Efforts Toward Development Of A High Resolution Global Climatology Of Overshooting Cloud Top Detections Using MODIS and Geostationary Satellite Imager Data

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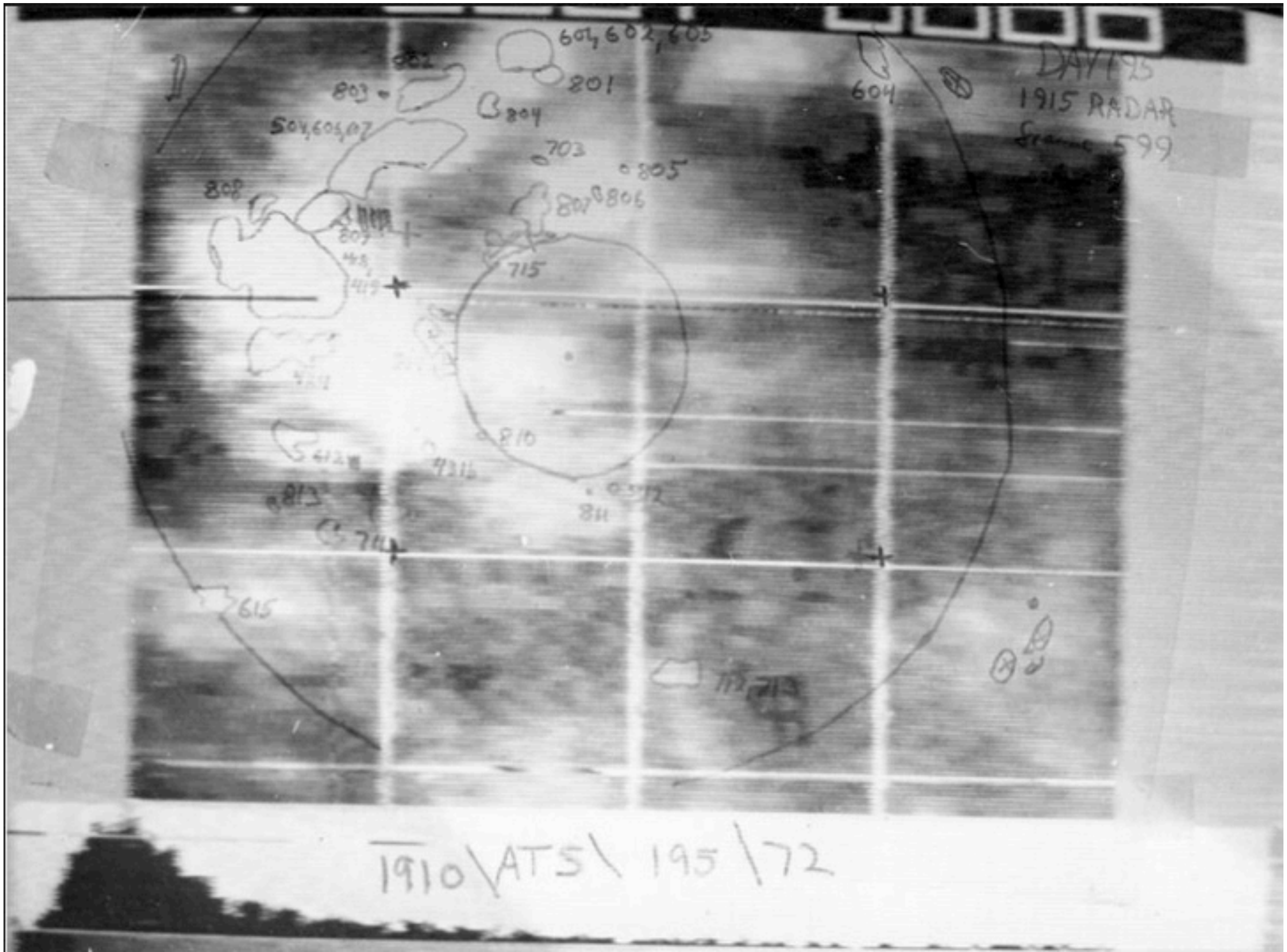
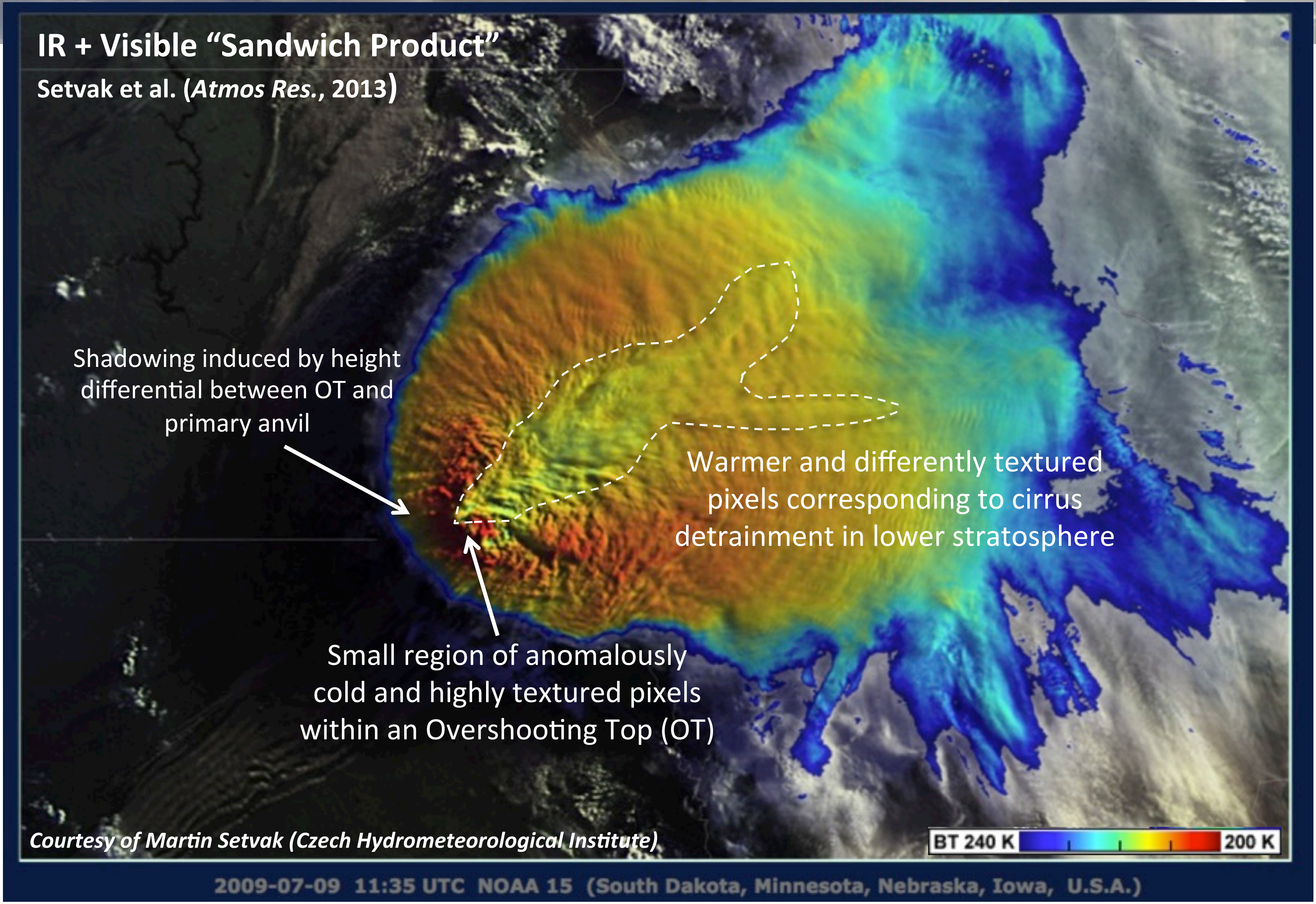
State-Of-The-Art
Overshooting Cloud Top Analyses (circa 1972)

- ATS-1 satellite imagery with hand contoured radar echoes taped to a monitor, 13 July 1972



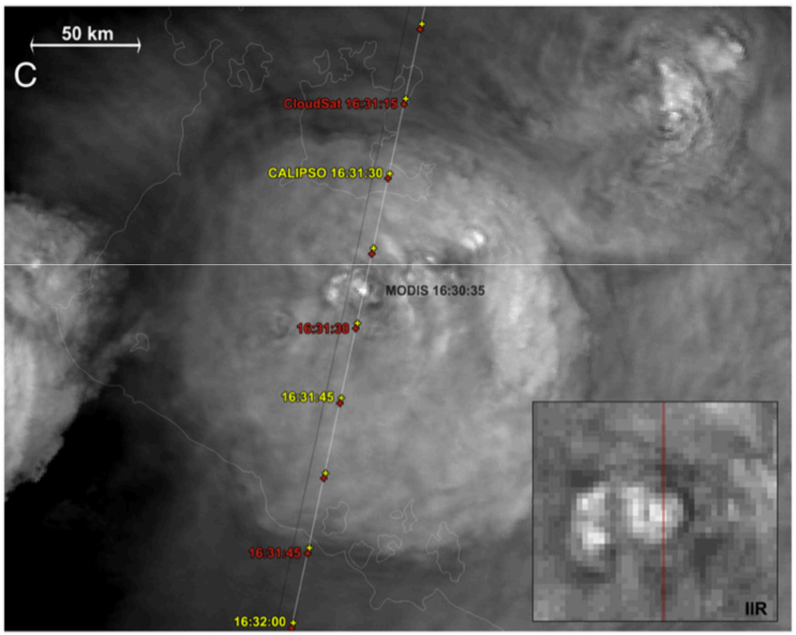
What Do I Consider To Be An Overshooting Top?

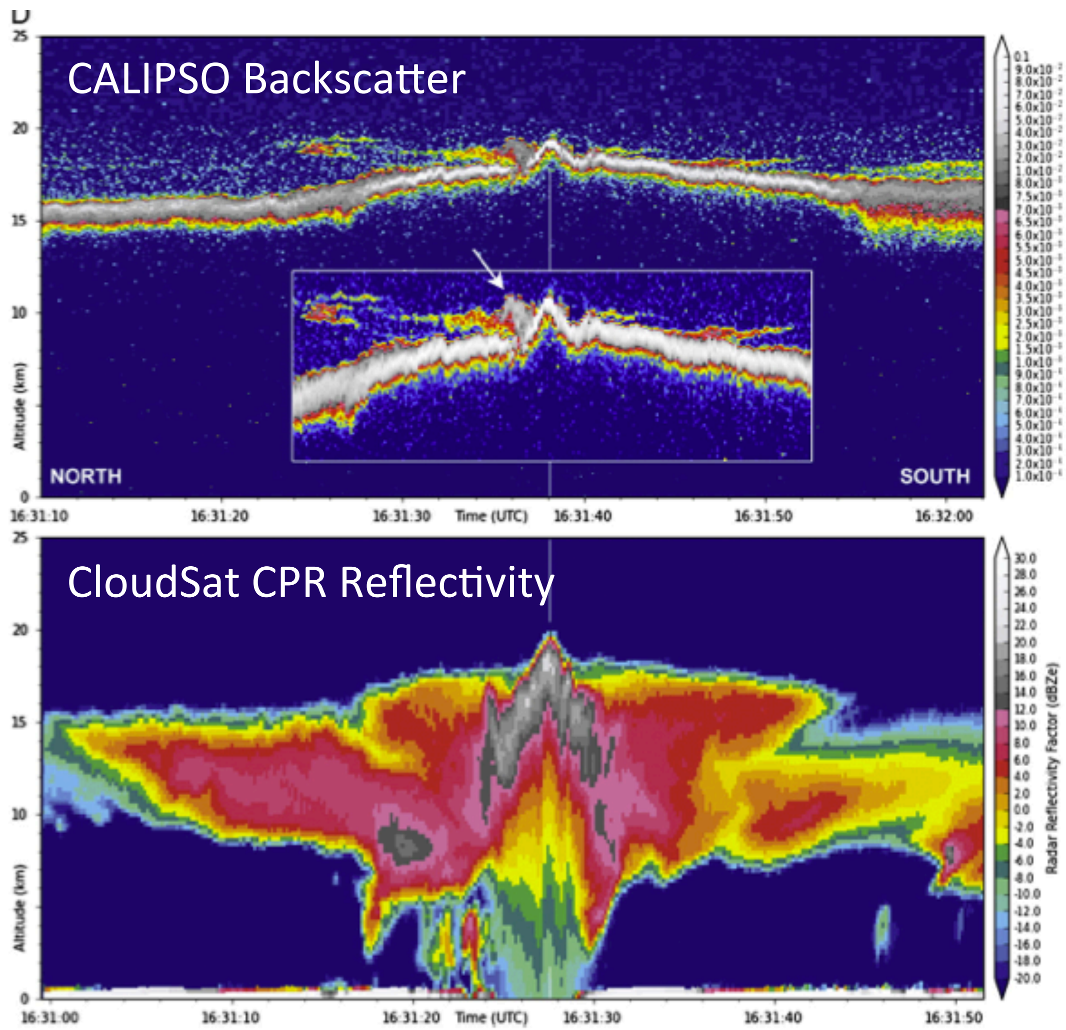


Ice Detrainment From OT Over Australia

‘‘One of the most striking features seen repeatedly above the anvil top is the formation of cirrus cloud which jumps upward from behind the overshooting dome as it collapses violently into the anvil cloud’’ **(Fujita, 1982)**

MODIS IR Over Gulf of Carpentaria
26 January 2010 1631 UTC

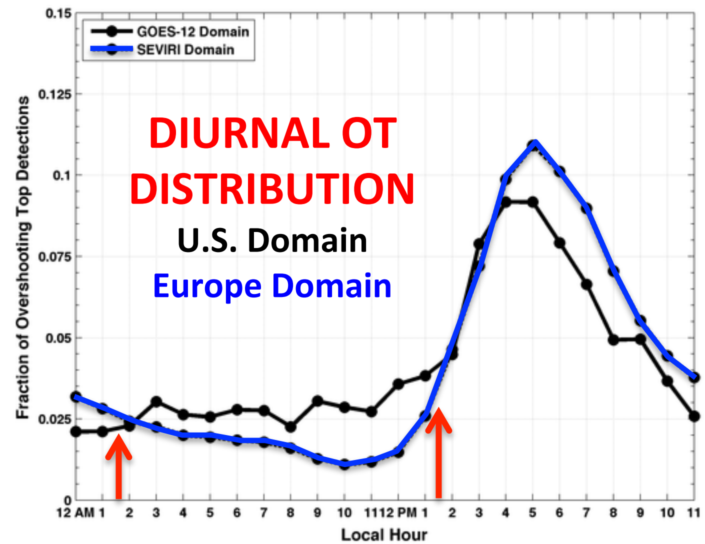




Setvak, Bedka, et al. (Atmos. Res. 2013)

Introduction: Description of Previous Long-Term Satellite Imager-Based Deep Convection Studies

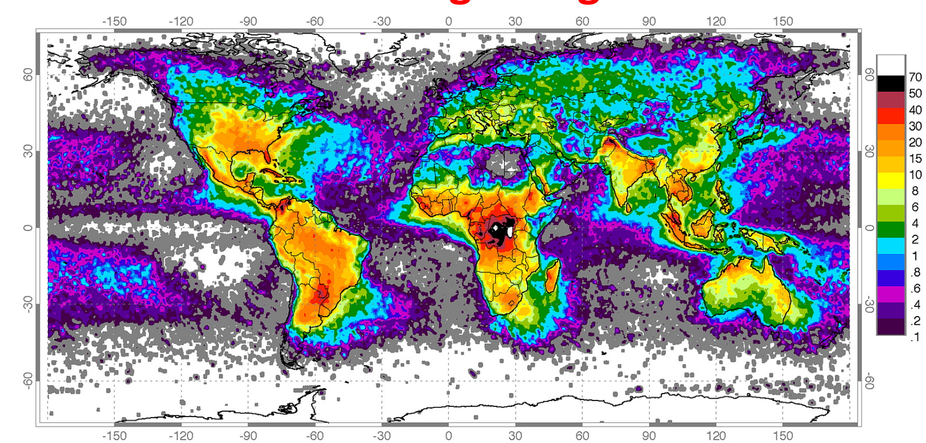
- **Existing Imager-based deep convection climatology studies typically rely on simple fixed thresholding of IR BTs and focus primarily over the tropics**
  - A particular threshold may work one day, but not the next
  - Entire anvil clouds are often detected, not just the active updraft region where weather hazards and UTLS transport are concentrated



- **NASA A-Train, Suomi NPP and AVHRR-based studies are hampered by the fact that the timing of peak storm activity is missed by their 1:30-2 PM overpass**

- **Storms analyzed using GEO data via the International Satellite Cloud Climatology Project (ISCCP, Rossow and Pearl 2007)**
  - ISCCP: 10 km resolution, 3-hourly
  - 10 km is quite coarse for studying small features like overshooting tops

TRMM LIS Number of Lightning Flashes Per km^2



- **TRMM/GPM radar profiles, imagery, and lightning flash detection data available since the late 90's**
  - Orbit inhibits repeated observation of hazardous convective storm events throughout their lifecycle

- ***Given the characteristics of these instruments and approaches. how can we determine if UTLS-penetrating storm activity has changed over time?***

Why Develop a New Geostationary Imager-Based UTLS-Penetrating Storm Climatology?

- Geostationary (GEO) satellite imagers have been collecting detailed observations (~ 5 km/pixel, 30 min frequency) of UTLS-penetrating storms for over 20 years

- UTLS-penetrating updrafts and evidence of above-anvil ice detrainment exhibit essentially the same patterns in visible and IR imagery, regardless of storm location or season

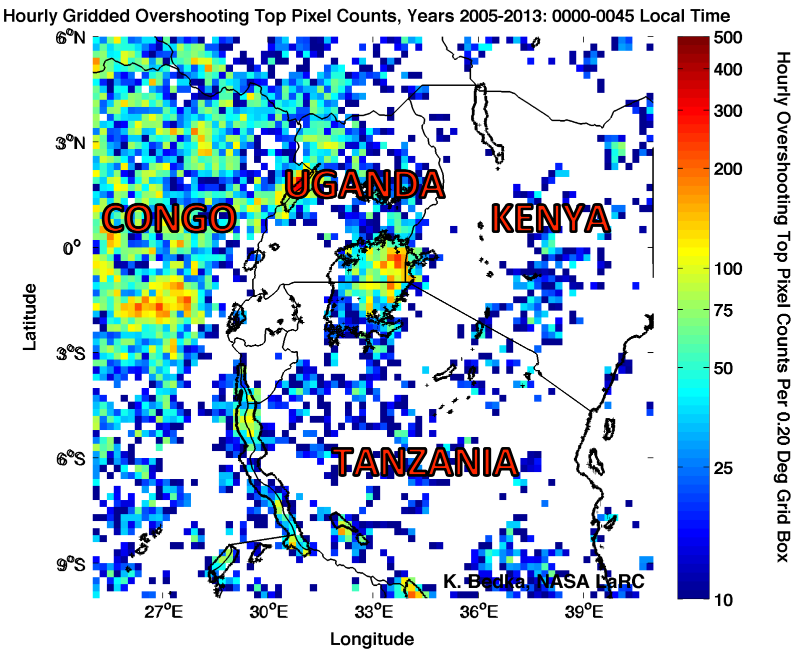
- Despite this fact, few approaches have been developed that can produce globally consistent, "climate-quality" analyses of historical UTLS-penetrating storm activity throughout the diurnal cycle

- If such an approach were developed, one could determine if/how storm frequency and distribution has changed in association with observed global temperature increase and land surface changes

- GEO climatology would provide context for temporally sparse LEO observations

- UTLS-penetrating storms are also often associated with hazardous weather
  - Strong demand from private industry for GEO-based storm analyses to develop weather hazard risk models

Animation below located at: http://cloudsgate2.larc.nasa.gov/site/people/data/kbedka/OTclimatology_2005-2013_Kenya_SEVIRI_houranim.gif



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

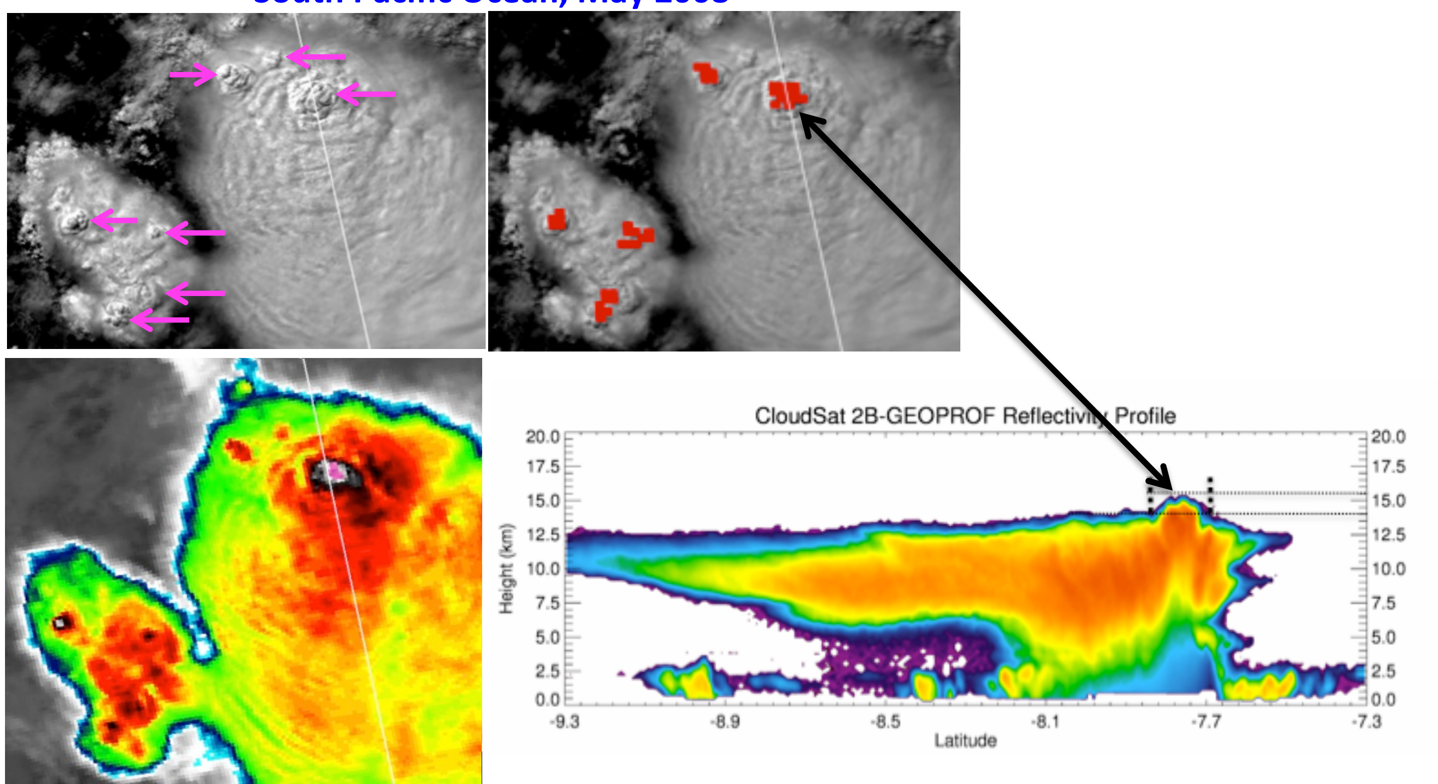
- Hazardous and UTLS-penetrating convective storms typically have one or more overshooting top (OT) regions

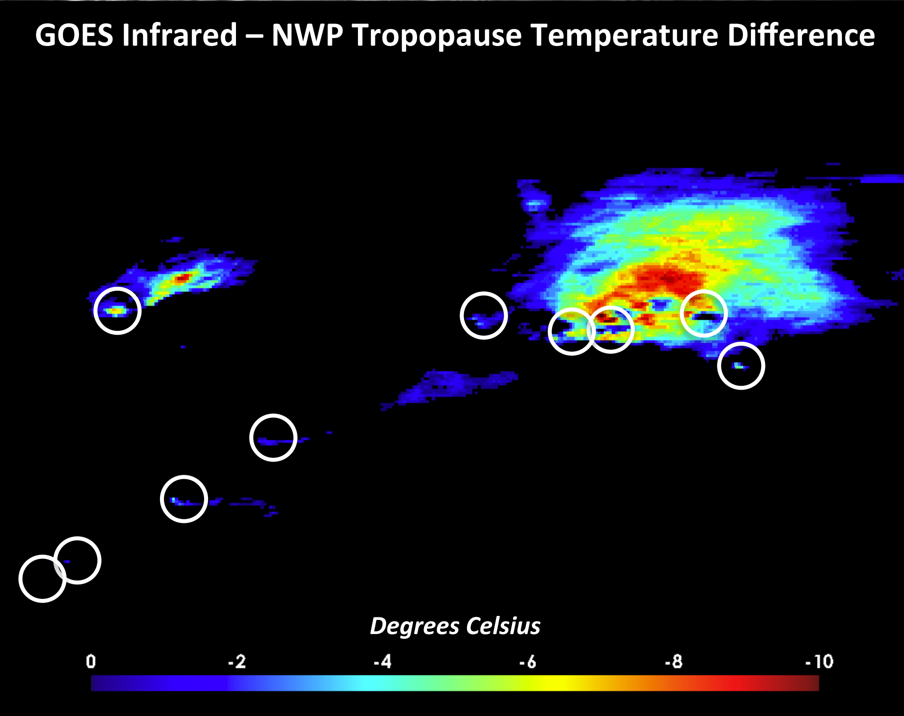
- A satellite-based OT detection method was funded by the NASA Applied Sciences Program and GOES-R ABI Aviation Algorithm Working Group for near real-time aviation safety and weather forecast applications (Bedka et al. 2010, 2012)

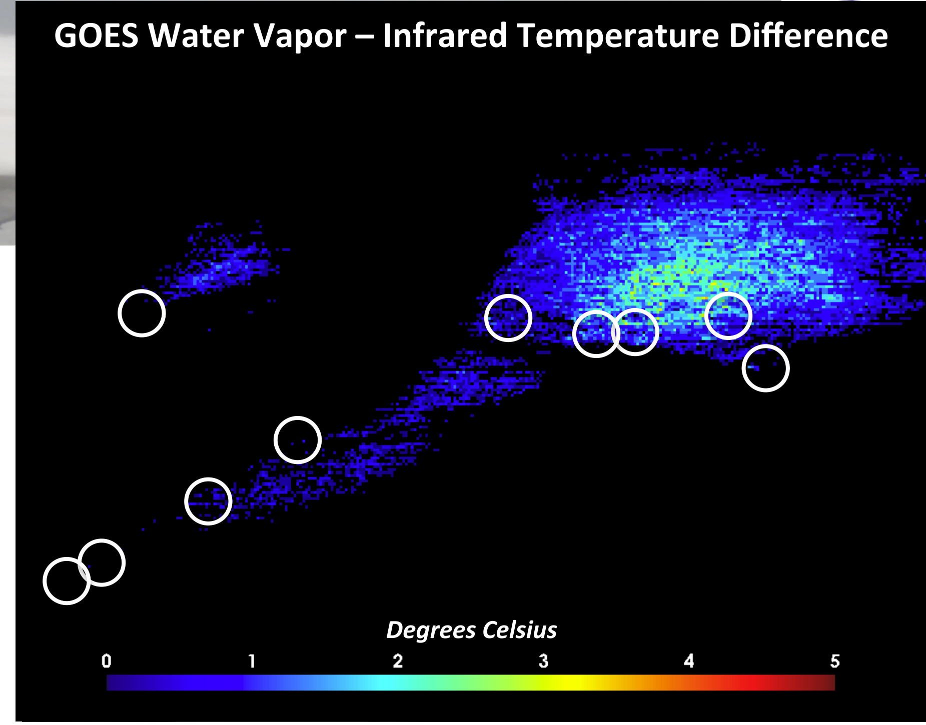
- The method uses spatial analysis and thresholding of satellite IR temperature combined with NWP tropopause tempature to automatically identify individual OT regions at the satellite pixel scale

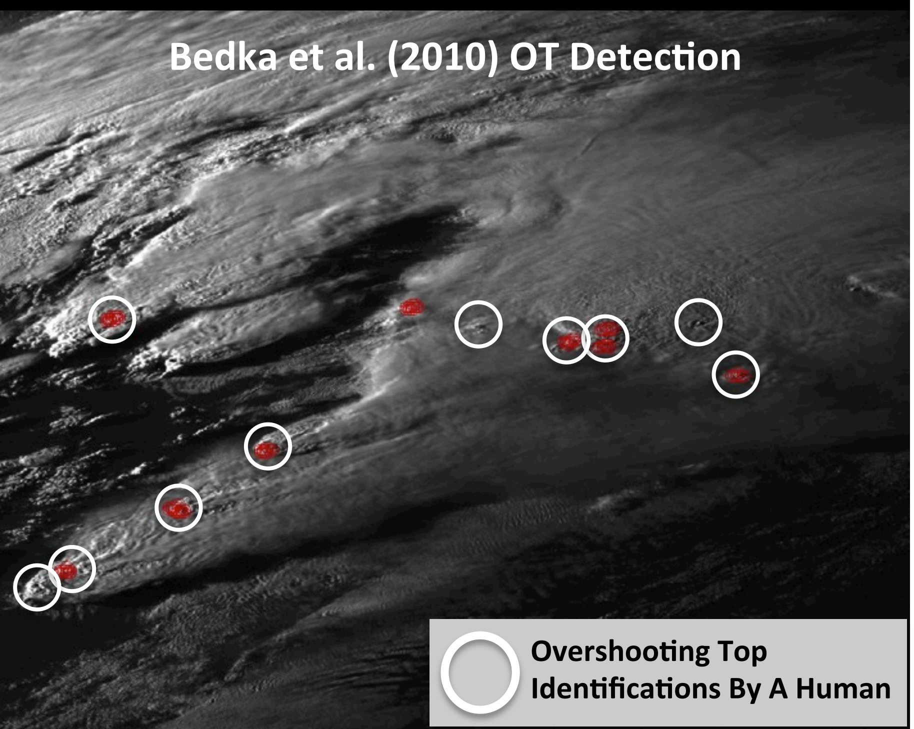
<u>MODIS 250 m Visible, 1 km IR, and Overshooting Cloud Top Detections</u>

South Pacific Ocean, May 2008









Limitations of Current OT Detection Approaches

- **All approaches use fixed criteria for binary yes/no OT detection**
- Detection techniques that use water vapor imagery identify large portions of the convective anvil and typically cannot isolate only the OT regions
- IR-Tropopause temp difference can suffer if tropopause analysis is errant and can be biased by image spatial resolution
- Bedka et al (2010) is the only approach that uses spatial analysis of the anvil cloud for detection
- No approaches use the visible channel which typically provides the clearest indication of an OT based on texture and shadowing

Probabilistic Overshooting Cloud Top Detection

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

Satellite IR and Visible OT Indicators Derived Via Pattern Recognition
+ NWP Level of Neutral Buoyancy and Tropopause Temperature Fields

↓

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

↓

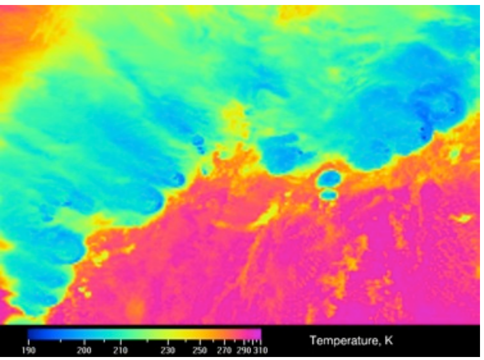
Logistic Regression Model Used To Discriminate Between The OT and Non-OT Anvil Populations

↓

OT Probability Product

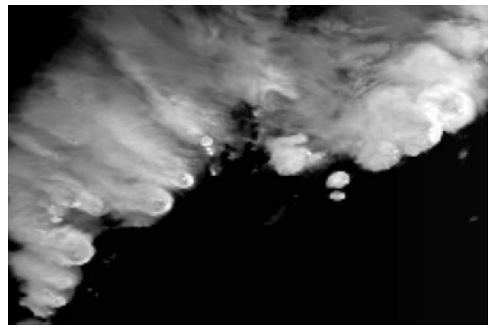
IR-Based Pattern Recognition Analysis

Input MODIS IR Temperature (BT) Image, Resampled To 4 km/Pixel 6 May 2007, 1925 UTC

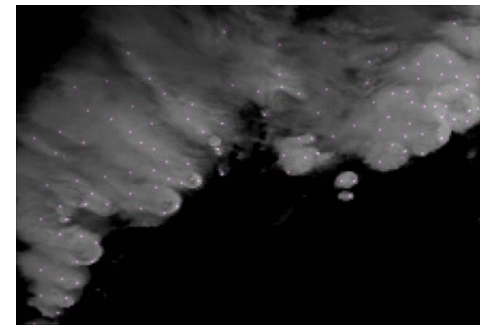


BT Score: $\text{BTscore} = (T_{avg} - T)^{0.7}(255 - T)^{1.3}/16 \quad + 2 \cdot \sigma(T)$

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

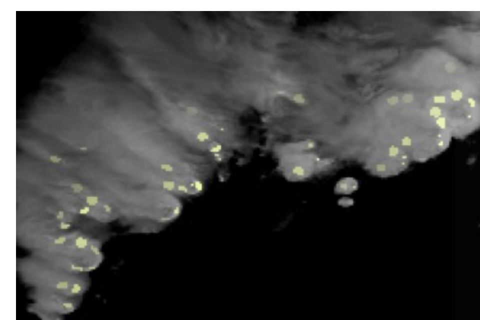
Pattern recognition used to ensure that the region being analyzed is within deep convection and 2) the feature of interest has a shape and prominence typical of OT regions

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

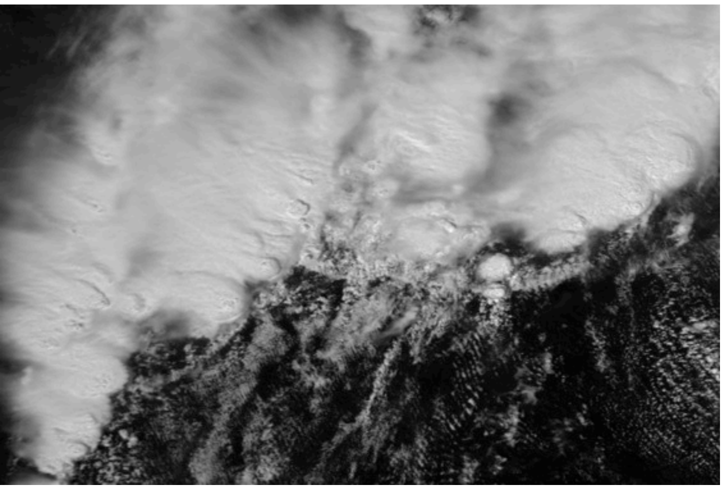
Final OT Candidate Regions Based on IR Analysis



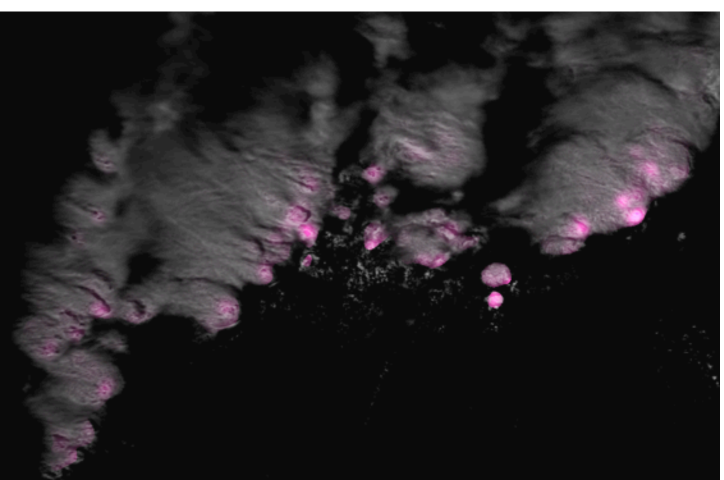
Visible Channel Analysis

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

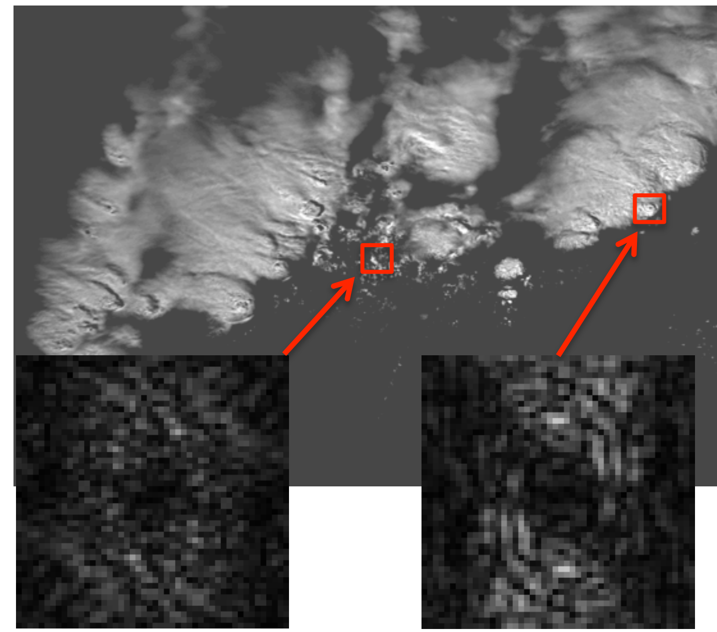
Input MODIS 1 km Visible Image



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

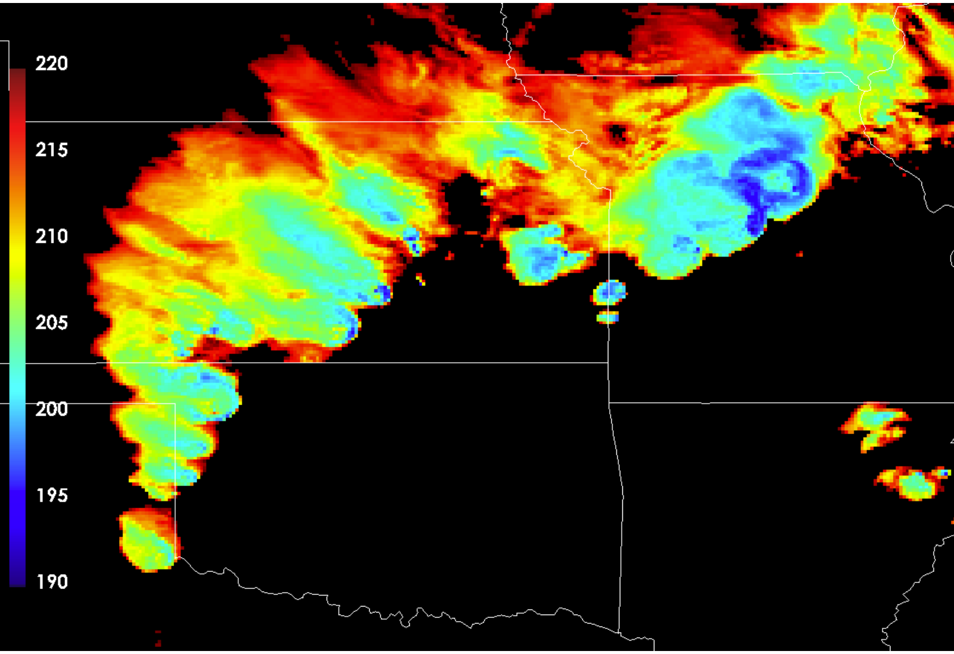
Ring fragments in the spectrum can be identified

Automated Shadow Detection Method Also Implemented

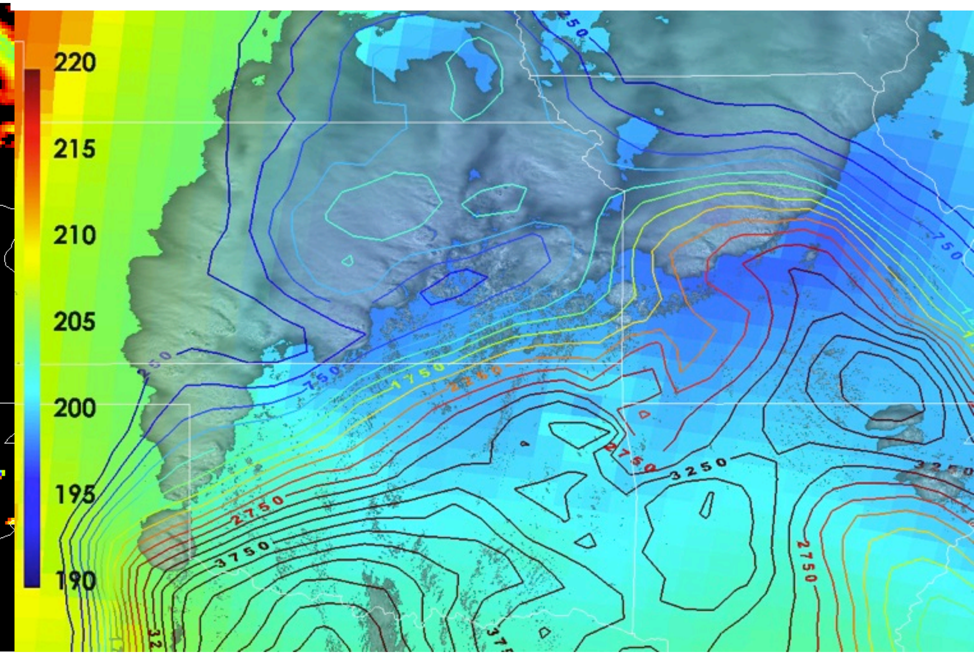
Automated Shadow Detection Method Also Implemented

Infrared Comparisons With Reanalysis Fields

Input MODIS Infrared Image



MODIS Visible Overlaid With NWP Tropopause Temp and CAPE Contours



- **A set of NWP- and Imager-based parameters were evaluated for statistical significance using logistic regression**

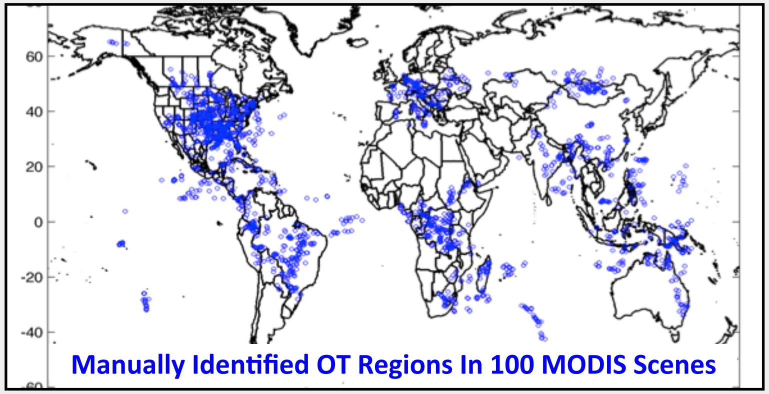
<u>Significant parameters for OT discrimination at the 99+% confidence level</u>

1) **Satellite IR – Lapse-Rate Tropopause Temperature Difference**
2) **Satellite IR– Most Unstable Level of Neutral Buoyancy Temperature Difference**
3) **OT-Anvil Mean Temperature difference (75%+ contribution)**

Logistic Regression and Final OT Detection Product

A database of ~2000 OT events were manually identified in 100 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 assign high detection probability to OT-like features

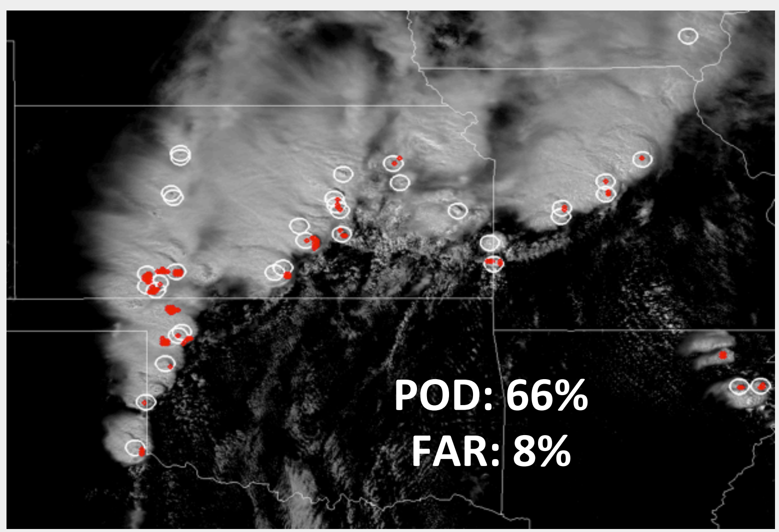


Regression Result $= W_0 + W_1 * (\text{OT-Mean Anvil IR BT}) + W_2 * (\text{IR BT} - \text{Tropopause Temp}) + W_3 * (\text{IR BT} - \text{MU LNB Temp})$

OT Probability

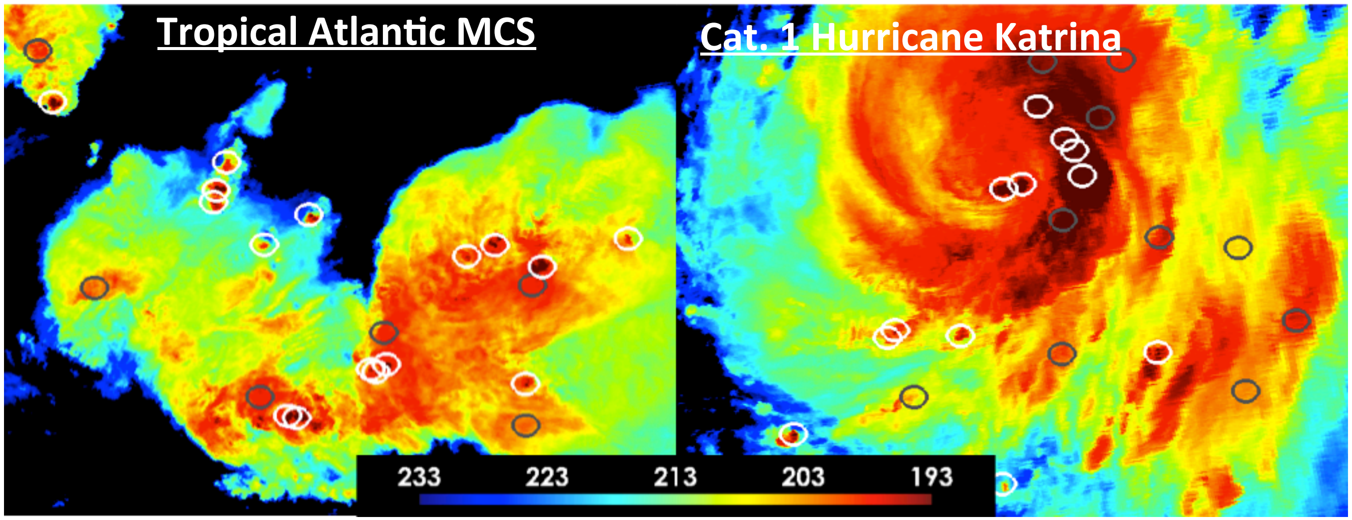
$$\text{OT Probability} = \frac{1}{(1+\exp(-1 * \text{Regression Result}))}$$

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



OT Detection Validation

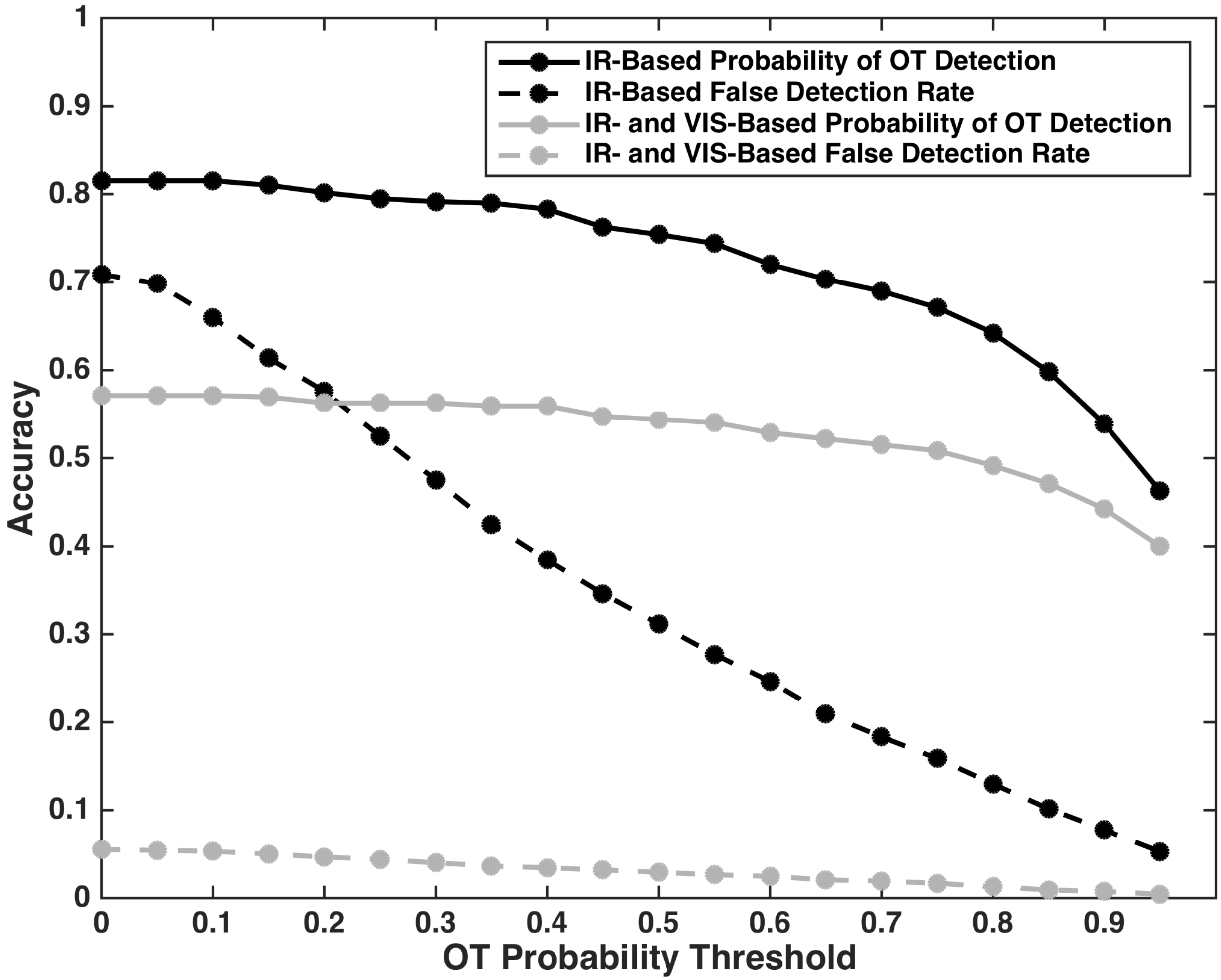
How Well Can The Algorithm Discriminate Between Human-Identified OT Regions (White Circles) and Non-OT Regions (Grey Circles)?



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%	

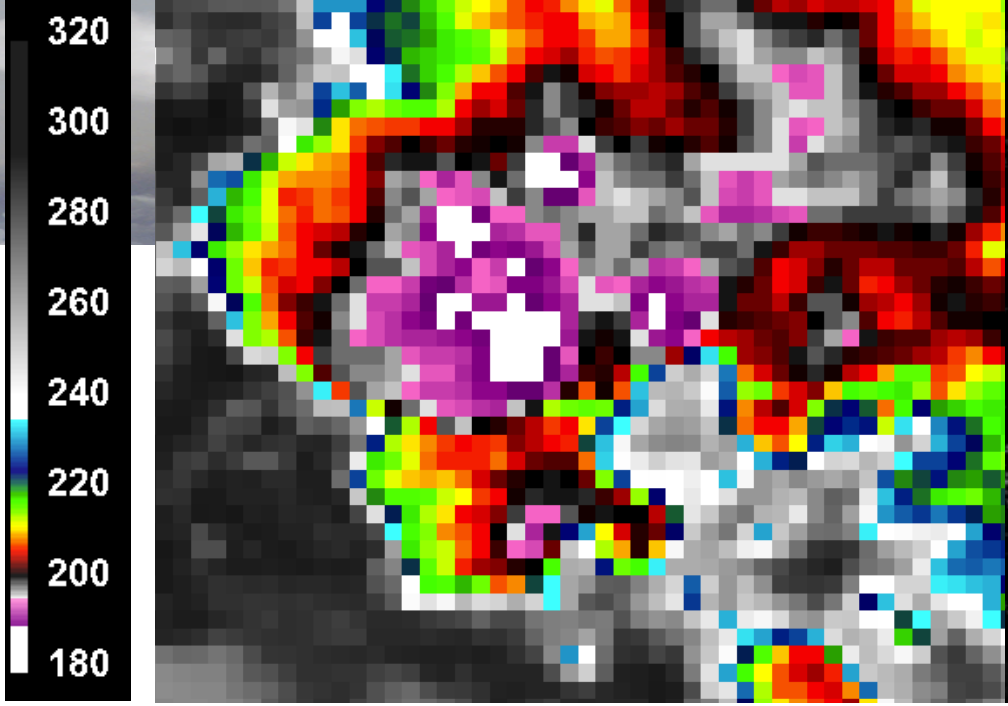
OT Detection Validation

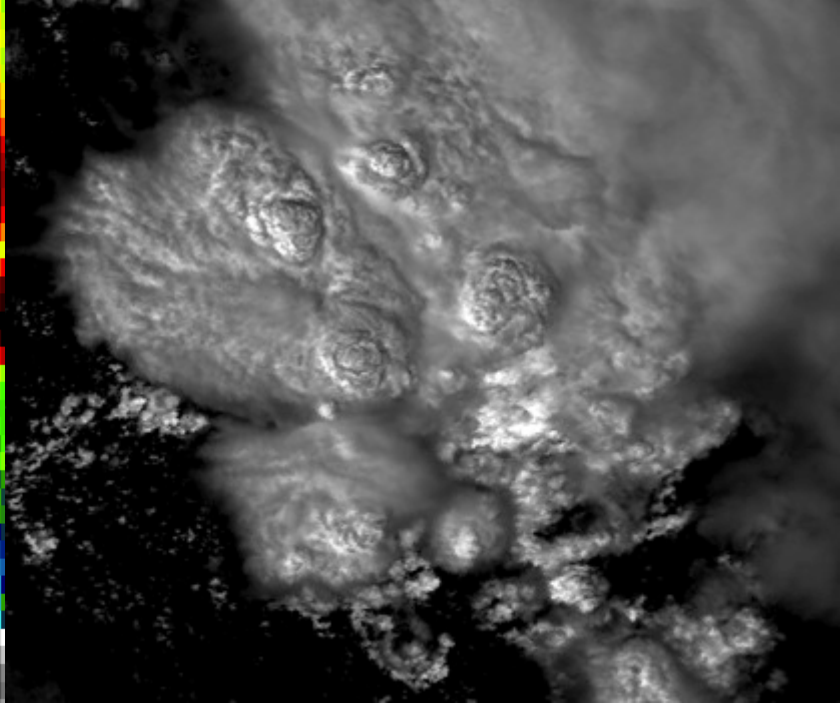
How Does The Algorithm Perform Relative to Human-Identified OTs Across 33 MODIS Scenes?

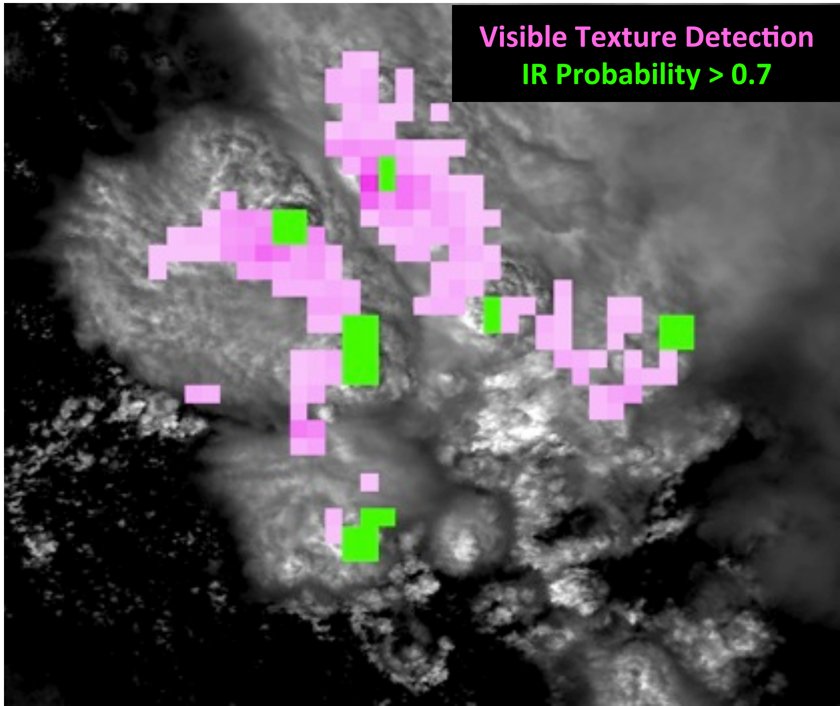


Bedka et al. (2010) Accuracy
55% POD
17% FAR

Biggest Challenge for Visible Detection=Storms with Small Anvils







MODIS Tropical OT Detection Example

Eastern Congo
29 November 2008, 1215 UTC

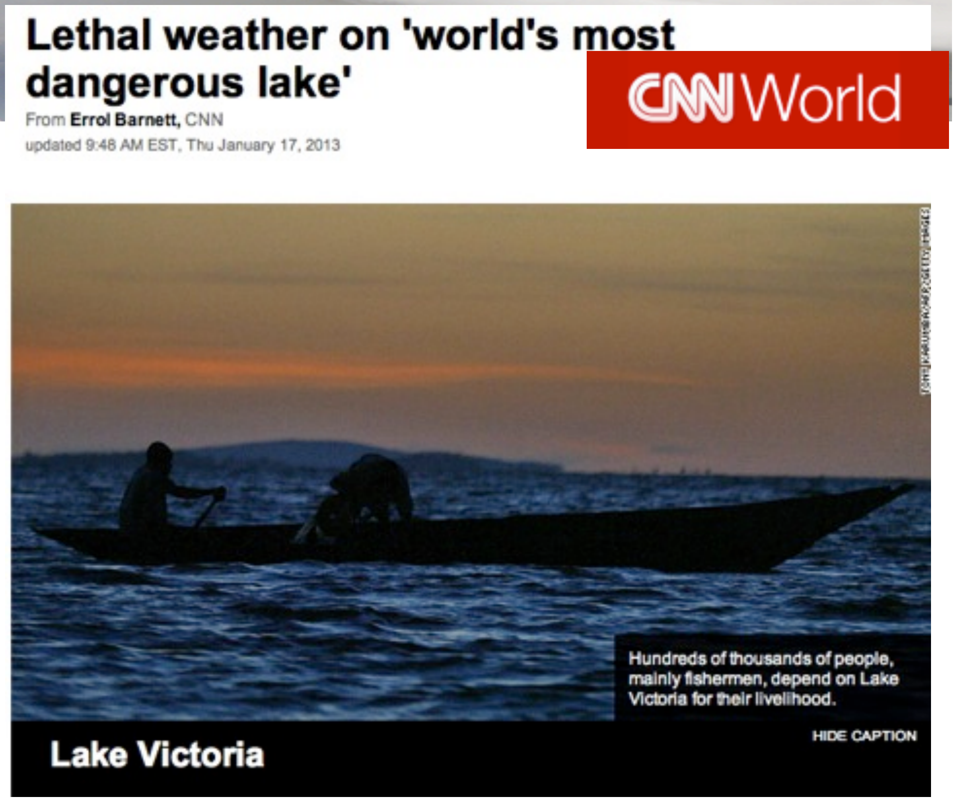
GOES High Temporal Resolution OT Detection Animations

CAUTION: Large (100+ Mb) Animated GIFs

kbedka@cloudsgate2:/www/production-website/htdocs/site/people/data/kbedka/visible_ir_and_rating_TX_SRSO_anim_May28.gif

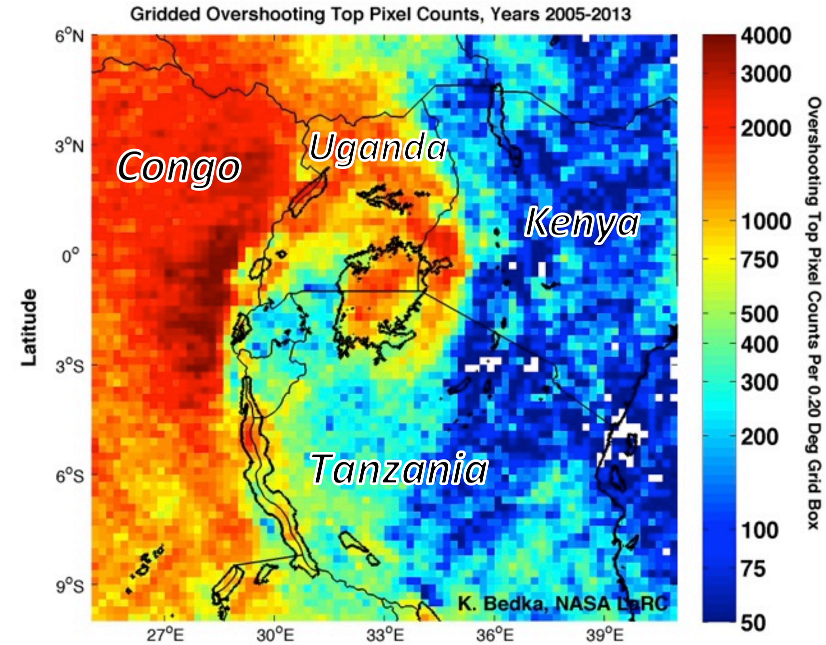
kbedka@cloudsgate2:/www/production-website/htdocs/site/people/data/kbedka/2014131_SRSO_OTD_Oklahoma.gif

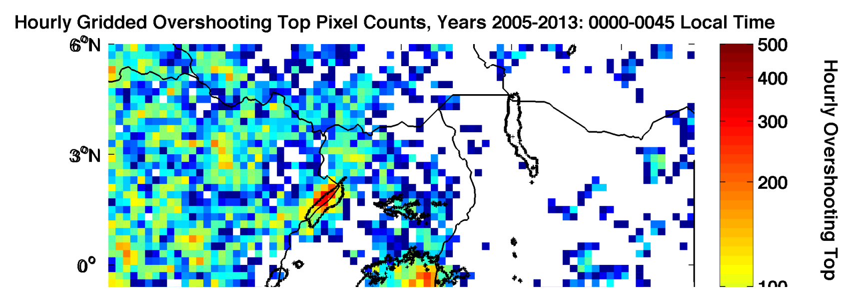
UTLS-Penetrating Storm Database over the African Great Lakes Region Using Bedka et al. (2010) Approach



5000+ people are killed on the African Great Lakes every year, most often caused by severe weather

NASA LaRC and international partners are determining 1) the controlling factors for the occurrence of hazardous thunderstorms over the African Great Lakes region and 2) how climate change could affect future storm activity via a regional climate model and satellite-based OT detection analysis





Animation located at:
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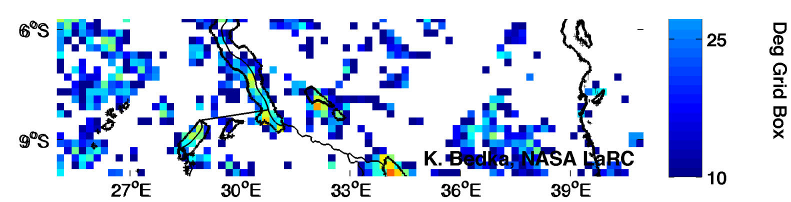
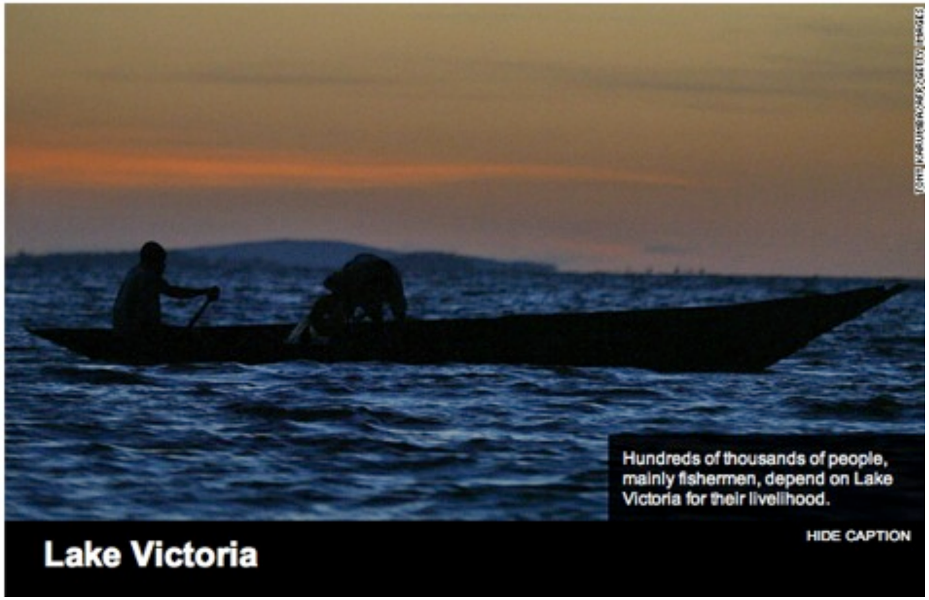


UTLS-Penetrating Storm Database over the African Great Lakes Region Using Bedka et al. (2010) Approach

Lethal weather on 'world's most dangerous lake'

CNN World

From **Errol Barnett**, CNN
updated 9:48 AM EST, Thu January 17, 2013



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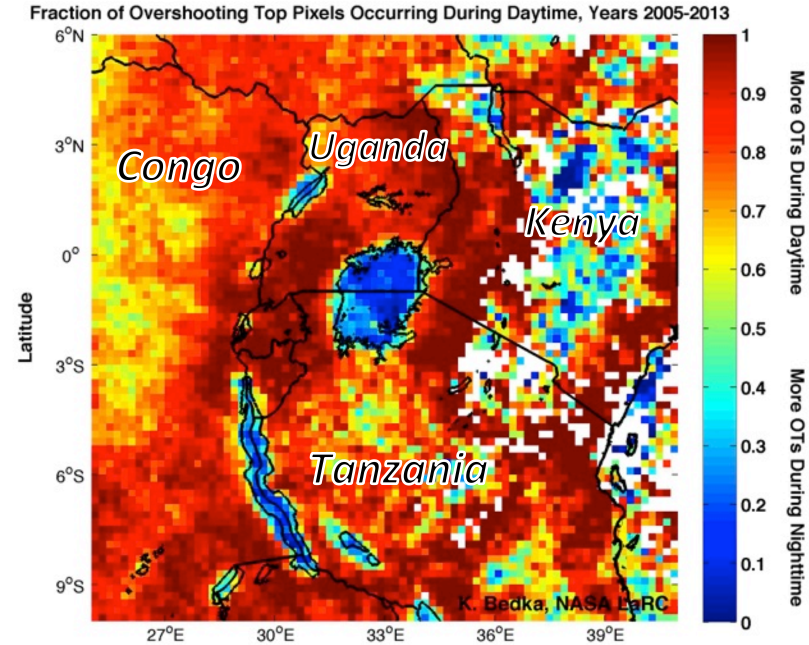

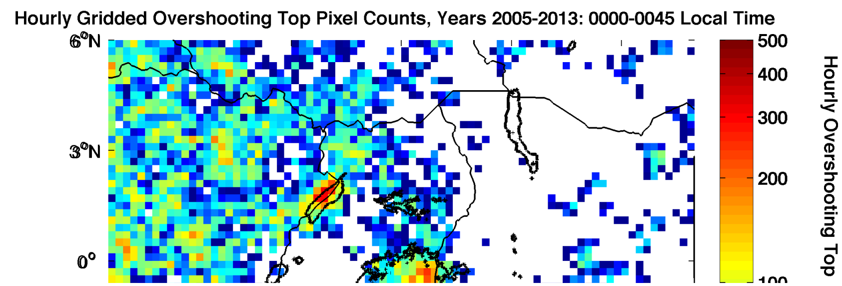

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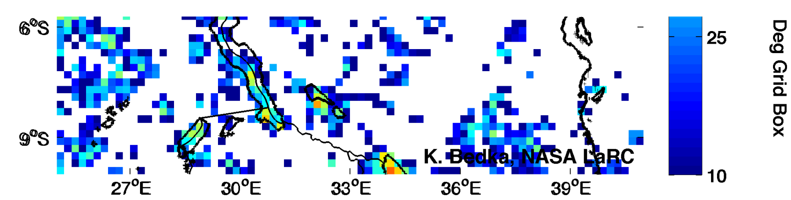
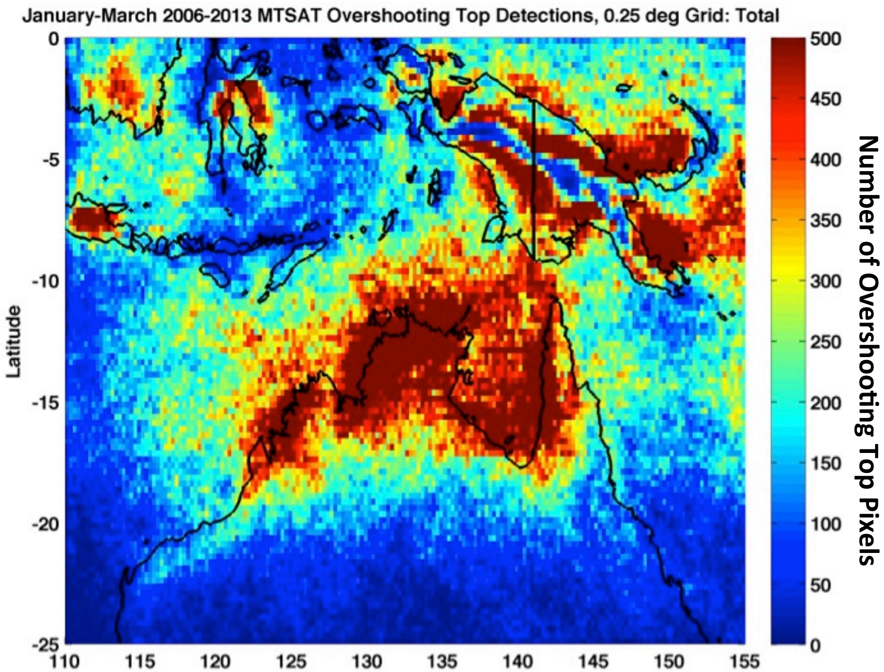
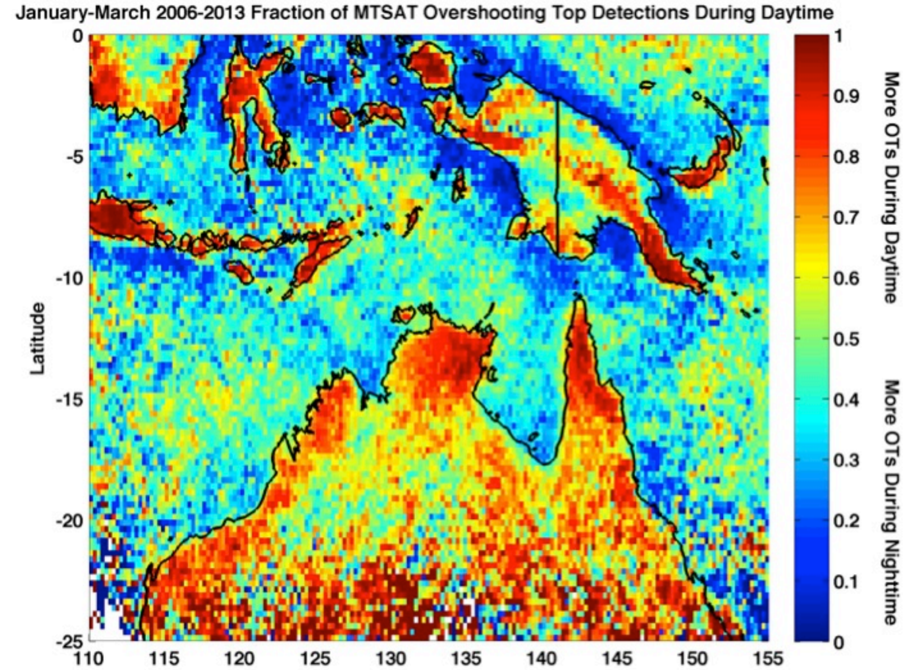
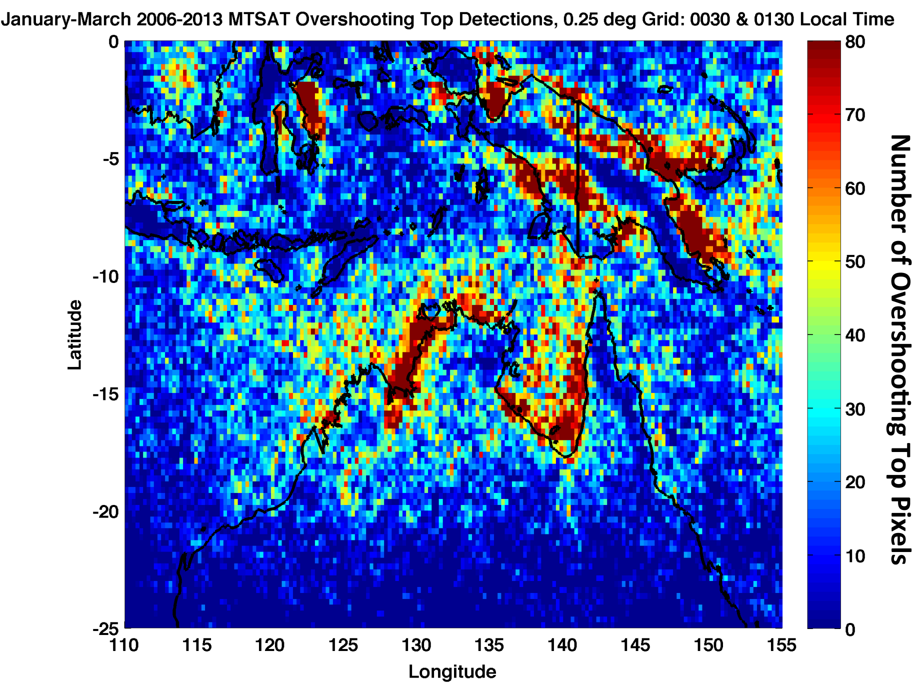








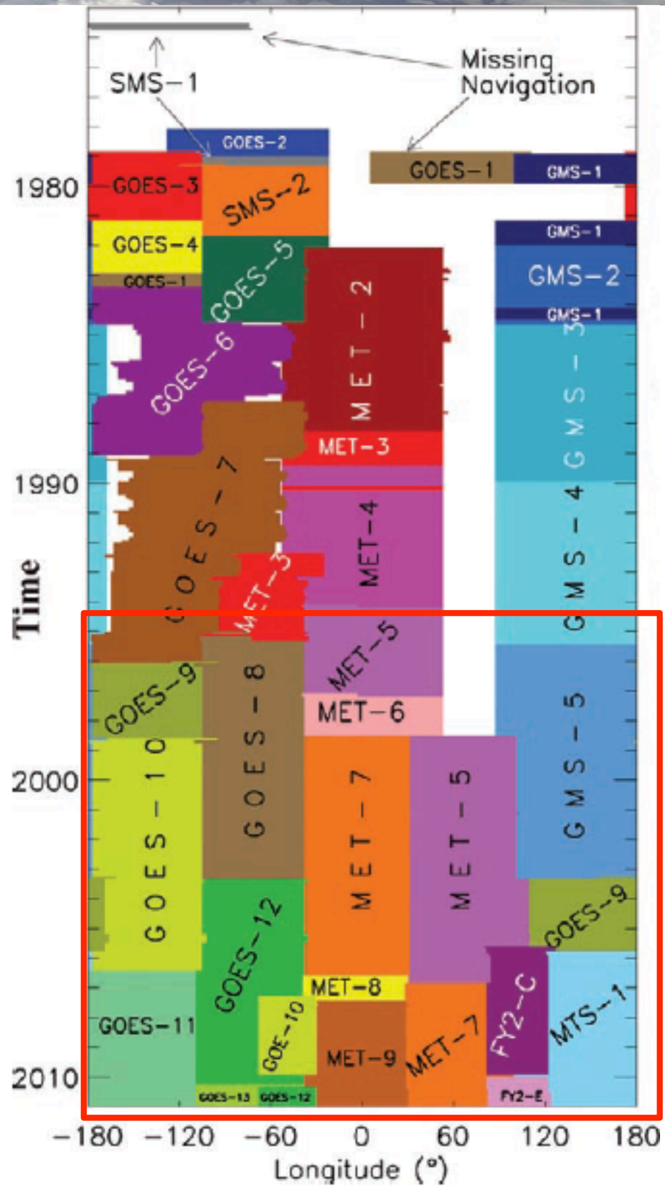
UTLS-Penetrating Storm Database over the Maritime Continent and Australia

- Generated using hourly data from MTSAT, January-March 2006-2013 in preparation for the international HIWC/HAIC field campaign
- Illustrates interesting diurnal variability in storm frequency and distribution associated with land vs. ocean and topography

Animation in lower-left located at:
http://cloudsgate2.larc.nasa.gov/site/people/data/kbedka/OTclimatology_2006-2013_MTSAT_HIWC_houranim.gif

Global GEO
Satellite Imager History
From Knapp et al. (BAMS, 2011)

Toward A Global GEO Climatology of Overshooting Cloud Top Events



≤ 5 km IR Spatial Resolution

- **The global constellation of geostationary (GEO) imagers have been collecting high spatial resolution (< 5 km) IR imagery since the mid-1990's. Resolution will increase by a factor of 4 in the GOES-R era.**

- **NASA LaRC has immediate access to the entire GEO image data archive via McIDAS. User requested data is available within < 30 seconds of request, enabling rapid development of a near-global UTLS-penetrating storm dataset**

- **Remaining challenges include:**
    1) GEO IR intercalibration
    2) Viewing angle induced biases on IR brightness temperature

- **Challenges can be addressed by anchoring GEO calibration to stable, long-lived LEO satellite imagers, i.e. MODIS, AVHRR, or HIRS and building LEO-GEO viewing angle dependency models**

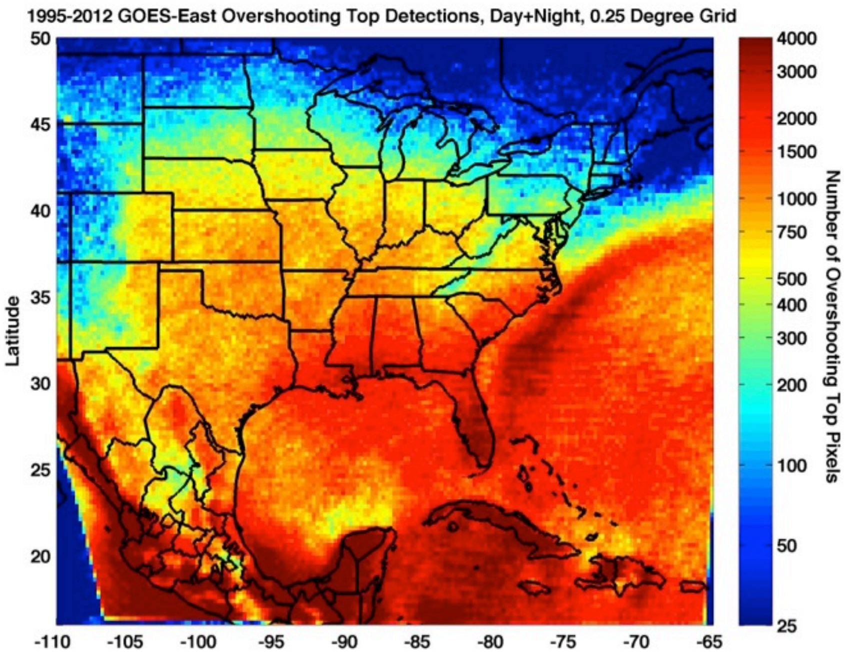
Summary

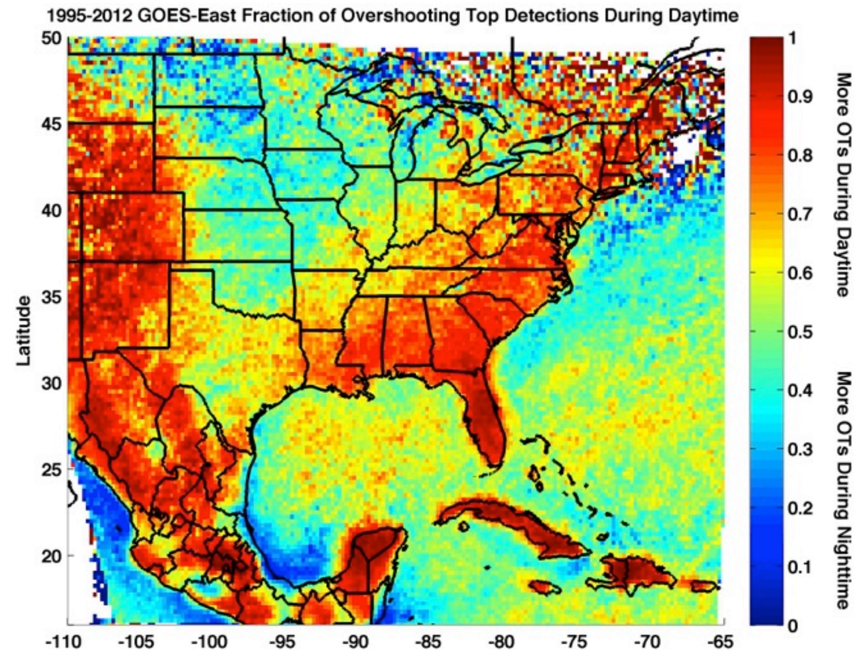
- **An automated overshooting cloud top (OT) detection algorithm has been recently improved in support of the GOES-R Advanced Baseline Imager program**

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

- **An automated OT detection product has been demonstrated or could be used in a number of applications:**
  1) Development of a weather hazard risk model for the reinsurance industry (Punge et al. 2014)
  2) Analysis of storm distribution throughout the diurnal cycle over the African Great Lakes region (Thiery et al. 2015)
  3) Hazardous storm nowcasting by NOAA and within airborne field campaigns (e.g. High Ice Water Content – High Altitude Ice Crystals (HIWC-HAIC), GRIP, and HS3)
  4) Analysis of the origin of stratospheric WV plumes during SEAC4RS and stratospheric cirrus observed by CALIPSO
  5) Validation of weather and climate model predictions of UTLS-penetrating storms

- **The highly efficient nature of the algorithm coupled with immediate access to the entire geostationary image archive from NASA LaRC enables development of a 20+ year OT event climate data record that can be used by the community to derive trends in global UTLS-penetrating storm frequency and distribution**

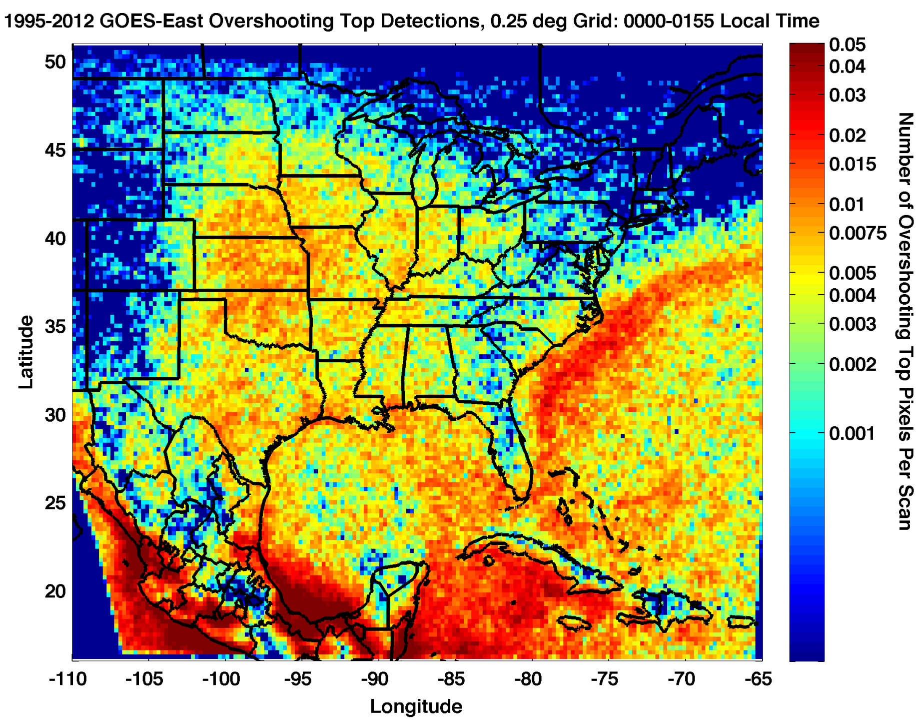




1995-2012 GOES-East OT Detections Using ~4 km Spatial Resolution Data and Two Images Per Hour

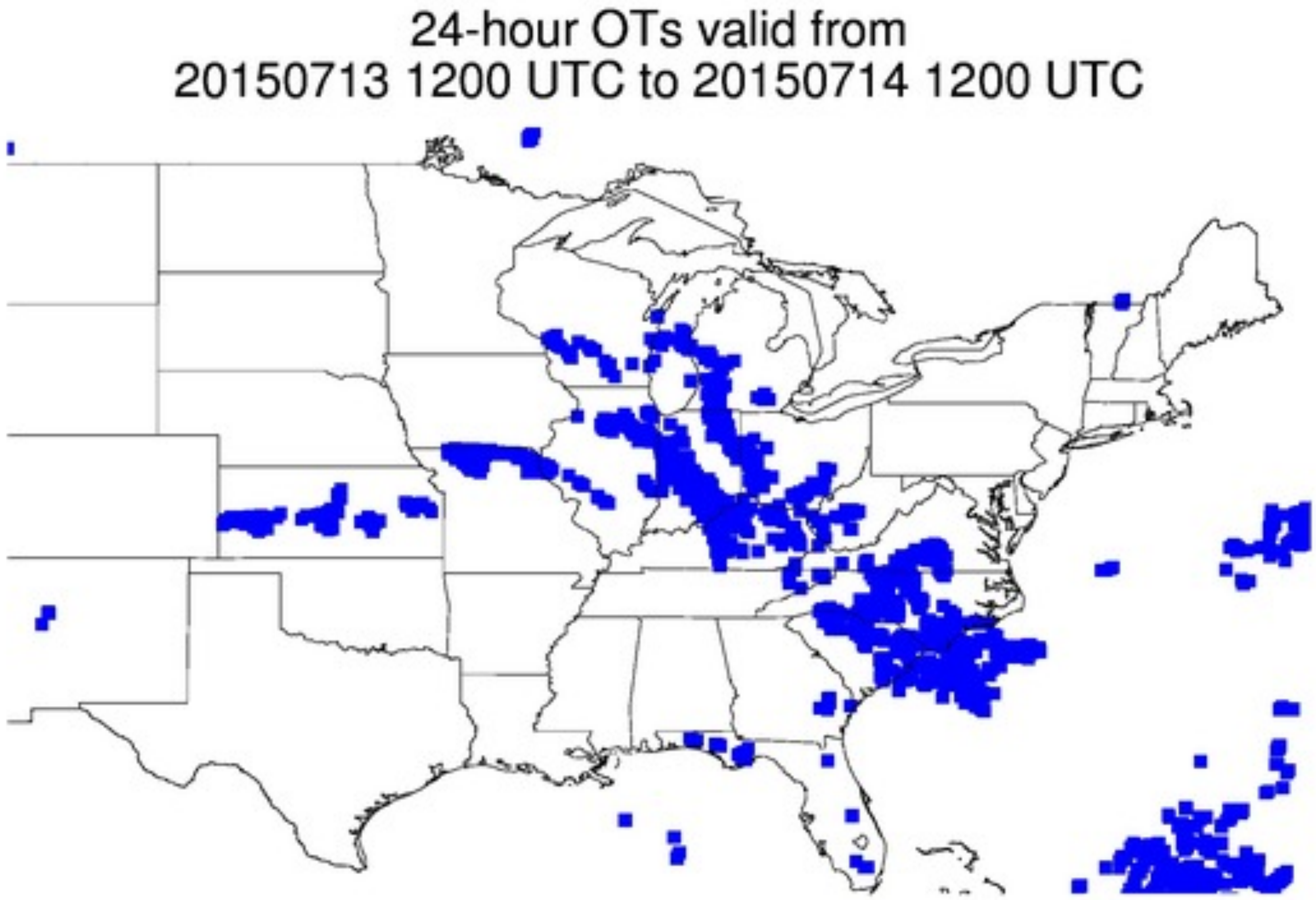
OT Detections Assigned To A 0.25 Degree Resolution Grid

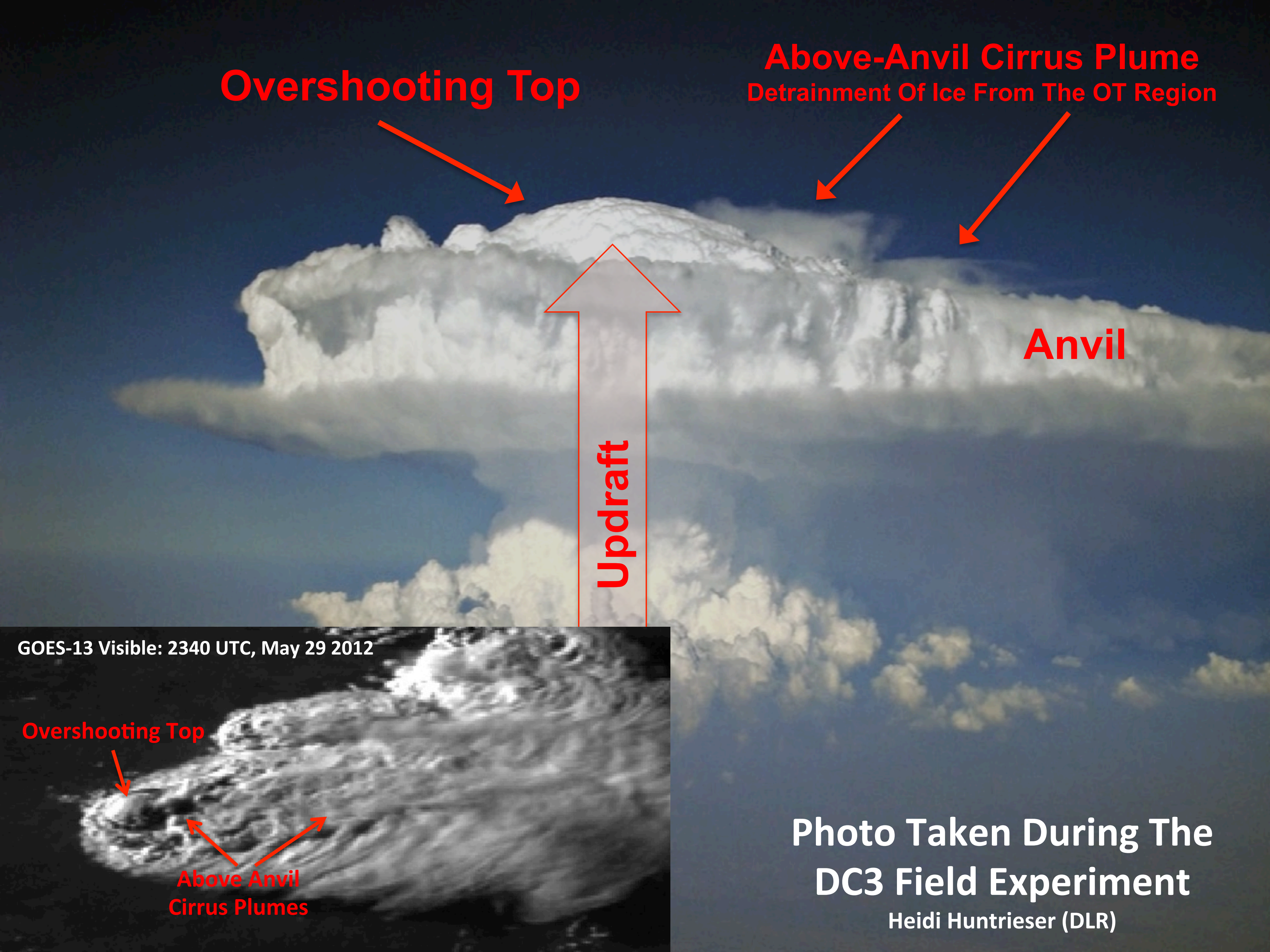
Animation In Lower Right Panel Located At:
[http://cloudsgate2.larc.nasa.gov/site/people/data/kbedka// OTclimatology_1995-2012_30minscans_solartime.gif](http://cloudsgate2.larc.nasa.gov/site/people/data/kbedka//OTclimatology_1995-2012_30minscans_solartime.gif)



Data Courtesy of
UW-SSEC Acquired Via McIDAS

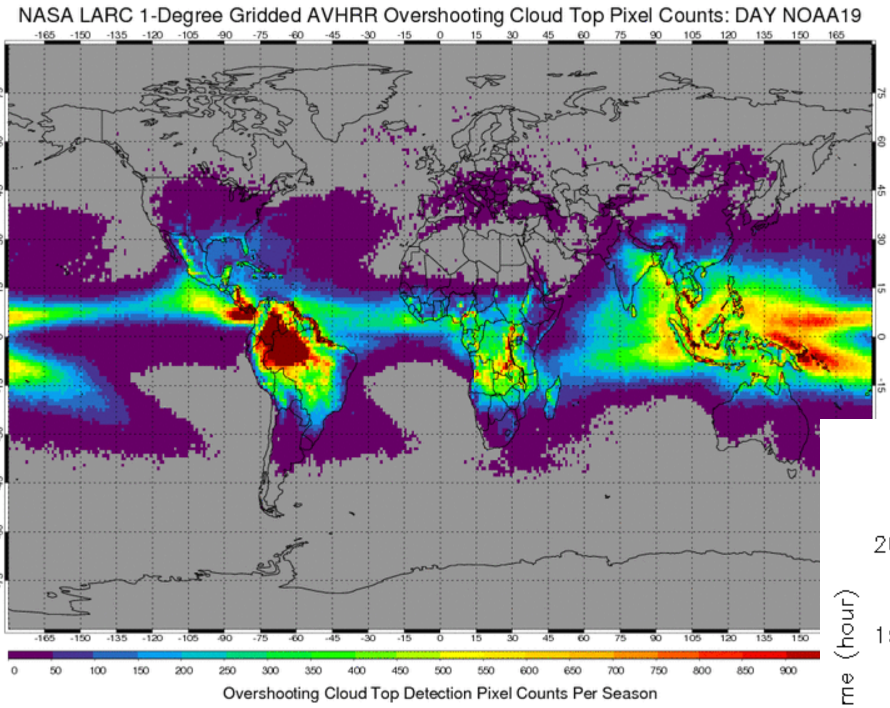
Example 24-Hour GOES-East OT Detection Map

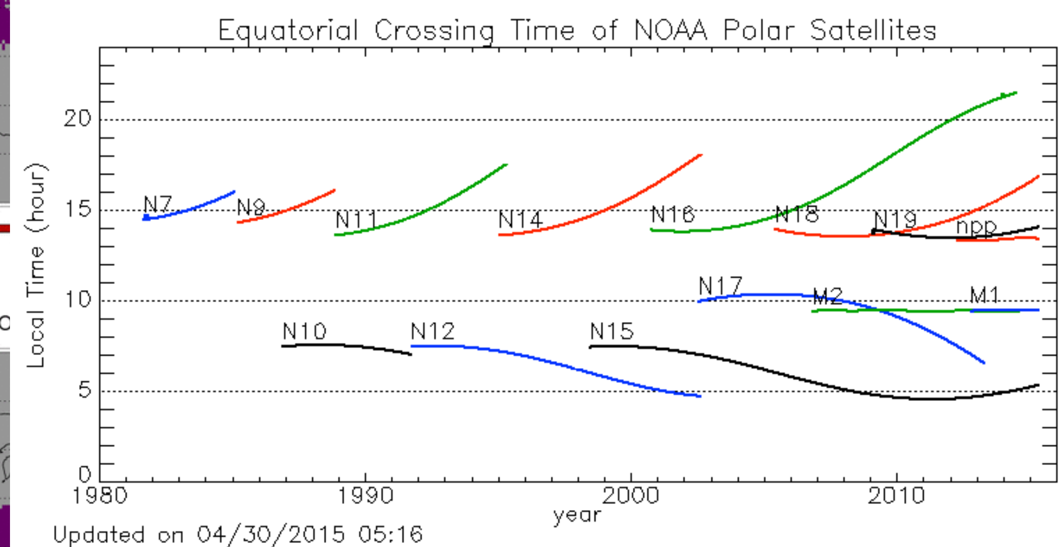


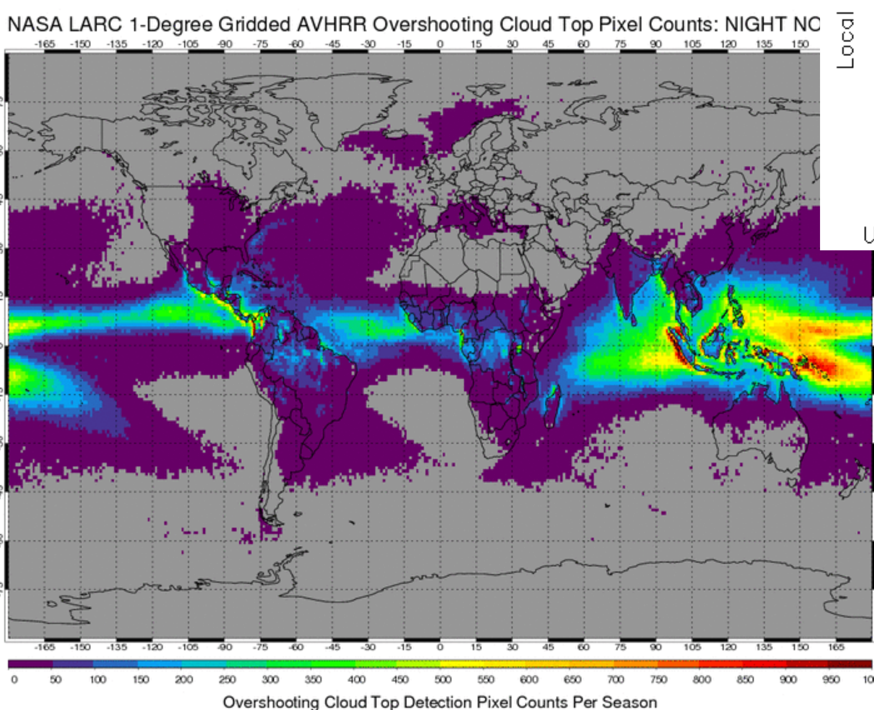


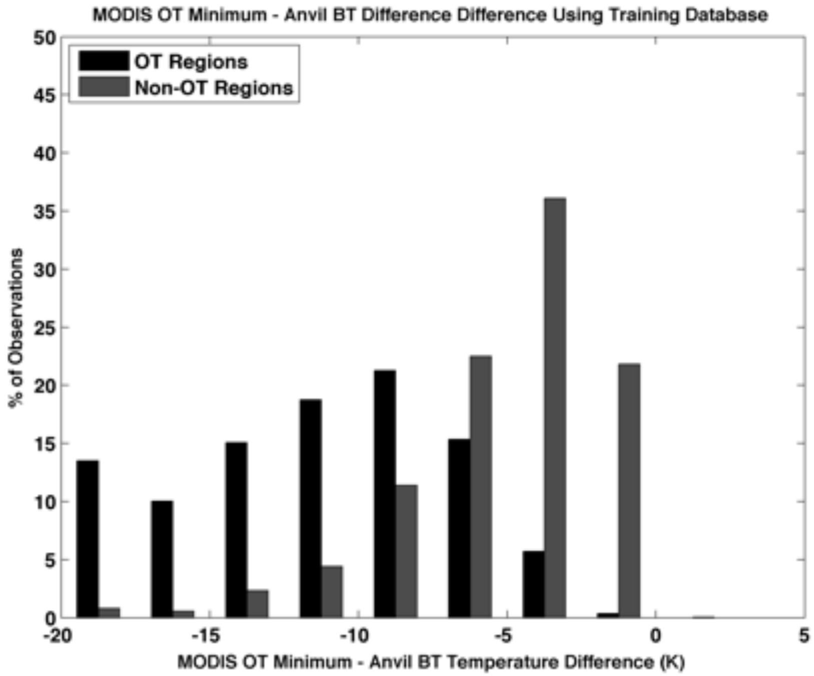
Overshooting Top
Above-Anvil Cirrus Plume
Detrainment Of Ice From The OT Region
Anvil
Updraft
GOES-13 Visible: 2340 UTC, May 29 2012
Overshooting Top
Above Anvil
Cirrus Plumes
Photo Taken During The
DC3 Field Experiment
Heidi Huntrieser (DLR)

27-Year AVHRR OT Detection Database

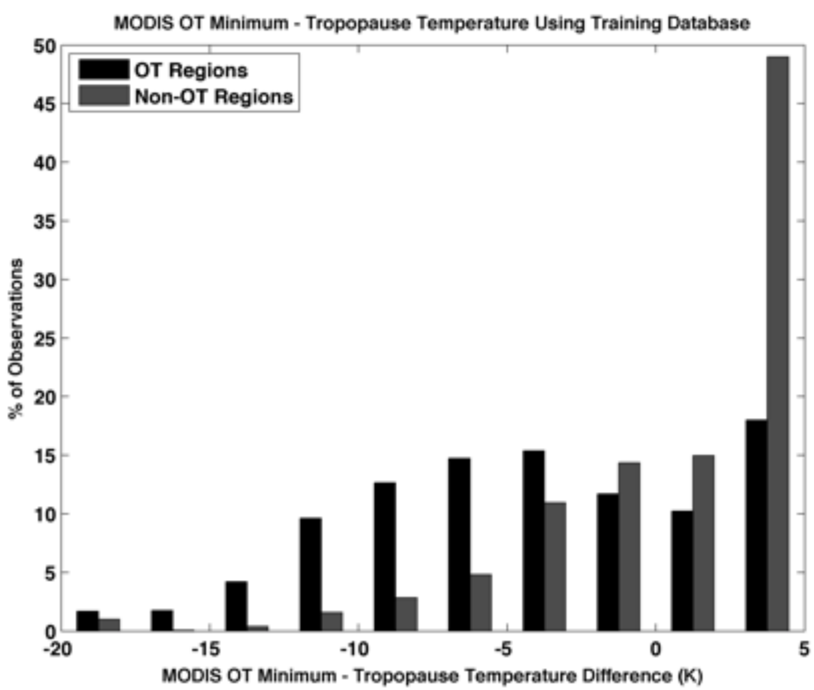


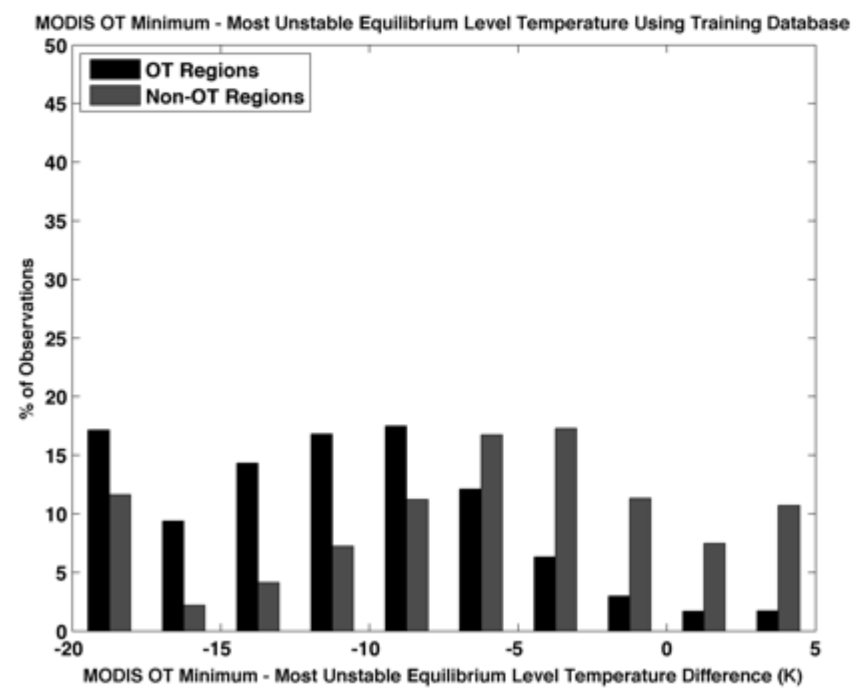


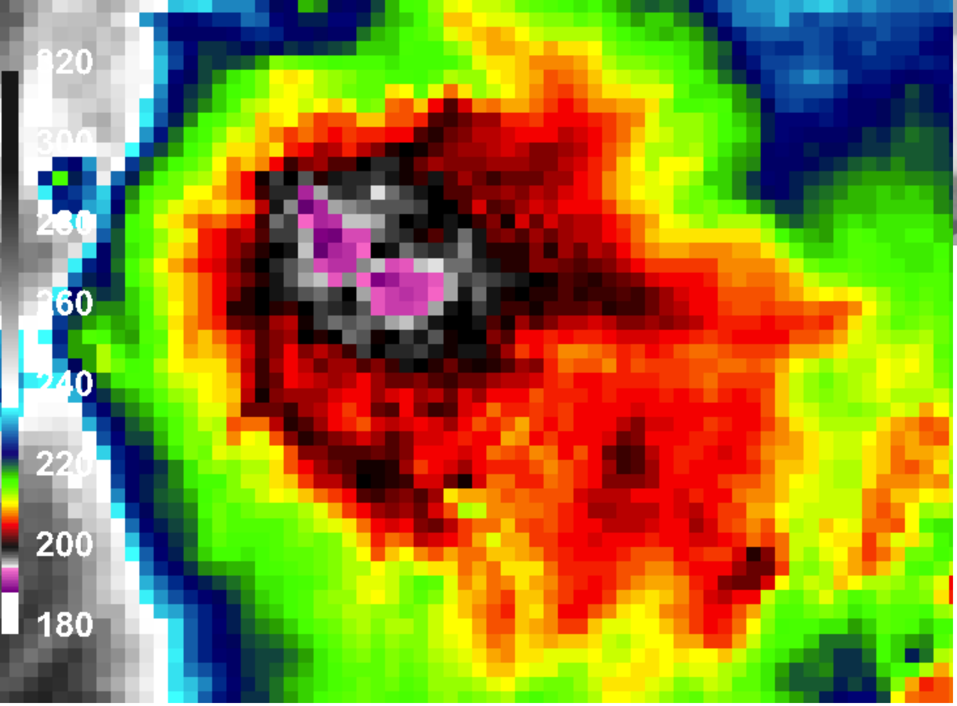


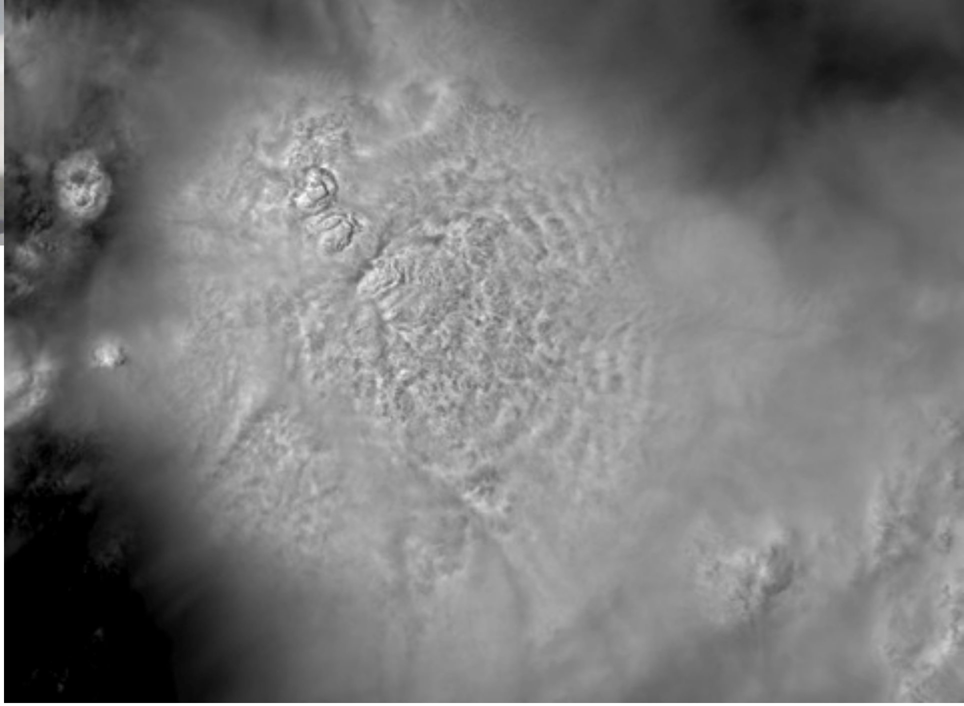


Histograms of OT and Non-OT Region Characteristics









MODIS Tropical OT Detection Example

Central Atlantic Ocean

5 August 2008, 1555 UTC