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Institute for Atmospheric and Climate Science

Identifying and Simulating Mesoscale Convective Systems in km-Scale Models

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GEWEX Upper Tropospheric Clouds and Convection Process Evaluation Study
May 20, 2025

Outline

1. How to slice and dice a cloud?

2. How to track an MCS?

3. How to simulate MCSs in numerical Models?

1. How to slice and dice a cloud?

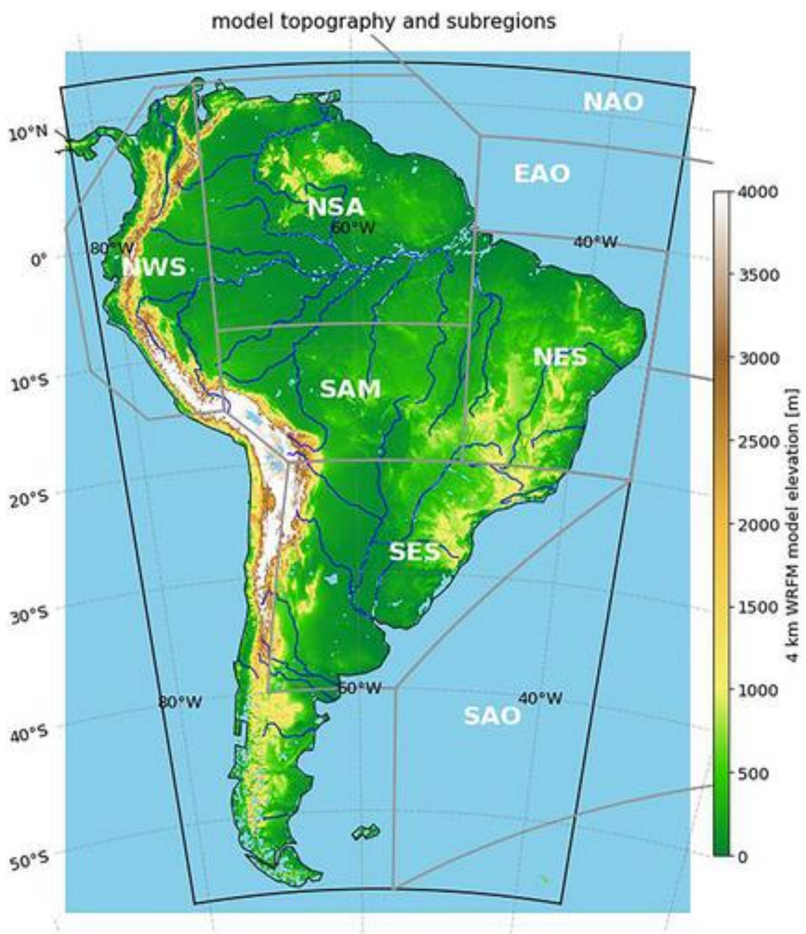
How many MCSs do you see?

1. How to slice and dice a cloud?

How many MCSs do you see?

What is an MCS?

What is an MCS?



SAAG
South American Affinity Group

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We are lacking a clear definition for automatic tracking

AMS Glossary
"A cloud system that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area on the order of 100 km or more in horizontal scale in at least one direction."
Based on Houze (2004)

In Prein et al. (2023) we agreed on:

1. The continuous brightness temperature (**T_b) ≤ 241 K** area must be at least **40,000 km²** for at least **four continuous hours**.
2. The **maximum hourly precipitation** underneath the ≤241 K T_b area must be larger than **10 mm hr⁻¹** for **at least 4 continuous hours**.
3. The **hourly precipitation volume** must exceed **20,000 km² mm h⁻¹** (e.g., 100 km × 100 km × 2 mm hr⁻¹) at least once in the lifetime of the MCS
4. The **minimum T_b** must be **<225 K** during the MCS lifetime to account for overshooting tops.

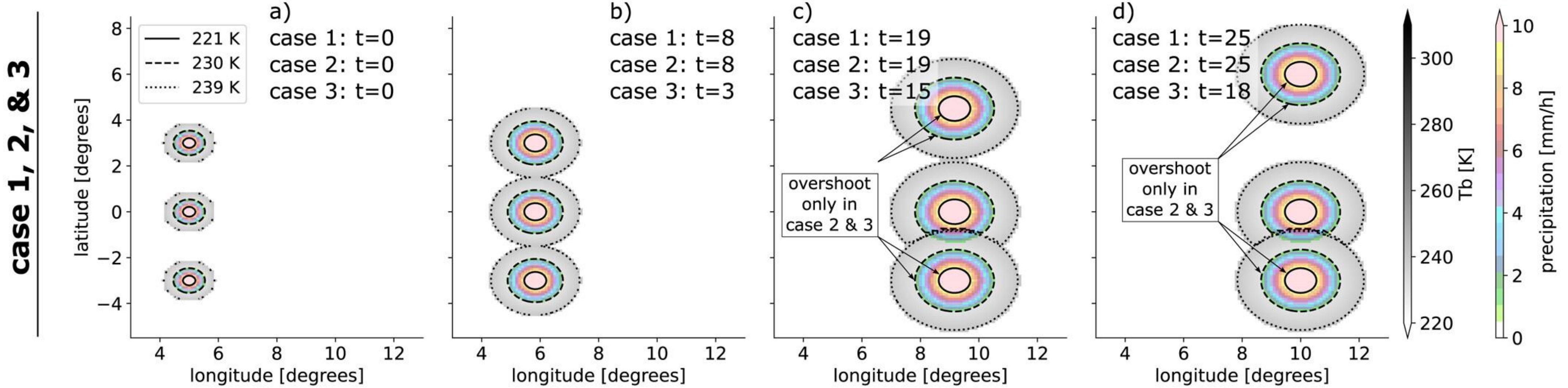
Outline

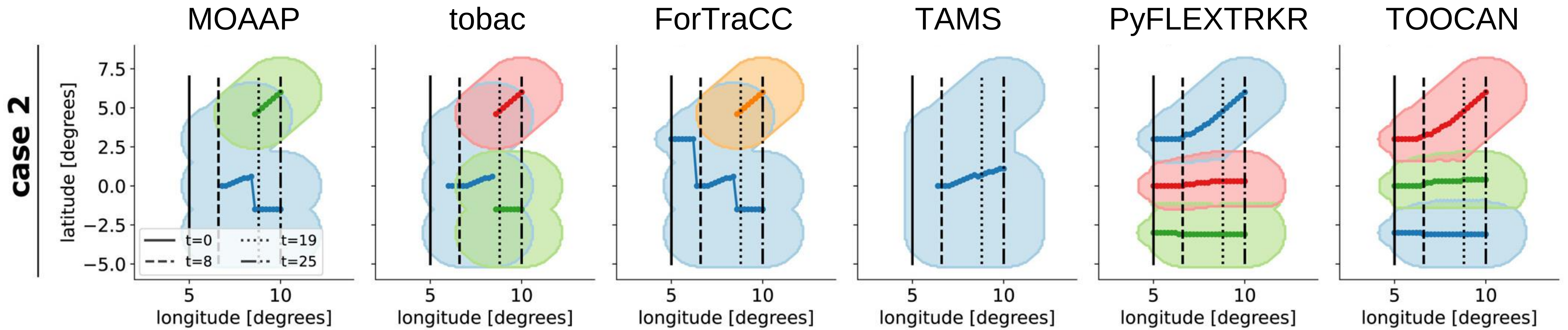
1. How to slice and dice a cloud?

2. **How to track an MCS?**

3. How to simulate MCSs in numerical Models?

Comparing MCS Trackers on Idealized Cases





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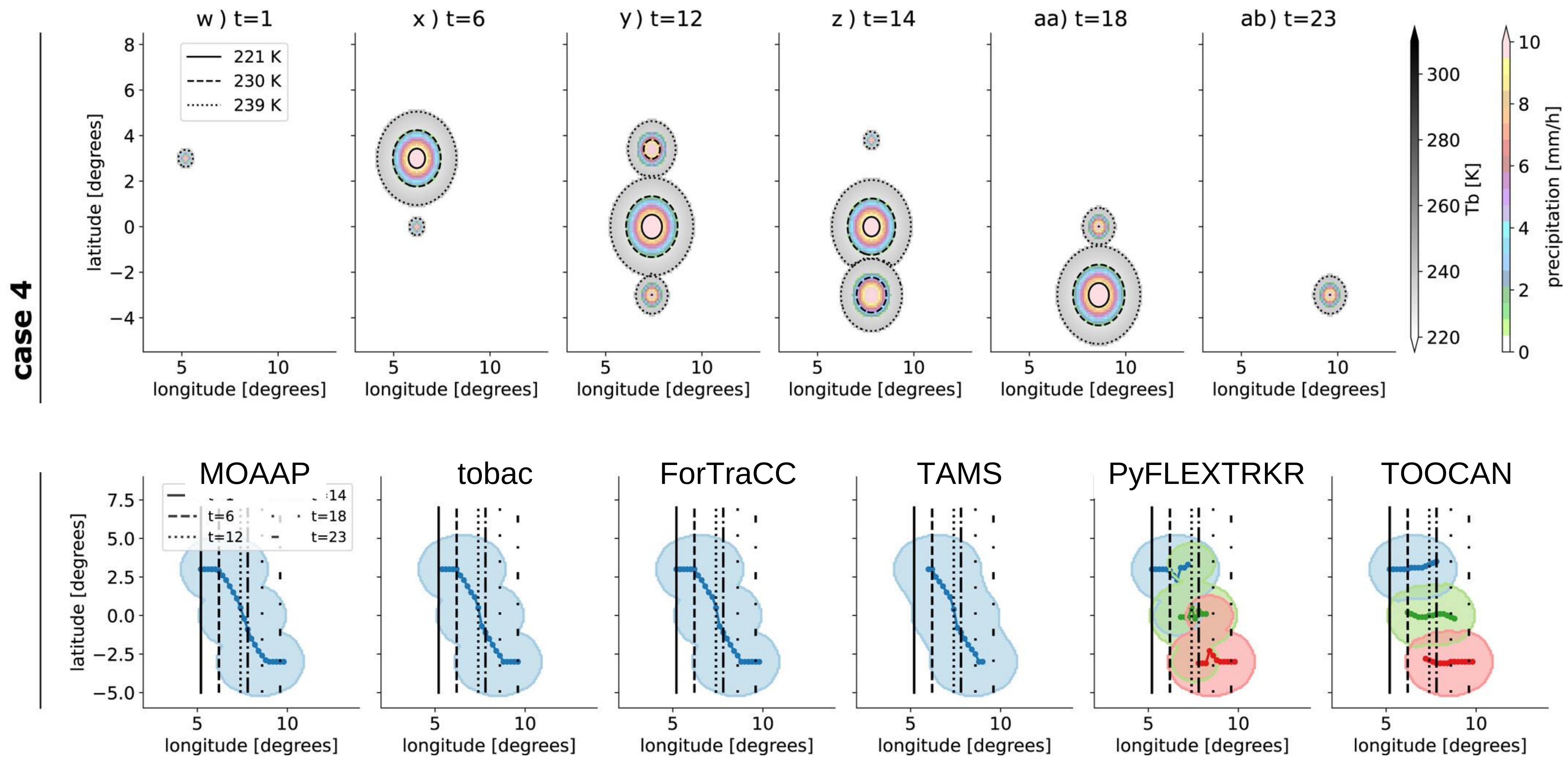
[Prein et al. (2023)](#)

Comparing MCS Trackers on Idealized Cases



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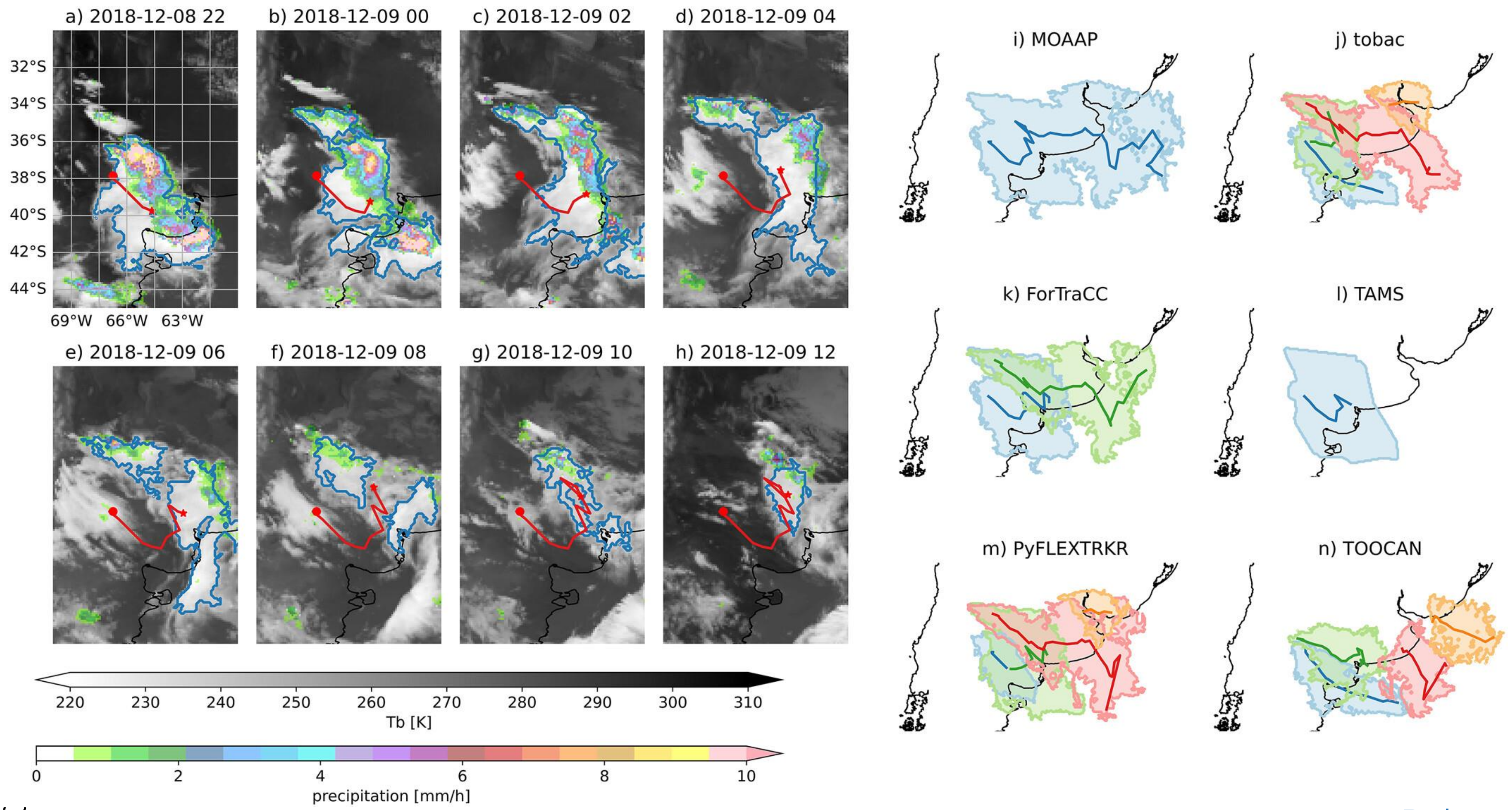
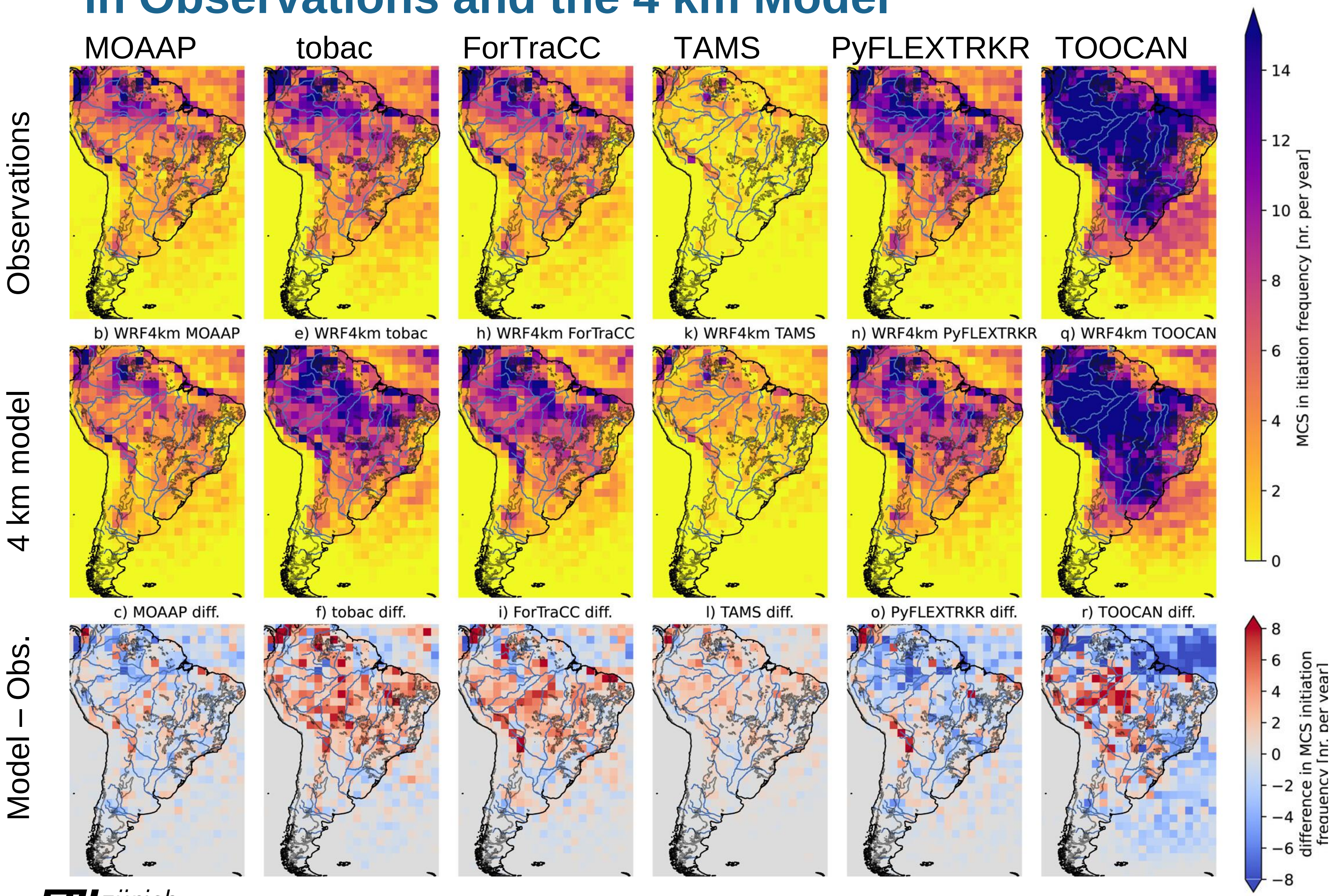
Prein et al. (2023)

Comparing the Trackers on a Real Case



Prein et al. (2023)

Large Variability in Initiation frequency of Mesoscale convective systems in Observations and the 4 km Model



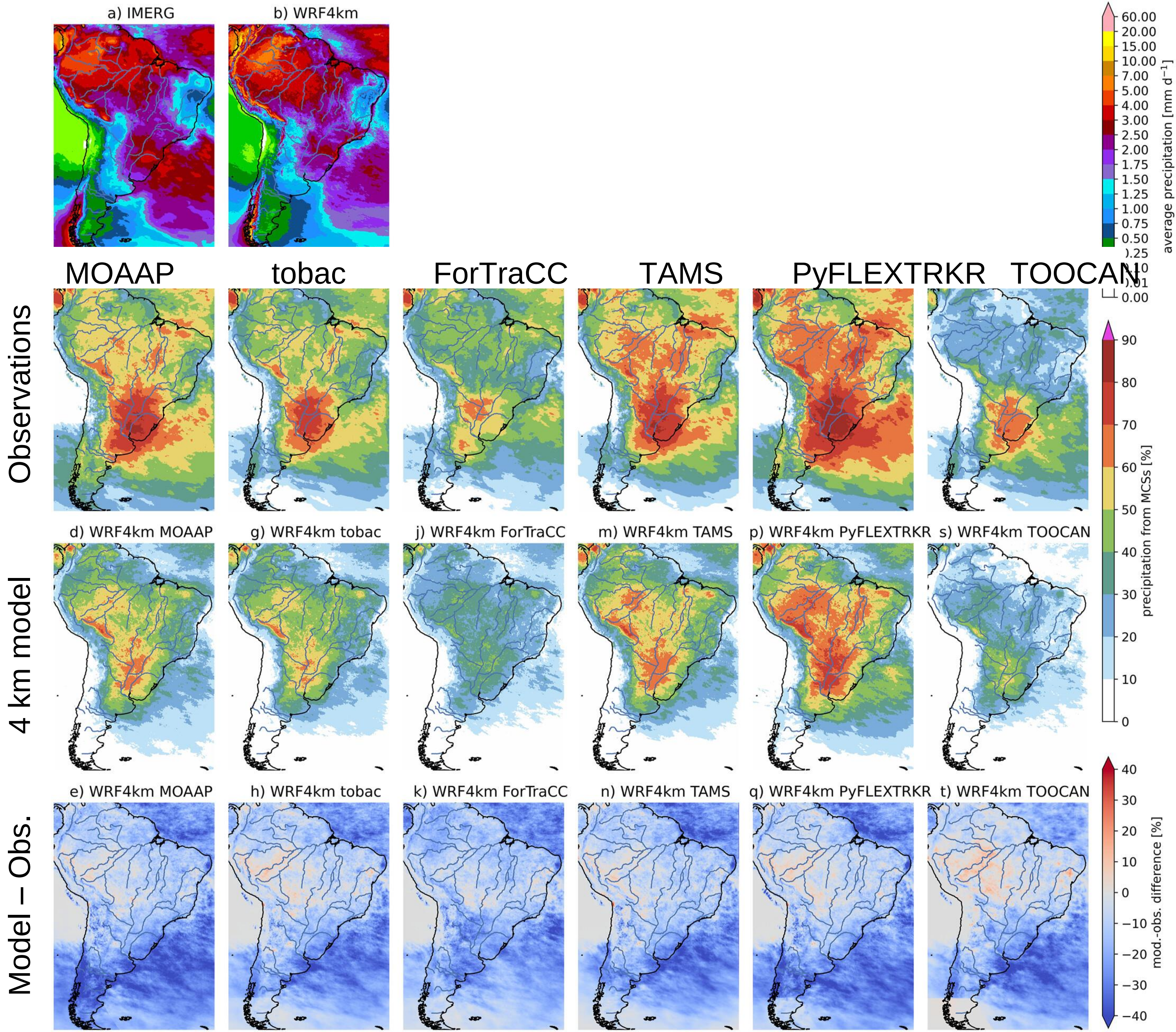
- MCS initiation frequency largely varies between trackers
- Some trackers result in many small MCSs while others have few large storms
- The MCS initiation evaluation also heavily depends on the tracker

Prein et al. (2023)

MCS precipitation contribution is also tracker sensitive but model biases are robust

- The MCS contribution to the total precipitation is very sensitive to the tracker formulation

- However, model biases in this metric are more robust.



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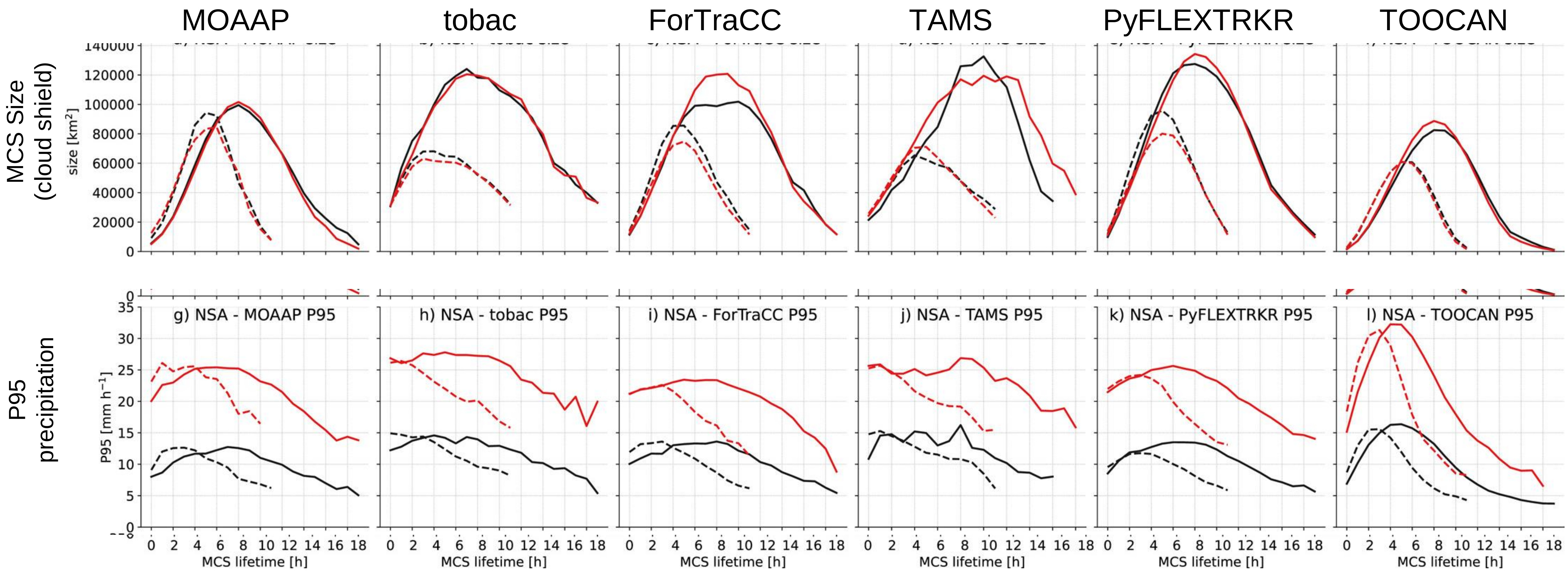
Prein et al. (2023)

MCS Development-characteristics are Tracker Sensitive but Model Biases are Largely Insensitive



Prein et al. (2023)

Convection in the Amazon Basin on a Typical Wet Season Day

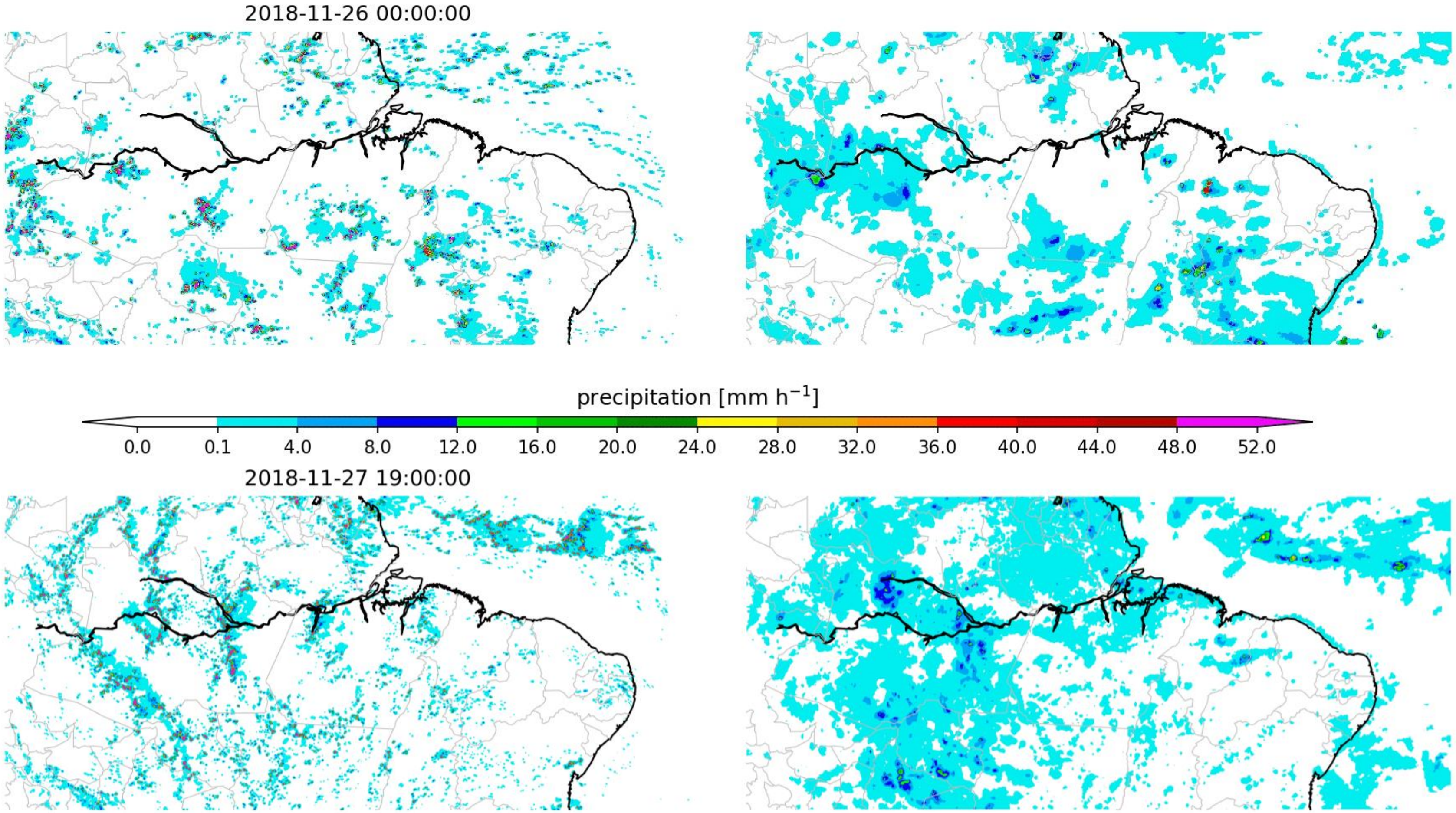
GPM IMERG v6 is used as ground truth

Freitas et al. 2020 (JoH)

- IMERG v6 is able to capture precipitation rates compared to stations in Brazil
- large overestimations of rainfall duration and underestimations of intensity

WRF 3 km
Test Simulation

GPM IMERG v6



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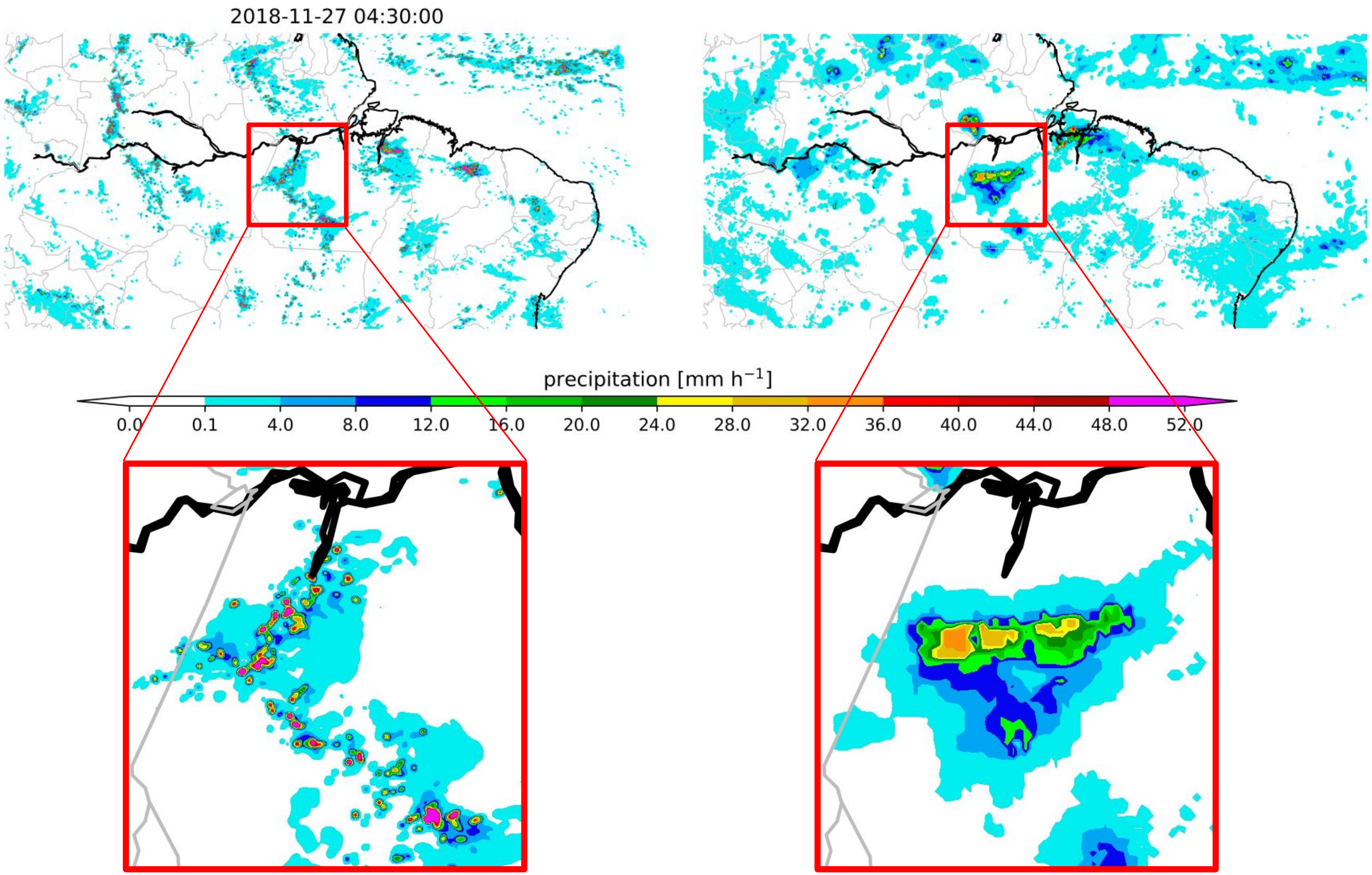
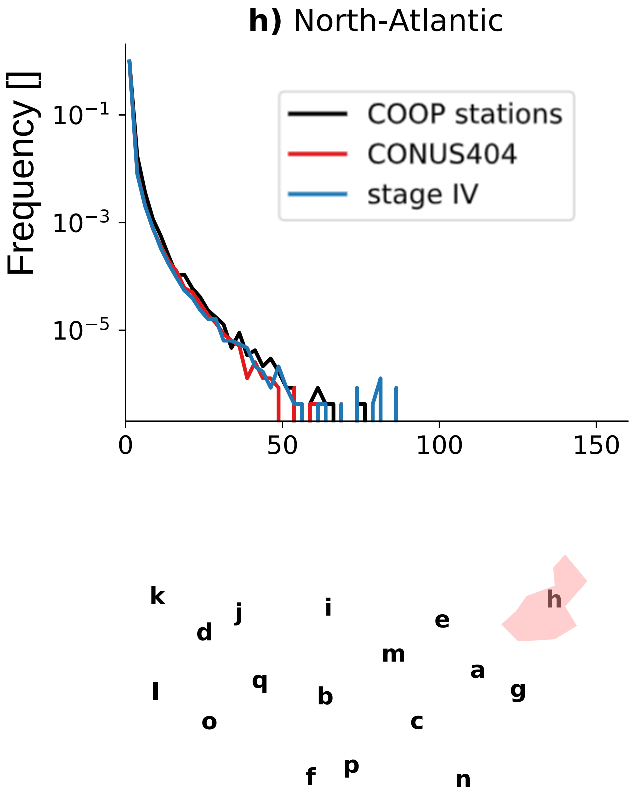
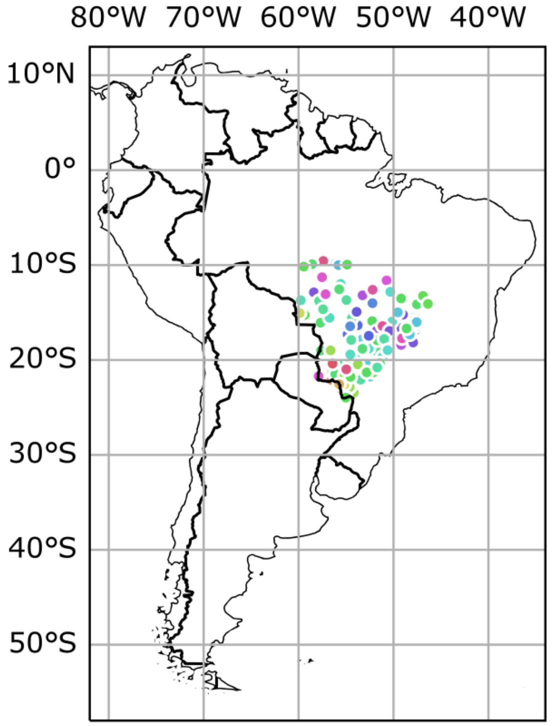


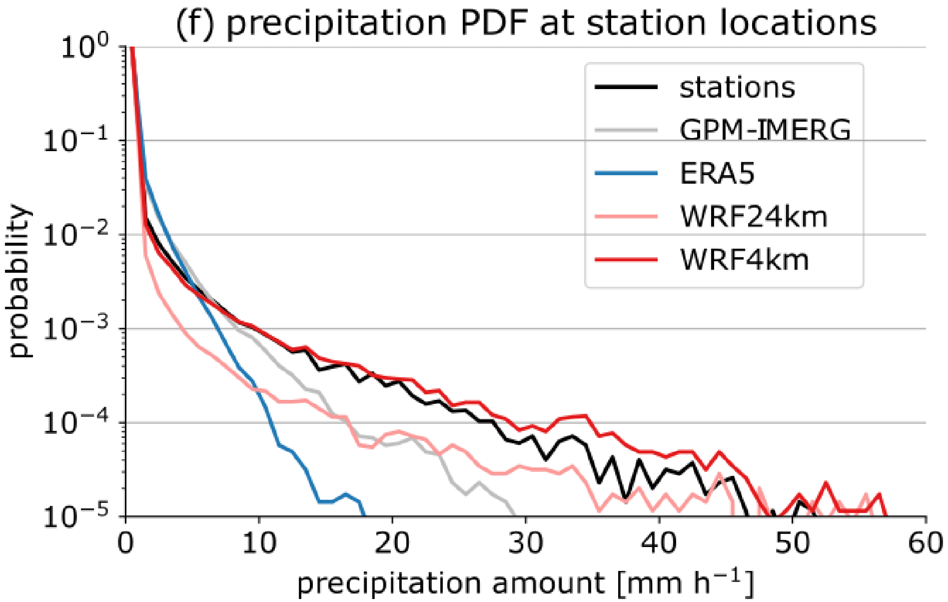
Simulation of Hourly Precipitation Frequencies

Period 2002-2019 at COOP station locations



4 km WRF simulations downscaling ERA5 over South America (June 2019 – May 2020)





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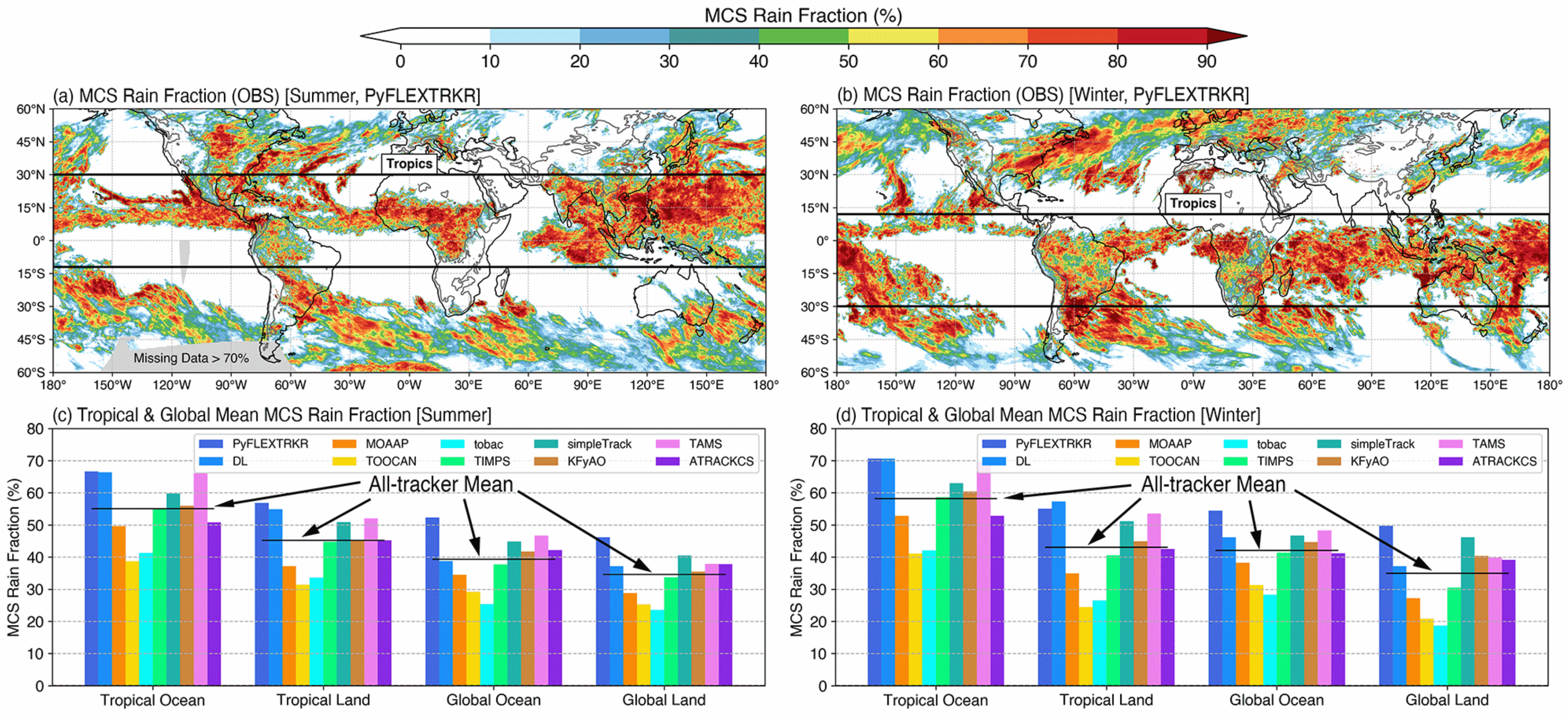
Dominguez et al. (2024)

Mesoscale Convective Systems tracking Method Intercomparison (MCSMIP)



Feng et al. (2024)

MCSMIP extends the South American Study to the Globe by evaluating the global DYAMOND storm resolving models.

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Outline

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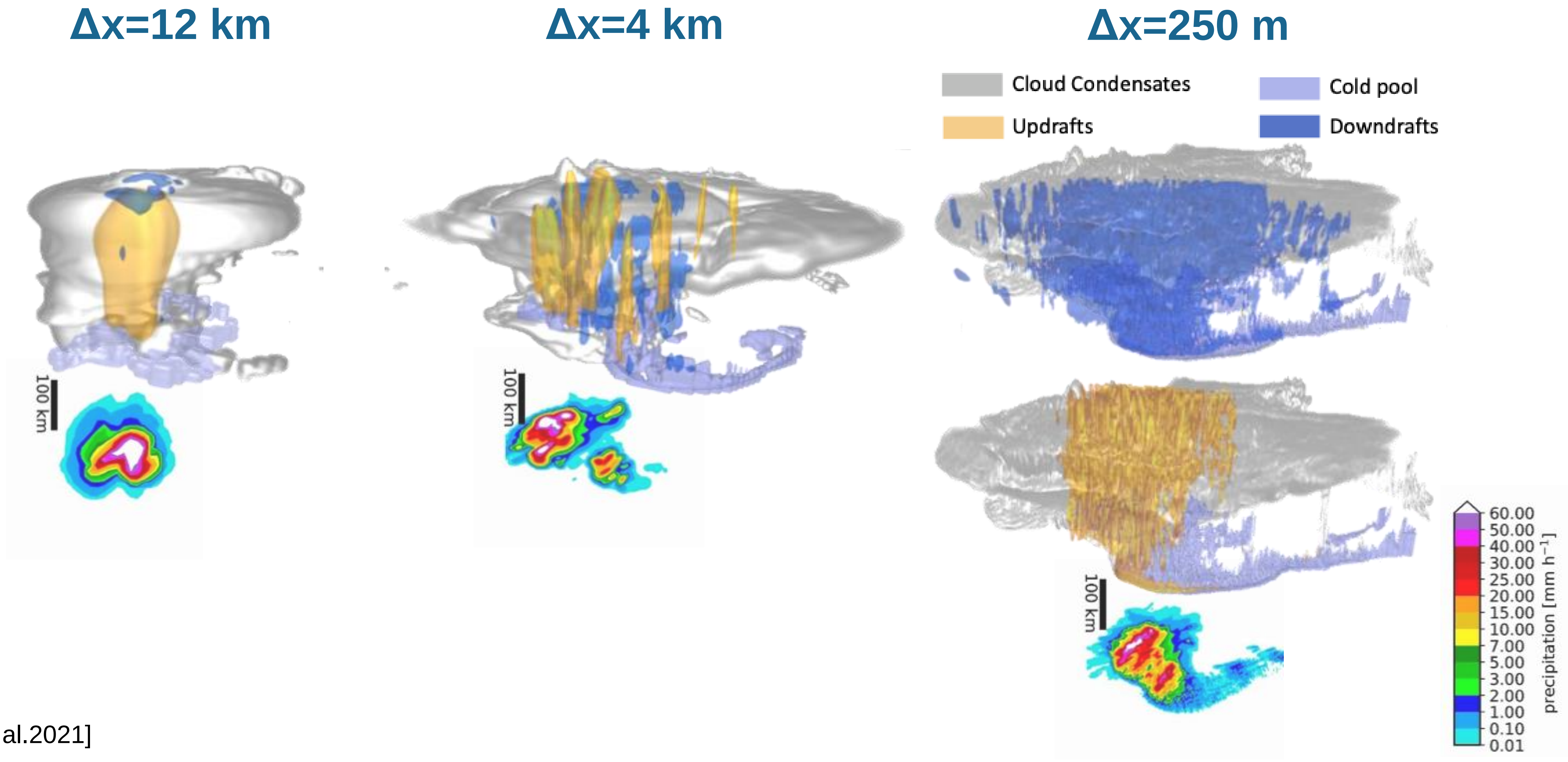
3. **How to simulate MCSs in numerical Models?**

Δx Sensitivity of Idealized MCSs



[Prein et al.2021]

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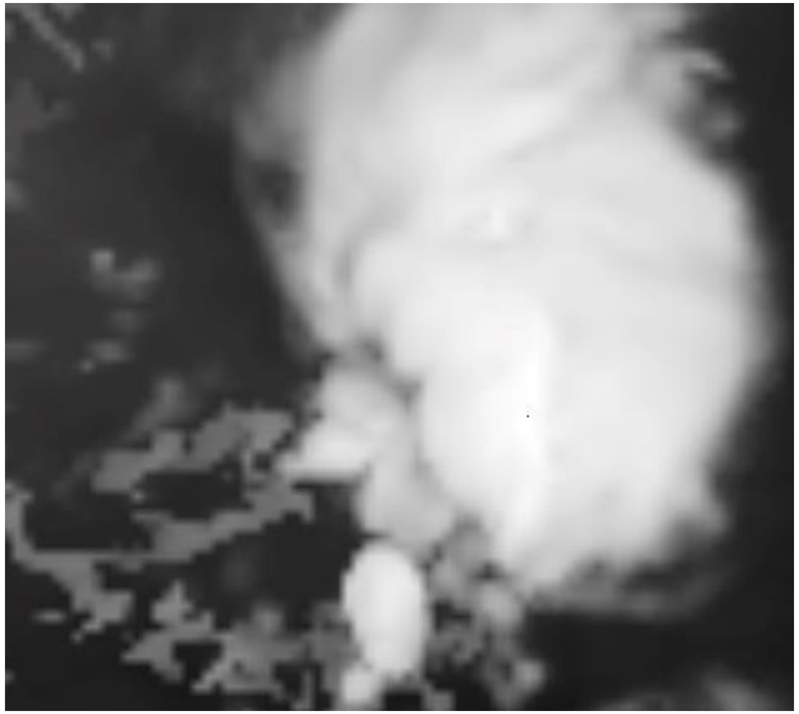
Simulation of Well Observed Mesoscale Convective Systems in the Southern Great Plains

Outgoing longwave radiation at:

12 km grid spacing

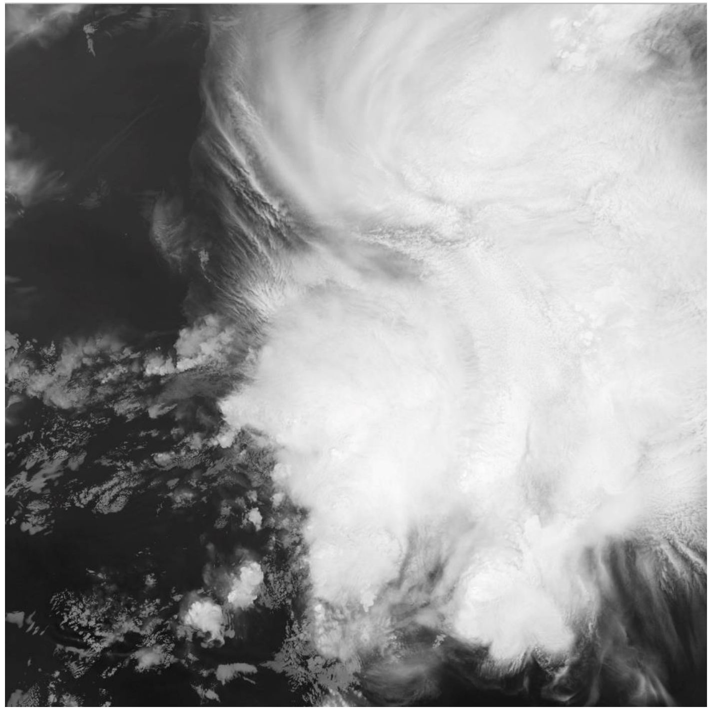


1,000,000 times cheaper

4 km grid spacing

30,000 times cheaper

125 m grid spacing



Which grid spacing is sufficient?

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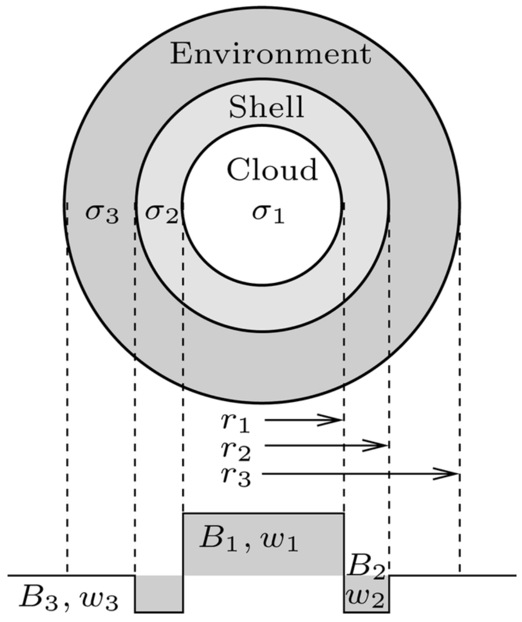
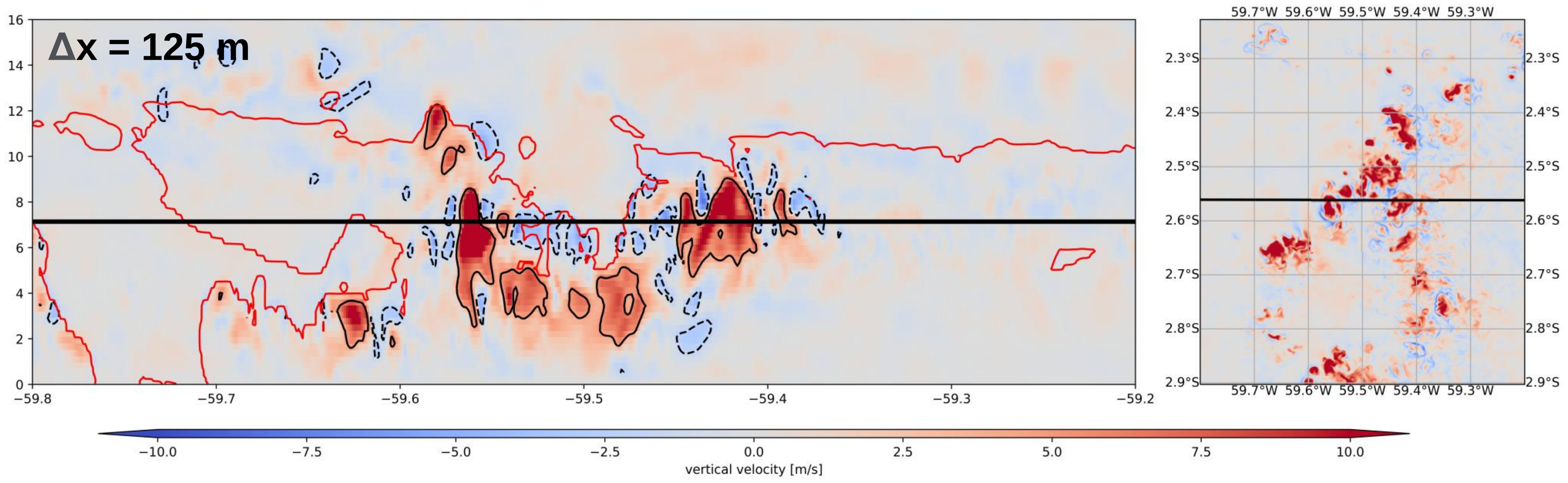
Prein et al. (2025)

Learning from LESs and ARM Observations

Amazon Basin on April 1 2014, 15 UTC



Heus and Jonker (2008)



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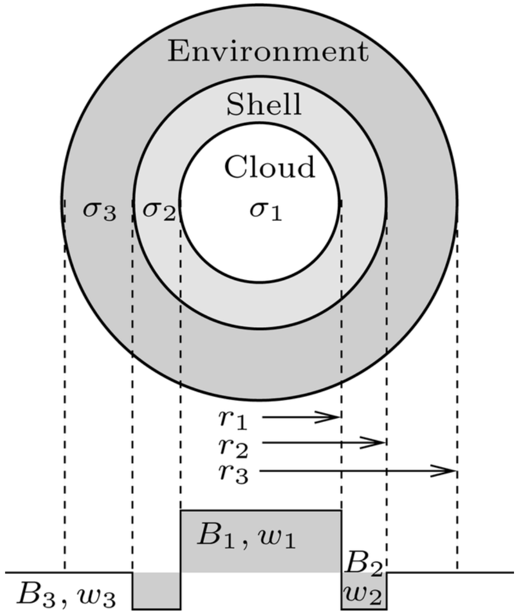

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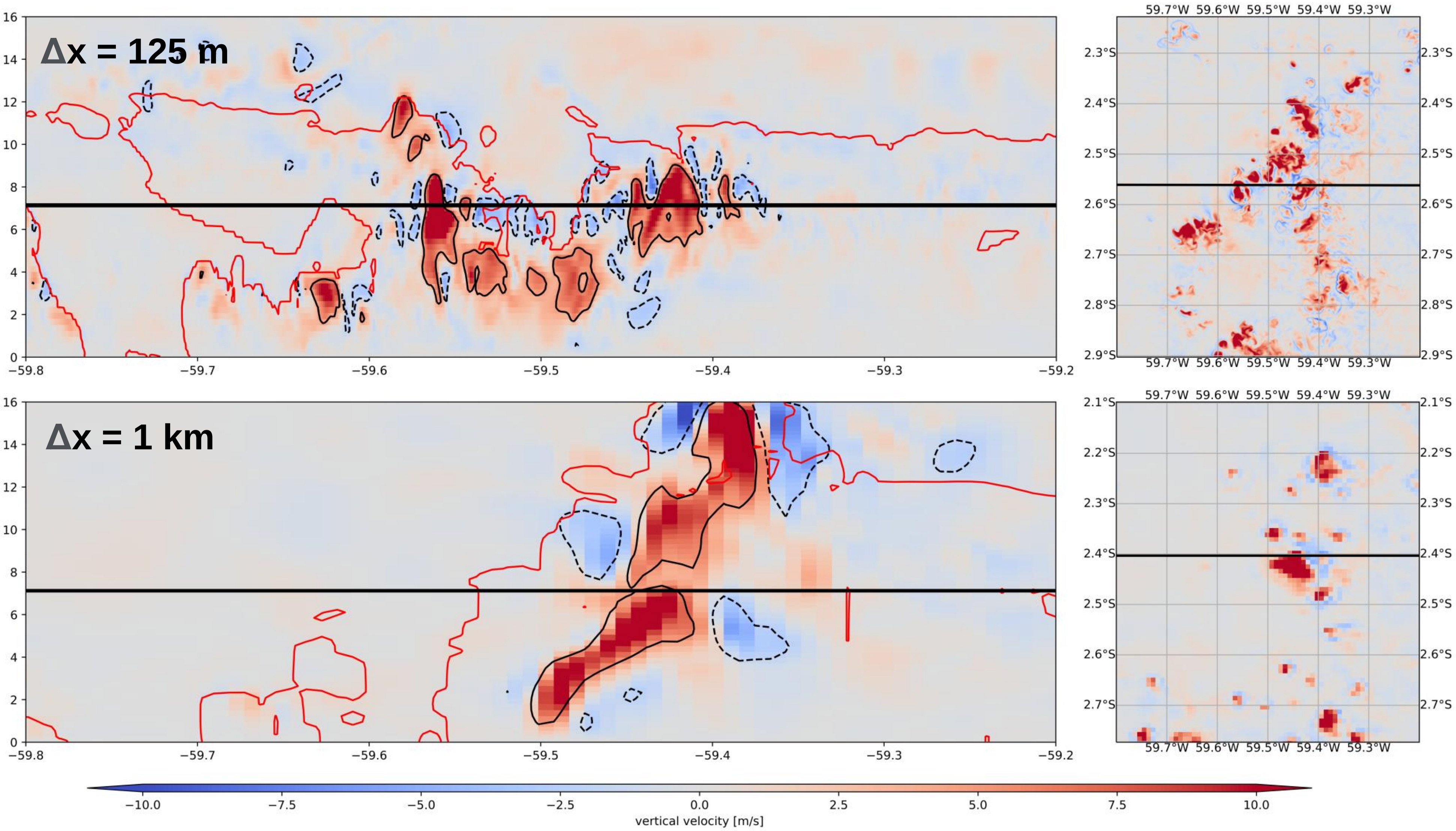
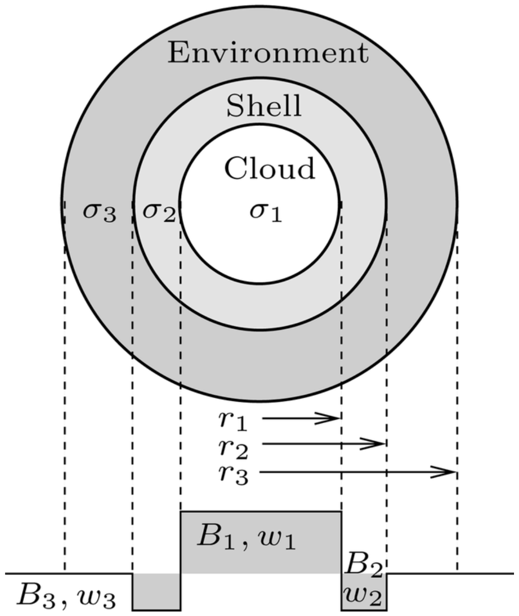


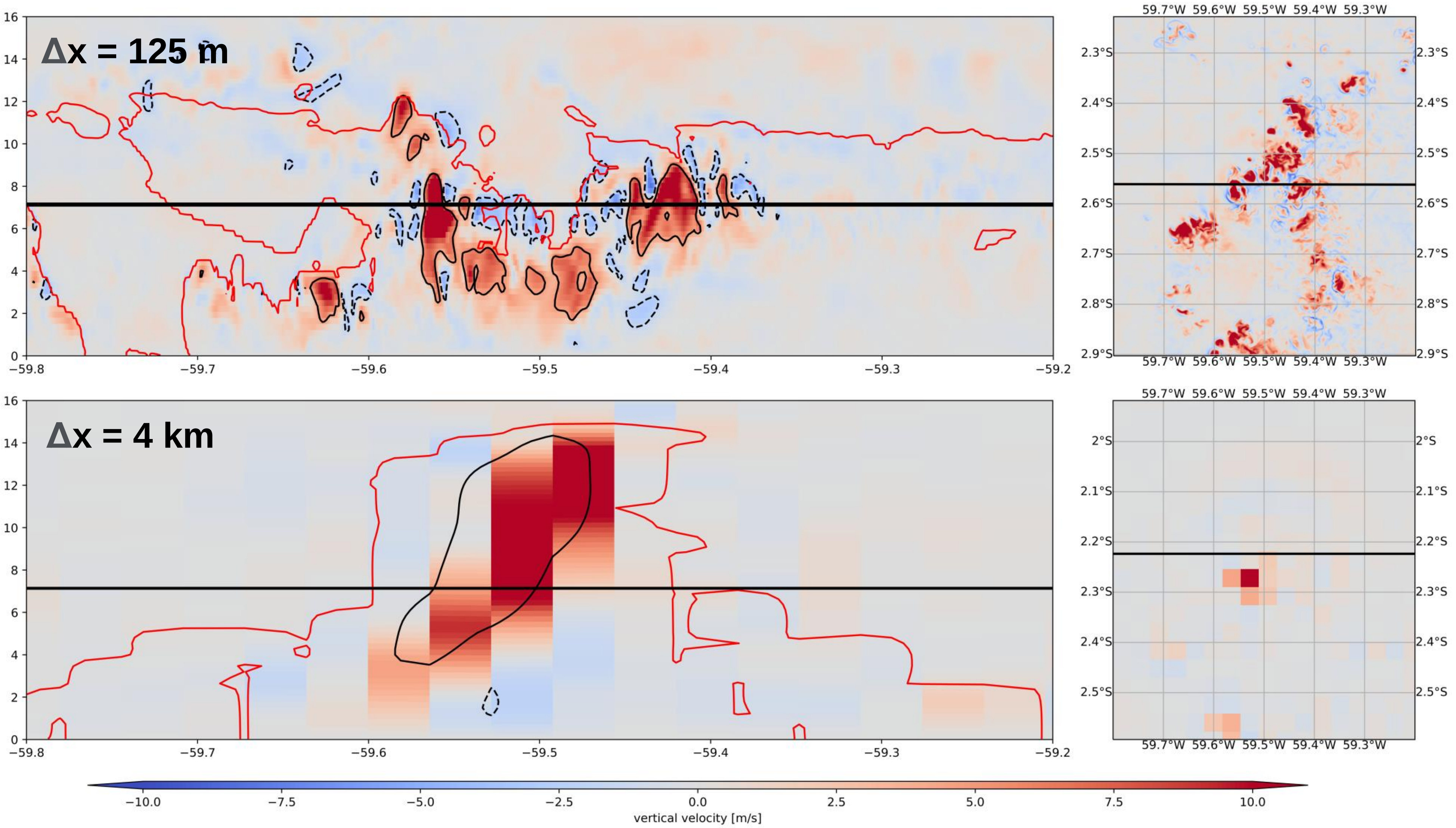
Learning from LESs and ARM Observations

Amazon Basin on April 1 2014, 15 UTC



Heus and Jonker (2008)

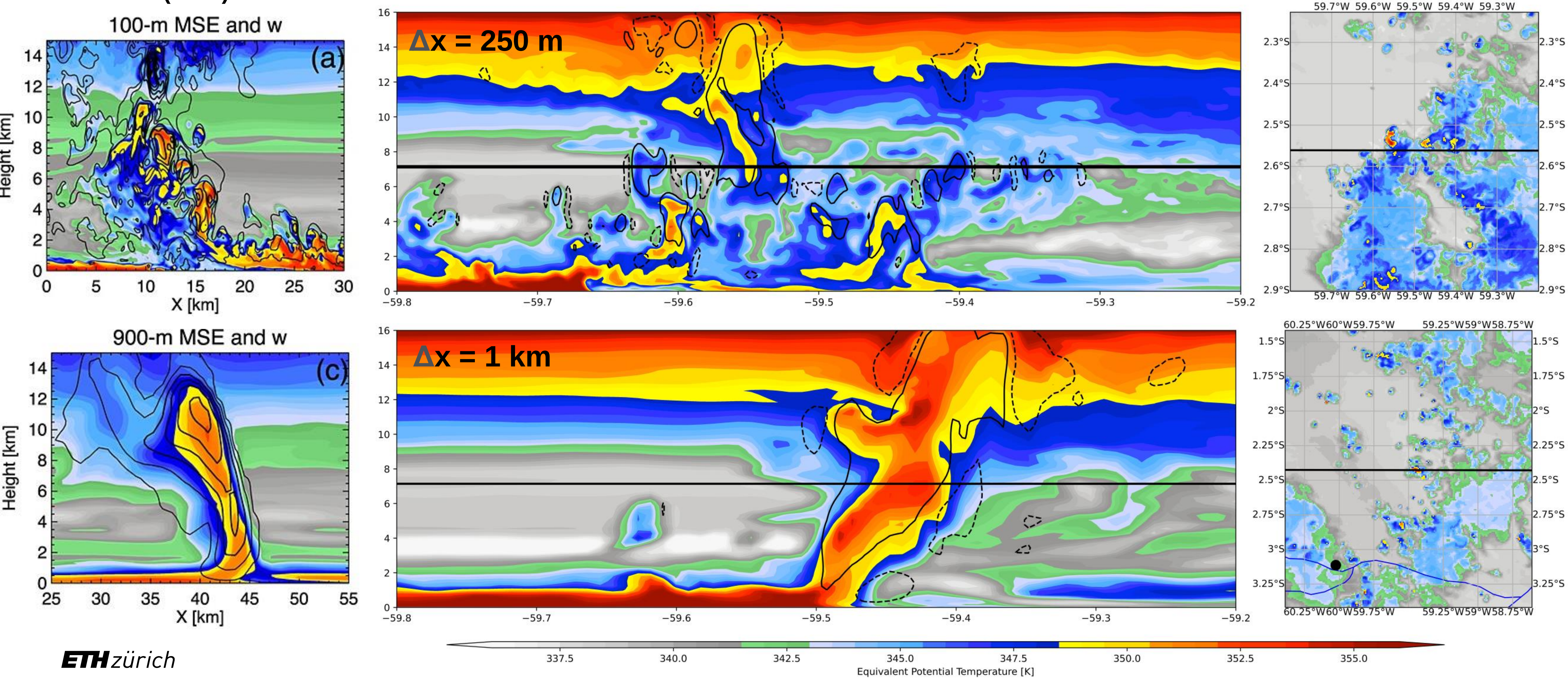
Stanford et al. (2020) show that the undermixing of updrafts at km-scales is difficult to improve.



Learning from LESs and ARM Observations

Amazon Basin on April 1 2014, 15 UTC

Varbel et al. (2014)



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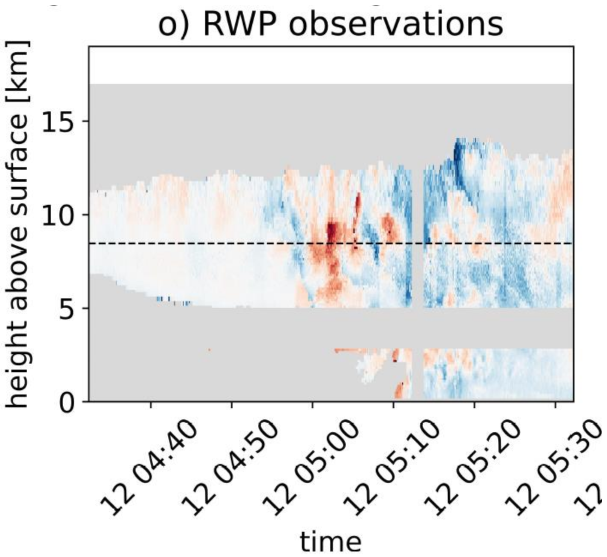
Evaluating the Structural and Bulk Convergence in Numerical Models

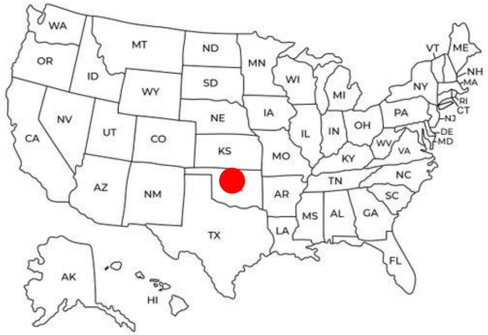
1) Derive vertical velocity output in observations and model data

Radar Wind Profiler observations



U.S. DEPARTMENT OF ENERGY

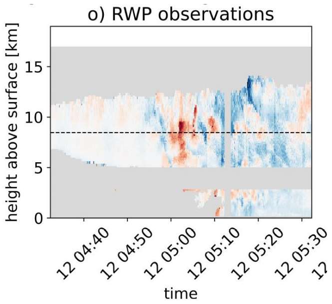
ASR Atmospheric System Research



Southern Great Plains

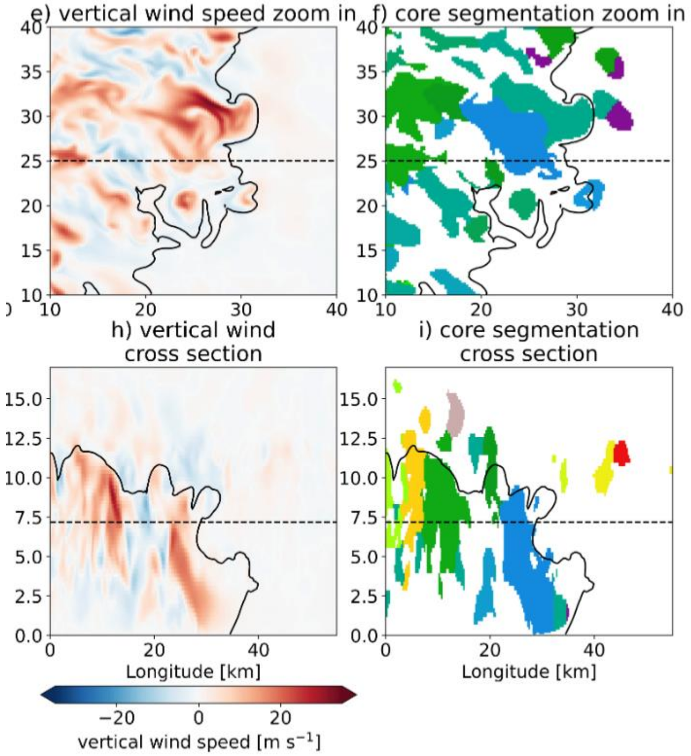
GoAmazon (Manaus)

Evaluating the Structural and Bulk Convergence in Numerical Models



1) Derive vertical velocity output in observations and model data

2) Identify draft objects as objects (using MOAAP)



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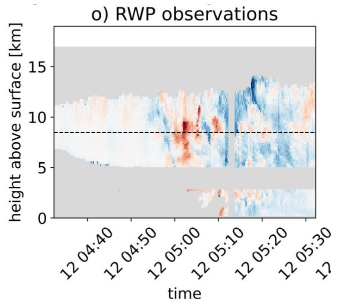
Evaluating the Structural and Bulk Convergence in Numerical Models



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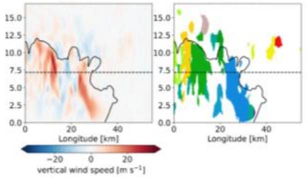
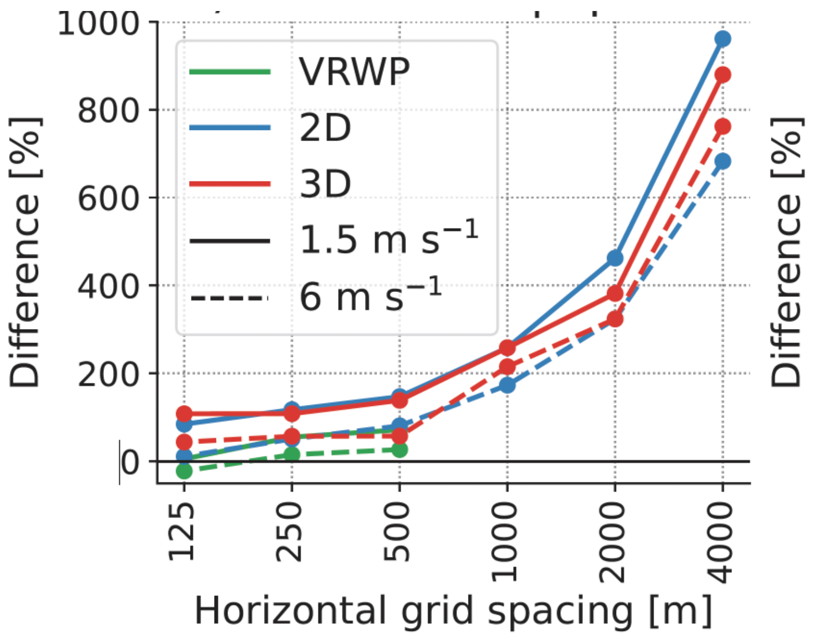
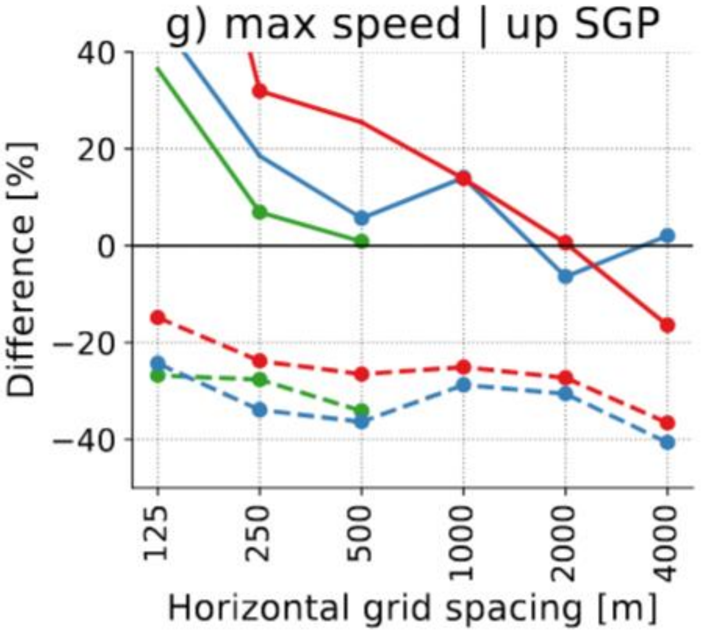


3) Calculate grid spacing sensitivity of core characteristics

Drafts are wider in coarser models



Maximum draft speed increases with resolution



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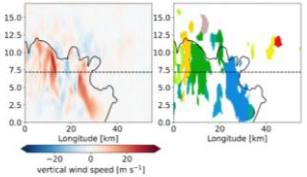
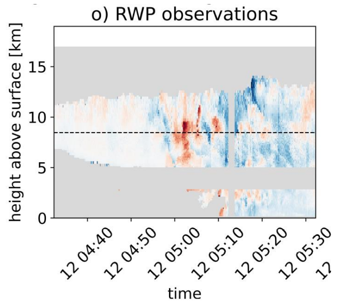
Evaluating the Structural and Bulk Convergence in Numerical Models

1) Derive vertical velocity output in observations and model data

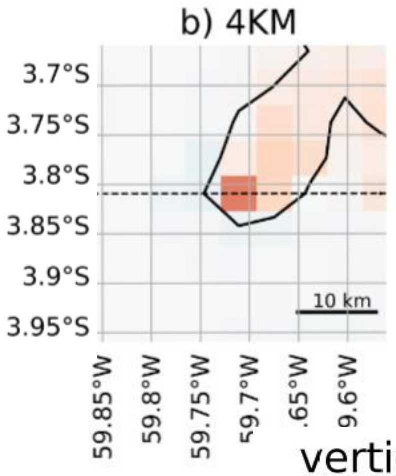




2) Identify draft objects as objects (using MOAAP)

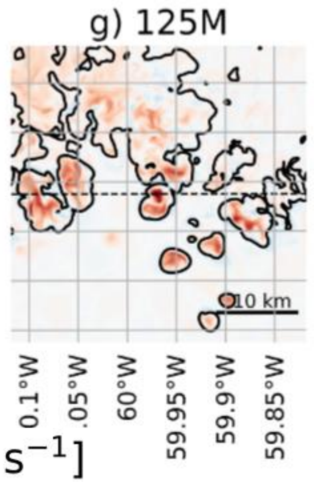
3) Calculate grid spacing sensitivity of core characteristics

Native model grid

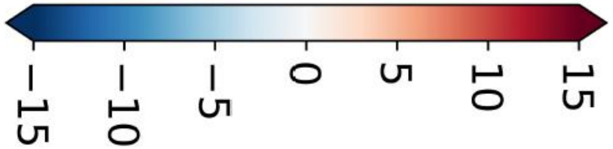


Many more smaller drafts

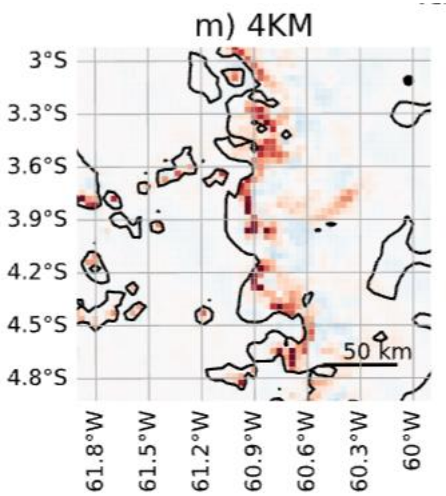
Higher max. windspeed



vertical wind speed [m s^{-1}]

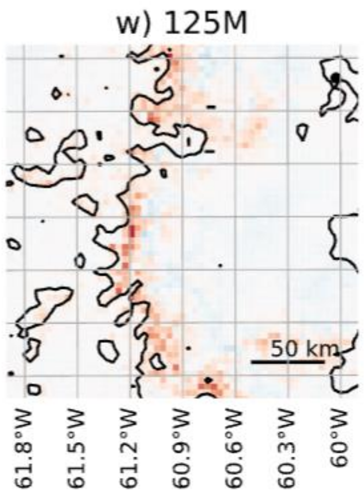


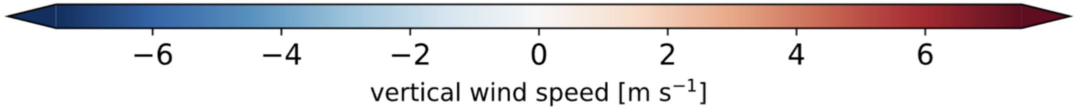
Common 4 km grid



Lower max. windspeed

Smaller spatial gradients



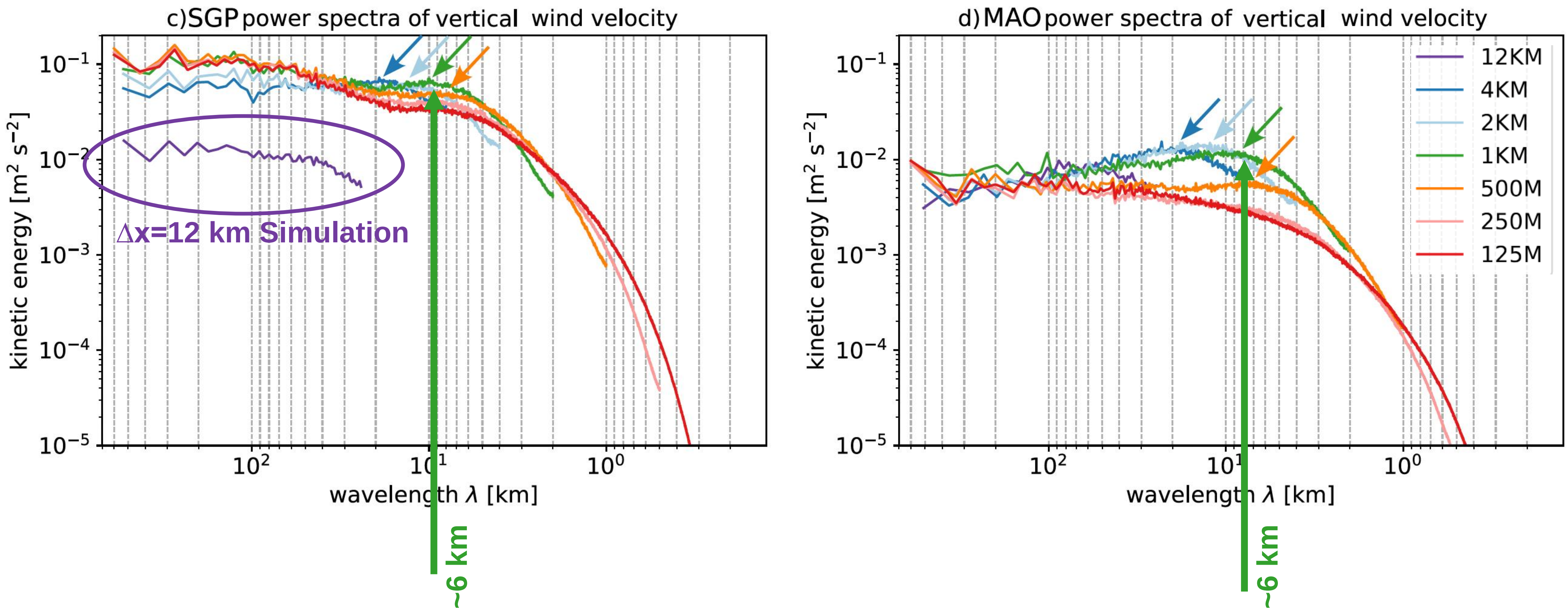


Vertical Kinetic Energy Spectra Show Artificial Energy Buildup in Under Resolved Simulations

Vertical kinetic energy spectra

Southern Great Plain MCSs

Amazonian Plain MCSs



Artificial build up of vertical kinetic energy at ~6 Δx

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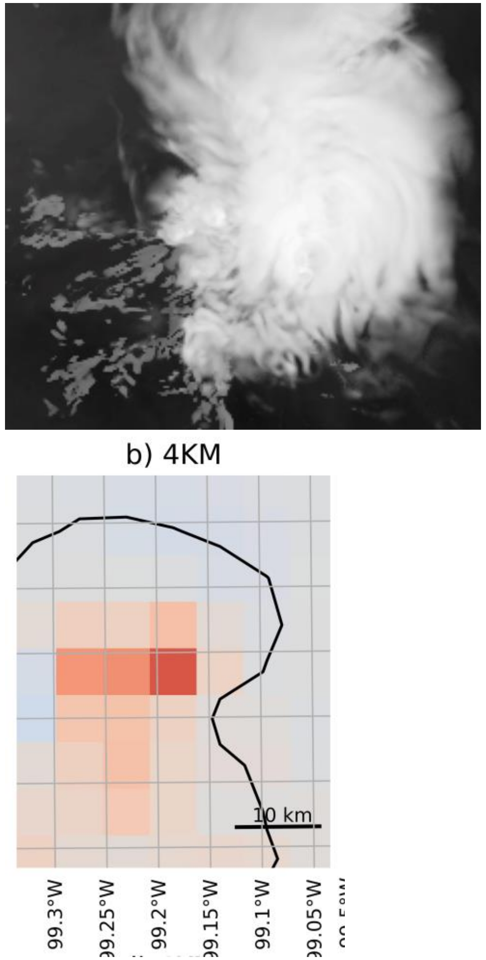
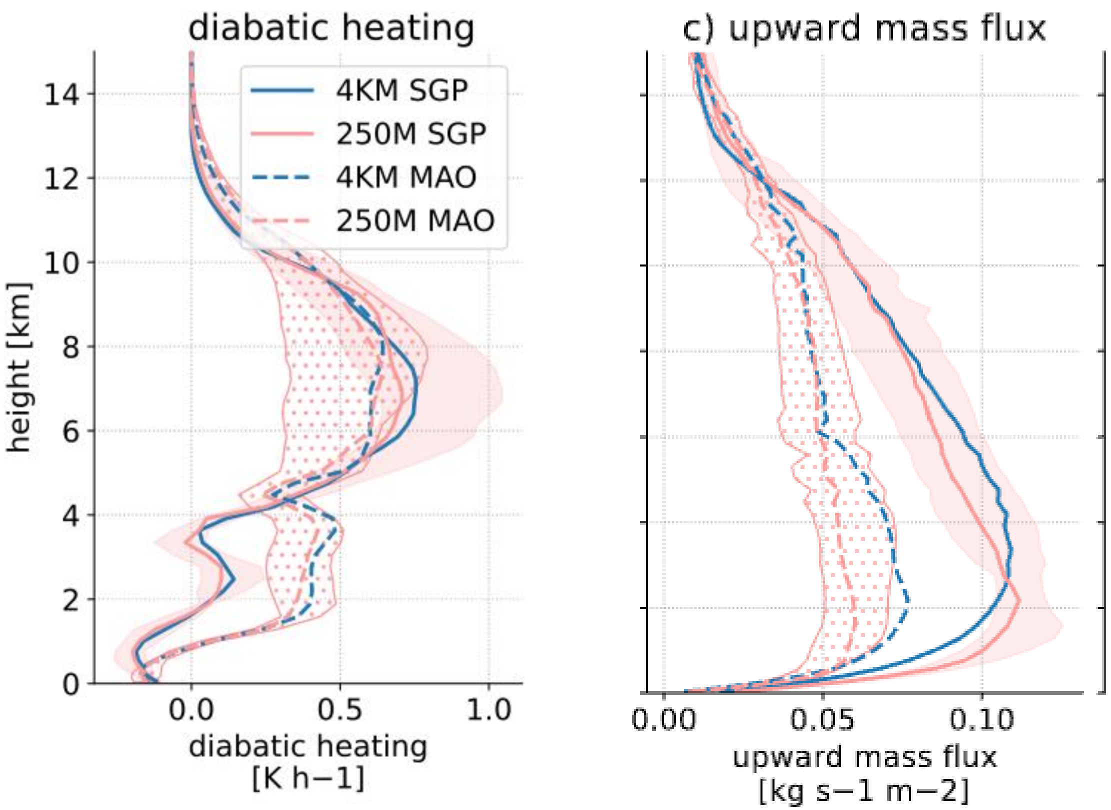
Prein et al. (2025, JGR-A)

4 km Grid Spacing is Under-resolving Convective Dynamics but can Capture Bulk Propoerties

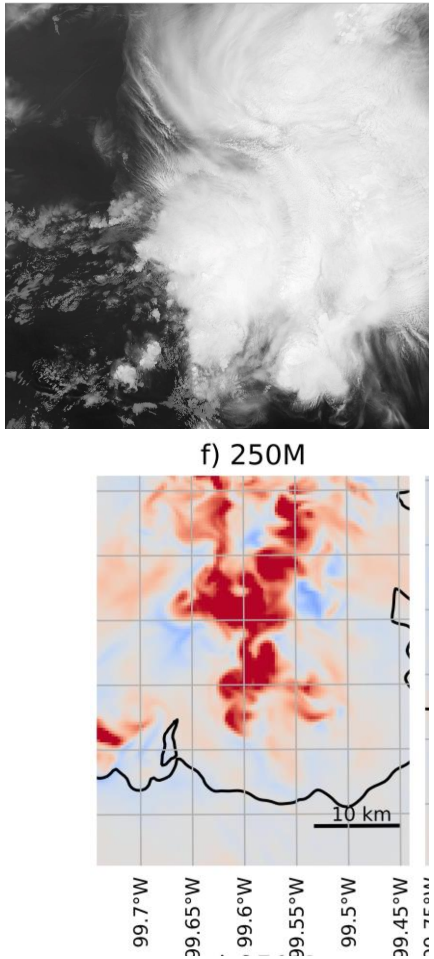
4 km grid spacing



Storm average bulk properties are surprisingly well simulated at 4 km compared to sub-km simulations. This is partly due to error cancelations.



250 m grid spacing



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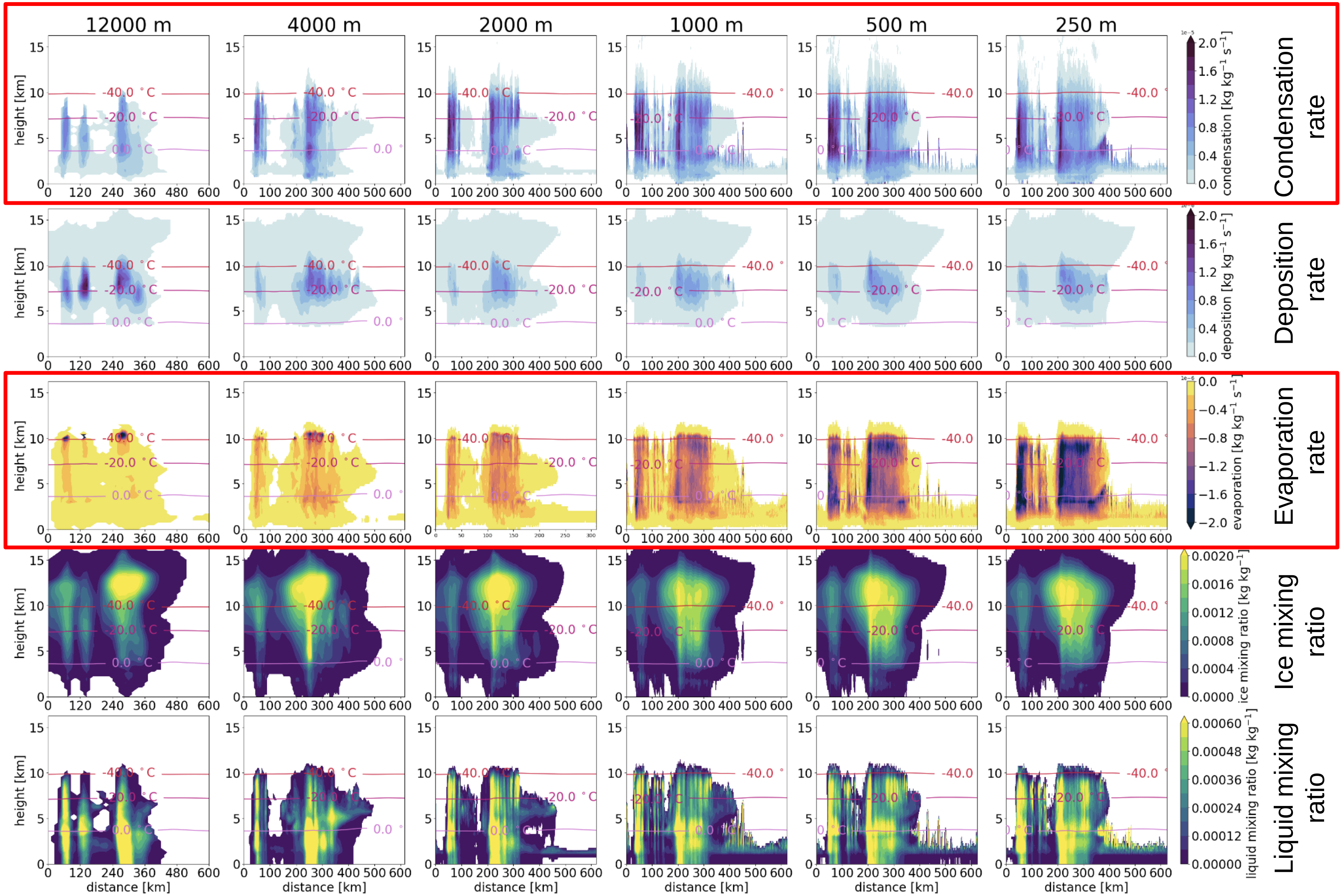
Prein et al. (2025)

Error Cancelation Effects



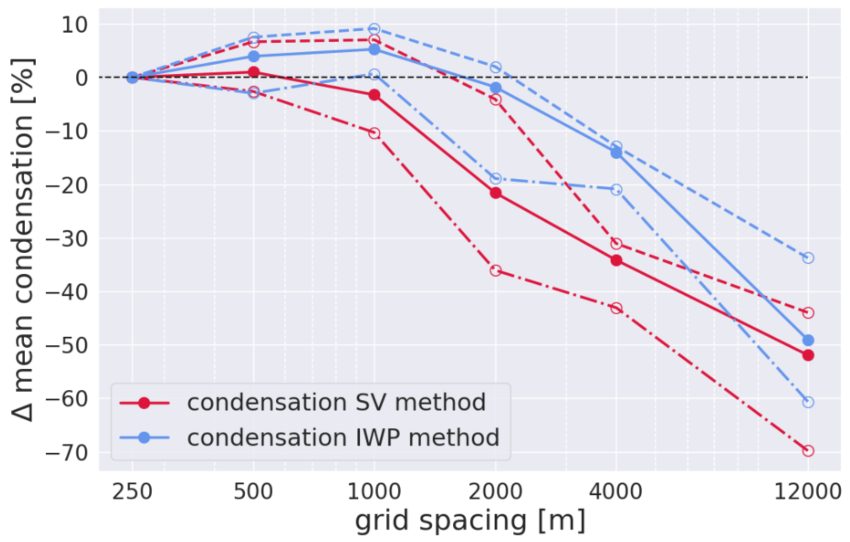
Error Cancelation

Increasing Δx leads to higher condensation and higher evaporation rates

Kukulies et al. (in review)

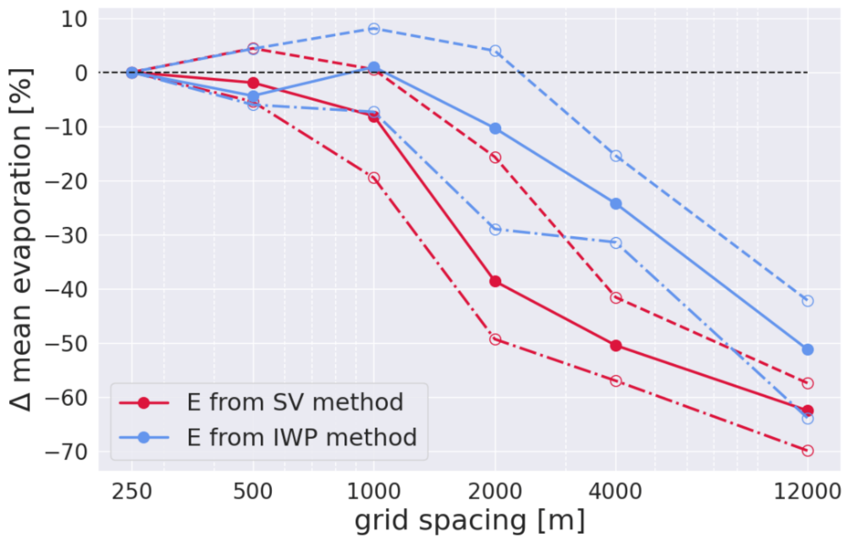
Error Cancelation Effects

Condensation



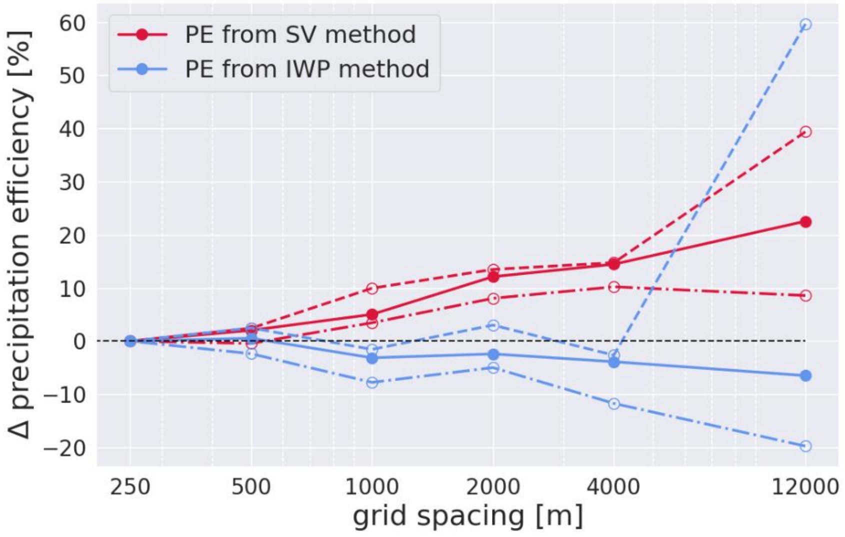
Condensation reduces with increasing grid spacing

Evaporation



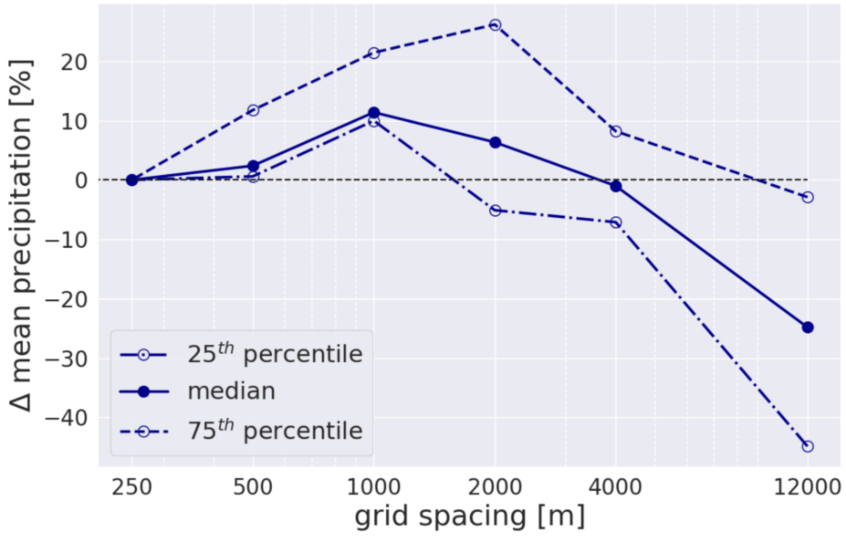
Evaporation reduces with increasing grid spacing

Precipitation Efficiency



Precipitation efficiency is simulated within ±20 % at Δx= *O*(km) due to error cancelation effects

Mean precipitation



Mean and extreme precipitation is simulated at ±20 % at Δx= *O*(km)

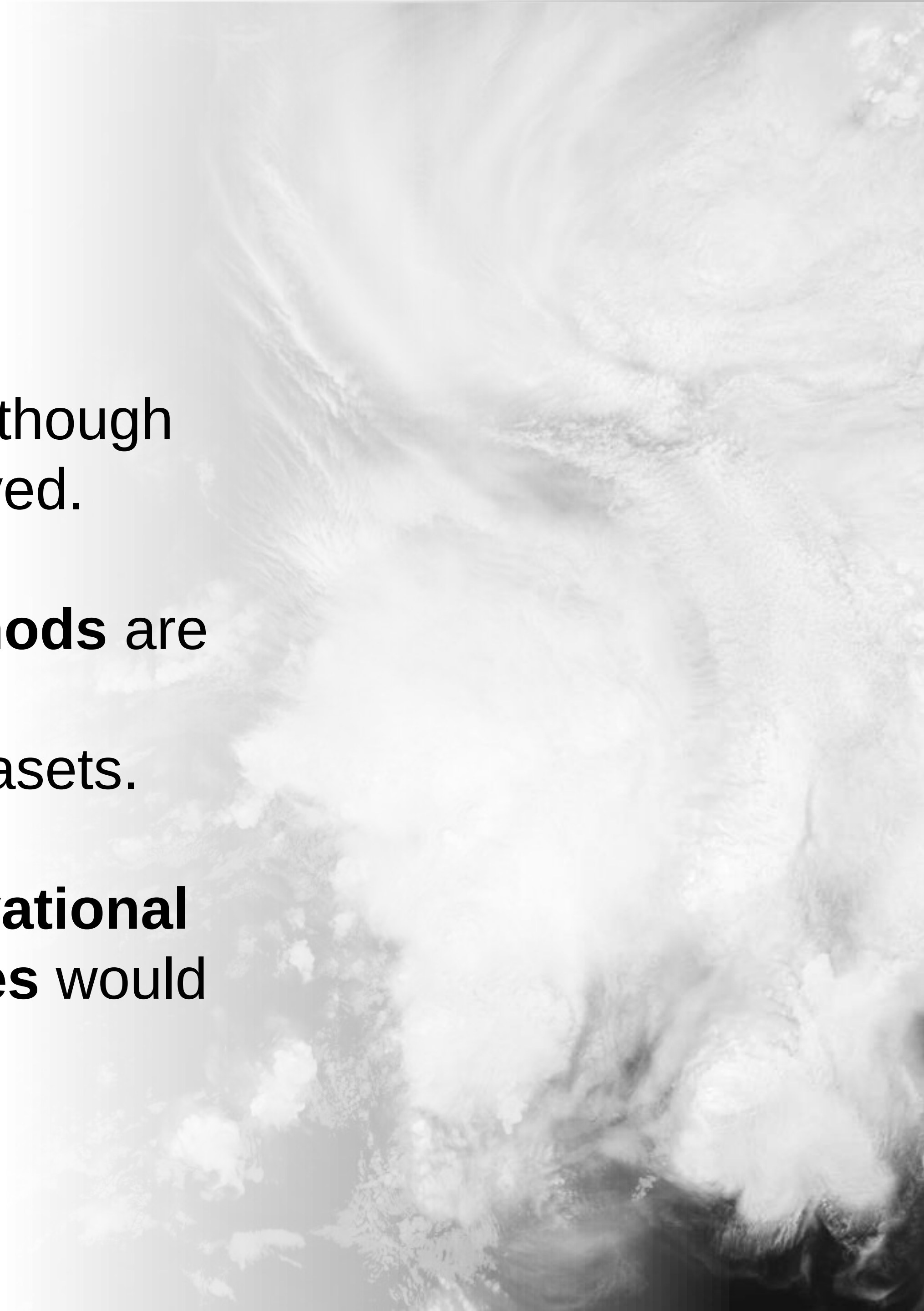
Kukulies et al. (in review)

Key Takeaways

1. **km-scale models revolutionize MCS research**, though critical small-scale processes remain under-resolved.

2. Robust **feature identification and tracking methods** are key to objectively evaluate and compare model performance across scales and observational datasets.

3. Further **improving connections** between **observational and modeling weather and climate communities** would help to accelerate advancements



What is Next?

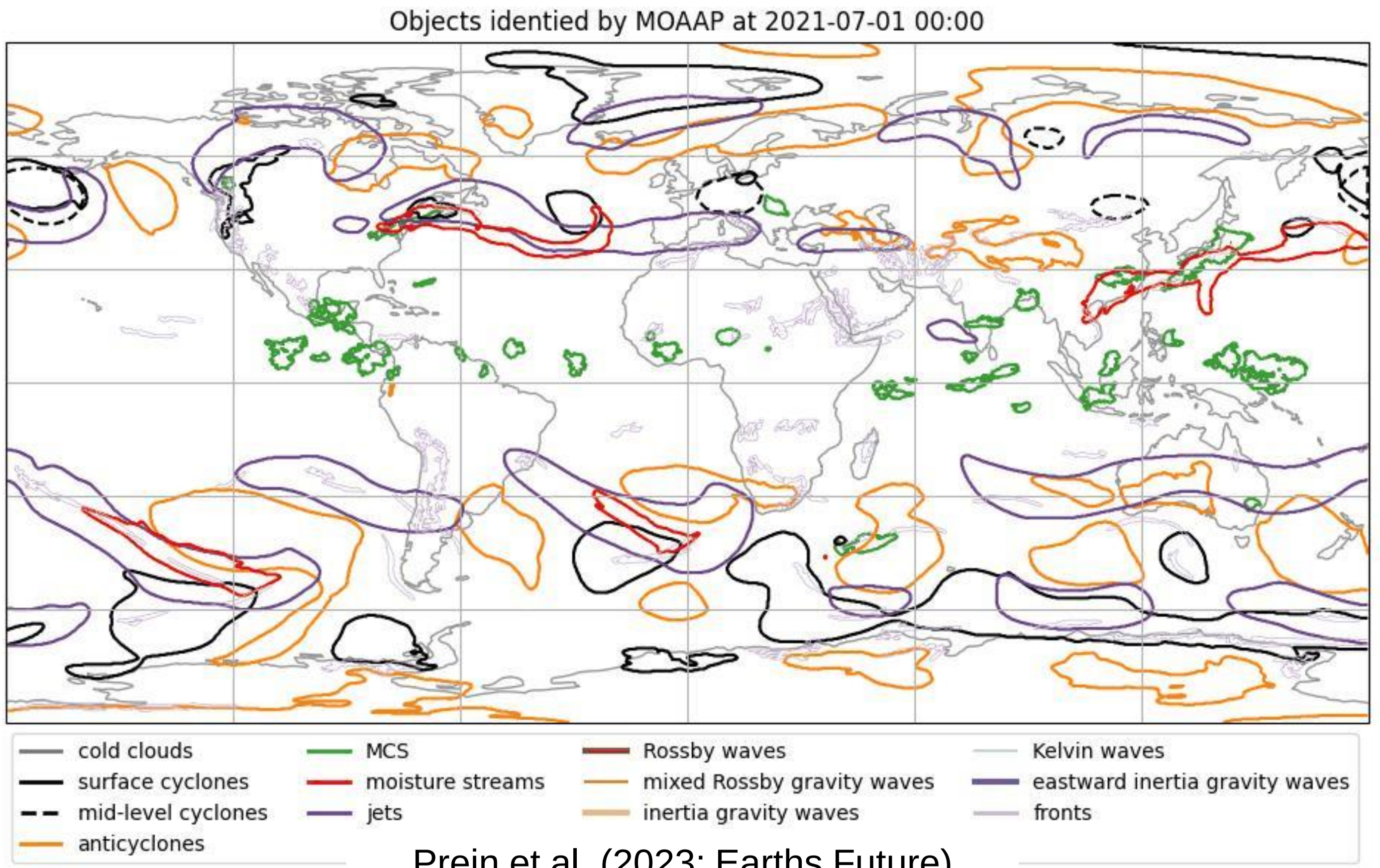
1. Improved understanding of MCS interactions in fully coupled system (ocean, land, atmosphere, biosphere).

What is Next?

1. Improved understanding of MCS interactions in fully coupled system (ocean, land, atmosphere, biosphere).
2. More holistic view of the role of MCSs in the global climate system.

Thank you!

1. Surface cyclones
2. Mid-level cyclones
3. Cut off lows
4. Tropical cyclones
5. Jet streams
6. Anticyclones
7. Atmospheric rivers
8. Mesoscale Convective Systems
9. Fronts
10. Equatorial Rossby waves
11. Kelvin Waves
12. Eastward inertia gravity waves
13. Inertia gravity waves
14. Mixed Rossby gravity waves



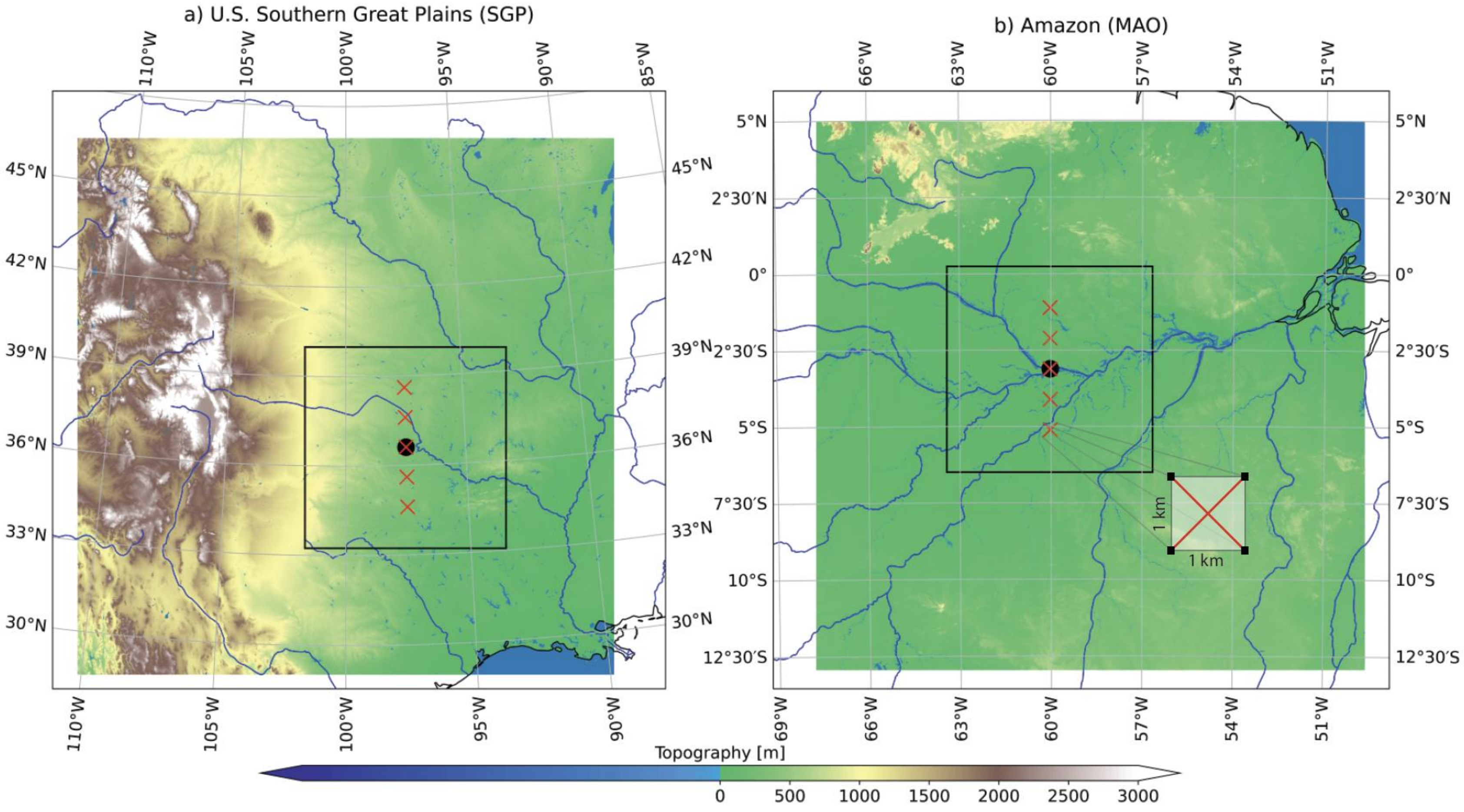
Prein et al. (2023; Earths Future)

Run the Interactive Tutorial on Google Colab

Grid Spacing Sensitivity Simulations With WRF Model

10 Mesoscale Convective Systems (MCSs) Southern Great Plains (SGP)

10 MCSs Amazon Basin (MAO)



- Weather Research and Forecasting (WRF) model

- Downscale ERA5 to
  - **Δ**x=12 km
  - **Δ**x=4 km
  - **Δ**x=2 km
  - **Δ**x=1 km

- Downscale 1 km sim. to
  - **Δ**x=500 m
  - **Δ**x=250 m
  - **Δ**x=125 m

- Optimized physiks options (Prein et al. 2022)
- LES options used in 250 m and 125 m simulaitons

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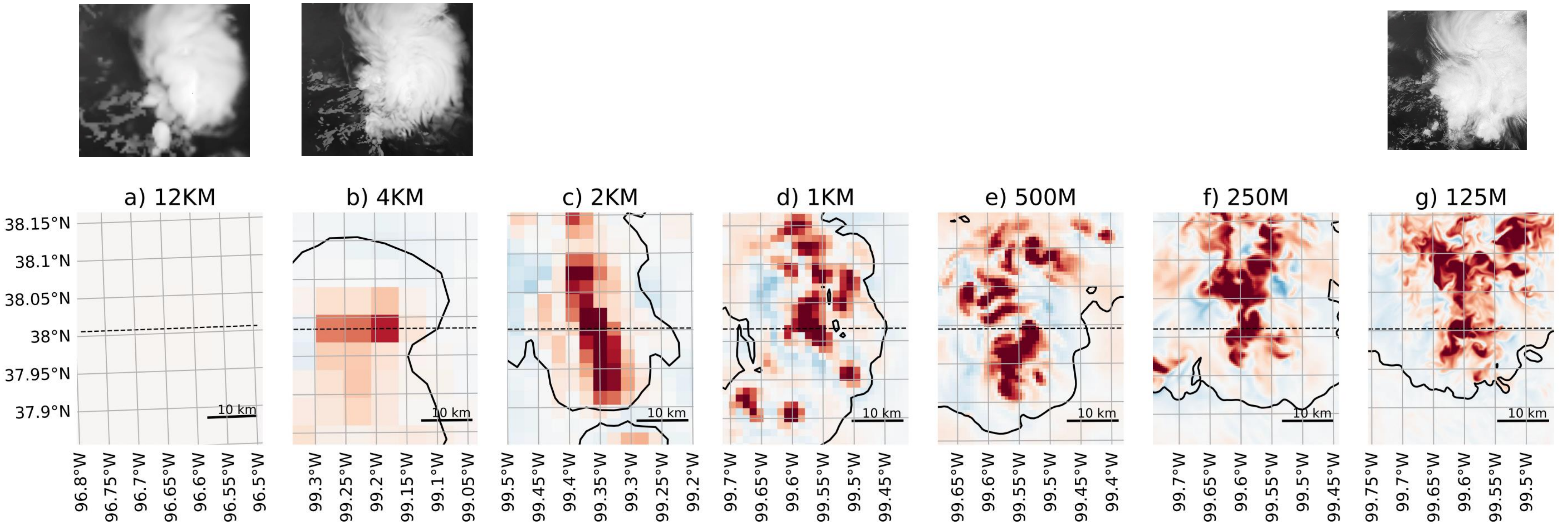
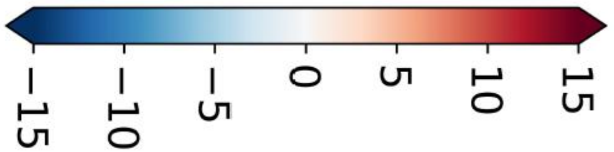
ARM

Which grid spacing is sufficient?

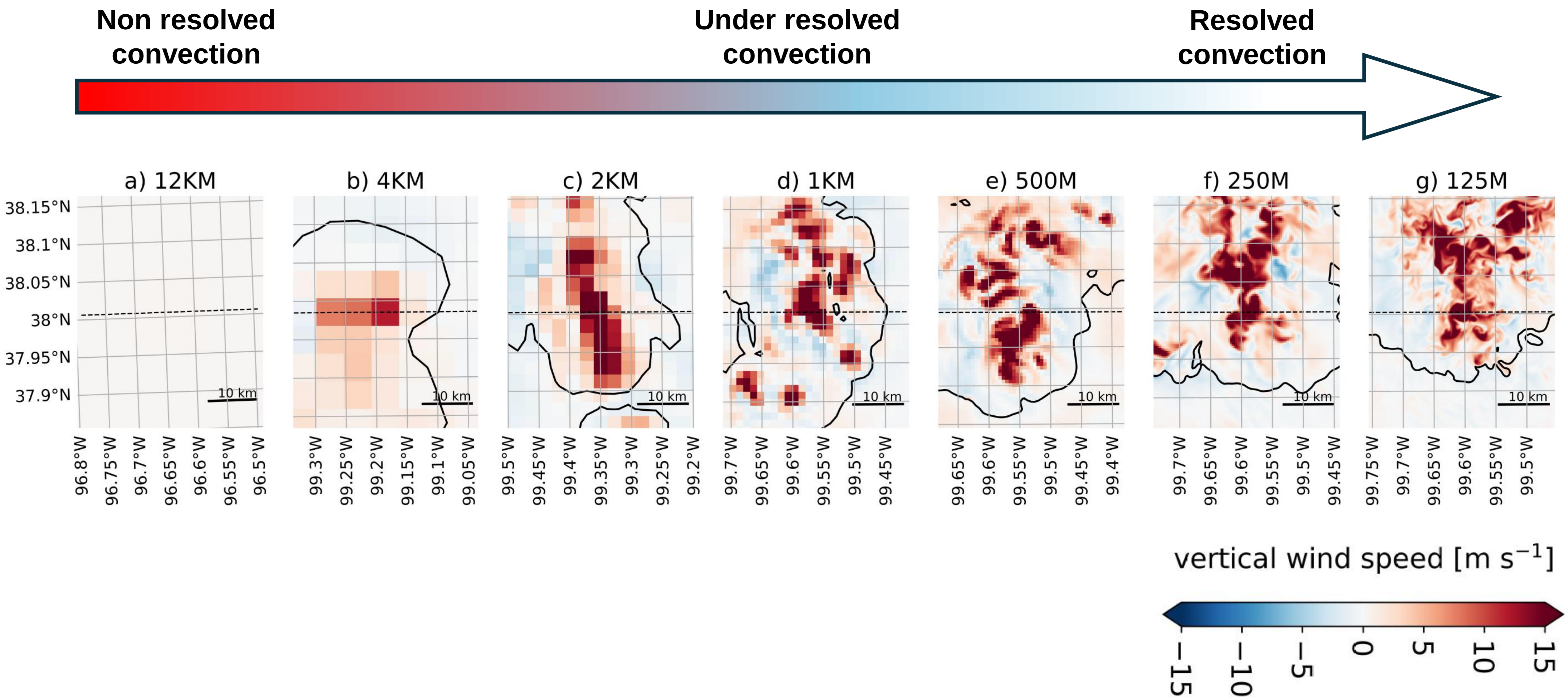


Vertical velocity at ~7 km altitude during the MCS overpass on June 12, 2014 over Southern Great Plains.



Prein et al. (2025, JGR-A)

Which grid spacing is sufficient?



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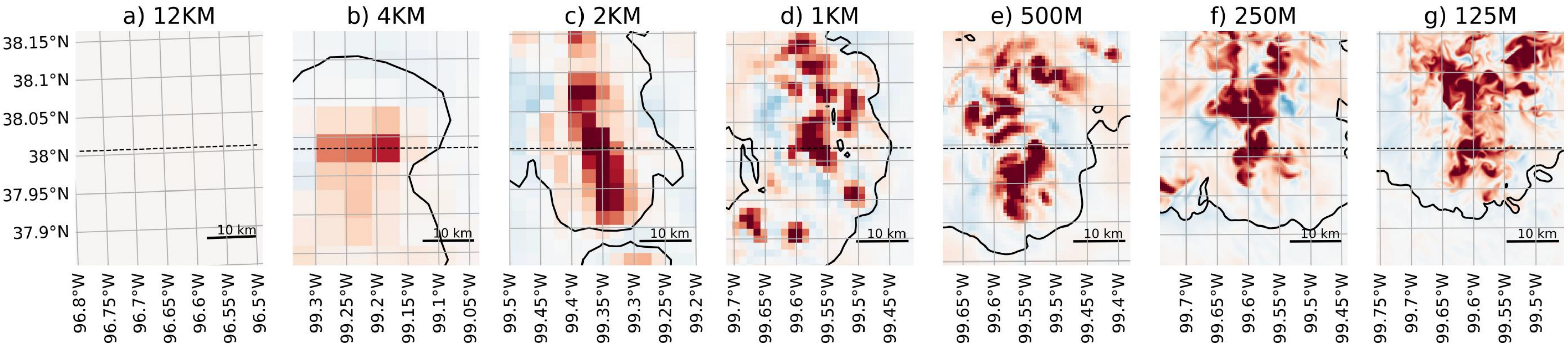
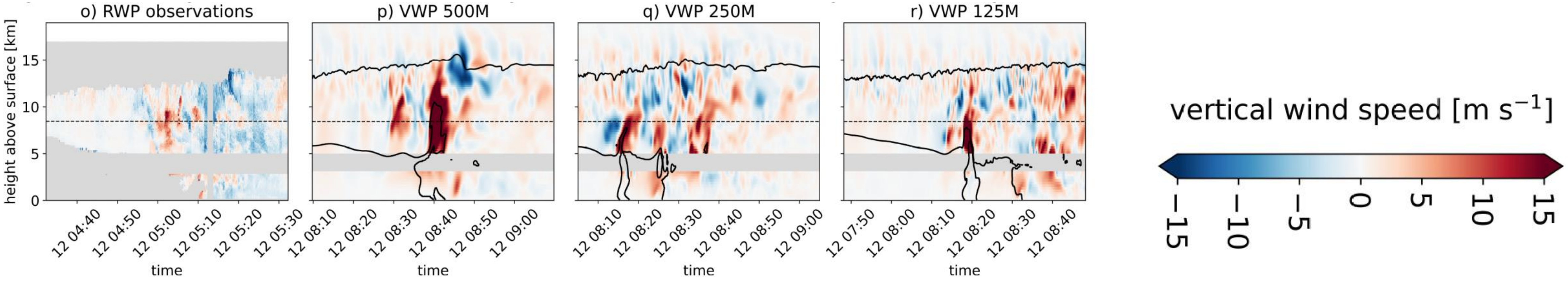
Prein et al. (2025, JGR-A)

Grid Spacing Sensitivity Simulations With WRF Model
Southern Great Plains Example



Time-height Crossections

observations



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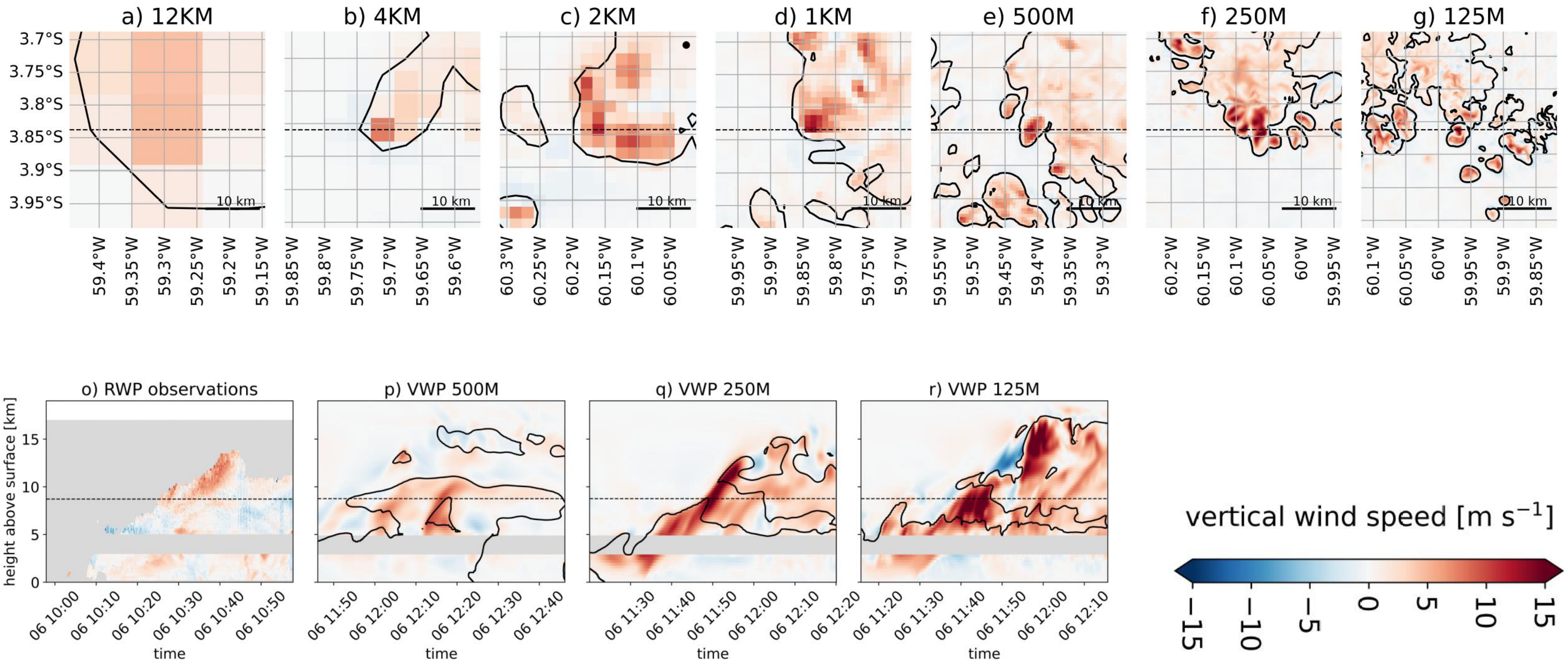
Grid Spacing Sensitivity Simulations With WRF Model
Amazon Basin Example



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