Current progress and challenges in understanding aerosols-deep convective cloud interactions

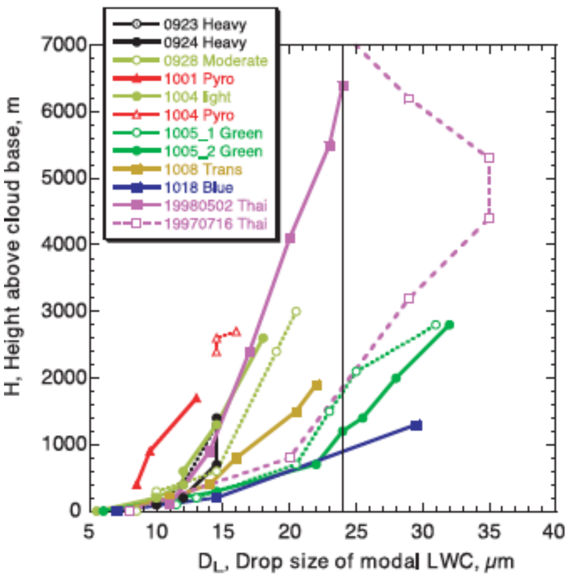
JIWEN FAN

Pacific Northwest National Laboratory

Richland, WA

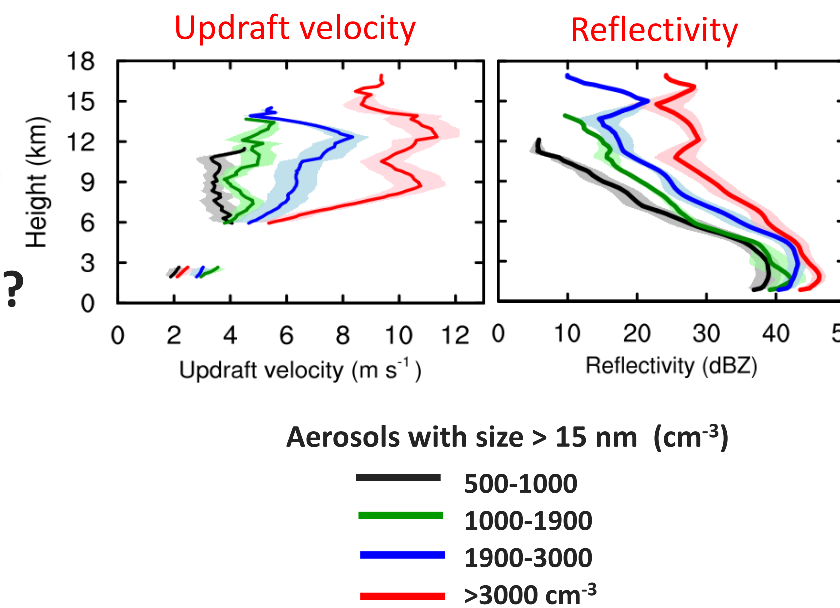
Progresses

Andreae et al. (Science, 2004): **observed** delay in the onset of warm rain for pyro-clouds over Amazon in the dry season, hypothesizing clouds can be invigorated due to the delay.



What we learned?

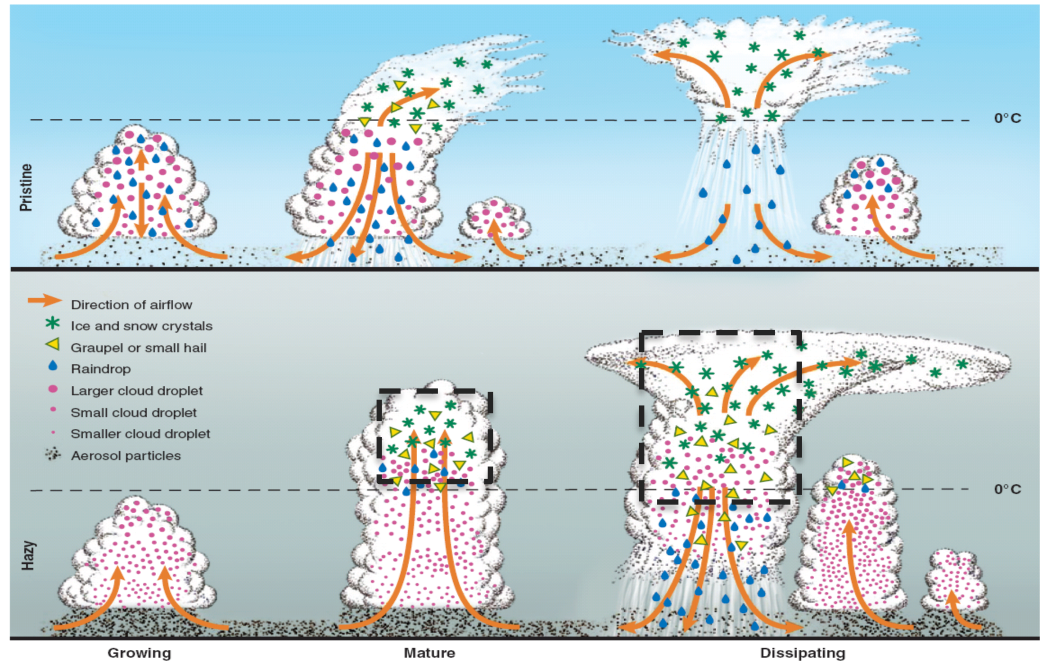
Fan et al. (Science, 2018): observed drastically enhanced updraft velocity and precipitation for the plume-influenced convective storms at the wet season of Amazon, by aerosols smaller than 50 nm through a new mechanism revealed by simulations.



Theory

- **Rosenfeld et al. (Sci. 2008)** did theoretical calculation and a summary for the idea hypothesized in Andreae et al. 2004 and shown in model simulation (e.g., Khain et al. 2005): the concept of "cold-phase invigoration".

By then, we learned for warm-based convective clouds, hygroscopic aerosols can invigorate convection through by more latent heat resulting from freezing of larger amount of cloud water at the cold phase due to the suppression of rain at warm phase.

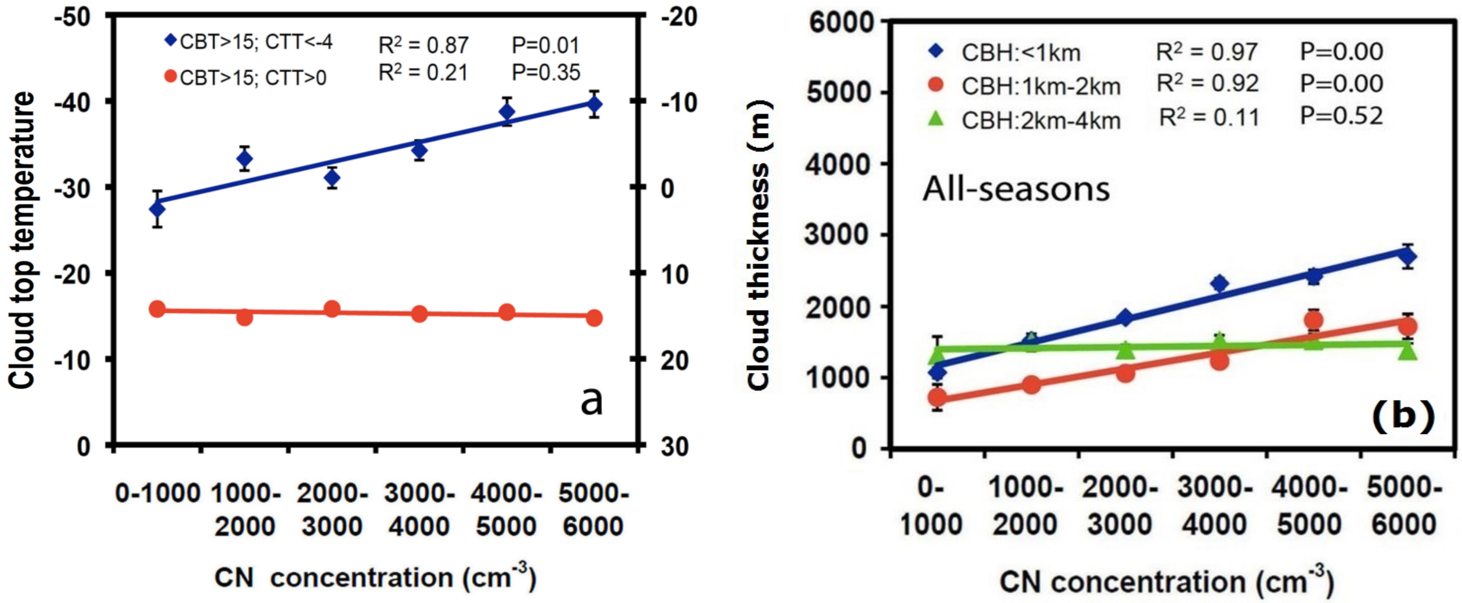


"Cold-phase invigoration"

Aerosol-DCC studies were booming since 2004, with case studies showing meteorological factors such as wind shear, RH, and CAPE would regulate aerosol impacts on DCCs (e.g., Fan et al. 2009, Khain et al. 2009, Storer et al., 2010, van den Heever et al. 2011)

Long-term observations

- **Li et al. (Nature-Geo. 2011)** observed increased cloud top height and cloud depth for warm-based DCCs with the increase of aerosols at SGP

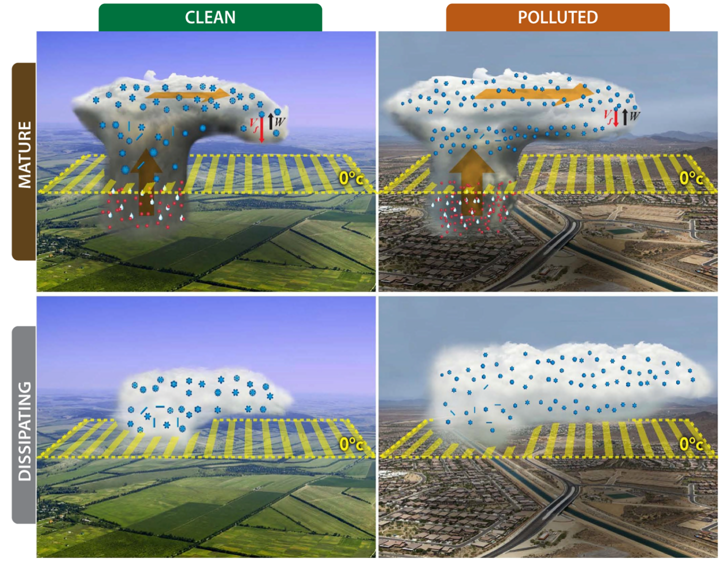


Long-term observations showed a signal of cloud (not convective) invigoration (10-yrs of statistical data).

Long-time model simulations with bin microphysics

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- **Fan et al. (PNAS, 2013)** found that a major mechanism for increased cloud top height and cloud fraction of DCCs over a monthly time period is the microphysical effect, not the convective invigoration.



We learned that 1) cloud invigoration ≠ convective invigoration. (2) Over a long-time scale, convective invigoration may be buffered; microphysical effect is more much important to cloud radiative forcing.

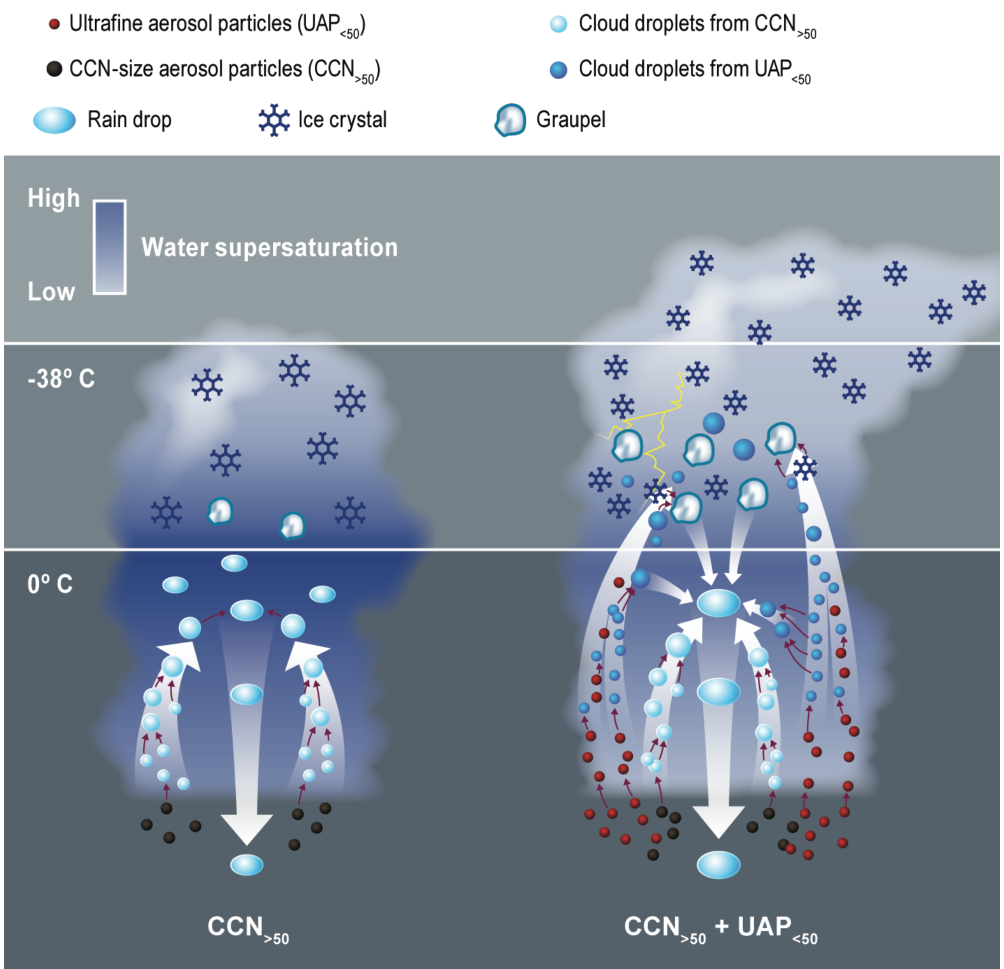
The microphysical piggybacking studies of Grabowski (2015, 2016) confirmed the significant microphysics effect by increasing aerosols, and they claimed the feedback to dynamics above the freezing level is small (their plots showed increased buoyancy and decreased supersaturation at lower-level by aerosols).

Note: the piggybacking approach has significant limitations in addressing the feedback (good for comparing differences in microphysics parameterizations) as well as the single and double moment schemes.

Observation and modeling – new concept

- **Fan et al. (Sci., 2018)** observed enhanced updraft velocity and precipitation for the plume-influenced convective storms over the wet season of Amazon and found convective invigoration is mainly contributed by aerosols smaller than 50 nm, through a new mechanism revealed by bin model simulations at 0.5 km res.

"Warm-phase invigoration"



We leaned by now:

- **Convective invigoration is really happening over the Amazon by ultrafine aerosol particles (UAP) through "warm-phase invigoration".**
- **Much more powerful than "cold-phase invigoration" by large particles.**
- **Does not delay warm rain because UAP can only be activated well above cloud base when rain has already formed and supersaturation has been enhanced.**

Note: prognostic droplet number and supersaturation are key for simulating such a effect.

Challenges

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

On observations

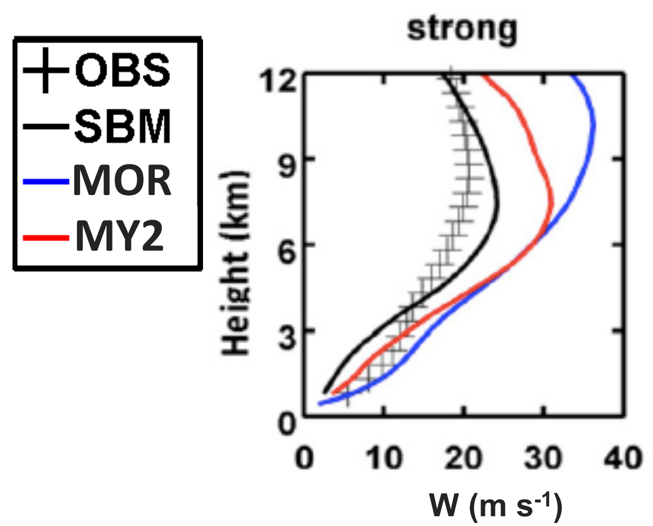
- Difficult to **single out aerosol impacts** due to a) co-variability of aerosols with dynamics and thermodynamics and b) strong sensitivity of deep convection to any small perturbation.
- Challenge to measure **convective intensity and supersaturation for convective cores**

GoAmazon field experiment design set up a good example to pinpoint aerosol impacts apart from the effect of meteorological conditions

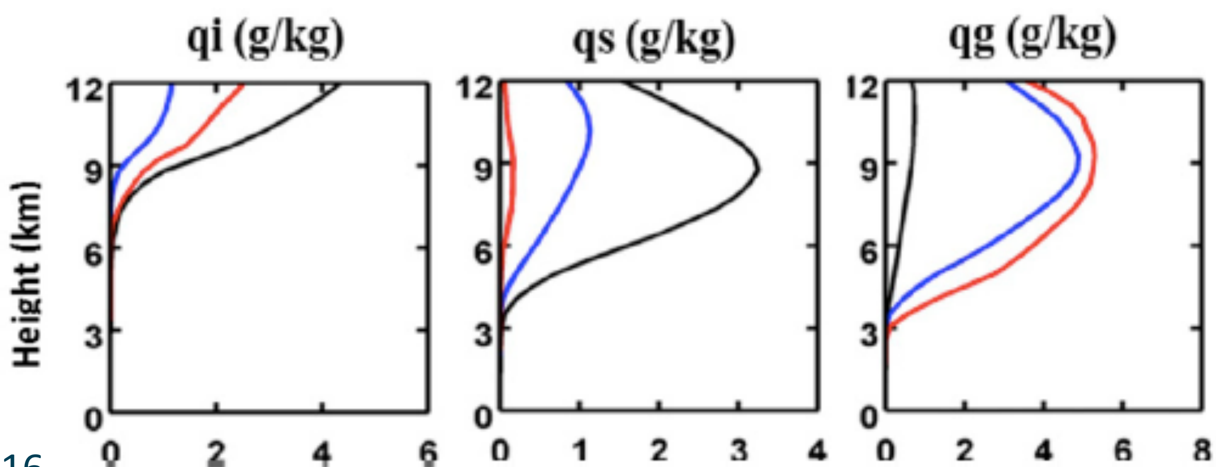
Challenges

- Difficult to measure **mixed-phase hydrometeor properties**.
- Lack of **concurrent** measurements of cloud dynamics, microphysics, and aerosols at convective cores.
- Lack of observations in **ice nuclei particles and ice nucleation processes**.

Convective core intensity (**with** obs.)



Convective core microphysics (**no** obs.)



Fan et al. JAS, 2016

Challenges

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

▶ On modeling

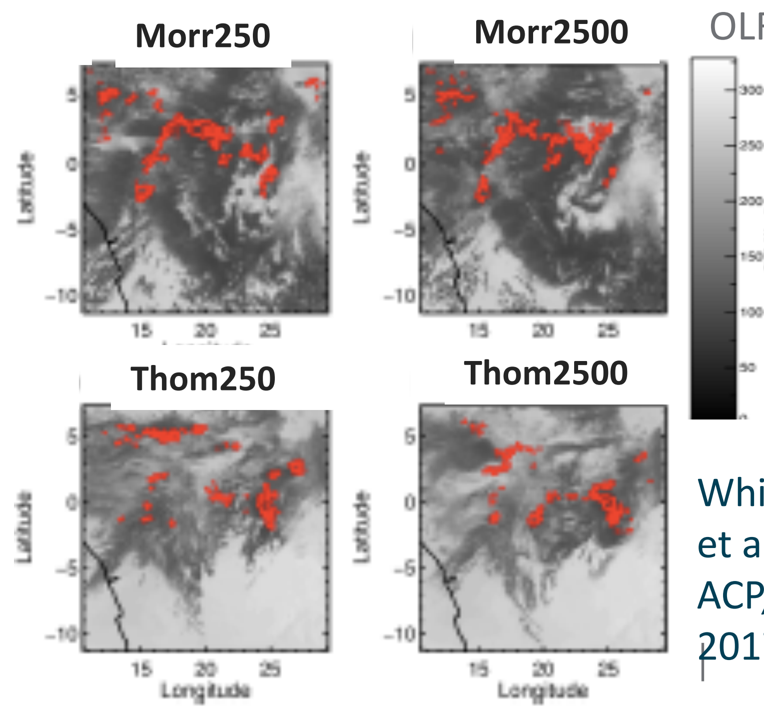
- **Problems with cloud microphysical parameterization:**

✓ Poor understanding of cloud microphysical processes particularly **conversions of hydrometeors**. Also, there is **no appropriate ice nucleation parameterizations for DCCs.**

✓ Commonly-used two moment schemes have significantly limitations in **representing ACI processes** (e.g., saturation adjustment for conde/evap, excessive size sorting, etc.), as detailed in Khain et al. (2015).

✓ Uncertainty between different microphysics schemes **is larger** than aerosol impacts.

Red contour: 5 mm h^{-1} surface rain rate



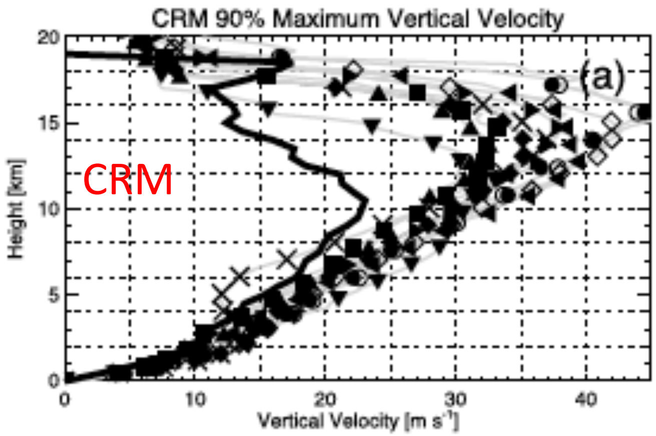
White et al., ACP, 2017

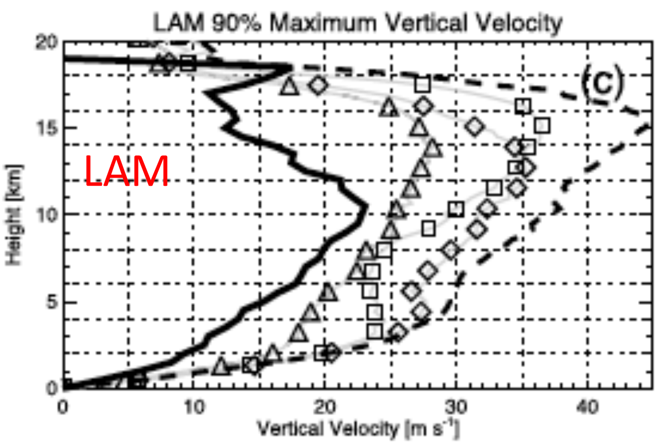
Challenges

- **CRM/LAM**: poor performances in simulating convective intensity, limiting its usage.

Tropical convection (TWP-ICE)

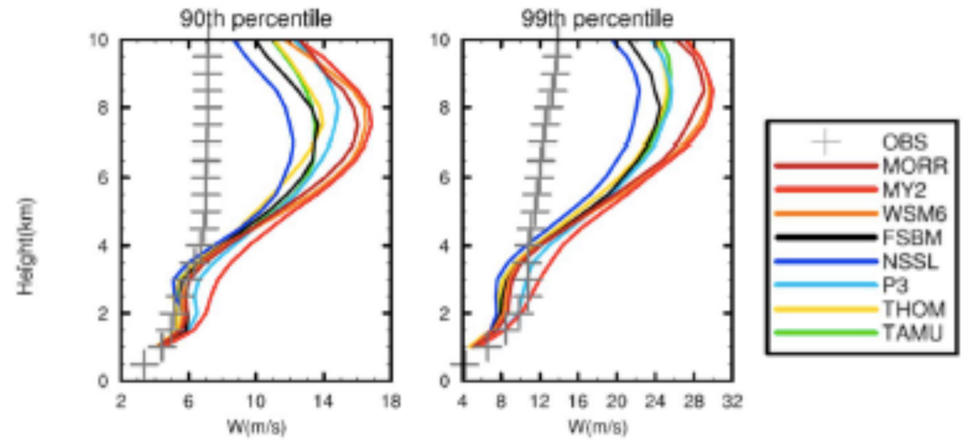
Varble et al., JGR, 2014



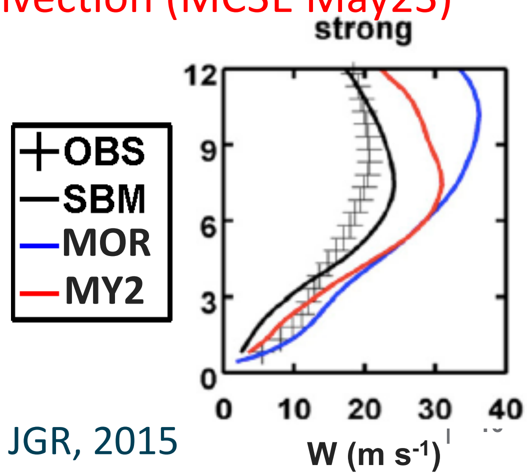


Mid-latitude convection (MC3E May20)

Fan et al., JGR, 2017



Mid-latitude convection (MC3E May23)



Fan et al., JGR, 2015

To move forward (for discussion)

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

▶ How to address observational challenges?

(**What can we do to address the main issues? Are additional key measurements, data products needed? What ARM can do?**)

- **More locations and long-term** field measurements like GoAmazon design at warm and humid regions will help tackle the aerosol-DCC interactions more **robustly** and **systematically**.
- Key data: updraft velocity, supersaturation, microphysical properties at convective cores

To move forward (for discussion)

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

▶ How to address modeling challenges?

- **Improve microphysical parameterizations, particularly on ice nucleation and mixed-phase processes.**

✓ Predicted ice particle properties - free ice category

- **CRM/LAM:**

✓ Simulate well-observed case and extensively evaluate the baseline simulation before examining aerosol impact.

✓ Try to use bin schemes: although lots of uncertainty, the response of microphysics processes to aerosol changes is more physically represented.

✓ About different microphysics parameterizations: the microphysics piggybacking approach to understand the differences

✓ About problem with dynamics part and large-scale forcing part: data assimilation