Key Aspects in Investigating Aerosol Impacts on Deep Convection

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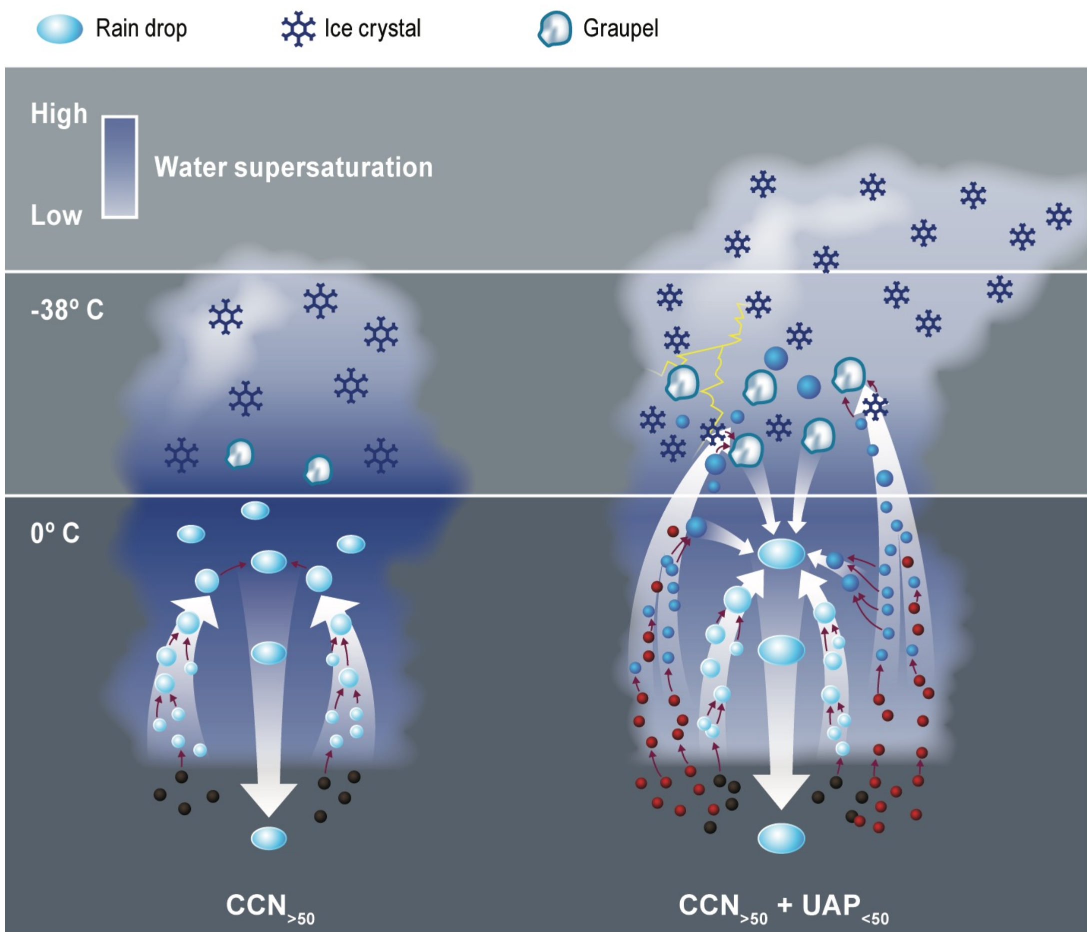
Water-phase invigoration (condensational invigoration)

"Water-phase invigoration": induced by enhanced condensation due to increased droplet number in the polluted convective clouds. So the magnitude of this effect is determined by how high the supersaturation can reach in the clean updrafts.

Documented in earlier studies such as Wang 2005, Fan et al. 2007, Khain et al., 2012; Sheffield et al., 2015).

Recent studies supported the concept (e.g., Lebo 2018, Chen et al., 2020; Igel and van den Heever 2021; Cotton and Walko 2023)

This effect is manifested by numerous ultrafine aerosol particles (UAPs; < 50 nm) from urban pollution plumes in Amazon (Fan et al., Science, 2018).



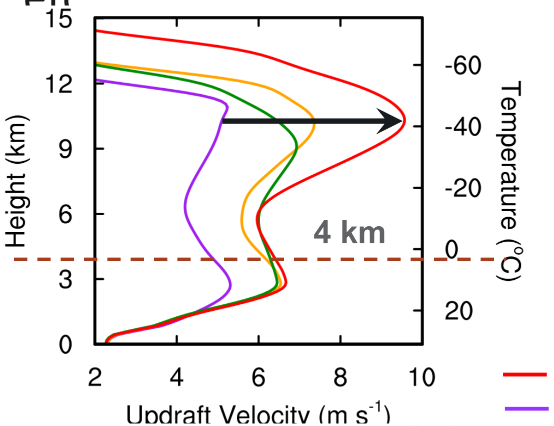
Fan et al., Science, 2018

1. Water-phase invigoration ≠ warm cloud invigoration

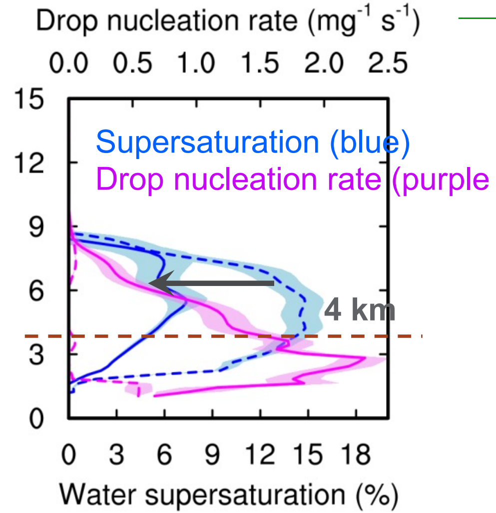
- **Deep convection is a vertical continuum and the strongest updraft speed (w) occurs at high -levels:** the low-level condensational heating leads to a large response in updraft velocity (w) at higher-levels, but not necessarily reflected at the low-levels because w at the low-levels are complicated by many other processes such as warm rain precipitating, cold-pool, entrainment etc

Romps et al., (2023, GRL; Romps23) looked at warm cloud from HALO aircraft data, not relevant to Fan2018 which studied the deep convective storms

The simulations appropriate for them to compare is Koren et al. (2014, Science) which was truly about warm cloud invigoration by aerosols



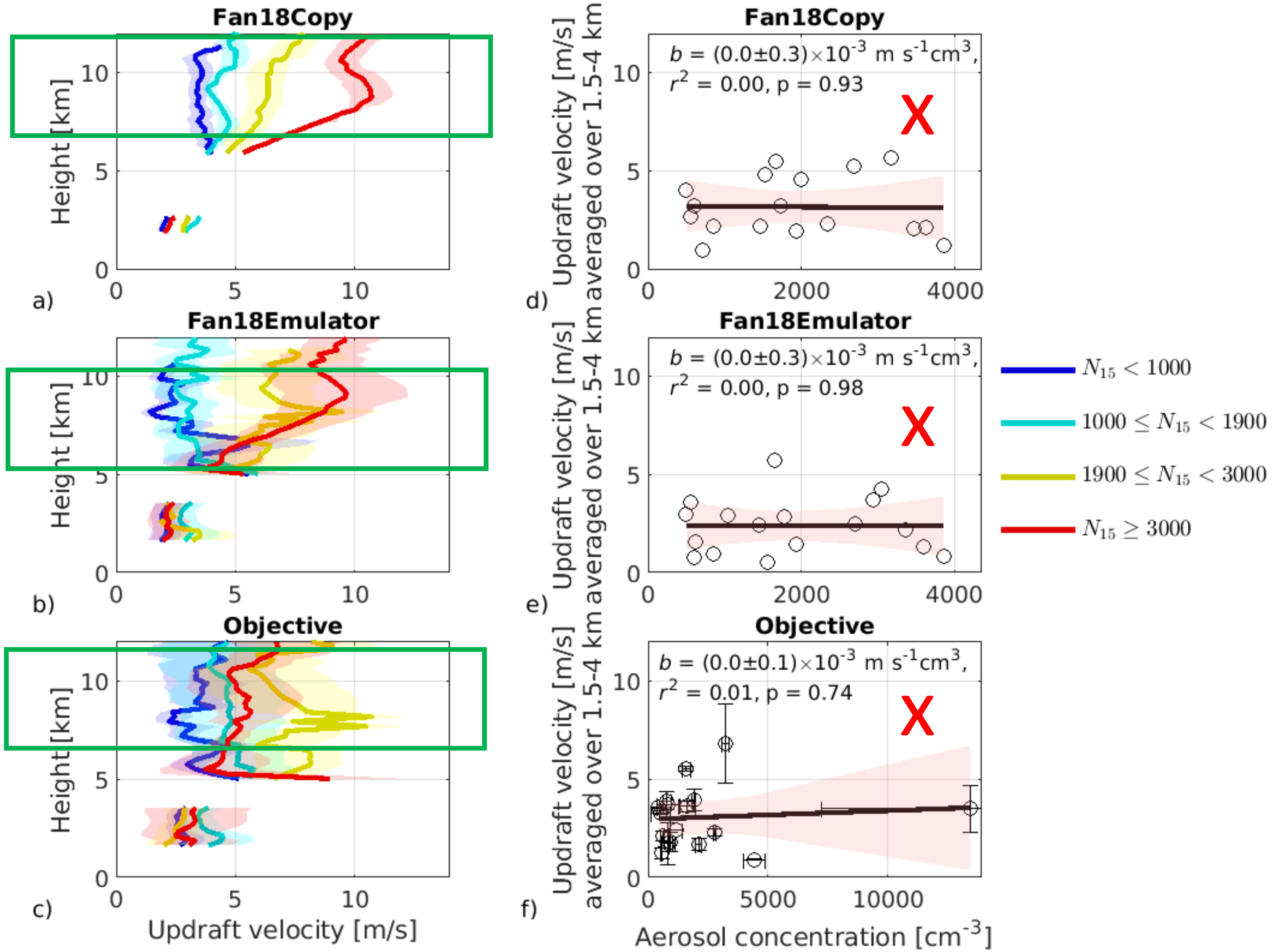
- W max peaks at ~ 10 km; the low level w is weak and does not determine storm intensity.
- Fan2018 showed the largest response to the increase of low level latent heating (purple to red) is at ~ 10 km



Supersaturation change by aerosols maximizes above 4 km (Fan2018)

Mean of top 10th percentiles

The 90th percentile



Oktem et al., JAS, 2023

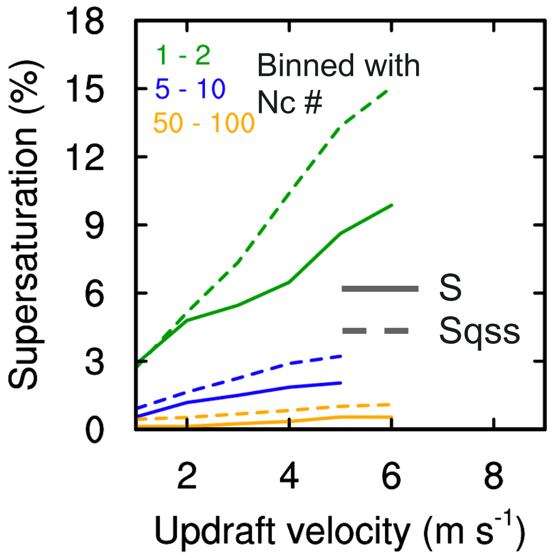
Their follow-on study Oktem et al. (2023, JAS; Oktem2023) followed the same misconception and analyzed the storm cases in Fan2018, but focused on the w change **at the low-levels (1.5-4 km, right)** and ignored the response at high-levels (above 6 km, green box), claiming no warm phase invigoration

Their results showed that w increases with aerosols until reaching an optimum, a typical phenomena shown in many previous studies. This is not against convective invigoration – simply the result was misinterpreted

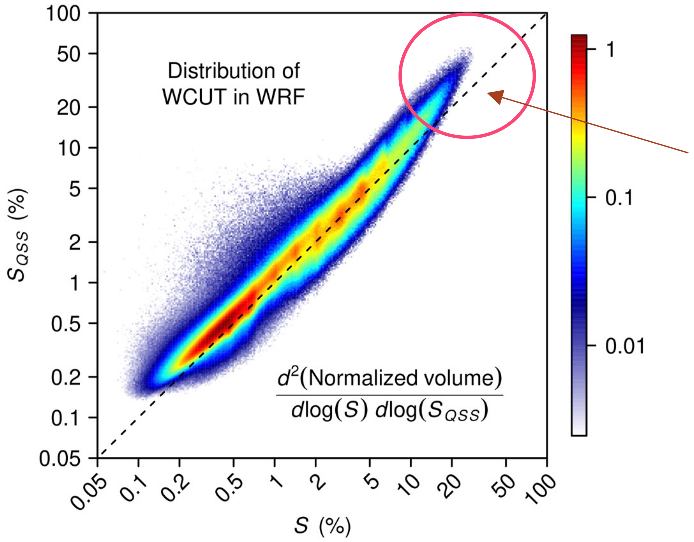
2. Prognostic supersaturation (S) is needed, not saturation-adjustment and quasi-steady state (QSS) assumptions

- **Saturation-adjustment and quasi-steady state (QSS) assumptions in models distort aerosol effects on convection (detailed in *Fan and Khain, 2020, JAS*)**

Deep cloud period (ultra-clean condition)



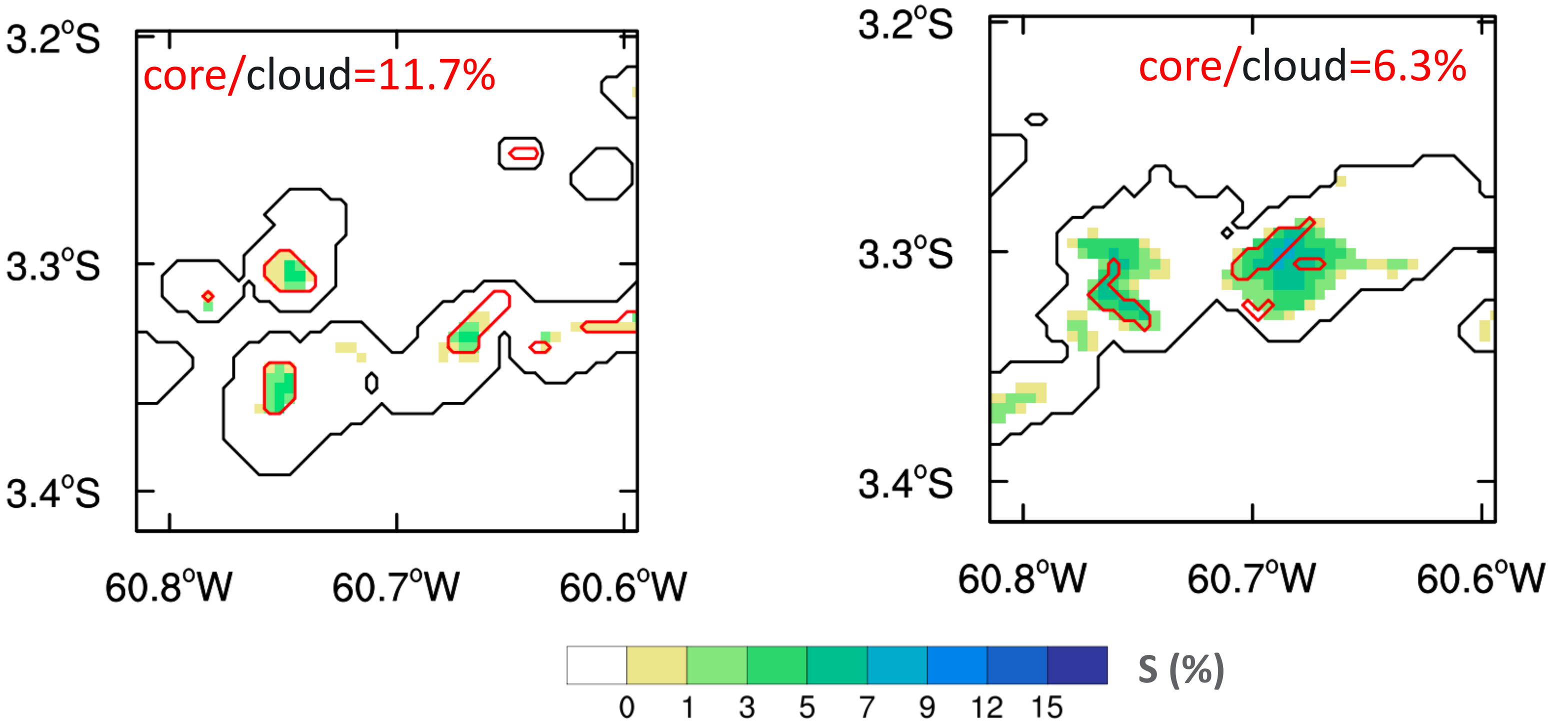
In strong and clean updrafts. S can be very different from Sqss.



Romps2023

High S is very different from high Sqss (log sacle), which is a very small portion of the data (convective core is only a very small fraction (next page)

3. Need to examine convective cores, a very small fraction of cloud body but determines convective intensity



Warm cloud at 2 km
(core: w > 1 m/s; cloud: qtot>1e-5 kg/kg)

Deep cloud at 5 km
(core: w > 2 m/s; cloud: qtot>1e-5 kg/kg)

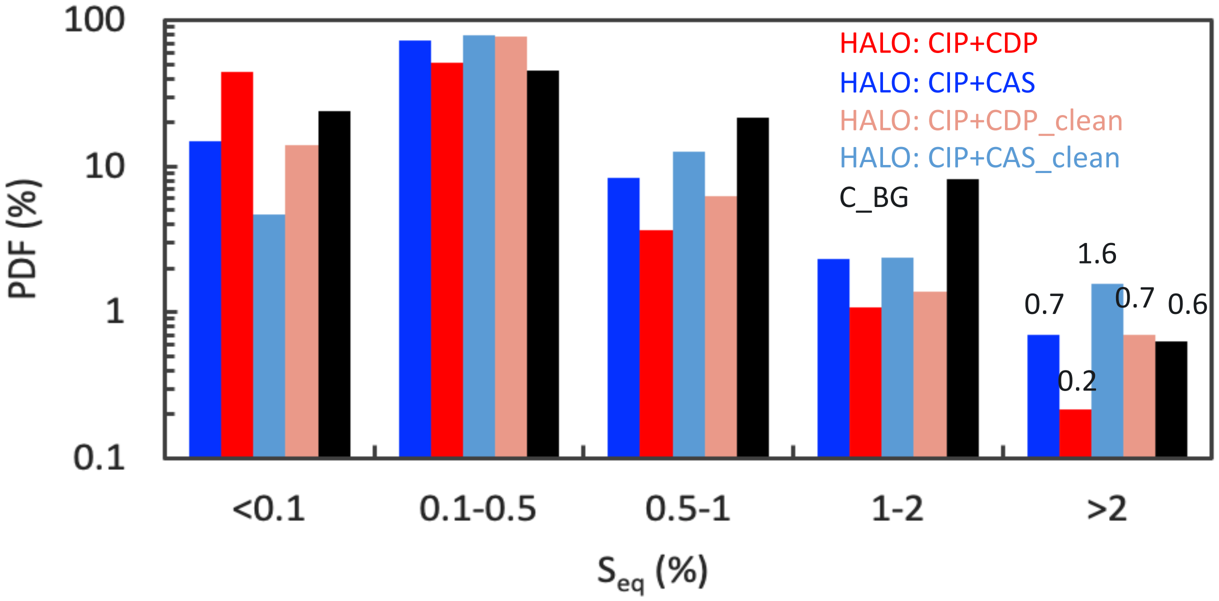
Simulation is C_BG which is for background aerosols in Fan et al., 2018.

4. Need to examine the high end (maximum) of supersaturation (S) in convective cores, not the mean S

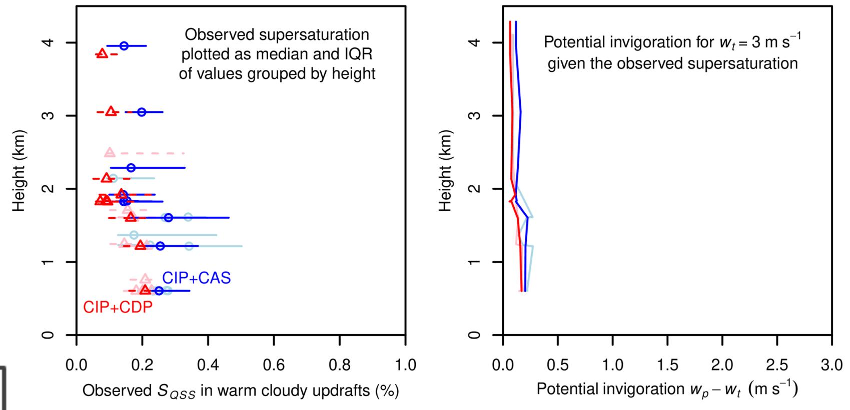
- High S is very unstable, with very low frequencies in the PDF plots

HALO data from Romps23

For warm cloud updraft tops (w > 1 m/s)



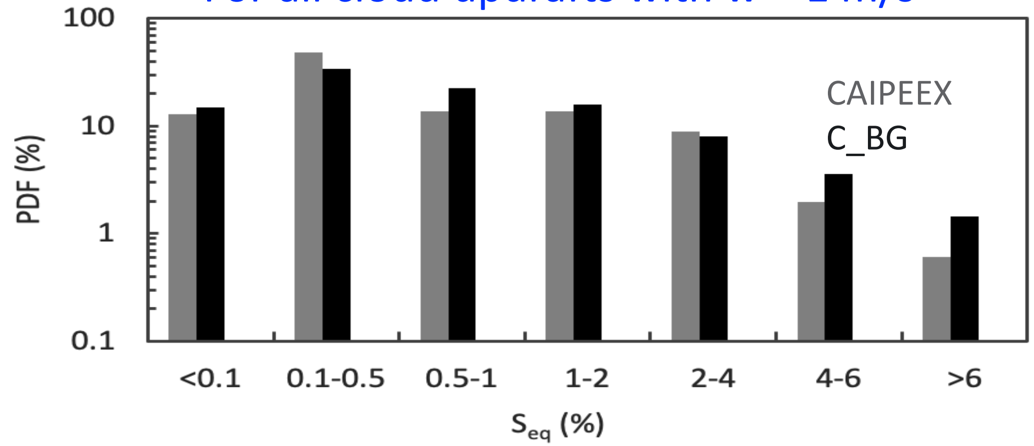
Freq. of S > 2% is 0.7% in HALO and 0.6% in warm clouds of C_BG simulation in Fan2018
Max S is 2.6% in HALO and 2.9% in C_BG



Romps2023: used mean supersaturation which is only 0.3% to derive a small increase in updraft speed (0.2 m/s).

CAIPEEX for Indian monsoon

For all cloud updrafts with w > 1 m/s

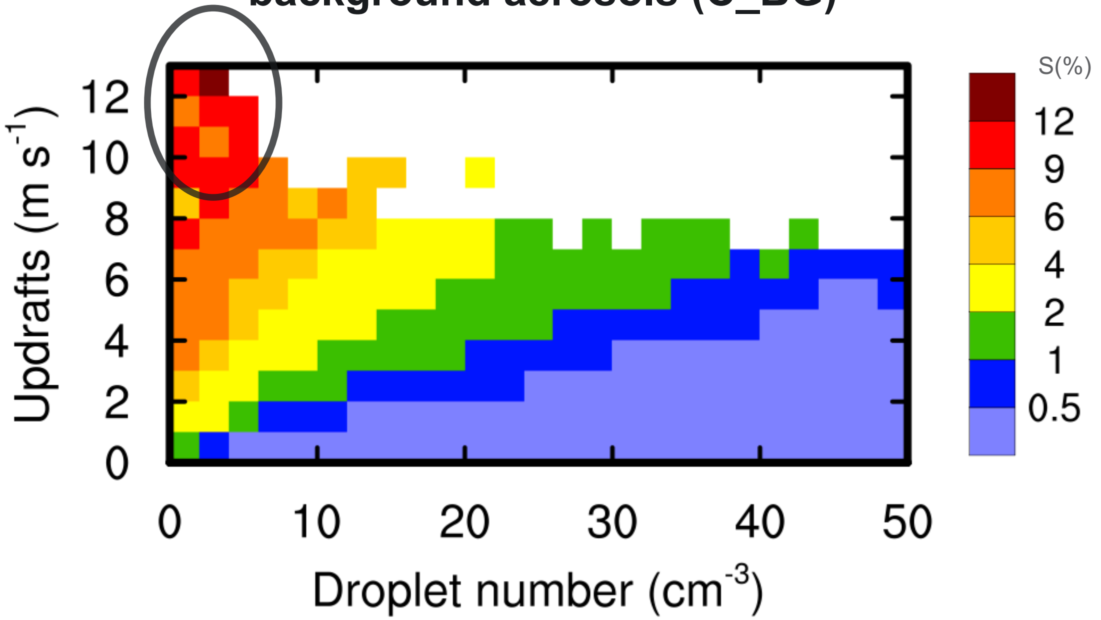


Freq. of S > 6%: 0.6% in CAIPEEX, and 1.4% in C_BG

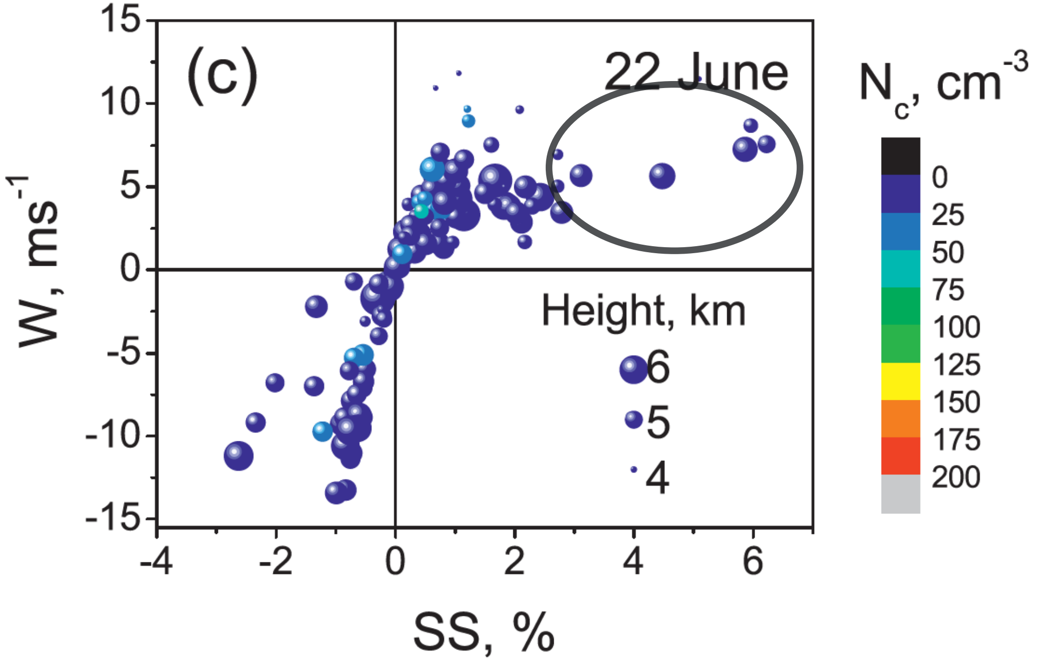
Max S: 9.9% in CAIPEEX; 12.7% in C_BG (Nc of 1.2 cm^{-3} and updraft speed of 9.2 m/s)

5. High supersaturation occurs only in high updraft speed and ultra-low Nc

SBM for Amazon wet season background aerosols (C_BG)



CAIPEEX for Indian monsoon



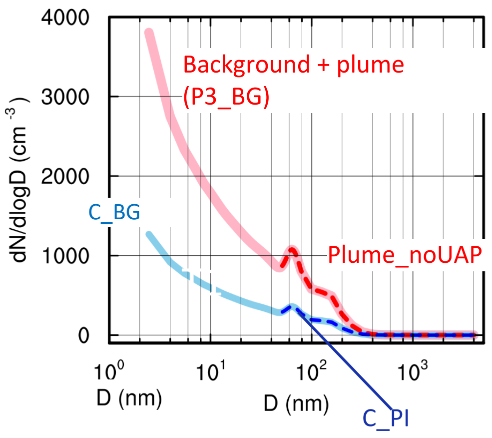
- In C_BG, mean Nc is 3.2 cm^{-3} for S of ~ 10%, similar to 3 cm^{-3} based on Eq. of Romps2023.

Prabha et al. (2011) showed high S existed in strong updraft with low Nc (< 25 cm^{-3}) in aircraft observations.

6. Droplet number is not only determined by aerosol number, but aerosol SD and hygroscopicity

- **Romps23 wrongly compared HALO with our simulation based on the similar total aerosol number**

Aerosol SD in Fan2018

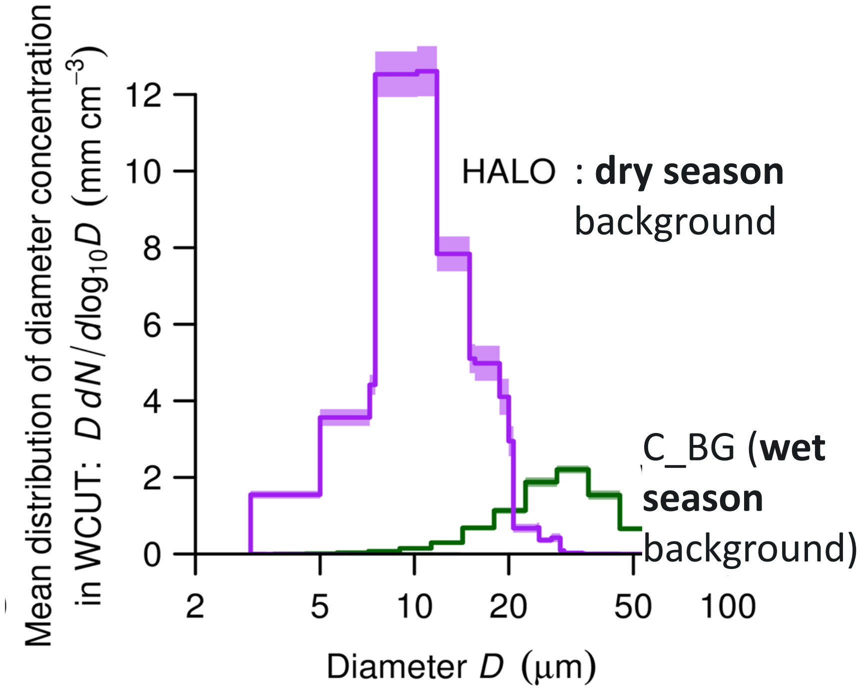


The SD has vast majority of ultra particles, which can not be activated at cloud base.

C_PI: 130 cm^{-3} (> 50 nm)
C_BG: 130 cm^{-3} (> 50 nm) +
820 cm^{-3} (<50 nm)

Also, the hygroscopicity is very low (0.12; observed), so aerosol activation is low!

Droplet SD (Romps23)



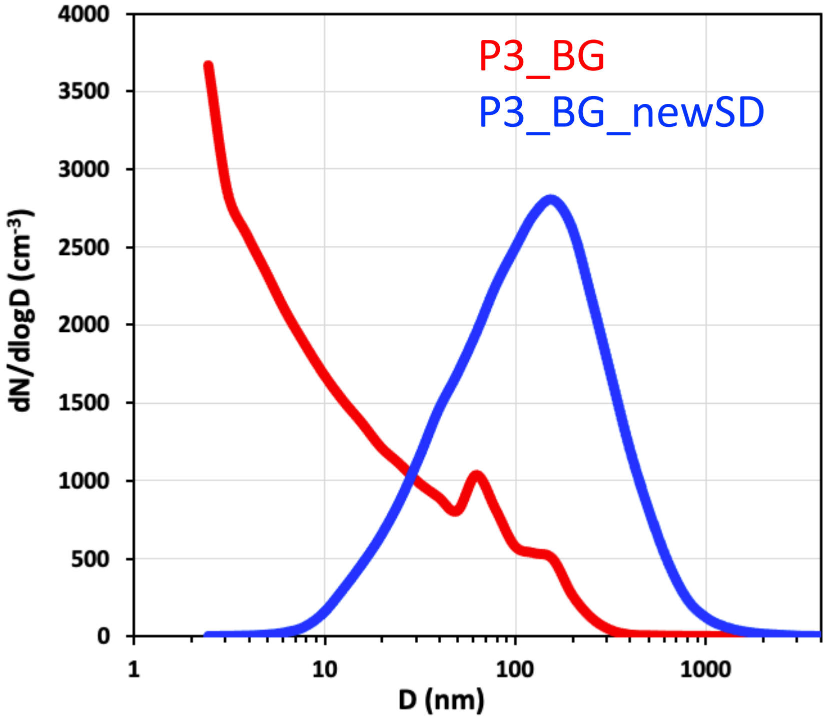
- **Large aerosols may have opposite effects on fine aerosols particles (**Pan et al. 2022, Nature communications; Liu et al., 2022, Communications Earth & Environment **)**

Thus, drastically different droplet number between HALO and our simulations – comparison is misleading!

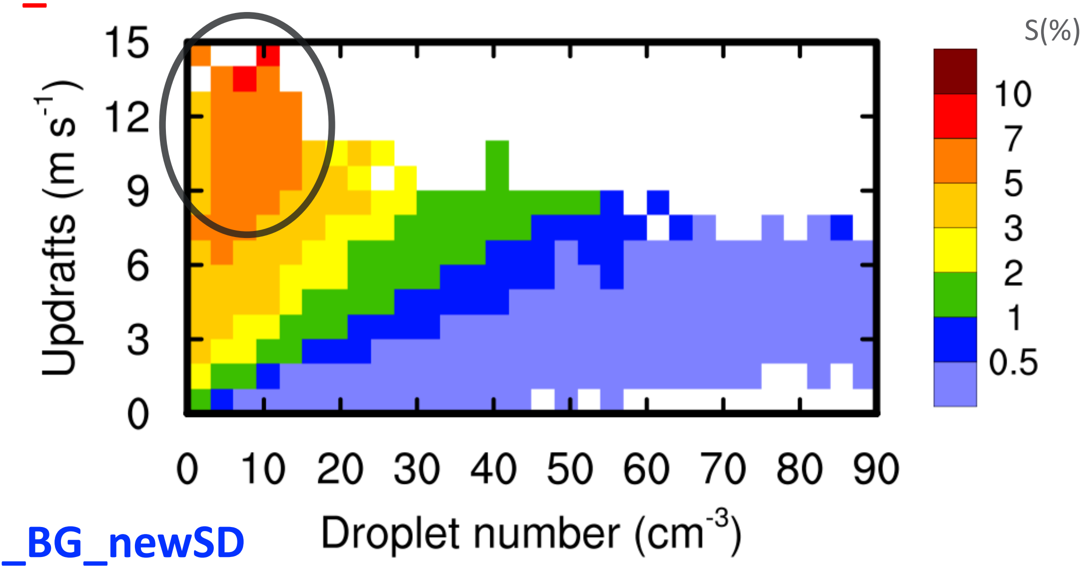
Very high S disappears when shifting SD to large aerosols

- Aerosol SD is shifted from high UAP in P3_BG to high accommodation mode aerosols (P3_BG_newSD), to allow high droplet activation near cloud bases (total aerosol number are kept the same: 950 cm^{-3})

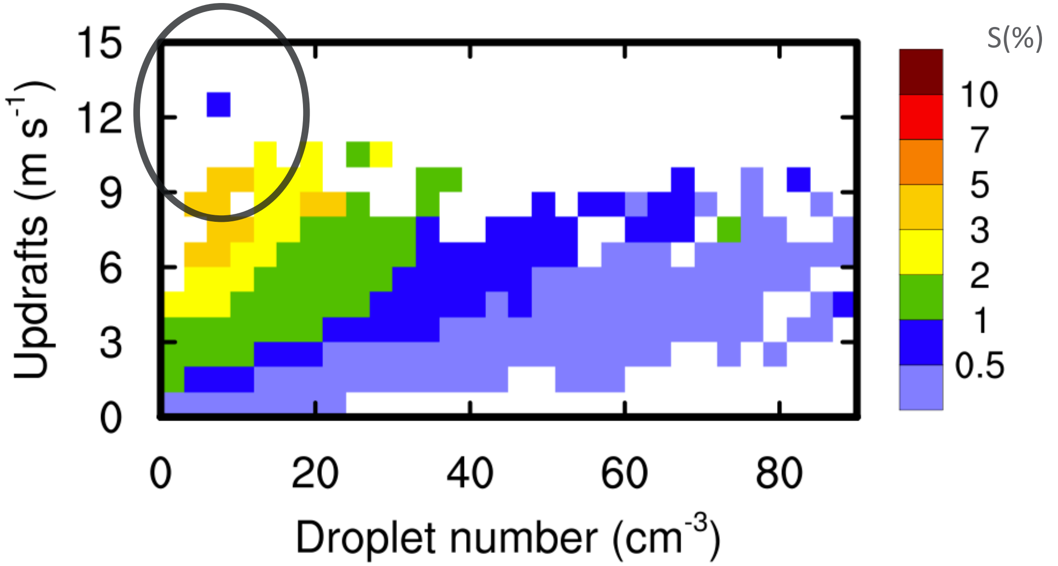
Total aerosol # is kept the same



P3_BG

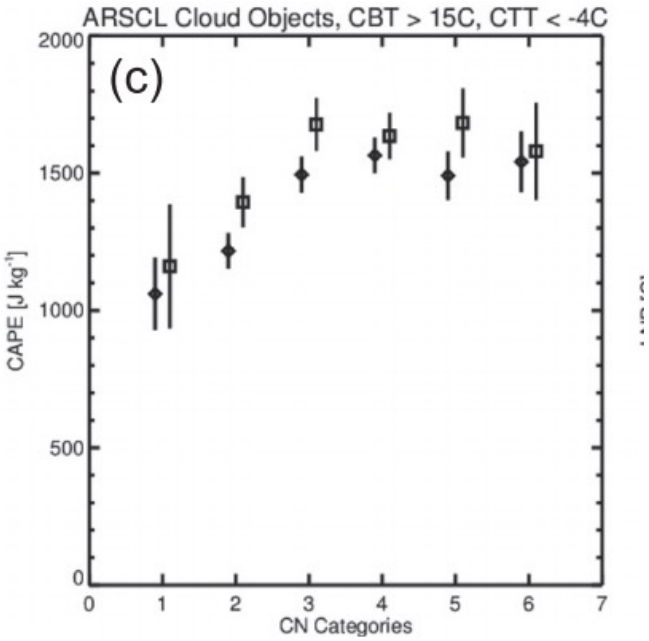


P3_BG_newSD



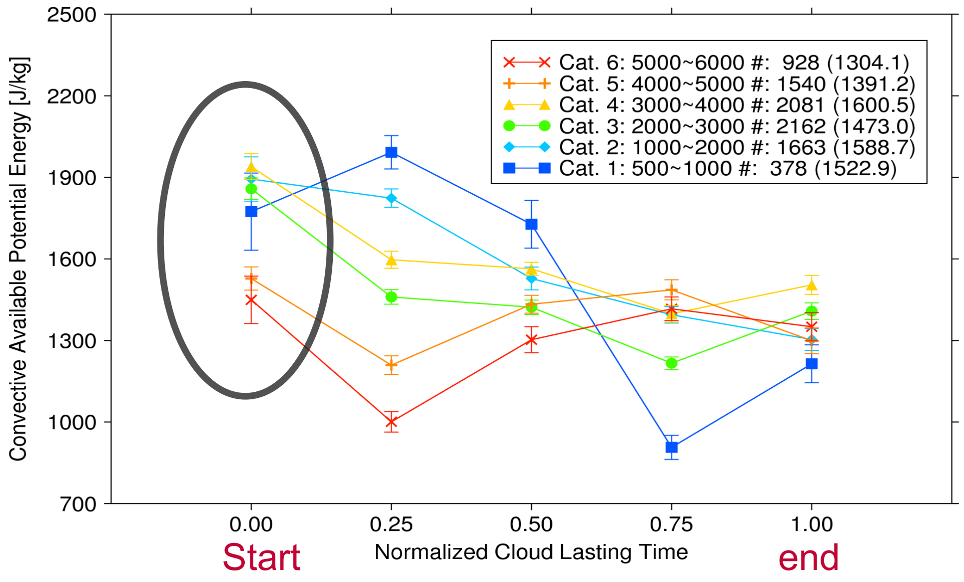
7. Examining meteorology co-variability requires using aerosol and meteorology before convection initiation, not during convection period

Aerosol is correlated with the maximum CAPE during the cloud period



Varble 2018

- Varble (2018) found aerosol is positively correlated with the max. CAPE during the cloud period, claiming the meteorology co-variability contributing to the increased updraft.
- CAPE during convective period is already changed by aerosol effect. The appropriate way is to look at the correlation right before convection. The aerosol is actually negatively correlated with CAPE at the start of deep clouds.



Correlation of aerosol with CAPE changes during the cloud evolution: negative at the initiation, become slightly positive at later stages

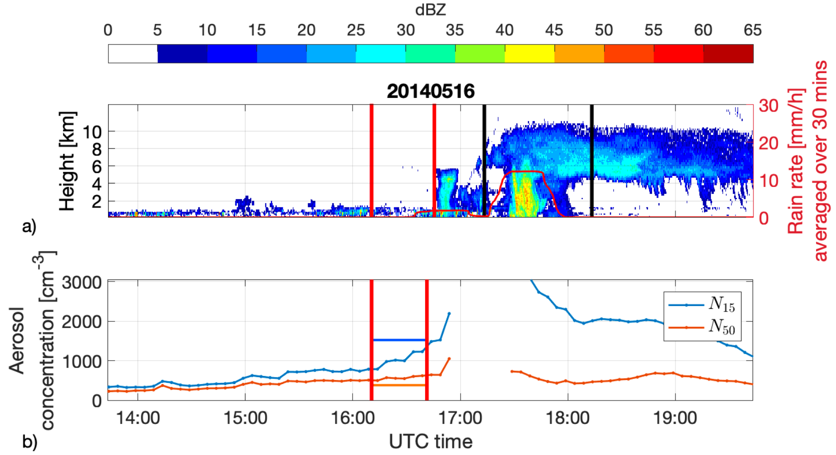
The key is the meteorology contribution can not be examined after convection starts (complicated by cloud and precip. processes)

From Zhanqing Li, based on the data from Varble2018

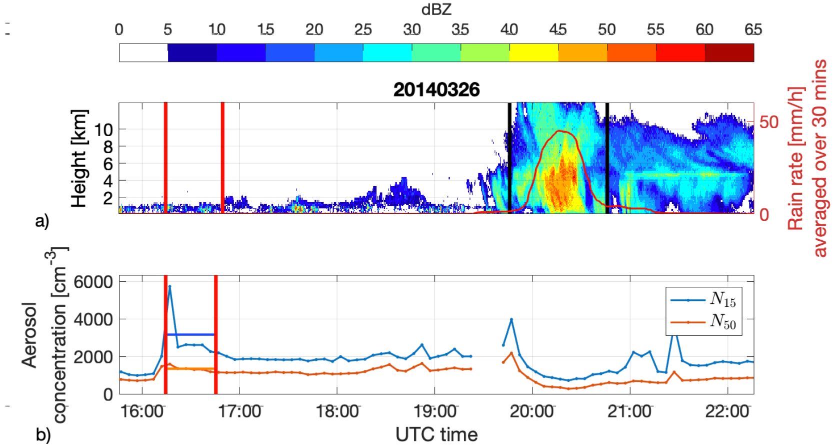
8. Identifying convective initiation and duration need strict selection

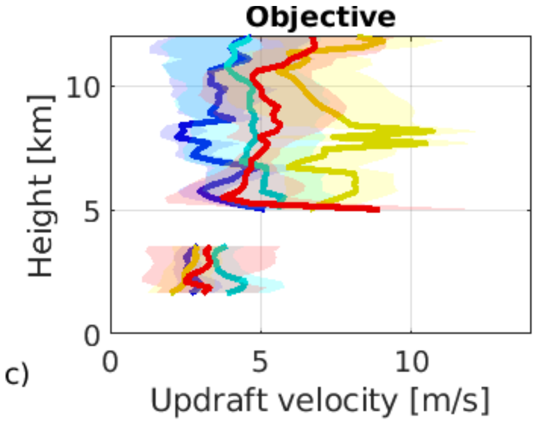
- **Oktem2023 used rain start time as convective initialization time, which is not appropriate.** For the local isolated thunderstorms in Amazon, they develop from shallow to deep which takes some period to develop rain

- Their convective periods were created with 1-, 2-, 3-, 4-, or 6-hour time intervals centered on the peak of convection, **which is not appropriate for these thunderstorms: generally last 1-2 hours; applying 3-6 hours to each case would include other clouds like stratiform.**



A couple of examples selected from Oktem2023: the convective period last 1-2 hours.





Oktem2023

Thus, a strong smoothing is seen compared to our results, but still not against the invigoration

Even more subjective compared to ours which strictly targeted at convective period.

Summary

Modeling and analyzing aerosol impacts on deep convective clouds are very tricky. Pitfalls can be avoided by learning from past studies.

- **General rules:**
  - Aerosol impact on convection needs to target at convective cores which are a very small fraction of cloudy area needing carefully identification of convective initiation and duration.
  - High supersaturation (not the mean) should be examined. It often occurs in the cores with low droplet number and strong updraft speed.
- **Model simulations:**
  - Determine what aerosol type you look at (hygroscopicity) and consider prognostic aerosol SD
  - Predict supersaturation and use aerosol activation based on SD and hygroscopicity. No saturation adjustment and Quasi-steady assumptions.
- **Observational analysis:**
  - Appropriately identify deep convection initiation and time period is very important (not including other clouds)
  - Use aerosols and meteorology before convection initiation to examine the meteorology co-variability.
  - Cloud top height in convective cores can indicate convective intensity, but not these including stratiform.