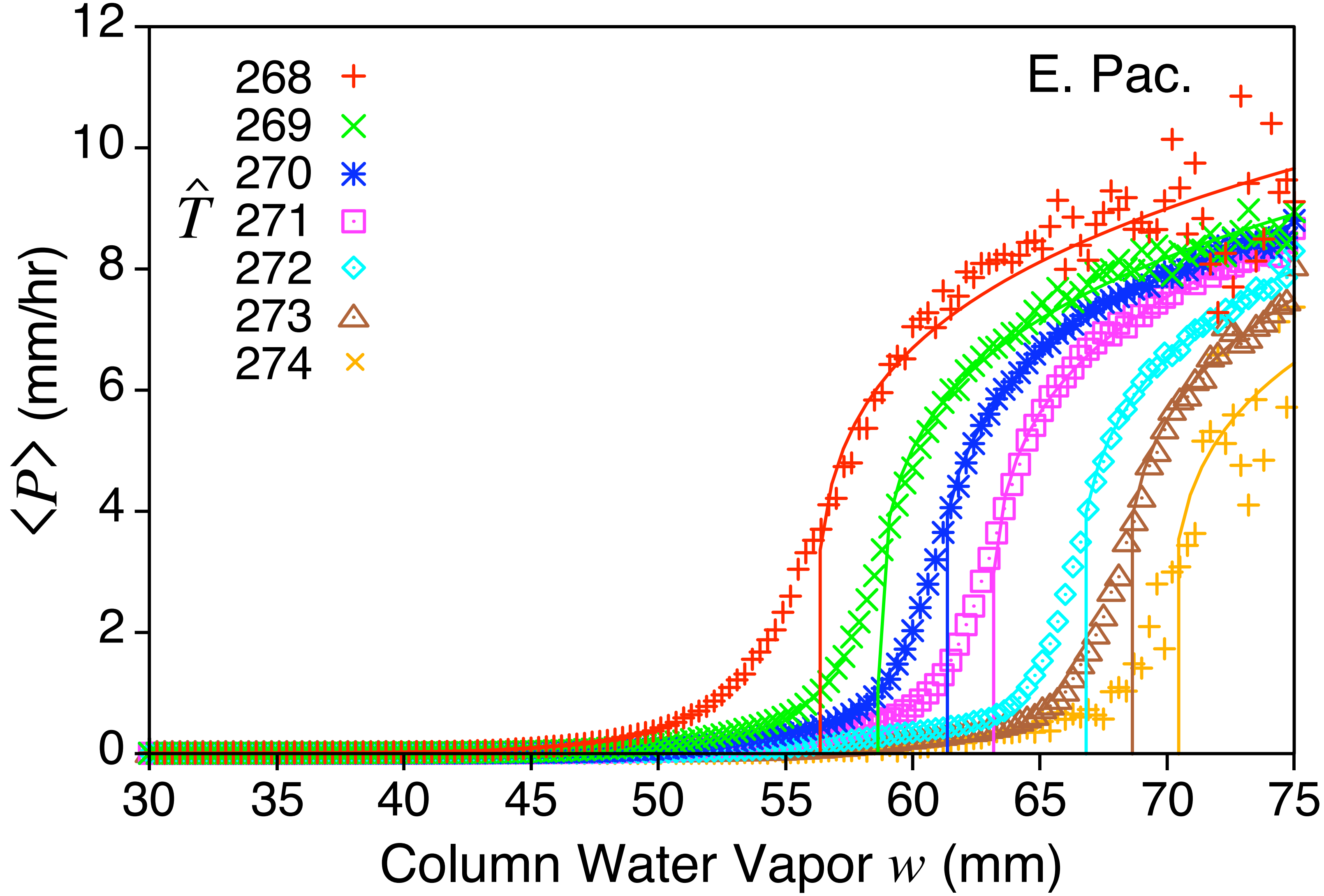
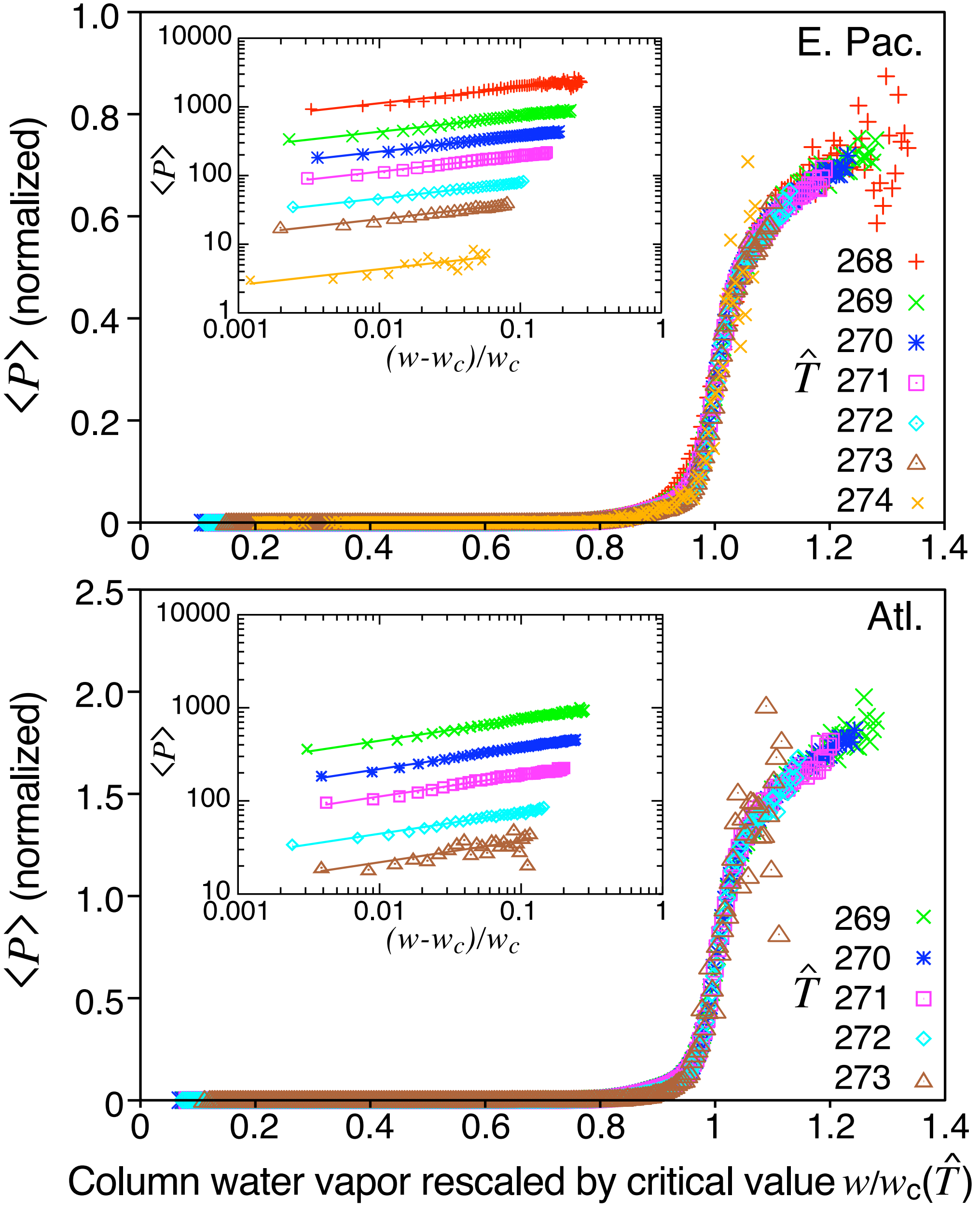
What can CRM and MMF Simulations Tell us About Critical Phenomena in Atmospheric Precipitation?

Steven K Krueger and Adam K Kochanski
University of Utah,
Salt Lake City, Utah, USA

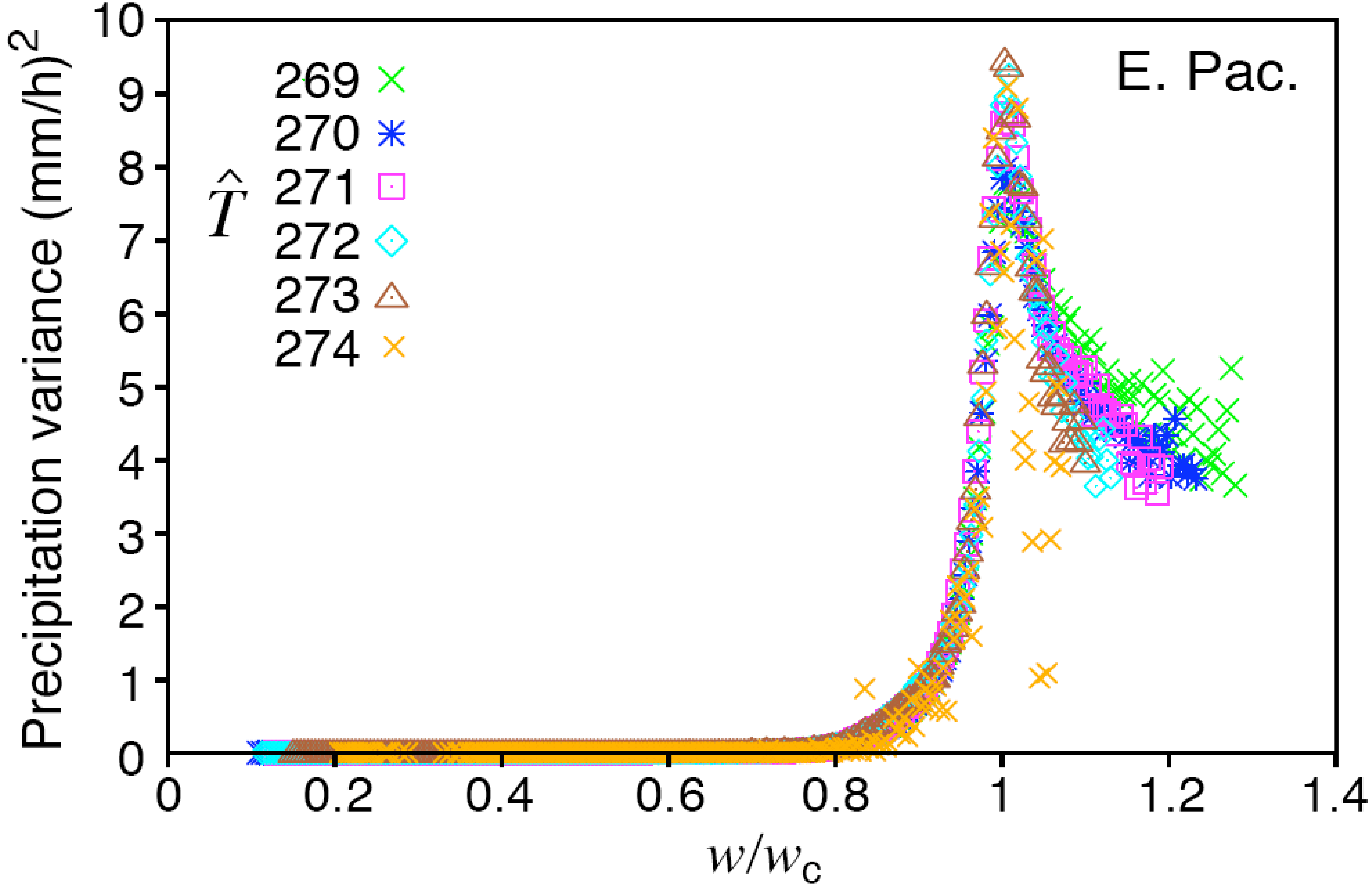
Neelin, Peters, and Hales (2008)



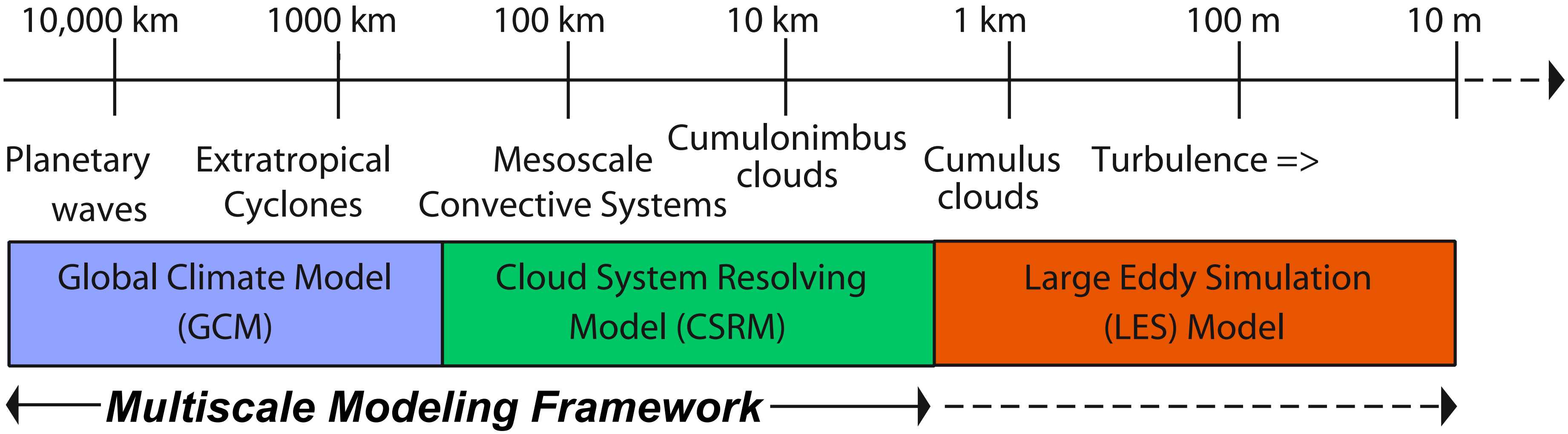
Neelin, Peters, and Hales (2008)



Neelin, Peters, and Hales (2008)



Scales of Atmospheric Motion

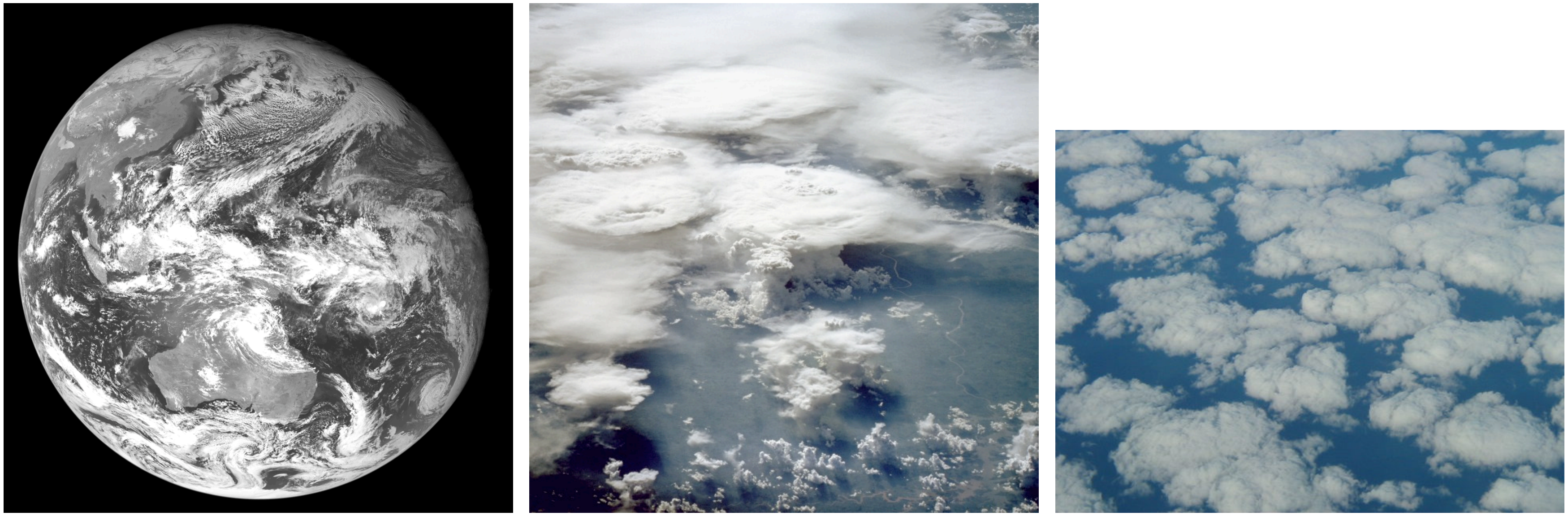


10,000 km
1000 km
100 km
10 km
1 km
100 m
10 m

Planetary waves
Extratropical Cyclones
Mesoscale Convective Systems
Cumulonimbus clouds
Cumulus clouds
Turbulence =>

Global Climate Model (GCM)
Cloud System Resolving Model (CSRM)
Large Eddy Simulation (LES) Model

Multiscale Modeling Framework



MMF Methodology

- We have compared satellite-based estimates of precipitation rate (P) conditioned on column water vapor (W) over the tropical oceans to the same quantities obtained from:

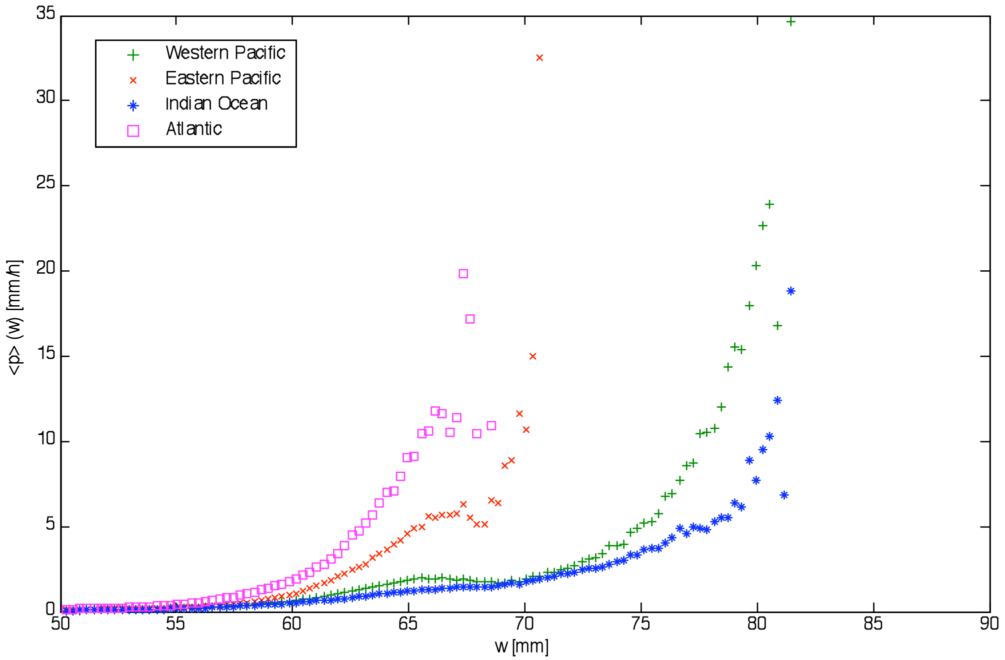
  - a 4-month, 32-column MMF simulation performed by Michael Pritchard (UCSD).

  - a 5-year, 64-column MMF simulation performed by Roger Marchand (UW).

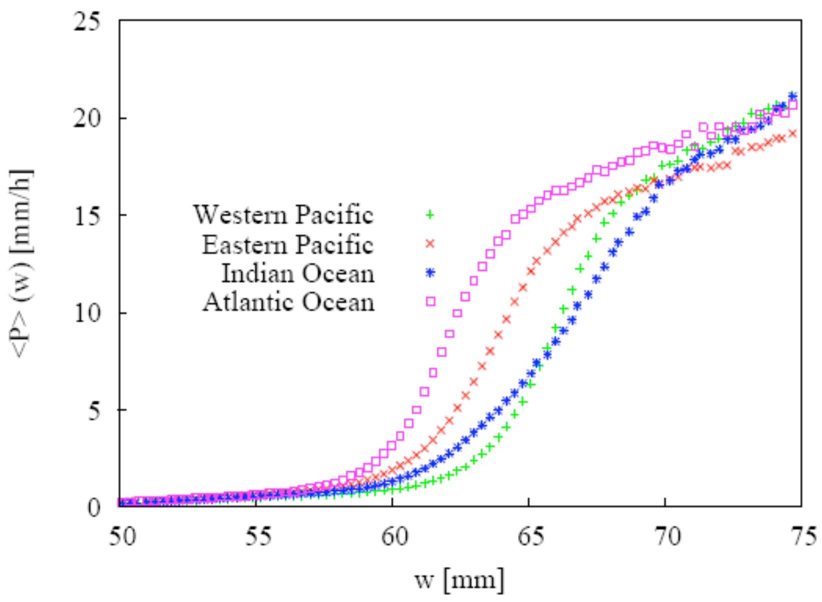
- The satellite estimates are for 25-km x 25-km areas; MMF are for 8-column (32-km) averages.

Ensemble average precipitation vs. column water vapor

SP-CAM 8-column average (32-km averages)



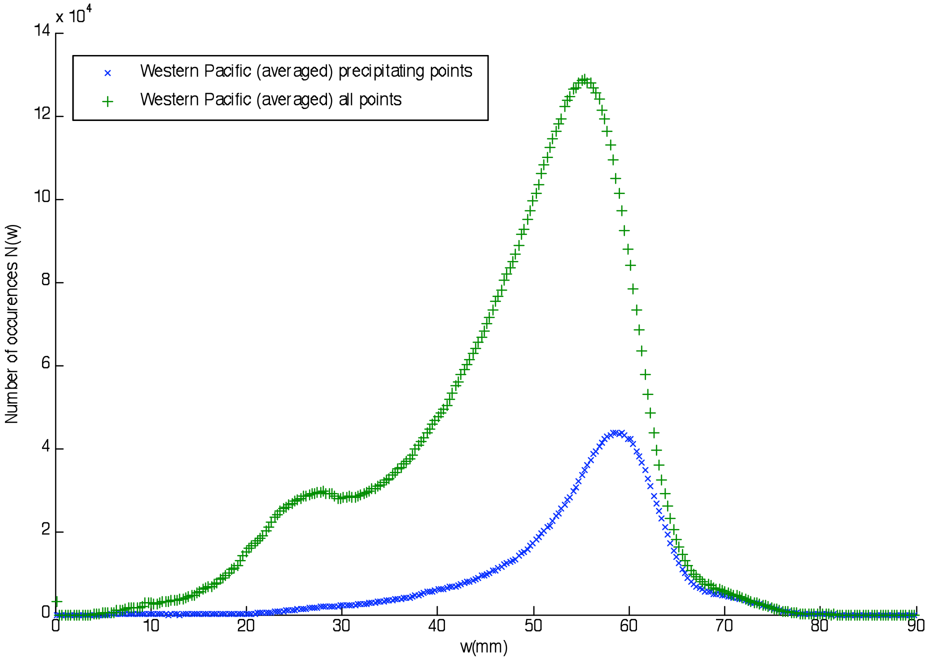
Measurements (Peters and Neelin 2006)



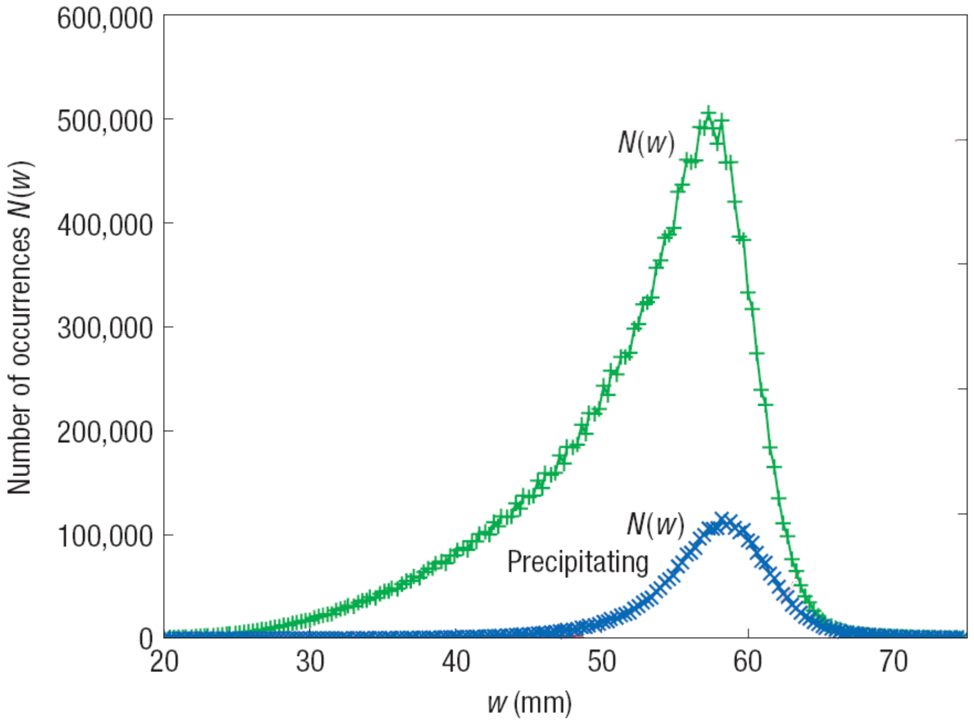
- No evident deflection corresponding to critical point, no flattening of the precipitation beyond the critical value of the water vapor.
- Slightly higher maximum precipitation rates after 32-km averaging as compared to satellite data, and evidently lower than for 4-km CRM data.
- Modeled critical column water vapors are still significantly greater than the ones derived from satellite data (precipitation pickup occurs at higher column water vapor rates).

Water vapor frequency distribution

SP-CAM 8-column average (32-km averages)



Measurements (Peters and Neelin 2006)



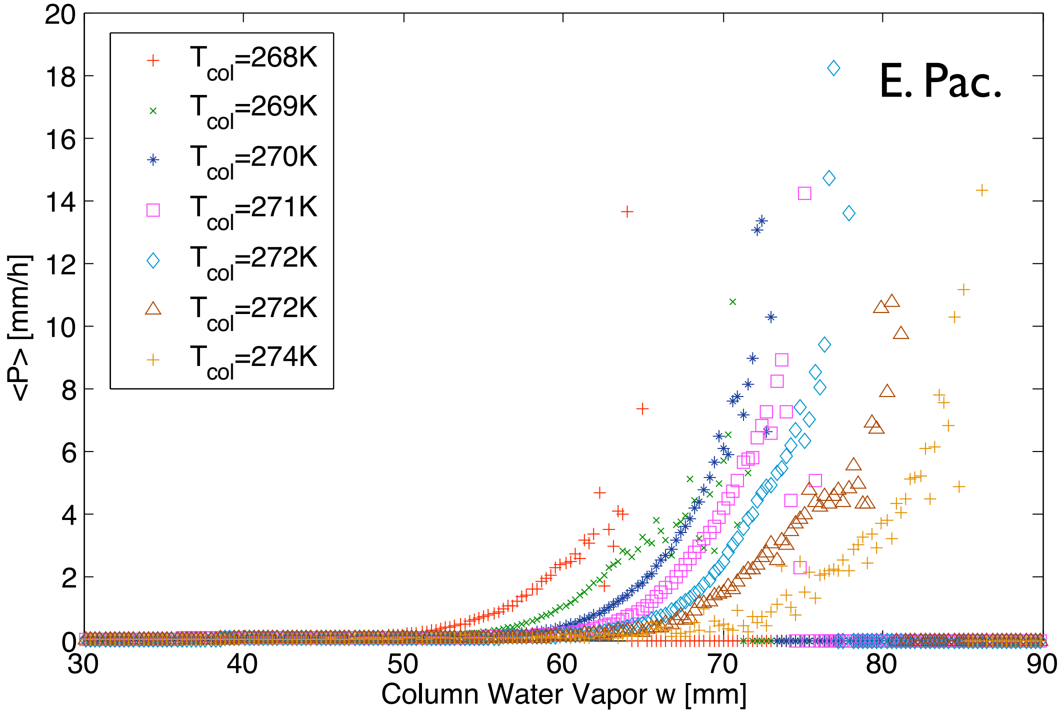
The frequency distribution of the SP-CAM 32-km averaged water vapor (for all and precipitating points only) exhibits similar features the as the one for satellite-derived data.

However, the number of occurrence for 32-km averaged dataset is smaller than the satellite-derived one by a factor of 5.

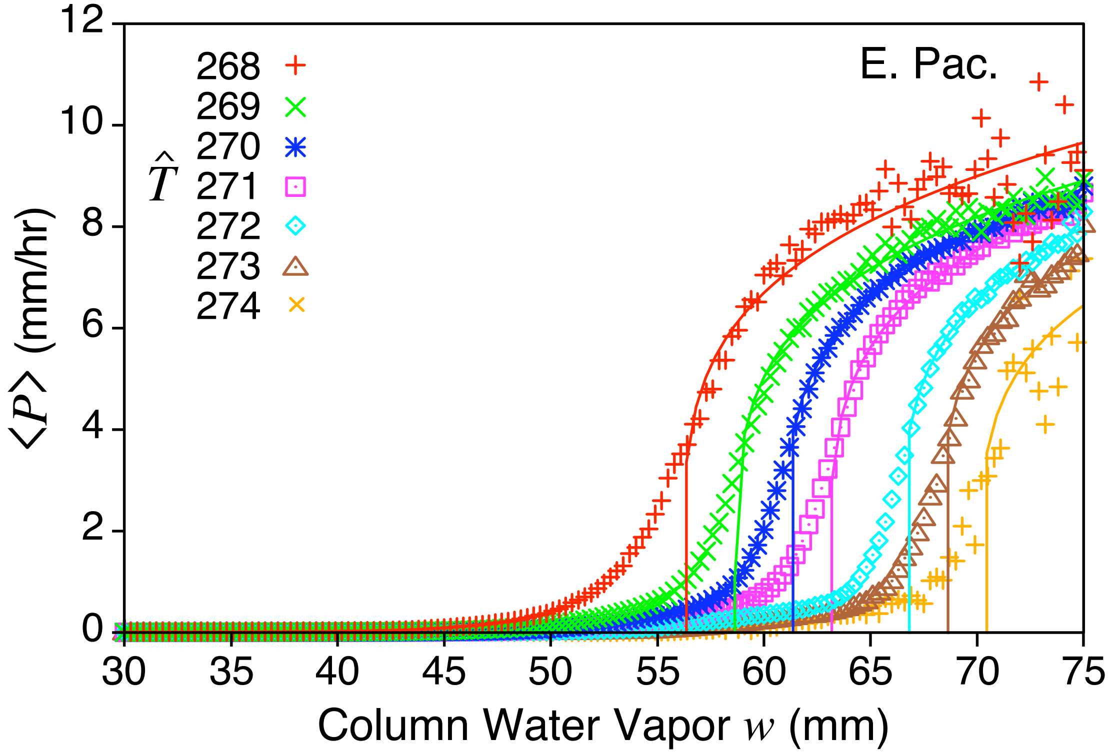
This suggests that the 4-month long SP-CAM simulation may be too short to capture features characteristic for critical phenomena evident in the 5-year long satellite-derived dataset.

Results from a 5-year MMF simulation

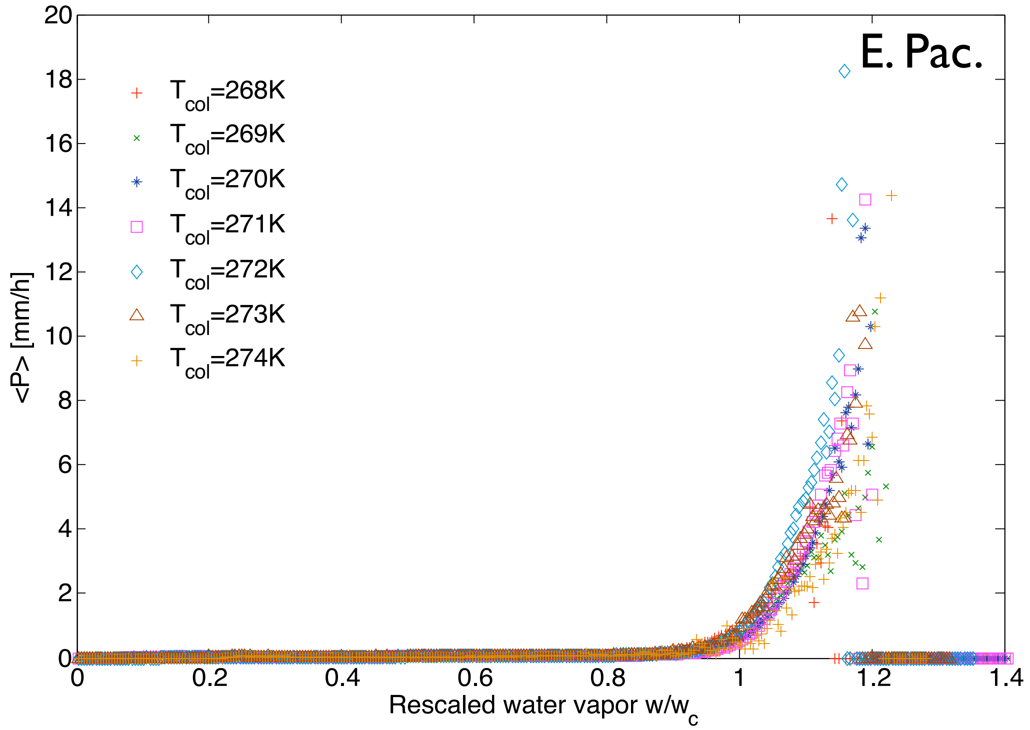
MMF (UW)



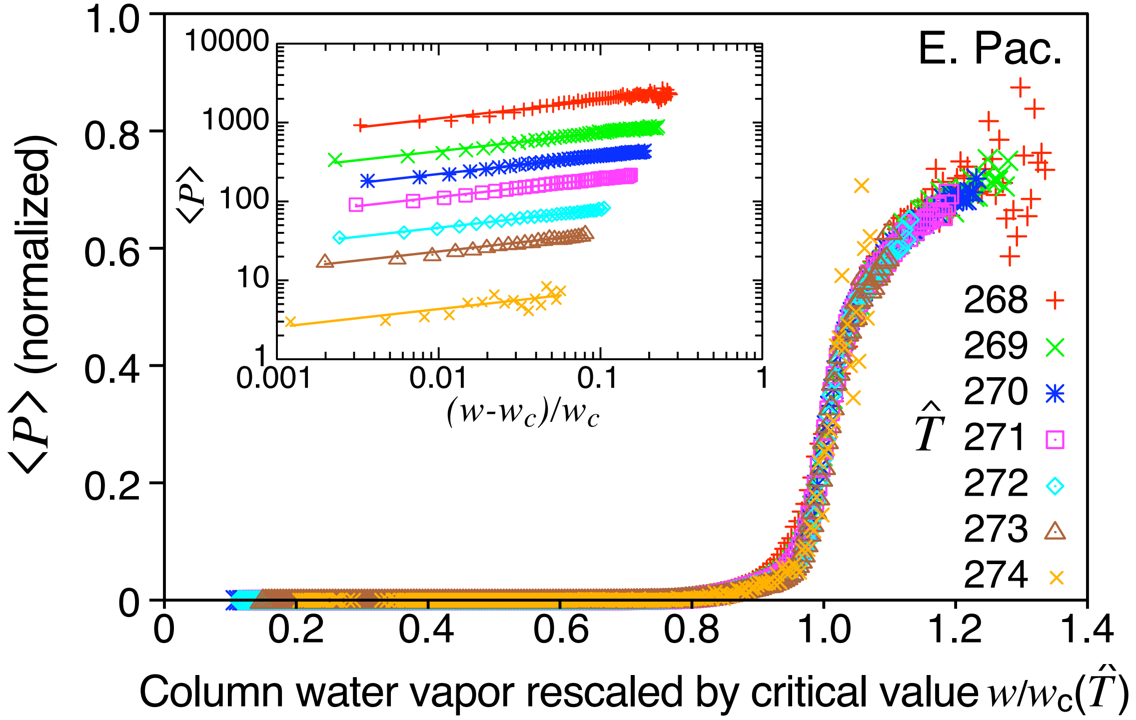
Neelin et al. (2008)



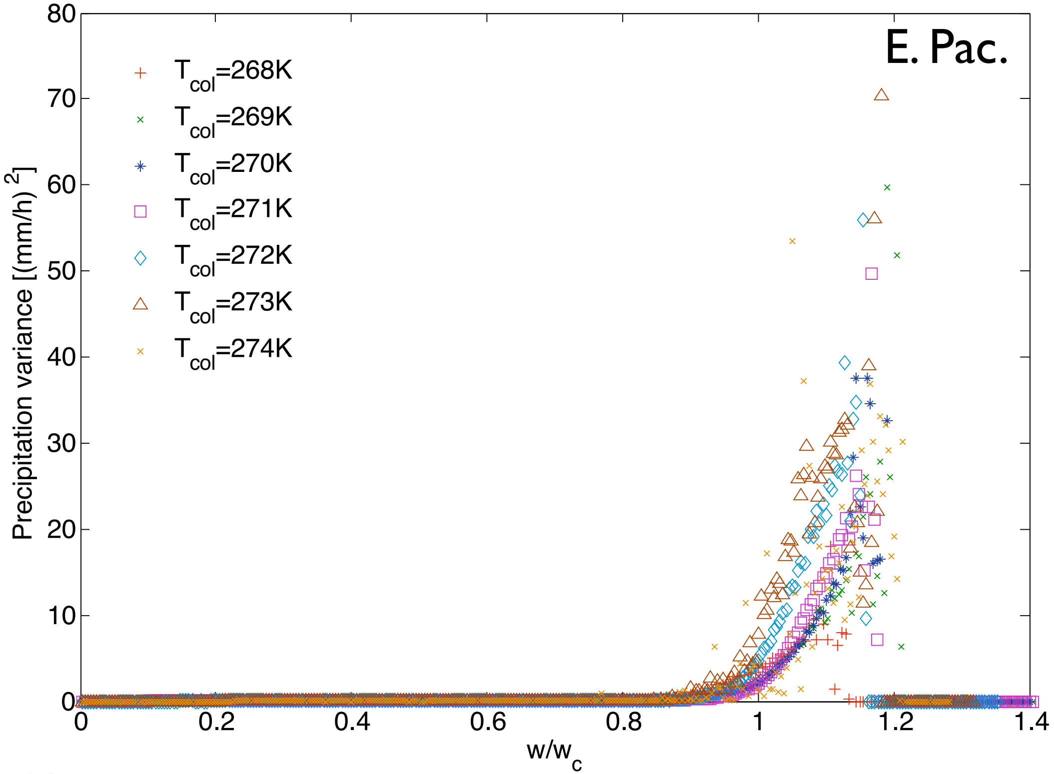
MMF (UW)



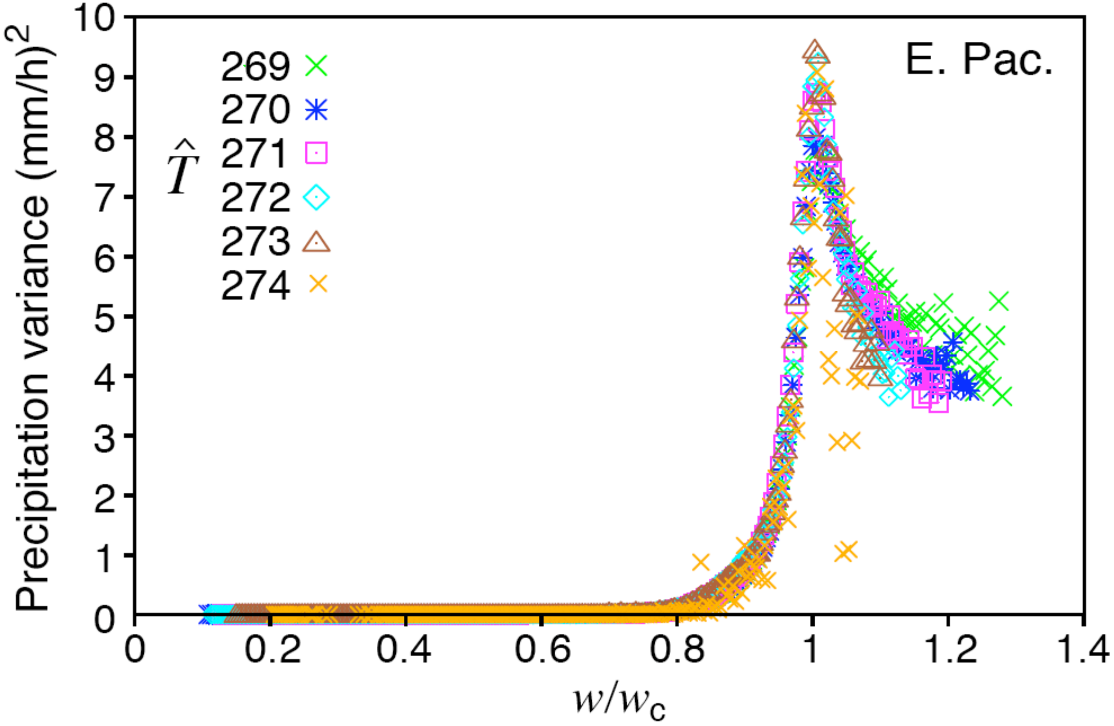
Neelin et al. (2008)



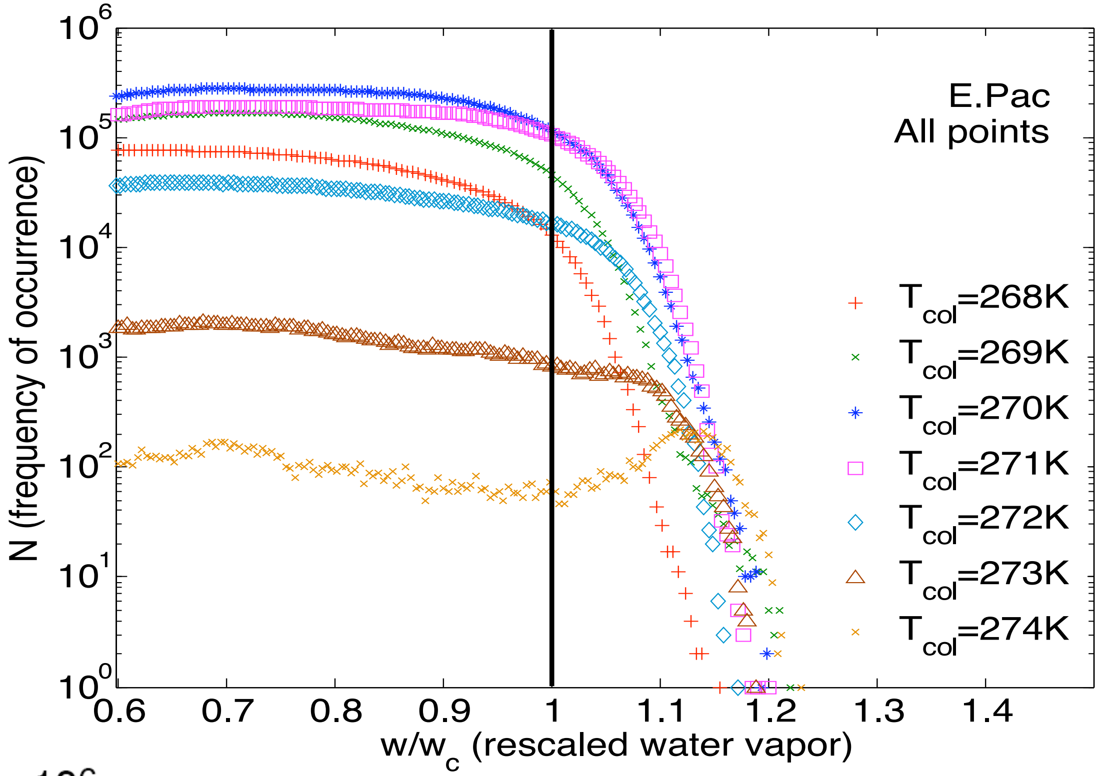
MMF (UW)



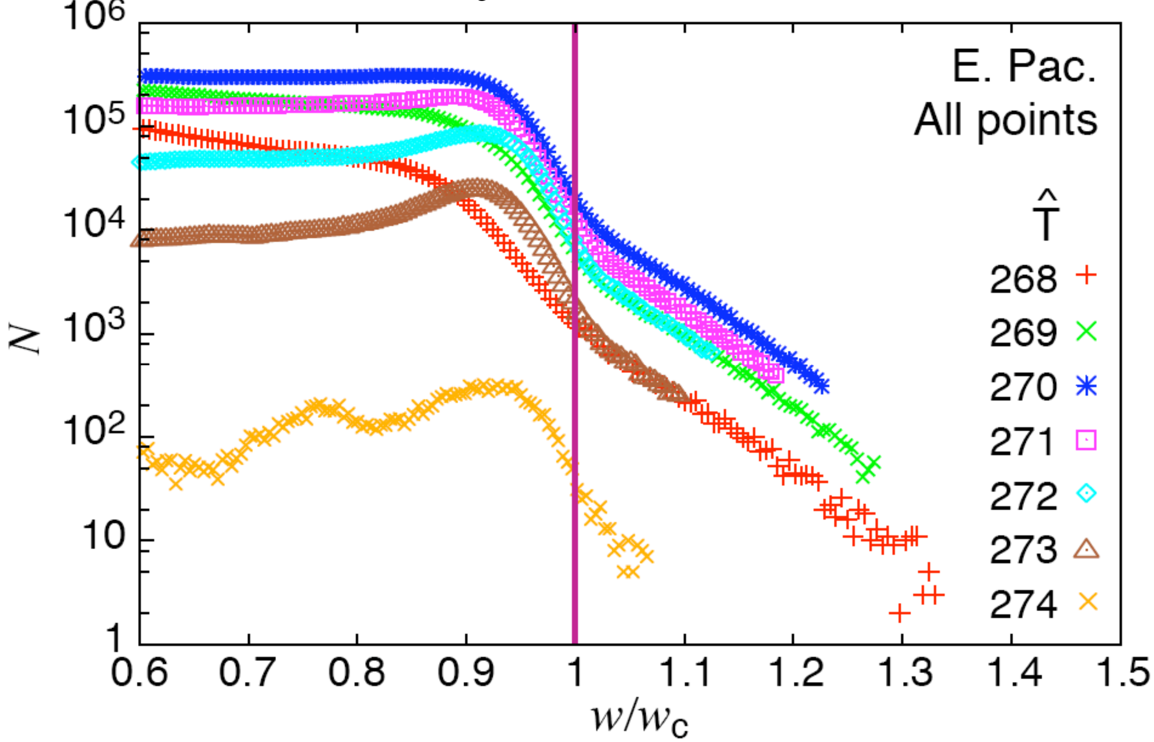
Neelin et al. (2008)



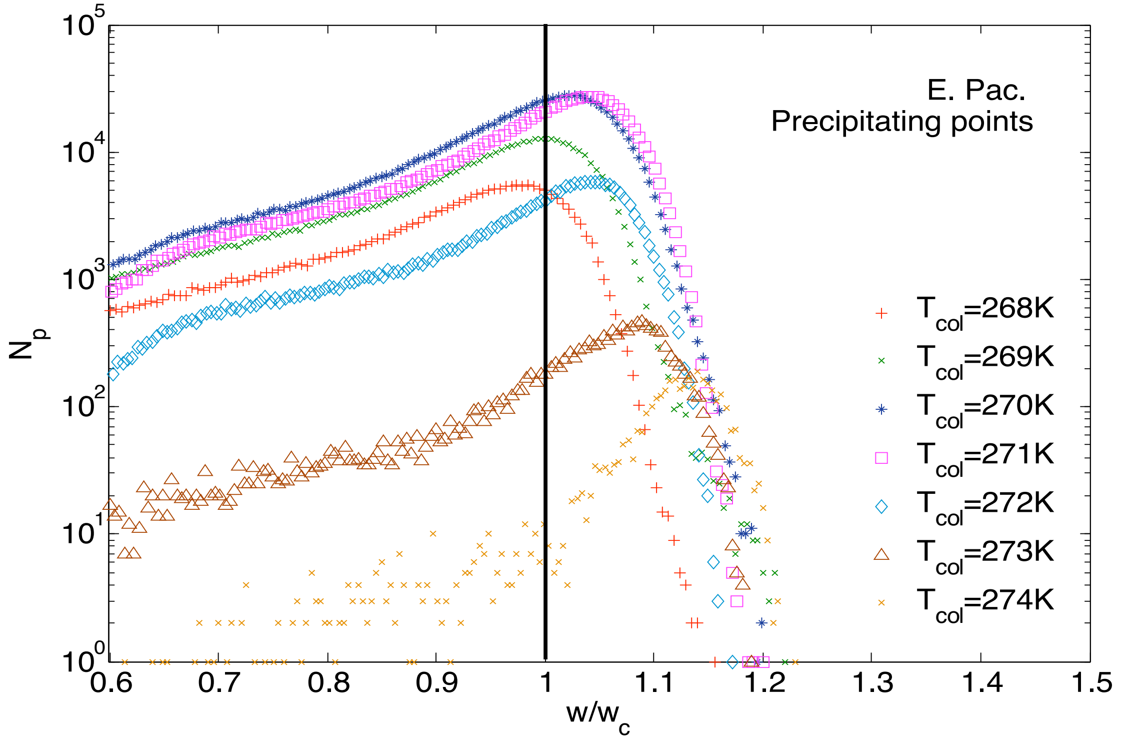
MMF (UW)



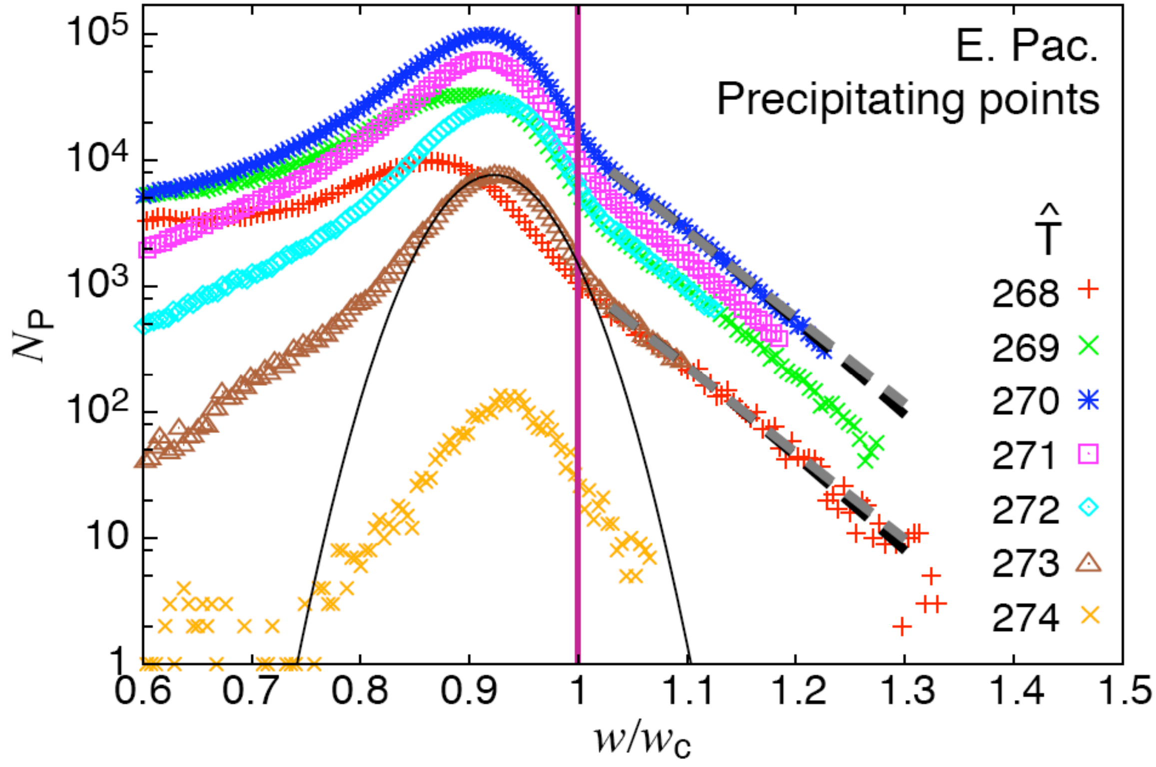
Neelin et al. (2008)



MMF (UW)



Neelin et al. (2008)



MMF Results

1. Which observed features are evident?

a. Increase of P beyond a critical PW.
b. Regional differences.
c. The dependence upon SST and column T.
d. Collapse upon scaling by the critical PW.

Which are not?

e. A roll-off of P at high PW.

2. How do the results depend on the analysis grid size?

Results for 4-km and and 32-km averages are essentially the same, except for a greater range of values at the smaller averaging size.

MMF Results vs Observations

What are the reasons for the discrepencies?

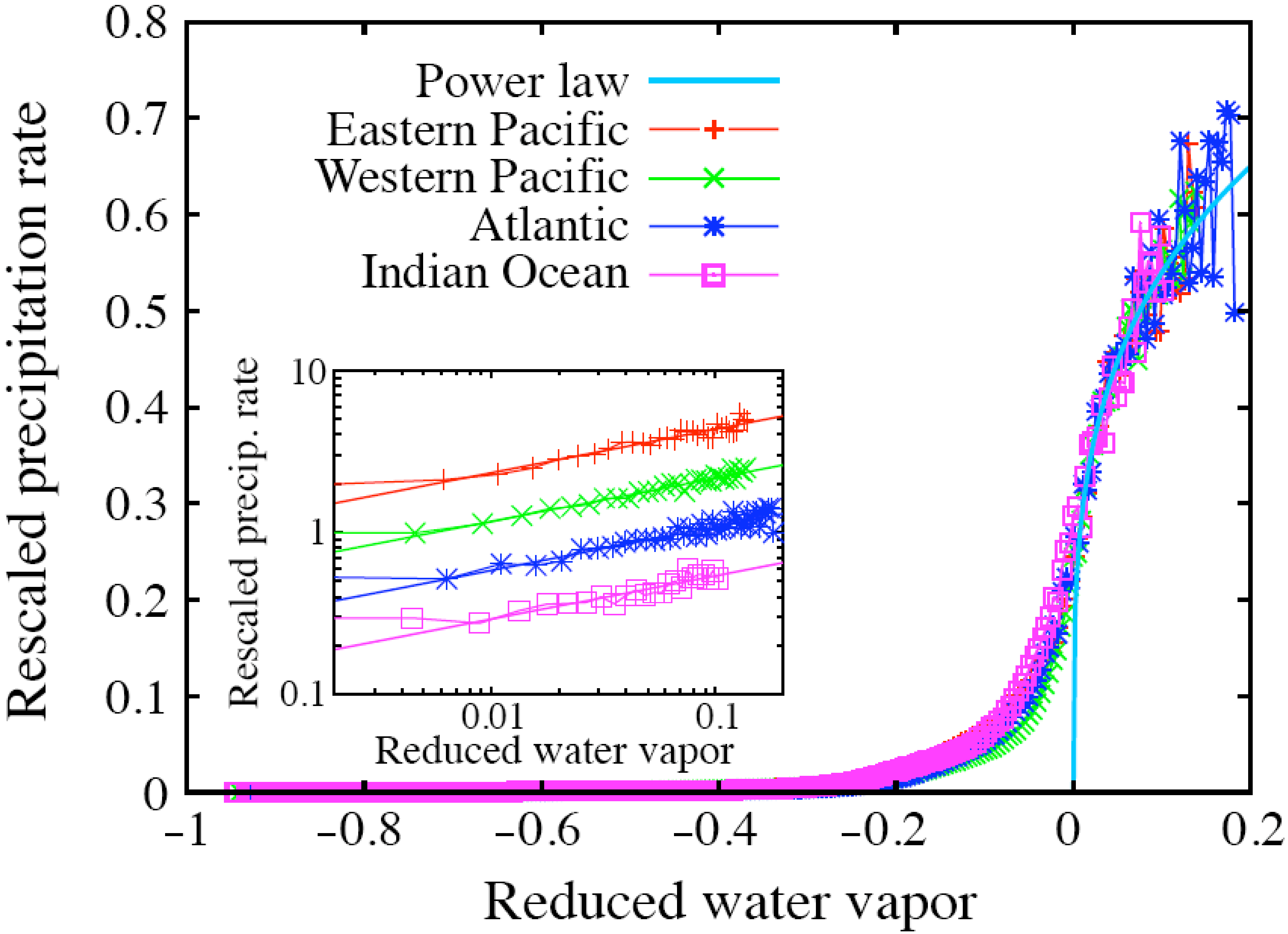
a. Model error(s)?

b. Measurement error(s)?

Our strategy: investigate both, but focus on model error(s).

Radar-derived Precip Rate vs Column Water Vapor

(Peters et al. 2009)



TRMM Radar vs TMI Rain Rates

(Seo et al. 2007)

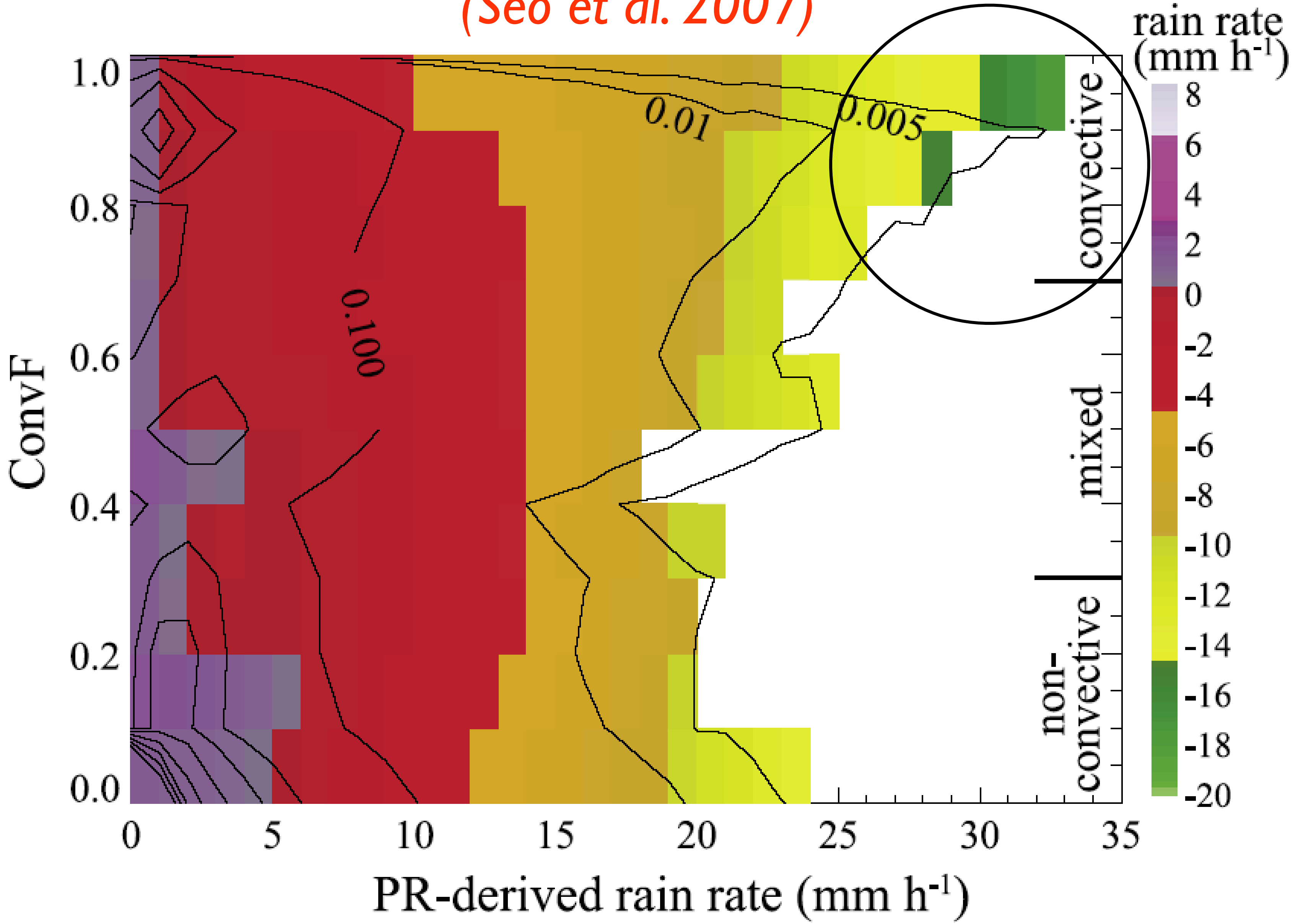
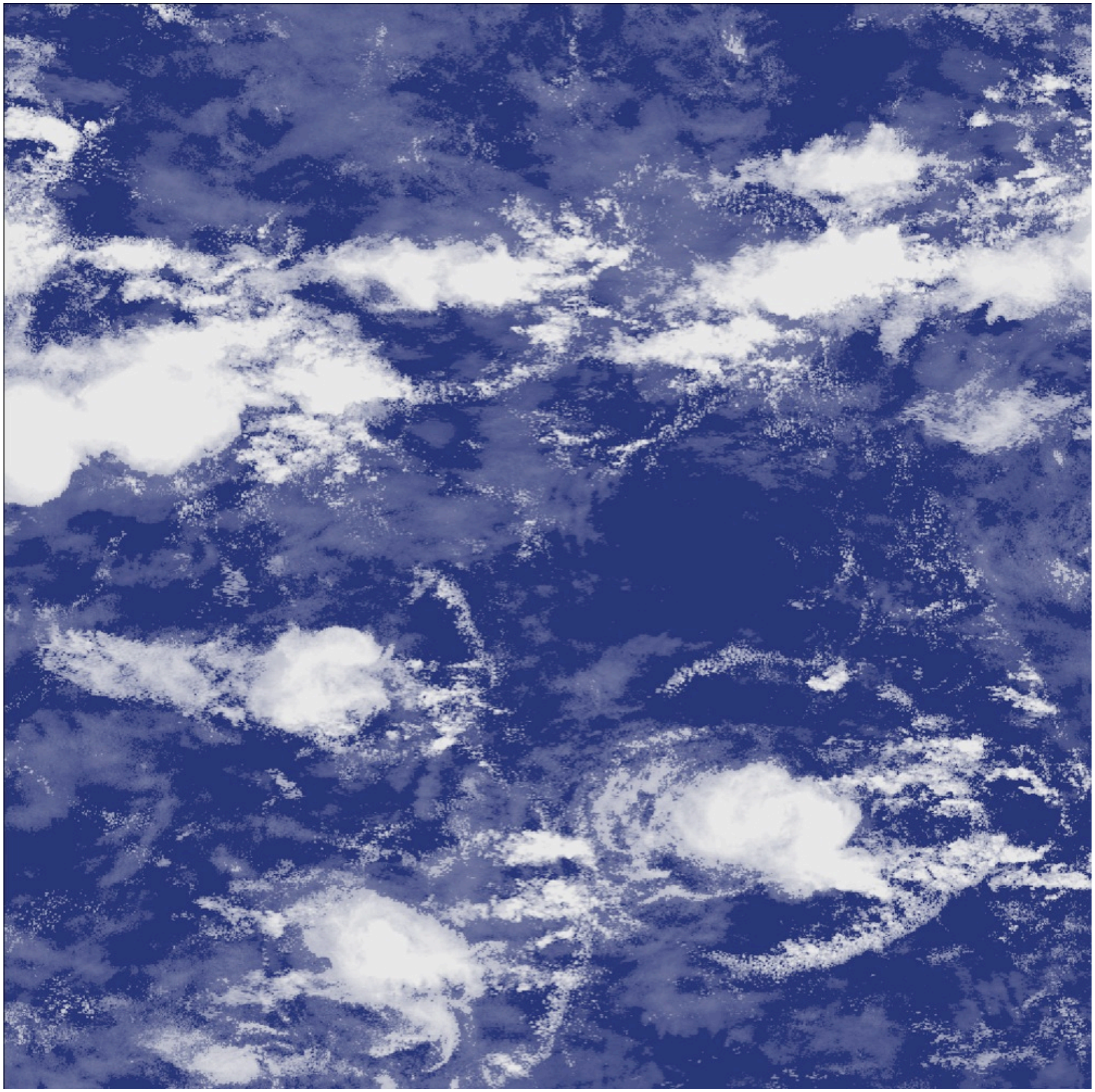


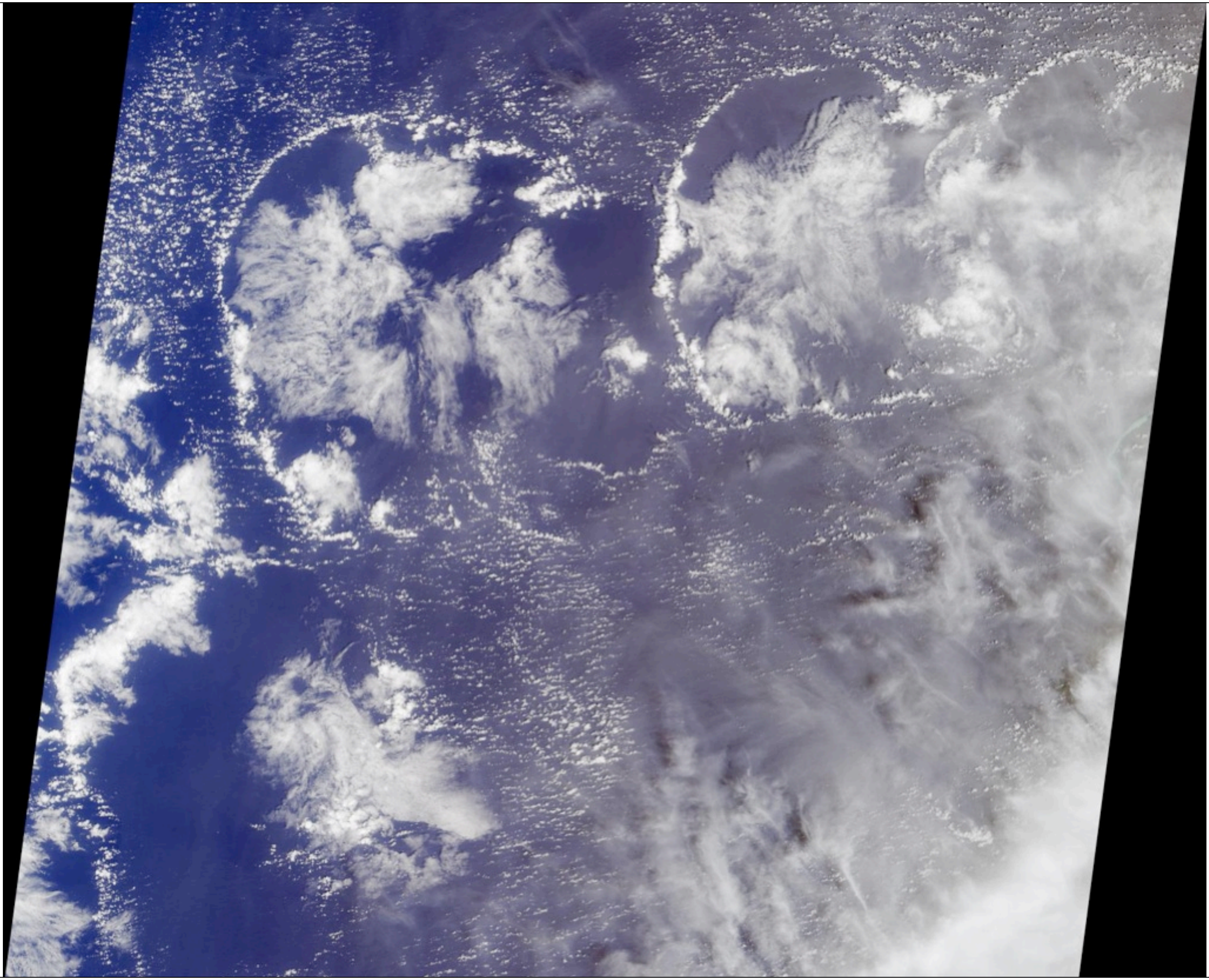
Figure 1. The difference (color pixels) in mm h^{-1} between TMI- minus PR-derived rain rate as a function of PR rain rate and *convF*. Contours represent occurrence frequency of rain pixels in % at the intervals of 0.005, 0.01, 0.1, 0.5, 1, 2, 4, 6, 8, 10.

Use a giga-LES of deep convection as a benchmark for the MMF CRM

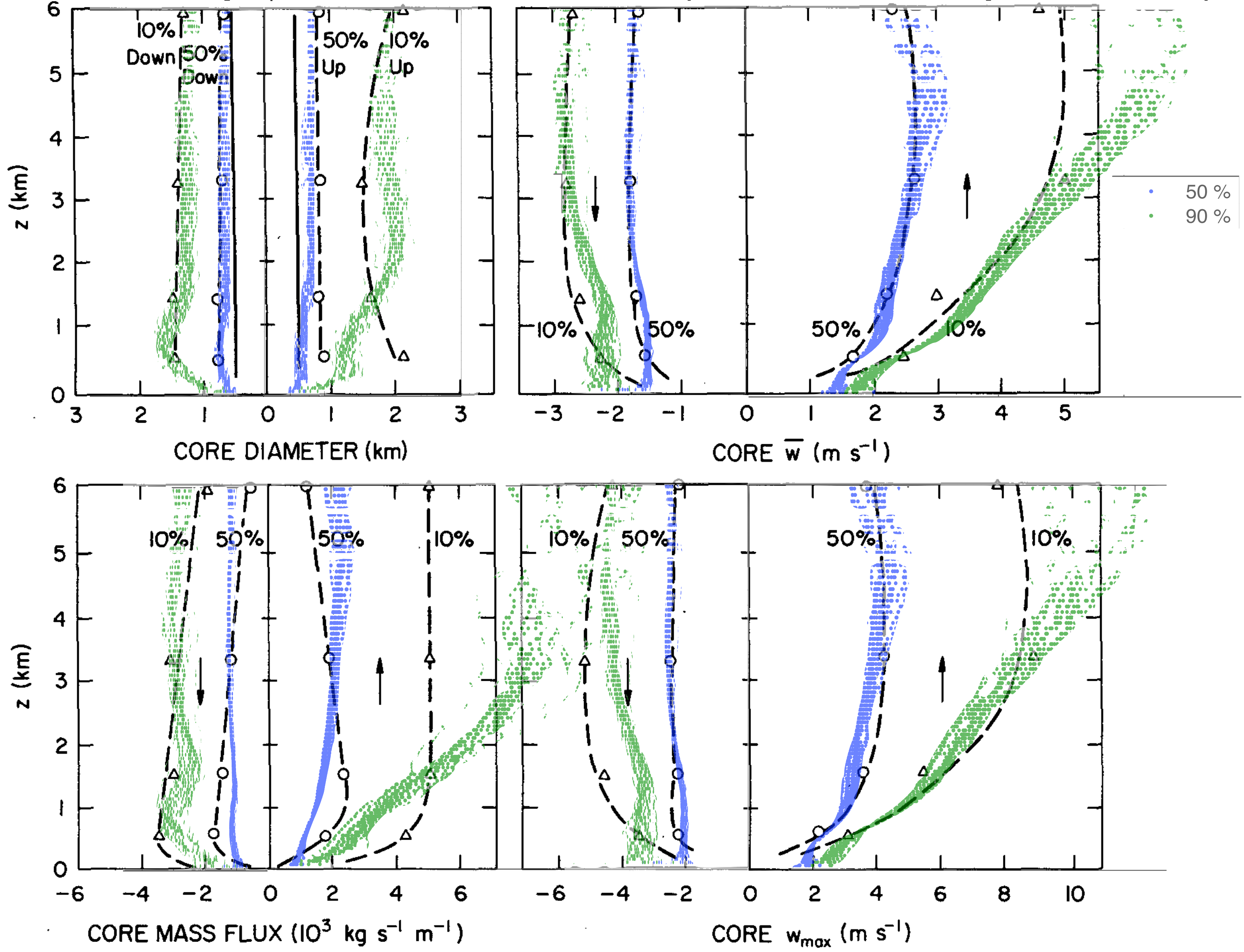
- Idealized GATE (tropical ocean) simulation with shear.
- Used a CSRM (SAM) with 2048 x 2048 x 256 (10^9) grid points and 100-m grid size for a 24-h LES.

Giga-LES "visible image" 180 km x 180 km

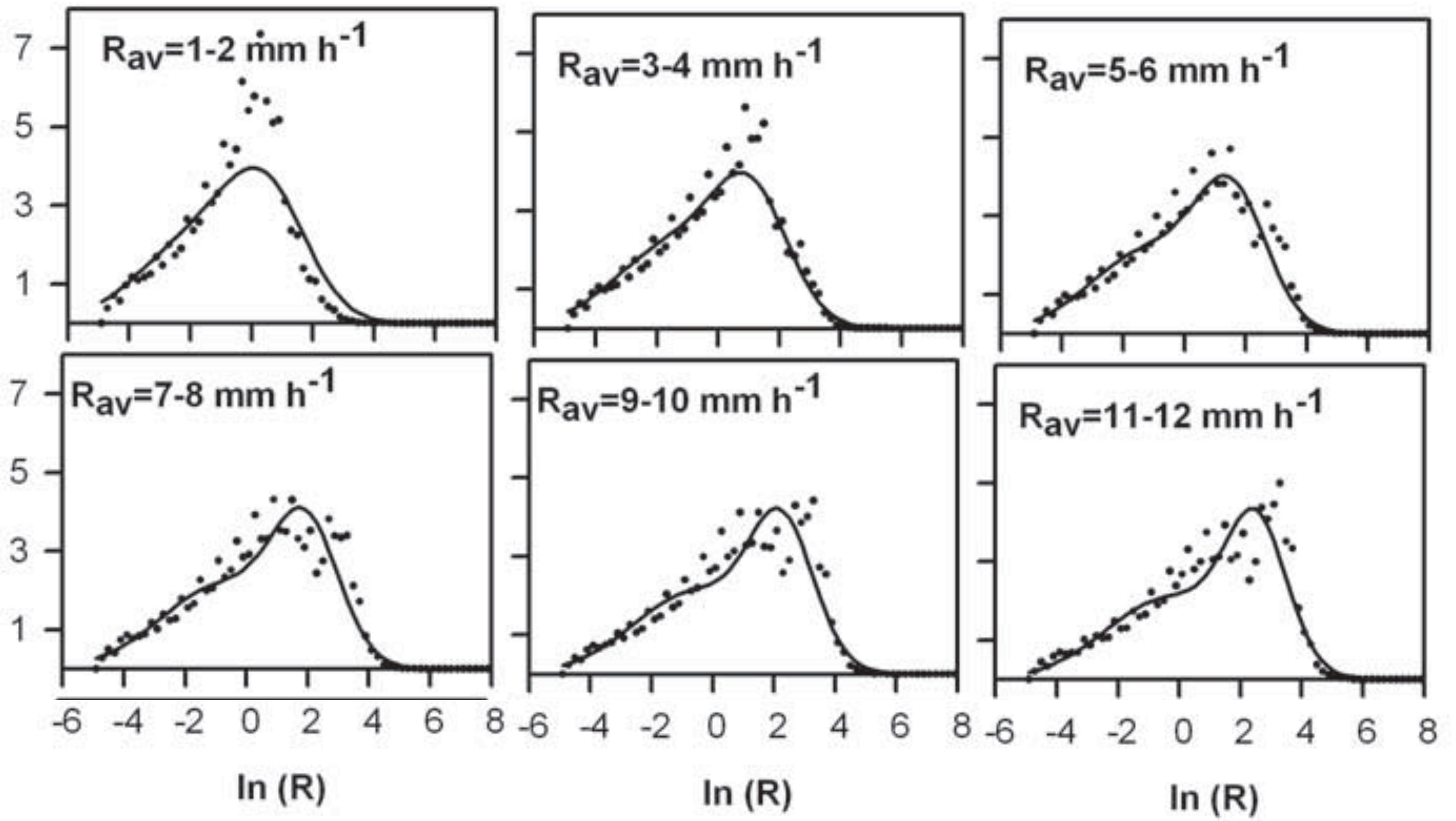




Vertical velocity statistics vs GATE (LeMone & Zipser 1980)

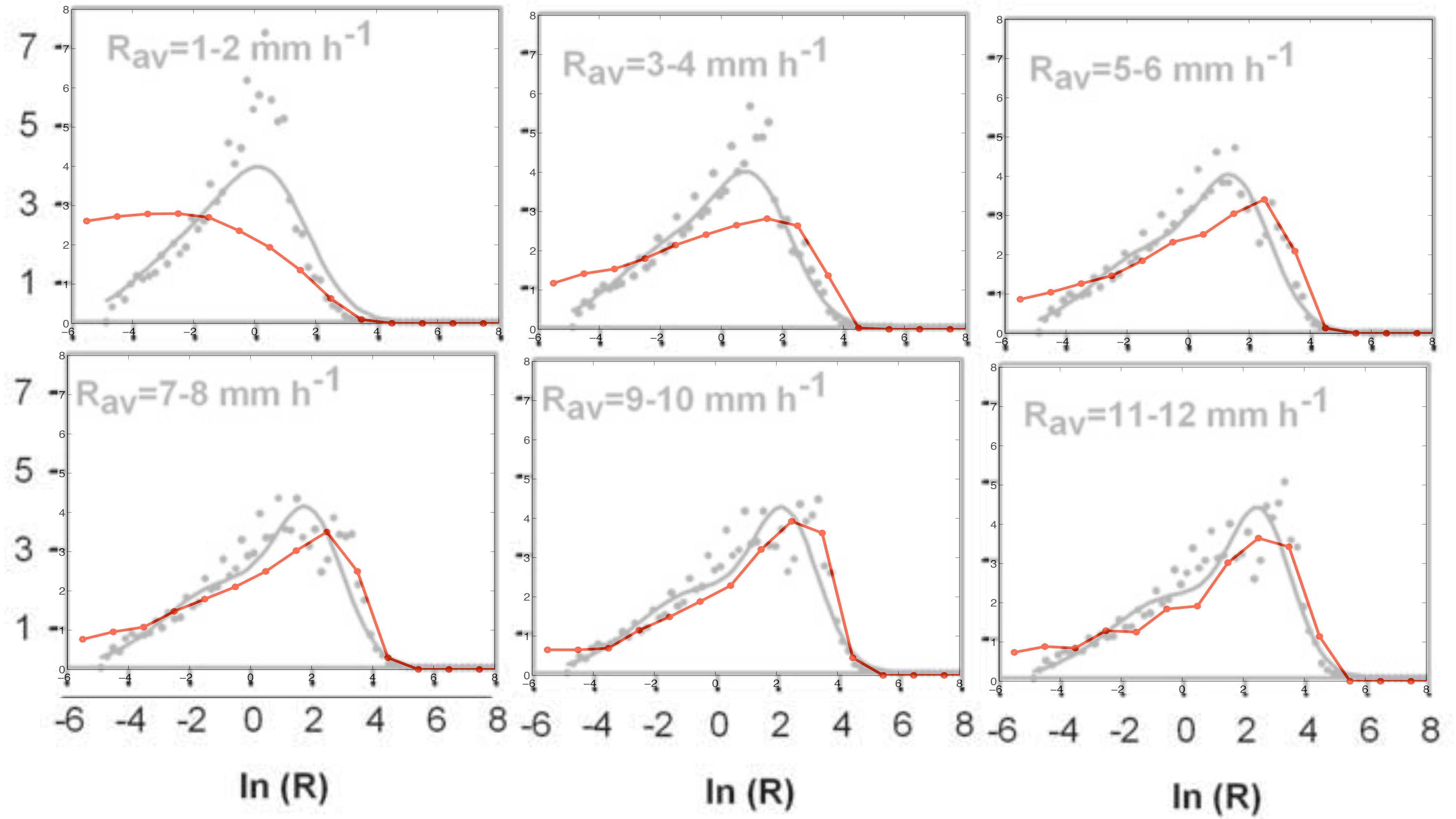


PDFs of TOGA COARE radar rain rate in (25-km)^2 areas

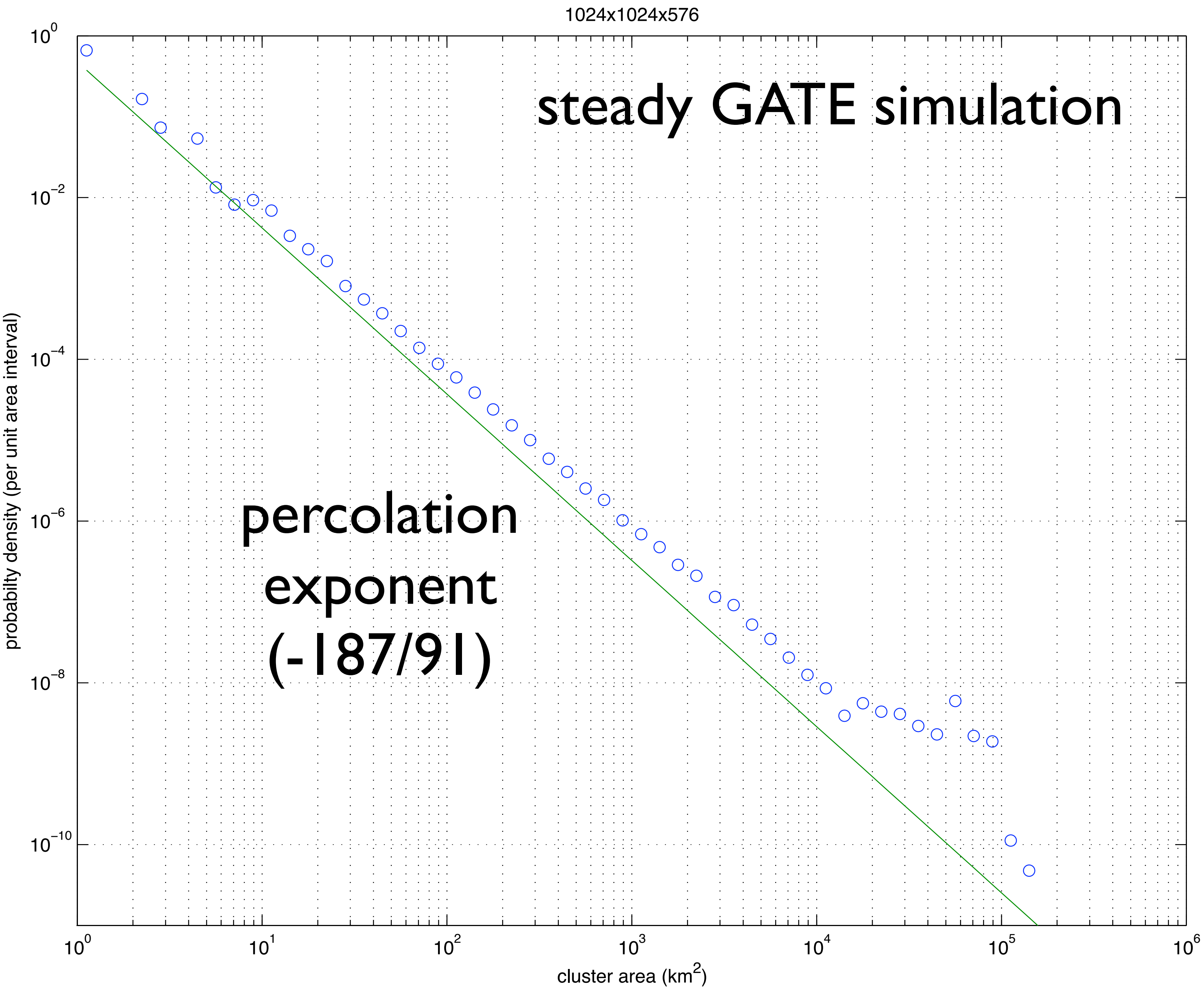


Varma et al. (2004)

PDFs of rain rate in $(25\text{-km})^2$ areas: Giga-LES (adjusted) vs TC radar



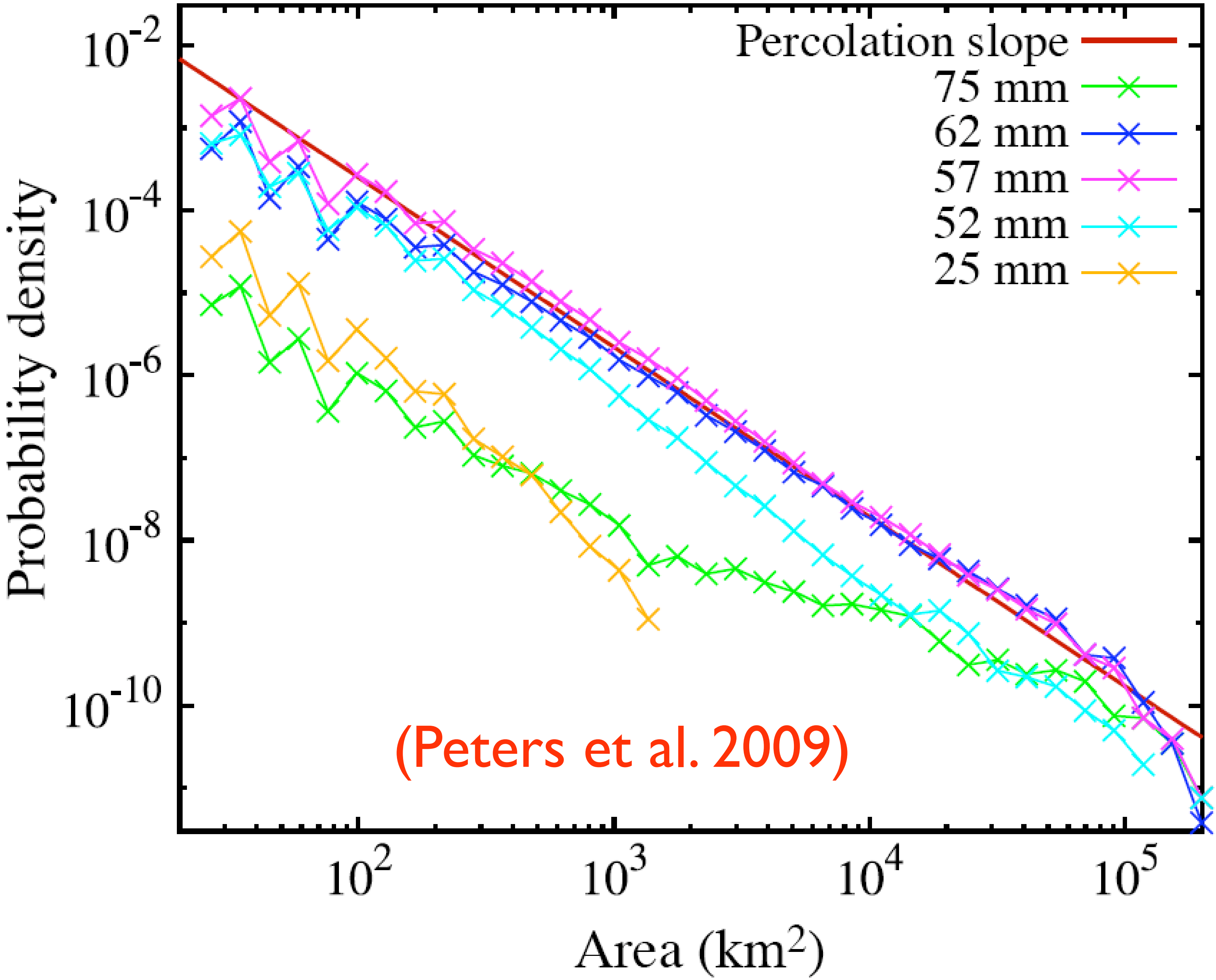
precipitation cluster size frequency



steady GATE simulation

percolation
exponent
(-187/91)

Cluster sizes from TRMM radar



(Peters et al. 2009)

CRM simulations for addressing precipitation vs column water observations

Recommended configurations:

- Large domain (for large clusters and rare events).
- Long time interval (for rare events).
- Realistic forcing.
- High resolution (to resolve convection).

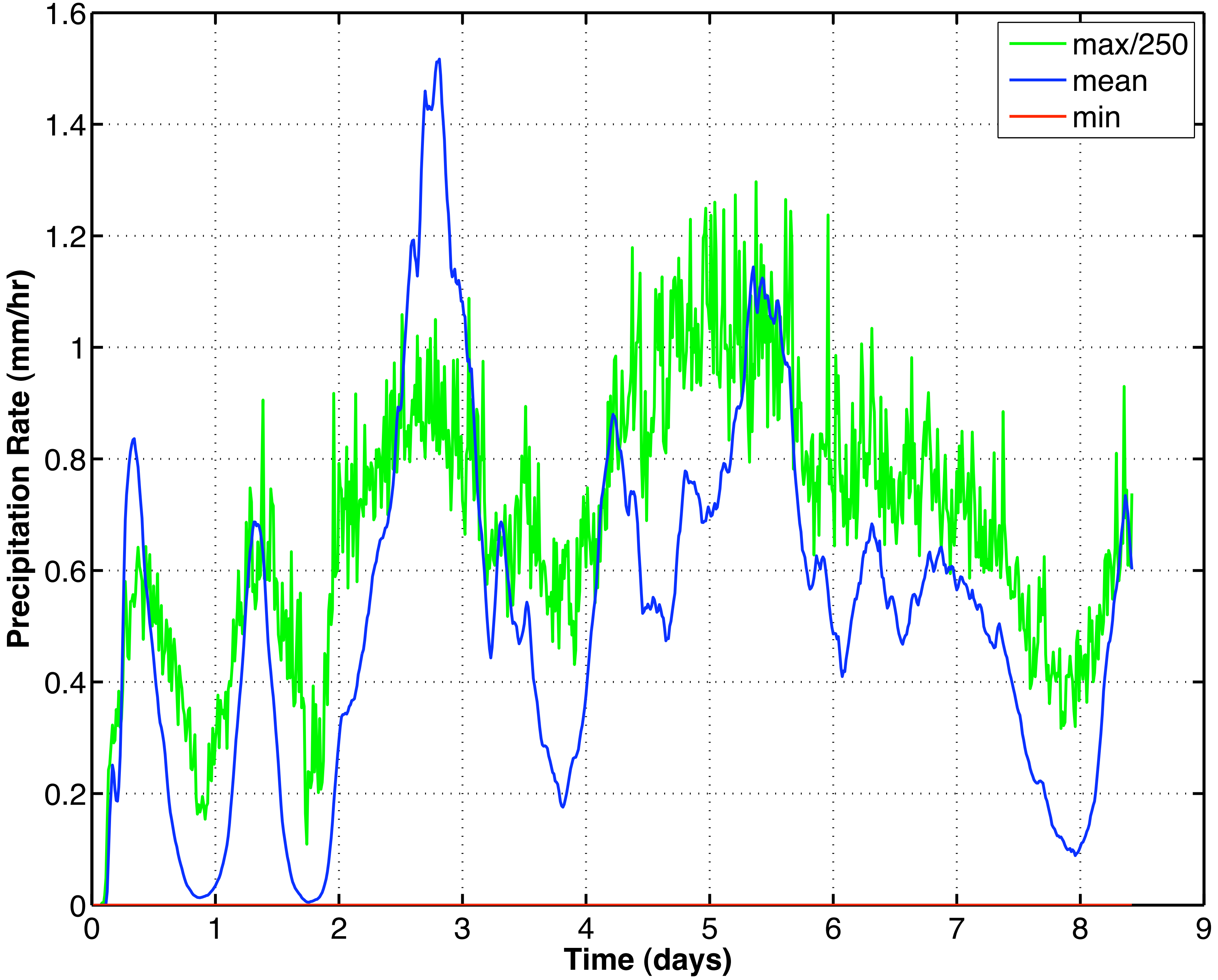
Our CRM simulations

- ***Giga-LES (benchmark):*** LES resolution (0.1 km, 256 levels), moderate domain (200 km x 200 km), 1 day, GATE steady forcing with shear.

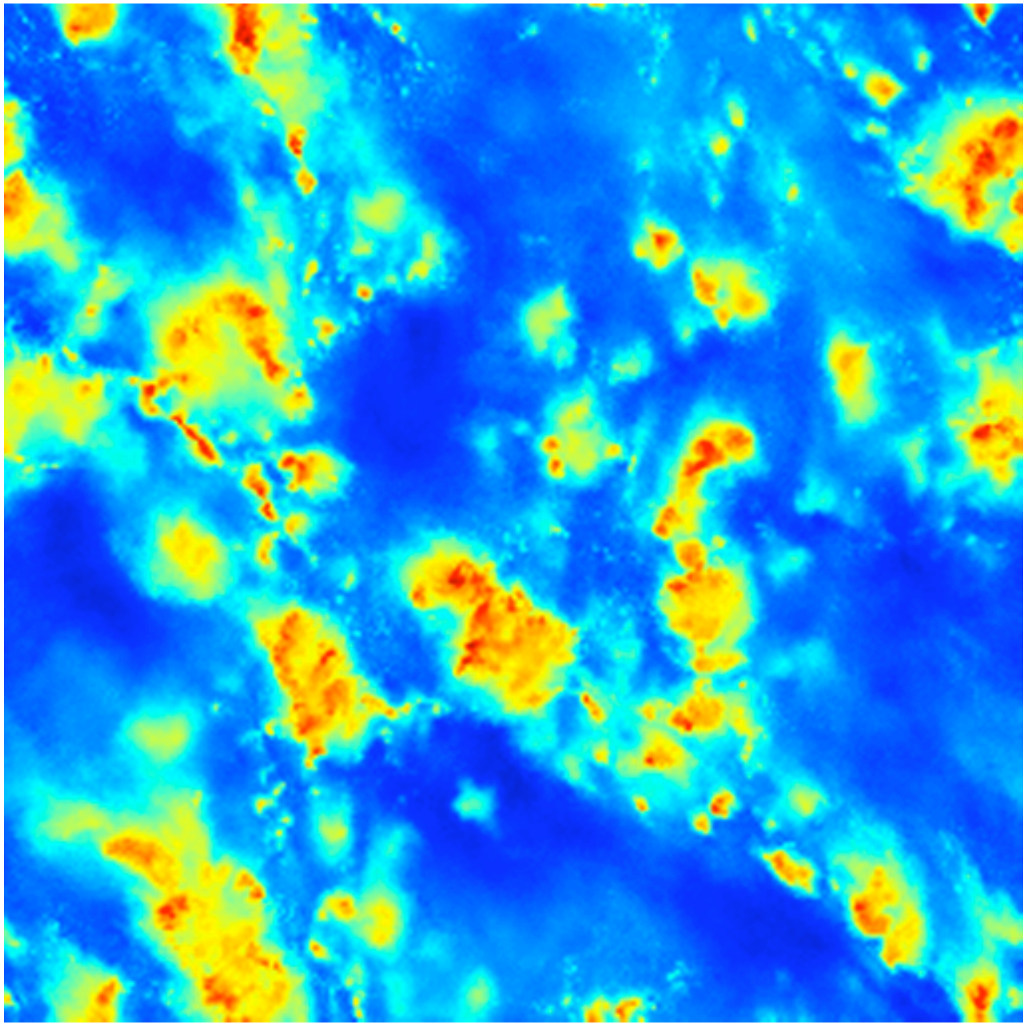
- ***GATE steady strong forcing with shear:*** Lower resolution (1 km, 33 levels), large domain (1000 km x 1000 km), several days.

- ***GATE actual time-varying forcing:*** Lower resolution (1 km, 96 levels), large domain (1000 km x 1000 km), several days.

Unsteady GATE



Column Water Vapor from GATE unsteady

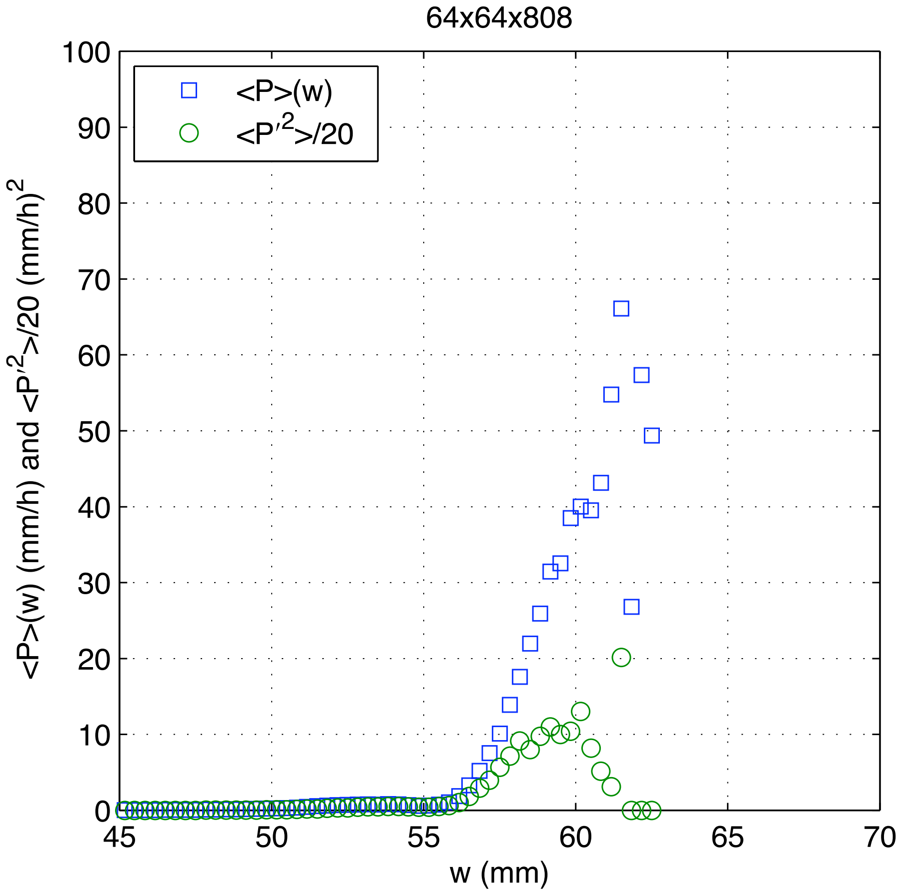


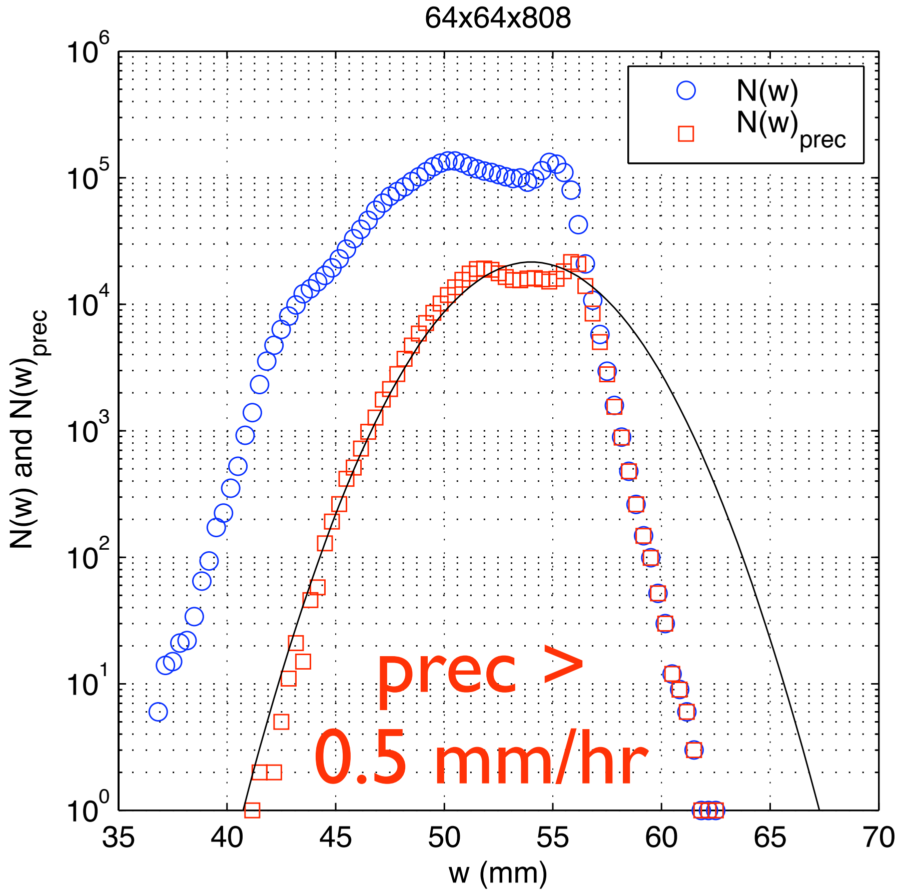
(1024 km x 1024 km)

broadly compare CRM results to observations using the same analysis method

Unsteady GATE: 16 km x 16 km (analysis) grid

P(w)

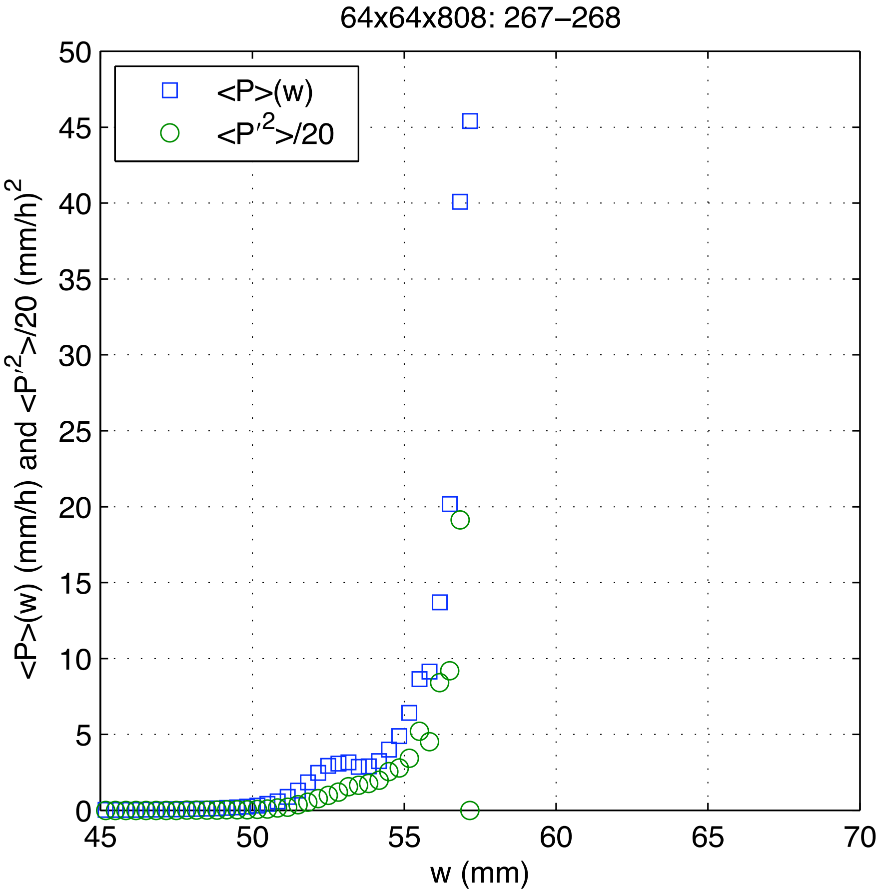


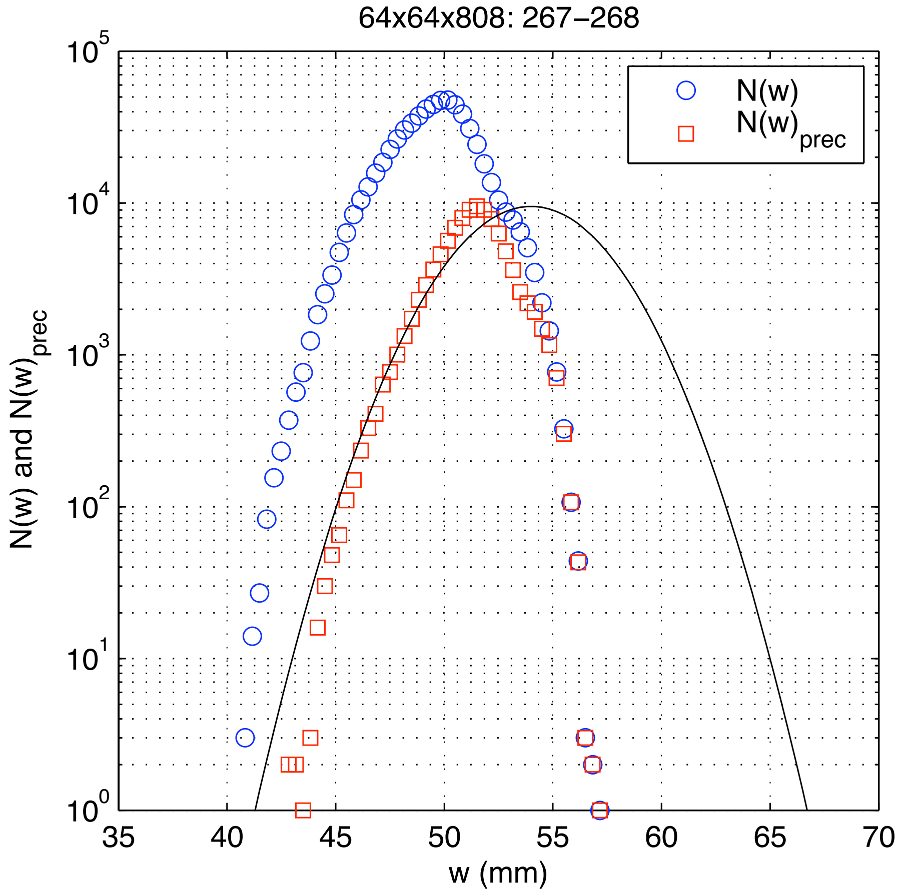


prec > 0.5 mm/hr

Unsteady GATE: 16 km x 16 km (analysis) grid

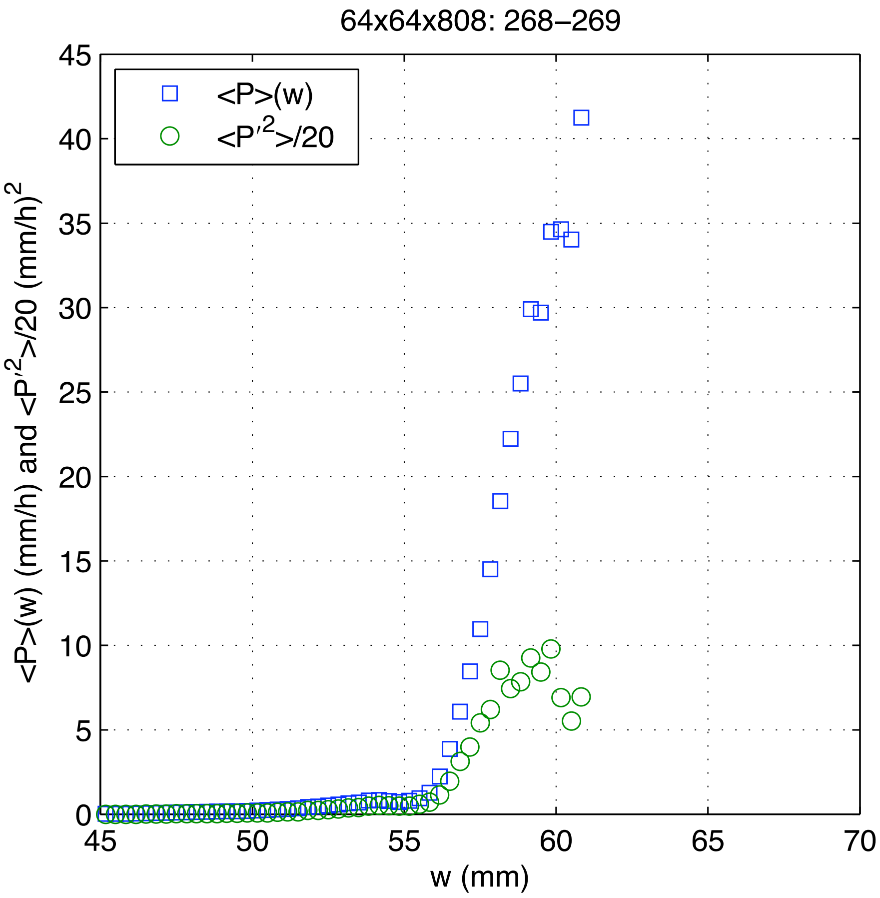
P(w): T= 267 to 268 K

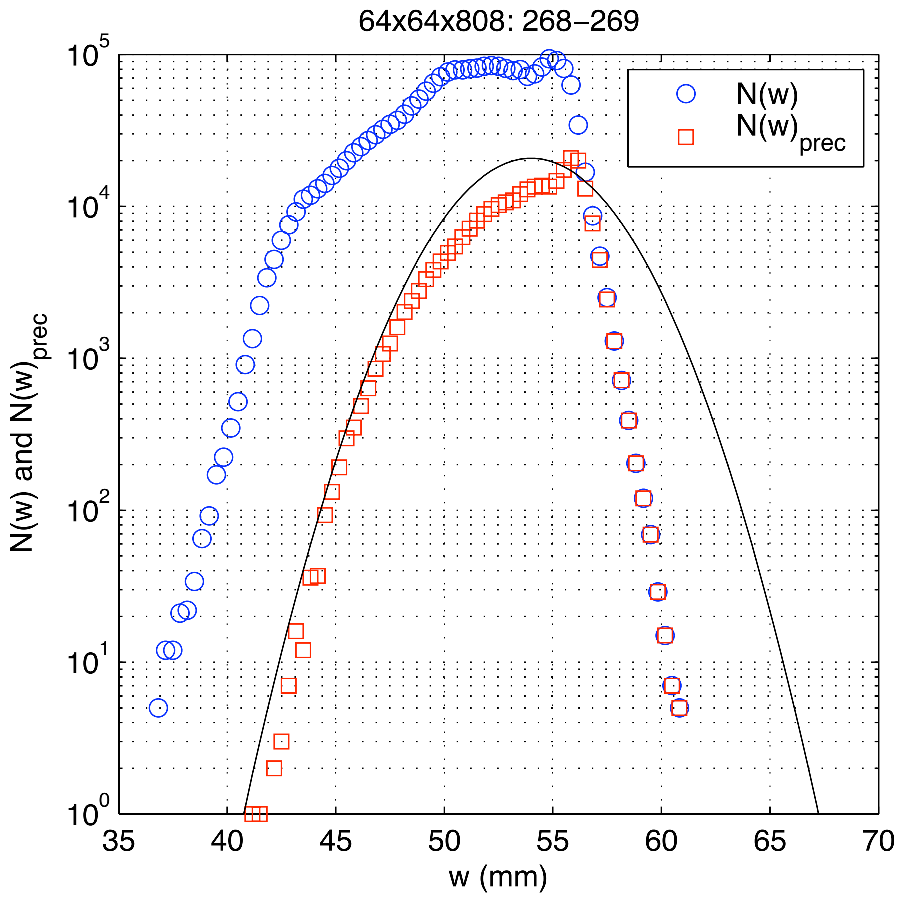




Unsteady GATE: 16 km x 16 km (analysis) grid

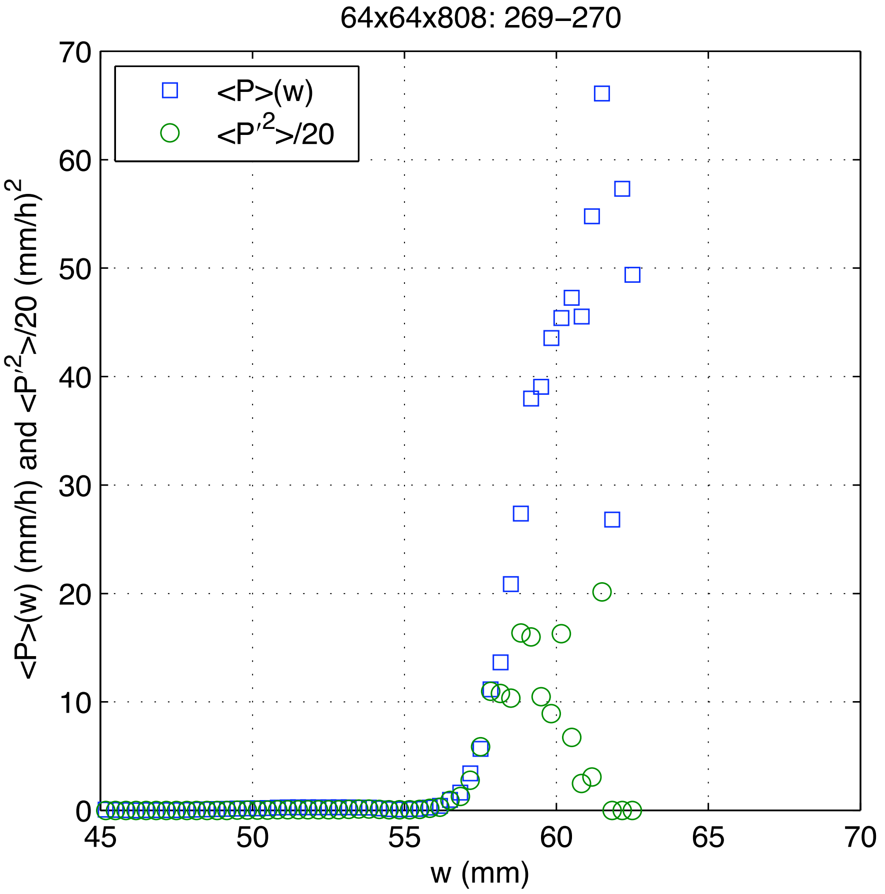
P(w): T= 268 to 269 K

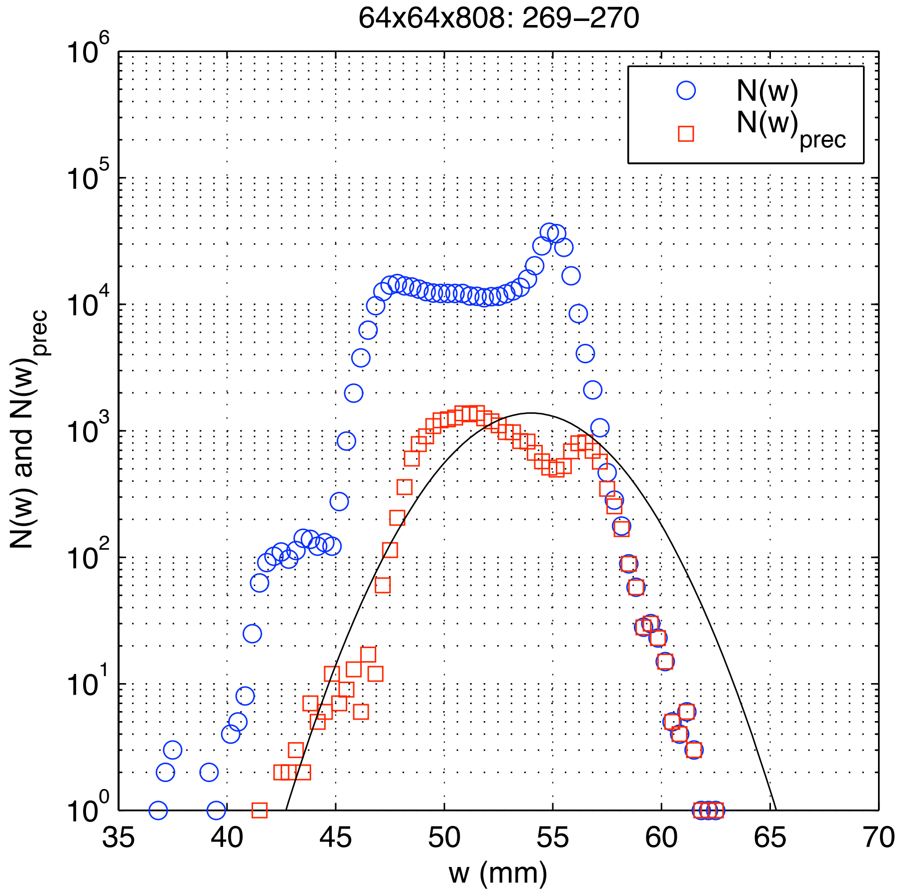




Unsteady GATE: 16 km x 16 km (analysis) grid

P(w): T= 269 to 270 K

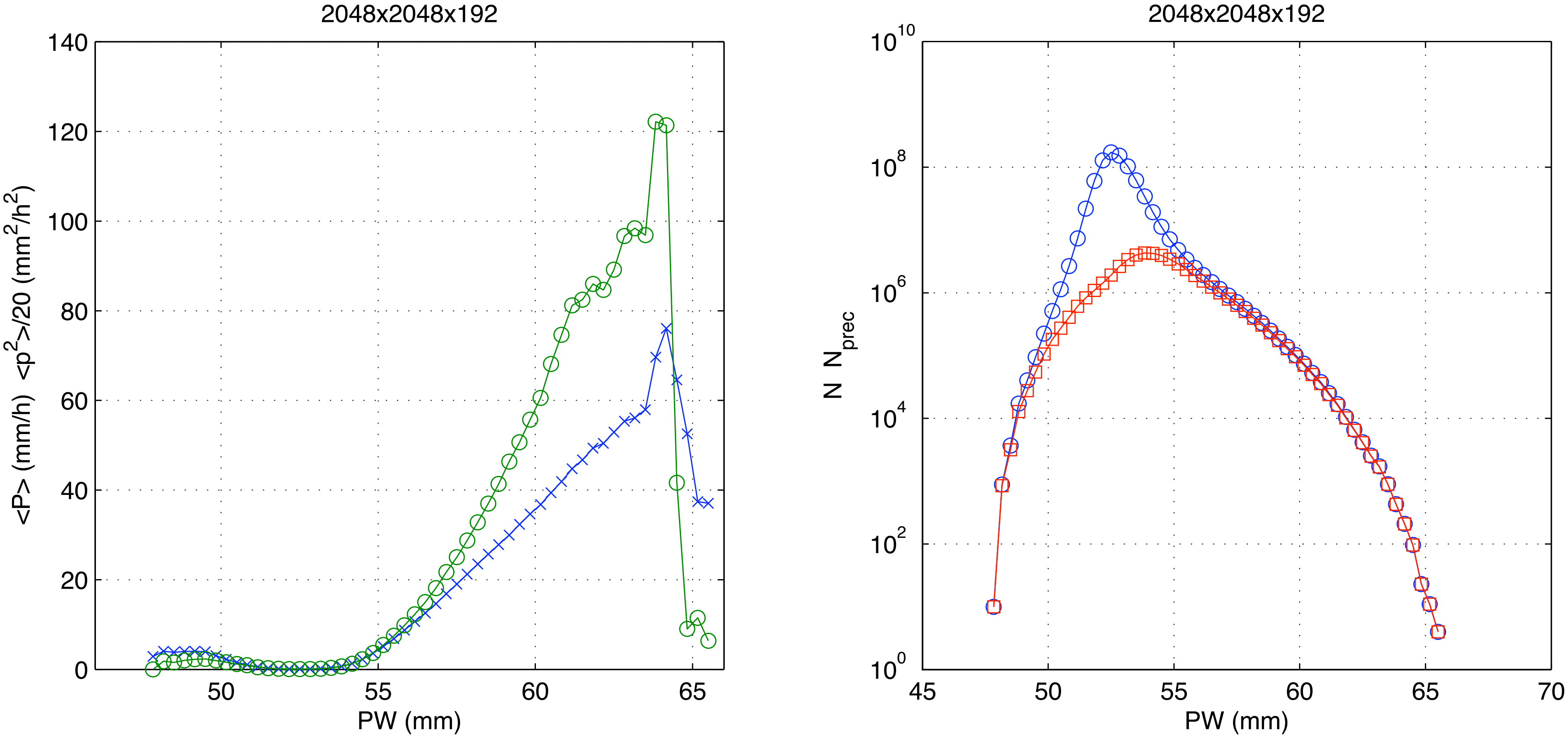




compare CRM results for various CRM configurations

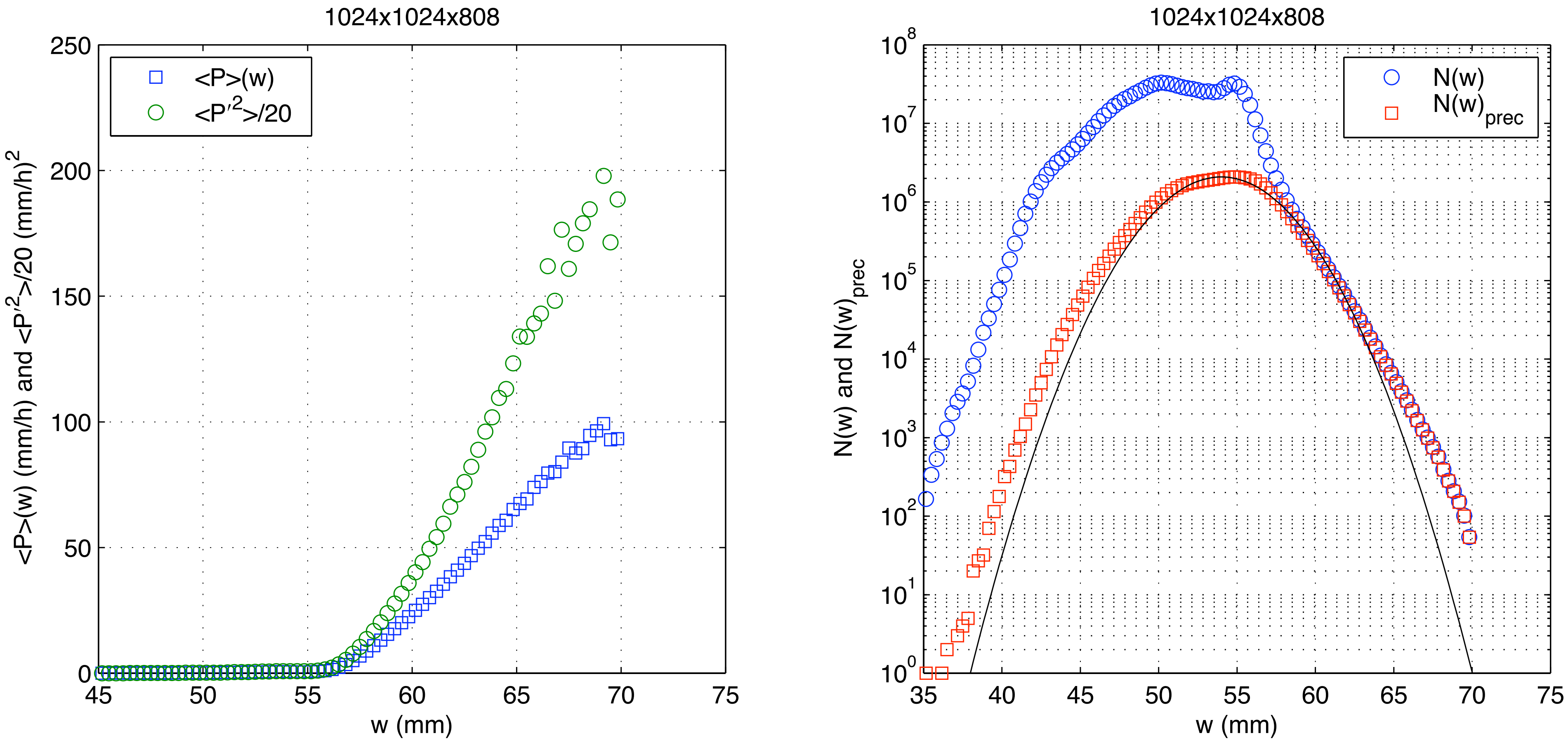
Giga-LES GATE: 0.1 km x 0.1 km (native) grid

<P>(w)



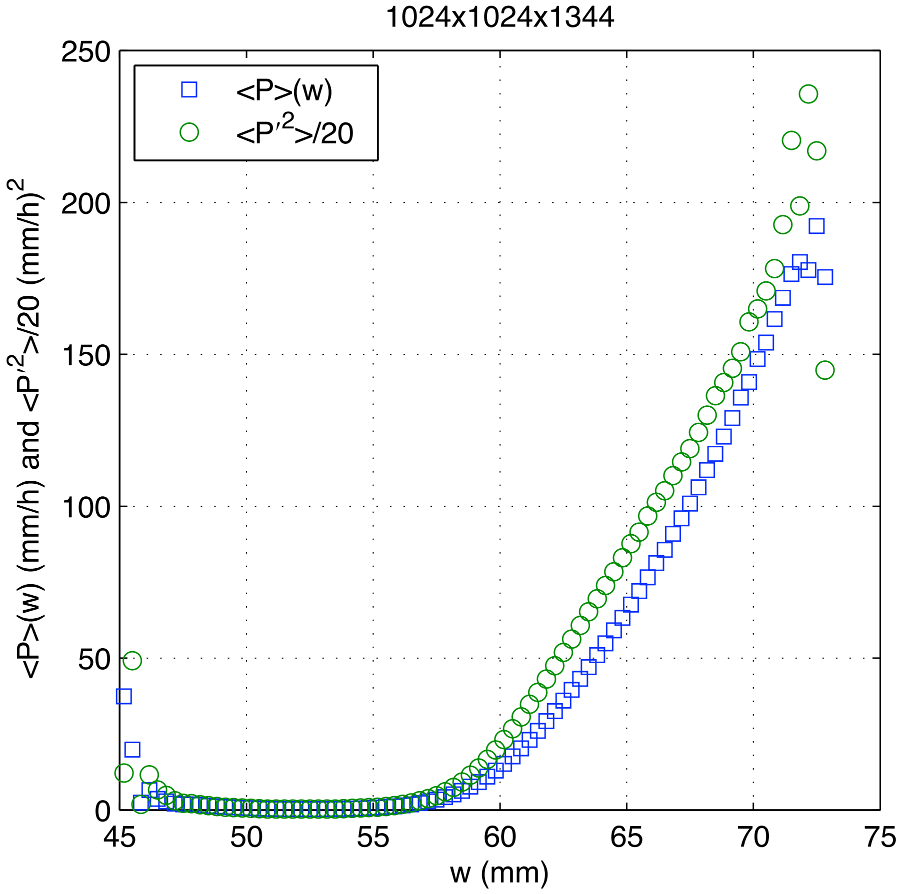
Unsteady GATE: 1 km x 1 km (native) grid

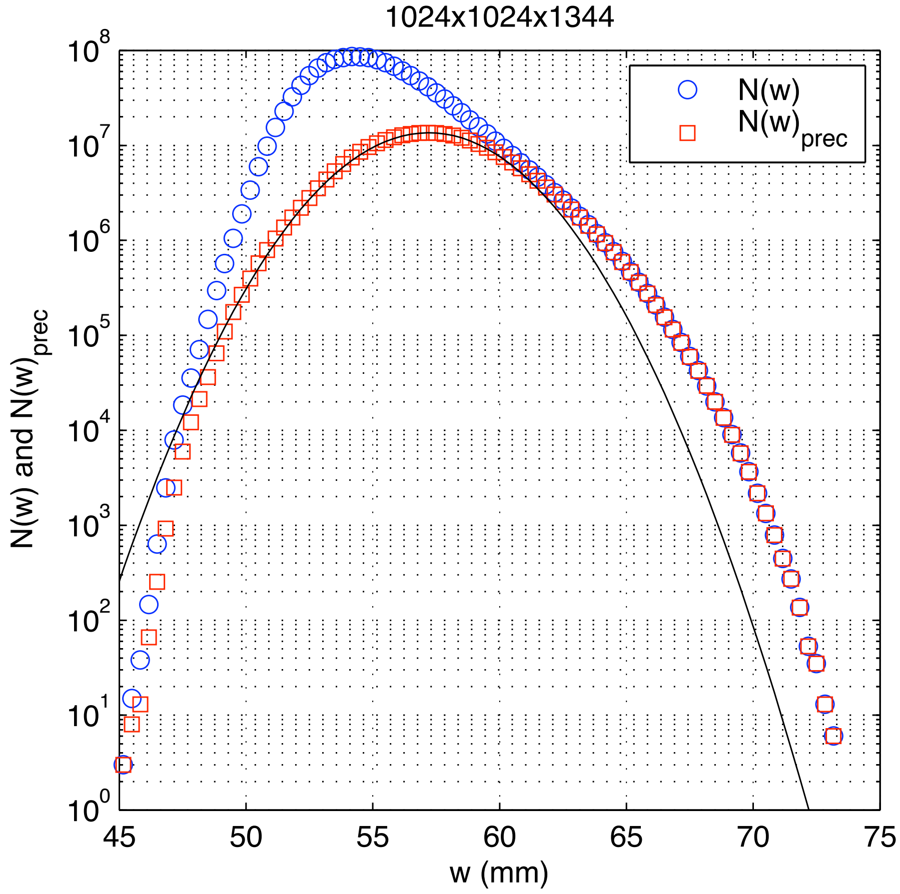
<P>(w)



Steady GATE: 1 km x 1 km (native) grid

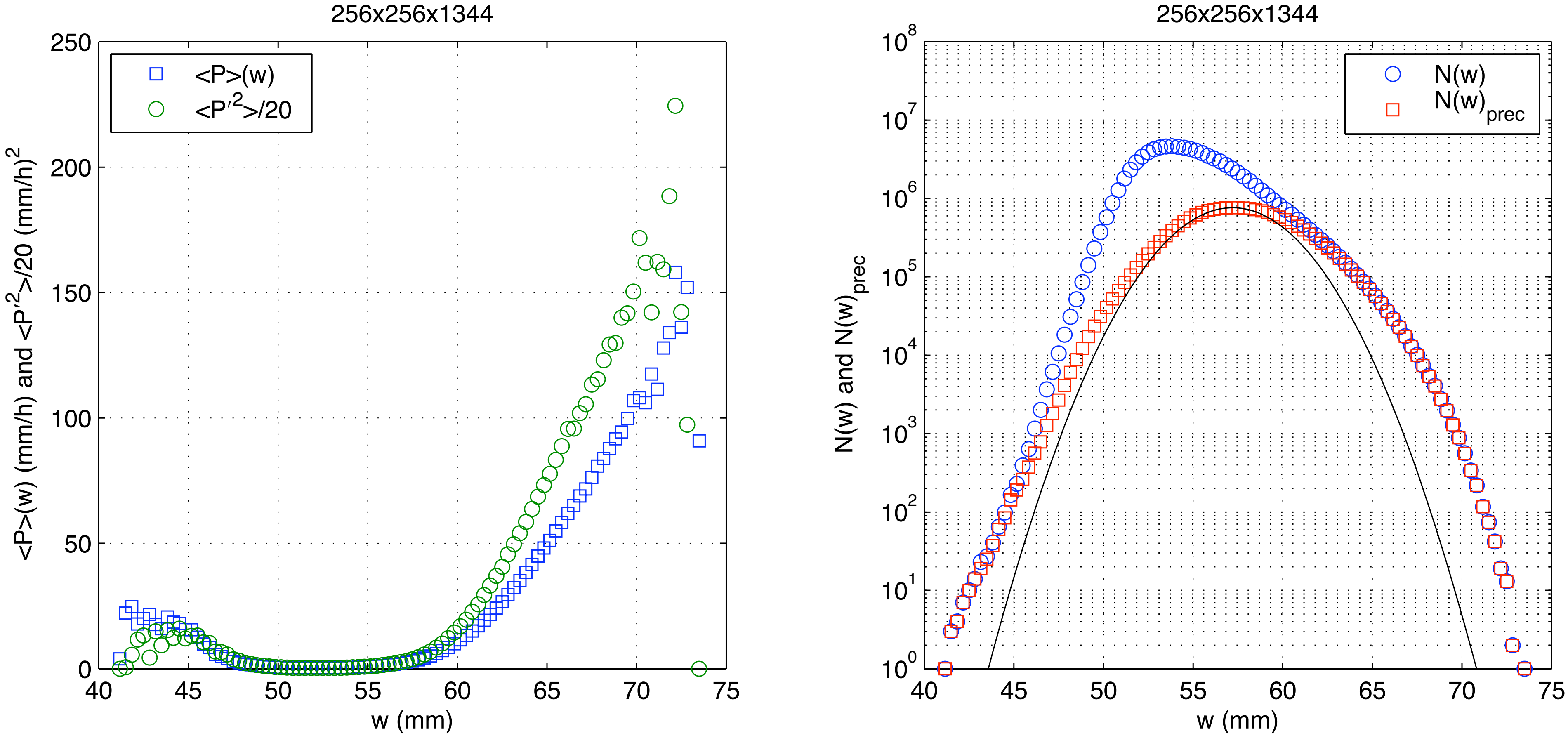
<P>(w)





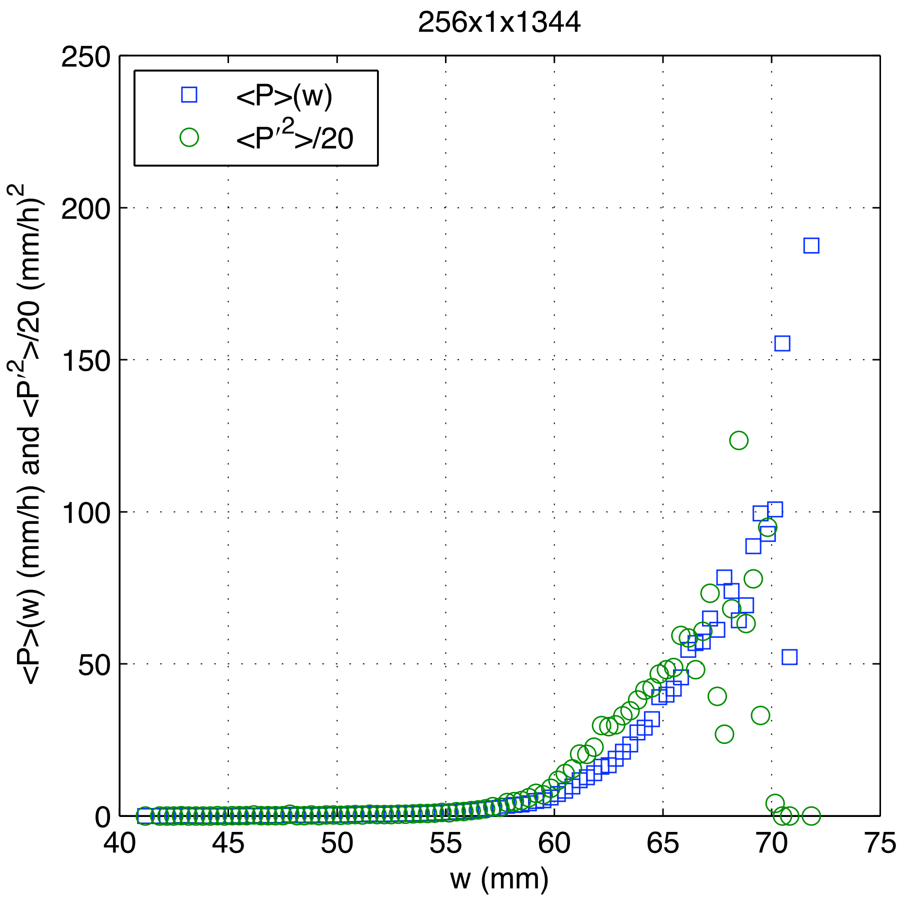
Steady GATE: 4 km x 4 km (native) grid

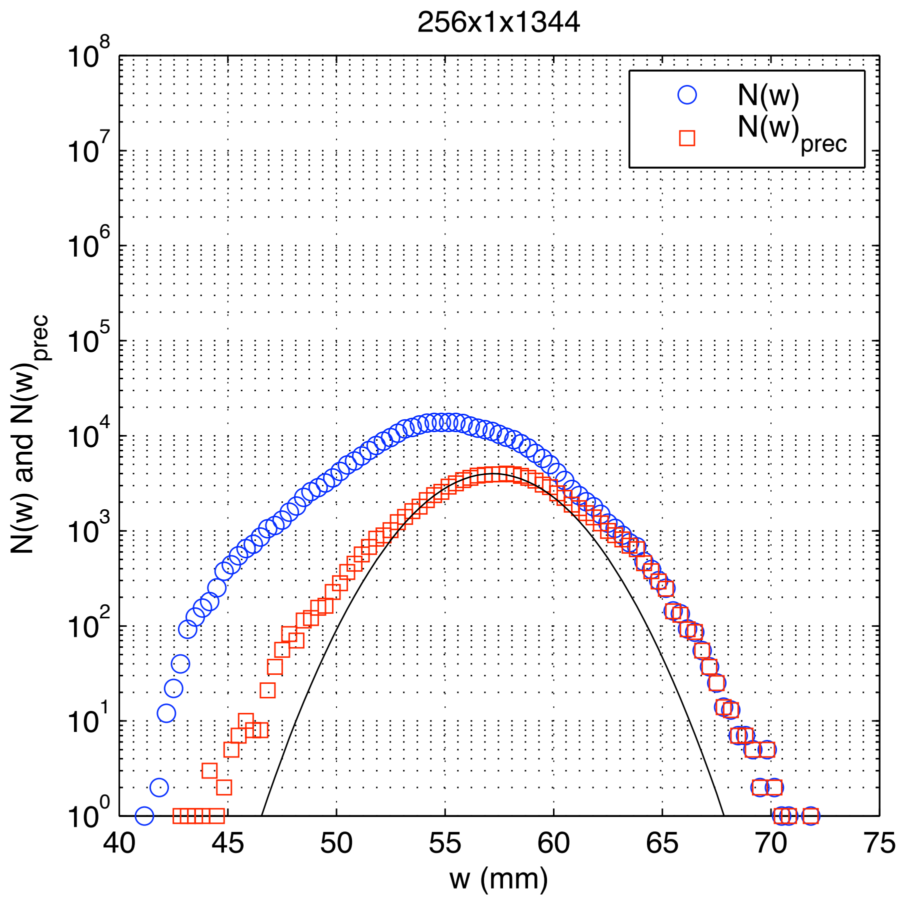
<P>(w)



Steady GATE: (2D 256 cols) 4 km (native) grid

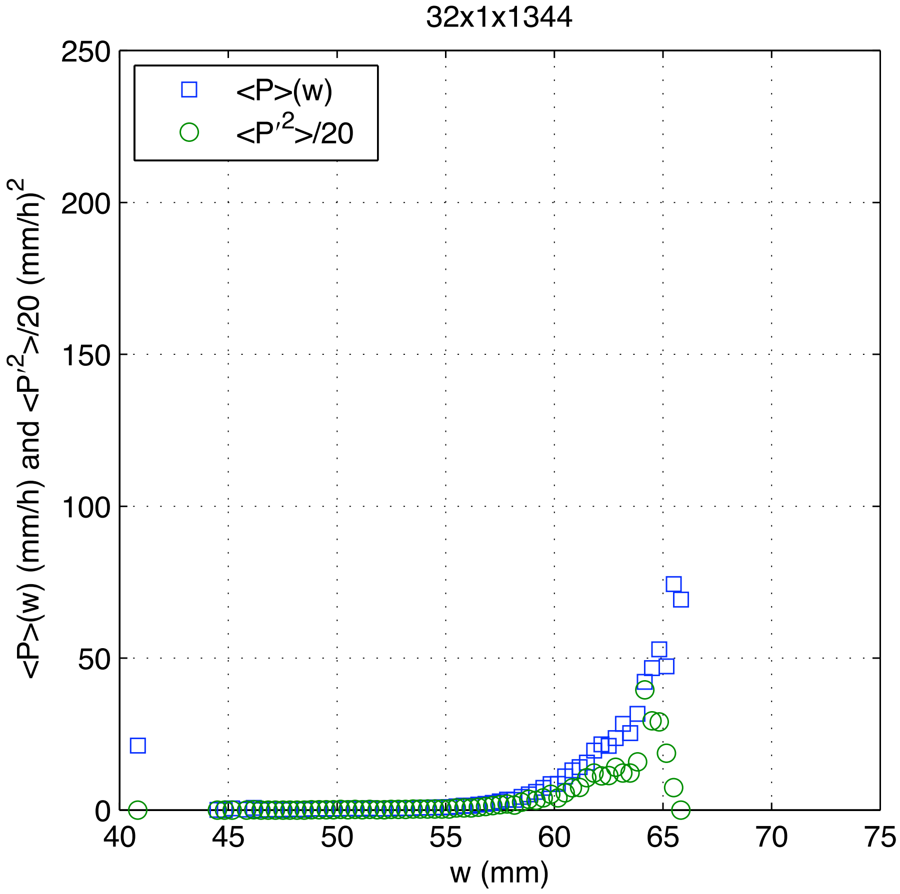
<P>(w)

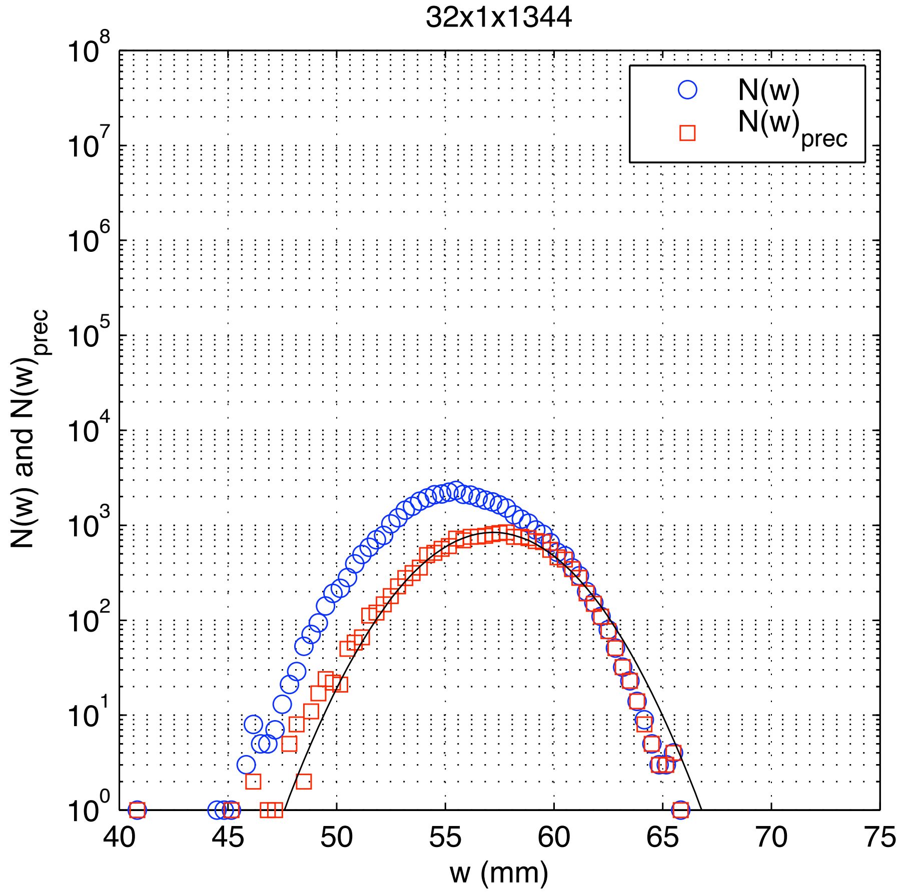




Steady GATE: (2D 32 cols) 4 km (native) grid

<P>(w)





CRM Results

1. Which observed features are evident?

a. Increase of P beyond a critical PW.

b. The dependence upon column T.

c. Cluster size frequency.

Which are not always?

d. A roll-off of P at high PW.

2. How do the results depend on the analysis grid size?

Results are essentially the same, except for a greater range of values of P, PW, and Tcol at smaller grid sizes.

More CRM Results

3. How do the results depend on various aspects of the simulations?

a. The essential features of <P>(w) are present in all of the simulations, including the MMF configuration (2D, 4-km grid size, 32 columns).

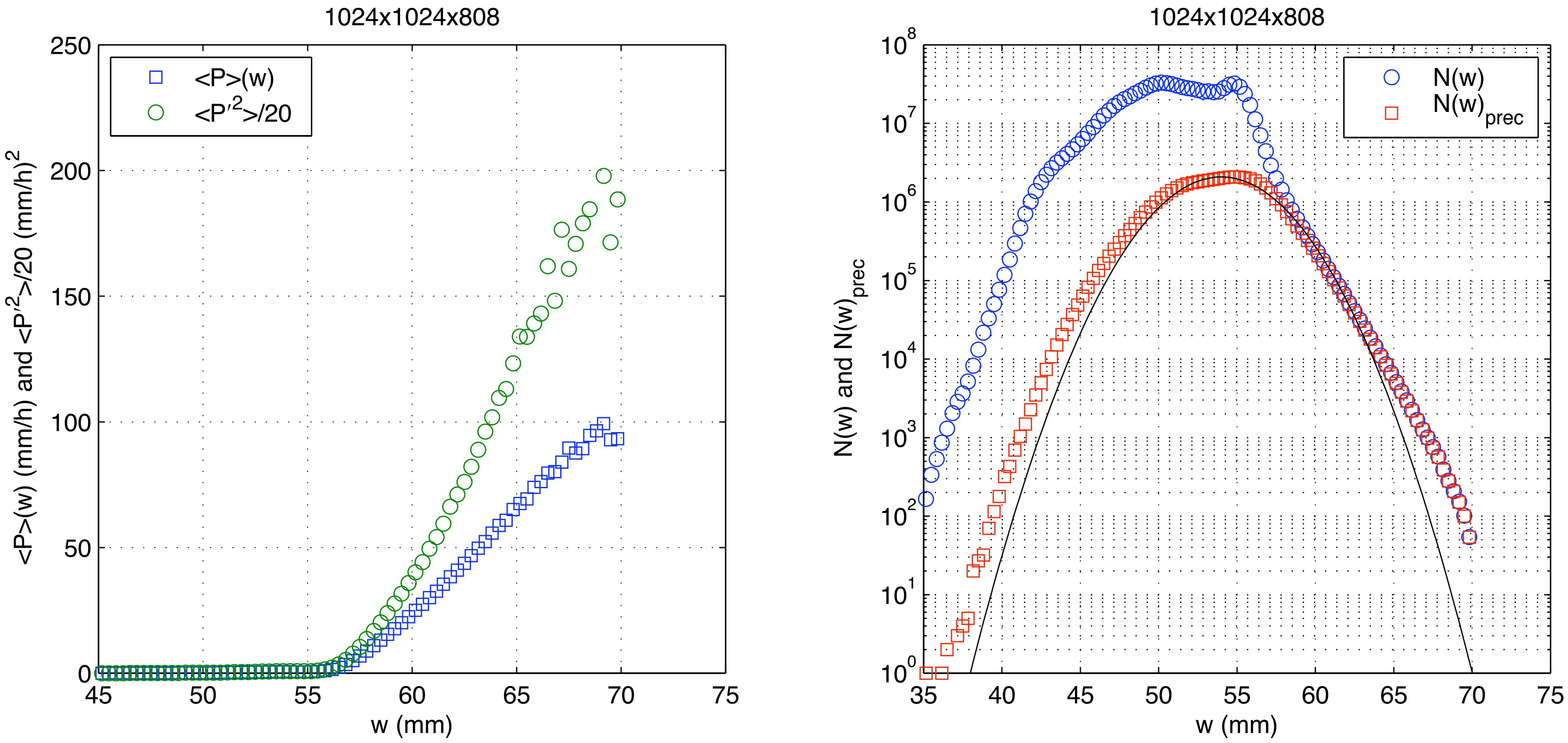
b. Cluster size statistics for rare large clusters depend on domain size.

c. Time-varying forcing offers more insight into the underlying physics.

broadly compare CRM results to observations using the same analysis method but on the native high-resolution CRM grid

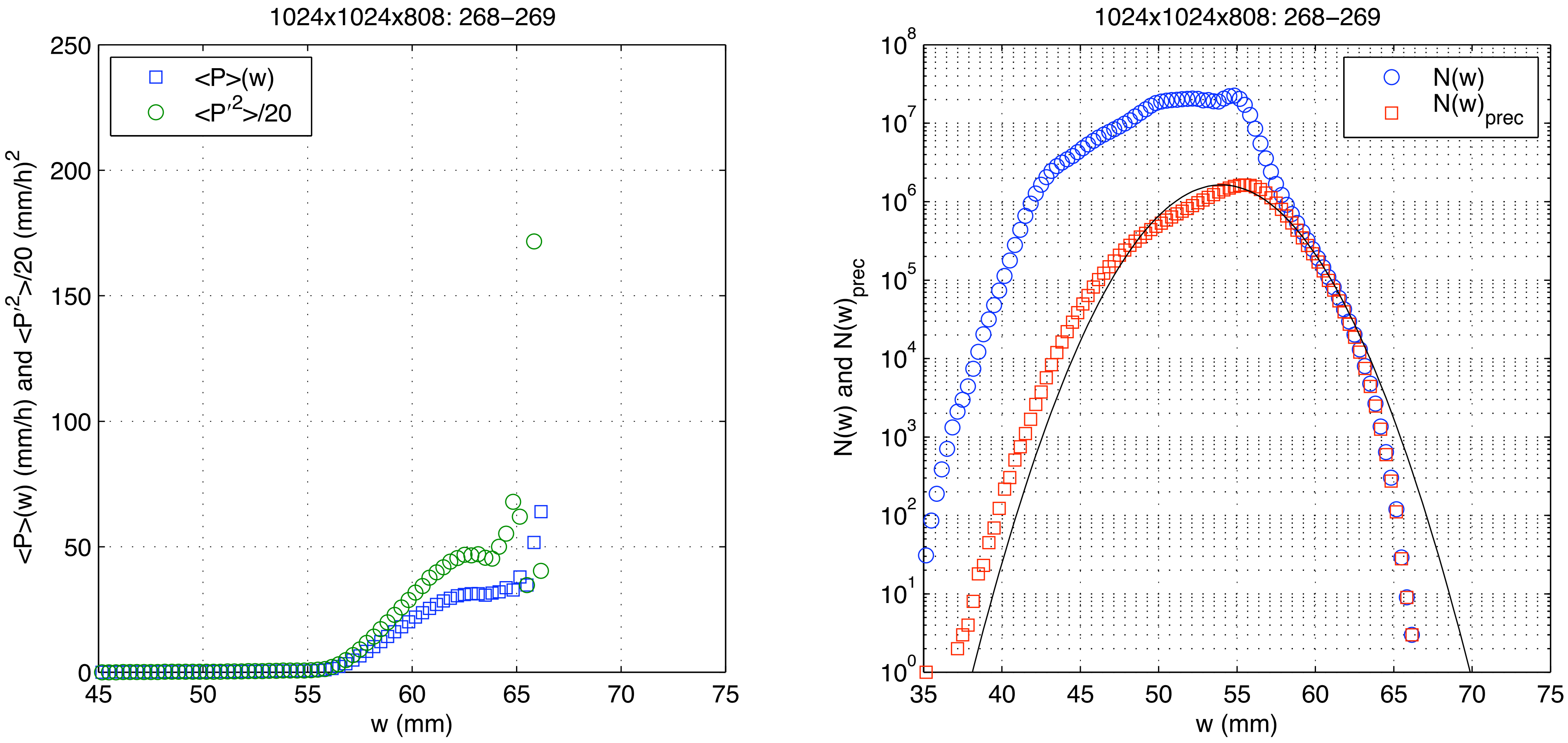
Unsteady GATE: 1 km x 1 km (native) grid

<P>(w)



Unsteady GATE: 1 km x 1 km (native) grid

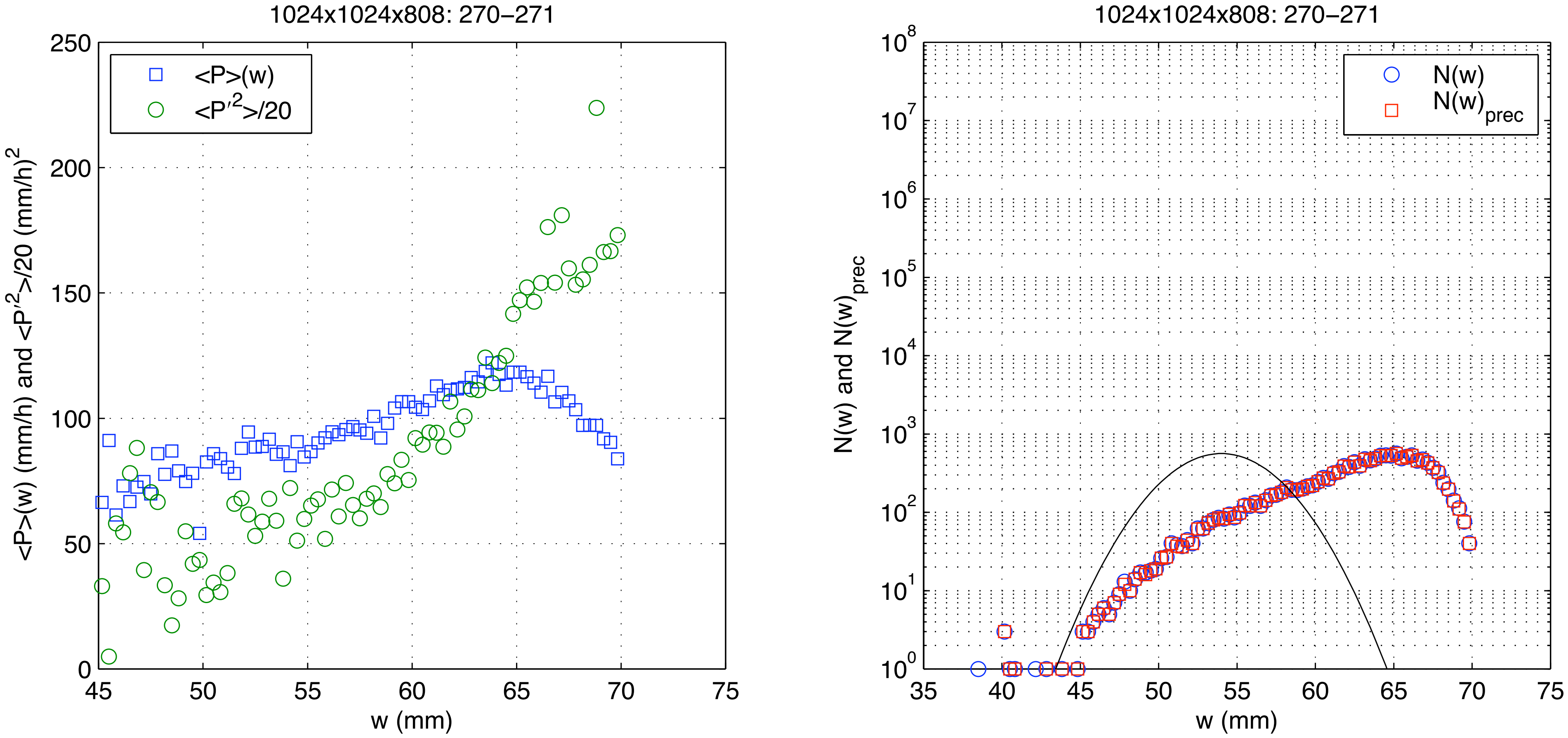
<P>(w): T= 268 to 269 K



Roll-off?

Unsteady GATE: 1 km x 1 km (native) grid

<P>(w): T= 270 to 271 K



All points at this T are precipitating.

High precip rates occur at subcritical PW.

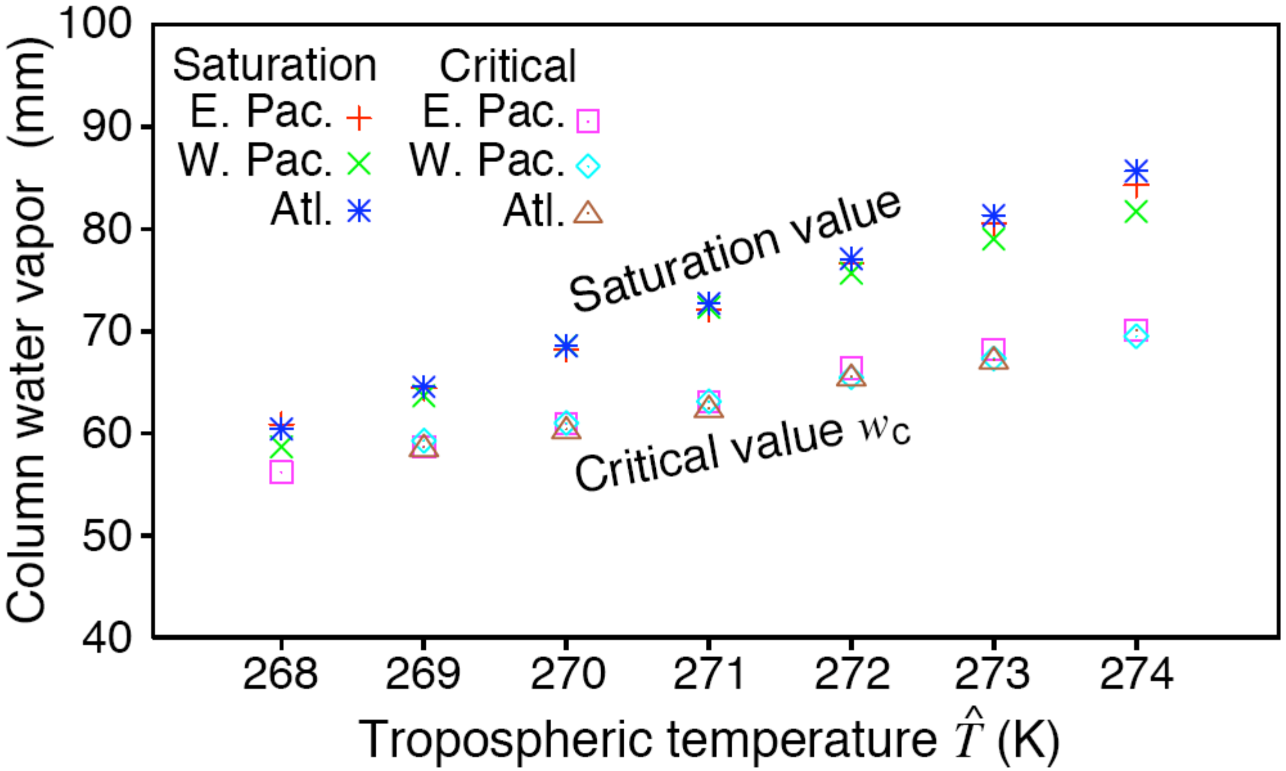
More Results

4. *How does deep convection produce the simulated (and observed) <P>(w)?*

a. Updraft saturates tropospheric column: increases PW (+9 mm) and produces P.

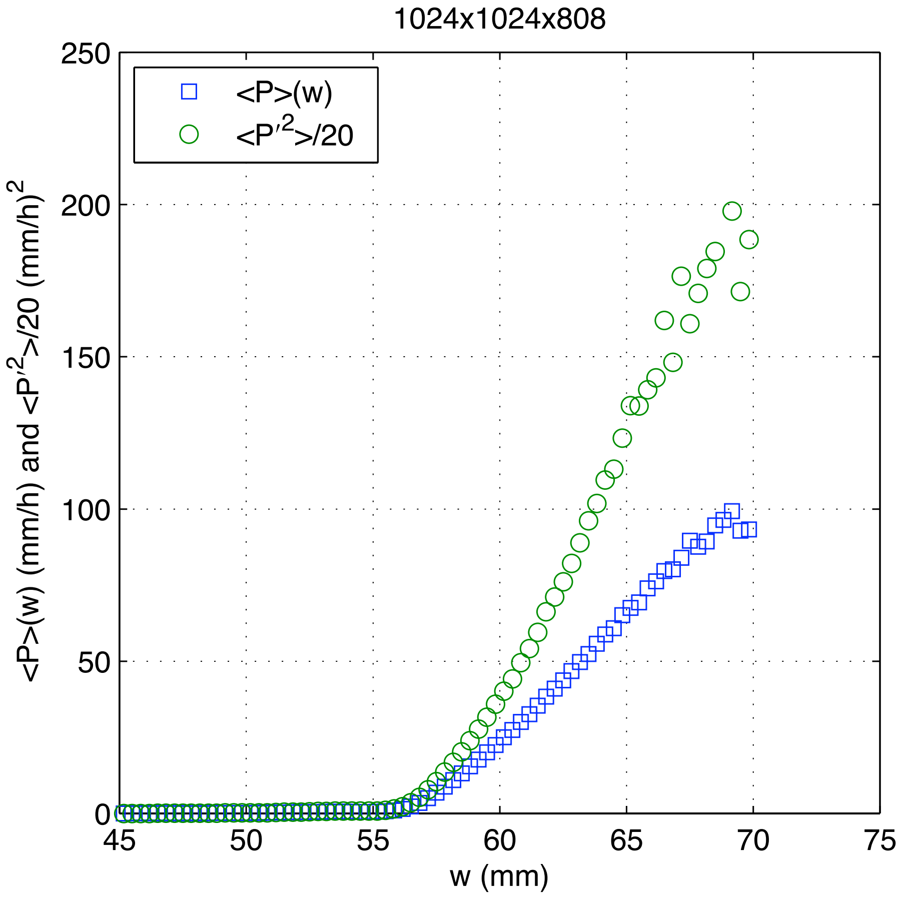
b. Precip. saturates subcloud layer: increases PW (+1 mm) and P.

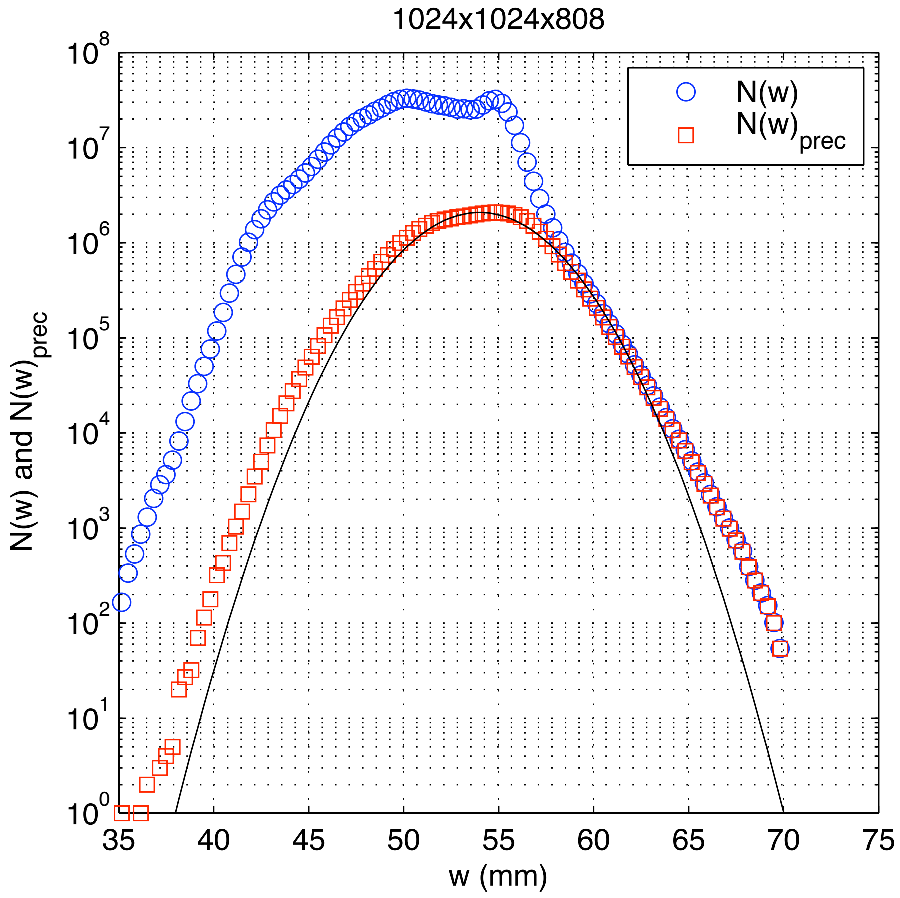
c. Updraft buoyancy increases Tcol, PW (+5 mm/K), and P.



Unsteady GATE: 1 km x 1 km (native) grid

<P>(w)

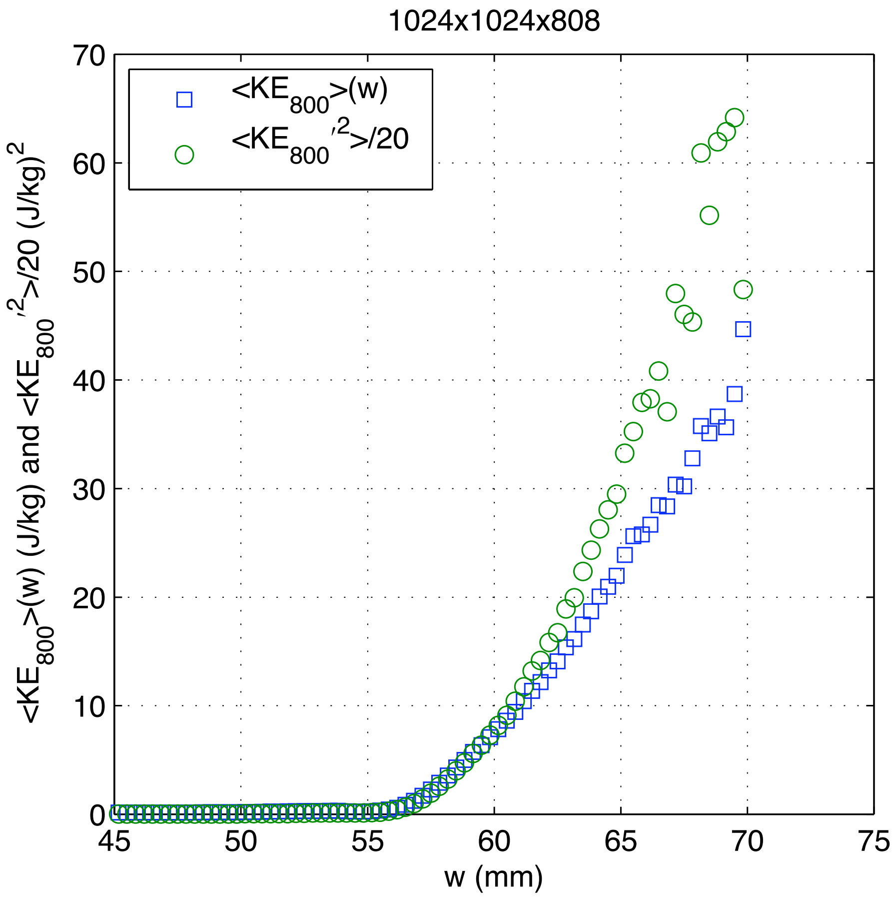


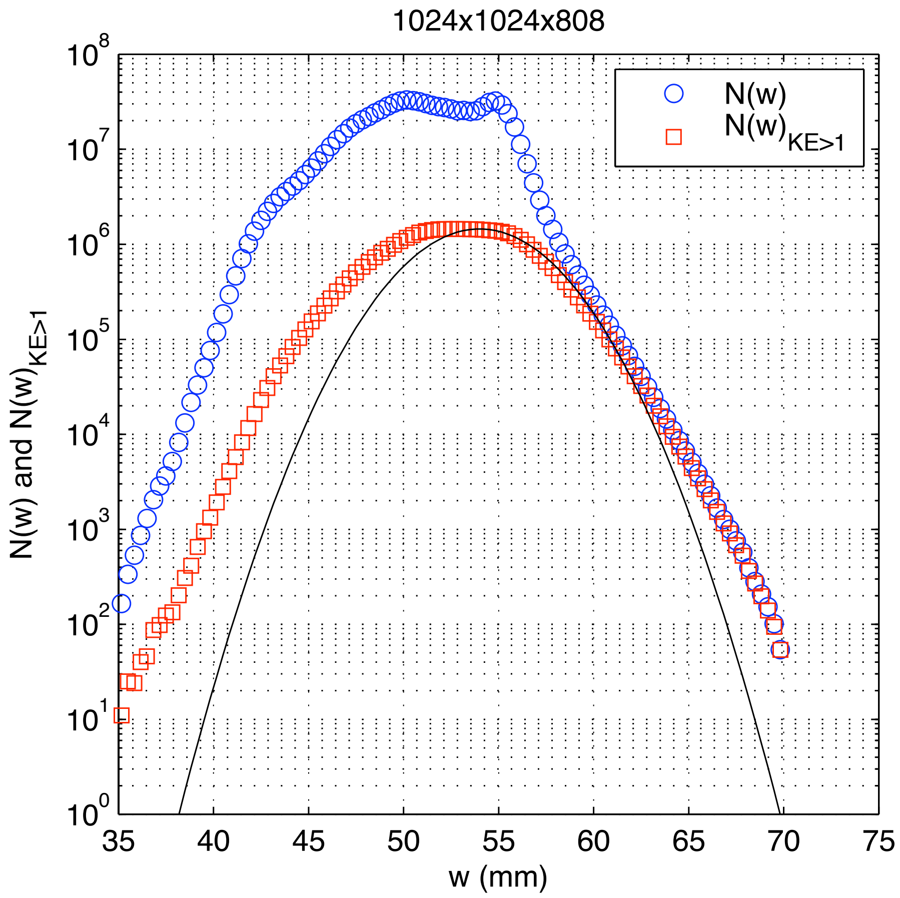


Precip Rate and Column Water Vapor are strongly coupled.

Unsteady GATE: 1 km x 1 km (native) grid

<Vertical kinetic energy at 800 mb>(w)





Precip Rate ~ Convection Intensity

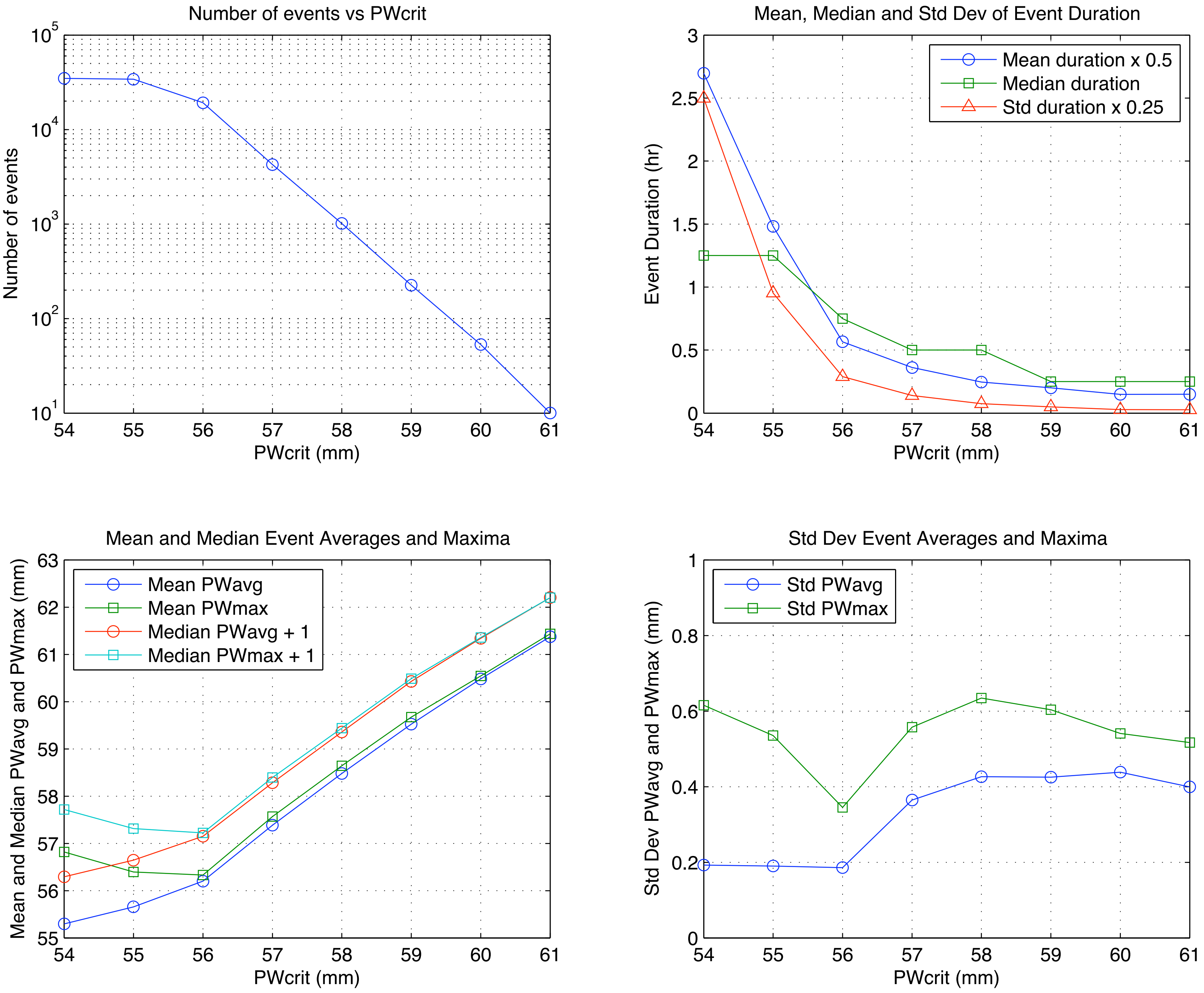
Time scales of large column water vapor events in strong convection

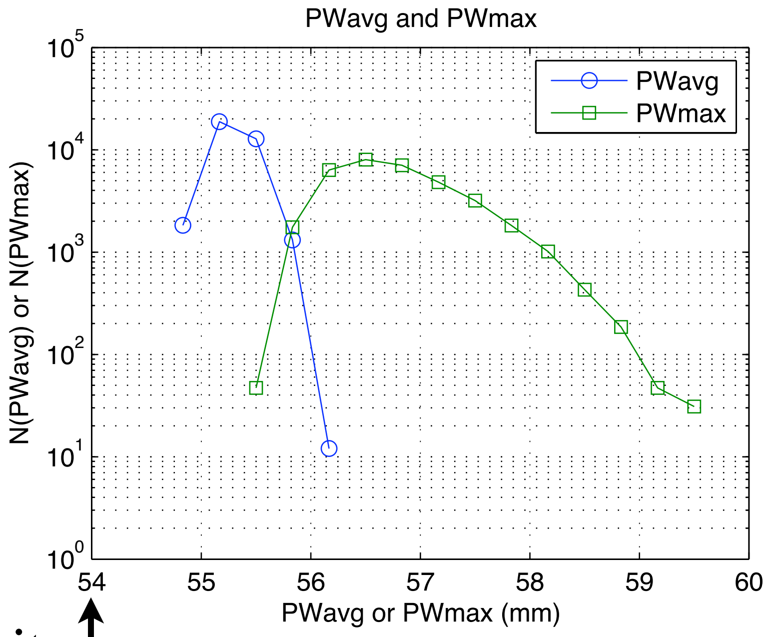
- I identified high PW events in the time series from the realistically forced GATE simulation (8 days long).

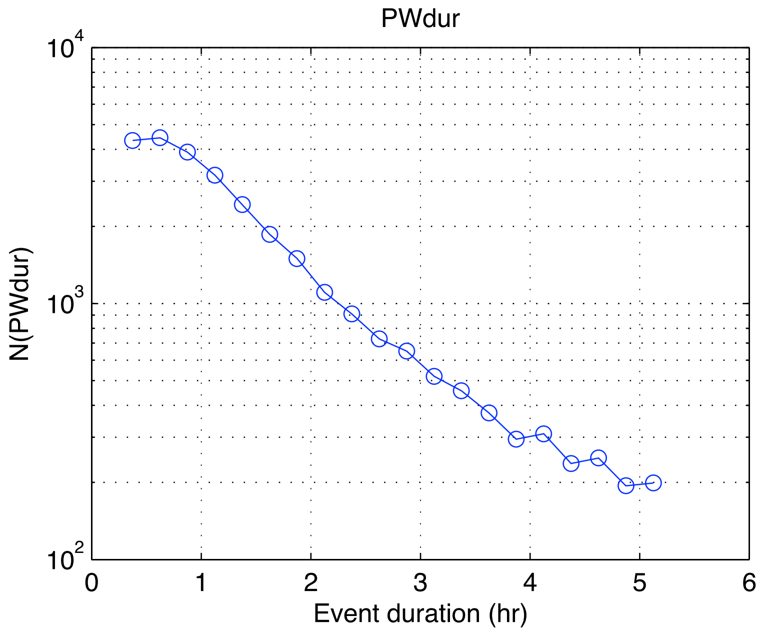
- For these plots, each time series is for a (16 km)^2 region (256 1 km x 1 km grid points averaged), with values every 15 minutes.

- I defined the high-PW events using a threshold value (called PWcrit on the plots).

- I generated statistics for a range of such thresholds from 54 to 61 mm.

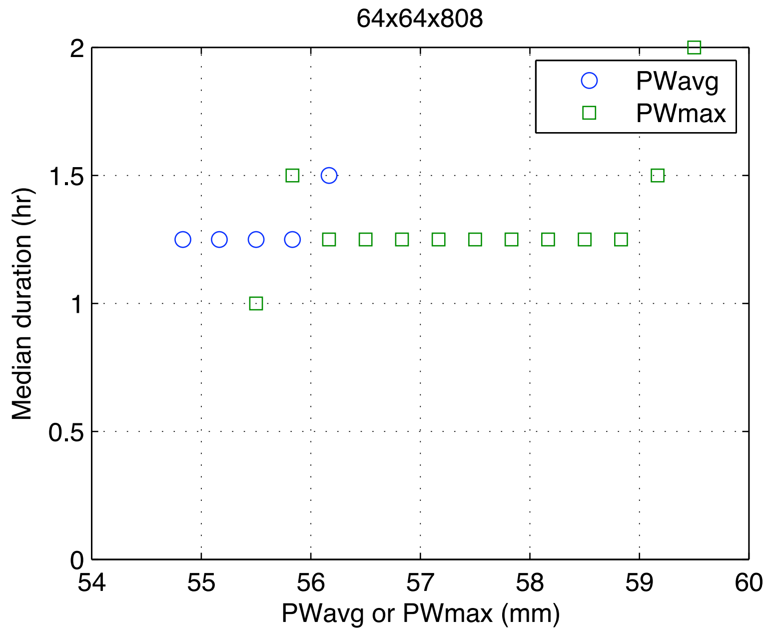

Number of events vs PWcrit
Number of events
10^1
10^2
10^3
10^4
10^5
54
55
56
57
58
59
60
61
PWcrit (mm)
Mean, Median and Std Dev of Event Duration
Event Duration (hr)
0
0.5
1
1.5
2
2.5
3
Mean duration x 0.5
Median duration
Std duration x 0.25
54
55
56
57
58
59
60
61
PWcrit (mm)
Mean and Median Event Averages and Maxima
Mean and Median PWavg and PWmax (mm)
55
56
57
58
59
60
61
62
63
Mean PWavg
Mean PWmax
Median PWavg + 1
Median PWmax + 1
54
55
56
57
58
59
60
61
PWcrit (mm)
Std Dev Event Averages and Maxima
Std Dev PWavg and PWmax (mm)
0
0.2
0.4
0.6
0.8
1
Std PWavg
Std PWmax
54
55
56
57
58
59
60
61
PWcrit (mm)

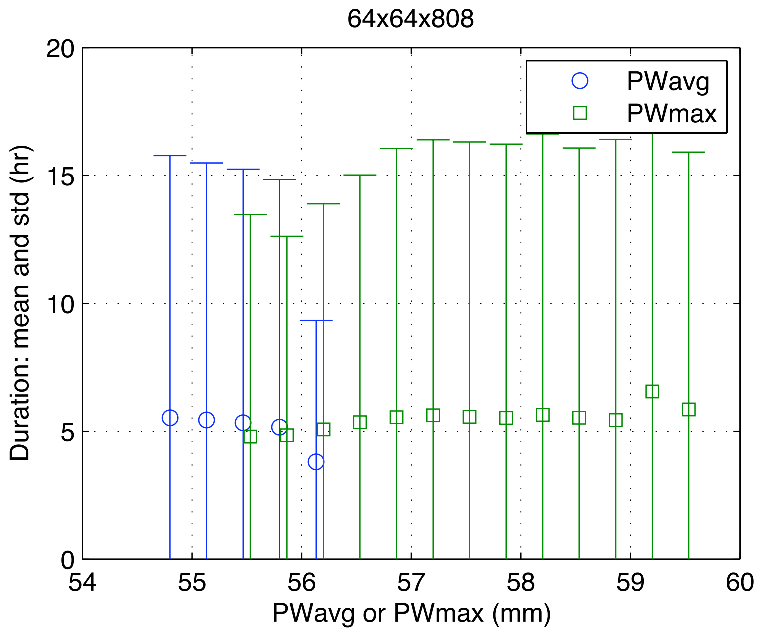


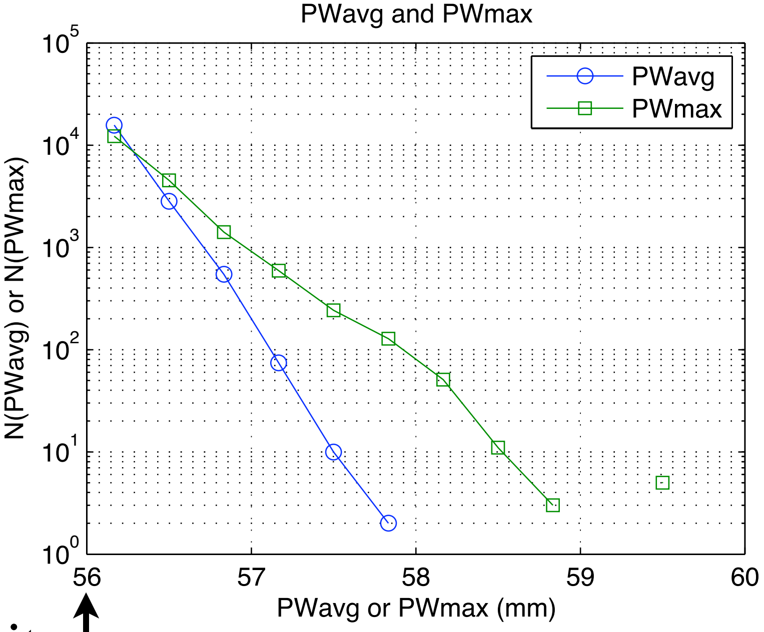


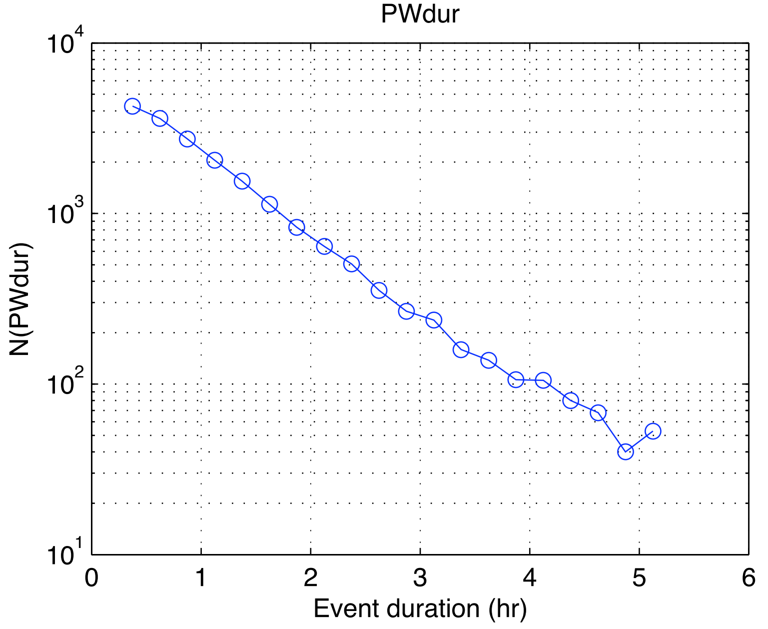
PWcrit ↑

subcritical



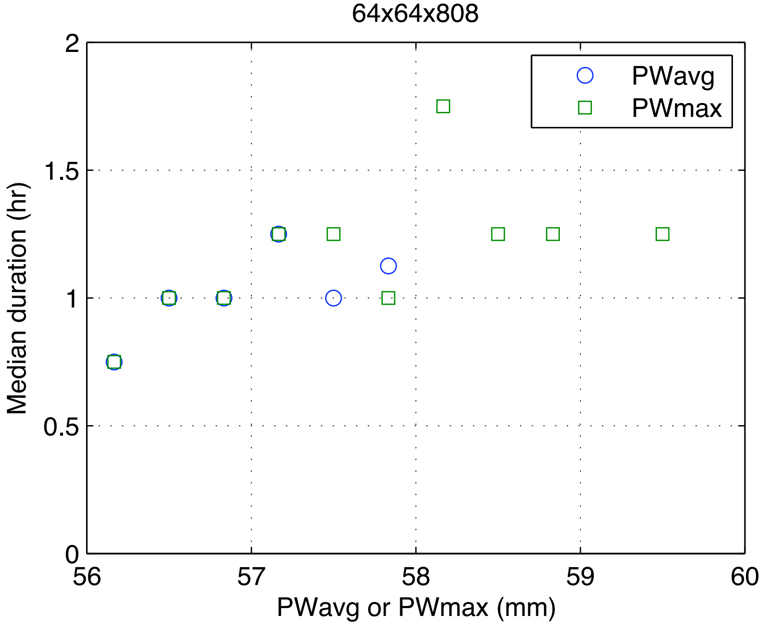


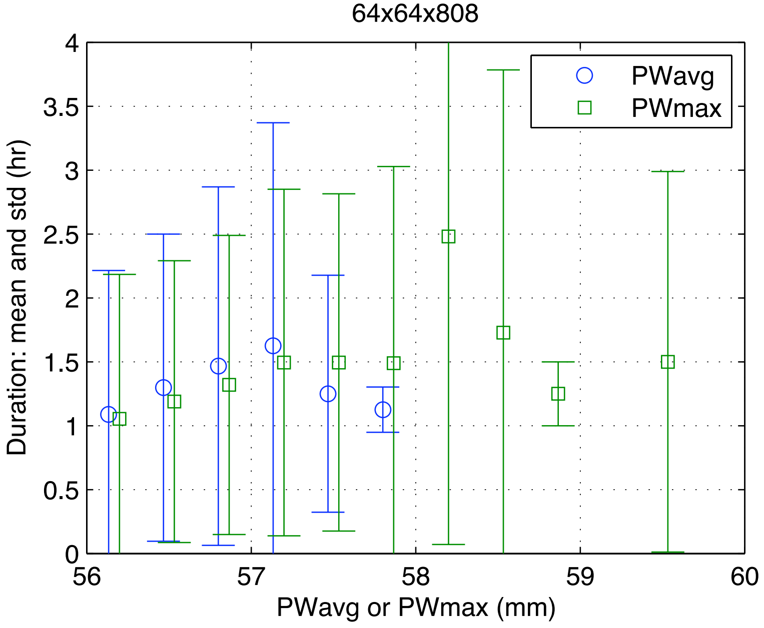




PWcrit ↑

supercritical





- Above PW=56 mm, the scalings for strong convection appear to be similar for any PWcrit chosen. The statistics plotted suggest that this is the case.
- So all this comes back to the question: what happens at PW=56 mm (in this case)? What determines that value?

Conclusions

- Cloud-resolving models (stand-alone and embedded in GCMs) are able to reproduce nearly all of the observed statistics of strong convective precipitation over tropical oceans.

- CRMs and MMFs do not generally reproduce the "observed" roll-off of precipitation rate at large column water values.

- Analysis of CRM results suggests that many of the observed features are due to the tight coupling between dynamics and moist thermodynamics in convective updrafts.