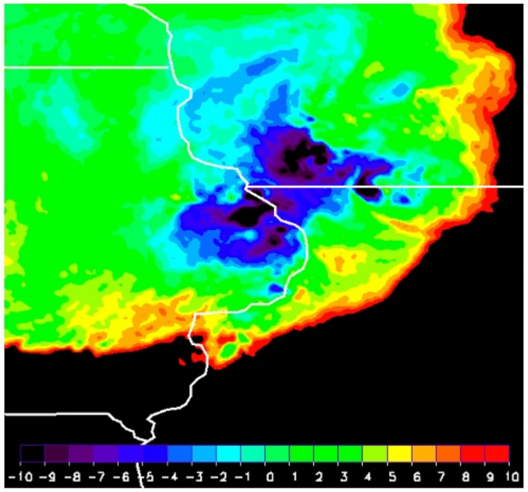
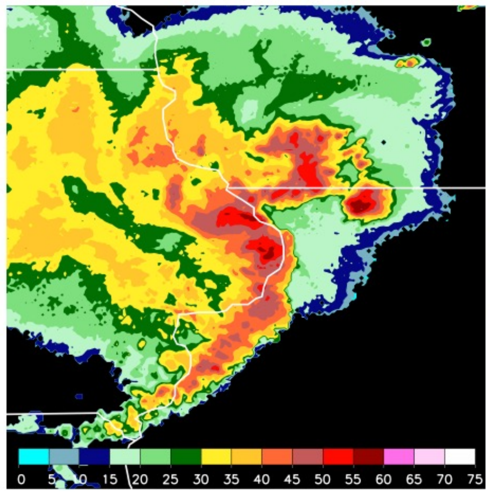
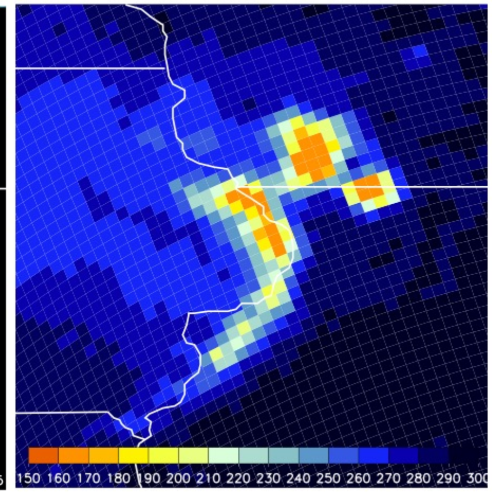






Storm Chasing from Space

Detecting severe weather phenomena from satellite platforms

Dr. Sarah D. Bang

NASA Marshall Space Flight Center

Huntsville, AL USA

Earth Science Branch
at NASA MSFC

- Atmospheric electricity
- Precipitation
- Atmospheric dynamics & weather
- Earth's energy and water cycle
- Data Science
  - Data management
  - Artificial Intelligence
  - Machine Learning
- Surface processes
  - Weather disasters
  - Detection & monitoring

NASA Applied Sciences
Disasters Program

NASA Earth Science DISASTERS PROGRAM

"use Earth-observing data and applied research to improve the *prediction of, preparation for, response to and recovery from* hazards and disasters around the world."

appliedsciences.nasa.gov/what-we-do/disasters

The "SMASH" Team:
Satellite Mapping and Analysis of Severe Hail

Kristopher Bedka
NASA LaRC
Sarah Bang, Jordan Bell,
Daniel Cecil, Christopher Schultz
NASA MSFC

Meet the Speaker: Buffalo native, UChicago & Utah alumna. Passionate about severe weather, open science, and meteorological fieldwork.

Specialize in severe weather phenomena (namely lightning and hail) and detecting them from satellite platforms.

Severe Weather

"A severe thunderstorm is one that produces winds 58 mph or stronger and/or hail 1 inch in diameter or larger."

weather.gov/bgm/severedefinitions

- Lightning
- Hail
- Severe winds
- Tornadoes

Globally, severe weather causes an annual average of $67B in insured losses
[Hail comprises ~70%]

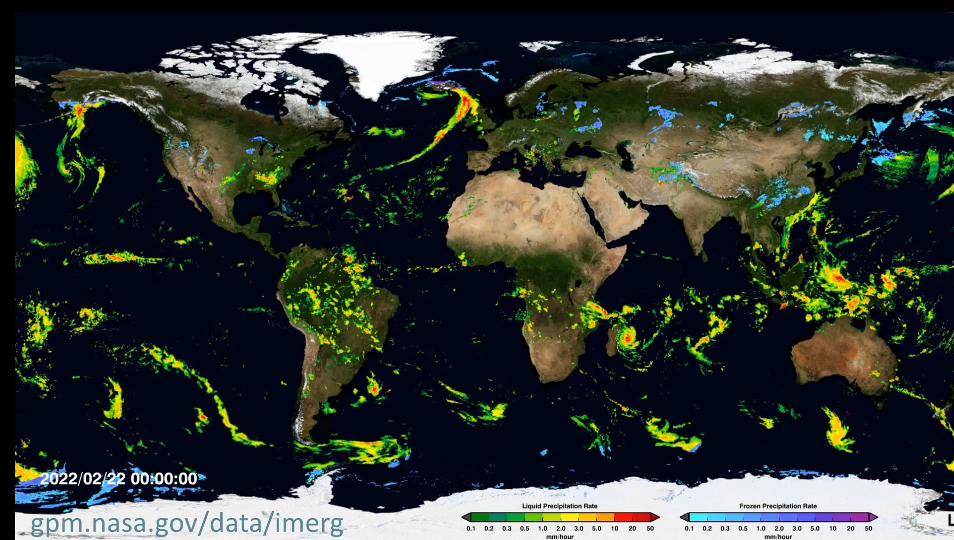
Aon Benfield, 2020

March 9, 2022

Severe weather poses threats to:

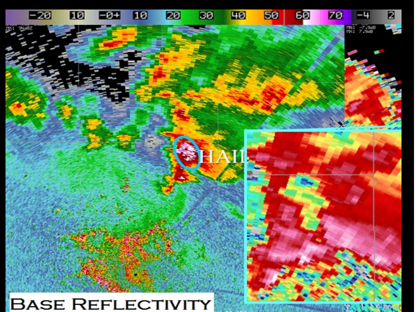
- Infrastructure
- Agriculture
- Aviation

When left out of precipitation retrievals, severe weather can cause large errors

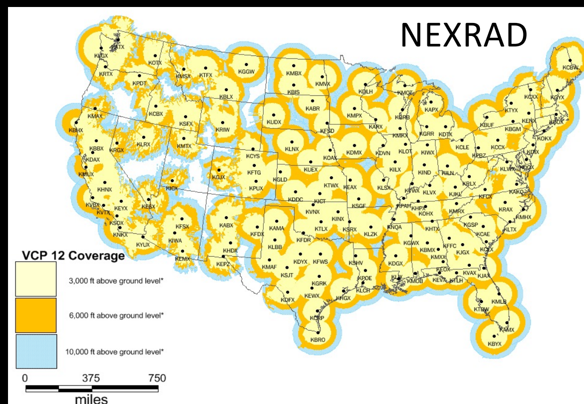


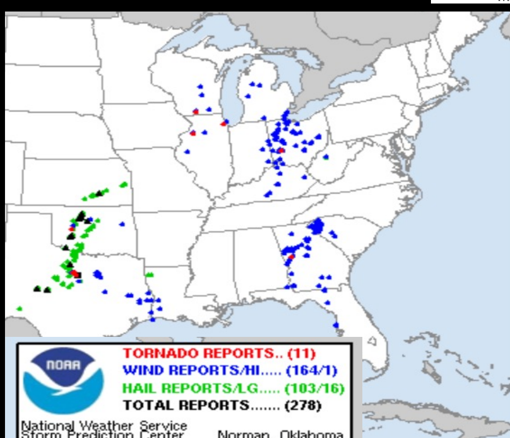
Observing Severe Weather

Ground Radar



NWS Birmingham

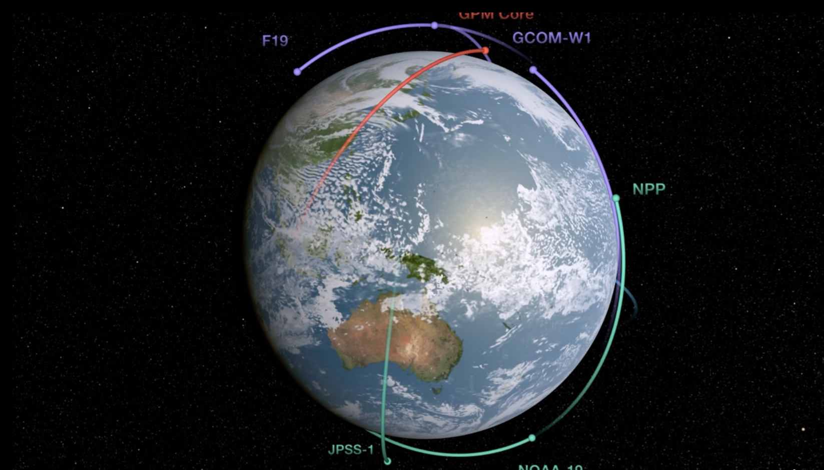




Human-Spotter Reports

However . . .

- Spotter reports are prone to bias (social, geographical)
- Radar coverage is not available everywhere



svs.gsfc.nasa.gov/

For consistency, uniformity and to avoid bias, satellite datasets are the best option

Can observe remote, data-sparse, and oceanic regions

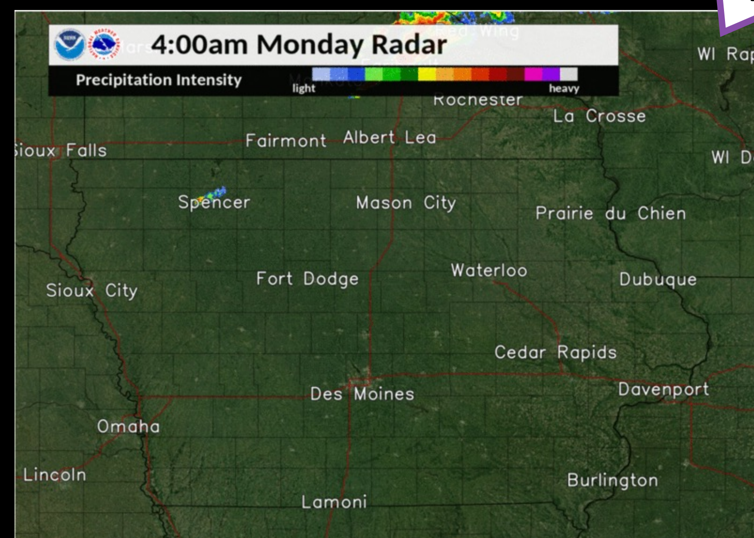
August 10, 2020 Derecho

a multi-satellite perspective

- Satellites in:
  - GEO: Geostationary orbit
  - LEO: Low-earth orbit
    - Polar orbit
    - Sun-synchronous orbit
- Passive sensors (receive radiation only)
  - Optical sensors
  - Passive microwave radiometers
- Active sensors (emit & receive)
  - Radar
  - SAR

- Traversed Nebraska, Iowa, Illinois
- Hail, tornadoes, winds >100 mph
- Millions of acres of crops damaged
- Urban and rural structures destroyed
- Extensive power outages (>16 days)
- Insured loss estimates $6.8B to $11B.

It was the costliest thunderstorm event in U.S. history.



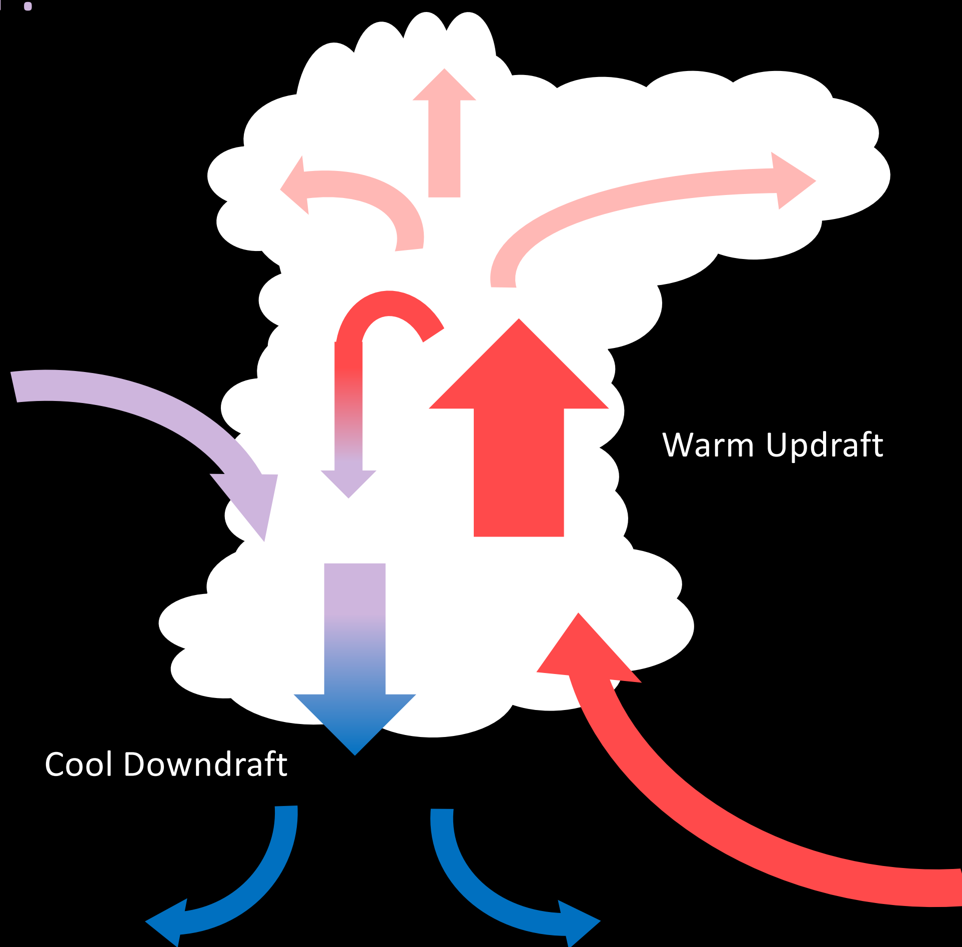
https://www.weather.gov/dmx/2020derecho

What makes a storm?

Thunderstorm Ingredients

- **Moisture**
- **Instability** (buoyant environment)
- **Lifting Mechanism**
- ***Wind Shear**

A lifting event (front, outflow boundary, topography) incites a bubble of air to rise. If the air is buoyant relative to its surroundings it will accelerate upward, condensing moisture and freezing ice particles as it rises and cools.



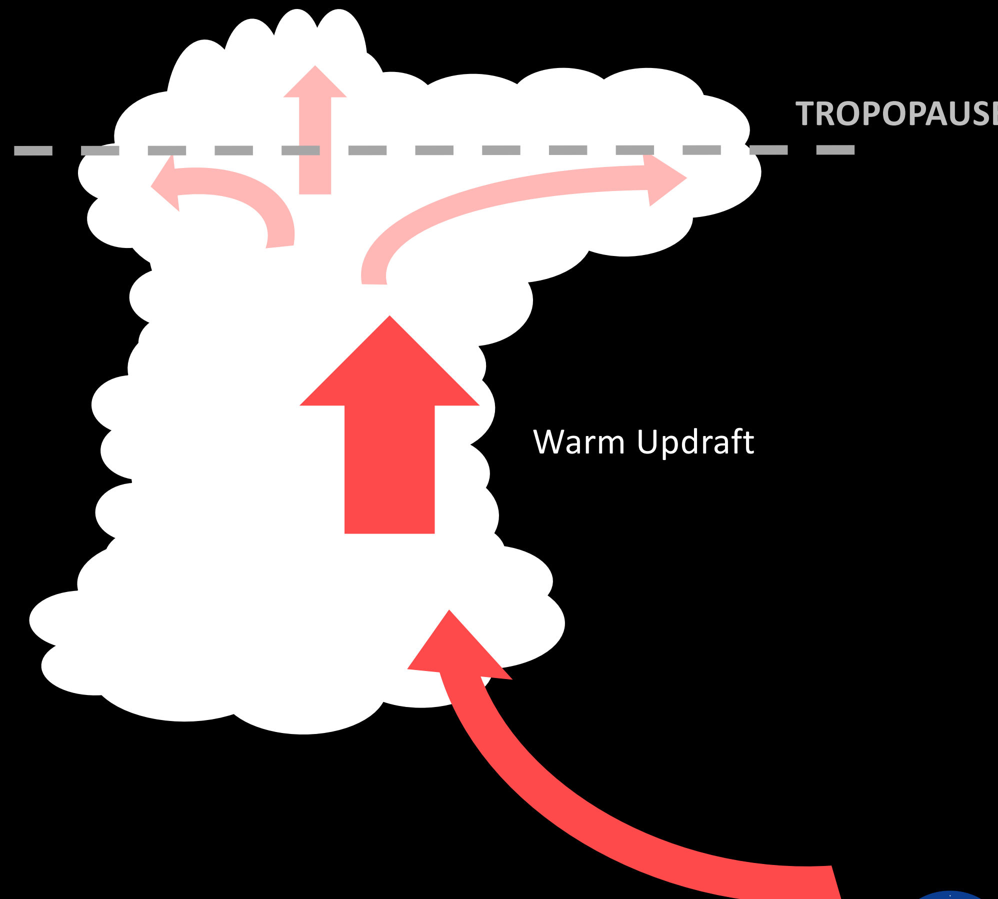
What makes a storm?

If the updraft reaches the tropopause, it often spreads outward horizontally, creating an “anvil.”

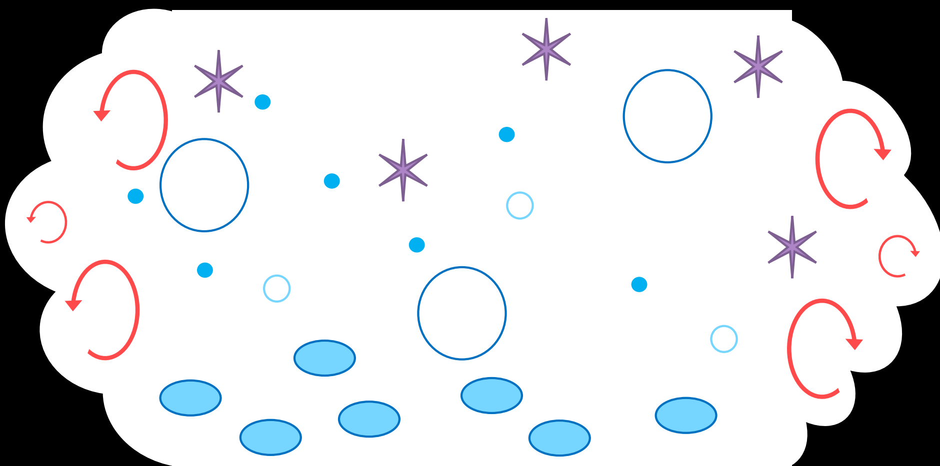
Sometimes, the updraft is so fast and strong that it will “overshoot” the neutral buoyancy level of the tropopause.

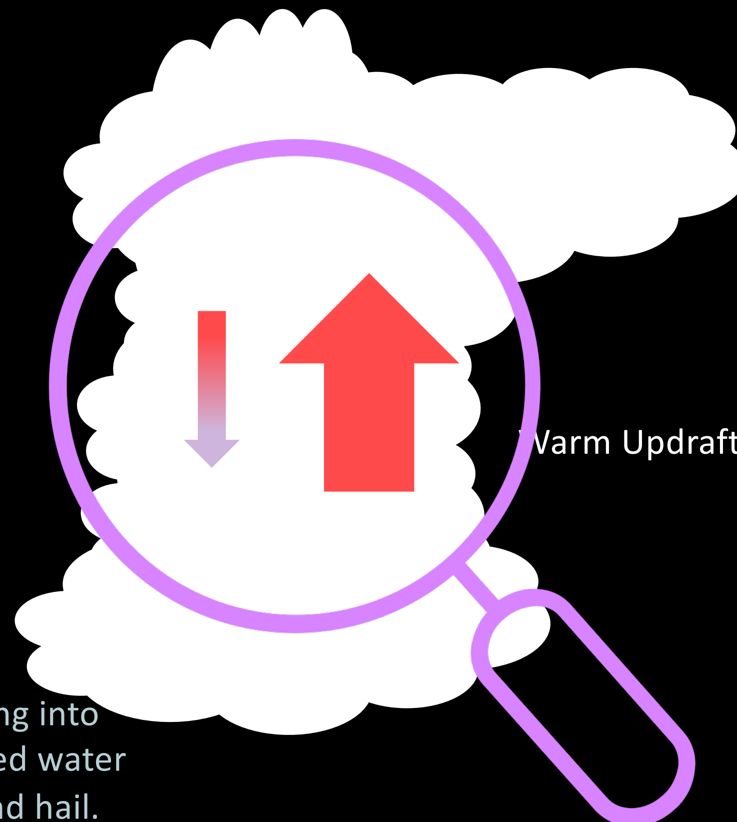
This is called an “overshooting top” or OT.

https://earthobservatory.nasa.gov/images/78101/the-anatomy-of-a-thunderstorm



What makes a storm?





Zooming in on the updraft, here is where moisture is condensing into droplets, rising and freezing, sometimes remaining as supercooled water droplets (below freezing), riming, and accreting into graupel and hail. To make grow and sustain hail, develop lightning, and loft lots of precipitation, the updraft needs to be sufficiently strong. Strong turbulent updrafts also cause lots of particle collisions.

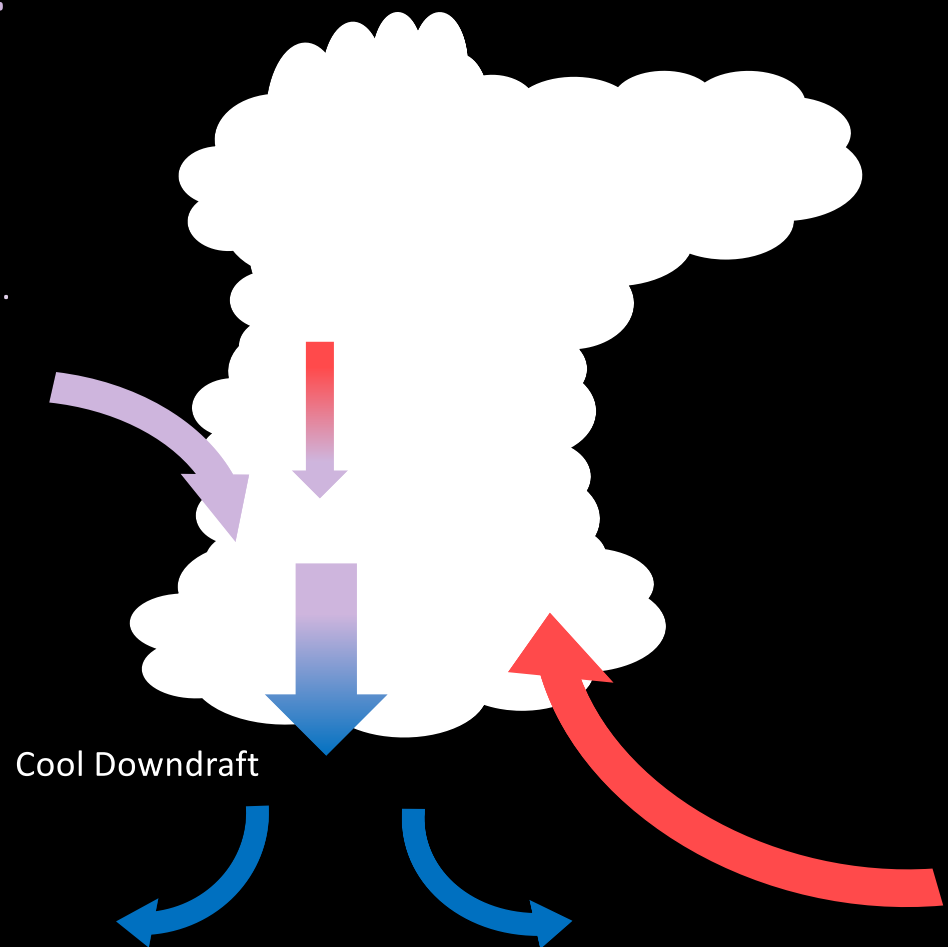
What makes a storm?

As precipitation (in this case, rain and hail) fall, evaporative cooling and cool inflow induce a downdraft, or sinking air. A strong downdraft can cause severe winds when it spreads out at the surface.

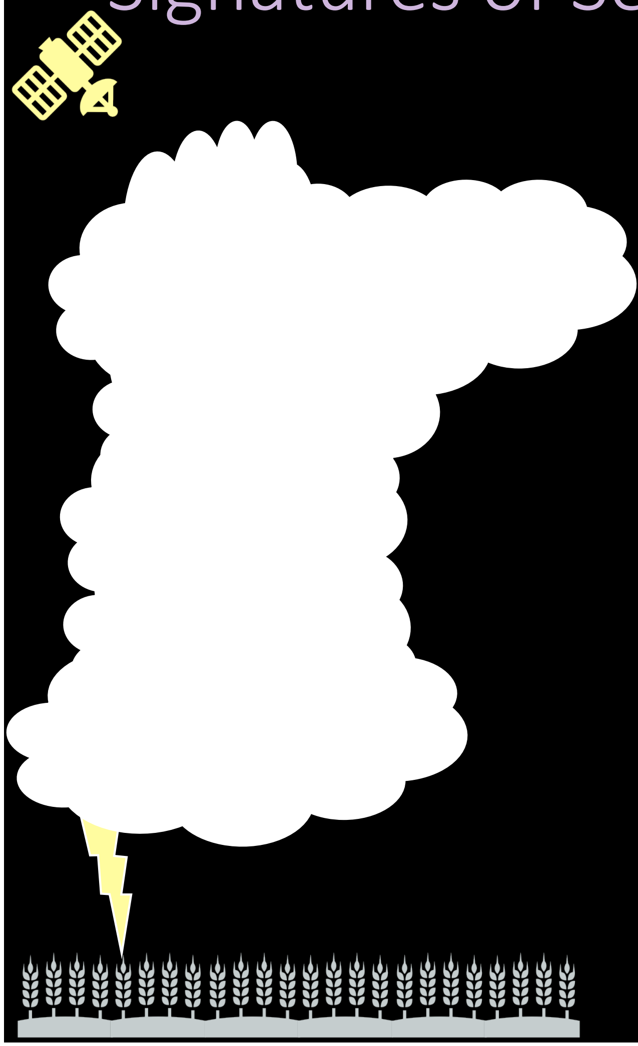
Depending on the environmental setup and the wind shear, some thunderstorms can be sustained for long periods of time and cover long distances.

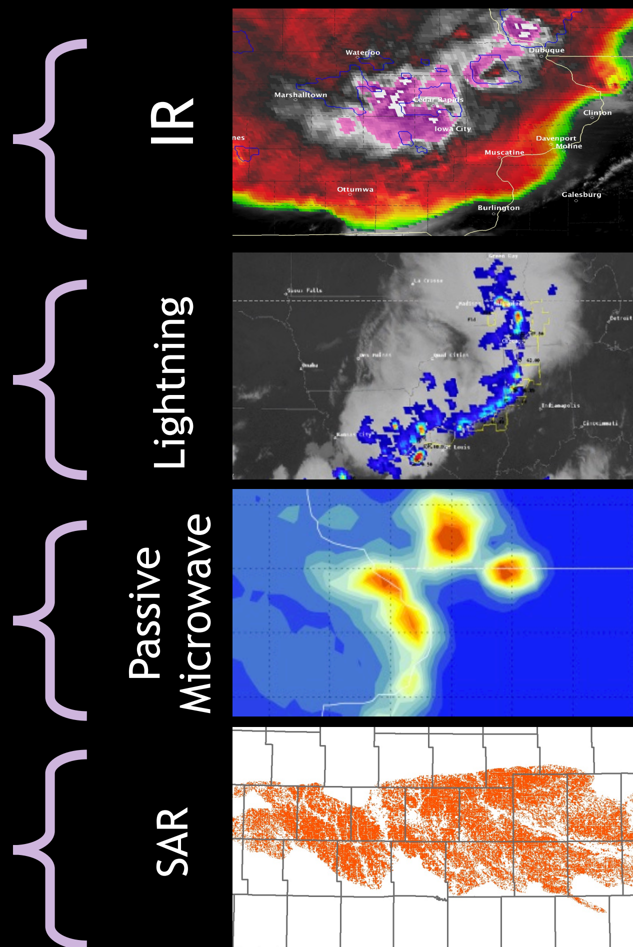
A prolonged storm-related damaging wind event is called a "derecho" (from the Spanish word for "straight," due to the damaging straight-line winds they cause).

https://www.weather.gov/lmk/derecho



Signatures of Severe Weather in Satellite Observations



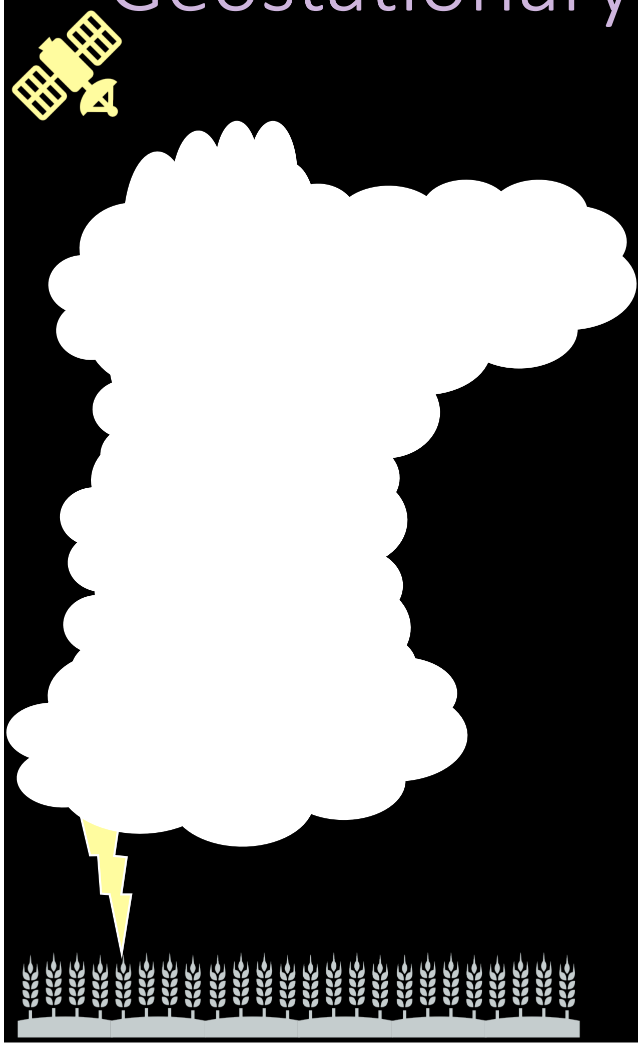


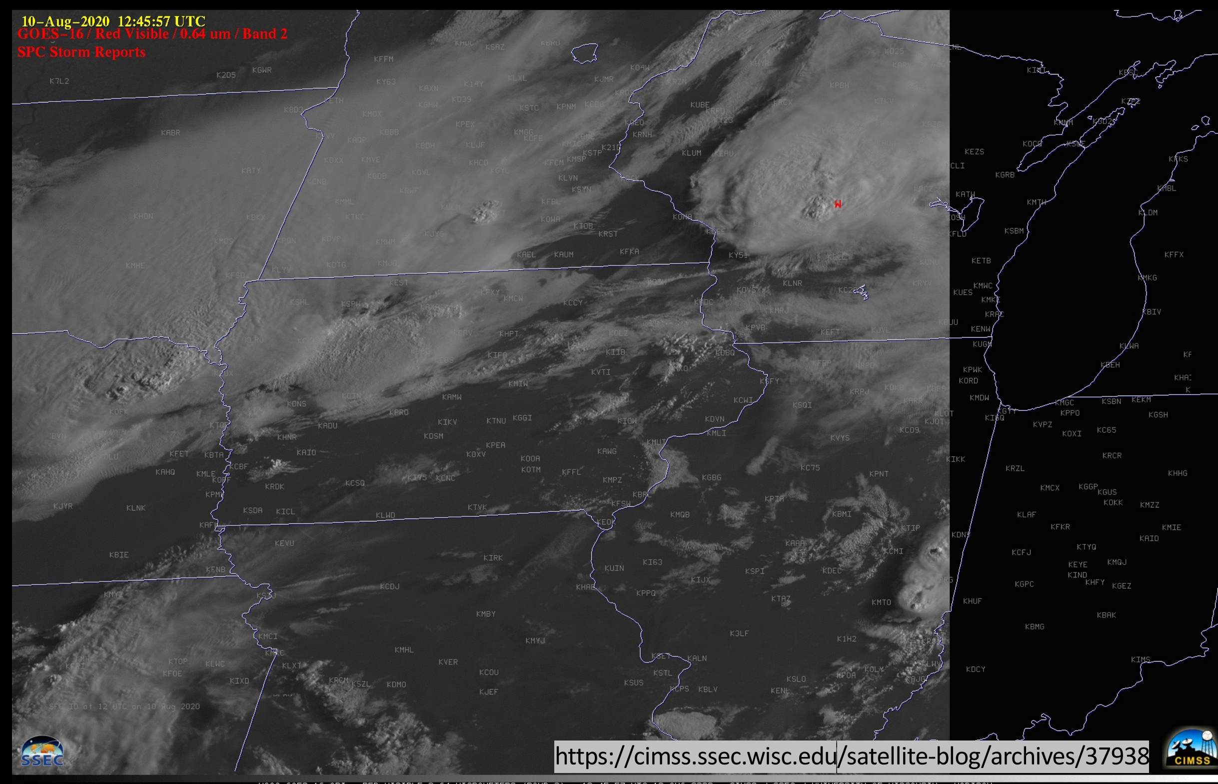
These storm structures and characteristics have distinct signatures in satellite imagery and datasets that we can use to detect and diagnose severe storms.

Let's now step through each of these detection methods as they observed the catastrophic August 10, 2020 derecho.

https://www.weather.gov/lot/2020aug10

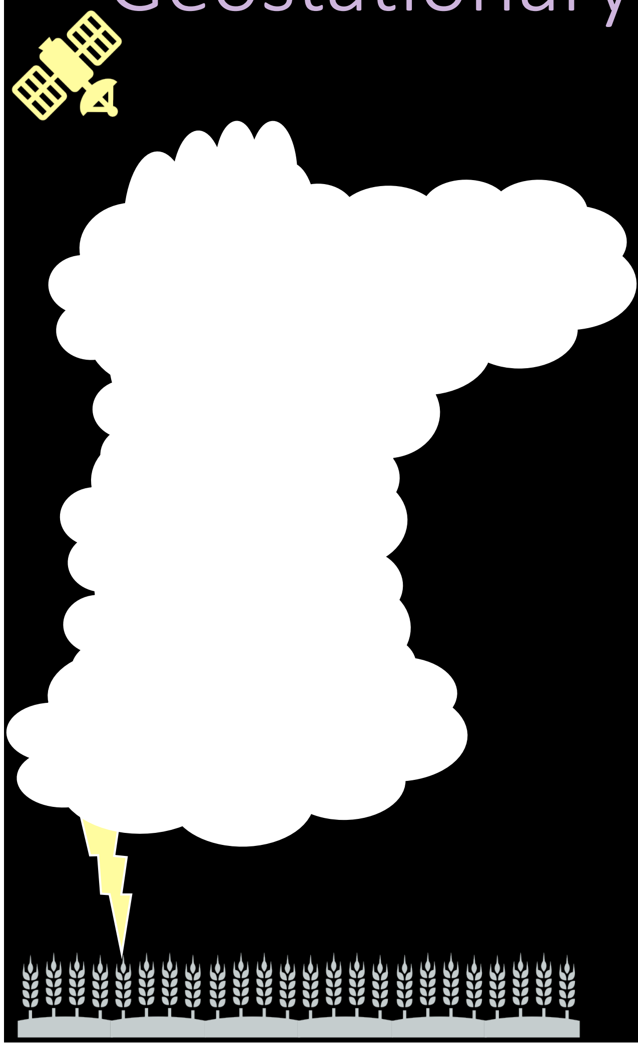
Geostationary Visible and IR: Cloud top structure

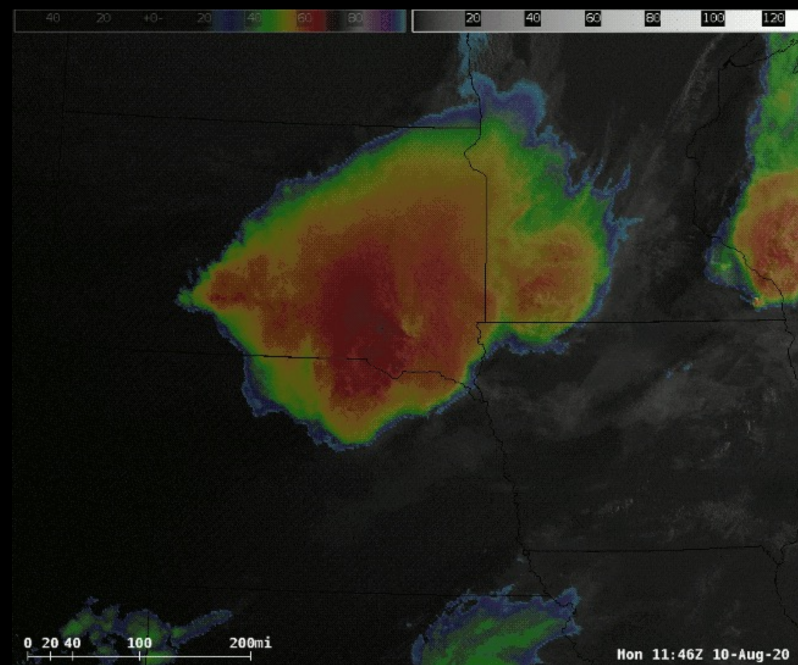




The NOAA GOES-16 satellite is in geostationary orbit focused on the western hemisphere. A geostationary orbit allows us to observe the same view of the earth's surface all the time, which is ideal for tracking a severe weather outbreak. Visible imagery, like this loop, shows the cloud top texture and extent.

Geostationary Visible and IR: Cloud top structure



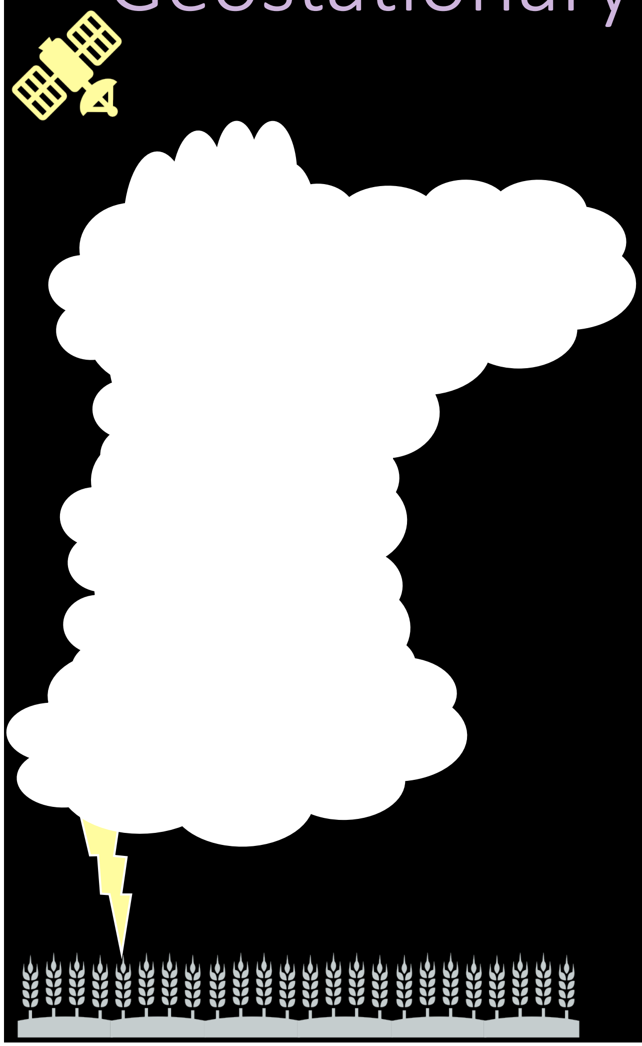


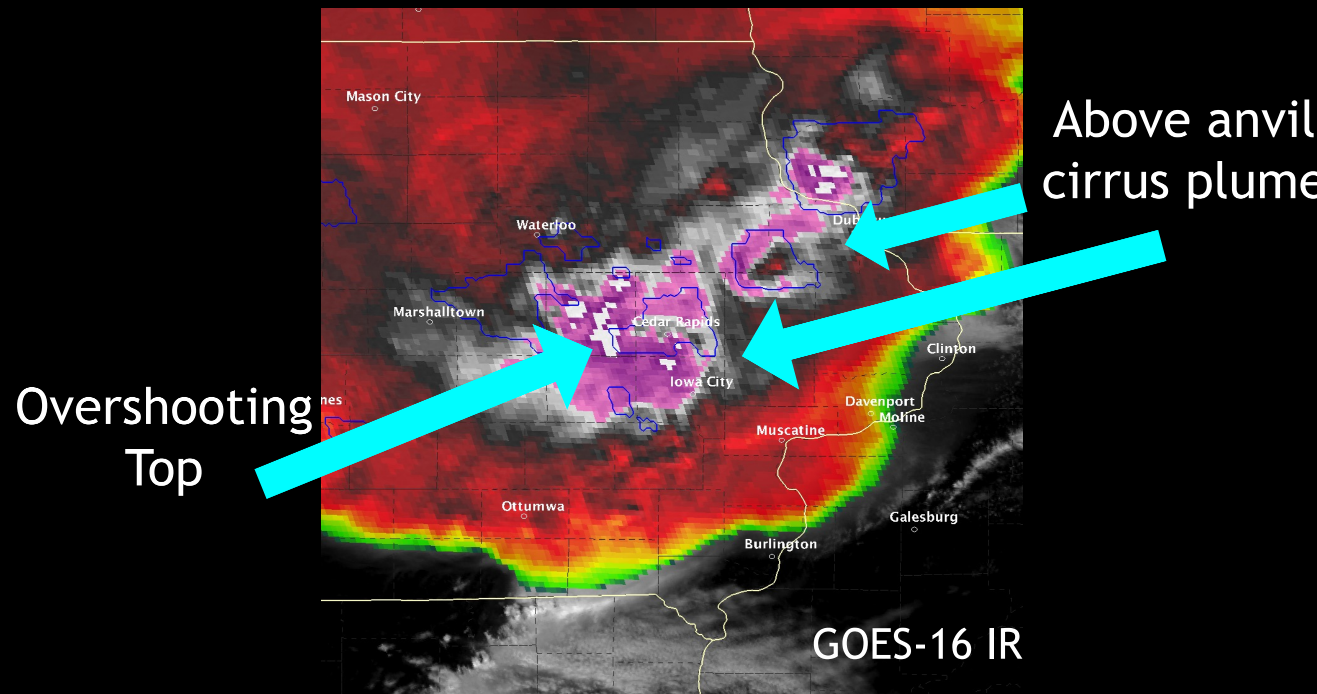
https://www.weather.gov/dmx/2020derecho

https://earthobservatory.nasa.gov/images/78101/the-anatomy-of-a-thunderstorm

Clouds absorb IR radiation from below and emit it at their current temperature. If you know the temperature profile of the environment (from a weather balloon or reanalysis dataset), the IR “brightness temperature” of a cloud can indicate its height, and thereby the strength of the updraft. You can also observe overshooting tops.

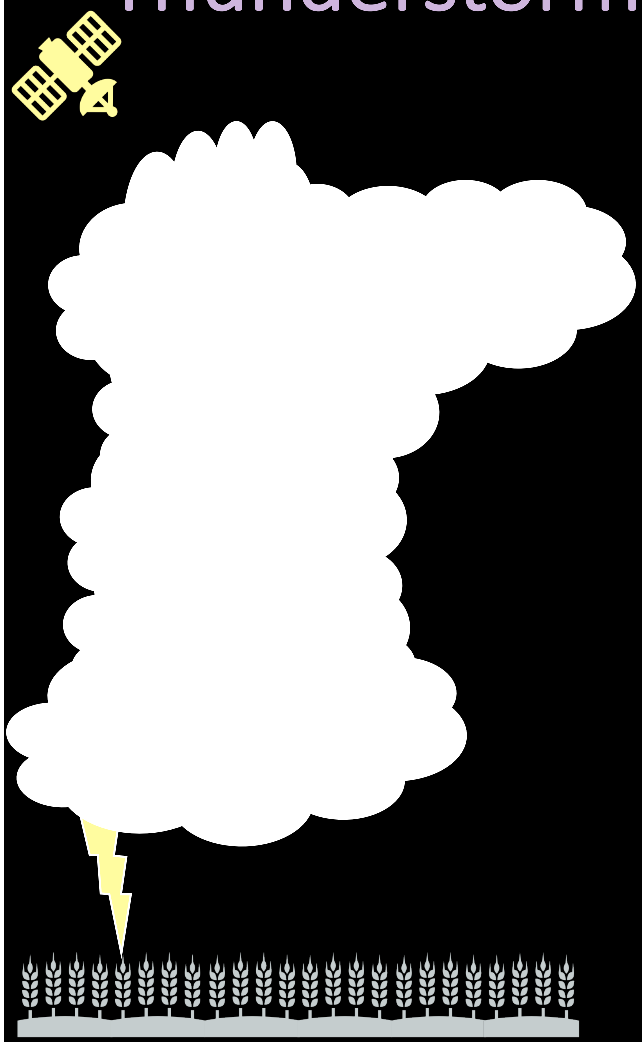
Geostationary Visible and IR: Cloud top structure

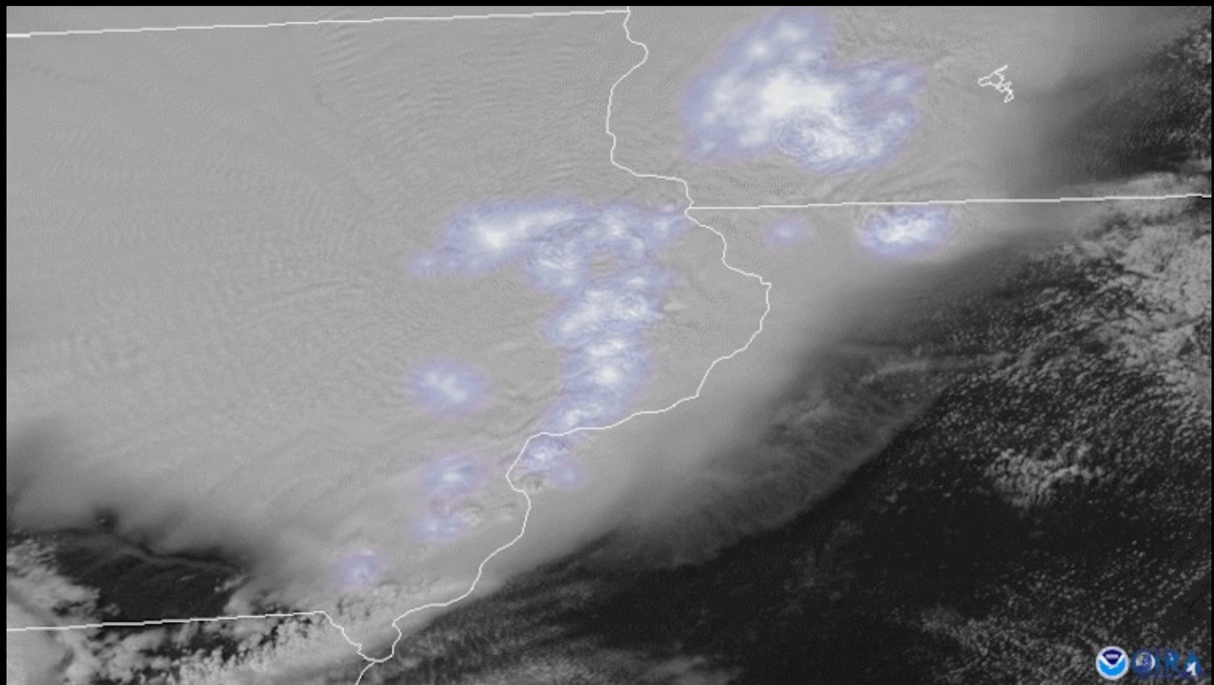




Structures that indicate severe convection, like overshooting tops, and enhanced-V pattern, and above-anvil cirrus plumes can be identified in IR imagery.

Thunderstorm Electrification: Lightning

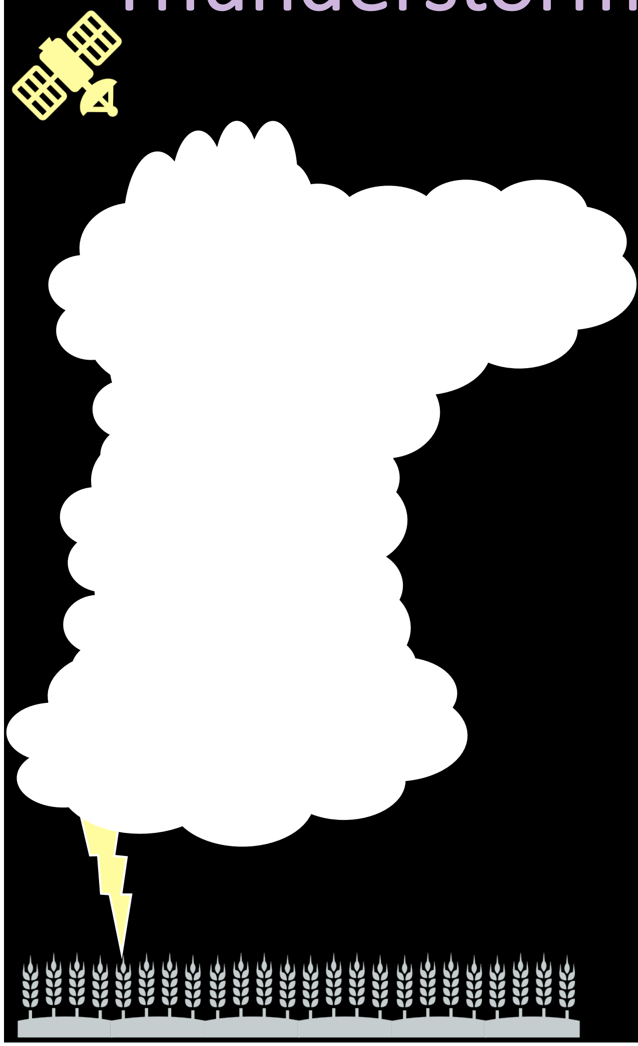


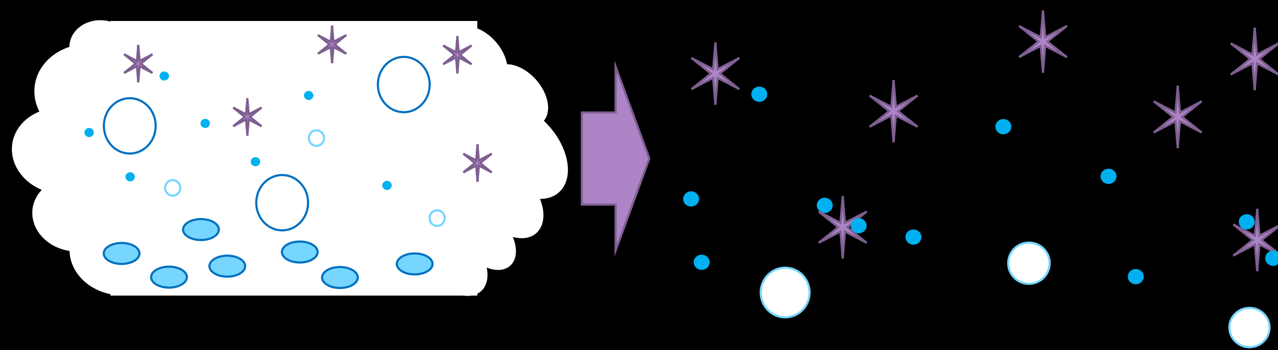


https://www.nesdis.noaa.gov/news/day-2020-goes-east-watches-derecho-slam-the-midwest

GOES visible imagery with lightning flashes superimposed

Thunderstorm Electrification: Lightning



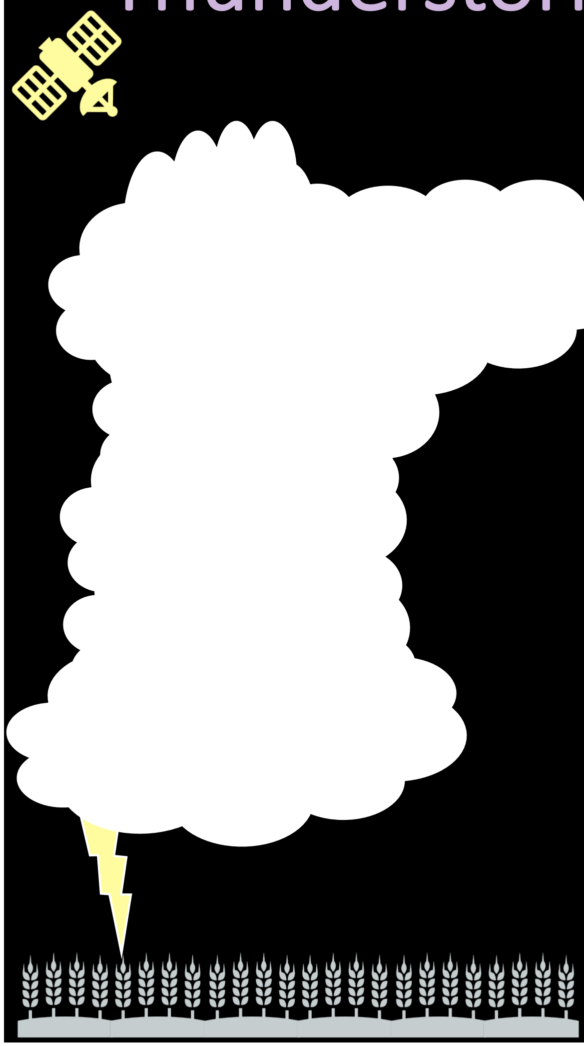


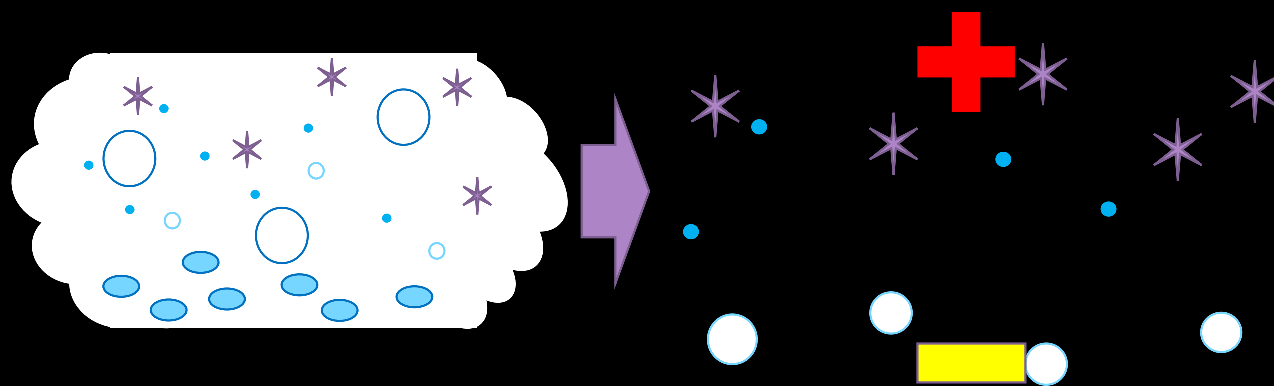
In a strong updraft, small water droplets can be accelerated upward so quickly they remain liquid at temperatures below freezing (“supercooled”).

In the updraft’s turbulence, they can land on ice particles and freeze on contact, known as “riming” grow into what’s called “graupel.”

In a turbulent updraft, the graupel colliding with the smaller ice particles in the presence of supercooled water can lead to the buildup of electrical charge. The sign of the charge depends on the temperature and humidity, but the particles rebound with opposite signed charge.

Thunderstorm Electrification: Lightning





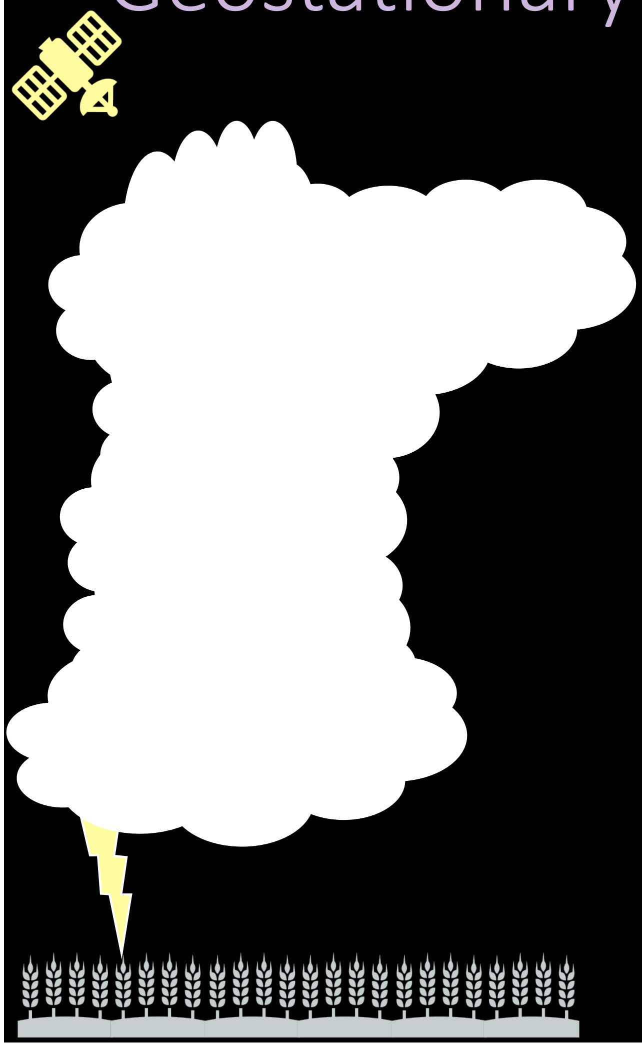
The differential fall speeds of the graupel and the smaller ice particles cause them to separate out into layers.

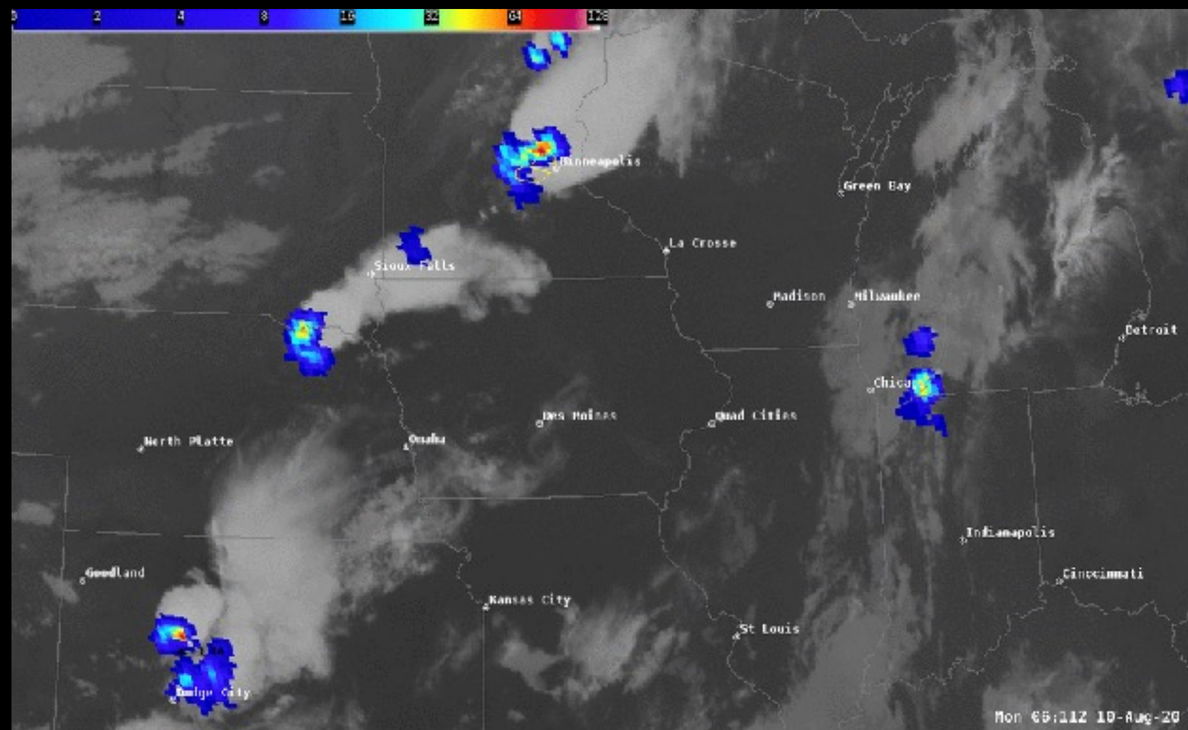
Eventually the charge buildup becomes so strong that it reaches the dielectric breakdown of air between the layers, initiating a lightning flash.

How rapidly and extensively this process occurs and the electrical characteristics give us insight into the intensity of the storm, its microphysical characteristics, and the strength of its convective updraft.

For more on the “non-inductive ice-ice collision theory of electrification, read Takahashi, 1978

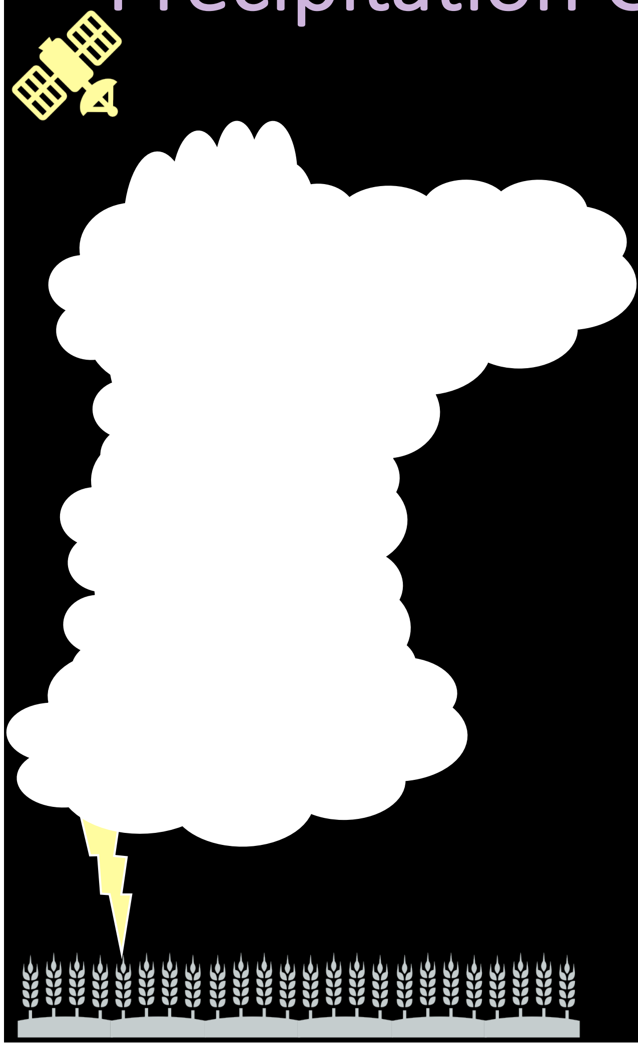
Geostationary Lightning Mapping



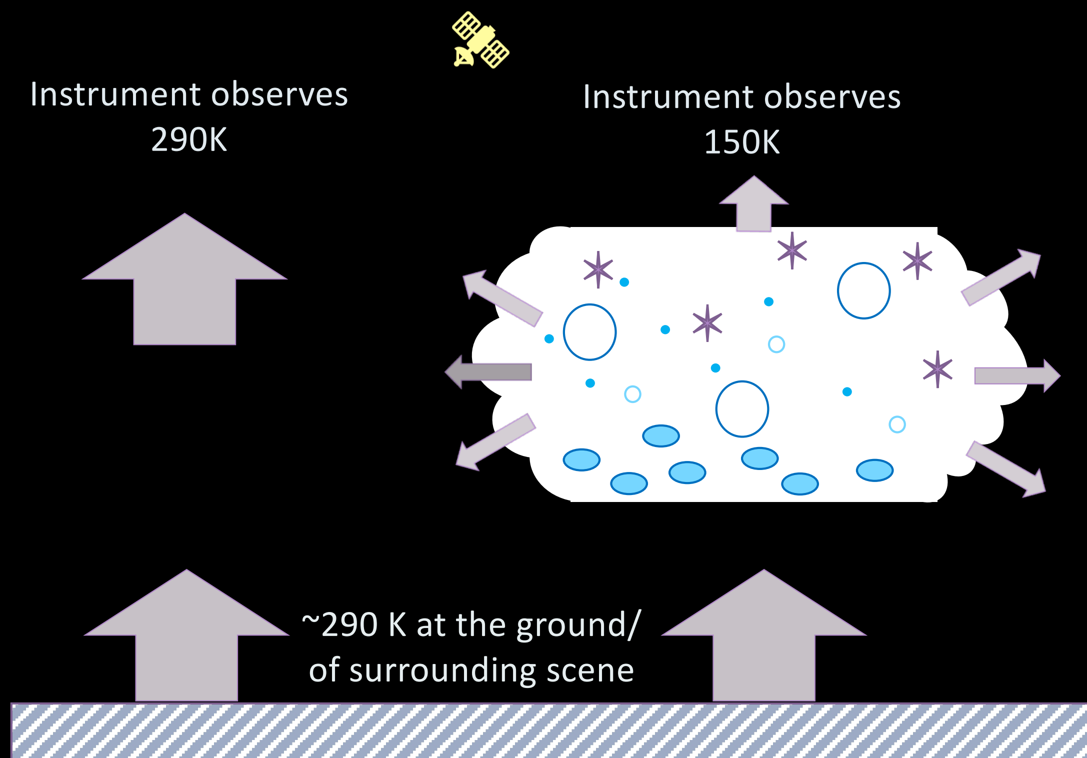


The Geostationary Lightning Mapper (GLM) onboard GOES-16 provides a constant view of the lightning field across the field of view. This allows us to track the electrical characteristics (flash rate, evolution of the flash rate, flash extent density) throughout the lifecycle of the storm.

Precipitation Characteristics: Passive Microwave

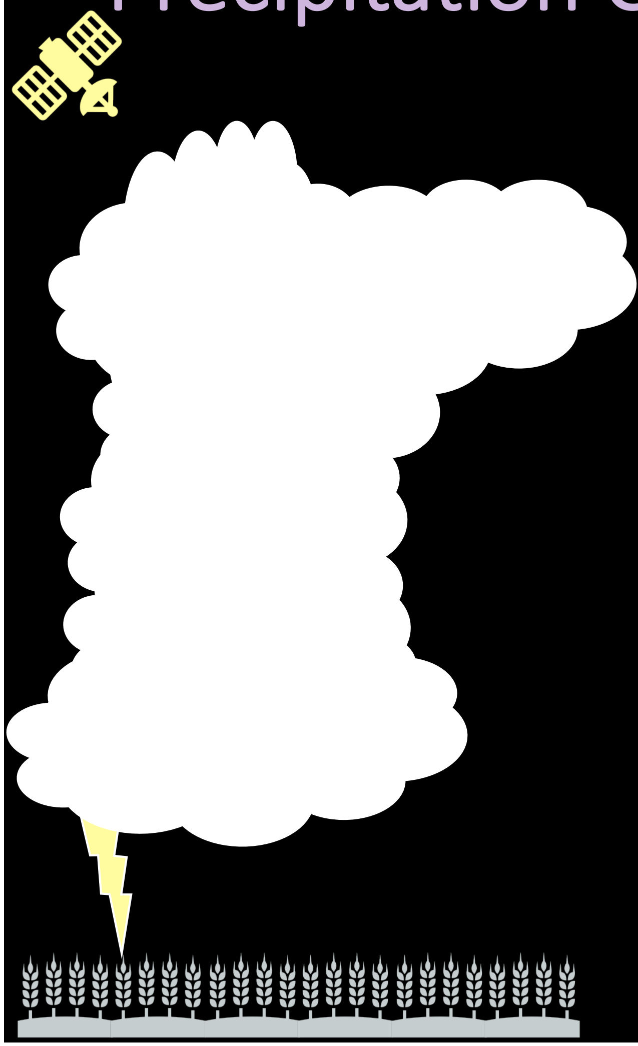


Precipitation Characteristics: Passive Microwave



Upwelling microwave radiation is scattered away by ice particles in the cloud.

Precipitation Characteristics: Passive Microwave

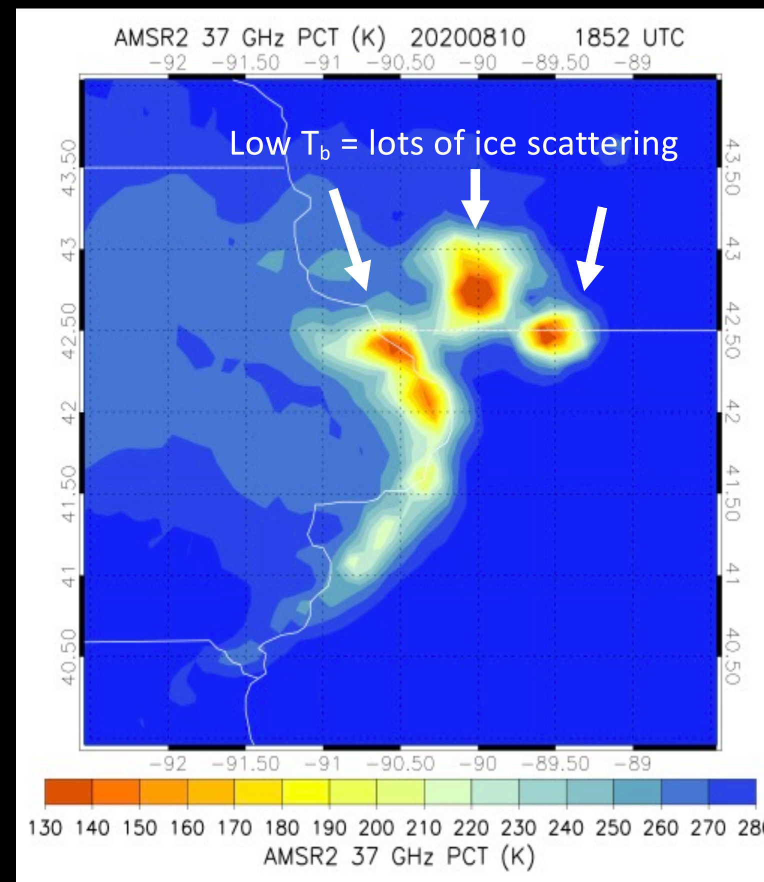


The scattering results in a lower (or "depressed") microwave brightness temperature relative to the scene around the cloud.

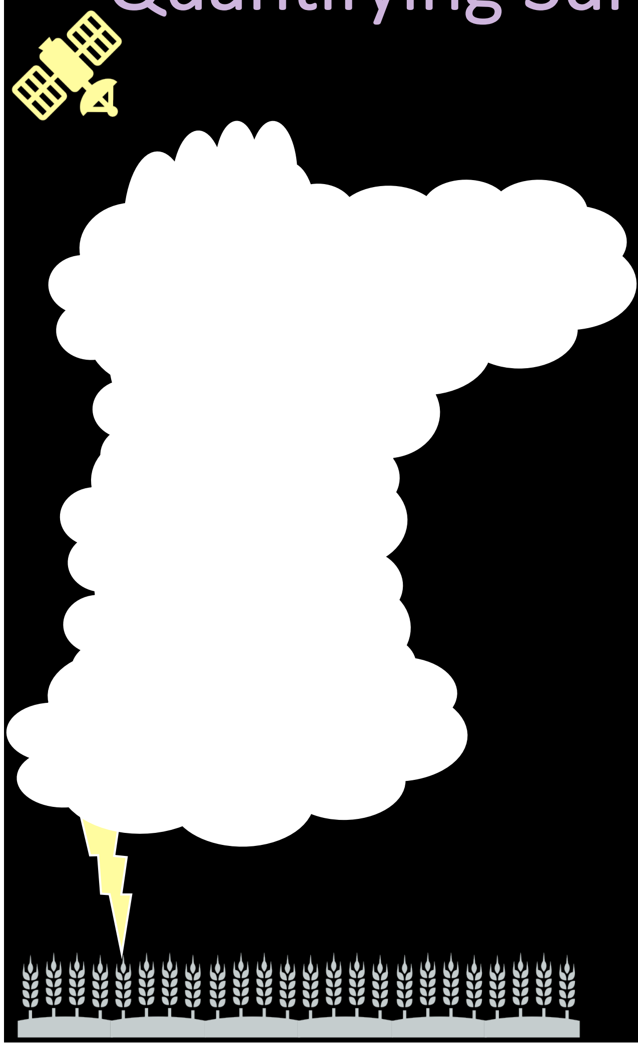
The AMSR2 instrument (onboard the satellite GCOM-W1 in sun-synchronous low-earth orbit) observed the derecho as it crossed into Illinois.

The pockets of very low brightness temperature (warm colors) indicate very strong updrafts, large ice (likely hail) particle scattering.

Near the time of this overpass, 2" hail and a tornado occurred.



Quantifying Surface Damage: Synthetic Aperture Radar

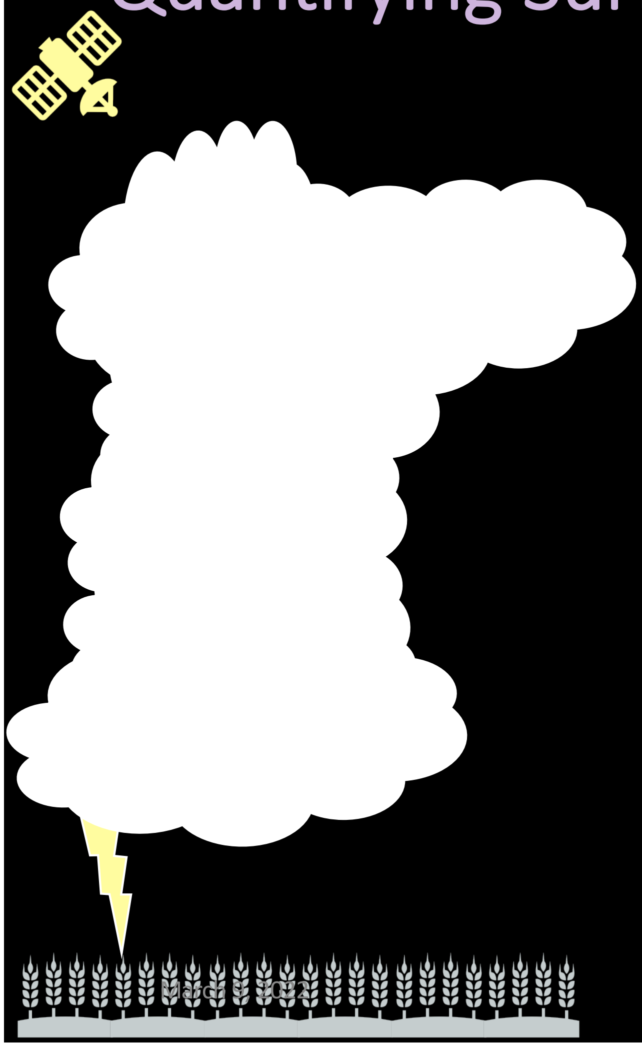


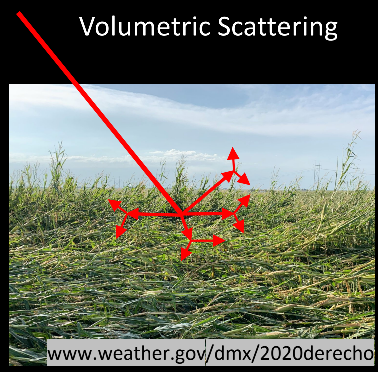
https://www.weather.gov/dmx/2020derecho

Traditional methods of assessing crop damage, from optical sensors or vegetation indices like NDVI (Normalized Difference Vegetation Index) underperformed in this case.

Many crop damage assessments are used to distinguish green crops from brown, dead, defoliated, or shredded crops.
The high winds flattened the near-mature crops, to the point they were lying on top of each other – but still green.

Quantifying Surface Damage: Synthetic Aperture Radar



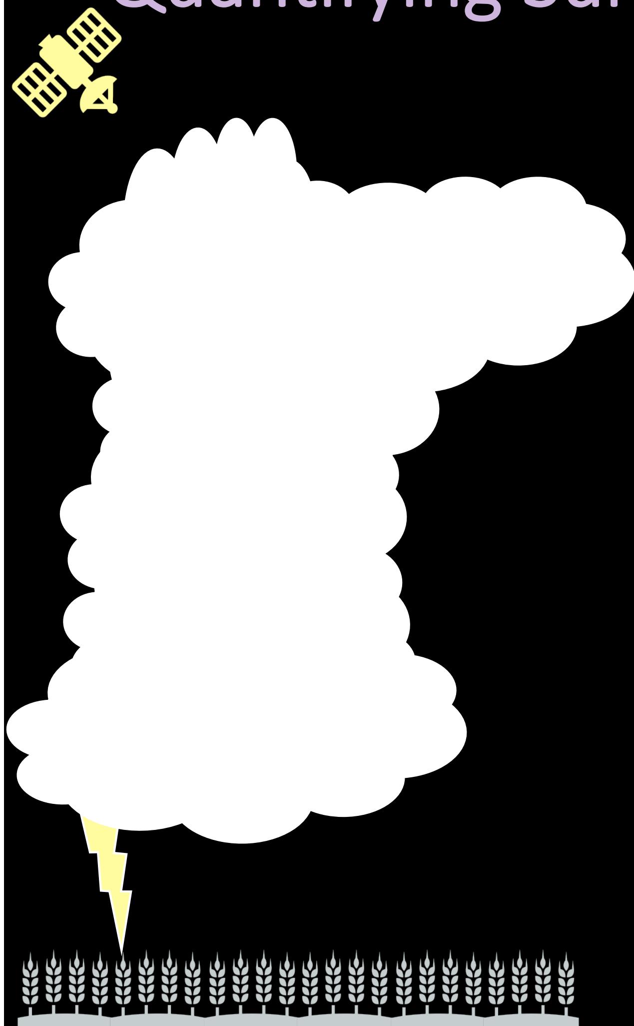


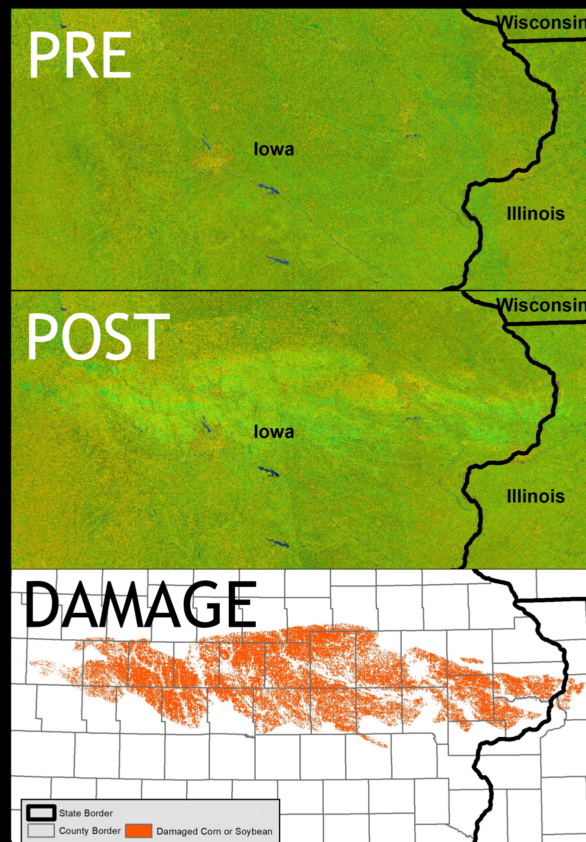
Synthetic Aperture Radar (SAR) is an active sensor – it emits and receives radiation.

The characteristics of the received "backscattered" radiation gives insight into the material on the ground.

The increased volumetric scattering of the damaged, laying down crops made the damaged areas return a "brighter" signal to the sensor than the undamaged crops. The team was able to leverage this difference between the undamaged and damaged crops to estimate the extent of the crop damage from SAR data.

Quantifying Surface Damage: Synthetic Aperture Radar

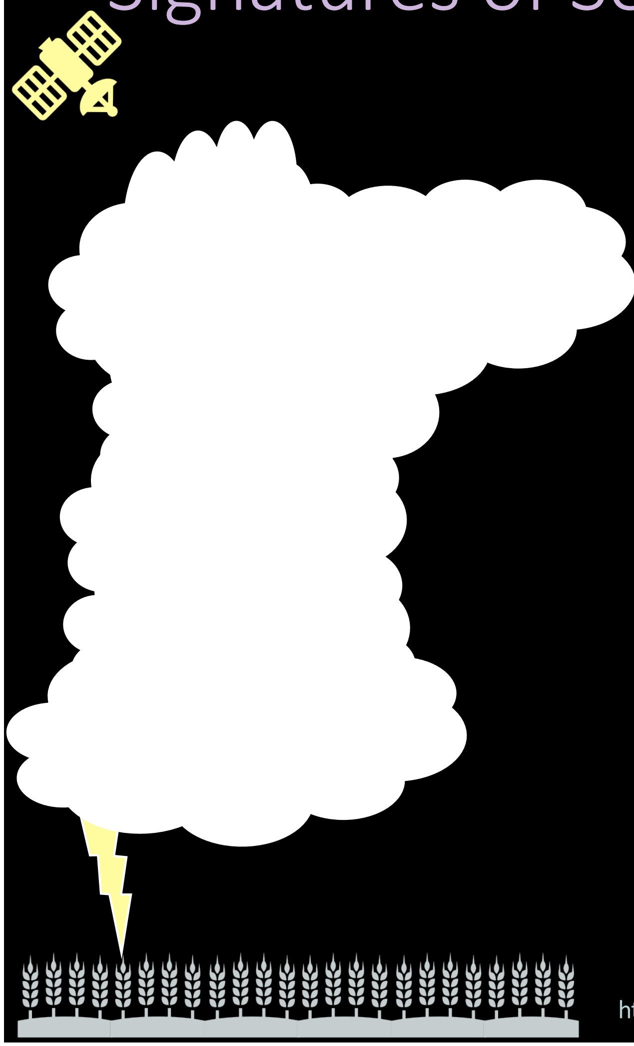


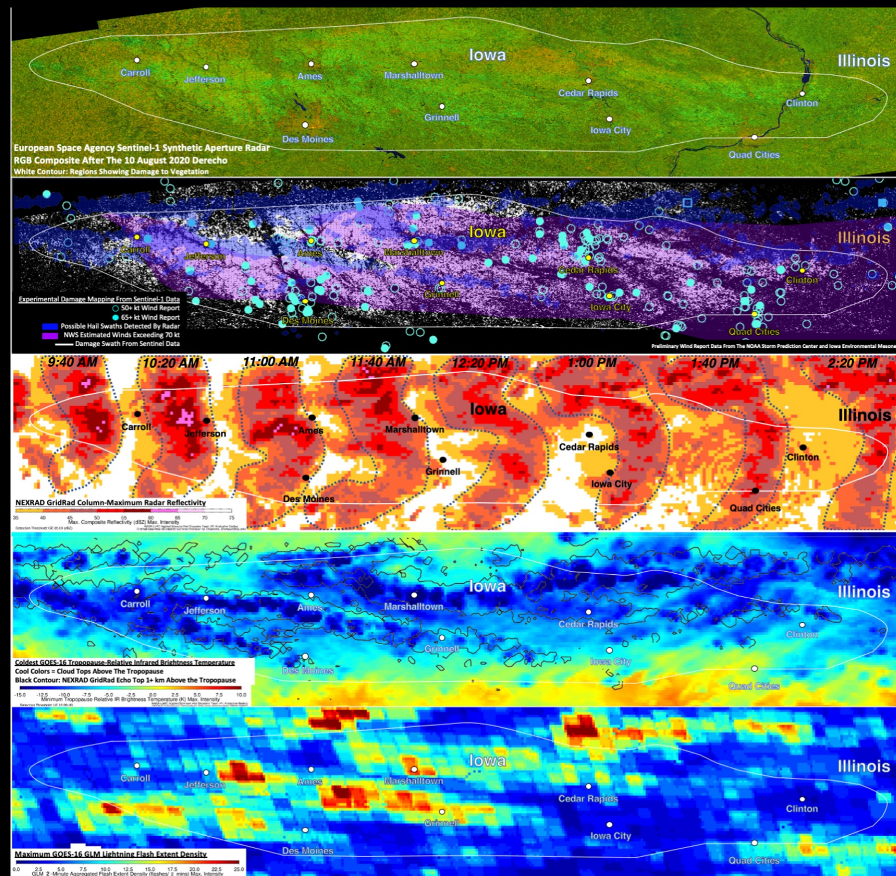


Using ESA Sentinel-1 SAR data acquisitions from before and after the event, the team was able to leverage the different backscattering signatures of damaged and undamaged crops.

Using this technique, the team estimated that **1.97 million acres of corn and 1.40 million acres of soybeans** were damaged in this event.

Signatures of Severe Weather in Satellite Observations





All of these signatures of strong convection as seen by different spaceborne instruments are powerful tools we use to detect and diagnose severe weather.

They are even more useful when they are used *together* as we have done for the August 2020 derecho to get a fuller, more holistic view of the storm's characteristics.

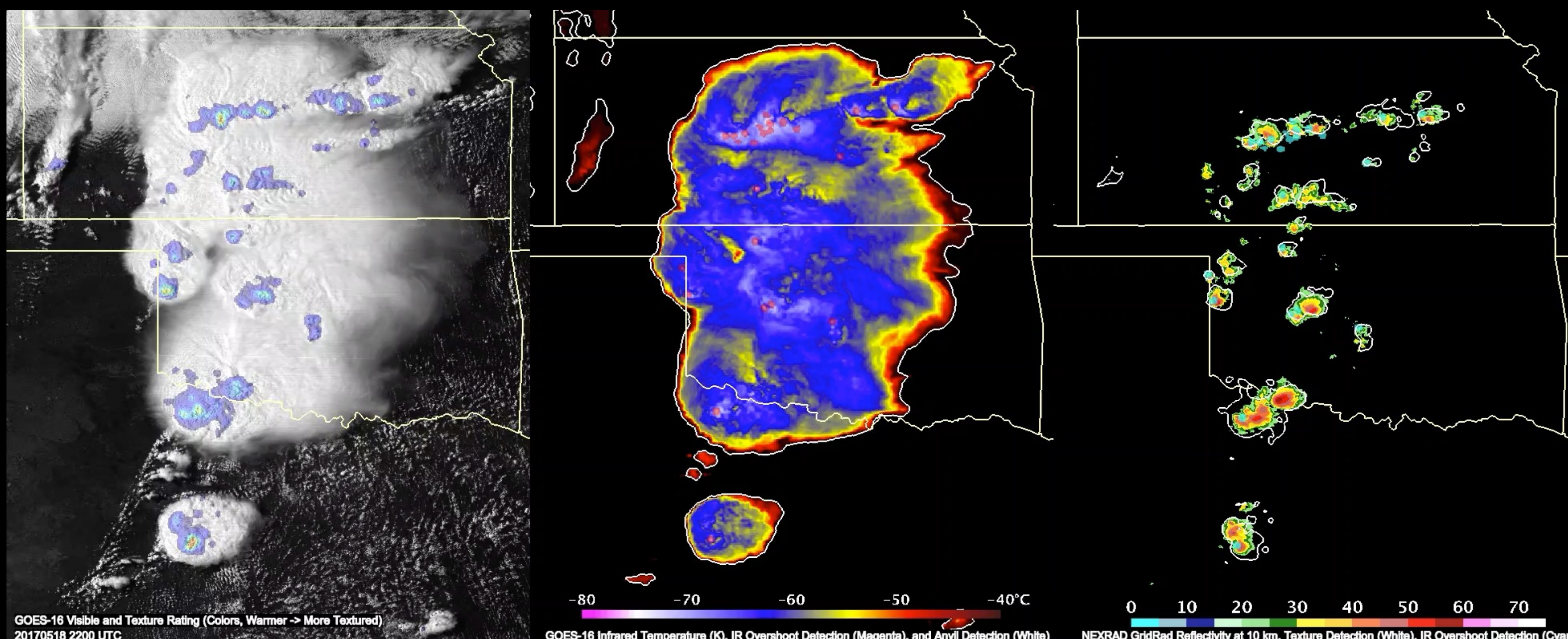
Where are we taking severe weather science?

https://appliedsciences.nasa.gov/our-impact/news/bedka-shares-how-nasa-research-helps-quantify-derecho-damage

Automated Detection Algorithms

The distinct signatures in satellite imagery that identify severe phenomena can be used to develop objective, automated detection algorithms.

The team at LaRC has developed automated detection algorithms for IR and visible imagery from low-earth and geostationary orbits and validates them using other storm data like severe reports and radar.



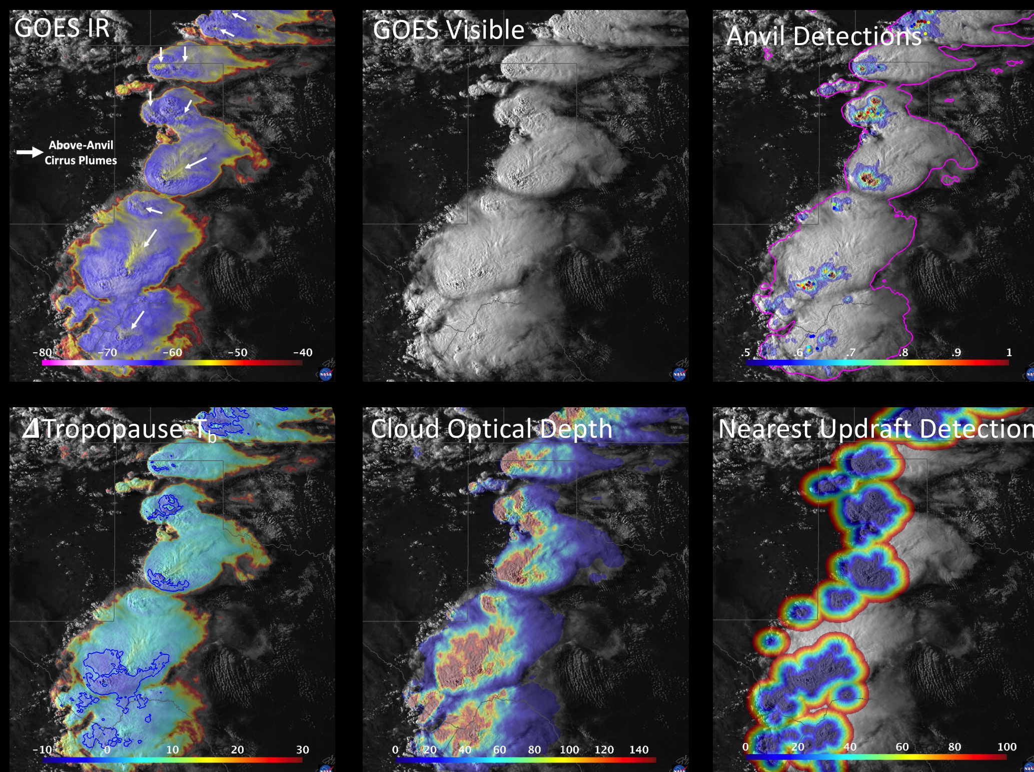
Kristopher Bedka (NASA LaRC), John Cooney (NASA Postdoctoral Program), Benjamin Scarino, Konstantin Khlopenkov, Kyle Itterly (SSAI), Cameron Homeyer (OU)

Aircraft Icing: High Ice Water Content (HIWC) Clouds

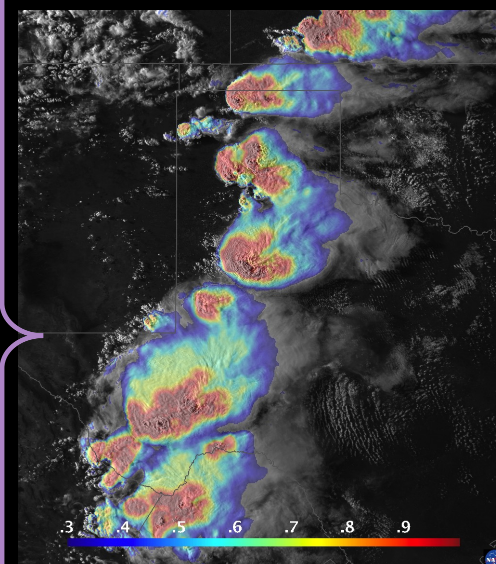
Kristopher Bedka (NASA LaRC)
Louid Nguyen, William Smith Jr. (NASA LaRC)
Christopher Yost, Konstantin Khlopenkov, Benjamin Scarino, Rajendra Bhatt, Douglas Spangenberg and Rabindra Palikonda (SSAI)
J. Walter Strapp (Met Analytics, Inc) and Thomas Ravatsky (NASA GRC)

Recorded instances of flights through thunderstorms resulting in air probe (e.g. TAT, pitot tube) malfunction, jet engine power loss, or engine damage thought to be due to HIWC clouds.

The LaRC team developed a product to capture spatial gradients in anvil IWC across a variety of storm types. These products prove useful for tactical decision making by NASA researchers and NOAA aviation weather forecasters.



High Ice Water Content and Ice Crystal Icing Probability Product



Automated Detection and Analysis of Severe, Hazardous Storm Patterns Using Remote Sensing Data Fusion and Deep Learning

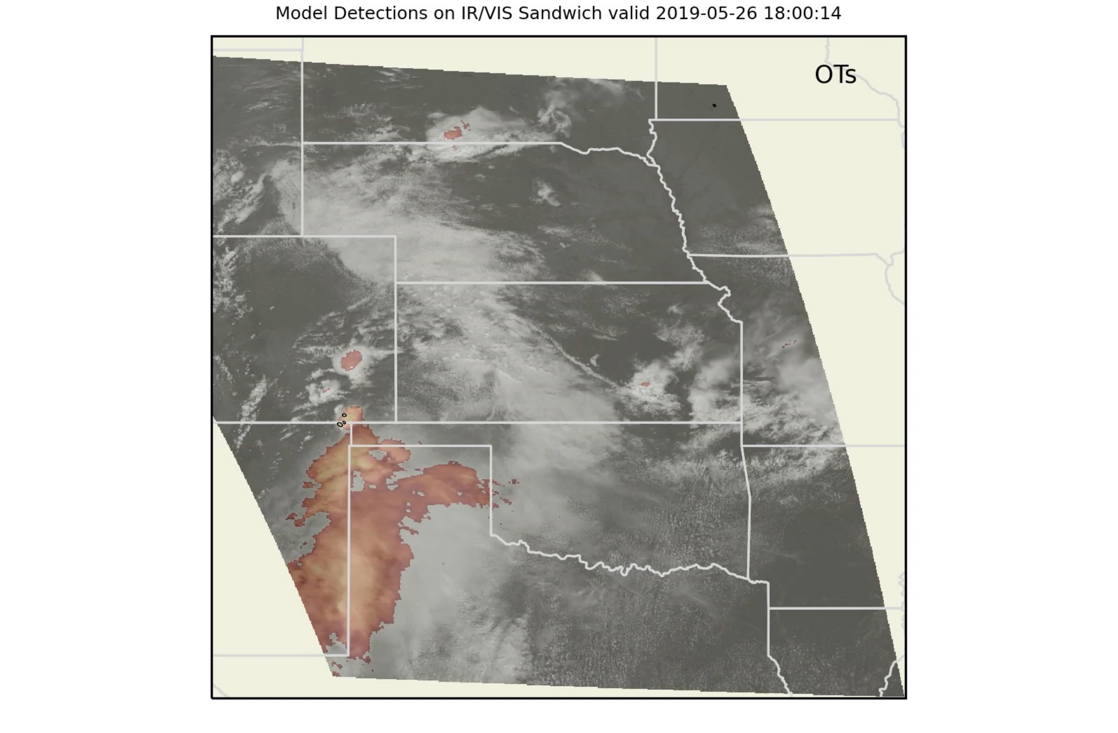
**Kristopher Bedka (NASA LaRC), John Cooney (NASA Postdoctoral Program),
Cameron Homeyer, Amy McGovern and Amanda Burke (U. Oklahoma), Chris Schultz (NASA MSFC),
Kelley Murphy and John Mecikalski (U. Alabama in Huntsville), Konstantin Khlopenkov (SSAI)
Project Collaborators: Collins Aerospace, The Met Office, Argentinian Met Service, The Weather Company**

Distinct signatures of overshooting top updrafts and above anvil cirrus plumes are easily identifiable by the human eye and therefore should be detectable via deep learning.

This NASA project seeks to:
Quantify how well state-of-the-art deep learning methods can detect hazardous storm patterns using GOES-16 30-sec to 1-min resolution infrared, visible, lightning flash detection imagery.

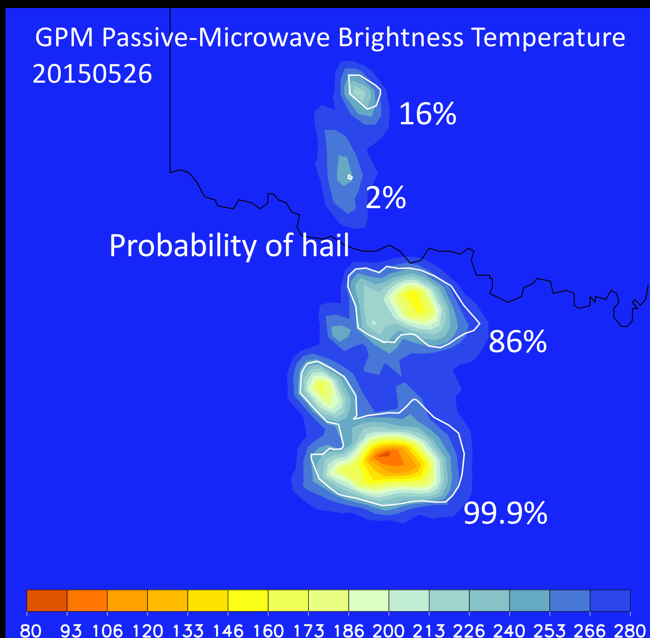
Provide open-source software tools to the community for detecting these patterns.

Animation of GOES-16 Updraft Detections At 1-Minute Intervals With Deep Learning

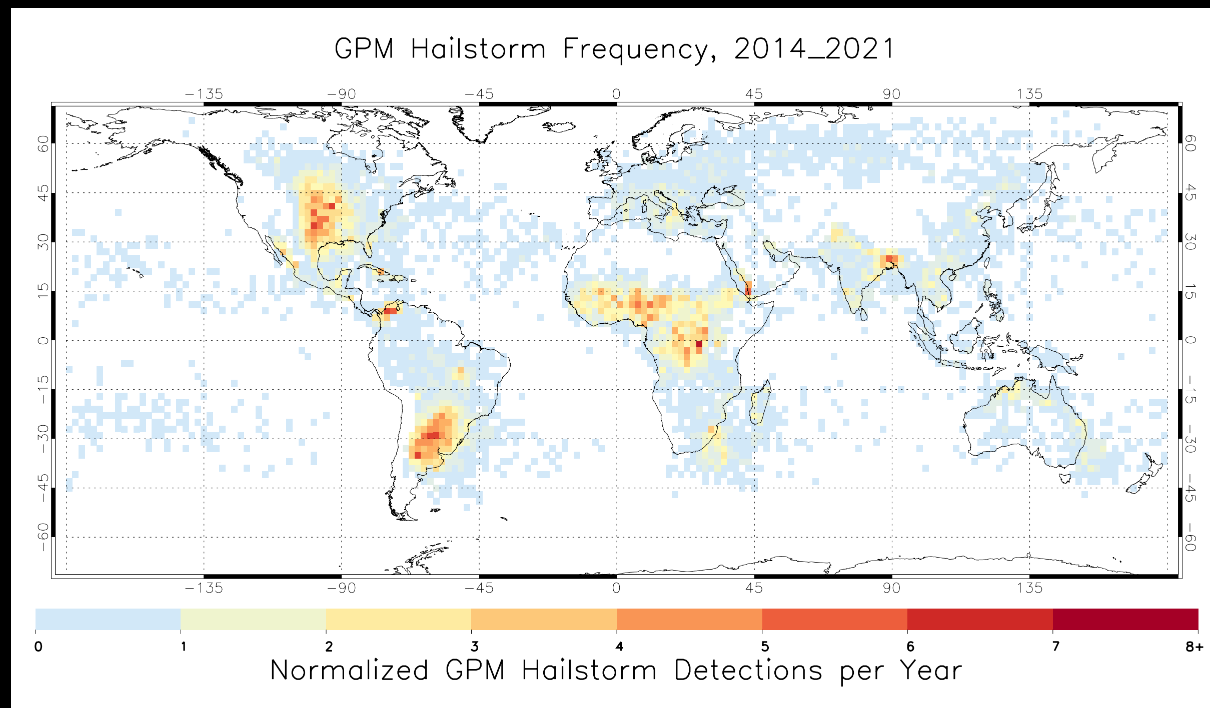


Passive-Microwave Severe Hail Detection

Sarah Bang, Daniel Cecil (NASA MSFC)



Using the relationship between hail and lower brightness temperature, we developed an algorithm that estimates the probability that an observed storm has hail.

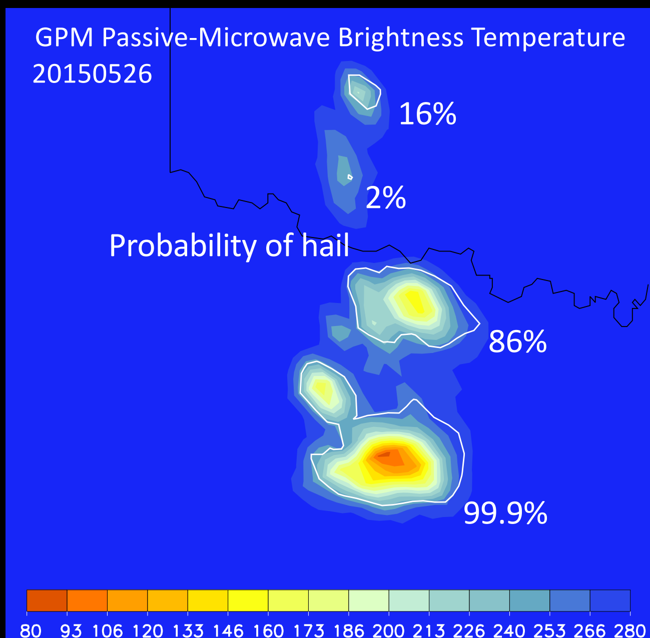


We can then tally up all the probabilities of hail over the orbit and lifetime of the satellite to create a climatology.
The climatologies are tools our stakeholders use to assess the global risk of severe hail.

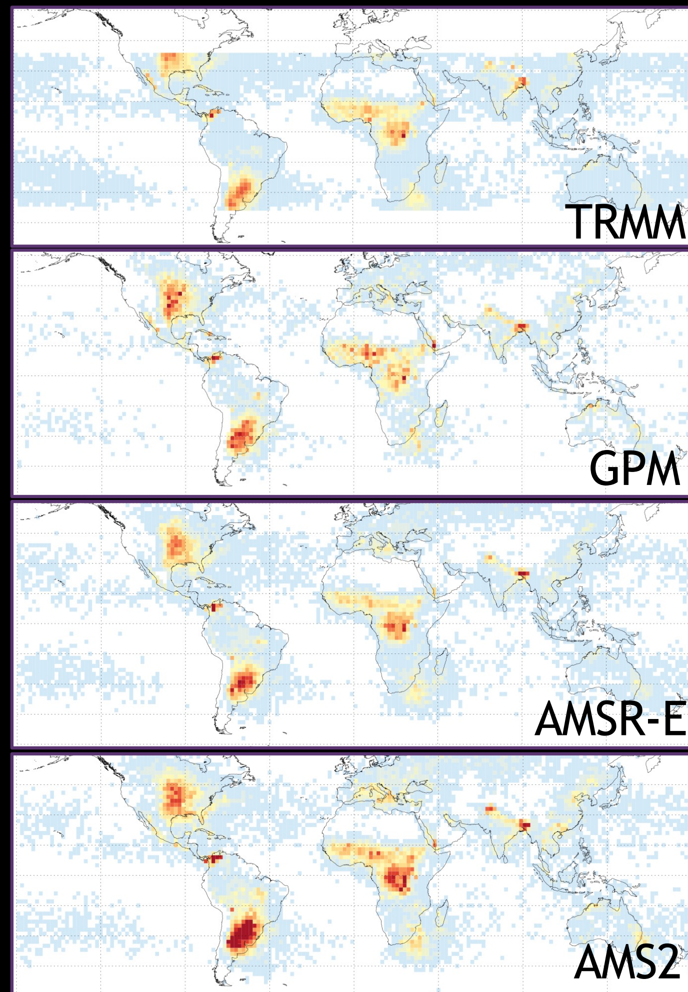
March 9, 2022

Passive-Microwave Severe Hail Detection

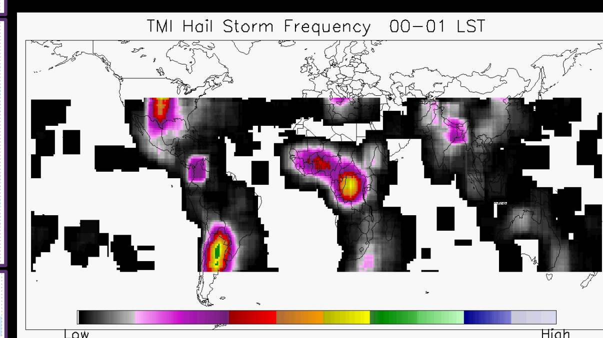
Sarah Bang, Daniel Cecil (NASA MSFC)



Using the relationship between hail and lower brightness temperature, we developed an algorithm that estimates the probability that an observed storm has hail.



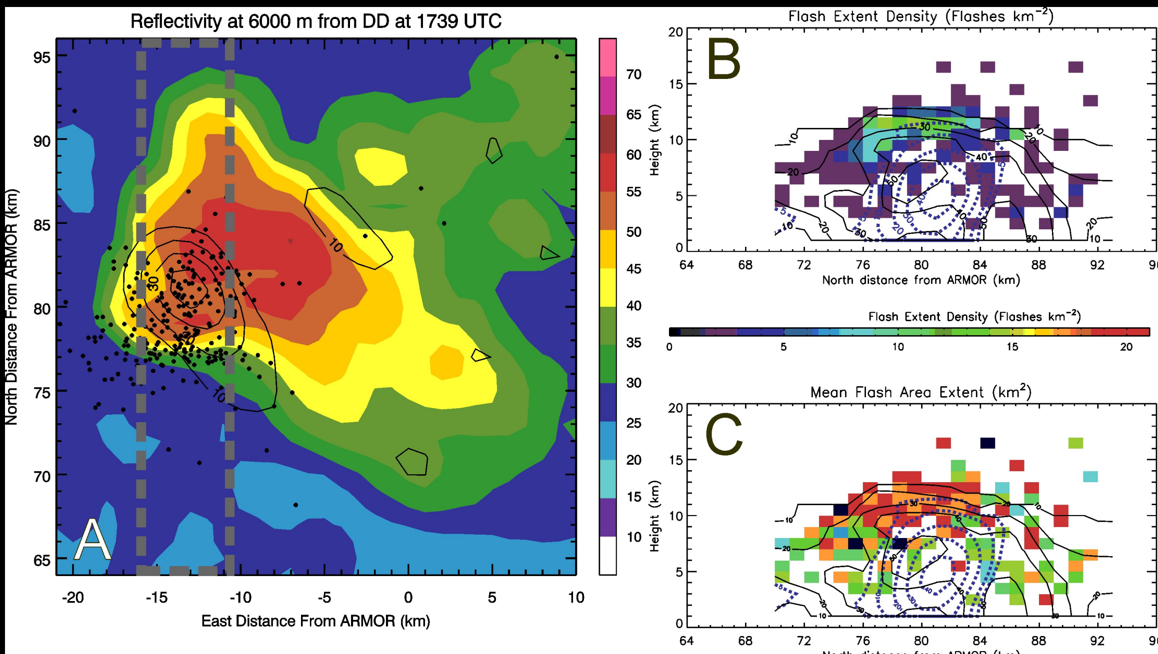
This algorithm can e applied to any satellite passive-microwave instrument with the same frequency channels – meaning we can create (and even combine) climatologies, with the goal of extending the global climatology of severe hail back to the late 1980's. Satellites in inclined orbits also allow us to study the diurnal (day/night) cycle of hail



March 9, 2022

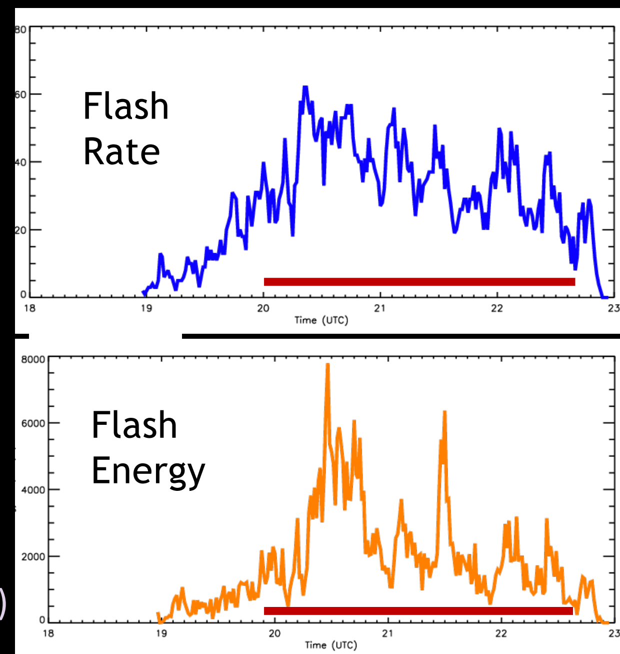
Lightning Jump Algorithm

Christopher Schultz, (NASA MSFC)



Schultz et al. 2017, Weather and Forecasting

Flash rate and energy peak during maximum storm intensity as derived from radar and storm reports.
This is known as a "flash jump"
In the case below, hail, wind, and a tornado were observed during the period in red.

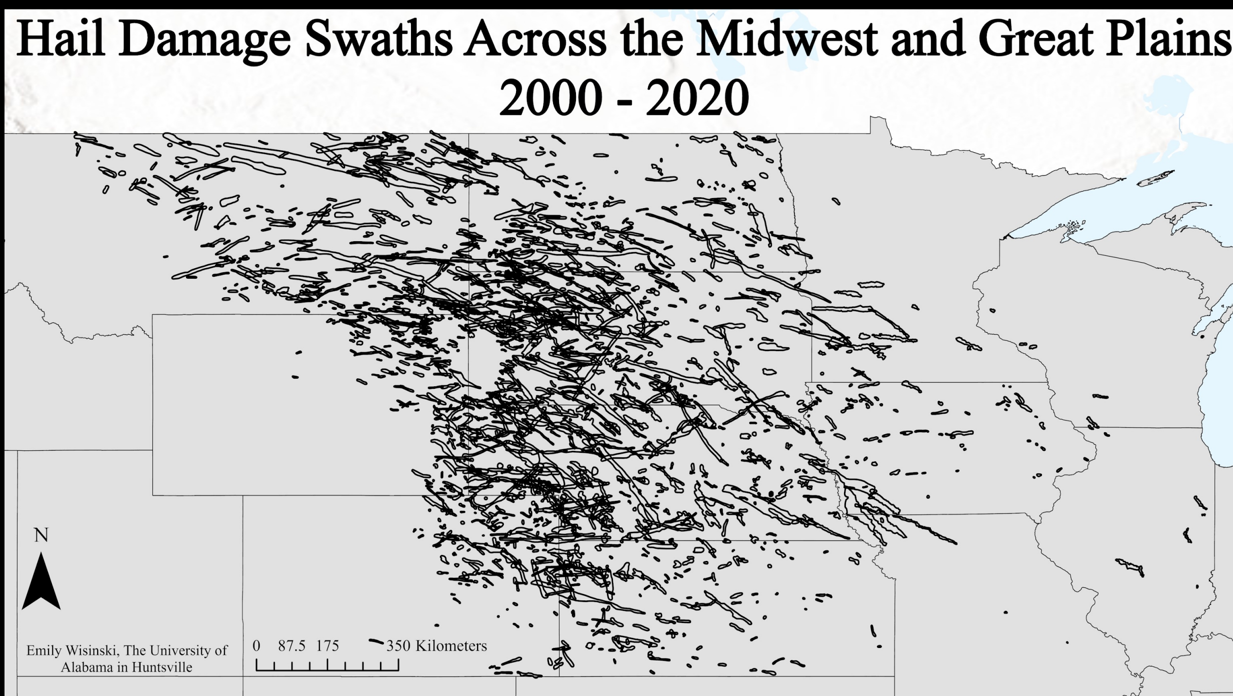


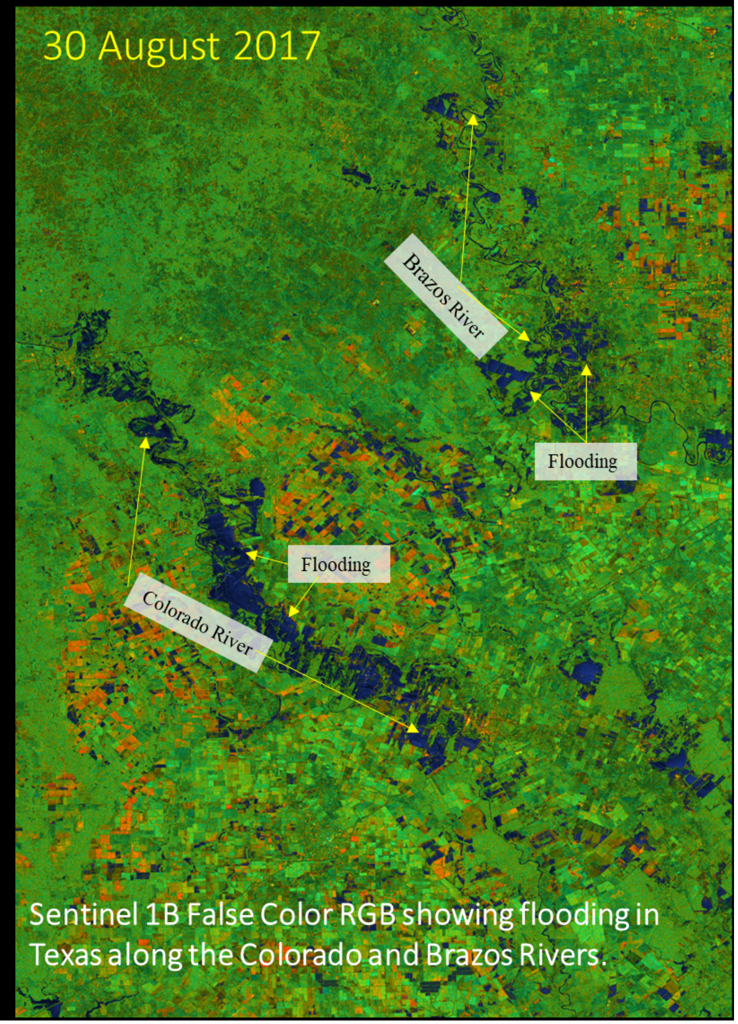
The electrical characteristics of a storm (flash rates, flash areas, flash extent density) are indicative of storm severity and lend insight into the microphysics within.

Mapping Surface Damage from Optical and SAR Platforms

Jordan Bell (NASA MSFC)
Emily Wisinski (UAH)

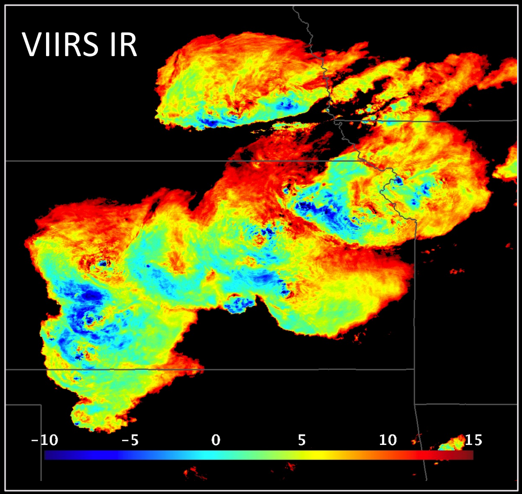
Develop applications and products to provide to end-users and stakeholders to evaluate the impact of severe hail, and wind, and flooding that occurs as a result of heavy rain and tropical cyclones.

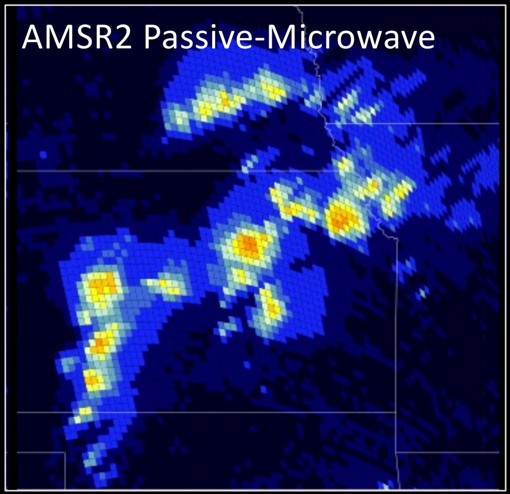




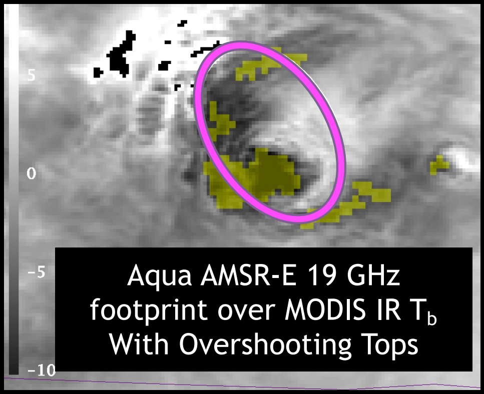
Sentinel 1B False Color RGB showing flooding in Texas along the Colorado and Brazos Rivers.

Combining satellite datasets



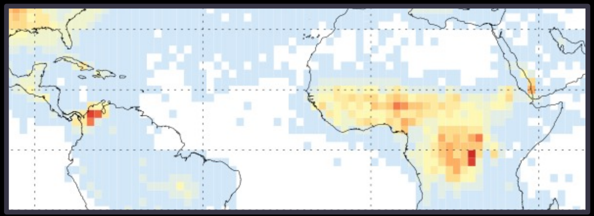


Fine-resolution IR and visible data can fill in gaps in our understanding of microwave instruments with large footprints, which are vulnerable to non-uniform beam filling.



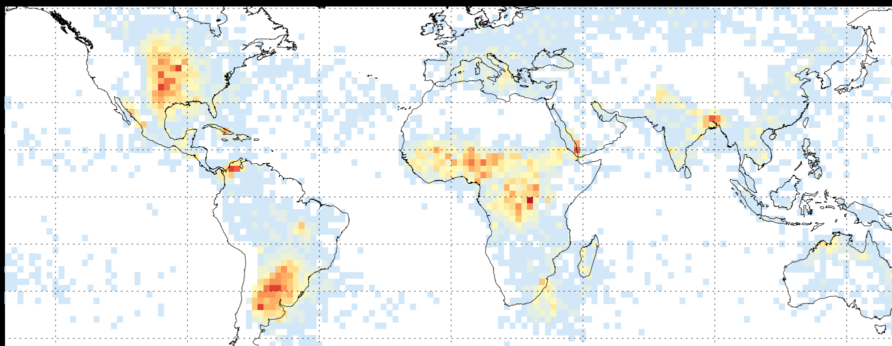
Combining and comparing satellite datasets has benefits beyond better characterization of storms. Different instruments that observe different signatures can be used to fill in the gaps.

For example, IR imagery has excellent spatial resolution, but can only show the texture of the cloud top. Passive-microwave imagery observes microphysical processes going on inside the cloud but tends to have poor resolution. *We work to leverage one instrument's strengths to help with the weaknesses of another.*



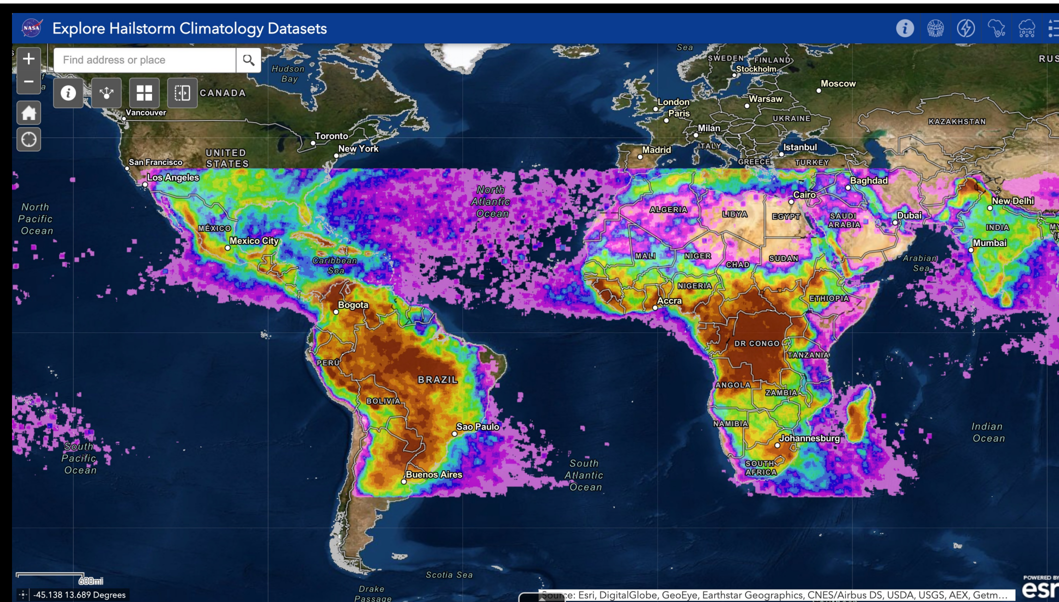
Future work includes a focus on assessing hail size distributions, melting, using aircraft field campaign data and simulations to understand how and how melting may be manifested in the passive-microwave T_bs.

Dive into Data Access



Hail Climatologies
NASA Global Hydrometeorology Resource Center

ghrc.nsstc.nasa.gov/pub/hail_climatology/data/



ArcGIS Hailstorm Climatology Visualization Portal
https://arcg.is/0C8eXC

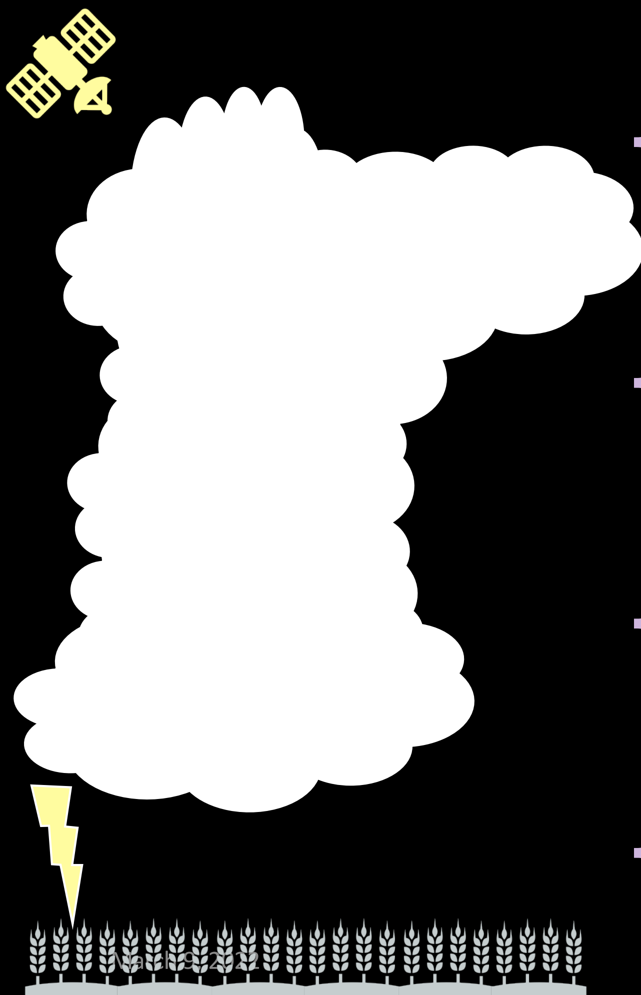
Satellite-Based Characterization of Convection and Impacts from the Catastrophic 10 August 2020 Midwest U.S. Derecho

Bell et al. (2022)
https://doi.org/10.1175/BAMS-D-21-0023.1

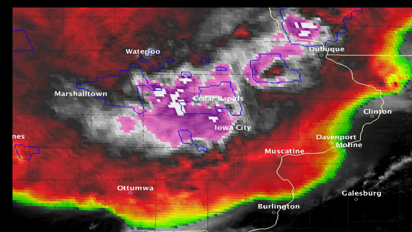
Derecho:

ArcGIS Story Map: https://storymaps.arcgis.com/stories/f98352e2153b4865b99ba53b86021b65
NASA Earth Observatory: https://earthobservatory.nasa.gov/images/147154/derecho-flattens-iowa-corn
Des Moines NWS Derecho Analysis: https://www.weather.gov/dmx/2020derecho

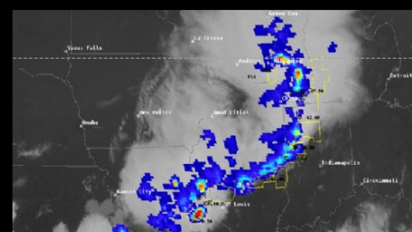
Thank you, IEEE Aerospace!



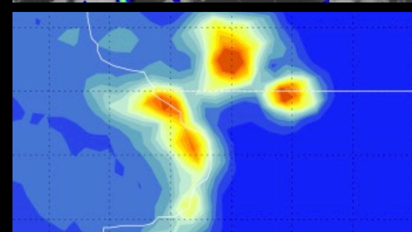
IR



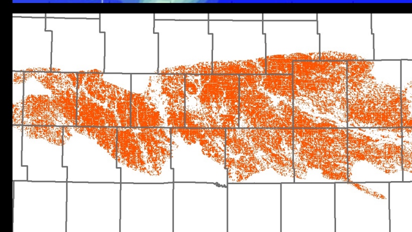
Lightning



Passive Microwave



SAR



Practice weather safety!

https://www.weather.gov/dmx/2020derecho

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