LES Intercomparison of Drizzling Stratocumulus: DYCOMS-II RF02

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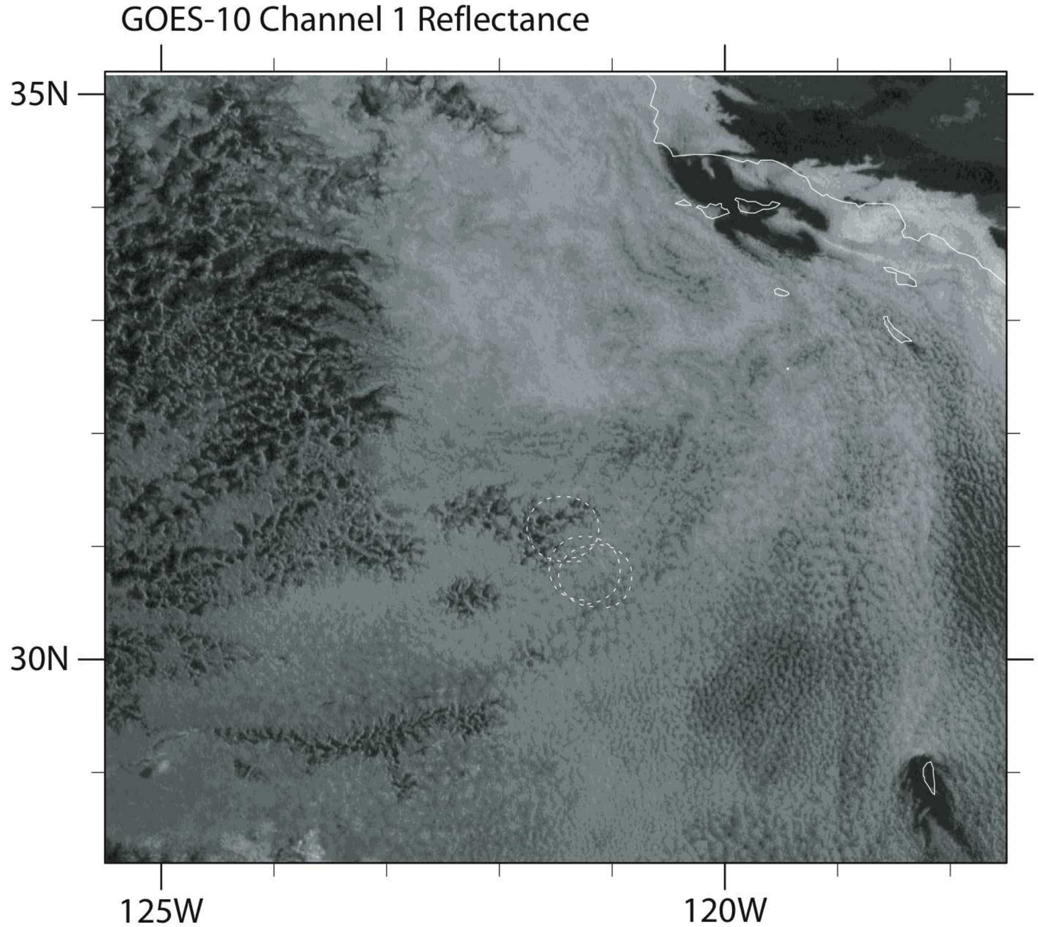
http://sky.arc.nasa.gov:6996/ack/gcss9



Acknowledgments
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Bjorn Stevens, UCLA
Markus Petters, CSU
Participating Groups

Outline

- Motivation
- Case specifications
- Some results (ensemble, then group by group)
  - time series
  - profiles
  - trends within ensemble
- Summary
- Questions and issues

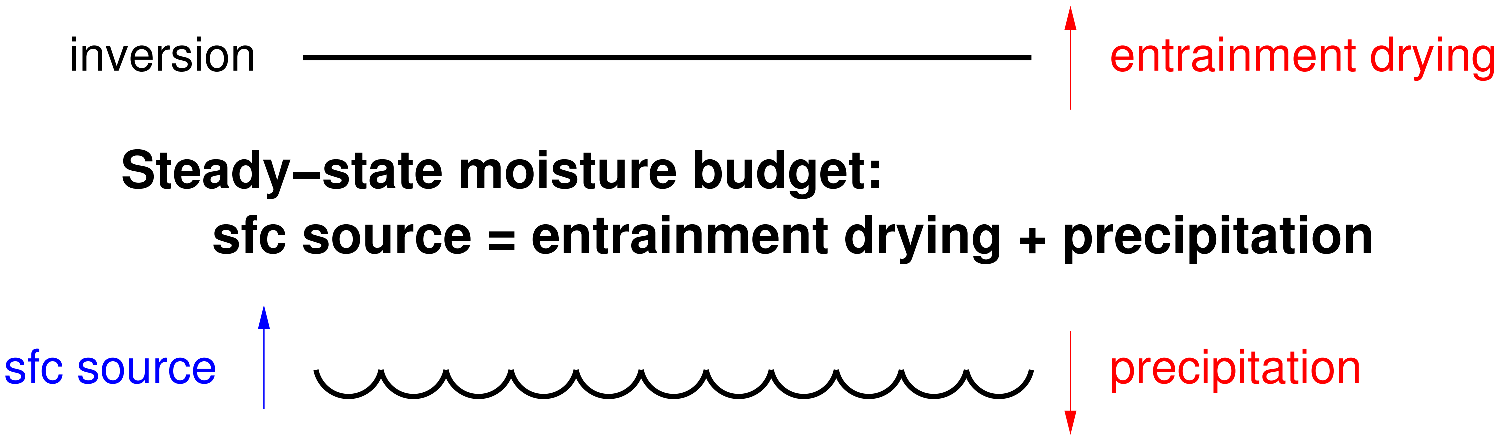
Scientific Focus

- How do increasing numbers of submicron aerosol affect stratocumulus
    - cloud cover
    - liquid water path
- How does drizzle affect
    - boundary layer dynamics
    - entrainment
    - bulk cloud properties
- How do predictions of drizzle in LES compare with observations?
- Does sedimentation of cloud droplets affect results?
- If so, is the response from different models consistent?

Results from Previous Workshop

- Case: DYCOMS-II RF01, with very dry inversion, droplet concentrations about 100 cm^{-3}, and no precipitation below cloud base
- Most LES entrained overlying air faster than measurements indicated, resulting in a thin, cloud layer with LWP lower than observed
- Reduction of radiative cooling by thin clouds results in poorly mixed boundary layers $\Rightarrow$ negative feedback on further entrainment
- Limiting subgrid-scale mixing at inversion (ad hoc or by skill or luck of SGS model) reduces entrainment, resulting in well-mixed boundary layer with thick cloud layer

Drizzle and Entrainment in a Mixed Layer Model



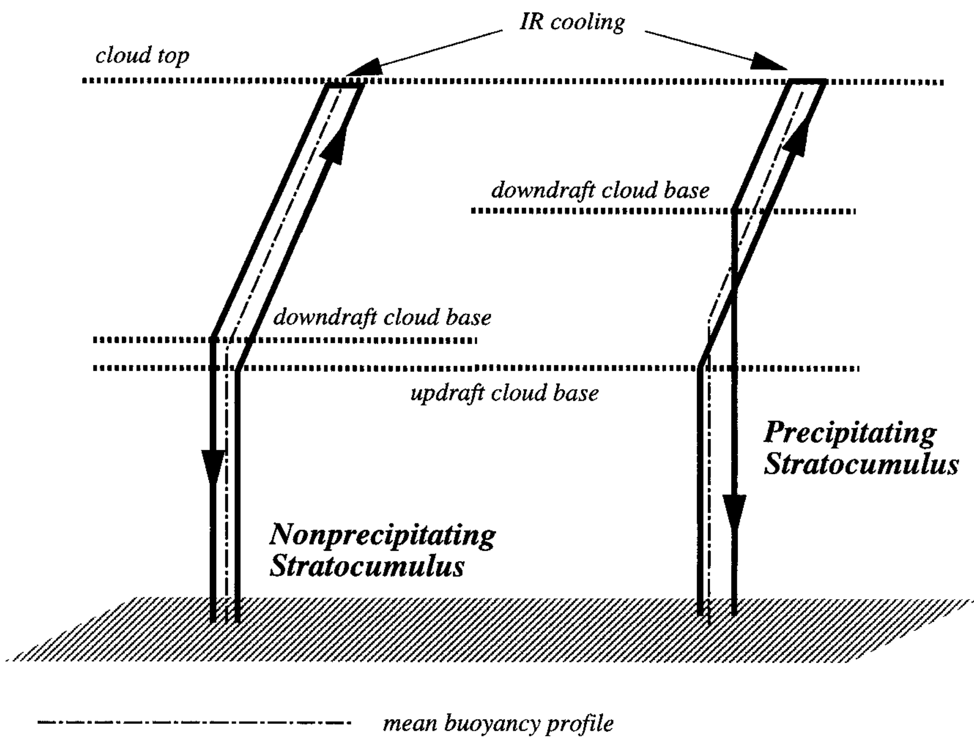
Steady–state moisture budget:
sfc source = entrainment drying + precipitation

- Decreased drizzle leads to deeper boundary layer and thicker cloud *(Pincus & Baker 1994)*
- Considered a single meteorological scenario, with a moist inversion
- Whether entrainment deepens or thins a cloud layer depends on thermodynamic jumps at top of BL *(Randall 1984)*

Large-Eddy Simulations of Strongly Precipitating, Shallow, Stratocumulus-Topped Boundary Layers *(Stevens et al. 1998)*

- ASTEX case study (moist inversion) with CCN concentration of 25 cm^{-3}, using bin microphysics and 2-stream radiative transfer

- Drizzle dries updrafts $\Rightarrow$ less evaporative cooling available to drive downdrafts



- Dry downdrafts $\Rightarrow$ cumuliform convection *(*Bjerknes 1938)

- *"Moreover, light drizzle – by reducing entrainment in PBLs with large jumps in moisture across the inversion – might actually lessen entrainment drying thereby leading to deeper PBL clouds. Such scenarios are largely speculative and need to be considered further."*

The Impact of Humidity above Stratiform Clouds on Indirect Aerosol Climate Forcing *(Ackerman et al. 2004)*

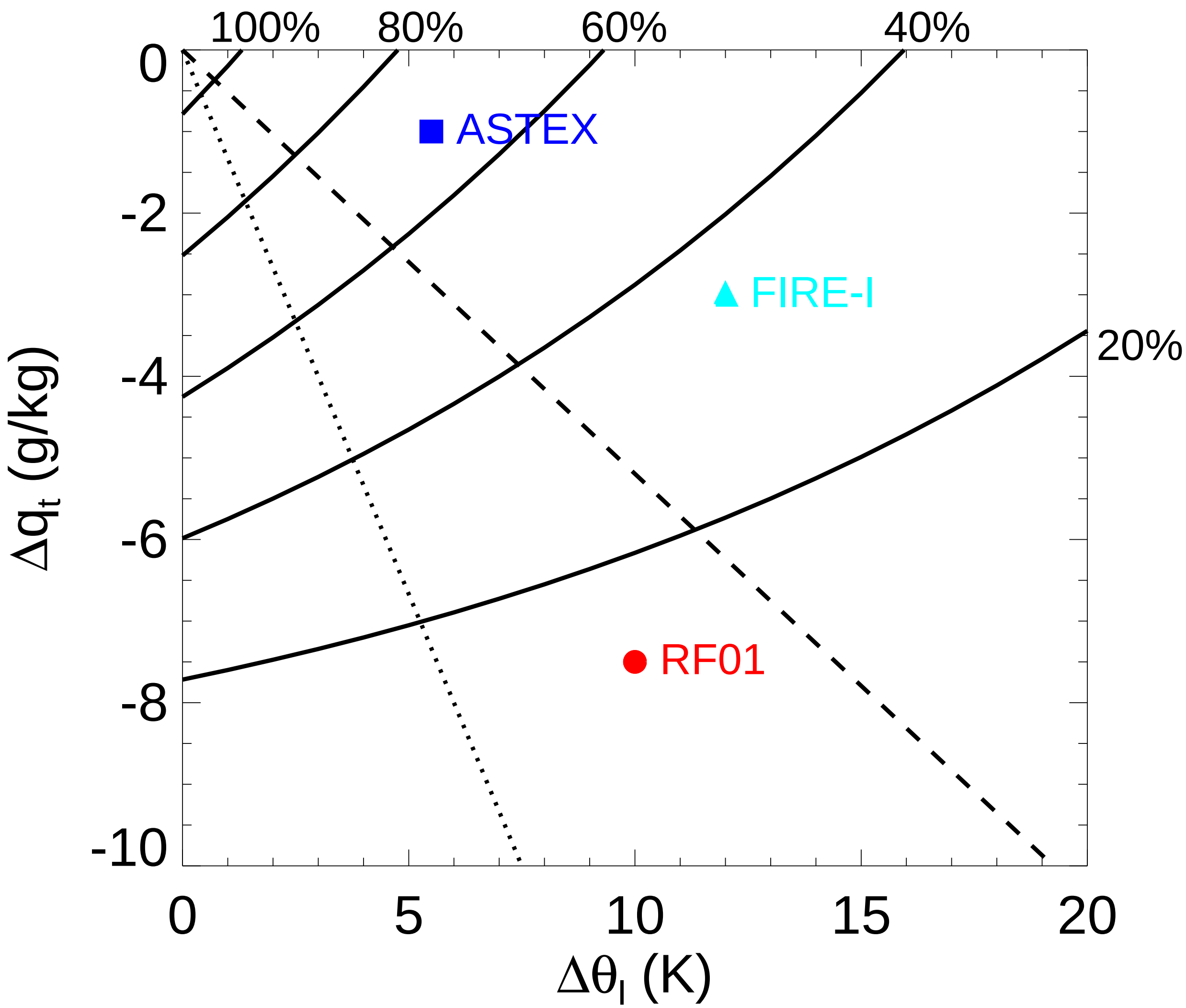
- LES with bin microphysics and 2-stream radiative transfer based on three case studies: ASTEX (A209, 4th GCSS WG1 Workshop), FIRE-I (EUROCS intercomparison), and DYCOMS-II (RF01, 8th GCSS WG1 Workshop)

- Droplet sedimentation and drizzle consistently decrease with increasing numbers of sub-micron aerosol

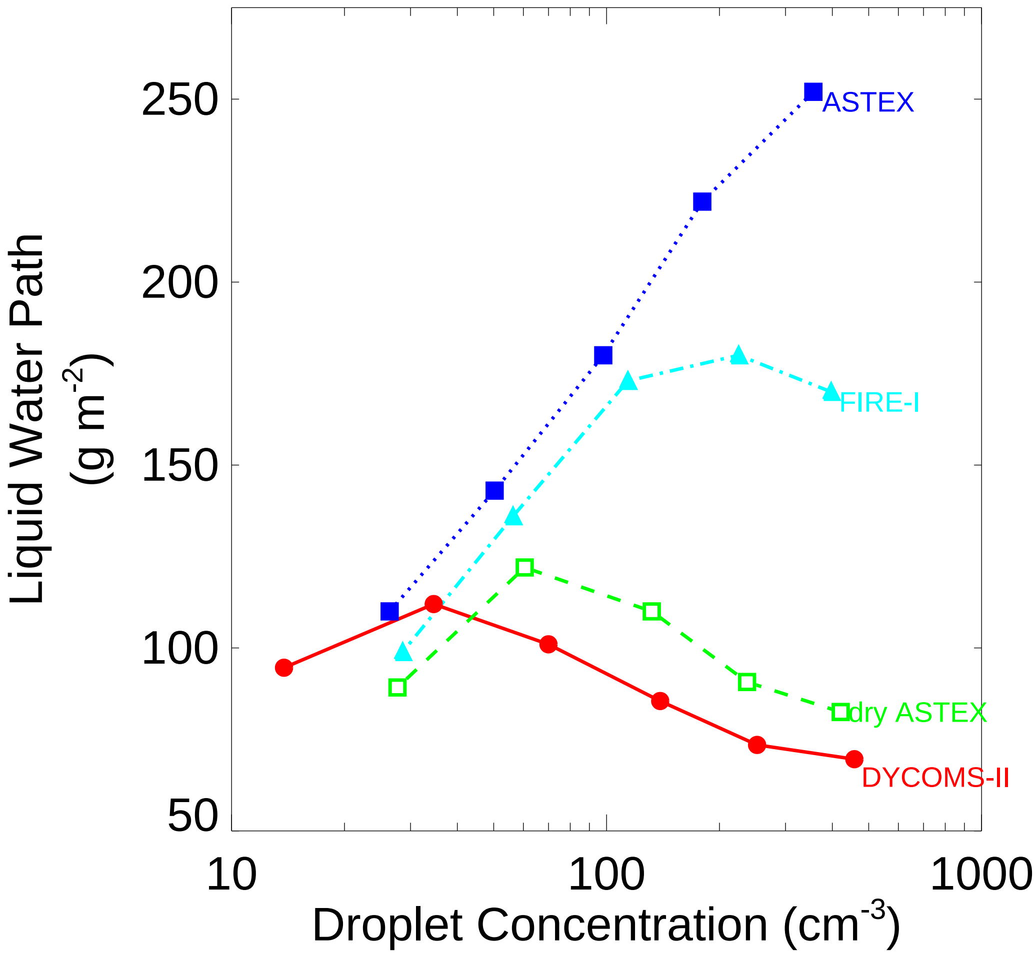
- Entrainment consistently increases as water sedimentation decreases

- Response of LWP depends on humidity of air overlying boundary layer

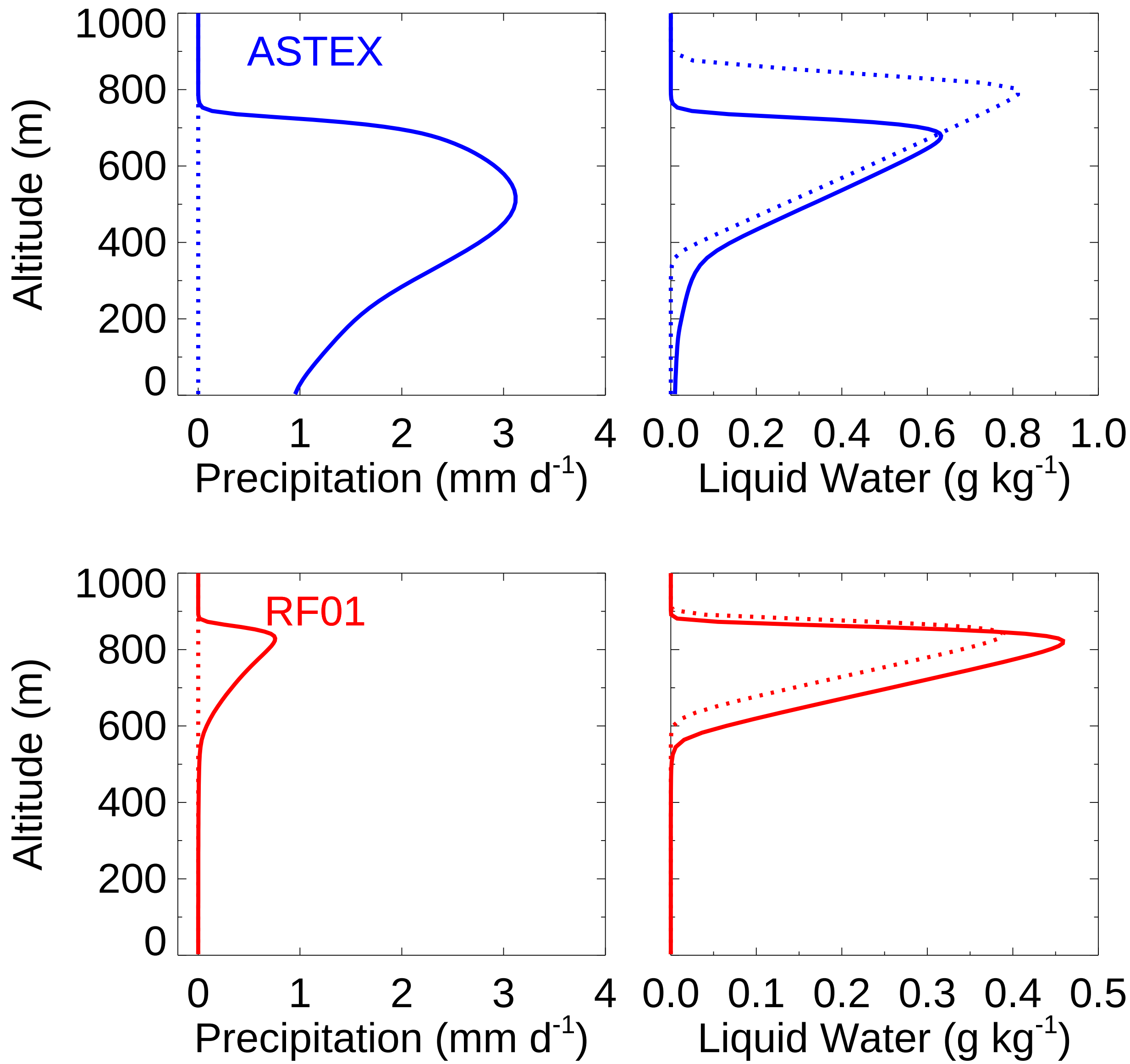
Temperature and Moisture Jumps above Cloud Top



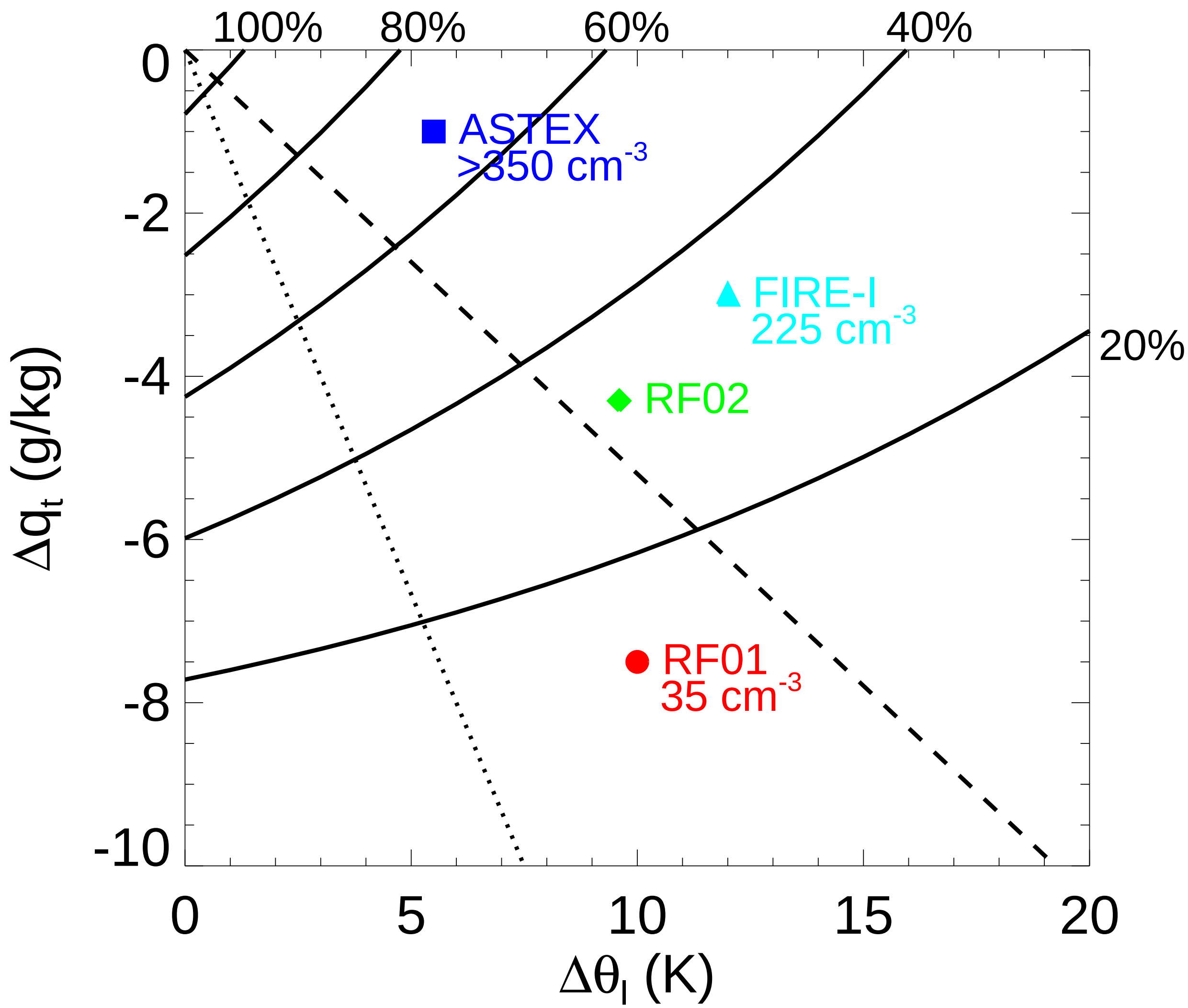
Domain Averages



Response to Suppressing Water Sedimentation



Temperature and Moisture Jumps above Cloud Top

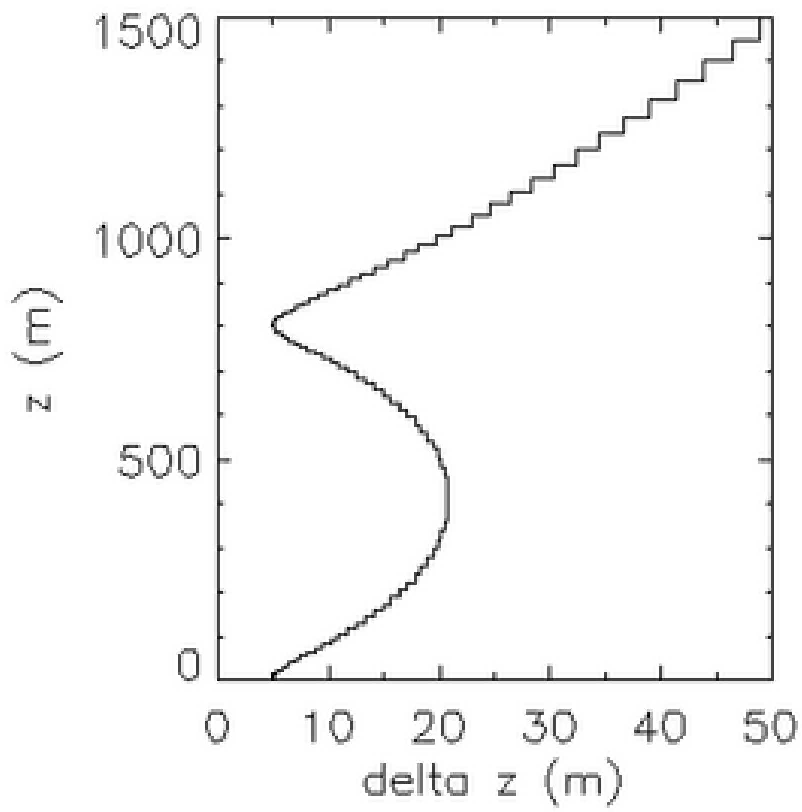


Model Domain

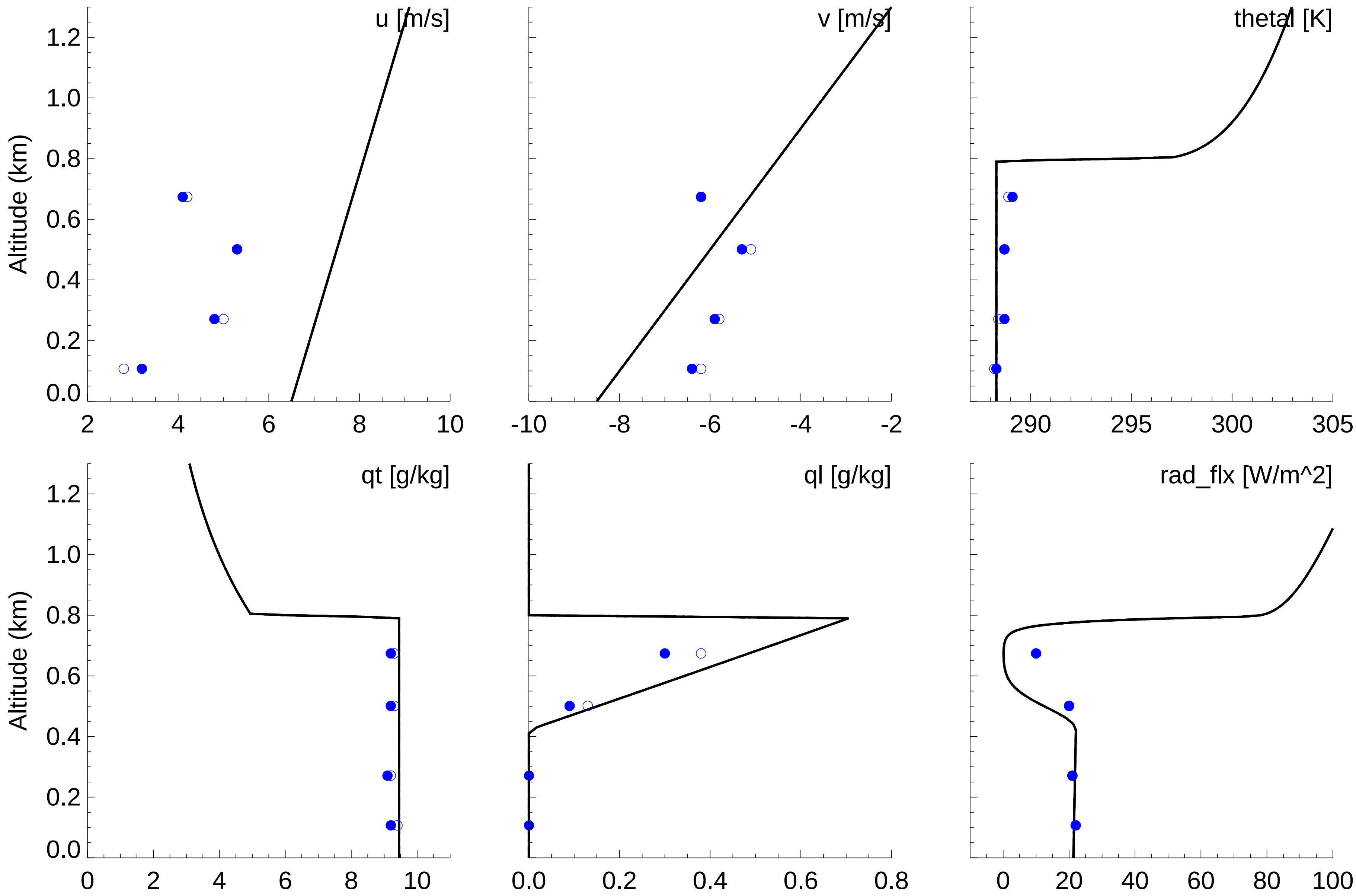
- Wider than past GCSS stratocumulus domains to allow for larger scales of convective organization expected in drizzling regime:

  6.4 x 6.4 x 1.5 km, $\Delta x = \Delta y$ = 50 m, Δz = 5 m near surface and initial inversion

- Those able to use a stretched grid requested to use specified grid, with 96 layers



Initial Conditions and Forcings



Initial Conditions and Forcings

- Radiation: Beer's Law parameterization from previous workshop, which includes heating at cloud base, cooling at and above cloud top (no hook for radiative term in droplet condensational growth equation)
- Subsidence: fixed divergence of horizontal wind (3.76 x 10^{-6} s^{-1})
- Coriolis: geostrophic wind profiles specified (by Bjorn)
- Surface fluxes: fix friction velocity at 0.28 m/s, surface Prandtl number at unity, surface temperature at 292 K, and 100% RH at surface (should be 98% because of salinity)
- Sponge: above 1250 m with time constant of 100 s

Cloud Microphysics

- Leg averages of droplet number concentrations (N, cm^{-3}) within cloudy air (defined by $N > 20$ cm^{-3}):

Flight Leg	Open Cells	Closed Cells
Cloud Top	54 ± 14	60 ± 13
Cloud Base	56 ± 16	80 ± 17

- Fix N at 65 cm^{-3}, if possible

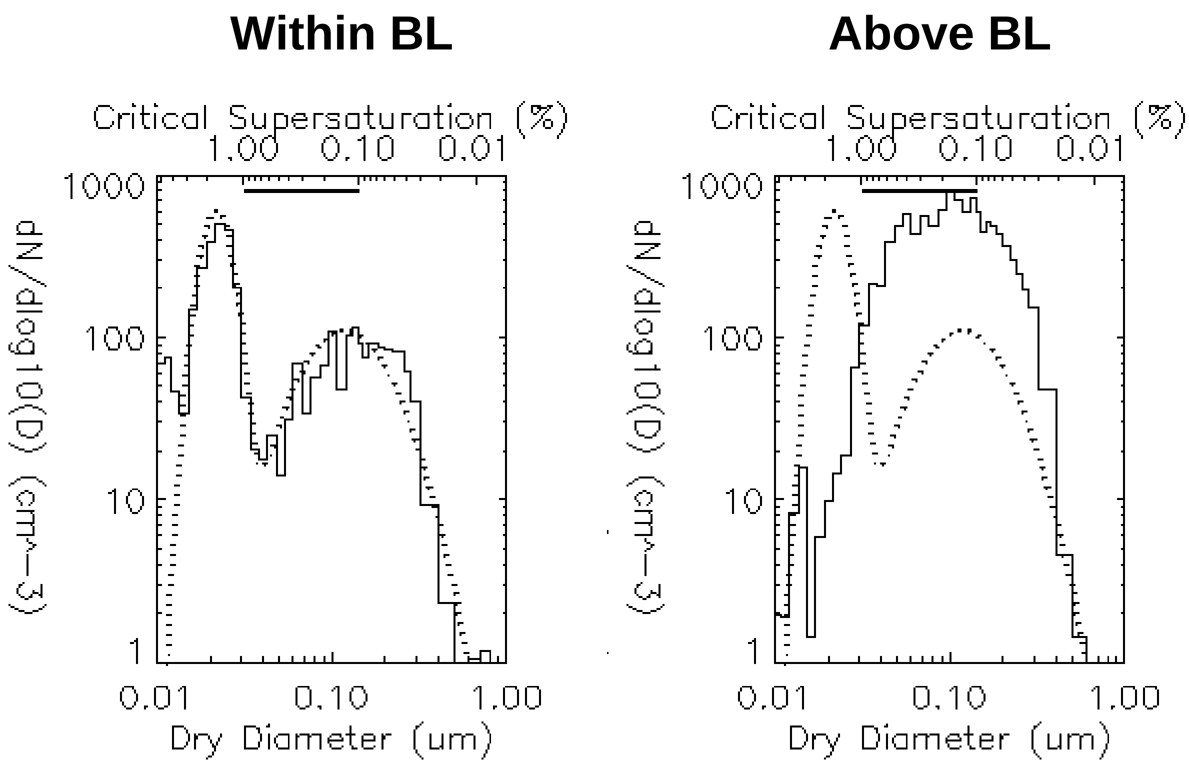
- If microphysics ignores sedimentation of cloud droplets, use integral over log-normal size distribution assuming Stokes sedimentation ($v \sim r^2$):

$$F = c(3/(4\pi N))^{2/3} q_l^{5/3} \exp(5 \ln^2 \sigma_g)$$

where c is taken from *Rogers and Yau (1989)* and σ_g = 1.5

- If unable to fix N, use idealized CCN spectrum based on measurements

Cloud Condensation Nuclei



- Using non-prognostic aerosol, cannot handle vertical variation in context of a BL that is deepening
- Dotted line is idealized bimodal fit for BL aerosol assuming ammonium bisulfate (log-normal, not a power law)
- Supersaturation for droplet activation specified to not to exceed 1% during first hour

Model Descriptions

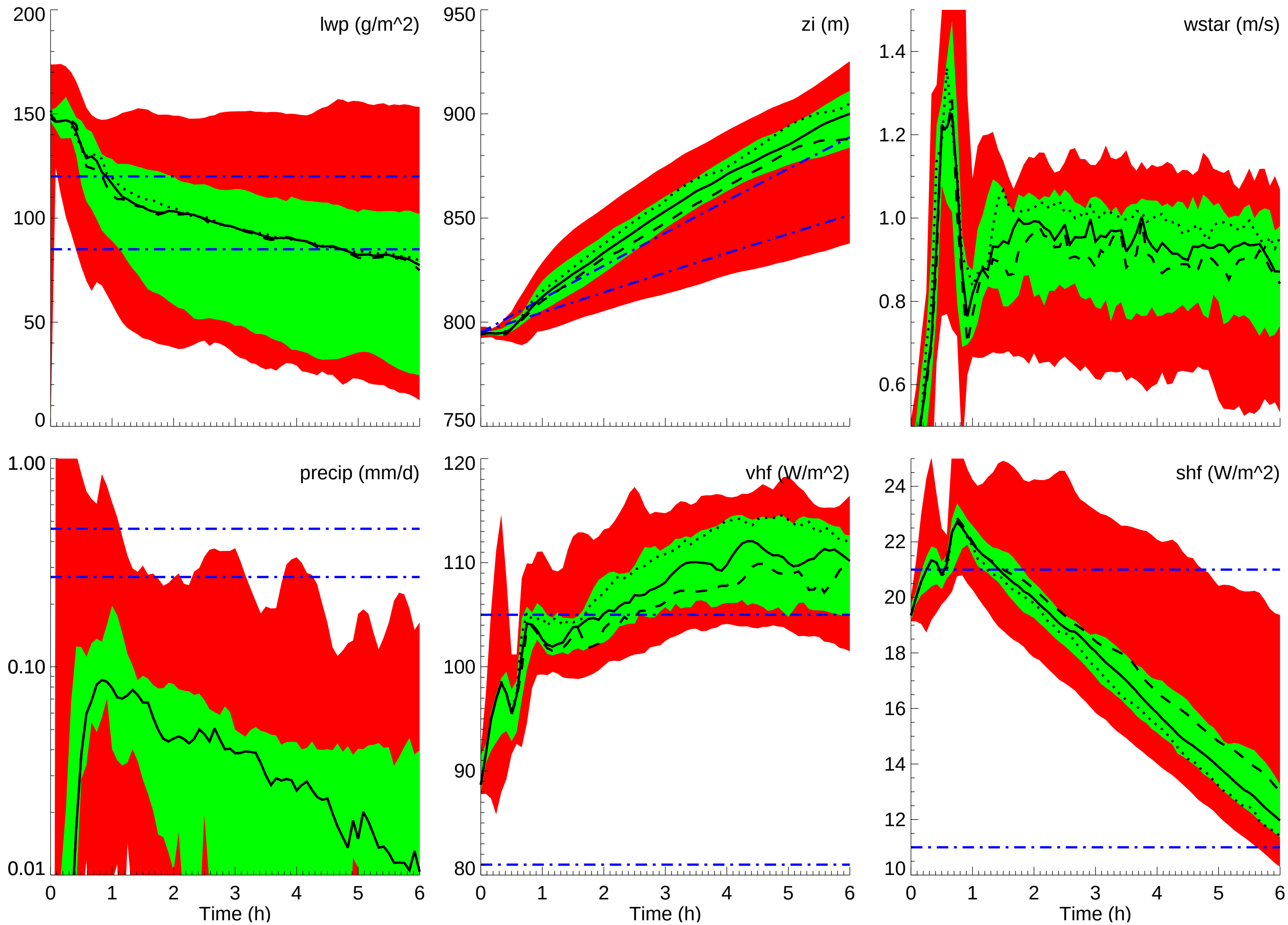
Group/Model Team	SGS Model	Precipitation Microphysics	Cloud Droplet Sedimentation
CSU/RAMS Jiang	Deardorff	2 moment	some
CSU/SAM Khairoutdinov	Deardorff	Khairoutdinov and Kogan (2 moment)	yes
MetO Lock	Smag-Lilly	2 moment	yes
MPI Chlond	Deardorff	1 moment, 2 moment	no
NASA/DHARMA Ackerman	dynamic Smag-Lilly	bin, Wyant et al. (2 moment)	yes
NCAR Moeng	Deardorff	Wyant et al.	no
NRL/COAMPS Golaz	Deardorff	Khairoutdinov and Kogan	
U Redding/LEM Weinbrecht	Smag-Lilly	1 moment	no
UCLA Savic-Jovcic, Stevens		none	
U Utah Zulauf, Krueger	Deardorff	1 moment?	yes
Utrecht-KNMI/DALES van Zanten, de Roode	Deardorff	none	yes
WVU Lewellen	Deardorff w/ partial cloudiness	Khairoutdinov and Kogan	yes

Ensemble Requirements

- One simulation from each group w/ and w/o precipitation
- Precipitation must include warm rain or drizzle, not just cloud droplet sedimentation, and no sedimentation permitted in run w/o precipitation
- Specification must be followed for both simulations
- Nine groups satisfied these constraints:

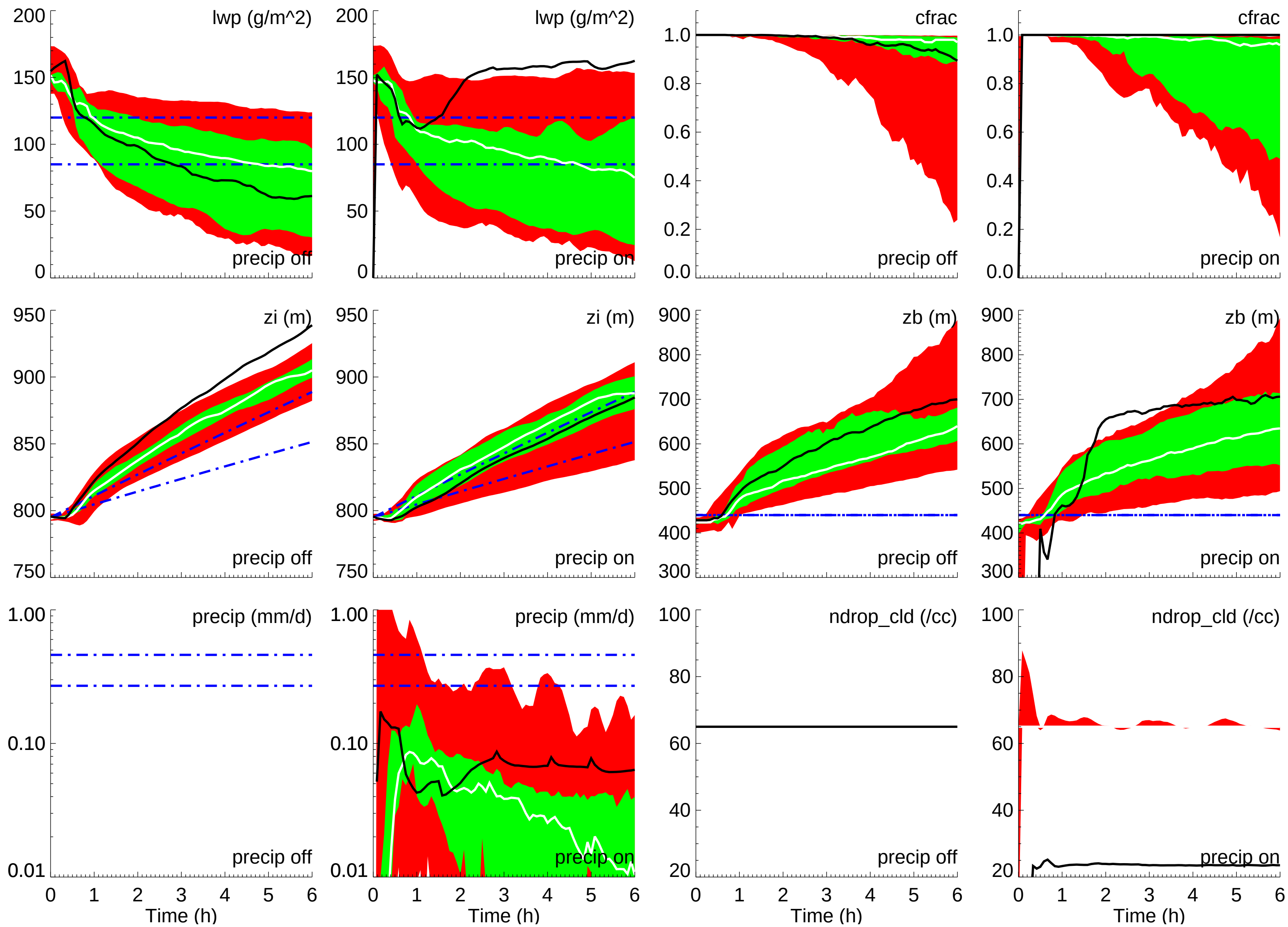
  CSU (Khairoutdinov), MetO, MPI, NASA, NCAR, NRL, U Reading, U Utah, WVU
- Results from 13 groups shown here, just not included in ensemble

Ensemble Time Series



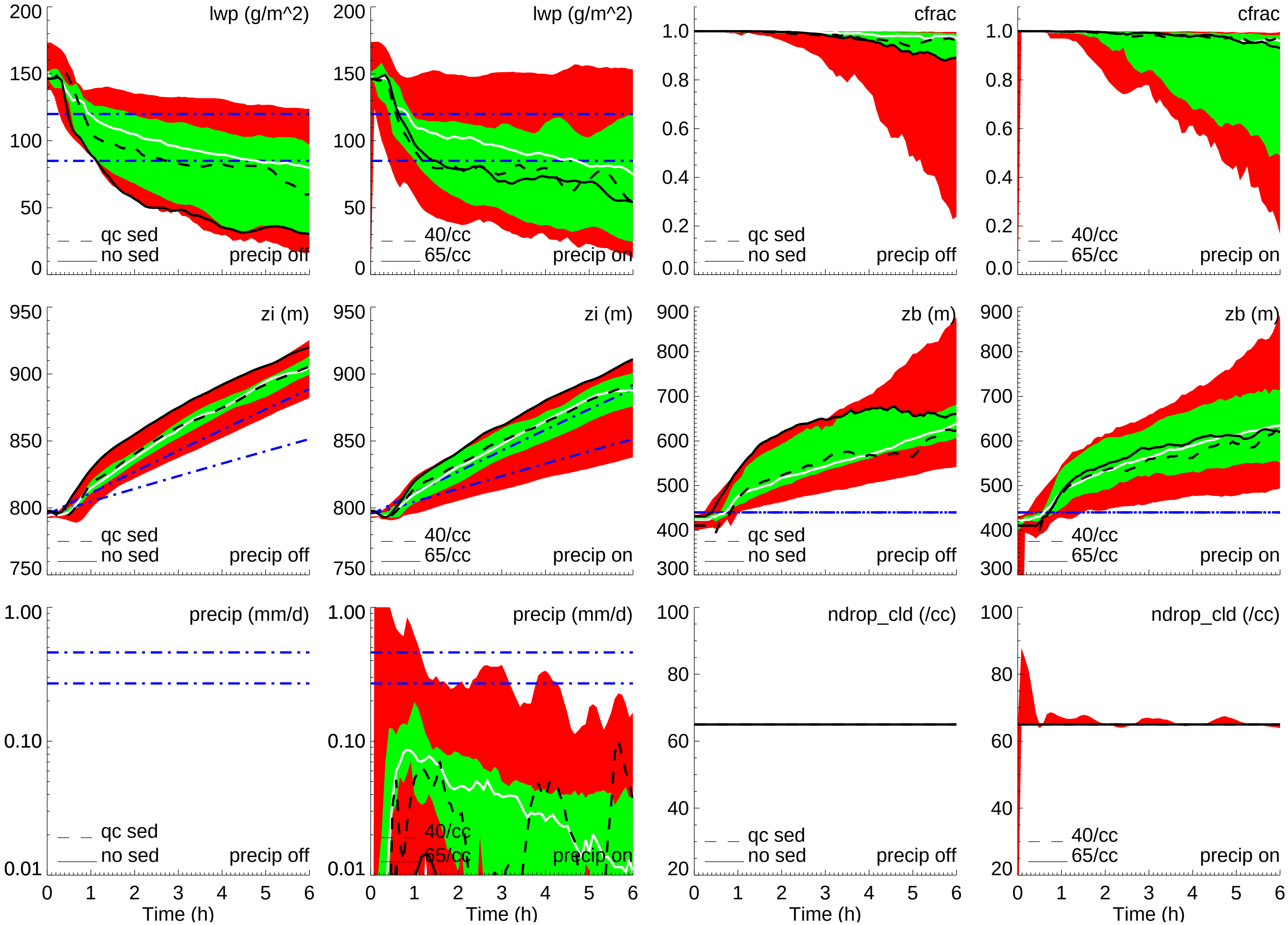
- A bit low on LWP and high on entrainment
- Nowhere near enough drizzle, and vapor flux too large
- Drizzle decreases entrainment, convective velocity scale (integral of buoyancy flux), and surface vapor flux, but not LWP median

CSU (Jiang)



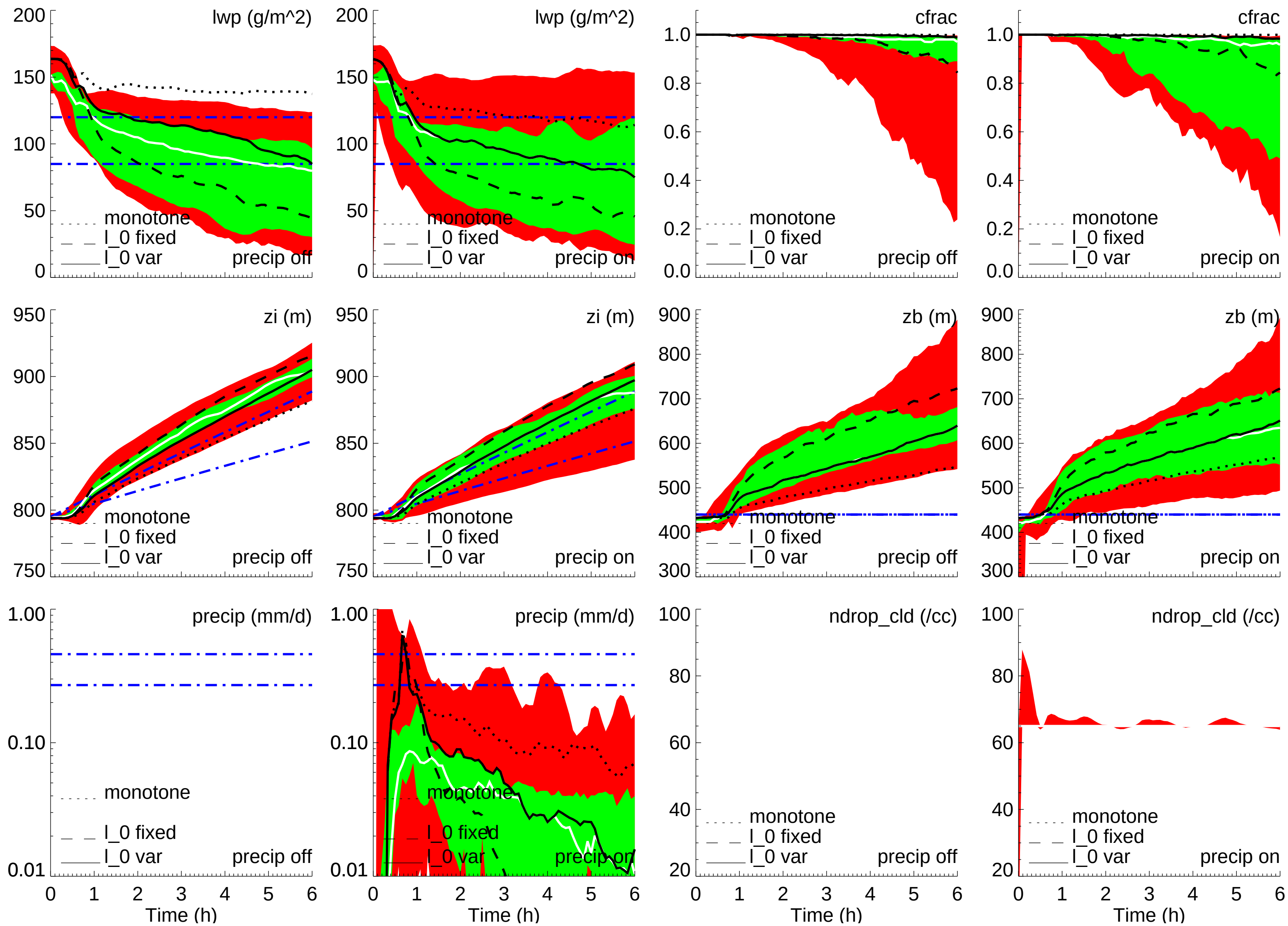
- Includes “giant” CCN, substantially suppressing droplet activation
- LWP nearly triples in response to light drizzle, and cloud cover increases

CSU (Khairoutdinov)



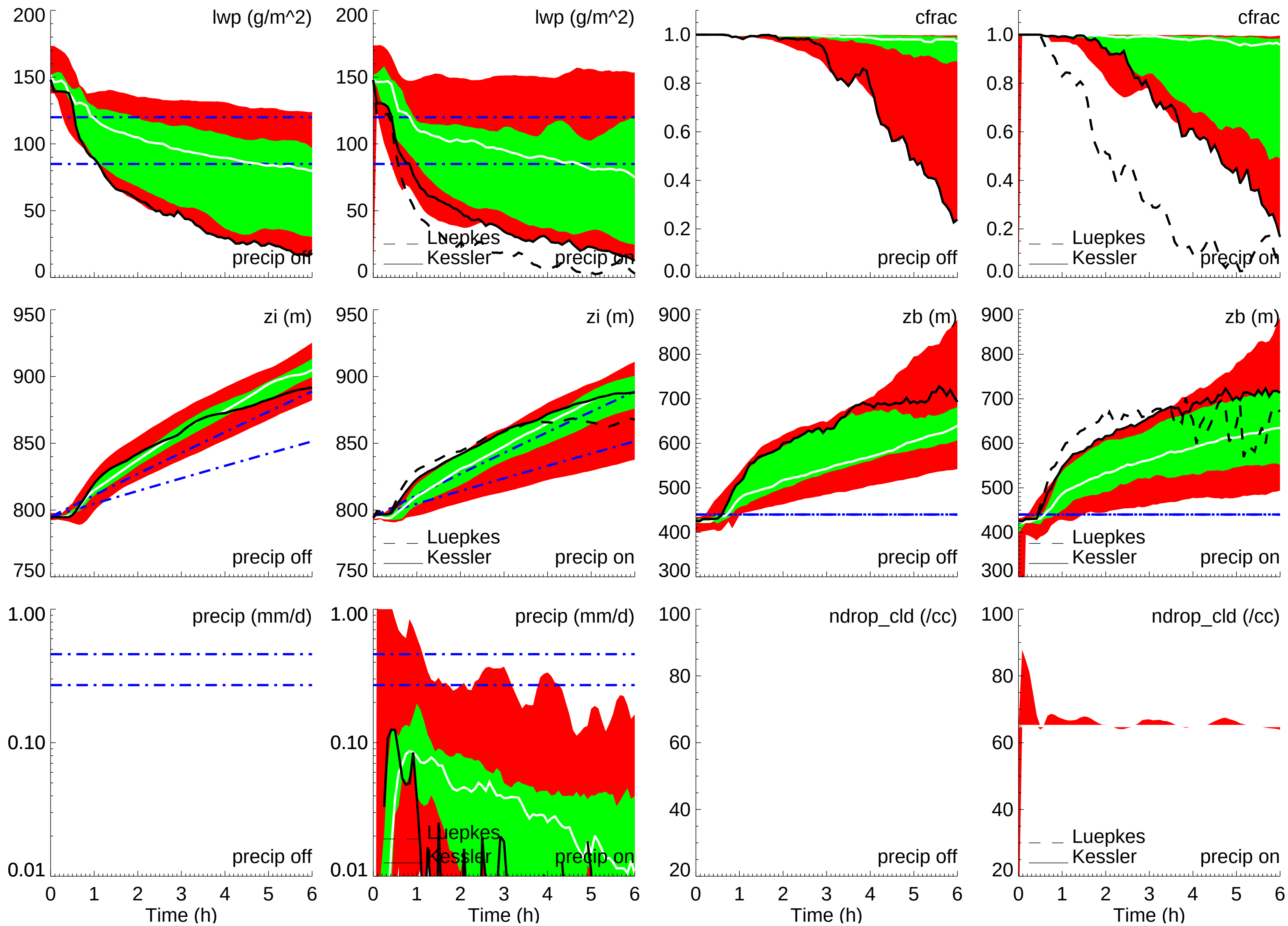
- LWP roughly doubles in response to cloud droplet sedimentation alone
  slightly decreases when drizzle is then included, and then increases when droplet concentrations reduced by 25%

MetO (Lock)



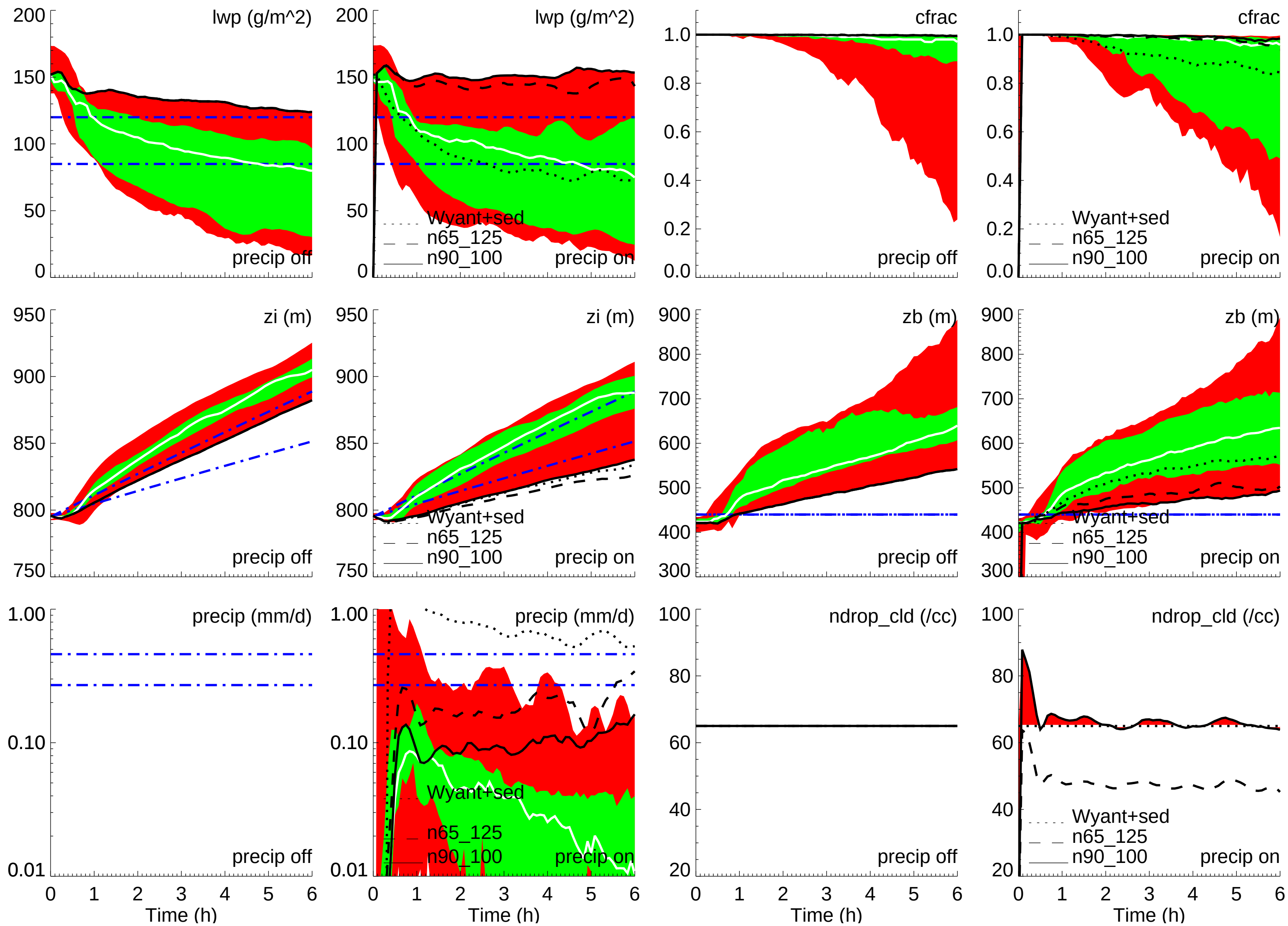
- Variable mixing length in SGS model diminishes entrainment and doubles LWP; monotone advection of scalars furthers both trends

MPI (Chlond)



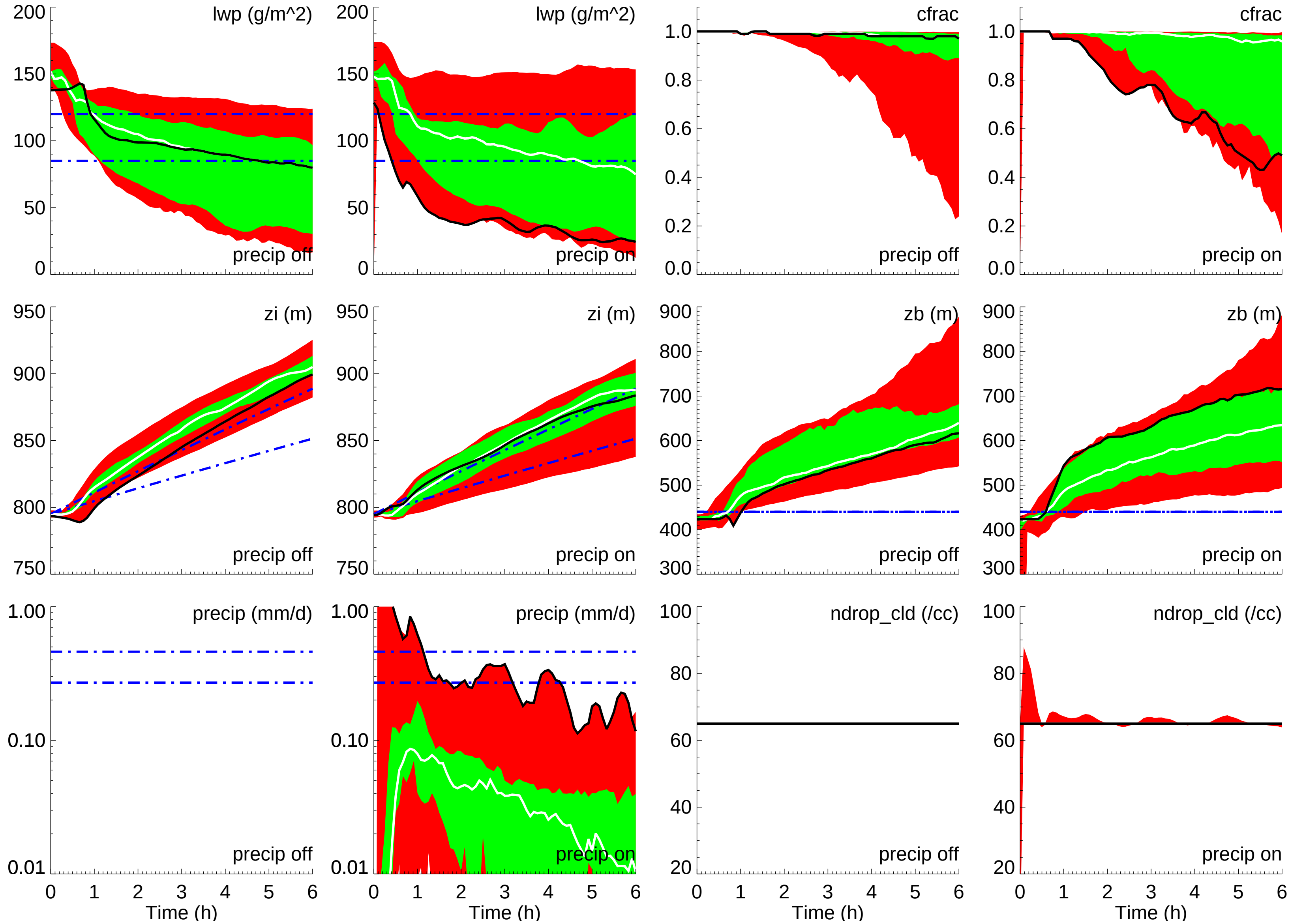
- Thick, overcast cloud is not maintained (w/ and w/o drizzle)
- Entrainment slows as radiative cooling diminishes
- One-parameter (Kessler) drizzle scheme has little effect; two-parameter scheme further diminishes LWP and cloud cover

NASA (Ackerman)



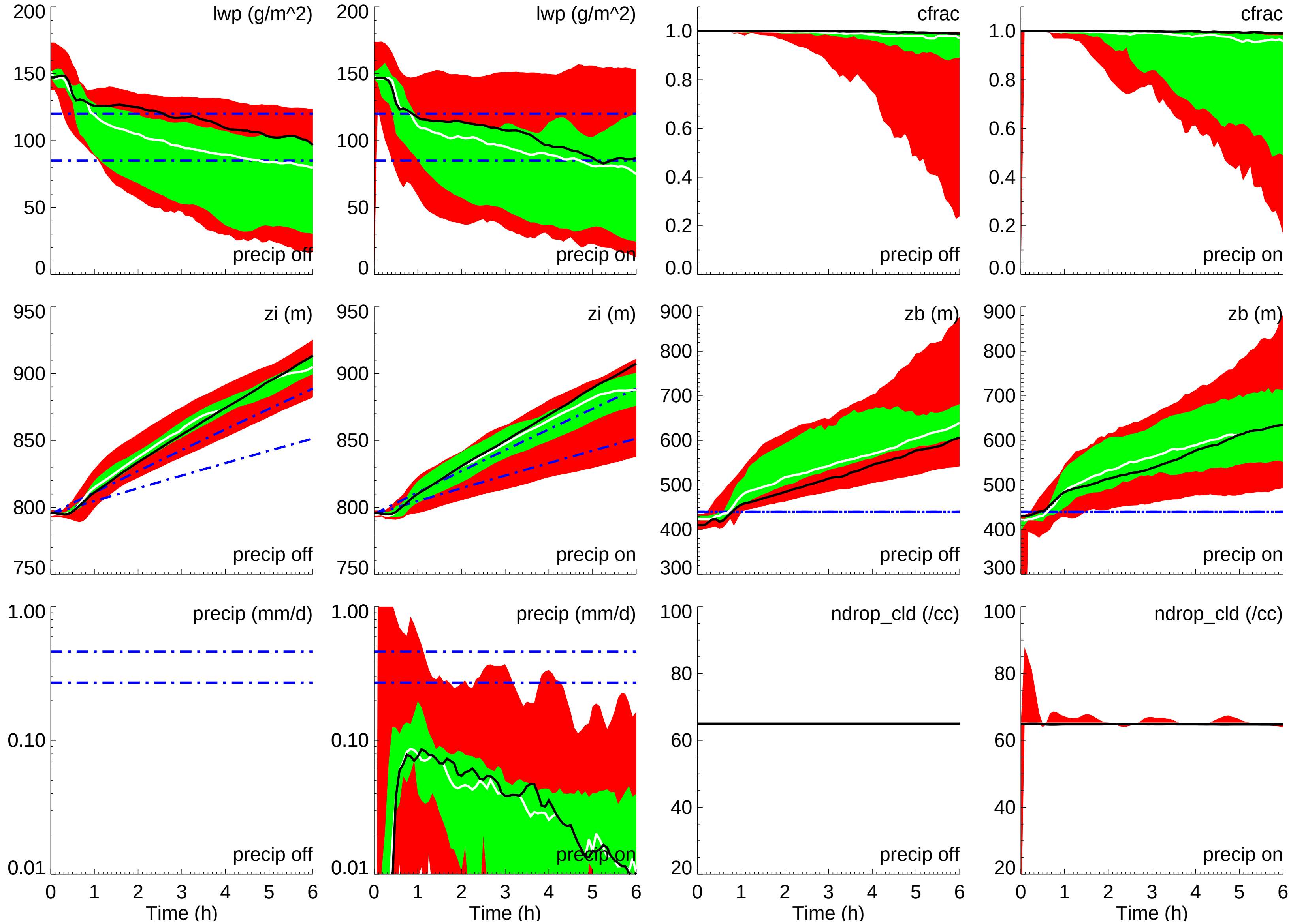
- LWP increases (too much) with bin microphysics (lack radiative effect on droplet growth)
- Precipitation (brackets measurements when parameterized) reduces entrainment too much
- CCN in boundary layer not enough to maintain measured droplet concentration

NCAR (Moeng)



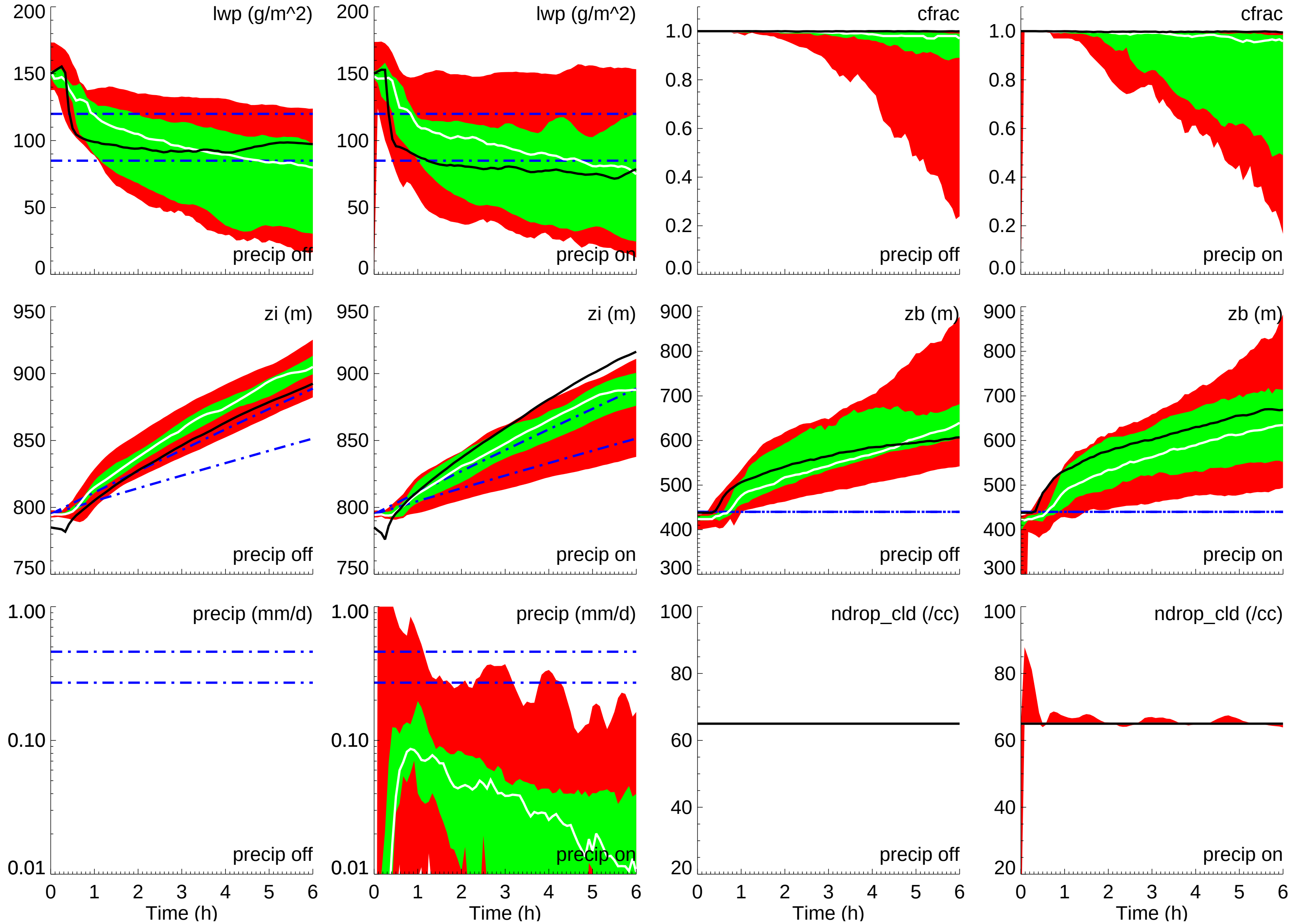
- Precipitation nearly as great as measured, substantially reduces LWP and cloud cover

NRL (Golaz)



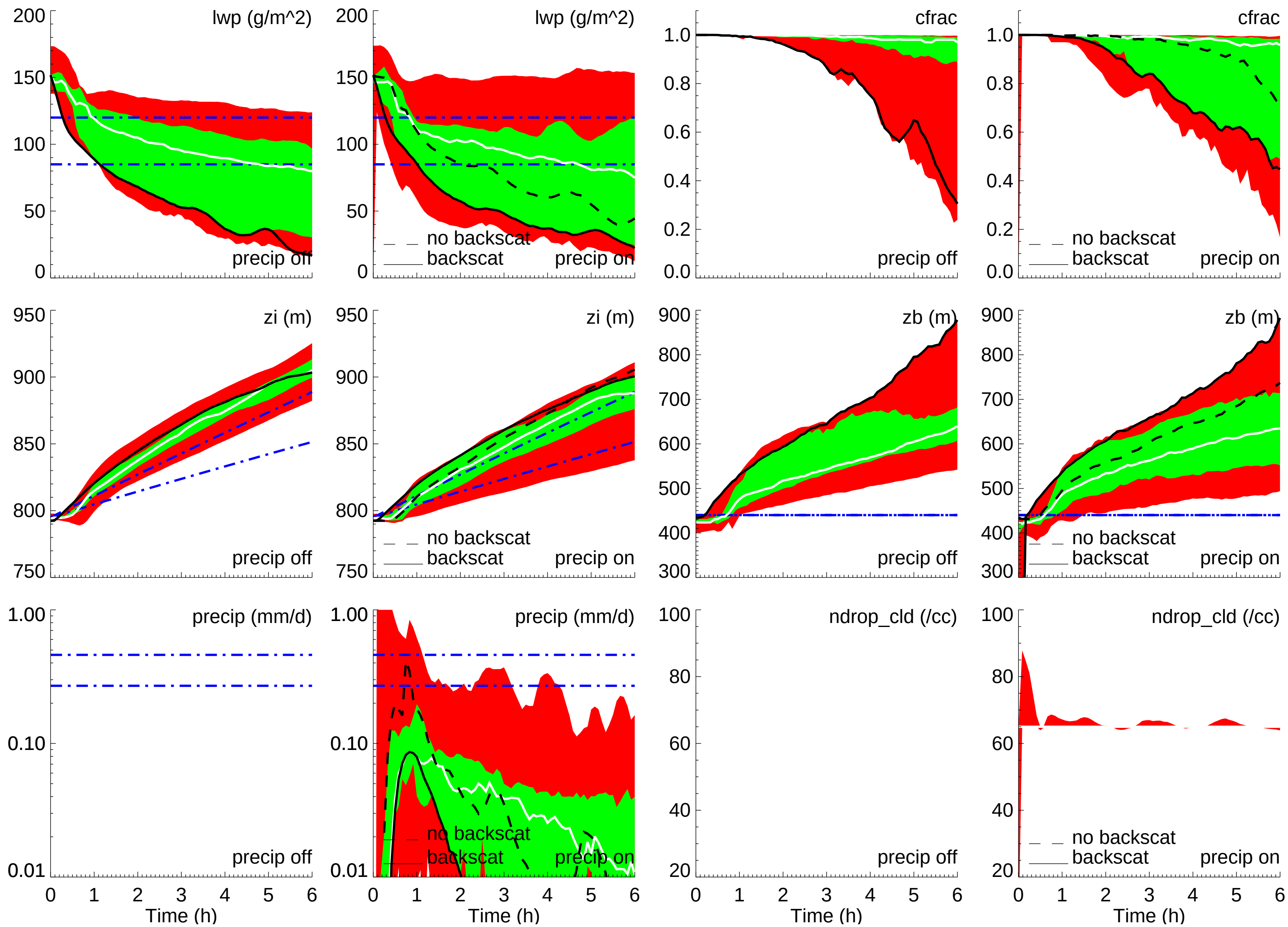
- Precipitation reduces LWP
- Precipitating simulation is archetypical ensemble member

UCLA (Savic-Jovcic and Stevens)



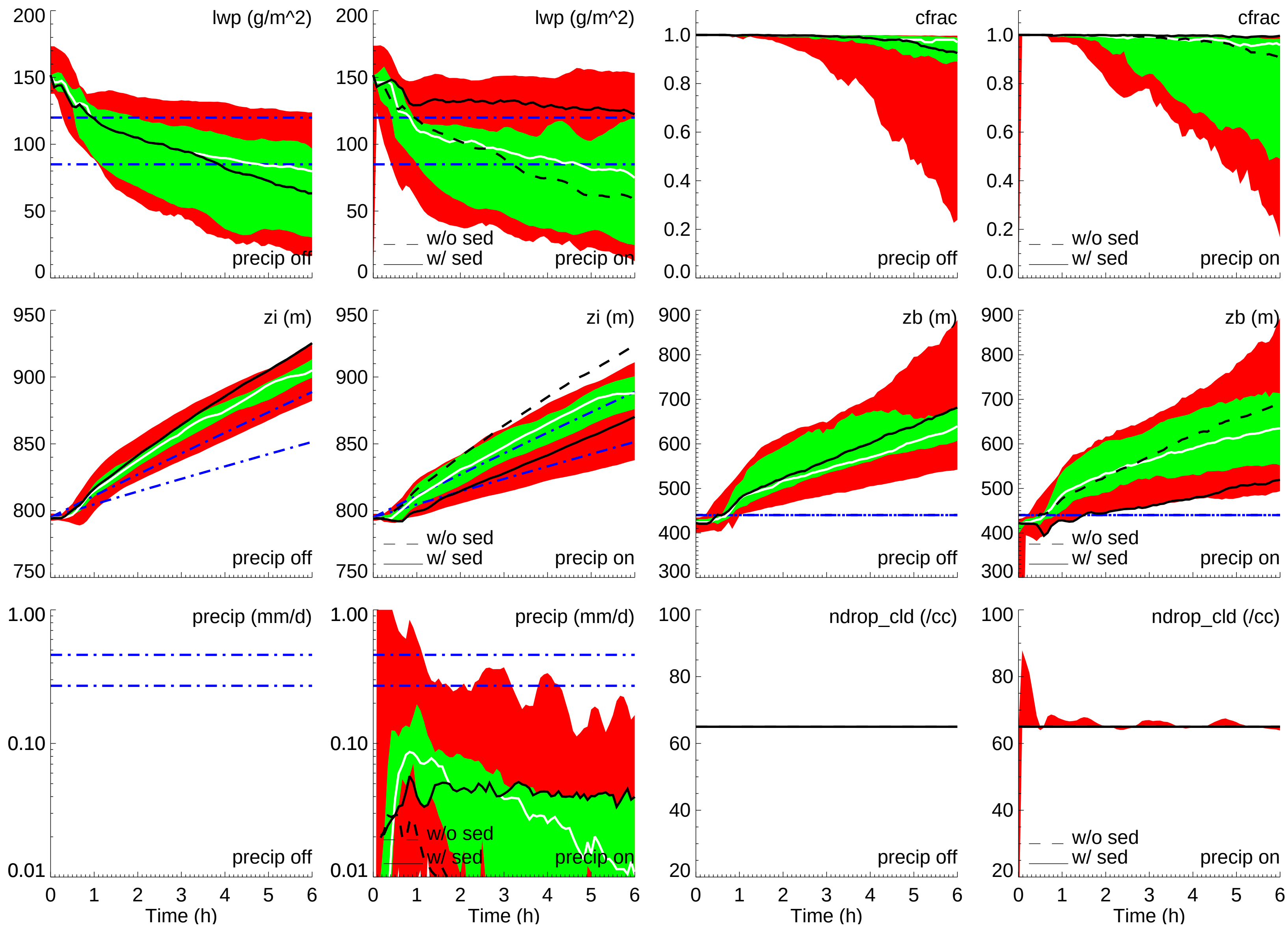
- Precipitation limited to cloud droplet sedimentation, which increases entrainment and decreases LWP

U Reading (Weinbrecht)



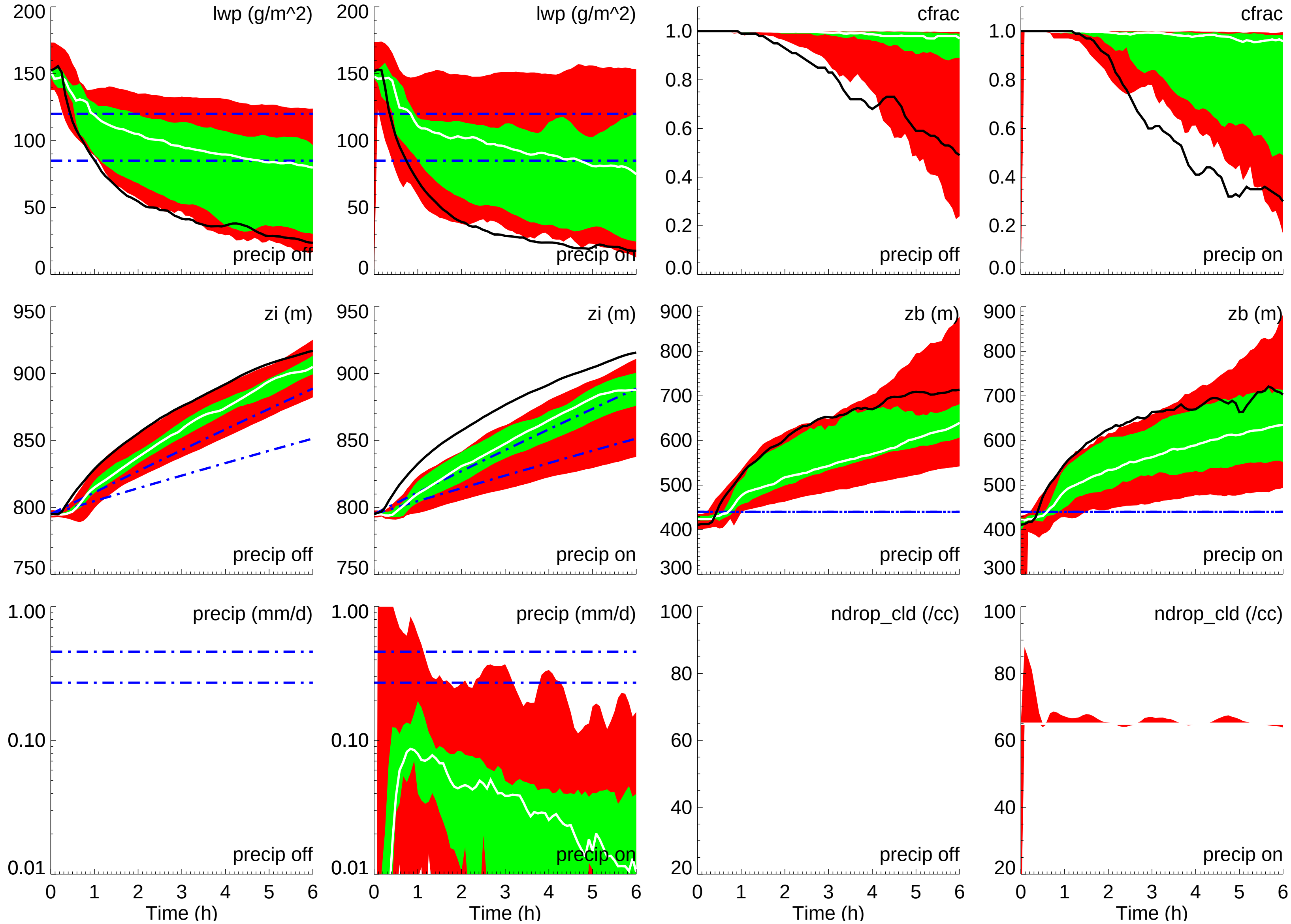
- Precipitation has little effect
- Turning of stochastic backscatter (negative viscosity) increases LWP and cloud cover

U Utah (Zulauf and Krueger)



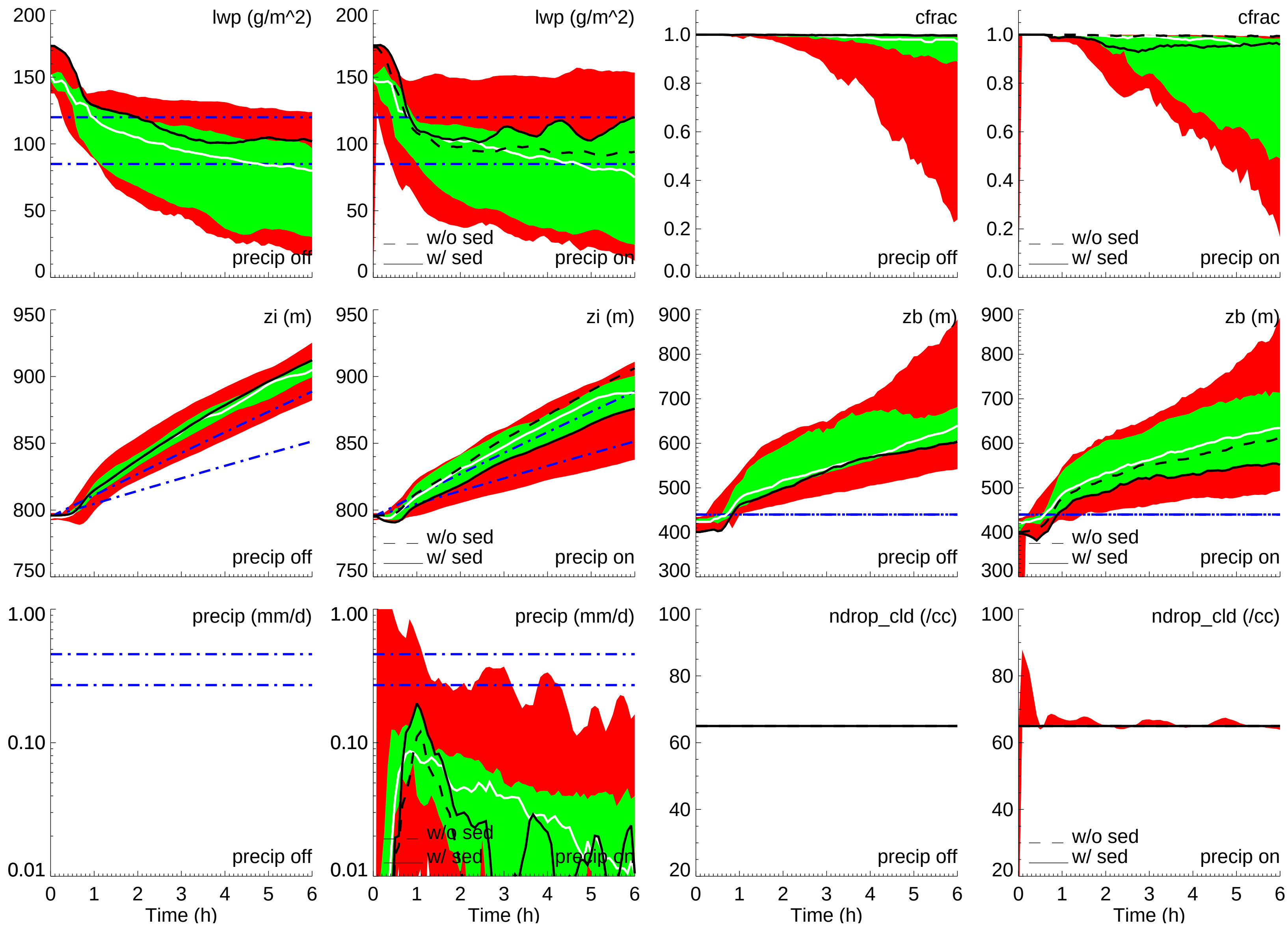
- Precipitation w/o cloud droplet sedimentation has little effect
- Precipitation w/ cloud droplet sedimentation decreases entrainment and increases LWP

Utrecht-KNMI (van Zanten and de Roode)



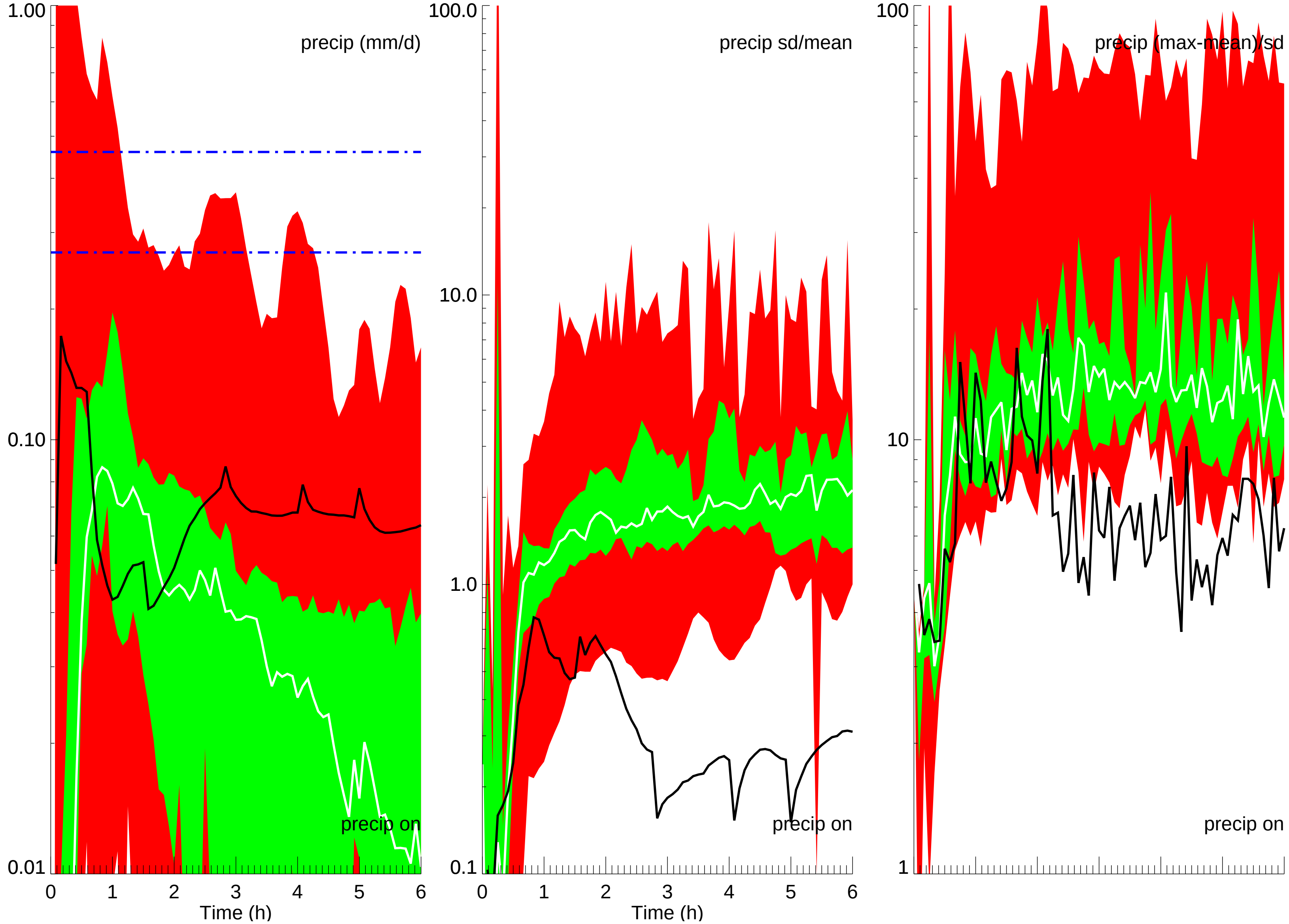
- Thick, overcast cloud is not maintained (w/ and w/o drizzle)
- Cloud droplet sedimentation (not drizzle) decreases LWP and cloud cover

WVU (Lewellen)



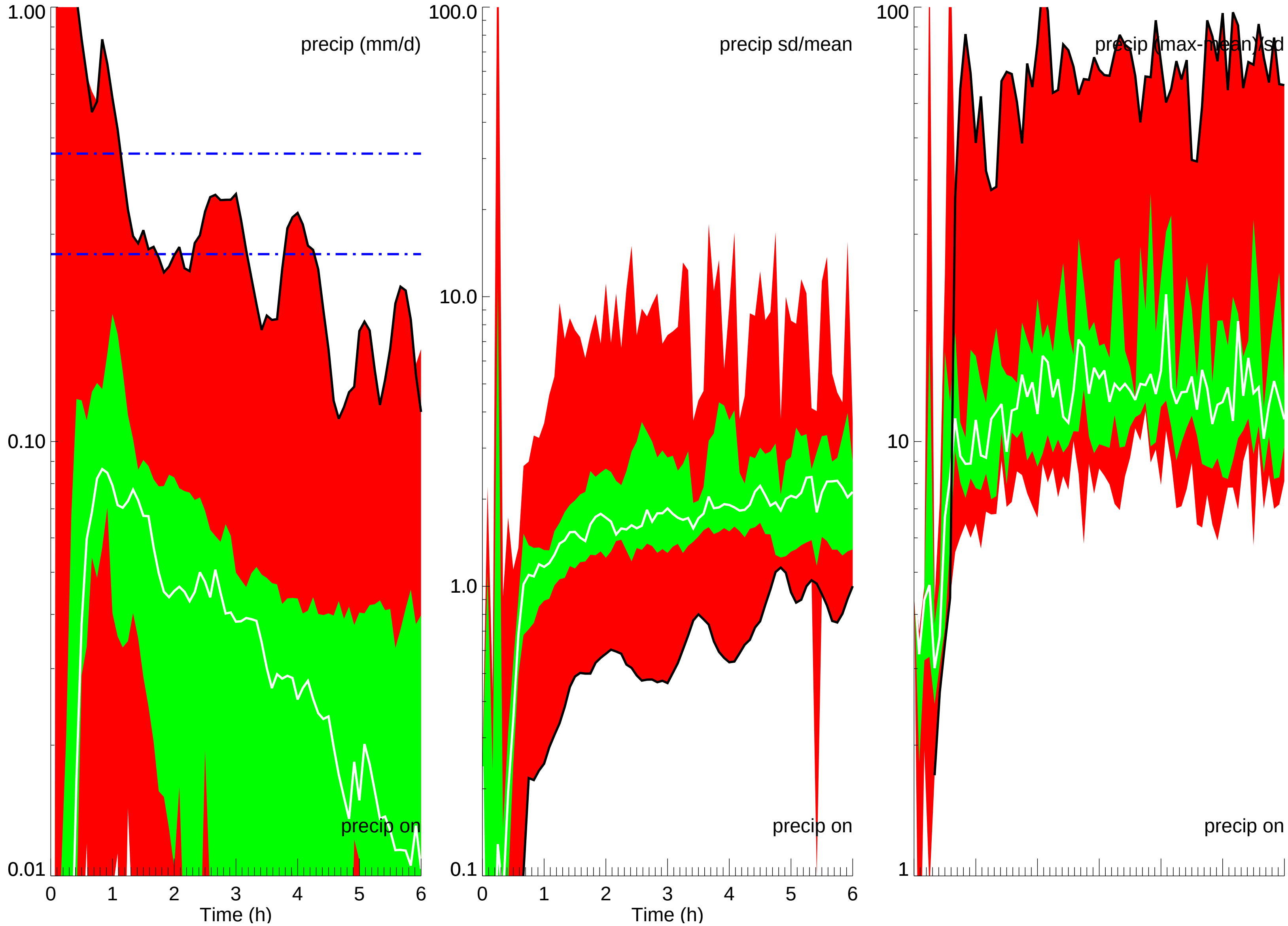
- Precipitation w/o cloud droplet sedimentation has little effect
- Precipitation w/ cloud droplet sedimentation decreases entrainment and increases LWP

CSU (Jiang)



- Particularly narrow dispersion and range of precipitation

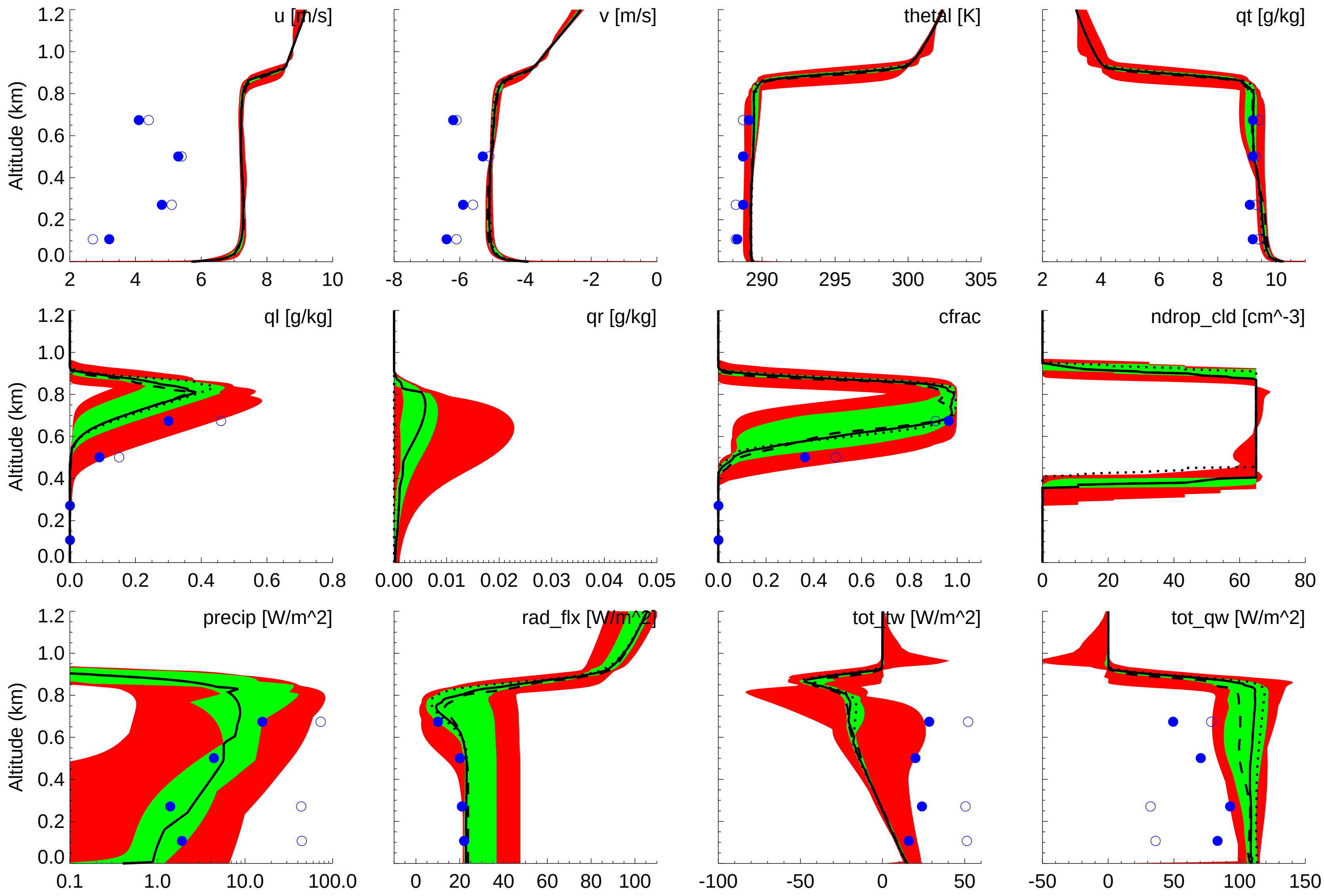
NCAR (Moeng)



- Dispersion low
- Peak values more than 50 standard deviations from mean

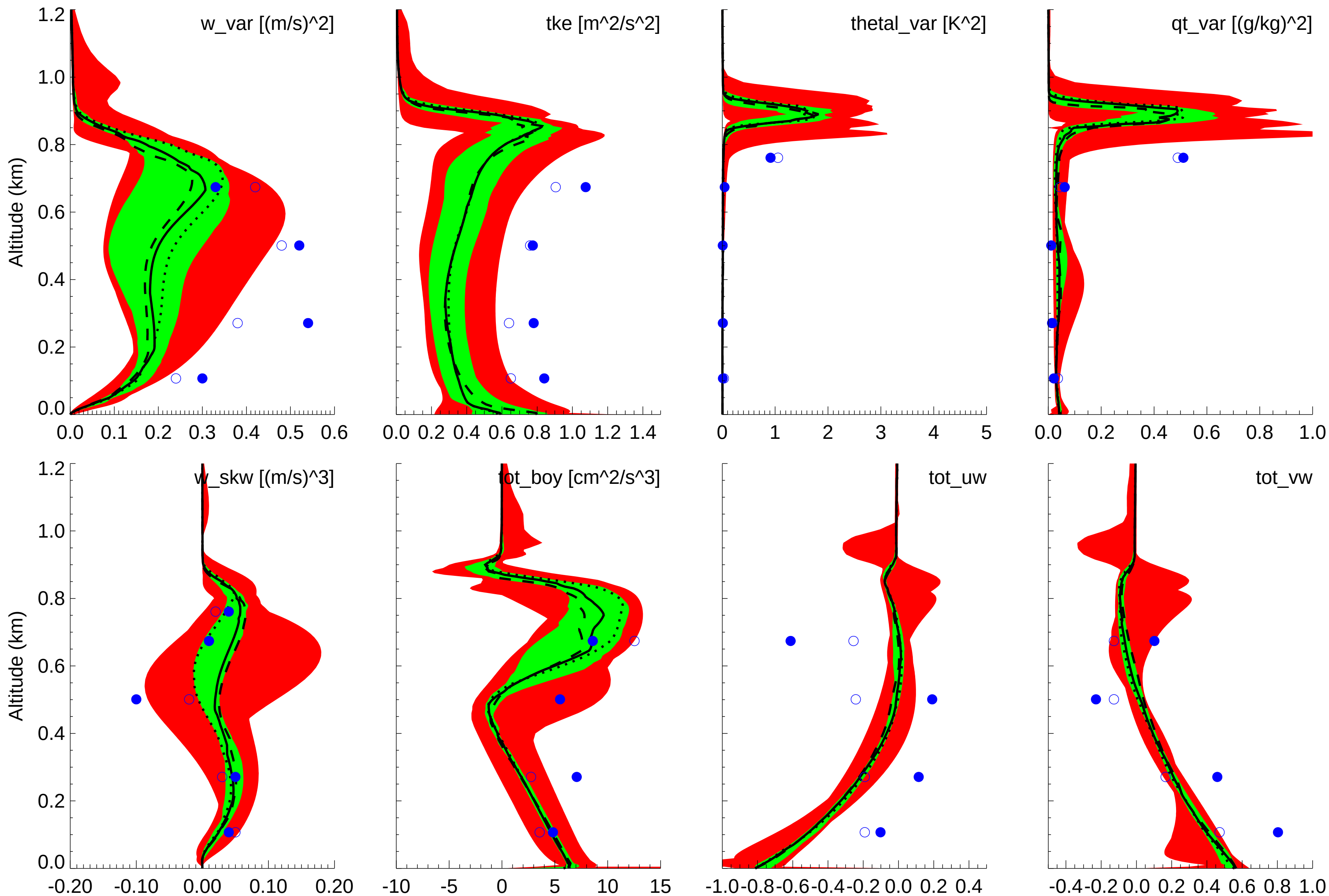
⇒ Precipitation limited to very small area

Ensemble Profiles



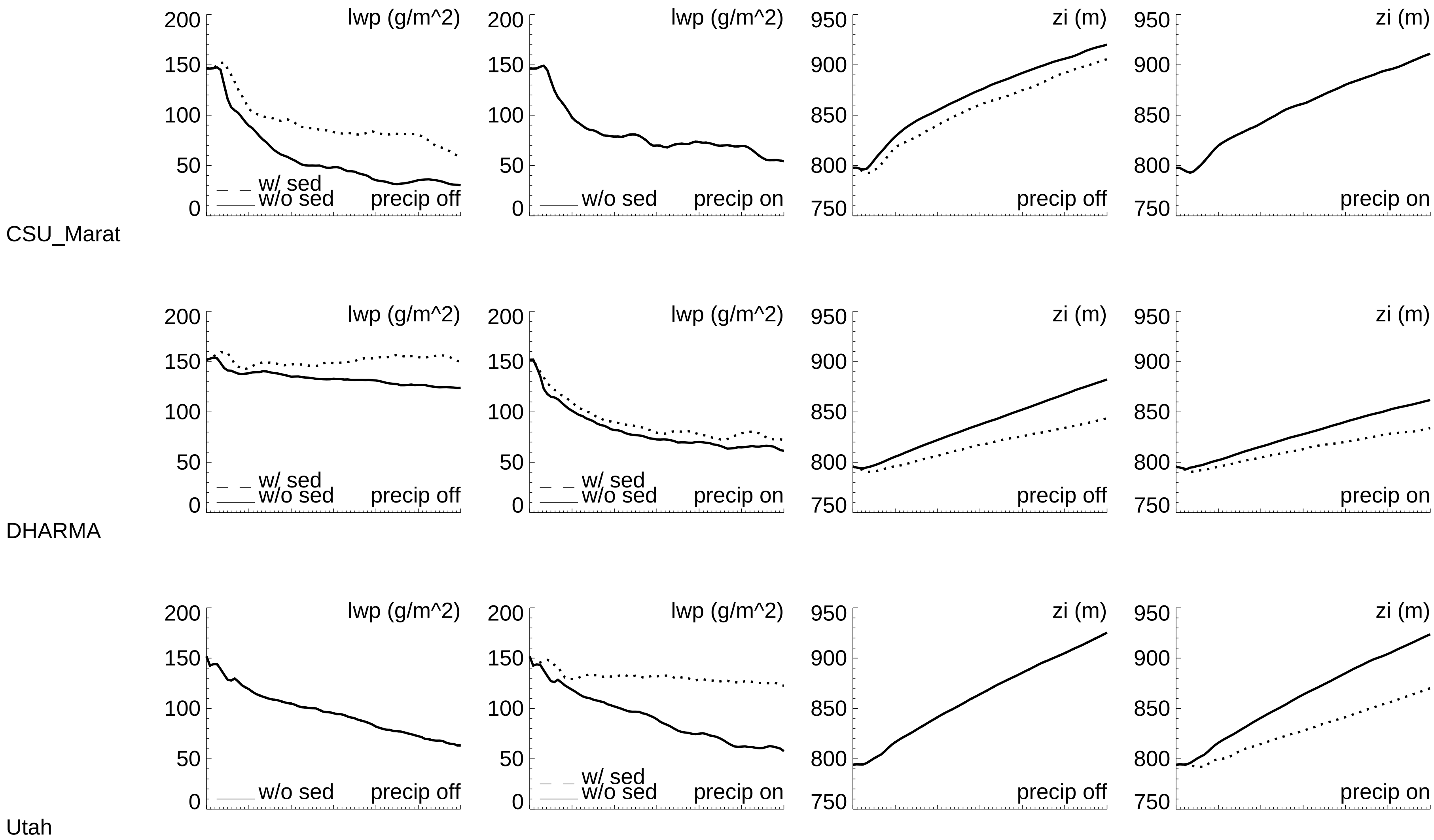
- Geostrophic wind speeds too high, and total fluxes far from measurements
- Median precipitation remarkably similar to average in closed cells
- Mistakenly included an extra member in ensemble for these profiles, but precipitation-induced changes in total moisture flux seems inconsistent with other results, suggesting possible internal inconsistencies in ensemble member(s)

Ensemble Profiles

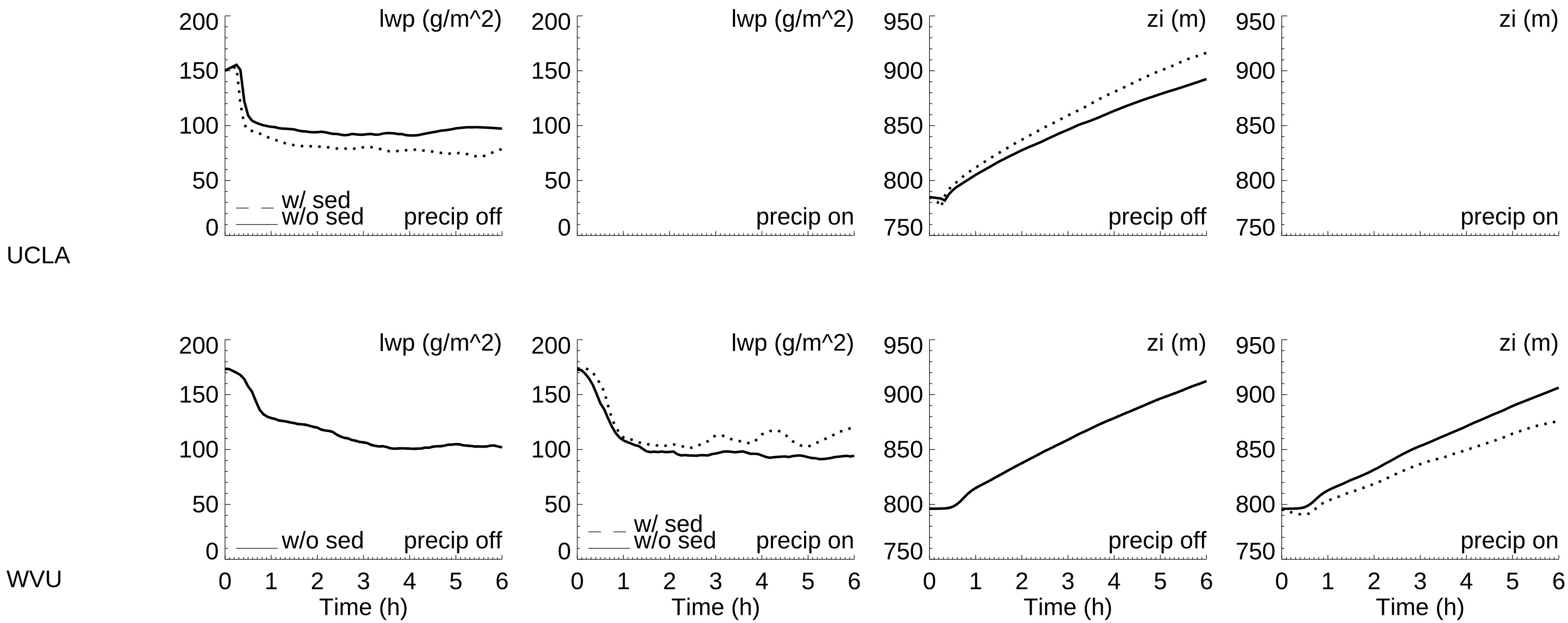


- Precipitation diminishes buoyancy flux and decreases $\overline{w'^2}$, and increases $\overline{w'^3}$ (away from observations)
- Precipitation diminishes buoyancy flux and decreases $\overline{w'^2}$, allow for more vigorous convection by decreasing entrainment through diminished surface fluxes and kinetic energy (?)
- Momentum flux disagreement suggests scales beyond extent of model domain

Response to Droplet Sedimentation

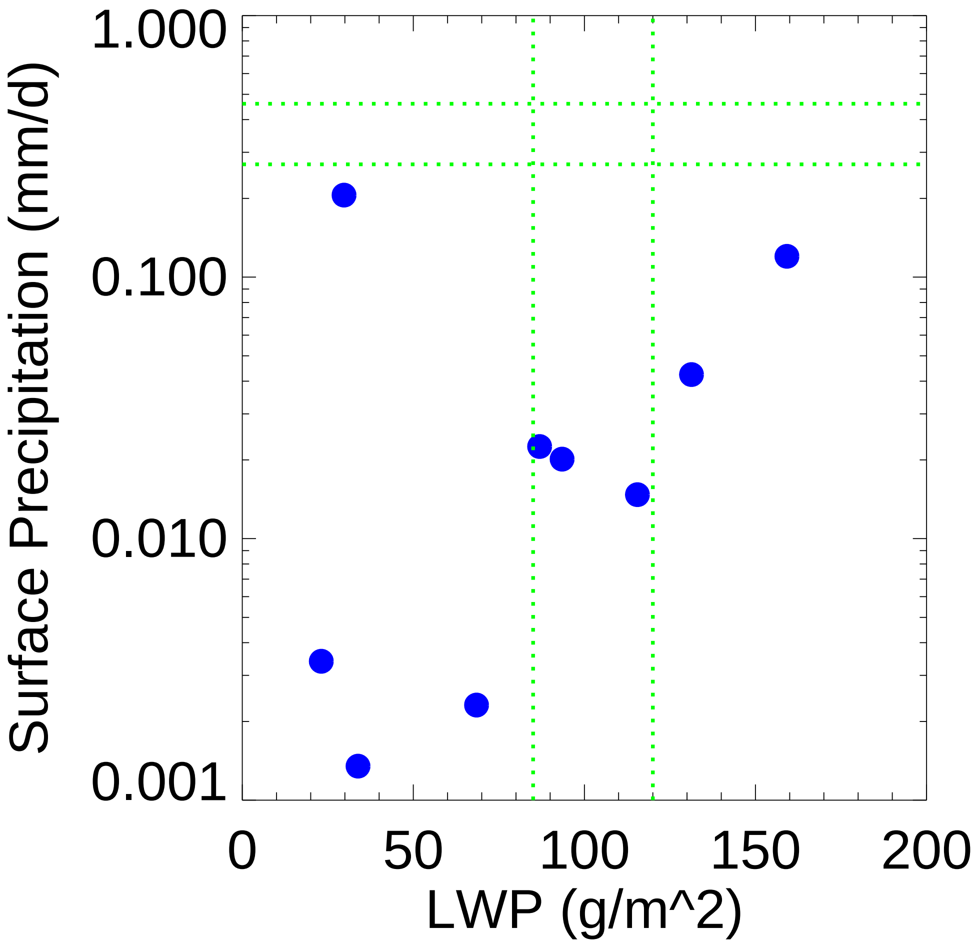


Response to Droplet Sedimentation



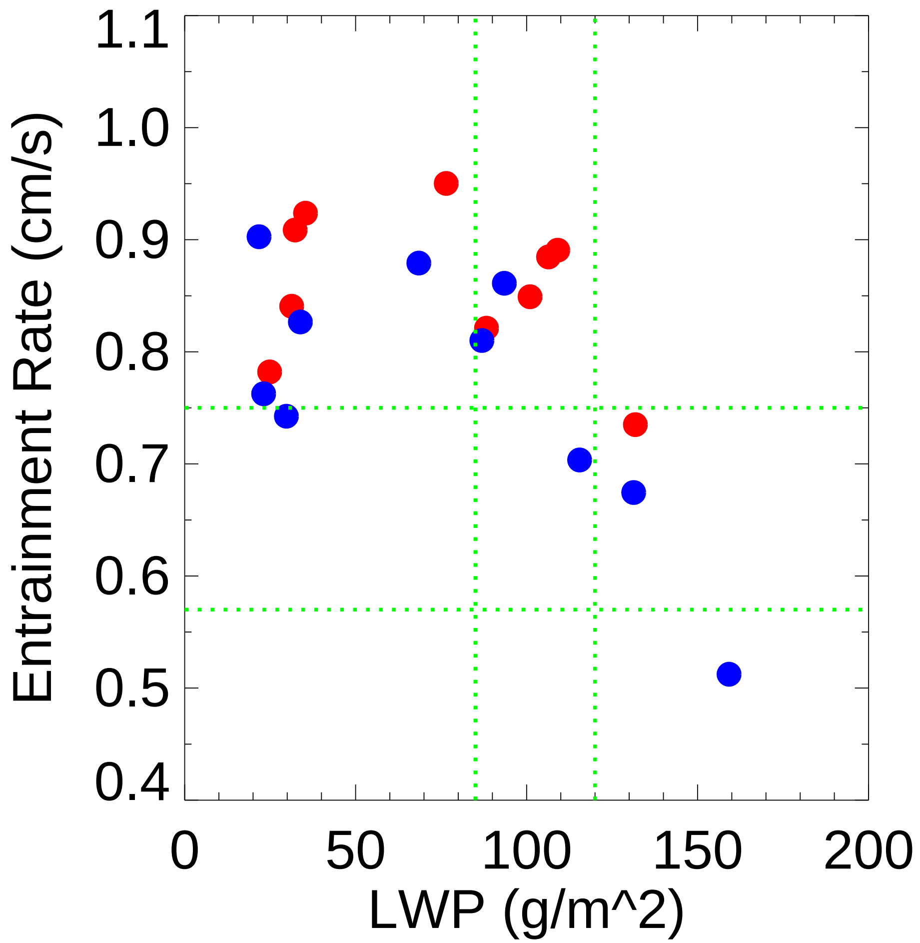
- For all but UCLA, droplet sedimentation results in reduced entrainment and increased LWP, consistent with *Ackerman et al. (2004)*

Trends within Ensemble



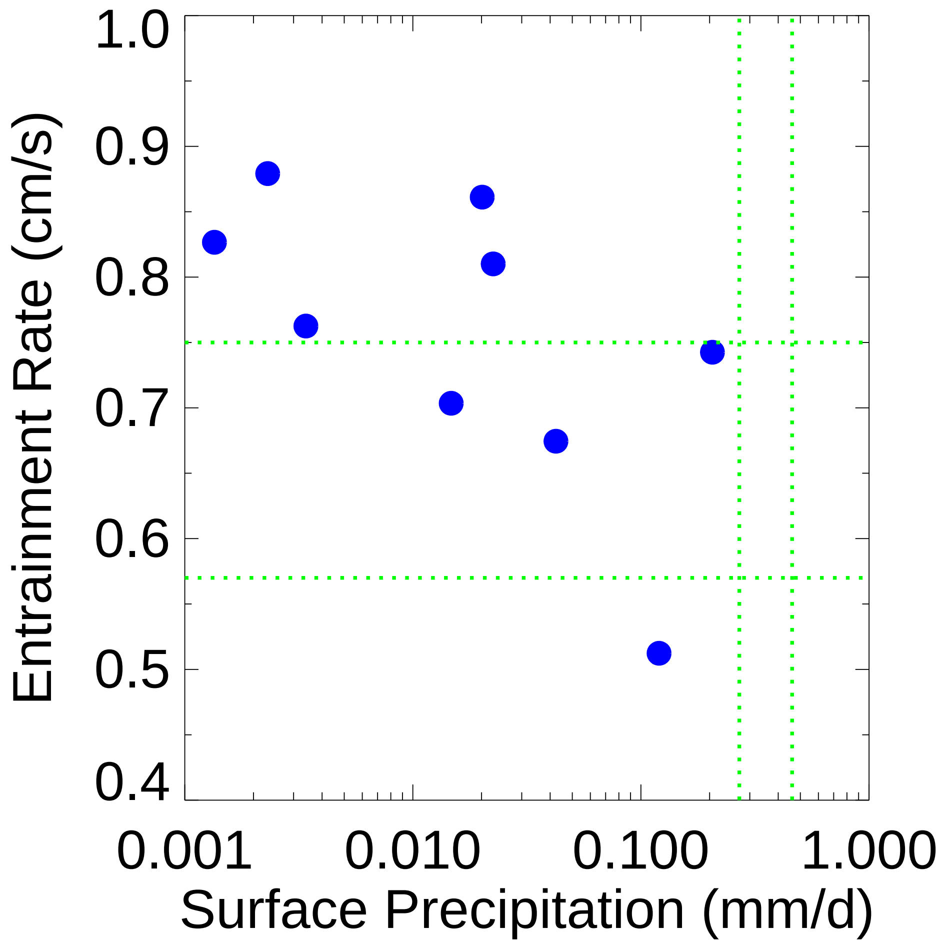
- Precipitation generally increases with LWP, as expected
- NCAR is exception to trend (LWP low and precipitation high)
- Should compare cloud base precipitation trend to H^3N scaling found by *Pawloska and Brenguier (2003)* and *van Zanten and Stevens (2005)*

Trends within Ensemble



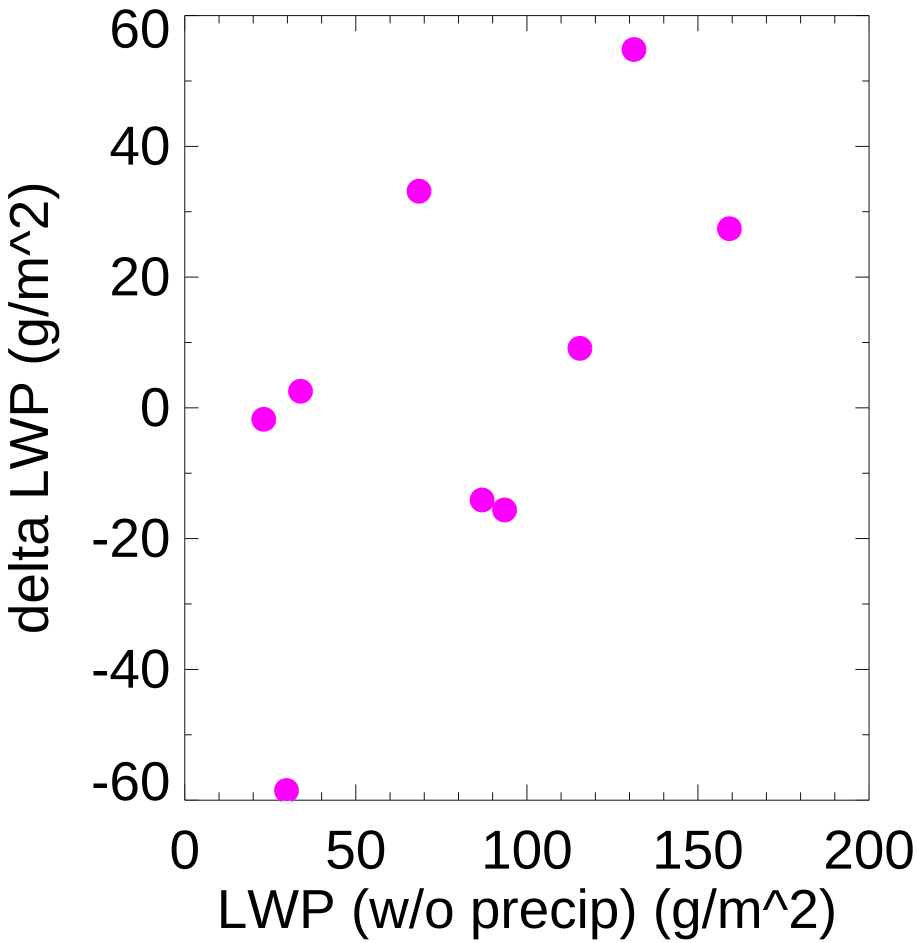
- At low LWP, entrainment tends to increase with LWP (radiative cooling)
- Tendency reverses at higher LWP (entrainment drying)
- Should consider more sophisticated analysis along the lines done by Bjorn for previous workshop

Trends within Ensemble



- Entrainment tends to decreases as precipitation increases

Trends within Ensemble



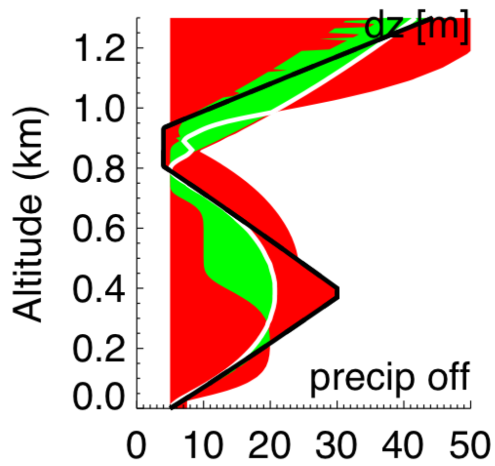
- The greater LWP is (well-mixed, radiatively driven stratocumulus), the more it tends to increase when precipitation is turned on
- X-axis was meant to be LWP w/o precipitation, but I mistakenly used LWP w/ precipitation instead

Summary

- Precipitation generally reduces $\overline{w'\theta_v}$, $\overline{w'^2}$, and entrainment, and increases $\overline{w'^3}$
- Precipitation leads to increases in LWP and cloud cover in some, and decreases in other simulations; ensemble medians of both are unchanged
- Cloud droplet sedimentation generally decreases entrainment and increases LWP
- Tendencies within ensemble hold promise and require deeper thought and analysis
- Any robustness of tendencies should not be considered universal to stratocumulus, since response of BL dynamics and cloud properties to precipitation depends strongly on thermodynamic jumps above BL
- I am deeply grateful for the efforts of all the participants and those providing measurement analyses

Questions and Issues

- Fix geostrophic winds
- For models that don't fix droplet number, scale accumulation-mode number concentration to give average cloud droplet number concentration of $\sim$ 65 cm^{-3}?
- While (if) changing the specification, might as well set RH at surface to 98%
- Any disagreement regarding 3-h averaging period?
- Should variations on grid stretching be permitted?
- If not, should we use WVU's grid above initial inversion?



- Assess significance of neglecting radiative term in droplet condensational growth