Sensitivity of Heavy Rainfall in Mountainous Terrain to Cloud Microphysical Processes

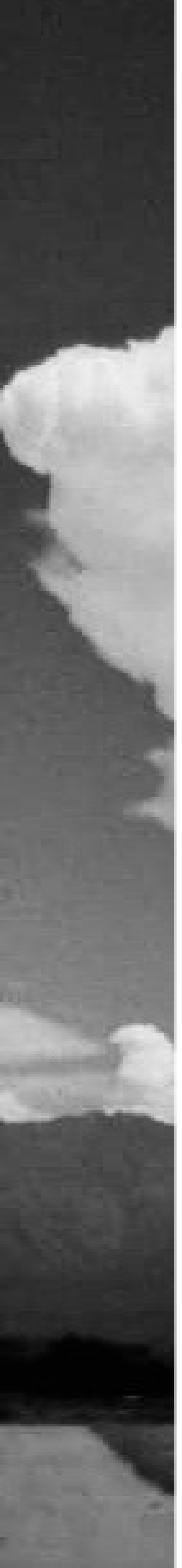
Adam Varble

Pacific Northwest National Laboratory

National Academies Workshop on Extreme Rainfall in Mountainous Terrain: Modeling and Observational Challenges for Warm-Season Precipitation

November 4, 2025

Photo courtesy of Ramón Alberto Acuña (SMN, Argentina)



Motivation

Increasing model resolution, improving physics parameterizations, and expanding ensembles have improved forecasts, *at times more accurate than gridded observational datasets over mountainous terrain where surface and low-level radar sampling is limited*

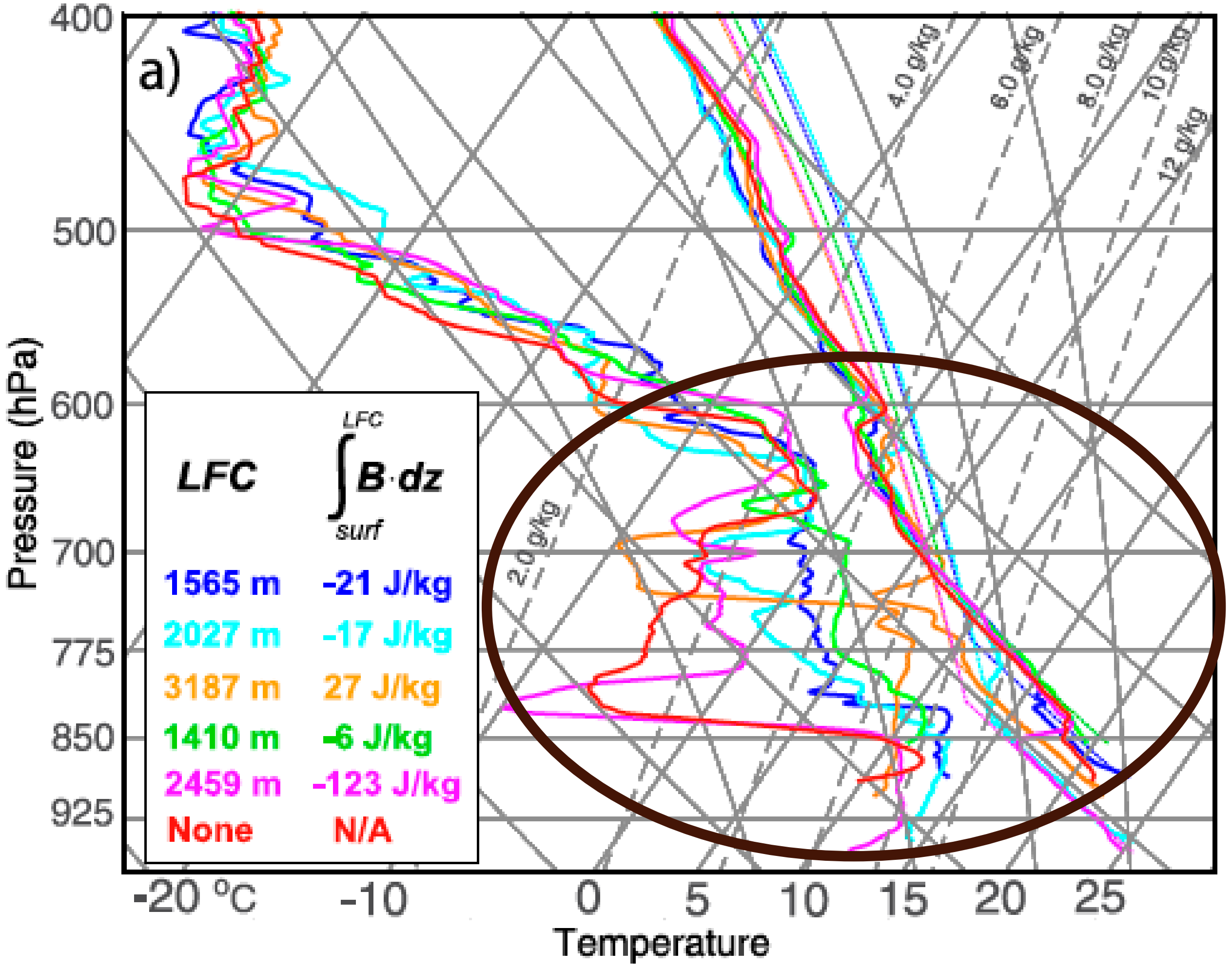
But there is still room for improvement:

Convective precipitation initiation and growth is extremely sensitive to low level moisture and stability that is often highly variable (and thus uncertain) on scales as small as O(10 km)

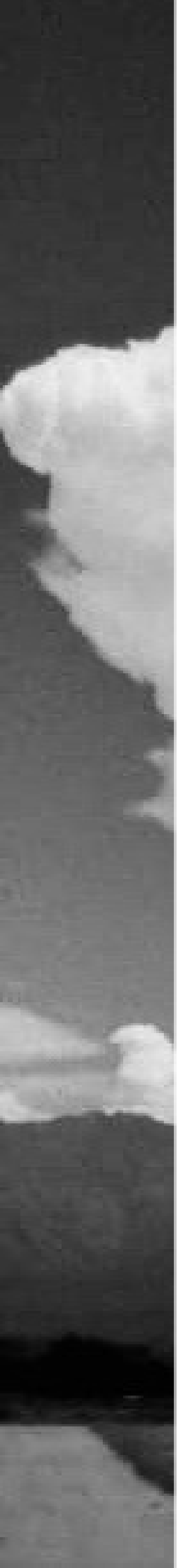
Primary convective updraft circulations remain under-resolved and too wide in km-scale models

Some precipitation biases have persisted due to physics (especially microphysics) parameterization shortcomings

RELAMPAGO-CACTI soundings separated by ~30 km launched at the same time (noon) across mountainous terrain

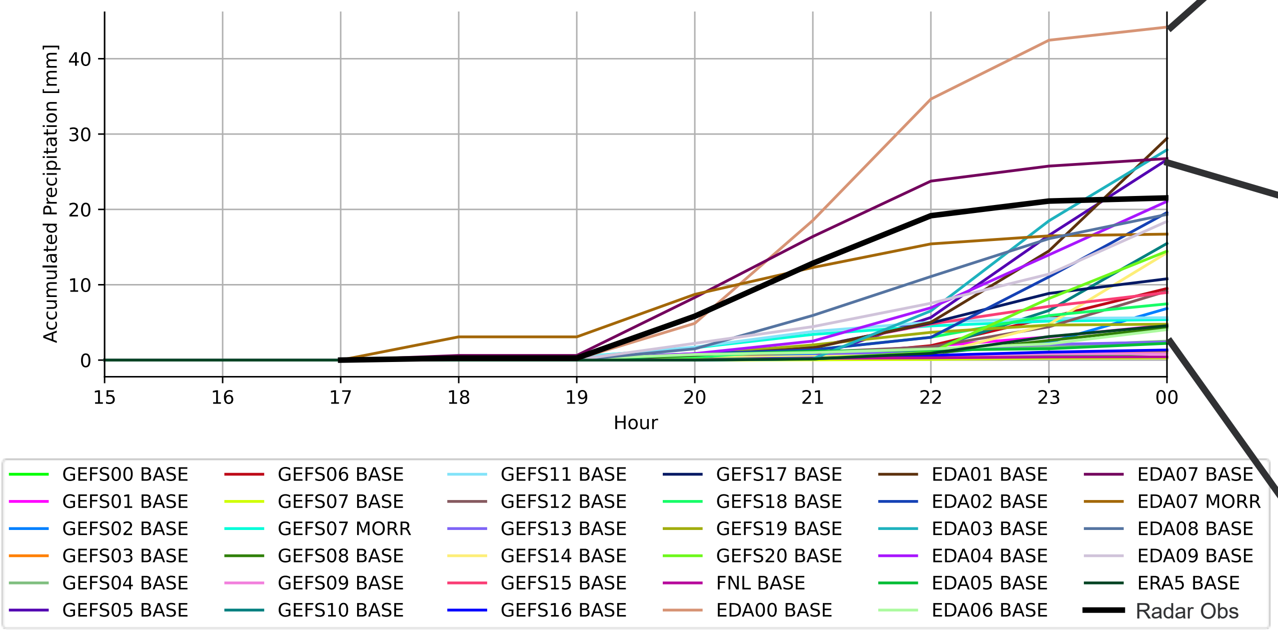


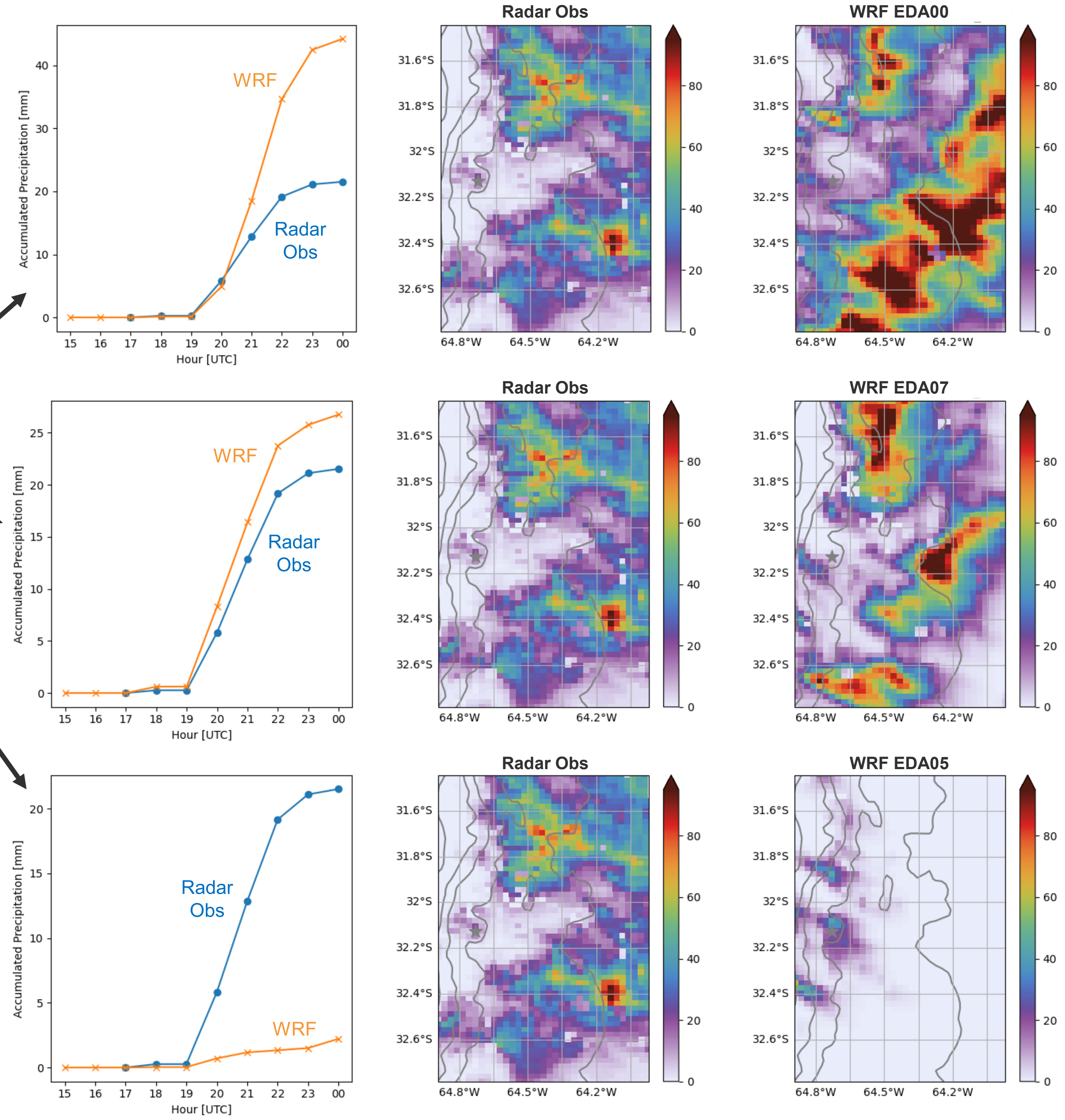
Marquis et al. (2021)



Initial/boundary condition ensembles with slight differences often produce a large spread in outcomes

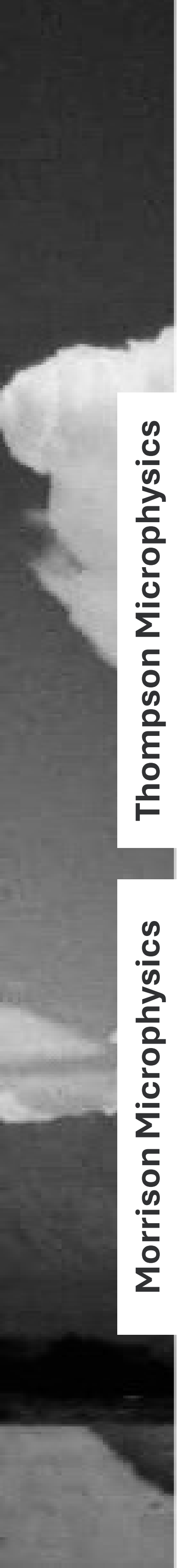
LASSO-CACTI 25 January 2019 Event 2.5-km WRF Accumulated Precipitation Ensemble



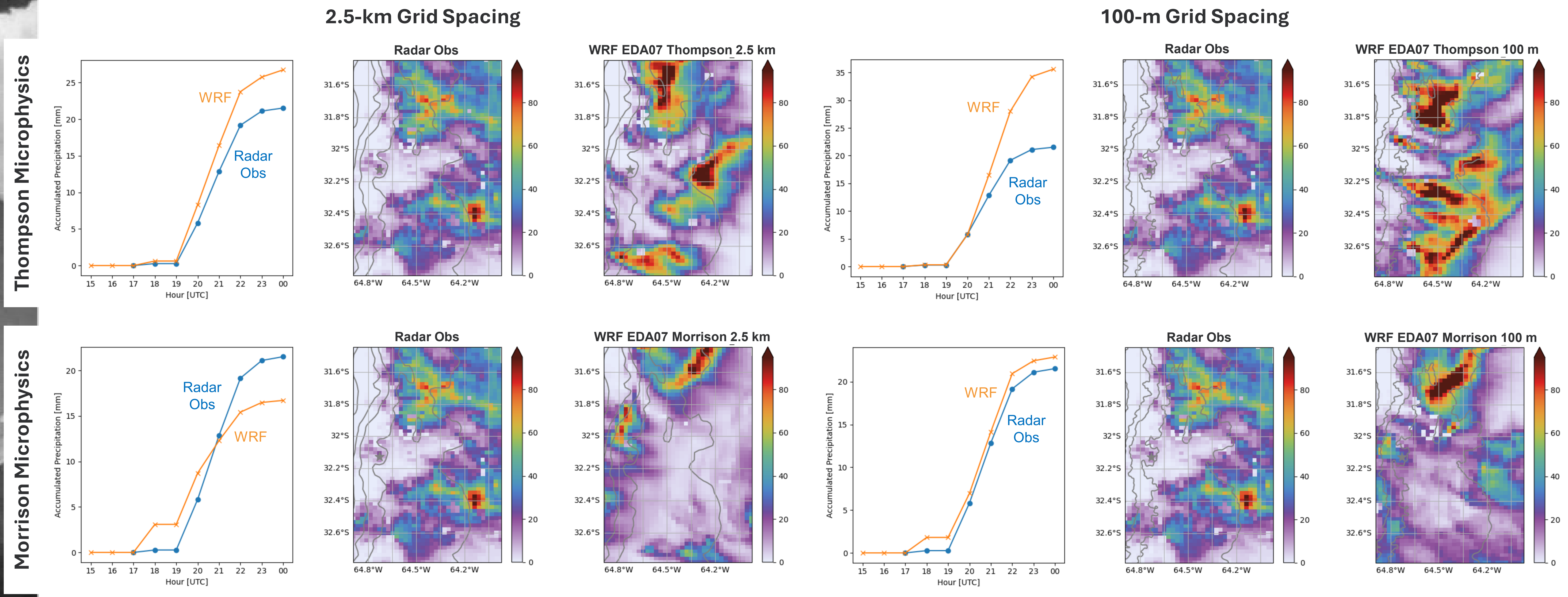


Source: https://adc.arm.gov/lasso/#/cacti/

Gustafson, WI, and coauthors. 2024. Description of the LASSO-CACTI Activity: A LASSO Scenario for Orographically Forced Deep Convection. DOE Atmospheric Radiation Measurement user facility. DOE/SC-ARM-TR-288, https://lasso-cacti-doc.arm.gov/latest/index.html, https://doi.org/10.2172/1905845



Model resolution and microphysics representation also change predictions, but it's unclear if changes are systematic



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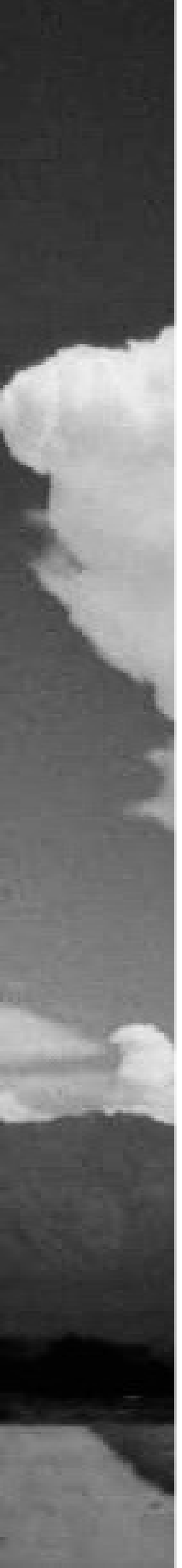
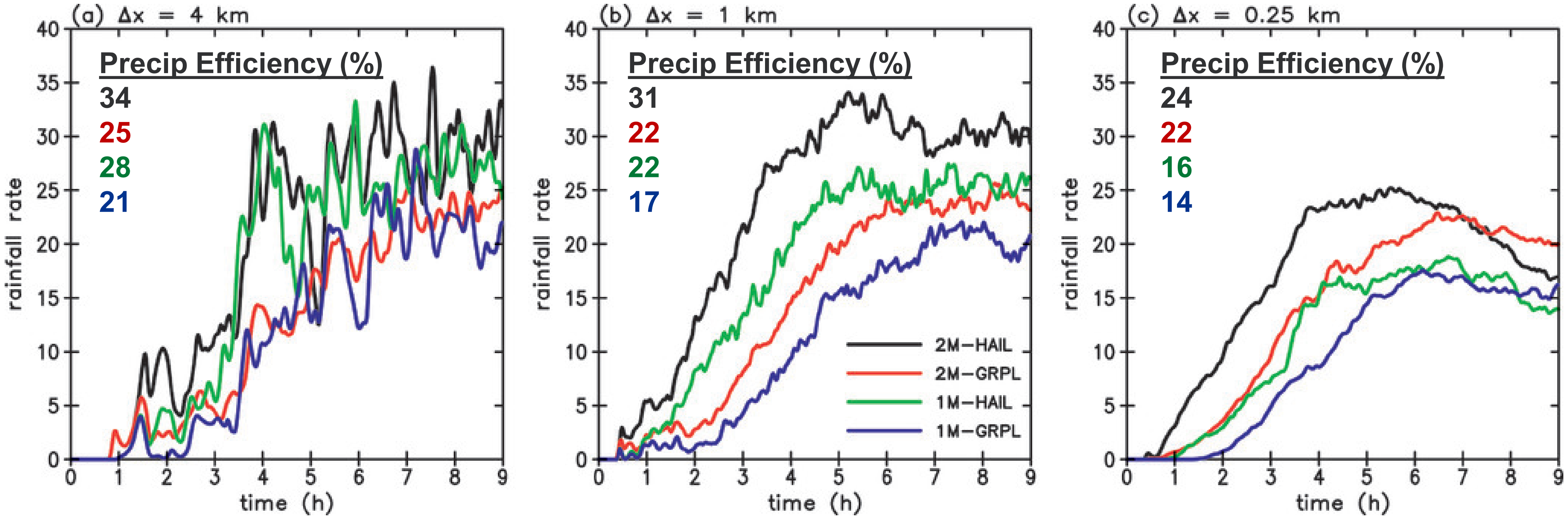


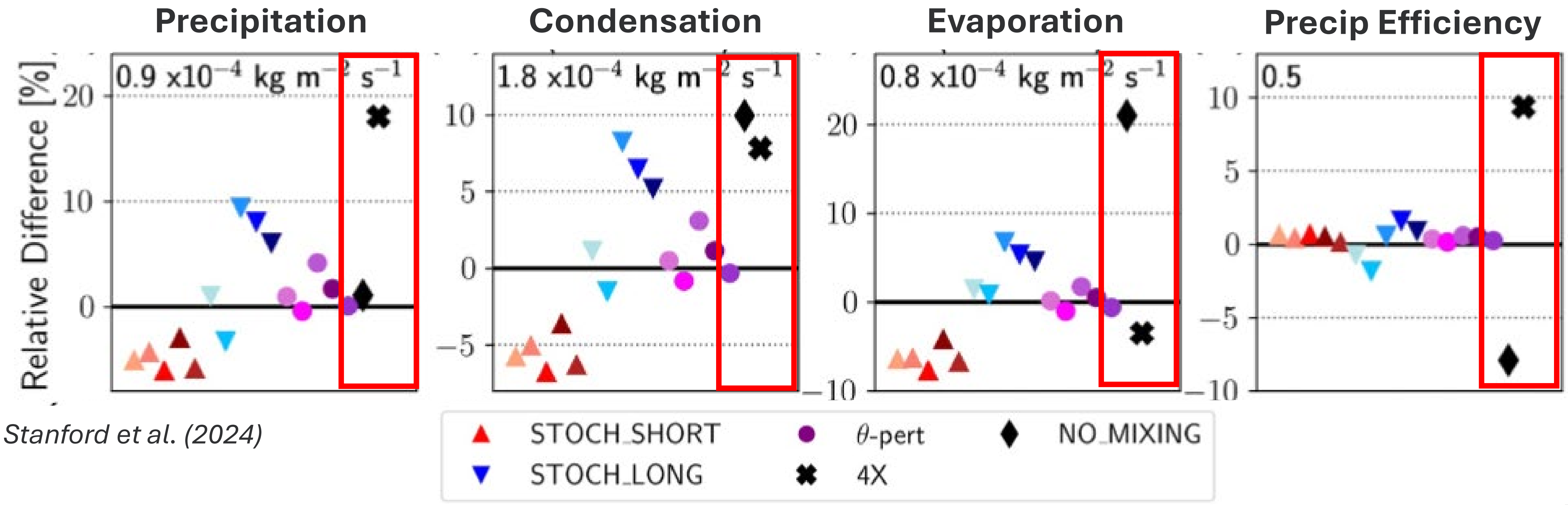
Model resolution, mixing, and microphysics modulate precipitation efficiency

Idealized Squall Line Simulations



Bryan and Morrison (2012)

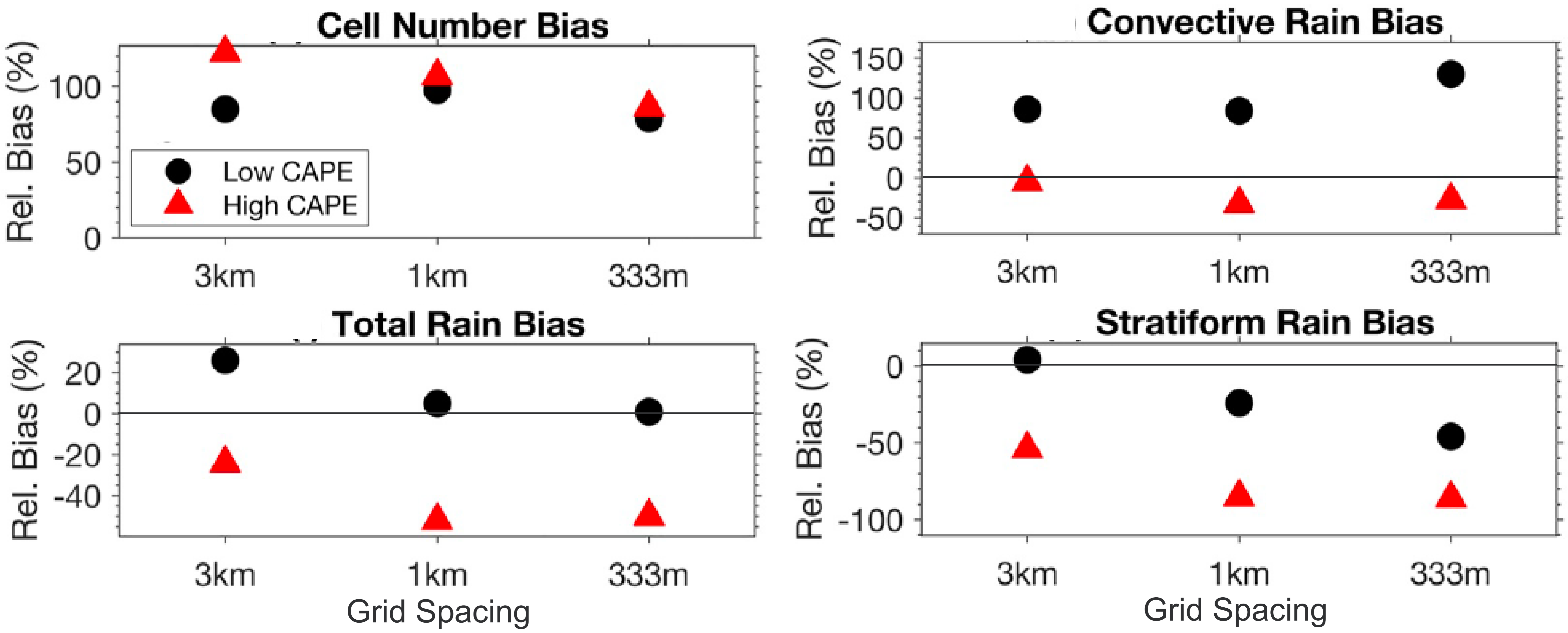
Real Case, 3-km Tropical Oceanic Deep Convection WRF Simulations



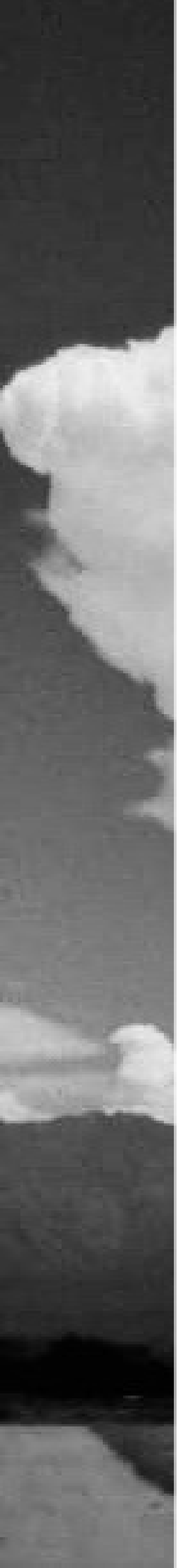
Stanford et al. (2024)

But…increasing resolution fails to eliminate convective precipitation biases and such biases vary as a function of CAPE

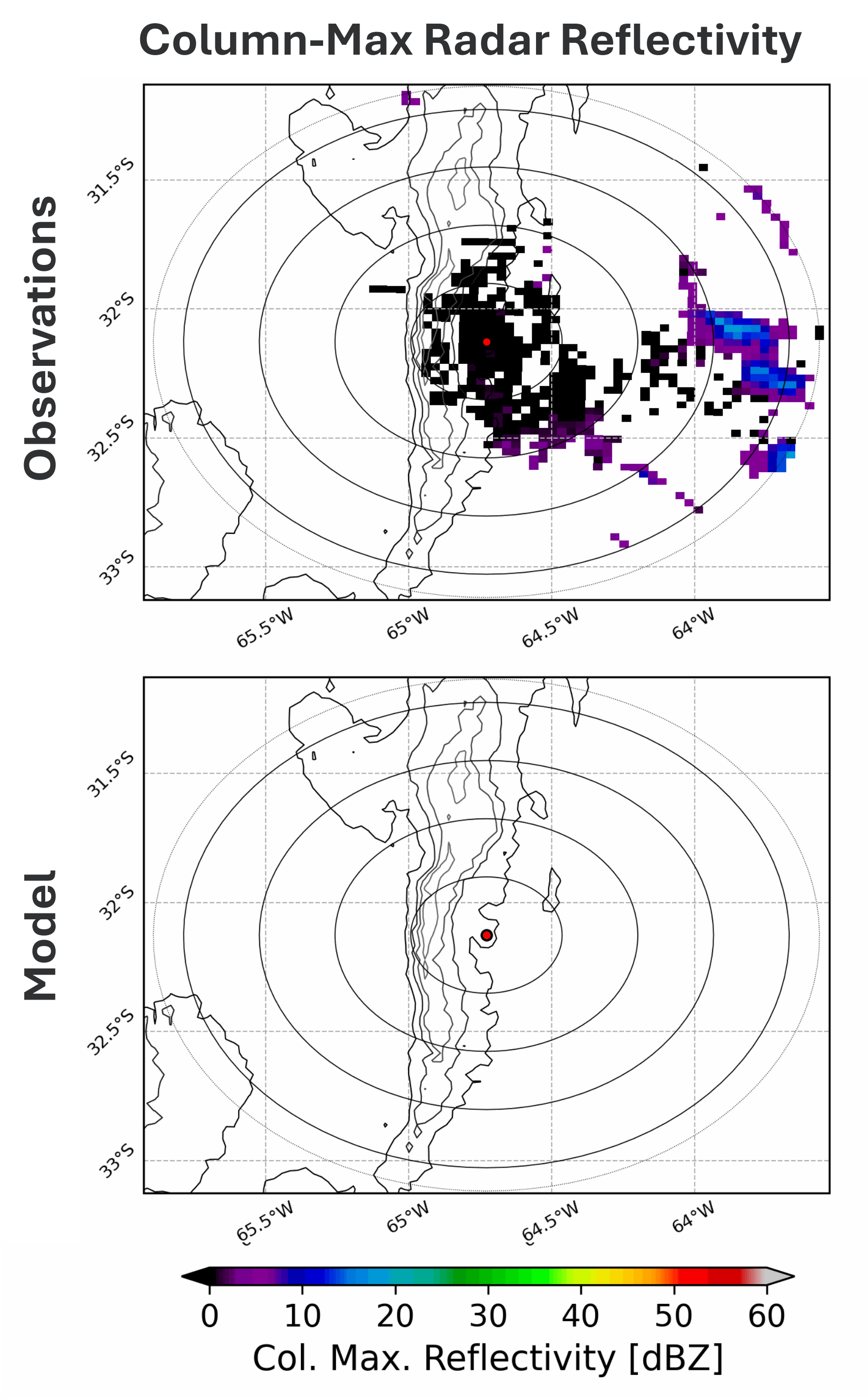
CACTI Low and High CAPE Event WRF Simulations With Differing Model Resolution

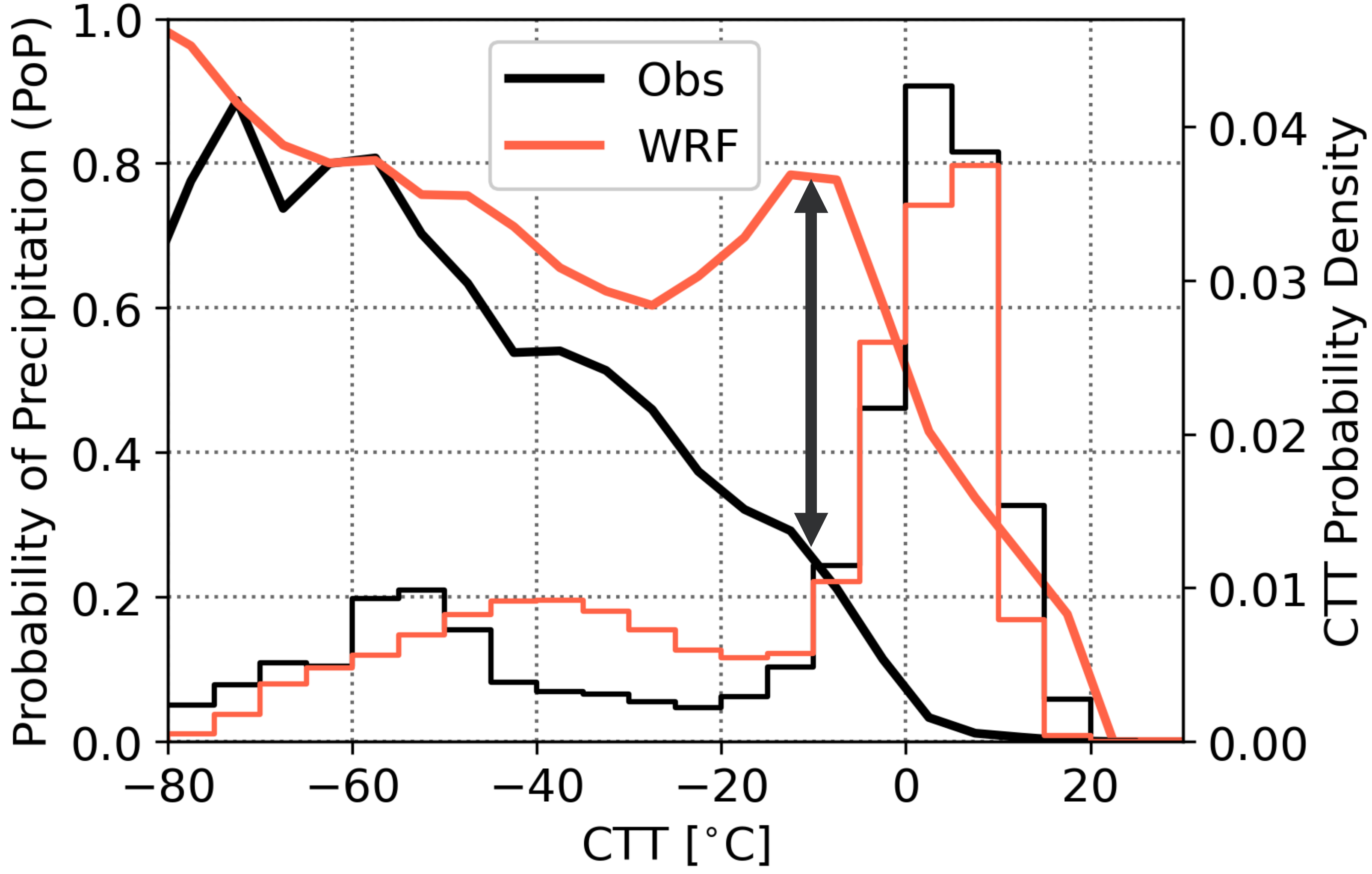


Zhang et al. (2024)

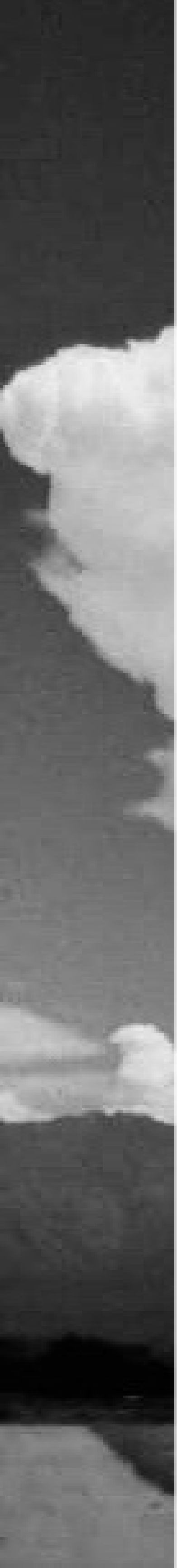


Orographic cumulus congestus clouds rain too frequently

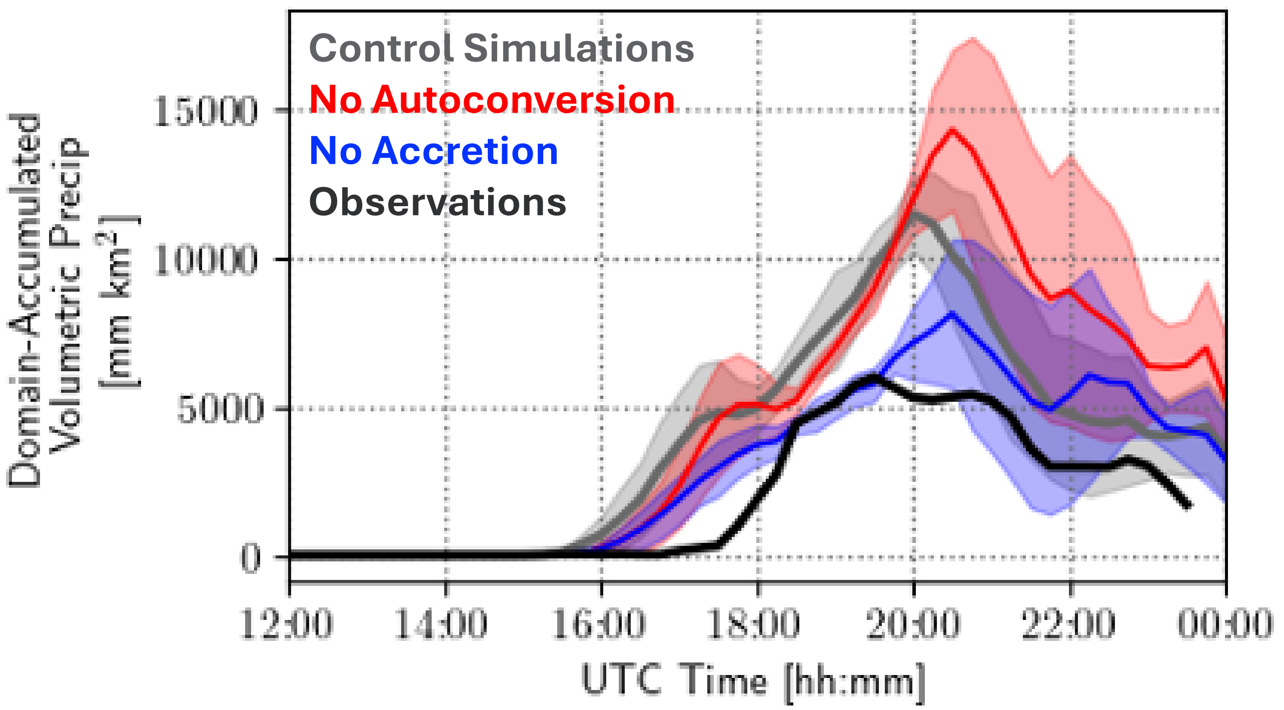




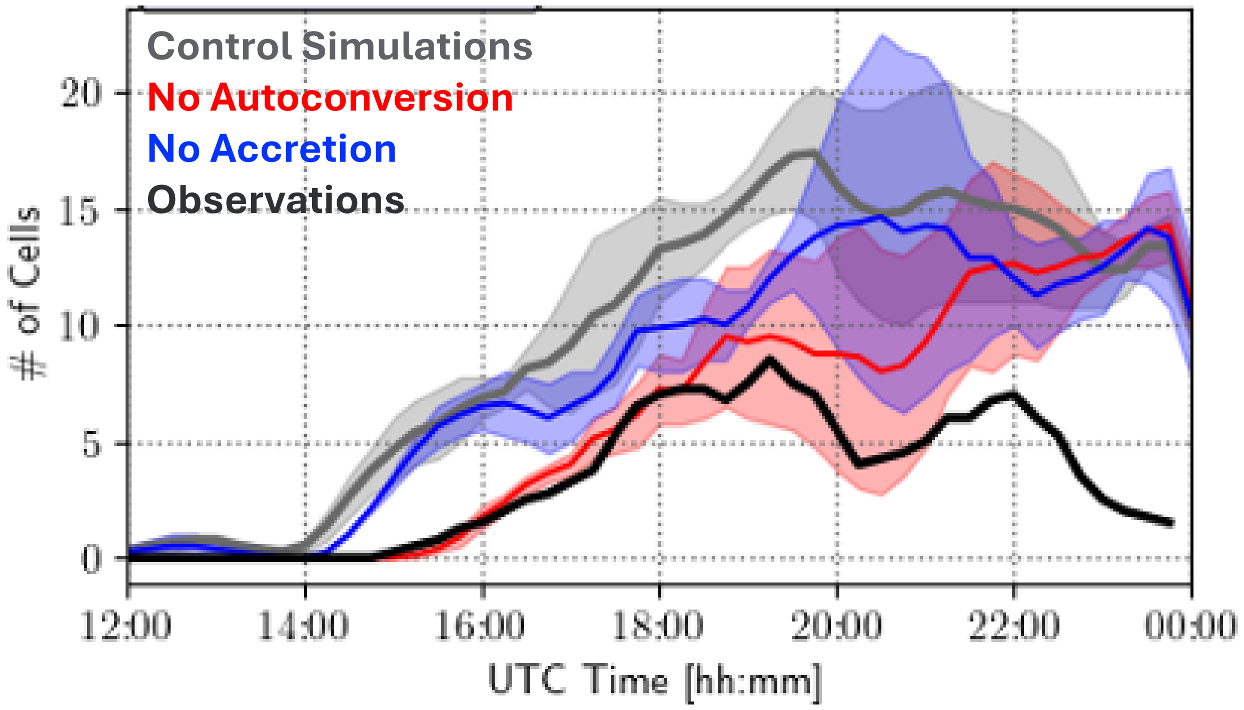
Courtesy: McKenna Stanford (PNNL)

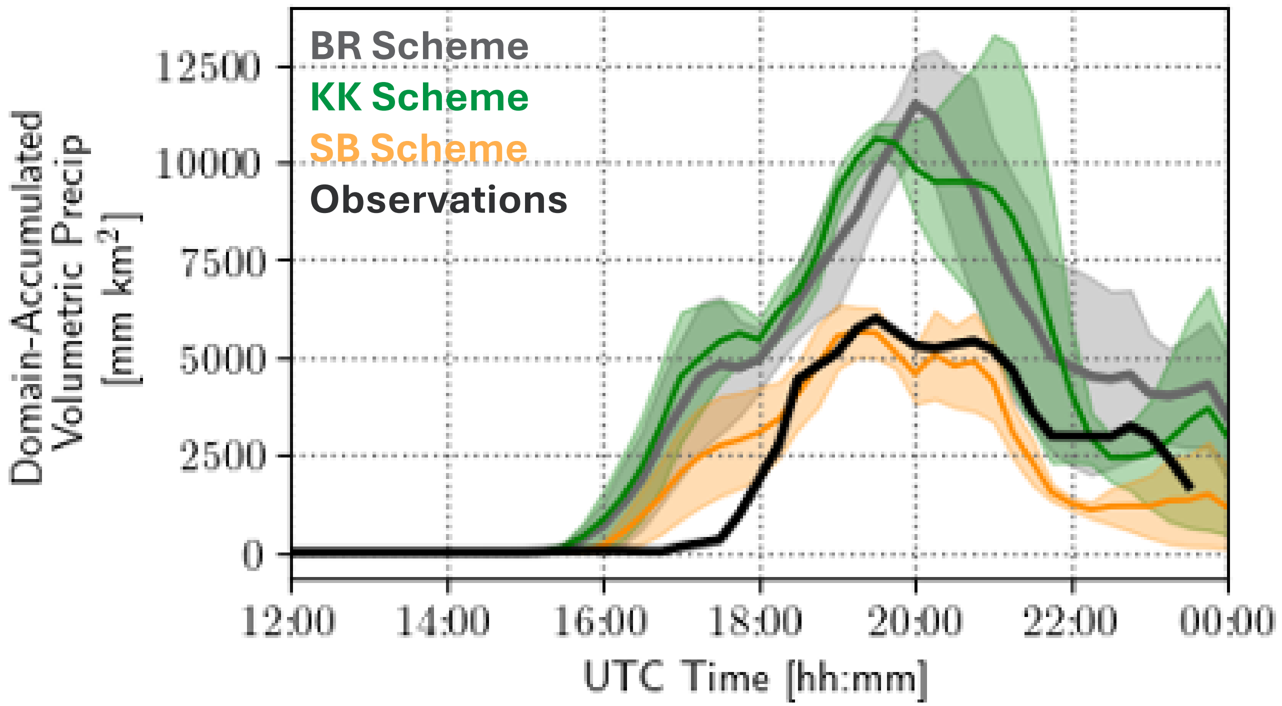


Autoconversion and accretion bulk parameterizations contribute to excessive convective cell number and variable effects on rainfall



CACTI 29 January 2019 Event Sensitivity to Autoconversion and Accretion





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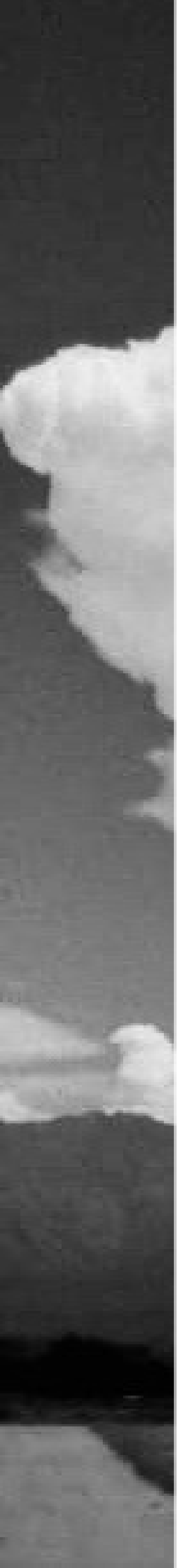
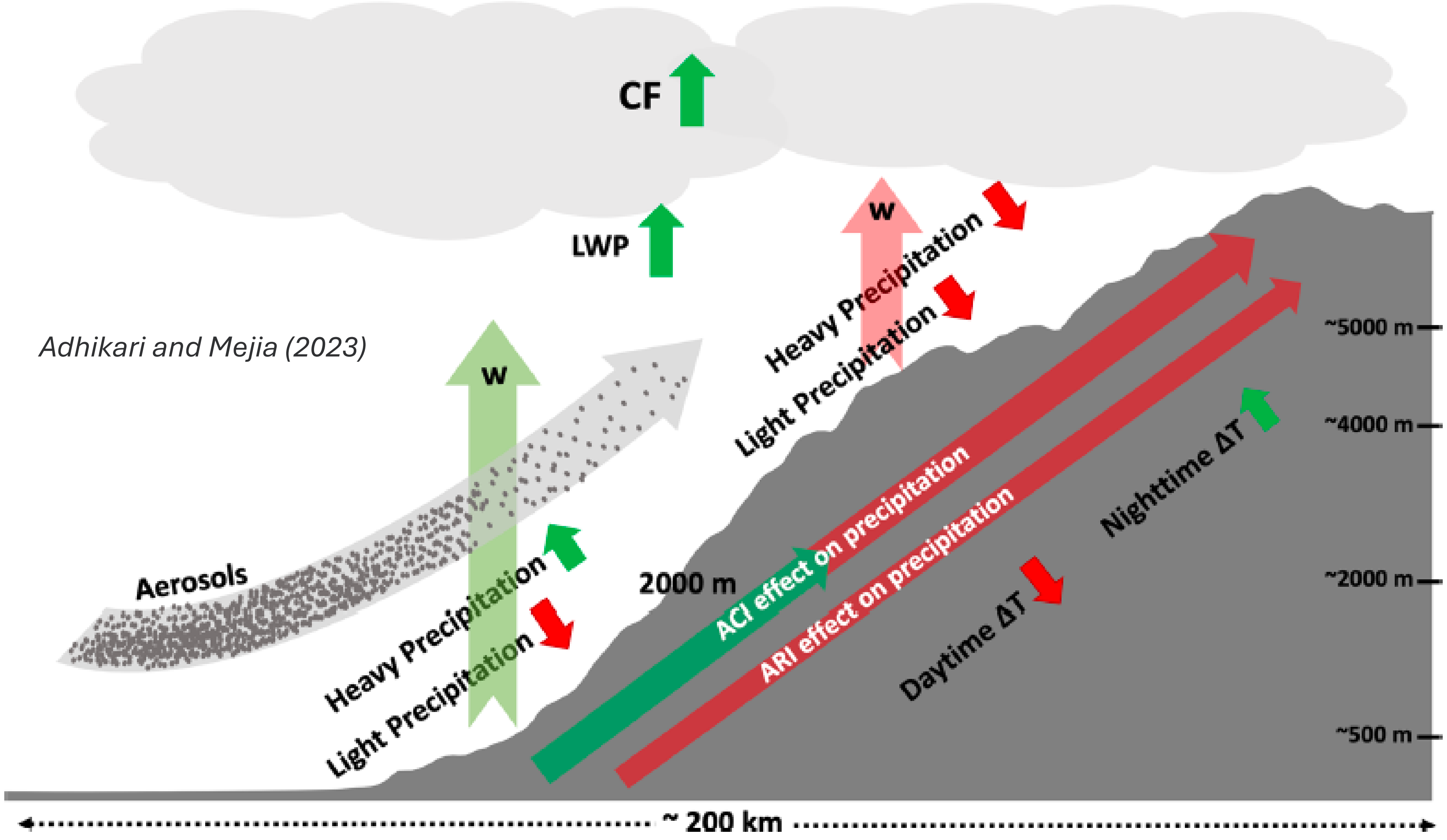
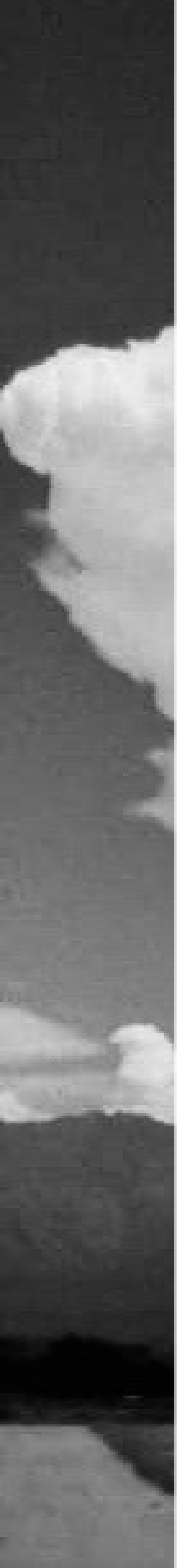


Aerosols can affect stability and warm rain, but effects remain uncertain and are often not fully represented in models

Aerosol Effects on Himalayan Monson Precipitation Based on 1-month 3-km WRF-Chem Simulations

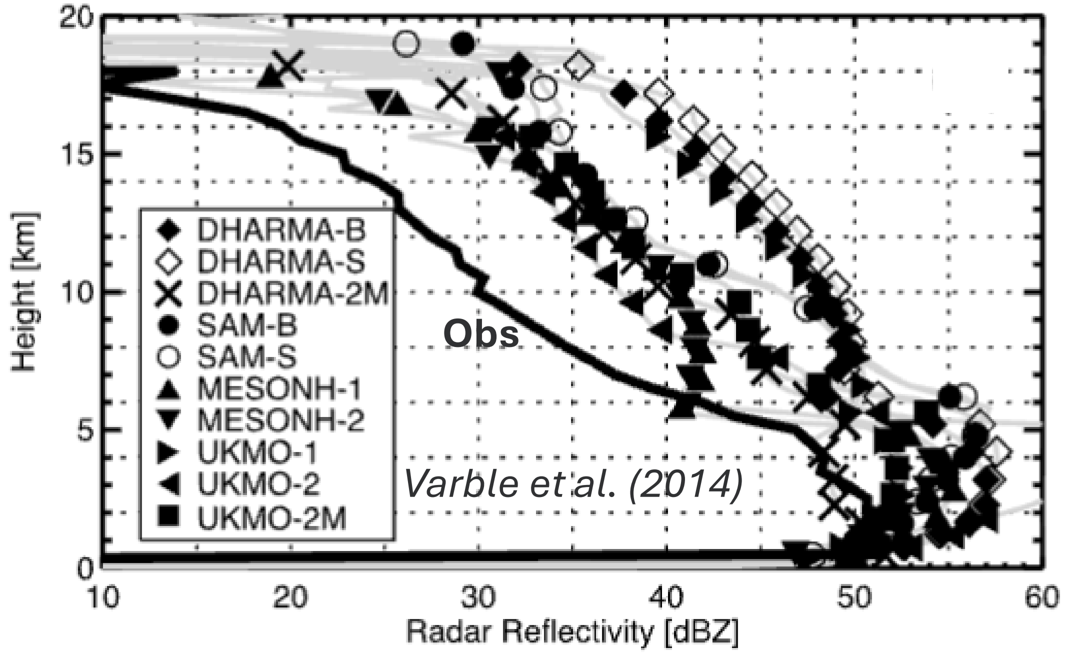
Adhikari and Mejia (2023)



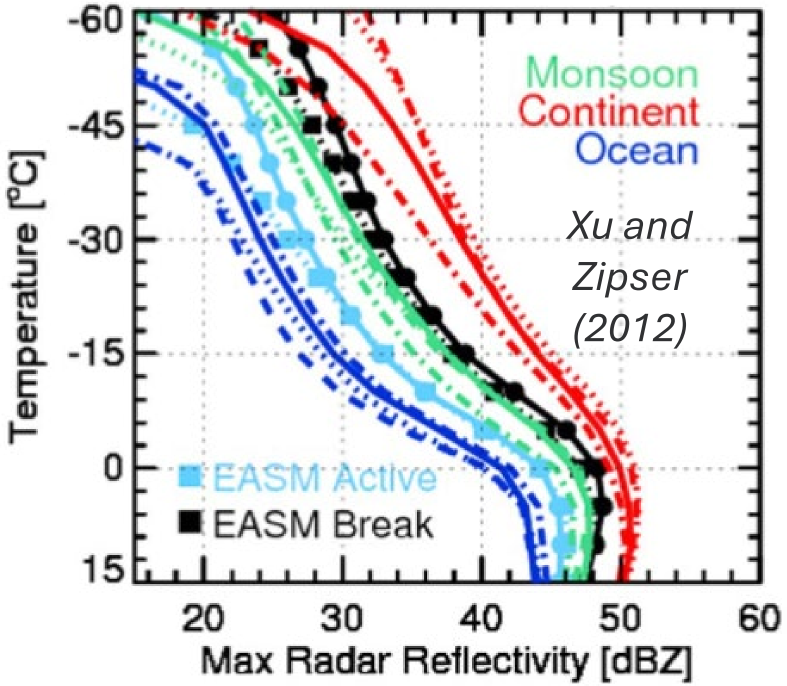


Current microphysics parameterizations tend to produce excessive supercooled liquid, riming, and ice size that likely impacts precipitation efficiency

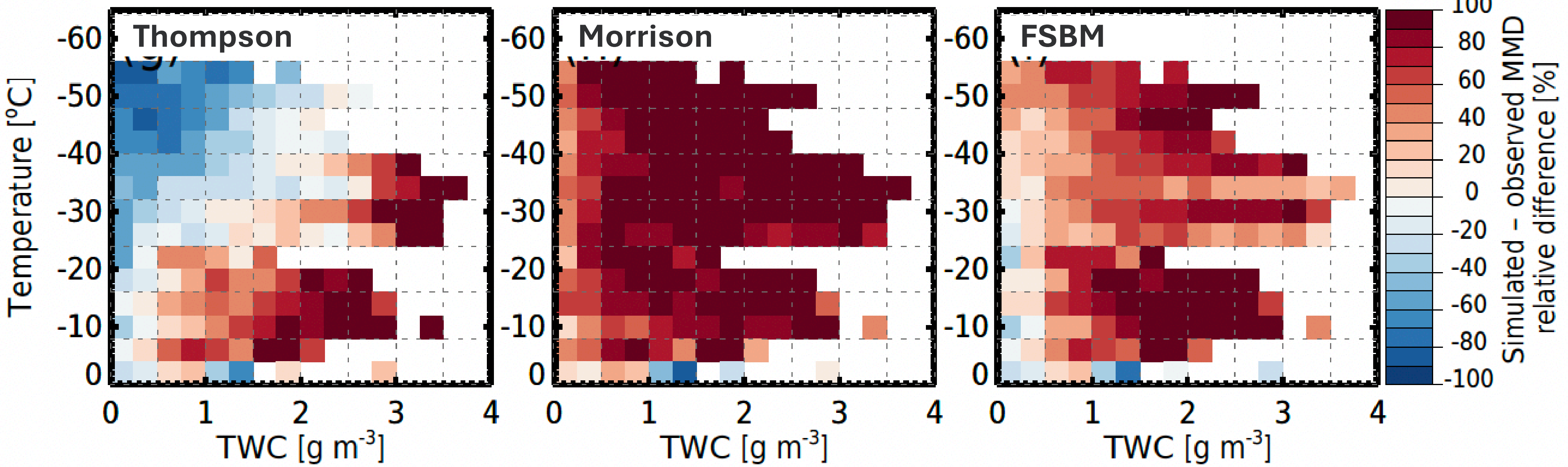
Km-Scale Model Median Tropical MCS Convective Radar Reflectivity vs. Observations



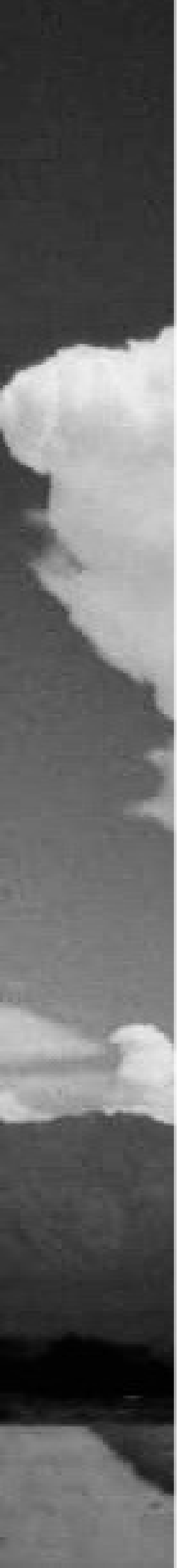
Observed Top 10% Radar Reflectivity Profiles By Region



Differences of Simulated and Aircraft Observed Hydrometeor Median Mass Diameters in 3 Microphysics Schemes

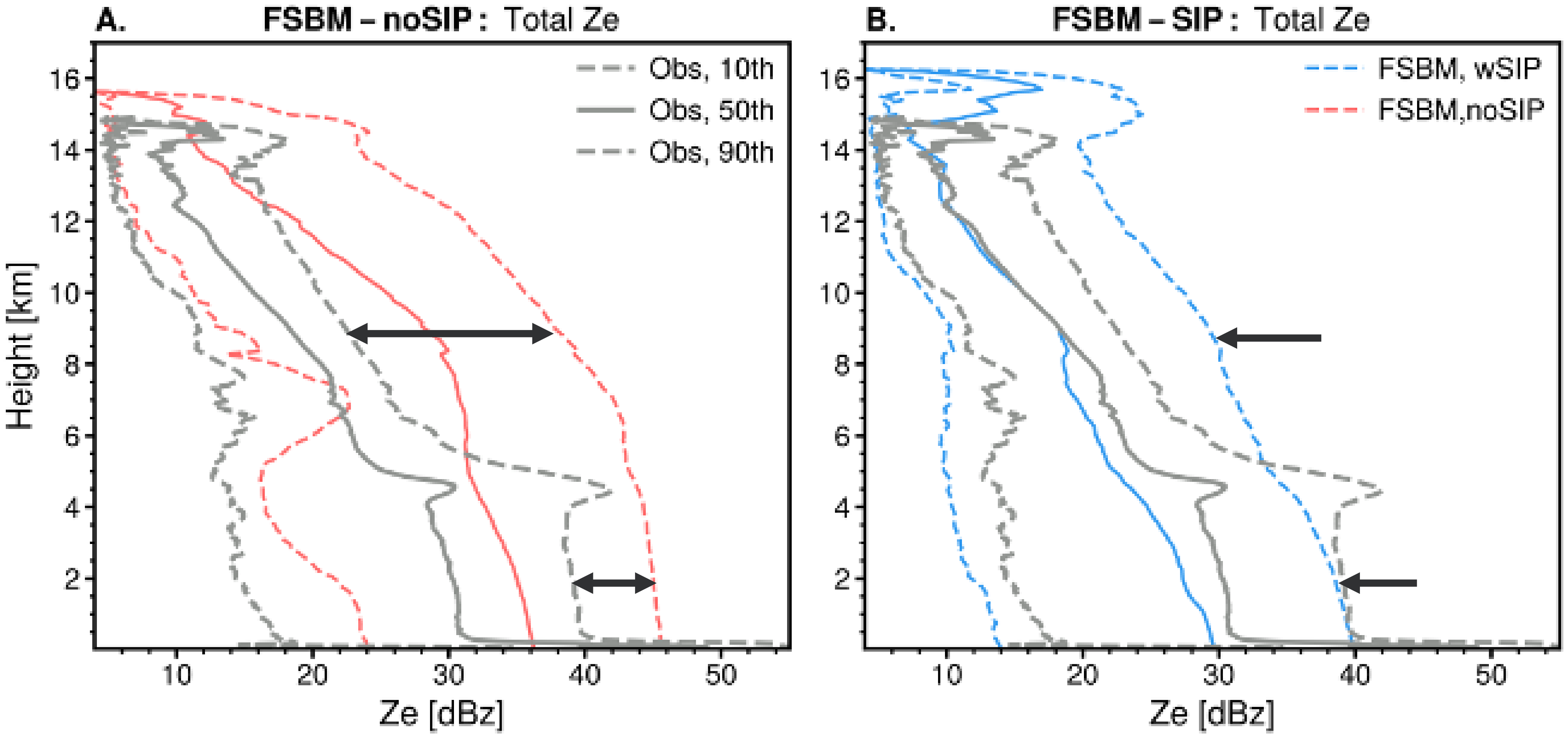


Stanford et al. (2017)



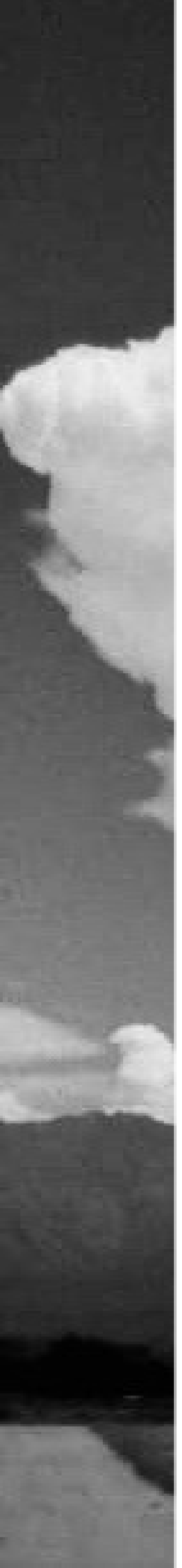
Mixed phase biases likely stem to a large degree from insufficient secondary ice production (SIP)

Observed vs. Bin Scheme Simulated Atlantic ITCZ MCS Radar Reflectivity Profiles

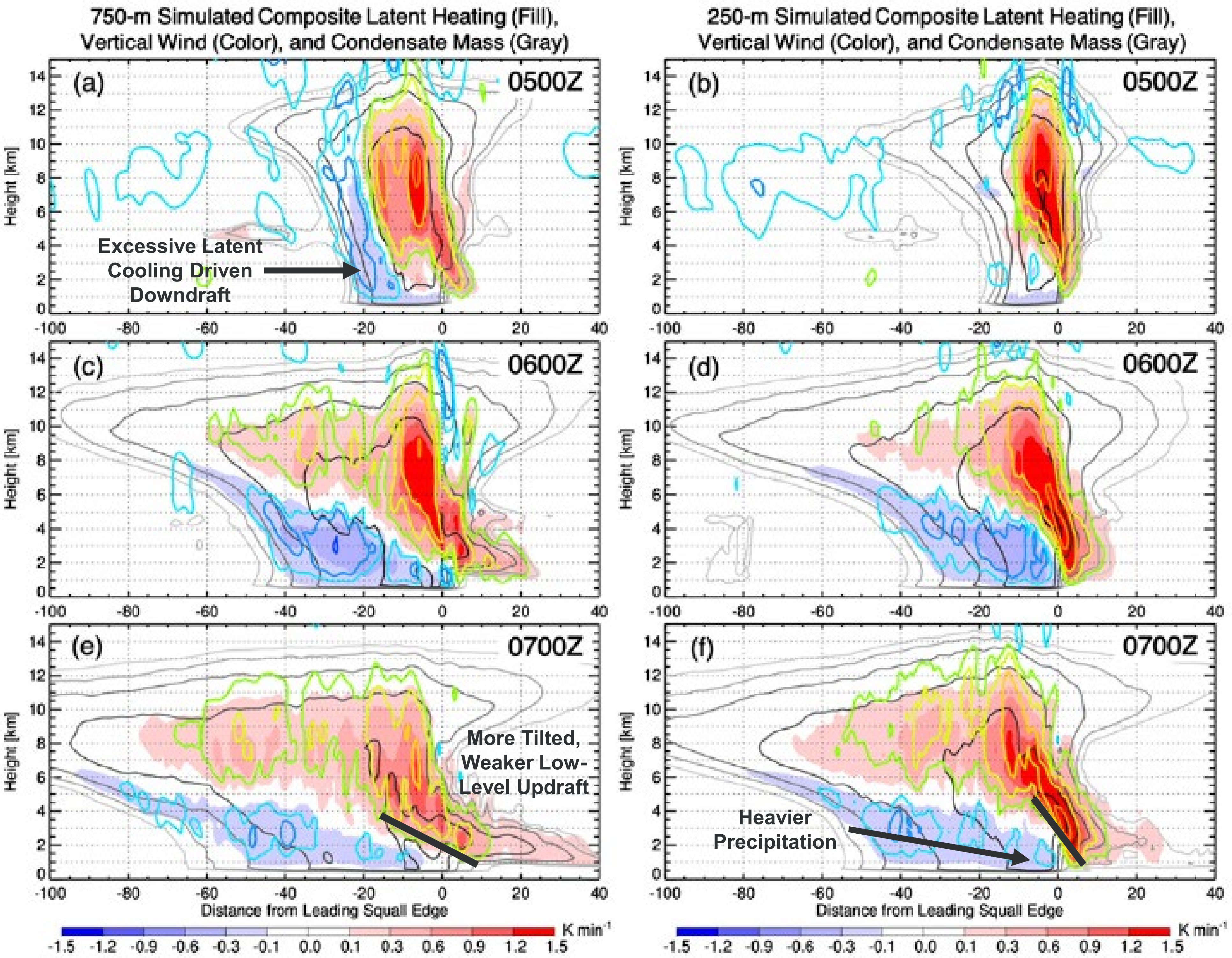


Courtesy: Jacob Shpund (former PNNL, now Hebrew U. of Jerusalem)

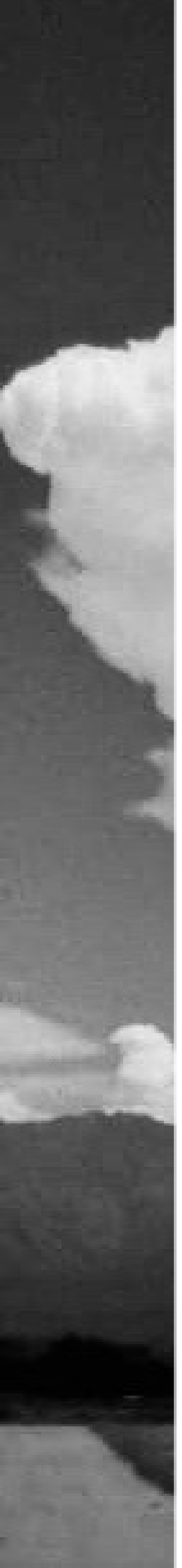
Aircraft in situ measurements of hydrometeor size distributions show simulations being more accurate (order of magnitude increase in ice concentrations) with new raindrop fragmentation and/or ice collisional breakup SIP processes parameterized



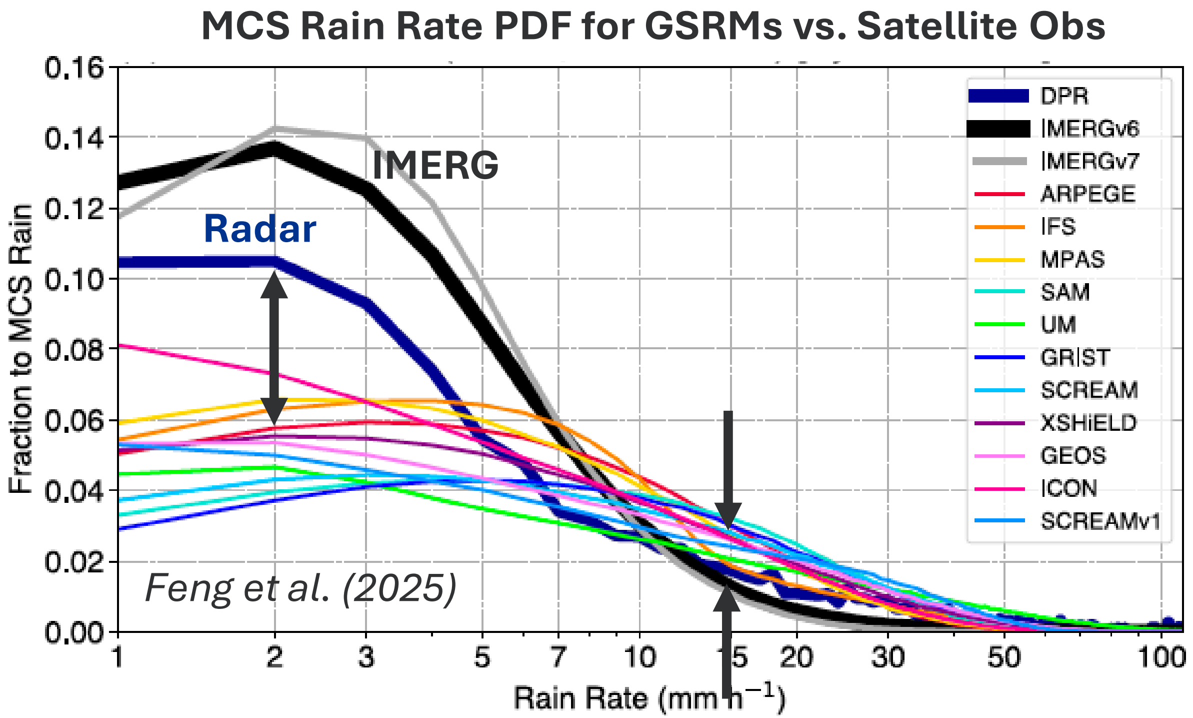
Storm upscale growth is also impacted by resolution and microphysics regulated downdrafts that affect convective tilt, propagation, and precipitation



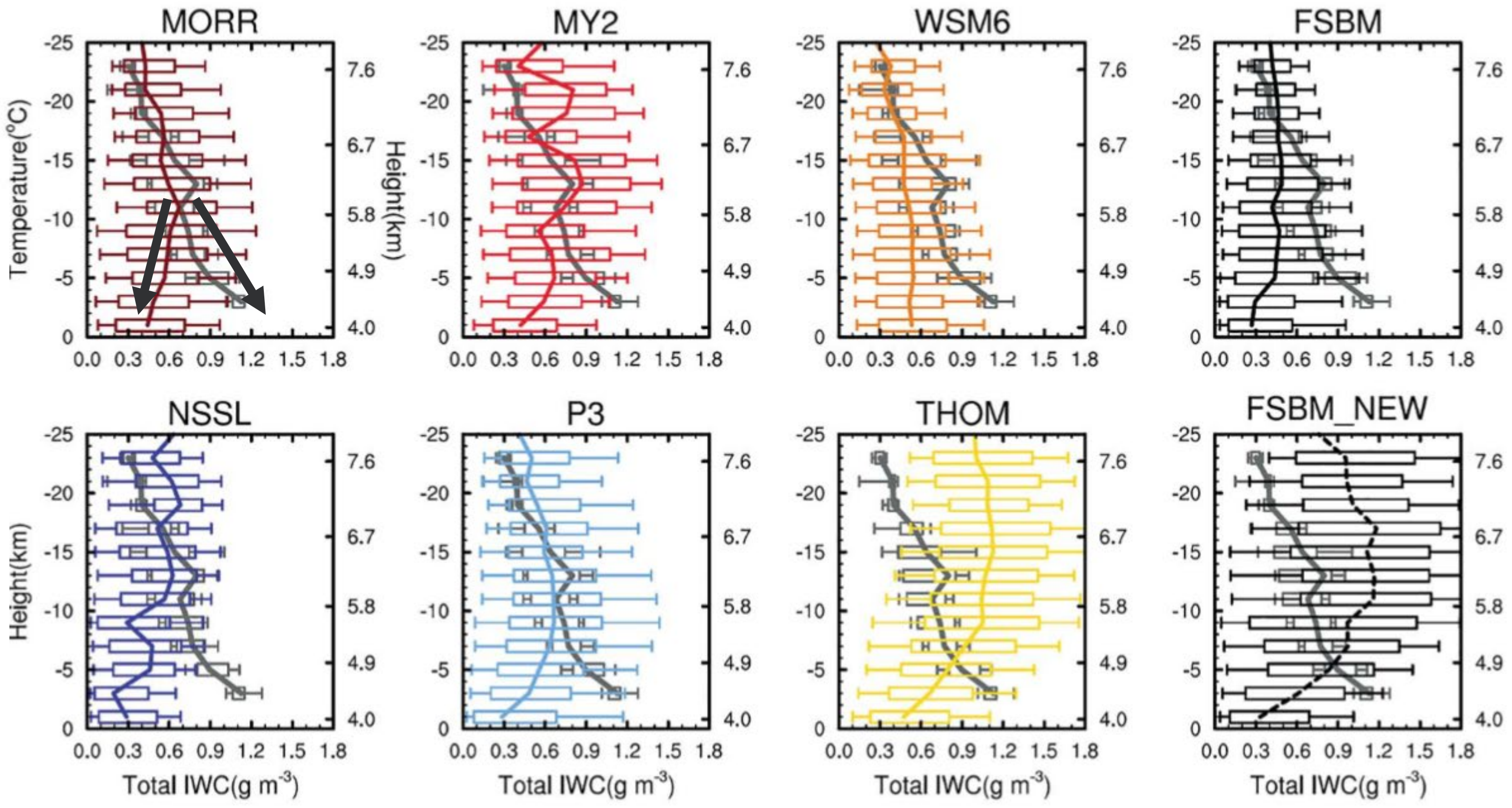
Varble et al. (2020)



Reducing convective-stratiform partitioning biases should be a key target because this bias (excessive convective, suppressed stratiform) is robust, observable, and depends on accurately representing updraft dynamics and microphysics



Simulated MCS Stratiform IWC Profiles (Color) Compared to Aircraft Obs (Gray)



Han et al. (2019)

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Concluding Perspectives

Given limitations in imperfect observations, transposition, and model evaluation, km-scale model ensembles may already be good enough to contribute to PMP estimates.

This is despite some persistent biases across common model setups in many meteorological scenarios including excessive riming that leads to excessive convective and suppressed stratiform rainfall.

O(100 m) grid spacing improves convective dynamics biases in km-scale models that affect precipitation efficiency and upscale growth, but these improvements do not overcome shortcomings in model microphysics parameterizations that may be more impactful.

Ongoing research is working to improve secondary ice, riming, autoconversion, and accretion processes, including sensitivities to aerosols, that are common sources for convective rainfall biases in bulk (and bin, perhaps to a lesser extent) schemes.

Because of computing limitations, emulators may be needed to allow for fast, inexpensive (i) parameterizations trained on more expensive, more accurate physics constrained by measurements and (ii) large ensembles capable of quantifying extremes.

Training data runs would need to sufficiently cover the spread of meteorological scenarios supportive of extreme precipitation events.

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Contact: adam.varble@pnnl.gov

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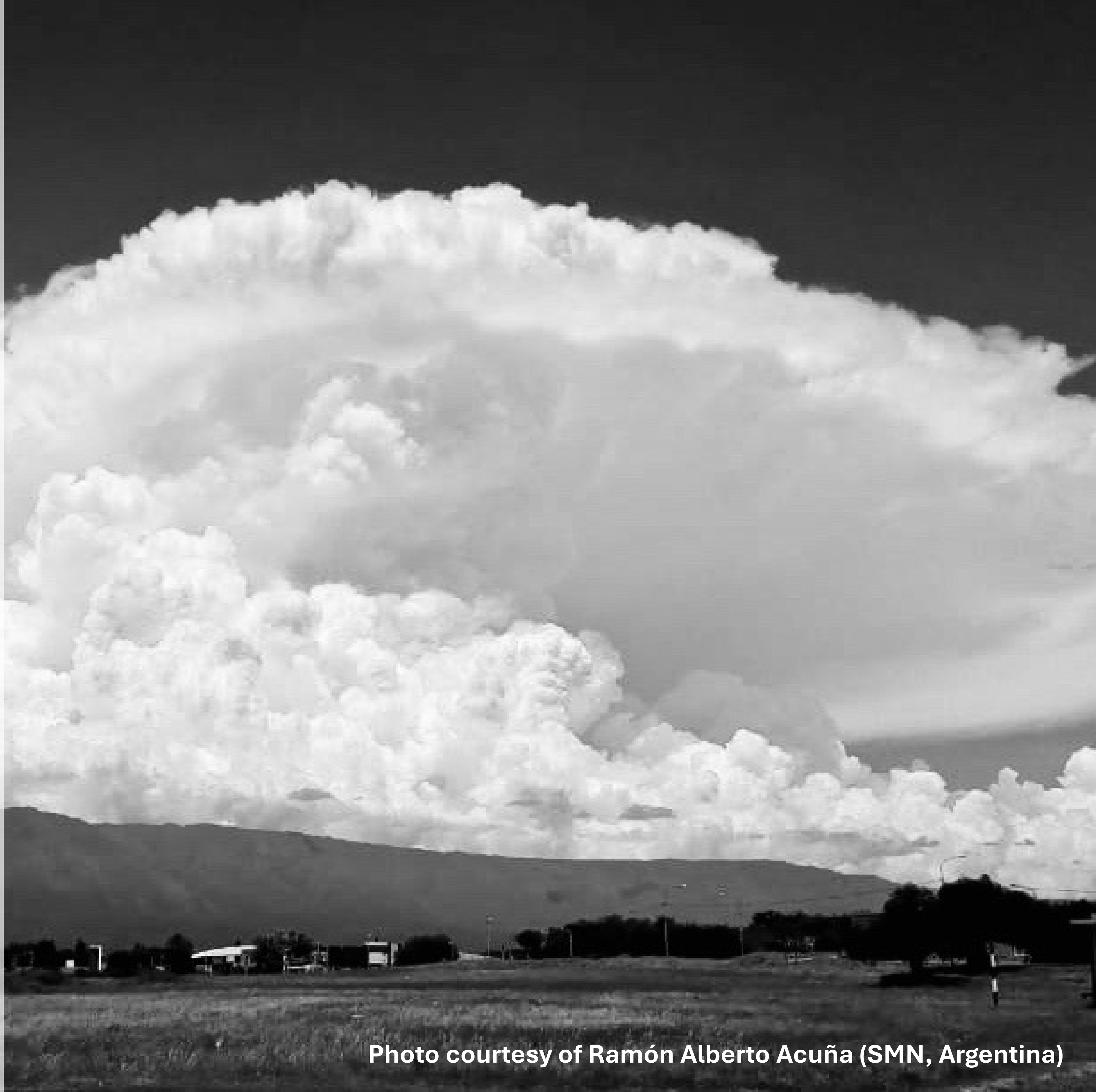

Photo courtesy of Ramón Alberto Acuña (SMN, Argentina)

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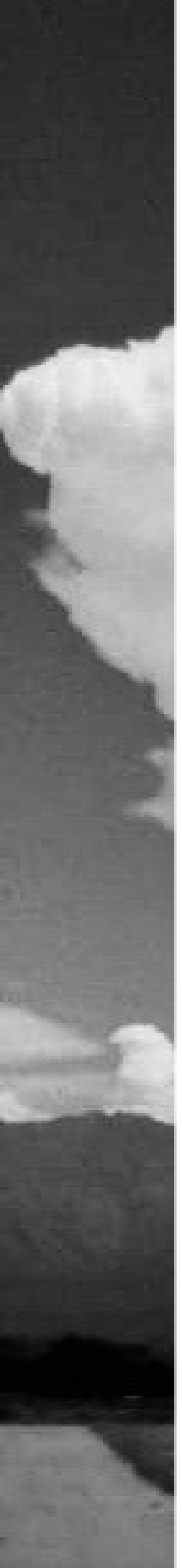
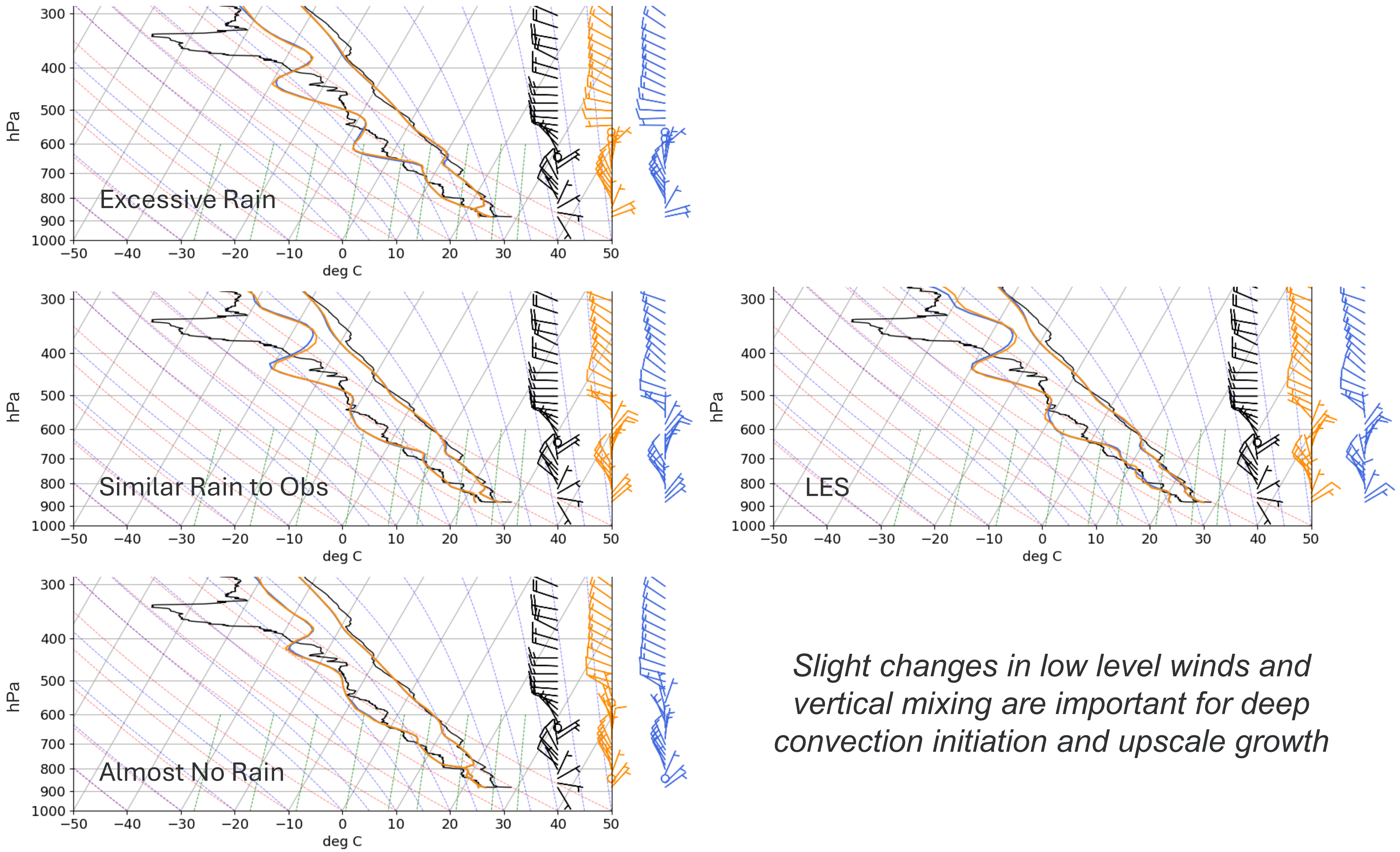


Initial/ boundary condition ensembles with slight differences often produce very large spread

25 January 2019 2.5-km WRF Ensemble Member Noon Soundings



Slight changes in low level winds and vertical mixing are important for deep convection initiation and upscale growth

Source: https://adc.arm.gov/lasso/#/cacti/

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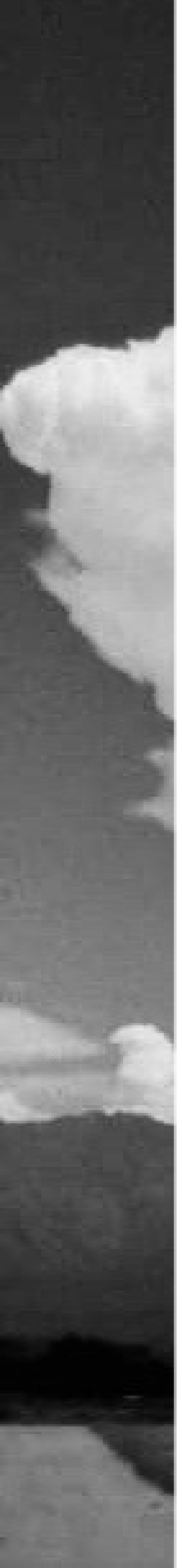

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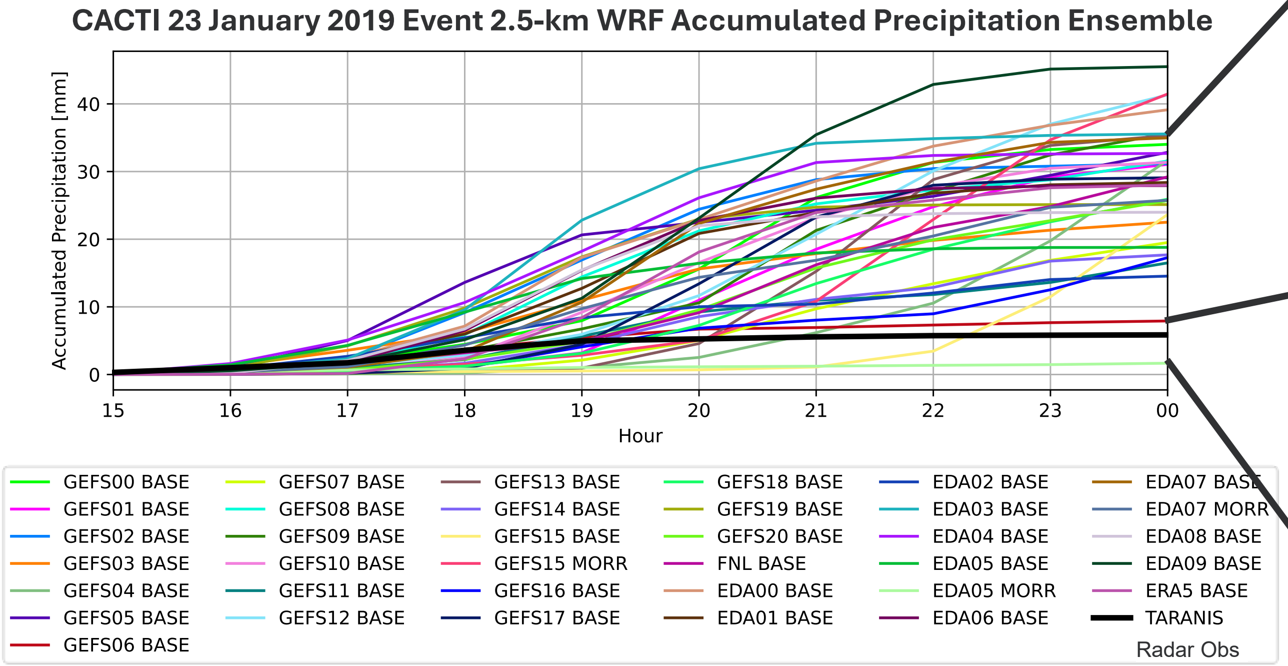

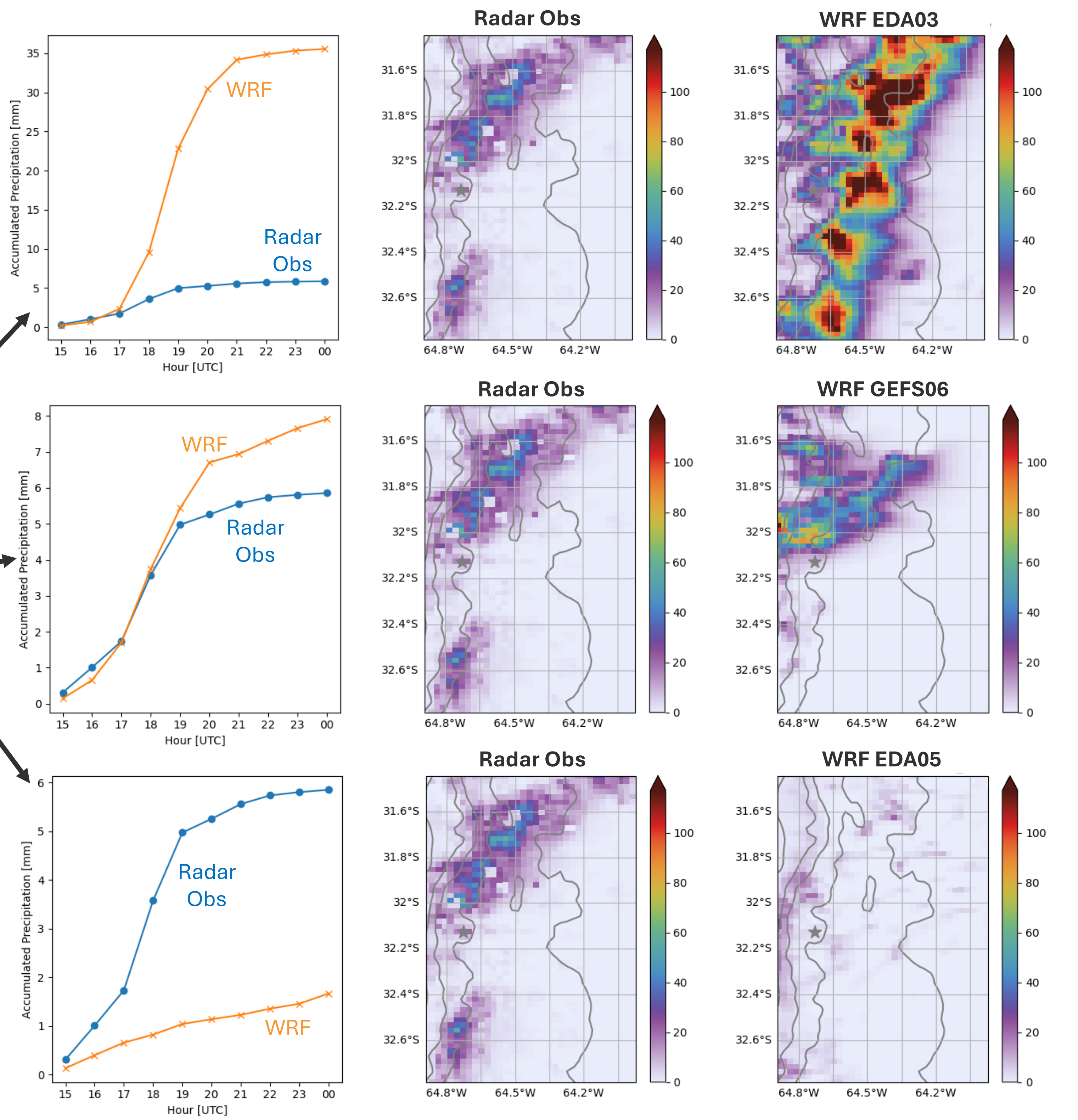

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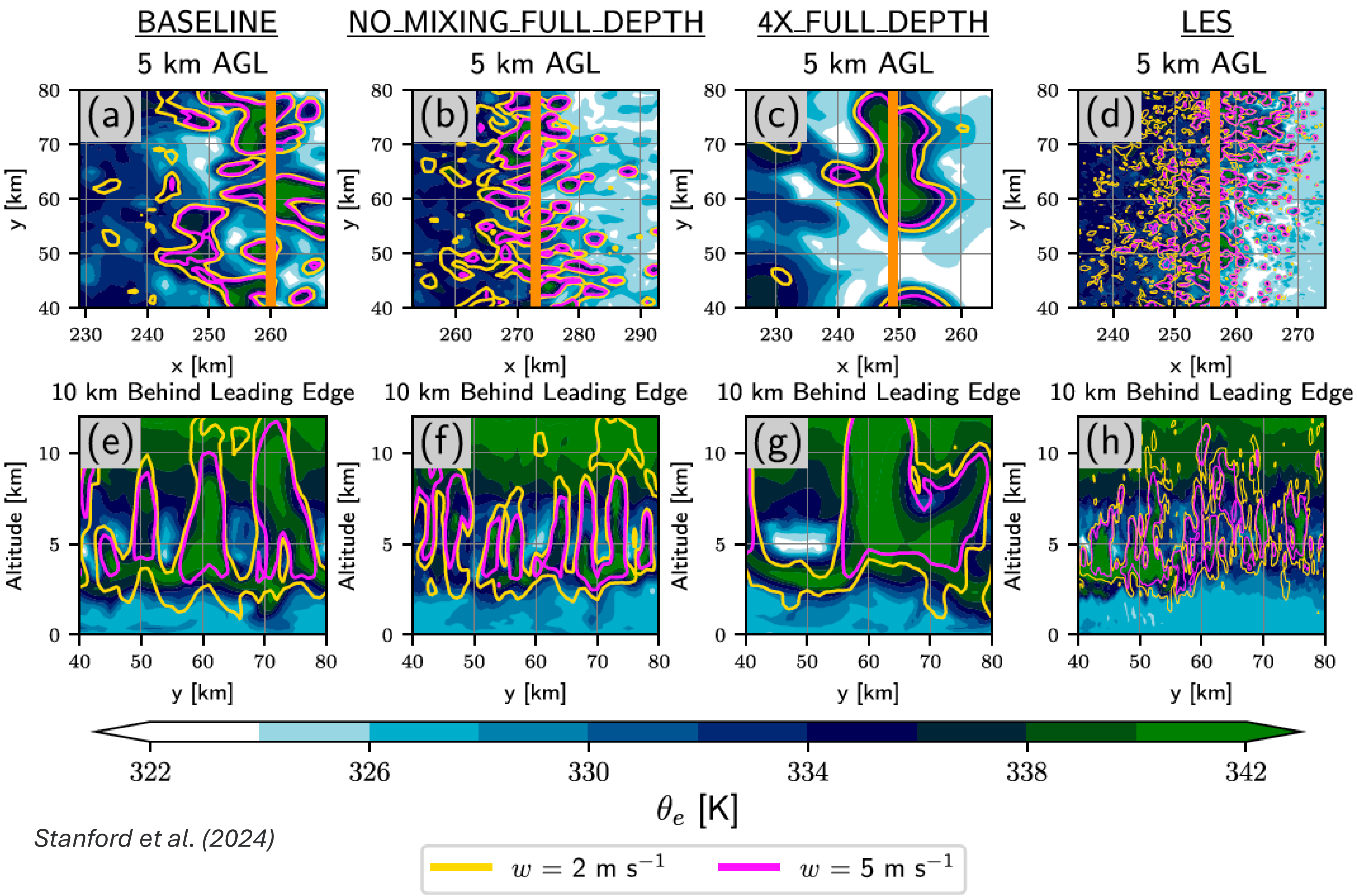
More numerous, smaller convective drafts result in more continuous thermodynamic (and precipitation) fields



Stanford et al. (2024)

Models may have an important role to play in quantifying low level accretion potential that can greatly amplify rain rates, but which is often poorly observed

Example Elevated Convection Seeding Low Level Drizzling Fog in Blocked Flow During CACTI

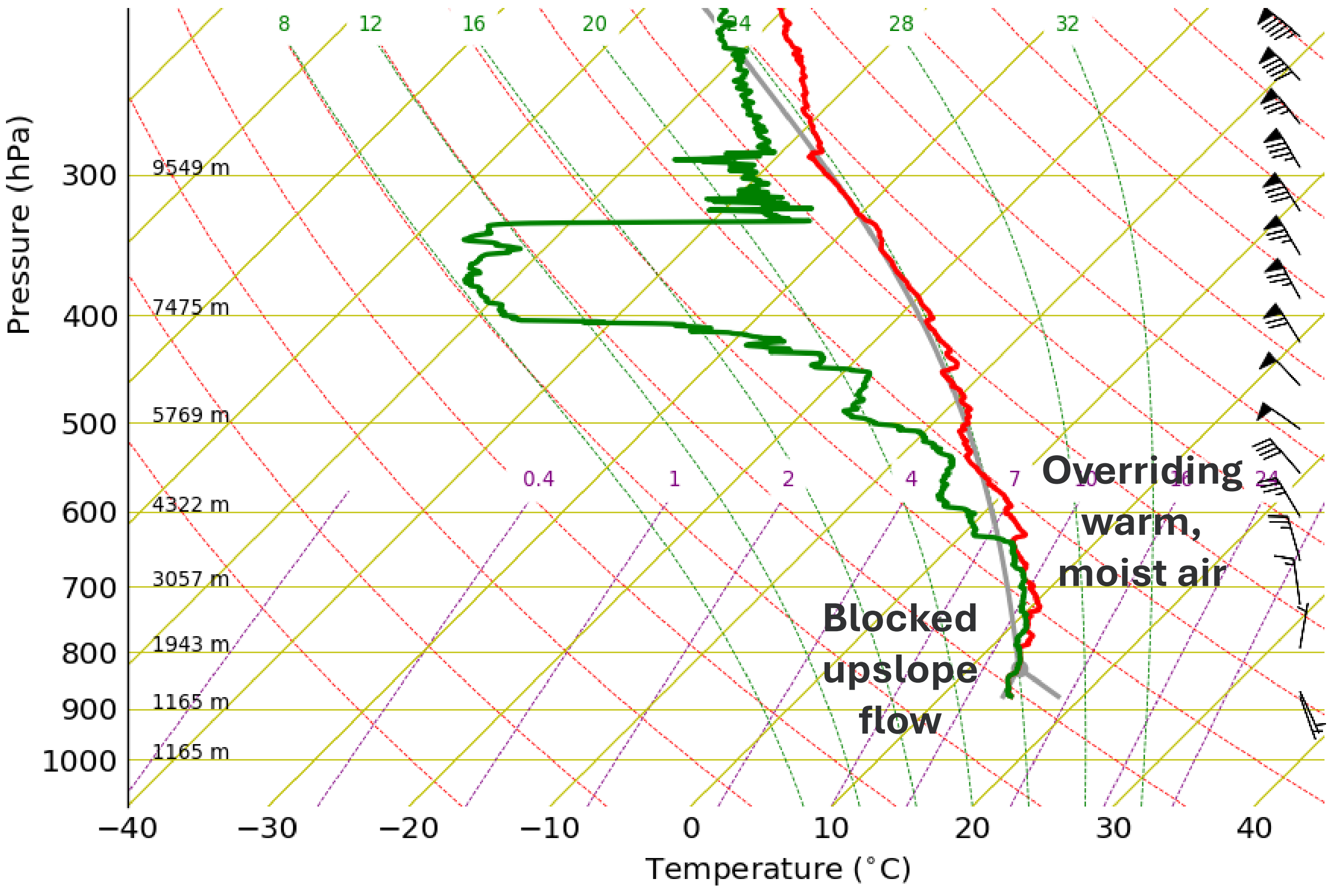


Image courtesy of Brody Fuchs (former CSU)

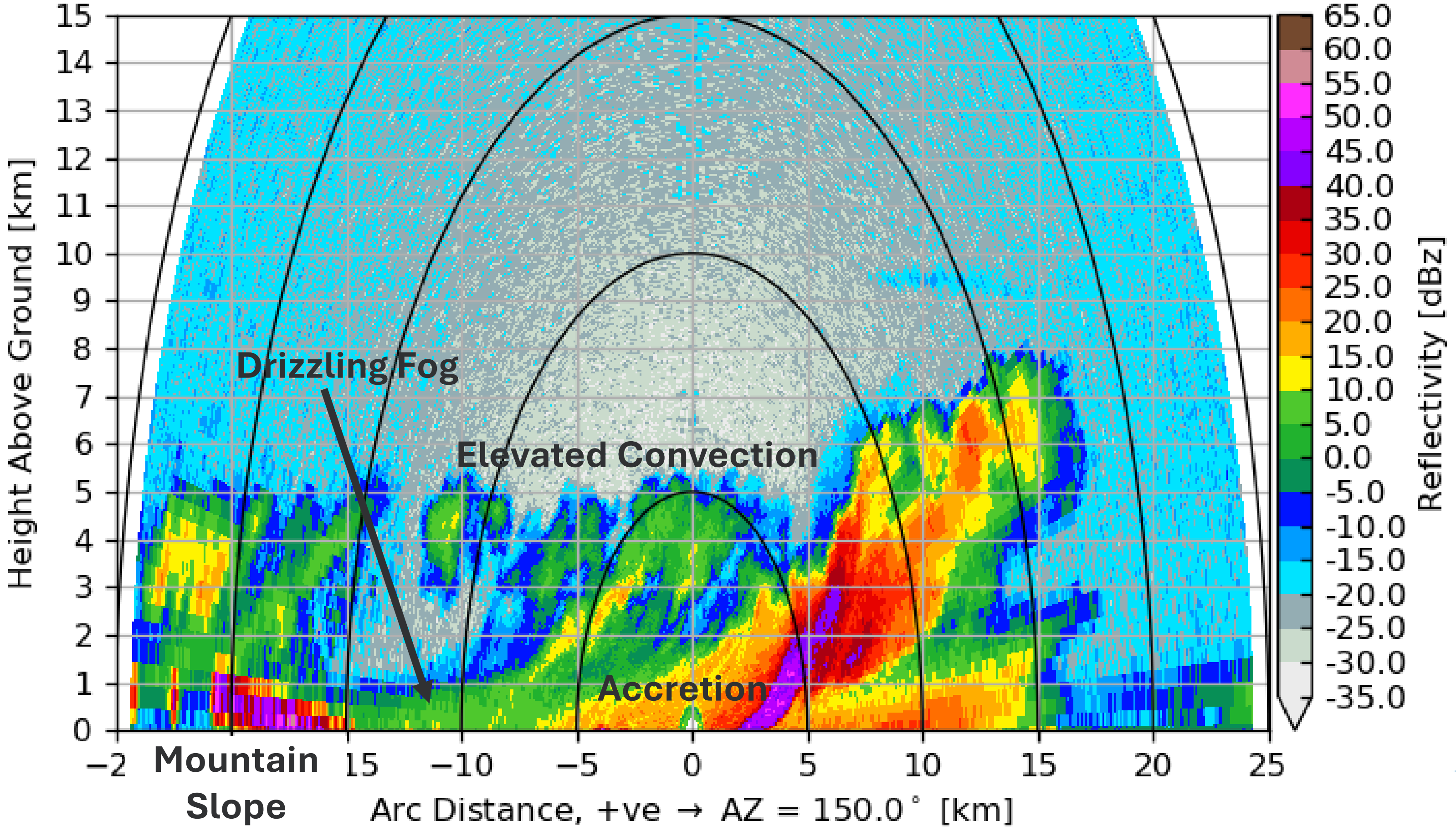


Image courtesy of DOE ARM, Joseph Hardin (former PNNL), and Nitin Bharadwaj (former PNNL)