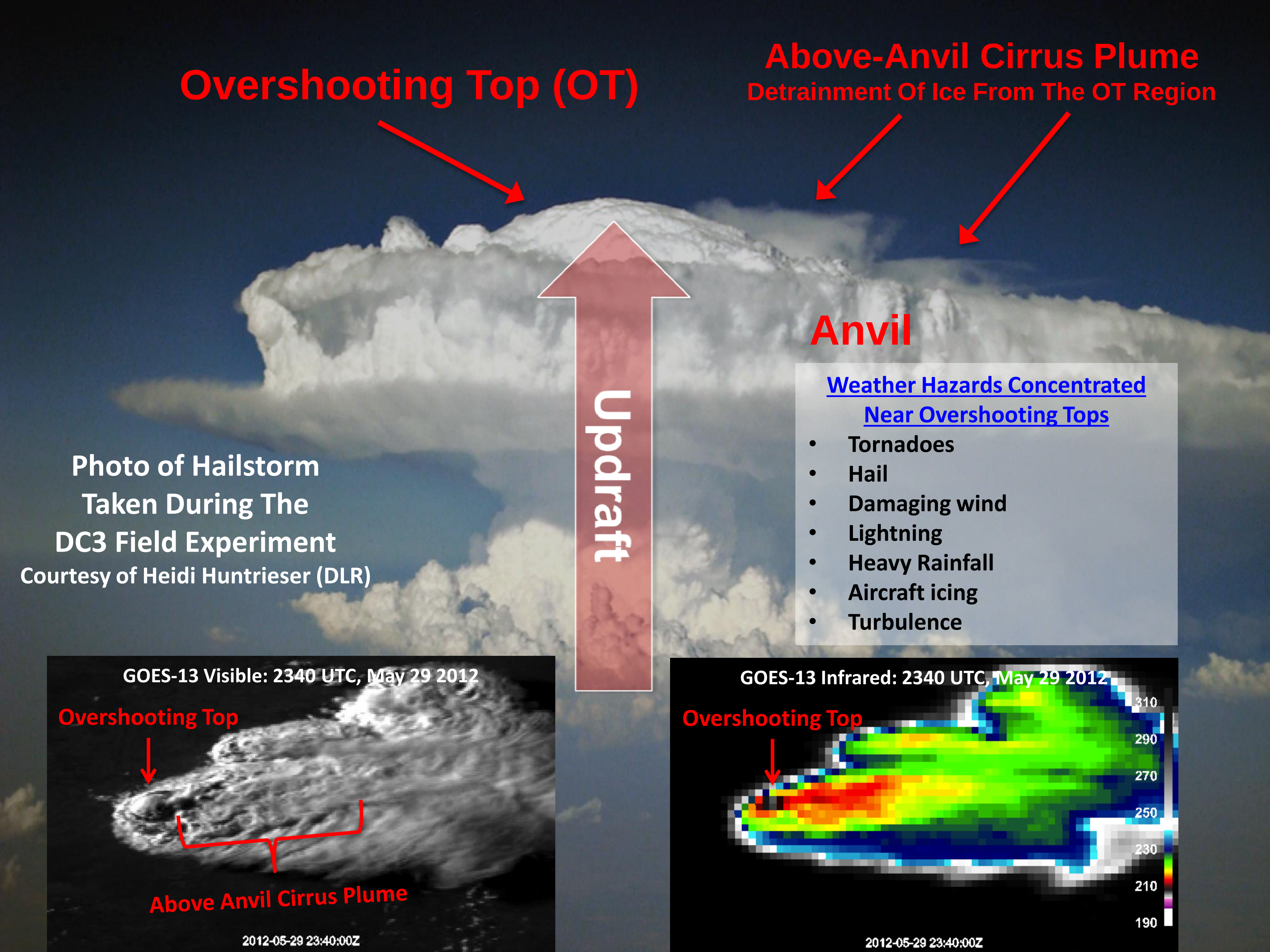
Talk Outline

- Science community needs for an automated satellite imager-based overshooting top (OT) detection product

- Previous and newly emerging automated OT detection methods

- Analysis of storms in Super Rapid Scan Satellite Imagery

FUNDING SUPPORT PROVIDED BY: NASA ROSES
NOAA GOES-R Risk Reduction Research Program



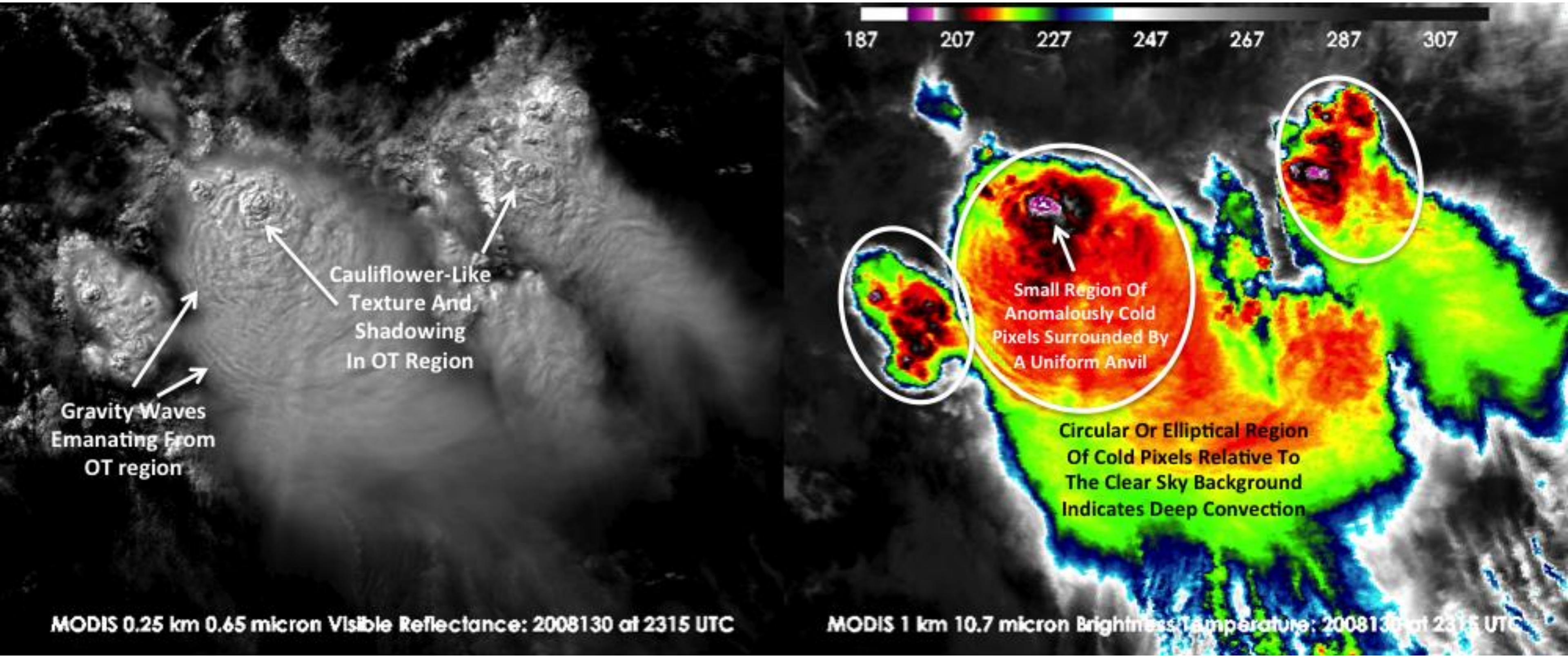
Overshooting Top (OT)
Above-Anvil Cirrus Plume
Detrainment Of Ice From The OT Region
Anvil
Updraft
Weather Hazards Concentrated Near Overshooting Tops
• Tornadoes
• Hail
• Damaging wind
• Lightning
• Heavy Rainfall
• Aircraft icing
• Turbulence
Photo of Hailstorm Taken During The DC3 Field Experiment
Courtesy of Heidi Huntrieser (DLR)
GOES-13 Visible: 2340 UTC, May 29 2012
Overshooting Top
Above Anvil Cirrus Plume
2012-05-29 23:40:00Z
GOES-13 Infrared: 2340 UTC, May 29 2012
Overshooting Top
310
290
270
250
230
210
190
2012-05-29 23:40:00Z

Why Bother Developing an Automated Satellite-Based OT Detection Algorithm?

FREQUENT QUESTION: If I can see an OT with my eyes in imagery, why do I need an OT detection product?

- **Trends in cloud top updraft intensity tell you a lot about the overall health of a storm and locations of possible hazards within a storm**
- As imager temporal resolution increases, one cannot monitor the details within the cloud tops of many storms occurring simultaneously
- Fixed IR color enhancements used in operational forecast centers can hide OT regions
- An OT detection product helps one to quickly identify where the most intense storms are within an image. This is especially useful when one is forecasting over a large region and cannot look at each and every storm in detail
- The climate community seeks to understand the frequency and location of tropopause- penetrating updrafts
- An accurate OT detection algorithm applied to a long-term satellite data record can produce a climatology to determine if hazardous storm activity is changing in response to observed climate change

How Do Our Human Minds Identify an Overshooting Top in Satellite Imagery?



How Can A Computer Emulate The Human Mind?

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

Things To Consider When Developing OT Detection Algorithms or Interpreting Their Output

What creates a "cold spot" in IR satellite imagery?

- An active updraft region -> a cloud top above the surrounding anvil

- Cloud top from a recently decayed updraft transported downstream by the wind flow

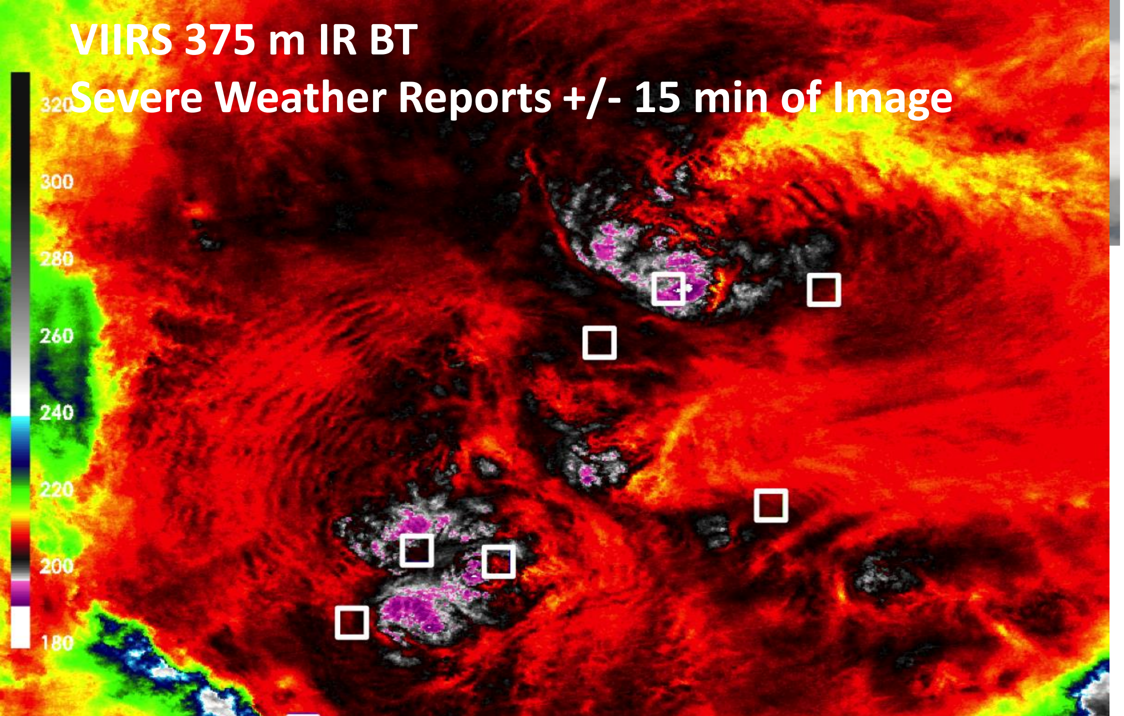
- Gravity/ship waves, transverse bands, or other turbulent phenomena within an 1) anvil, 2) tropical or mid-latitude cyclone cloud system, 3) mountain ranges, or 4) ordinary "jet stream" cirrus

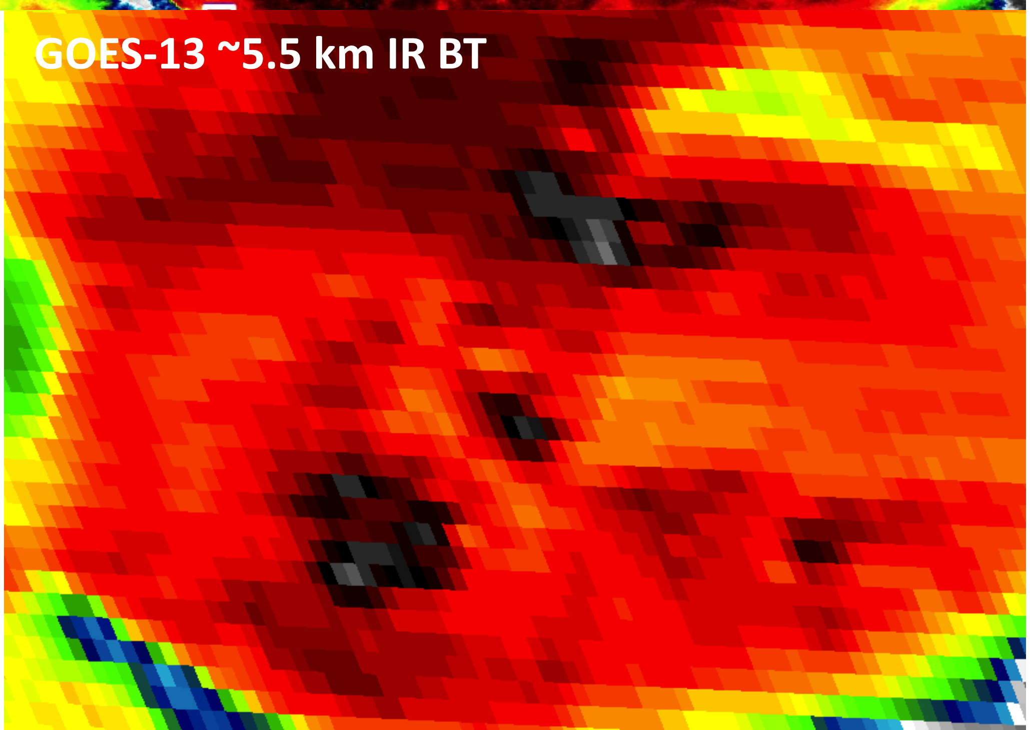
Things To Consider When Developing OT Detection Algorithms or Interpreting Their Output

OT-related cold spots can appear very similar to non-OT cold spots from an automated computer algorithm's perspective!

- **You can set your 'cold spot detection' thresholds to be very strict which will help to eliminate false detections**
  - But some true OTs do not produce prominent IR signals, especially over Europe, and would not be detected with these strict thresholds

- **An IR-only OT detection approach will not effective unless you:**
  1) Take the spatial characteristics of the cloud into account
  2) Analyze visible channel imagery if available to constrain IR OT detections
  3) Bring in NWP model fields to ensure that the feature of interest is indeed overshooting convection





Impact of Imager Spatial Resolution on Severe Storm Appearance

- **High spatial resolution data is critical for resolving the coldest IR BTs present within hazardous storm tops**
- **IR BT within OT regions are found to be 7-12 K colder on average in 1 km LEO imagery than GOES.**
- **375 m VIIRS IR BTs are ~20 K colder than GOES for the most intense storms in this case**
  - 200+ VIIRS pixels within 1 GOES IR pixel over the Central Plains
- **We expect OT regions observed by GOES-R ABI to be ~3-5 K colder than what would be observed by current GOES**

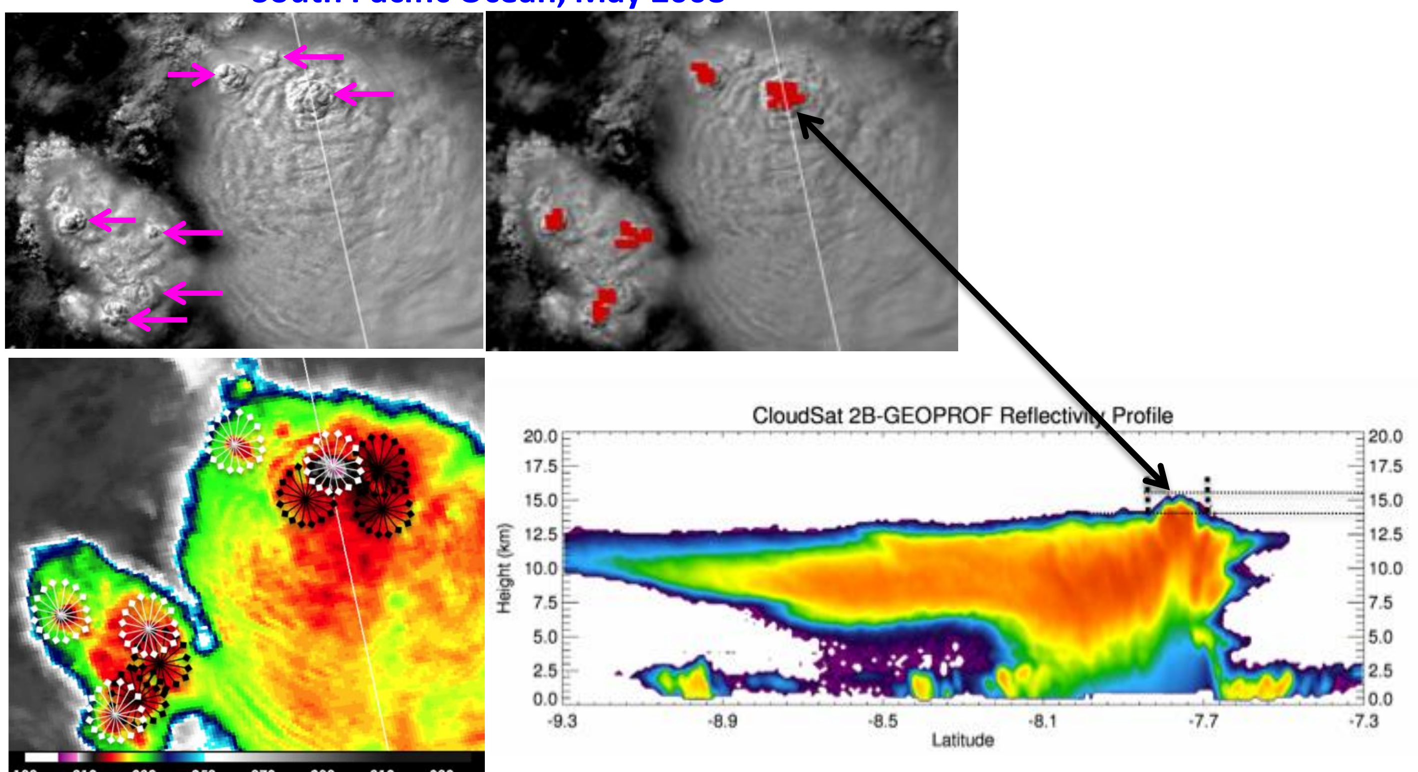
Bedka et al. (2010) IR-Based Overshooting Cloud Top Detection

- A satellite-based OT detection method was funded by the NASA Applied Sciences Program and GOES-R ABI Aviation Algorithm Working Group for near real-time aviation safety and weather forecast applications (Bedka et al. 2010-2012)

- The method uses spatial analysis and strict thresholding of satellite IR temperature/gradients combined with NWP tropopause tempature to automatically identify individual OT regions at the satellite pixel scale

<u>MODIS 250 m Visible, 1 km IR, and Overshooting Cloud Top Detections</u>

South Pacific Ocean, May 2008

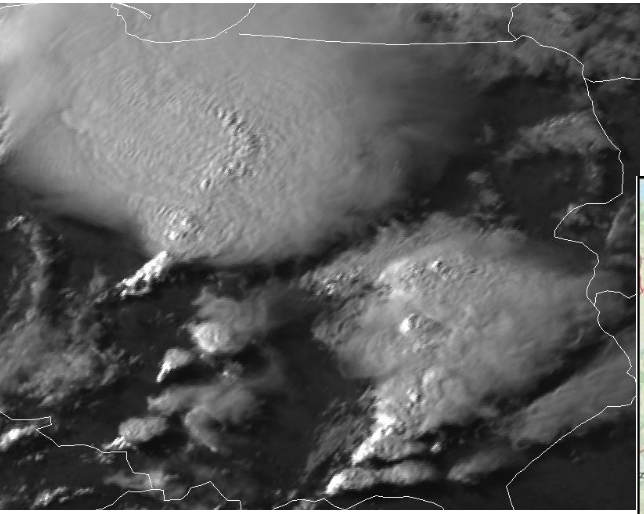


White: Region colder than tropopause and > 6.5 K colder than surrounding anvil

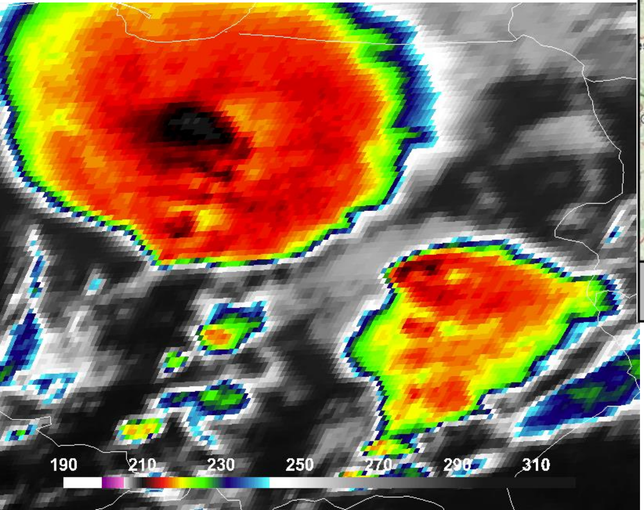
Black: Region colder than tropopause but not significantly colder than anvil

Examples of Current OT Detection Methods
Severe Storms over Poland

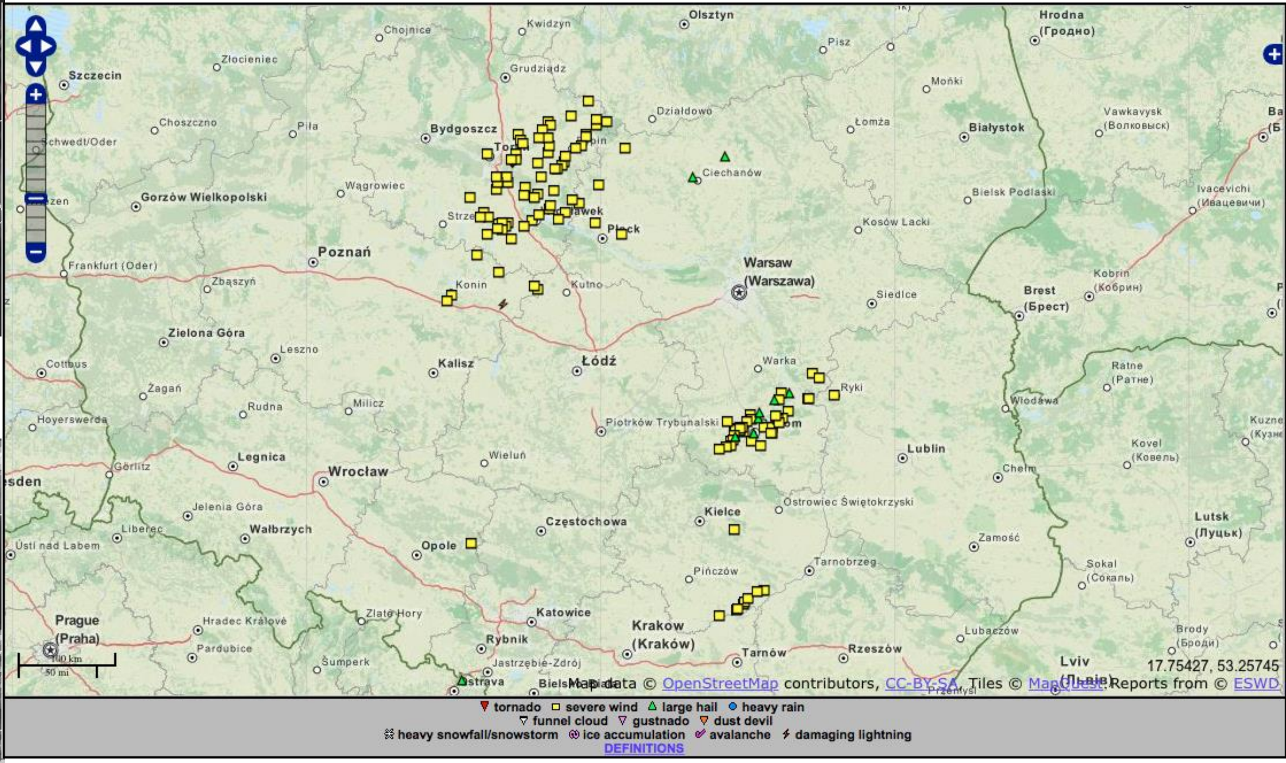
Meteosat-10 HRV: 20 July 2015 1545 UTC



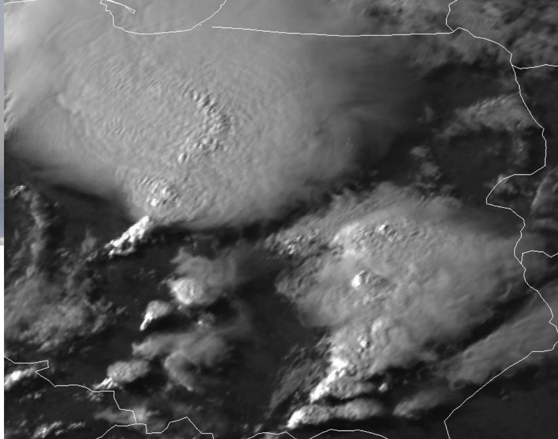
Meteosat-10 IR: 20 July 2015

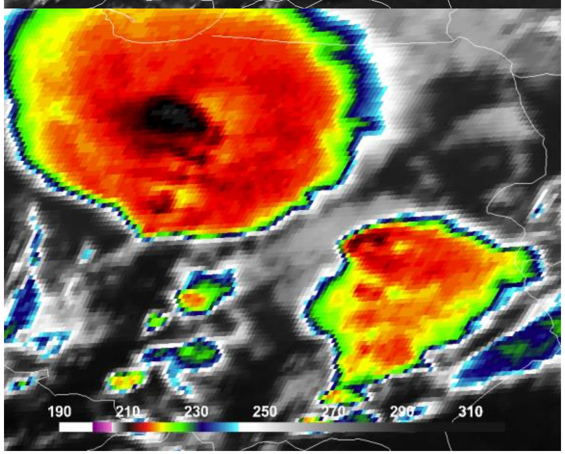


ESWD Severe Weather Reports: 20 July 2015 15-16 UTC

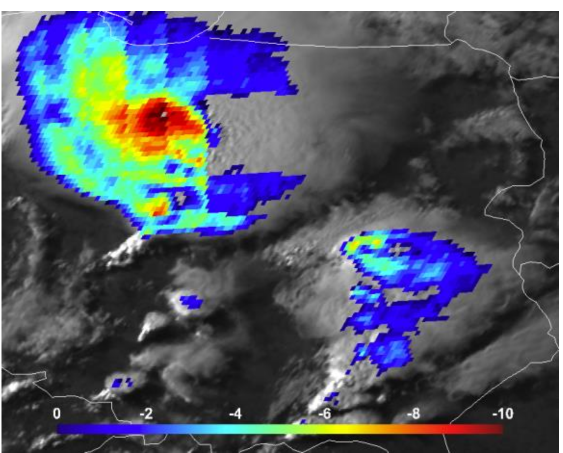


Examples of Current OT Detection Methods: Severe Storms over Poland



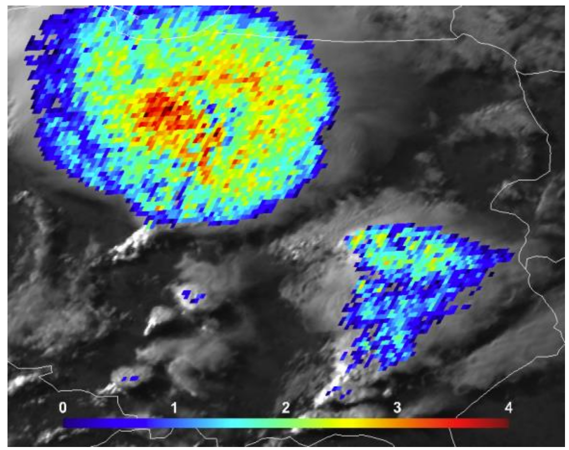


IR BT Colder Than GFS Tropopause

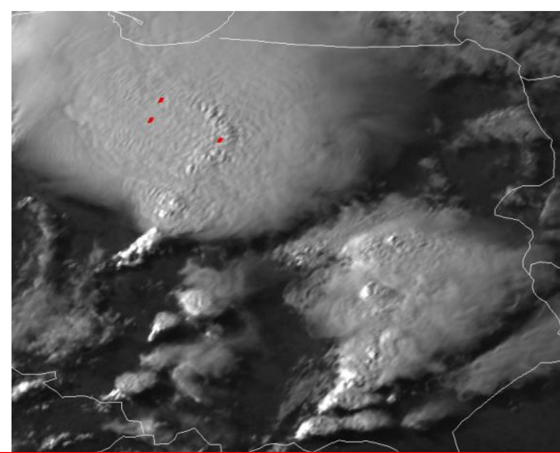


Spectral Differencing Methods

WV-IR BTD

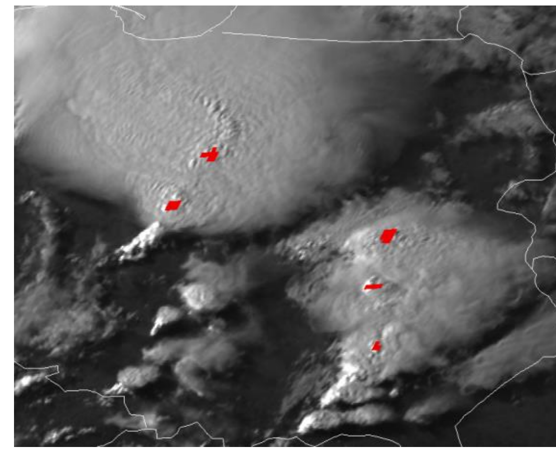


COMB Method

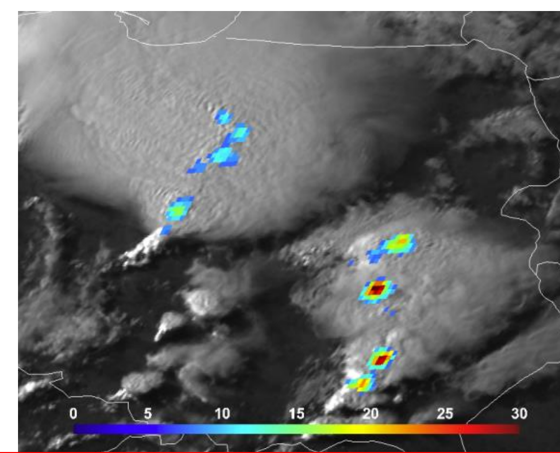


Spatial Analysis Methods

Bedka et al. (2010) IR OT-Anvil BTD

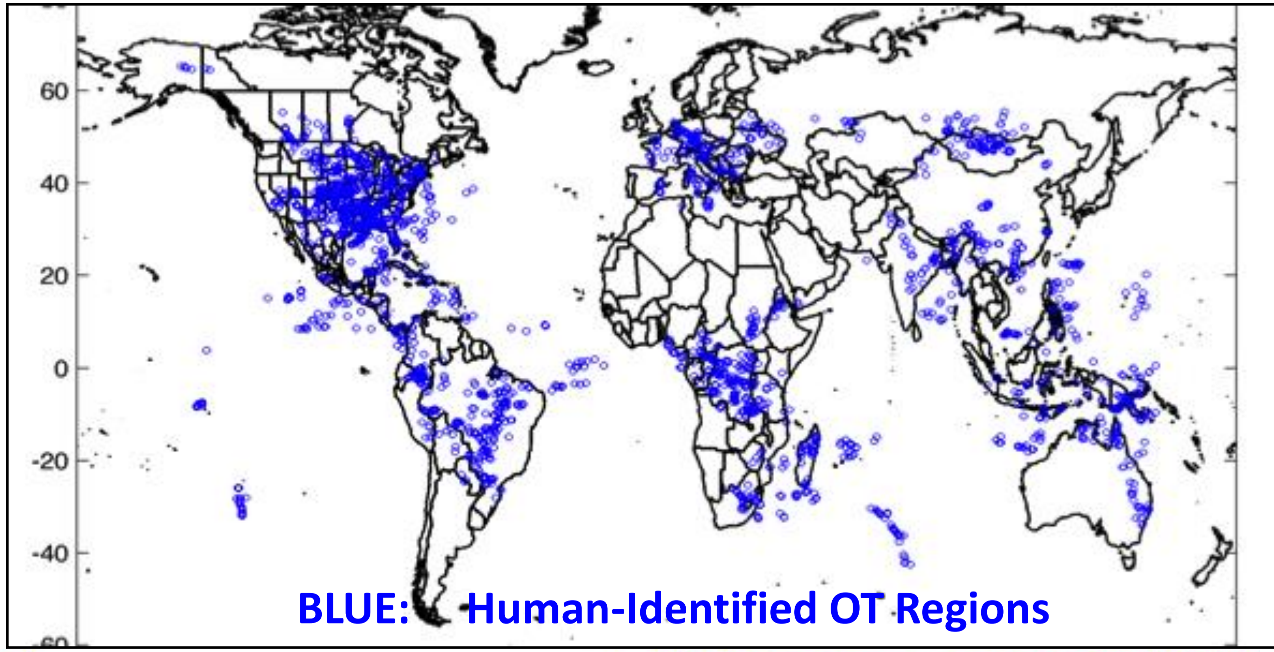


Bedka and Khlopenkov (2016)
Visible Texture Detection

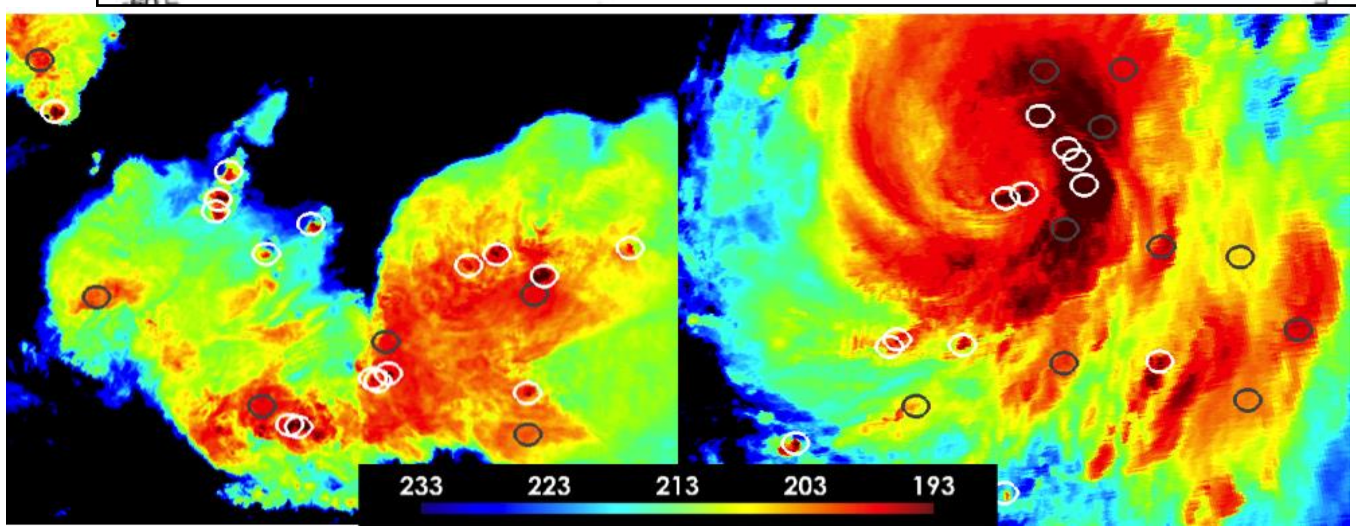


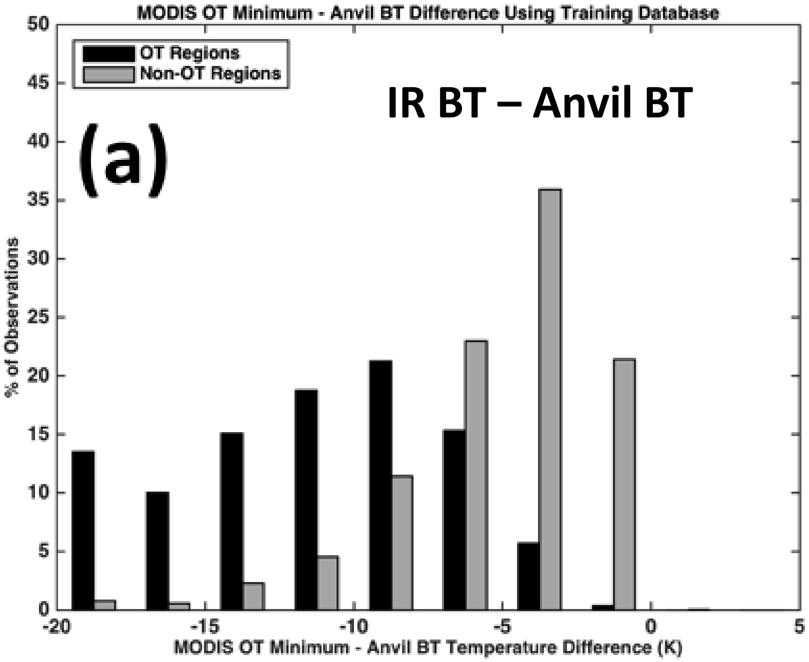
Characteristics of OT and Non-OT Anvil Regions

4000+ OT and Non-OT Anvil Regions Manually Identified in MODIS 0.25 km Visible and 1 km IR Imagery



WHITE Circle = OT Region
GREY Circle = Non-OT Anvil Region





Histograms of OT and Non-OT Region Characteristics

Thoughts on Development of an Optimal Satellite-Based Hazardous Convective Storm Detection Algorithm

- **An optimal framework for detecting hazardous storms and OTs should have many of the following characteristics:**

1) Mimic the process used by the human mind to identify hazardous storms
2) Dynamic, no fixed regional/seasonal thresholds
3) Probabilistic to reflect uncertainty in detection
4) Ability to seamlessly process long-term data record of global LEO and GEO imagery
5) Account for and quantify detection biases arising from variations in instrument calibration, view angle, spatial resolution, and satellite (G-8, -12, -13, ABI) over time
6) Incorporate numerical weather analysis fields to adjust detection confidence and estimate storm severity based on storm environment

CURRENT EFFORT: Develop improved OT detection algorithm that satisfies most of these requirements, supported by the GOES-R Risk Reduction Research program

Bedka and Khlopenkov (2016) "Version 2"
Visible and IR-Based Probabilistic Overshooting Cloud Top Detection

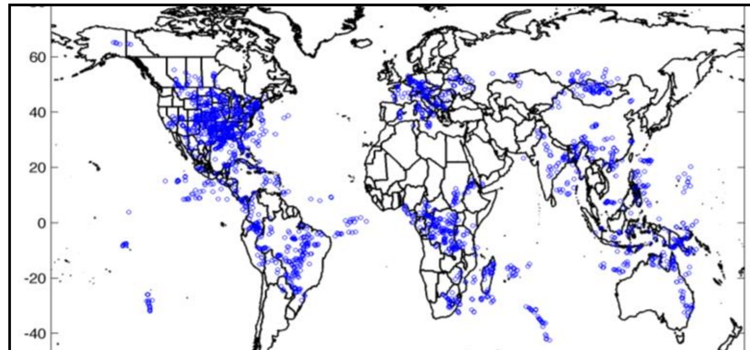
GOAL: Mimic the human OT identification process using IR & visible imagery and NWP data within an automated computer algorithm

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

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

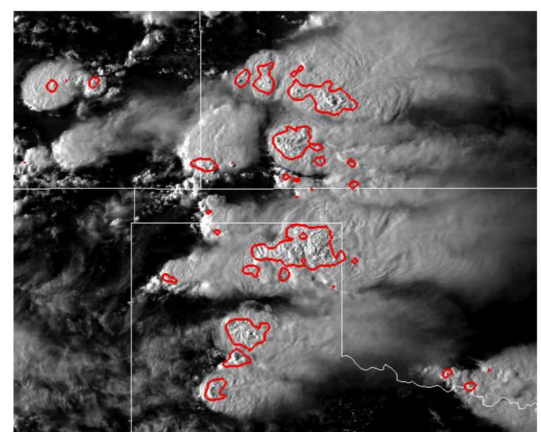
Statistical Model Used To Discriminate Between The OT and Non-OT Anvil Populations

Visible OT Texture Detection and IR+NWP OT Probability Products



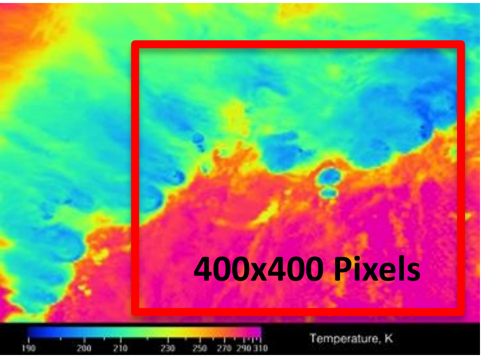
2000+ Manually Identified OT Regions In 100 MODIS Scenes

Automated Satellite-Based Hazardous Storm Detections (red) Overlaid on GOES Visible Satellite Imagery



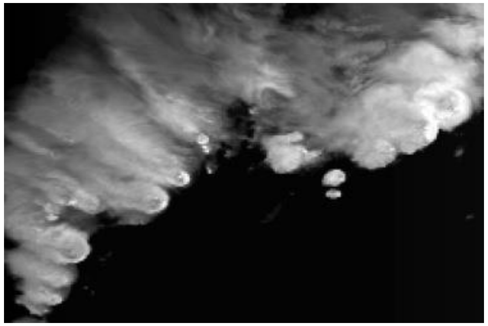
IR-Based OT Pattern Recognition Analysis

Input MODIS IR Temperature (BT) Image, 6 May 2007, 1925 UTC

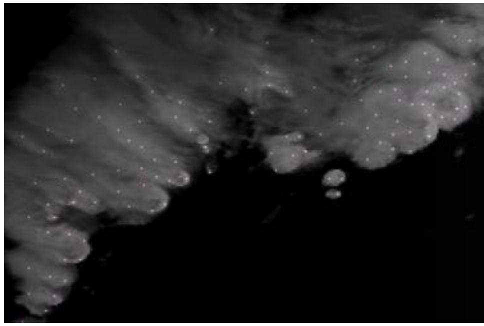


BT Score: $\text{BTscore} = (T_{avg} - T)^{0.7}(255 - T)^{1.3}/16 \quad + 2 \cdot \sigma(T)$

Used to eliminate need for a fixed BT threshold, enhance deep convection, and separate likely 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

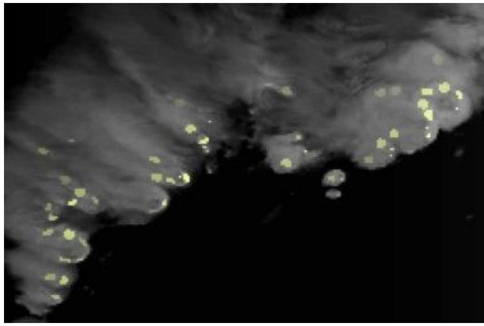
Pattern recognition used to ensure that the region being analyzed is within deep convection and 2) the feature of interest has a shape and prominence typical of OT regions

Pattern recognition uses

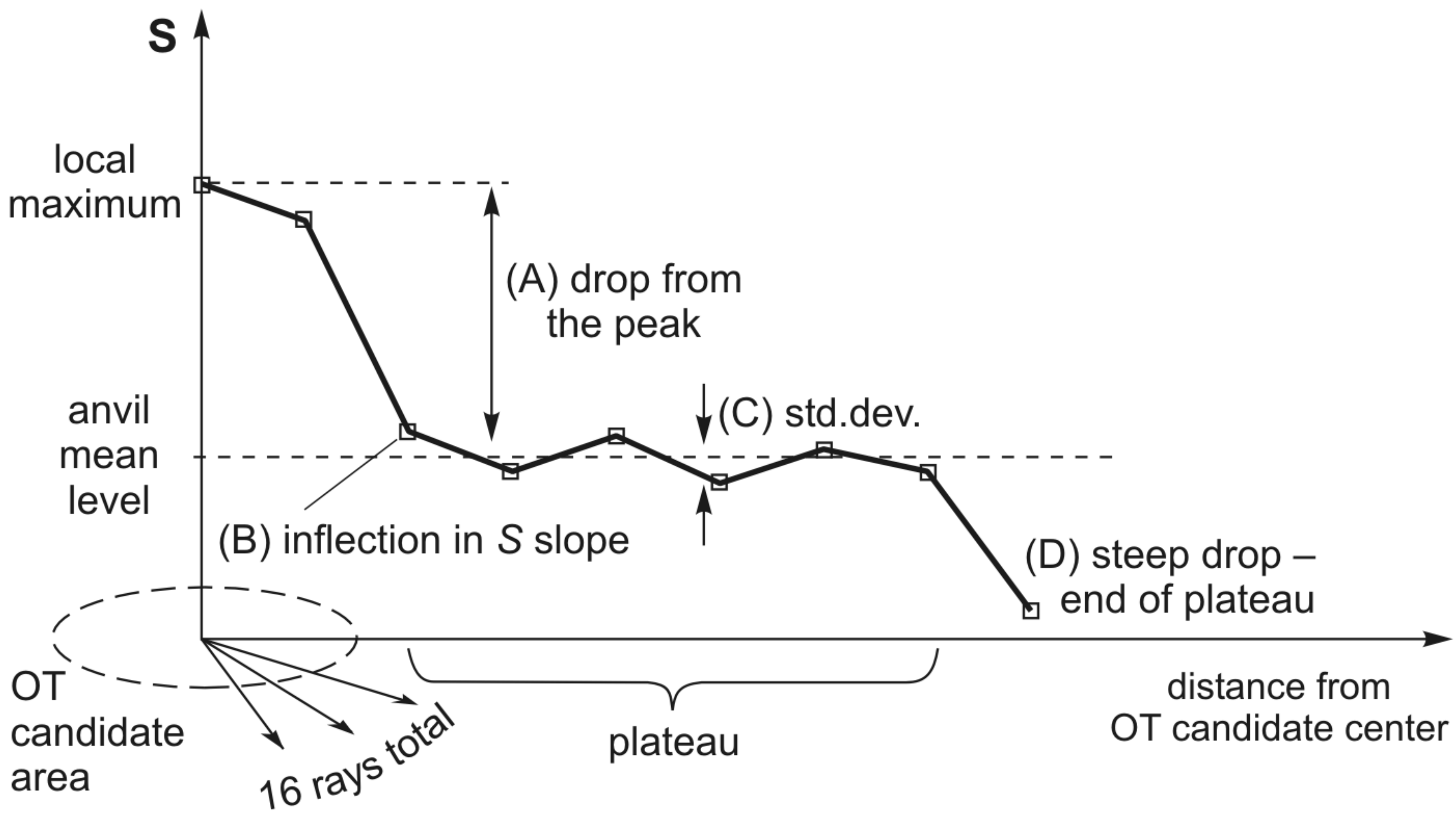
- OT shape correlation
- BT Score prominence relative to surrounding anvil
- Anvil flatness, roundness, and edge sharpness

The net result is a cumulative rating obtained for each possible OT region. Pixels with a non-zero rating are considered final "OT Candidate" regions

Final OT Candidate Regions Based on IR Analysis



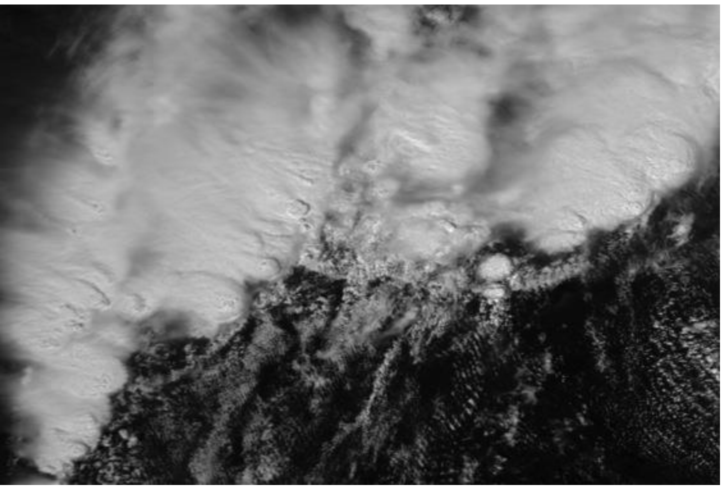
IR-Based OT Pattern Recognition Analysis



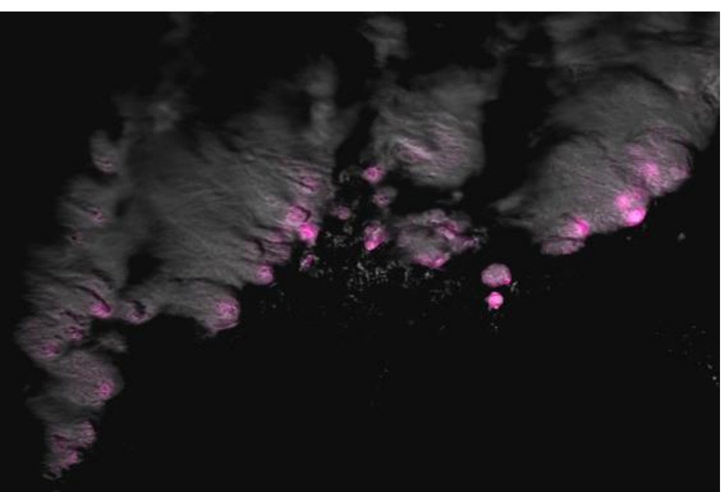
Visible Channel Texture Detection

Use a combination of statistical, frequency, and spatial analyses to identify anvils and quantify the degree of "texture" and shadowing present in a visible image associated with OT regions and gravity waves

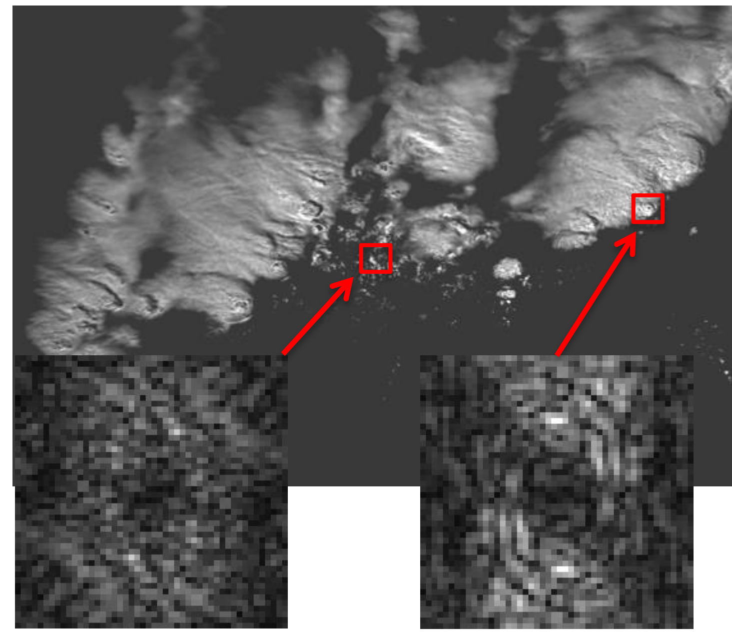
Input MODIS 1 km Visible Image



Final OT Candidate Regions Based on Visible Analysis



Statistical and Spectral Analysis To Identify Convective Anvils, OTs, and Nearby Gravity Waves



Fourier frequency spectrum of an area with random spatial variability.

No ring pattern in the spectrum

Fourier frequency spectrum of a typical OT region

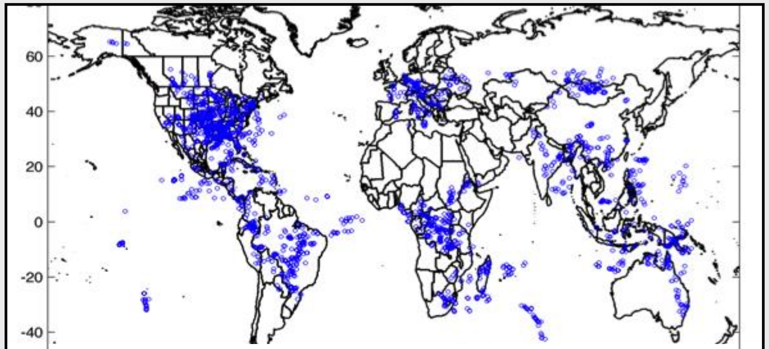
Ring fragments in the spectrum can be identified

To learn more about interpreting 2-D Fourier Transforms

http://qsimaging.com/ccd_noise_interpret_ffts.html

Logistic Regression and Final OT Detection Product

A database of ~2000 OT and non-OT events were manually identified in 100 Aqua MODIS 250 m visible images. This database is used to train and validate a logistic regression model to assign high detection probability to OT-like features



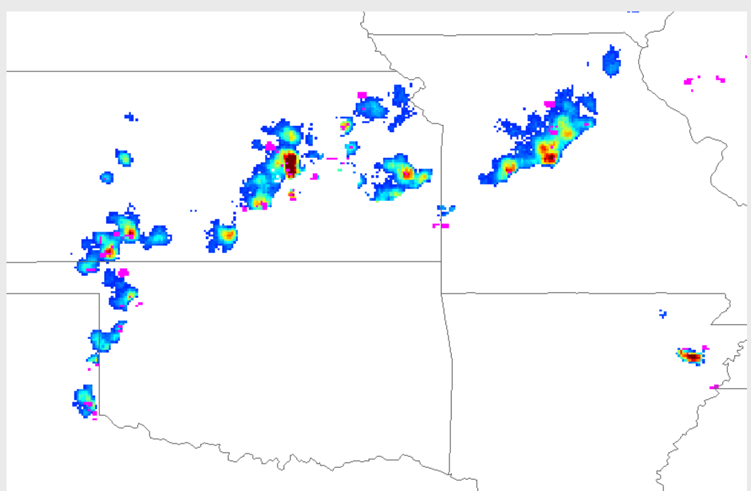
Manually Identified OT Regions In 100 MODIS Scenes

Regression Result = $W_0 + W_1$(OT-Mean Anvil IR BT) + W_2*(IR BT –Tropopause Temp) + W_3*(IR BT – MU LNB Temp)*

OT Probability

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

OT Probability ≥ 0.9 (Magenta) Atop Visible Texture Detection



GOES-R OT Detection Product Suite

A set of products are provided to allow a user to customize output for use in a variety of weather and climate analysis applications

1) **IR OT Detection Rating -> Quantifies how much a region 'looks like' an OT**

2) **IR-Based Anvil Cloud Detection**

3) **OT – Anvil Mean BT Difference -> Updraft intensity**

4) **IR/NWP-Based OT Probability**

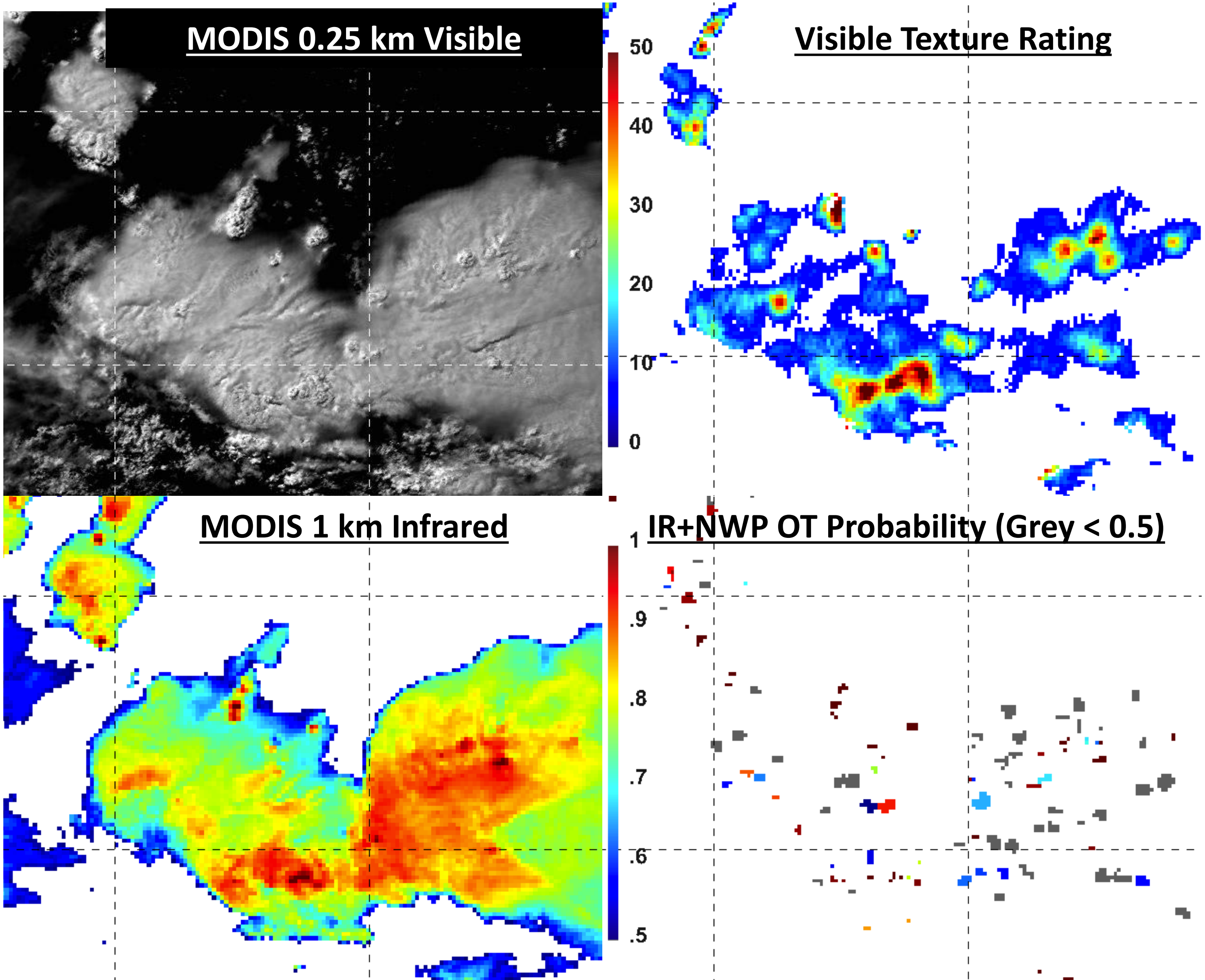
5) **Tropopause and Most Unstable Equilibrium Level Temperatures**

6) **Visible Texture Detection Rating**

1) **OT Height, Pressure, and Potential Temperature**

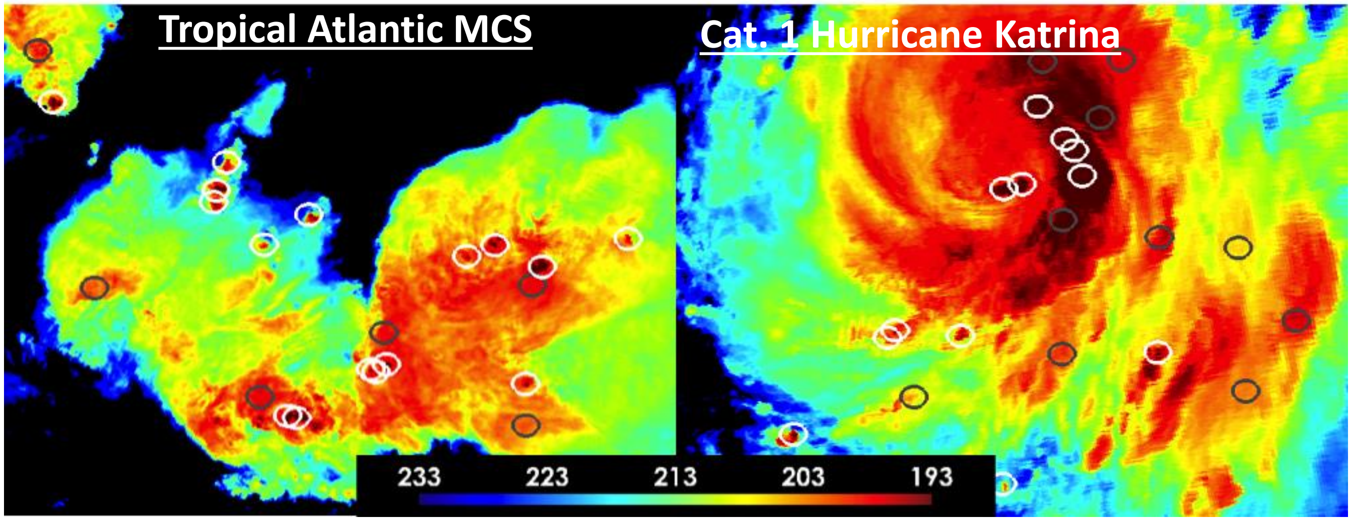
2) **Parallax correction magnitude**

Automated Overshooting Cloud Top Detection
Aqua MODIS, Southern Brazil, 8 March 2009 at 1735 UTC



OT Detection Validation

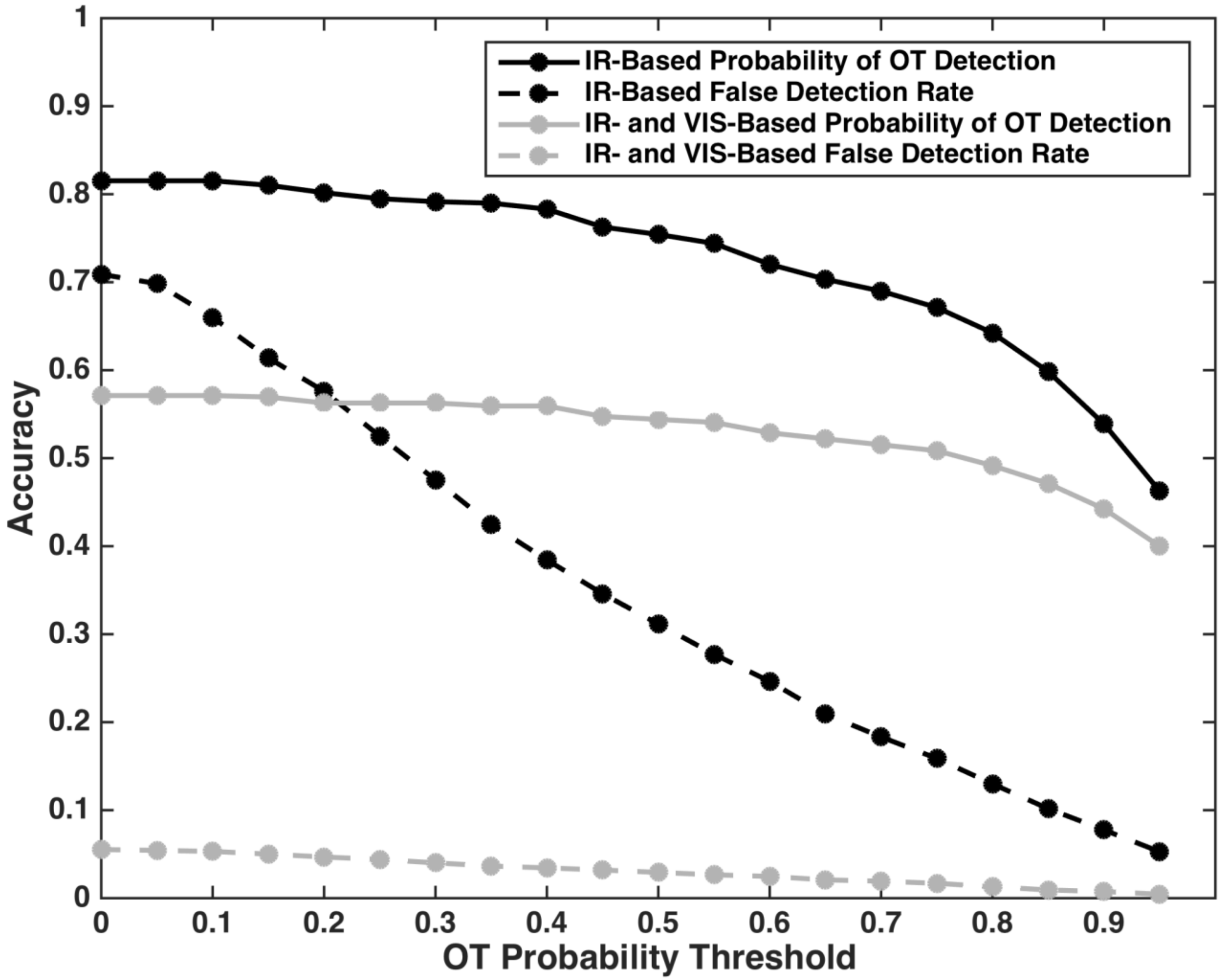
How Well Can The Algorithm Discriminate Between Human-Identified OT Regions (White Circles) and Non-OT Regions (Grey Circles)?



Number of OT Regions 809	**Number of Non-OT Regions 615**
Number of OT Regions With OT Probability ≥ 0.5 593 (41.6%)	Number of Non-OT Regions With OT Probability ≥ 0.5 58 (4.1%)
Number OT Regions With OT Probability < 0.5 or Lack of OT Detection 216 (15.2%)	Number of Non-OT Regions With OT Probability < 0.5 or Lack of OT Detection 423 (39.1%)
OT Discrimination Skill: 80.7%	

OT Detection Validation

How Does The Algorithm Perform Relative to Human-Identified OTs Across 33 MODIS Scenes?



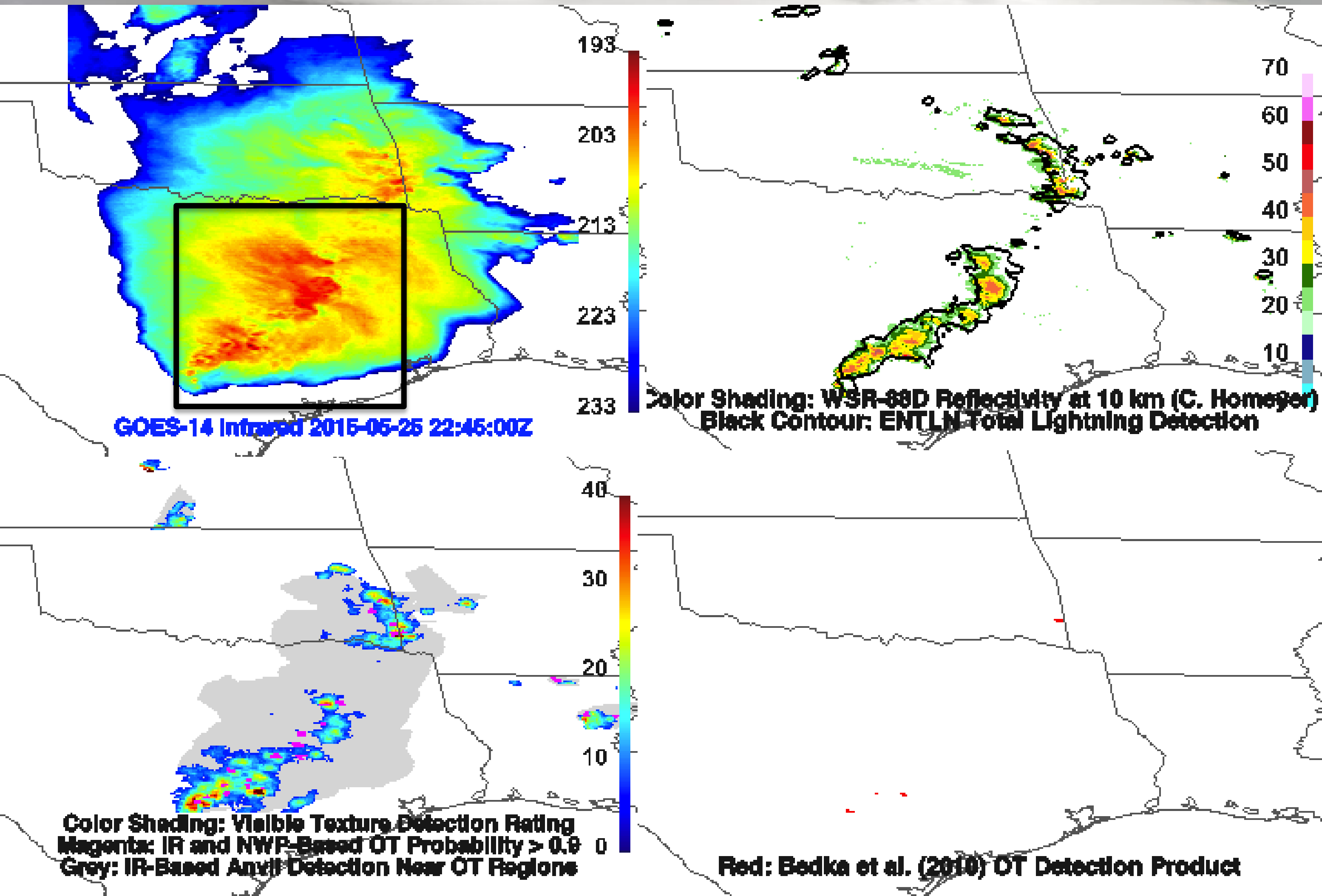
Biggest Challenge for Visible Detection

Storms with Small Anvils

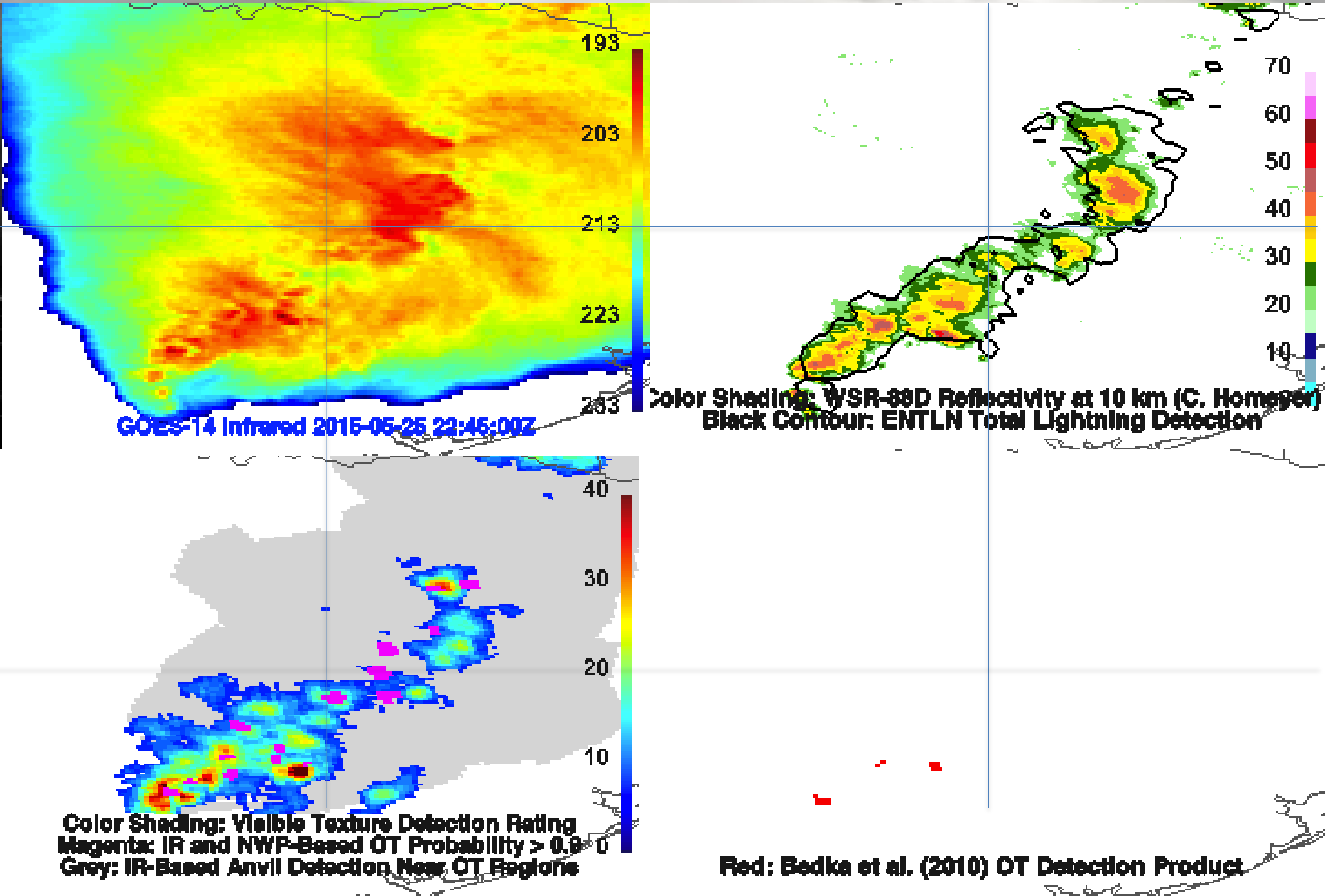
OT Detection Validation

	Probability of OT Detection (POD)	False Detection Rate (FAR)
Bedka et al. (2010) Candidates and Detection Criteria	35.1%	24.9%
Improved Candidates and Bedka et al. (2010) Detection Criteria	27.3%	1.1%
OT Probability ≥ 0.7	69.2%	18.4%
OT Probability ≥ 0.7 and VIS Rating Detection	51.4%	1.6%

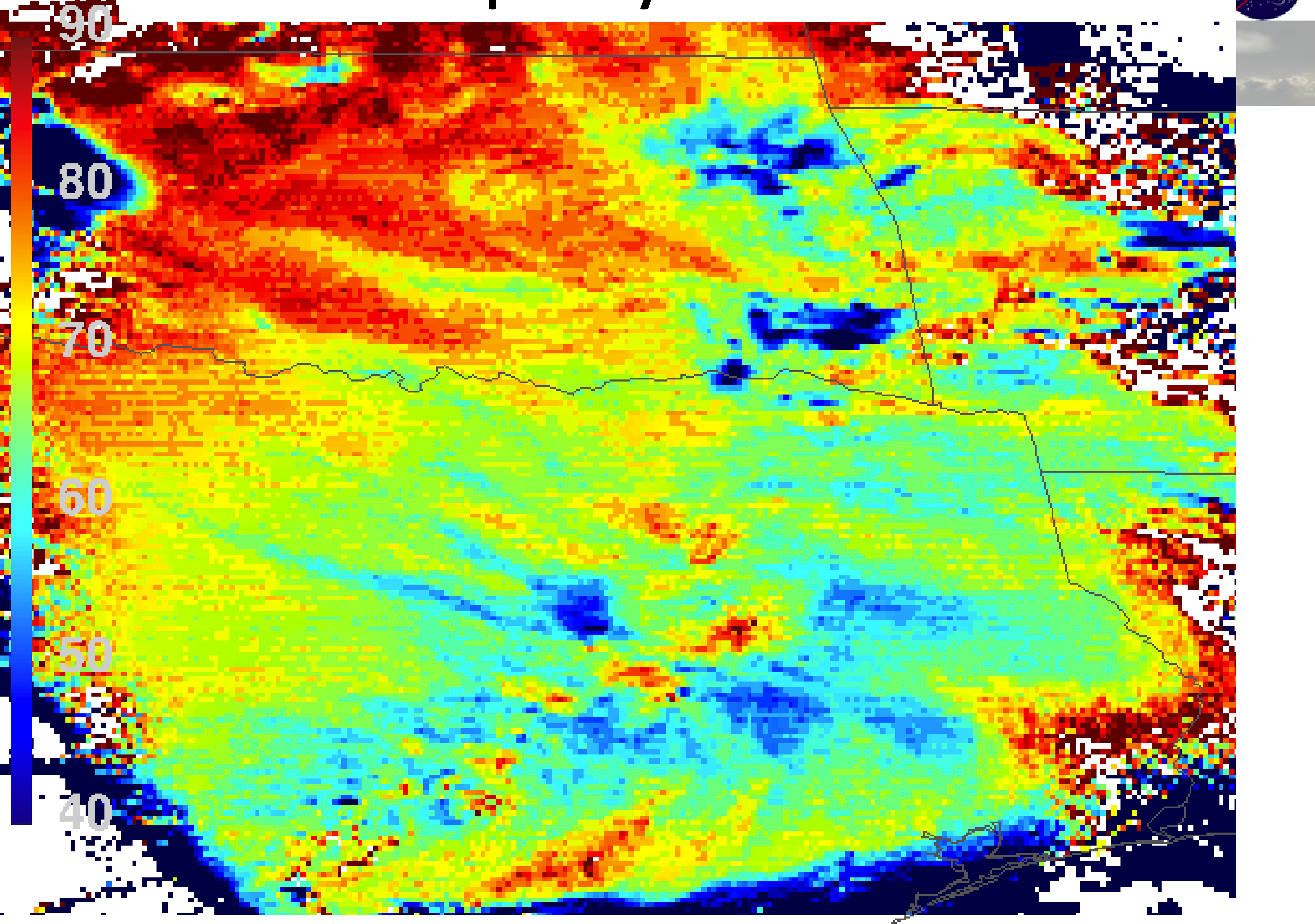
GOES-14 Severe Storms Over Texas: 25 May 2015 at 2245 UTC



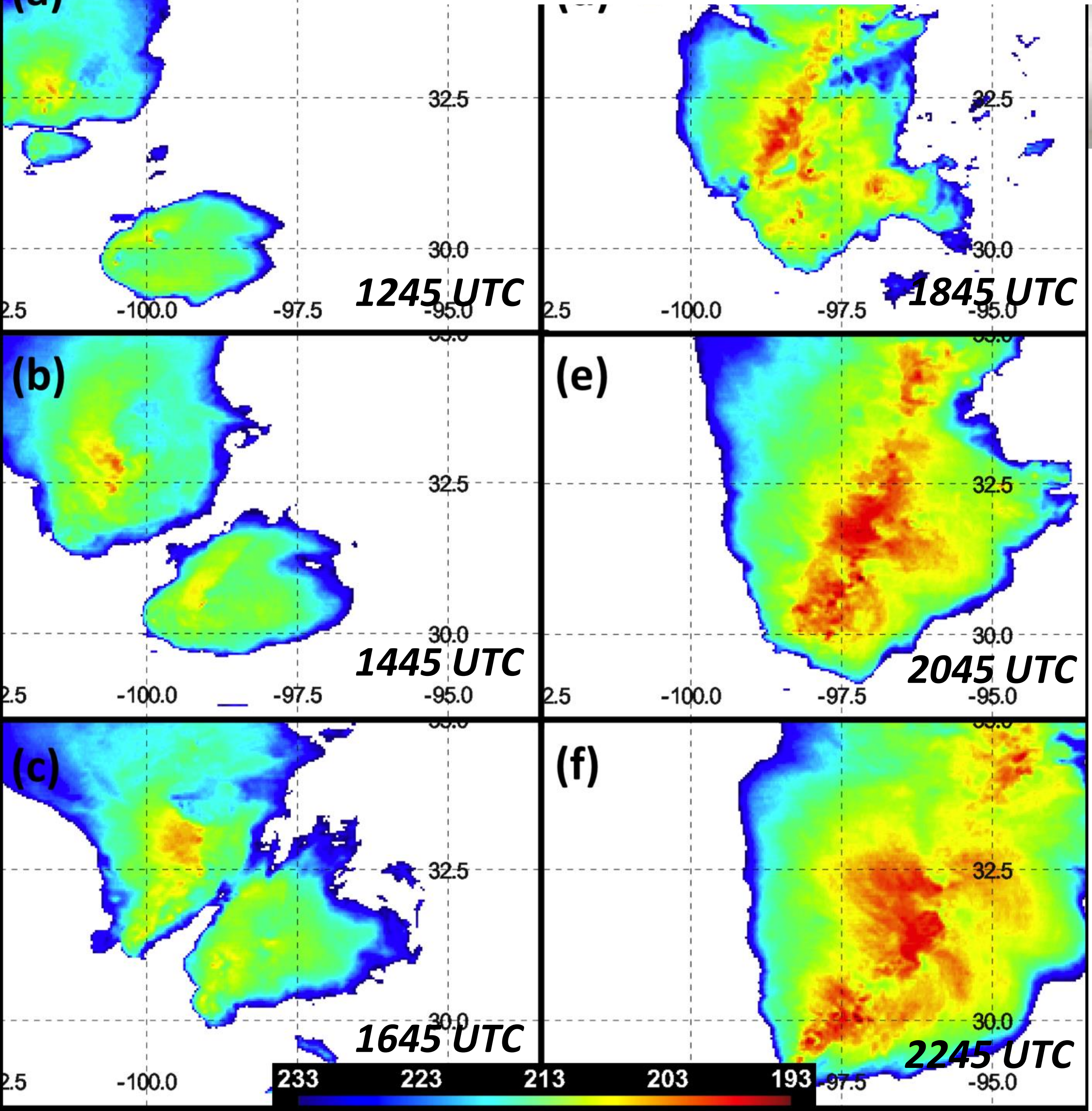
GOES-14 Severe Storms Over Texas: 25 May 2015 at 2245 UTC



Small Ice In Optically Thick Anvil = Plume

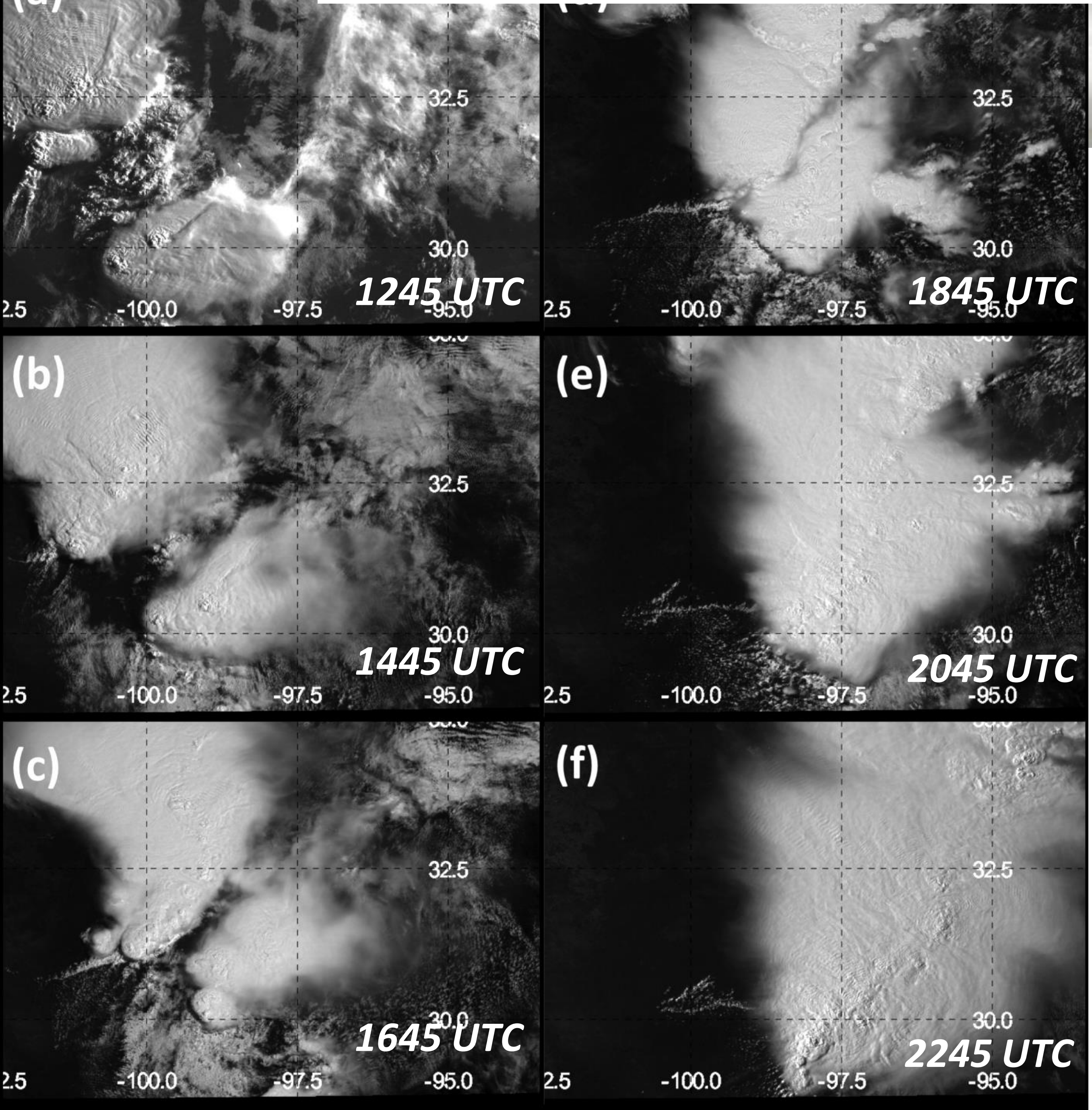


GOES-14 Severe Storms Over Texas: 25 May 2015



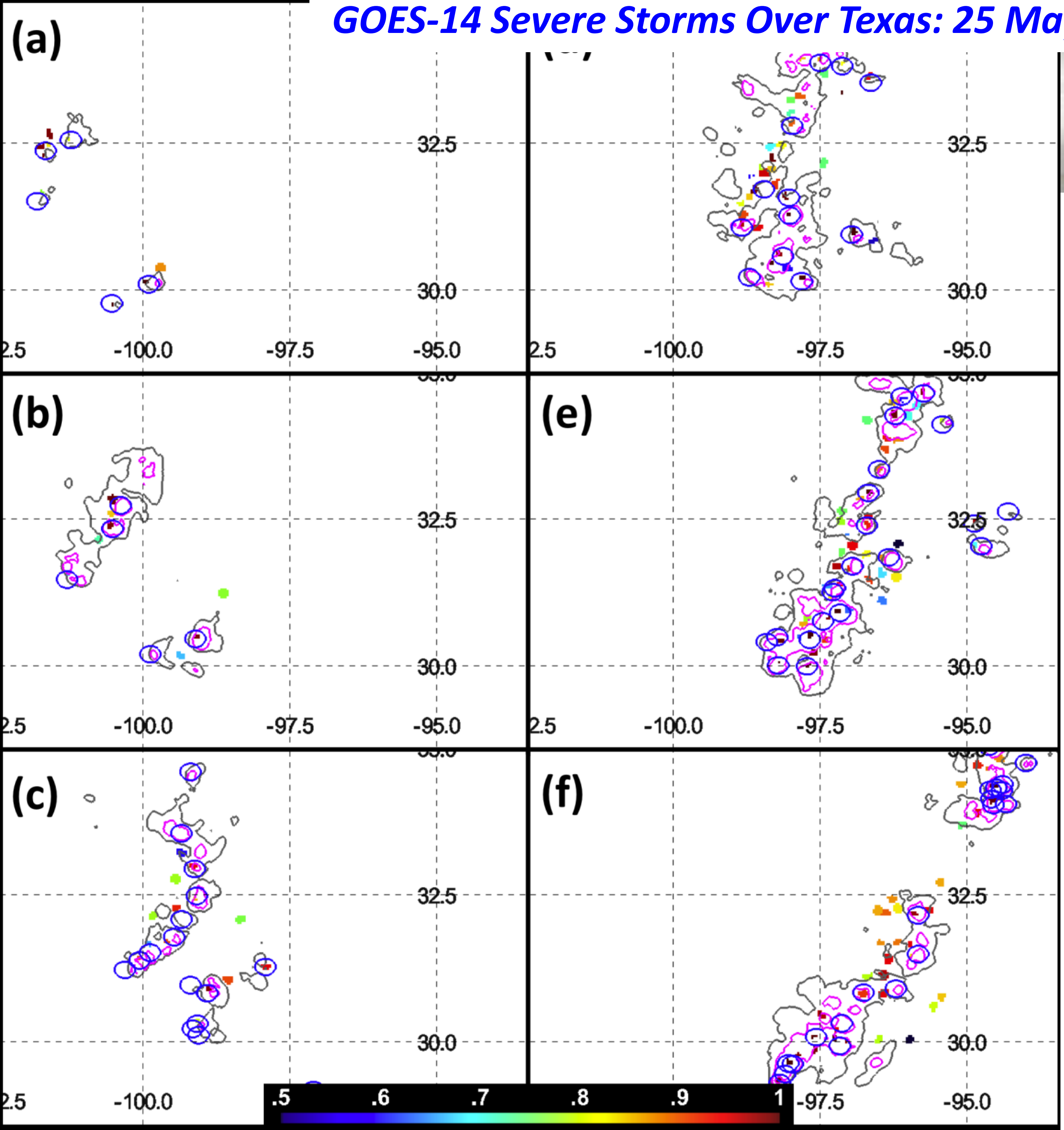
GOES-14 Infrared

GOES-14 Severe Storms Over Texas: 25 May 2015



GOES-14 Visible

GOES-14 Severe Storms Over Texas: 25 May 2015



Blue Circles

Human OT Identifications

Grey Contours

VIS Texture Detection

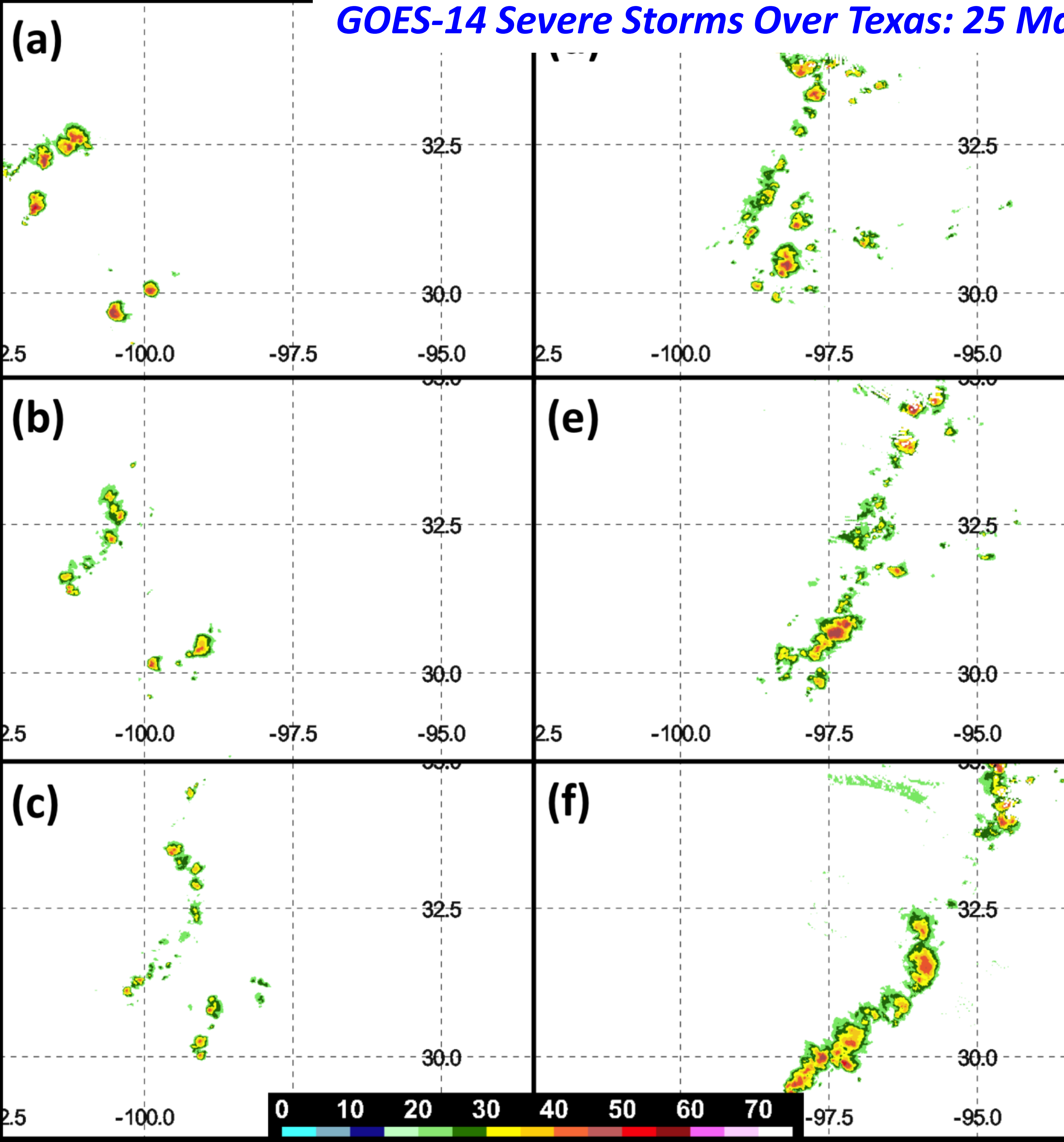
Magenta Contours

Significant VIS Texture Detection

Color Shading

OT Probability

GOES-14 Severe Storms Over Texas: 25 May 2015

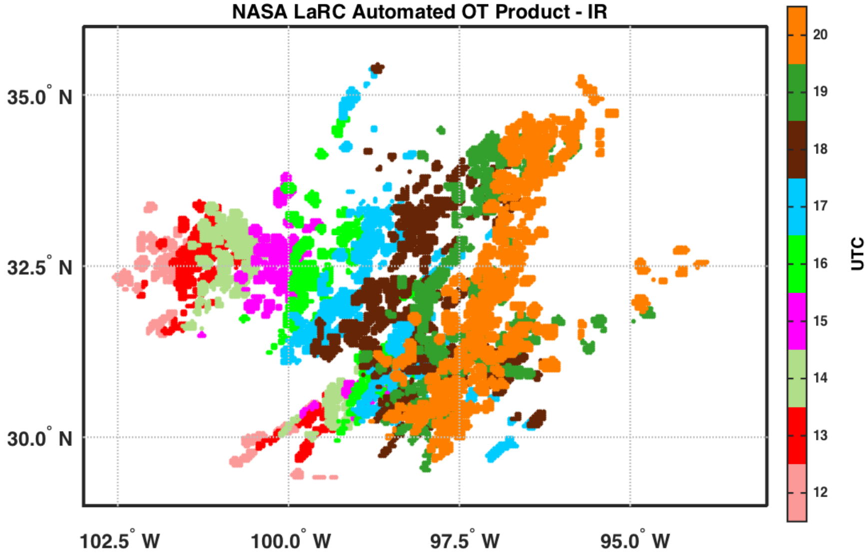


Radar Reflectvity at 10 km

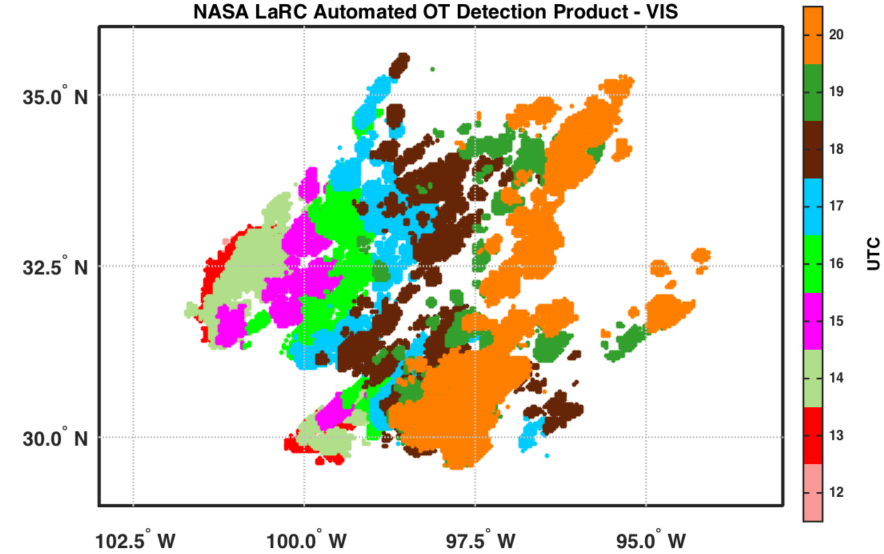
Data Courtesy of Cameron Homeyer (University of Oklahoma)

25 May 2015 GOES-14 Super Rapid Scan OT Detection Animation

IR/NWP-Based OT Detection

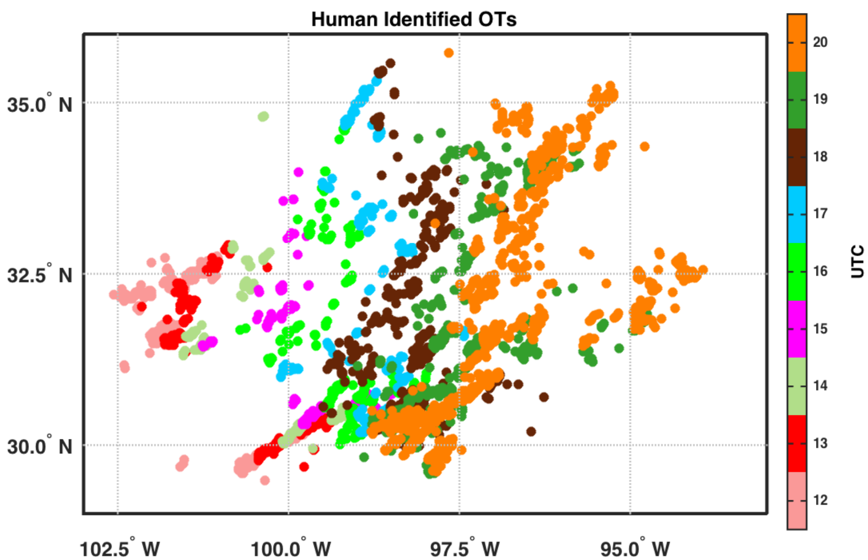


Visible OT Texture Detection

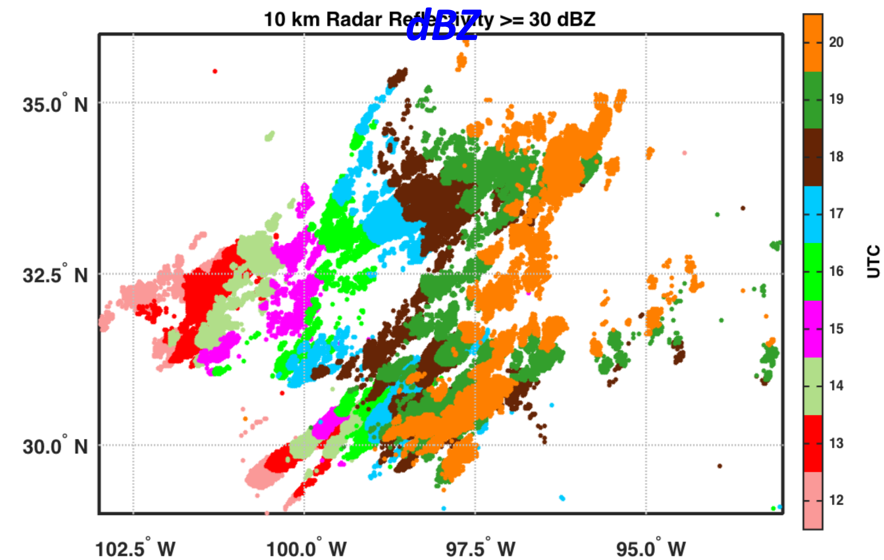


25 MAY 2015: 1200-2100 UTC

Human OT Identifications



10 km Radar Reflectivity > 30 dBZ

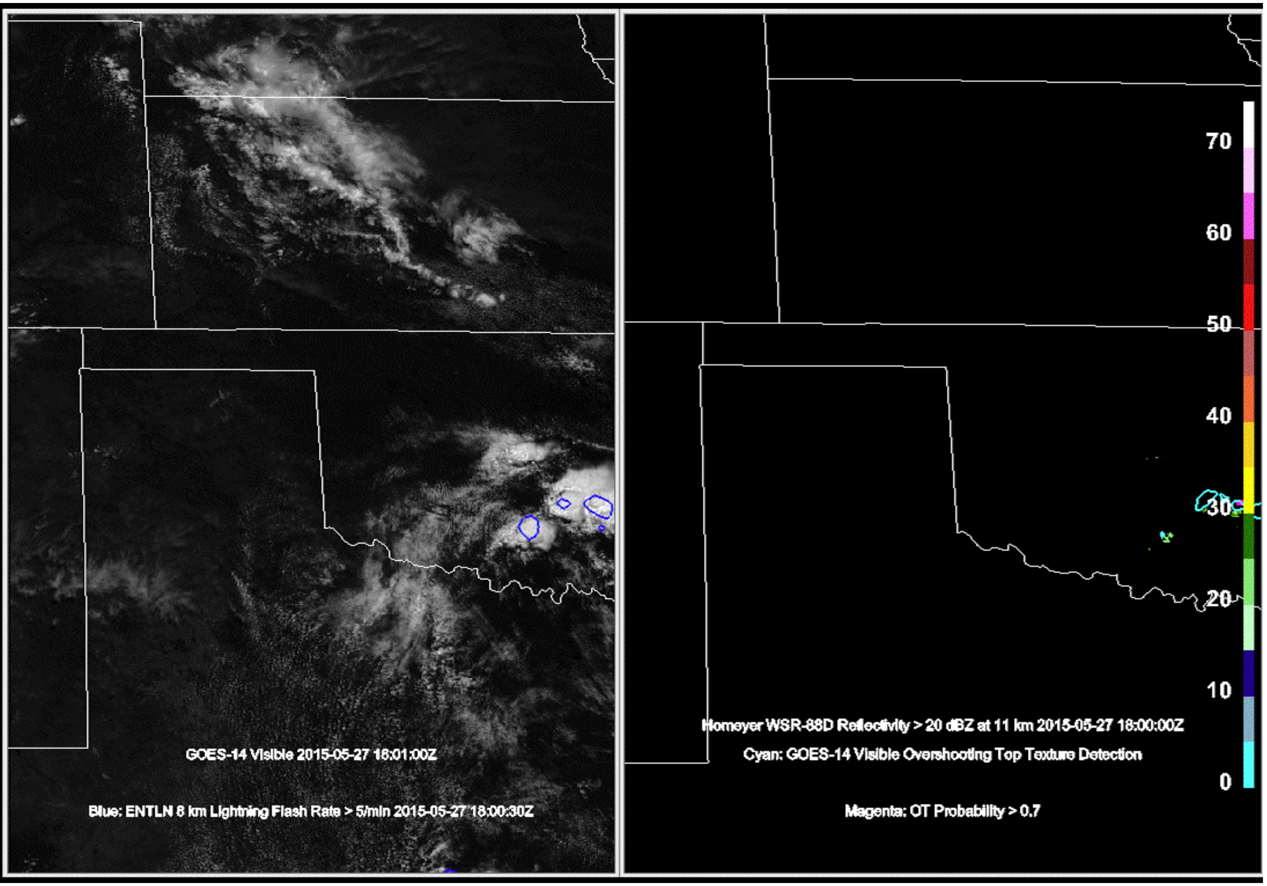


GOES-14 Super Rapid Scan Imagery and OT Detection Products, ENTLN Total Lightning Detection, and Radar Reflectivity: 27 May 2015

YOU SHOULD WATCH THIS ANIMATION! https://youtu.be/SXZbMjb6aNw

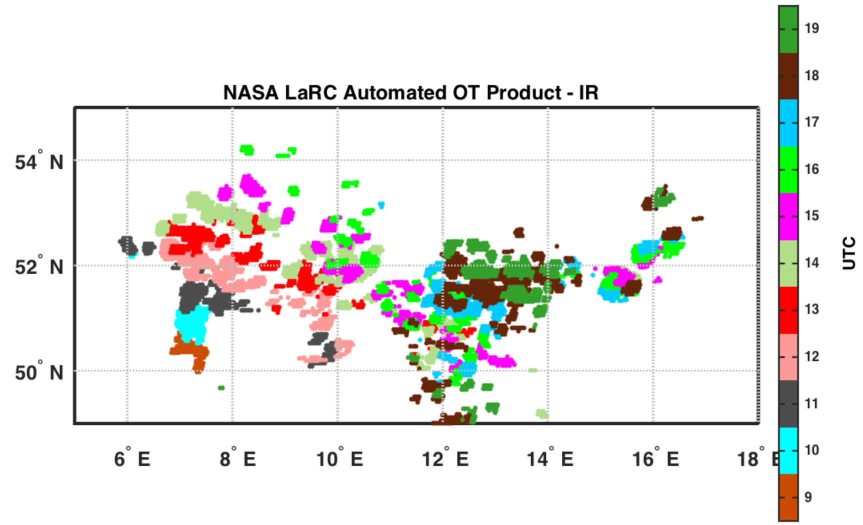
27 May 2015 at 2255 UTC
GOES-14 Visible Overlaid With Total Lightning Flash Rate (blue)

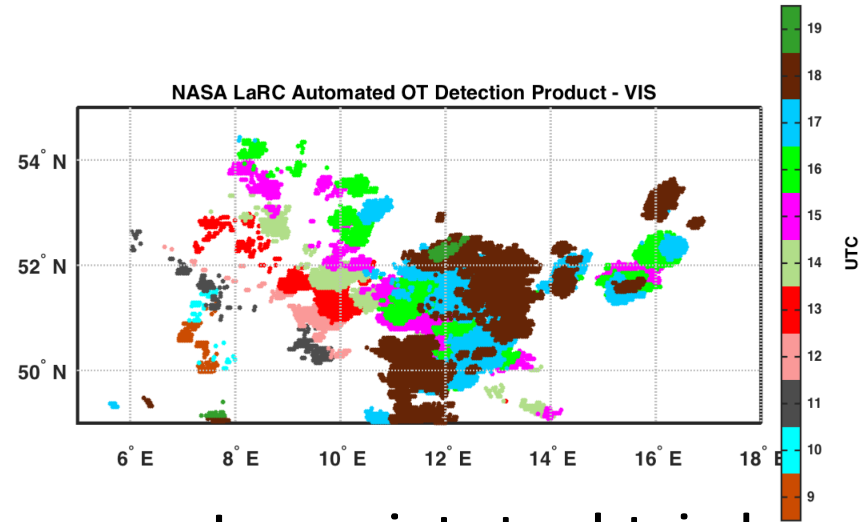
Visible Texture Detection (cyan), IR+NWP OT Detections (magenta), and Radar Reflectivity at 11 km (colors)



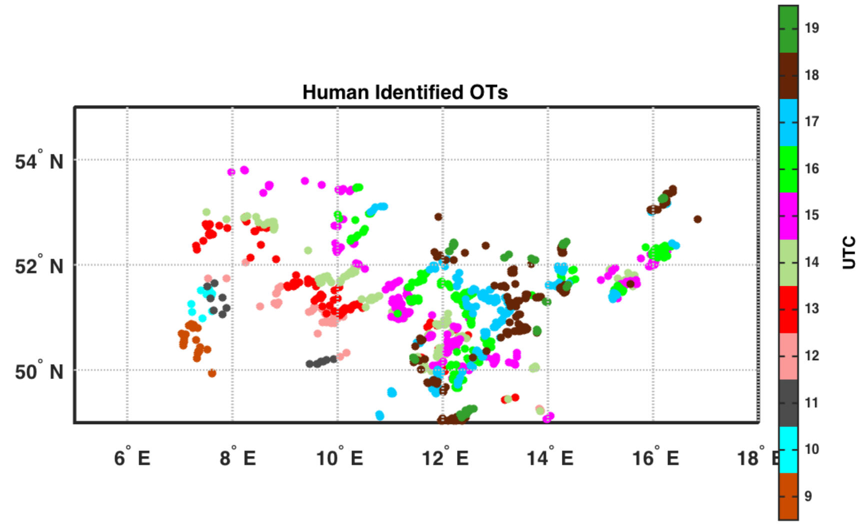
20 June 2013 MSG SEVIRI Super Rapid Scan OT Detection Animation

20 June 2013 MSG SEVIRI Super Rapid Scan OT Detection Map

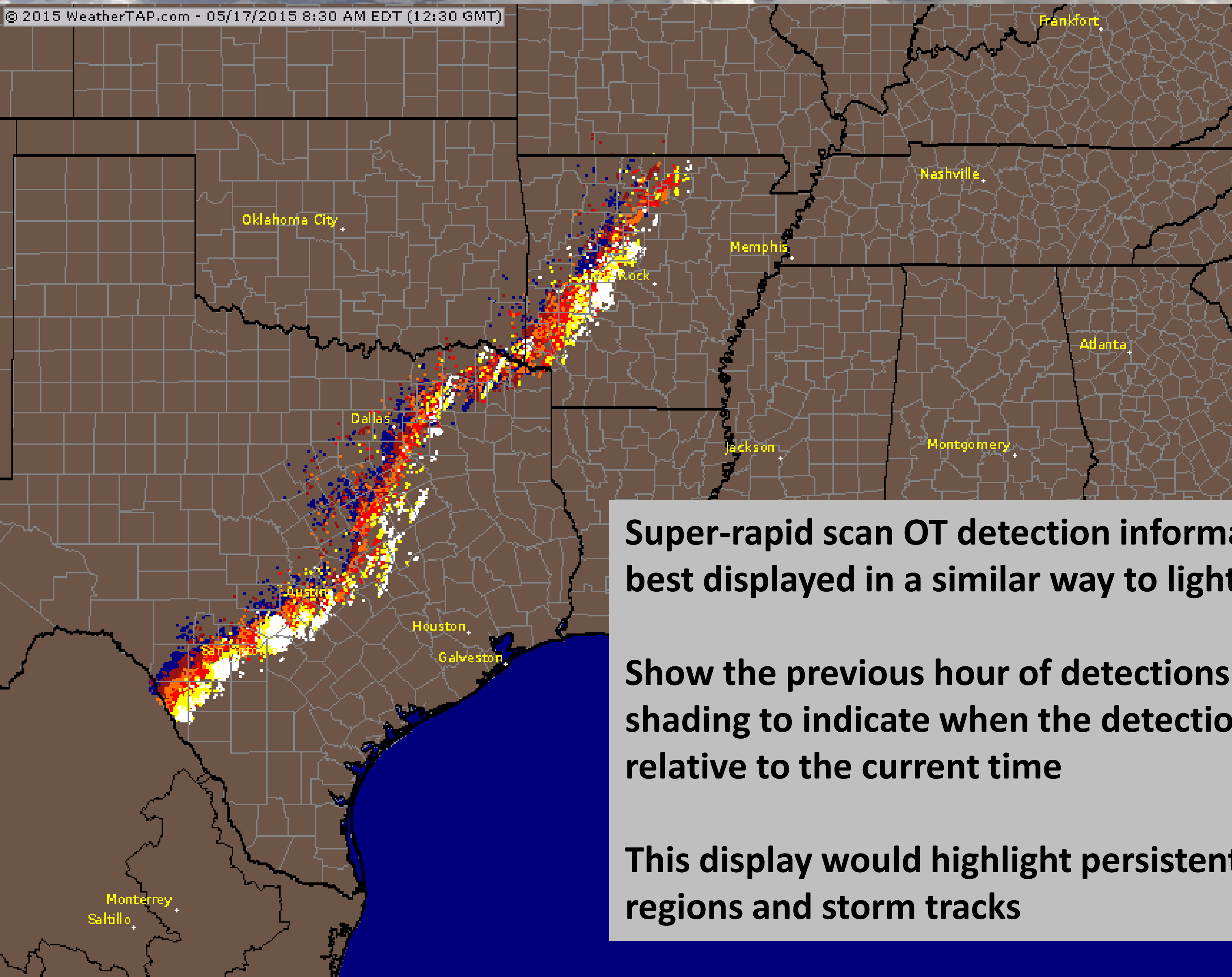




Increase in texture late in day fixed in latest code version



Time Relative Lightning Detection Animation



Super-rapid scan OT detection information would be best displayed in a similar way to lightning detections

Show the previous hour of detections with color shading to indicate when the detection occurred relative to the current time

This display would highlight persistent intense updraft regions and storm tracks

Summary: Automated OT Detection

- **OT detection based on IR BT thresholding or spectral tests *without taking into account cloud spatial characteristics* will not provide a product that is accurate enough for the weather and climate community**

- **An automated overshooting cloud top (OT) detection algorithm has been recently improved at NASA LaRC in support of the GOES-R Risk Reduction Research program**

- **The algorithm uses advanced statistical, spatial, and spectral analyses to identify OT signatures at the individual satellite imager (~5 km) pixel scale using data**

- **An automated OT detection product has been demonstrated or could be used in a number of applications:**
  1) Real-time hazardous storm and aviation weather nowcasting
  2) Development of weather hazard risk models by the reinsurance industry
  3) Analysis of storm distribution throughout the diurnal cycle in data poor regions
  4) Analysis of the origin of anomalous stratospheric water vapor
  5) Validation of weather and climate model predictions of UTLS-penetrating storms

- **The algorithm has been tested extensively using data with ~1.5 km Visible and ~6 km IR imagery, making it applicable to historical GEO and LEO imager data**

- **The highly efficient nature of the algorithm coupled with immediate access to the entire geostationary image archive enables development of long-term OT climate data records that can be used by the community to derive trends in hazardous storm frequency and distribution**

Analysis of Hazardous Storms in Super Rapid Scan Imagery

Introduction

- GOES-14 operated in an experimental 1-minute "super-rapid scan" observations for GOES-R (SRSOR) mode during many days from 2012-2016 to emulate the high temporal resolution sampling of the future GOES-R Advanced Baseline Imager (ABI)

- MSG SEVIRI has also been operated in 2.5 min mode for a limited number of events

- GOES (MSG) is often operated in 7.5 min (5 min) rapid-scan mode. This imagery has been used to study signatures present within severe storms such as rapid cloud-top cooling, OTs, and the cold-ring/U/V signatures

Introduction

- **Though the GOES/MSG imaging is "rapid", ~5 min gaps between images cause some uncertainty regarding:**
  1) *When do these signatures first appear and why did they form (or dissipate)?*
  2) *How do the signatures evolve over time?*
  3) *How do satellite observations complement and add value to radar and lightning observations and their derived products in the storm forecast/warning process?*

- **GOES-14 1-min SRSOR and 2.5 min SEVIRI data provide a unique opportunities to address these questions and highlight the value of high frequency satellite observations to the operational forecasting and research communities**

What Are Your Thoughts On Super Rapid Scan Satellite Imagery?

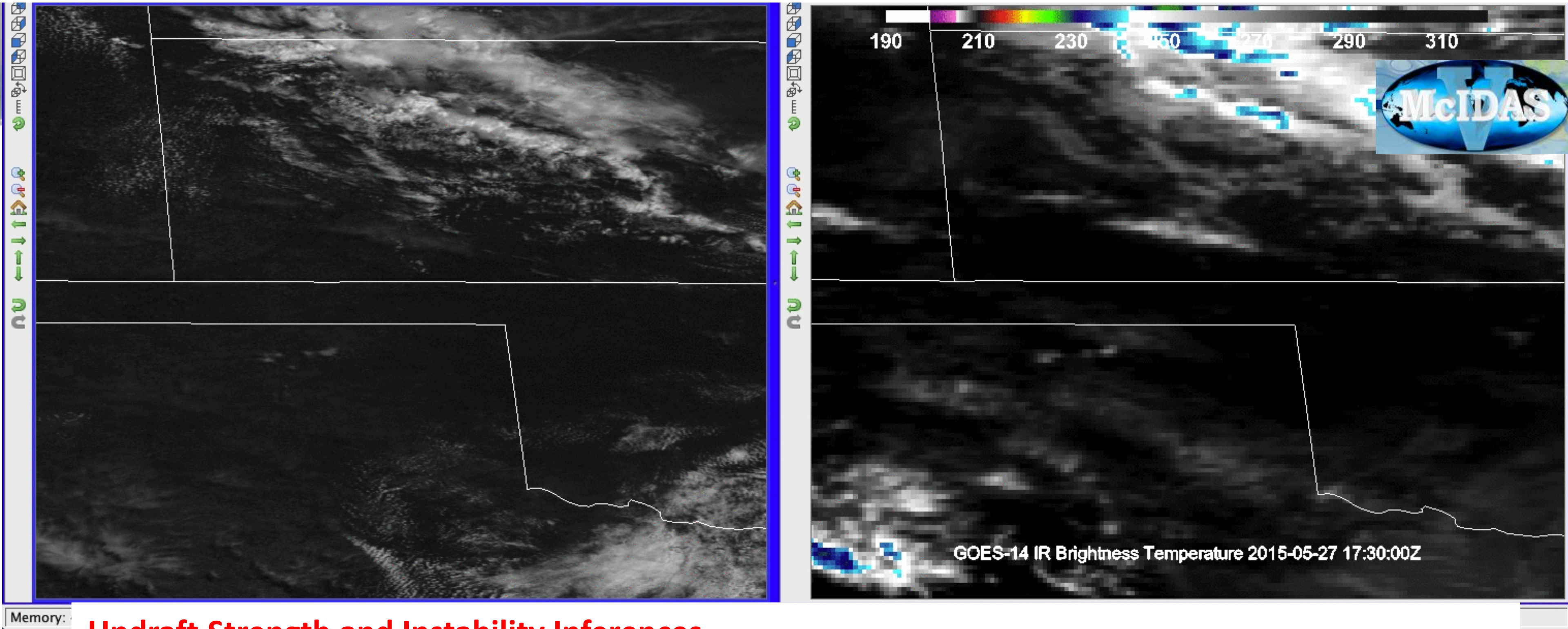
Positive Thoughts I've heard

- Beautiful animations
- Can monitor rapidly evolving mesoscale processes (early cumulus evolution, convective initiation, overshooting, above-anvil plume initiation) not seen in 15 minute data
- Enables earlier and more accurate warnings
- Great for research purposes

Negative Thoughts I've Heard

- Simply "pretty pictures"
- Little practical or operational value
- Cost of collecting/storing the data greater than the value
- It doesn't matter how fast the satellite scans…satellite cloud top information doesn't offer value beyond what is provided by NWP, radar, and total lightning datasets

How Can We Identify Severe Storms Within Satellite Imager Data?



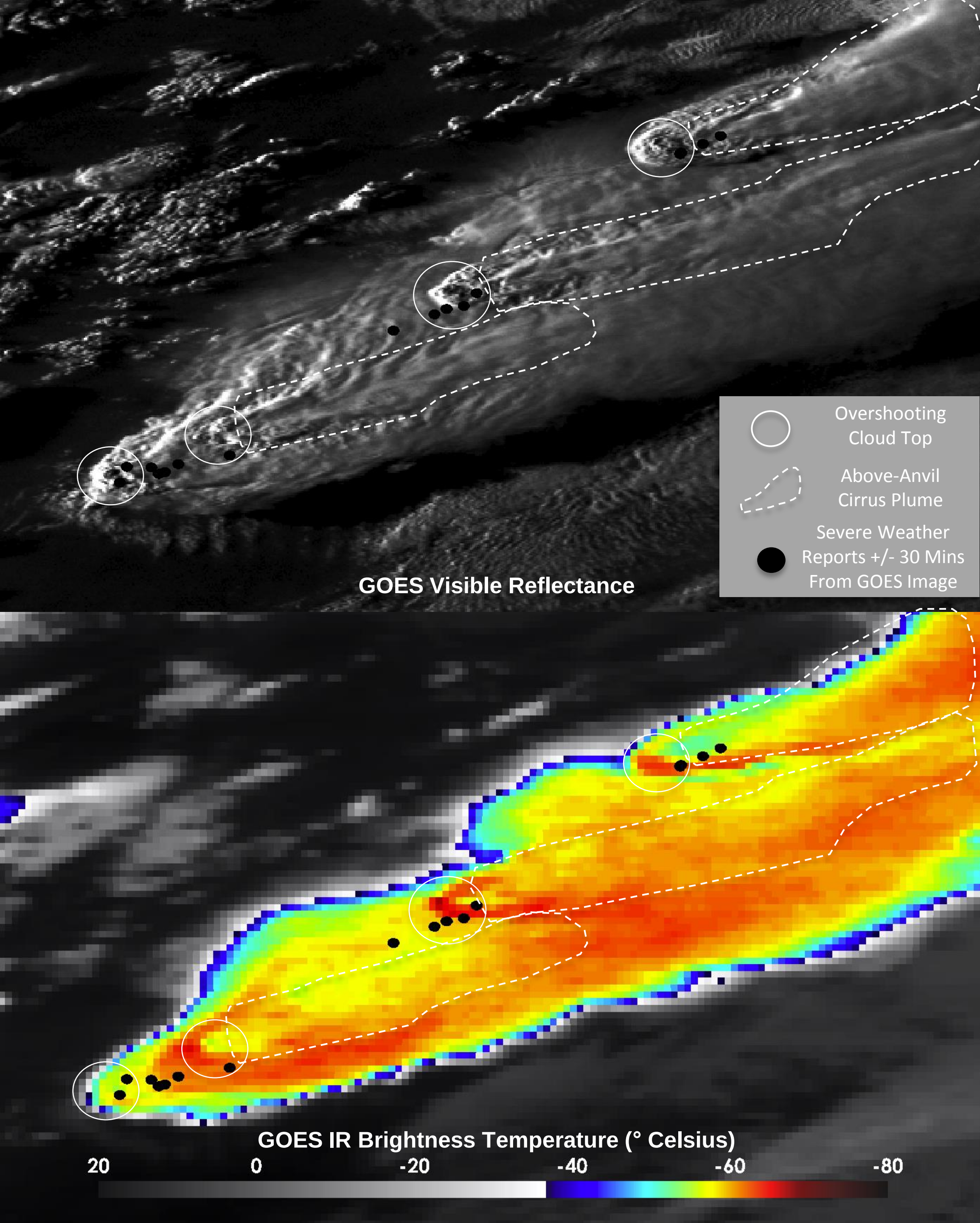
Updraft Strength and Instability Inferences

- GOES instability indices in clear sky regions (Li et al. 2012)
- Rapid cloud top cooling during storm initiation (Mecikalski and Bedka 2006; Cintineo et al 2013)
- Rapid anvil expansion (Machado et al 1998)
- Overshooting cloud tops (Bedka at al. 2010-2012, 2015)
- Enhanced-V / Cold-Ring / Above-anvil cirrus plume signatures (Stevak et al. 2010, 2013, Bedka et al. 2015)
- Small ice crystals near updrafts (Rosenfeld et al. 2008, Lindsey et al 2006)

Wind Shear and Storm Rotation

- Vorticity/Divergence near overshooting top region (Apke et al. 2016)
- Anomalous storm movement relative to neighboring storms (Lindsey and Bunkers 2005)
- Anomalous inflow bands / RFD clouds (Weaver and Lindsey 2004)

Above Anvil Cirrus Plume and Severe Weather Relationships



- **Detailed analysis of every daytime storm present during the 2012 GOES-14 1-min SRSO period indicates that 57% (33 of 58) of plume-producing storms were severe**

- **Plumes appeared in advance of a severe weather report for 28 of the 33 (85%) events**

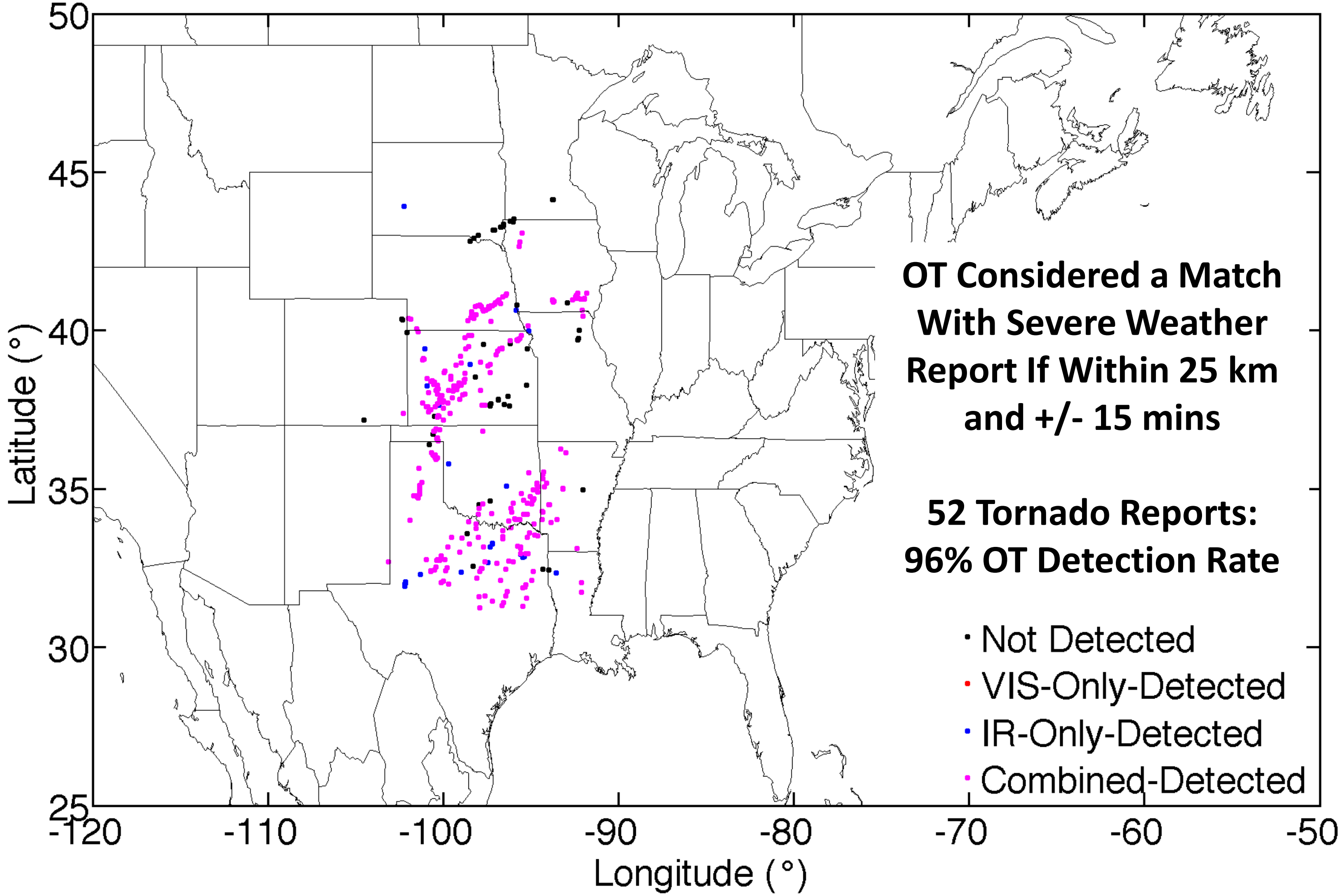
- Plumes appeared an average of 18 mins in advance of severe weather with a standard deviation of 14 mins.

- **For the 48% of the events observed by all GOES scan modes:**

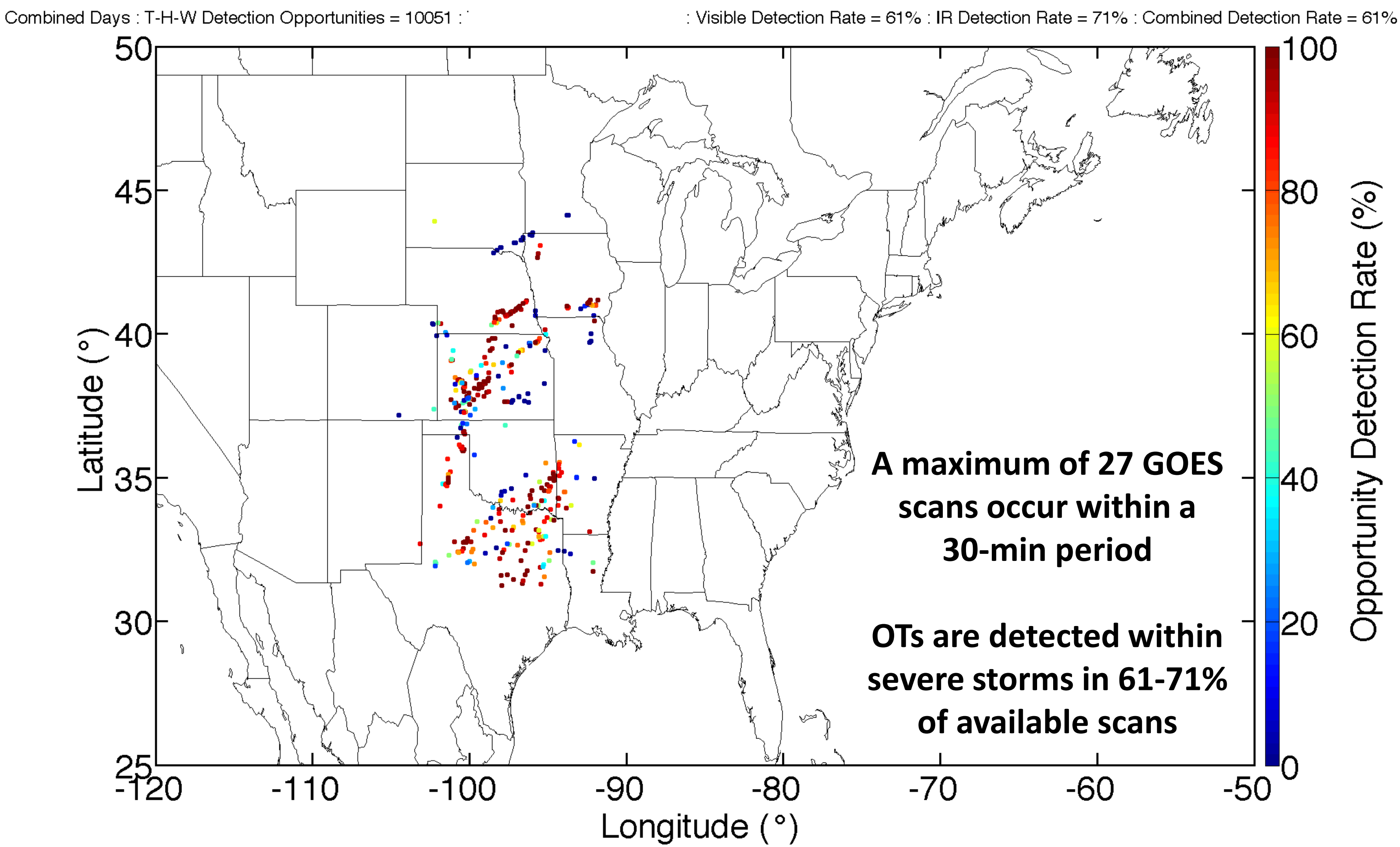
- 1-min SRSO lead time=27 mins
- 7.5 min rapid scan lead time=22 mins
- 15-30 min operational lead time= 18 mins

Super Rapid Scan OT Detection
Severe Weather Report Comparisons
11 May 2014, 25, 27 May 2015

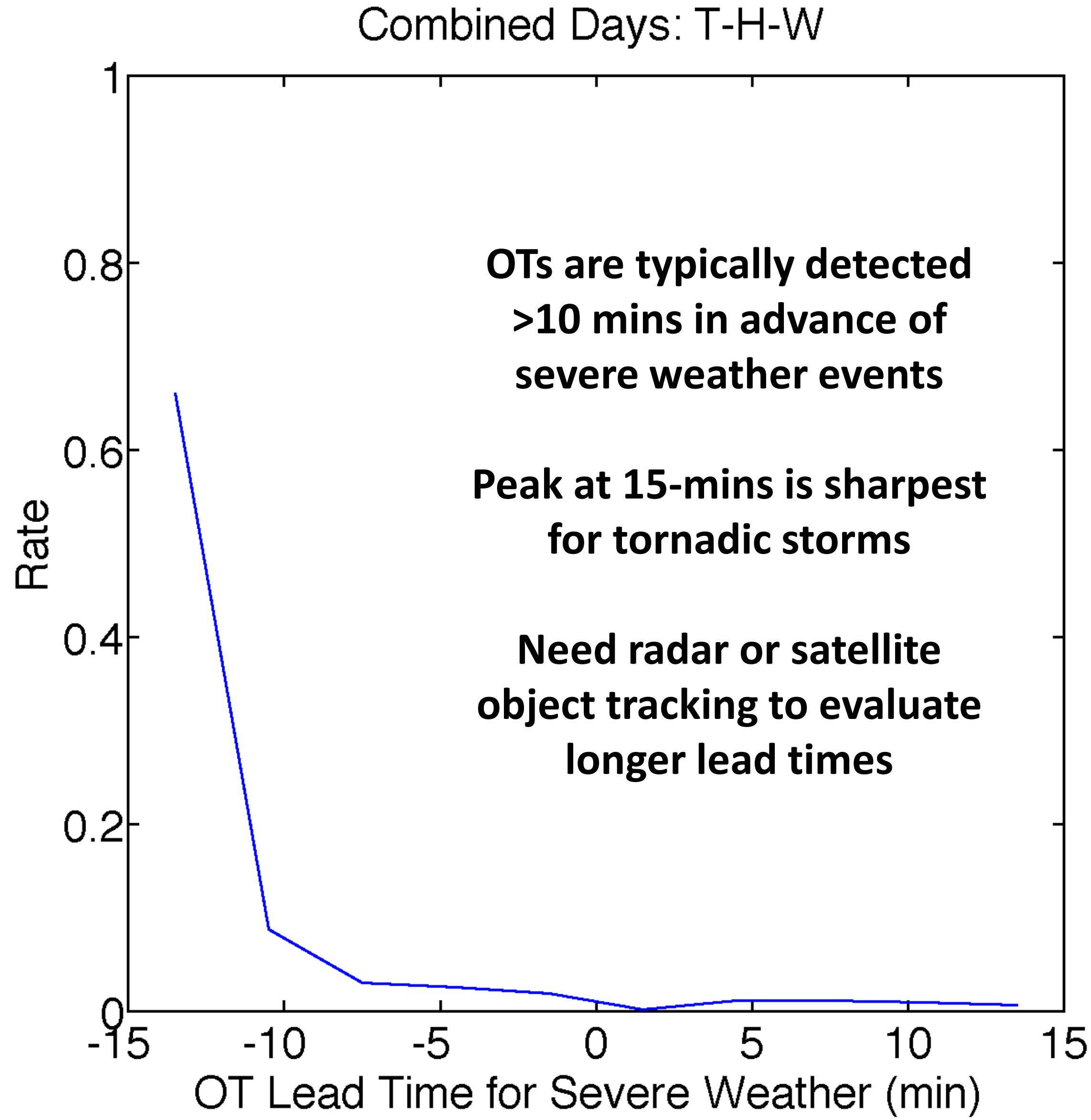
Combined Days : T-H-W Reports = 424 : : Visible Detection Rate = 78% : IR Detection Rate = 87% : Combined Detection Rate = 78%



What Fraction of the Total Number of 1-min Images Surrounding a Severe Weather Report Was An OT Detected?

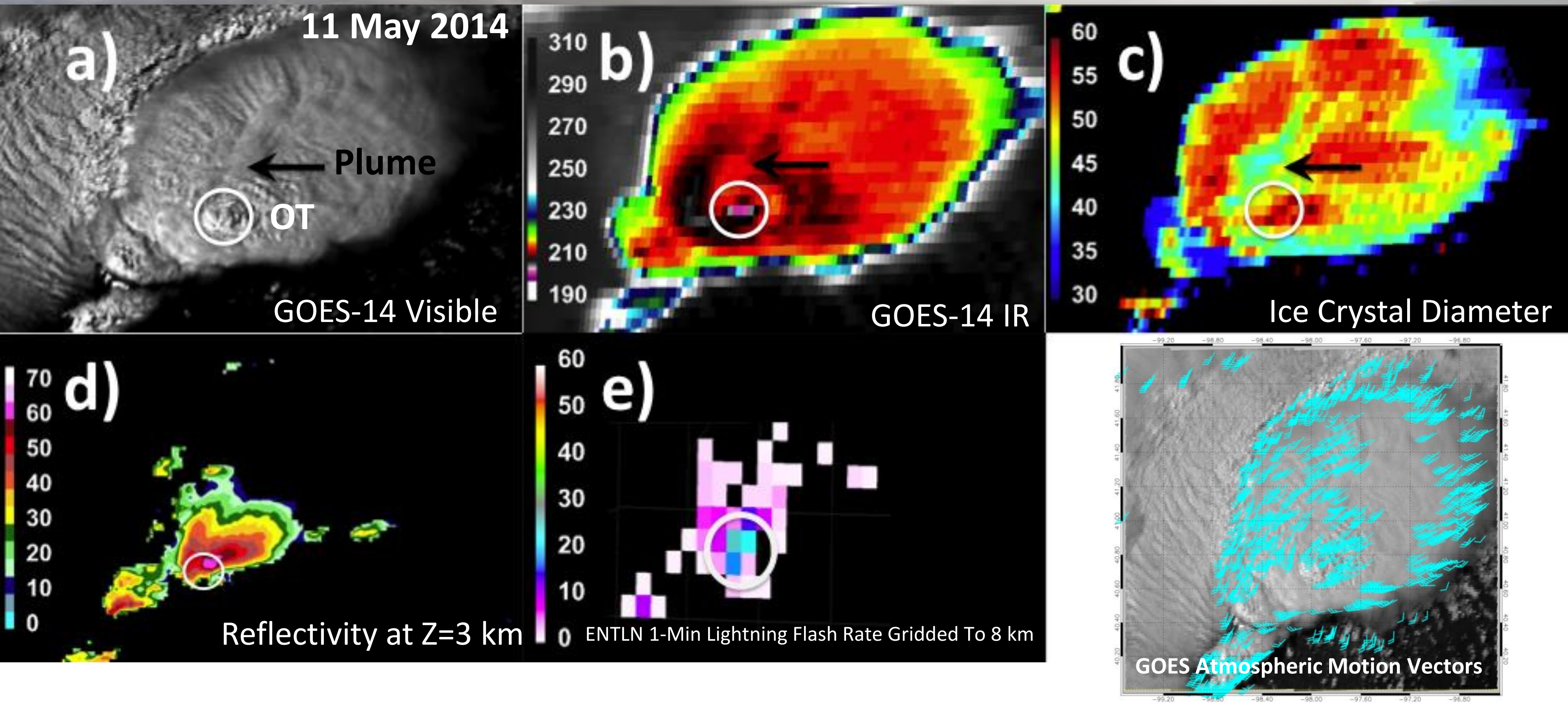


When Was The First OT Detected With Respect to the Time of a Severe Weather Report?



NASA ROSES Tornadic Storm Research

K. Bedka (NASA LaRC), C. Homeyer (OU), and J. Mecikalski (UAH)



The primary objectives of this effort are to use advanced satellite-based observations and products to be available at up to 30-sec frequency during the GOES-R era to:

1) Characterize severe hail, wind, and tornadic storm evolution depicted by remote sensing data

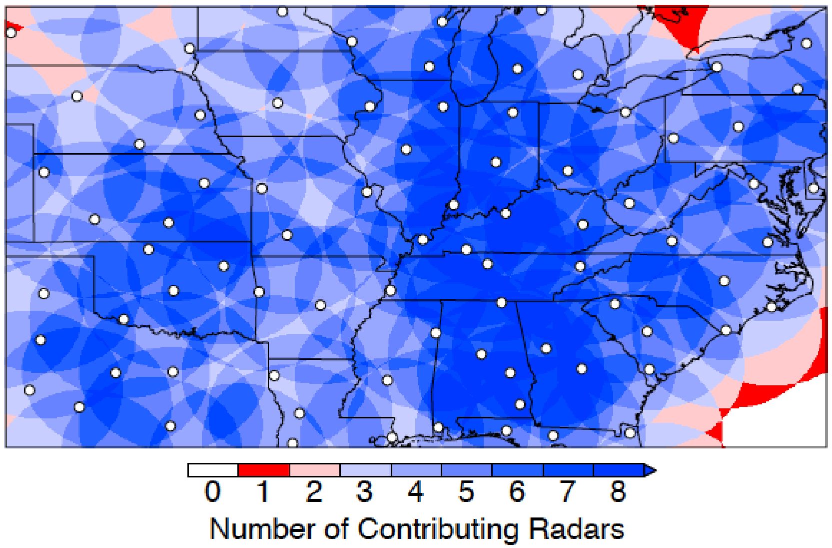
2) Recognize unique signatures that occur in advance of severe weather

3) Develop and demonstrate state-of-the-art satellite-derived products that could potentially improve severe storm detection and forecast lead-time

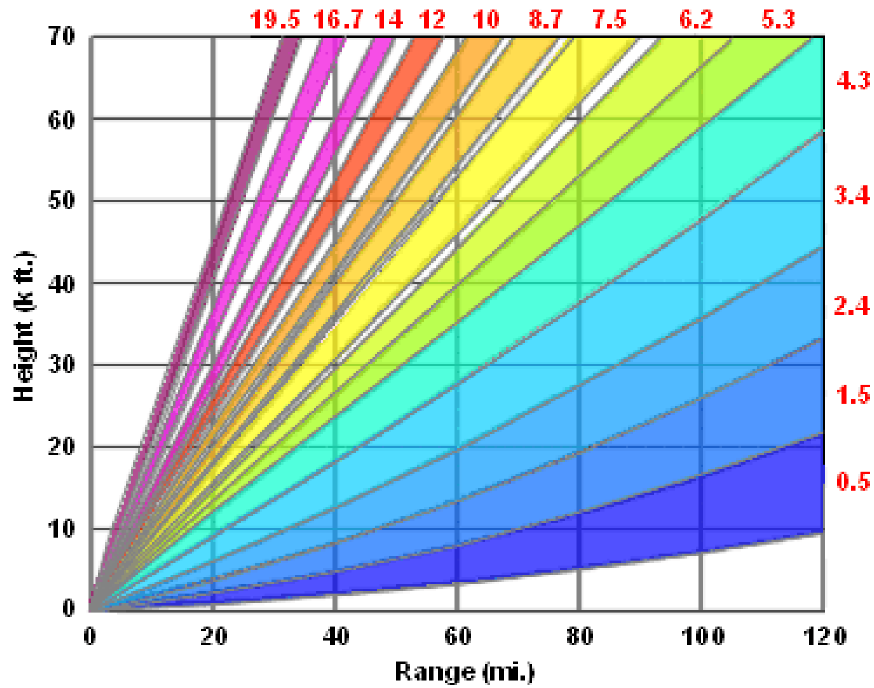
Radar-Based Automated Storm Object Tracking

Cameron Homeyer (University of Oklahoma)

Number of WSR-88D Contributing to 4-D Radar Mosaic Product



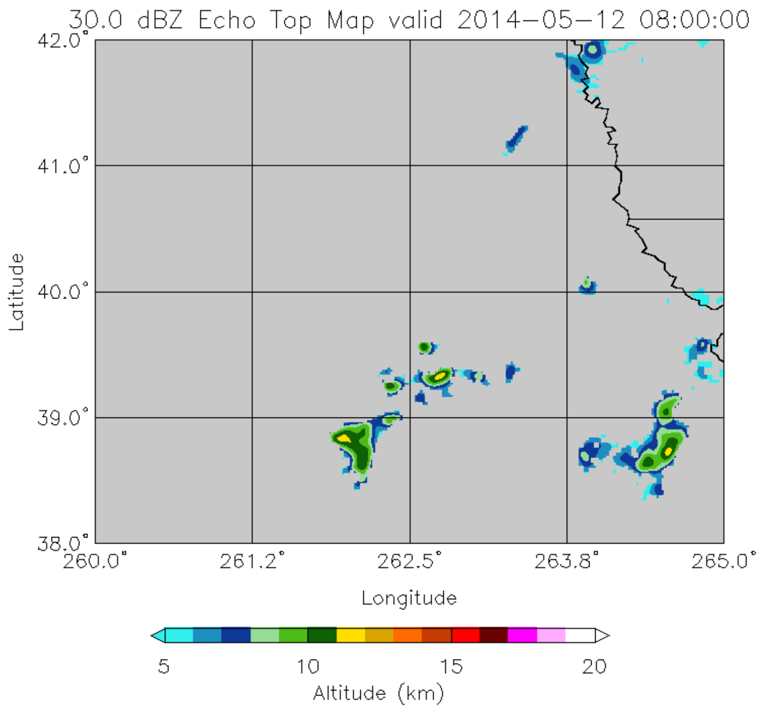
Solomon et al. (JAMC, 2016)

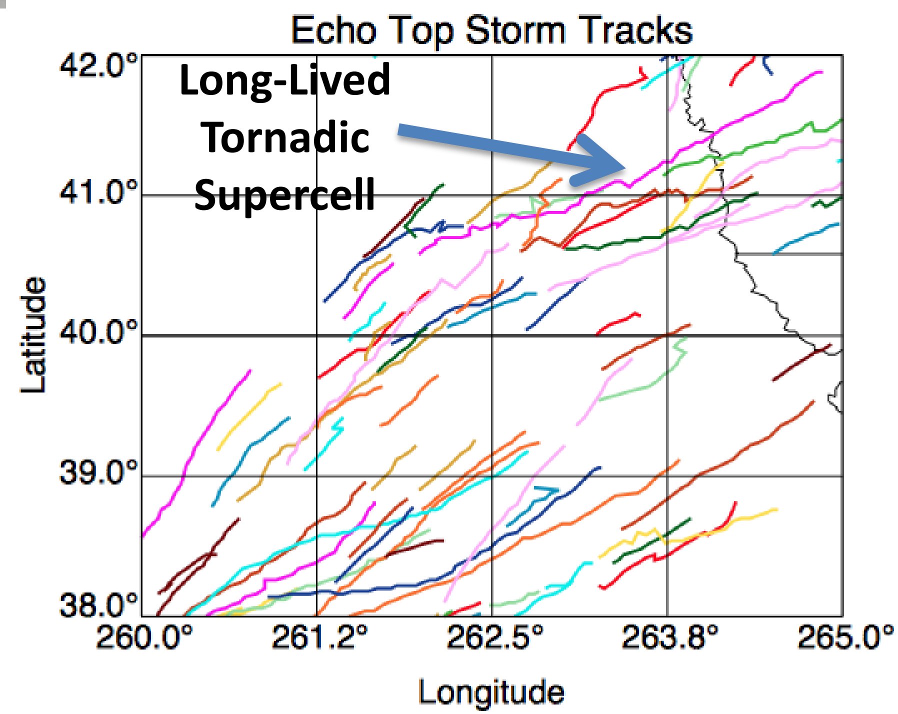


- **4-D Volumes of radar data at 5-min temporal, 2 km spatial, and 1 km vertical resolution can be constructed using the NOAA doppler weather radar network (WSR-88D, Homeyer and Kumijan 2015)**

Radar-Based Automated Storm Object Tracking

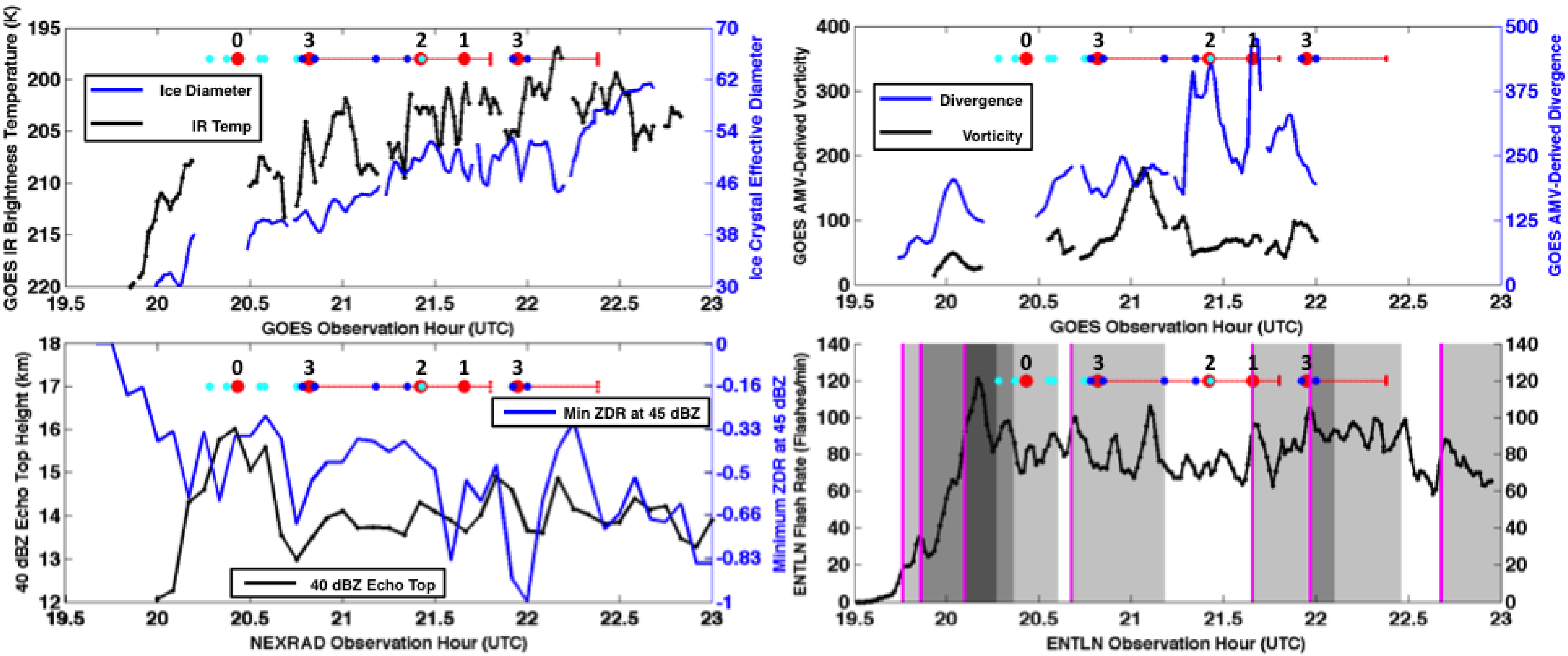
Cameron Homeyer (University of Oklahoma)





- **Storm objects can be defined and tracked using echo tops identified within 4-D radar data**
- **Some storms persisted and were tracked using an automated method for several hours during the 11 May 2014 event**
- **Satellite, lightning, NWP, and severe weather report data can be associated with these objects, allowing one to identify trends in these data not apparent within imagery**

Multi-Sensor Product Time Series
Long-Lived Tornadic Supercell, 11 May 2014 over Nebraska



Time series of satellite-, radar-, and lightning-derived products for the 11 May Nebraska supercell storm. Times of tornado touchdowns (red) and tornado duration (red horizontal lines), EF scale (black numbers), hail reports (cyan), and wind reports (blue) are shown in each panel:

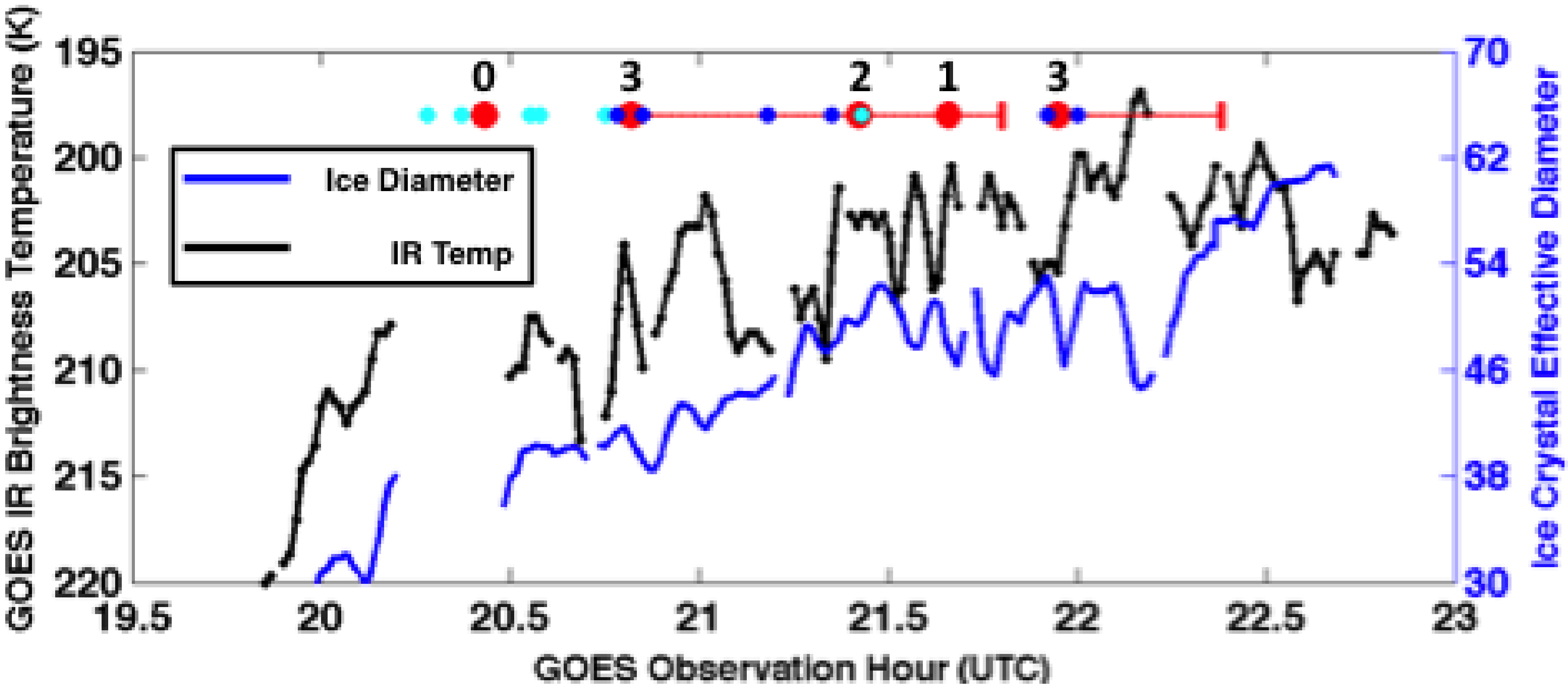
(a) GOES minimum IR BT and minimum ice diameter near the updraft region.

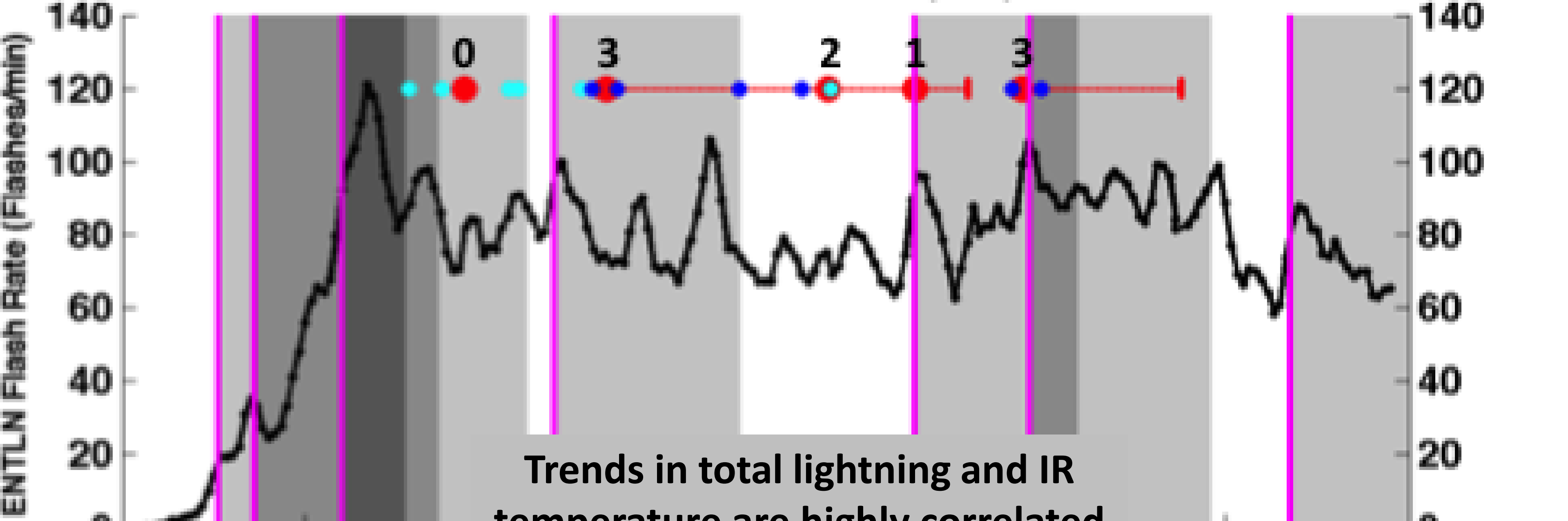
(b) mAMV-derived divergence and vorticity.

(c) Radar-derived 40 dBZ echo top and minimum Z_{DR} at the 45 dBZ reflectivity level.

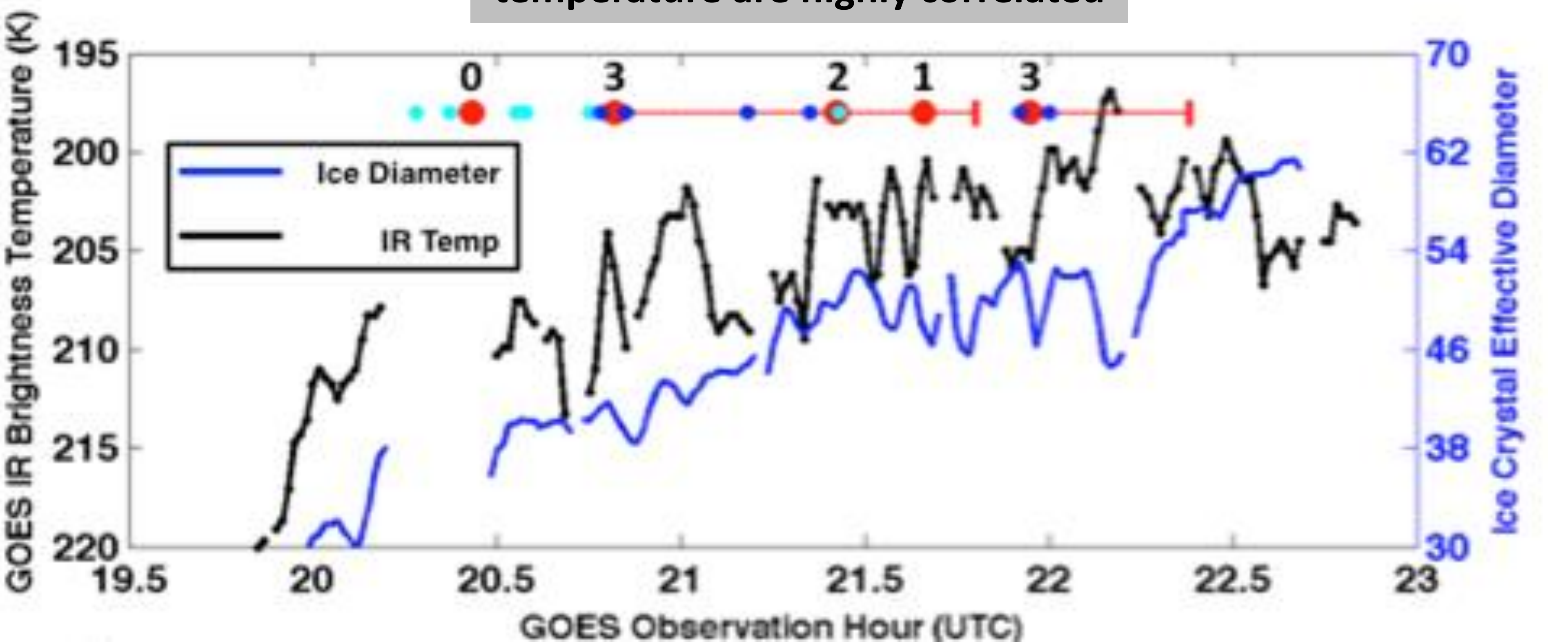
(d) 1-minute lightning flash rate within the storm updraft using ENTLN data gridded to the ~8 km GLM resolution. Lightning jumps are identified with magenta lines. The 30-min active period of each jump is shown by grey shading with overlaps becoming progressively darker.

Multi-Sensor Product Time Series
Long-Lived Tornadic Supercell, 11 May 2014 over Nebraska

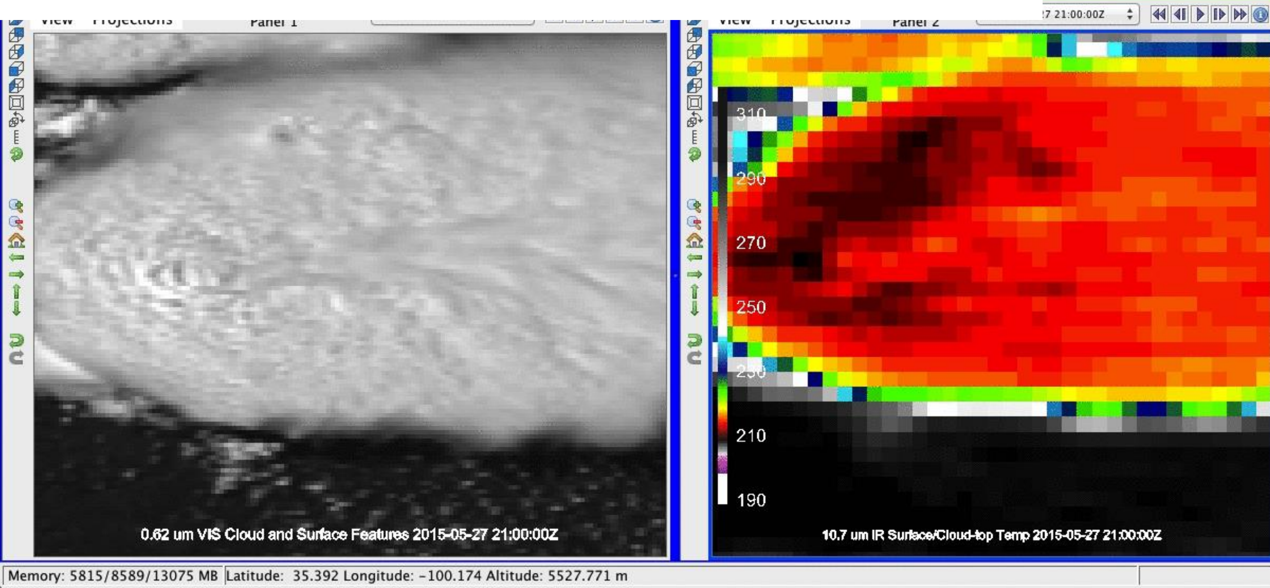


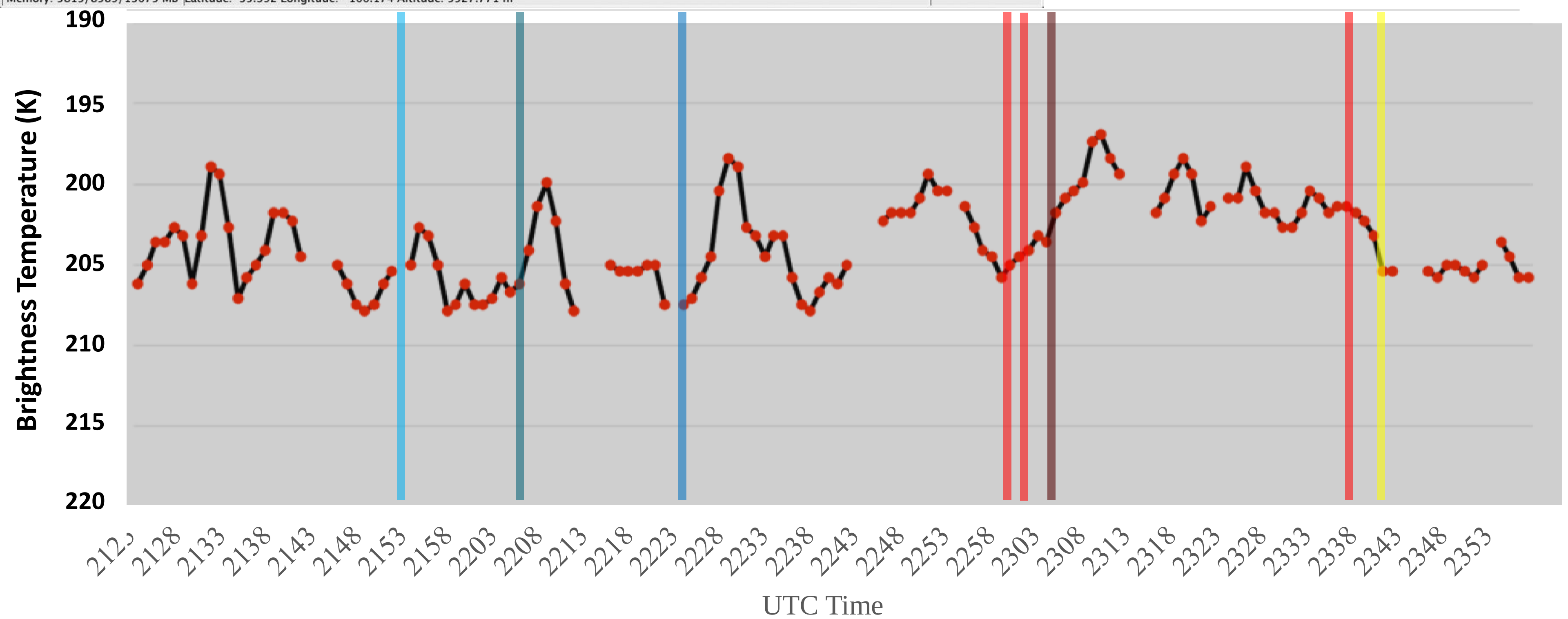


Trends in total lightning and IR temperature are highly correlated



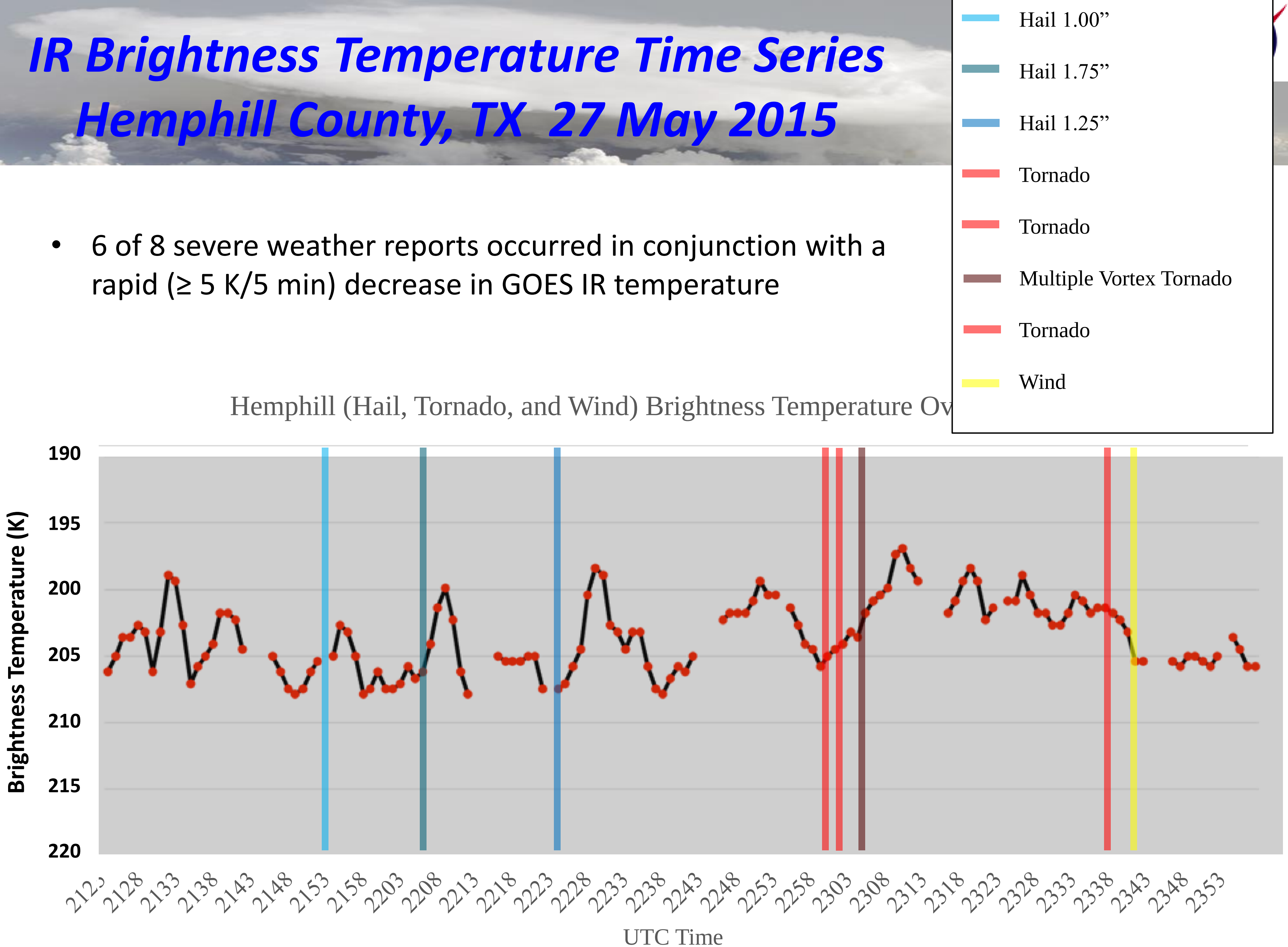
27 May 2015 Hemphill County Texas



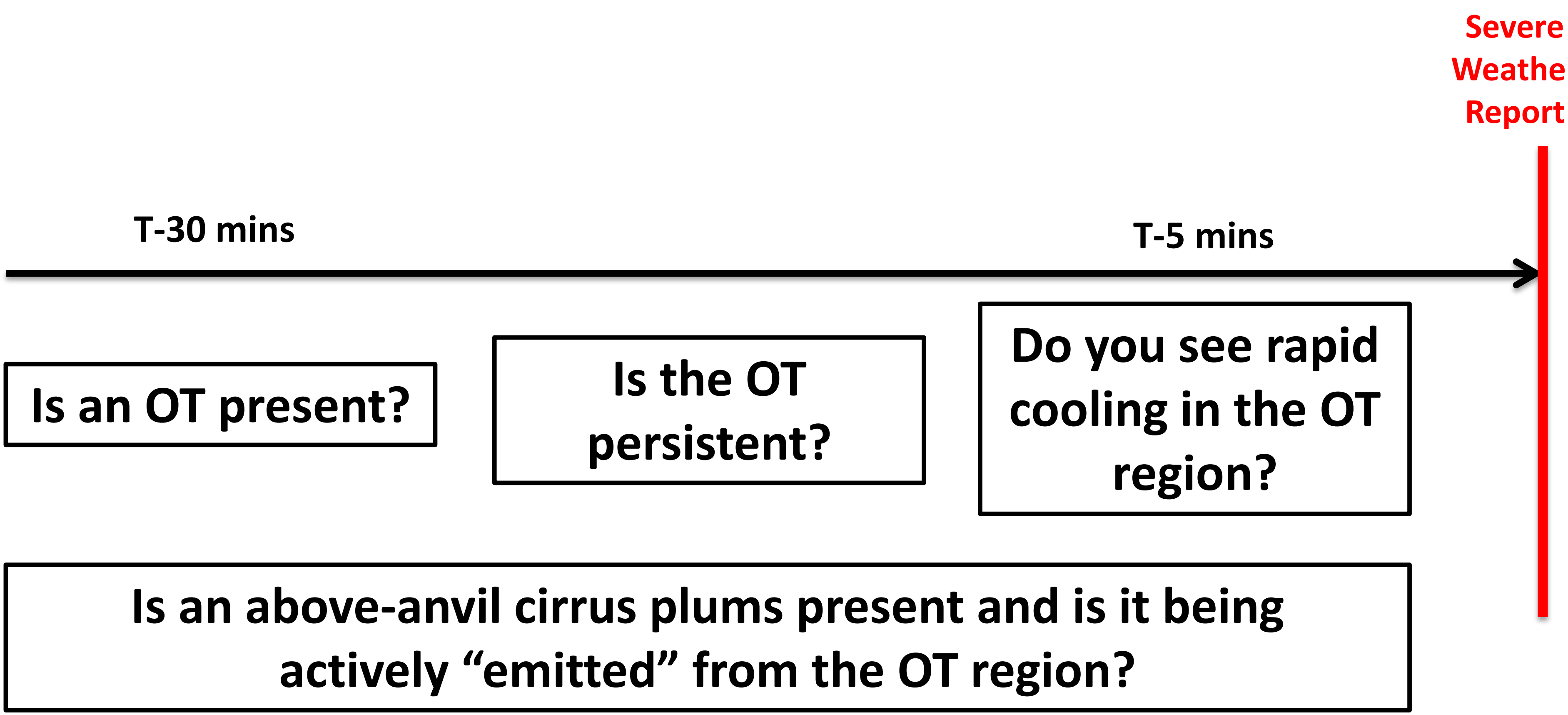


IR Brightness Temperature Time Series
Hemphill County, TX 27 May 2015

- 6 of 8 severe weather reports occurred in conjunction with a rapid (≥ 5 K/5 min) decrease in GOES IR temperature



How Might You Use Deep Convective Cloud Top Signatures For Severe Storm Nowcasting With Super Rapid Scan Data?



Summary

- **A number of severe weather indicators will either be depicted by the GOES-R / MTG imagery or can be detected using automated algorithms**

- **Signatures such as above anvil cirrus plumes and overshooting tops can be evident up to 30 mins before severe weather occurs**

- **Automated satellite-derived OT detection can highlight updraft persistence and intensity which will help to identify hazardous storms**

- **GOES-14 IR temperature data shows that rapid cloud top temperature changes (~5 K / 5 mins) occurred in conjunction with many tornado and other severe weather reports.**
  - Note: Some EF-0 and EF-1 tornado-producing storms did not exhibit this pattern

- **The improved GOES-R ABI and MTG FCI spatial resolution will enhance these rapid temperature changes, perhaps up to ~10 K / 5 mins. Trends of this magnitude should be quite evident to forecasters, highlighting impending tornado-genesis or severe weather**

- **Super rapid scan imagery is critical for capturing these rapid temperature changes; 5-min resolution ABI operational imagery will often be insufficient**