Assessment of Convective-scale Attributes of the FV3 Dycore using Idealized Simulations

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Corey Potvin, Bill Skamarock, Curtis Alexander, Jacob Carley, Christiane Jablonowski, Stan Benjamin,
and all the members of the Dycore Discussion Group for all their support and helpful suggestions!

NSSL has an opening for MS/PhD graduate to work on 3D Convective Reanalysis Project (https://ciwro.ou.edu/careers)

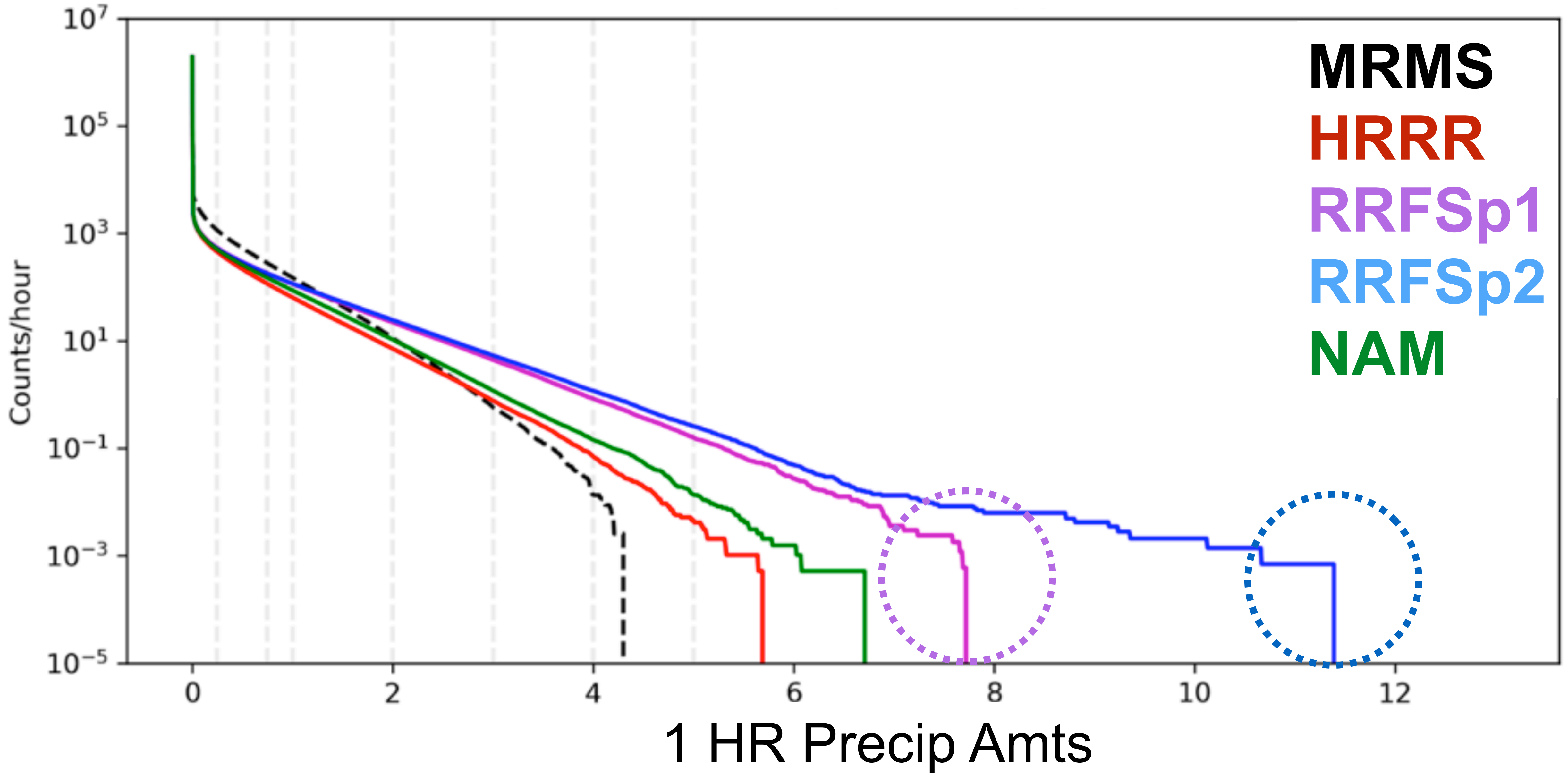
I am also looking for new NRC Post-Doc to improve radial velocity and dual-pol data assimilation in WRF and MPAS (email at Louis.Wicker@noaa.gov)

Focus on Two FV3 Issues

- Our point of view: NSSL's Warn on Forecast System
  - Focused on predicting behavior of ***individual cells***
  - ***Details*** of the convective structure, rotation, and evolution are ***important*** - model output needs to look like the ***radar!***
- FV3 dynamical core appears to have lower "effective" resolution for convective storm structures as well as some other differences (precip, updrafts) when compared to current CAMs.
  - Will show that this is true, but degree of impact depends on the environmental parameters
- FV3 updraft profiles are often 1-3 km deeper than WRF or CM1 profiles in squall lines.
  - Will present a new hypothesis to understand this behavior.
- Both lead to a number of issues, including storms which are too large have excessive precipitation

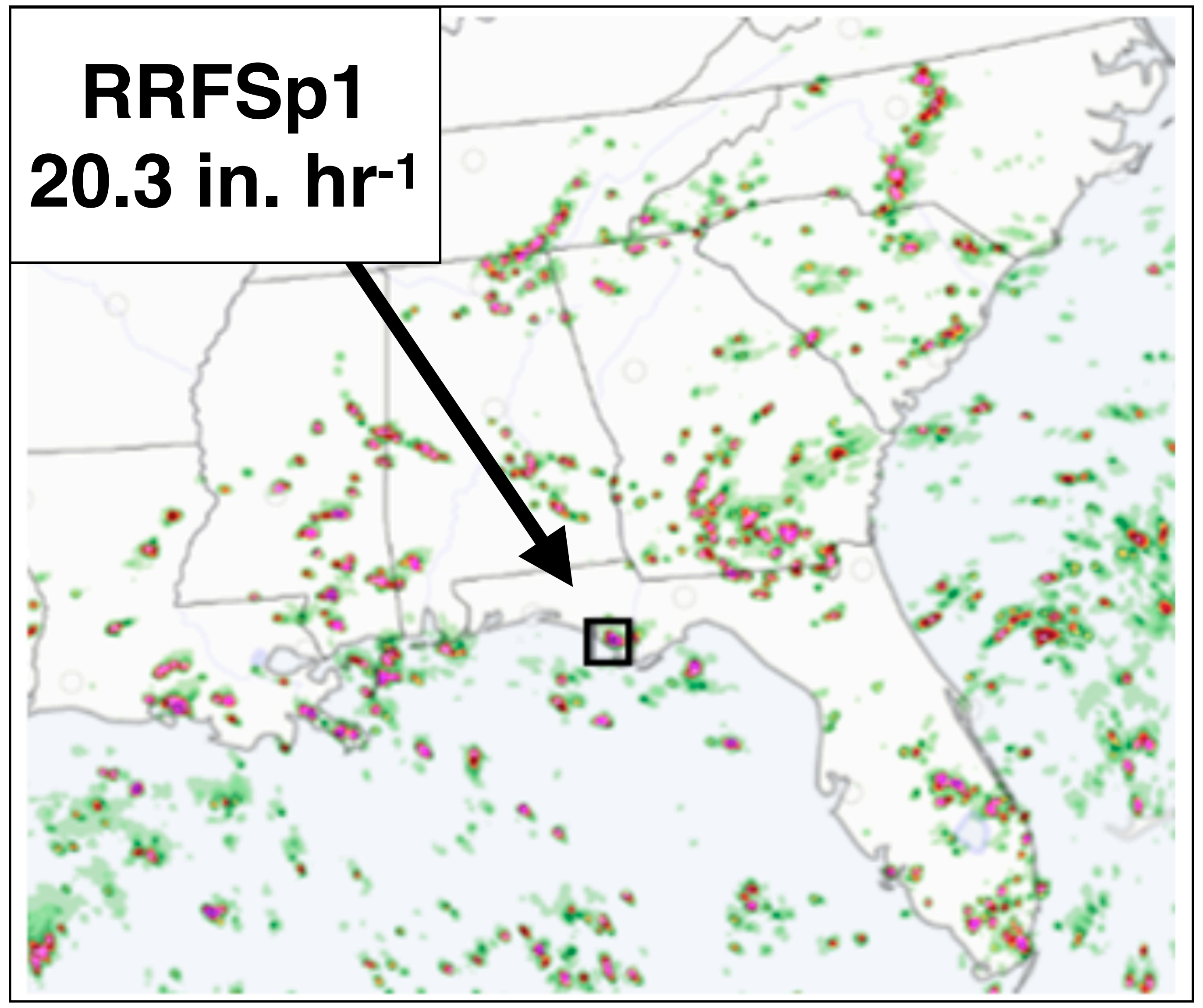
Motivation: UFS CAM (RRFS) vs HRRR CAM

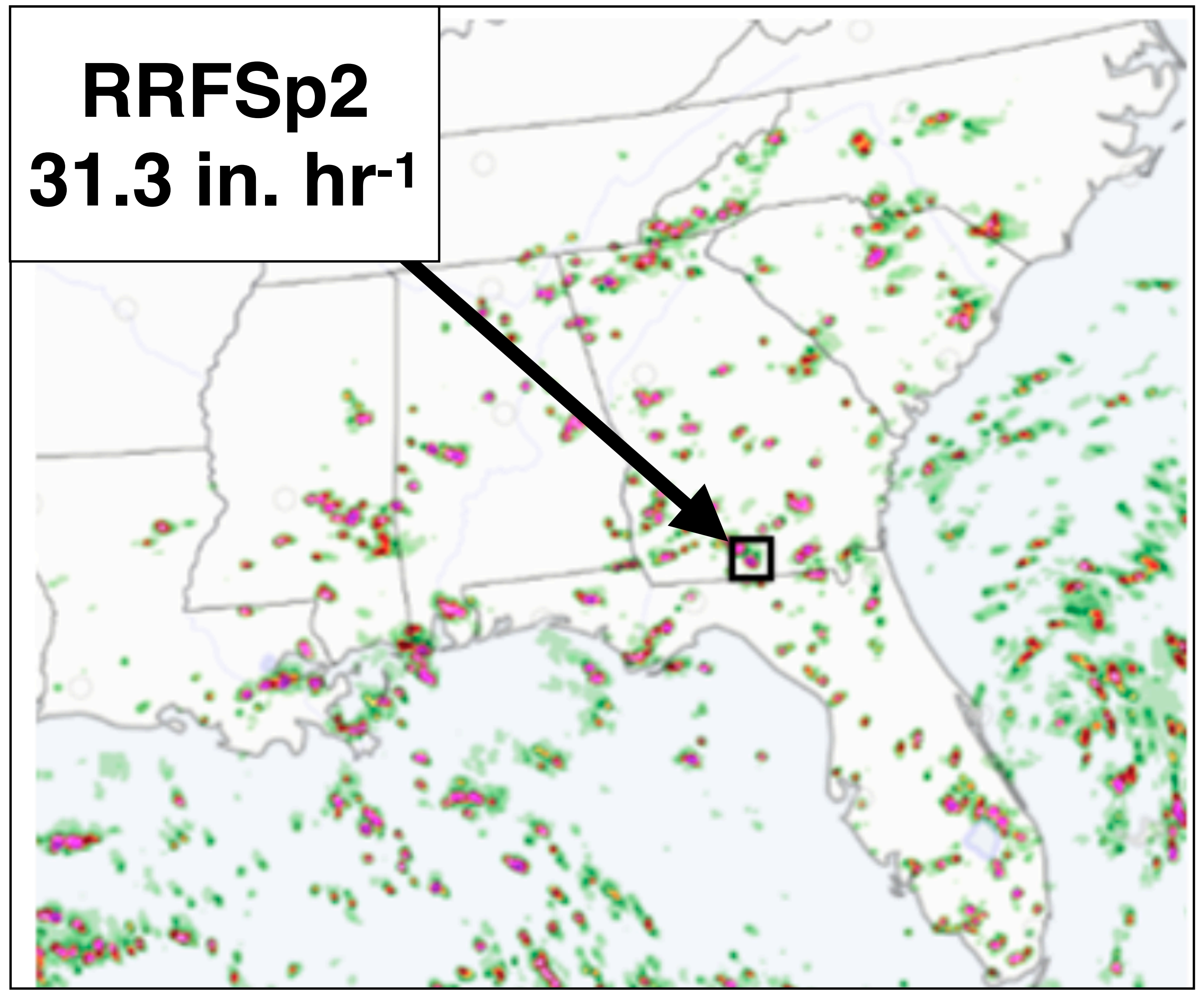
2022 FFAIR Frequency Diagram
1 HR Precip Accum - SE Region



"When compared to the operational models and MRMS precipitation rates, both instantaneous (p-rate) and hourly max (pmax), the RRFS deterministic and ensemble members had high to extreme rates. This included some simulated pmax values over 100 in h^{-1}. Often these high rates were collocated with popcorn storms."

Source: 2022 FFAIR Final Report (https://www.wpc.ncep.noaa.gov/hmt/2022_FFaIR_Final_Report.pdf)

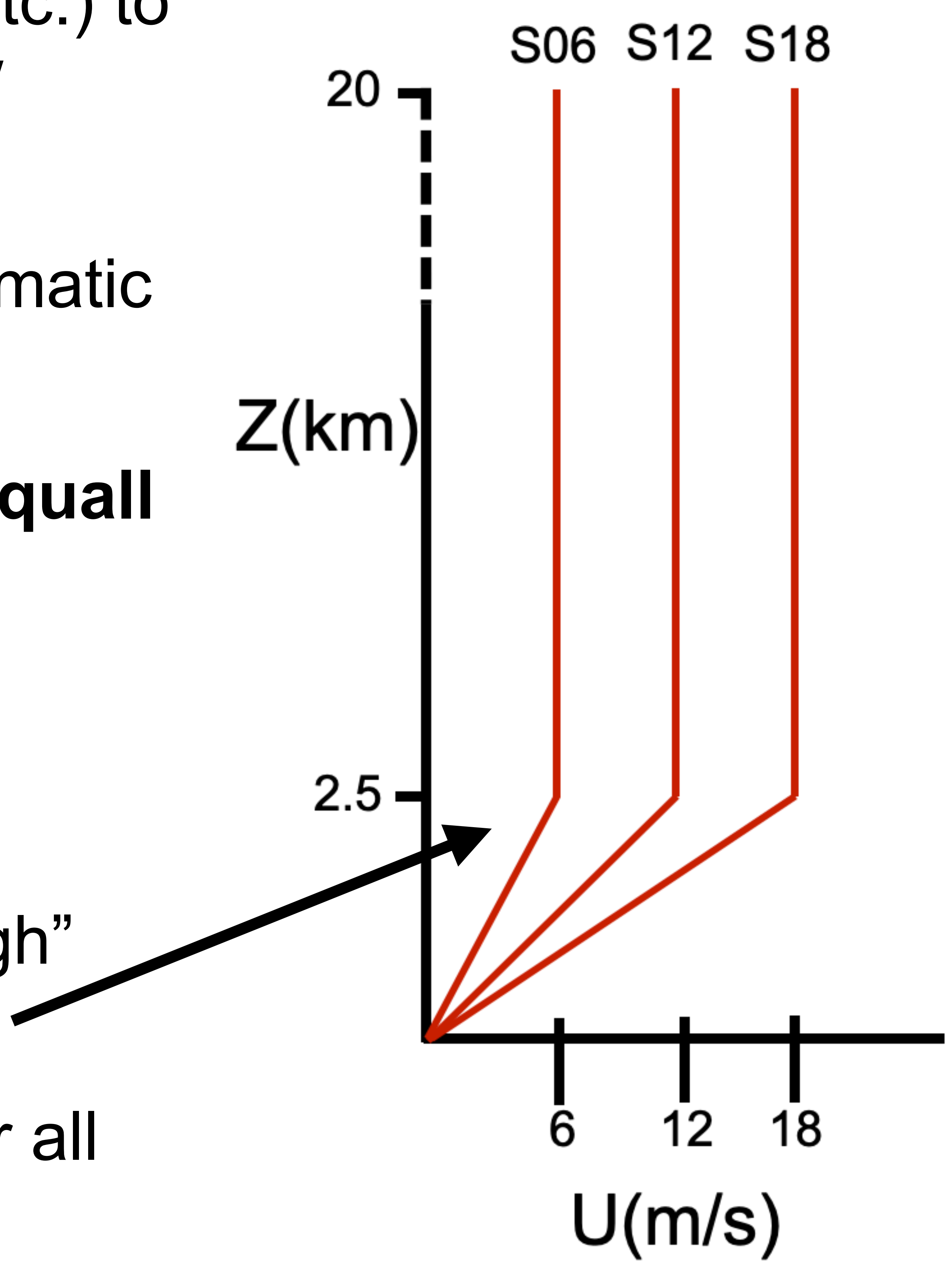




Maximum Rain Rates from MRMS (obs) ~7.9 in. hr^{-1}

A Test Suite for CAMs using Squall Line Simulations?

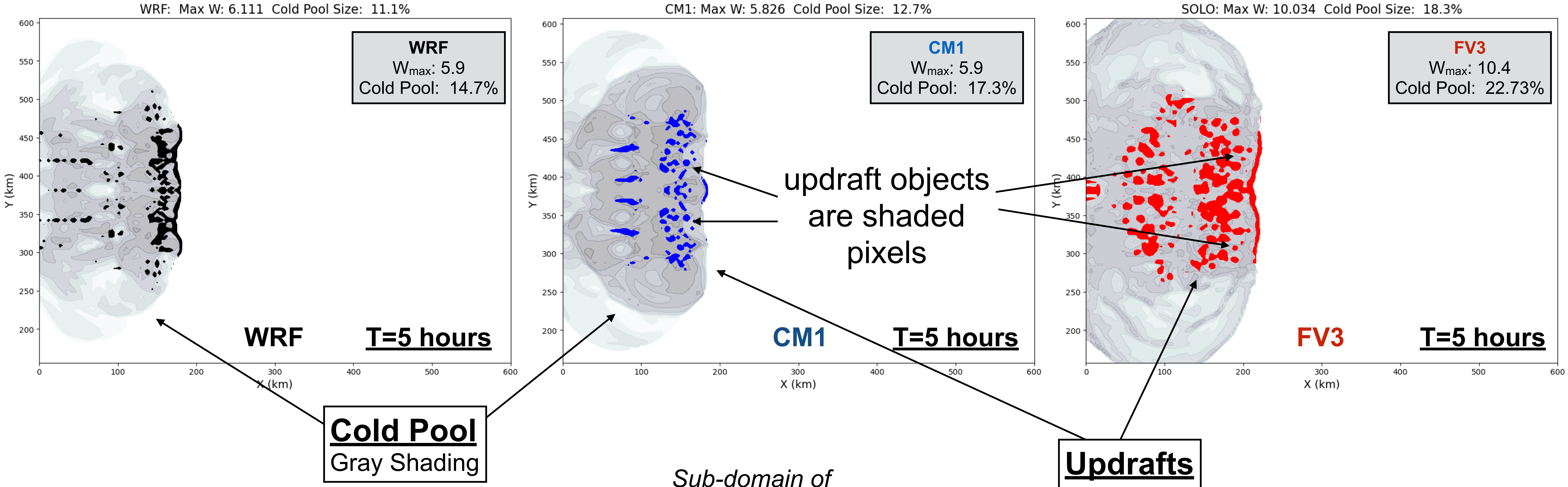
- Real data cases, while important, are hard to control for (config, physics, IC, etc.) to understand model behaviors and biases. Particularly true for convection - few observations are are available to validate the model solutions.
- **A less complex framework would be helpful** to better understand the systematic biases seen in the real data runs from the RRFS and HRRR.
- Most CONUS convection occurs in *lines* or *clusters* - **Lets look at idealized squall lines!**
- Models: ***FV3-Solo**, **WRF**, **CM1*** running KESSLER MICROPHYSICS
- Discuss two CAPEs: 2000 & 3500 J/kg, using *(McCaul and Weisman 2000)*
- Discuss two shear profiles: “low” shear (6 m/s over a depth of 2.5 km) and “high” shear (18 m/s over a depth of 2.5 km depth)
- Grid: 256 x 256 x 60, 3 km spacing, RRFS NWP vertical grid spacing used for all models (dz ~ 12 m near ground)
- Initial Conditions: 7 warm bubbles aligned N-S near western part of domain, centers are 40 km apart.



What do the the squall lines look like?

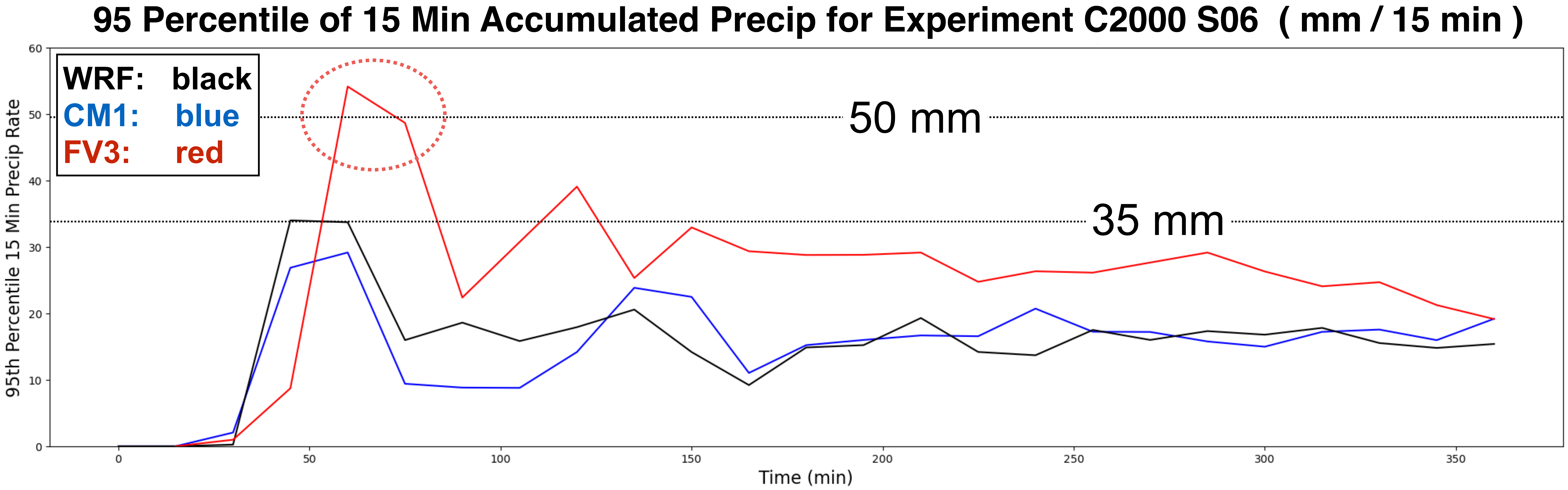
WRF: black
CM1: blue
FV3: red

Experiment Cape=2000 Shear=06



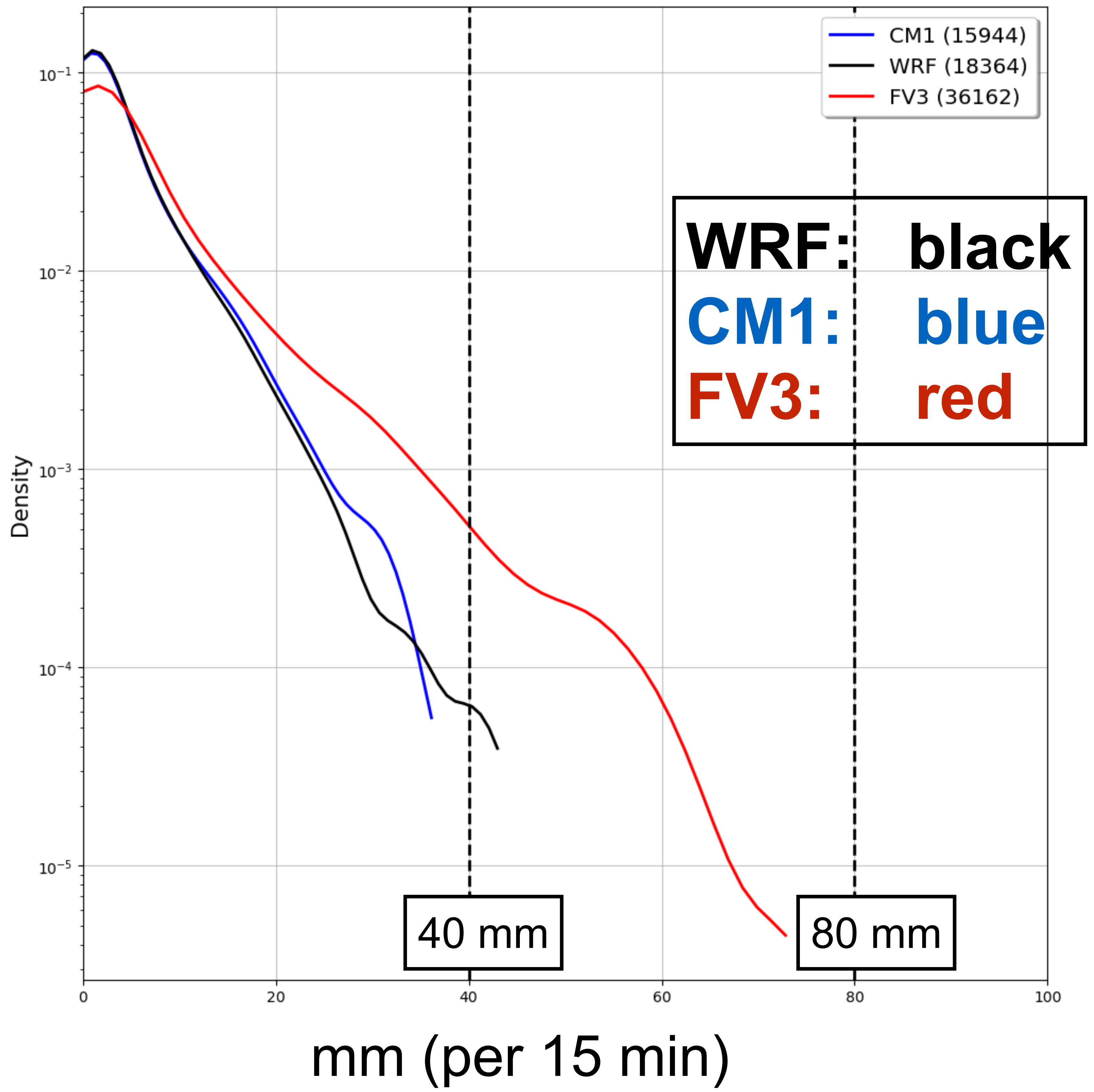
Sub-domain of 600^2 km shown

15 min Precipitation Rates over 6 hrs

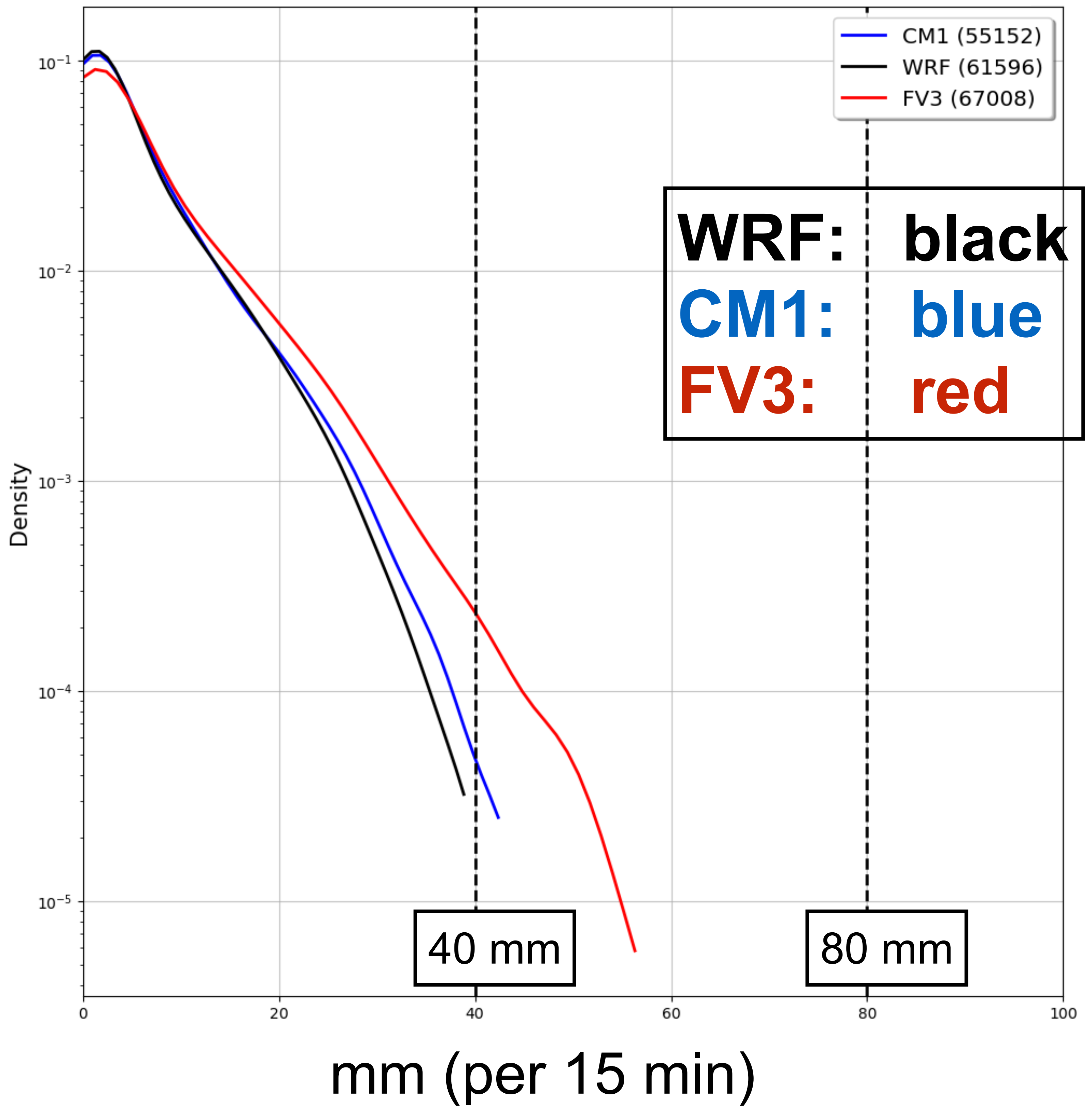


KDE of 15 min Precipitation Rates over 6 hrs

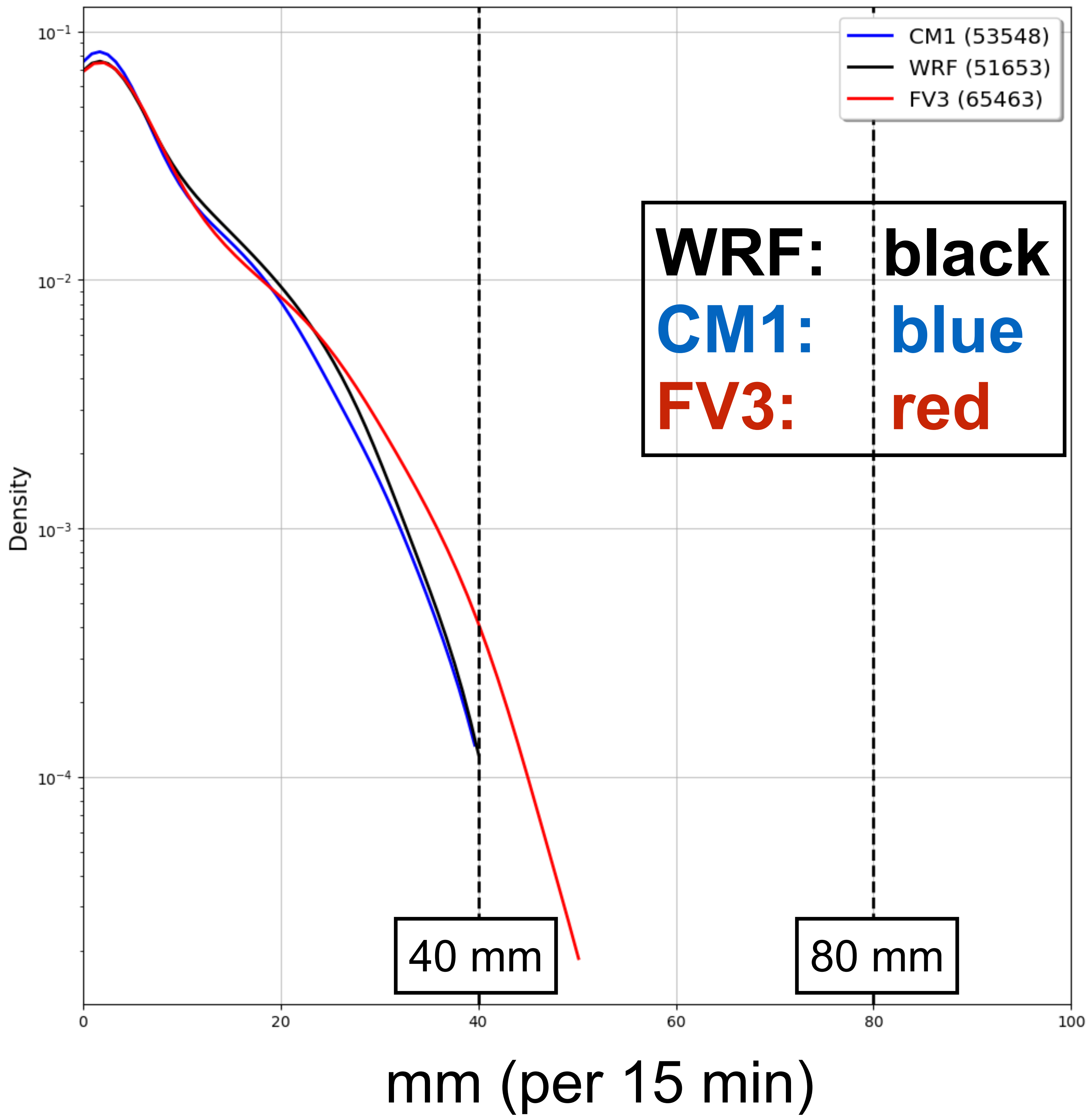
Experiment Cape=2000 Shear=06



Experiment Cape=3500 Shear=06



Experiment Cape=3500 Shear=18

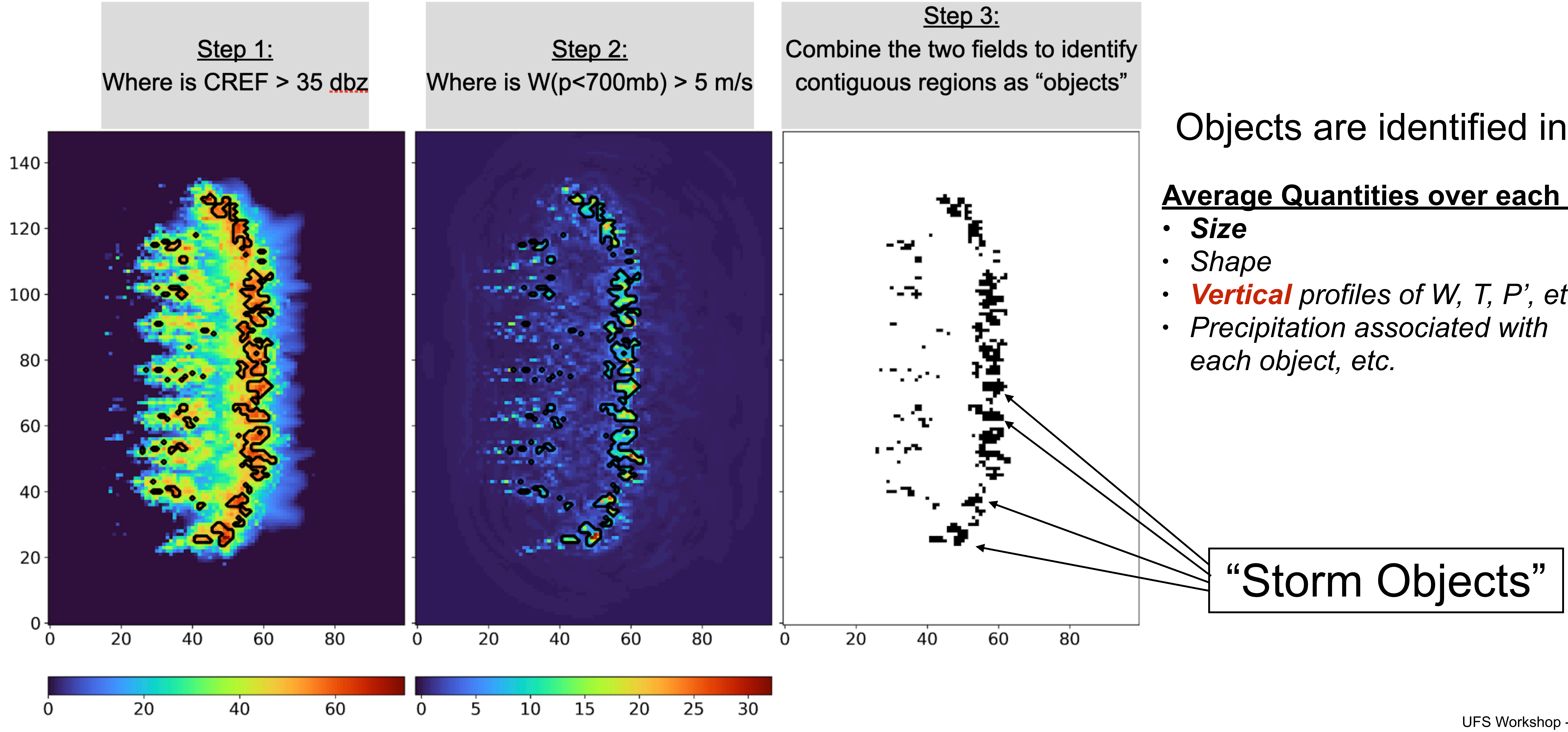


IDEALIZED squall lines with RRFS and Kessler reproduce the excessive precipitation rates seen in full physics RRFS runs!

- **C2000_06: FV3-Solo has extreme precipitation rates (10x more points larger than 40 mm than NCAR models, extreme values exceed 60 mm)**
- **As CAPE increases - differences are smaller / As SHEAR increases - differences are again smaller**
- Precipitation rates are functions of environment! => FV3 has excessive precipitation in the low-moderate CAPE, weak shear (same as FFAIR results!)

Analysis Methodology: Identify Storm "Objects"

Look at properties of storm objects – not fields! (e.g., Potvin et al. 2019 WAF)

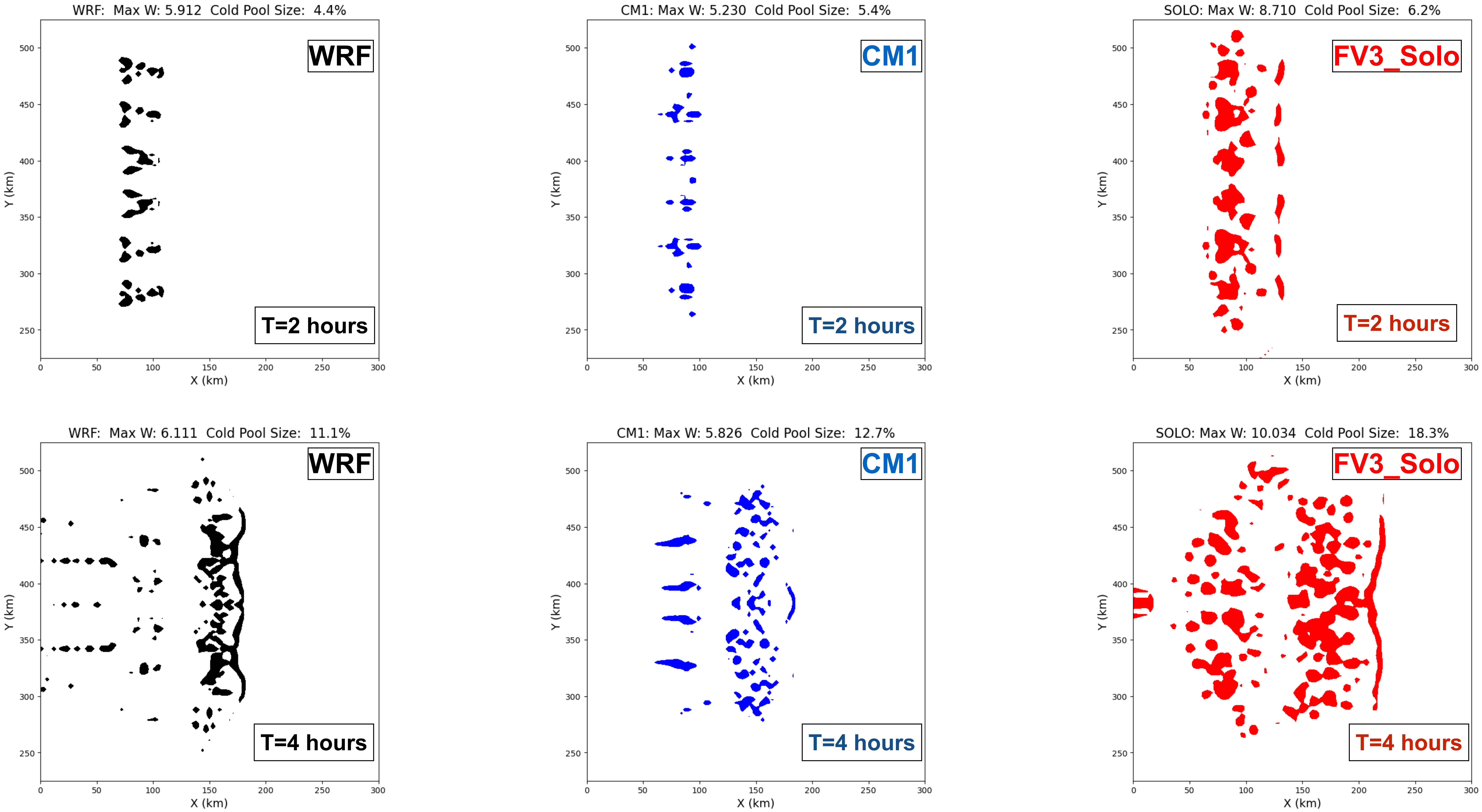


Objects are identified in 2D

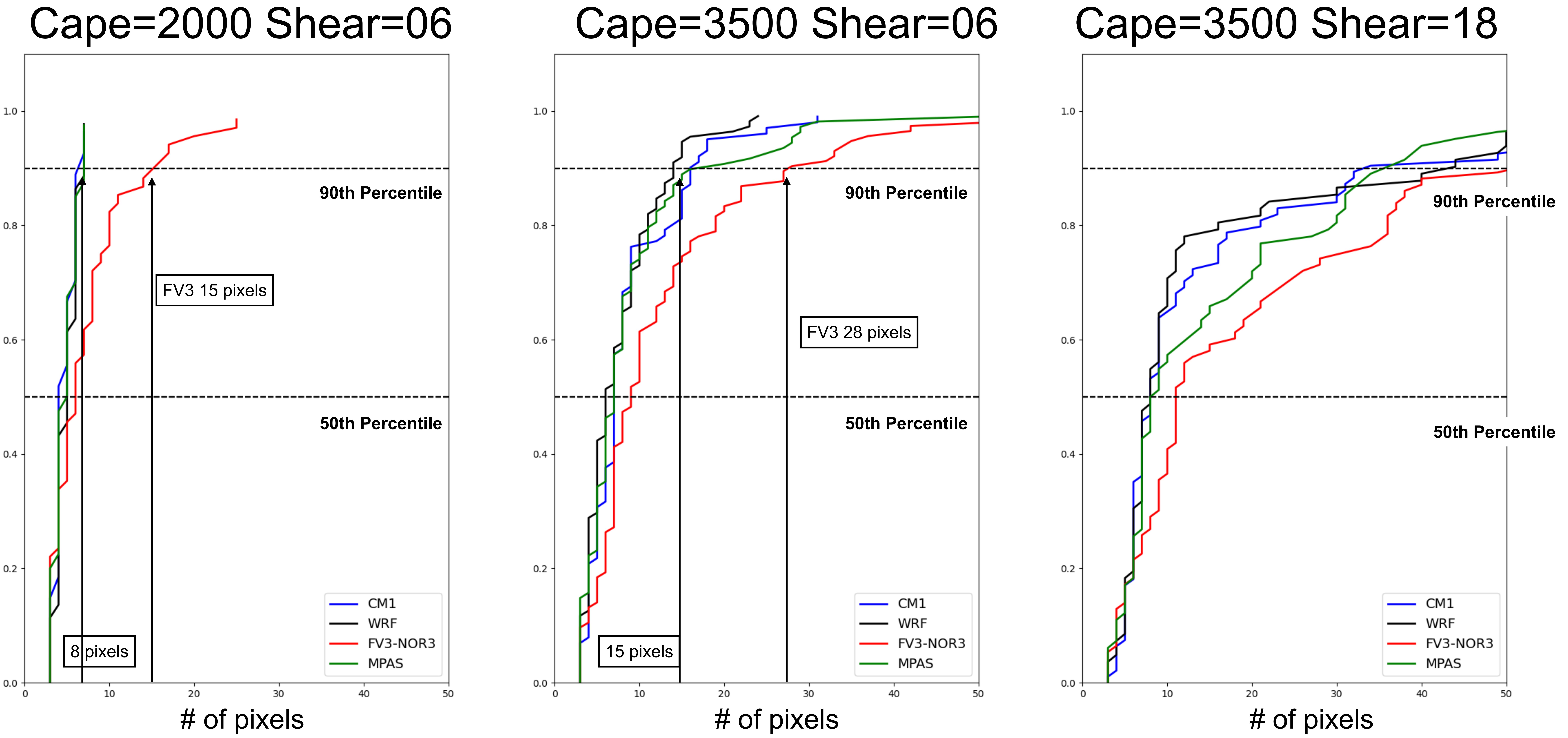
Average Quantities over each object

- ***Size***
- *Shape*
- ***Vertical** profiles of W, T, P', etc.*
- *Precipitation associated with each object, etc.*

Measuring Horizontal Resolution:
2D Plots of Object Areas for 3 models for Cape=2000 and Shear=6 m/s



Measuring Horizontal Resolution:
Cumulative Histograms of Updraft Storm Object Size for 0-2 Hours



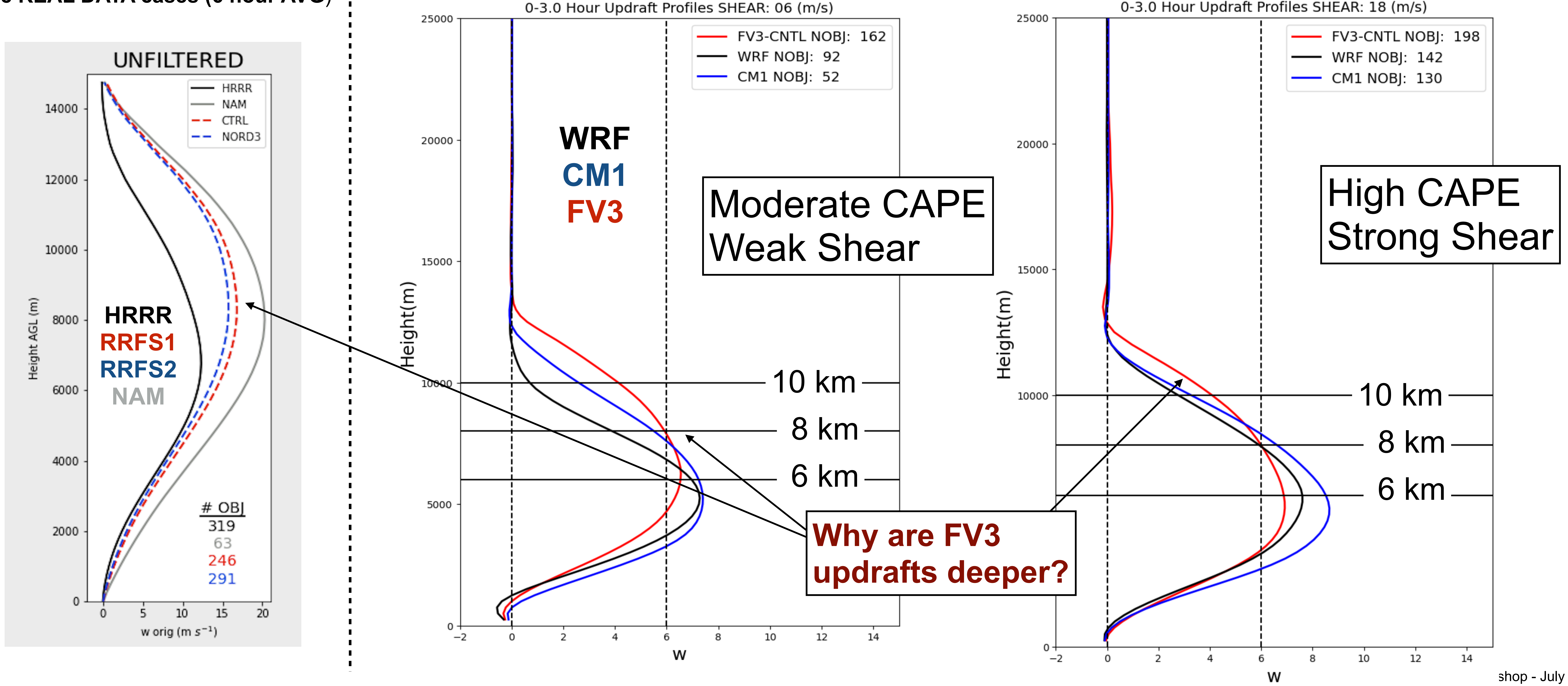
Understanding Updraft Characteristics:

3 hour Average Storm Object Updraft Profiles for 2 CAPE/SHEAR Environments

Mean CAM W-Profiles from 8 REAL DATA cases (6 hour AVG)

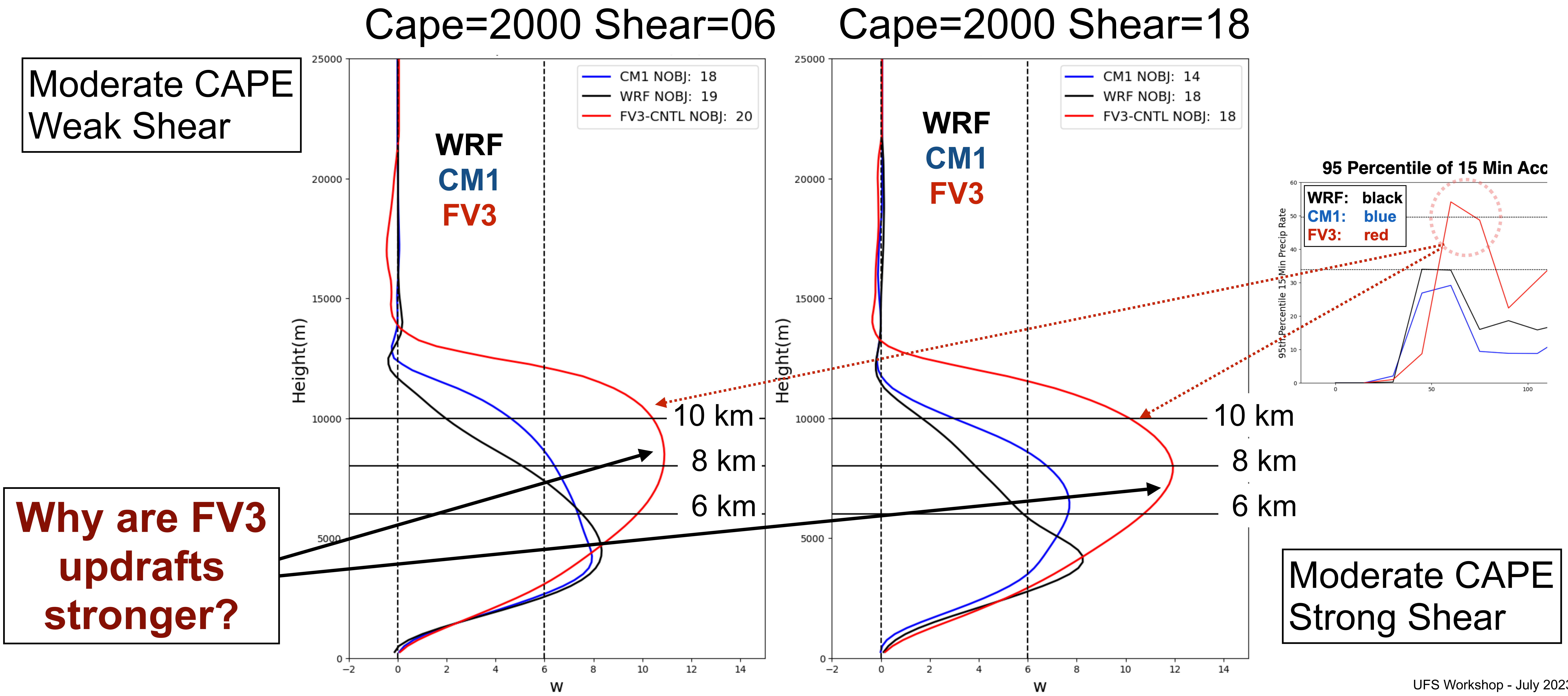
Cape=2000 Shear=06

Cape=3500 Shear=18



Understanding Updraft Characteristics:

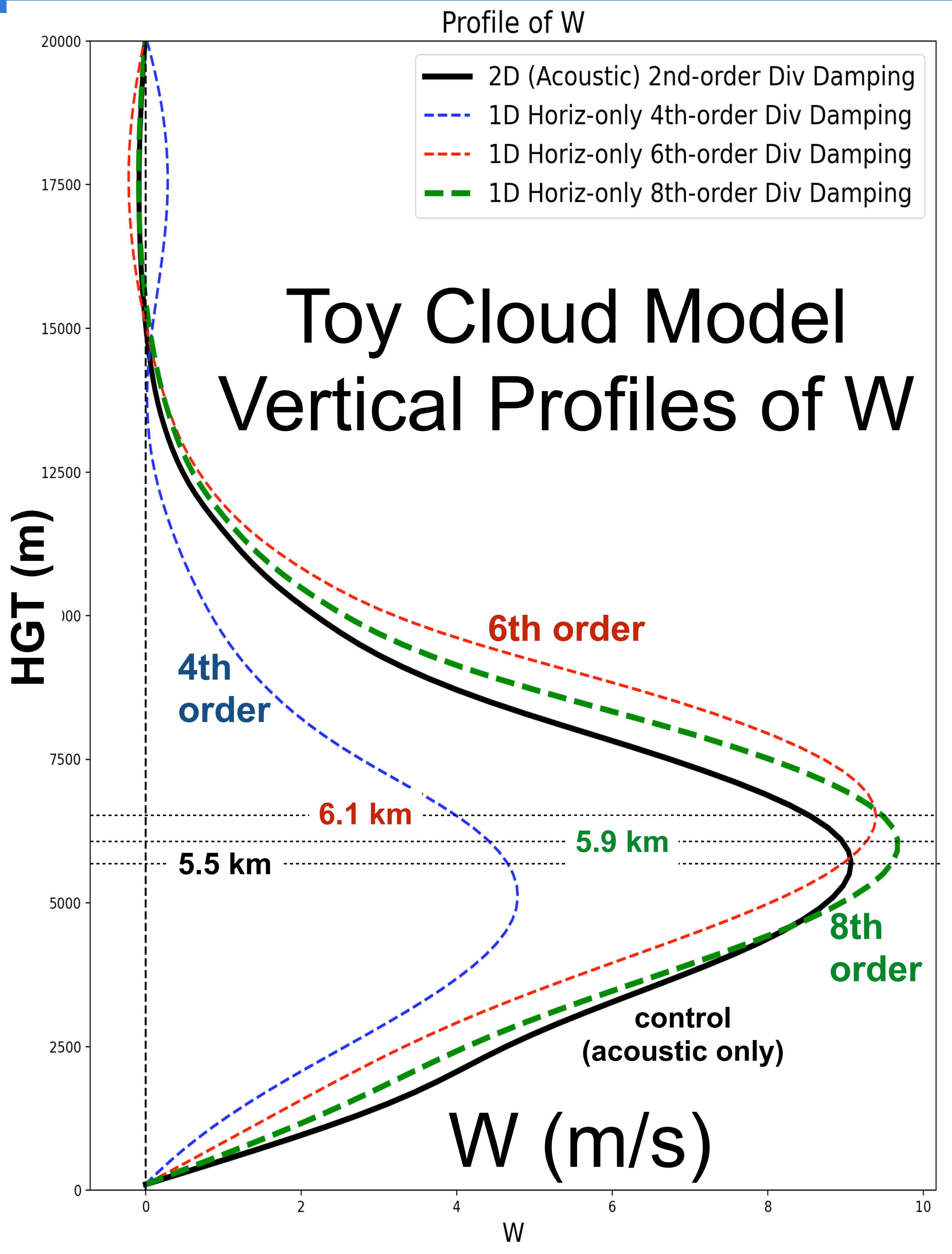
1 hour Average Storm Object Updraft Profiles for 2000 S06 & S18 Environment



Hypothesis: Impact from Horizontal Divergent Damping?

- FV3 uses two-dimensional divergent damping to remove grid-scale noise
- While 2D div-damping is used in many models, the coefficient controlling the damping is very large relative to other models
- Higher-order divergent damping (FV3 & RRFS use ∇^8(Div)) is used to only remove smallest scales.

- Test the impact of horizontal divergent damping on updrafts profiles
- A **moist** X-Z toy cloud model is initialized with a bubble and no vertical wind shear. (Δx = 3 km, Δz = 200 m).
- Vary the order (4th, 6th, 8th) of the *Horizontal-only divergent damping* (HoDD).
  - HoDD coefficient (i.e., the d4_bg parameter) is 0.12, same as FV3
  - 6th and 8th order HoDD changes the height of the maximum updraft
  - 6th and 8th order HoDD increases the updraft maxima by 10-15%
- *Do large values of HoDD impact updraft dynamics in ways not previously understood?*

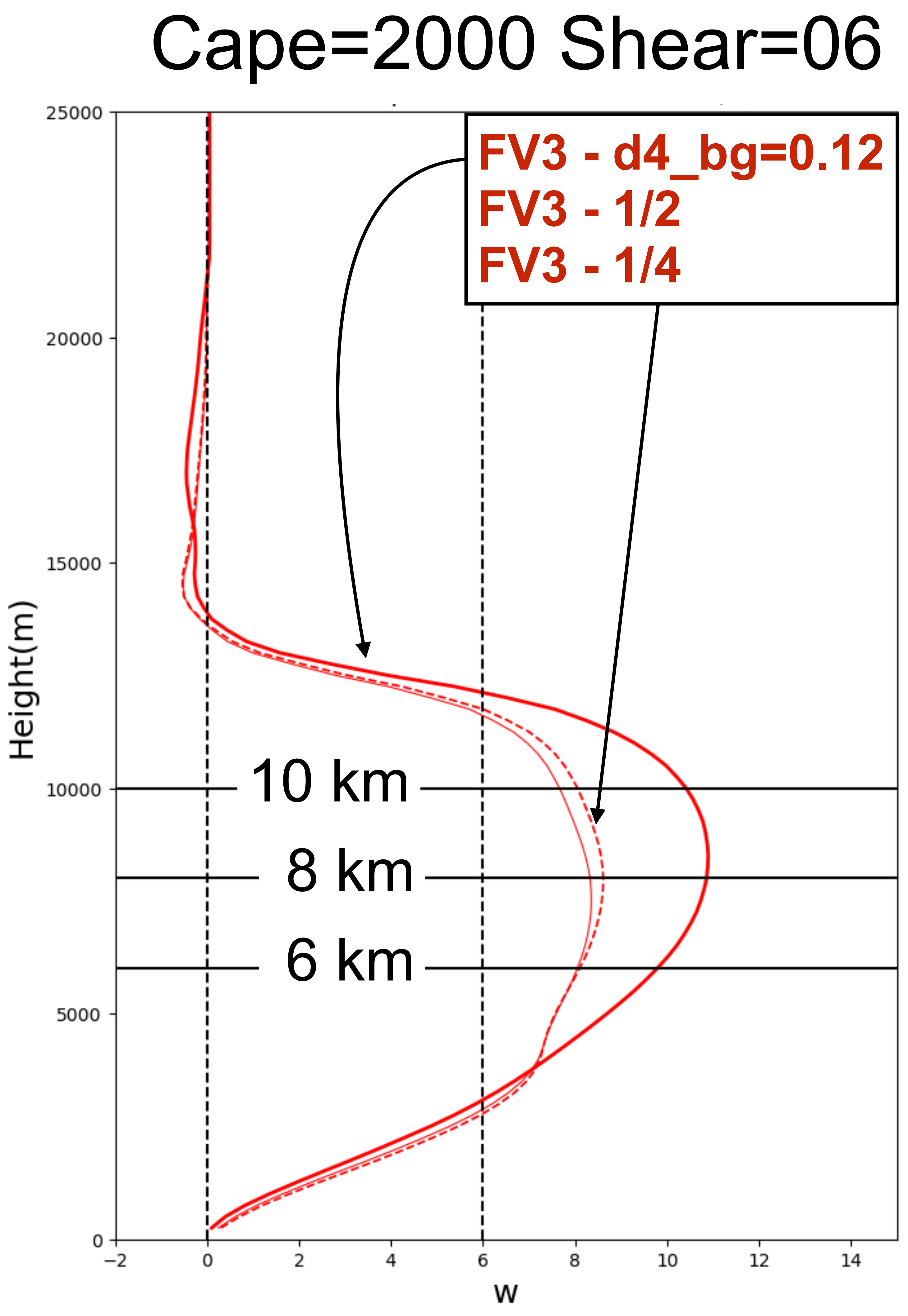


Can we show this behavior the FV3 Squall Line Simulations?

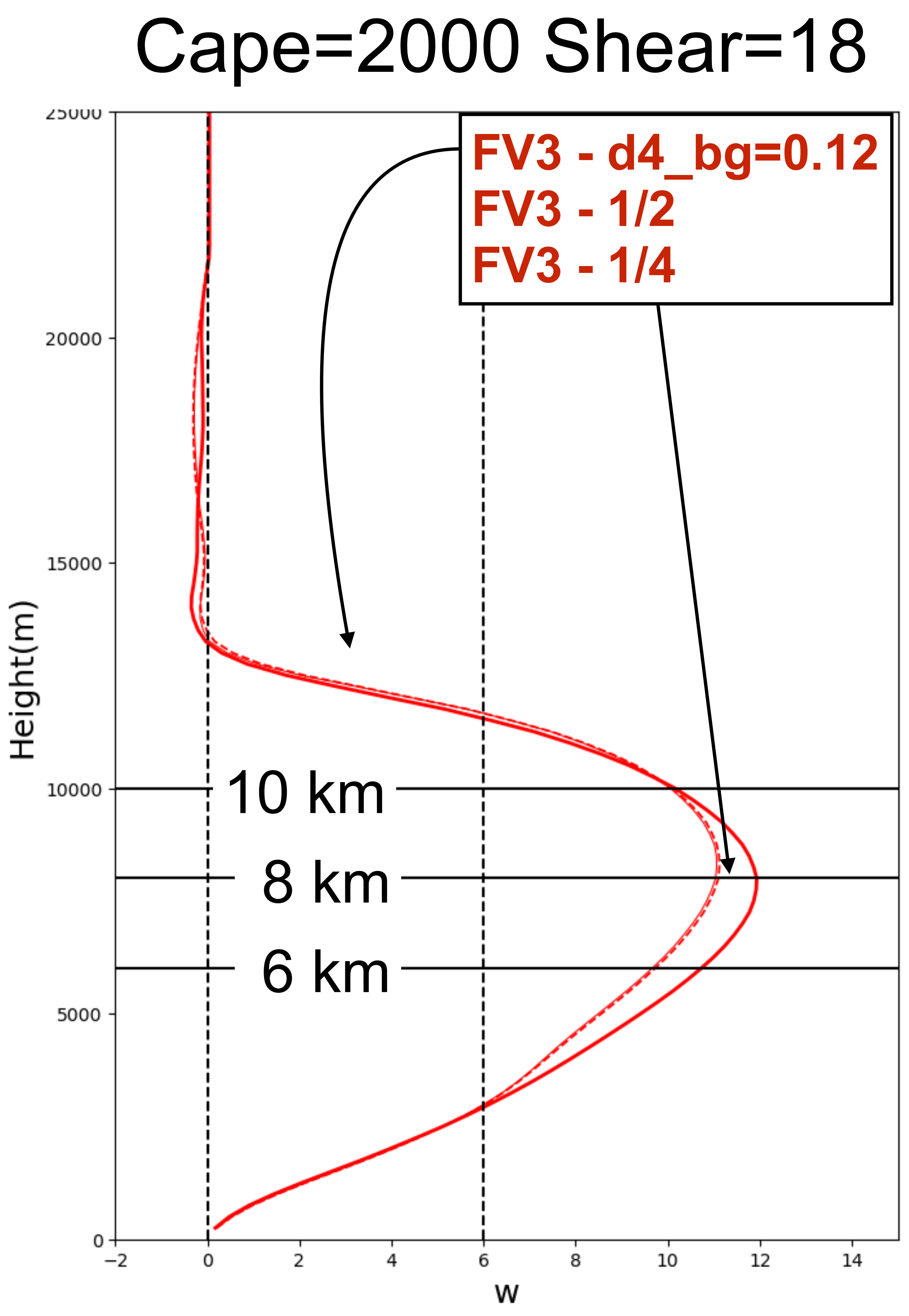
(*1* hour Average Storm Object Updraft Profiles for 2000 S06 & S18 Environment)

FV3 already uses maximum stable HoDD coefficient, so lets reduce it!

Moderate CAPE
Weak Shear



Again see that filters change the updraft profiles more in lower shears



Moderate CAPE
Strong Shear

At higher shear, other processes (entrainment?) reduce the differences

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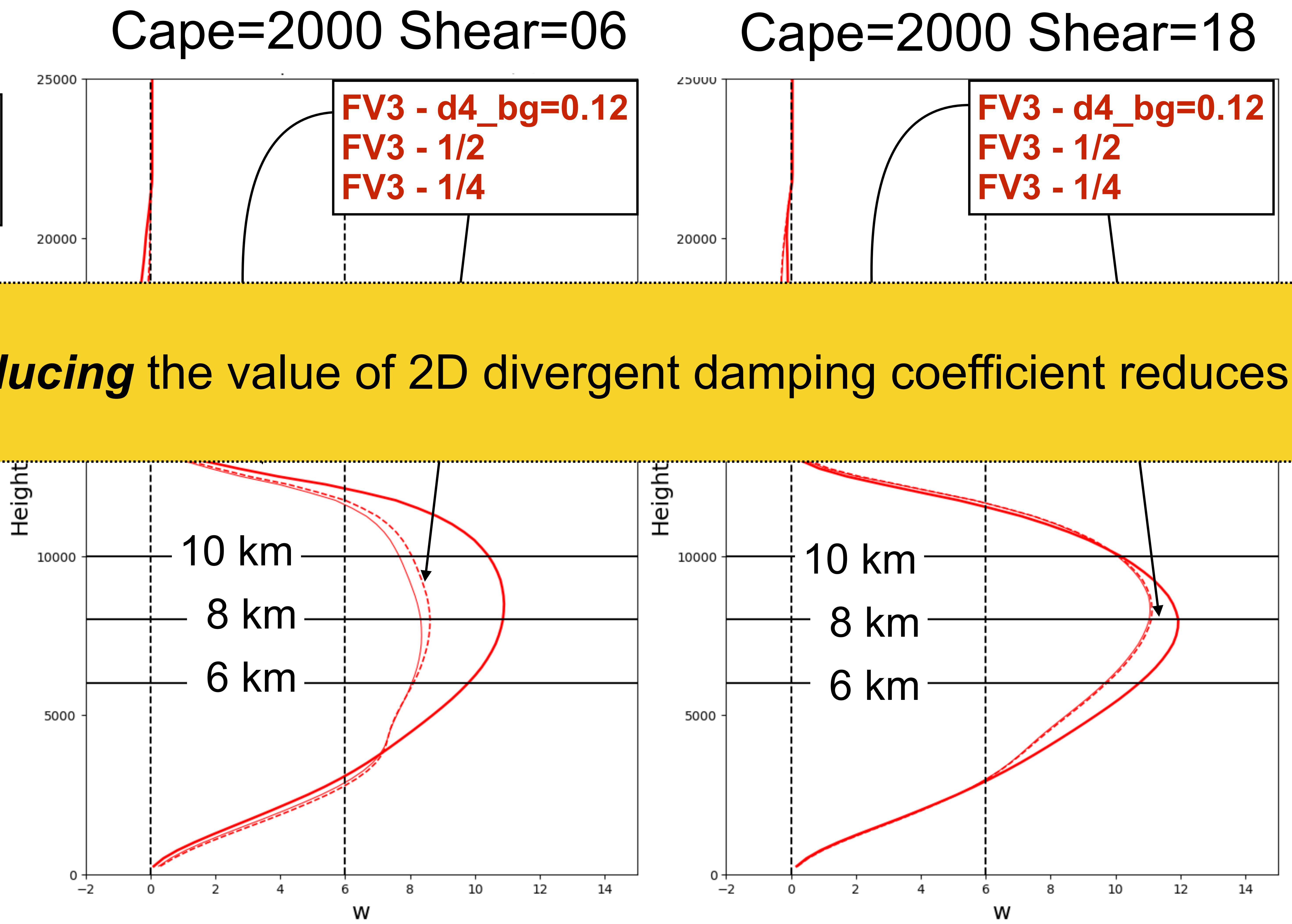

Moderate CAPE
Strong Shear

Reducing the value of 2D divergent damping coefficient reduces updraft intensity!

Again see that filters impact updrafts more in lower shear environments

At higher shear, other mixing (entrainment?) and processes reduce the differences

Summary

- A comparison of similarly configured models (FV3, WRF, CM1) has been performed using idealized squall line experiments
- Precipitation and updraft profile differences seen in full physics runs (HRRR vs. RRFS) are reproduced in this simple controlled setting
  - Conclusion: differences in the ***underlying dynamical core design between FV3 and CM1 / WRF*** result in creating these differences
- Despite the FV3 designers' best well-intentioned efforts, using the horizontal D-grid for convective-scale prediction, inevitably:
  - D-grid requires a ***large*** amount of 2D divergent damping (as well as other filters) to ***stabilize model solutions*** (much more filtering than WRF or MPAS)
  - ***More filtering*** leads to ***larger storms***. Paradoxically, ***2D divergence damping creates deeper updrafts that initially can be very intense.***
  - **Result: FV3** convective storms are ***often too large & intense*** and have ***excessive/extreme precipitation rates*** (especially in low-shear environments)
- Full mitigation of these issues likely requires a new dynamical core. What is **cost/benefit** of *building vs. adopting* an existing model?
- Further: An FV3 version of NSSL's Warn on Forecast ensemble prediction system was tested in 2022-2023 on a set of cases.
  - Rapid data assimilation (e.g., 15 min cycling) of satellite and radar creates large model imbalances that generates excessive spurious convection within FV3
  - Difficult to filter out without impacting physical solution, and spurious convection often degrades environment for actual storms.

Due to this evidence: NSSL's WoFS group is now testing NCAR's regional MPAS model for our next generation WoFS system

Extra

Impacts from reducing d4_bg on pressure fields

Squall Lines at 10.5 hours