Aerosol effect in deep convective clouds under different monsoon environments over the Indian peninsula: a CAIPEEX-Case study

Short summary

LES or regional model (CRM) simulations with the following focus:

- **Aerosol effect on mixed-phase cloud processes and impact on precipitation**
- **Initialization from different domains on cloud-aerosol interaction**
- **Impact of domain size on cloud-aerosol interaction**
- **Impact of environmental parameters on deep convective cloud**

Case reference study:
Gayatri, K., S. Patade, and T. V. Prabha, 2017: Aerosol–cloud interaction in deep convective clouds over the Indian Peninsula using spectral (bin) microphysics. J. Atmos. Sci., 74, 3145–3166, https://doi.org/10.1175/JAS-D-17-0034.1.

Use model and observed sounding, fluxes, cloud microphysics observations from CAIPEEX aircraft

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Modified Timeline

Registration: 15 February 2021

15 Apr 2021: 1st communication with participants

15 May 2021: Gather all the results from the participants

15 Jun 2021: 2nd communication with participants

27th -31st July 2021: ICMW

1. Overview

This study uses a deep convective cloud case from the Cloud Aerosol Interaction and Precipitation enhancement Experiment; CAIPEEX over the rain shadow region of the Indian peninsula.

Physical evaluation of the simulations is done by reproducing the vertical structure of the particle size distributions (PSDs) from observations in the warm and mixed-phase regions of clouds (Gayatri et al., 2018). Intercomparison of particle size distributions (PSDs), liquid water content, effective radius and temperature are made from model simulations and airborne observations.

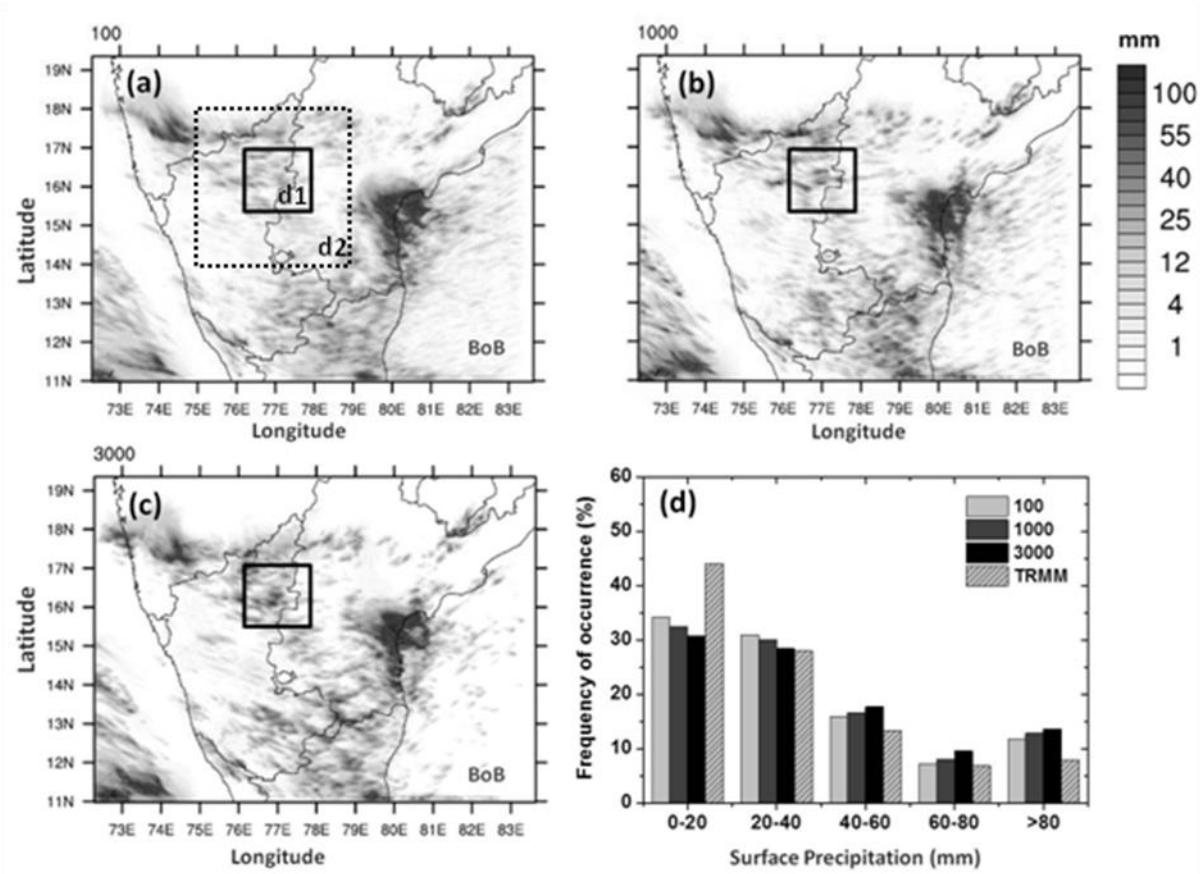


Figure 1: Surface precipitation a-c: from model simulation with 100, 1000 and 3000 CCN and d) comparison of precipitation from three simulations and TRMM. (Gayatri et al., 2017)

Numerical experiments are conducted with different initial cloud condensation nuclei (CCN) concentrations in the WRF model and using the observations available from the CAIPEEX (Low-100, CONTROL-1000, and High-3000 cm^{-3}) with an objective to study the CCN effects on deep convective clouds over the study-region (Gayatri et al., 2017).

Results indicated that for the high CCN experiment, a decrease in effective radius of cloud droplets is seen which narrowed the cloud DSD spectra and resulted in the suppression of the collision-coalescence process and depper cloud depth which are consistent with the earlier studies (van den Heever et al., 2011). However, there are a sufficient number of droplets available within the size range of 10-30 μm in diameter to enhance the growth of ice particles by riming to form graupel particle and is supported by much broader graupel spectra. Results are consistent with the previous studies which showed an increase in graupel mass under polluted conditions due to efficient riming (Khain et al., 2011; Xiao et al., 2015) and are inconsistent with the earlier modeling studies that showed less graupel production under polluted conditions due to inefficient riming (Seifert and Beheng, 2006). The surface precipitation increased up to 20% in localized convective cores as CCN was increased over the study-region. However, this enhancement in surface rainfall is confined to 5% on domain average over the study region. The 5% increase in precipitation over the whole domain could not be attributed to thermodynamic invigoration as illustrated in the study.

2. Scientific objectives

Investigate the small and large domain impact on aerosol effect with a LES/CRM model using model outputs from weather model and investigate the impact on mixed-phase cloud processes in the polluted conditions.

3. Case description

Deep convective clouds were observed on 27th October 2011 during the CAIPEEX field experiment over the peninsular India referred to as the "study-region" (solid white box in Figure 1), in the leeward side of the Western Ghats around Mahabubnagar (16.46 ^{o}N, 77.56 ^{o}E). This region receives ≅ 20 % less rainfall (as per climatology) than the windward side of Western Ghats and is called the rain shadow region. This region also gets rain from October to December from a retreating monsoon known as the North-East (NE) monsoon, during which only peninsular region of India receives rainfall. The onset of the NE monsoon was on 24th October and several places in the southern peninsula received rainfall.

Convective clouds were seen in the satellite image with both shallow and deep convection resembling mesoscale convective clusters over coastal areas. These systems moved west/north-westward, inland during the diurnal cycle. The deep convective system observed over the study-region was profiled by a research aircraft and monitored by a radar. The maximum reflectivity observed was approximately 42 dBZ, and a vertical cross-section of the radar reflectivity showed echo tops at 9 km. The deep cloud system lasted for about 2 hours with an area covering about 90 km^2, and the maximum vertical integrated liquid water was about 7.4 kg m^{-2} which indicates quite deeper cloud development. Aircraft observations were conducted up to an altitude of 7.5 km. Radiosonde observation showed very high CAPE (2216 Jkg^{-1}) and precipitable water (PW) nearly 5 cm. Initial conditions for model run used for the environmental potential temperature (θ) and dew point temperature (T_d) are depicted in Figure (2) below. Surface values of observed pressure (P), θ, and T_d are respectively 960 mb, 305.4 K, 15.4 ^oC which are used for initializing WRF-LES model.

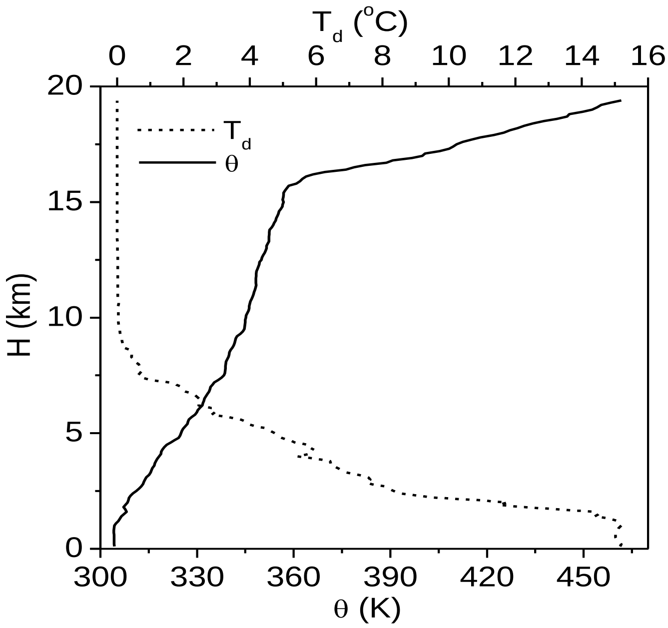


Figure 2: Observed profile of potential temperature and dew point temperature used for model initialization.

Aerosol particle size distribution below the cloud base was measured by *in situ* aircraft instruments (DMA, PCASP and CAS) and is provided below (Figure 3). The aerosol size spectrum can be described by a single-mode lognormal distribution with geometric mean diameter 194 μm and a geometric standard deviation (σ_g) of 1.35.

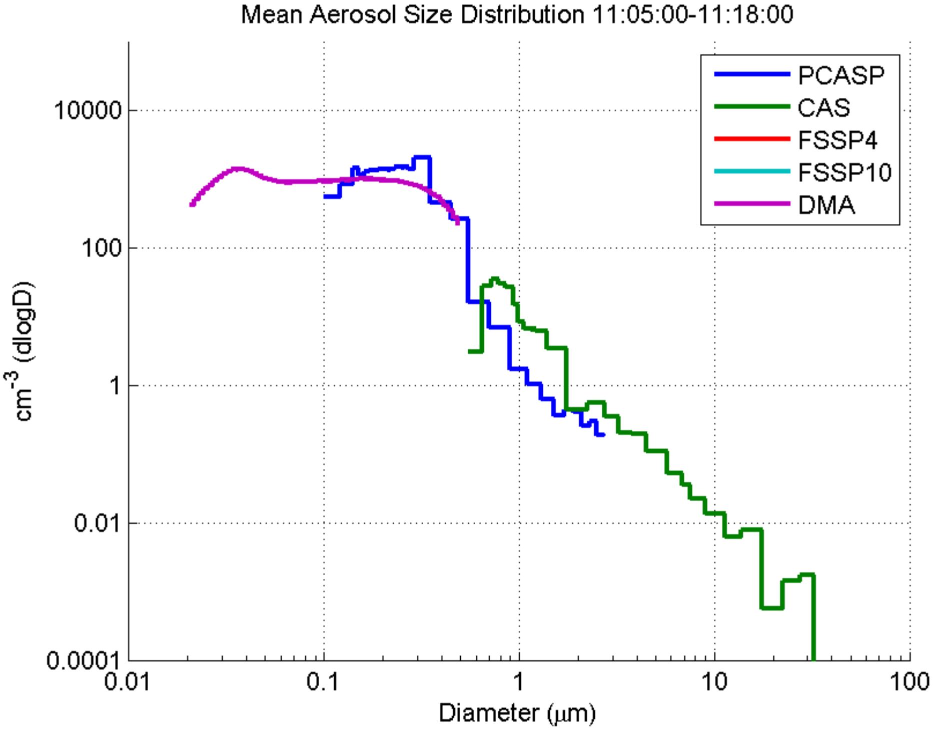


Figure 3: Aerosol size distribution constructed from different probes for the cloud base observation.

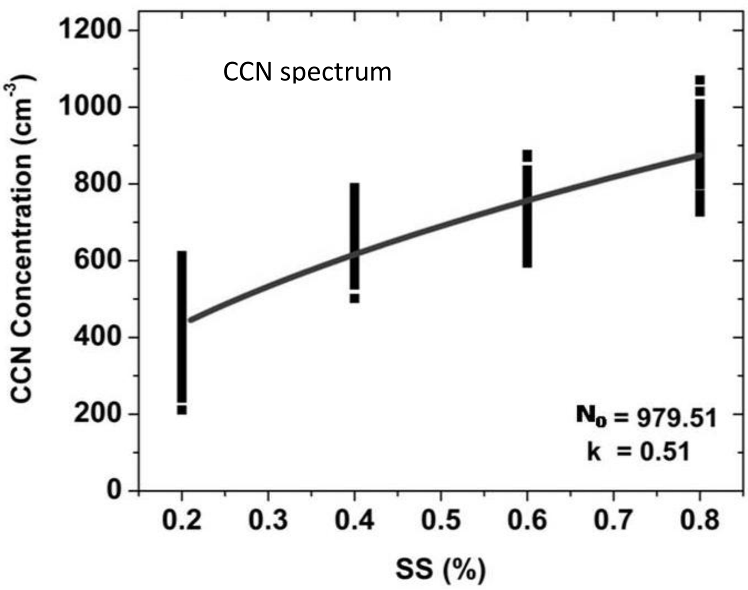


Figure 4: CCN spectra from in situ aircraft observations near the cloud base.

The observed number concentration of CCN (N_0) at 1% supersaturation was 979 cm^{-3}, where the slope parameter k was 0.51. Therefore, the simulation with moderate CCN (N_0=1000 cm^{-}

[3]) was considered as a CONTROL and that simulation was compared with aircraft observation in the paper.

4. Background results

Here we show how the simulated particle size distribution (PSD) spectra compared with observations. The upper panel (a, b, c, d) shows a comparison of PSD in updrafts and the lower panel (e, f, g, h) shows comparison of PSD in downdraft regions. Symbols represent observed data from various instruments and lines represent results from simulation. It is clear from the figure that DSDs and PSDs simulated by the model are compared with the observations at warmer as well as colder temperatures. Both the shape and number concentrations of spectra were in good agreement. This provides confidence that our simulations were able to represent the deep convective clouds (DCC) development and can be used to study aerosol effects on cloud properties and precipitation

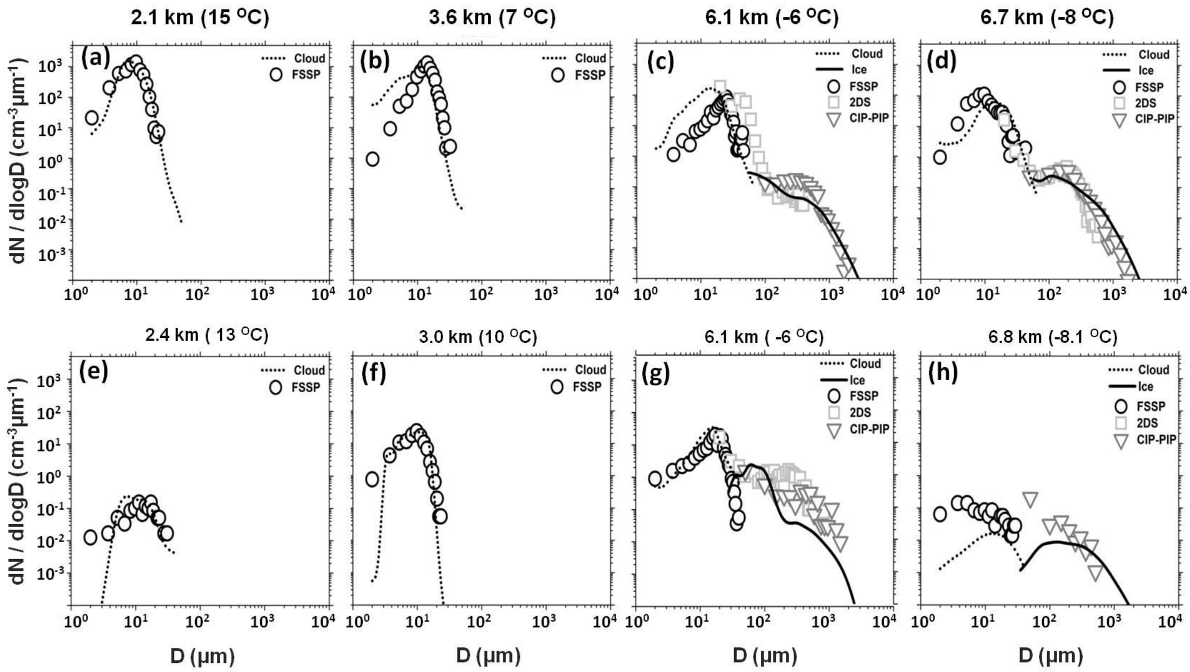


Figure 5: Particle size distribution at different altitudes from observations and model in updrafts (top panel) and downdrafts (bottom panel). Both cloud and ice particle size distribution is presented in comparison with CDP, 2DS and CIP-PIP.

4.1 Effects on surface precipitation

Three different simulations with varying CCN concentrations are conducted (Figure 1). The spatial distribution of accumulated precipitation for three simulations during the time of peak convection (at 17:30 LST) is shown in Figure 6 (a, b, c) for the whole domain (3rd domain). There are significant differences in the spatial distribution and intensity of rain between low (CCN= 100cm^{-3}) and high CCN (CCN= 3000cm^{-3}) concentration. We can see an increase in precipitation over the study-region for high CCN case (black box), especially with several high precipitating clusters compared to the low CCN case. The precipitation over the Bay of Bengal (BoB) for low CCN cases is higher and higher numbers of small precipitation cells are seen compared to the high CCN simulation. The probability density function (PDF) for accumulated surface precipitation for 6:00-24:00 LST from the simulations and the Tropical Rainfall Measuring Mission (TRMM) over the whole domain is shown in Figure 6d. The probabilities for the precipitation amount of 40-60 mm, 60-80 mm and > 80 mm are increased for high CCN concentrations**.** However, the overall changes in surface precipitation due to changes in CCN are small.

4.2 Effect on cloud drop and particle spectra

To illustrate the effect of an increase in CCN on the DSD and PSD, Figure 6 shows the simulated droplet mass distribution (a, b) and graupel mass distribution (c, d) spectra at different altitudes for two extreme CCN concentrations (low-100 cm^{-3} and high-3000 cm^{-3}). These spectra are averaged for the cloudy points (or cloud core) where updrafts were greater than 2 ms^{-1} at 17:00 LST. The DSD (Figure 6a, b) clearly showed two modes, one for cloud droplets (left peak, less than 50μm) and one for raindrops (right). Under high CCN conditions the peak of cloud droplet spectra was shifted to a smaller diameter. However, the cloud droplet mass increased. As the CCN concentration increases, more droplets are activated, which led to an increase in droplet mass. The raindrop spectra (right peak in Figure 6a, b) was slightly shifted to the larger diameter, and there was an increase in the raindrop mass especially for diameters larger than 400 μm under high CCN environment. As the CCN concentration is increased, the size distribution of liquid drops changed, leading to a change in ice phase processes such as riming and melting. This can be seen in the graupel mass spectra (Figure 6c, d) which became broader and graupel mass was increased with an increase in CCN concentration.

Though, the cloud drop spectra shifted to smaller sizes under high CCN; there was an increase in drops between 10-30 μm in diameter. This promoted an increase in riming leading to an enhancement in the graupel mass. In addition, the melting of ice phase particles contributed to larger drops (greater than 400 μm). These large drops further promoted collision-coalescence that affected the raindrop size distribution, leading to wider DSDs and increase in precipitation at the surface. Similar results were noted by many studies (Fan et al., 2007; Xiao et al., 2015). The sensitivity of riming to CCN concentration varies from case to case and from model to model. More studies with bin microphysics are needed to provide detailed insights on the effects of changing CCN on mixed-phase DSD under different conditions.

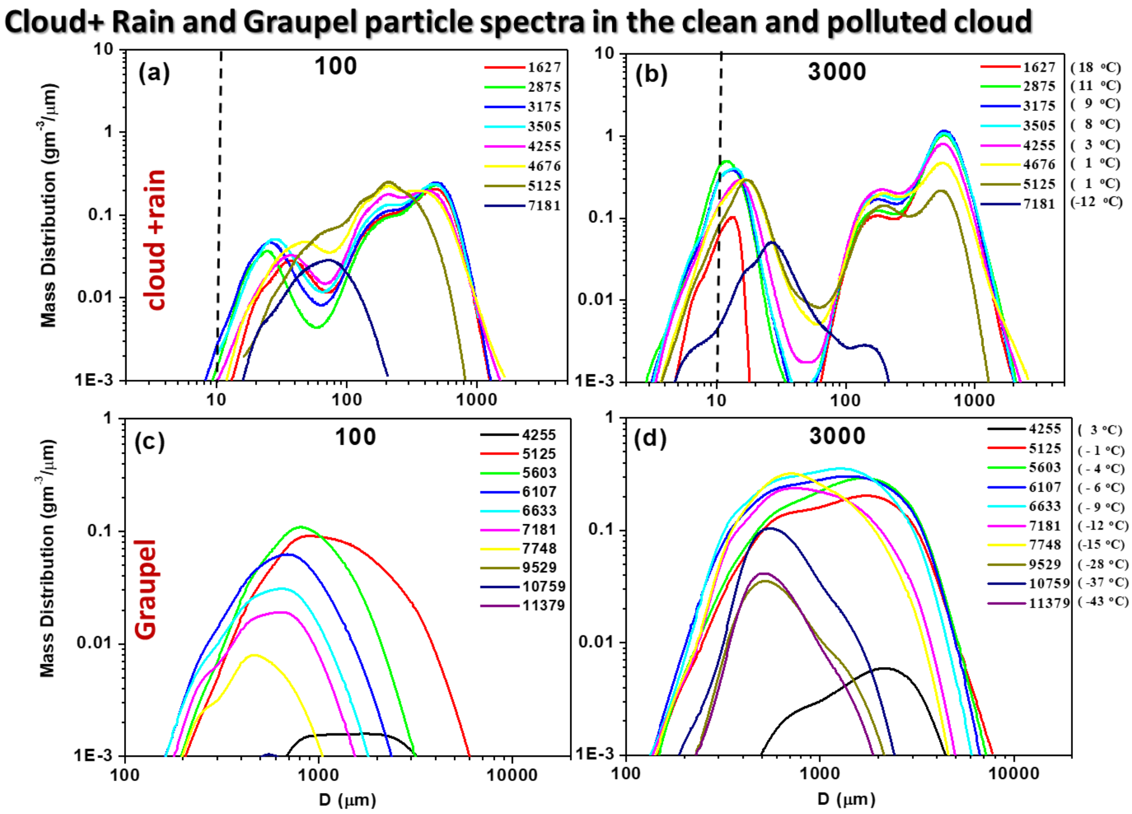
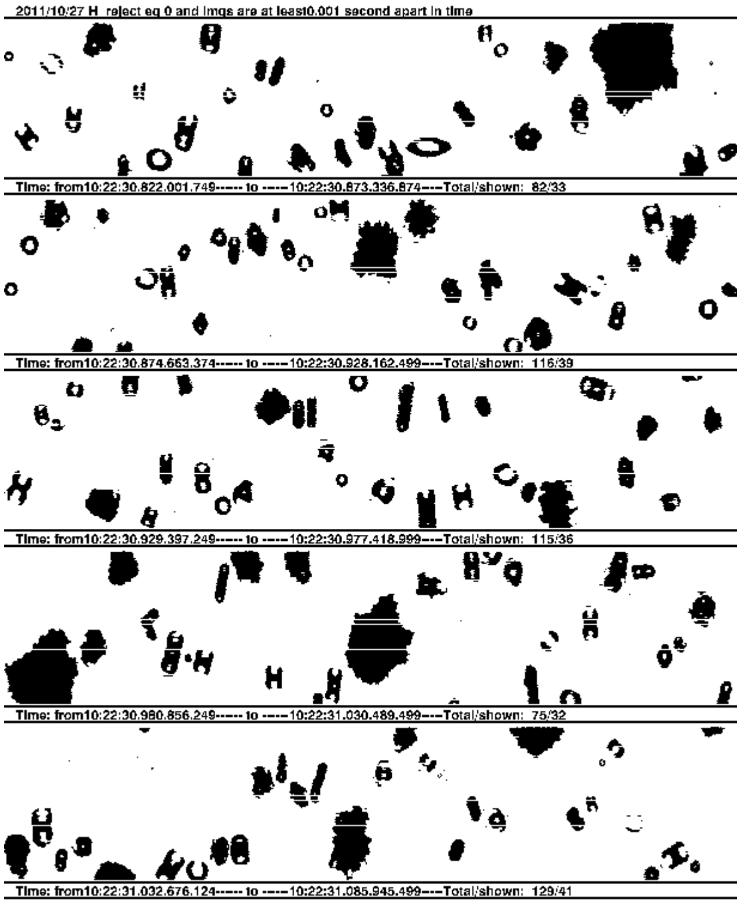


Figure 6: Particle size distribution (both cloud droplet and raindrop) for different CCNC case runs.

a)



b)

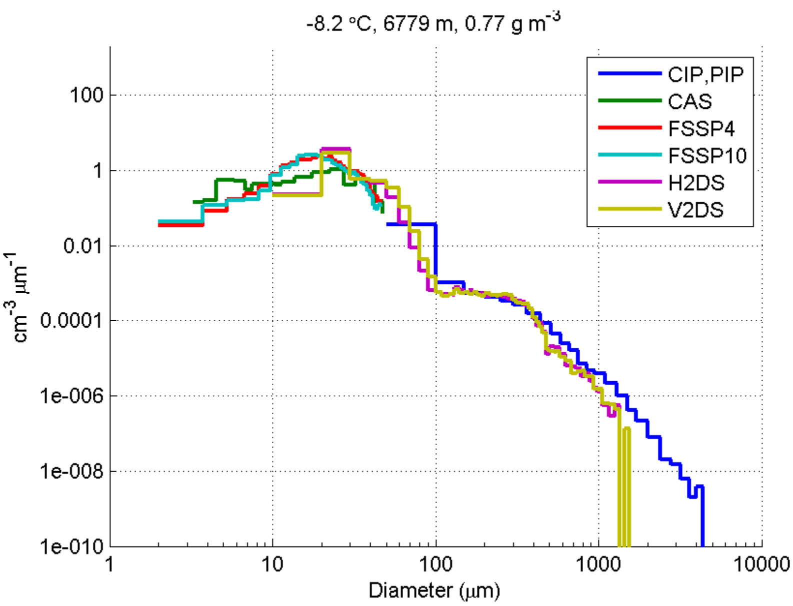


Figure 7: a) Observed particle images using 2DS indicating drops, graupel, columns and b) corresponding size distribution spectra.

5. Experiments proposed and the setup

High CCN cases showed a higher LWP compared to the low CCN case. Response of precipitation in both the boxess are considerably different. The clean cases indeed showed less precipitation and later development of precipitation.

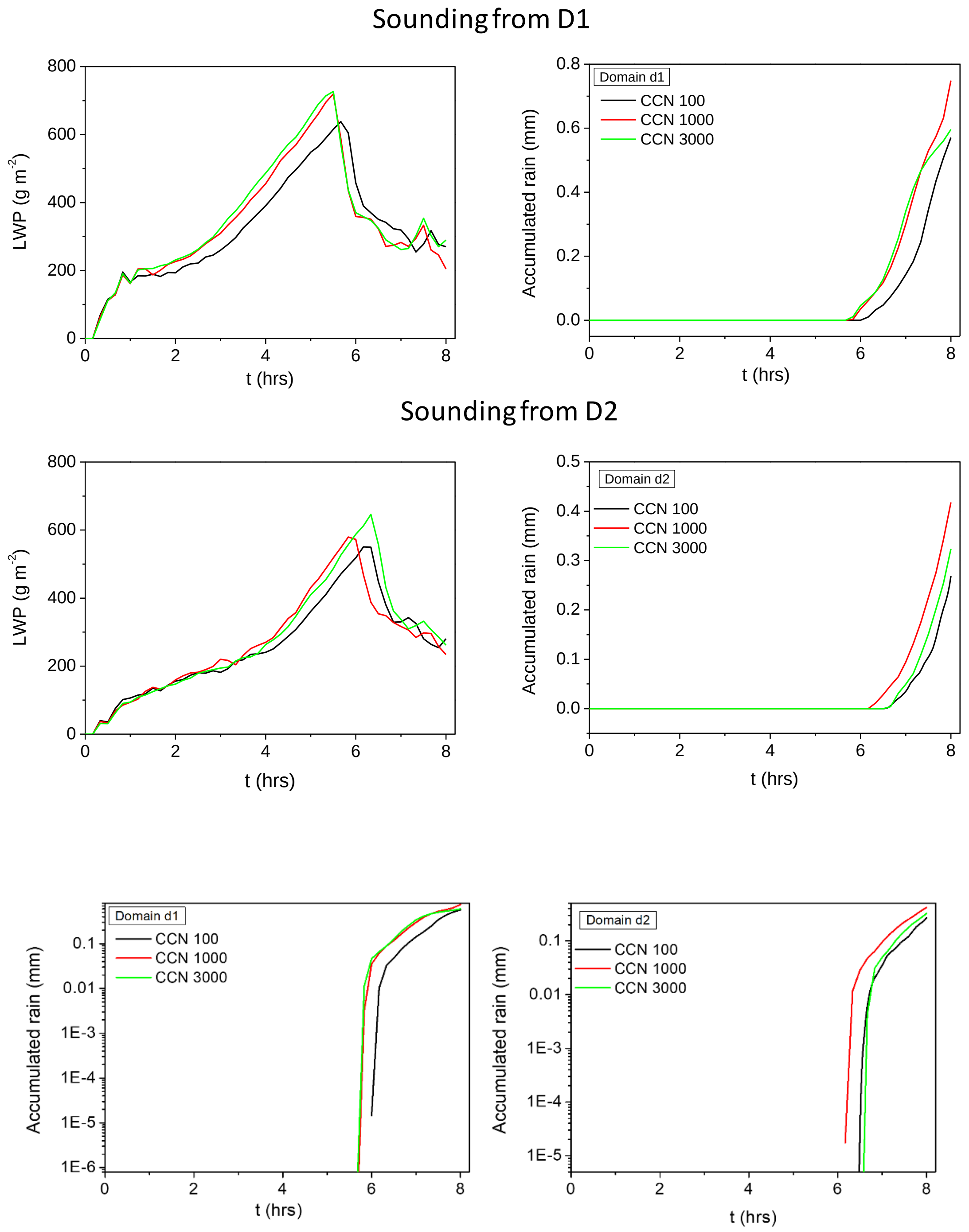


Figure 8: LES results of LWP (left) and accumulated surface rainfall (right) from the six runs. The accumulated rainfall is also shown in log scale (Bottom)

Suggested experimental setup for WRF-LES simulation is given below:

Model parameter	**Setting**
Model grid **Horizontal (for LES)** **Vertical (for LES)** **Horizontal (for CRM)** **Vertical (for CRM)**	 100 m or 200m resolution , 20 - 50 km X 20 - 50km domain (for LES) 30-50 m with model top at 20 km (For LES) 1 km and 400 km x 400 km (for CRM) 200 m with model top at 20 km (for CRM)
Initialization	a) Model sounding from two domains at 530 UTC for different CCN simulations b) Radiosonde sounding/model sounding at 530 UTC
Boundary condition **Lateral** **Model top** **Surface**	 Doubly periodic Radiative type Using surface fluxes OR with prescribed surface temperature
Radiation scheme	Optional
Duration of simulation	8 hours (24 hours for diurnal cycle)
Microphysics	Bulk or Spectral bin microphysics
CCN setup	Initial CCN = 100, 1000 and 3000 cm^{-3}

6. Details of the input files:

Data is shared at the following link

https://drive.google.com/drive/folders/10JF2CCzOv4Nqj2G_6EJENuV4exMbIAiM?usp=sharing

a) Model sounding data
b) Observed sounding
c) Observed fluxes and other parameters
d) Tendencies from model
e) Cloud microphysics data (DSDs and PSDs)
f) Cloud microphysics bulk parameter profiles

Data README:

D1 is for 200x200 km box average and D2 is for 400x400 km box average from the real simulations.
100,1000,3000: three files three different CCN concentrations
Columns in the data are - height , pressure, theta, WV mixing ratio, u ,v, w.

For LES runs in Figure 8, we have taken mean sounding from WRF-Mesoscale model run with different boxes (D1 and D2 as shown in Figure 1a).

Mean soundings over two boxes from WRF runs at 11 AM IST (local time) and the same have been used as initial input sounding in WRF-LES ideal case run and LES results are compared.

The data file d1_sounding (ZIP file) corresponds to the mean sounding from WRF-Mesoscale run over box D1 and the data file d2_sounding (ZIP file) corresponds to mean sounding from WRF-Mesoscale run over box D2.

Each of these ZIP files contains three CCN sounding files from the three CCN runs of WRF-mesoscale.

Every file inside the ZIP file is .txt file and can be opened as text file.

First row of the data (.txt) file contains three columns (surface pressure, temperature and water vapour mixing ratio in units of hPa, K, and g/kg, respectively.)

"Input_sounding_radiosonde.txt" is the datafile from the observations and has the same frmat as mentioned above

Second row to the last row, it contains five columns (height, potential temperature, water vapour mixing ratio, zonal wind and meredional wind in units of meters, K, g/kg, m/s and m/s, respectively).

The height provided here is above surface in meters.

Surfaces fluxes from the two averaged over two boxes are in "d1_flux_all_times_100/1000/3000.txt" and "d2_flux_all_times_100/1000/3000.txt" respectively for thre CCN simulations. Columns include time (LST), sensible heat flux, Latent heat flux , short waveflux and longwave flux.

7. Parameters for the case study:

Note: if you are unable to give the parameters, may provide basic fields from model outputs.

7.1 Time varying mean parameters (2-10 min interval for maximum of 8 hours)

Parameter	**Unit**
Liquid Water Path	g/m2
Ice Water Path	g/m2
Cloud fraction	%
Accumuated rainfall	mm
Rain rate	mm/hr
Maximum updraft	m/s
Area fraction of updrafts Area fraction of downdrafts	

Entrainment rate	/meter
Latent heating rate Cooling rate	K/s
Cloud base height, Cloud top height	km
Boundary layer height	km
Mean water vapour in the boundary layer	g/kg
Cloud width	km
Updraft mass flux downdraft mass flux	Kg/m2/s
Potential temperature vertical profile	K
Water vapour mixing ratio, cloud water, ice water and rainwater mixing ratio profiles	g/kg
Vertical profile of effective radius of cloud and ice particles	μm
Buoyancy	
Vertical profiles of Heat flux, moisture flux, Turbulent Kinetic Energy	Km/s, g/kg m/s, m2/s2
Moist static energy	Jkg-1
Process rates (if available)	g/kg s-1
Maximum Reflectivity	dBZ
Any other parameter of interest to the investigators	

Consideration of different parameters and analysis:

Grabowski et al 2006, Daytime convective development over land: A model intercomparison based on LBA observations, Q. J. R. Meteorol. Soc.(2006),132, pp. 317–344doi: 10.1256/qj.04.147

Entrainment rate calculation:

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019JD031078

References:

Fan, J., R. Zhang, G. Li, and W.-K. Tao, 2007: Effects of aerosols and relative humidity on cumulus clouds. J. Geophys. Res., 112, D14204, doi:10.1029/2006JD008136.

Van den Heever, S. C., G. L. Stephens, and N. B. Wood, 2011: Aerosol indirect effects on tropical convection characteristics under conditions of radiative–convective equilibrium. J. Atmos. Sci., 68, 699–718, doi:10.1175/2010JAS3603.1

Xiao, H., Y. Yin, L. Jin, Q. Chen, and J. Chen, 2015: Simulation of the effects of aerosol on mixed-phase orographic clouds using the WRF Model with a detailed bin microphysics scheme. J. Geophys. Res. Atmos., 120, 8345–8358, doi:10.1002/ 2014JD022988.

Khain, A. P., A. Pokrovsky, M. Pinsky, A. Seifert, and V. Phillips, 2004: Simulation of effects of atmospheric aerosols on deep turbulent convective clouds using a spectral microphysics mixedphase cumulus cloud model. Part I: Model description and possible applications. J. Atmos. Sci., 61, 2963–2982, doi:10.1175/ JAS-3350.1.

Khain, A. P., L. R. Leung, B. Lynn, and S. Ghan, 2009: Effects of aerosols on the dynamics and microphysics of squall lines simulated by spectral bin and bulk parameterization schemes. J. Geophys. Res., 114, D22203, doi:10.1029/2009JD011902

Khain, A. P., D. Rosenfeld, A. Pokrovsky, U. Blahak, and A. Ryzhkov, 2011: The role of CCN in precipitation and hail in a midlatitude storm as seen in simulations using a spectral (bin) microphysics model in a 2D dynamic frame. Atmos. Res., 99, 129–146, doi:10.1016/j.atmosres.2010.09.015.

Seifert, A., and K. D. Beheng, 2006: A two-moment cloud microphysics parameterization for mixed-phase clouds. Part 2: Maritime vs. continental deep convective storms. Meteor. Atmos. Phys., 92, 67–82, doi:10.1007/s00703-005-0113-3.

Gayatri, K., S. Patade, and T. V. Prabha, 2017: Aerosol–cloud interaction in deep convective clouds over the Indian Peninsula using spectral (bin) microphysics. J. Atmos. Sci., 74, 3145–3166, https://doi.org/10.1175/JAS-D-17-0034.1.

Appendix: Case Participants, objectives and model as of Jan 2020			
No	**Name /Institution**	**Specific objective**	**Model**
1	Sudarsan Bera/IITM	LES simulation Envionmental humidity: Massflux and entrainment rate	WRF LES
2	Gayatri Kulkarni/IITM	LES simulation for aerosol, humidity: Impact on precipitation	WRF LES
3	Sandeep J/IITM	LES simulation for different microphysics	PAM LES / SAM LES
4	Neelam Malap/IITM	Diurnal cycle	EULAG LES
5	Wojtek Grabowski/NCAR	Piggybacking	EULAG LES Piggybacking
6	Rama Govindaraj/ICTS	Rain drop formation	Inhouse model
7	Saurab Patil and Thara / SSPU/IITM	Cloud resolving model simulations with different microphysics schemes investigate autoconversion parameterization for warm rain physics	WRF-CRM
8	Jayakumar NCMRWF , Delhi	Cloud resolving model	NCUM/UK Met
9	Sachin Patade/V Phillip (To be discussed)	Ice nucleation	In house model
10	Soumya Samanta /IITM	Comparing bin and bulk schemes cloud-resolving model	WRF ARW mesoscale model
11	Prof. Pinaki Chakraborty, Okinawa Institute of Science and Technology Graduate University, Japan	To be announced	Cloud model
12	Dr. Adrian Hill, Dr Jonathan Wilkinson UK Met office	Unified Model with the CASIM Microphysics	Met office NERC cloud model MONC
13	Dr. Andrea Flassman (to be confirmed)		
14	Dr. Kobby		WRF bin
15	Ms. Snehlata Tirkey, Mr. Malay Ganai, Mr. Sarkar Sahadat, IITM	Cloud and convective processes analysis	GFS/CLUBB SCM
16	Emmanuel Rongmie, Mano Kranthi Ganadhi, IITM		WRF-LES / MPAS (Model for Prediction Across Scales)
17	Shivsai Dixit, IITM	Dynamics	MicroHH LES model
*Sudarsan and Gayatri will make presentations in the workshop compiling results from various IITM group efforts			