Aerosol Impacts on Tropical Convective Clouds

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- DOE ASR and RGCM programs

Outline

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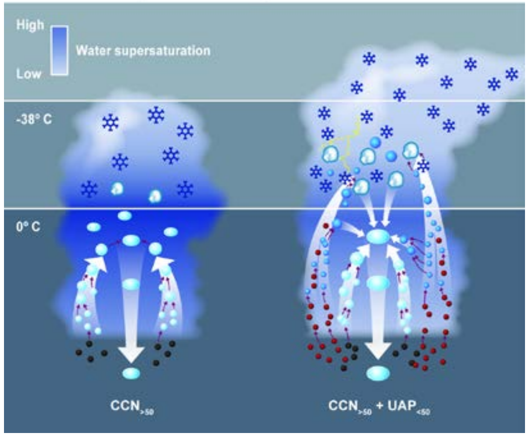
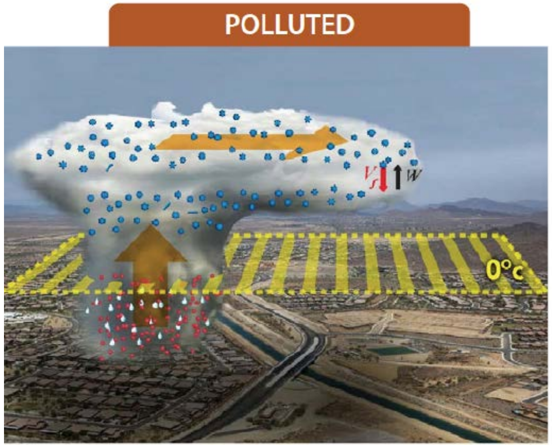
- Convective invigoration – substantial contribution of ultrafine aerosol particles to convection and precipitation enhancements over Amazon (*Fan et al. 2018, Science*)



- Microphysical effect – large contribution of CCN to the increase of stratiform/anvil top height and area over the Tropical Warm Pool (TWP) region (*Fan et al. 2013, PNAS*)



Convective invigoration

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

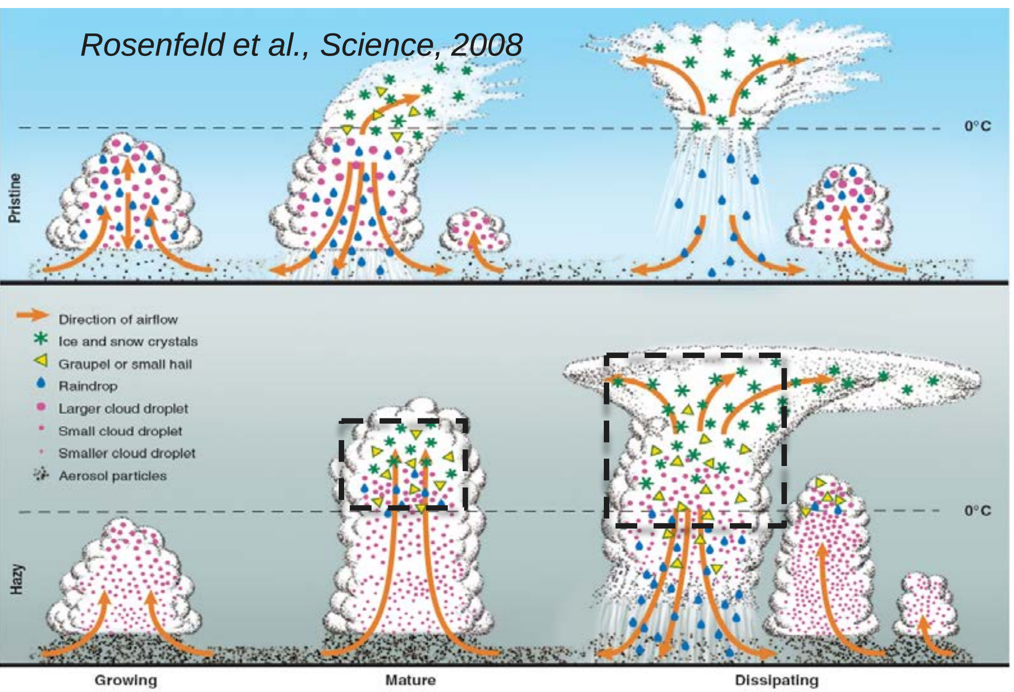
Biomass burning: large particles

invigoration"

- **Fan et al. (*Science*, 2018)**: **observed** drastically enhanced updraft velocity and precipitation for convective storms influenced by urban pollution plume at the **wet**

Urban pollution: small particles

invigoration"

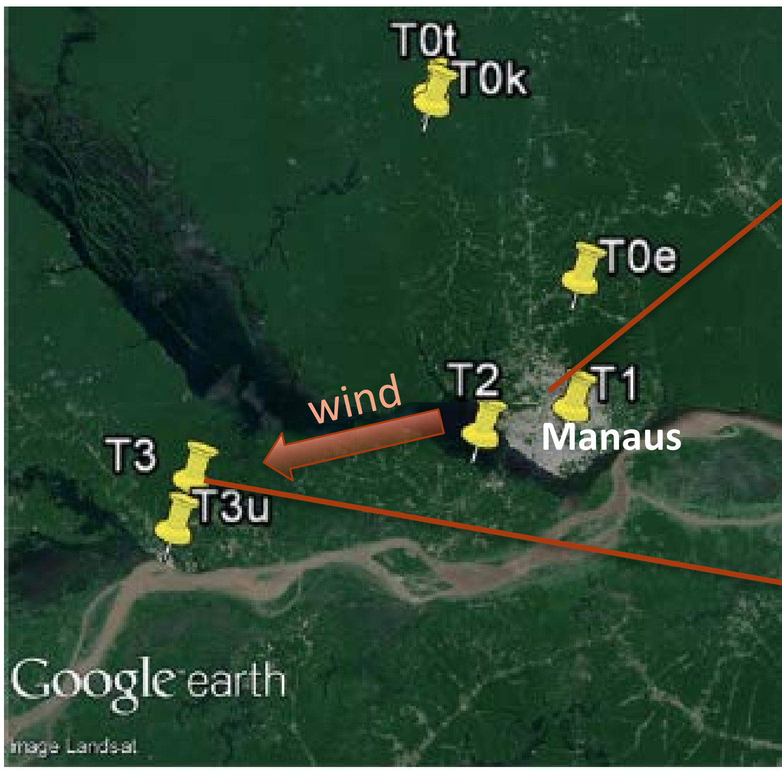


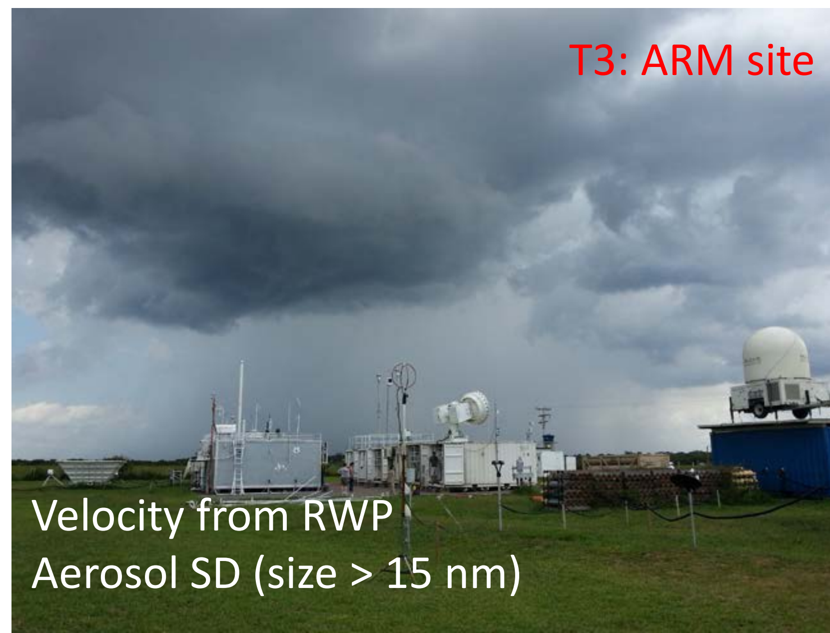
- Stimulated many studies, showing that meteorological factors such as wind shear, RH, and CAPE would modulate CCN impacts on DCCs (e.g., *Fan et al. 2007, 2009, Khain et al.2005, 2009, Storer et al., 2010, van den Heever et al. 2011*).

A major bottleneck is the lack of observations of updraft speeds and to disentangle aerosol impacts from the impact of meteorological variables.

Unique observations

- Unique experimental setting and observational data from GoAmazon allowed us at the first time to **pinpoint aerosol impacts** apart from changes of meteorological fields





Observed Enhancement of Convective Intensity and Precipitation by Aerosols

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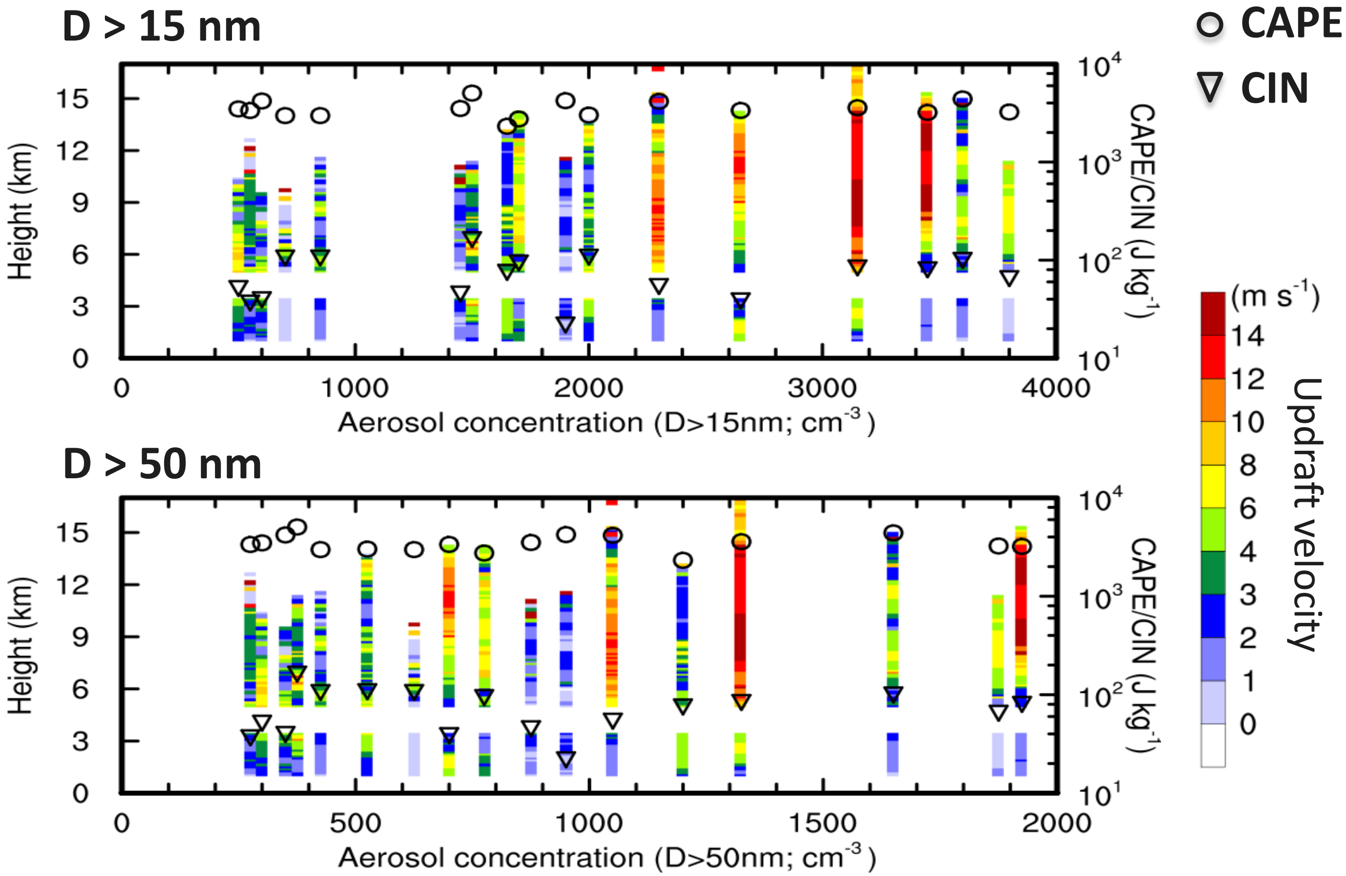
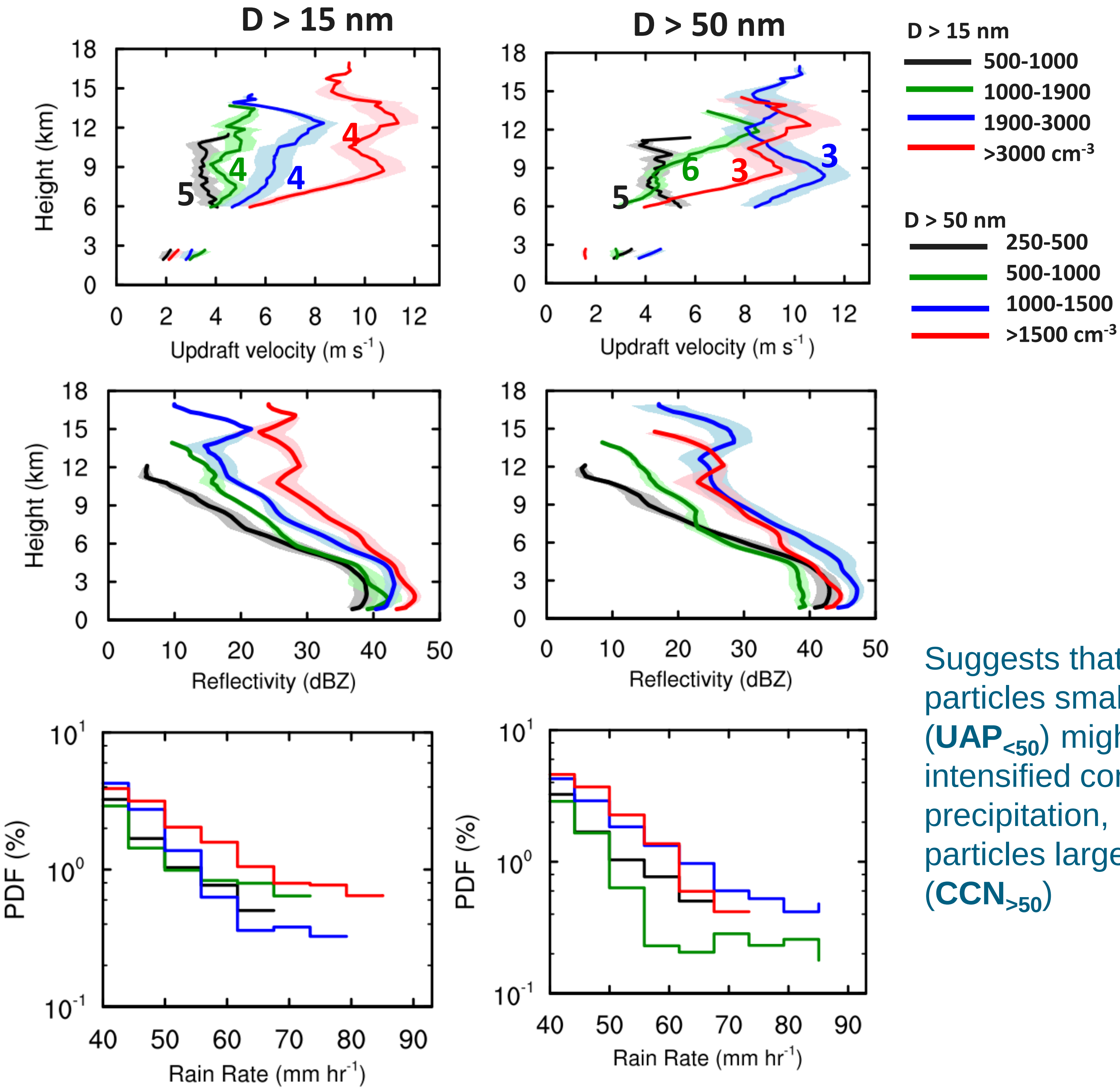
Carefully selected the locally-occurring storm cases observed in the 2014 wet season over March-May: 17 DCCs with valid aerosol measurements



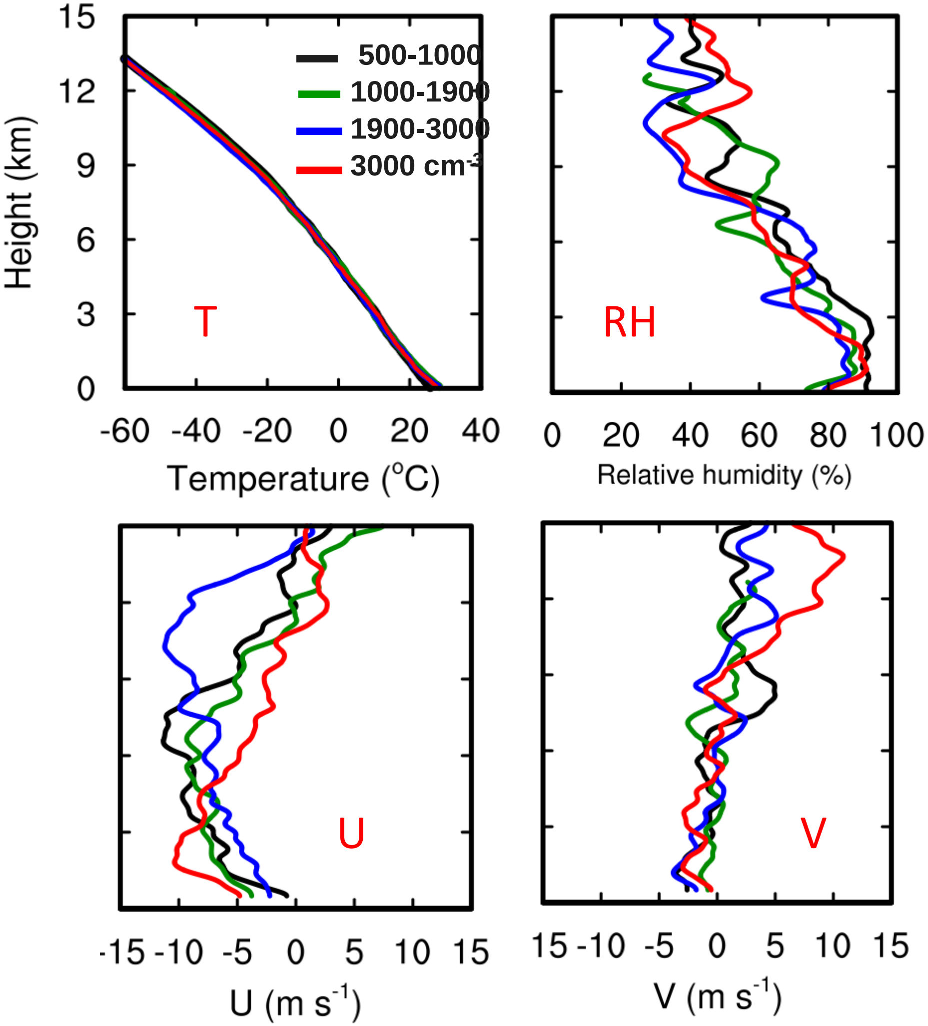
- Updraft velocity increases with an increase of aerosols counting *D* > 15 nm.
- However, when excluding aerosols smaller than 50 nm, the relationship with aerosols does not hold well



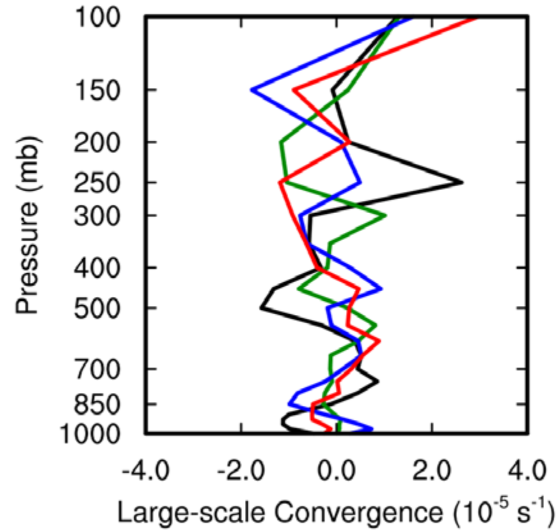
Suggests that ultrafine aerosol particles smaller than 50 nm (**UAP**$_{<50}$) might be responsible for intensified convection and precipitation, not the aerosol particles larger than 50 nm (**CCN**$_{>50}$)

No correlation with the trends of meteorological factors

D >15 nm: **pre-storm environment**



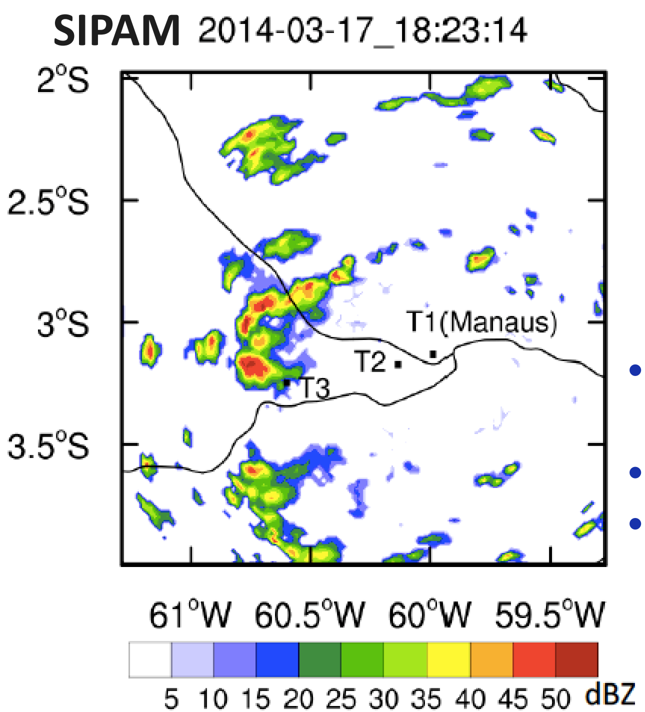
Large scale convergence



- Profiles of T, RH, and U- and V- wind as well as large-scale convergence indicate that none of them correlates with an increase of updraft intensity as UAP<50 increases.

Similarly large enhancement from model simulations

- To reveal the mechanisms responsible for the observed intensification of updrafts by $UAP_{<50}$, we conducted WRF with **spectral-bin microphysics (WRF-SBM)** for a typical wet season convective event on **17 March 2014 (0.5 km resolution)**

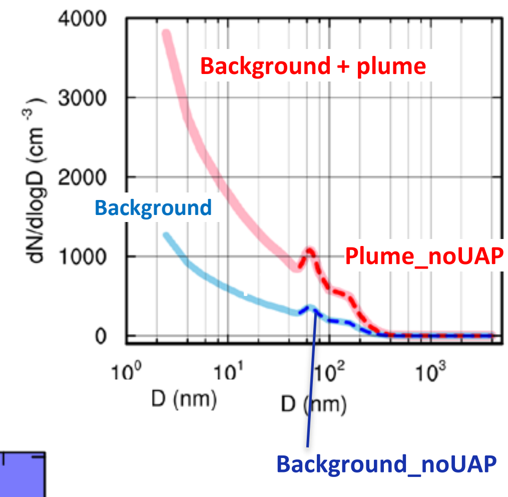


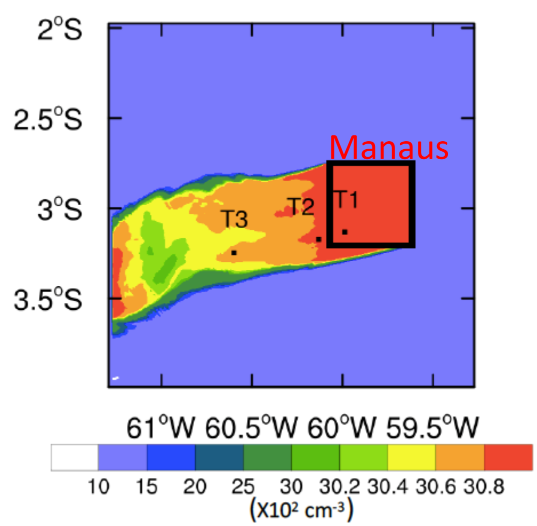
- Weak wind shear
- High CAPE
- Winds were northeasterly at the 850 hPa level

Background: Manaus background (820 cm^{-3} UAP +130 cm^{-3} $CCN_{>50}$)

Background + plume: Manaus background with Manaus plume (2460 cm^{-3} UAP +390 cm^{-3} $CCN_{>50}$ for Manaus)

Background_noUAP and **Plume_noUAP** are the corresponding cases by removing UAP





Validation of the baseline run: Background + plume

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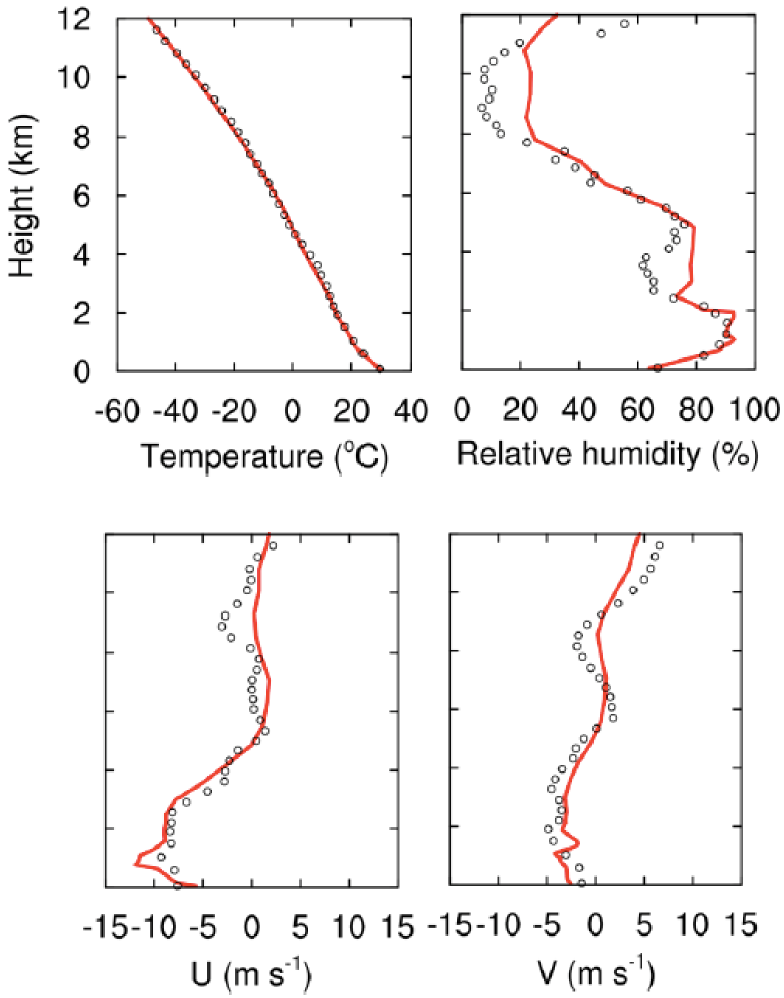
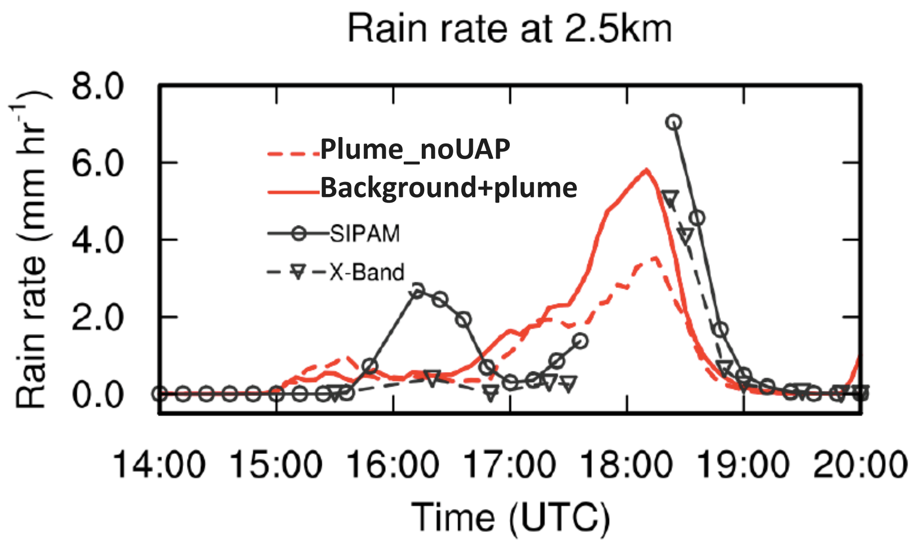
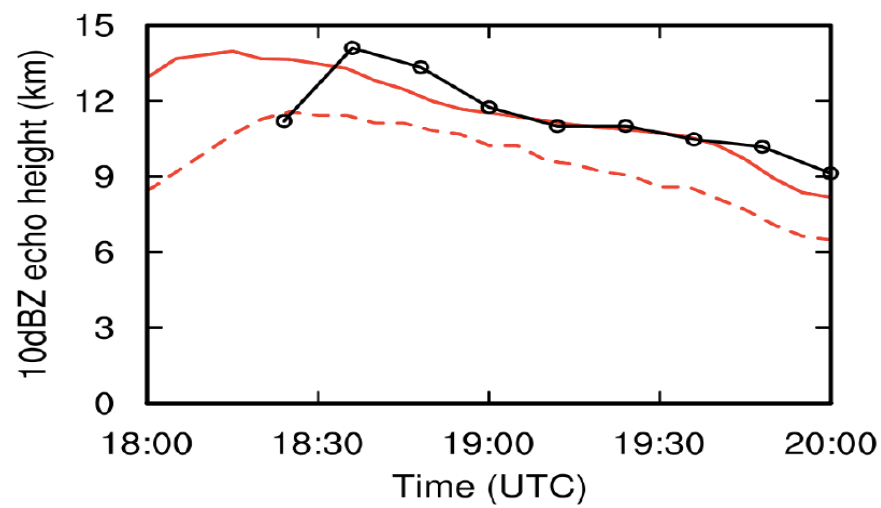
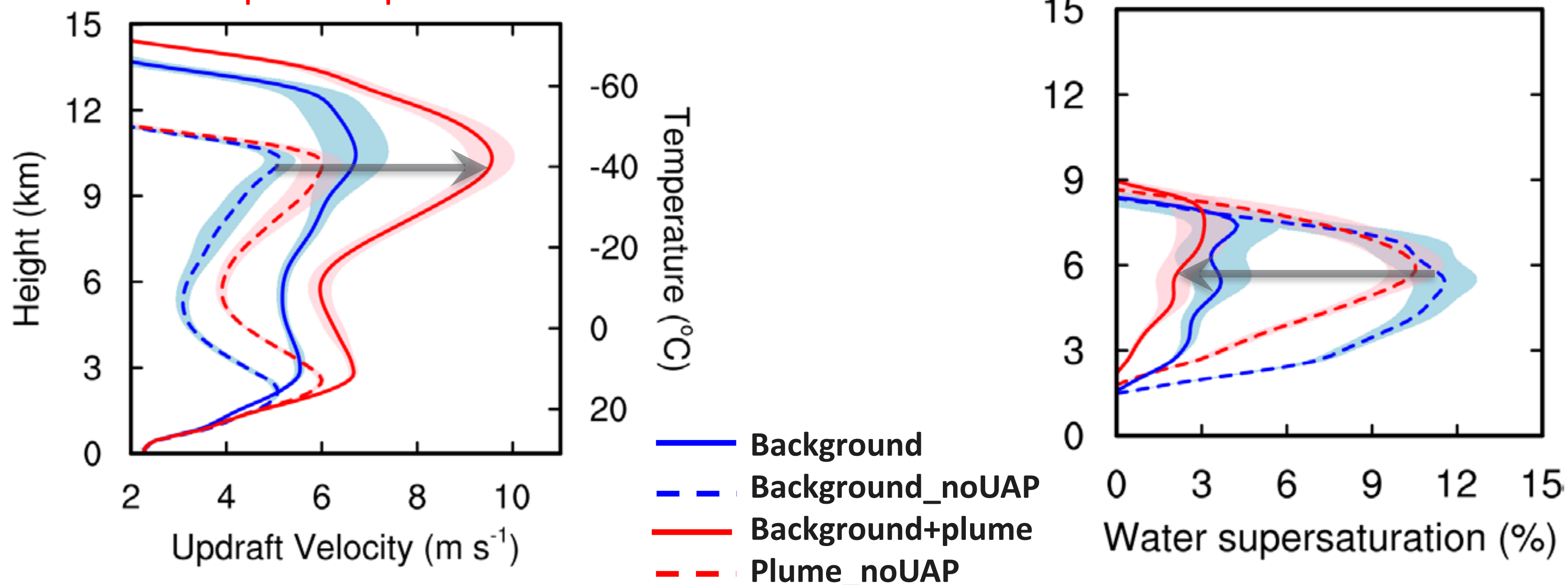




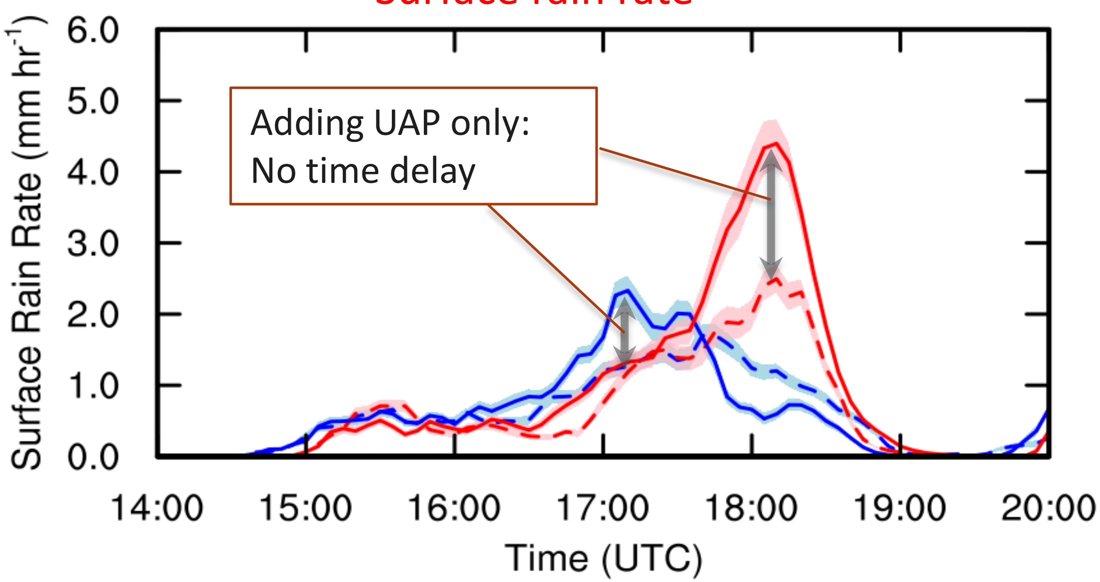


Updraft speed

Supersaturation



Surface rain rate



- The observed **large enhancements** in convective intensity and precipitation by $UAP_{<50}$ from Manaus pollution plume are reproduced.
- Corresponding to drastic decrease in **supersaturation**

“Warm-phase invigoration” mechanism

Features of “warm-phase invigoration”

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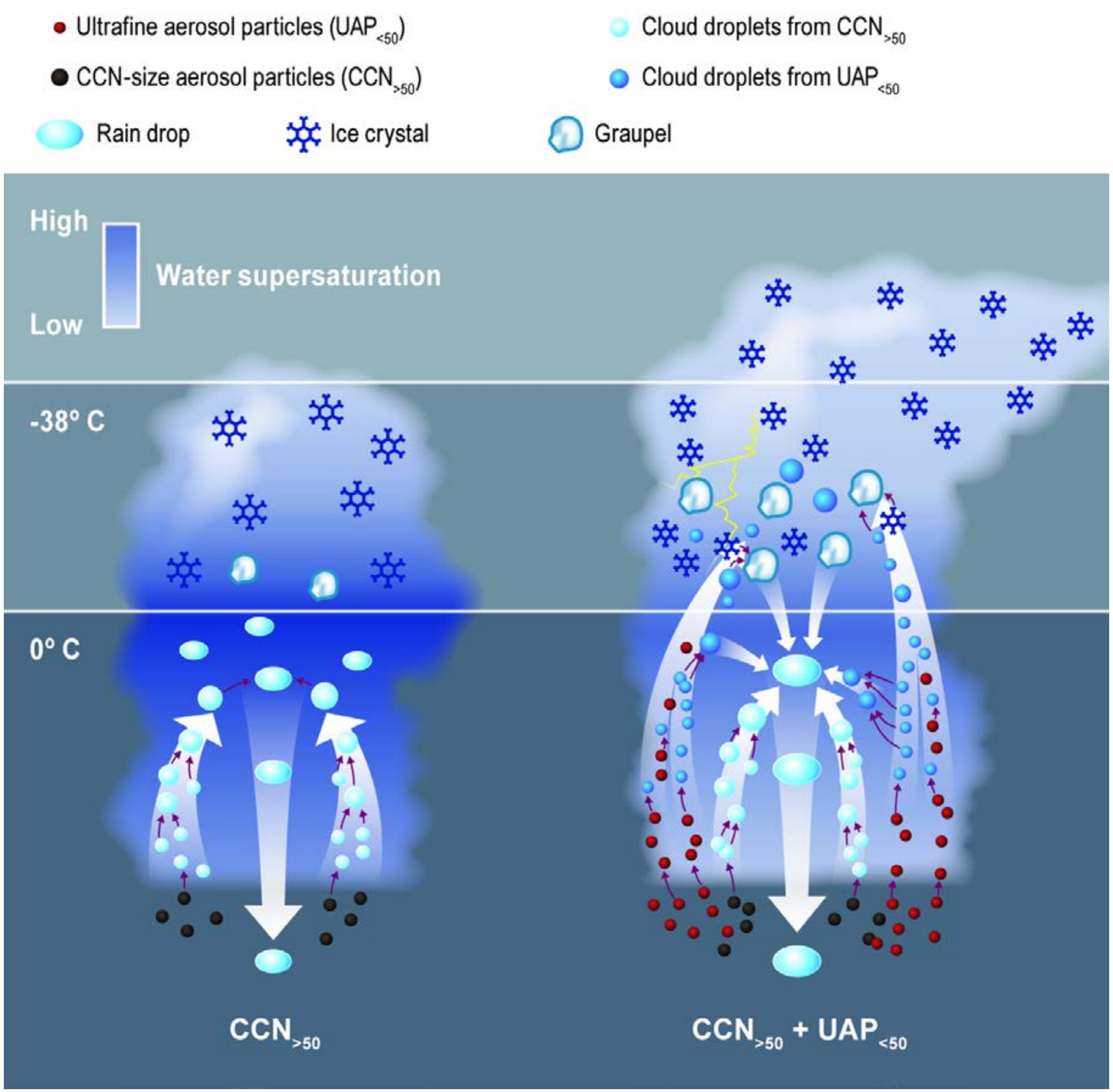
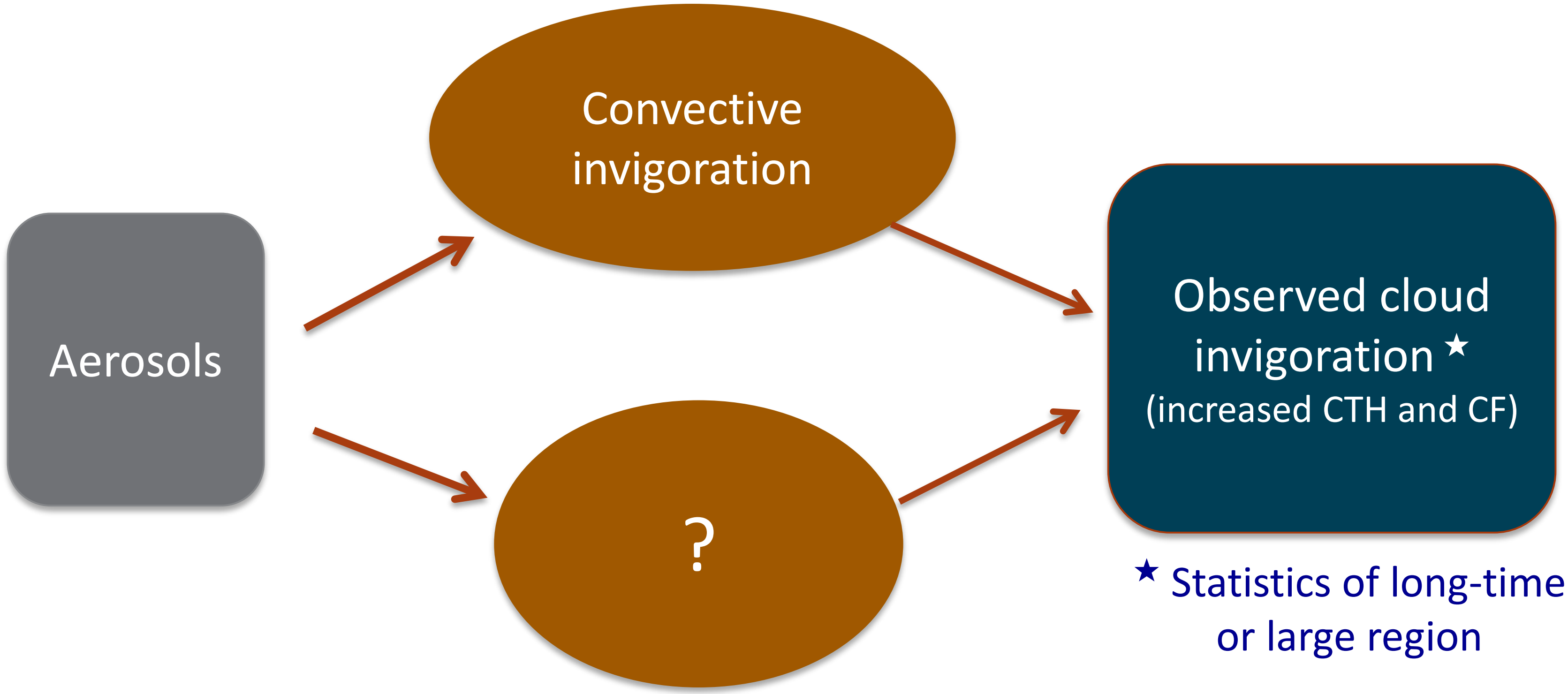


- **Does not delay rain or suppress warm rain** (in contrast to the effect of $CCN_{>50}$)
- The effect is **much more powerful** compared to “cold-phase invigoration” because (a) the enhanced heat is much larger and (b) the heating is at the lower part of storm clouds.

Microphysical effects: increased cloud top height and cloud cover

- **Can model reproduce the ubiquitously-observed increases in cloud top height and cloud fraction? If yes, what is the major mechanism?**



★ Statistics of long-time or large region

Fan et al., PNAS, 2013

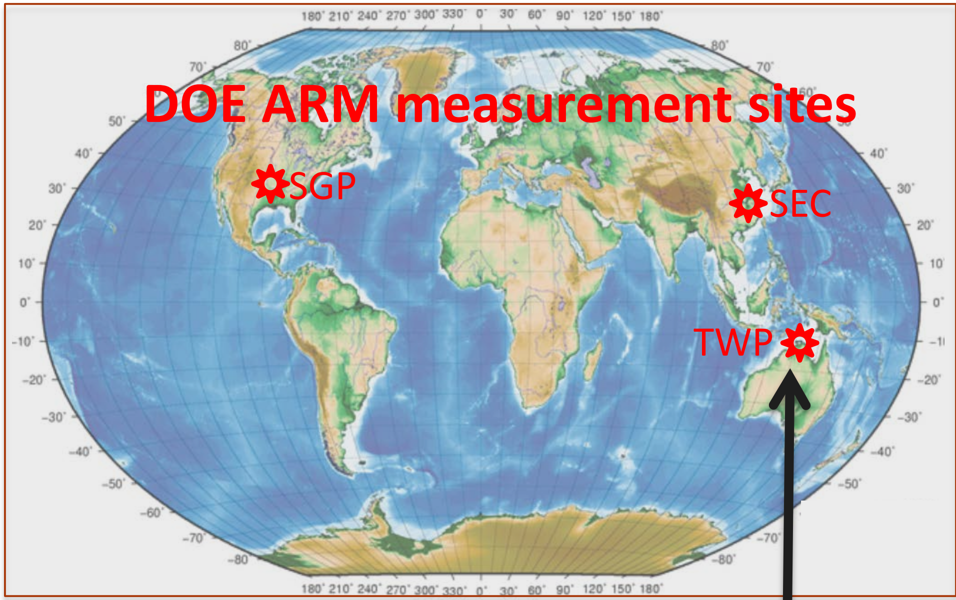
Long-time CRM simulations over a regional domain

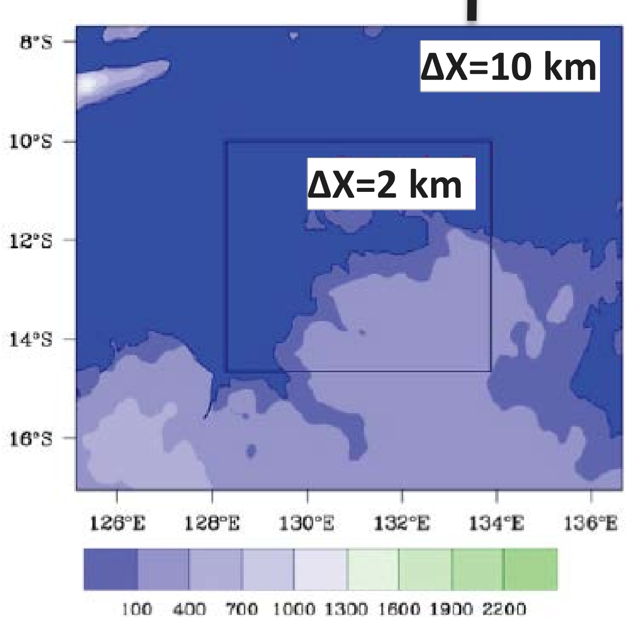
- **One-month regional CRM simulations with spectral-bin microphysics (SBM)**

- **TWP** (Jan.15-Feb.15, 2006): tropic oceanic convection
- **SEC**- SE China (July 2008): summer convection of mid-latitude coastal area
- **SGP** (June 2008): mid-latitude inland summer convection.

Covering all kinds of environment conditions: from dry to humid, weak to strong wind shear, isolated convection to convection system

- **Clean (280 cm^{-3}) vs. polluted (6*280 cm^{-3}) conditions**





Are simulated clouds close to reality?

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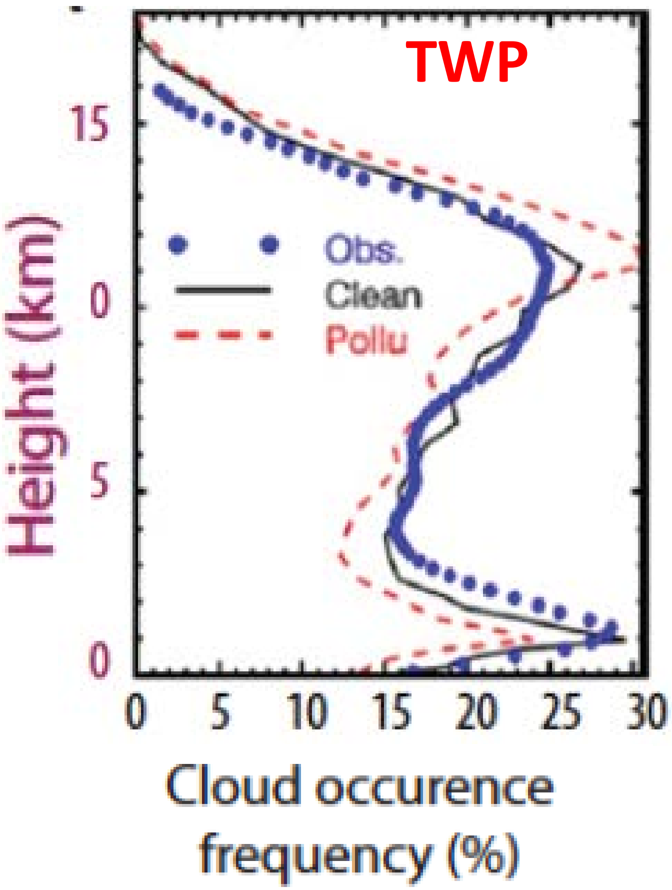

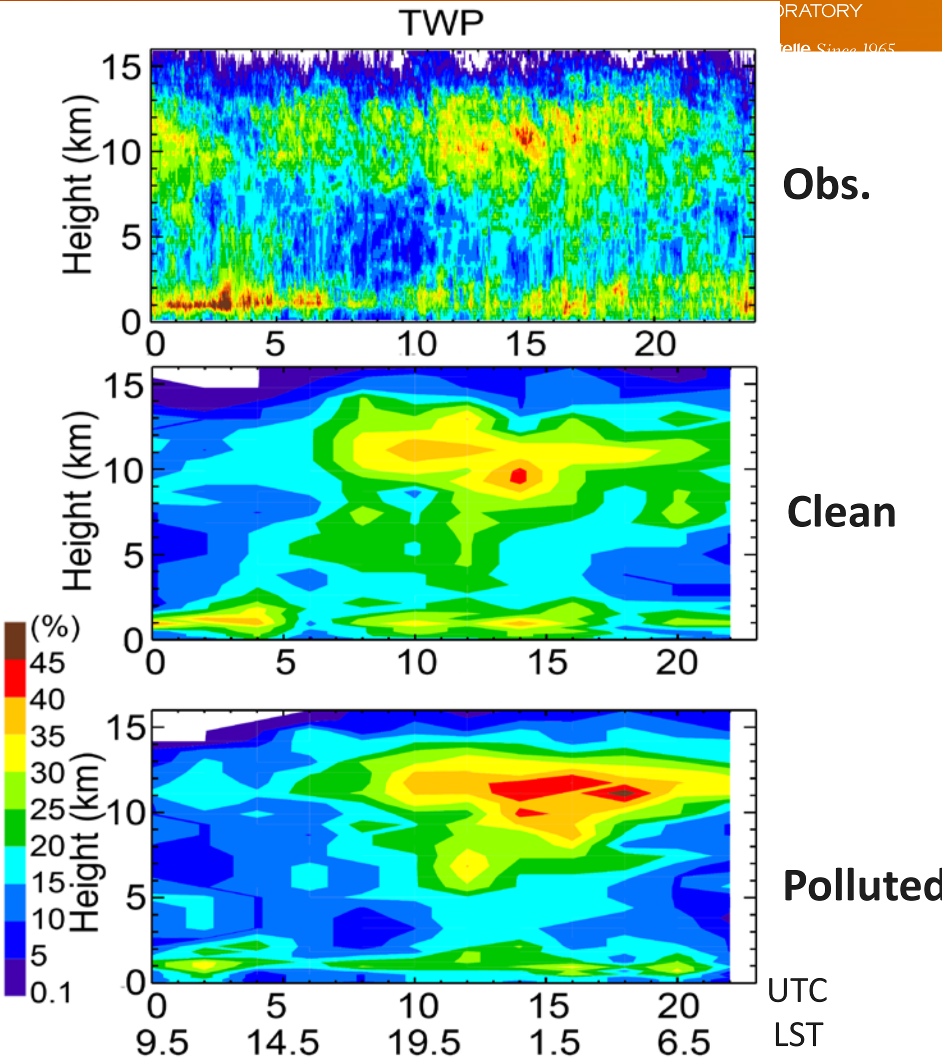

- Cloud vertical structure and diurnal variation under the clean conditions, which is closer to reality at TWP and SGP, agree well with observations.
- Polluted simulations predict many more high clouds and fewer low clouds.

Consistent increases in cloud fraction aloft, cloud top height (CTH), and cloud thickness

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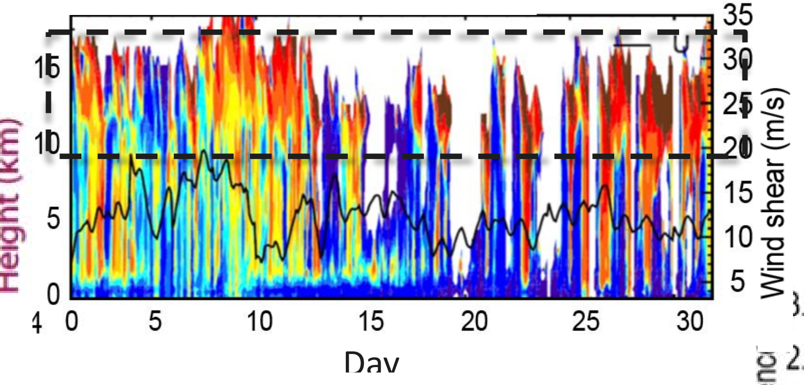
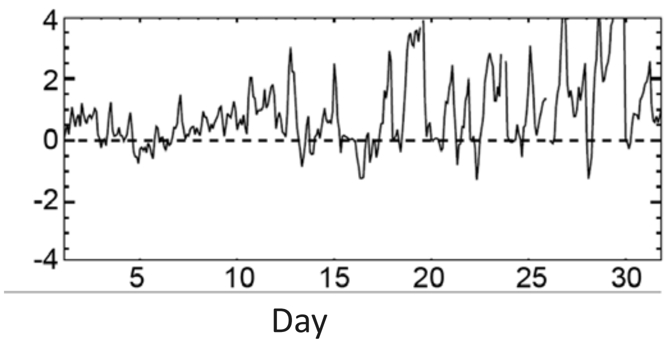
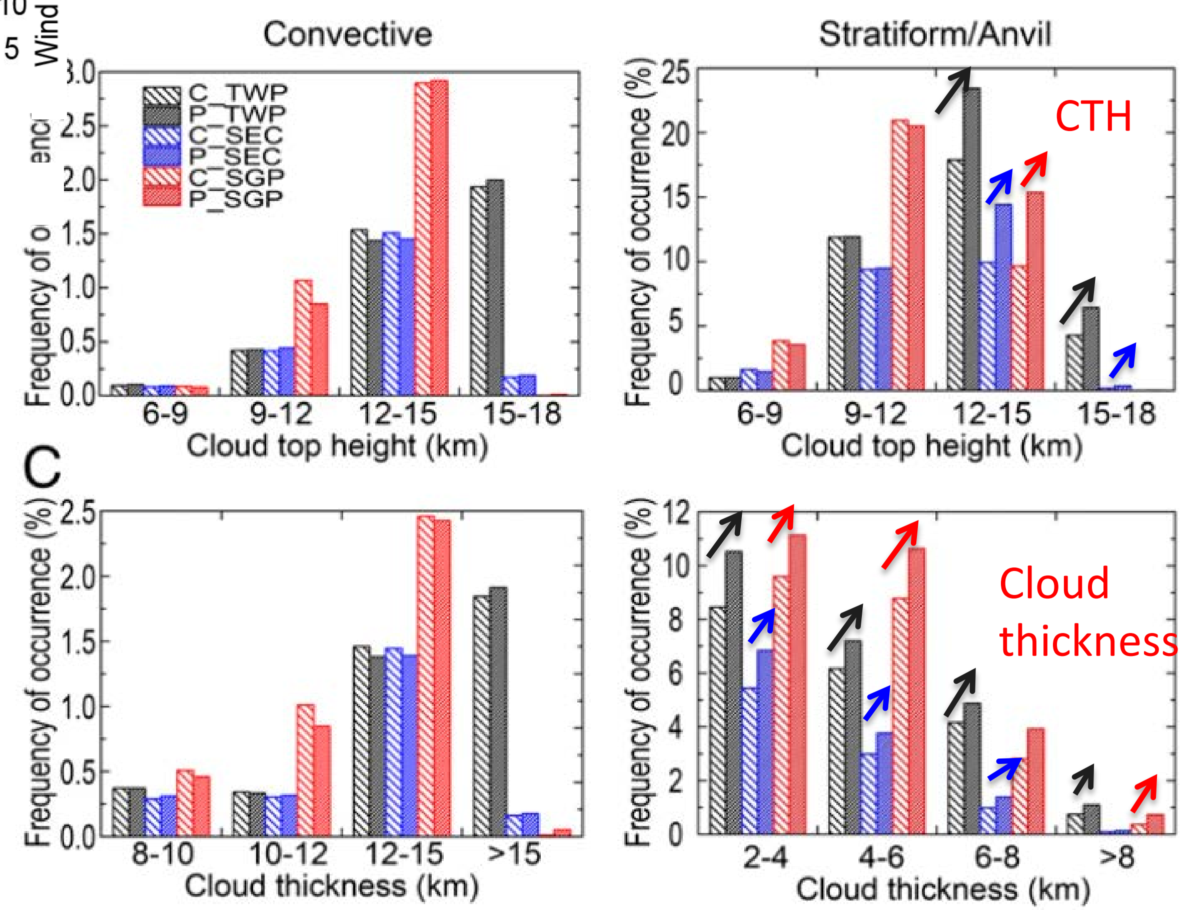
Cloud fraction (TWP)



Cloud top height (TWP)





Convective invigoration or not?

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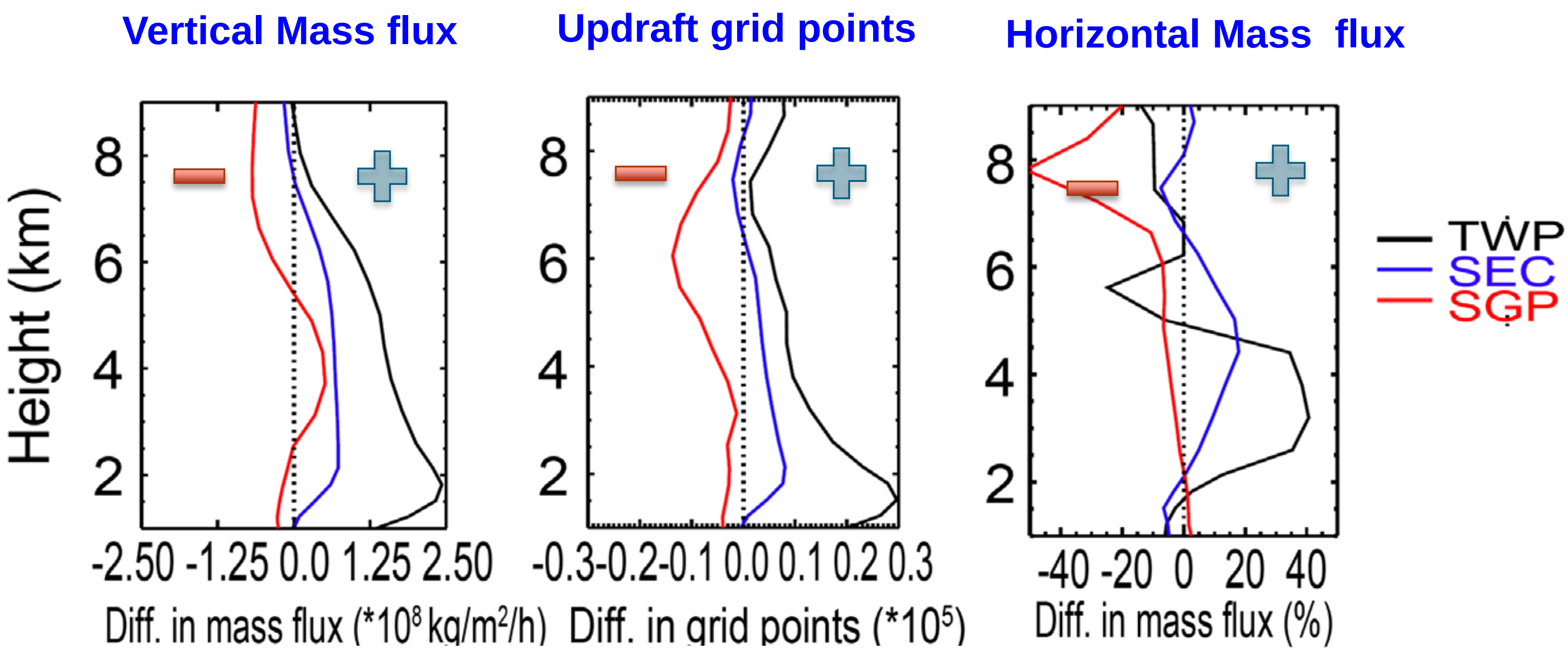

- **Convective invigoration can not unanimously explain the phenomena.**
- **TWP does have the strongest convective invigoration, which is mainly due to the enhanced condensation heating.**

Microphysical effects

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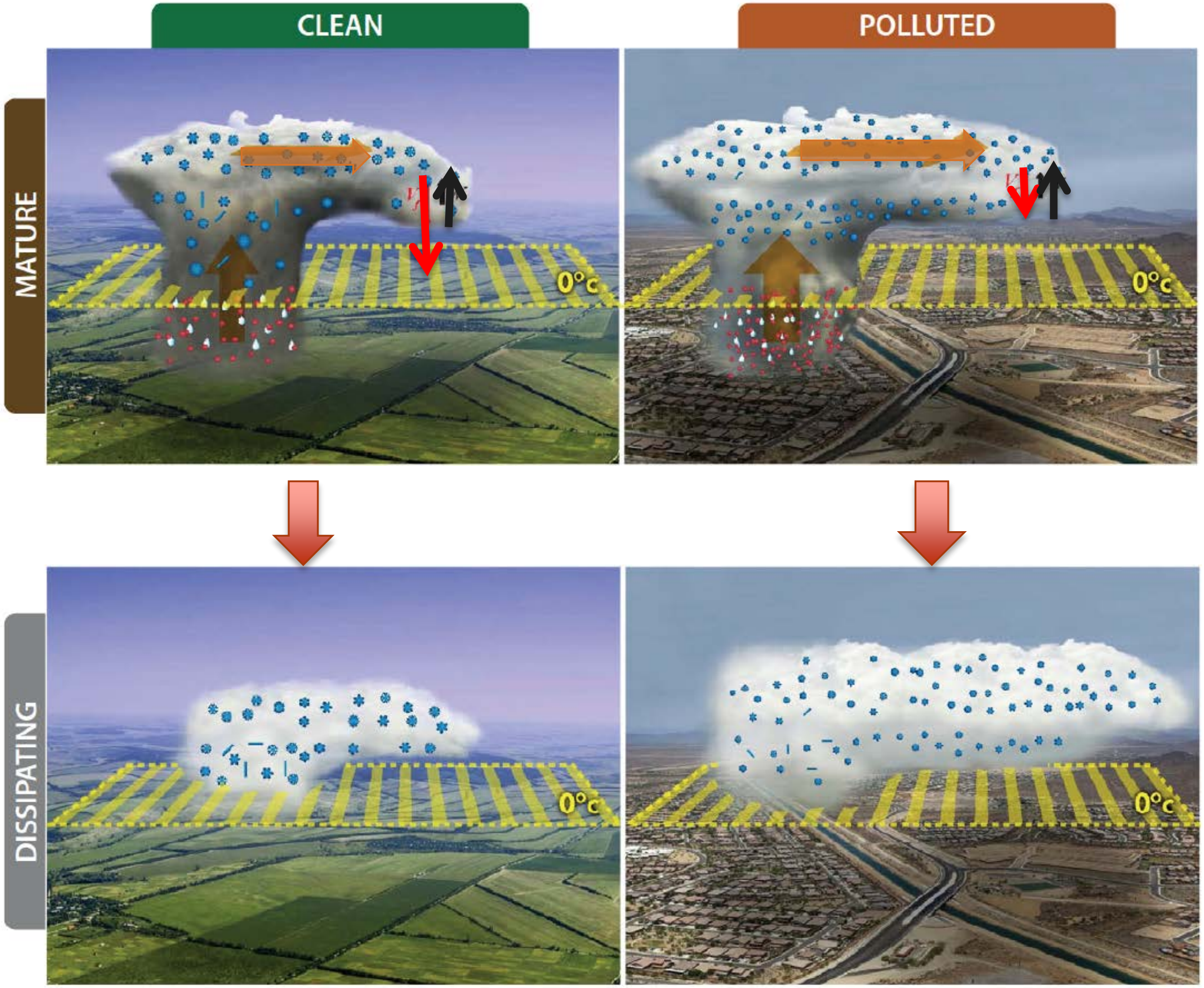

The increased CTH and CF is mainly a result of:

- Overall larger amount of detrained cloud mass in the polluted clouds;
- Much smaller ice/snow size leads to much slower dissipation of stratiform/anvil resulted from smaller fall velocity.

A tentative separation shows that convective invigoration over the tropical region TWP contributes only about 25% of the increase in cloud fraction

Strong TOA and surface Cooling and atmospheric warming

		SW	+	LW	=	NET
TOA	(TWP)	-8.6±0.9		+5.6±0.5	=	-3.0
	(SEC)	-8.0±0.8		+4.3±0.5		-3.7
	(SGP)	-6.3±0.9		+4.4±0.5		-1.9
Atmosphere		-0.5		+5.2		+4.7
		-0.3		+3.4		+3.1
		-0.4		+3.4		+3.0
Surface		-8.1±0.8		+0.4±0.1		-7.7
		-7.7±0.7		+0.9±0.1		-6.8
		-5.9±0.9		+1.0±0.1		-4.9

	SW	LW	LW
(TWP)	-17.8±1.5	+4.9±0.7	+6.7±0.8
(SEC)	-14.3±1.2	+3.4±0.6	+5.8±0.8
(SGP)	-9.7±1.4	+3.7±0.7	+5.7±0.7
	-0.9	+4.2	+6.7
	-0.6	+2.1	+5.4
	-0.6	+2.4	+5.3
	-16.9±1.4	+0.7±0.1	0.0±0.0
	-13.7±1.1	+1.3±0.1	+0.4±0.0
	-9.1±1.3	+1.3±0.2	+0.4±0.1

- **Surface cooling combined with upper-level radiative warming stabilizes atmosphere, countering the thermodynamical invigoration effect.**
- **Climate model could miss this important effect on forcing.**

Summary

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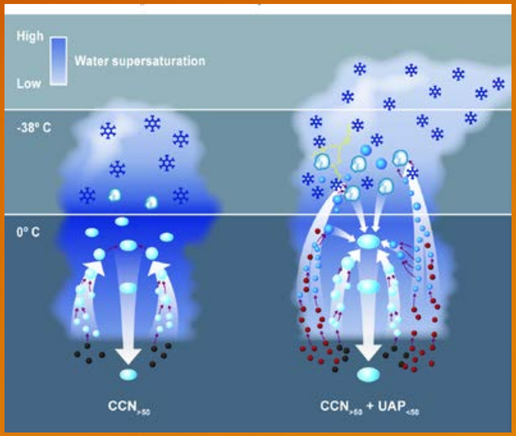
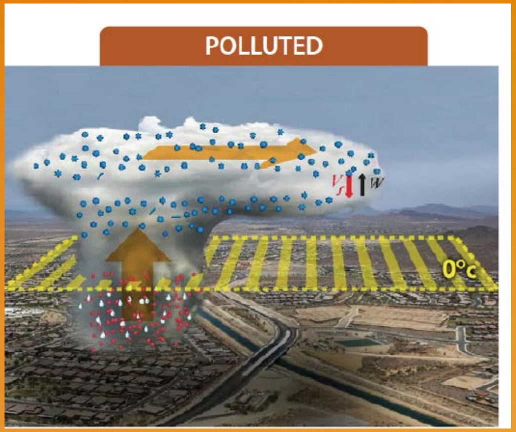
- Aerosols from human activity may significantly influence storms in warm and humid regions especially through warm-phase invigoration. Need more field campaigns over those regions to tackle this problem more robustly and systematically.



- Over a monthly time scale in a large region, aerosols can make summer convective clouds larger and taller through the microphysical effect (smaller but longer-lasting ice particles), explaining observed larger cloud fraction and taller clouds in high aerosol conditions.



Mechanism

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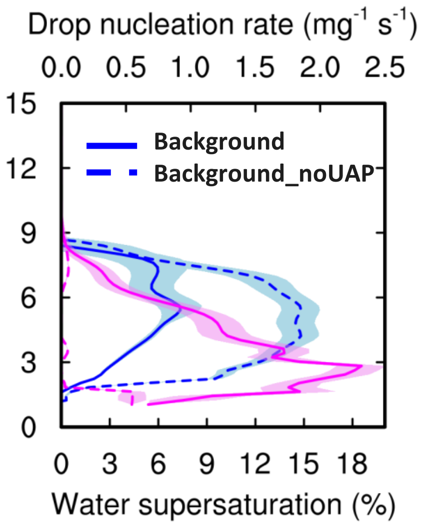
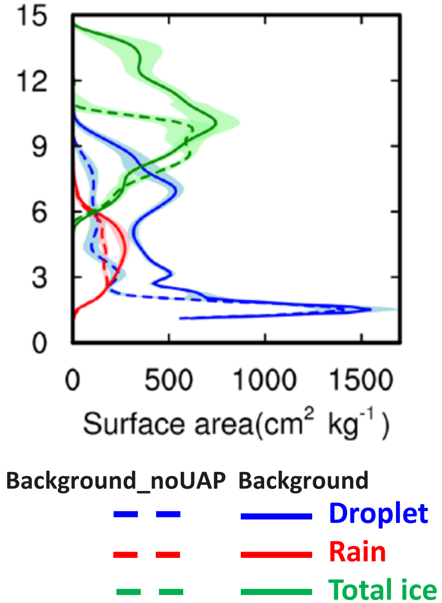
Use **Background** (solid) and **Background_noUAP (dashed)** to illustrate

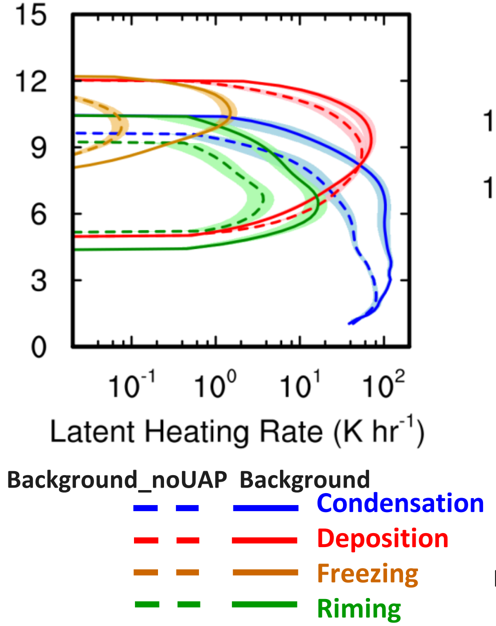
Drop nucleation rate



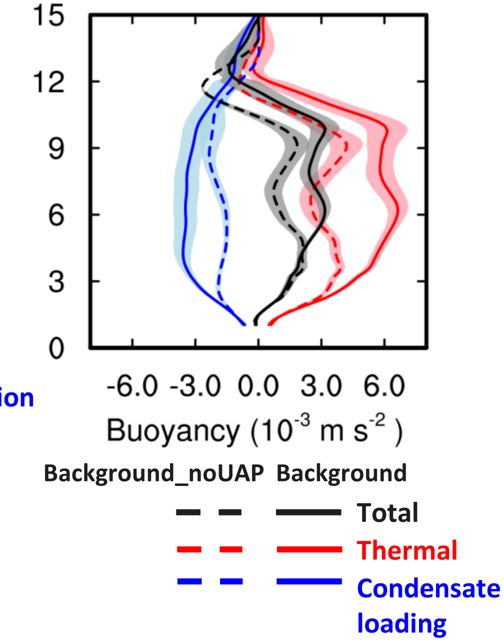
Surface area



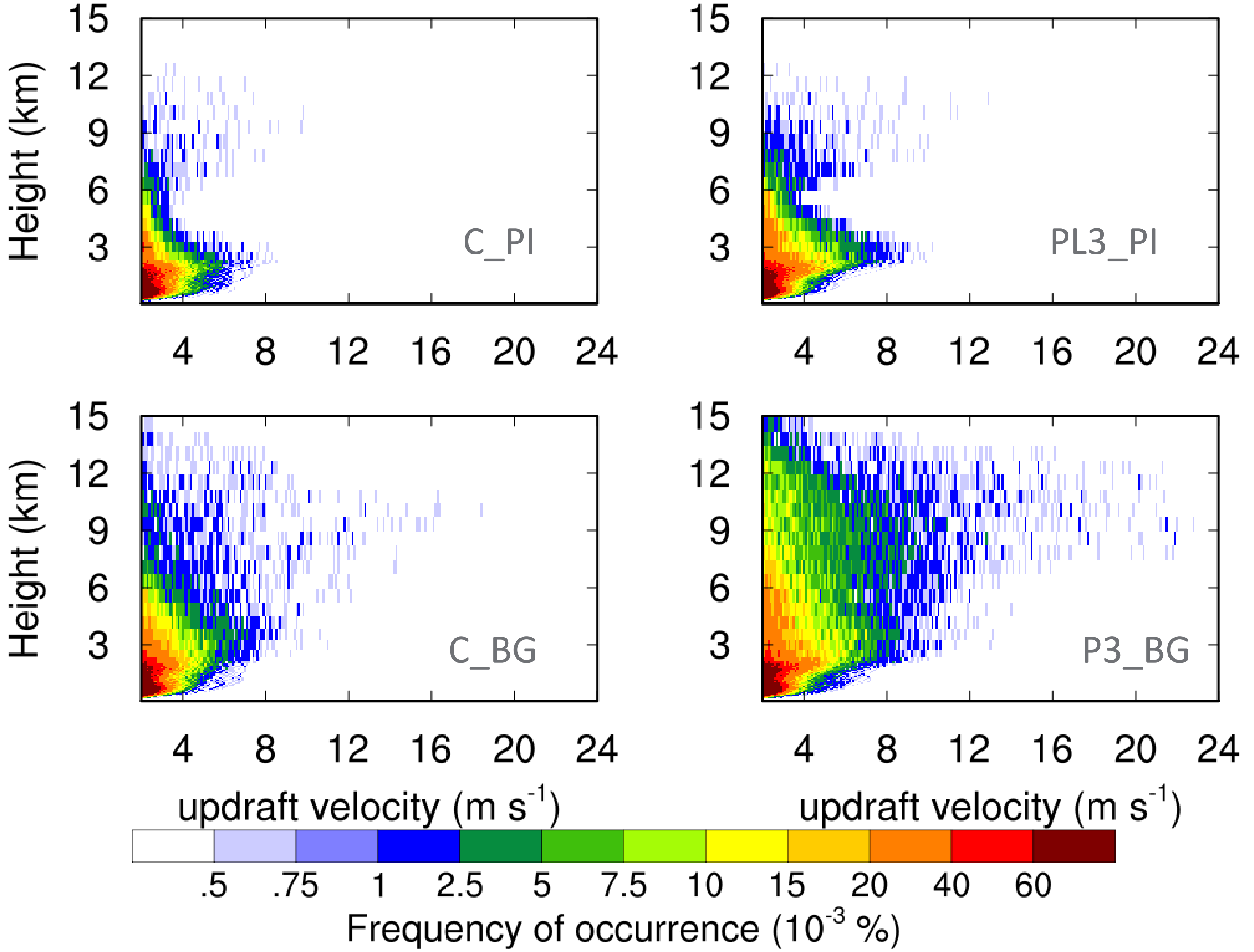
Latent heat



Buoyancy



PDF of updraft velocity



Sensitivity tests on different aerosol SD and VD

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