Objective Satellite-Based Overshooting Top and Enhanced-V/Cold Ring Signature Detection: Product Validation and Relationships With Severe Weather

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What Is An Overshooting Top?

Overshooting Top: A domelike protrusion above a cumulonimbus anvil, representing the intrusion of an updraft through its equilibrium level (from the AMS Glossary of Meteorology)

• Small in size (< 15 km) and short lived

• Indicates a storm with a strong updraft. Storms with strong updrafts and OT signatures often produce large hail, damaging winds, tornadoes, and heavy rainfall. The region within and near OT regions should be avoided by aircraft.

• OTs inject moisture into the stratosphere and this has significant climate impacts because water vapor is an important greenhouse gas.

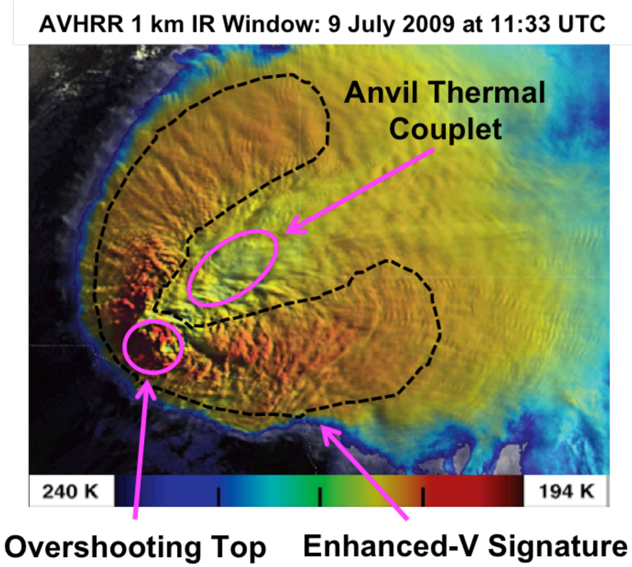
• The OT is a component of the enhanced-V and cold ring signature

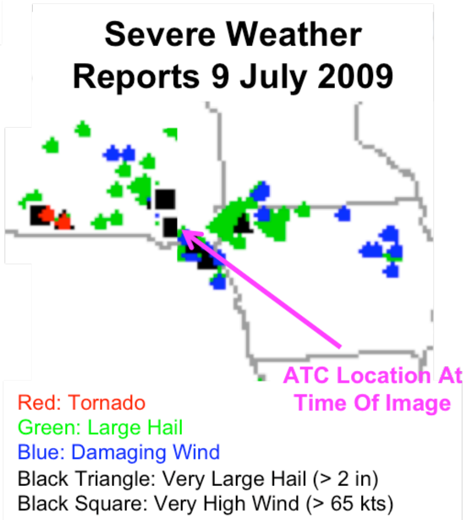
What Is An Enhanced-V?

The appearance of an enhanced-V in infrared imagery resembles a V- or boomerang-shaped area of cold IR window channel BTs bordering an area of warm BT downstream. (From *Meteorology: Understanding the Atmosphere* (Ackerman and Knox, 2001))

- **Hypotheses for the presence of a downstream warm region include 1) subsidence from OT and 2) existence of a cirrus plume at some height above the anvil which radiates at the stratospheric temperature that is warmer than the anvil below**
    - **The OT and warm region together form an "anvil thermal couplet"**

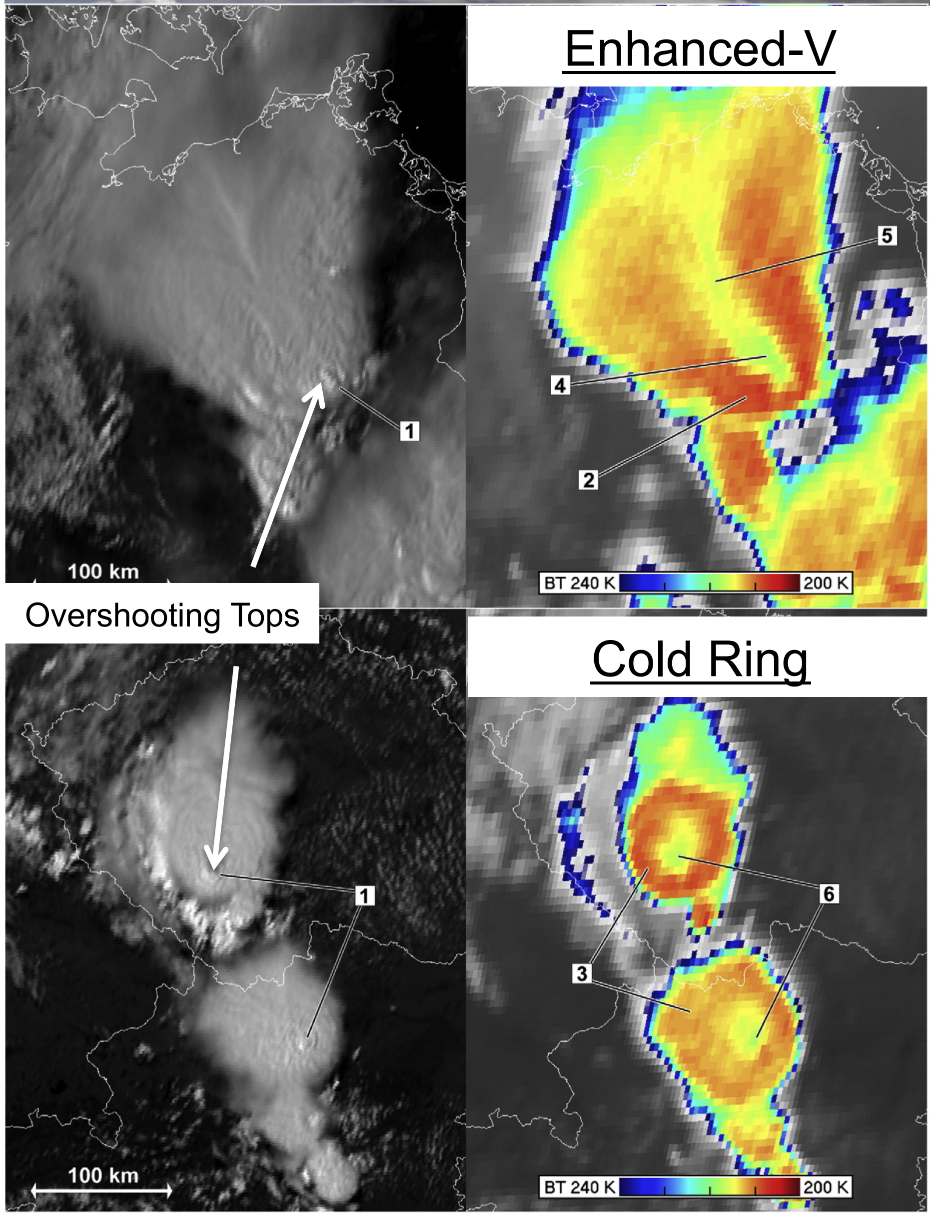
- **An enhanced-V can be seen in ~11 µm IR satellite imagery before the onset of severe weather and is an strong indicator of a severe thunderstorm**





AVHRR image courtesy of Martin Setvak (CHMI)

Enhanced-V vs. Cold Ring Signature



- Cloud-resolving model simulations indicate that the cold ring signature often occurs in weaker jet stream vertical wind shear environments than the enhanced-V (Setvak et al. (Atmos. Res., 2010))

- Cold ring signatures appear similar to an enhanced-V in that they exhibit pronounced anvil thermal couplets

- A storm can evolve from exhibiting a cold ring into an enhanced-V during its lifetime

- Both of these signatures often indicate a severe storm

From Setvak et al. (Atmos. Res. 2010)

Introduction

Due to the hazards associated with overshooting top and enhanced-V / cold ring producing storms, objective detection of these features are product requirements for the future GOES-R Advanced Baseline Imager (ABI) to be launched in ~2016.

- While Doppler radar and total lightning are preferred datasets for assessing storm severity, geostationary satellite-observed IR cloud top temperature field offers a unique perspective of deep convection that can provide additional indications that a storm is severe, provided the satellite data is of "**high**" temporal/spatial resolution
    - -OT/V detection products can be used to save time for forecasters

- Development of these algorithms has been underway for ~3 years
    - Algorithm optimized for MODIS/AVHRR/ABI over CONUS, but is adapted to work with all current geostationary data. Required algorithm FAR for the ABI program < 25%

- ABI Visible channel spatial resolution: 0.5 km   IR spatial resolution: 2 km
Temporal resolution: 5 minutes Full Disk, 30 second Rapid Scan over 1000 x 1000 km Region

- SEVIRI has comparable spatial resolution and spectral channels to the future GOES-R ABI, making its data a useful testbed for the development of ABI algorithms

Introduction

- Numerous papers describe objective OT detection methods and some have qualitatively examined the OT/V/ring signature within severe storms in case studies

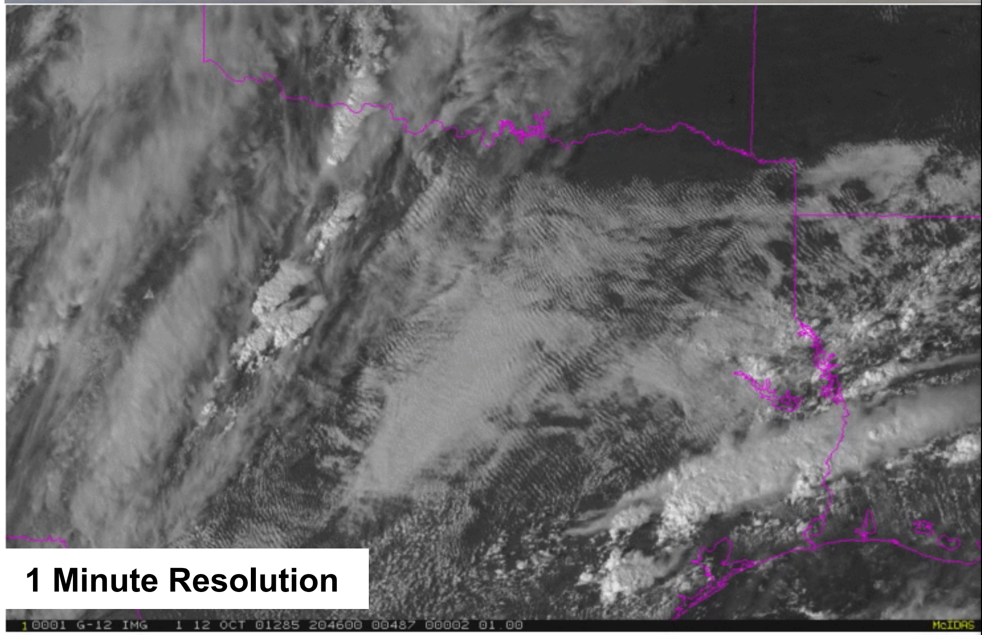
- While case studies are certainly worthwhile, it is important to quantify how these methods can help forecasters diagnose and nowcast hazardous convection across a diversity regions and convective regimes
  - This is especially beneficial over regions with inadequate radar coverage

- In this study, satellite OT and enhanced-V detection product output is compared with ground/space-based radar observations and severe weather reports to:

1) Determine the accuracy of these detection products
2) Better understand how satellite-observed OT signatures relate to (S-band) radar reflectivity observations and echo tops
3) Evaluate relationships between OT and enhanced-V detections, severe storm reports, and severe weather warnings issued by operational forecasters

SEVERE WEATHER DEFINITION: > 50 kt winds, > 2 cm hail, and/or tornado

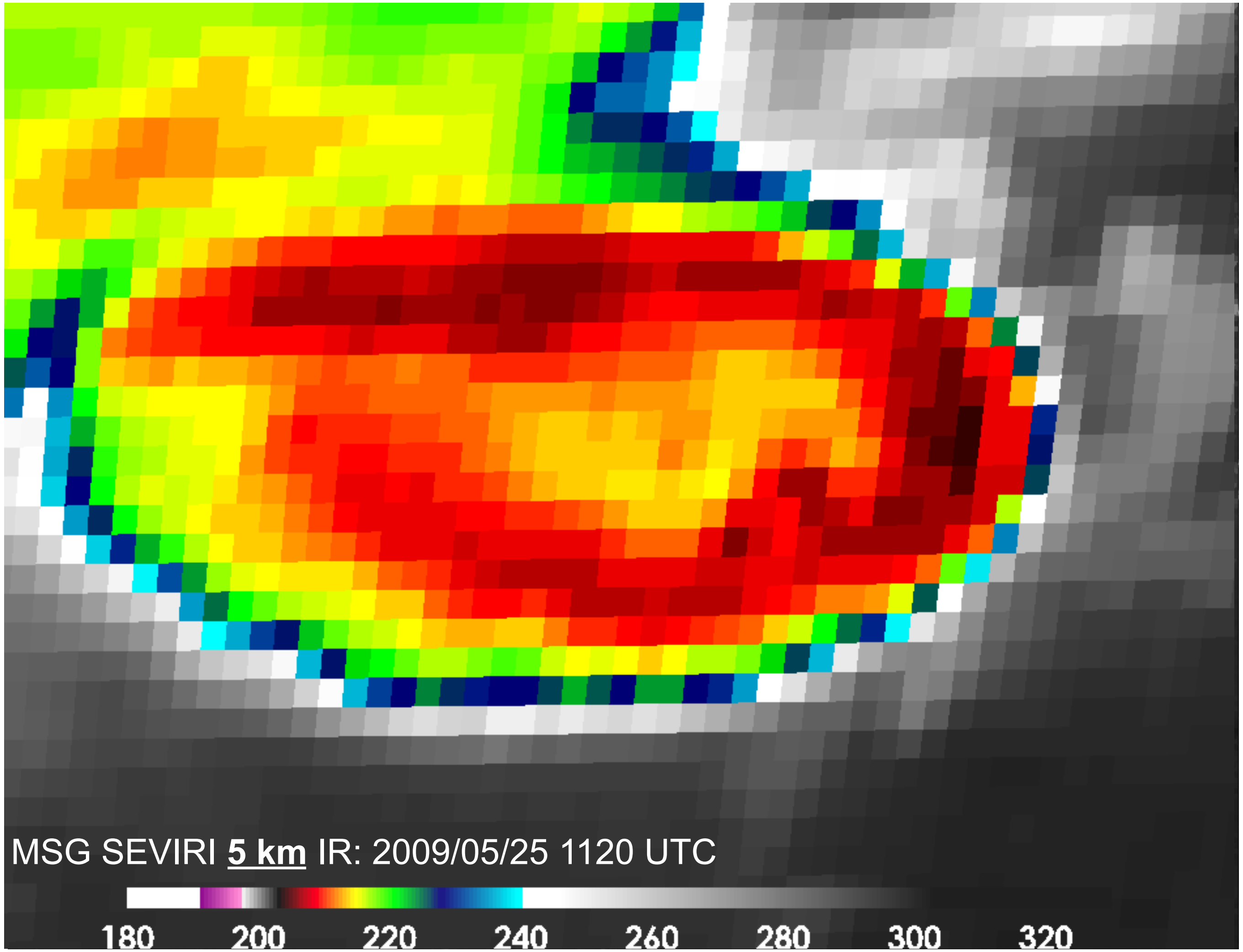
Evolution of Deep Convection in Current Generation Geostationary Imagery



- 1-minute imagery shows that an individual overshooting top often exists for < 5 mins, so several tops can grow and decay in the time between the 15 min operational scan frequency of GOES and SEVIRI

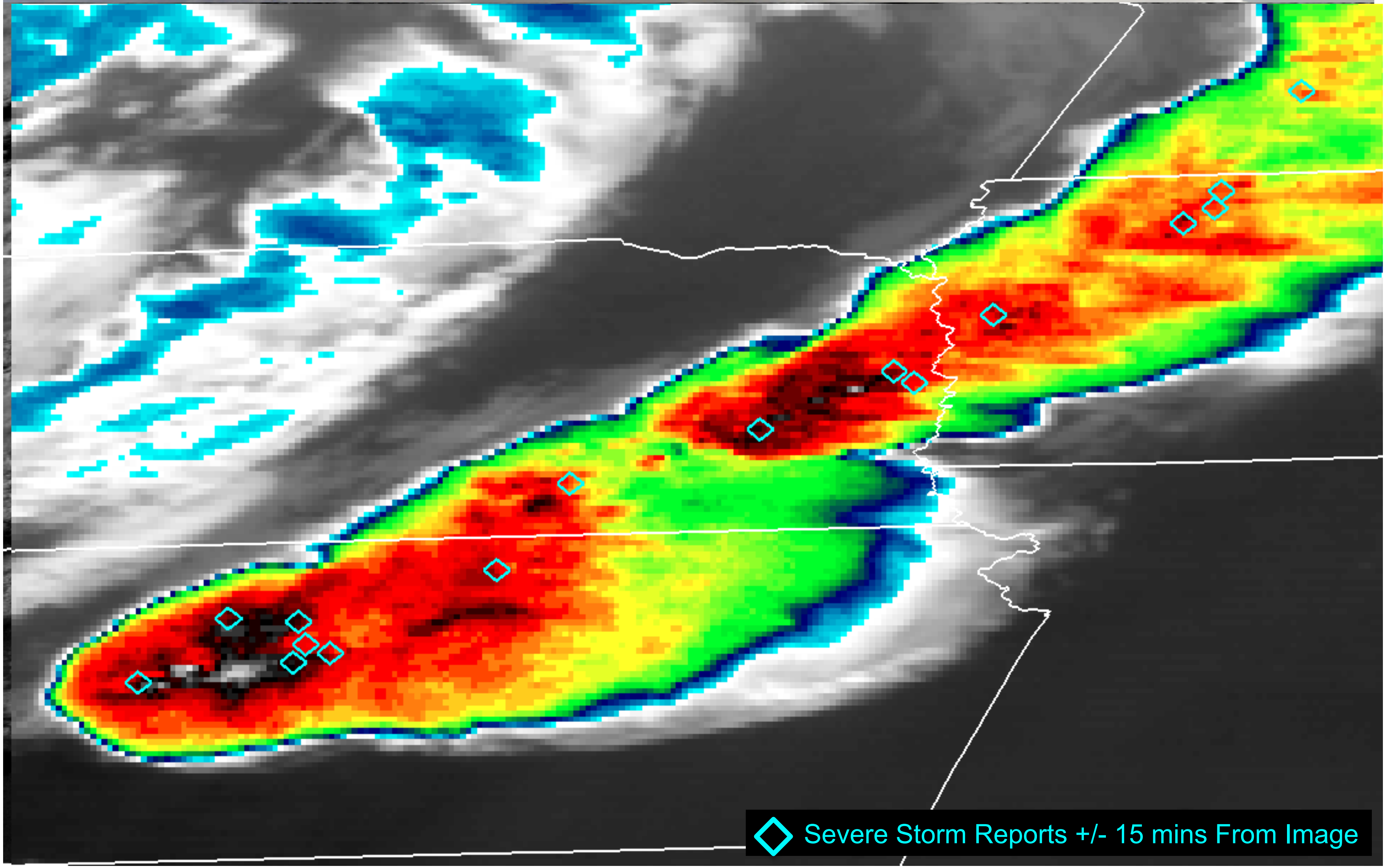
- As the number of observed OT/V/ring features is far fewer in current generation 15 min imagery than those actually present, the probability of detection for severe weather decreases

Appearance of Overshooting Tops and Cold Ring in Current Generation Geostationary Imagery



- Image spatial resolution has a significant impact on the appearance of OTs and the enhanced-V/cold ring signature
- Analysis of 125 time-matched 4 km GOES and 1 km AVHRR/ MODIS images shows that the OT minimum IR temp is 12 K colder on average in 1 km imagery
- Weaker contrast between OT/ warm region and remainder of anvil is detrimental to our ability to objectively detect these features. Algorithm detection thresholds need to be less strict for lower resolution imagery, potentially causing greater false detections in complex scenes

Overshooting Tops in Current Generation Geostationary Imagery With Severe Storm



Overshooting Top and Enhanced-V/Cold Ring Detection Methods for GOES-R ABI

Overshooting Top Detection Processing Schematic: IRW-Texture Technique

INPUT: IR BT and NWP Tropopause Temperature

↓

Find Pixels Colder Than 215 K and NWP Tropopause + 2.5 K

↓

Filter List of Cold Pixels To Identify Regional BT Minima: Overshoot Candidates

↓

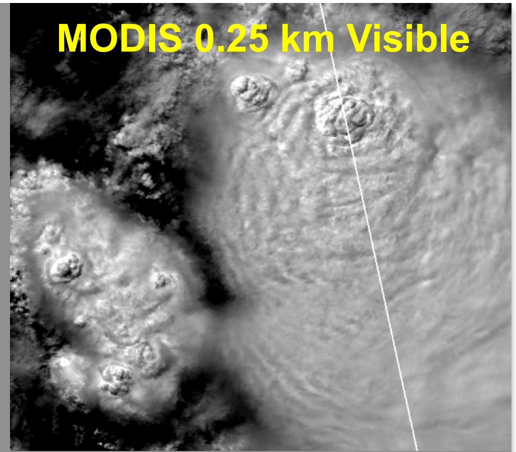
Compute BT Difference Between Candidates and Surrounding Anvil Cloud

↓

Pixels With BT > 6.5 K Colder Than Mean Surrounding Anvil Are Overshooting Tops, Flag Remaining Pixels That Compose The Entire Top

↓

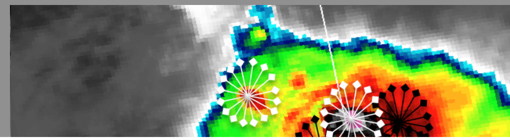
Output Overshooting Top Mask

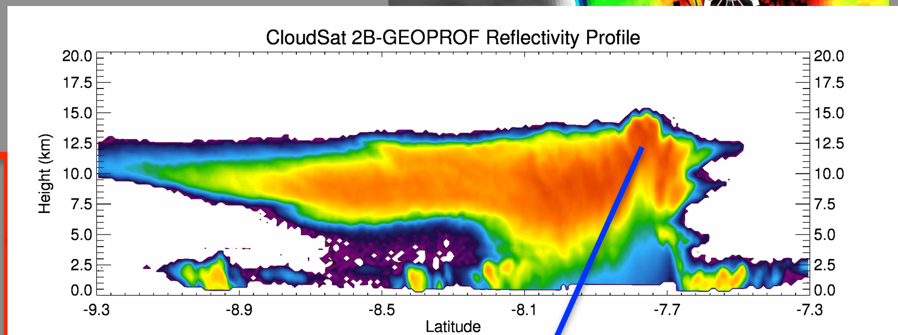


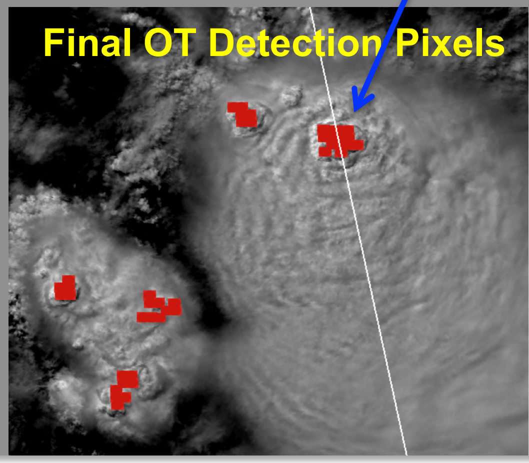
IRW-Texture Candidate Pixels: Anvil BT Sampling

White Pinwheels: Candidate OT Significantly Colder Than Anvil

Black Pinwheels: Cloud Top BT Pattern Too Uniform=Not an OT







Bedka et al. (JAMC, 2010), Bedka (Atmos Res., 2011)

Enhanced-V Anvil Thermal Couplet Detection Processing Schematic

INPUT: IR BT, NWP 250 hPa Wind Field, and Overshooting Top Detection Mask

↓

Search region up to 40 km away from the OT within +/- 45° of the NWP 250 hPa wind direction for potential couplet

↓

Ensure that potential couplet is not along the anvil cloud edge

↓

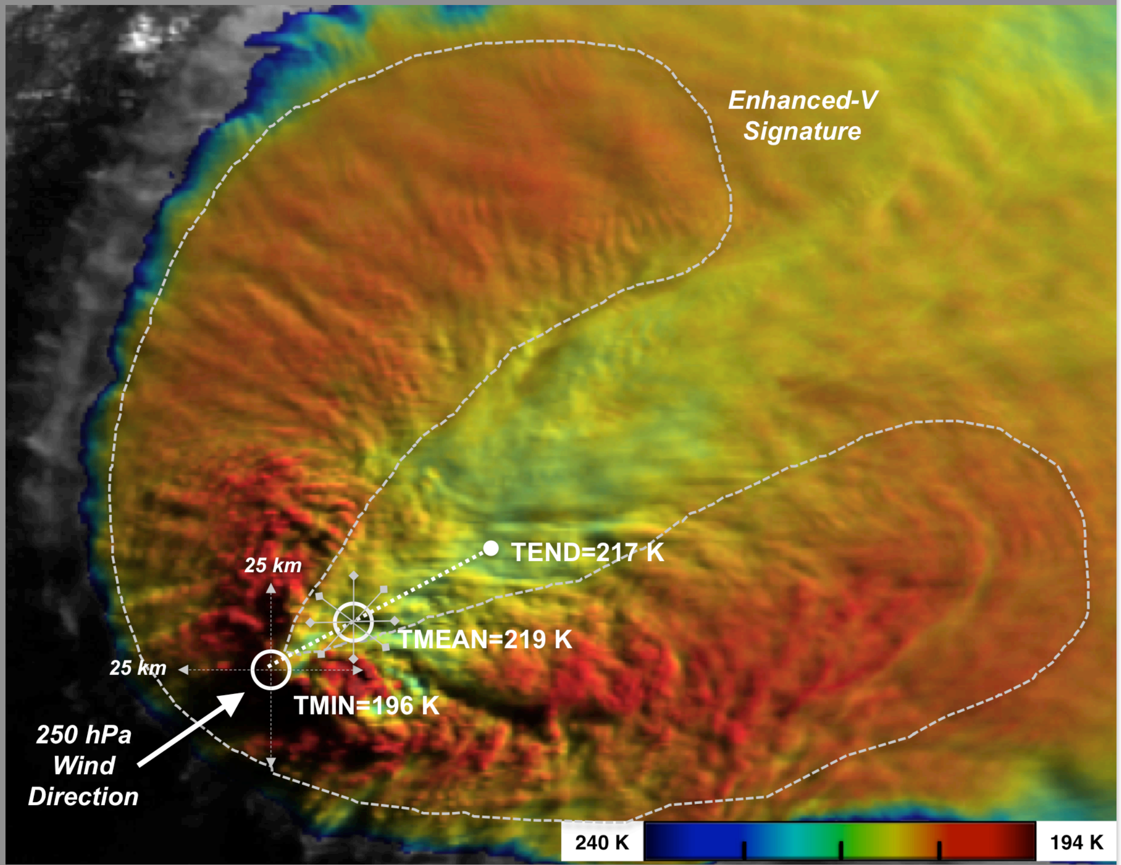
Ensure that potential couplet is a focused area of warm BT surrounded by colder anvil

↓

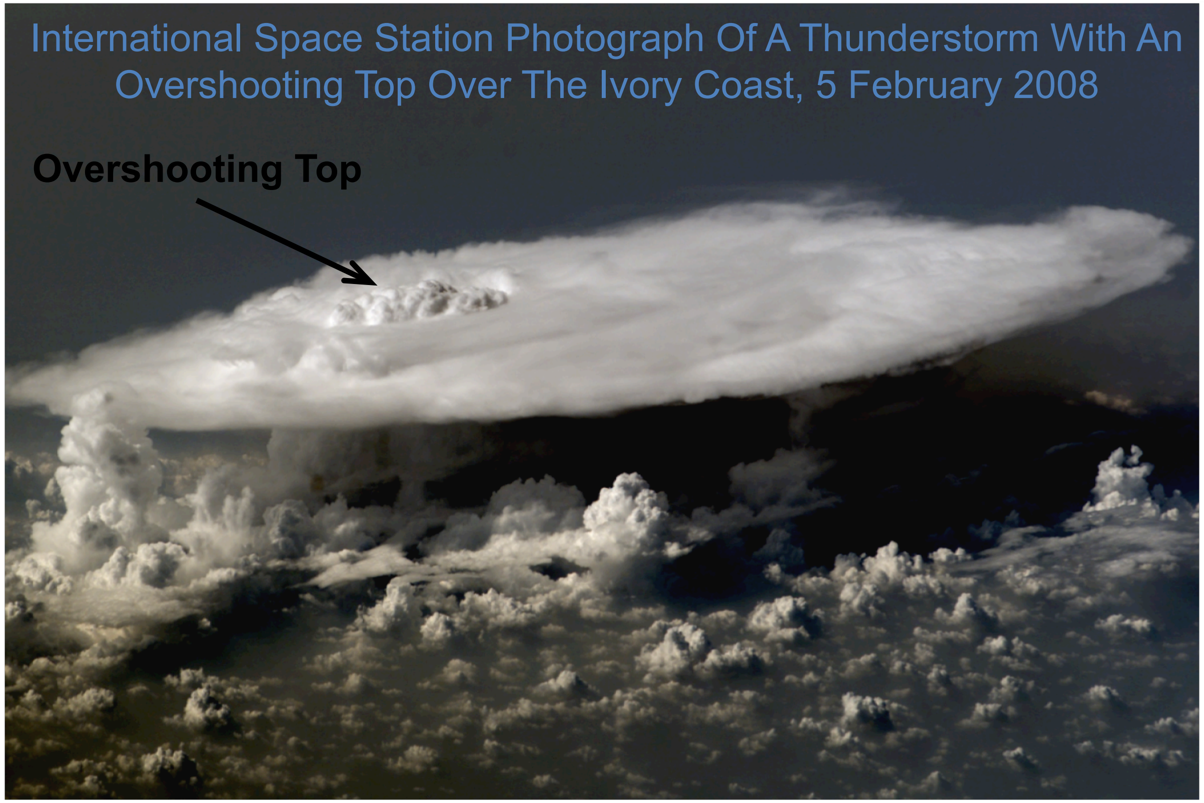
Ensure presence of a relatively large anvil cloud downstream of the OT and couplet

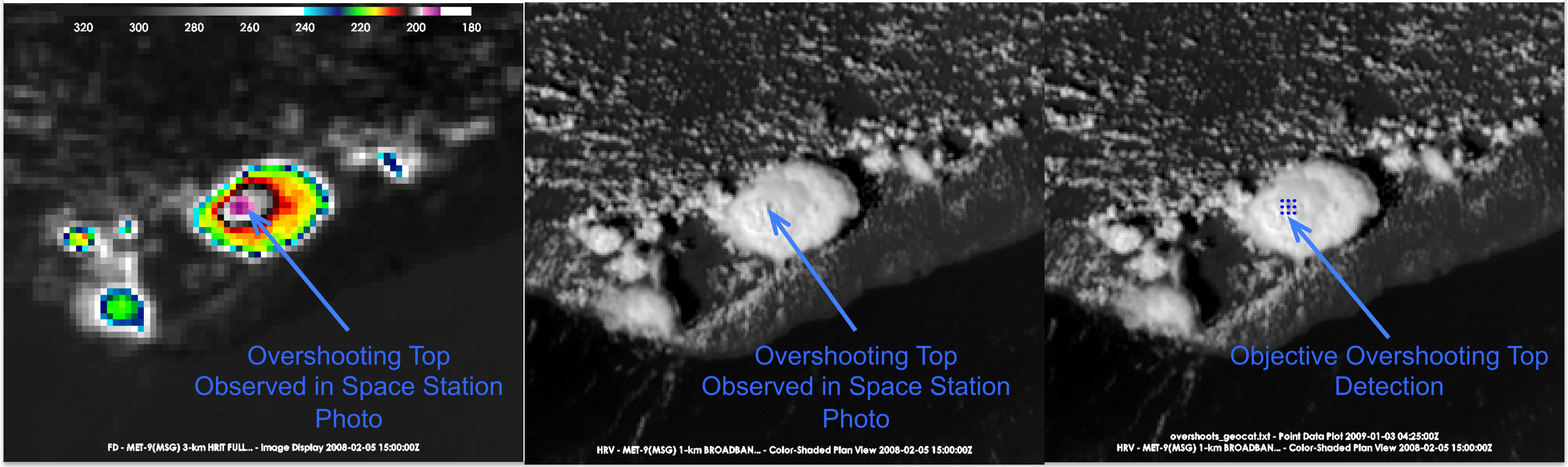
↓

Output Enhanced-V Thermal Couplet Mask

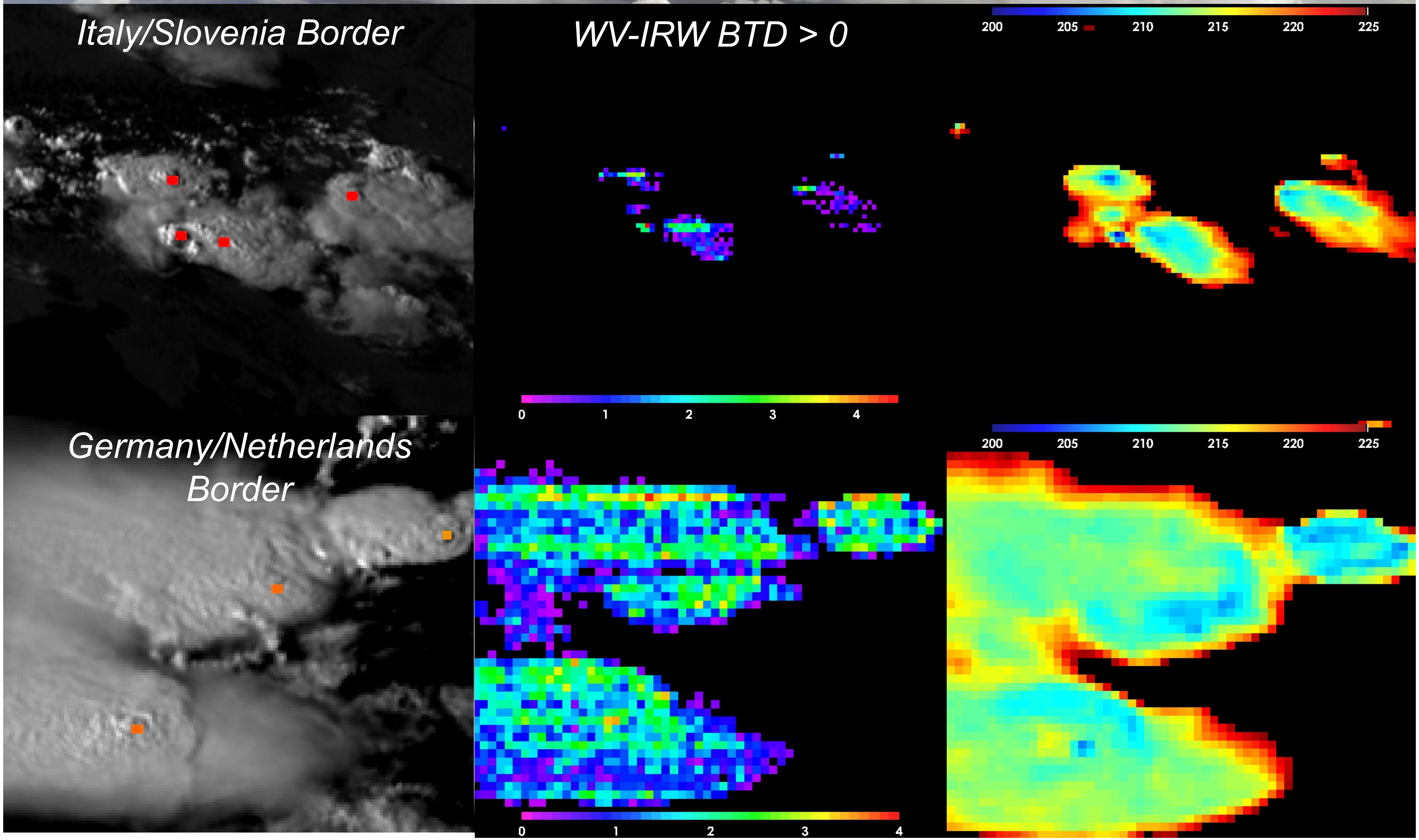


Examples of Product Output

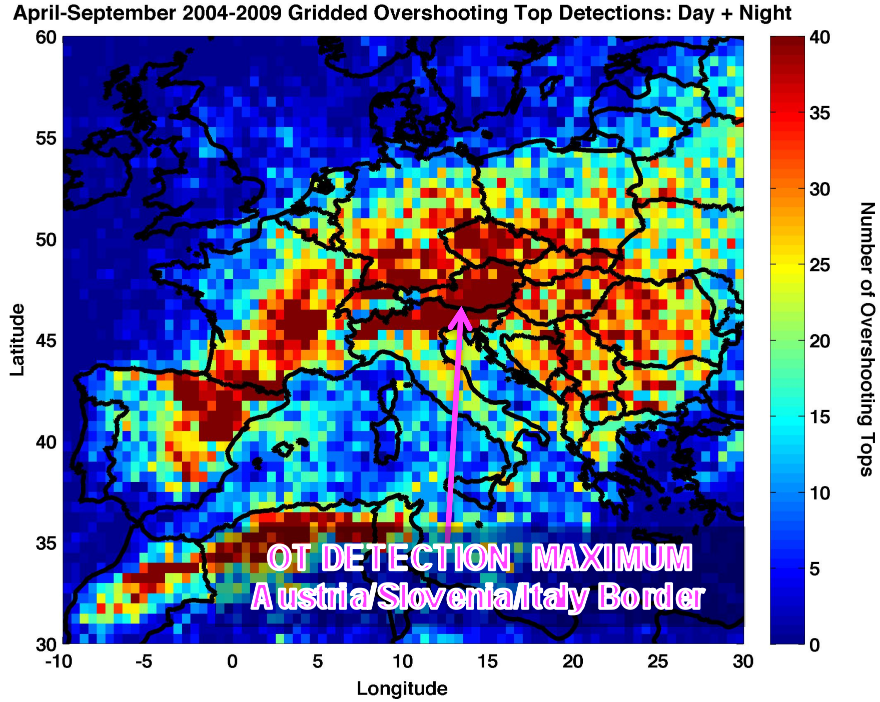

International Space Station Photograph Of A Thunderstorm With An Overshooting Top Over The Ivory Coast, 5 February 2008
Overshooting Top

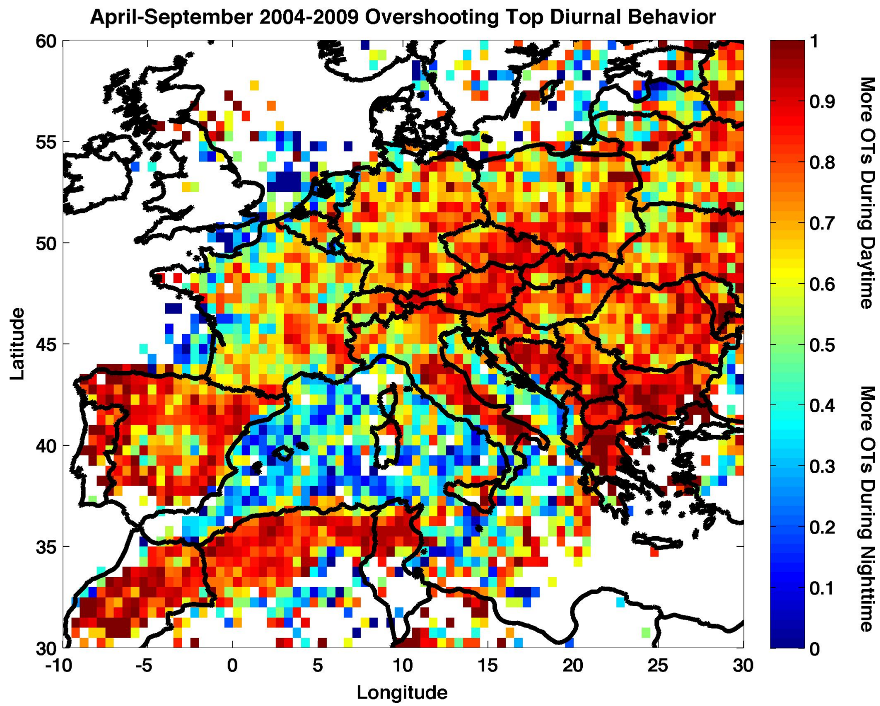

320
300
280
260
240
220
200
180
Overshooting Top Observed in Space Station Photo
FD - MET-9(MSG) 3-km HRIT FULL... - Image Display 2008-02-05 15:00:00Z
Overshooting Top Observed in Space Station Photo
HRV - MET-9(MSG) 1-km BROADBAN... - Color-Shaded Plan View 2008-02-05 15:00:00Z
Objective Overshooting Top Detection
overshoots_geocat.txt - Point Data Plot 2009-01-03 04:25:00Z
HRV - MET-9(MSG) 1-km BROADBAN... - Color-Shaded Plan View 2008-02-05 15:00:00Z

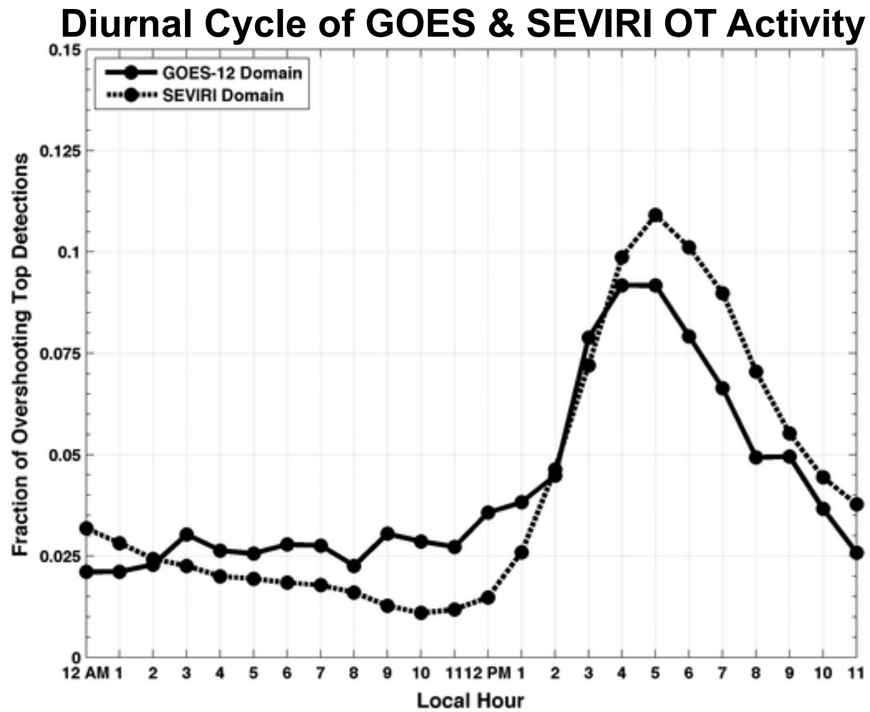
MSG SEVIRI OT Detection Examples
25 May 2009



2004-2009 Warm Season SEVIRI OT Detection Climatology



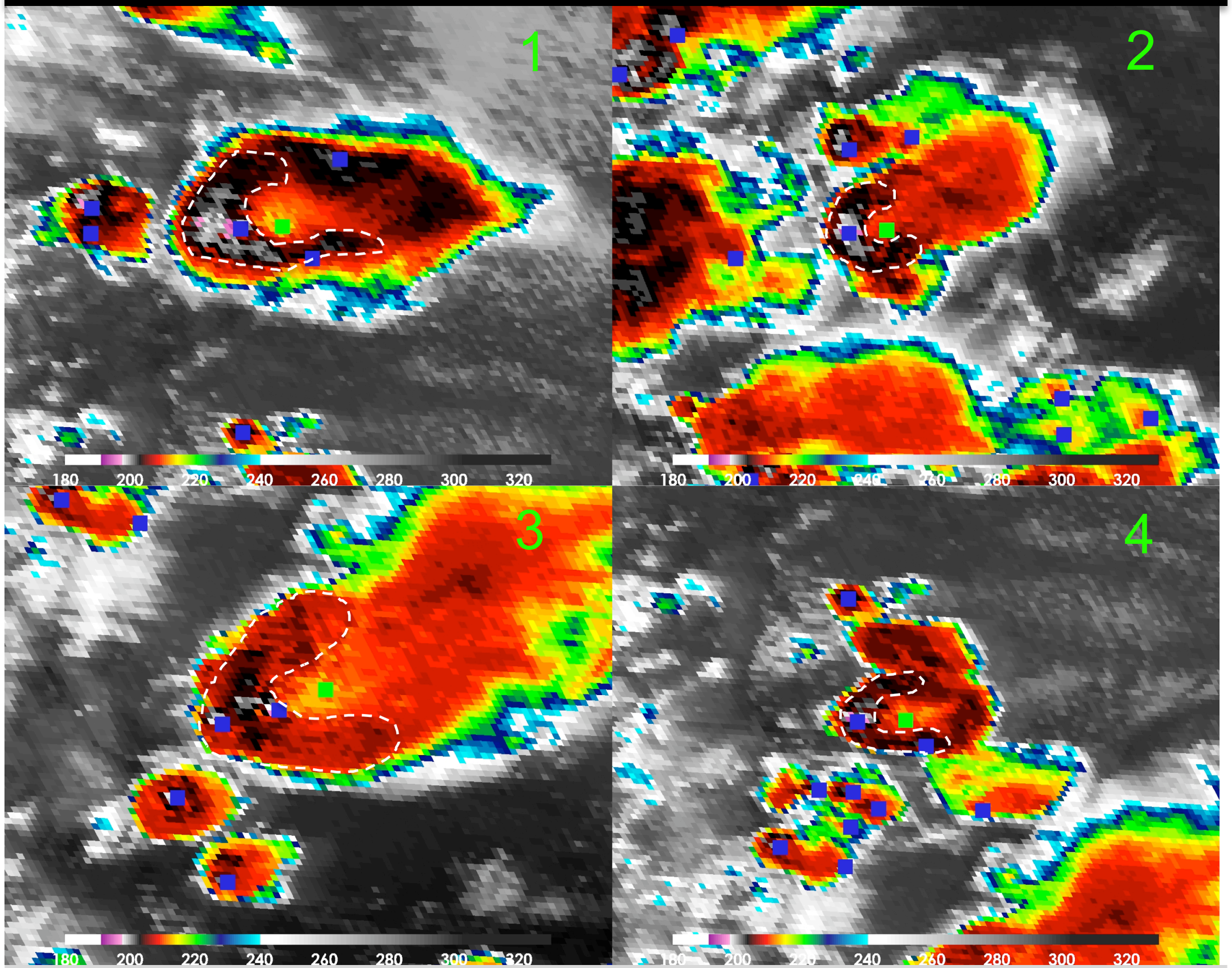




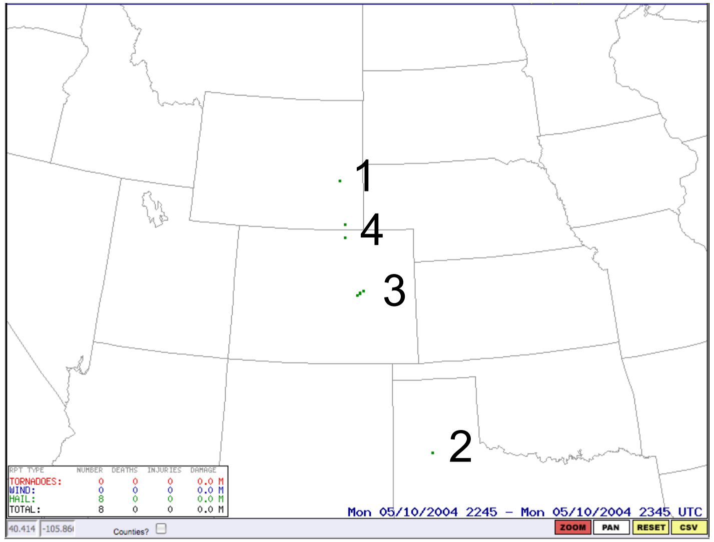
- OTs across the SEVIRI domain are well correlated with the presence of topographical features
- The time of peak OT activity is approximately the same between Europe and the U.S.
- OTs are more frequent over the GOES-12 domain at night. The U.S. Great Plains and Gulf Stream Ocean current both show a night-time bias in OT activity. See Bedka et al. (JAMC, 2010) for details

Overshooting Top and Enhanced-V Anvil Thermal Couplet Detection in AVHRR Imagery

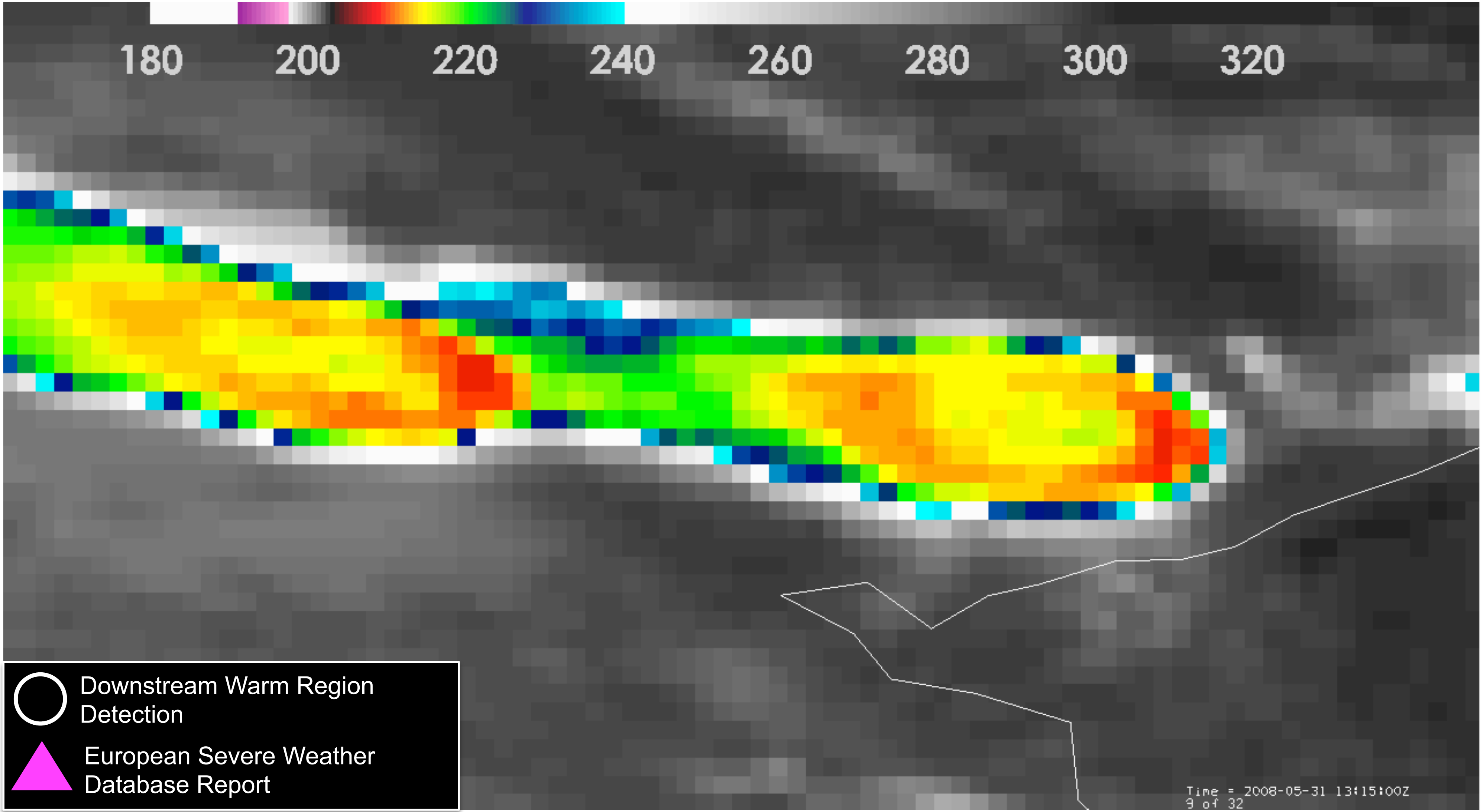
5/10/2004 2317 UTC
Blue Box: OT Detections
Green Box: Enhanced-V ATC Detections
White Lines: Enhanced-V Signatures



Severe Storm Reports +/- 30 Mins From Image Time
Numbers Correspond To The Storms Labeled In the Left Panels

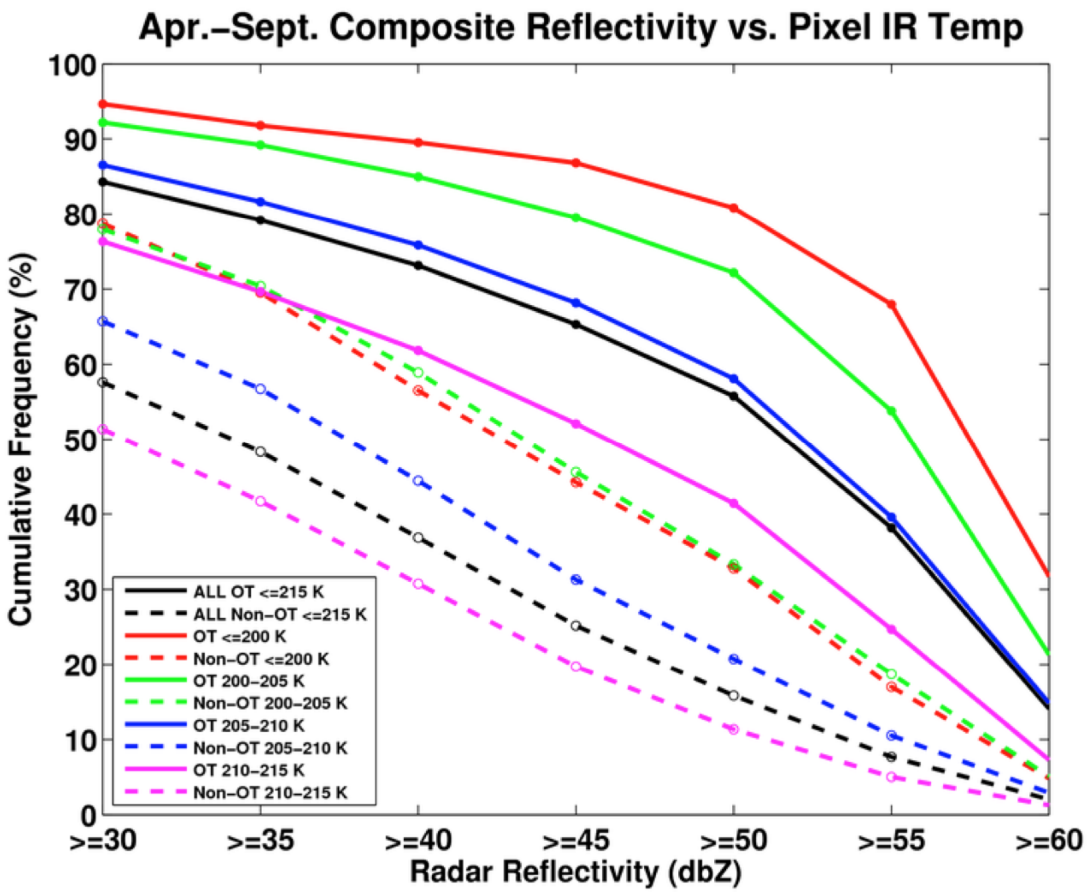


Enhanced-V Downstream Warm Region Detection MSG SEVIRI Imagery



Product Validation

Comparison Between GOES OT Detection and Composite Radar Reflectivity



[1]Composite Reflectivity: Max reflectivity in a vertical column of elevation slices

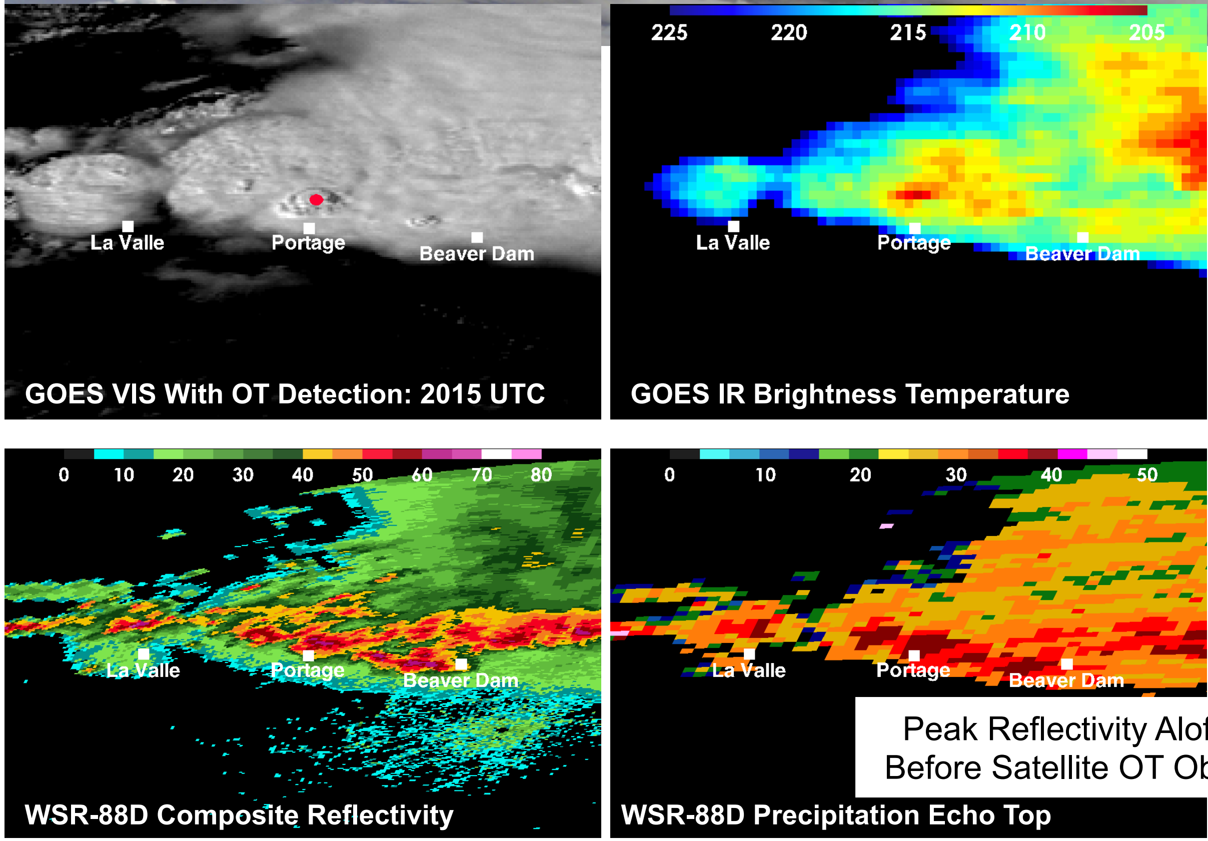
- OT detections were compared with UNIDATA 1 km radar composite reflectivity[1] across the eastern 2/3 of the US during 2008

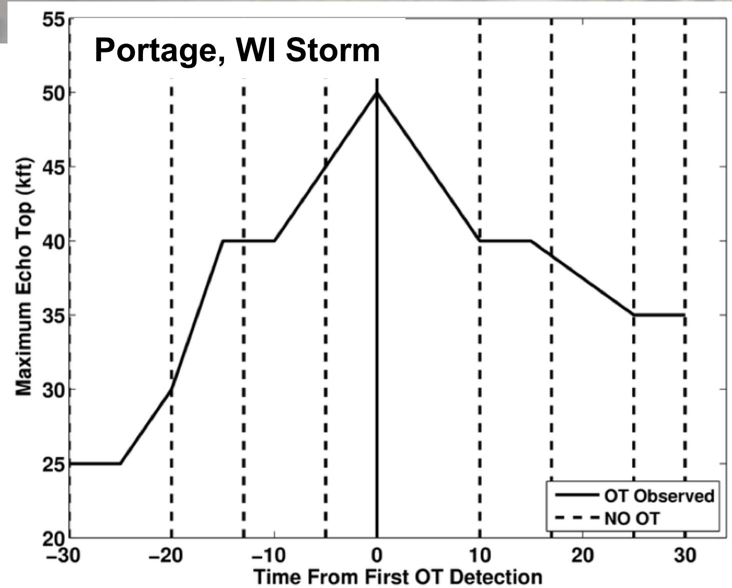
- If we assume an OT must be associated with a reflectivity > 30 dBZ, the mean FAR of the detection algorithm is ~15%

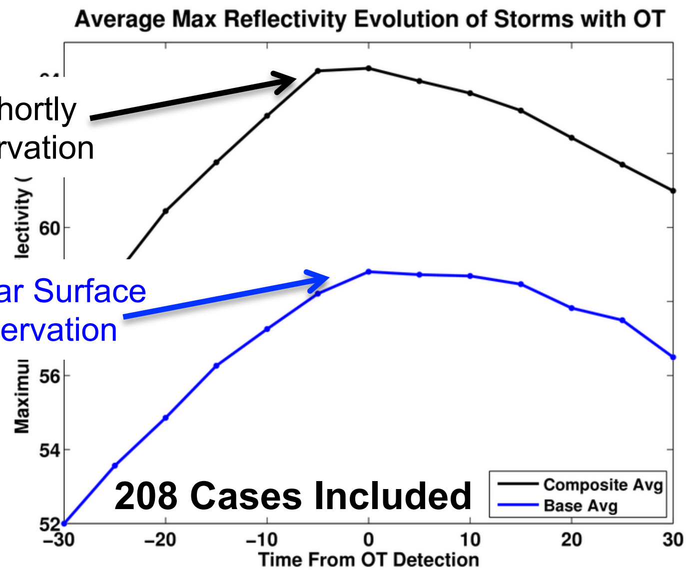
- Greater composite reflectivity occurs with colder IR temps

- For equivalent IR BTs, pixels that are within significant localized IR BT minima are associated with heavier rainfall than those in a more spatially uniform temp field

GOES-13 Detections of OT Events Observed Within WSR-88D Echo Top Data







- GOES OT detections correlate with the timing and location of local echo top maxima and maximum radar reflectivity aloft

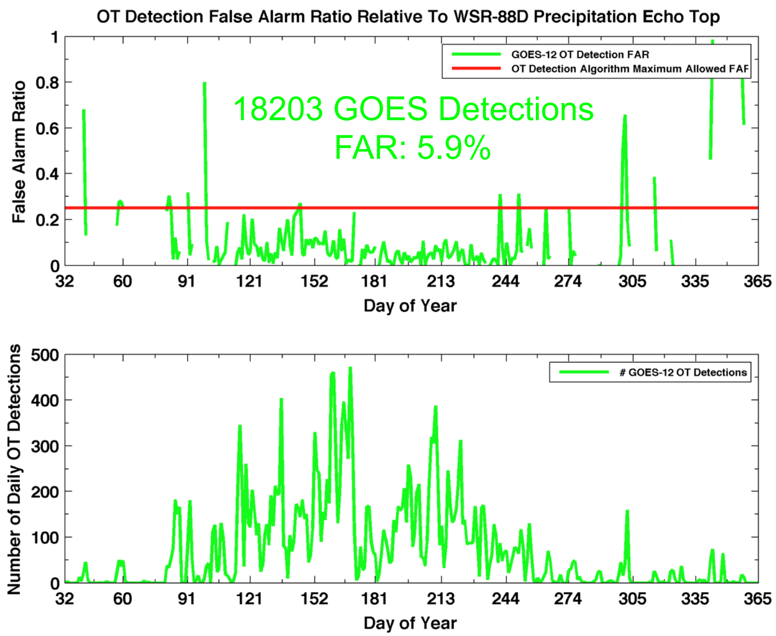
Validation of Current Generation Geostationary OT Detections

• The OT detection product was also compared with echo top from the NOAA NSSL 3-D radar mosaic over the entire U.S. and 114 OT observations from the NASA CloudSat Cloud Profiling Radar

• Average daily FAR based on comparison with echo tops > NWP tropopause-0.5 km is 6%

• POD decreases by 20% when image resolution is degraded from the ABI to current GEO imagers (CloudSat overshoot magnitude > 0.5 km)

Validation of GOES-12 OT Detections Relative to WSR-88D Echo Top OT Inferences: February-December 2009

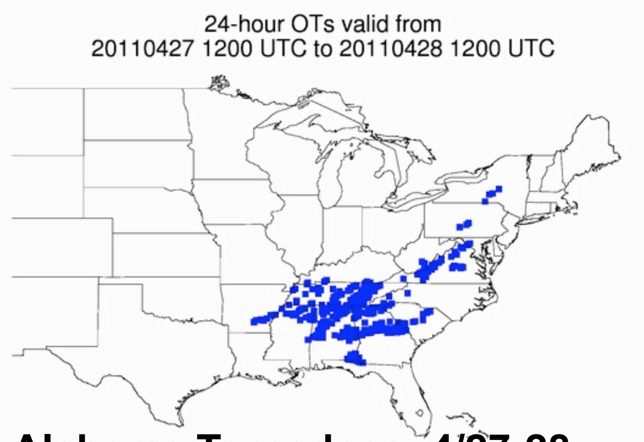


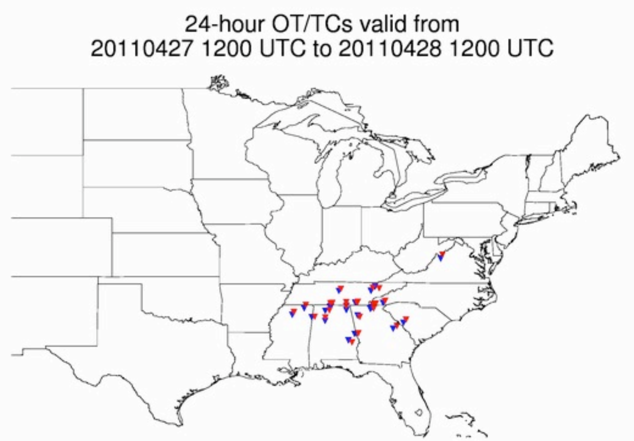
Validation of OT Detections Relative to NASA CloudSat OT Observations: April 2008 – September 2009 (Bedka et al. (in review, JAMC 2011))

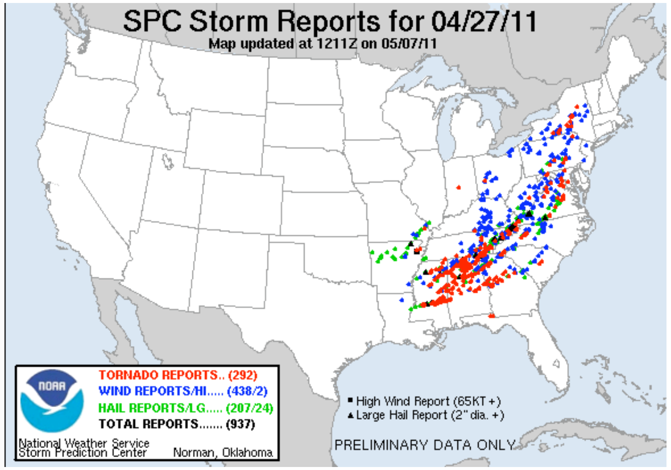
OT Detection Method	OT Pixel FAR	OT Top Region POD	Total Number of OT Detection Pixels Along CloudSat Track for 114 OT Cases
IR-only OT Algorithm Using MODIS-based Synthetic ABI	17%	76%	940 (114 Cases)
IR-only OT Algorithm Using Current GOES, MSG SEVIRI, and MTSAT	17%	55%	265 (72 Cases)
WV-IRW BTD > 1 K	75%	80%	6979 (114 Cases)

Comparisons With Severe Weather Reports

Overshooting Top/Anvil Thermal Couplet Detection Output: 2011 U.S. Severe Weather Outbreaks

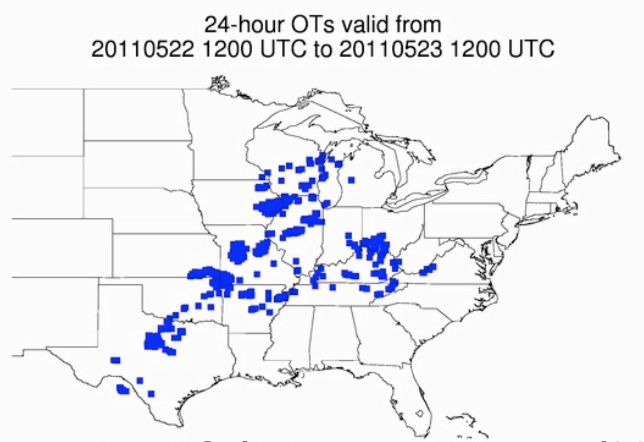


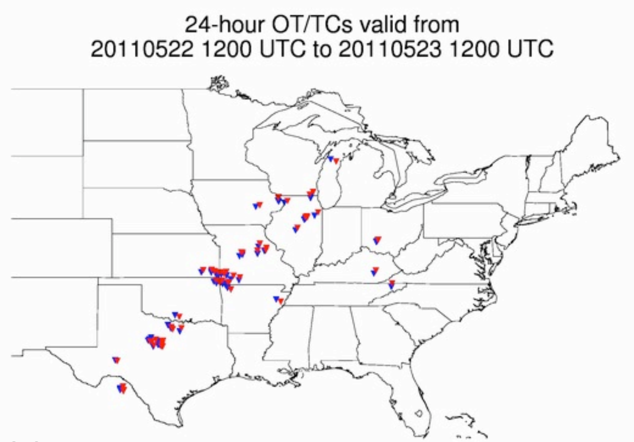


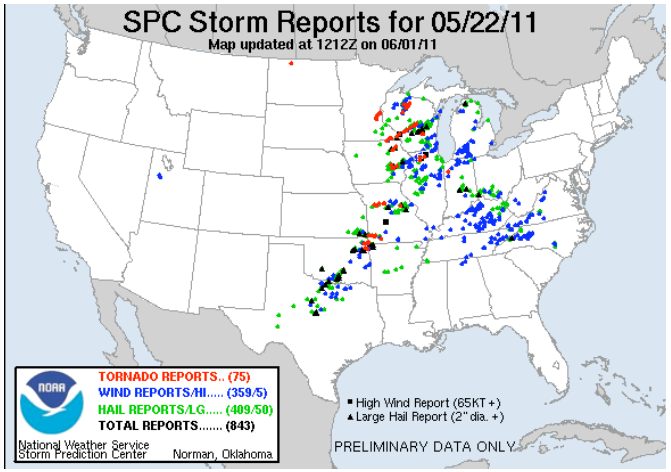


Alabama Tornadoes: 4/27-28

All GOES-13 OTs (blue) with Enhanced-V Anvil Thermal Couplets (red)



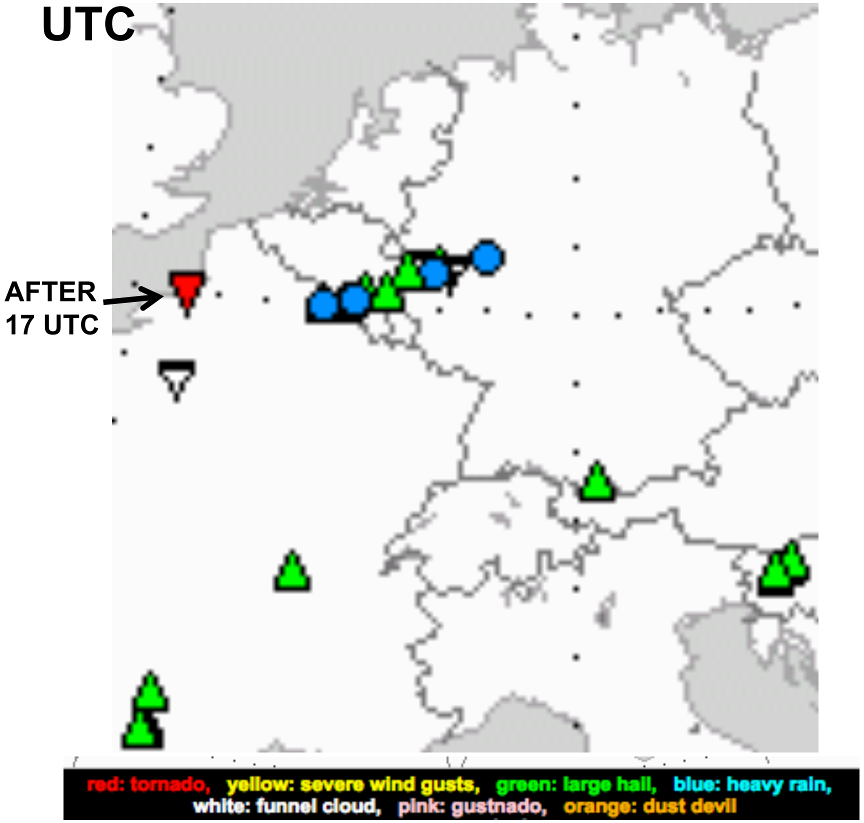


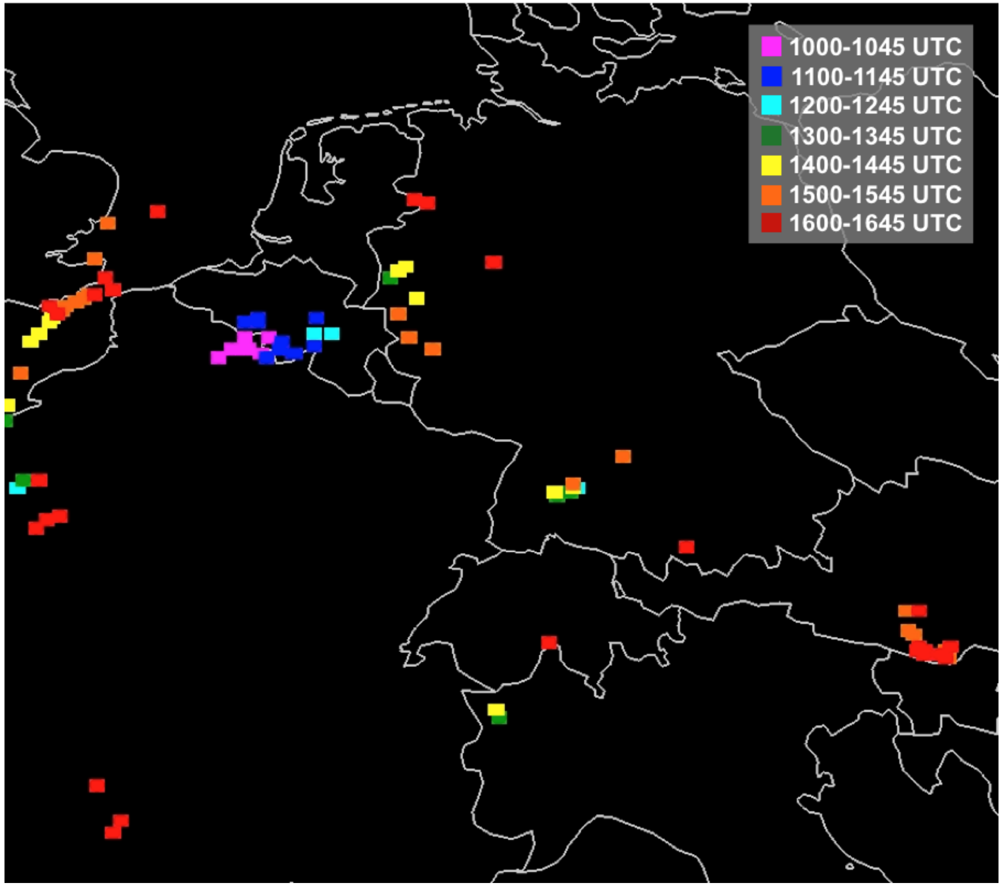


Joplin, MO / Midwest Event: 5/22-23

Overshooting Top Detections vs. European Severe Weather Database Reports

ESWD Storm Reports: 25 May '09, 10-17 UTC





This comparison suggests that there is a relationship between detected OTs and reported severe weather, though it is clear that: 1) all OT-producing storms are not reported as severe, and 2) a storm can be severe without a detected OT

Quantitative Comparisons of OT Detections With Severe Weather Reports

• **Statistical comparisons of OT detections with severe weather events can be challenging and may produce misrepresentative results because:**

1) Not all severe weather events are reported (e,g. events during the night and/or in sparsely areas, see Dotzek et al. (*Atmos. Res.*,2009) and Cecil (*JAMC*, 2009)

2) Satellite scanning frequency ranges from 5 to 30 mins. An individual OT can emerge and collapse between images

3) The reported time and location of events may not be perfectly accurate which can affect comparisons since fixed time/distance match criteria are often used

• **The OT-severe weather event comparisons were done for this talk in two ways:**

1) Determine how often OTs were detected within a given time/distance from a confirmed severe event (GOES-12 & SEVIRI)

2) Determine how often severe weather is found within a given time/distance from a detected OT (GOES-12 only)

Comparison of 2004-2009 Severe Weather Reports With SEVIRI OT Detections

Severe Weather Type	Number of Matching Overshooting Tops	Number of Severe Weather Occurrences	Match Percentage
Tornado	48	345	14%
Severe Wind	248	477	52%
Large Hail	347	653	53%
All Types	643	1475	44%

- Confirmed (QC1 and QC2) ESWD events are compared with SEVIRI OT detections for the 2004-09 warm seasons. Events with a temporal confidence of +/- 1 hour are used. Distance match criterion based on temporal confidence. See Bedka (*Atmos. Res.*, 2011) for methodology

- Severe wind and large hail stats are consistent with those over the U.S., but the tornado stats are significantly different (46% vs. 14%). Further research should be done to understand this difference

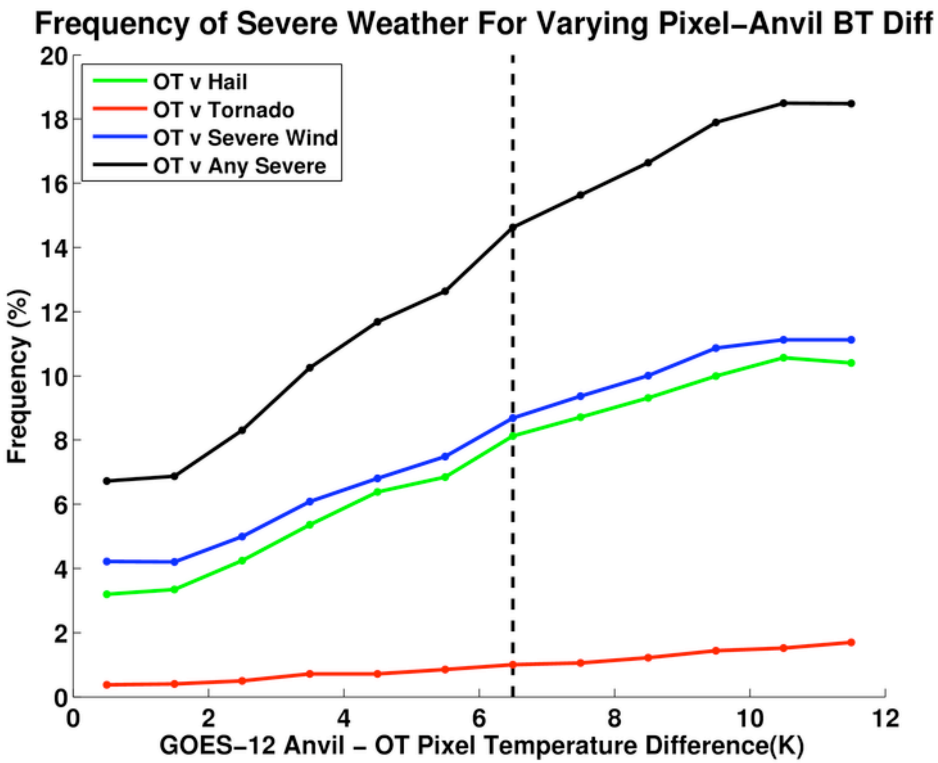
Comparison of GOES-12 OT Detections With Severe Weather Reports: 2004-2009 Warm Seasons

SEVERE WEATHER to OT COMPARISON Number of Severe Reports: 113541	
Severe Weather Type	**Match Frequency at 30 minute and 30 km (60 km) Radius**
Tornado	45.9% (56.2%)
Severe Wind	43.0% (58.4%)
Large Hail	40.8% (51.3%)
All Types	42.0% (54.8%)
OT to SEVERE WEATHER COMPARISON Number of OT Detections: 497529	
Only Tornado	1.2% (2.1%)
Only Severe Wind	9.6% (16.7%)
Only Hail	8.9% (14.1%)
Any Combo of Types	16.0% (25.1%)

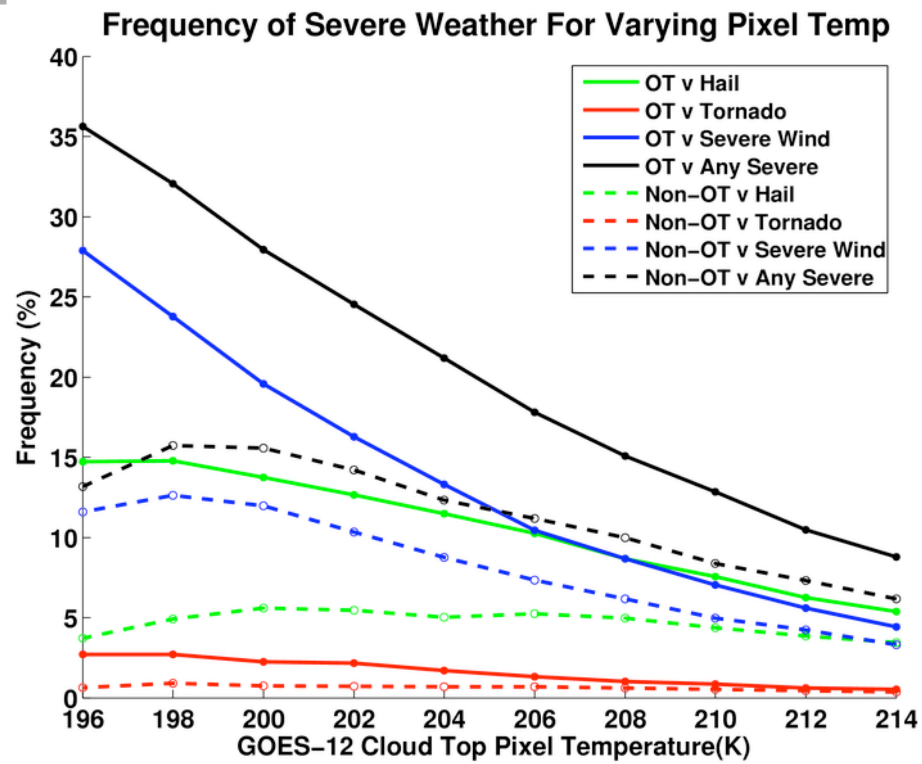
- Match criteria: +/- 30 mins and 30-60 km
- Despite coarse GOES spatial and temporal resolution, OTs were detected near 42% of all severe storms
- The 16% OT-svr report relationship illustrates that the presence of an OT signature in satellite imagery does not guarantee that a storm is severe
- An OT detection can be used to increase forecaster situational awareness that a storm may be severe, encouraging them to examine additional data fields in that region

NOTE: 75% of tornado warnings over the US were false alarms during 2008 (Brotzge et al. (*WAF*, 2011). 51% of severe weather warnings from 10 randomly selected NOAA NWS offices were false alarms from 2005-2009

Relationships Between OT Magnitude, Minimum IR BT, and Severe Weather: 2004-2009 Warm Seasons

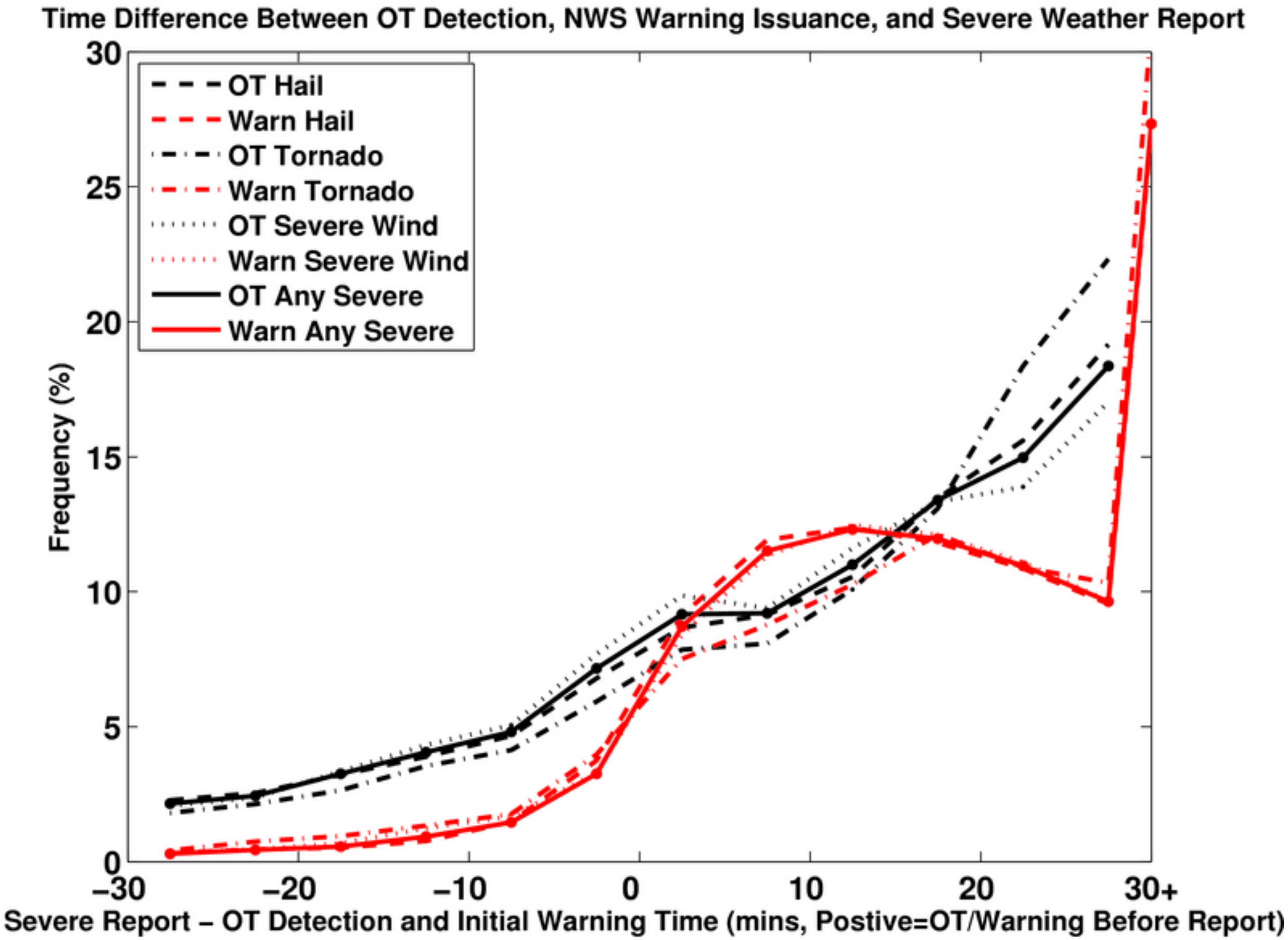


• Greater BT difference between pixel and surrounding anvil = stronger updraft and greater frequency of severe weather



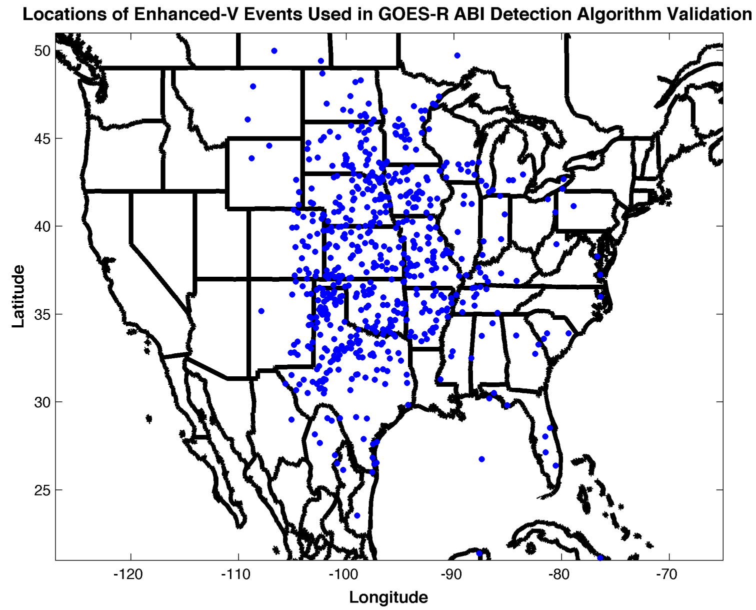
• For equivalent IR temps, pixels that are within significant localized IR BT minima more often signify a severe storm than those in a more spatially uniform BT field.

• Cold IR BTs alone do not guarantee a higher risk of hail or tornado


Time Difference Between OT Detection, NWS Warning Issuance, and Severe Weather Report
OT Hail
Warn Hail
OT Tornado
Warn Tornado
OT Severe Wind
Warn Severe Wind
OT Any Severe
Warn Any Severe
Frequency (%)
0
5
10
15
20
25
30
−30
−20
−10
0
10
20
30+
Severe Report − OT Detection and Initial Warning Time (mins, Postive=OT/Warning Before Report)

Synthetic GOES-R ABI Enhanced-V/Ring Detection Validation and Severe Weather

Enhanced-V/Ring Probability Of Detection	Enhanced-V/Ring Detection False Alarm Ratio	Frequency of Severe Weather
53%	24.9%	74%



- **There is no objective means for determining the presence of an enhanced-V or cold ring signature. Subjective IR image analysis by a human expert is required**
- Brunner et al. (*WAF*, 2007) have identified 450 enhanced-V cases within MODIS and AVHRR data during the 2003 and 2004 warm seasons. GOES imagery has been analyzed during 2010 to identify additional cases. Other random V-signature cases from recent years are also included
    - Total number of events (scenes) is 628 (196)

- The 74% relationship with severe weather shows that the V/ring signature is a better indicator of a severe storm than an OT alone

- Validation of the V/ring detection product for current GOES and SEVIRI is forthcoming

Summary

• Using relatively imperfect "truth" data sources, validation of an IR-only OT detection method indicates a FAR ranging from 6 to 20%, with the highest accuracy attributed to the coldest pixels with the greatest OT-anvil BT diff.

• POD for current GEO imagers was found to be 55% using a limited sample size of CloudSat OT overpasses with OT magnitude > 0.5 km, but practical experience analyzing visible channel OT signatures suggests that the true value is likely 10-20% for all OTs

• Despite the low POD, OTs were detected near 50% of all warm season severe events from 2004-2009, illustrating the importance of strong updrafts in severe storms

• Identification of focused regions of cold IR BTs is critical for estimating regions of heavy rain and severe weather…simple BT thresholding is insufficient

• 53% of subjectively identified enhanced-V / cold rings were detected in synthetic GOES-R ABI imagery, but 74% of the detected storms were severe

- Preliminary analyses suggest a far lower POD and FAR, but a greater relationship with severe weather. This suggests that if V-signature is prominent in coarse current GEO imagery, then the storm is hazardous