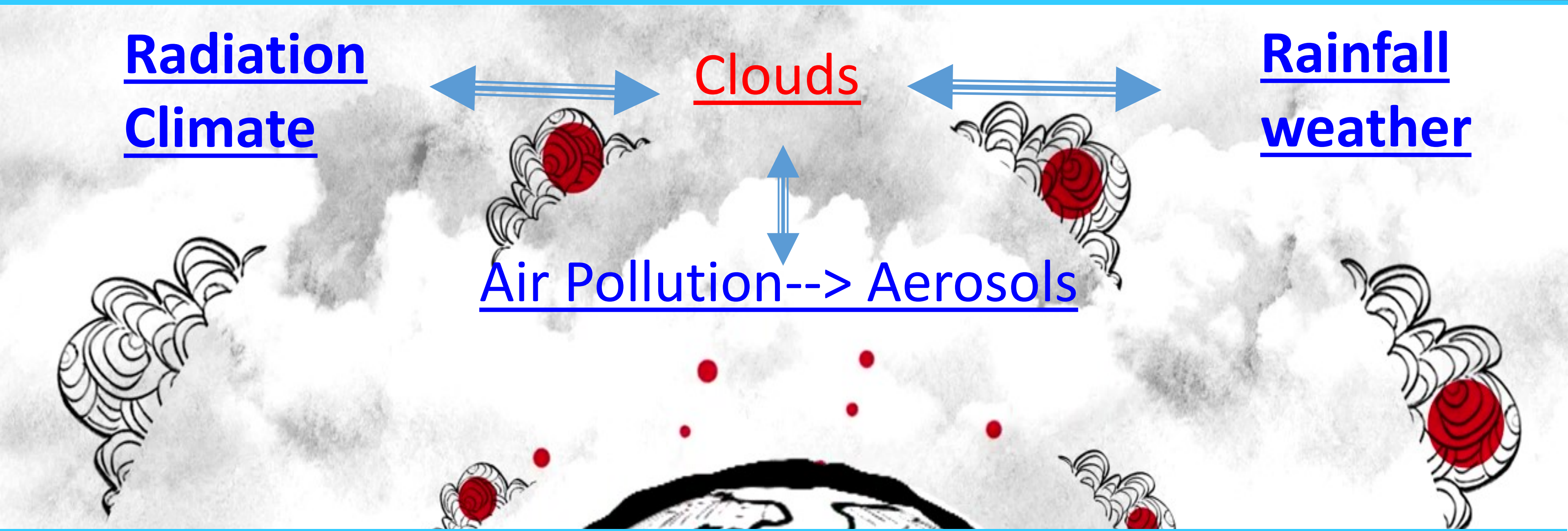
Aerosol > Cloud > Rainfall > Radiation Associations during Indian Summer Monsoon

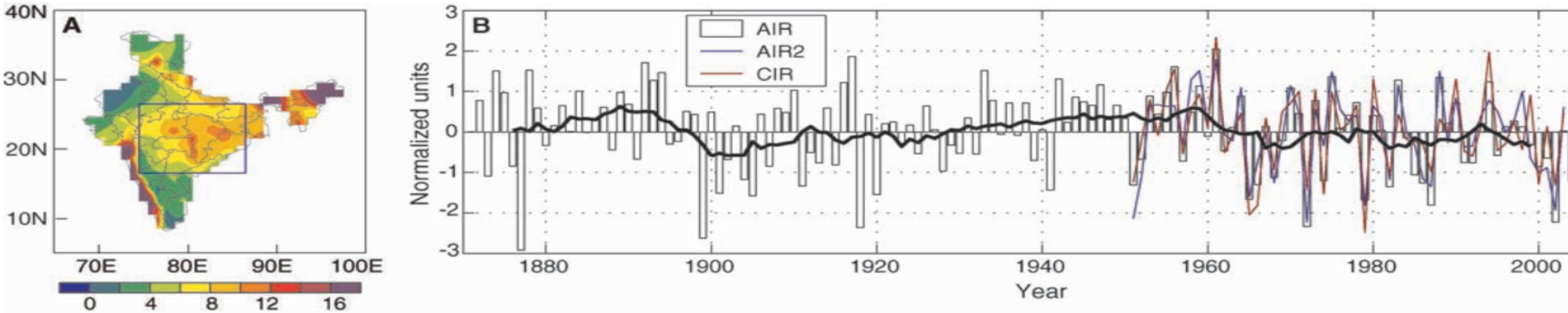


Chandan Sarangi

Collaborators:

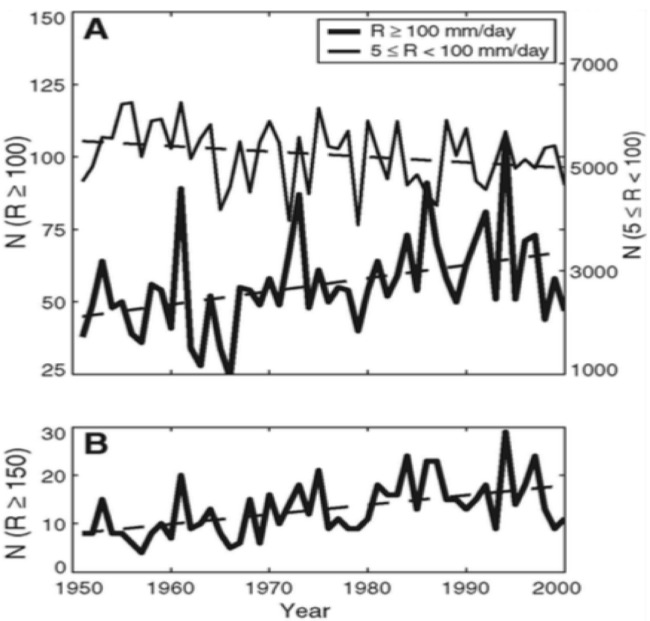
S. N. Tripathi (IITK, India), Geet George (IITK, MPI-Germany)
Vijay Kanawade (Uni. of Hyd.), Abin Thomas (Uni. of Hyd, India)
Ilan Koren (Weizmann inst., Israel)
Yun Qian (PNNL, USA),

Radiative impact of aerosols on monsoonal rainfall



Increasing Trend of Extreme Rain Events Over India in a Warming Environment

B. N. Goswami,[1]* V. Venugopal,[2] D. Sengupta,[2] M. S. Madhusoodanan

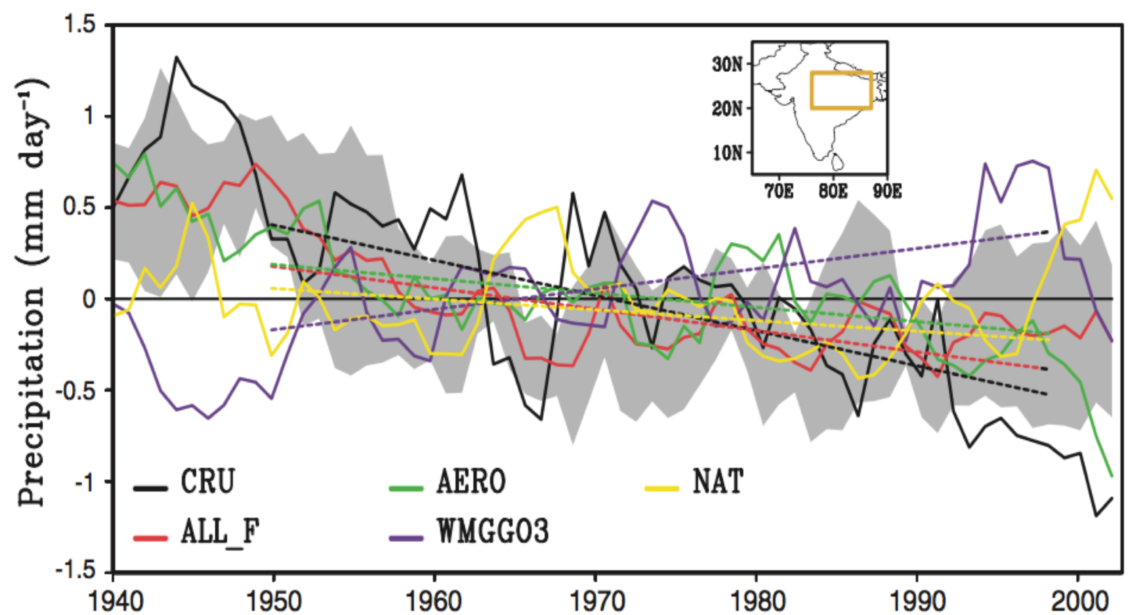


Goswami et al., Science, 2006

Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon

Massimo A. Bollasina,[1] Yi Ming,[2]* V. Ramaswamy[2]

Bollasina et al., Science, 2011

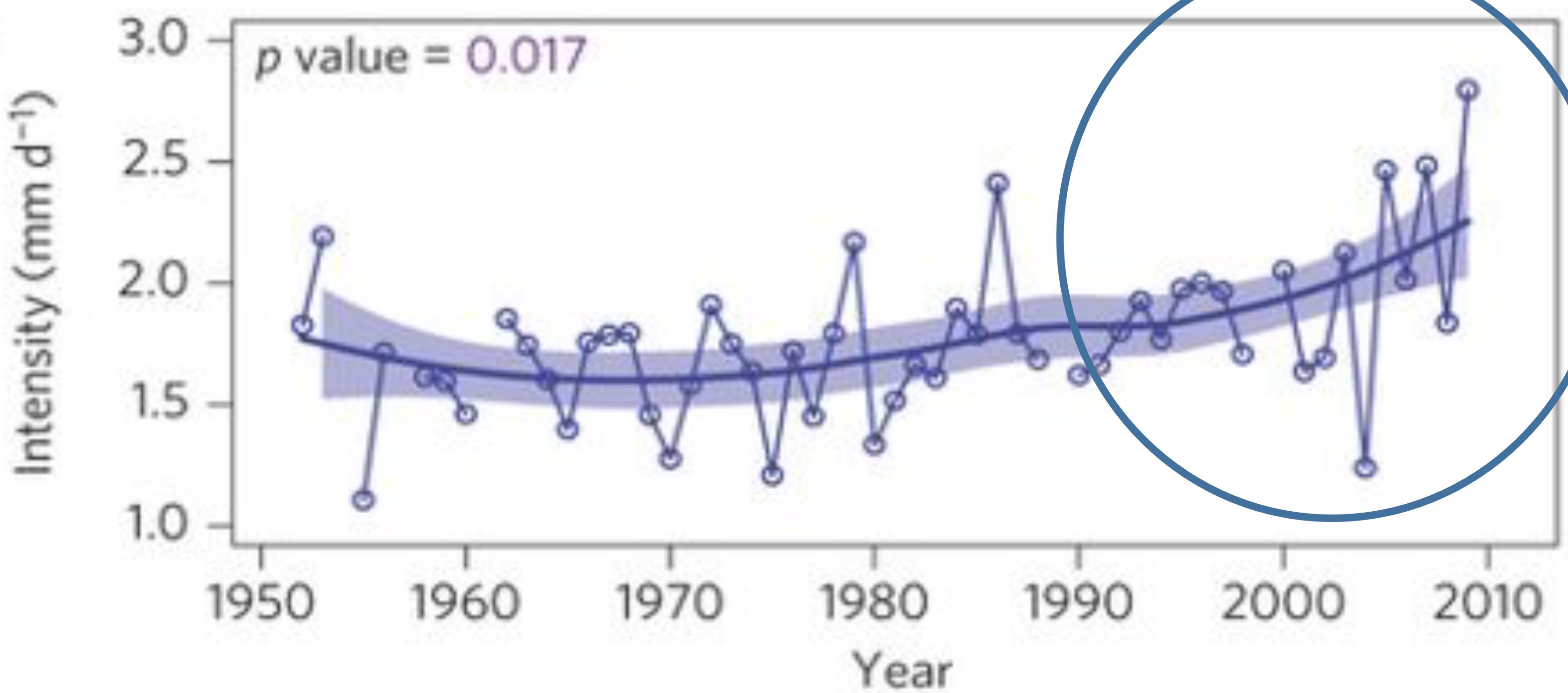


Extreme rainfall intensity is increasing

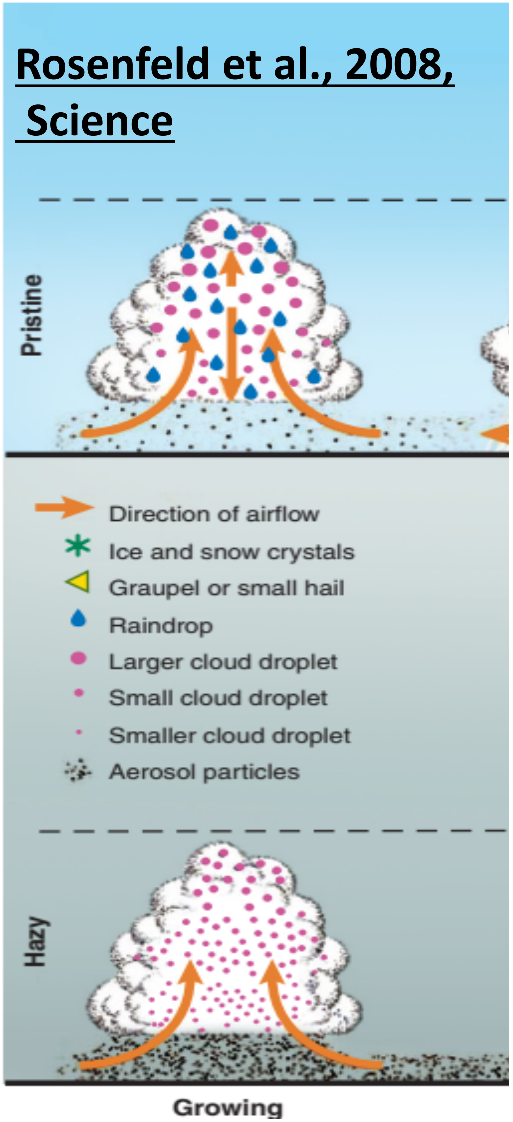
LETTERS
PUBLISHED ONLINE: 28 APRIL 2014 | DOI: 10.1038/NCLIMATE2208
nature climate change

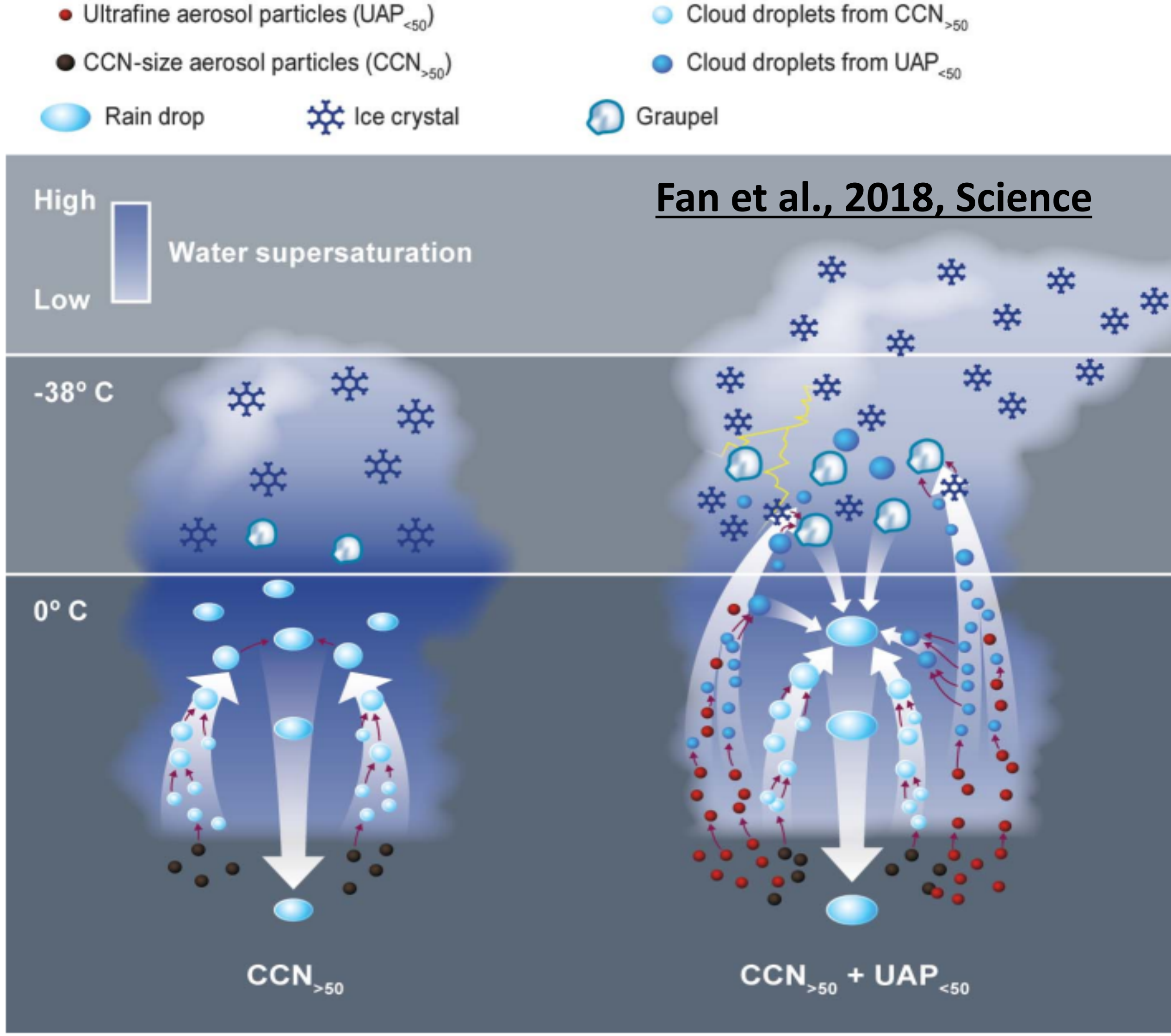
Observed changes in extreme wet and dry spells during the South Asian summer monsoon season

Deepti Singh[1*], Michael Tsiang[1], Bala Rajaratnam[1,2,3] and Noah S. Diffenbaugh[1,2]



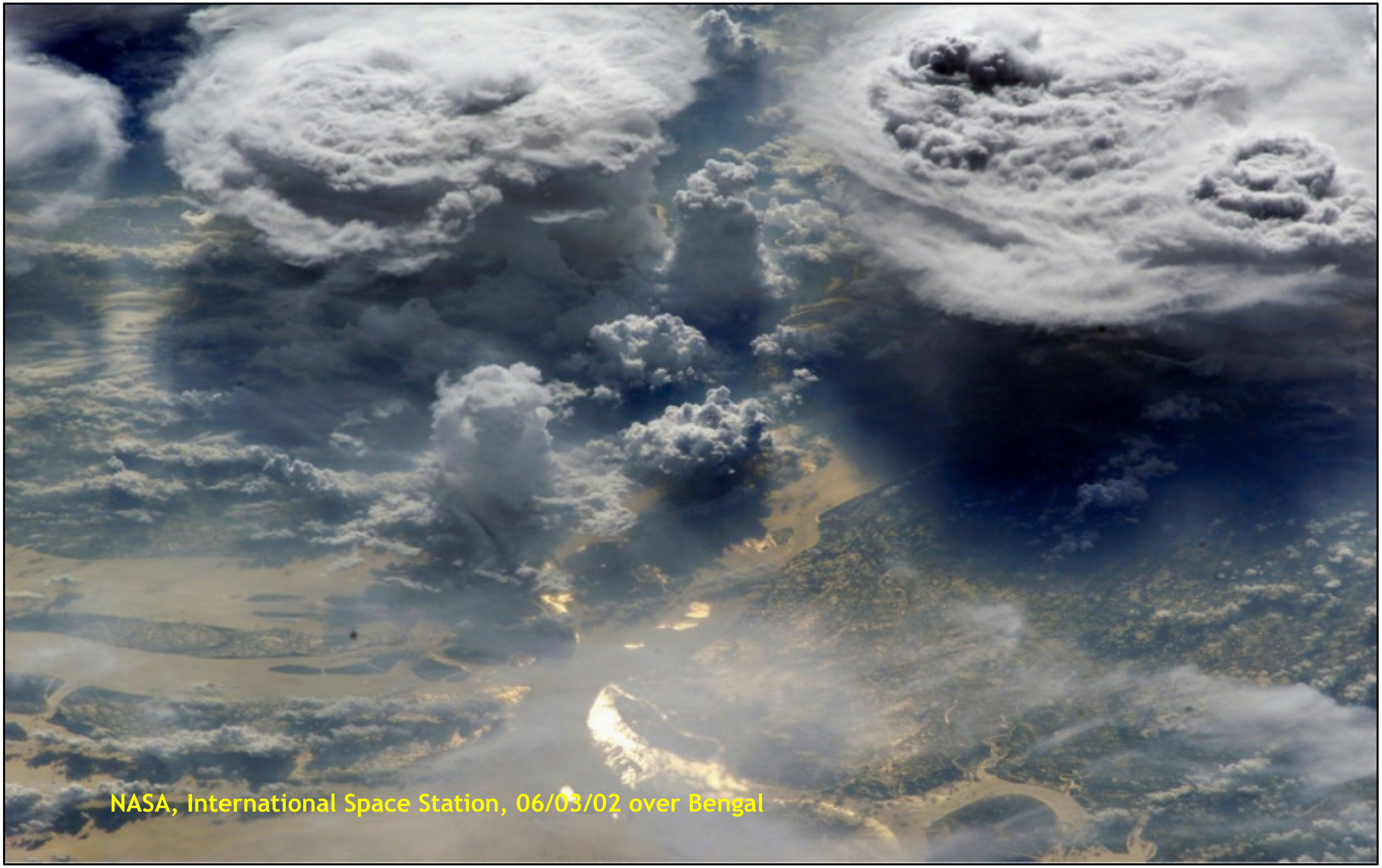
Aerosols can act as cloud condensation nuclei and intensify rainfall





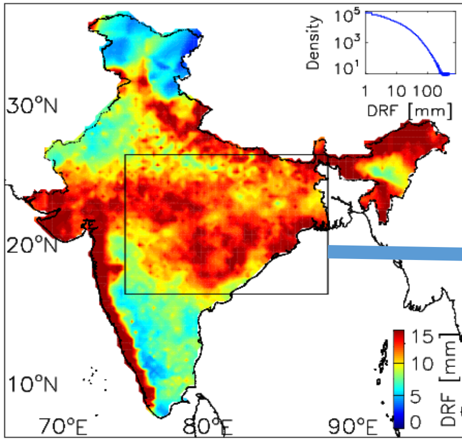
Fundamentally, Clouds are composed of droplets formed due to condensation of moisture on aerosols (CCN) under supersaturated conditions

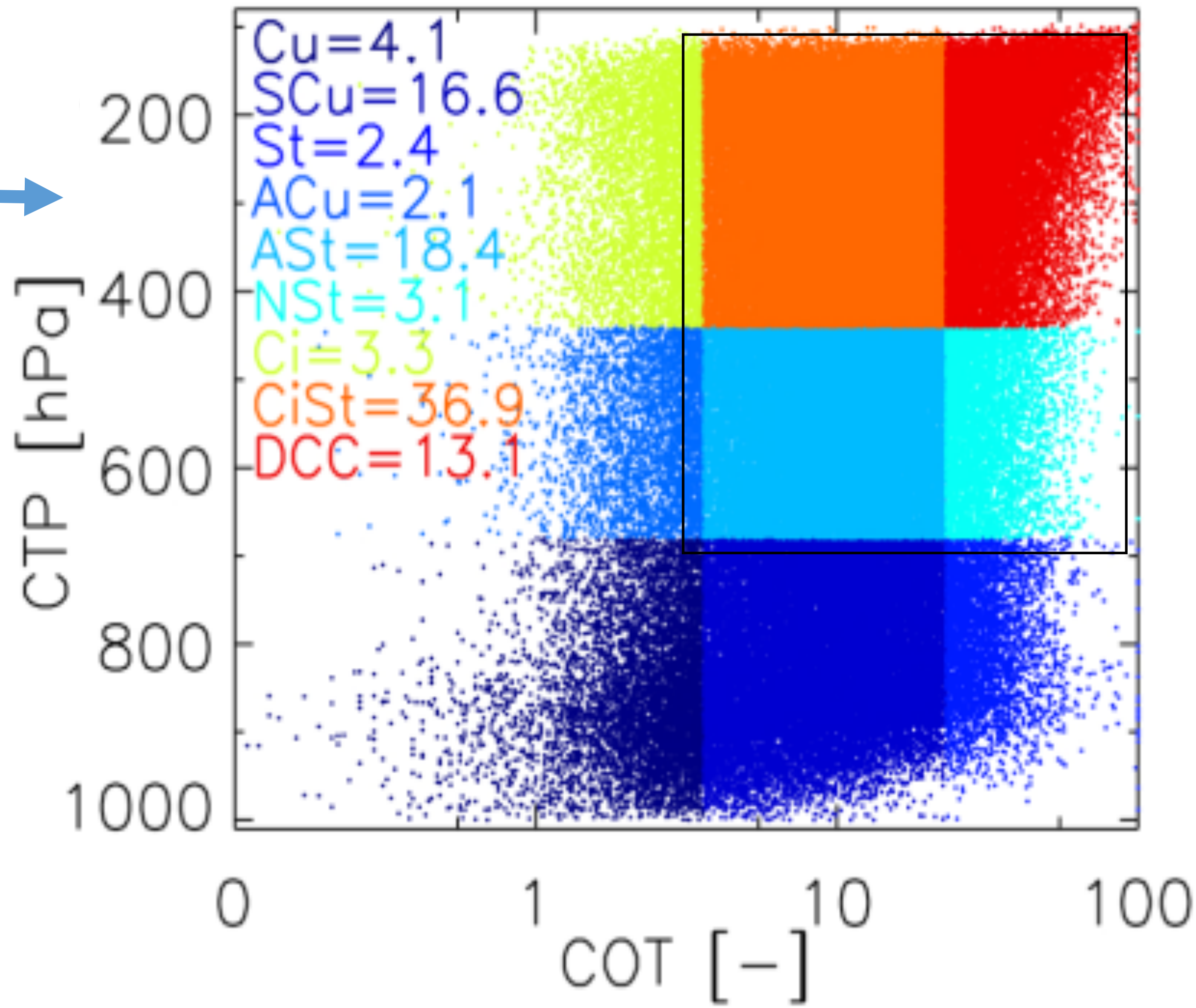
Complexity : Convective Cloud Systems India



Mesoscale cloud systems are combination of Anvils & Towers

Which cloud regime dominates rainfall over ISMReg?

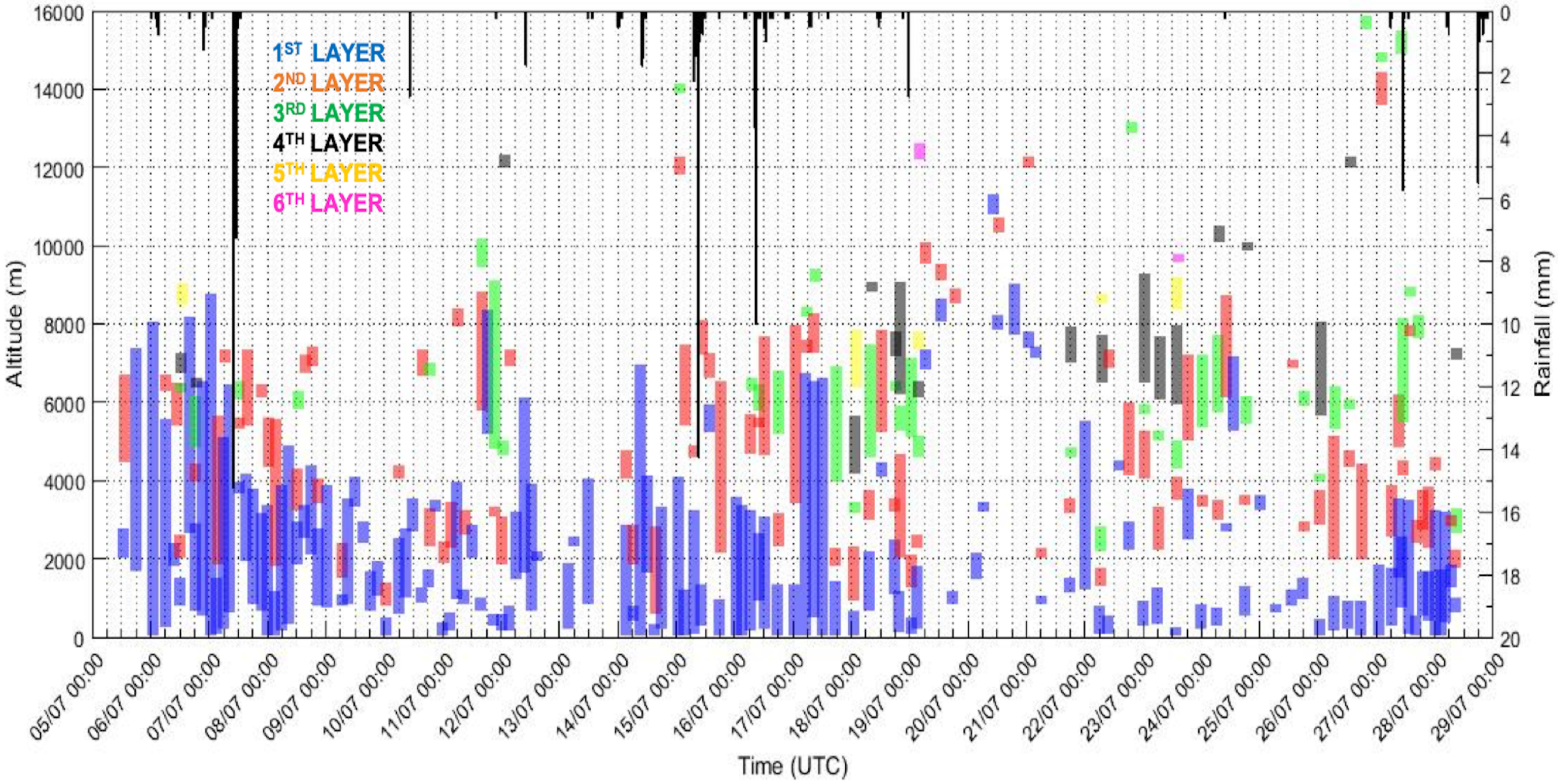




~70% of clouds over the ISMReg are convective cloud systems.

AIvE on transition of convective clouds from Tower to strati-form

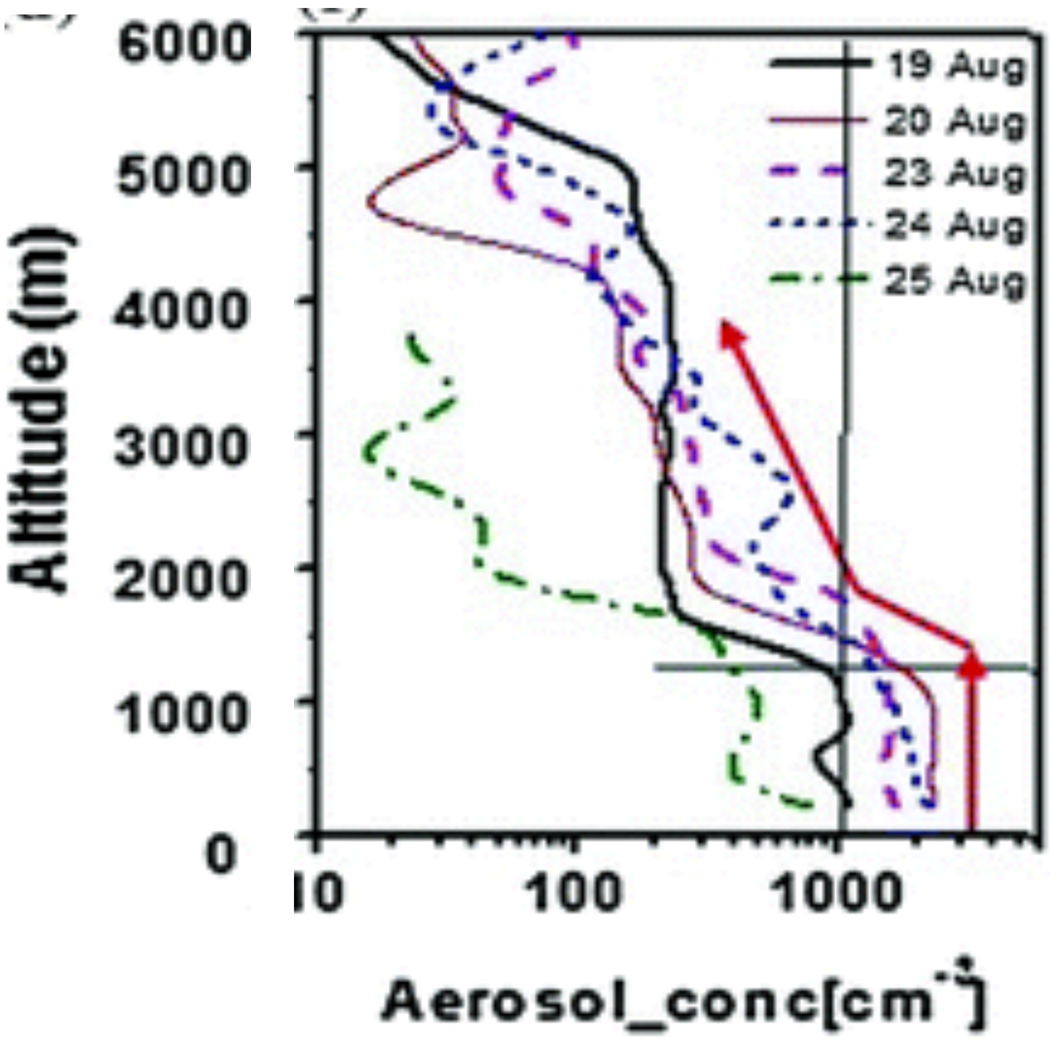
High frequency and high resolution Radiosondes were used to estimate the cloud layers over the atmospheric column of Kanpur during July, 2016.



[George, Sarangi et al., 2018, JGR]

Aerosol vertical distribution during monsoon

CAIPEEX flight measurements over Bareilly

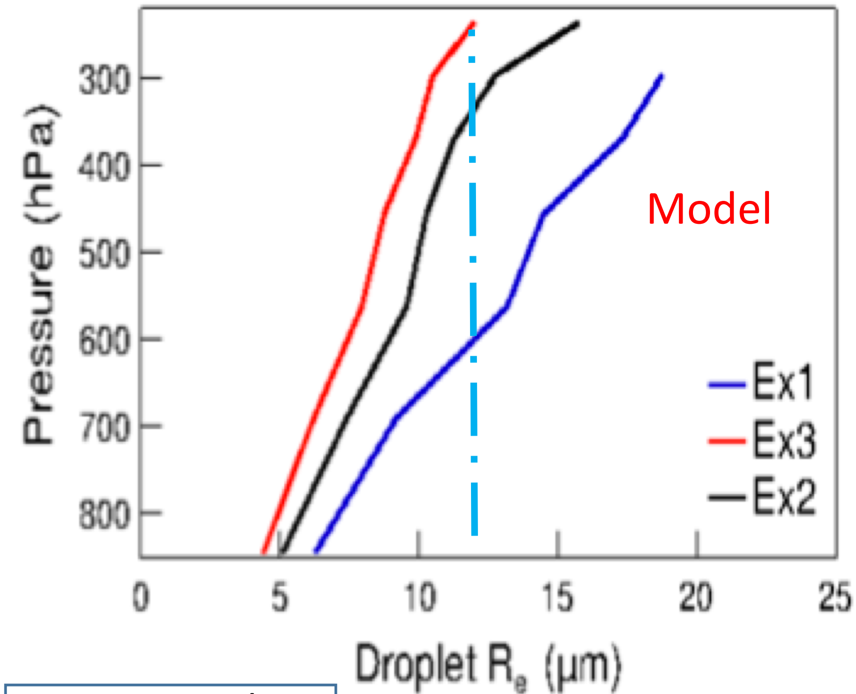


High Aerosol concentration below 1 km altitude

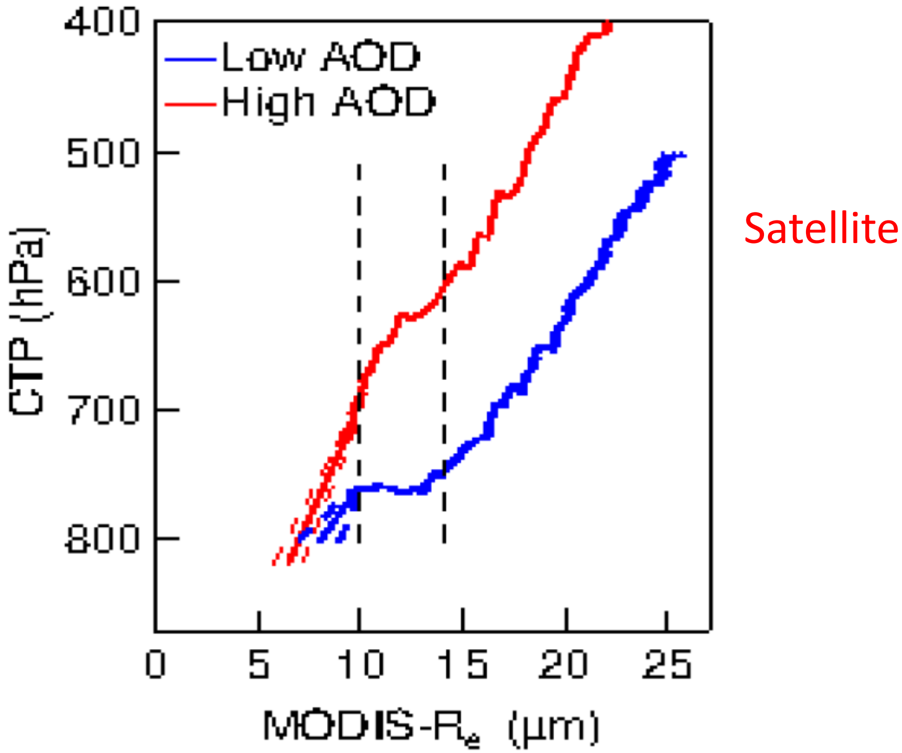
Natural laboratory for aerosol-cloud-rainfall research

Prabha et al., 2012

Lower elevational gradient in droplet size under high pollution



Ex1. 4500/cc
Ex2. 9000/cc
Ex3. 15500/cc



[Sarangi et al., 2017, ACP]

Growth rate of Cloud droplet size with altitude decreases for high CCN loading

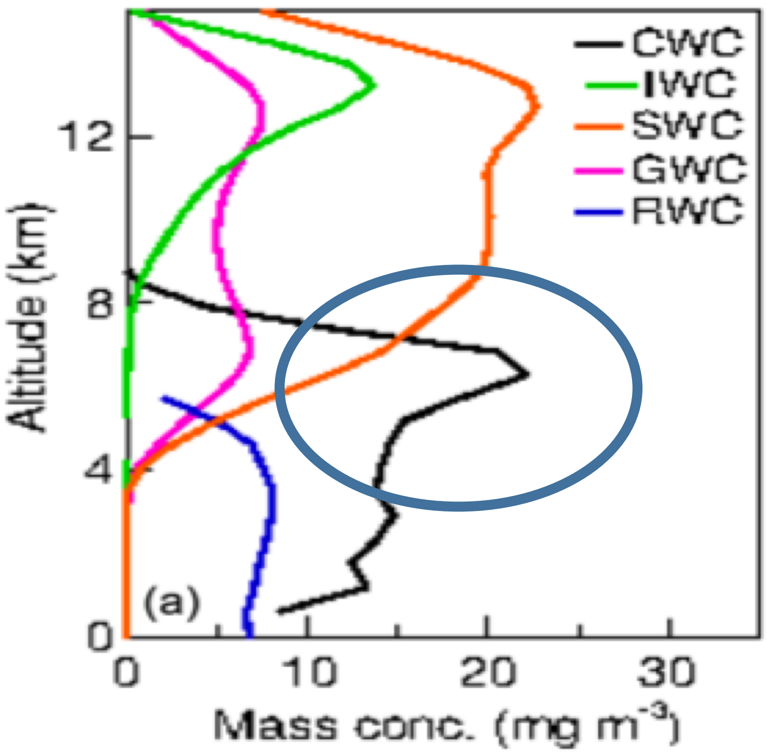
Thus, delaying initial rain formation and pushing more liquid mass into upper/cooler atmosphere

Cloud Ice to cloud liquid ratio increases with aerosol loading

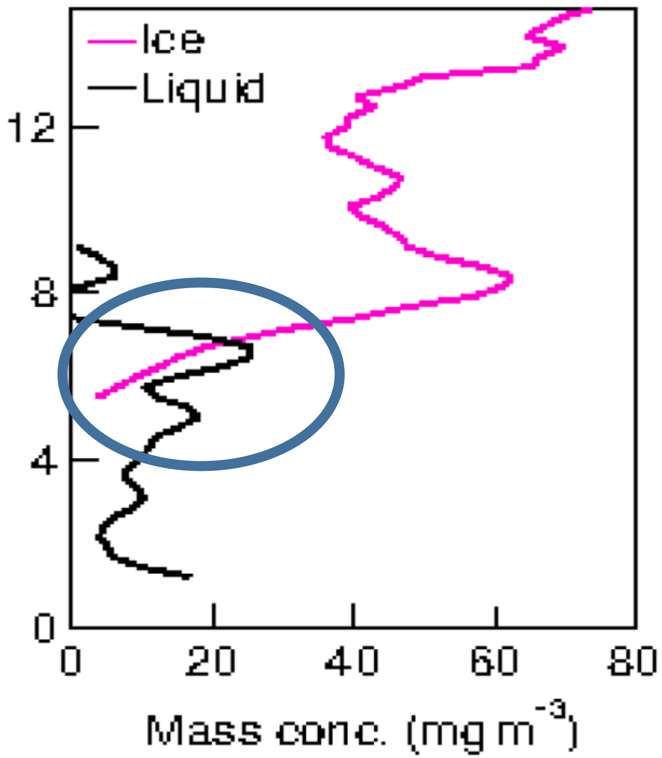
Increase in AOD is associated with –

1. Increase in elevated layer of super-cooled rain drops
2. Enhancement ice phase mass concentration

model

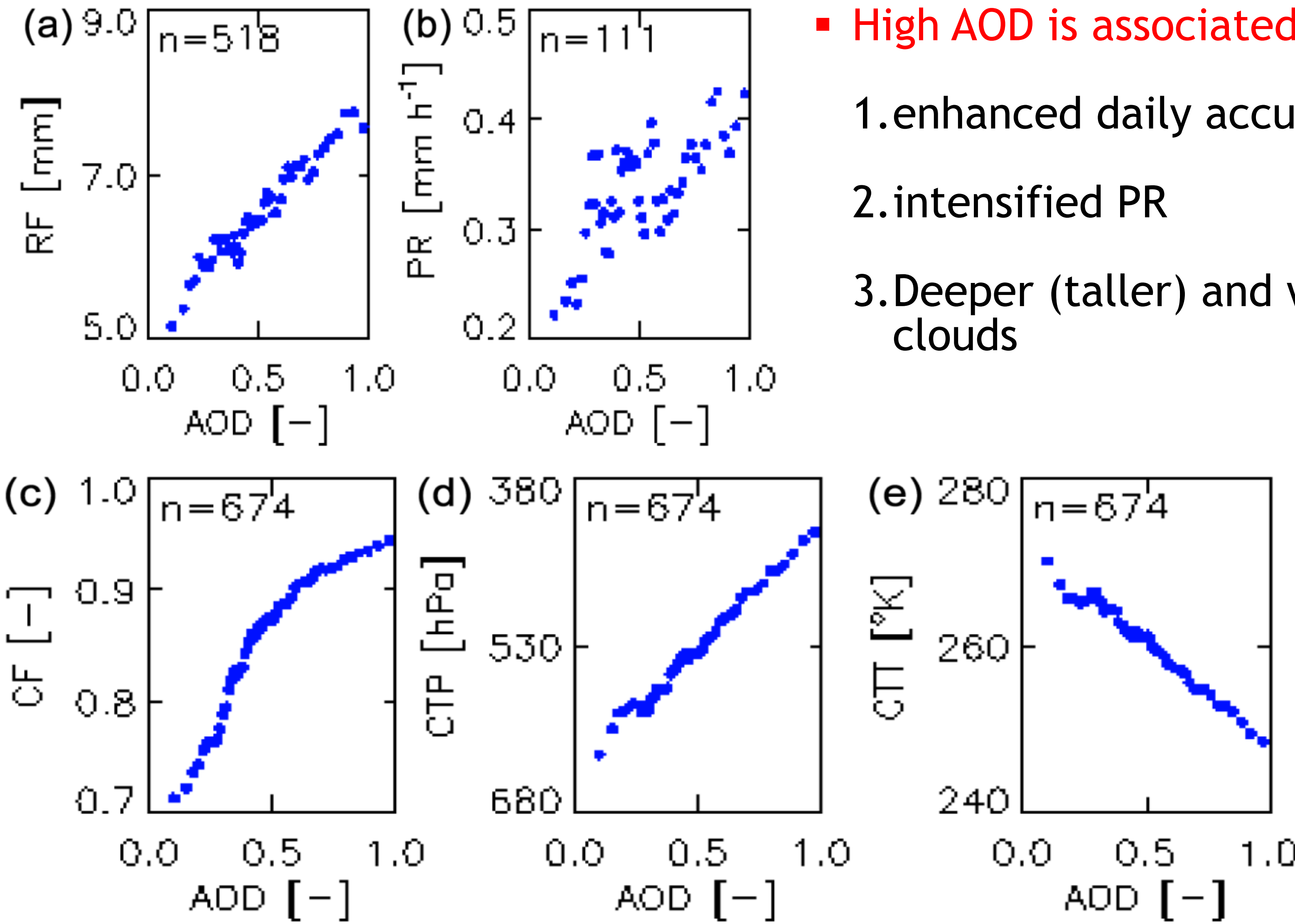


Satellite (HAS-LAS)



[Sarangi et al., 2017, ACP]

Aerosol-Cloud-Rainfall satellite measurements over ISMReg

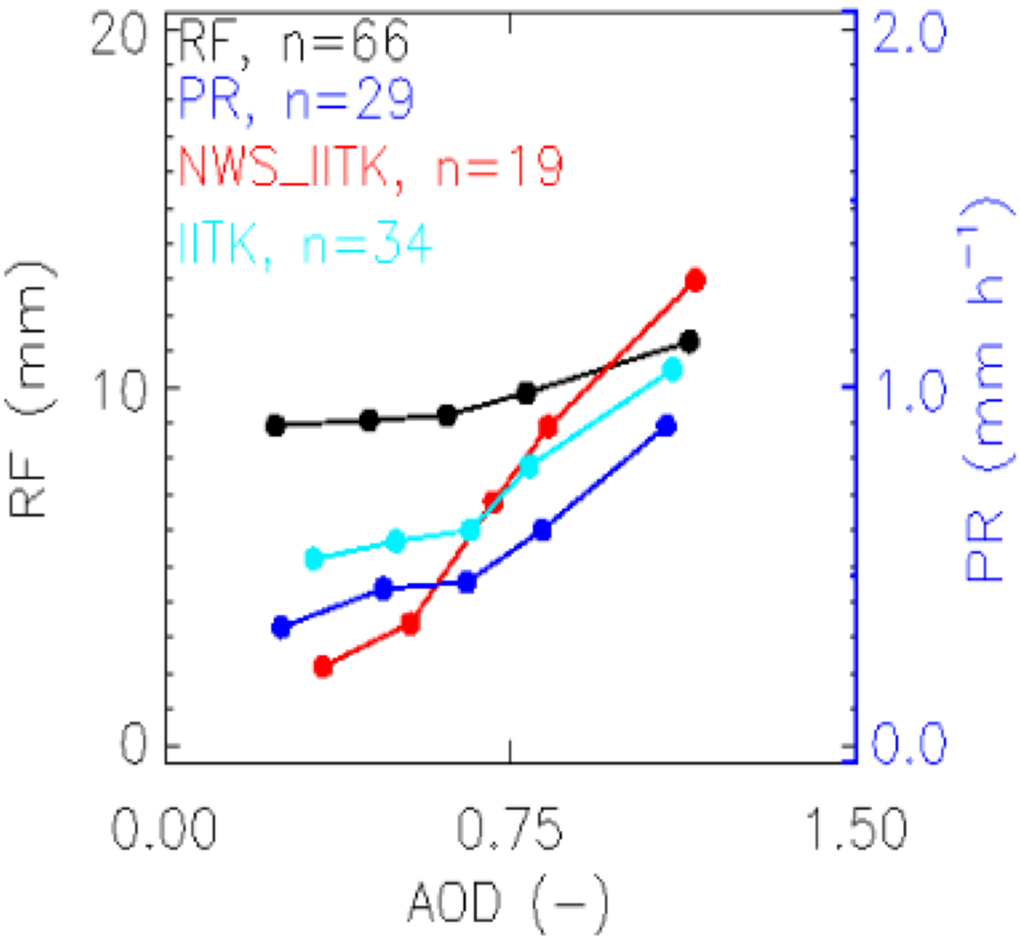


- High AOD is associated with –
  1. enhanced daily accumulated RF
  2. intensified PR
  3. Deeper (taller) and wider clouds

RF, PR and cloud properties with collocated AOD measurements during 2002-2013 are used.

[Sarangi, et al, ACP, 2017]

Aerosol-rainfall in-situ measurements over Kanpur



RF is daily IMD .25 deg gridded product over Kanpur

PR is daily precipitation rate at .25 deg gridded TRMM data product over Kanpur

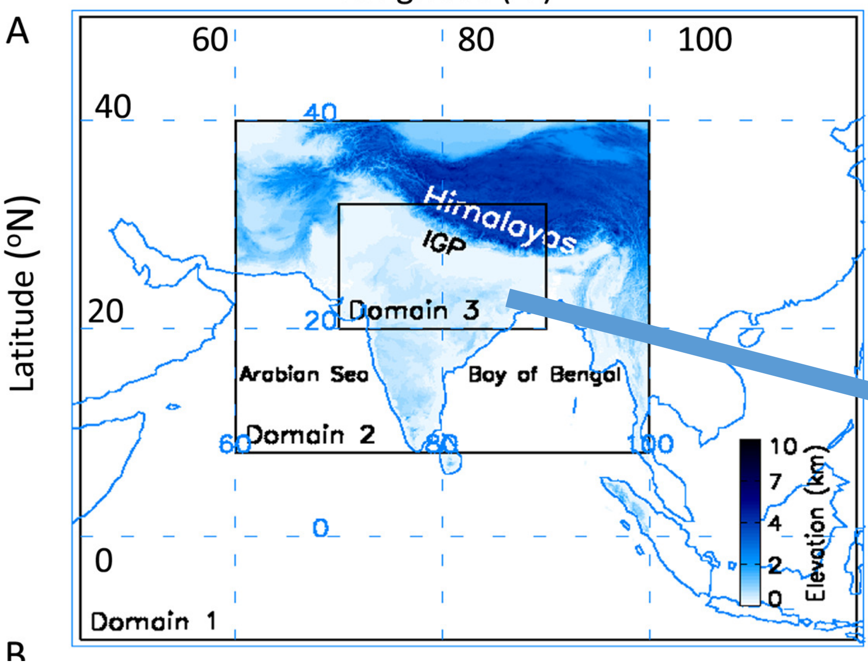
IITK is hourly rainfall point measurement over IIT, Kanpur

NWS_IITK is same as IITK but for days with no prior rain and AOD is only for pre-rainfall hour

Rainfall and aerosol loading has a positive association irrespective of wet scavenging effect

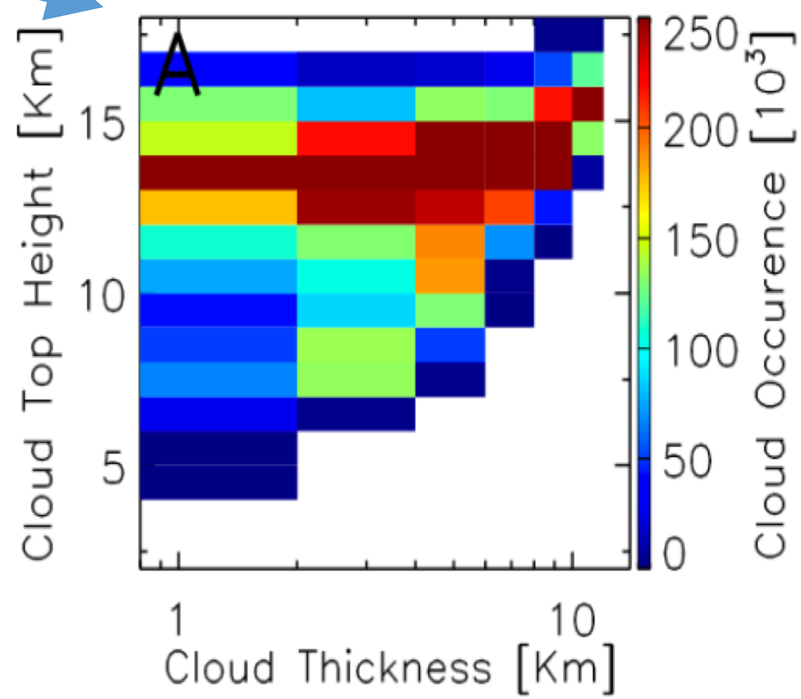
[Sarangi, et al, ACP, 2017]

Simulations infuse causality: Mesoscale cloud systems



Two aerosol sensitivity WRF experiments were performed and compared

1. HAS: CCN emission fluxes based on 7-year Global reanalysis climatology
2. LAS: Value of fluxes used in sim#1 was divided by 100



Cloud population analysis

For each grid within Domain 3, every hour, if the CWC > .0001 g/m^3

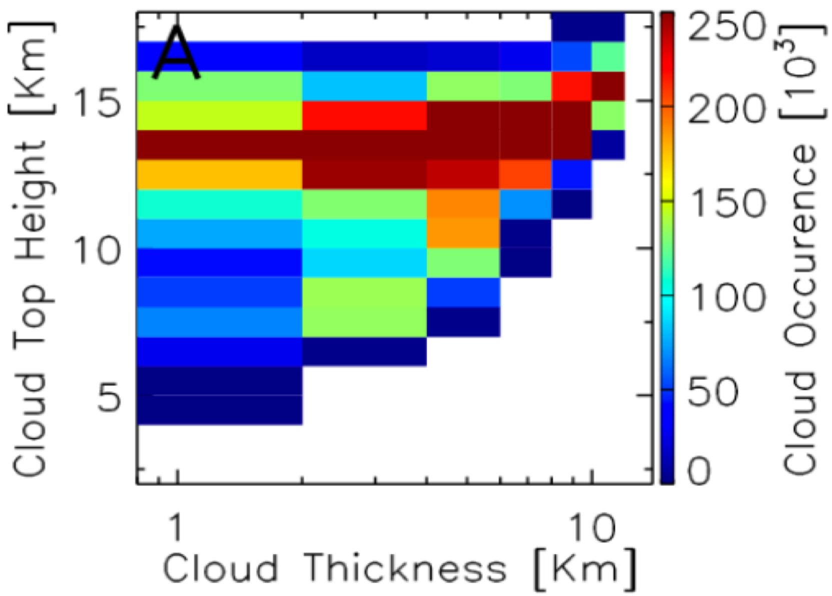
The Cloud base height, cloud top height (CTH) and thus cloud thickness (CT) is registered

The cloud population for the entire simulation is plotted on a CTH and CT axes.

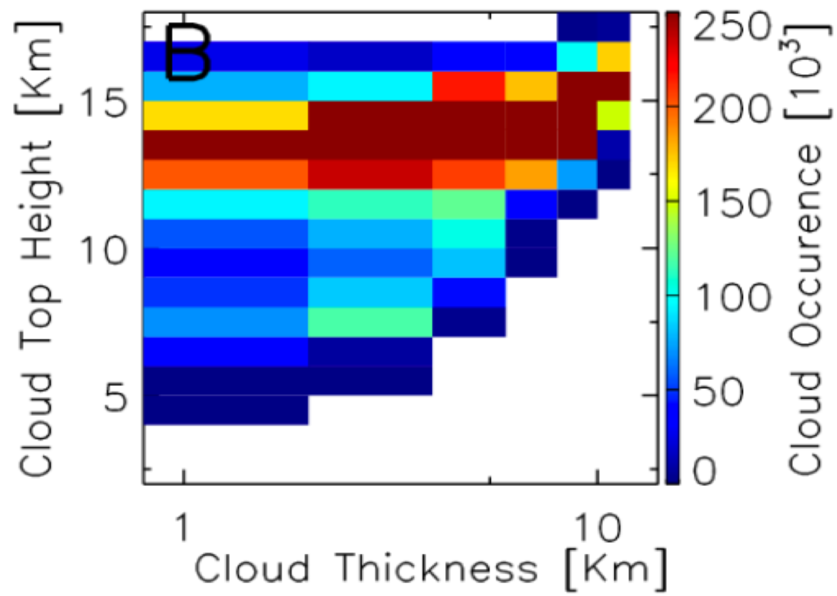
[Sarangi et al., 2018, Nat. Comm.]

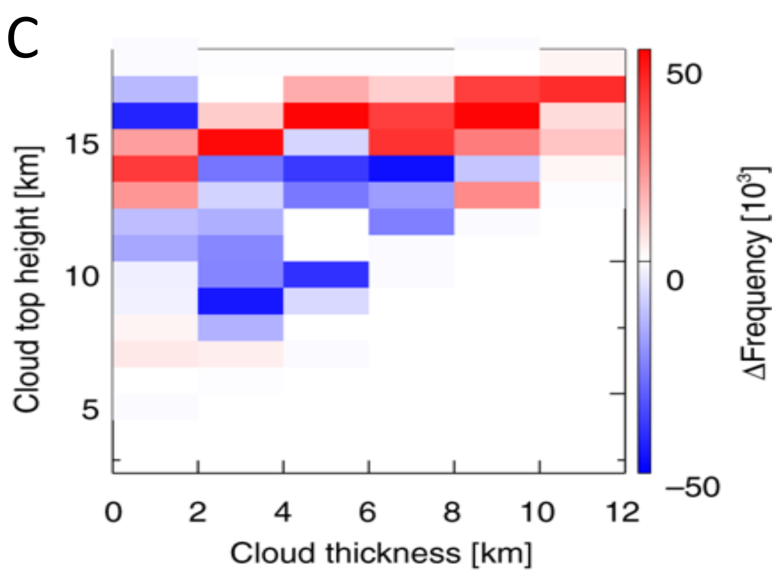
CCN-induced increase in cloud macro-physics

HAS



LAS





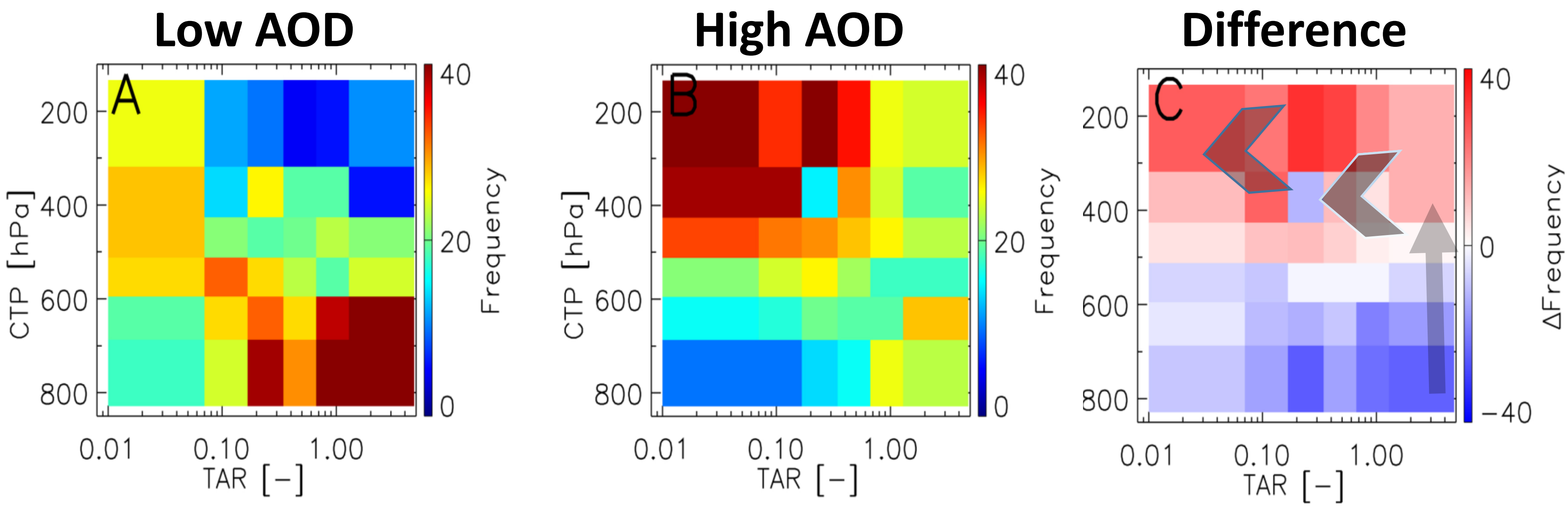
Under high CCN loading

1) **Cloud top height increases for both deep convective clouds**

2) **Deeper convective clouds enhances**

[Sarangi et al., 2018, Nat. Comm.]

AIvE on transition of convective clouds from Tower to strati-form



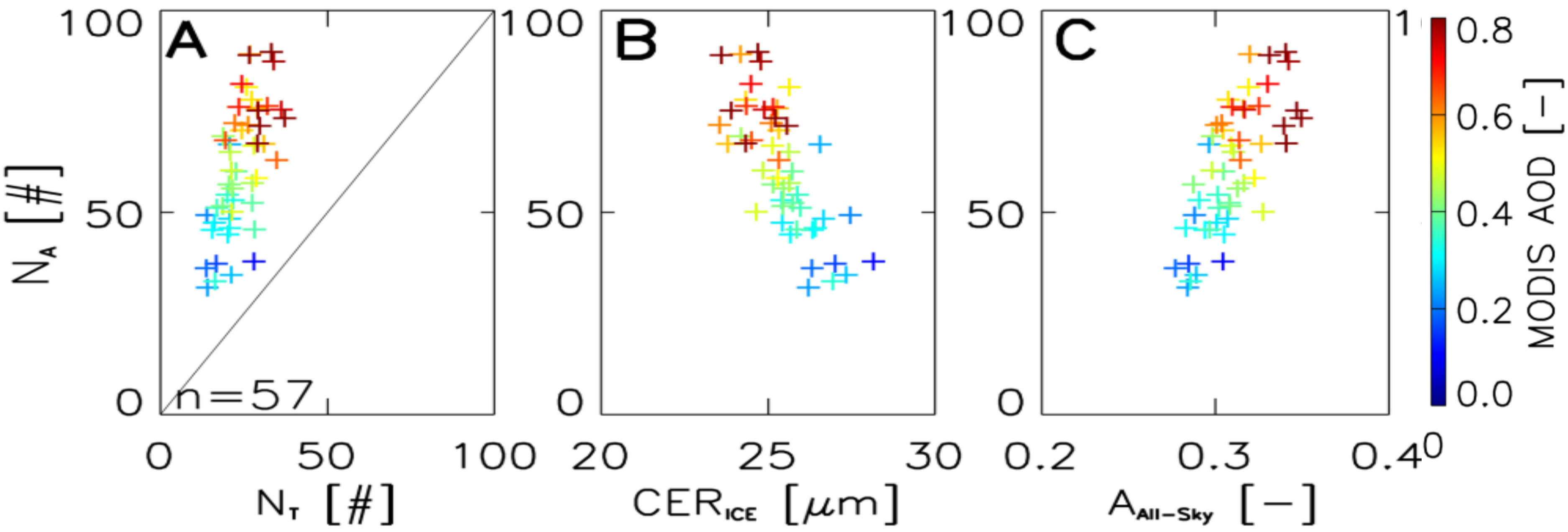
- Tower regime: COT_{ICE}> 10; Anvil regime: COT_{ICE}< 10

- TAR is given by number of pixels in the tower regime (N_T) divided by the number of pixels in the anvil regime (N_A).

- TAR>1 → Tower cloud
- TAR<1 → Anvil Stratiform cloud

[Sarangi et al, Nat. Comm., 2018]

AIvE magnifies cloud brightening effect

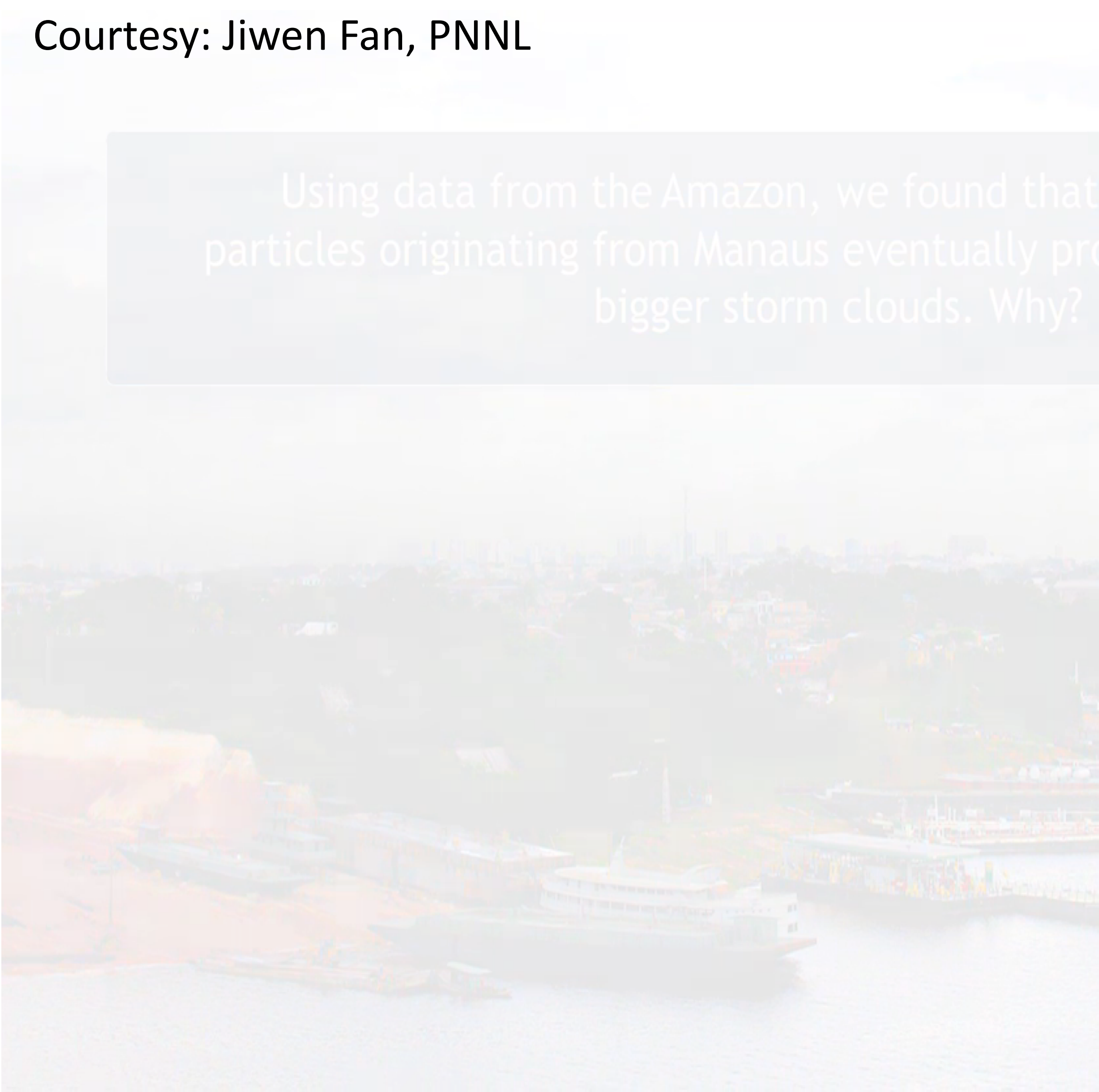


- The frequency of occurrence of SACs increases and the particle size decreases with AOD(*A&B*).
- The decrease in size and enhancement of SACs due to AIvE causes increased albedo and decrease in OLR with AOD.
- which cause enhanced SW reflectance and cooling; Longer life of SACs also adds on to the net cooling effect

[Sarangi et al, Nat. Comm., 2018]

Summary

Courtesy: Jiwen Fan, PNNL



More aerosol

↓

Higher conc. of smaller droplets

↓

Less warm rain & more latent heat release

↓

Increase in flux of liquid mass across FL

Increase in concentration of super-cooled droplets above FL

More ice hydrometeor formation

More latent heat release

Increase in cloudiness (tower depth and cloud spread)

↓

Increase in rainfall intensity, stratiform clouds and surface cooling

Summary, implications and future vision

- Aerosol-induced cloud invigoration shows clear signature of intensifing rainfall during Indian monsoon period
- AIvE induces changes in mesoscale cloud structure enhancing surface cooling effects of clouds

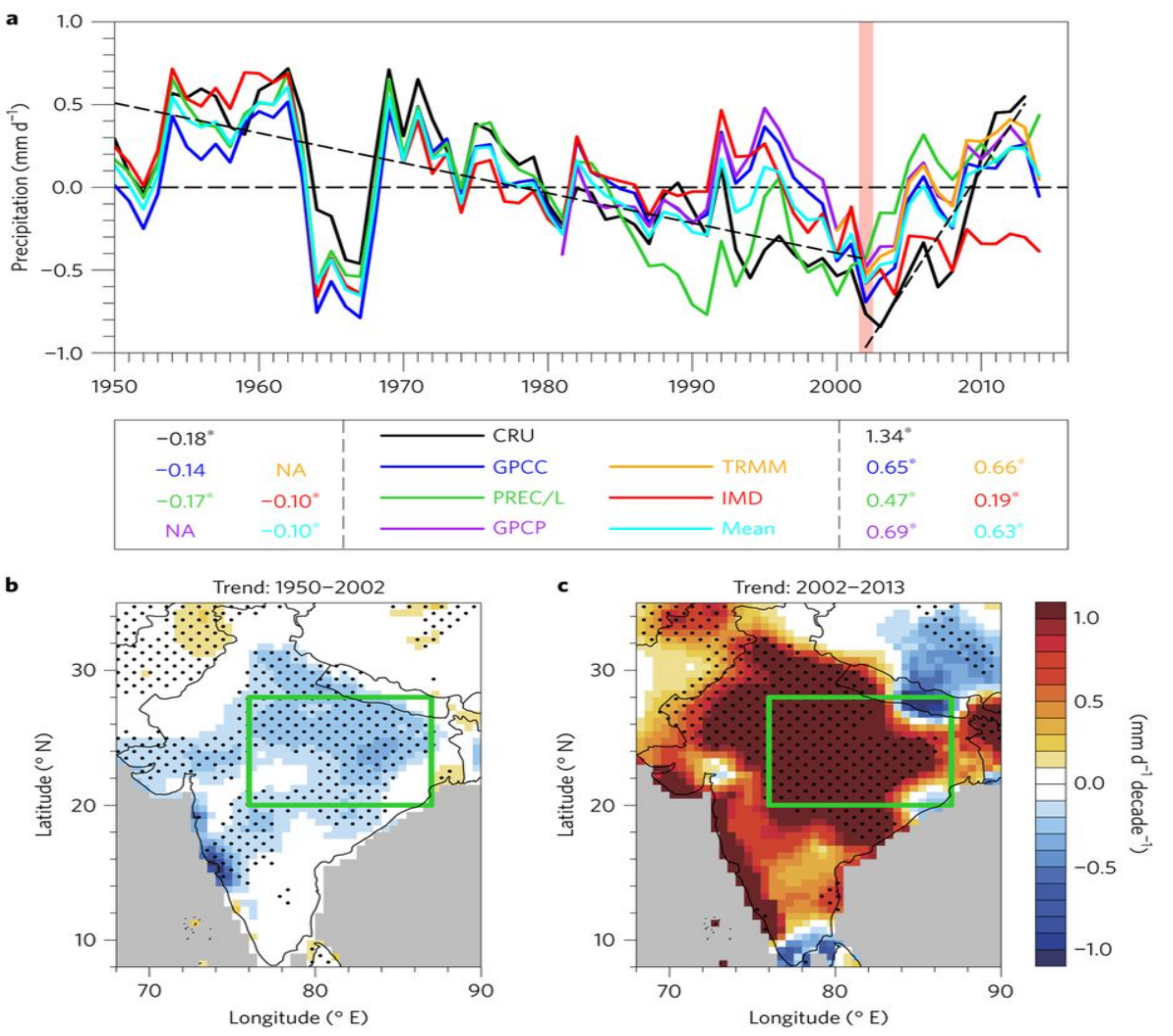
Quantification of AIvE over India

Reviving Indian monsoon

Goswami et al., 2006, Science >> Jin et al., 2017, Nat. Clim. change

Recent publications in support of this work:

Kant et al., 2019



$$\frac{\partial U}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial \lambda} + v\cos\theta\frac{\partial U}{\partial \theta}\right\} + \dot{\eta}\frac{\partial U}{\partial \eta}$$

East-west wind

$$(-fv) + \frac{1}{a}\left\{\frac{\partial \phi}{\partial \lambda} + R_{dry}T_v\frac{\partial}{\partial \lambda}(\ln p)\right\} = \underline{P_U + K_U}$$

$$\frac{\partial V}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda} + V\cos\theta\frac{\partial V}{\partial \theta} + \sin\theta(U^2 + V^2)\right\} + \dot{\eta}\frac{\partial V}{\partial \eta}$$

North-south wind

$$+ fU + \frac{\cos\theta}{a}\left\{\frac{\partial \phi}{\partial \theta} + R_{dry}T_v\frac{\partial}{\partial \theta}(\ln p)\right\} = \underline{P_V + K_V}$$

$$\frac{\partial T}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial \theta} + V\cos\theta\frac{\partial T}{\partial \theta}\right\} + \dot{\eta}\frac{\partial T}{\partial \eta} - \frac{\kappa T_v \omega}{(1 + (\delta - 1)q)p} = \underline{P_T + K_T}$$

Temperature

$$\frac{\partial q}{\partial t} = \frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda} + V\cos\theta\frac{\partial q}{\partial \theta}\right\} = \eta\frac{\partial q}{\partial \eta} = \underline{P_q + K_q}$$

Humidity

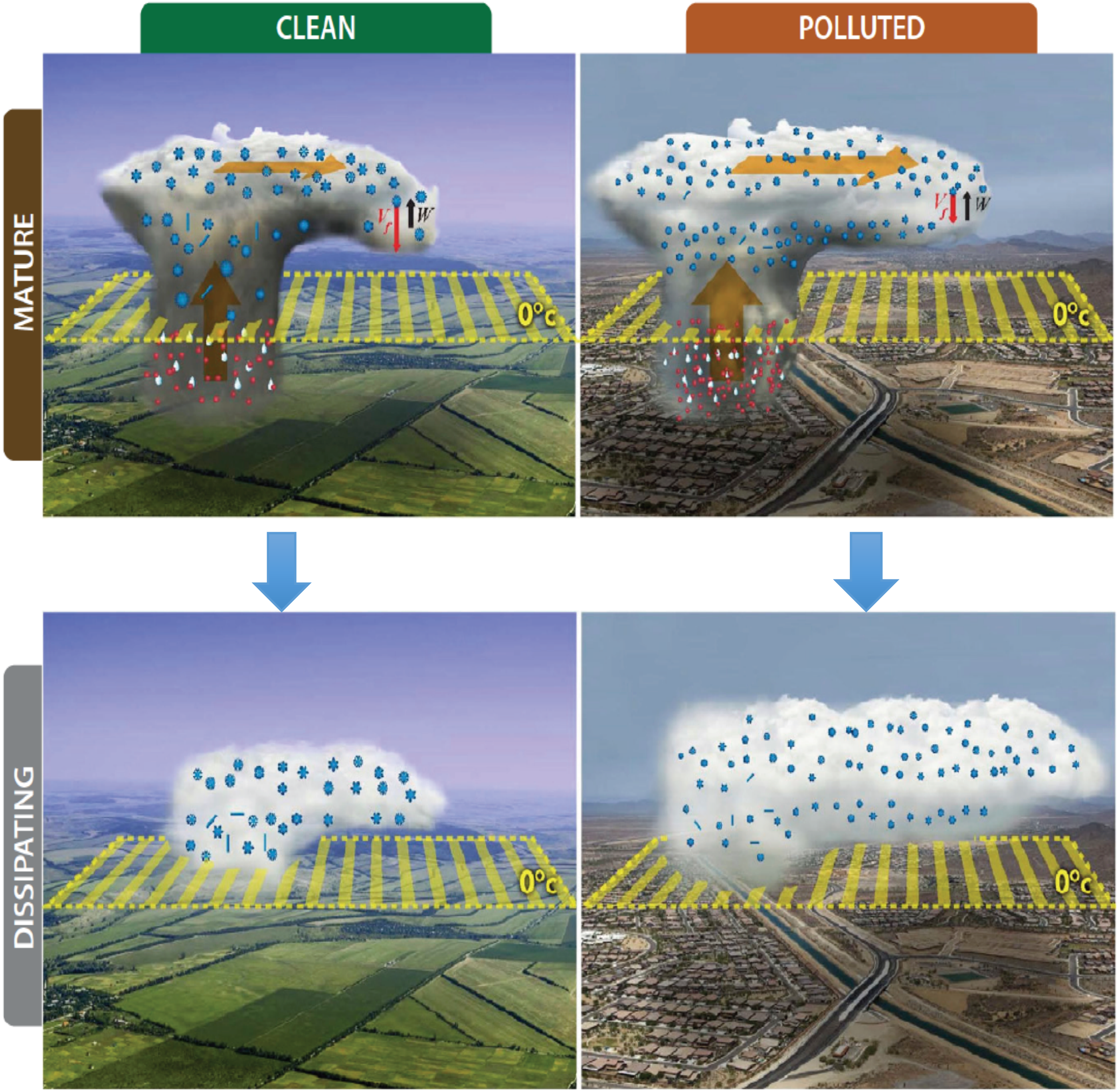
$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right) + \nabla.\left(\mathbf{v}_H\frac{\partial p}{\partial \eta}\right) + \frac{\partial}{\partial \eta}\left(\dot{\eta}\frac{\partial p}{\partial \eta}\right) = 0$$

Continuity of mass

$$\frac{\partial p_{surf}}{\partial t} = -\int_0^1 \nabla.\left(\mathbf{v}_H\frac{\partial p}{\partial \eta}\right)d\eta$$

Surface pressure

Where is the cloud base and top generally located ?



The increased CTH and CF is mainly a result of:

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

A tentative separation shows that convective invigoration can contributes up to 25% of the increase in cloud fraction

Weather Research and Forecasting (WRF) model : Regional Numerical weather Prediction model

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla p - g\mathbf{k} - 2\Omega \times \mathbf{v} + \frac{1}{\rho}\nabla \cdot \mu \nabla \mathbf{v} + \ldots$$

$$c_V \rho \frac{dT}{dt} + p\nabla \cdot \mathbf{v} = -\nabla \cdot R + \nabla \cdot k\nabla T + C + \mu |\nabla \mathbf{v}|^2 + \ldots$$

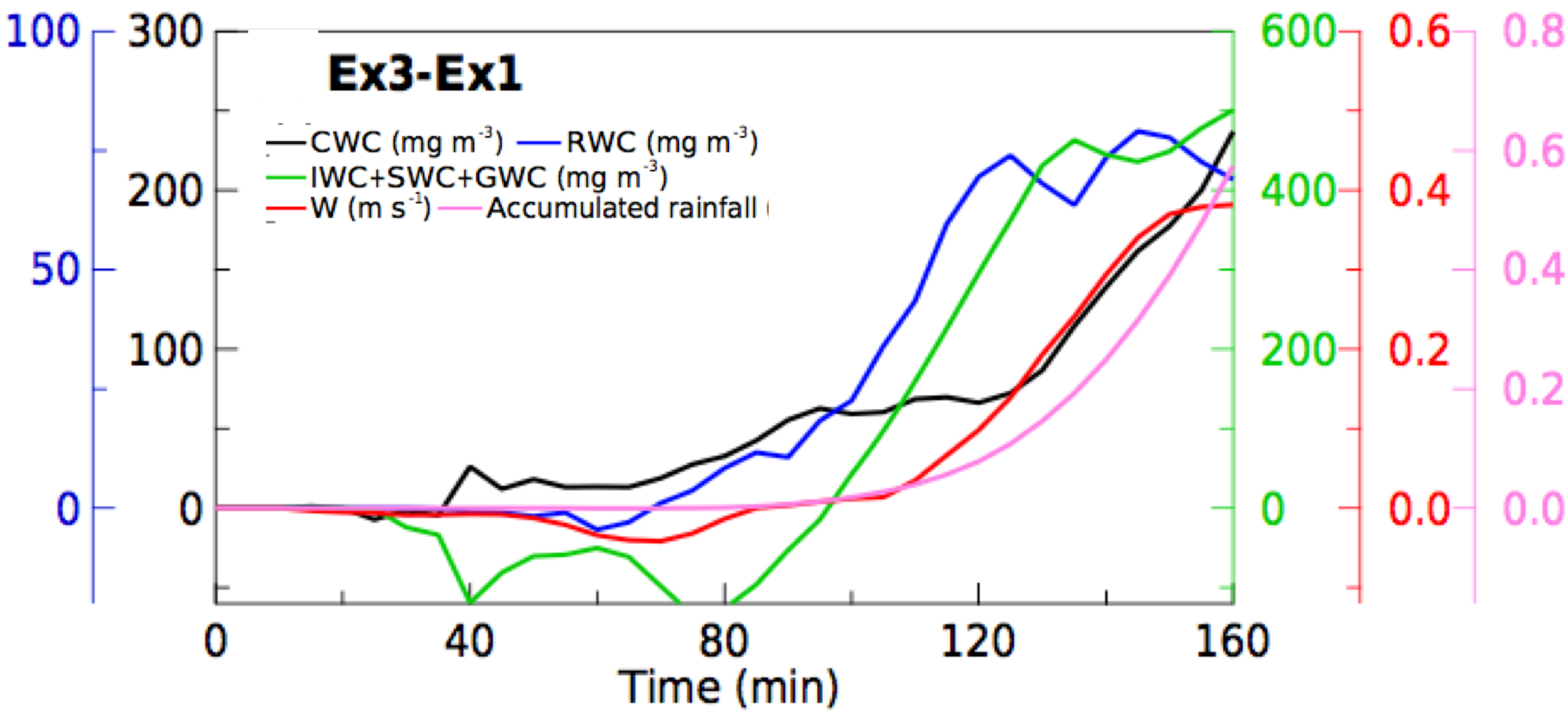
$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0$$

$$\frac{dq}{dt} + q\nabla \cdot \mathbf{v} = S + \nabla \cdot k_q \nabla q$$

$$p = \rho R T$$

$$\frac{d(\bullet)}{dt} = \frac{\partial(\bullet)}{\partial t} + \mathbf{v} \cdot \nabla(\bullet)$$

AIvE causes initial delay and temporal and spatial shift in rainfall towards downwind direction

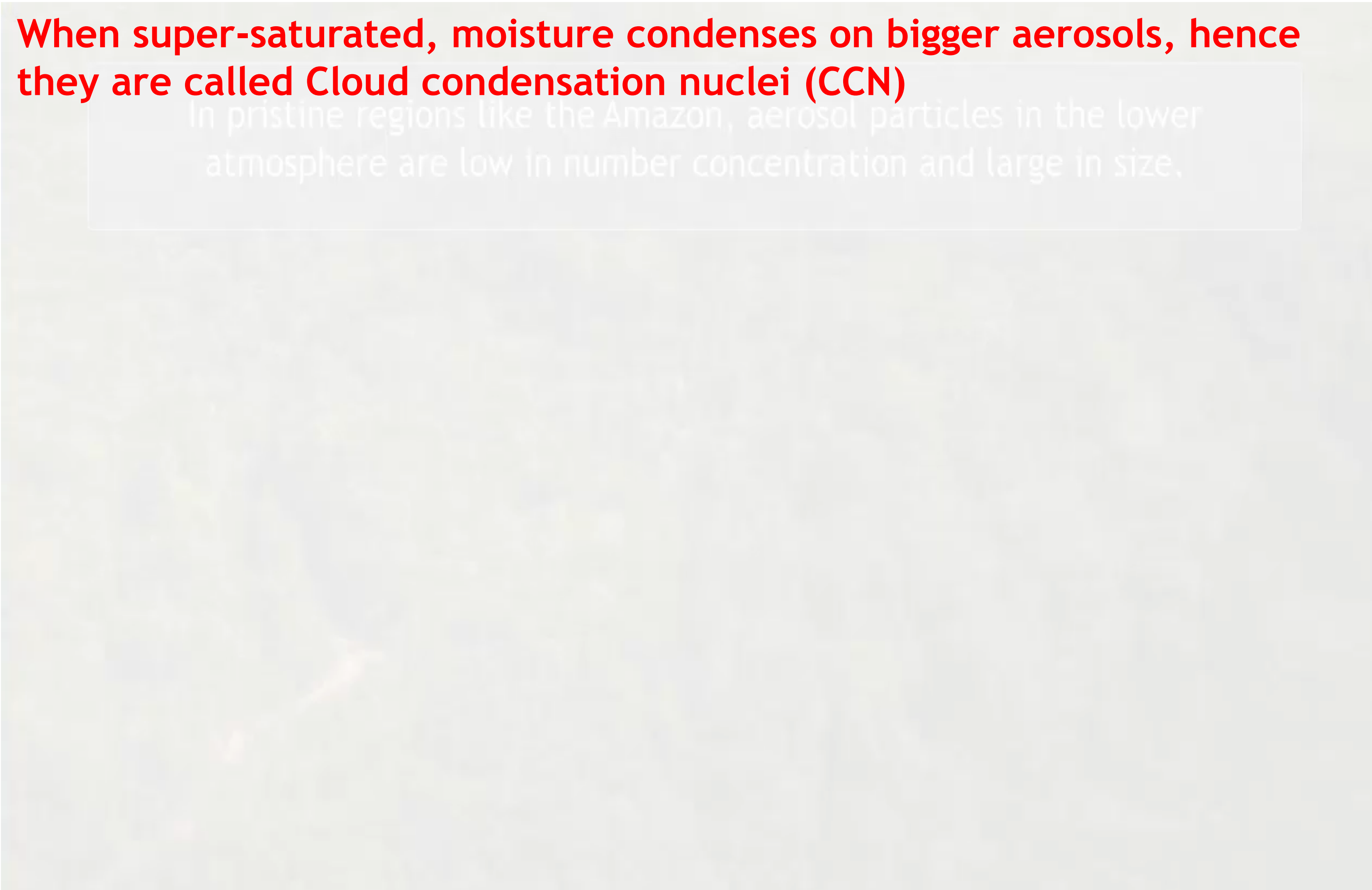


- Rain water content, cloud water content and ice water content increases with CCN content
- **Initial delay results in enhancement in ice and rain formation is simulated**

[Sarangi et al., 2017, ACP]

Rain101

When super-saturated, moisture condenses on bigger aerosols, hence they are called Cloud condensation nuclei (CCN)



Courtesy: Jiwen Fan, PNNL