# Requisite Measurements to Close Critical Gaps in Our Understanding of Deep Convective Processes

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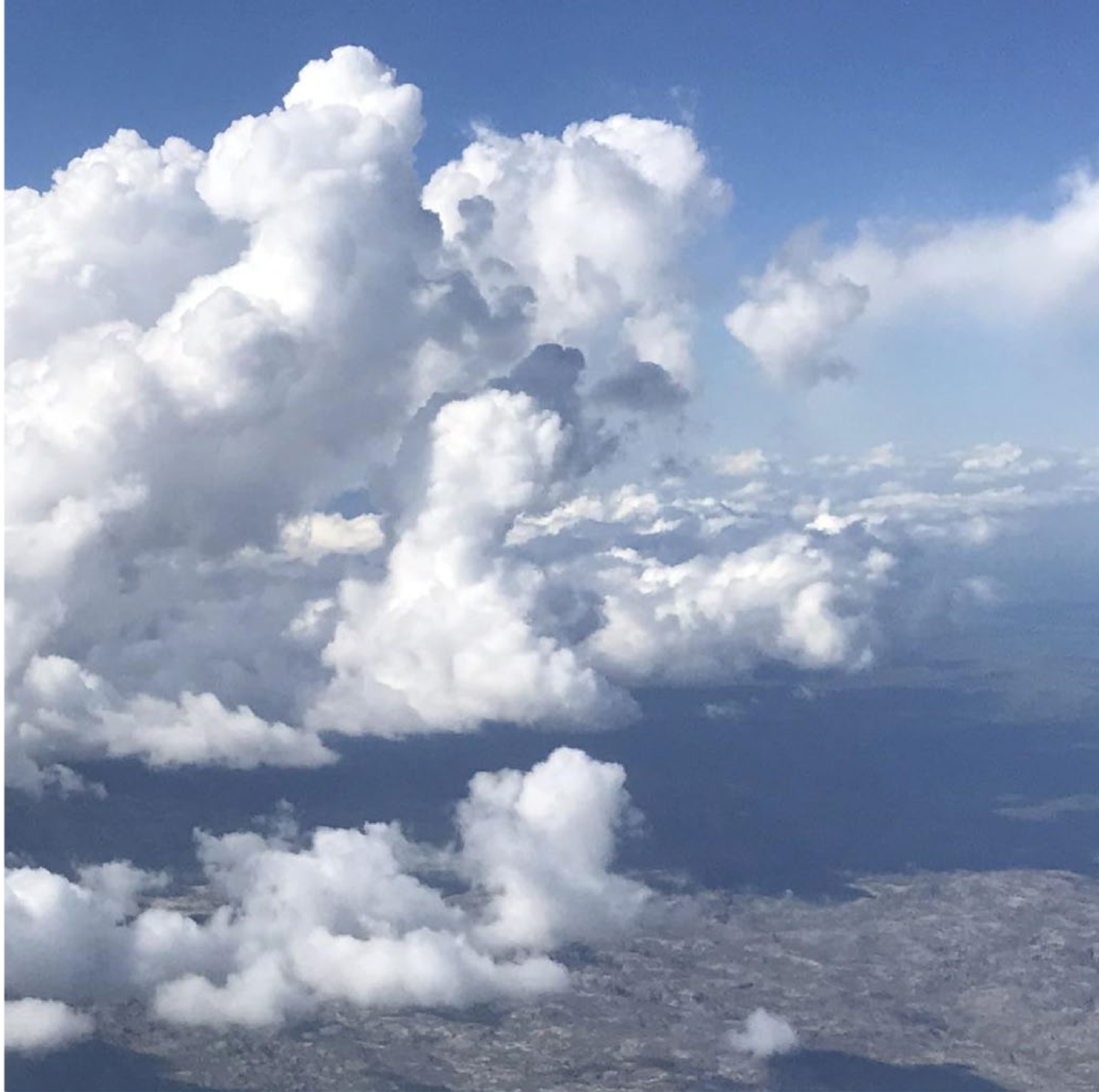
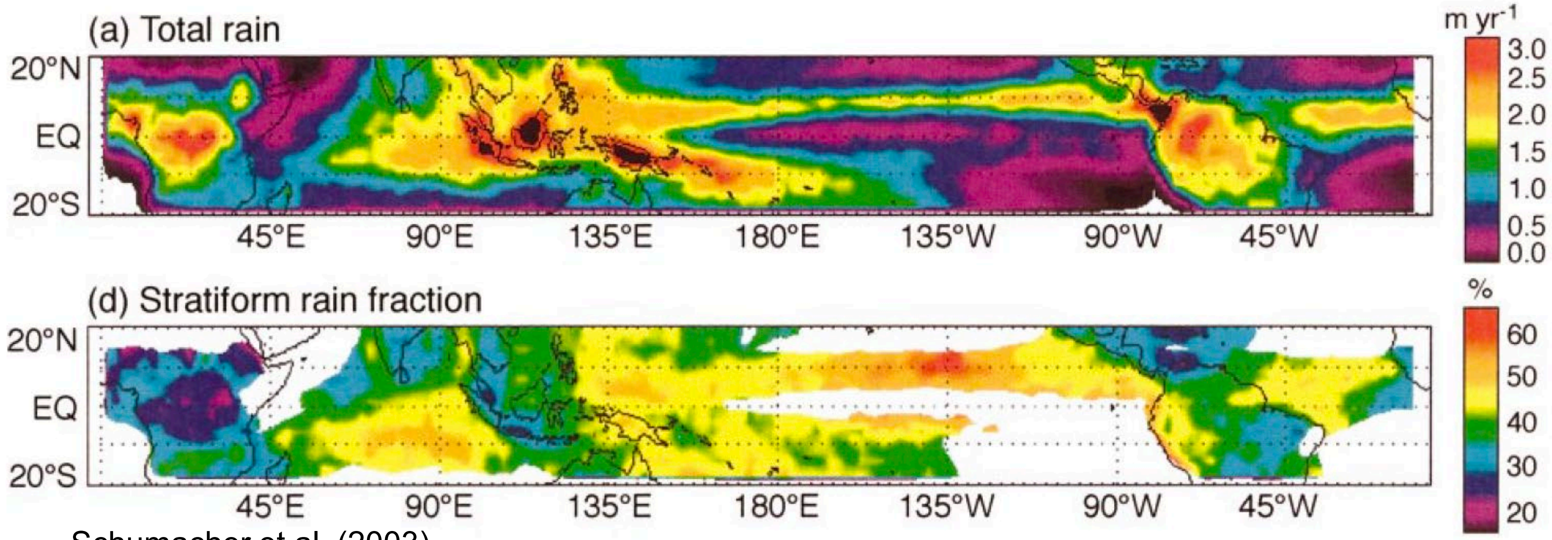


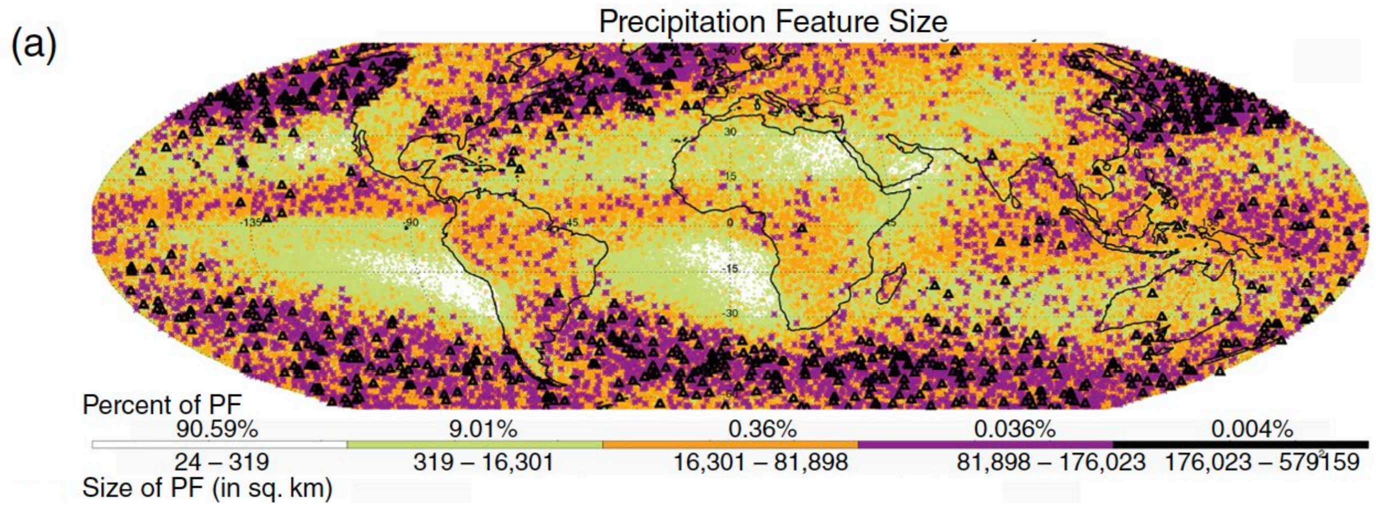
# Measurement Guidance

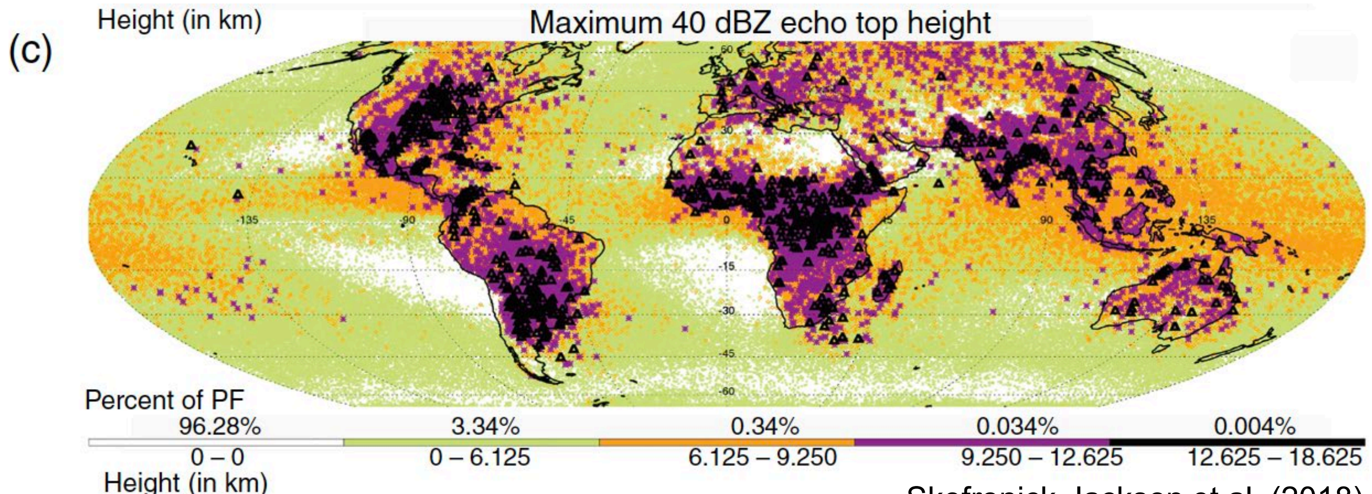
# What dictates measurement needs?

- My perspective: (i) Observations to improve predictive models and (ii) coupled observations and models to improve understanding
- Deep convection varies tremendously by location and time, a result of many interacting processes and conditions that control their evolution with impacts on weather and climate that we must be able to predict



Schumacher et al. (2003)

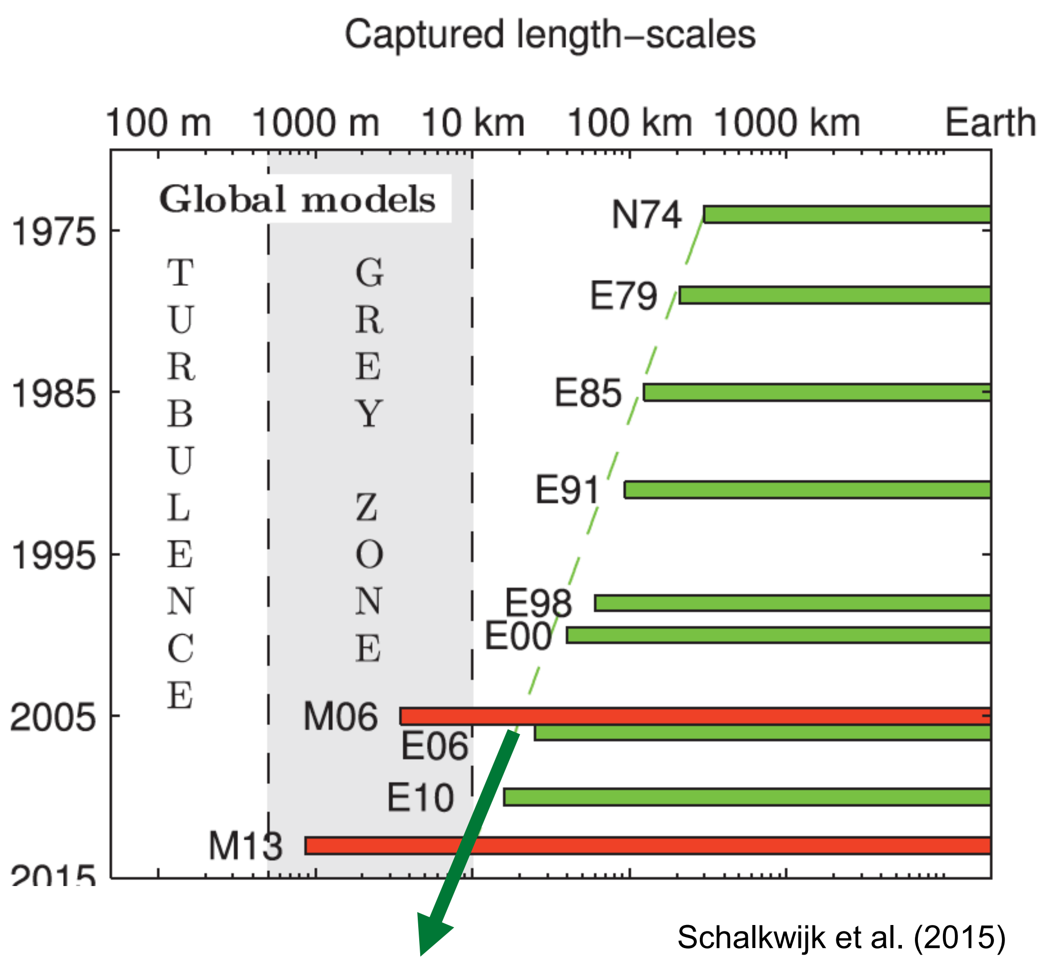




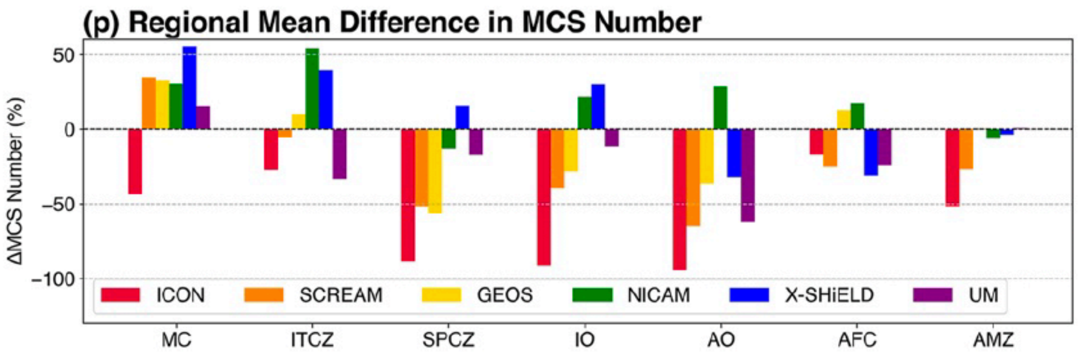
Skofronick-Jackson et al. (2018)

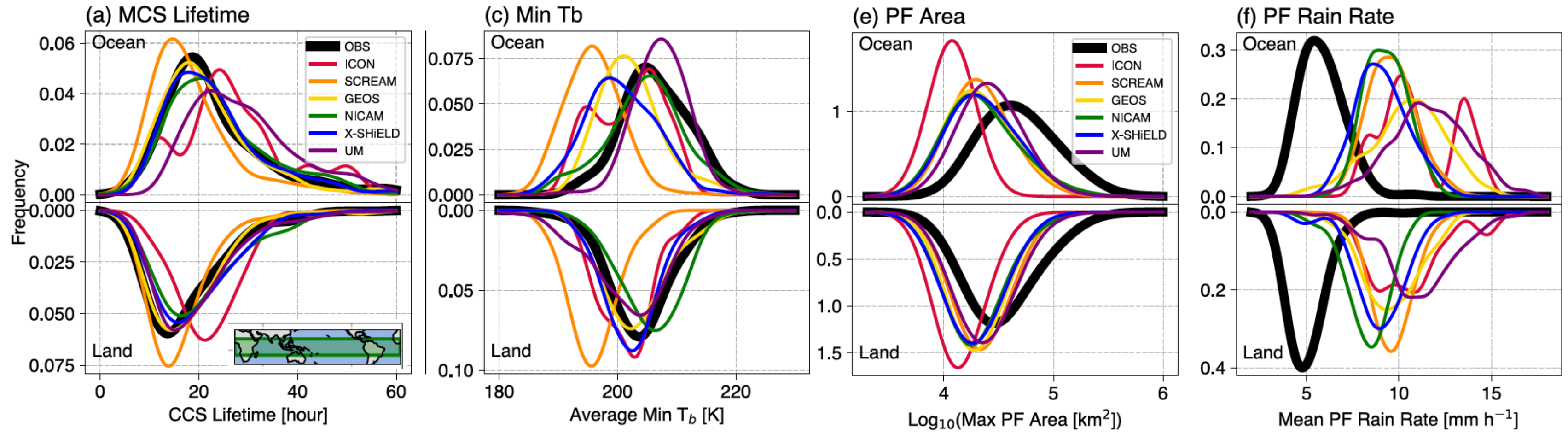
# Where models deviate from observations tells us where to focus efforts

- Model resolution has rapidly advanced with computing power
- Weather and climate prediction are now run at km scales, with large ensembles and advanced DA facilitated by ML advances
- But biases and large model spread exist; satellite retrievals are not truth

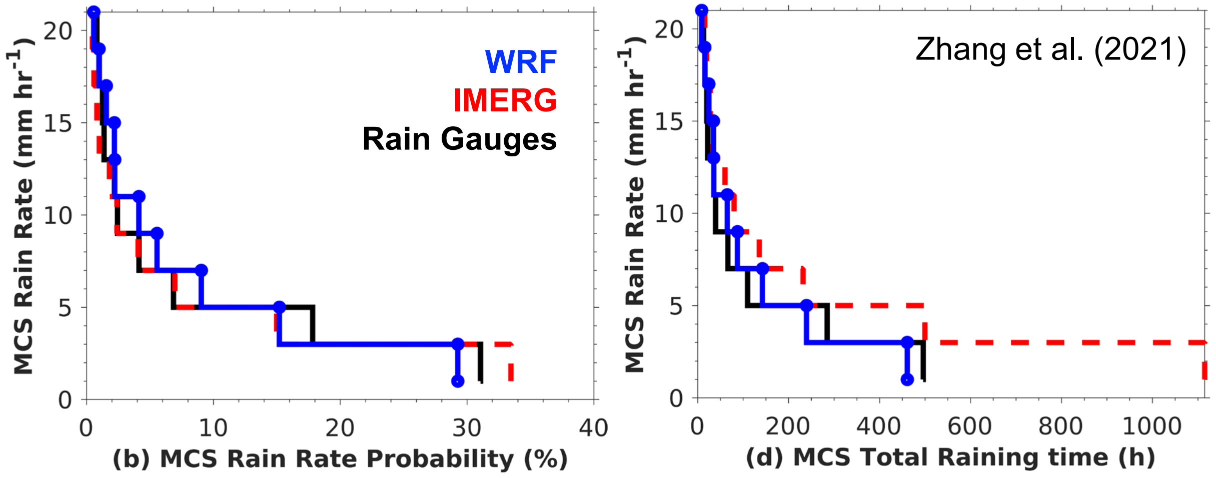


Schalkwijk et al. (2015)





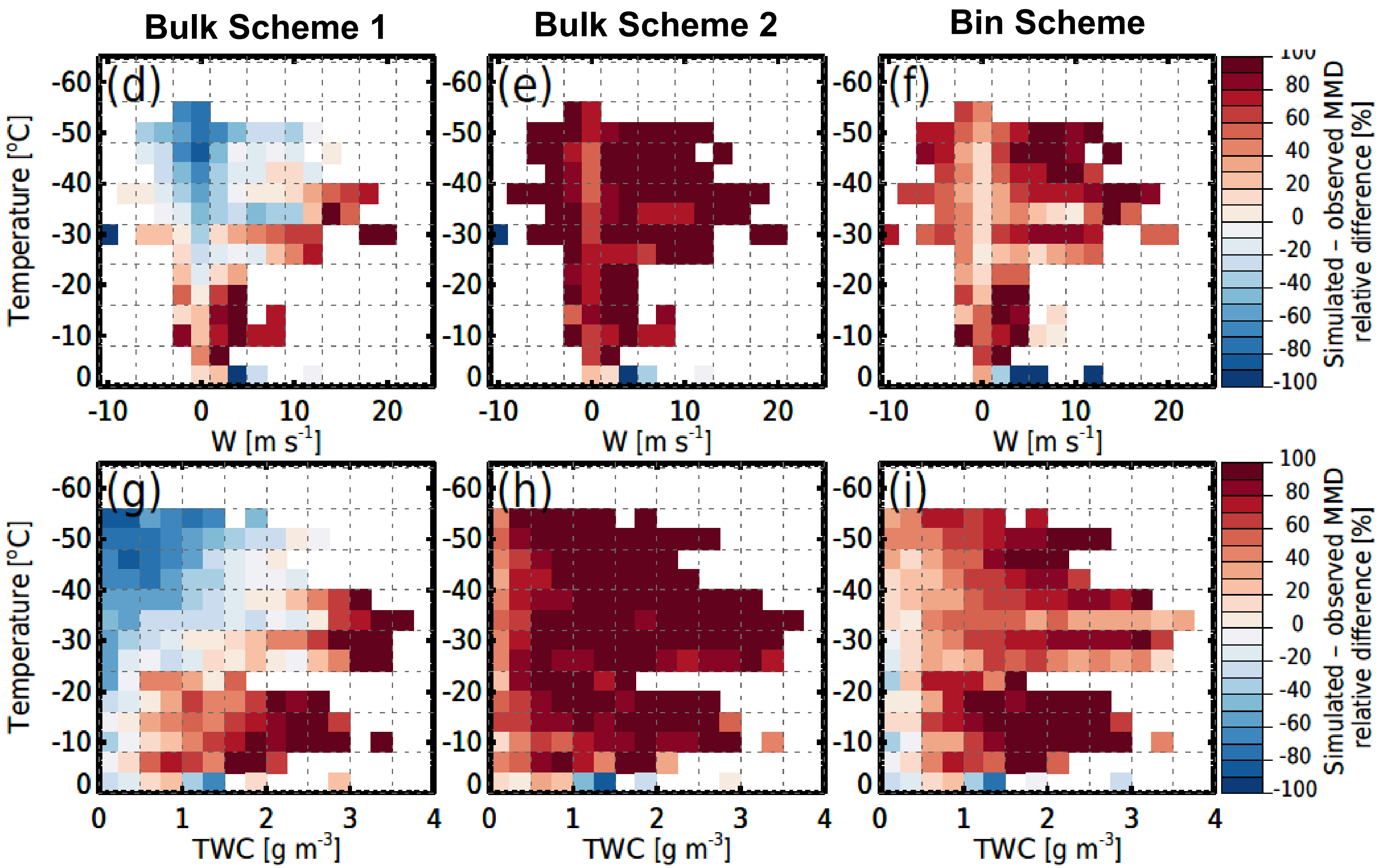
Feng et al. (2023)



# Where models deviate from observations tells us where to focus efforts

- Despite model resolution and parameterization improvements, persistent biases remain
  - Convective radar reflectivity high bias with excessive riming growth
  - Insufficient stratiform precipitation
  - Sensitivity to environmental conditions is too limited (e.g., land vs. ocean)
- We know these biases stem from:
  - under-resolved updrafts,
  - insufficient (incomplete) parameterization of microphysics, and
  - likely other under-resolved phenomena such as cold pools

**Model - Observations Hydrometeor Mass Median Diameter Differences (%)**

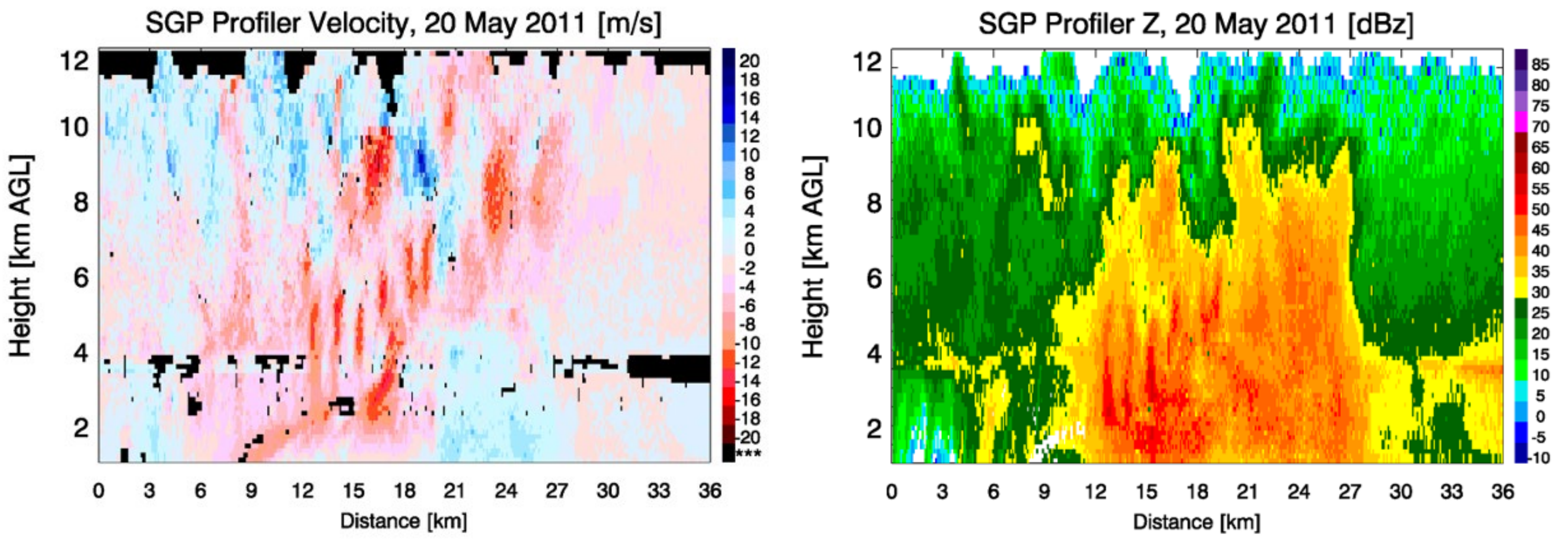


Stanford et al. (2017)

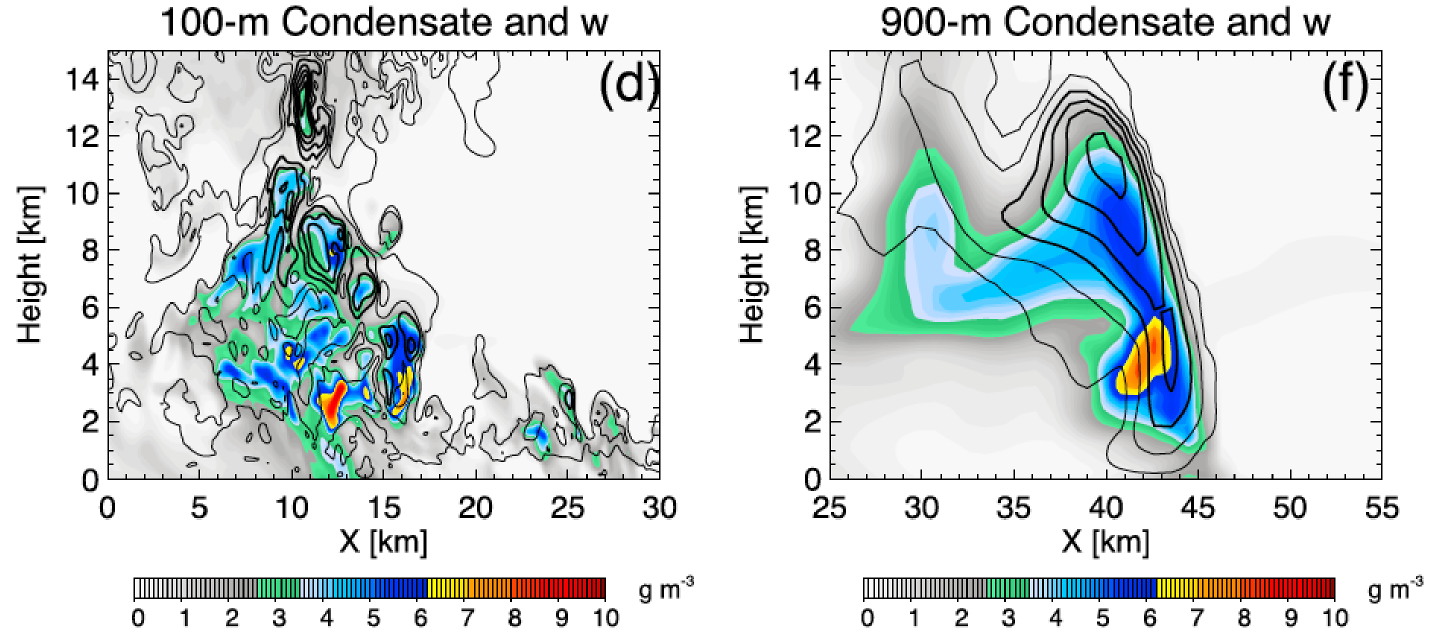
# Measurement Targets

# Critical unknown: Convective dynamics

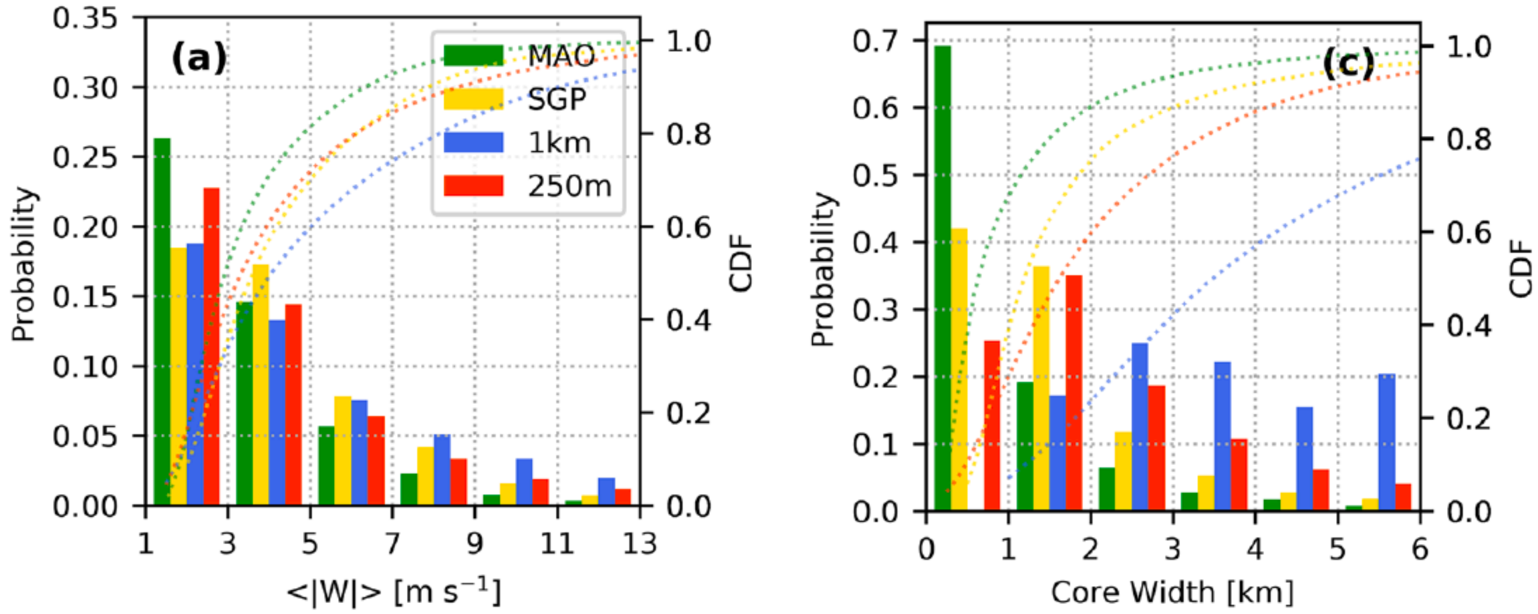
- Vertical wind speed is critical, but so is updraft spatial structure
  - Thermal to plume spectrum dependent on initial updraft width, CAPE, RH, and vertical wind shear, affecting entrainment, detrainment, and vertical transport
  - Vertical profiler and aircraft multi-Doppler retrievals can resolve these features, but few measurements exist



Courtesy Scott Giangrande (BNL)



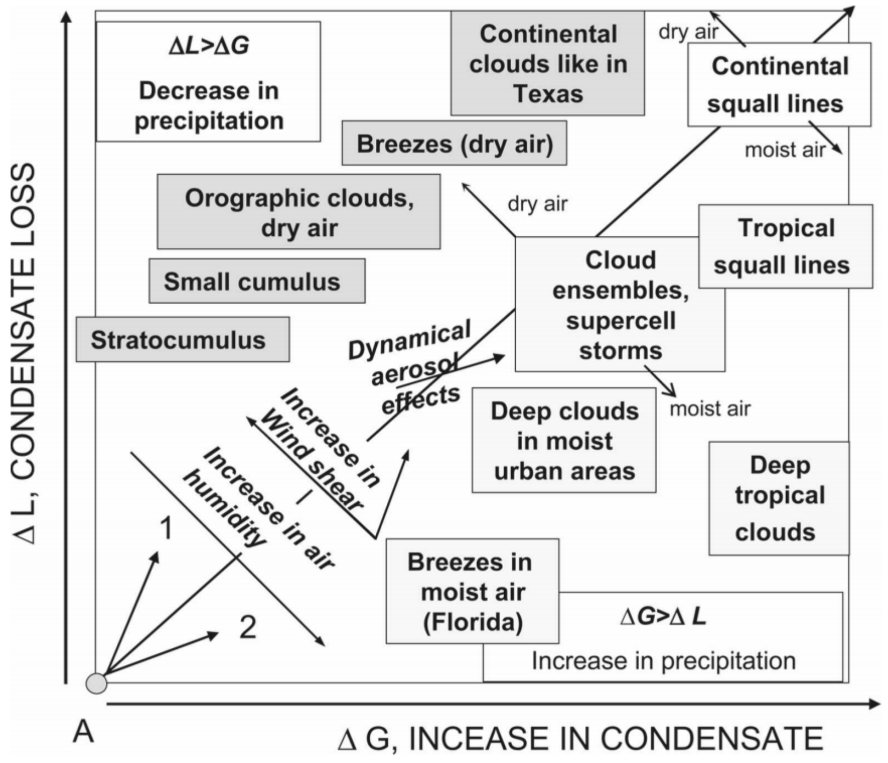
Varble et al. (2014)



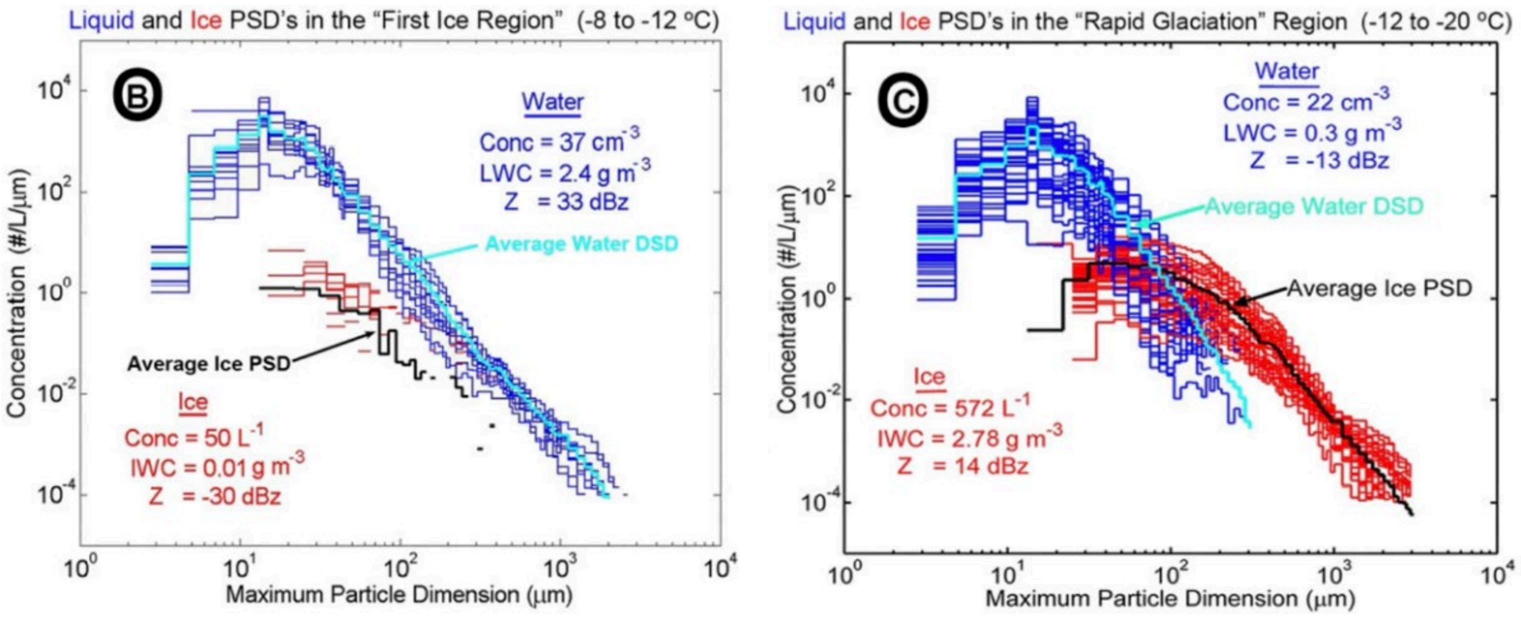
Wang et al. (2020)

# Critical unknown: Microphysics

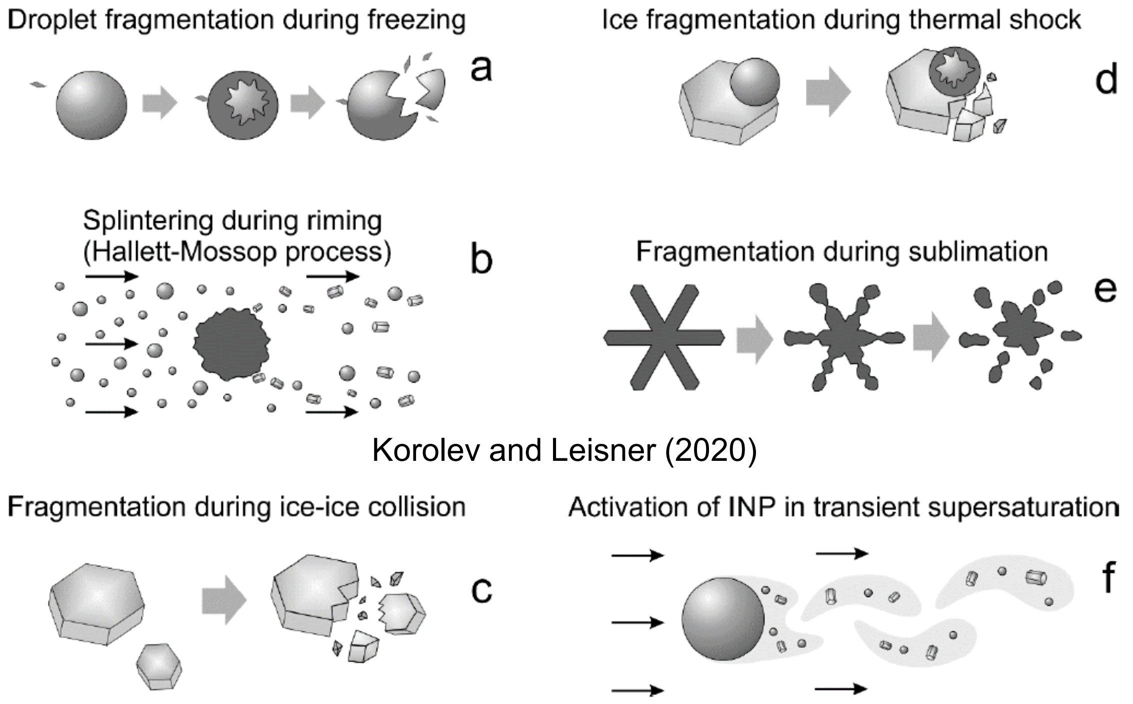
- Mixed phase and ice processes (e.g., secondary ice production) are not fully understood, and some would say liquid processes also lack full constraint producing tremendous inter-model spreads
    - In situ measurements are vital but are more valuable with additional comprehensive measurements including remote sensing context
- We lack a full understanding of how convective and stratiform anvil microphysics tie together with each other and circulations including cold pools as a function of ambient environment including aerosols



Khain et al. (2008)



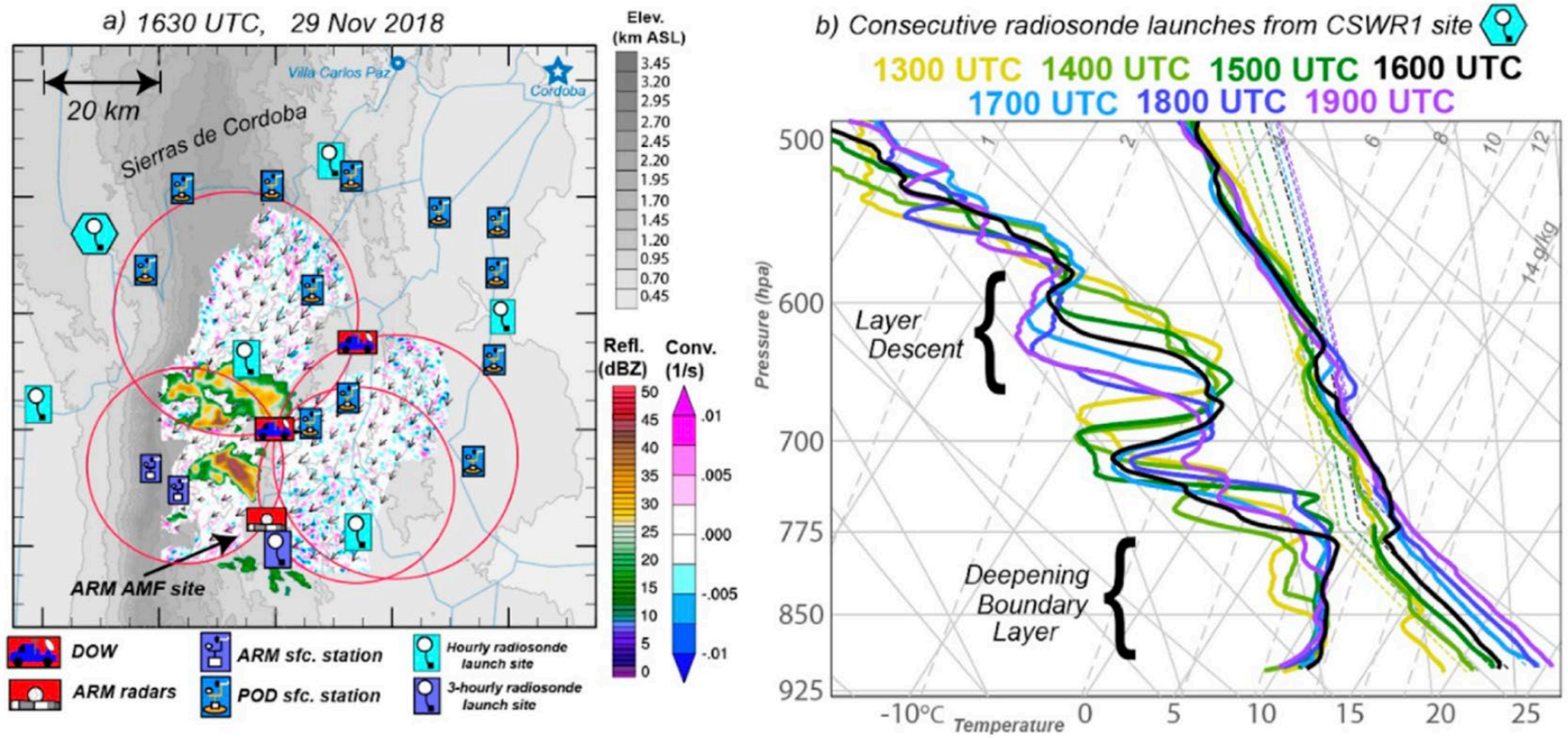
Lawson et al. (2015)



Korolev and Leisner (2020)

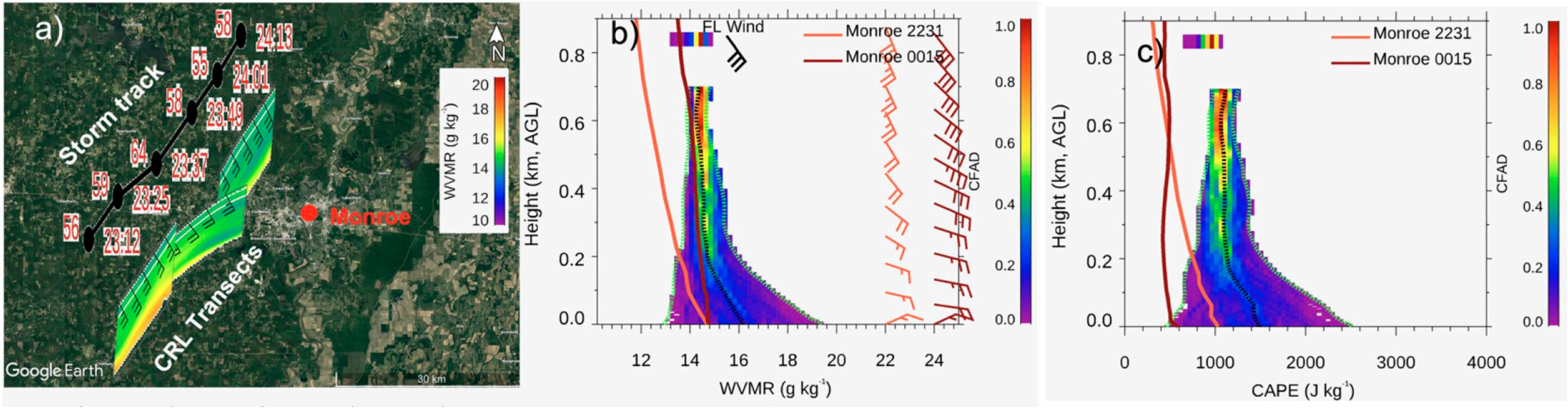
# Critical unknown: Near cloud environment

- Deep convection has critical 2-way interactions with near cloud atmospheric conditions that are highly variable and usually poorly characterized
  - First order effects need constraint before key second order effects can be isolated
  - Remote sensing retrievals (e.g., Raman and wind lidar) show tremendous promise



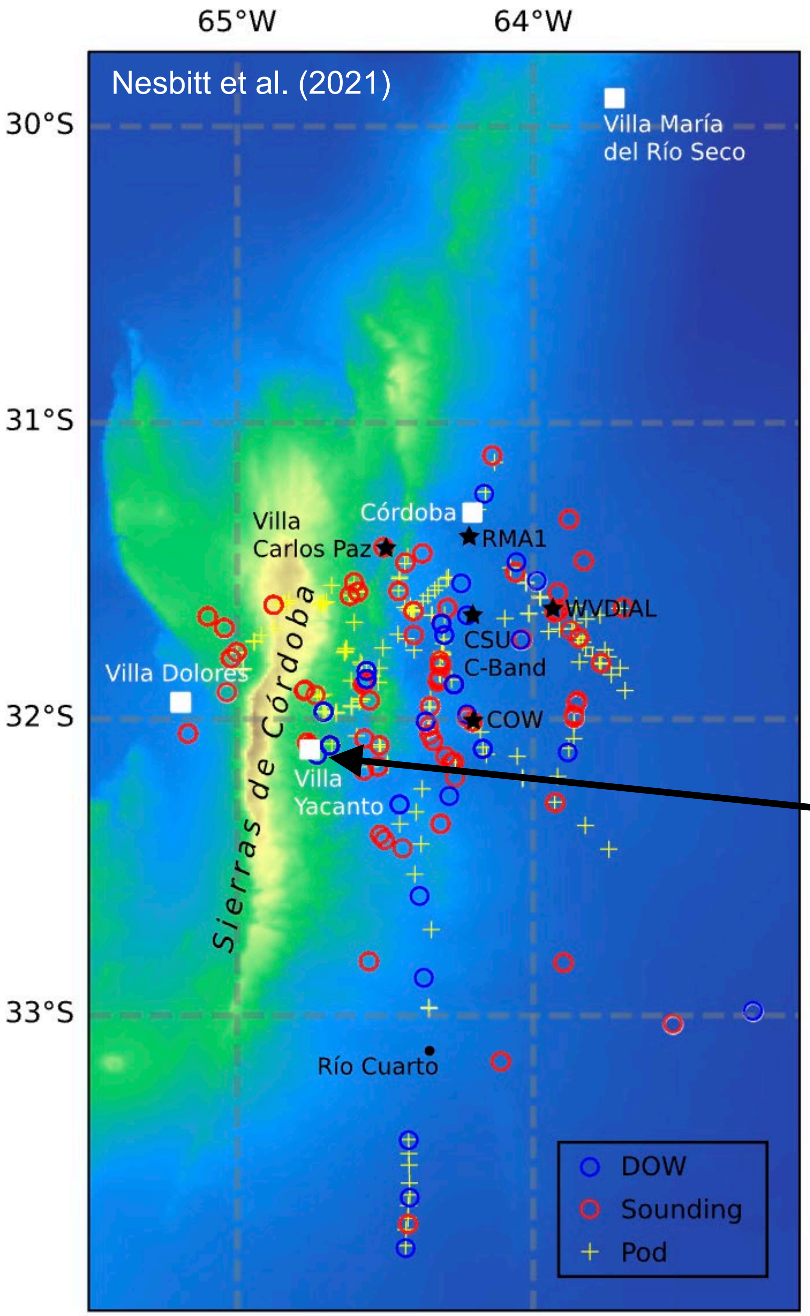
Marquis et al. (2021), Nesbitt et al. (2021)

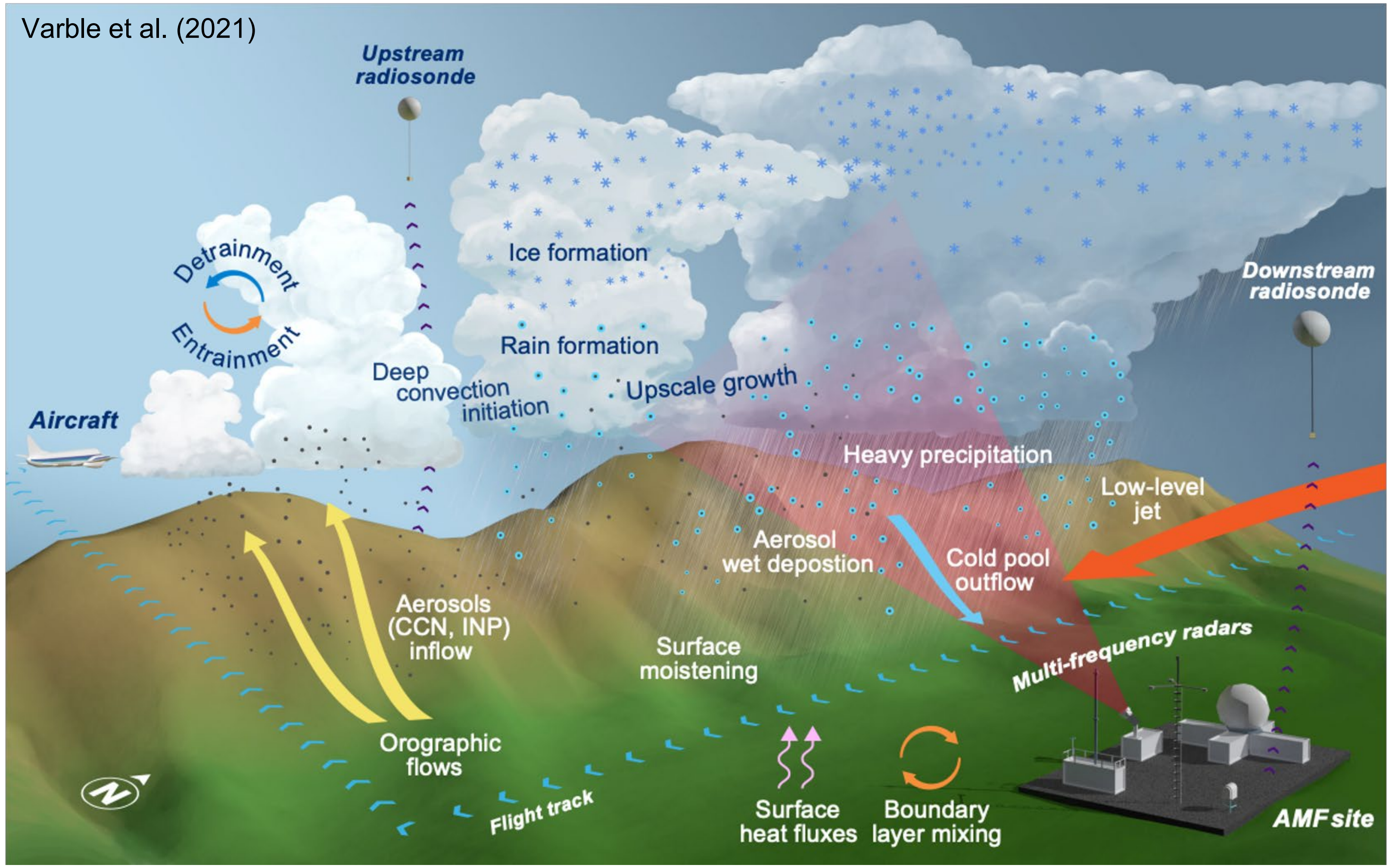
Lin et al. (2023)



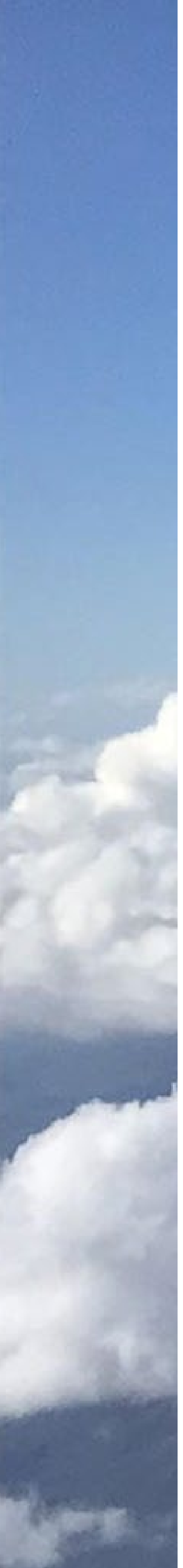
# Comprehensive measurements are essential

Measurements have greatly improved in quality over time, and field campaigns are more numerous. But, campaigns are more limited in measurement scope while still expansive in research scope. This restricts progress, requiring a rethinking of measurement strategies.


Nesbitt et al. (2021)

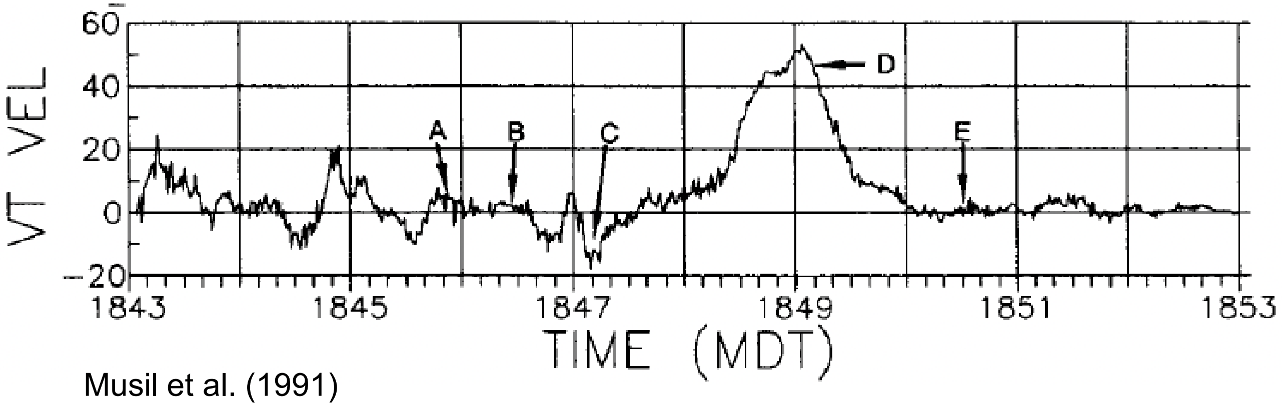

Varble et al. (2021)

# Measurement Strategies

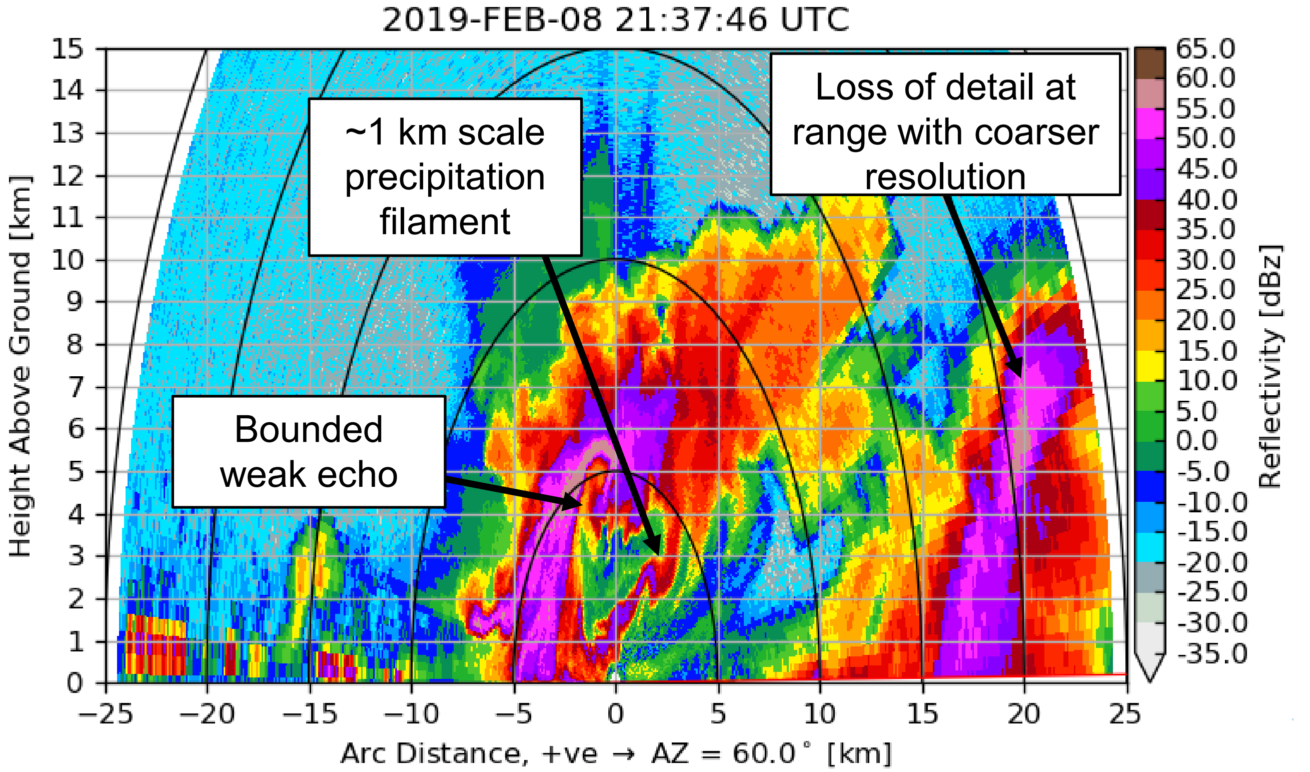


# Balance resolution and representativeness

- Inherent resolution vs. representativeness dilemma
  - Scanning Doppler, polarimetric radar is critical, but how to best scan for any given target is unclear
  - Phased array radar can potentially help
- Resolution needs depend on the feature being targeted
  - Insufficient resolution obscures key processes, but maximally extracting information content from detailed, coupled measurements remains challenging
- Need to sample full convective variability (geographical, diurnal, organizational, life cycle, extremes)
- In situ observations remain essential
  - More updraft penetrations were done historically but with subpar instruments and poor data archiving



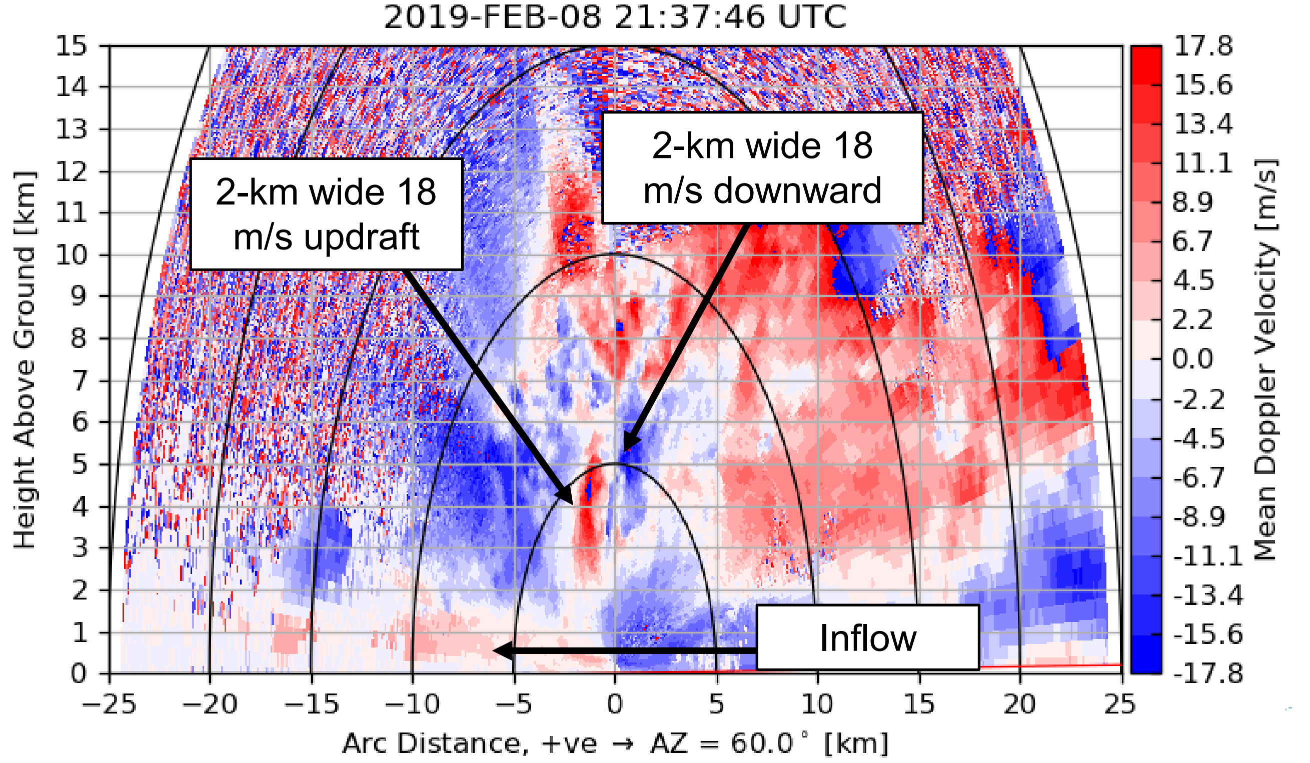
Musil et al. (1991)



~1 km scale precipitation filament

Loss of detail at range with coarser resolution

Bounded weak echo



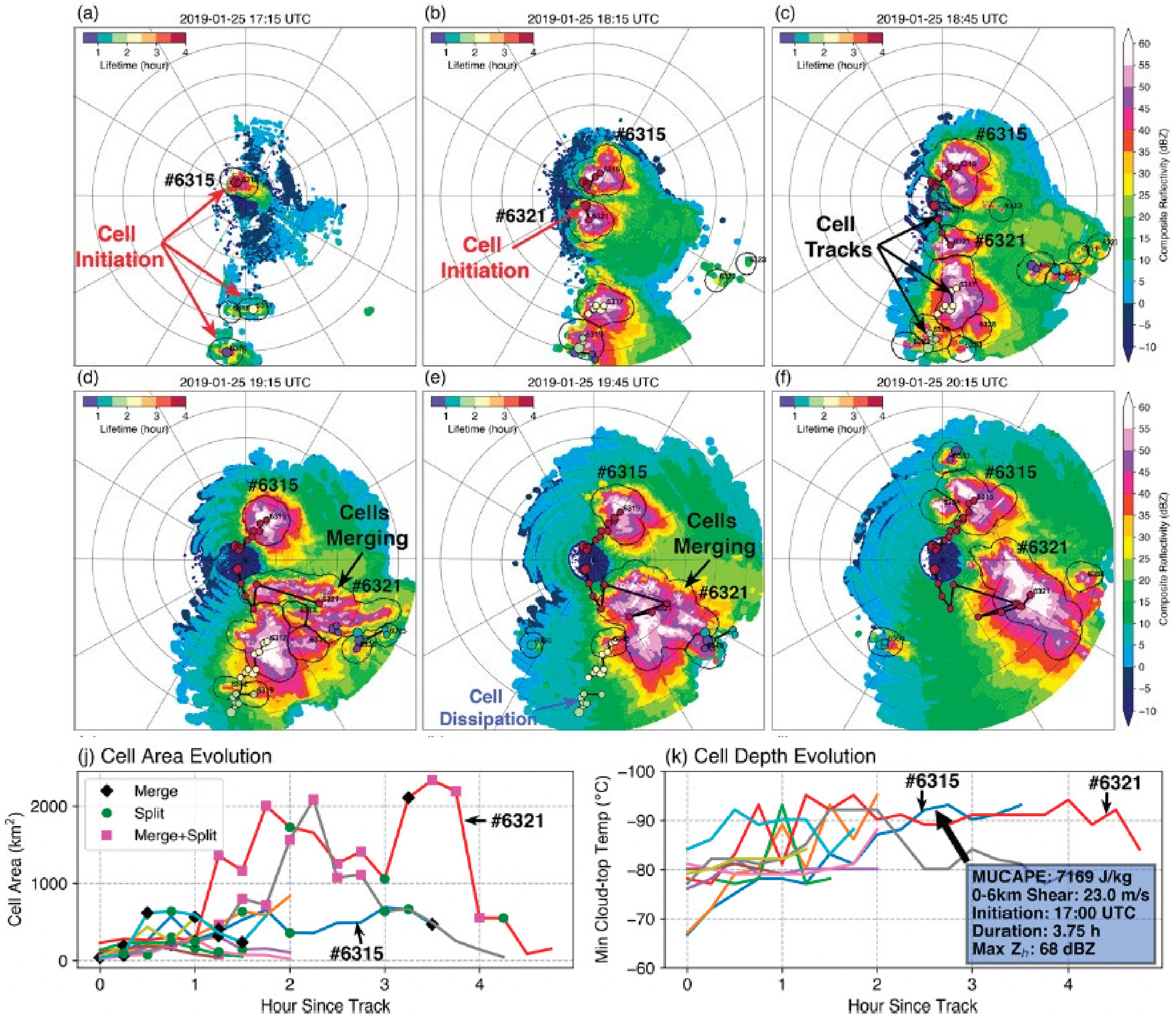
2-km wide 18 m/s updraft

2-km wide 18 m/s downward

Inflow

Courtesy Joseph Hardin and Nitin Bharadwaj (PNNL)

# Spatiotemporal evolution of properties informs process understanding

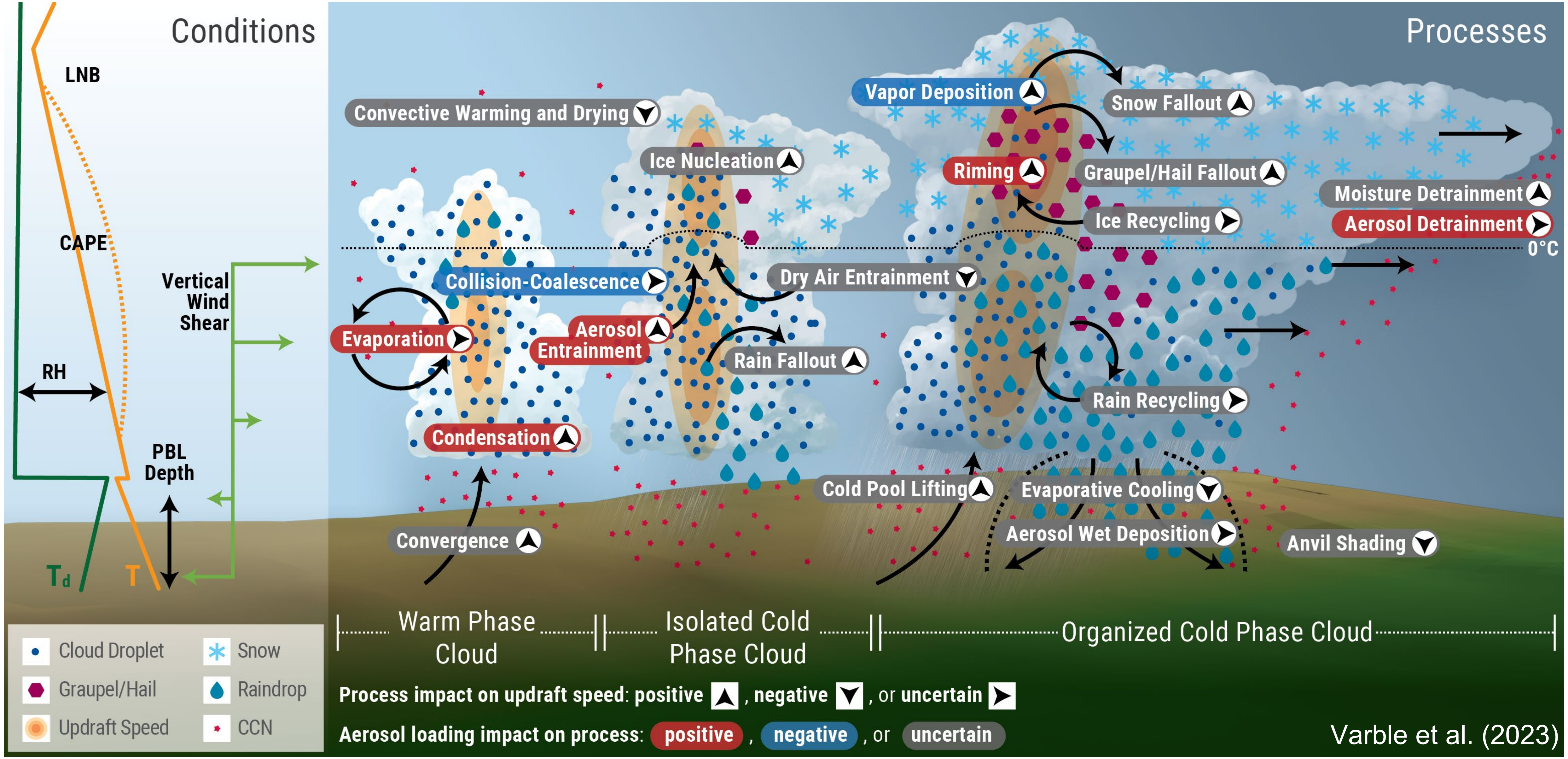


Feng et al. (2022, 2023)

- Structure snapshot changes in space and time (D/Dt) are the result of processes operating over time to produce such changes
  - Dynamical and microphysical properties are lagged in time
  - Convective cell and system tracking via radar and satellite is an example
  - Another example is recording properties along estimated Lagrangian flows
- Work to be done linking representative tracked feature datasets to lesser sample high resolution, advanced retrieval, and comprehensive measurement (e.g., field campaign) datasets targeting specific processes
  - Some new measurement strategies adapt to moving, evolving clouds but are not yet perfected and how to best use them is still unclear

# Isolating and quantifying individual processes remains incredibly challenging

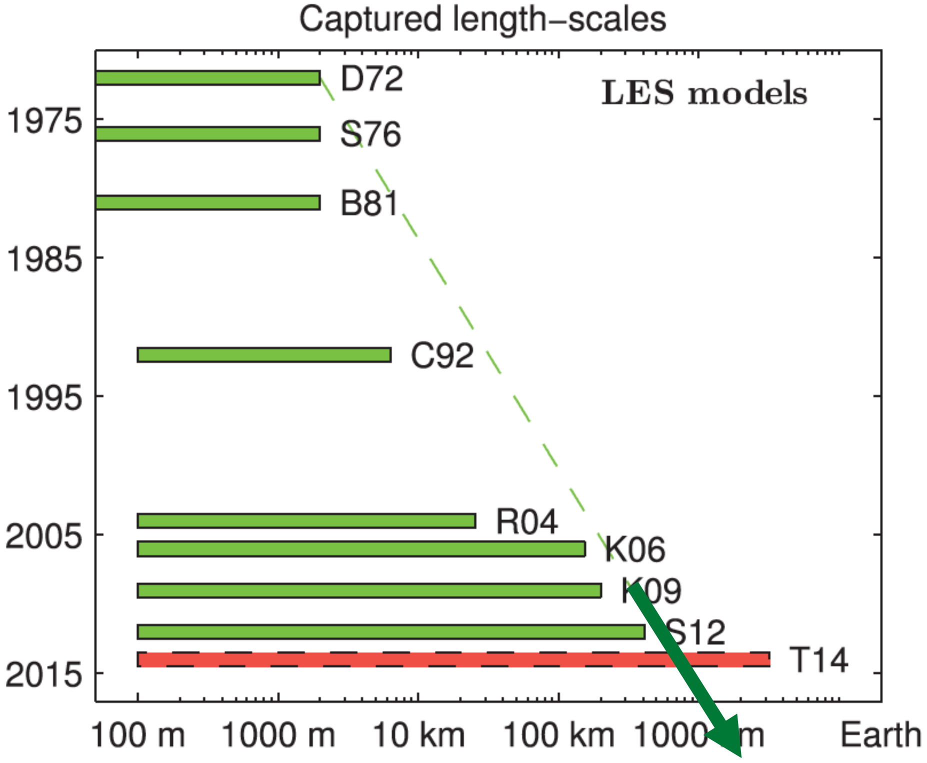
As an example, even the sign of many process impacts on updrafts and aerosol impacts on processes are unknown:



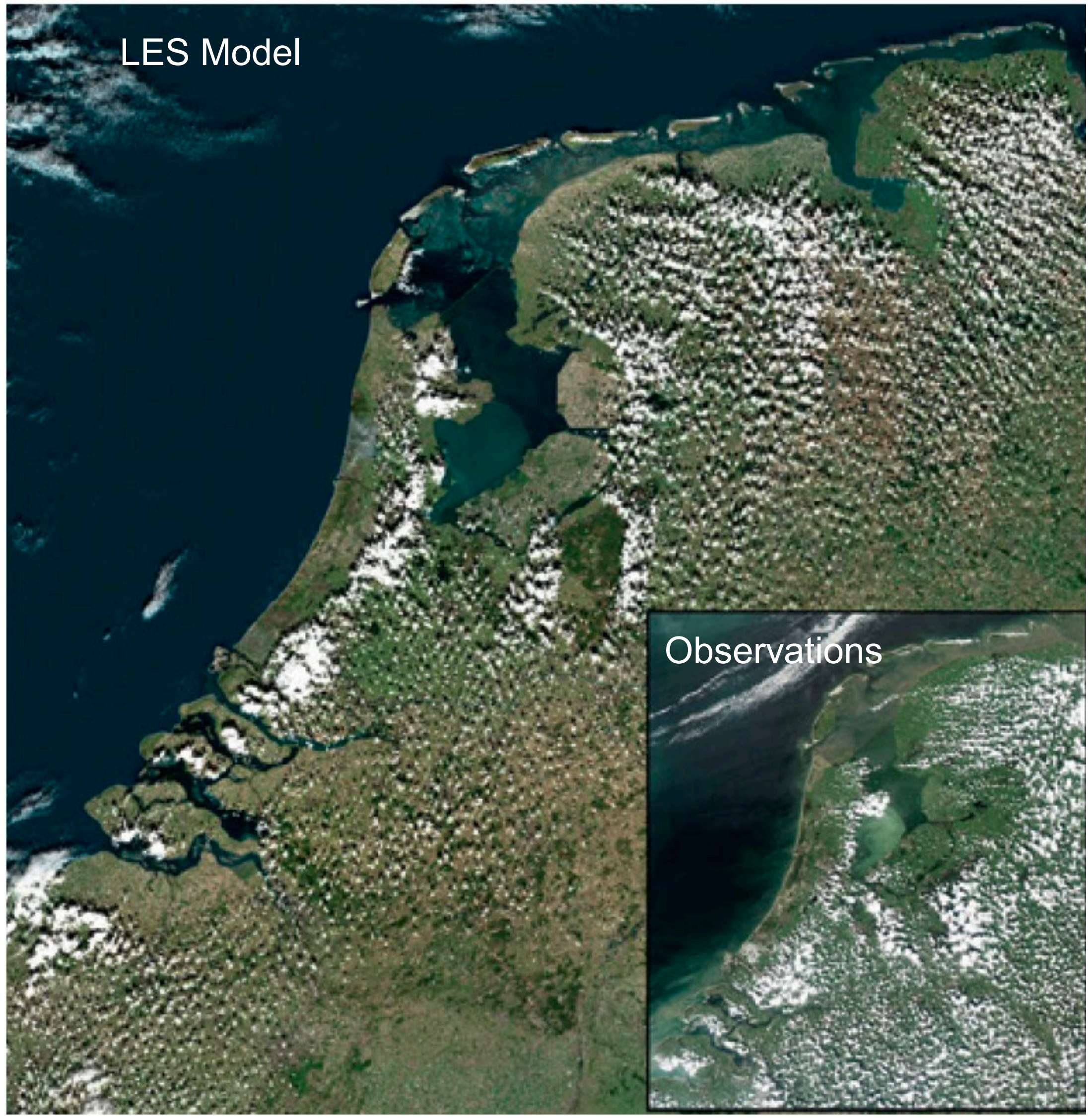
Varble et al. (2023)

# LES and parameterizations have greatly advanced

These are not free from bias, but are increasingly used for understanding and evaluating coarser models and require more observational validation



Schalkwijk et al. (2015)



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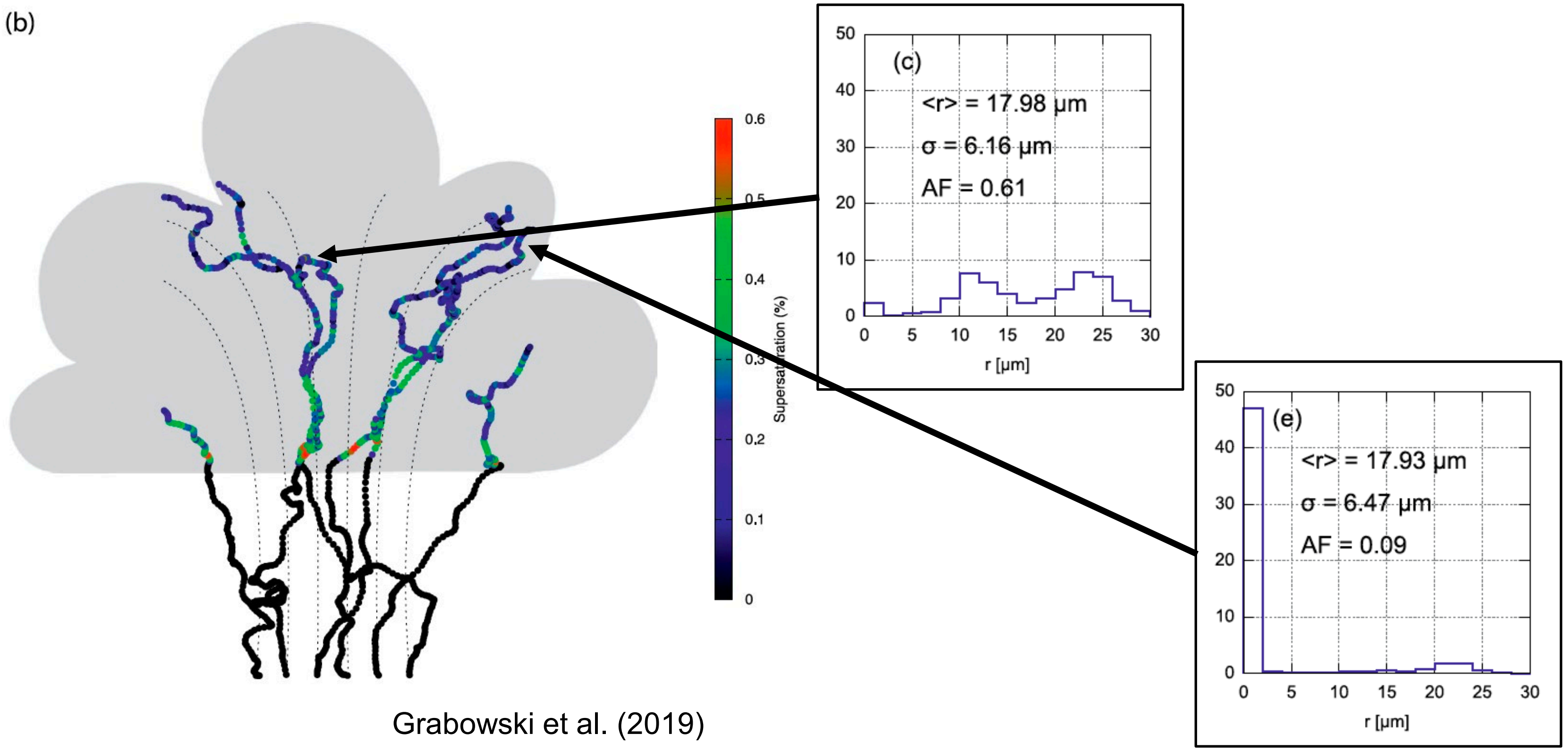
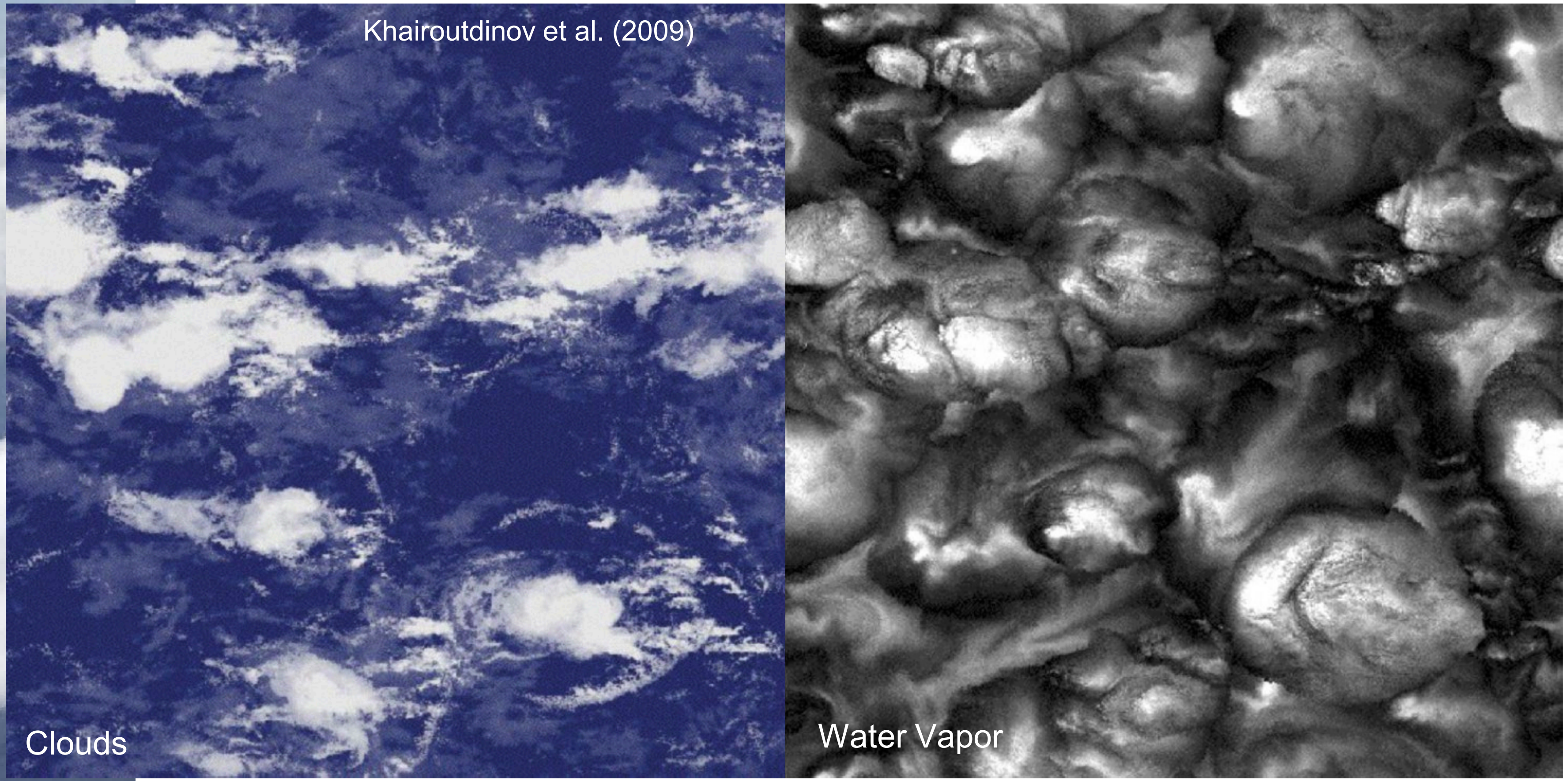


Grabowski et al. (2019)

# Can we better integrate models and observations to improve one another?

- We still suffer from limited sampling, the need for proxies, and process obscuration by feedbacks
- Can we fill gaps with LES and km-scale ensembles, despite their shortcomings, making use of instrument simulators to connect to unobservable processes?



Clouds in the mesoscale LES run of tropical oceanic deep convection (Khairoutdinov et al. 2009). Image courtesy of Ian Glenn and Steve Krueger.

# Summary

- Measurement Guidance
  - We need to be able to predict the vast variety of deep convection, which means coordinated model and observation improvement
  - Modeling capabilities have tremendously improved but persistent biases remain, highlighting gaps in our understanding
- Measurement Targets
  - Convective dynamics: size, shape, and strength of updrafts and downdrafts including sensitivities to environment
  - Microphysics: particularly mixed phase and ice processes including interactions with circulations and effects on precipitation and radiation
  - Near cloud environmental variability such that convective dynamics and microphysics dependencies and interactions with the environment can be quantified and understood
  - Comprehensive measurements mixing objective and adaptive sampling with carefully planned strategies
- Measurement Strategies
  - Retrieval resolution at the scale of key processes without loss of context and representativeness
  - Tracking 2D and 3D features in time to link properties to processes
  - Sample full convective variability (geographical, diurnal, organizational, life cycle, extremes)
  - More innovative integration of process models with field campaigns and operational networks to fill gaps via complementary strengths and weaknesses
- Data archiving with standardized metadata, documentation, and easy access is also critical

# Thank you

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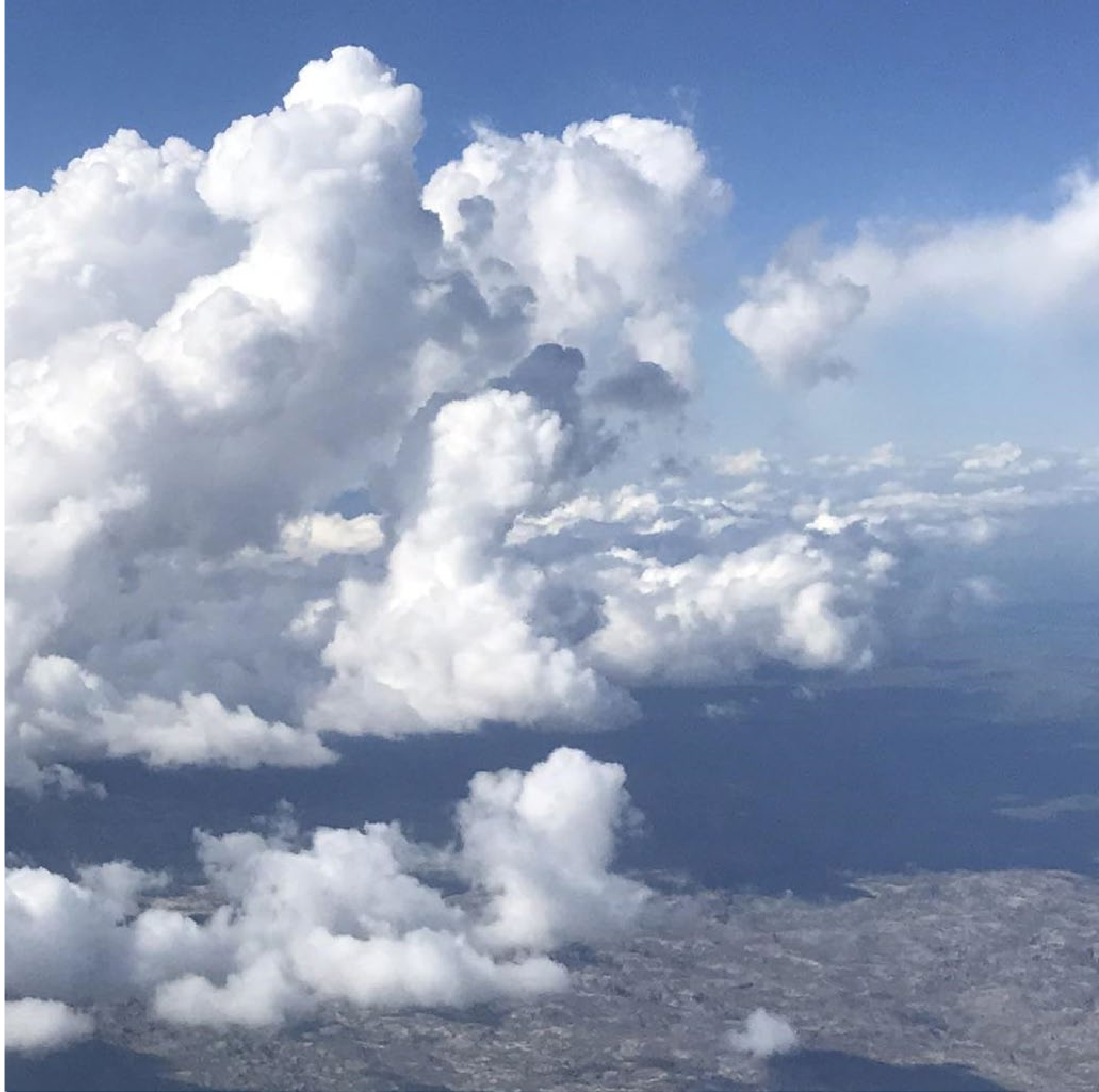

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