Aerosol Impacts on Tropical Convective Clouds

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Acknowledgement:
• Many coauthors, particularly my visiting scholars Yuwei Zhang and Chen Qian.
• DOE ASR and RGCM programs
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 can be invigorated due to the delay: “cold-phase invigoration”

Biomass burning: large particles

Fan et al. (*Science*, 2018): observed drastically enhanced updraft velocity and precipitation for convective storms influenced by urban pollution plume at the wet season of Amazon, mainly through: “warm-phase invigoration”

Urban pollution: small particles

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

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

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)

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

• Weak wind shear
• High CAPE
• Winds were northeasterly at the 850 hPa level
Validation of the baseline run: Background + plume

Rain rate at 2.5km

Rain rate (mm hr⁻¹)

- Plume_noUAP
- Background+plume
- SIPAM
- X Band

U (m s⁻¹) V (m s⁻¹)

Height (km)

Temperature (°C) Relative humidity (%)
The observed large enhancements in convective intensity and precipitation by UAP from Manaus pollution plume are reproduced.

Corresponding to drastic decrease in supersaturation.
“Warm-phase invigoration” mechanism
Features of “warm-phase invigoration”

- 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?

* Convective invigoration
* Observed cloud invigoration ★ (increased CTH and CF)
* 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?

- 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

Cloud fraction (TWP)

Cloud top height (TWP)

Convective

CTH

Stratiform/Anvil

Cloud thickness
Convective invigoration or not?

- 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

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**

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<th>SW</th>
<th>LW</th>
<th>NET</th>
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<td><strong>TOA</strong></td>
<td>-8.6±0.9</td>
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<td>(SEC)</td>
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<td>(SGP)</td>
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<td><strong>Atmosphere</strong></td>
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<td>+5.2</td>
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<tr>
<td><strong>Surface</strong></td>
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**Surface cooling combined with upper-level radiative warming stabilizes atmosphere, countering the thermodynamical invigoration effect.**

**Climate model could miss this important effect on forcing.**
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

Drop nucleation rate

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

- **Surface area**
- **Latent heat**
- **Buoyancy**

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PDF of updraft velocity
Sensitivity tests on different aerosol SD and VD