Analysis of Ice Crystal Icing Conditions and Severe Storms Using Remote Sensing and In Situ Data

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Supported by the NASA ROSES Severe Weather Research Program,
ROSES NASA Data For Operations and Assessment Program,
and NASA Advanced Air Transport Technology Project

Talk Outline

NASA LaRC and research partners are analyzing geostationary satellite observations and products *available at up to 30-sec frequency from GOES-16*, in combination with ground-based and in-situ datasets, to better understand and detect aviation and severe weather hazards

This talk will highlight recent work on:

1) Analysis and detection of ice crystal icing conditions due to High Ice Water Content (HIWC)

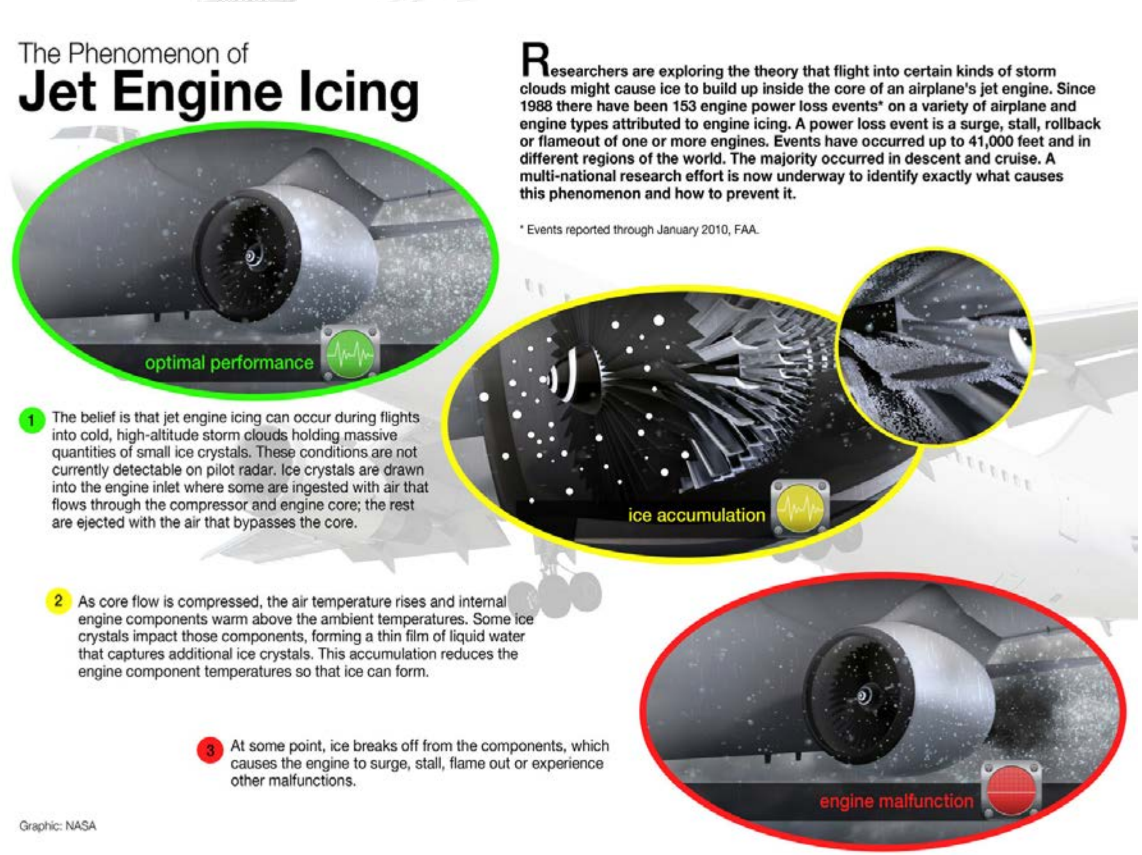
2) Analysis of severe storms, their updrafts, and associated ice transport into the stratosphere

Aircraft Engine and Air Probe Icing From High Ice Water Content (HIWC)

Supported by the NASA ARMD Advanced Air Transport Technology Project, NASA GRC PM: Thomas Ratvasky, LaRC PM: Steve Harrah, LaRC Satellite Science Lead: Kris Bedka

- **There have been many recorded events where flight through thunderstorms has resulted in air probe (e.g. TAT, pitot tube) malfunction, jet engine power loss, and/or engine damage**
- **Hypothesis: Aircraft encountered high ice water content (HIWC), and ice accretion on the air probes or engine was likely the cause**
- **Ice crystals causing the icing are small and difficult to detect with onboard weather radar systems.**
- **HIWC research aircraft avoid intense updrafts ("red echoes") and lightning, yet they still encounter extreme ice contents**
- **Additional remote sensing guidance denoting HIWC regions is desired**
- **Four international airborne field campaigns (57 flights) were conducted in 2014-2015, and 2018 to accomplish many science and regulatory goals, including:**
  1) Better characterize cloud conditions that cause engine powerloss/damage and air probe anomalies

  2) Develop detection methods for HIWC conditions using radar and/or satellite remote sensing data



The Phenomenon of

Jet Engine Icing

Researchers are exploring the theory that flight into certain kinds of storm clouds might cause ice to build up inside the core of an airplane's jet engine. Since 1988 there have been 153 engine power loss events* on a variety of airplane and engine types attributed to engine icing. A power loss event is a surge, stall, rollback or flameout of one or more engines. Events have occurred up to 41,000 feet and in different regions of the world. The majority occurred in descent and cruise. A multi-national research effort is now underway to identify exactly what causes this phenomenon and how to prevent it.

* Events reported through January 2010, FAA.

1 The belief is that jet engine icing can occur during flights into cold, high-altitude storm clouds holding massive quantities of small ice crystals. These conditions are not currently detectable on pilot radar. Ice crystals are drawn into the engine inlet where some are ingested with air that flows through the compressor and engine core; the rest are ejected with the air that bypasses the core.

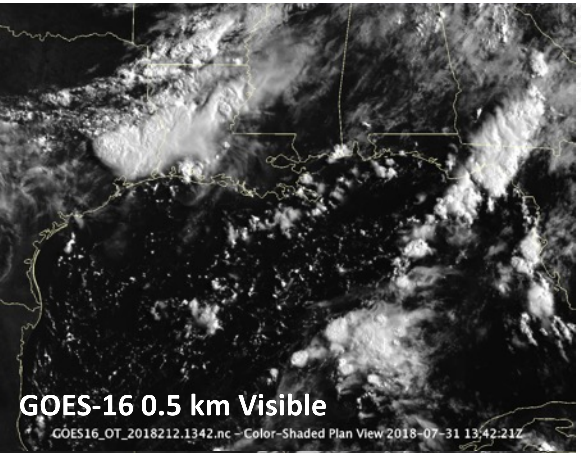
2 As core flow is compressed, the air temperature rises and internal engine components warm above the ambient temperatures. Some ice crystals impact those components, forming a thin film of liquid water that captures additional ice crystals. This accumulation reduces the engine component temperatures so that ice can form.

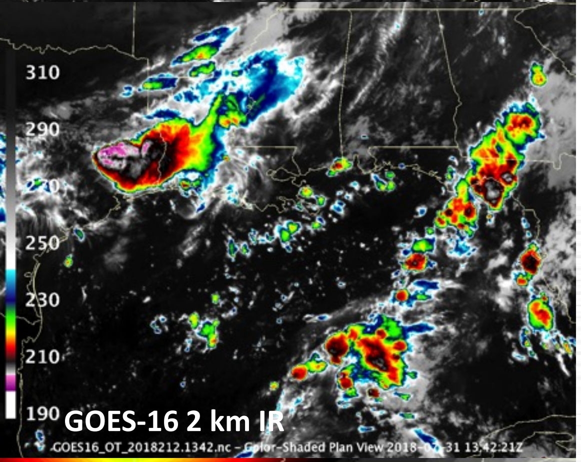
3 At some point, ice breaks off from the components, which causes the engine to surge, stall, flame out or experience other malfunctions.

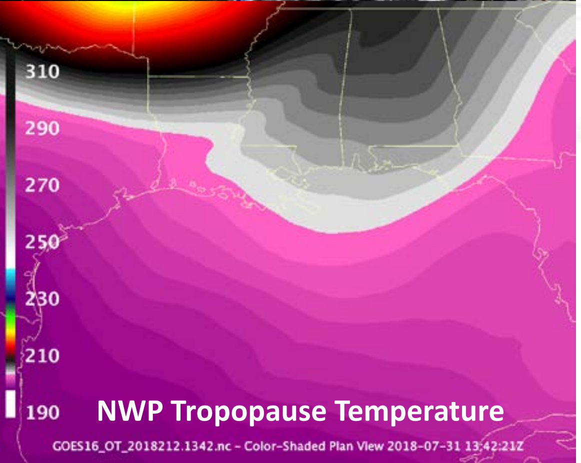
Graphic: NASA

LaRC HIWC Probability Product Description

Input Satellite + NWP Data

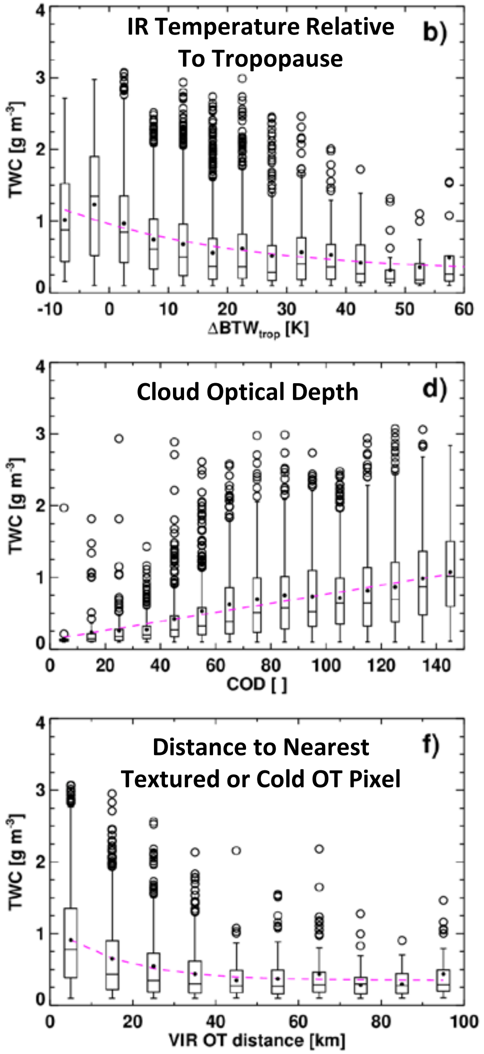




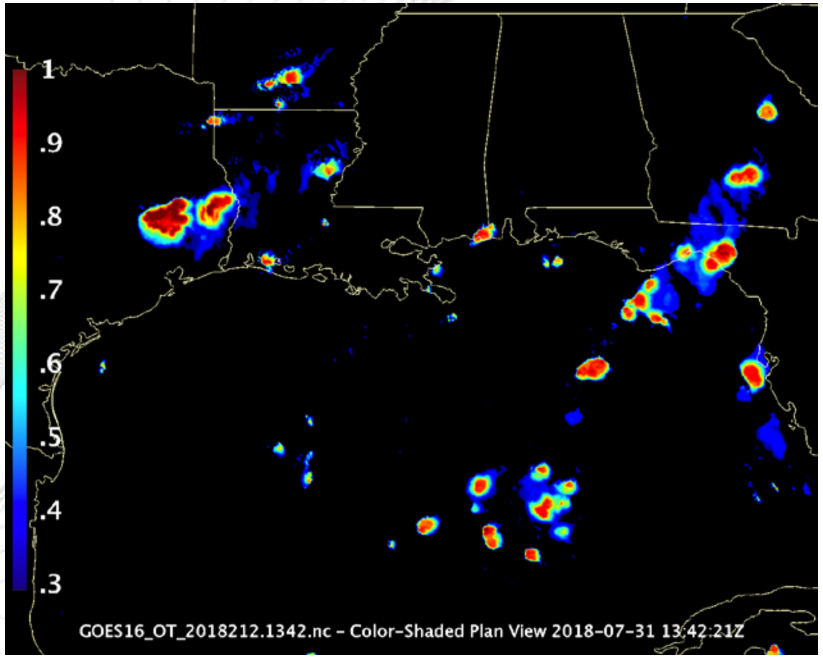


Statistical Relationships Between IKP-2 Ice Water Content and Satellite+NWP Fields

(Magenta: Statistical Fit to Mean)

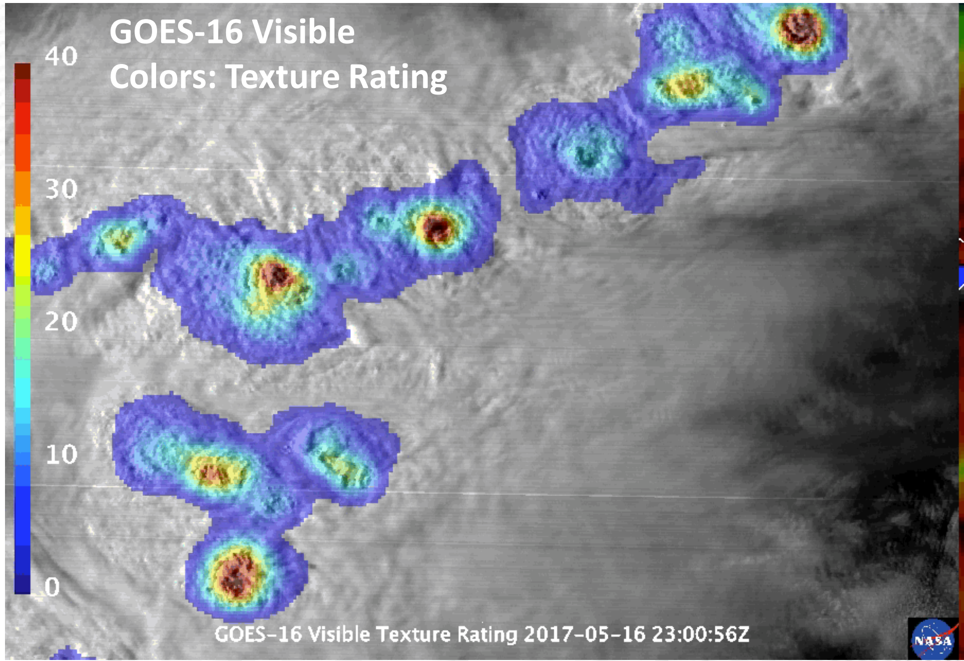


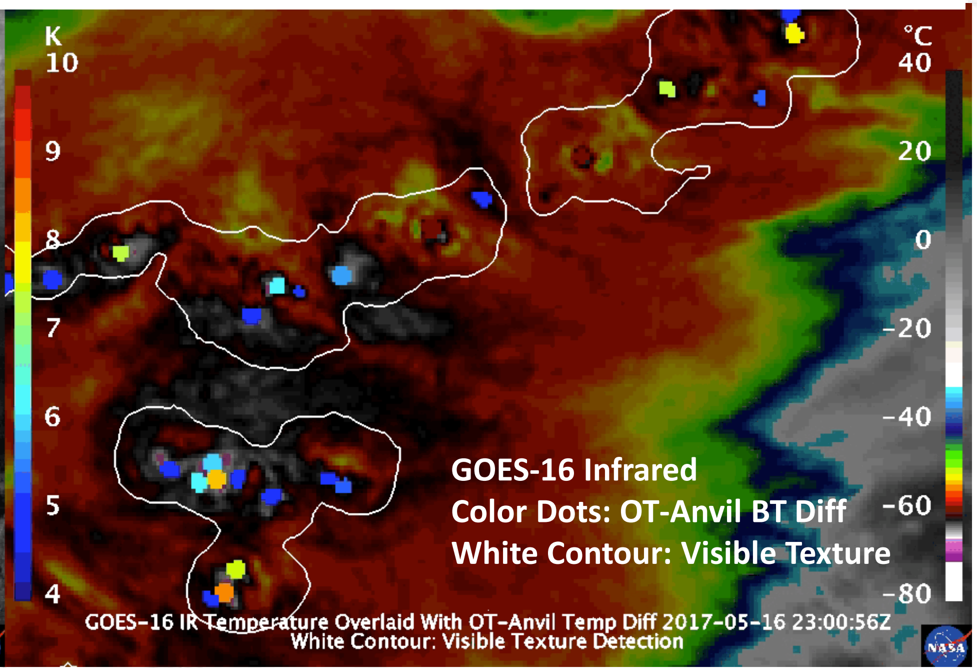
HIWC Probability



- 5371 matches between 45-sec (~8 km) in-situ total water content (TWC) and cloudy satellite pixels across 50 flights out of Darwin (Australia), Cayenne (French Guyana) and Ft. Lauderdale (U.S.)
- Flight within or beneath optically thick, cold anvils within 40 km of overshooting tops (OTs) is most likely to encounter HIWC (> 1 g m^{-3})
- These results suggest that commerical aircraft encountering engine / air probe anomalies are avoiding updrafts based on onboard radar, but flying within anvil close enough to updrafts to experience HIWC
- Little to no unique information for HIWC discrimination provided by other satellite- or NWP-based parameters

Automated Overshooting Top and Convectively-Generated Gravity Wave Detection

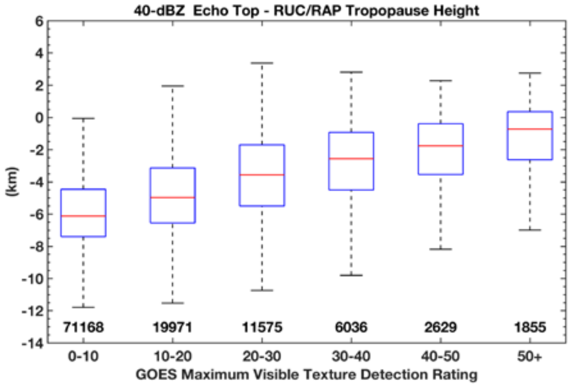




GOAL: Develop automated, pattern recognition methods for identifying embedded cold and textured areas within anvils using IR and visible imagery

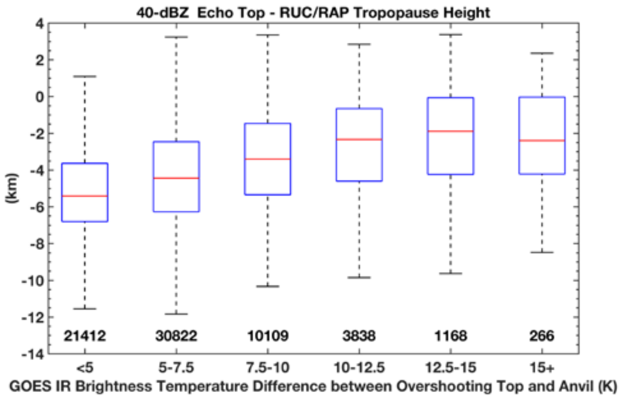
WHY?: Thunderstorm updrafts indicate where aviation weather hazards (turbulence, ice crystal icing) and severe weather occur. An automated product can map locations impacted by these hazards anywhere and any time

Based on analysis of 2000+ radar object tracks and 1-min GOES-16 data



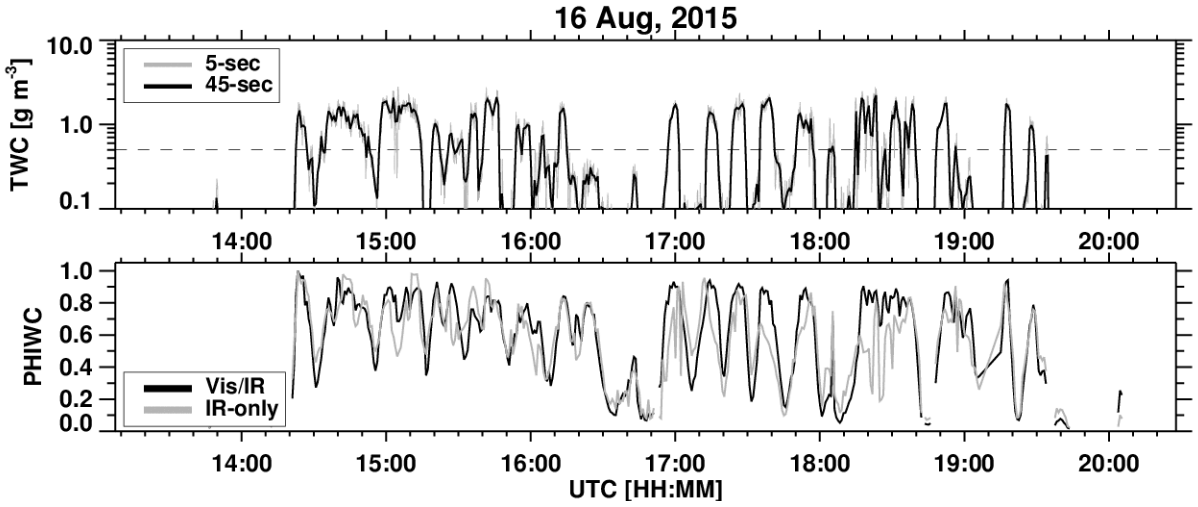
Increasing visible texture (left) and IR temperature contrast from anvil (right) indicates increasingly strong updraft and higher 40 dBZ echo top

An automated capability for pinpointing updraft regions is critical for HIWC prediction



LaRC HIWC Probability vs In-Situ Ice Water Content Using 1-Min GOES-14 Super Rapid Scan Observations

Moving X's, NASA DC-8 Location,
Colored By In-Situ Ice Content,
Pink = HIWC, Cyan = Moderate IWC

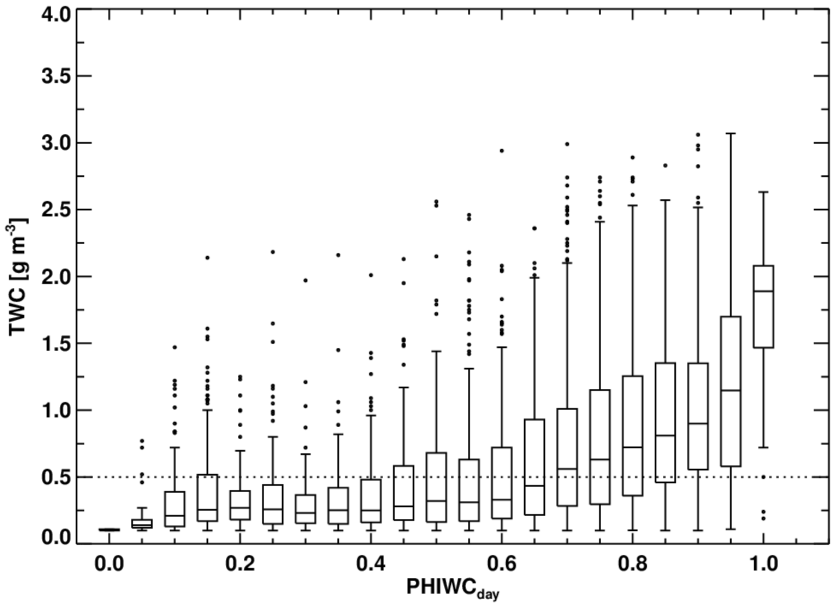


- LaRC HIWC probability (PHIWC) was derived using 1-min GOES-14 imagery during 3 flights from the 2015 NASA HIWC Radar-1 campaign
- PHIWC is quite well correlated with ice water content trends
- PHIWC peaks (> 0.7) identify all HIWC (> 1.0 g m^{-3}) events but also many moderate (> 0.5 g m^{-3}) events.
- Moderate ice content conditions are very difficult to differentiate from HIWC using satellite data alone

45-sec averaged TWC percentiles across the 3 campaigns, assuming TWC > 0.10 g m^{-3} is cloud:
0.5 g m^{-3} 50th %, 1.0 g m^{-3} 75th %, 2.0 g m^{-3}, 95th %

LaRC HIWC Probability Validation and Future Work

HIWC Probability vs Ice Water Content Across 50 Flights



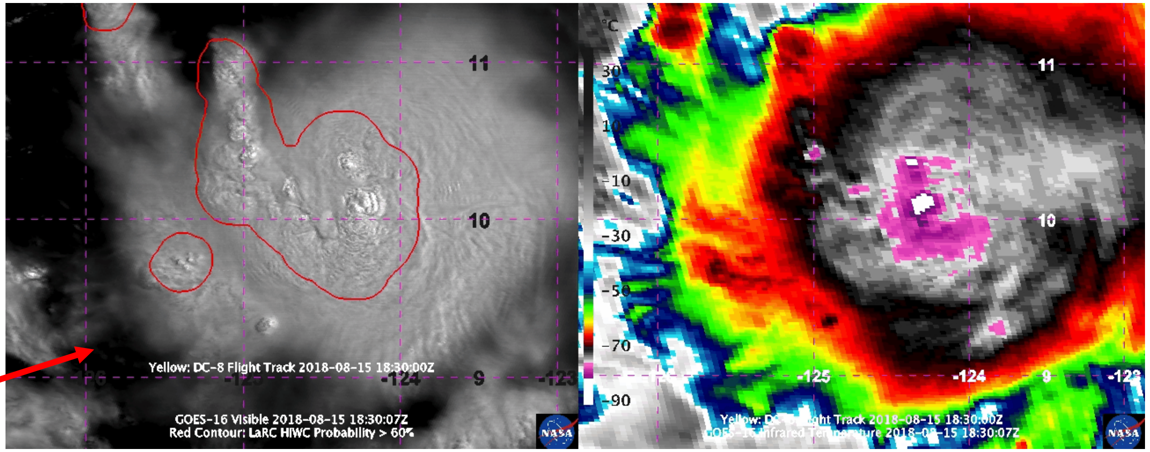
- A steady increase in observed ice water content as a function of PHIWC
- High PHIWC at low TWC is due to coarse GEO resolution and inability of VIS and IR to ”see” conditions at flight level, far below cloud top
- The HIWC research community has yet to agree upon validation metrics, so stats cannot be compared between products (e.g. NCAR ALPHA)

LEARN MORE AT:
Yost, C. R., Bedka, K. M., Minnis, P., Nguyen, L., Strapp, J. W., Palikonda, R., Khlopenkov, K., Spangenberg, D., Smith Jr., W. L., Protat, A., and Delanoe, J., 2018: A prototype method for diagnosing high ice water content probability using satellite imager data, Atmos. Meas. Tech., 11, 1615-1637, https://doi.org/10.5194/amt-11-1615-2018

Summary and Future Work

August 15, 2018 NASA DC-8 HIWC Radar 2 Flight: Tropical Storm Lane

Red Contour, Left Panel: LaRC HIWC Probability > 60%

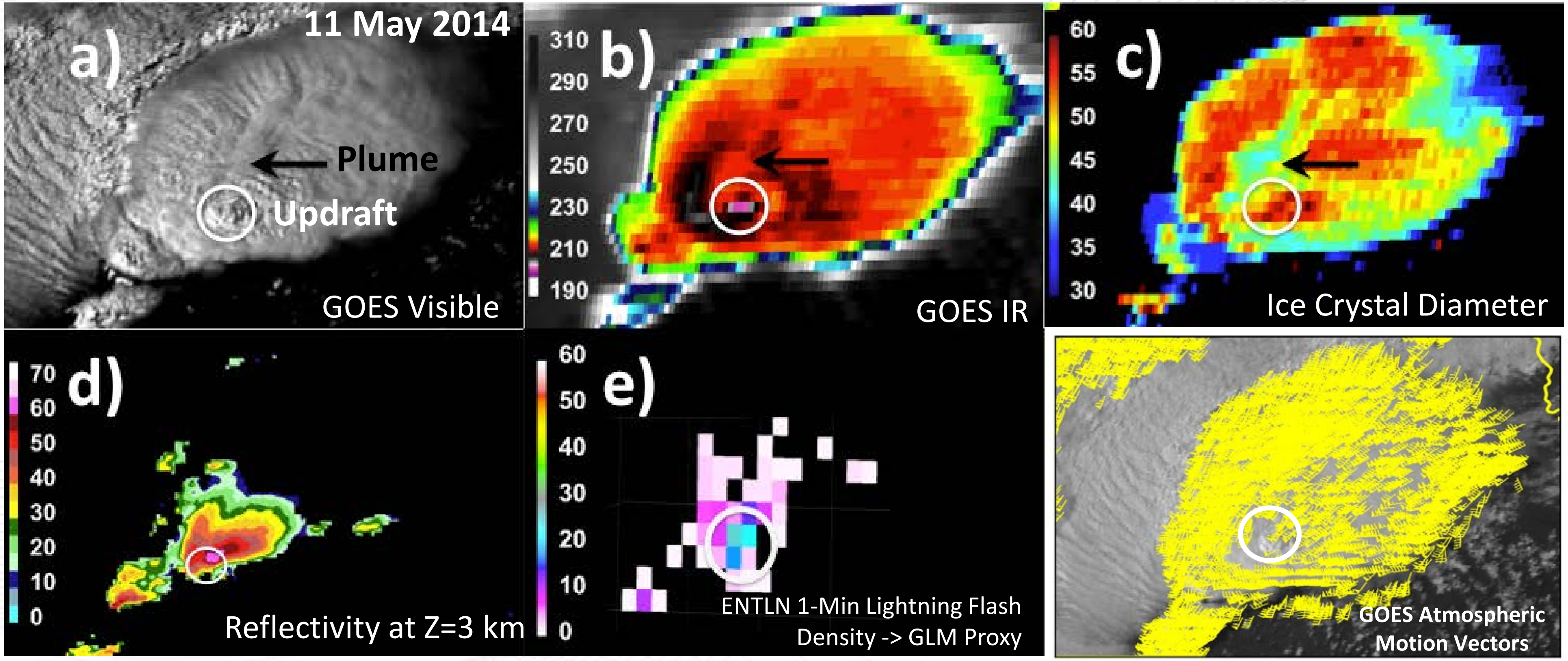


Pitot Tube De-Icing Procedure Due To Long Exposure To HIWC Conditions

- The LaRC PHIWC product is the one of the first of its kind in the aviation weather community
- Real-time LaRC GOES PHIWC was used extensively to guide the NASA DC-8 during the HIWC-Radar 2 flight campaign in August 2018
- Upcoming research will analyze HIWC Radar 2 datasets for 7 flights and explore additional GOES-16/17 HIWC predictors
- LaRC overshooting top, HIWC and winter-time supercooled water airframe icing products are being evaluated by NOAA aviation weather forecasters at the Dallas, Houston, and Memphis Central Weather Service Units (CWSUs)
- Collaborations and Product Evaluations Welcomed!!!

NASA ROSES Severe Weather Research

PIs: Kristopher Bedka (NASA LaRC), C. Homeyer (OU), J. Mecikalski and J. Apke (UAH)



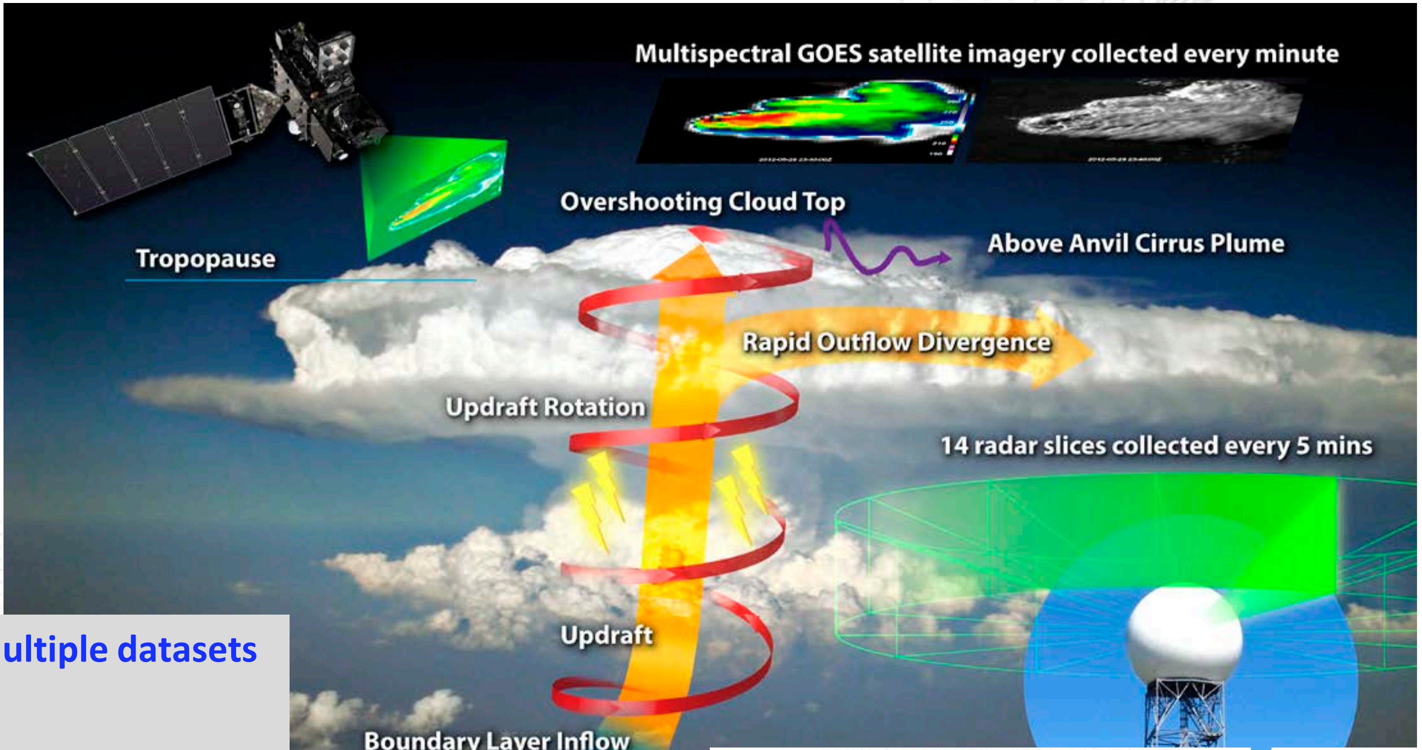
The primary objectives of this effort are to use advanced satellite-based observations and products available at up to 30-sec frequency from GOES-16 to:

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 analyses and products that could potentially improve severe storm detection and forecast lead-time

Satellite and Ground-Based Remote Sensing Data Fusion For Severe Storm Analysis

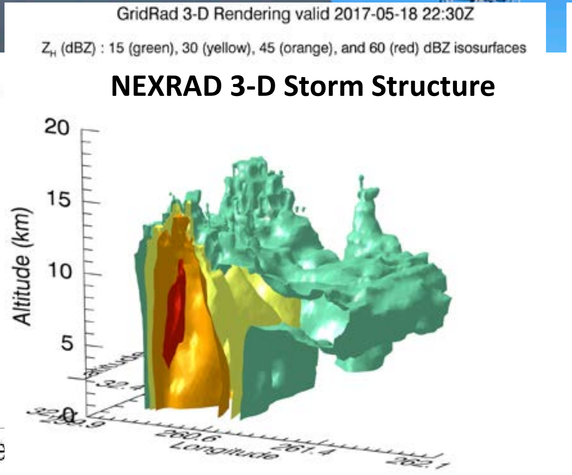


Data Fusion: The process of integrating multiple datasets for combined analysis

Radar-based storm tracking is used to combine

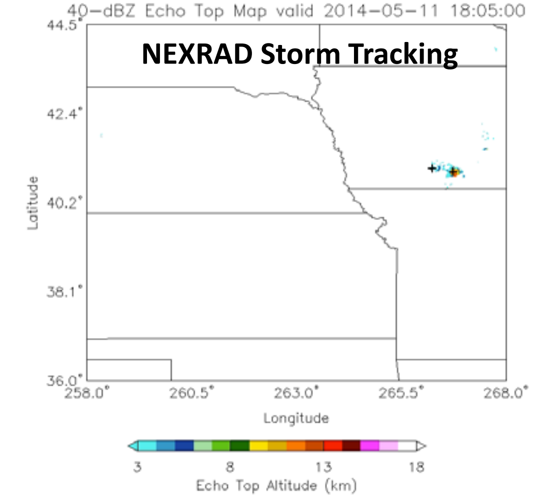
1) GOES multispectral imagery and derived products
2) NEXRAD updraft intensity, storm rotation, and cloud microphysical metrics
3) Ground or GOES-based total lightning flash rate

to identify early indicators of severe and tornadic storms


GridRad 3-D Rendering valid 2017-05-18 22:30Z

Z_H (dBZ) : 15 (green), 30 (yellow), 45 (orange), and 60 (red) dBZ isosurfaces

NEXRAD 3-D Storm Structure


40–dBZ Echo Top Map valid 2014–05–11 18:05:00

NEXRAD Storm Tracking

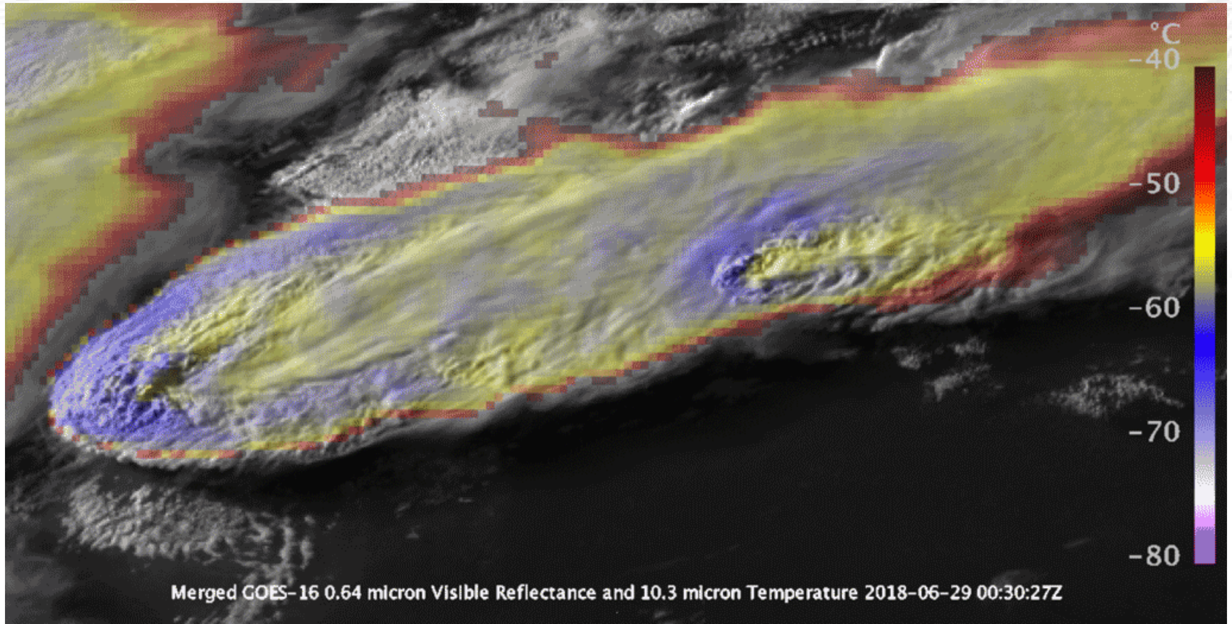
Photograph By: Roland Welser (DLR) over Northern Texas on 29 May 2012 during the DC3 Field Campaign
Storm is producing 2.5 inch diameter hail at the time of the photo
Graphic Designed By Timothy Marvel, Kristopher Bedka (NASA LaRC) and Cameron Homeyer (University of Oklahoma)

Above Anvil Cirrus Plumes

An Indicator of Intense Updrafts, Gravity Wave Breaking, Ice Injection Into the Stratosphere, and an Extremely Severe Storm

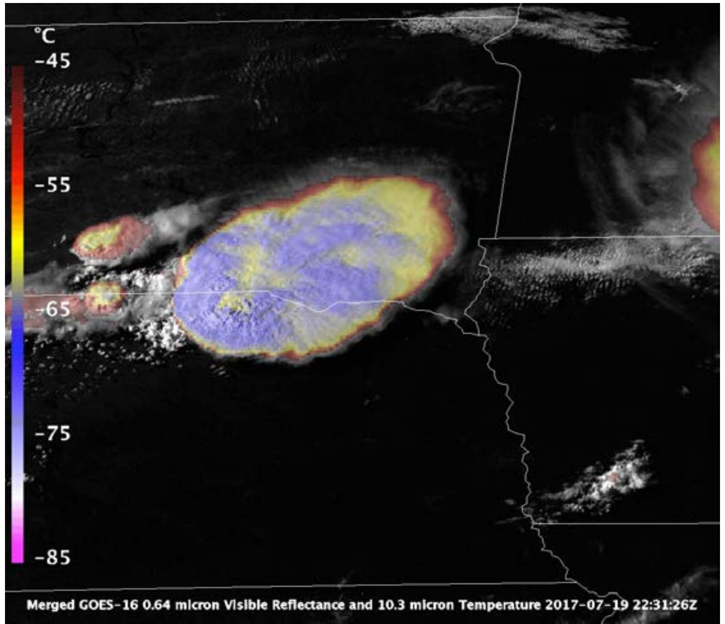
- **Research within this NASA Severe Weather Research program study has demonstrated the importance of intense updrafts in generating severe weather (e.g. Apke et al. (MWR, 2018), Sandmael et al. (submitted to JAMC, 2018), Bedka et al. (JAMC, 2018))**
- **Above anvil plumes are a visual indicator of an especially intense updraft occurring in a strong storm-relative wind shear environment**
- **Updraft – shear combination generates unstable layers -> enabling gravity wave breaking, injection of ice several kilometers into the stratosphere and stratospheric moistening**
- **The stratosphere is generally warmer than the anvil, causing plumes to be anomalously warm. IR-based cloud top height algorithms assign plumes to the troposphere, causing retrievals to be biased low by 5+ kilometers in some cases**

1-Minute GOES-16 Merged Visible and IR Animation of Above Anvil Producing Storms Over North Dakota



Merged GOES-16 0.64 micron Visible Reflectance and 10.3 micron Temperature 2018-06-29 00:30:27Z

1-Minute GOES-16 Merged Visible and IR Animation of an Above Anvil Producing Storm Over Nebraska



Merged GOES-16 0.64 micron Visible Reflectance and 10.3 micron Temperature 2017-07-19 22:31:26Z

Analysis of 100’s of 4+ inch Hail, EF-4+ Tornado, and 90+ mph Wind Storms Indicates That *Most Extremely Severe Storms Generate Above-Anvil Cirrus Plumes*

GOES-13
Aurora, NE 7 Inch Hail
23 Jun 2003

GOES-13
Vivian, SD 8 Inch Hail
23 Jul 2010

GOES-13
Eagle Butte, SD
107 mph Wind
17 Jun 2010

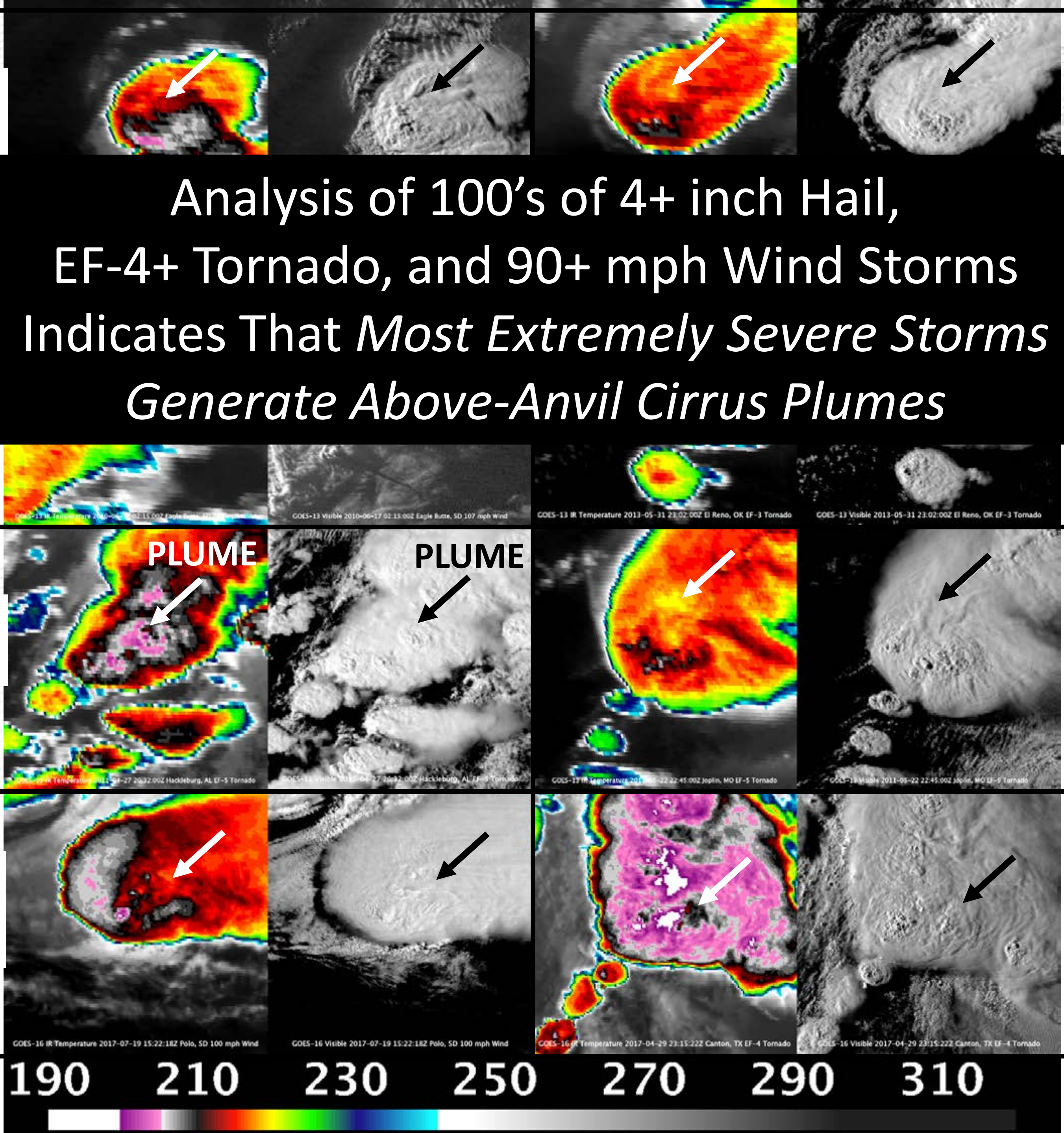
GOES-13
El Reno, OK EF-3
31 May 2013

GOES-13
Hackleberg, AL EF-5
27 Apr 2011

GOES-13
Joplin, MO EF-5
22 May 2011

GOES-16
Polo, SD
100 mph Wind
19 Jul 2017

GOES-16
Canton, TX EF-4
29 Apr 2017



Degrees K

Above Anvil Cirrus Plumes (AACP)

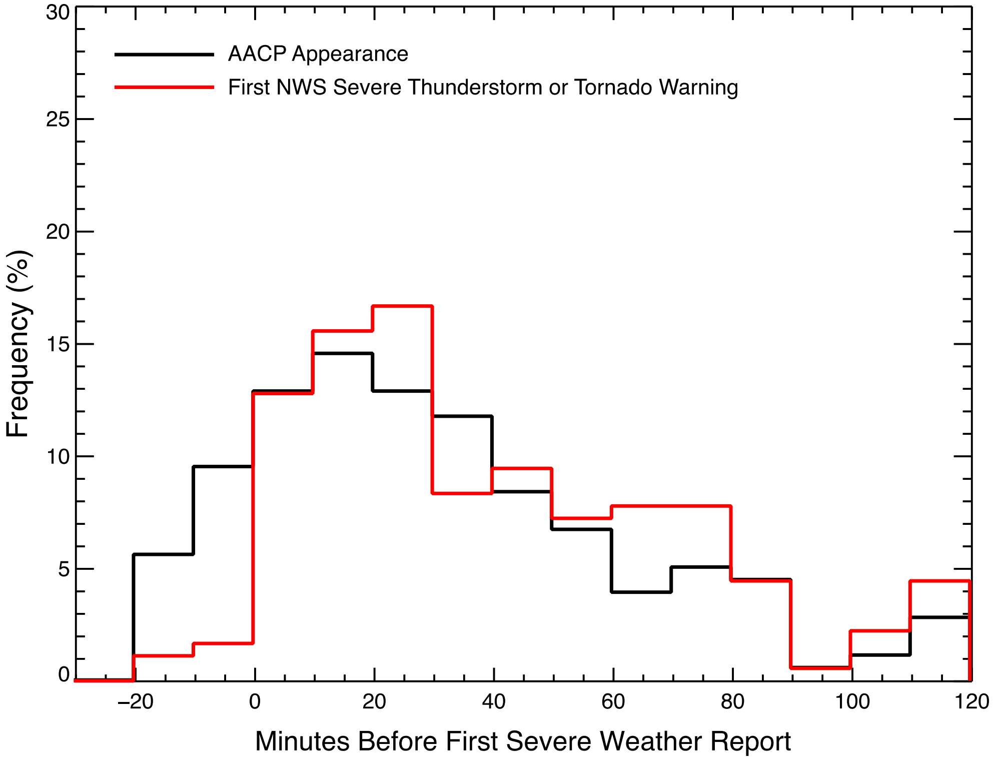
A Multi-Sensor Investigation Into AACP Storm Characteristics and Severity

We use a large sample of manual plume identifications (N=405 storms) based on 1-min GOES-14/16 imagery, objective storm tracks (N=4583) from 5-min Gridded NEXRAD WSR-88D radar observations (GridRad), NWS warnings, and severe weather reports from 13 recent severe weather outbreaks to answer questions such as:

1. ***What is the severe weather frequency for AACP storms compared to storms without plumes?***
2. ***Are certain types of severe weather more likely to be produced by AACP storms?***
3. ***How far in advance do AACPs occur ahead of severe weather?***
4. ***What is the relationship between AACPs and supercells?***
5. ***How can severe weather warning be augmented by knowledge of the presence of an AACP?***

Quantifying the Utility of Plume Recognition for Severe Weather Forecasting

- **Plumes appeared an average of ~30 minutes before the first severe weather was produced by the parent storm**
- **Comparable lead time on average to the first National Weather Service severe weather warnings per storm**
- **Plumes preceded the first NWS warning for 25% of storms, but typically only by 0-10 mins**
- **Analysis of National Weather Service "hail size tags" shows that the presence of a plume can increase confidence that 2+ inch diameter hail will occur**



Doppler radar datasets, recently augmented by space-borne lightning observations, are the primary remote sensing observations to identify severe storms and issue warnings

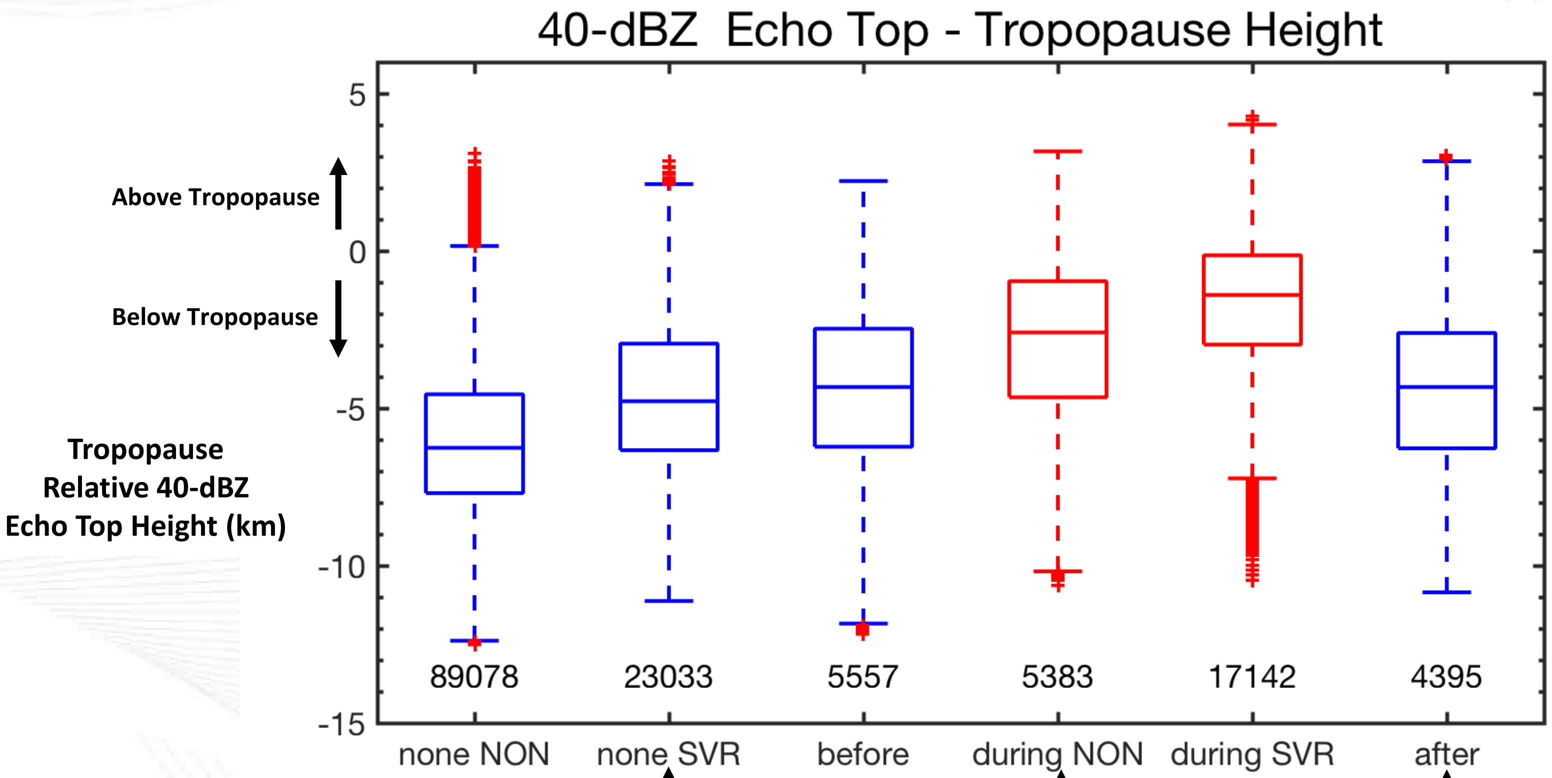
Storms with plumes routinely occur throughout the world, including in the tropics and high latitudes

In areas with poor or non-existent radar coverage, i.e. most of the world, a plume can be used to quickly recognize significant severe storms using satellite imagery alone

SA's Langley Research Center

Characteristics of Plume and Non-Plume Storms: 40 dBZ Echo Top

40 dBZ -> Heavy ice/liquid precip, graupel, and/or large hail



No Plume
Non-Severe Storm

No Plume
Severe Storm

Before a
Plume Forms

During Plume
Non-Severe Storm

During Plume
Severe Storm

Plume No Longer
Generated

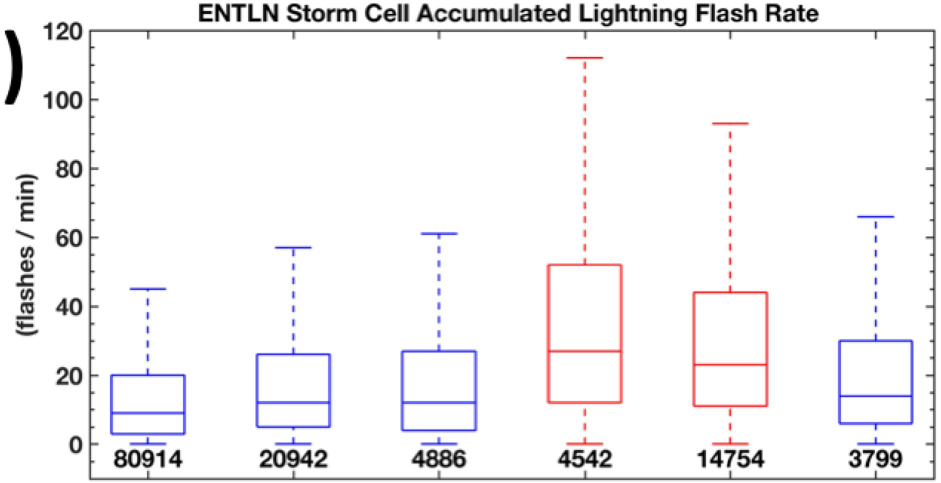
Radar, satellite, and lightning analyses like these show that, on average, plume storms produce:

- the highest echo tops,
- strongest updrafts,
- most lightning,
- a high frequency of severe weather,
- and characteristics similar to a supercell storm

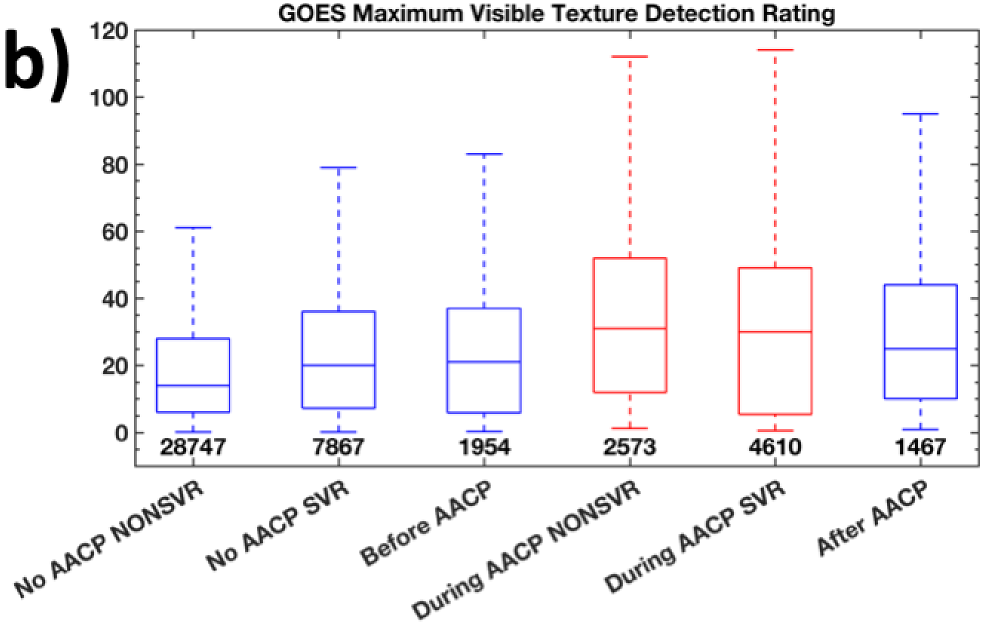
Characteristics of Plume and Non-Plume Storms

Total Lightning, GOES Visible Texture, and Overshoot-Anvil Mean IR Temperature Difference

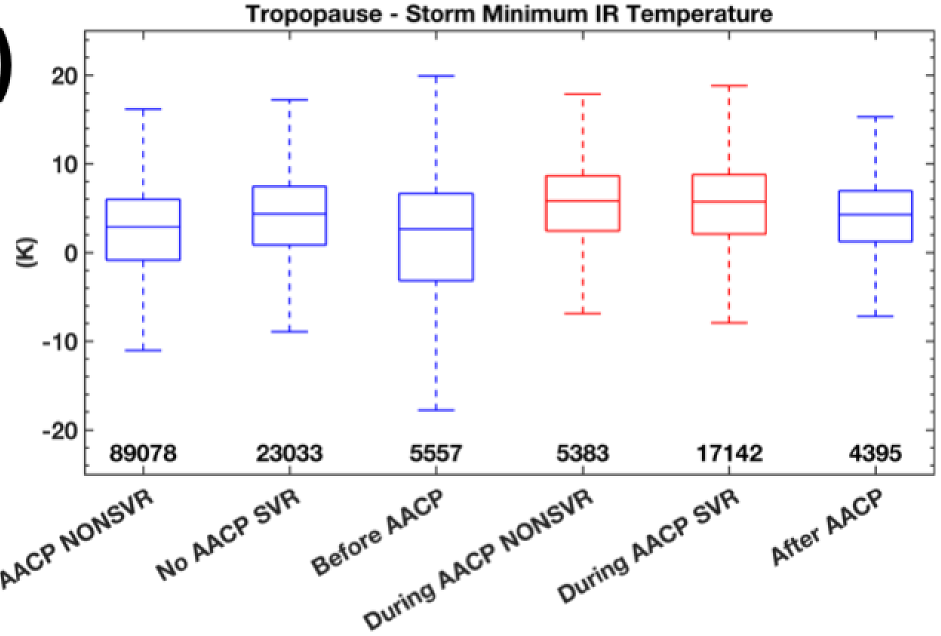
a)



b)



c)



- **Visible texture and lightning flash rate is stronger in plume storms, consistent with radar-derived inferences of strong updrafts**
- **Both non-severe and severe storms can have comparably cold IR BT, difference between plume and non-plume storms only ~3 K on average**
- **Given such little variance, neither cold IR BT alone (nor IR-Water Vapor BT Difference) can be used to discriminate a severe storm**

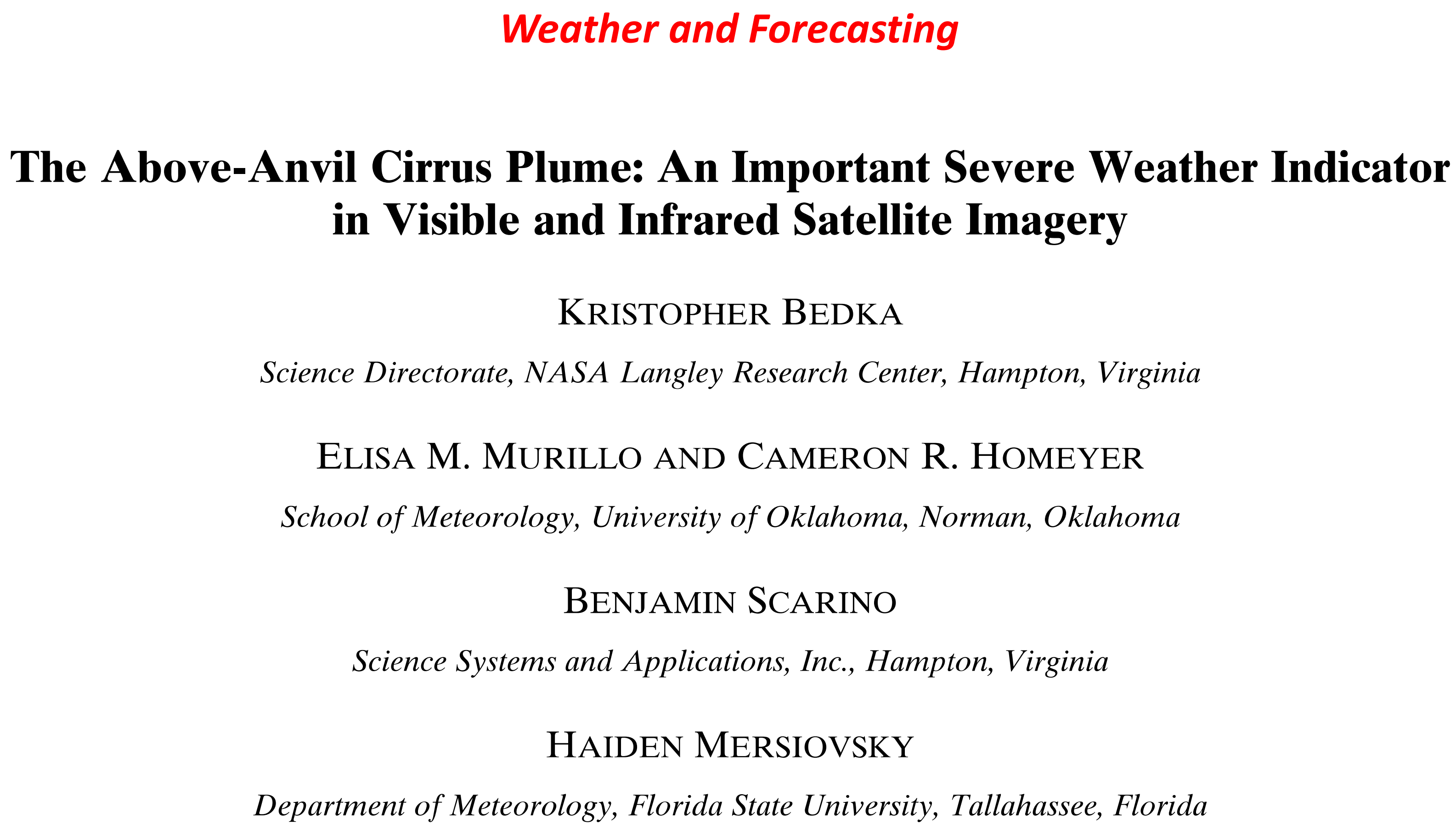
The Above Anvil Cirrus Plume (AACP)

An Important Indicator of a Severe Storm in Visible and Infrared Imagery

- **AACP storms (N=405) were 14 times more severe than 40+ dBZ non-AACP storms (N=~4180)**
  - AACP storms: 6.33 reports/storm   Non-AACP 0.46 reports/storm
  - Even if non-severe storms disregarded: AACP severe storms: 10.8 reports/storm   Non-AACP severe storms: 4.2 reports/storm
- **59% of AACP storms were severe**
  - An underestimate due to known biases in severe weather reporting (fewer reports at night and in population-sparse areas)
- **Over 85% of the 2+ inch hail and strong tornado events were generated by AACP storms**
- **48% of AACP storms were supercells (N=194)**
- **75% of supercells created AACP; AACP supercells produced ~2.5 times more severe weather than supercells without**

- **Though many severe storms do not produce plumes, the above-anvil cirrus plume is the strongest known indicator of a severe storm from visible and IR satellite imagery**
- **Plume identification can be done quickly by the human eye and is extremely useful for recognizing some of the most severe storms on Earth**
- **NASA Earth Venture-Suborbital "Dynamics and Chemistry of the Summer Stratosphere (DCOTSS, http://dcotss.org)" field campaign will use models, NEXRAD, GOES-16/17 and ER-2 in-situ measurements to study severe storm impacts on stratospheric composition (PI: Ken Bowman, Texas A&M). First Science Flights-> Spring 2020**

Want To Learn More About Plumes?



Weather and Forecasting

The Above-Anvil Cirrus Plume: An Important Severe Weather Indicator in Visible and Infrared Satellite Imagery

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BENJAMIN SCARINO

Science Systems and Applications, Inc., Hampton, Virginia

HAIDEN MERSIOVSKY

Department of Meteorology, Florida State University, Tallahassee, Florida

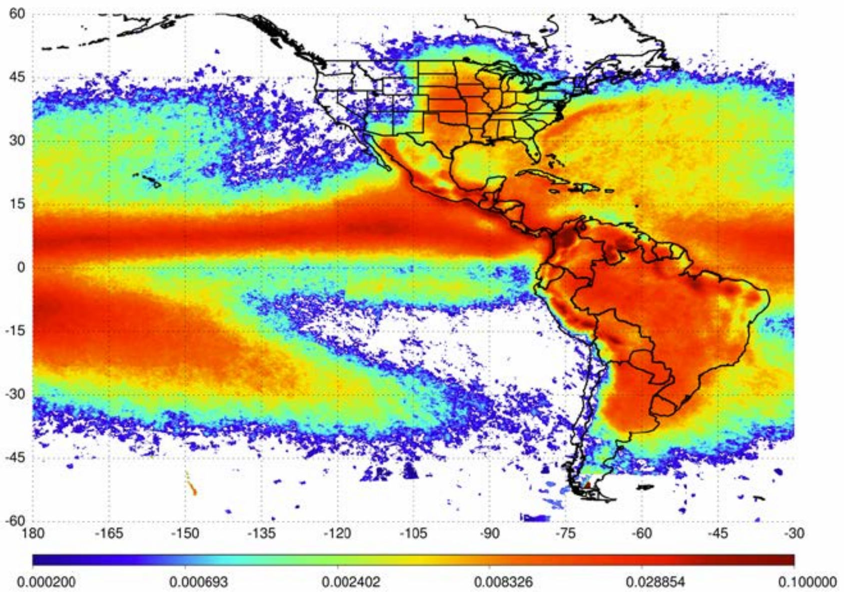
Upcoming Work

- **Analyze August 2018 NASA HIWC Radar-2 campaign data. Improve HIWC detection capabilities, especially night-time using GOES-16 IR-only or IR+GLM fields**
    - GLM indicates hazardous updrafts, but HIWC is routinely present in storms with little/no lightning
    - 7 total flights in 2018 HIWC Radar-2 campaign, 3 flights with GOES-16 1-min data -> 1 in Gulf of Mexico convection, 2 in Tropical Storm / Hurricane Lane
- **Machine learning analysis of 1-min GOES products, 1-min total lightning, and 5-min NEXRAD products to quantify severe weather detection and predictability using GOES-14 and GOES-16 datasets (J. Mecikalski - UAH)**
- **Automated above anvil plume detection algorithm development, and additional analyses to better understand satellite-observed plume temperature and microphysics using CALIPSO and insitu observations**
- **Application of LaRC automated plume, overshooting cloud top, and anvil cloud detection to long-term records of geostationary imagery for climate analysis**

20-Year Hourly, 16 km Resolution GOES Climatology of Anvil Clouds

Anvil Fraction

Jan-Dec 1996-2015 Hour: 00 Local



Warm Colors
Greater Thunderstorm Frequency In An Hour Of Day
Maroon-> 10% of Pixels in an Hour Are Anvils

THANK YOU!!!! Contact Info:
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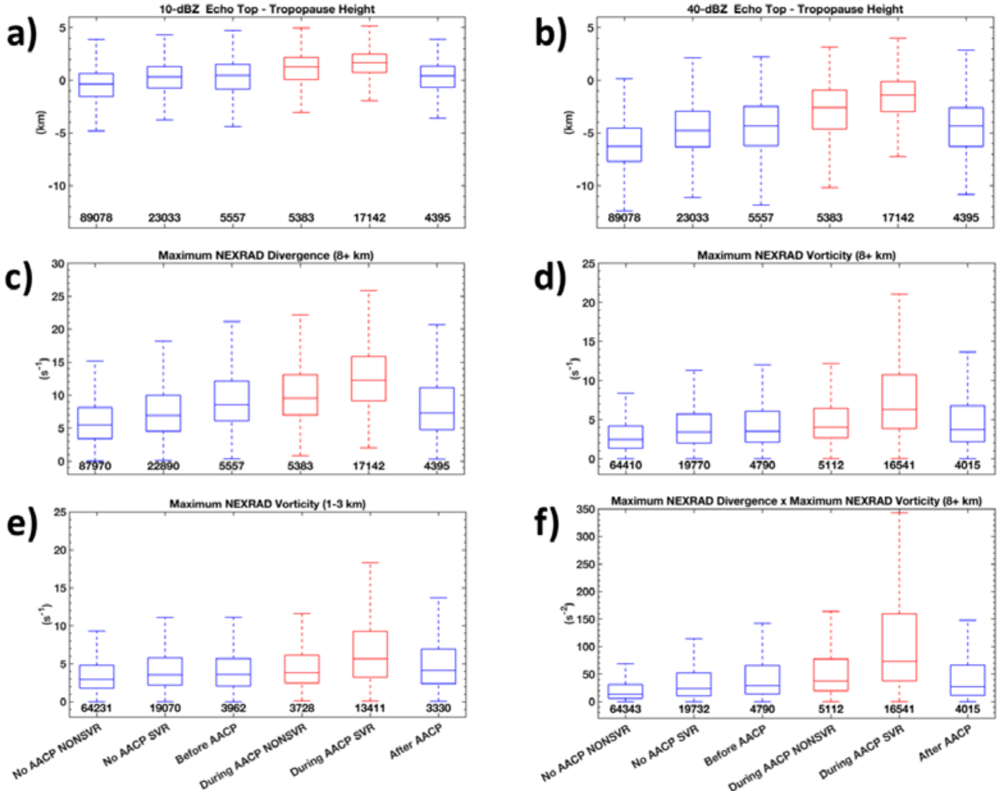
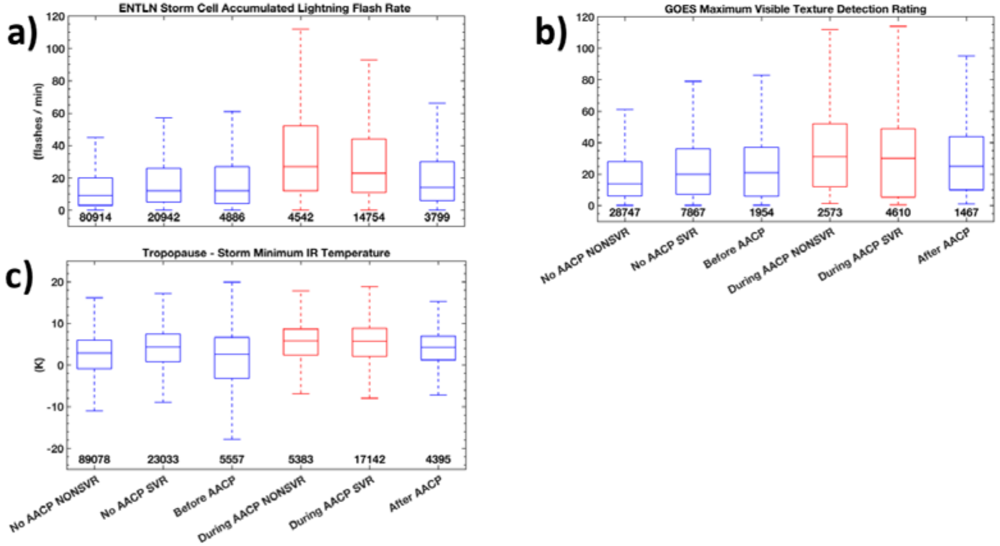
BACKUPS

Characteristics of Plume and Non-Plume Storms

Radar-Derived Products



Satellite and Lightning-Derived Products



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- strongest updrafts,
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- and characteristics similar to a supercell storm

Damaging-Wind Producing MCS's Can Also Generate Plumes

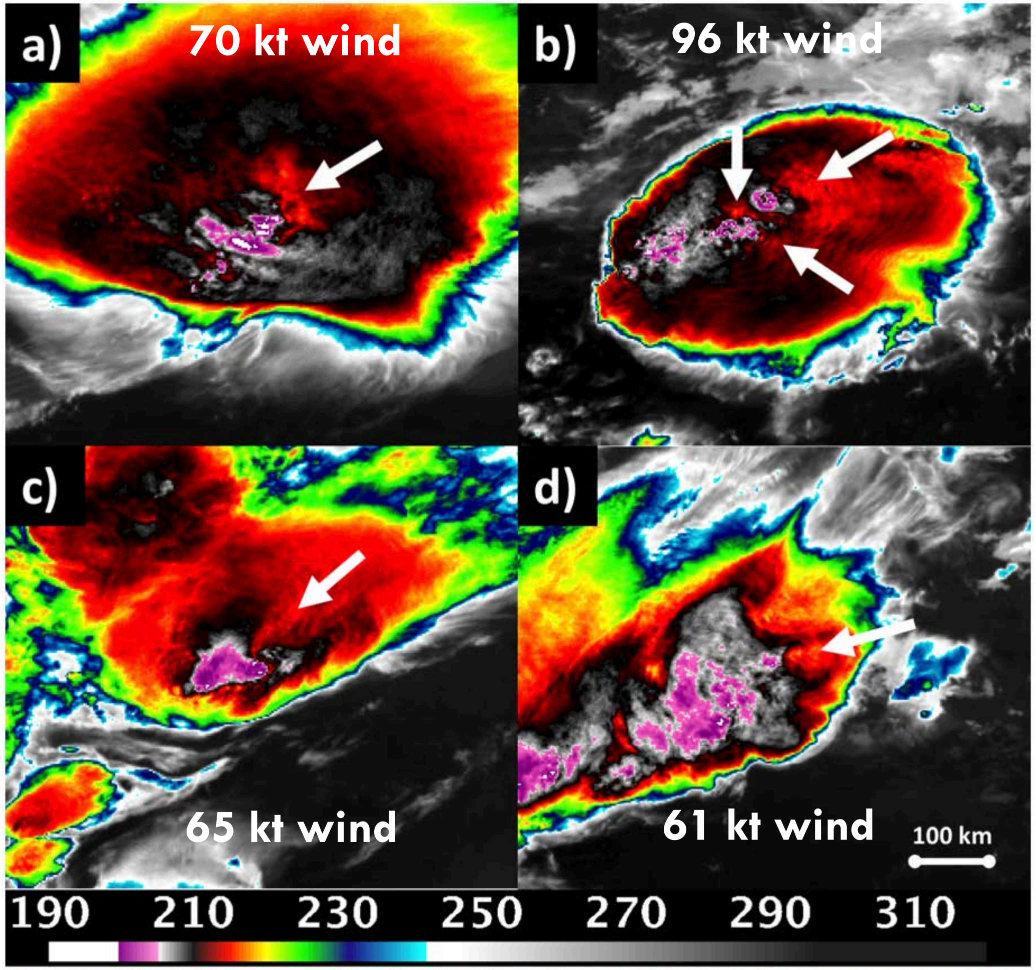
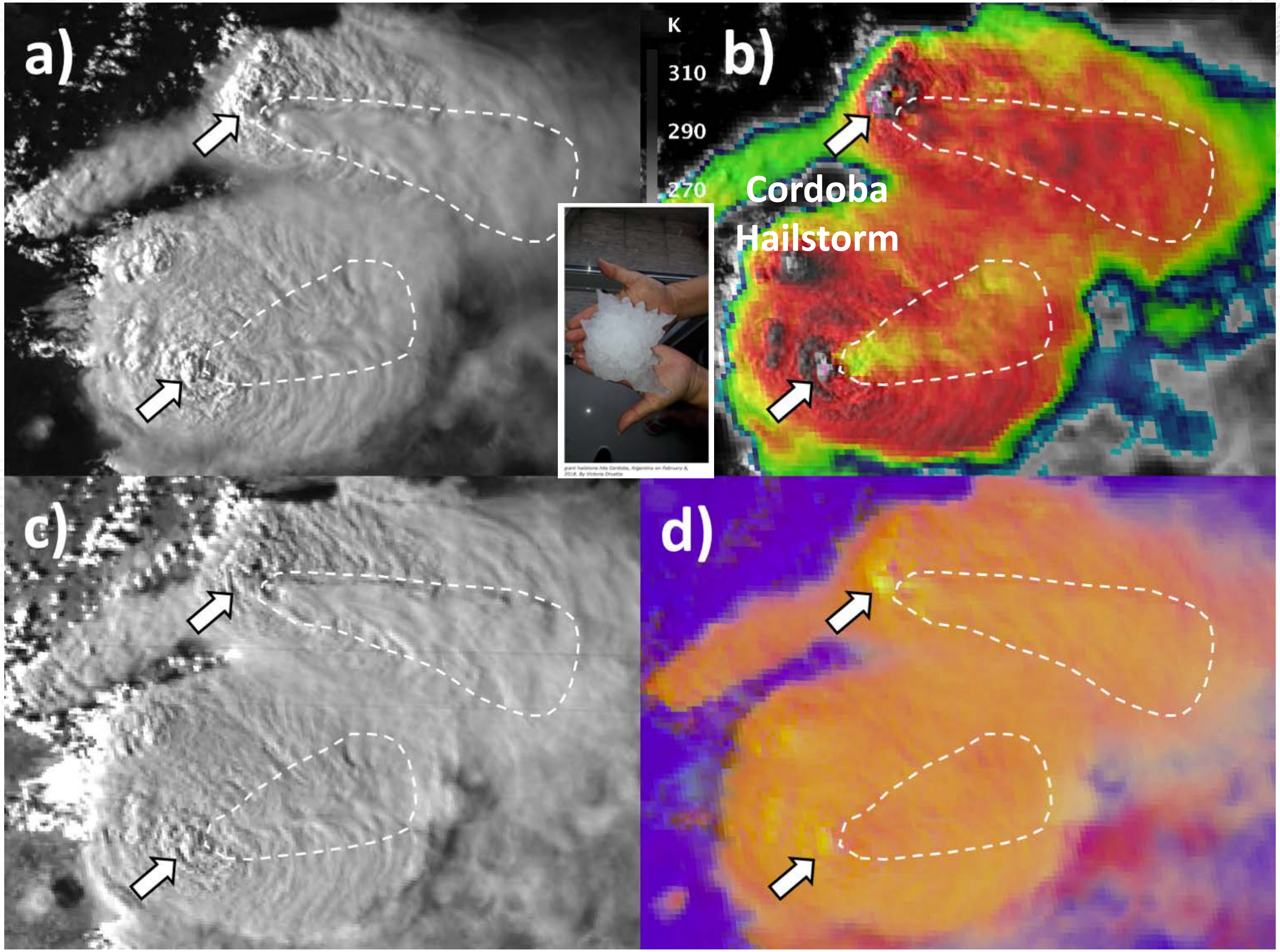


Figure 9: GOES-16 IR imagery of randomly selected mesoscale convective systems at the time when severe winds were reported. Images are centered on the location where severe wind was reported. AACPs embedded within the MCS anvils are identified with white arrows. a) 11 June 2017 at 1302 UTC over Minnesota with 70 kt wind, b) 17 June 2017 at 0032 UTC over Nebraska and Iowa with up to 96 kt wind, c) 3 July 2017 at 0242 UTC over Nebraska with 65 kt wind, d) 4 July 2017 at 0302 UTC over Oklahoma with 61 kt wind.

Córdoba, Argentina 7-inch Hail Event

Visible

IR+Visible Sandwich



1.6 micron near-IR

Daytime RGB Composite

2 plumes, 1 warm, 1 cold
Why does plume temperature vary? Plume optical depth? Evaporative cooling?

Published studies by Setvak et al. show enhanced near-IR reflectance in plumes. Reflectance is fairly constant across in the anvil in this case? Why do some plumes exhibit small ice but others do not?

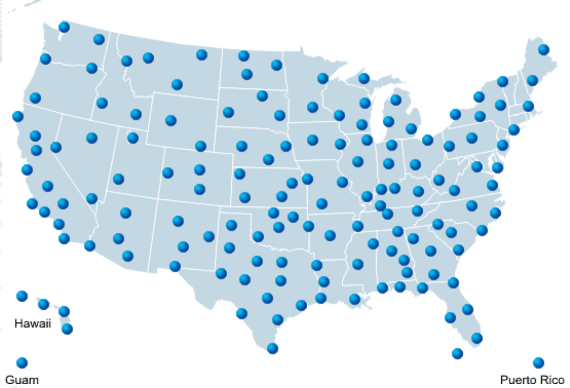
U. Oklahoma / Texas A&M GridRad System

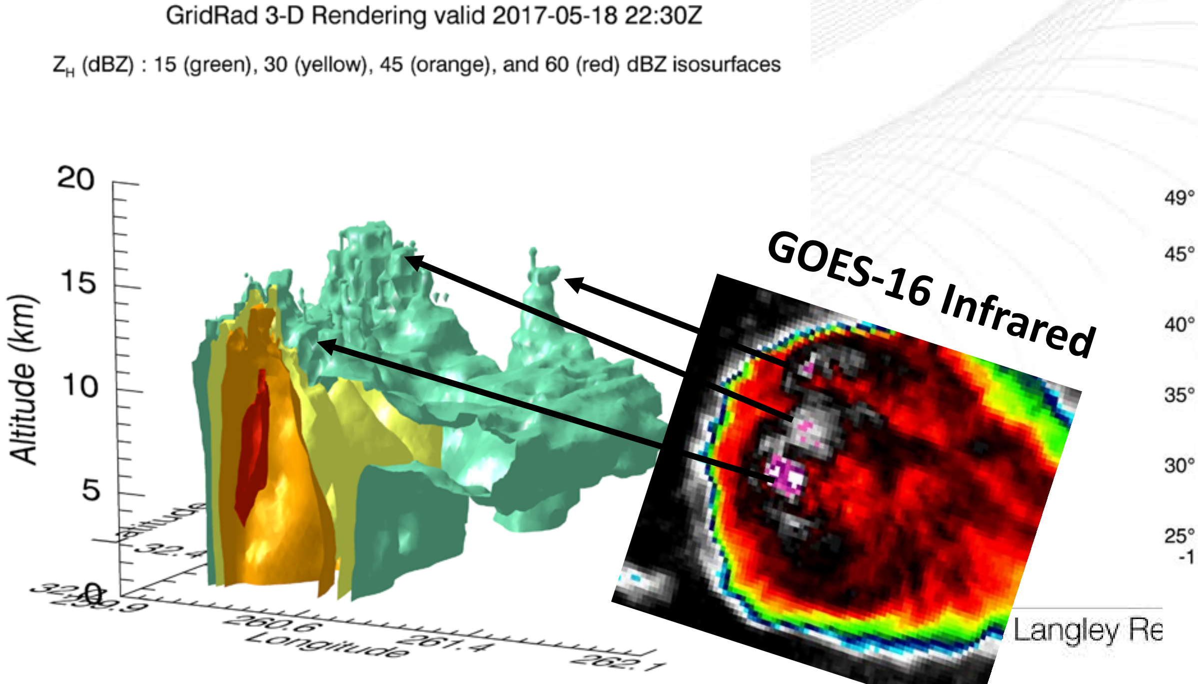
(http://www.gridrad.org)

GOAL: Use Overlapping NOAA NEXRAD Radar Volumes To Construct High Spatial (2 km), Temporal (5-Min), and Vertical (0.5 km) Resolution Composites

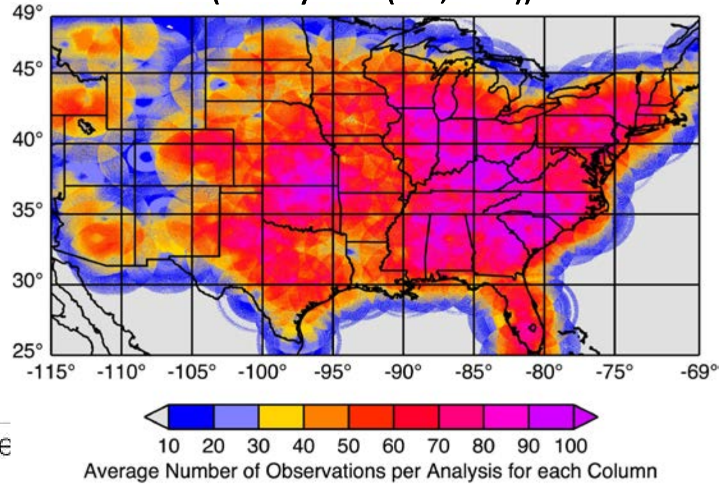
- **Comparable to the NOAA Multi-Radar Multi-Sensor (MRMS) system, but emphasizes resolving the 3-D structure of the storm, especially in the upper troposphere / lower stratosphere**
- **Products Include: Echo Tops at varying dBZ, Radial Divergence, Azimuthal Shear (i.e. ”Rotation”), Spectrum Width, Hydrometeor Classification, Dual-Polarization Fields, Hail Detection / Hail Size Estimates, and Many More**

NOAA NEXRAD Doppler Radar Sites
15 Elevation Scans Per 5-Min Volume





Mean Number of Radar Slices
Through An Atmospheric Column
(Cooney et al. (JGR, 2018))



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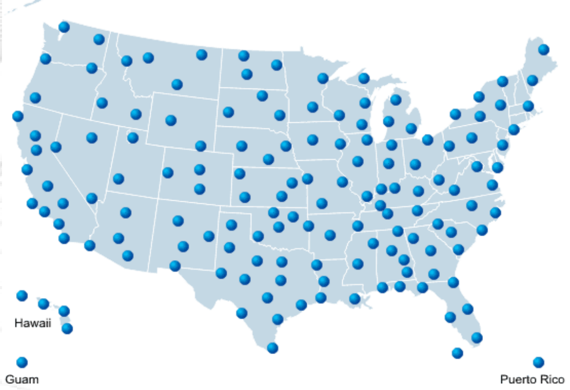
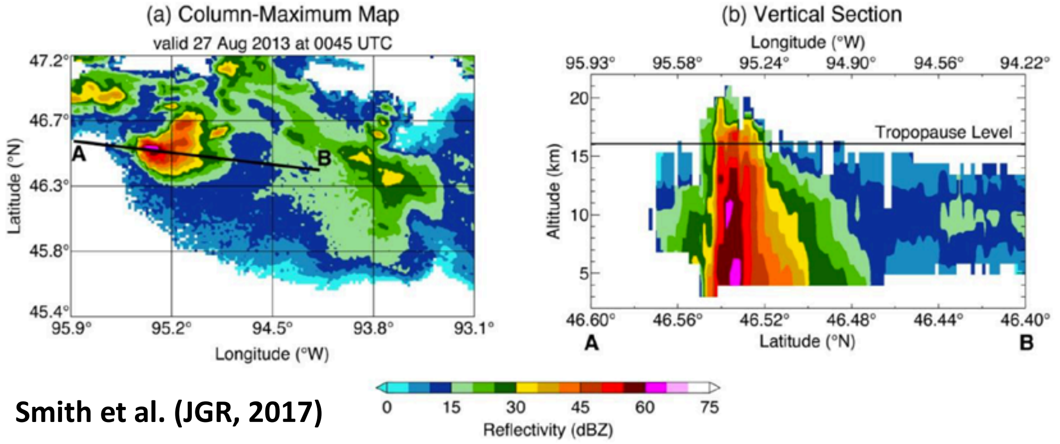
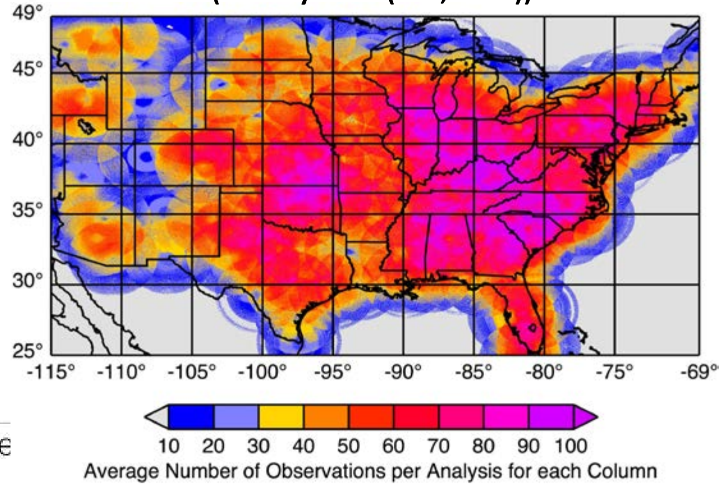




Smith et al. (JGR, 2017)

Figure 8. High resolution storm map and 2-D cross-section showing 4 – 5 km penetration into the stratosphere. **(a)** This map shows column-maximum radar reflectivity at a time of strong tropopause-penetrating convection (00:45 UTC on 27-Aug-2013) from composite NEXRAD observations. **(b)** A vertical cross-section along the line labeled ‘A-B’ in (a), highlighting the depth of penetration above the local tropopause (as determined using 00:00 UTC radiosonde observations from nearby Minneapolis, Minnesota). The reflectivity data reveal that significant condensate was carried to altitudes >4 km above the tropopause level.

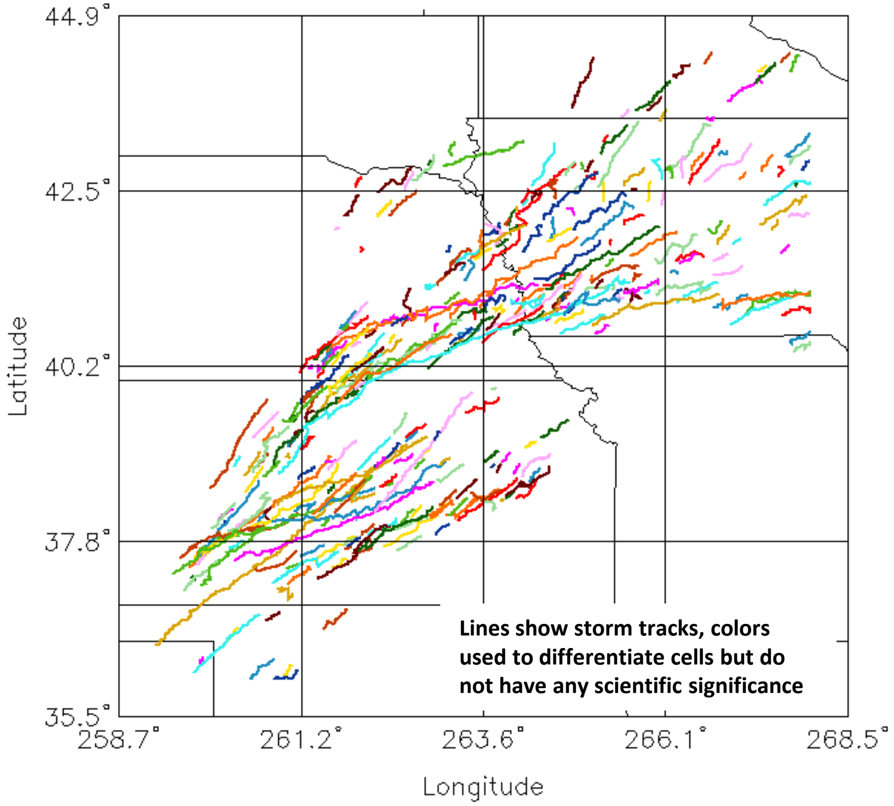
Mean Number of Radar Slices Through An Atmospheric Column (Cooney et al. (JGR, 2018))



GridRad Storm Cell Tracking

Critical For Data Fusion and Severe Storm Analysis

11-12 May 2014 Storm Tracks



Lines show storm tracks, colors used to differentiate cells but do not have any scientific significance

Graphic Courtesy of Cameron Homeyer (OU)

- **GridRad 40 dBZ convective radar echoes** (Storm Labeling in Three Dimensions, Starzec et al. 2017) **define storm objects that are tracked in each 5-min volume**
- **Results quite comparable to tracks available in NOAA Weather Service operations** (Homeyer et al. 2017)
- **Radar objects enable accumulation of radar, satellite, and severe weather report data throughout storm lifetimes**

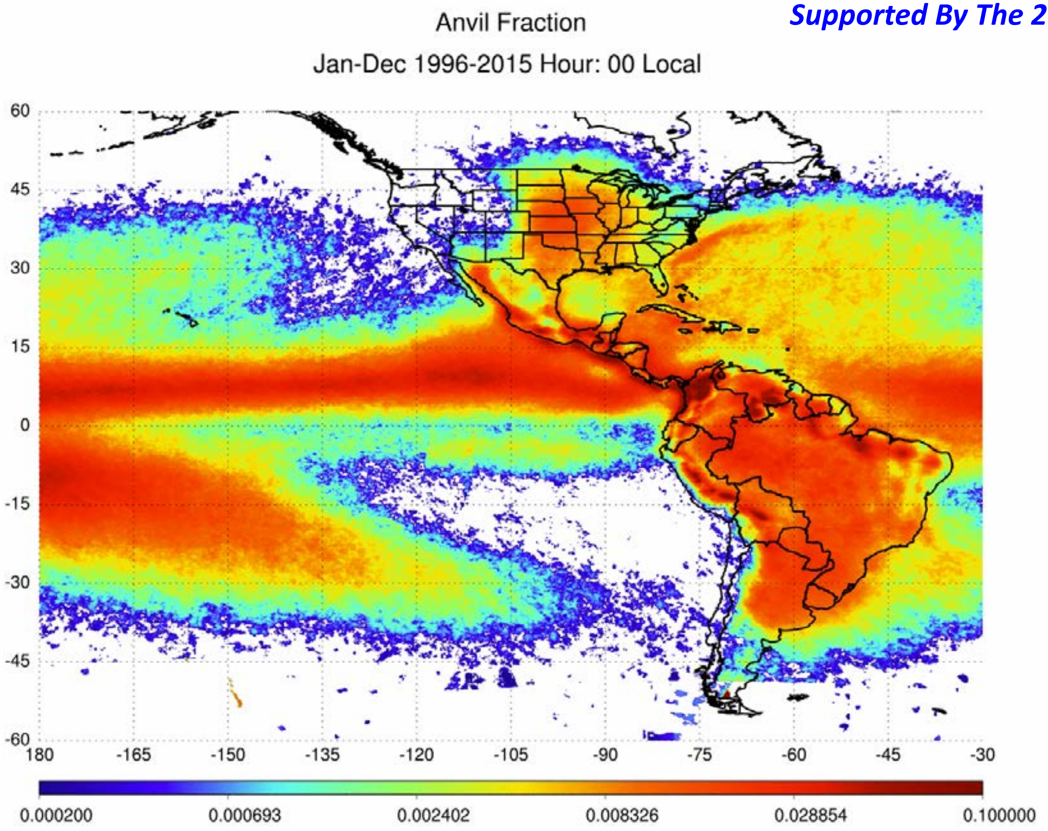
Above Anvil Plume Relationship to Supercells

- **We use a combination of objective and subjective methods to classify storms as supercells**
  - First, we identify potential supercells by requiring storms to exceed minimum thresholds in lifetime, azimuthal shear, and echo top altitudes
  - Second, we subjectively evaluate candidate storms to confirm/deny supercellular characteristics (e.g., deviant motion, hook echo, weak echo regions, differential reflectivity arcs)
- **Of the ~200 identified supercell storms, 75% produced an AACP**
- **However, only 48% of AACP storms were supercells**
- **Supercells without AACPs either did not penetrate the tropopause, or did so only marginally (< 1 km) and intermittently**
- **Supercells with AACPs produced ~2.5 times more severe weather than supercells without**
- **Supercells with AACPs produced 94% of all tornadoes associated with supercells**

Bridging The Gap Between Weather and Climate

Combining Pattern Recognition With Big Data Analytics To Develop A 20-Year Hazardous Storm Climatology Over The Western Hemisphere

Supported By The 2016 NASA Science Innovation Fund (SIF)


Anvil Fraction

Jan-Dec 1996-2015 Hour: 00 Local

Warm Colors: Greater Thunderstorm Frequency In An Hour Of Day

Challenges: Severe weather occurs in small regions and for short times. Making this incredibly large and detailed GOES pixel-scale database and atmospheric reanalysis data available to users requires innovative IT solutions

Sophisticated pattern recognition in reanalysis data is required to develop analog based forecasting approaches

Quality of imagery from other global satellites varies in throughout history, making expansion of this work to global and climate time scales quite challenging

Important Driver For This Work: 2017 National Academies Earth Science Decadal Survey "Most Important Question" For The Next Decade: "Why Do Convective Storms Occur Where and When They Do?"

- **The GOES satellite series has been collecting half-hourly, ~0.75 to 3 mile/pixel observations over much of the Western Hemisphere since 1996, an ideal dataset for responding to the Decadal Survey**
- **The SatCORPS team has used pattern recognition methods to identify hazardous thunderstorm regions in GOES multi-spectral imagery**
- **Trillions of GOES pixels were acquired from a remote server and processed on a LaRC ASDC computing cluster to generate a 20-year storm detection climatology**

Science Questions:

1) When and where do hazardous storms most frequently occur?

2) How do storms vary throughout the day/year, and across the 20-year period?

3) Are there any trends in storm activity?

4) Can we pair this satellite information with "re-analyses" of airmasses around thunderstorms to discriminate likely hail, wind, tornado, and/or flooding conditions?

5) How accurate are weather prediction model thunderstorm forecasts?

6) Can we pair long term databases of storm detections with historical re-analyses of atmospheric temperature, moisture, and wind flows to develop probabilistic "analog" based forecasts? Did severe storms occur in the past when the weather conditions have been "the same"?