Uncertainties in Convective Storm Modeling

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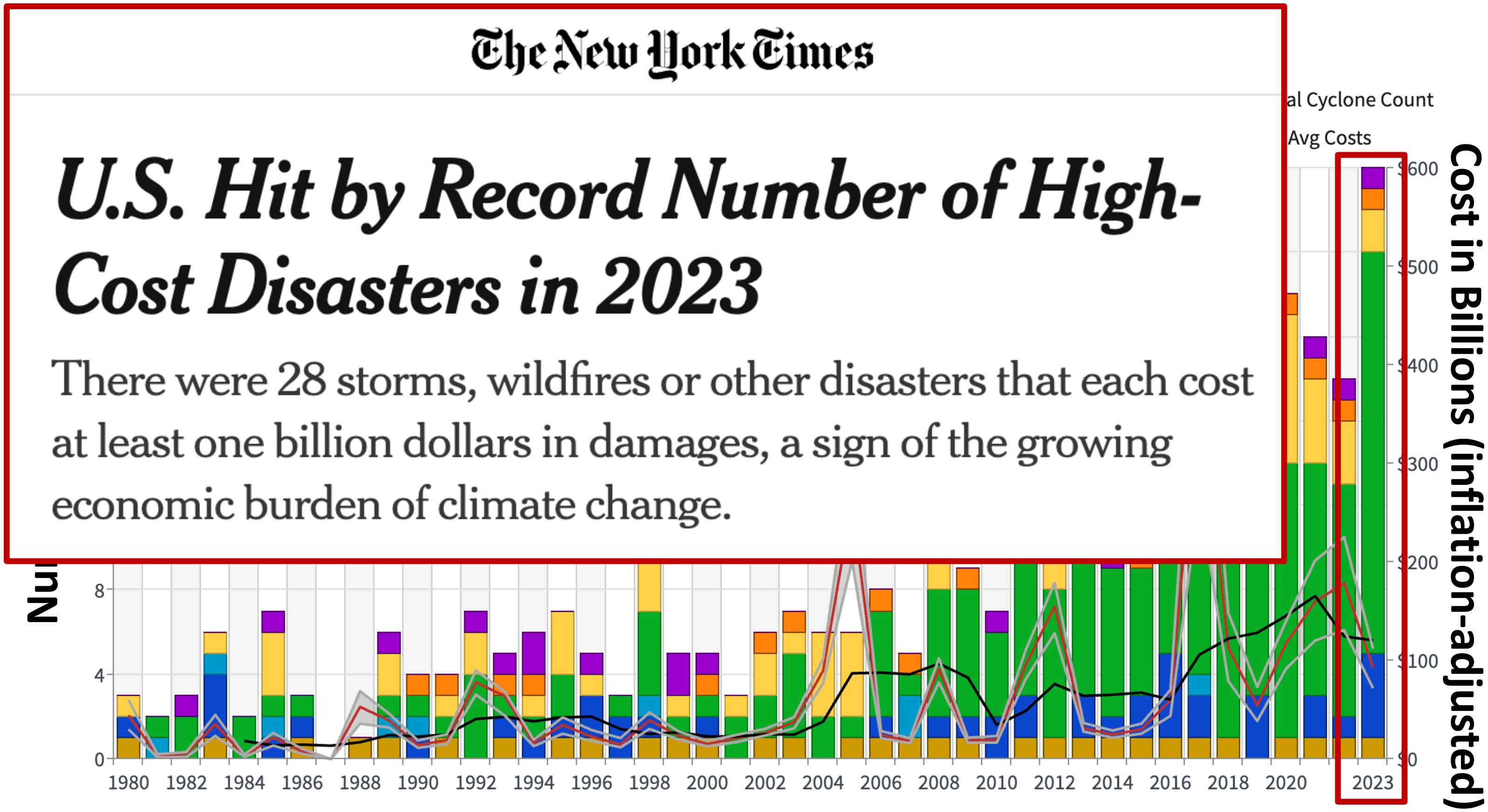
Weather disasters are becoming more frequent

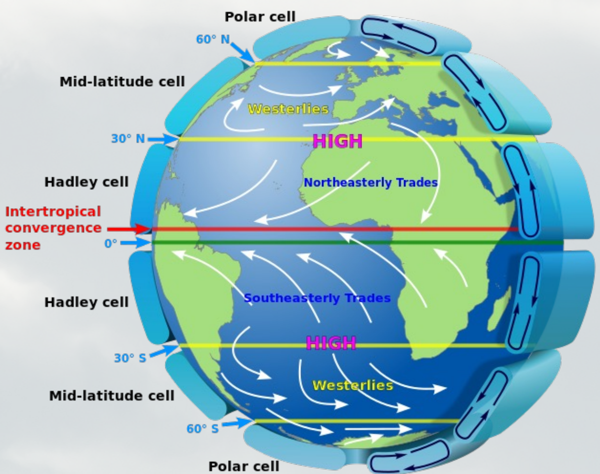

The New York Times

U.S. Hit by Record Number of High-Cost Disasters in 2023

There were 28 storms, wildfires or other disasters that each cost at least one billion dollars in damages, a sign of the growing economic burden of climate change.

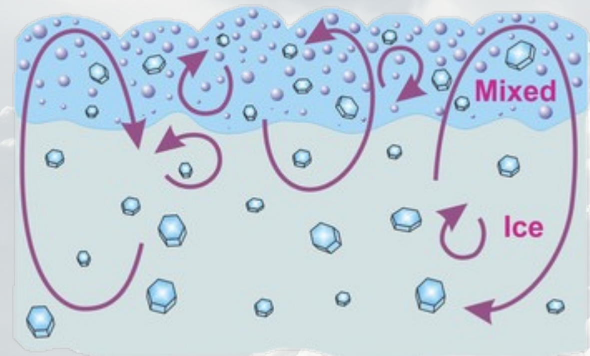
NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2024). https://www.ncei.noaa.gov/access/billions/, DOI: 10.25921/stkw-7w73

Atmospheric science fundamentally involves processes across scales



Climate controls large-scale environment

Locations of clouds influence their properties



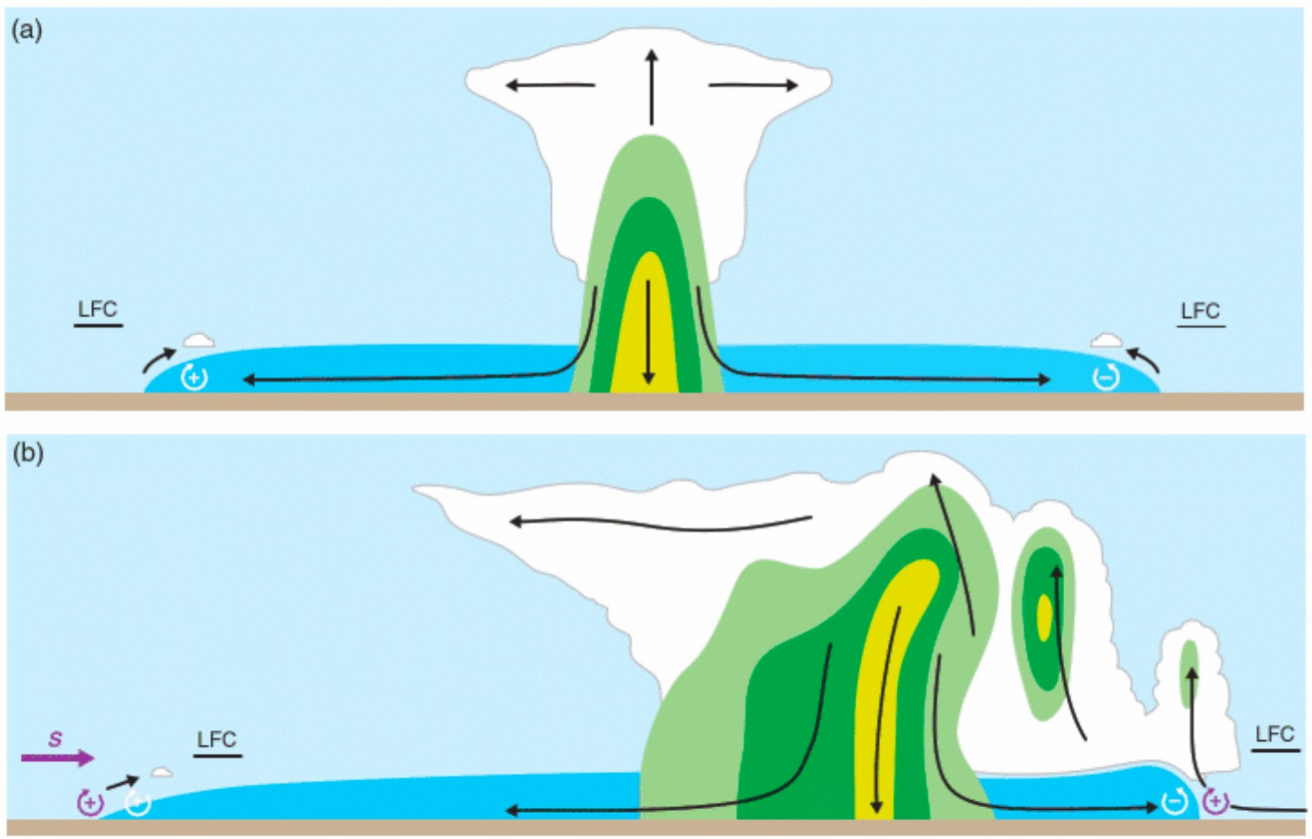
Organization of clouds influences global albedo, rainfall patterns, etc…

Latent heat release influences strength of updrafts

Conceptual diagram of convective storms

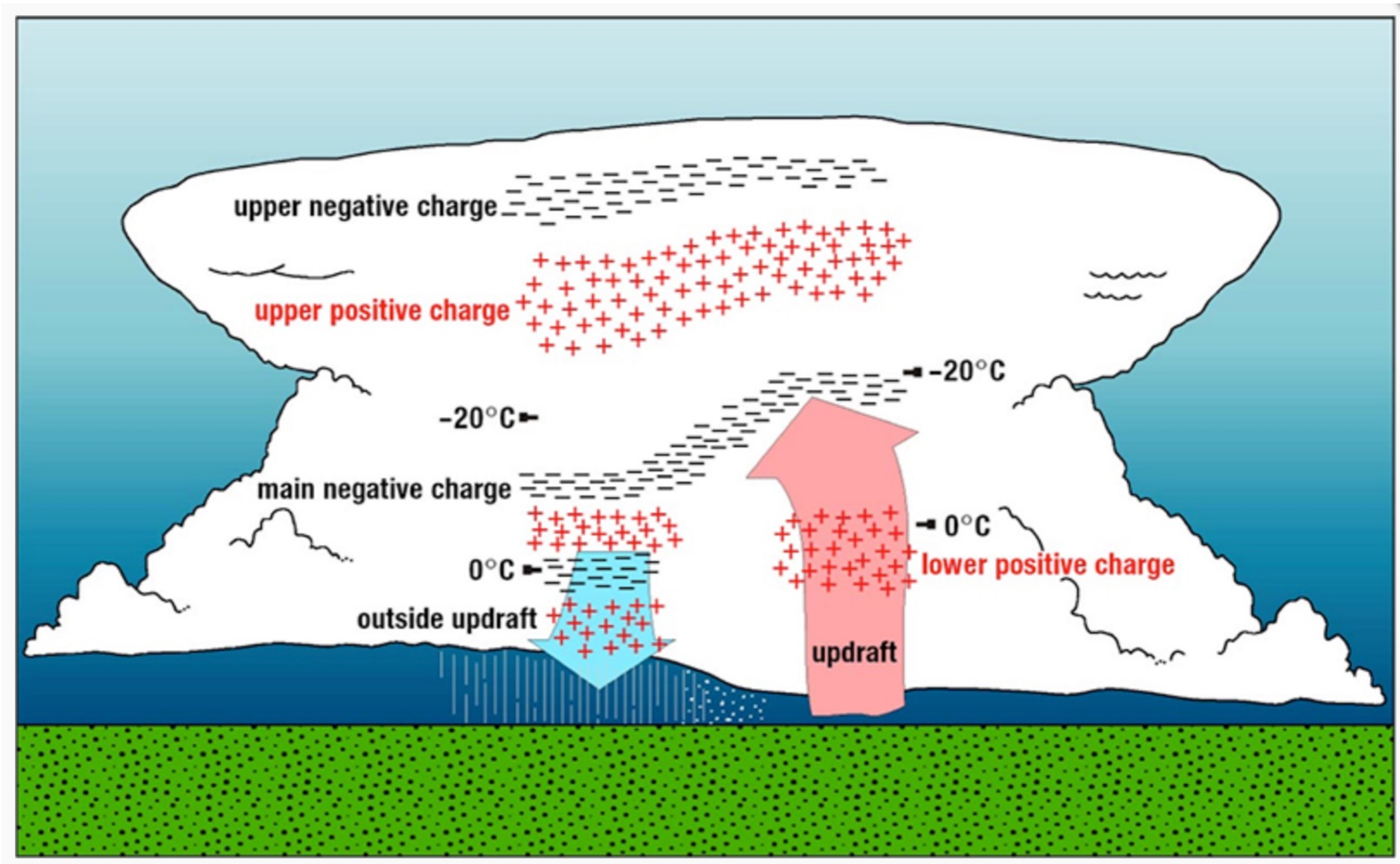
Ordinary cell, no wind shear

Muticellular storm, wind shear



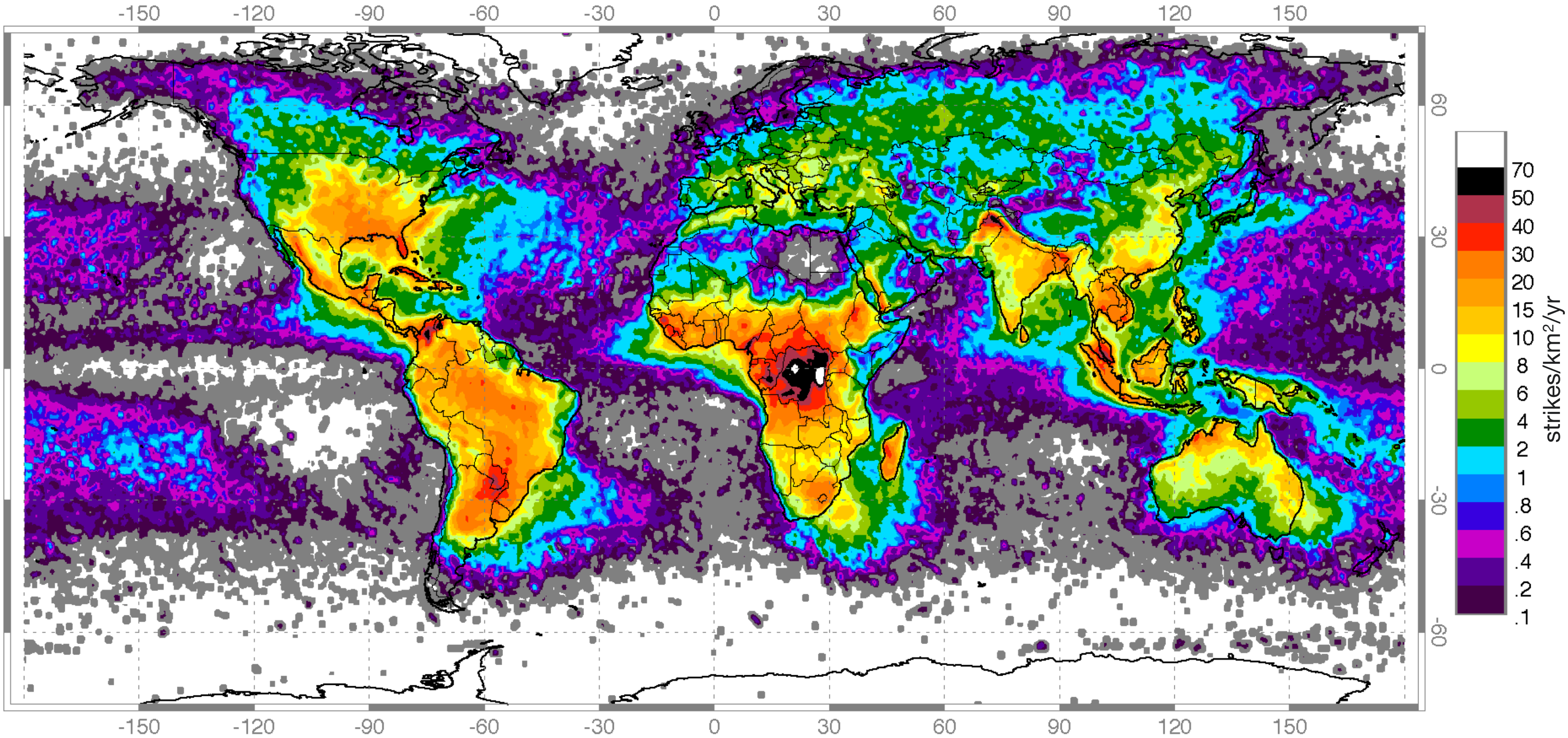
From Markowski and Richardson

Conceptual model of lightning charge distribution



Source: NSSL

Global Lightning Frequency

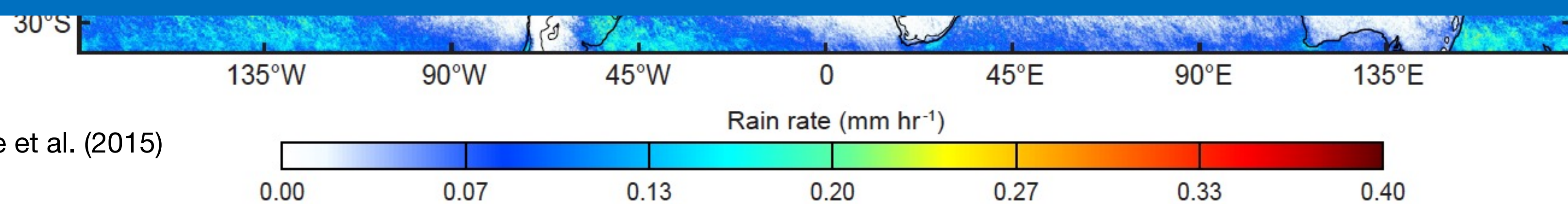


Source: NASA/GHRC/NSSTC Lightning Team

Rainfall from the TRMM Satellite
(1st Precipitation Radar in Space; 1997-2014)

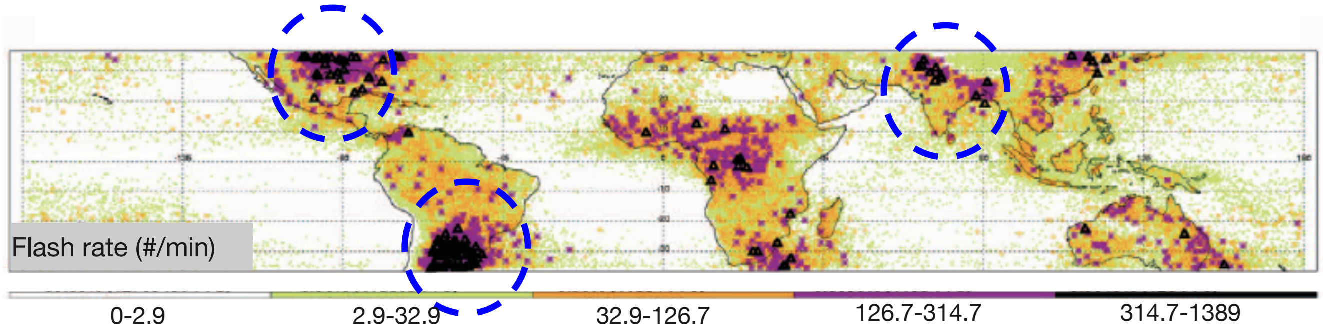
(a) DJF

Revolutionized our understanding of clouds and precipitation in the tropics and subtropics



Houze et al. (2015)

Most Intense Thunderstorms on Earth



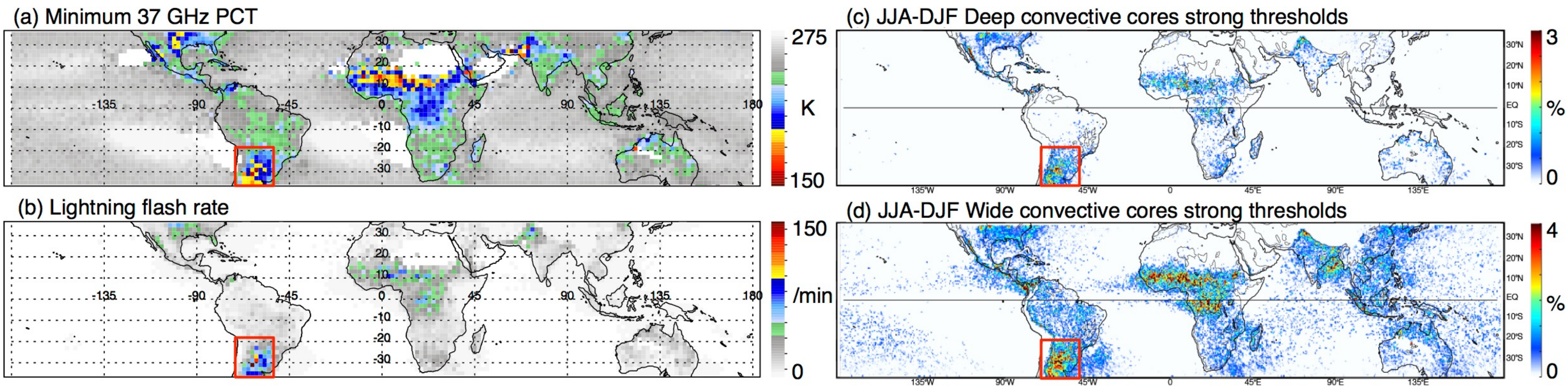
Zipser et al. (2006)

Environments supporting the deepest convection on Earth have ***both*** convective instability ***and*** convective inhibition

→ Allows for the build-up of convective energy that is critical for generating deep intense convection

→ Combination of Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) generated from mountain flows (i.e., low level jets, elevated flows over mountains, etc.)

“The most intense thunderstorms on earth” according to satellite observed storm height, organization, severe hail, lightning proxies

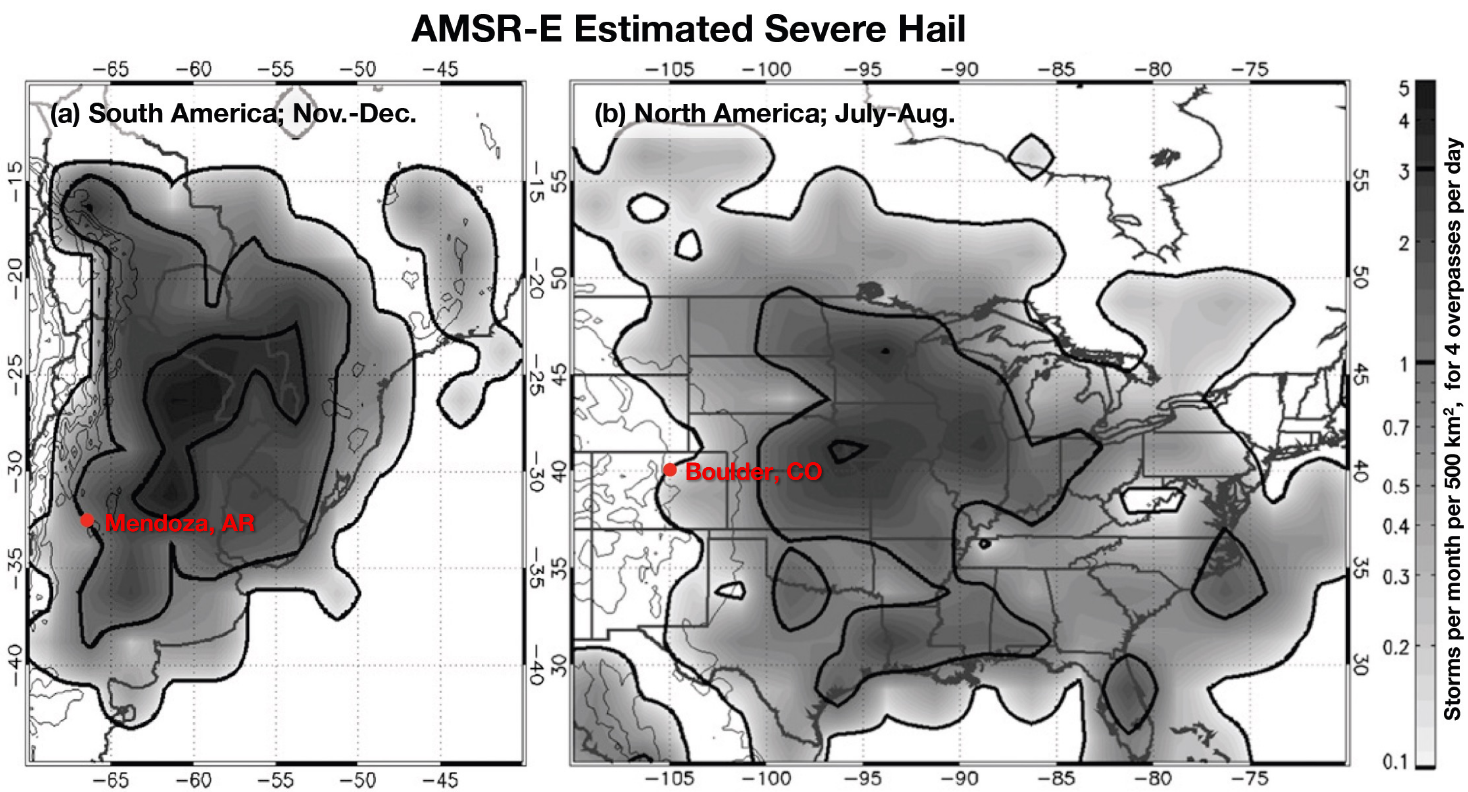


Nesbitt and Zipser (2003)
Zipser et al. (2006)
Nesbitt et al. (2006)

Houze et al (2015)
Romatschke and Houze (2011. 13)
Rasmussen et al. (2014)
Rasmussen and Houze (2011, 2016)

Source: Steve Nesbitt

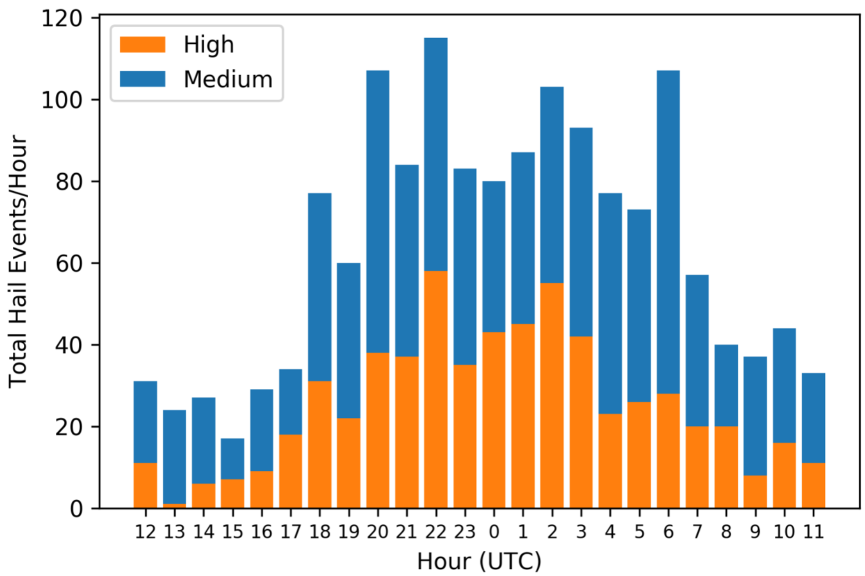
Hail Frequency Comparison



Cecil and Blankenship (2012)

Diurnal Cycle of Lightning in Argentina

Hailstorms tend to be multicellular with a nocturnal maximum
(Bruick et al. 2019)

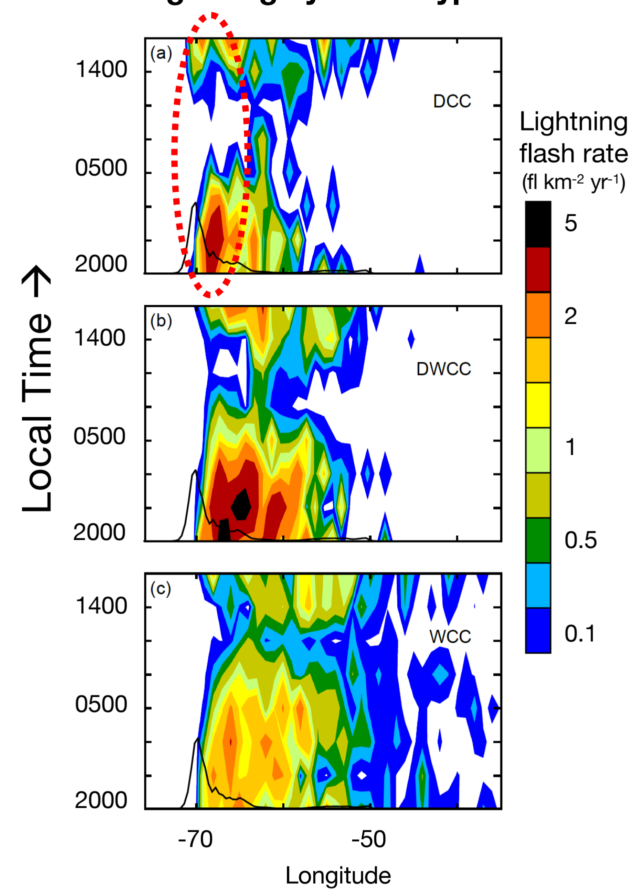


Deep Convective Cores
(40 dBZ > 10 km in height)

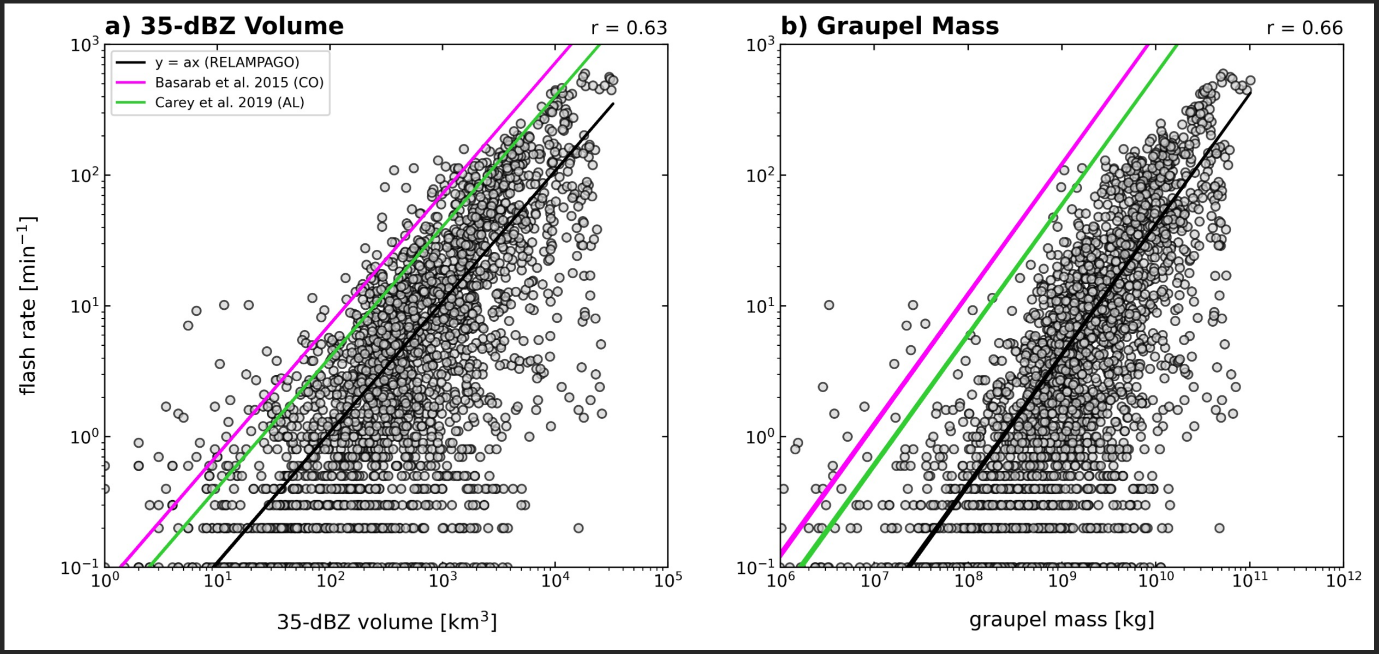
Deep and Wide Convective Cores
(Intersection of Deep and Wide categories)

Wide Convective Cores
(40 dBZ > 1,000 km² in area)

Lightning by storm type



Significantly more intense echoes and graupel are found in South American storms compared to Colorado and Alabama storms



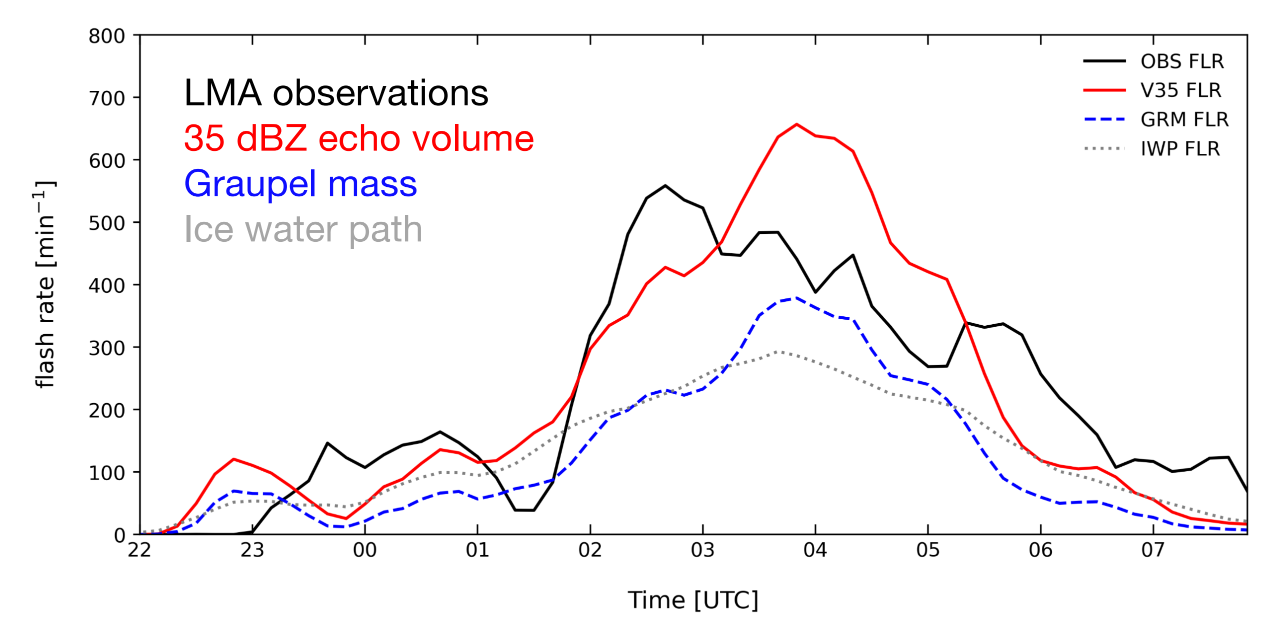
Rocque et al. (2023)

Lightning flash regressions applied to 1-km WRF simulations agree well with observations

$f = (1.08 \times 10^{-2}) \times V35$

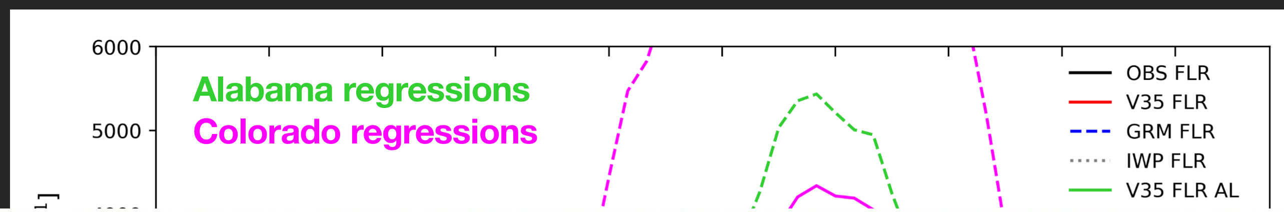
$f = (4.18 \times 10^{-9}) \times GRM$

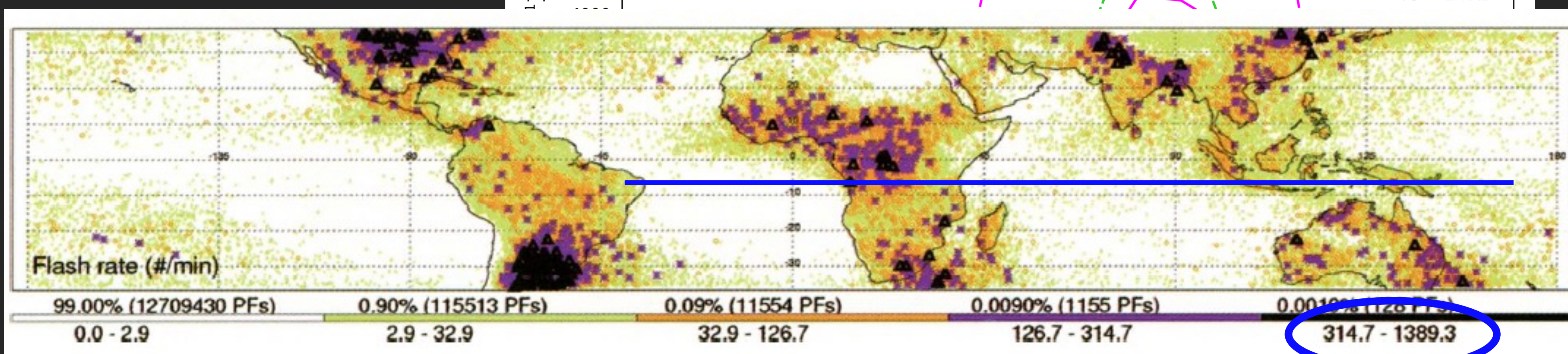
$f = (3.24 \times 10^{-1}) \times IWP$



Rocque et al. (2023)

Lightning regressions based on U.S. storms *significantly* overestimate flash rates in South America





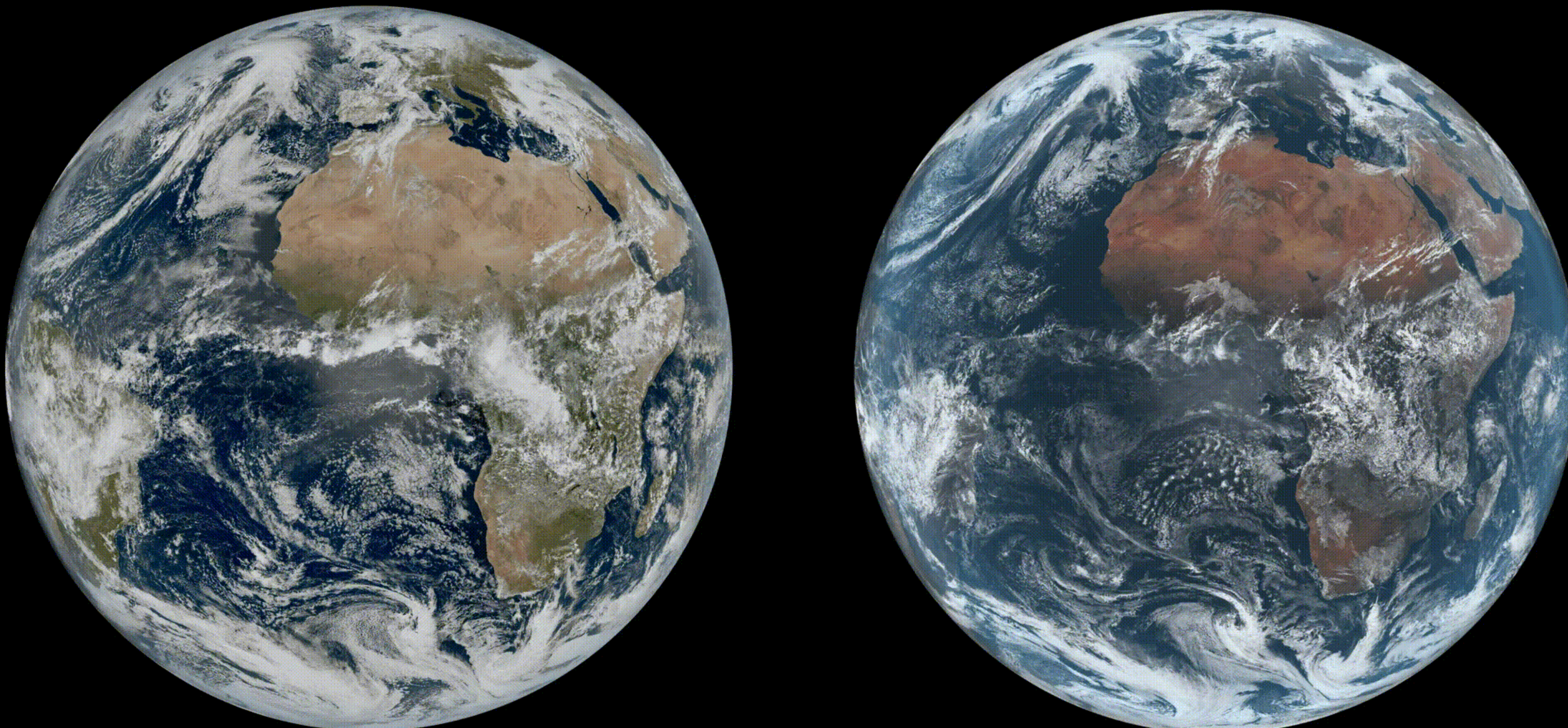
Rocque et al. (2023)

Physical Approach

- What physics are implemented in modeling convective storms?
  - Mesoscale models using community-developed parameterizations to represent unresolved processes
    - Planetary boundary layer
    - Cloud microphysics
    - Land surface processes
    - Lightning
    - And many more
  - How has this modeling activity been motivated by a larger scientific problem?
    - Severe weather hazards
    - Numerical Weather Prediction efforts

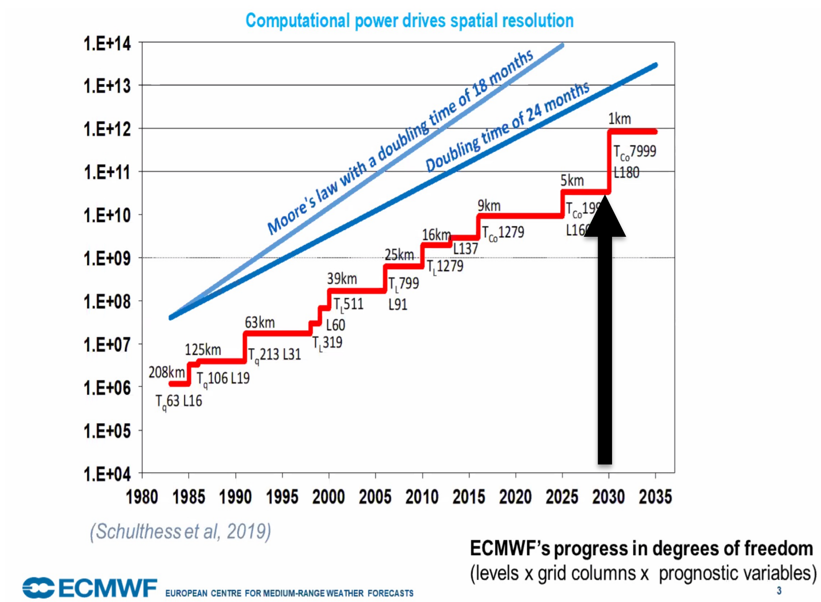
Physical Approach

- **What physics are implemented in modeling convective storms?**
  - Describe the current capability
    - Very well–developed mesoscale models with known challenges
    - Hard to get the right storm in the right place at the right time
  - How does the wider scientific community use this model component and similar tools?
    - Regularly used for operational Numerical Weather Prediction efforts (e.g., HRRR, FV3 operational models)
    - Used for research studies from case studies to high-resolution convection-permitting regional climate simulations

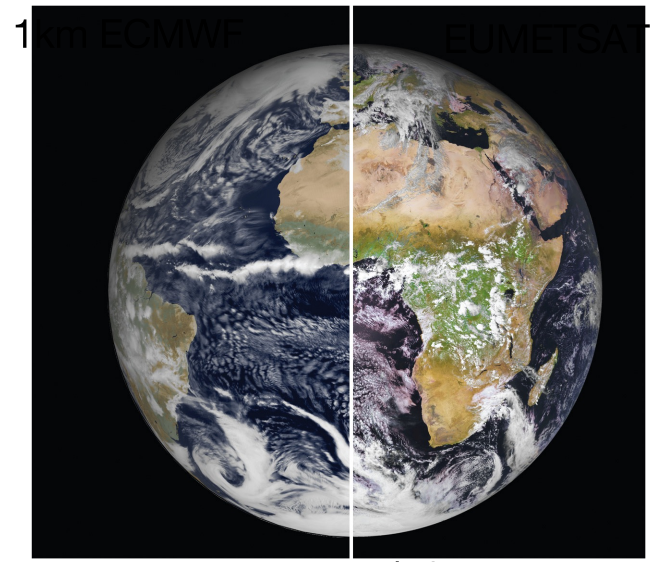


Future of Weather and Climate Forecasting

Climate models implicitly represent convective mass flux (CMF) → processes important to CMF not captured



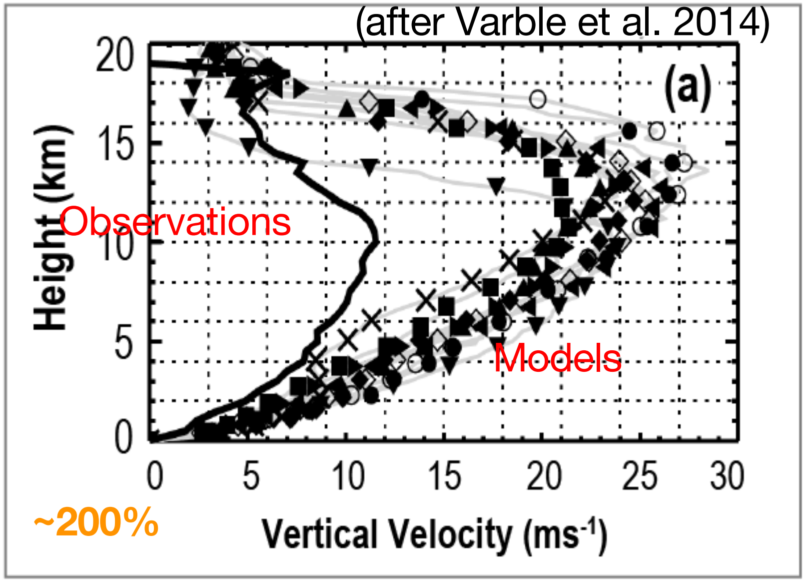
Digital twins are a current reality

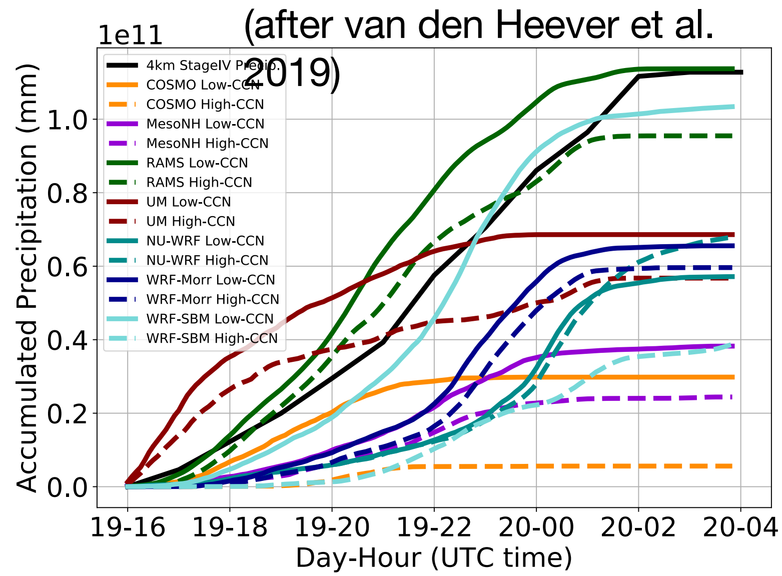


(after Voosen 2020)

So all problems solved then?

Ongoing Challenges in State-of-the Art Models

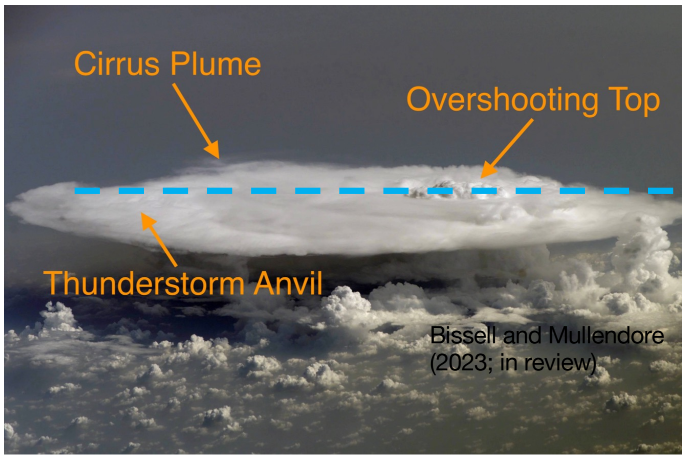




Vertical motion is a major source of error in our weather and climate models

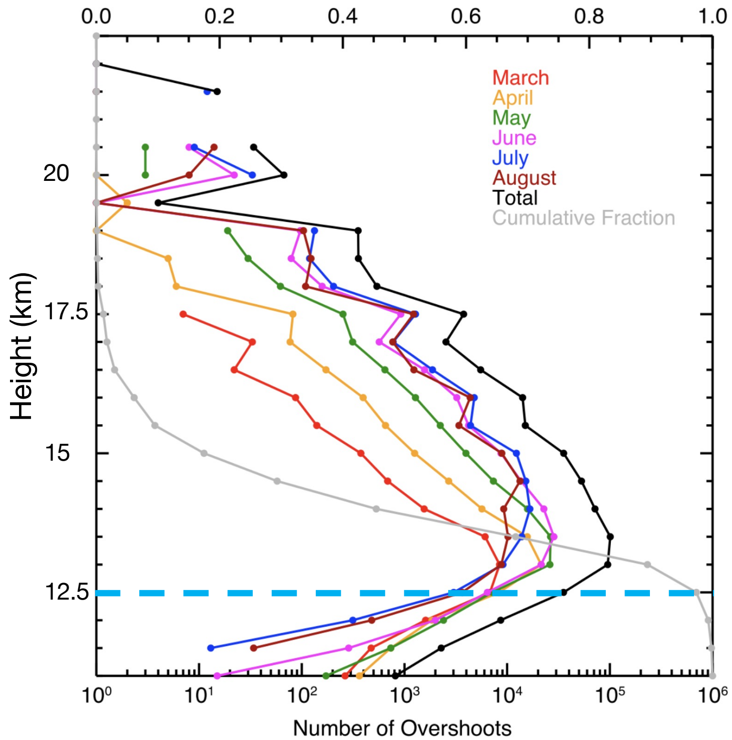
Deep convection overshoots in NWP forecasts

- 10-year ground-based U.S. radar climatology of **overshooting top** echo-top heights connected with very intense convective storms
- Very strong convective mass flux required to support overshooting tops above the tropopause



Courtesy: Ken Bowman; NASA DCOTSS Campaign

Deep convection overshooting tops from a 10-year radar climatology (2004-2013)



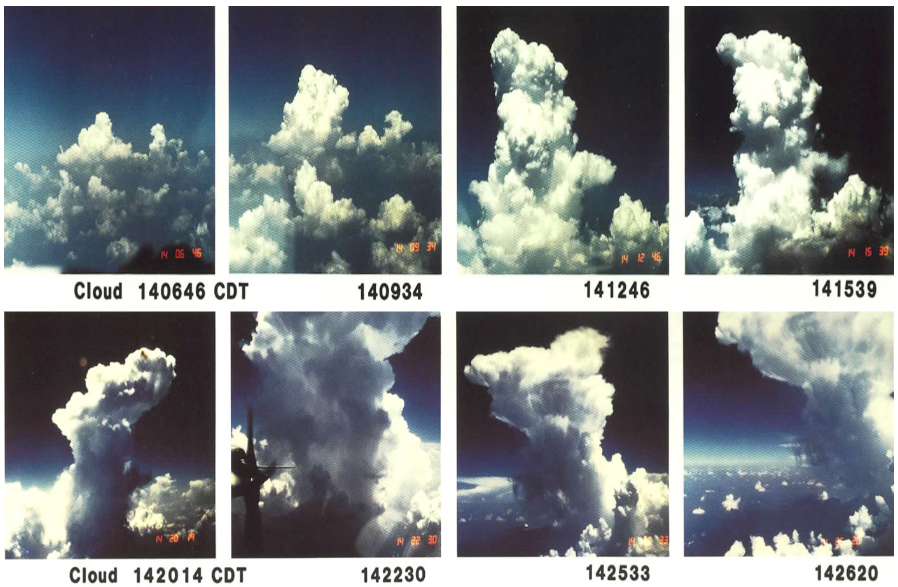
Cooney et al. (2018)

- Comparison between overshooting tops in a 3-km operational NWP model (HRRR; left) and ground-based radar observations (right)
- Consistent methodology using 10 dBZ echo tops extending above the tropopause
- **Model significantly underestimates the height of overshooting tops associated with deep convection compared to observations**

Physical Approach

- What are the gaps
  - Most mesoscale model overestimate the vertical motion in strong convective storms
  - At the same time, the HRRR model underestimates the height of overshooting tops
  - Bulk microphysics schemes greatly simplify the complexity of dynamic-microphysics interactions
  - Resolve different components of the storms with different grid spacings
    - Mesoscale processes are reasonably well represented at ~4km horizontal grid spacing
    - Thermals and individual updrafts are well represented at LES (~100m) grid spacing

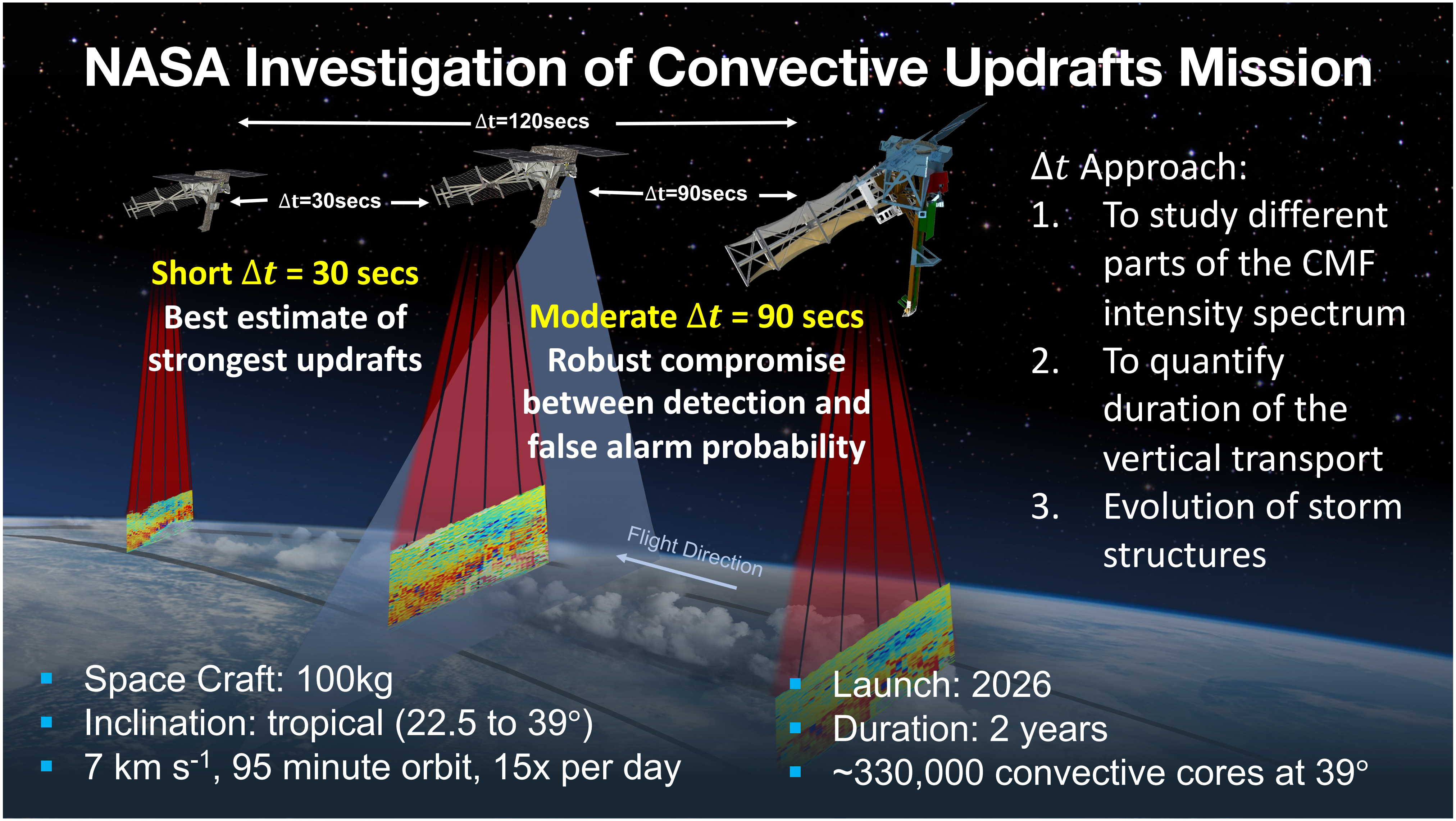
Convection Evolves Rapidly



Development of a deep convective cloud over a 20 minute time period (images: Ted Fujita)

Convective development - 30 min period

Convective storms vertically transport and mix the atmosphere


NASA Investigation of Convective Updrafts Mission
Δt=120secs
Δt=30secs
Δt=90secs
Short Δt = 30 secs
Best estimate of strongest updrafts
Moderate Δt = 90 secs
Robust compromise between detection and false alarm probability
Flight Direction
Δt Approach:
1. To study different parts of the CMF intensity spectrum
2. To quantify duration of the vertical transport
3. Evolution of storm structures
Space Craft: 100kg
Inclination: tropical (22.5 to 39°)
7 km s-1, 95 minute orbit, 15x per day
Launch: 2026
Duration: 2 years
~330,000 convective cores at 39°

Model Use and Validation

- How is this model component validated?
  - Comparisons to available observations
  - Limited in time/space around the world

- How will model errors be quantified?
  - Overestimates of vertical motion in convective storms has been quantified by 3D wind retrievals from field campaigns → limited in availability and the estimates have their own uncertainties
  - Radar reflectivity structures (i.e. storm modes) provides a useful validation opportunity
  - Rainfall

- What observations are necessary for validation
  - Concurrent radar, lightning, and vertical motion estimates
  - Available now in limited regions (i.e., field campaigns)

Funding Sources

Provide a list of programs that fund research in your focus area. The purpose of this section is to survey how we might organize long-term support for the work.

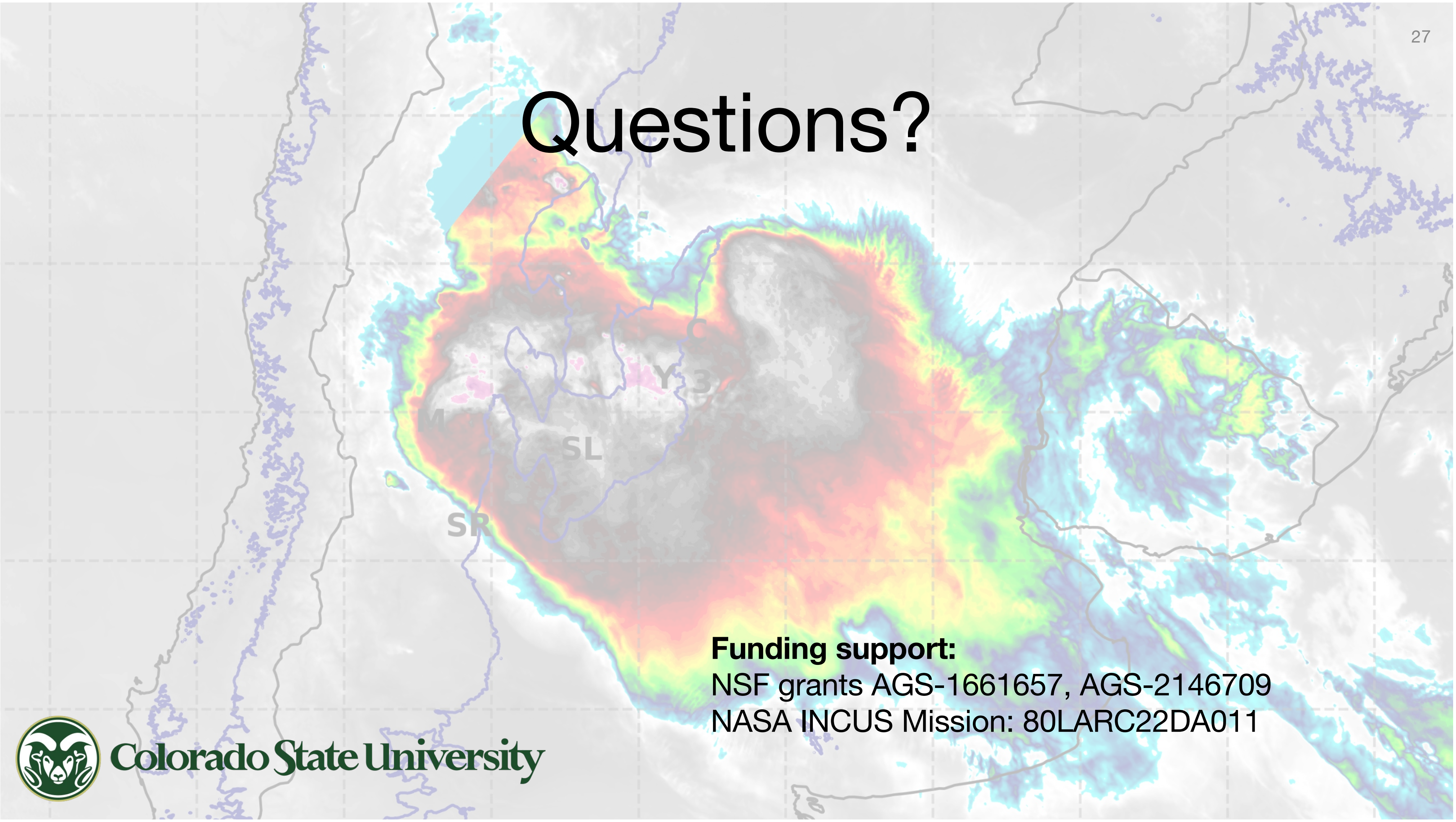
Sponsoring organization	Funding program	Funding program element	Funding cadence (R = regular interval; I = irregular intervals; L = time-limited opportunity)	Comments
NASA	ESSP	Earth Venture Mission 3 (INCUS Mission)	R	Interest in connecting CMF with lightning across the storm lifecycle
NSF	PDM		R	Storm comparisons between Colorado and Argentina

Avenues for Collaborations

Describe the type of collaborations that have been beneficial for your field of research, what challenges currently exist for establishing collaborations, and/or what type of collaborations you would like to see better supported.

- Across national organizations or agencies (public and private)
  - Satellite missions like INCUS
- International partnerships
  - Field campaigns (e.g., RELAMPAGO, KPOP-MS in South Korea, etc.)
- What is the balance of student, postdoc, and career-expert work?
  - 1-3 students, 1-2 postdocs and 1-2 career-experts in my research group working on convective storms and lightning

Questions?



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Colorado State University