Effect of atmospheric aerosol on cloud microphysics as observed from Western Ghats

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Acknowledgements: Anil Kumar, Subrata, Utsav, Sachin, Madhu

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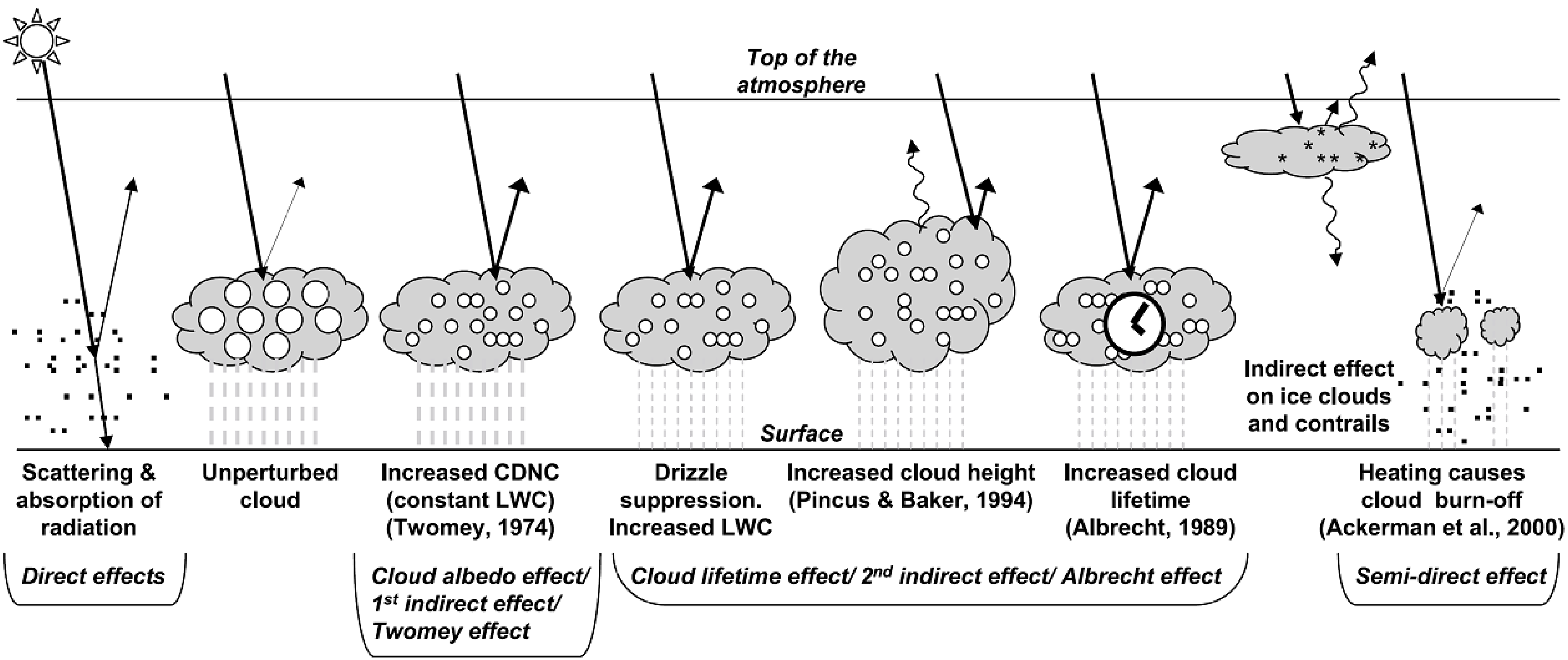
Outline

- Motivation
- Aerosol-CCN closure, impact of aerosol chemistry
- Aerosol indirect effect estimates
- Discrepancies between number and size effects
- Ice Nuclei (Initial results)
- Radar derived convective cloud statistics
- Summary

• Aerosols, and especially their effect on clouds and precipitation, are one of the key components of the climate system and the hydrological cycle.

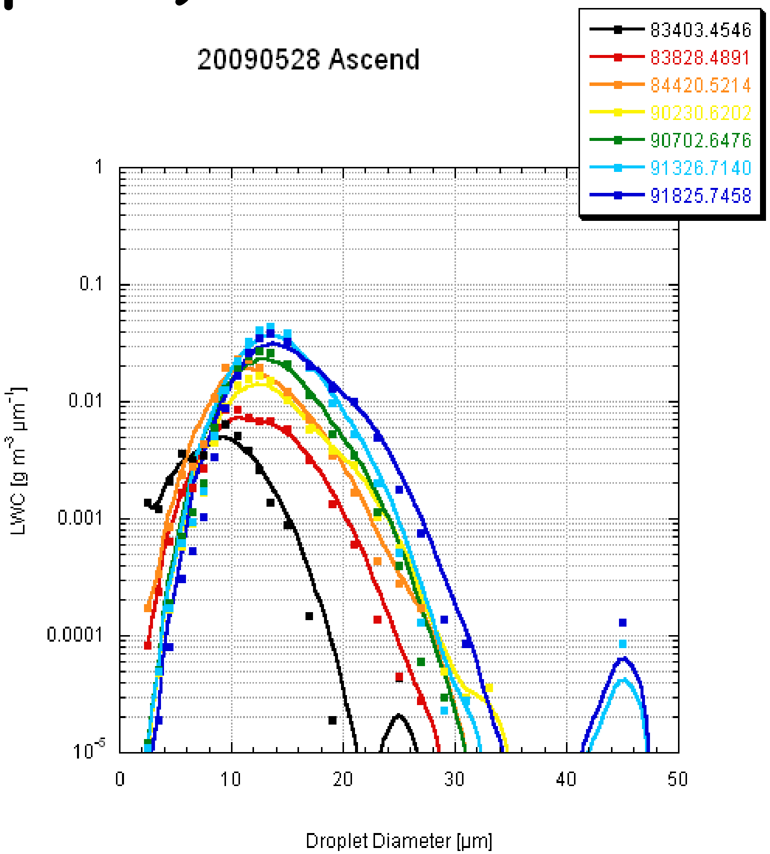
• "*The largest of all the uncertainties about global climate forcing—is probably the indirect effect of aerosols on clouds and precipitation*"

Aerosol-Cloud-Precipitation interactions

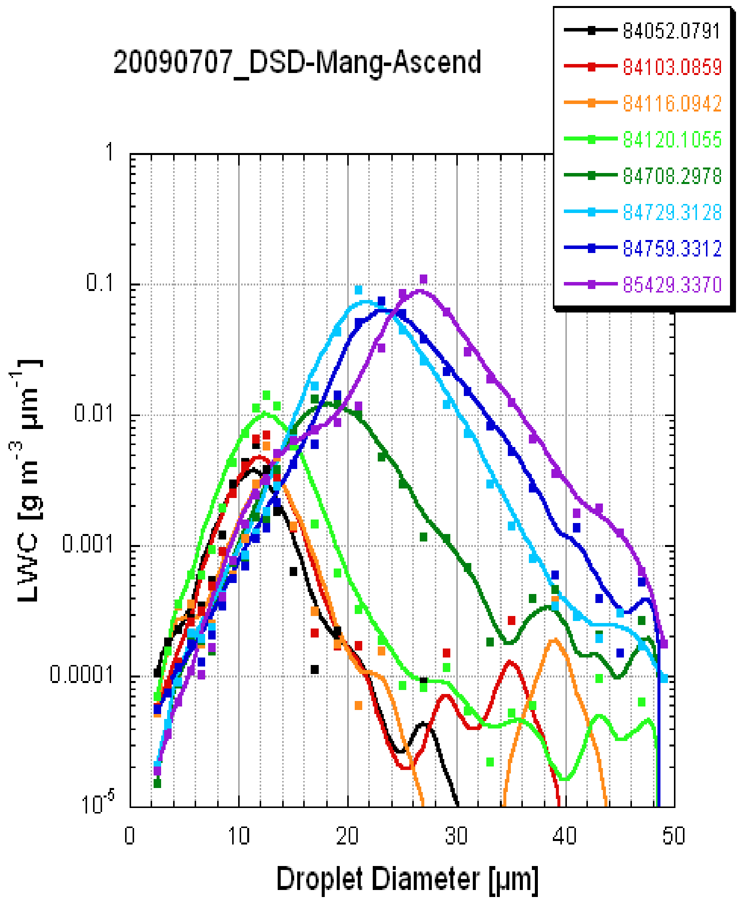


Vertical profiles of cloud liquid water content Distributions from CAIPEEX aircraft measurements

Continental (Indo-Gangetic plains)



Marine (West coast)



Aerosol-cloud-precipitation related processes

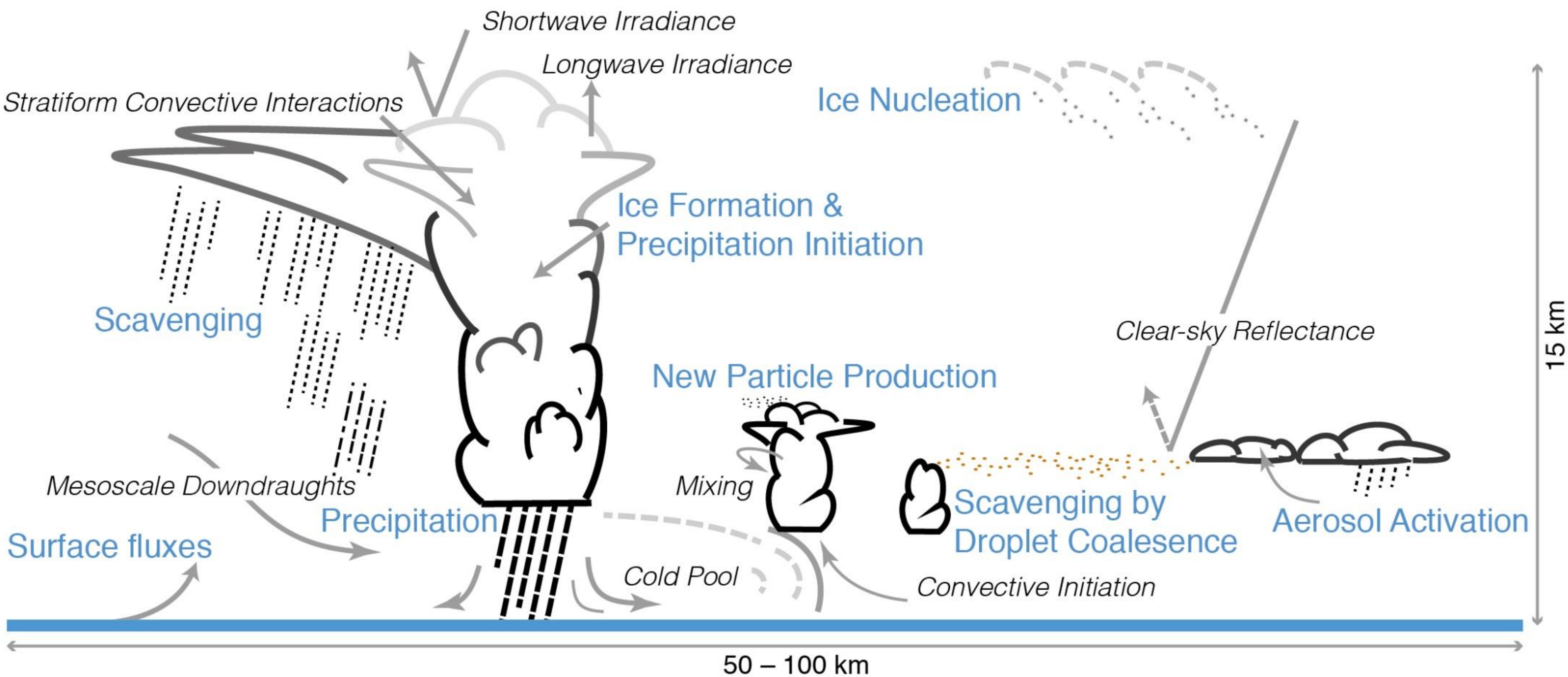


Figure 7.16 | Schematic depicting the myriad aerosol–cloud–precipitation related processes occurring within a typical GCM grid box. The schematic conveys the importance of considering aerosol–cloud–precipitation processes as part of an interactive system encompassing a large range of spatiotemporal scales. Cloud types include low-level stratocumulus and cumulus where research focuses on aerosol activation, mixing between cloudy and environmental air, droplet coalescence and scavenging which results in cloud processing of aerosol particles, and new particle production near clouds; cirrus clouds where a key issue is ice nucleation through homogeneous and heterogeneous freezing; and deep convective clouds where some of the key questions relate to aerosol influences on liquid, ice, and liquid–ice pathways for precipitation formation, cold pool formation and scavenging. These processes influence the shortwave and longwave cloud radiative effect and hence climate. Primary processes that affect aerosol–cloud interactions are labelled in blue while secondary processes that result from and influence aerosol–cloud interactions are in grey.

Source: IPCC AR5

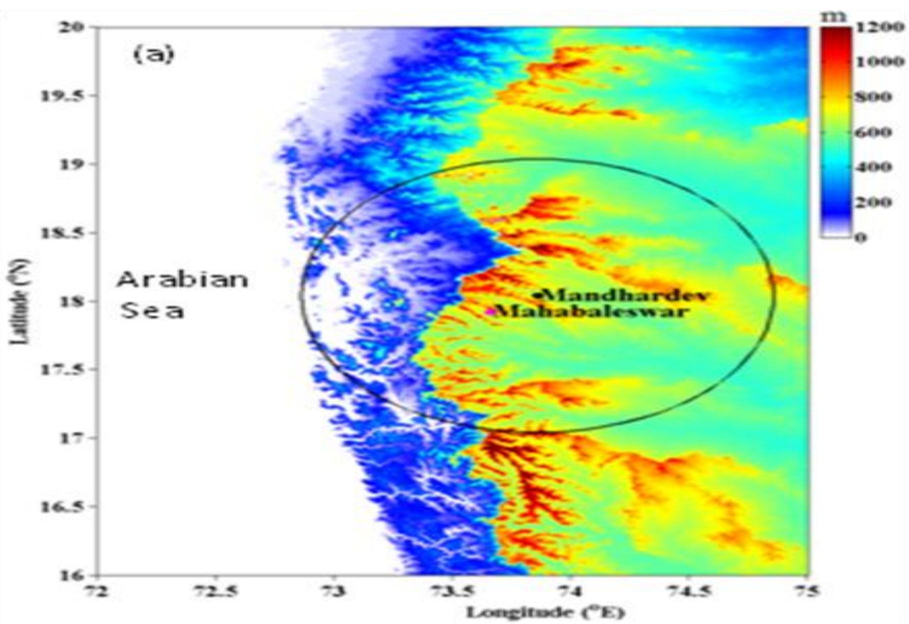
<u>Why cloud physics laboratory established in Western Ghats</u>

1. **HACPL is a natural laboratory where in clouds float close to surface and interact with aerosols** which can be monitored to better understand the aerosol physical/chemical processes influencing the microphysics of clouds and precipitation.

2. **Orograpic precipitation** which is a source for hydrological cycle showing **decreasing trend**. Increase in anthropogenic emissions and land-use land-cover changes could play a role in modifying the microphysical processes in cloud and precipitation.

It is important to note that the role microphysical and dynamical processes play in the water cycle is less clear.

Mahabaleshwar (17.9 N, 73.6 E, 1349 m AMSL)



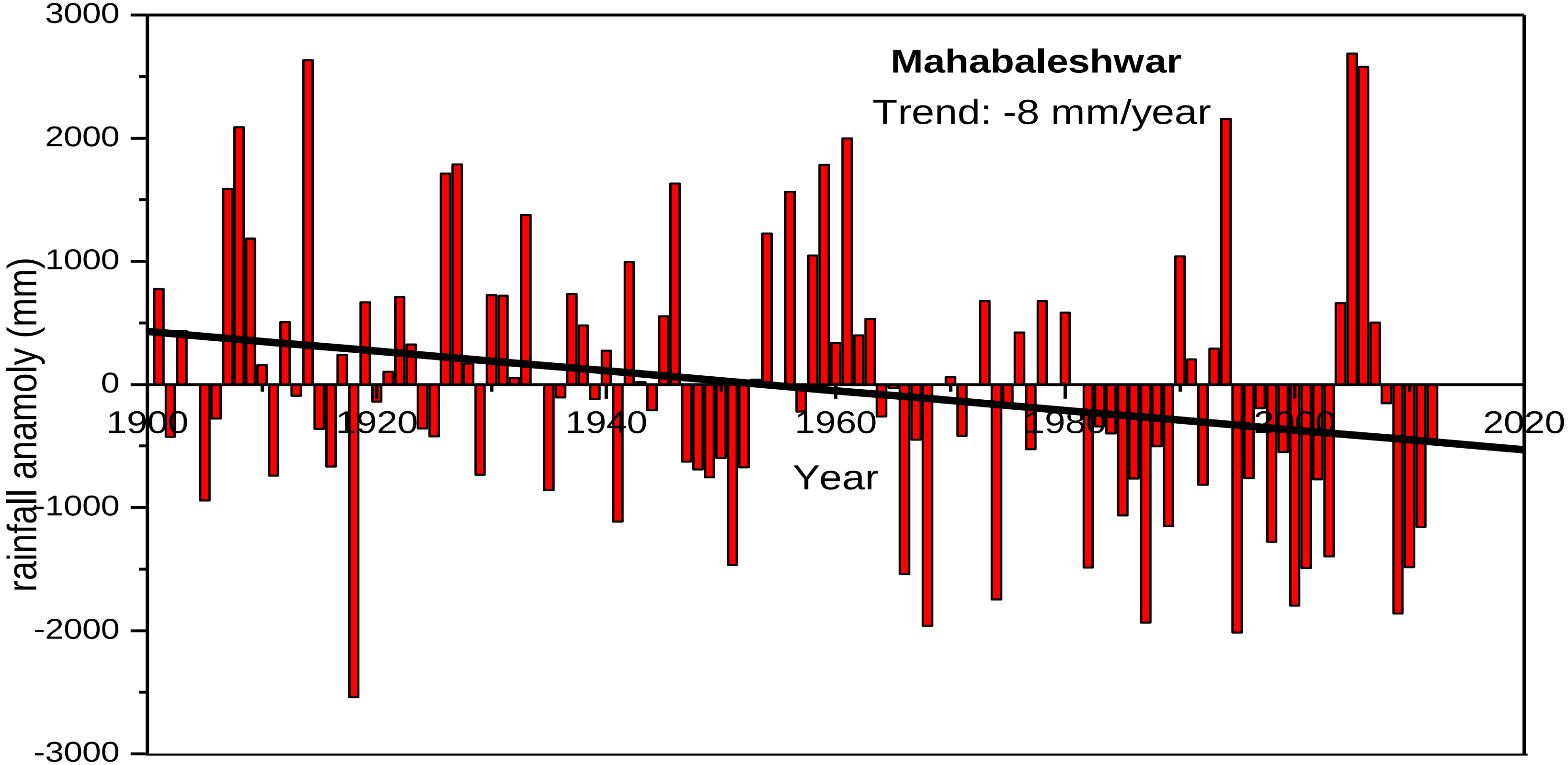
- Warm clouds float close to surface which could be monitored

- WG is one of the two most heavy rainfall regions during summer monsoon.

- Long-term seasonal average rainfall = 5719 mm which has been decreasing in recent decades

- Rainfall in this region mostly comes from shallow clouds

Rainfall trend over Mahabaleshwar, Western Ghats



Average Rainfall over Mahabaleshwar = 5719 mm

Data Source: IMD

High-Altitude Cloud Physics Laboratory (HACPL), Mahabaleshwar, Western Ghats

Experimental Facilities at HACPL

Aerosol/CCN

- SMPS/APS
- CCN counter
- Nephelometer
- Aethalometer
- MFRSR
- Sun/skyradiometer
- ACSM
- PILS-IC for chemistry

Cloud

- CCP probe
- Radiometer profiler
- Whole sky imager
- Ice Nuclei Counter
- Ka-band radar

Precipitation

- Optical/Impact/ Video Disdrometers
- Micro rain radar
- X-band radar
- Rain Gauge

\+ GPS radiosonde

To be added

HTDMA – for hygroscopic growth factor

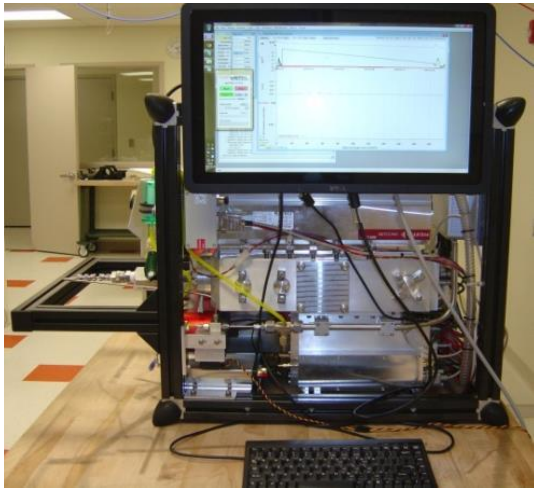
PTRMS - VOC measurements

Lidar


1
2
3
4
5
6
7
Cloud
Condensation
Nuclei
Counter
8
radiometrics
CORPORATION
DO NOT TOUCH
9

Spectrometer for Ice Nuclei

Aerosol Chemical Speciation Monitor



Whole Sky Imager

Scanning Mobility Particle Sizer

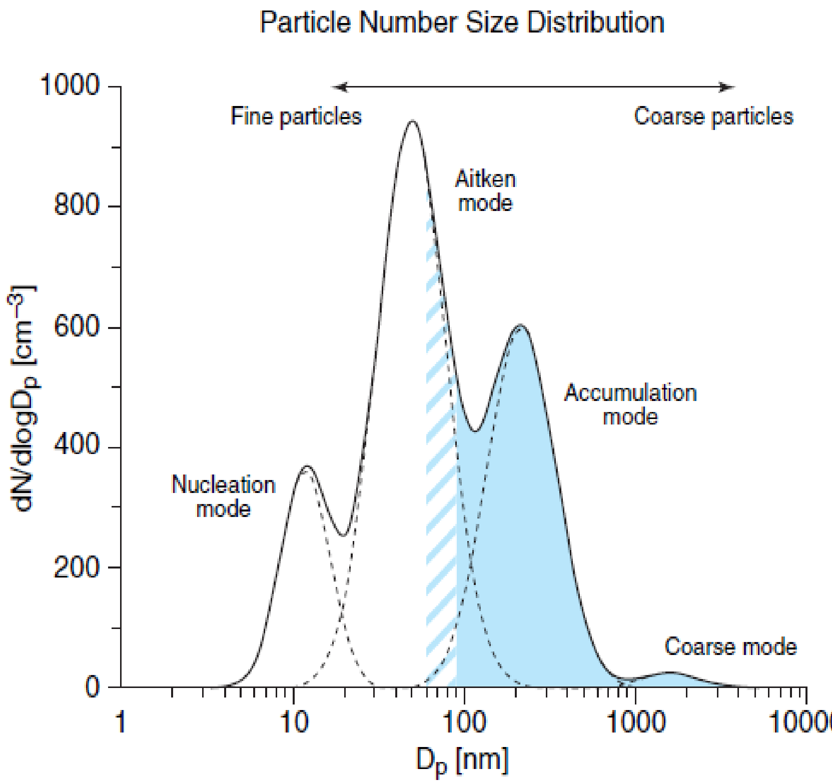
Neutral Cluster Air Ion Spectrometer

Aerosol-CCN relationships

- Atmospheric aerosol size distributions are highly variable

- The number of particles in a given size range and <u>the gradient of the distribution in certain critical size ranges</u> will determine activation behavior

- Size distribution characteristics strongly interact with the dynamics to determine the number of activated droplets



Meteorol Atmos Phys
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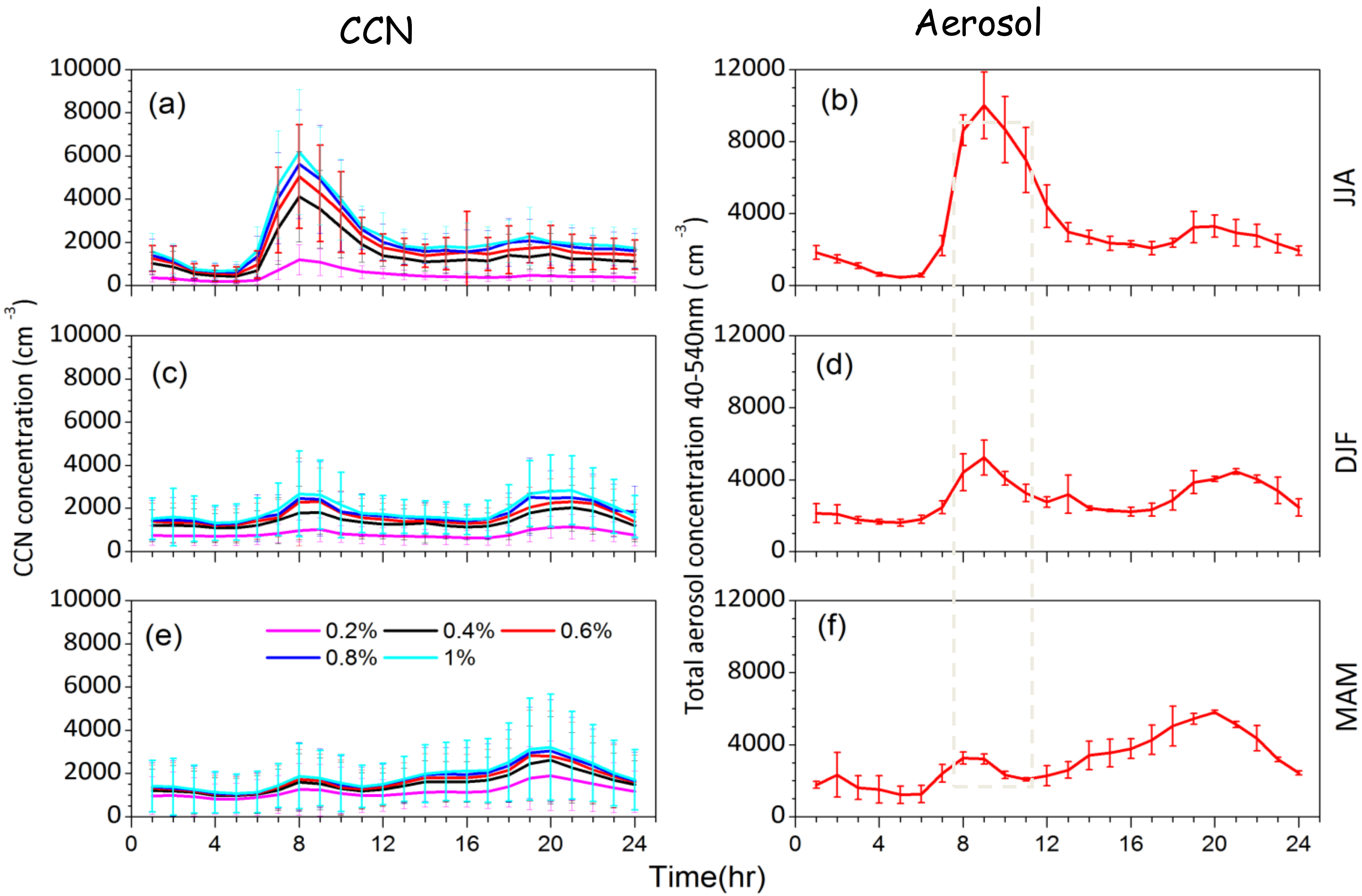
CrossMark

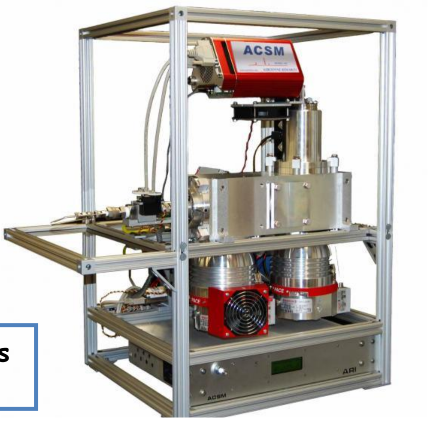
Seasonal variability in aerosol, CCN and their relationship observed at a high altitude site in Western Ghats

P. P. Leena[1] · G. Pandithurai[1] · V. Anilkumar[1] · P. Murugavel[1] · S. M. Sonbawne[1] · K. K. Dani[1]

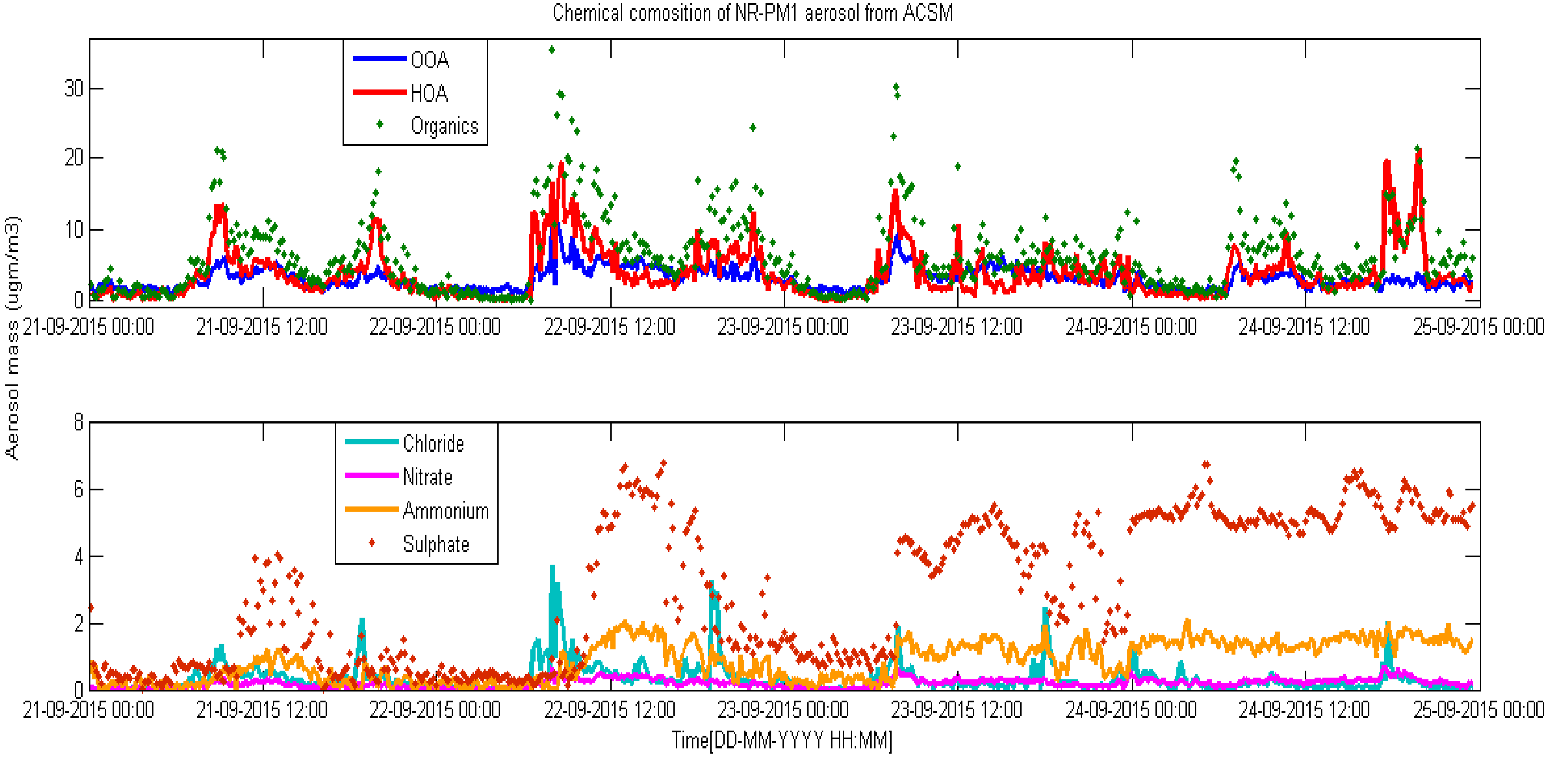


Aerosol Chemical Speciation Monitor (ACSM)

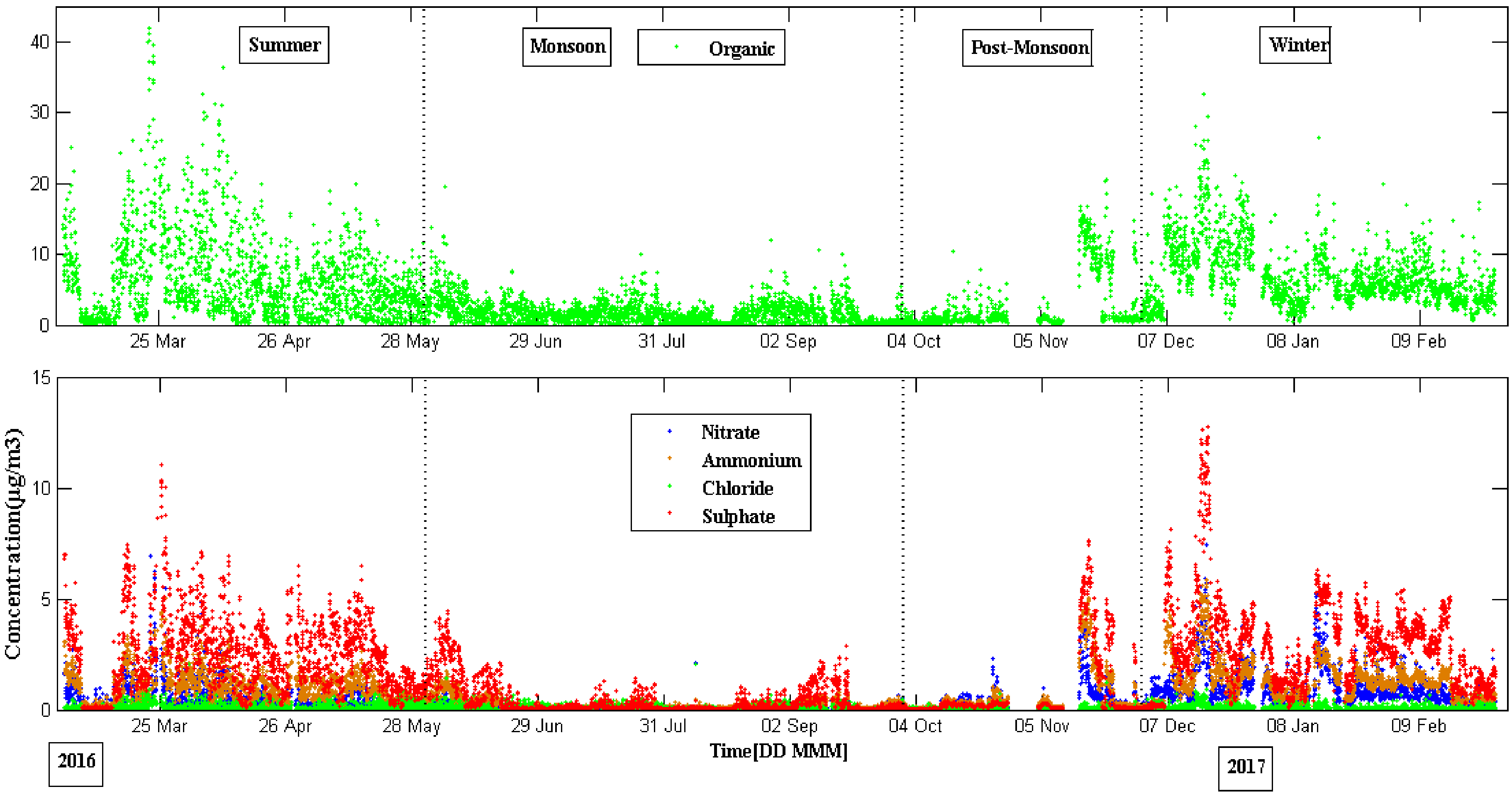
- **Organics is dominant. Possible contribution of Biogenic VOC emissions from forest contribute to SOA**
- **This will be used to address the role of aerosol chemistry in CCN efficiency, droplet activation, aerosol-CCN closure etc.**



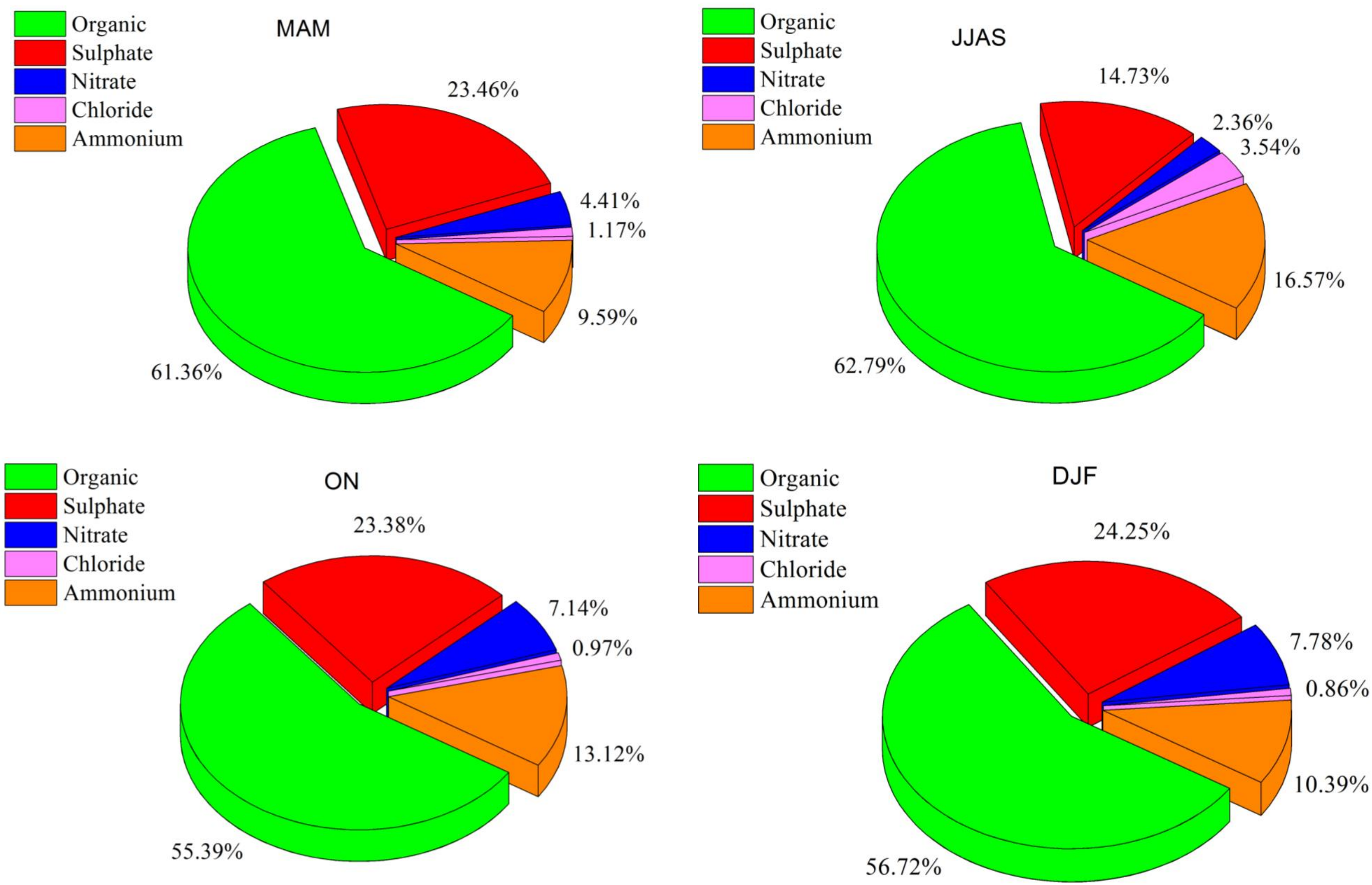
❖*HOA – hydrocarbon-like organic aerosols*
❖*OOA – Oxygenated Organic aerosols*

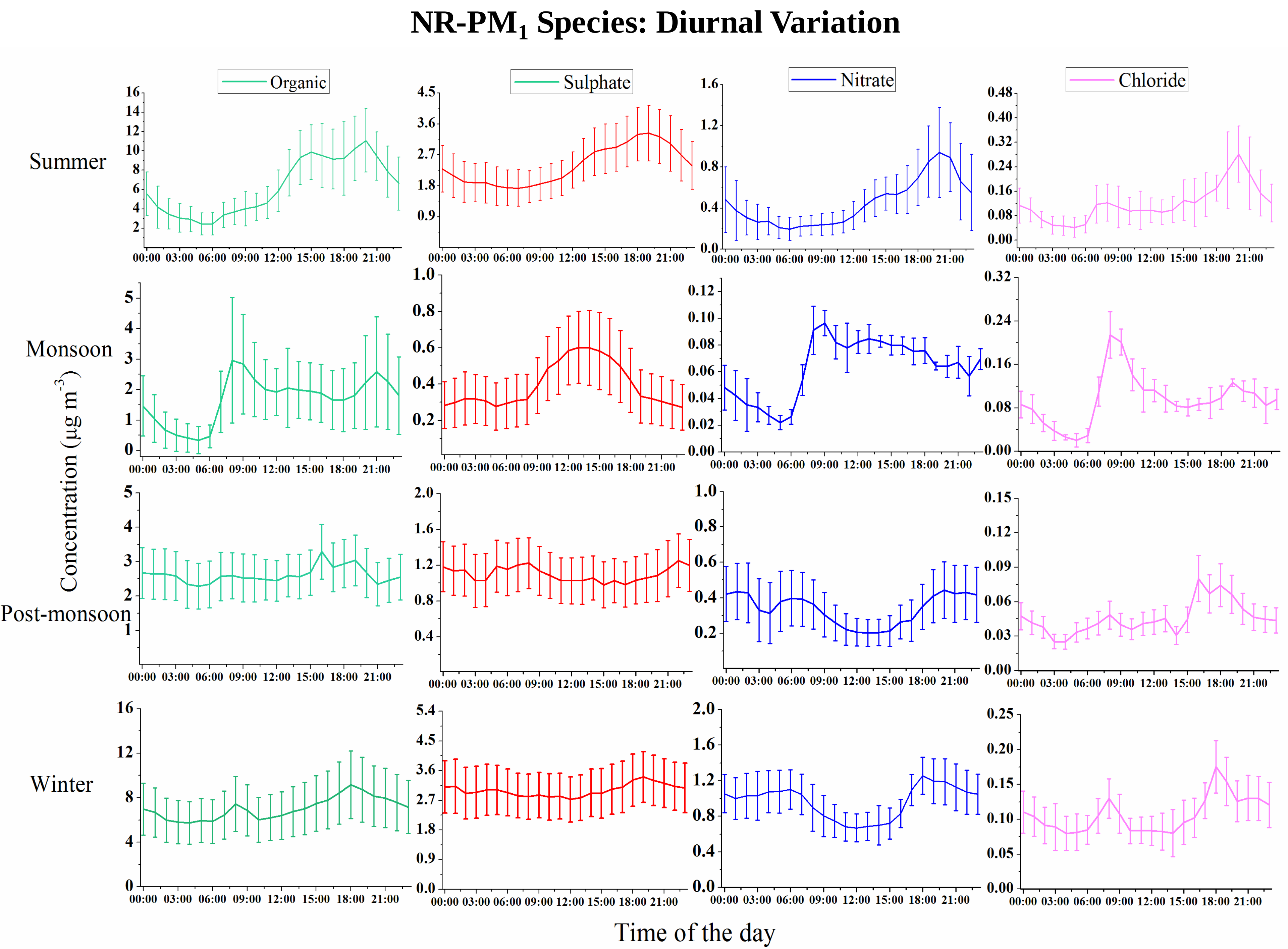


Non-Refractory-Particulate Matter (≤1 μm) ($NR\text{-}PM_1$) Species: Time Series



NR-PM$_1$ Species: Percentage Fraction



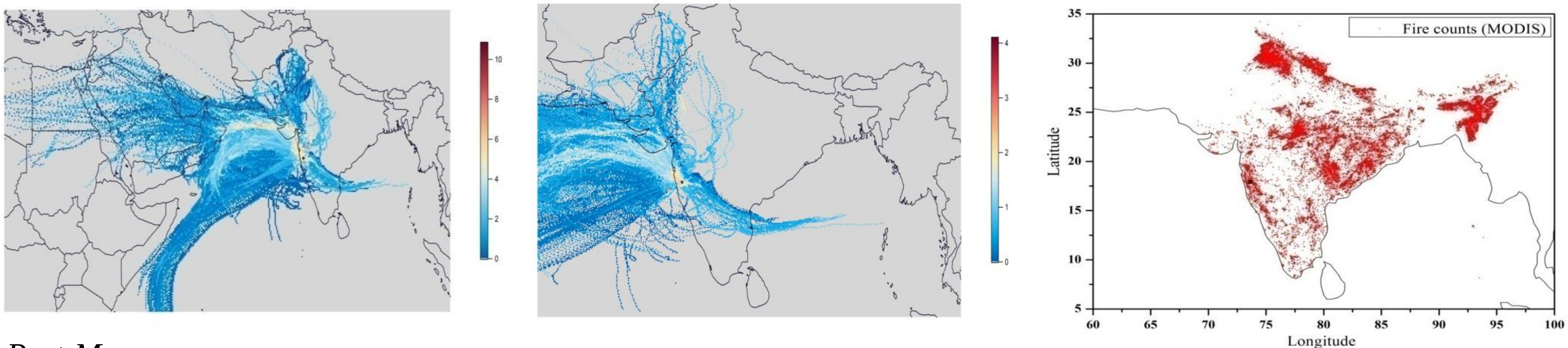


NR-PM1 Species: Diurnal Variation
Organic
Sulphate
Nitrate
Chloride
Summer
Monsoon
Post-monsoon
Winter
Concentration (μg m-3)
Time of the day
00:00 03:00 06:00 09:00 12:00 15:00 18:00 21:00

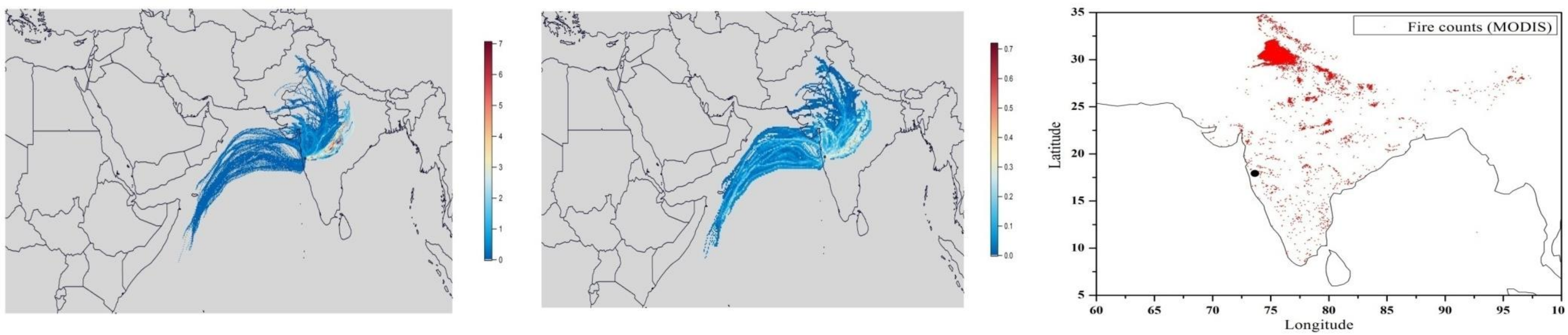
Cluster Weighted Trajectory

Organics | Sulphate | MODIS fire count data

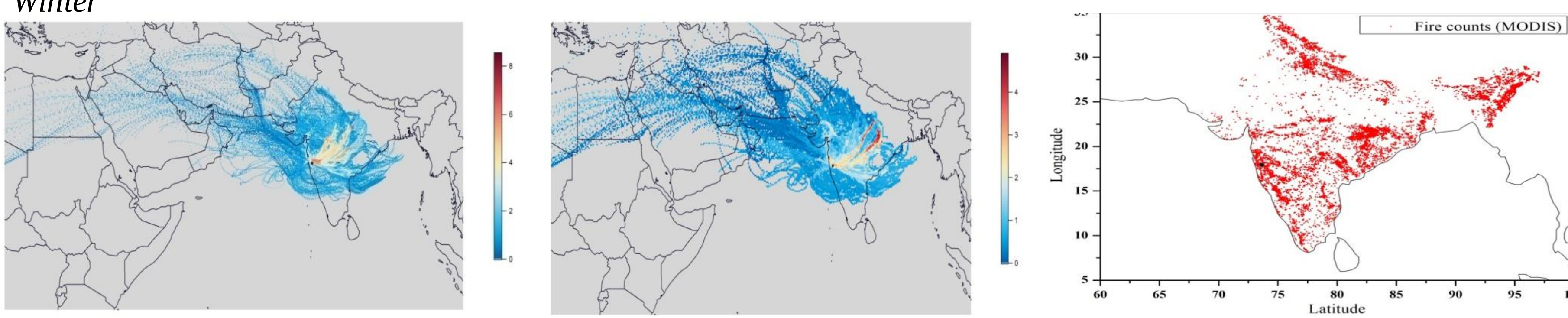
Summer



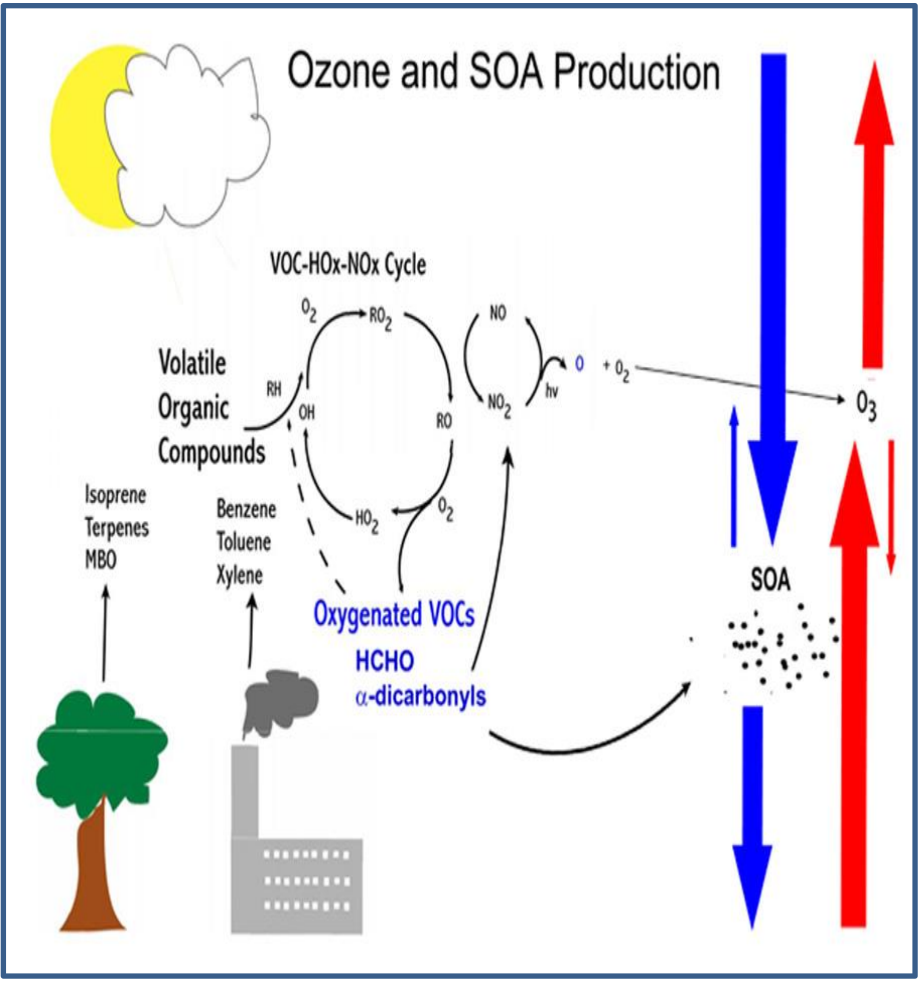
Post-Monsoon



Winter



Role of VOCs on Secondary organic aerosols



- **Secondary organic aerosols (SOA)** - generated from oxidation of biogenic and anthropogenic VOCs.

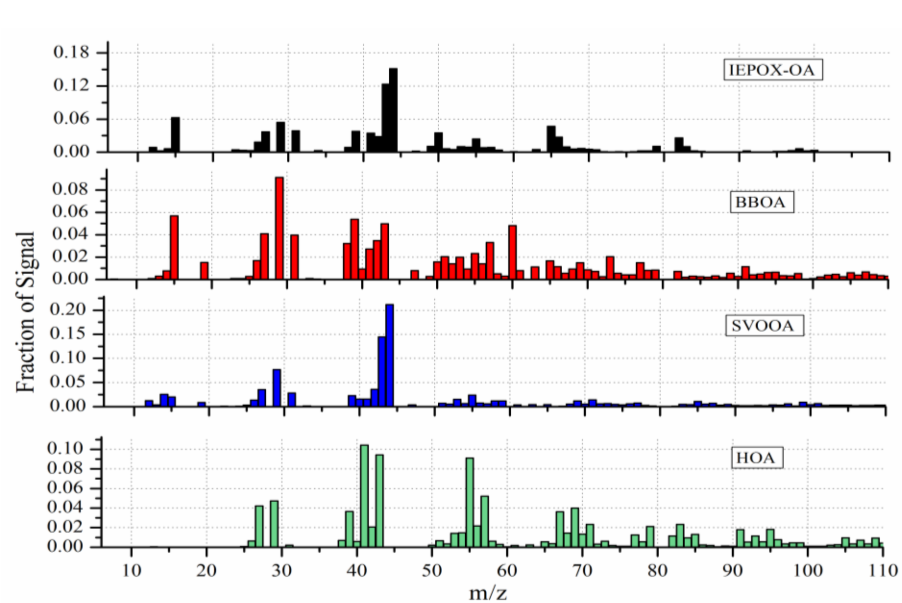
- **Isoprene, Monoterpene (alphapinene)** generated from biogenic sources have high propensity towards SOA formation.

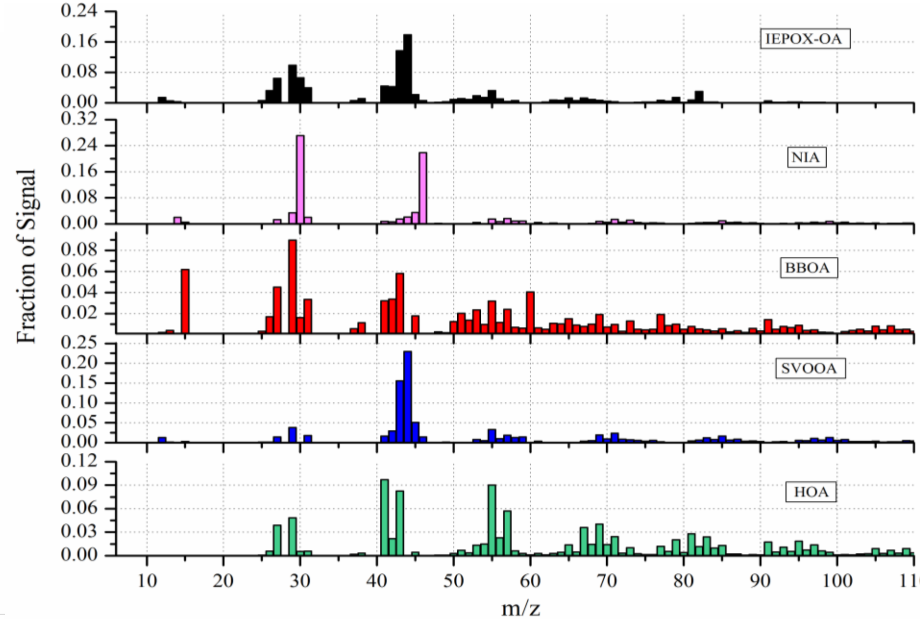
- **Biogenic VOC emissions** on a global scale, (1150 Tg yr^{-1}) are found to be **one order of magnitude larger** than those of anthropogenic VOCs (**Guenther et al., 2006**).

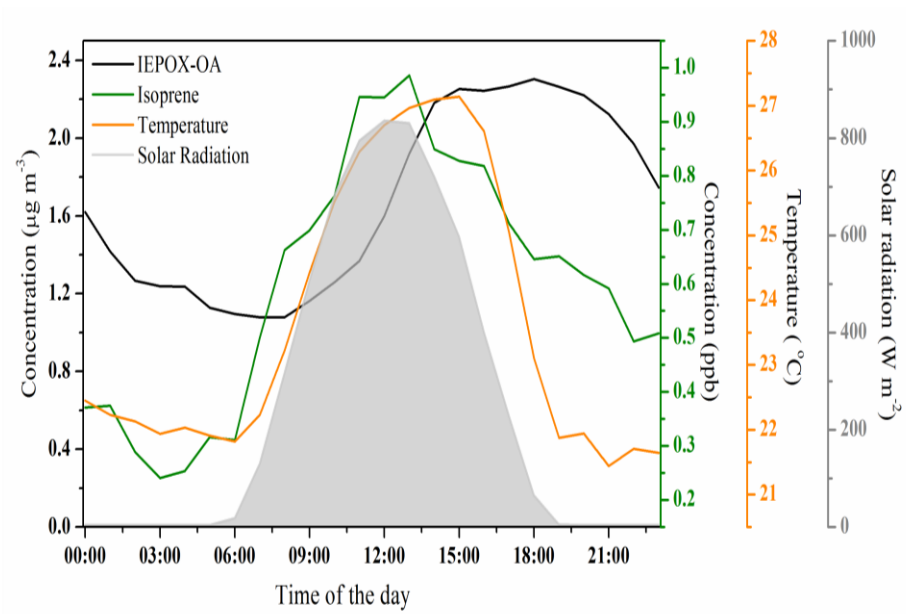
- These **oxidised VOCs are easily soluble in water and can act as CCN** to form clouds.

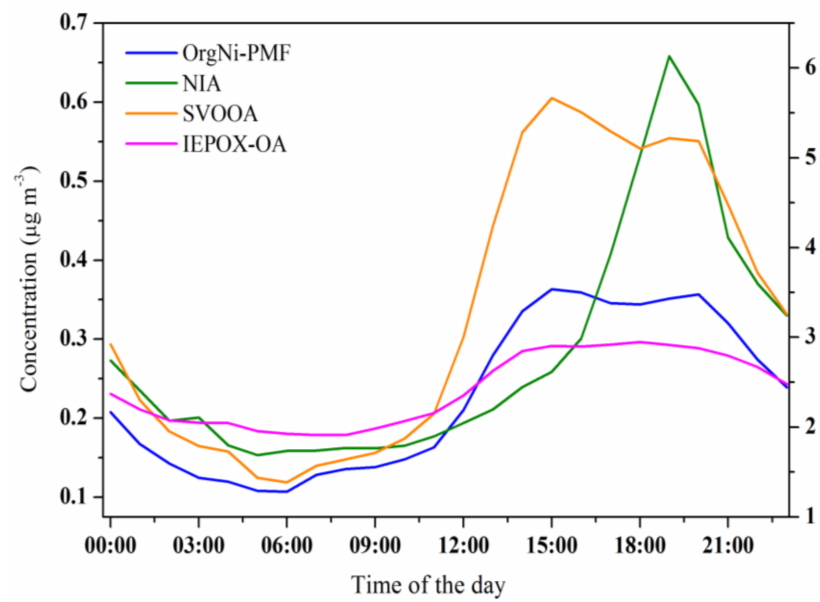
Linking Organic aerosols with Volatile Organic Compounds

IEPOX-OA and Organic Nitrates: Oxidized products of VOCs

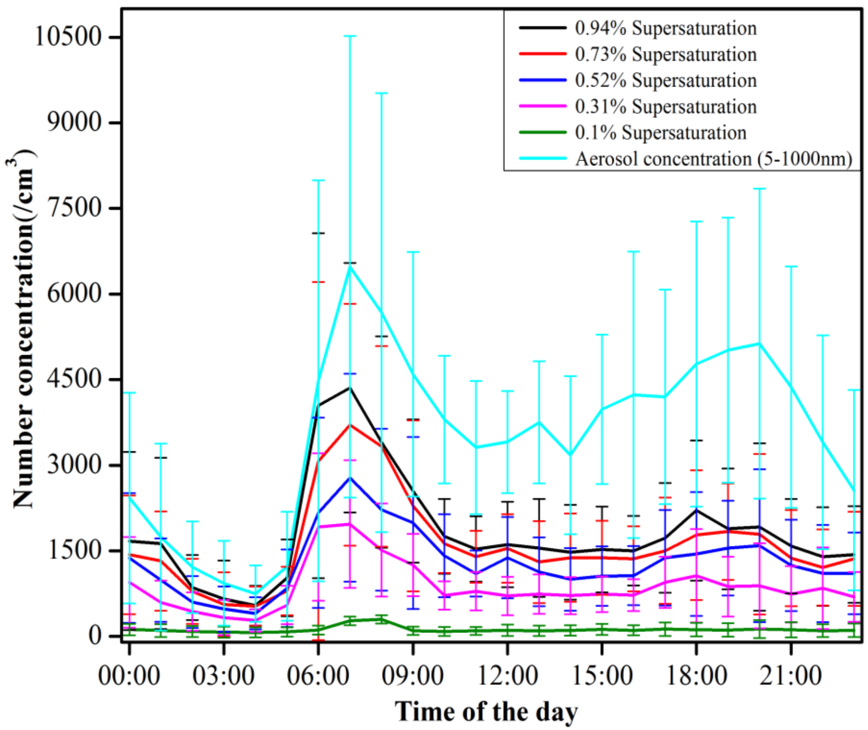


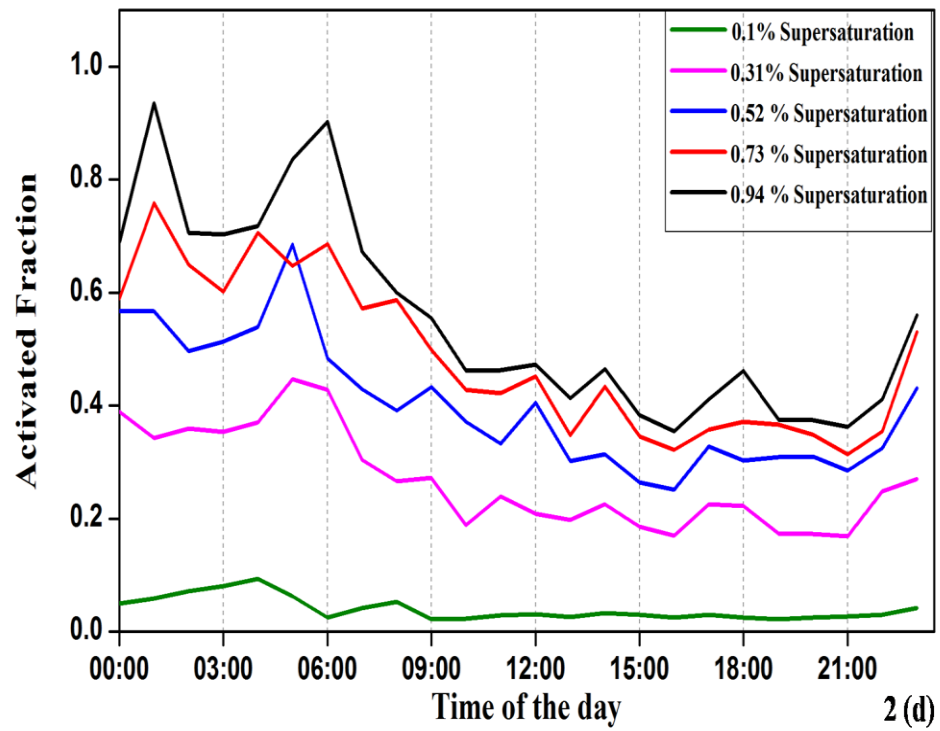






From Aerosol to CCN concentrations





Modelled CCN concentrations based on Köhler theory:

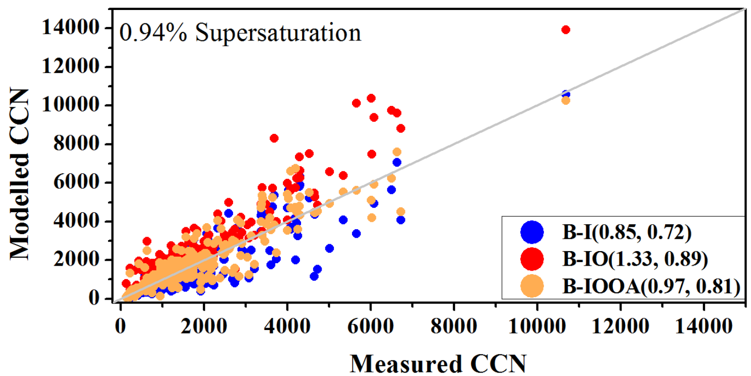
i) Aerosol particle number size distribution

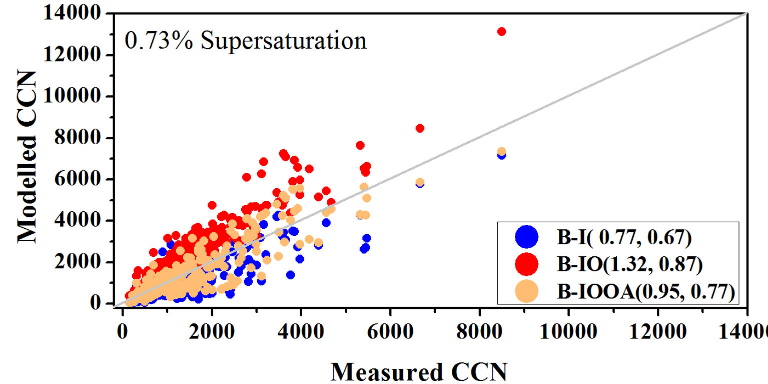
ii) Size independent NR-PM_1 chemical composition

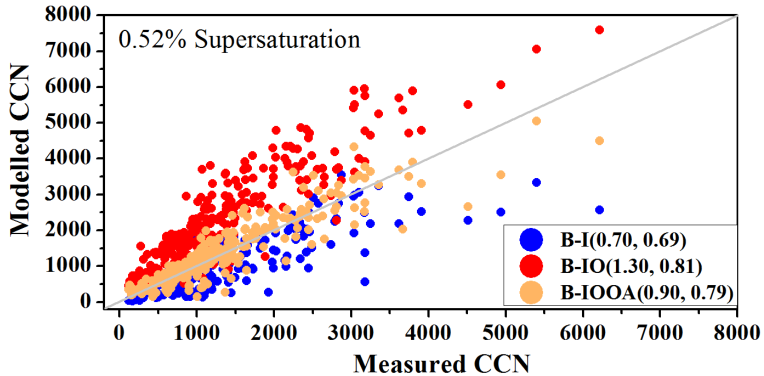
iii) Calculated hygroscopicity ($\kappa_{total} = f_{org}\,\kappa_{org} + f_{inorg}\,\kappa_{inorg}$)

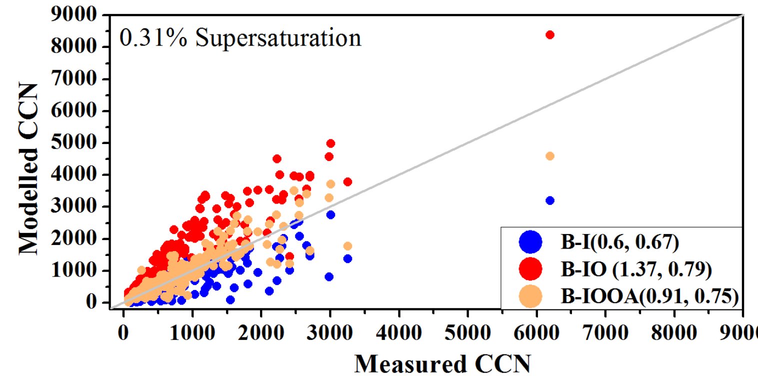
Supersaturation: $$S = \left(1 + \kappa \frac{D_p^3}{D_{drop}^3 + D_p^3}\right)^{-1} \exp\left(\frac{4\sigma M_w}{RT\rho_w D_{drop}}\right)$$

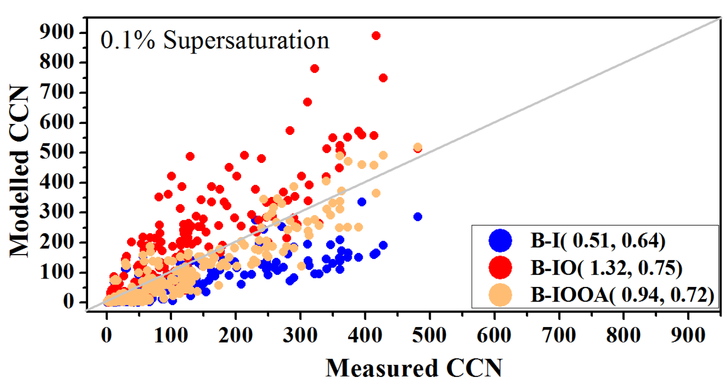
CCN closure for different aerosol chemistry scenarios









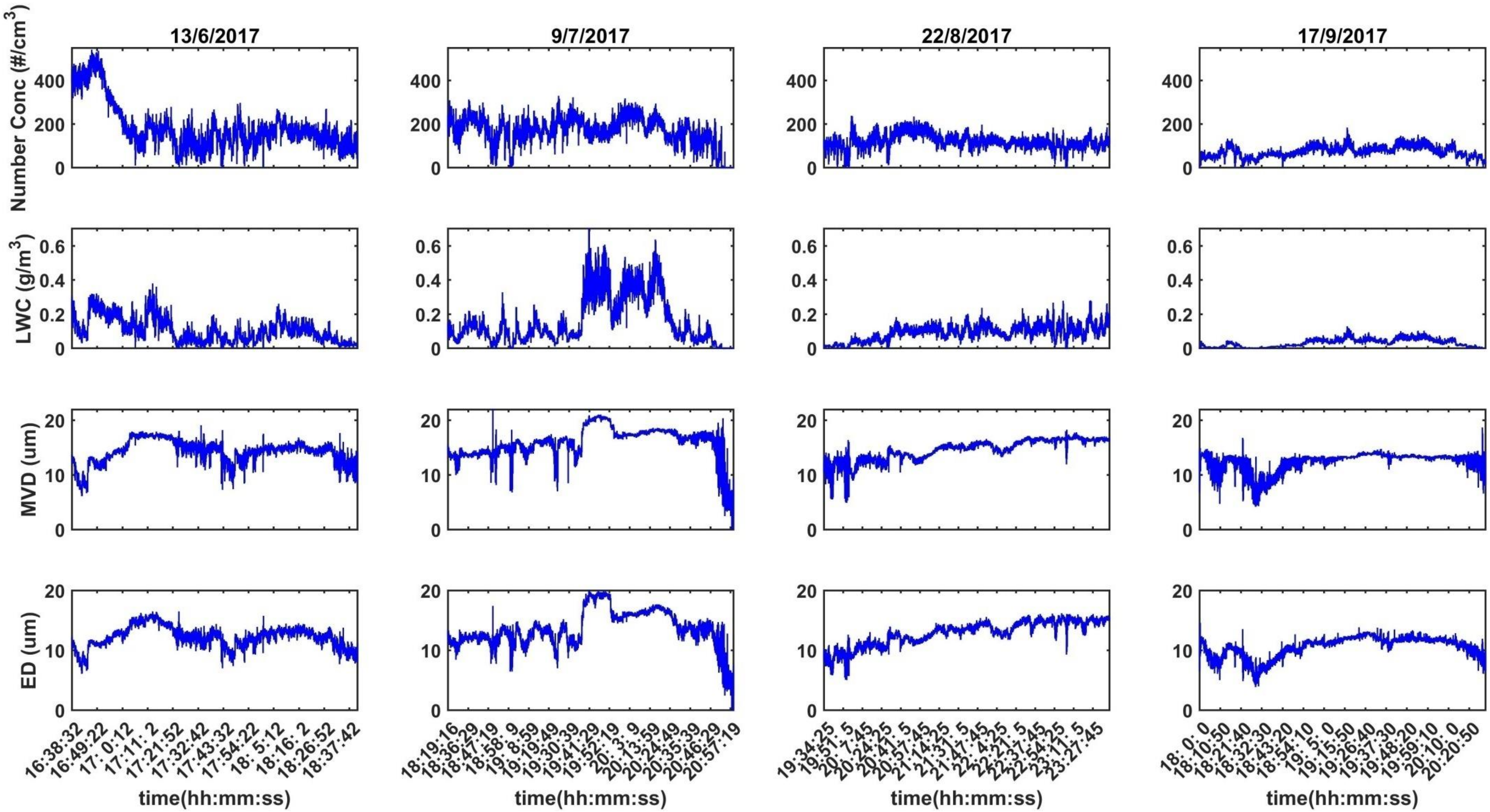


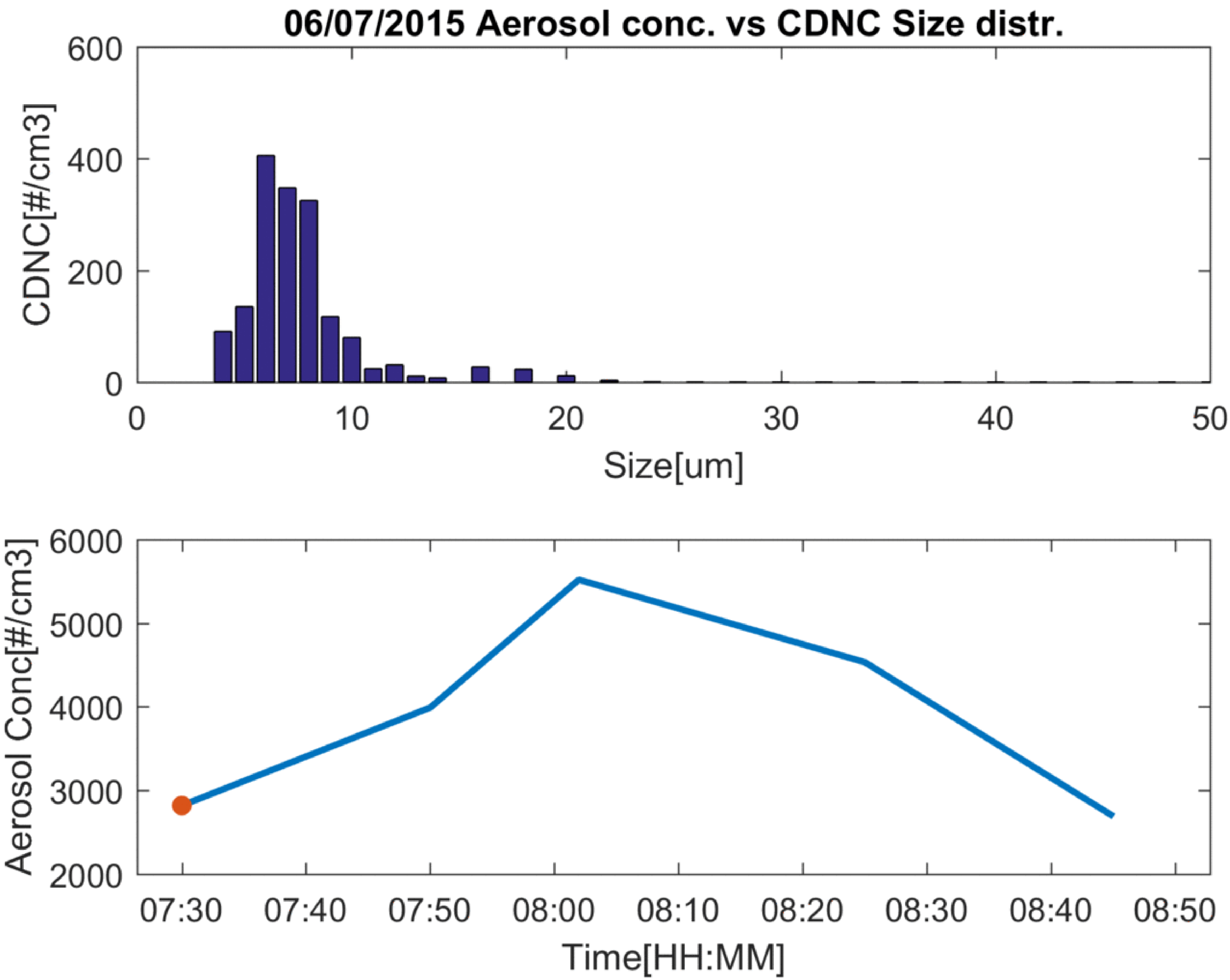
I- Inorganics

IO-Inorganics and Organics

IOOA-Inorganics and Oxygenated Organic Aerosols

Cloud microphysics observations





06/07/2015 Aerosol conc. vs CDNC Size distr.
CDNC[#/cm3]
600
400
200
0
0
10
20
30
40
50
Size[um]
Aerosol Conc[#/cm3]
6000
5000
4000
3000
2000
07:30
07:40
07:50
08:00
08:10
08:20
08:30
08:40
08:50
Time[HH:MM]

Investigation of aerosol indirect effects on monsoon clouds using ground-based measurements over a high-altitude site in Western Ghats

Vasudevan Anil Kumar, Govindan Pandithurai, Parakkatt Parambil Leena, Kundan K. Dani, Palani Murugavel, Sunil M. Sonbawne, Rohit D. Patil, and Rajamma Sukumaran Maheskumar

Indian Institute of Tropical Meteorology, Pune, 411008, India

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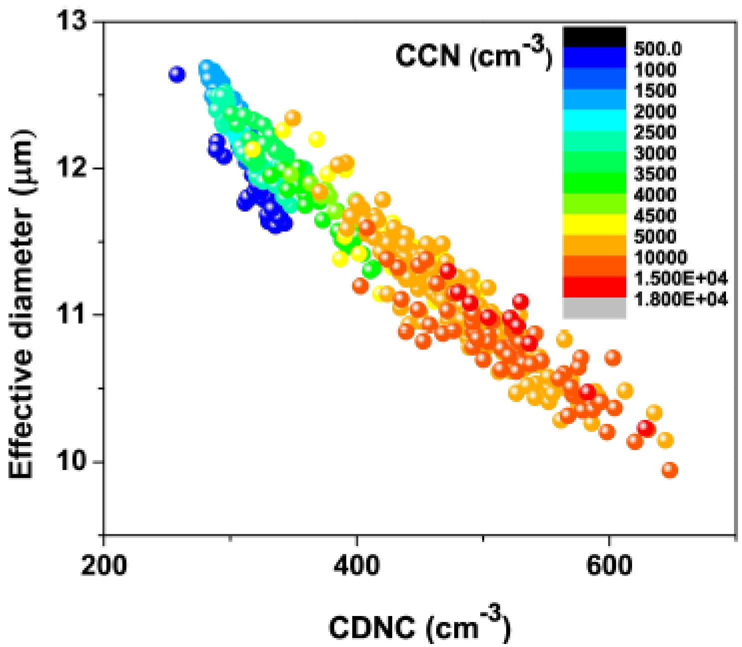


Figure 1. Variation of cloud microphysical parameters (droplet number concentration and effective diameter) with CCN number concentration.

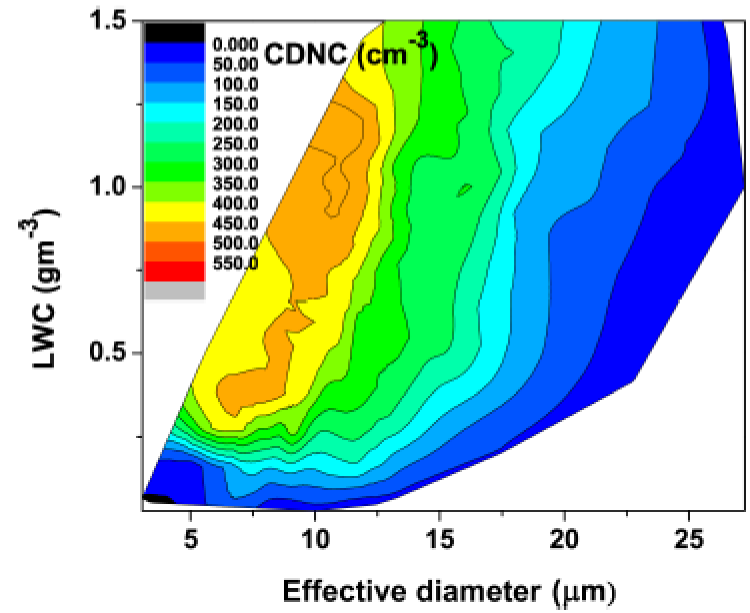
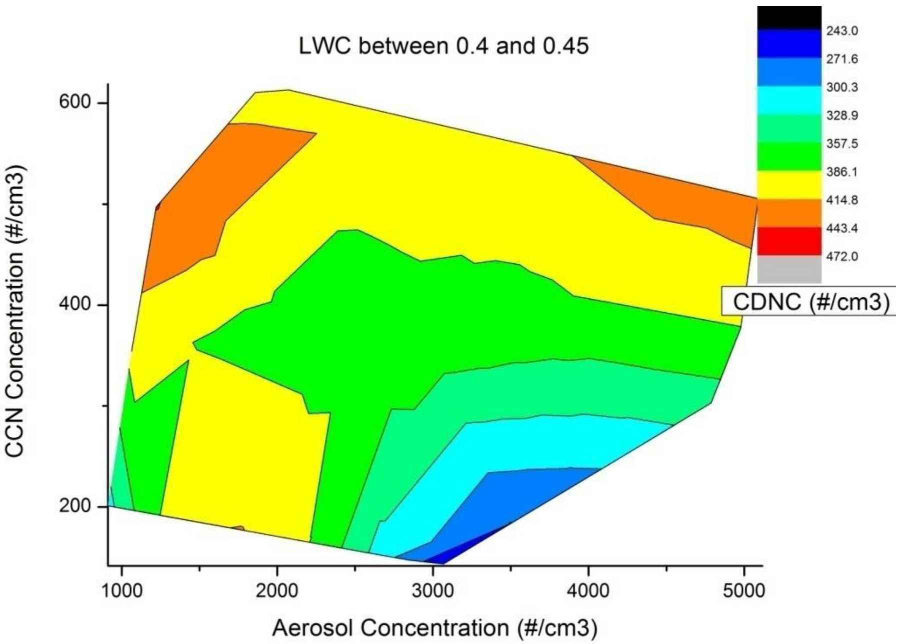
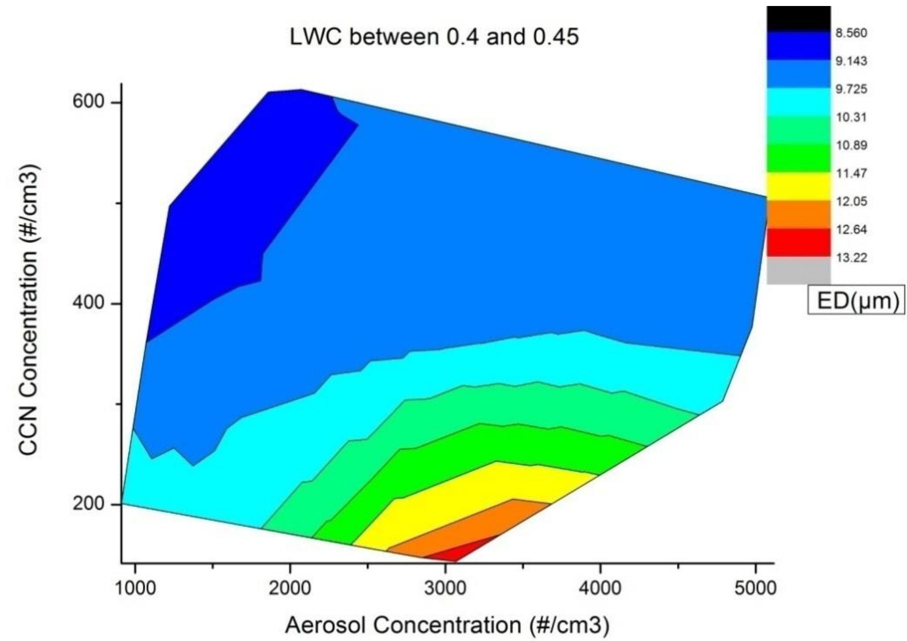
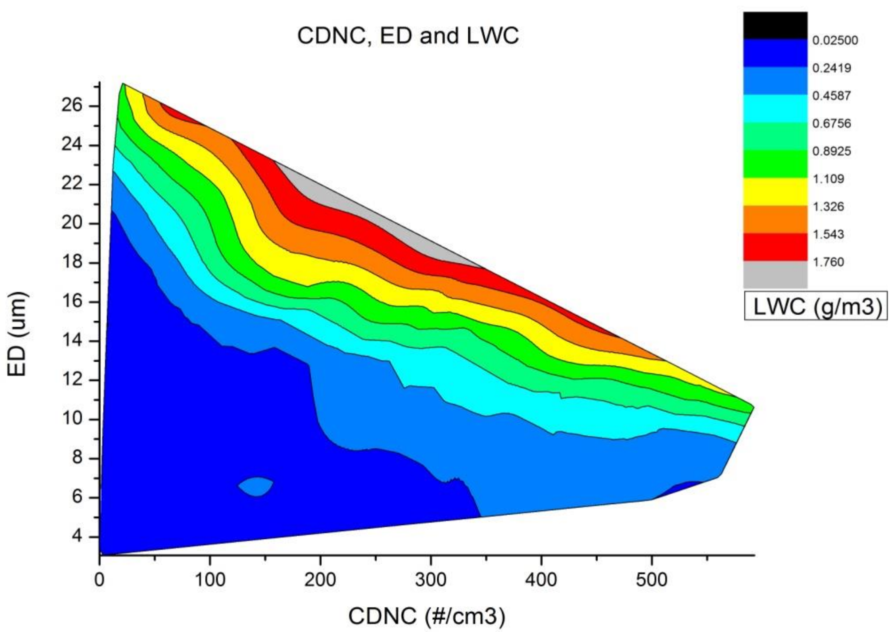


Figure 2. The contour plot shows the relationship between cloud microphysical parameters, cloud droplet number concentration (CDNC), droplet effective diameter (ED), and LWC. ED decreases with increase in CDNC for all LWCs.

Aerosol indirect effect estimates







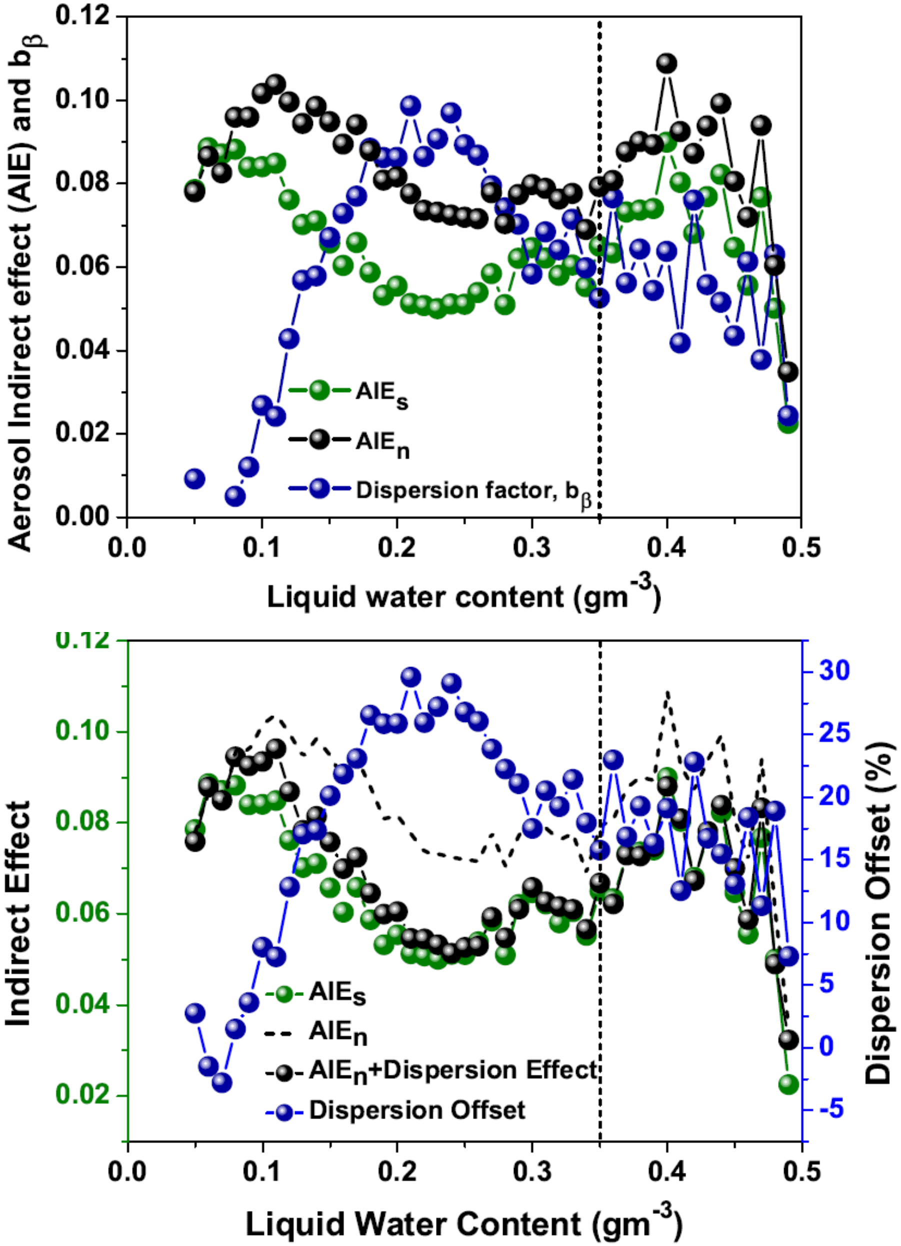
$$\mathrm{ACI}_\tau = \left.\frac{\partial \ln \tau_c}{\partial \ln \alpha}\right|_L \qquad 0 < \mathrm{ACI}_\tau < 0.33 \tag{1a}$$

$$\mathrm{ACI}_r = -\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_L \qquad 0 < \mathrm{ACI}_r < 0.33 \tag{1b}$$

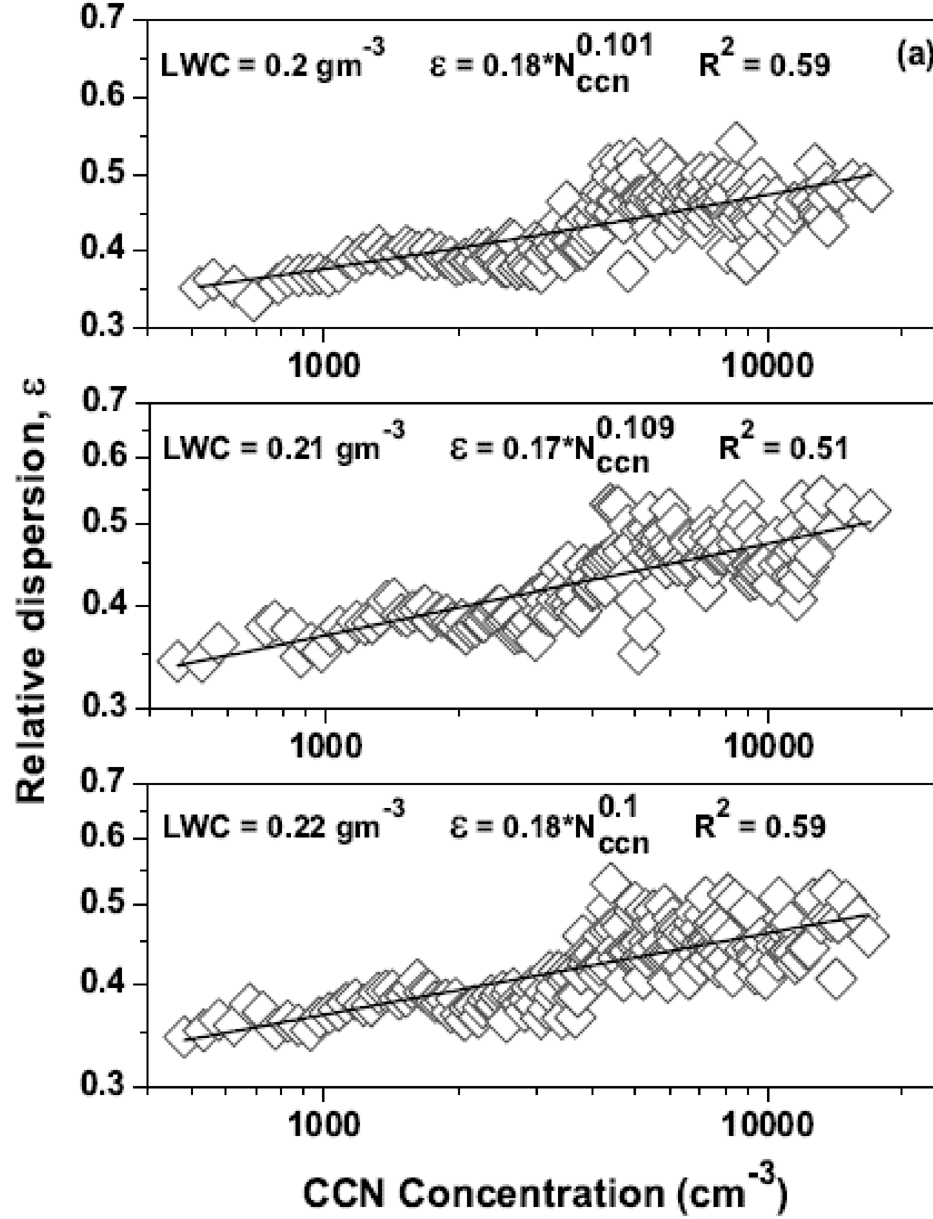
$$\mathrm{ACI}_N = \frac{d \ln N_d}{d \ln \alpha} \qquad 0 < \mathrm{ACI}_N < 1 \tag{1c}$$

$$\mathrm{ACI}_\tau = -\mathrm{ACI}_r = \frac{1}{3}\mathrm{ACI}_N. \tag{1d}$$

Discrepancies in AIE



CCN vs Relative Dispersion



New Particle formation processes and their effect on CCN

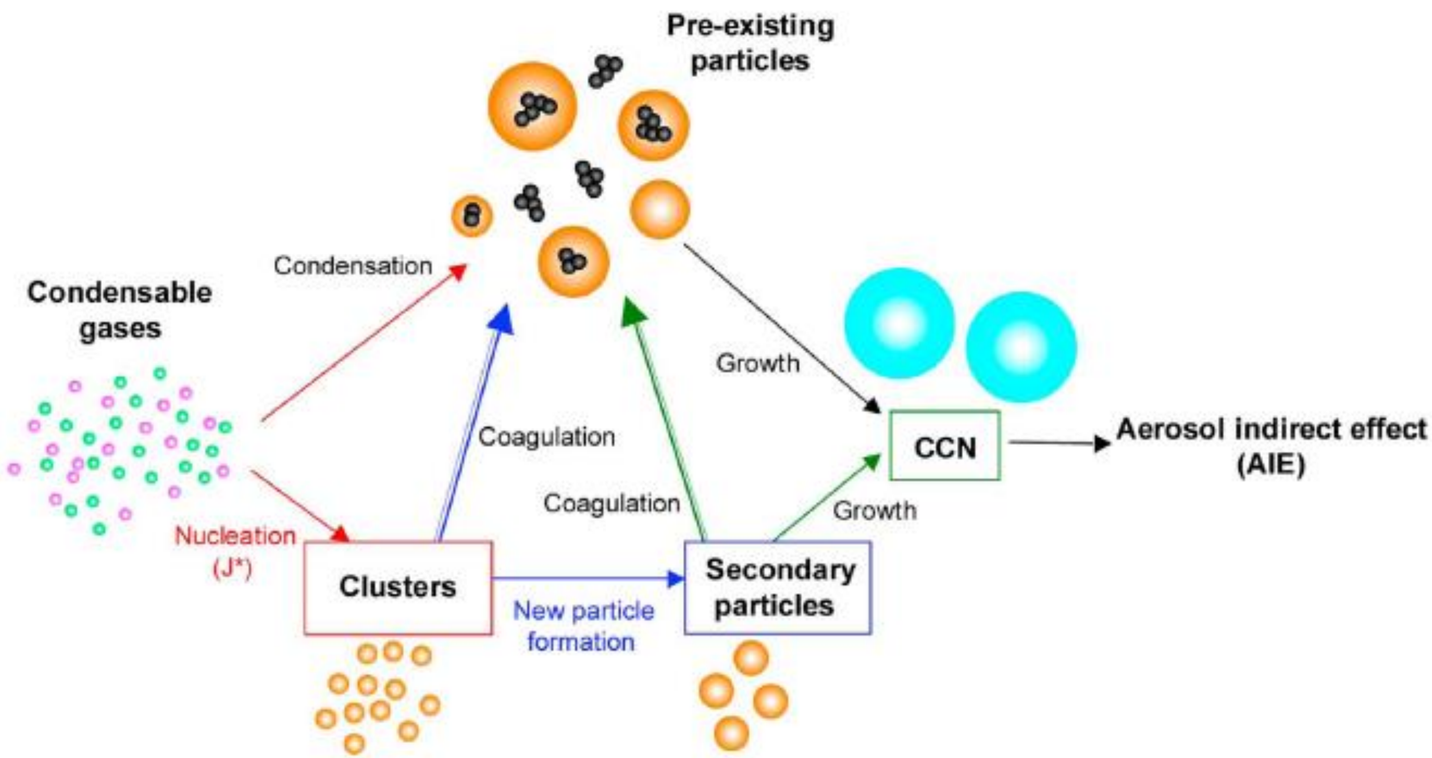
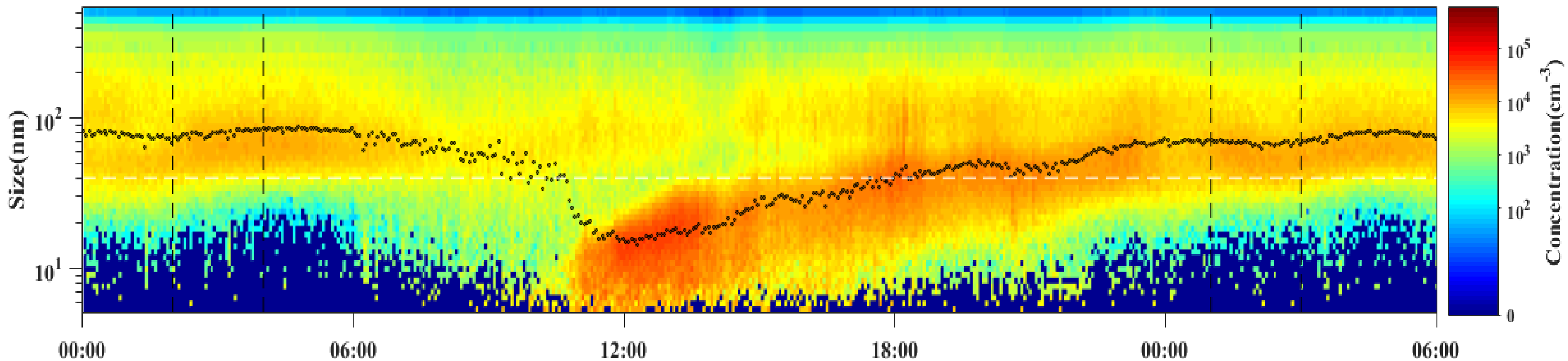


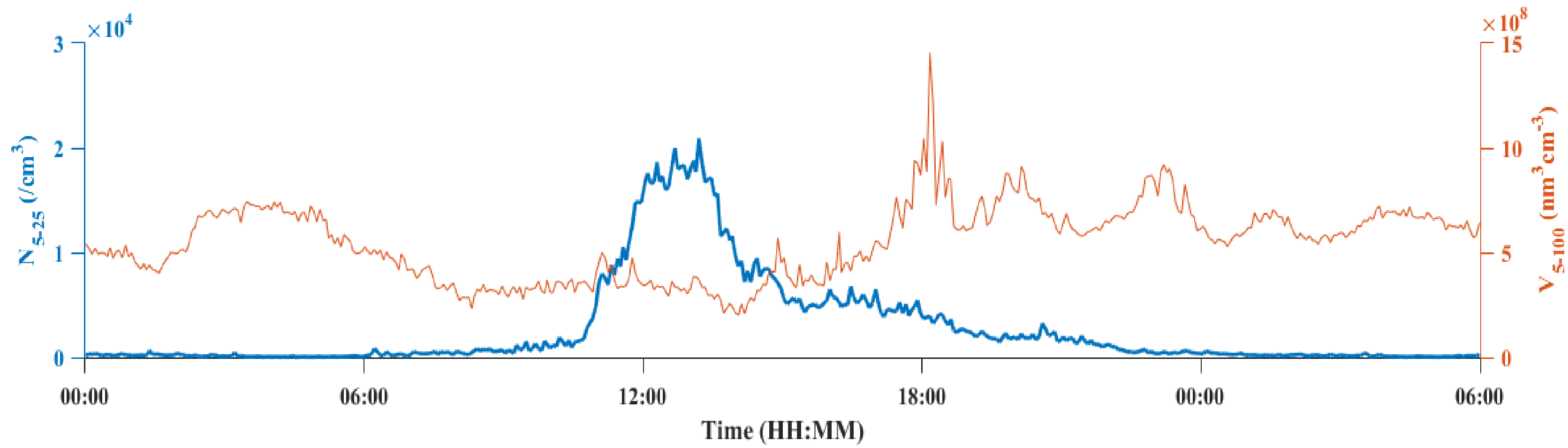
Figure 1. Diagram for nucleation and new particle formation processes and their impact on condensation nuclei (CN) and cloud condensation nuclei (CCN) concentrations and aerosol indirect effects. The red, blue, and green arrows show the competing processes of condensable gases between preexisting particles and nucleated secondary particles. J^* denotes the formation rate of clusters and is defined by equations (1) and (2) in this study.

Binary homogeneous nucleation (sulfuric acid+water vapor)
Ternary nucleation (H_2SO_4 - NH_3 – H_2O)

Source: Matsui et al (2011)

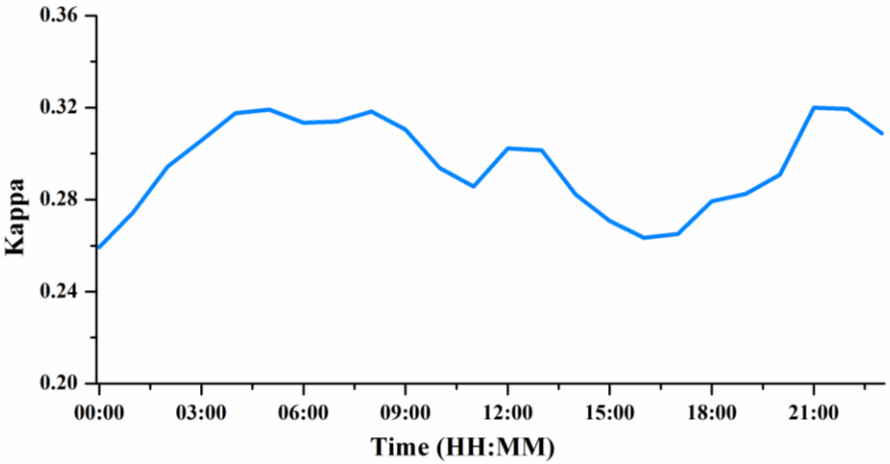
Size Distribution of aerosol particles on NPF day – 12th Dec 2016

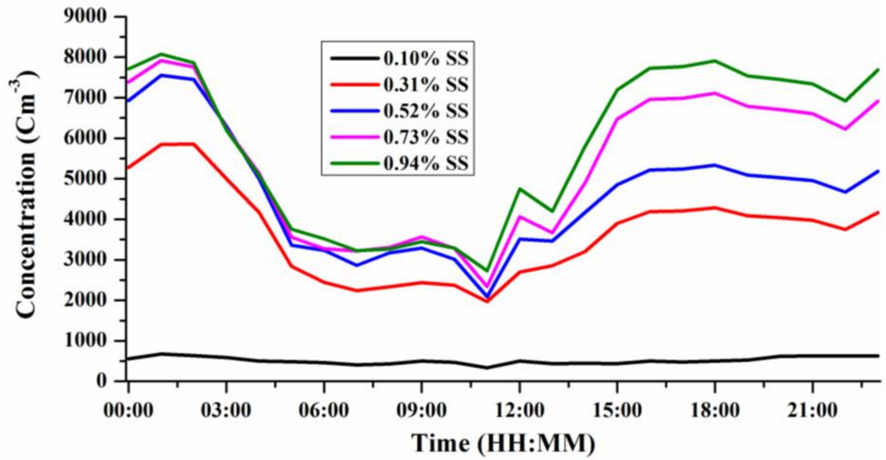




Average Concentration of N_{nucl} particles (10:30 to 18:00 hrs) : $9.32*10^3 \pm 5.40*10^3$ cm^{-3}
Peak concentration of N_{nucl} particles at 13:10 hrs $2.10*10^4$ cm^{-3}
Growth rate of N_{nucl} particles : 2.87 nm hr^{-1}

NPF Event: Link with CCN





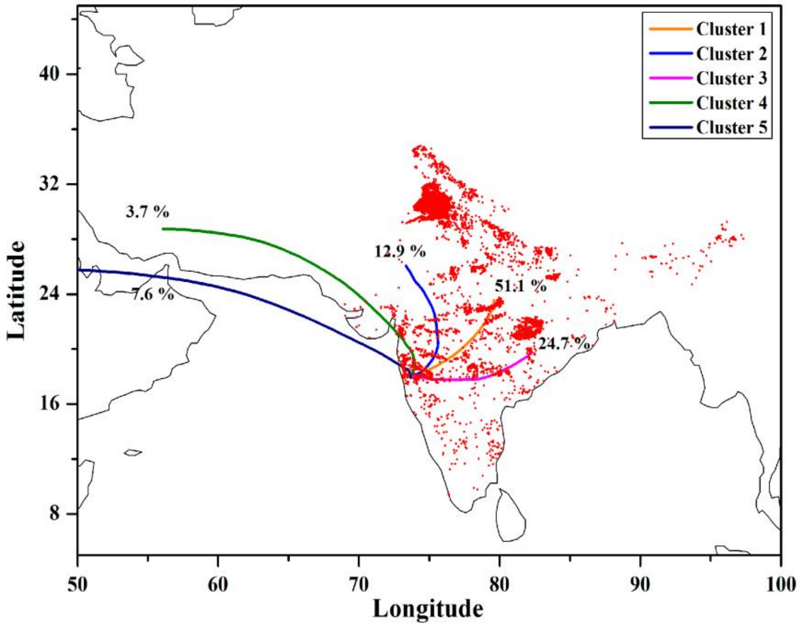
Increase in kappa and CCN concentration: Probably due to the growth of newly formed particles, which attained the threshold size required to get activate as CCN

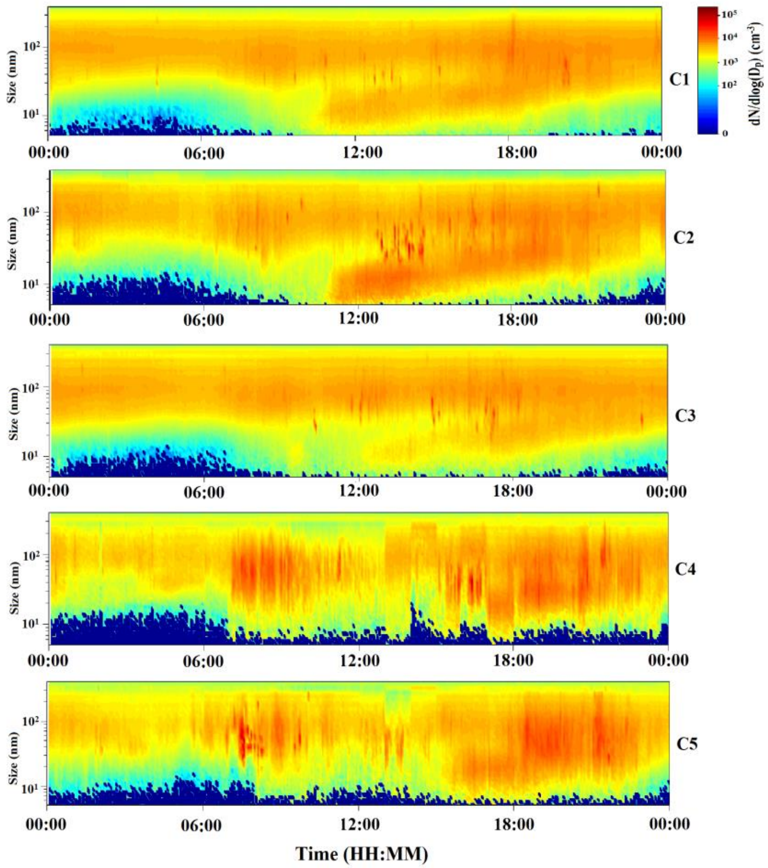
Change in CCN Concentration

$$\Delta CCN = \frac{CCN_{W_2} - CCN_{W_1}}{CCN_{W_1}}$$

W_1 = Time period before the nucleation
W_2 = Time period when (i) the particle growth terminated or (ii) the growth was interrupted, either by a change in origin of air mass or by significant primary emissions

Cluster analysis: Identification of origin of air mass

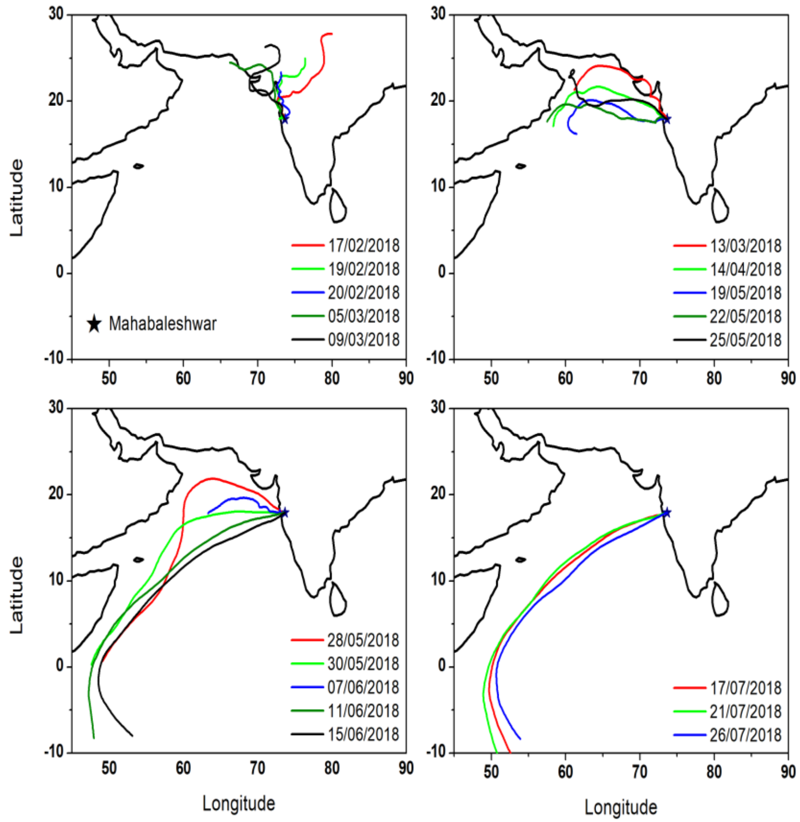




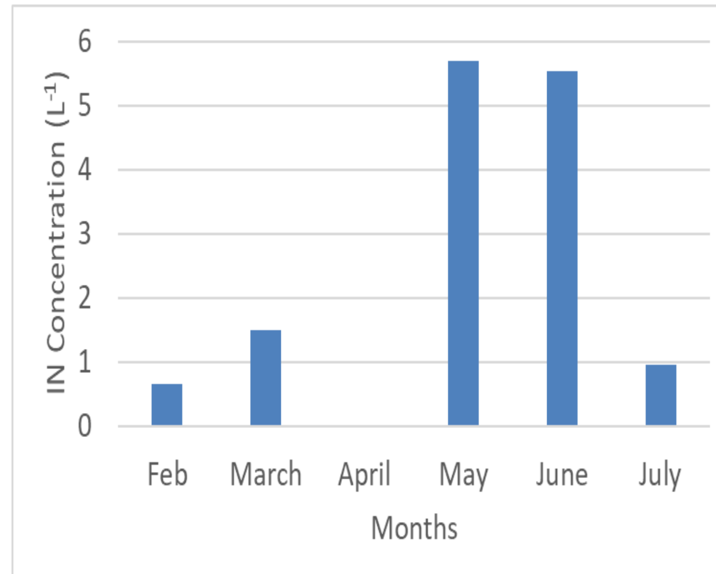
- The air masses coming from biomass burning influenced areas leads to formation of new particles (Cluster 1, 2 and 3).
- The cleaner air masses not favored NPF (Cluster 4 and 5).

Cluster analysis indicates possible transport of precursor gases required for new particle formation at the receptor site.

Ice Nuclei vs Airmass back trajectory



HYSPLIT 5 day (120 hr) back trajectory for the observation days.

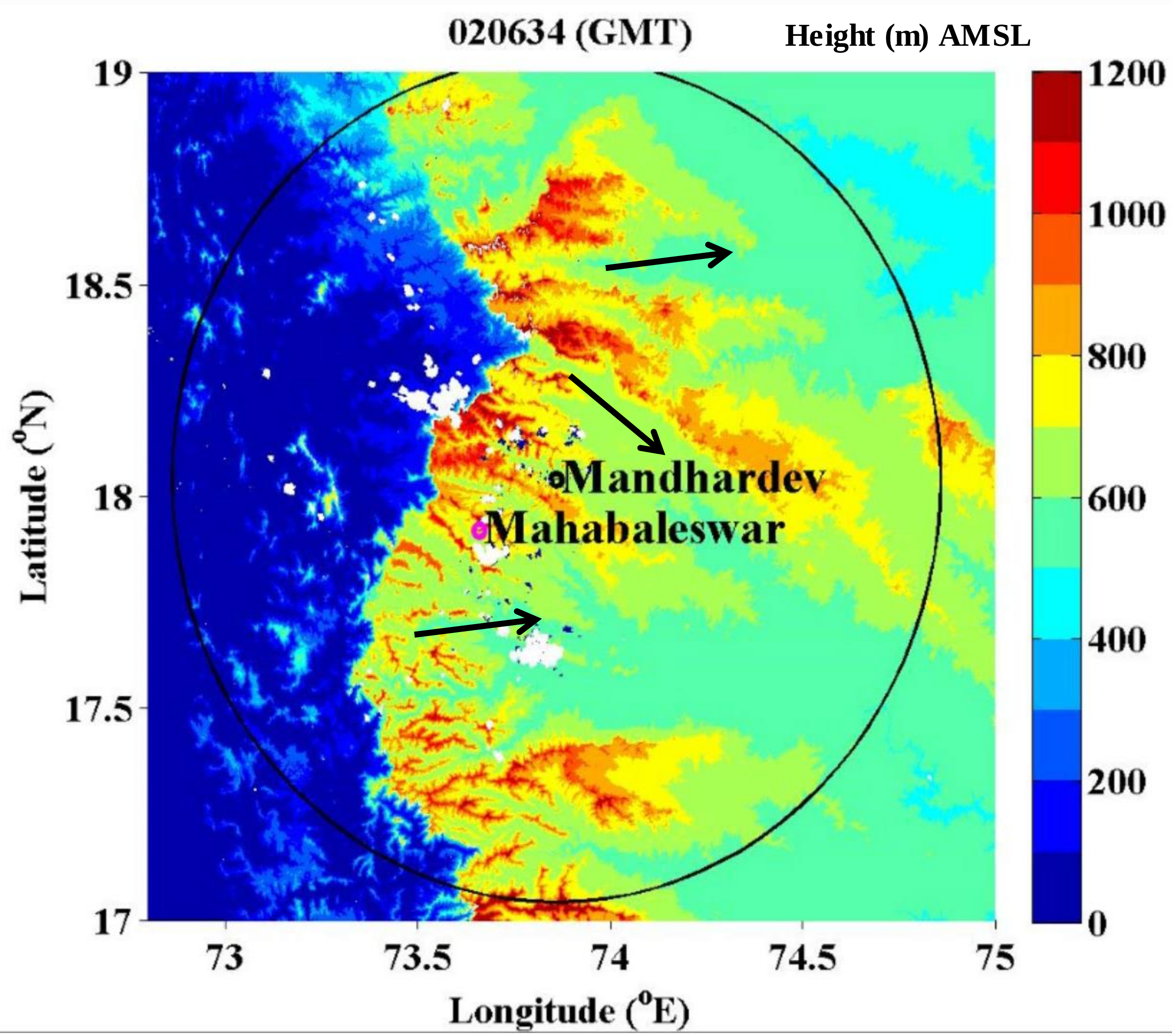


- Monthly averaged IN concentration,
- IN concentration found to he high when the air masses from Arabian sea.
- In July IN concentration reduced because of wash out by heavy rain.

Cloud and Precipitation Radars

X-band (10 GHz); 3-D structure of **precipitating clouds- 125 km range**
Ka-band (35 GHz); 3-D structure of **non-precipitating clouds- 25 km range**

Clouds movement over Western Ghats: X-band radar

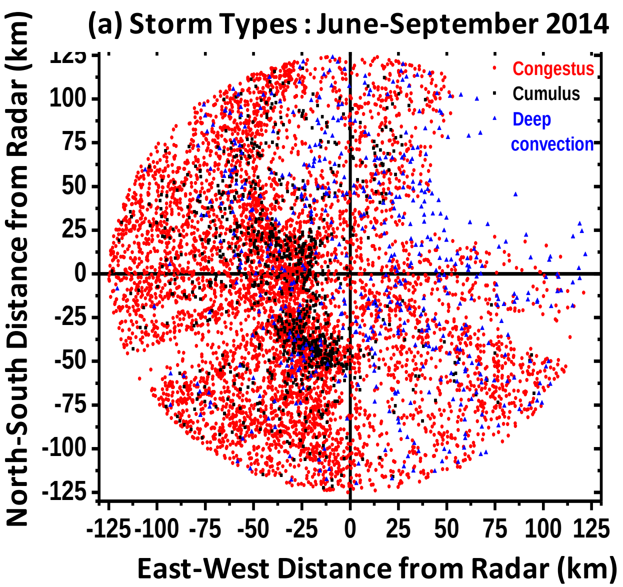


- ❖ Enhanced radar echoes indicating convective system intensification over the mountain ridge and inland
- ❖ Suppressed radar echoes upstream of the mountain ridges.
- ❖ Identification of squall line features

✓ Radar echoes are shown by WHITE COLOUR.

✓ Contour shows the topography map.

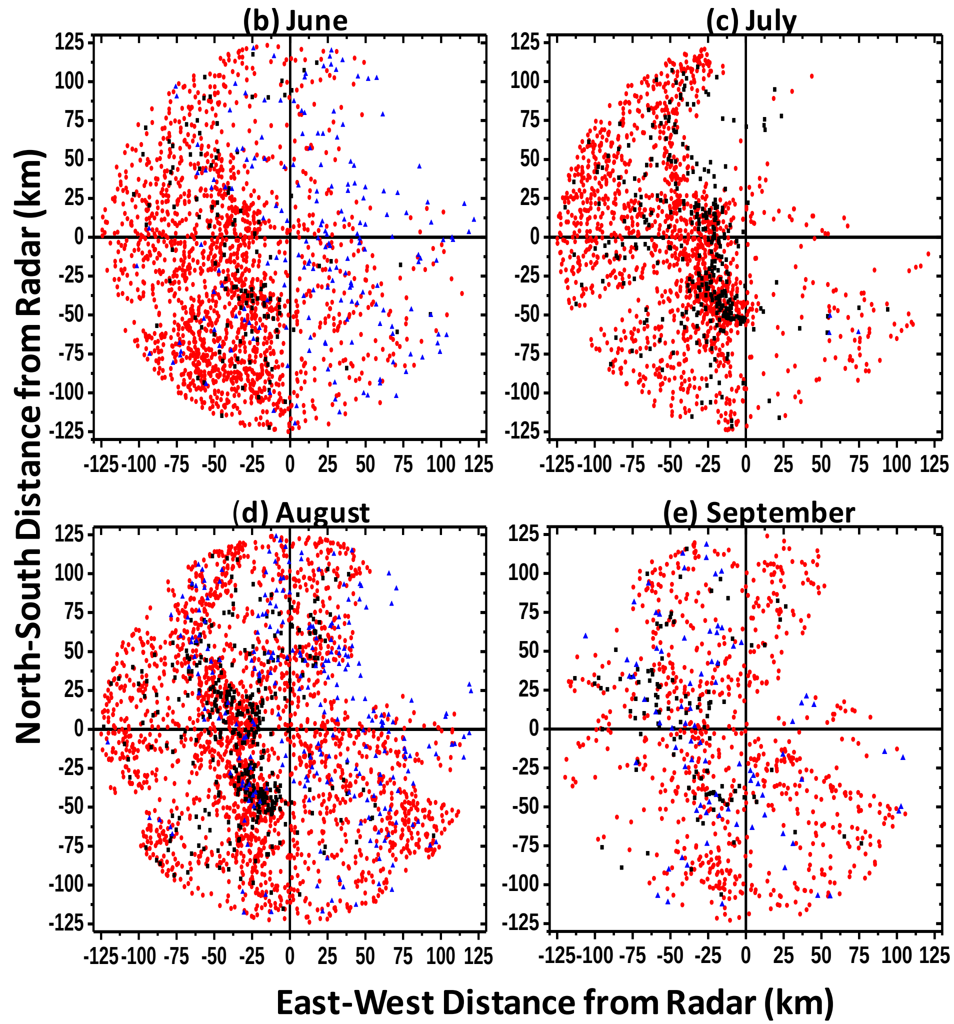
Convective Cell types - Spatial Variation



■ **Cumulus : 0-4 km**

● **Congestus : 4-9 km**

▲ **Deep convection : >9 km**



Congestus (deep) cells numerous on the windward (leeward)sides : preferential NS cluster

June : deep cells: lee side: isolated thunderstorms :onset conditions, shallower windward.

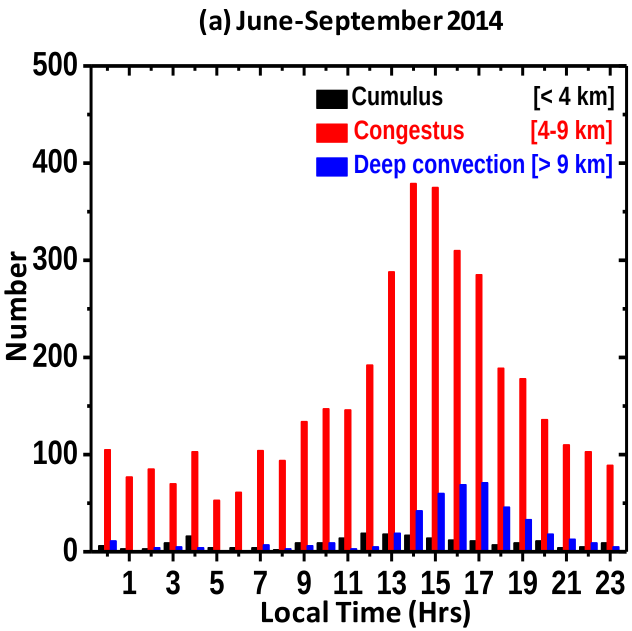
July : no deep cells, Cu and CG, NS cluster, shallow

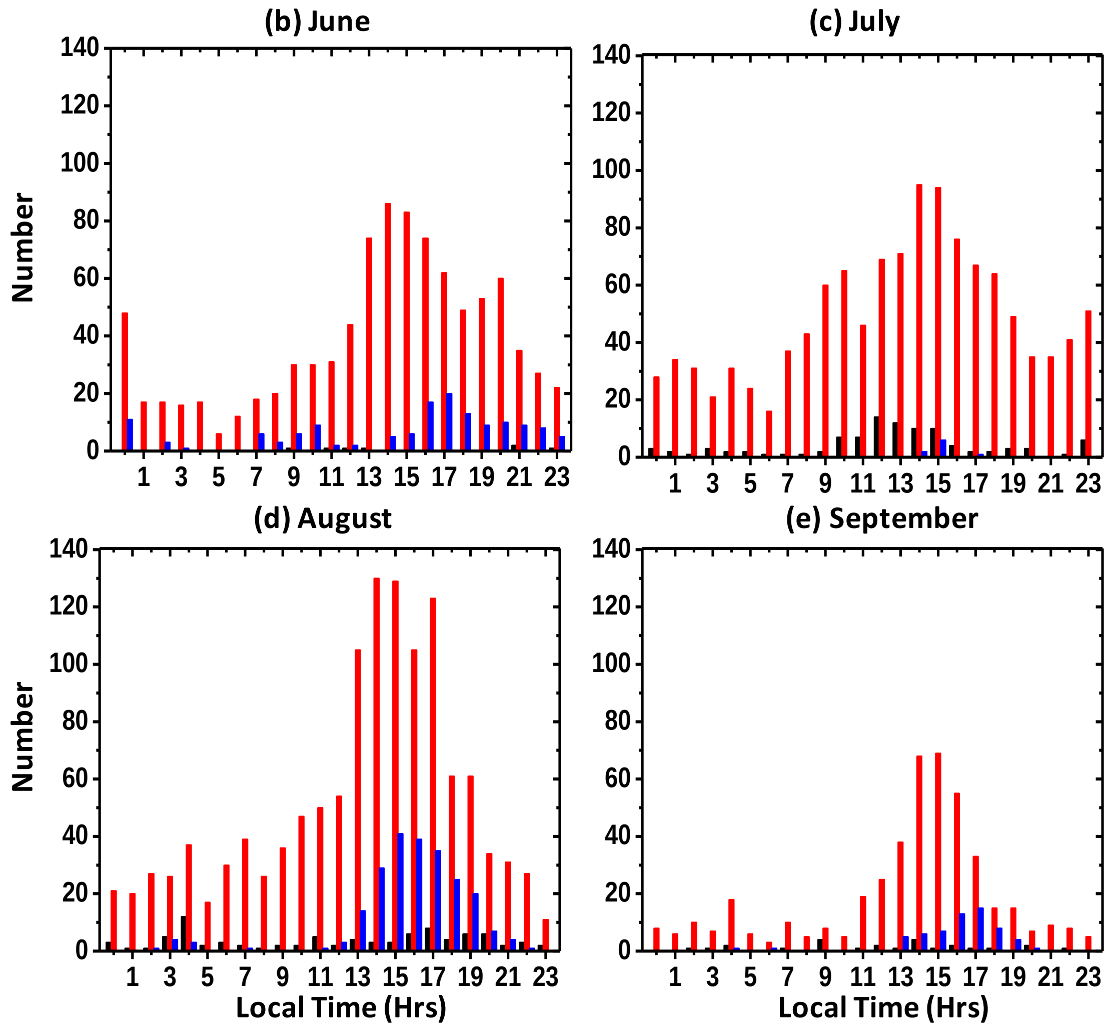
Aug : Deep storms reappear over lee and mountains.

Sept :overall reduction, withdrawal

Utsav, Deshpande et al (JGR 2017)

Convective Cell types – Diurnal Variation





- **Cumulus : daylong occurrence**
- **Congestus : all day, peak in afternoon**
- **Deep (13-21 LT)**

Congestus (Deep cells) peak ~ 1400 (1600) LT

Lead Lag relation : shallow to deep transition
Congestus heating and moistening is important in such transitions.

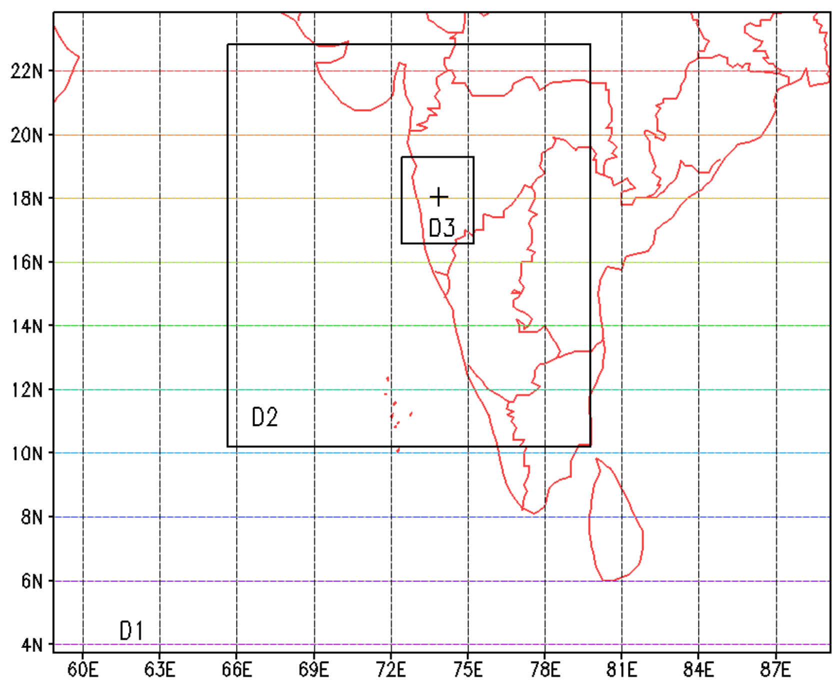
Statistical comparison of convection-permitting model simulations with radar observations

- ✓ WRF Model (version 3.7) is used to **simulate convection** occurring **over the Western Ghats** during **26-30 July 2014** (wet monsoon conditions).
- ✓ **Used 3 one-way nested domains:**

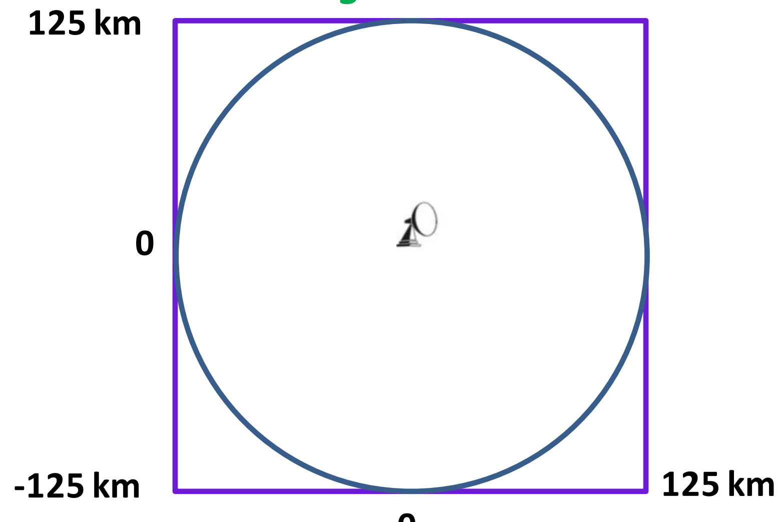
  Domain 1 (25km resolution), Domain 2 (5km res): BMJ convective parameterization

  Domain 3 (1 km resolution): Convection permitting (Explicit convective processes)

Model Domains used in WRF Simulations



Domain D3 Encompassing Range of Radar

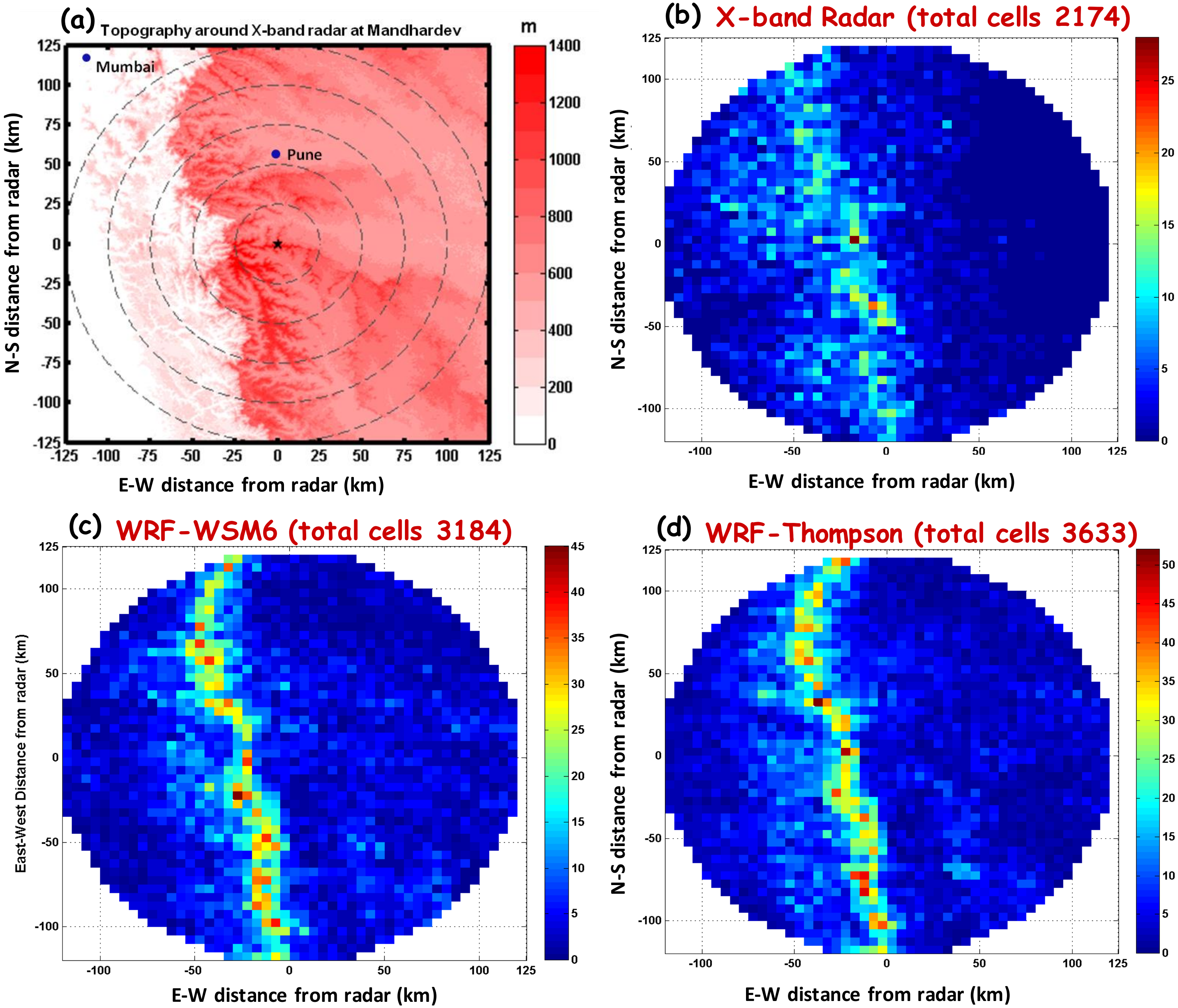


Spatial (1 km) and temporal (12 min) scales matched

Cell-tracking algorithm -> 4 days simulation period -> objectively identify, track & provide 3-D characteristics of convective cells in **simulations and observation**.

Spatial Occurrence of Convective Cells in 5 km x 5 km Bins Over the Period 27-30 July 2014

Comparison between Radar observations and WRF simulations

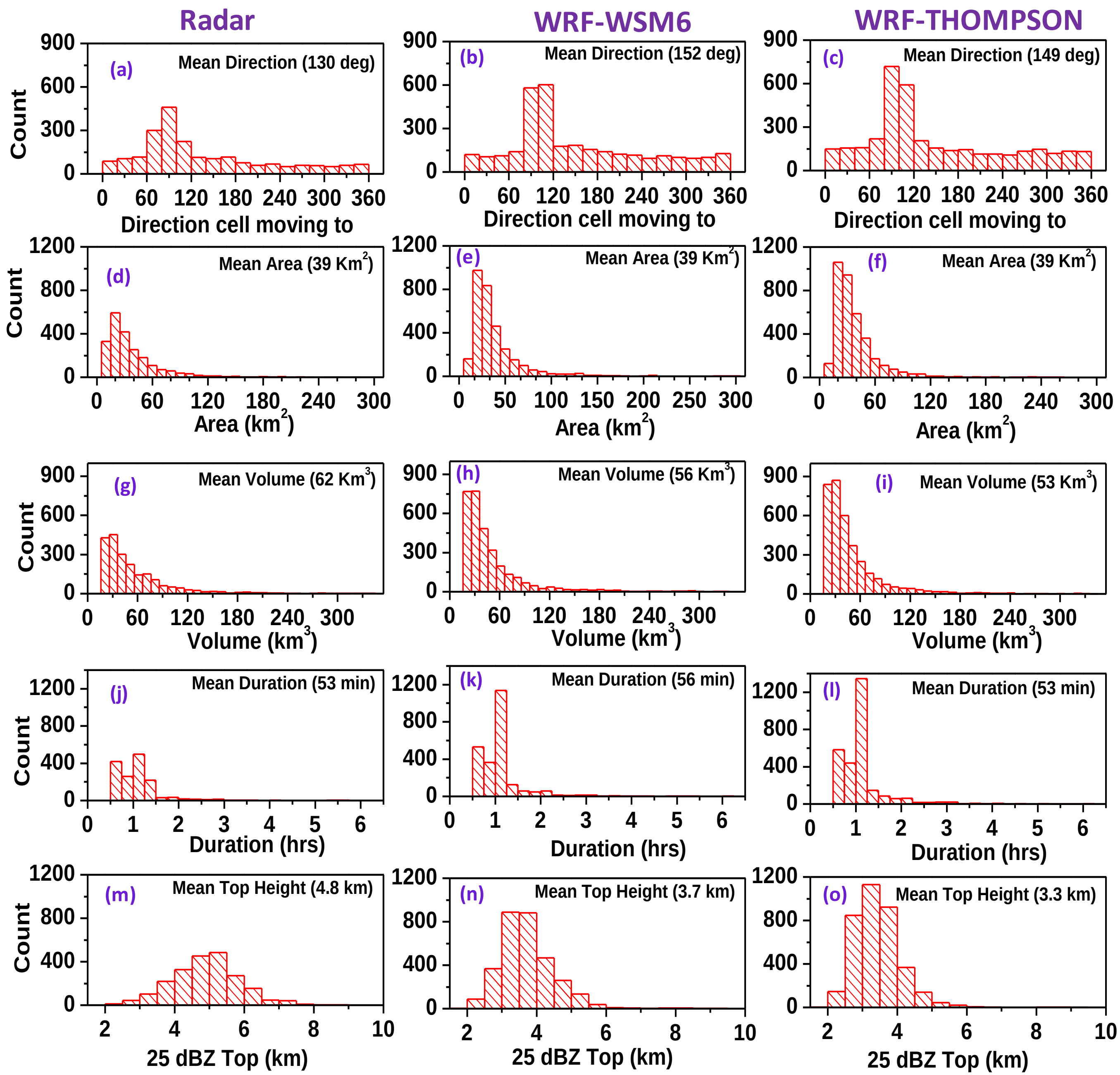


Increased frequency of convective cells along the windward slopes of mountains compared to coastal & lee sides, highlights orographic influence.

Despite model over numbered convective cells, radar and model posses a similar statistical properties of cells (e.g. area, volume, duration)

Deshpande et al (2017)

Frequency Distributions of Convective Properties: Area, volume, duration, height



Model simulations provide a realistic representation of convection & its spatial characteristics.

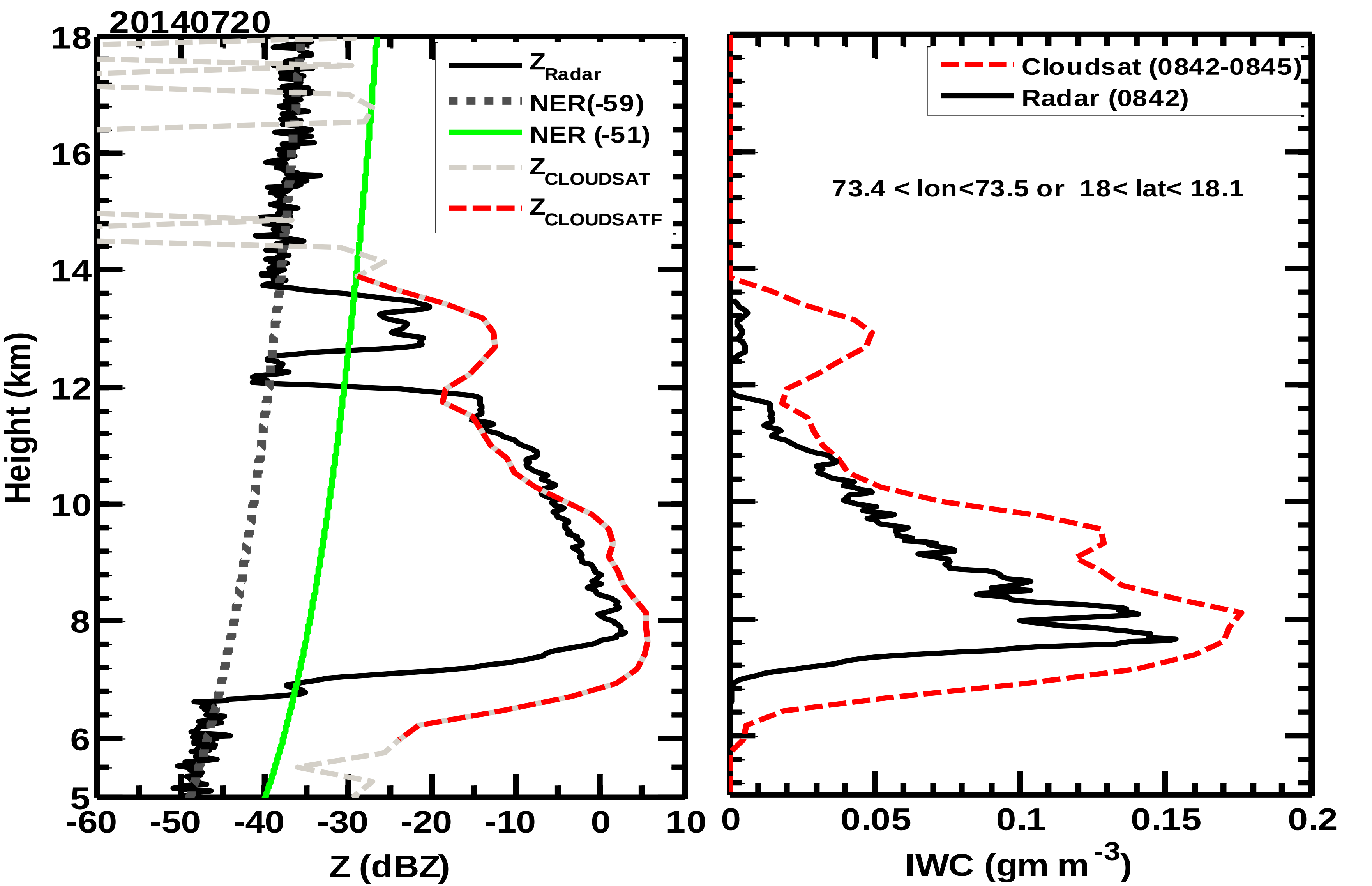
Contribution of small sized cells to total cloud population is more compared to large size storms- **sub-MCS convection**

Convective cell area, height, duration follows **Lognormal distribution**

Shallow convection dominates in Western Ghats & persist for mean duration of 53 min.

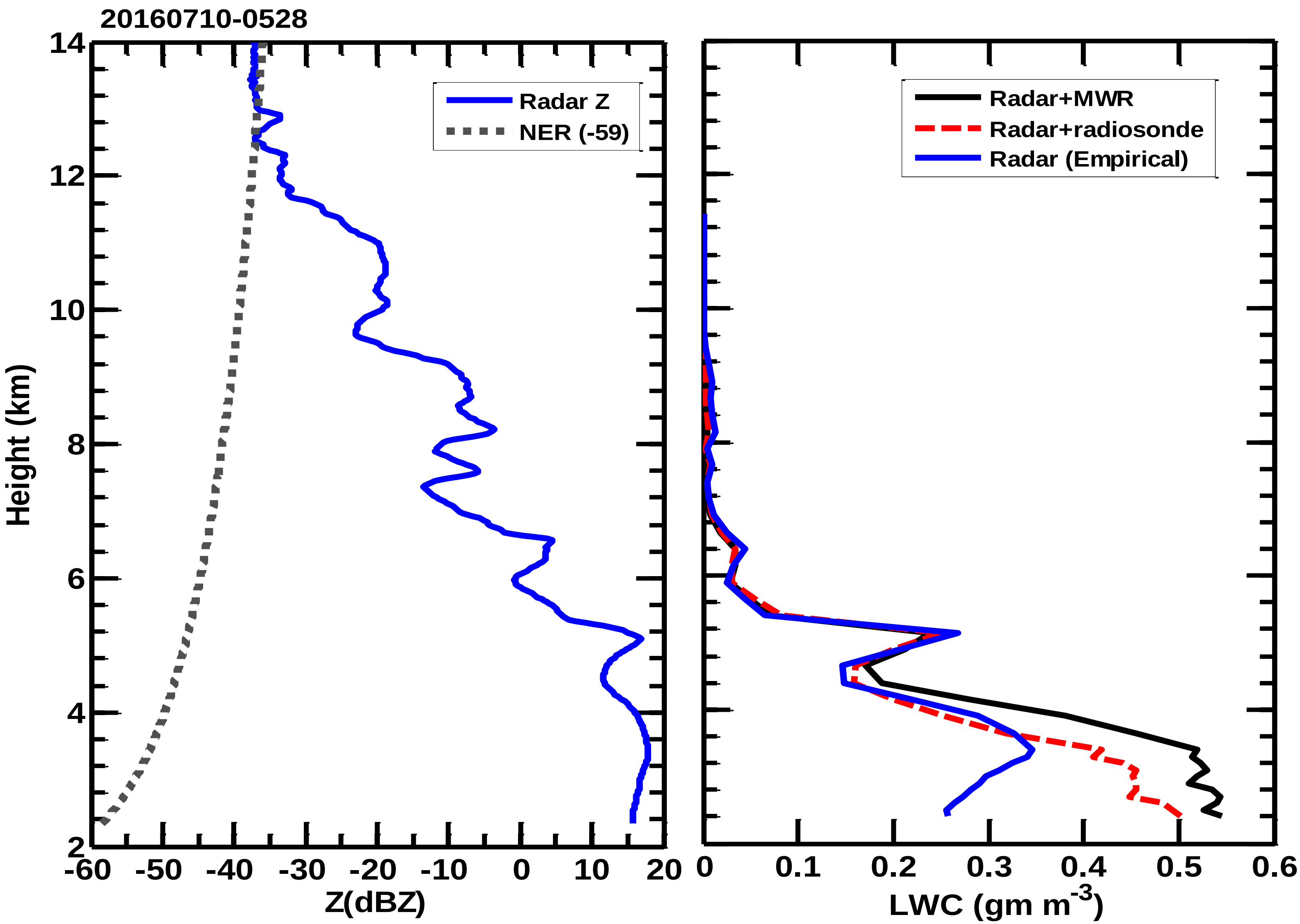
Simulated convective cells reached lower altitudes than the observations.

Cloud Ice Water profile comparison with CLOUDSAT



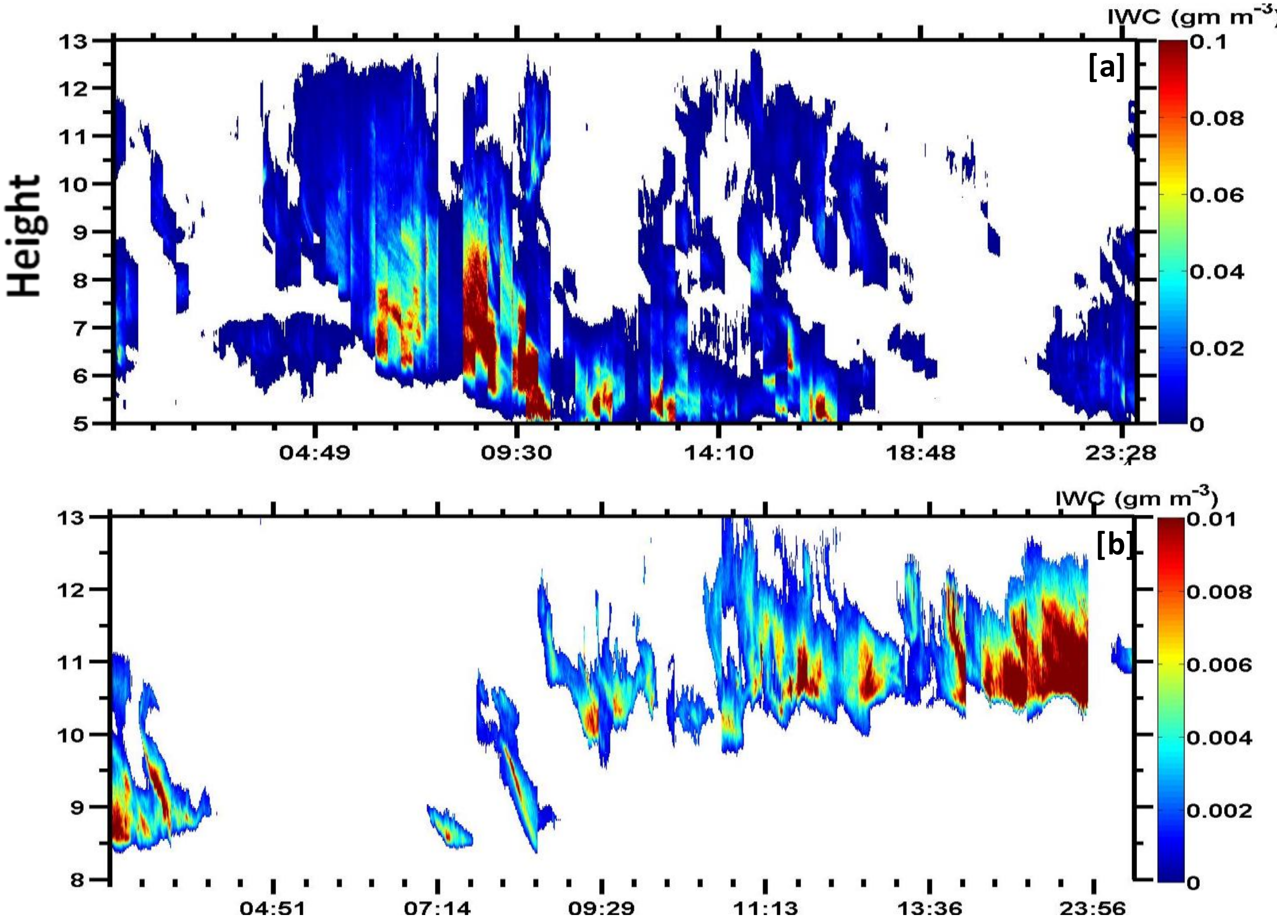
Source: Sukanya, Madhu

Cloud Radar: Liquid Water profiles



Source: Sukanya, Madhu

HTI plot of Diurnal cycle of IWC for an typical (a) active and a (b) break monsoon spell



Time (hh:mm;UT)

Source: Sukanya, Madhu

Summary

- Observational demonstration of over estimate of aerosol number effect as compared to size effect.
- Dispersion effect can offset the number effect.
- CCN could be modeled better if OOA is considered in chemical composition.
- Organic aerosols found to dominate through out the year, contributing >55%.
- PMF analysis on source apportionment identified the secondary organic aerosol (SOA) as dominant during summer.
- Identification of IEPOX-derived SOA during summer season.
- Cluster analysis suggested that the origin of NPF formation lies north east of the receptor site and is a major contributor to the total CCN concentration observed.
- The time-continuous aspects of convective features in terms of their formation, growth, movement, and duration are studied quantitatively