On the precipitation susceptibility of monsoon clouds to aerosols using high altitude ground-based observations over Western Ghats, India

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On the precipitation susceptibility of monsoon clouds to aerosols using high-altitude ground-based observations over Western Ghats, India

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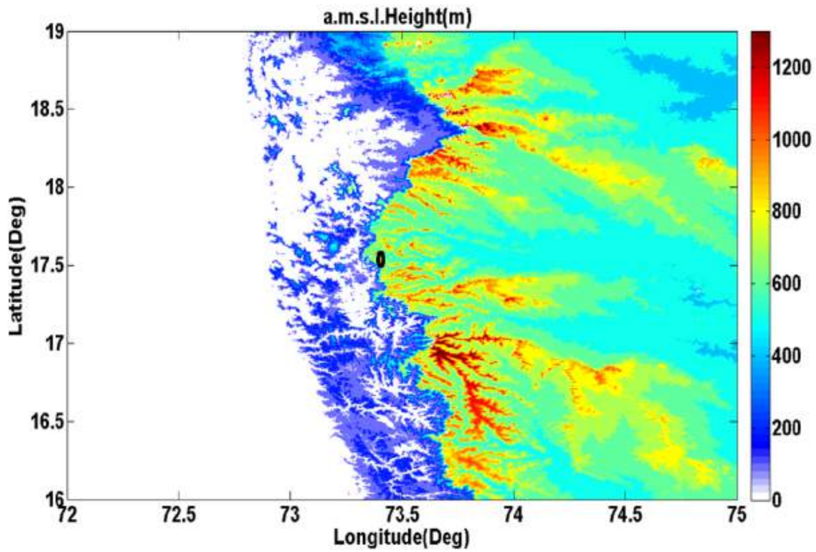
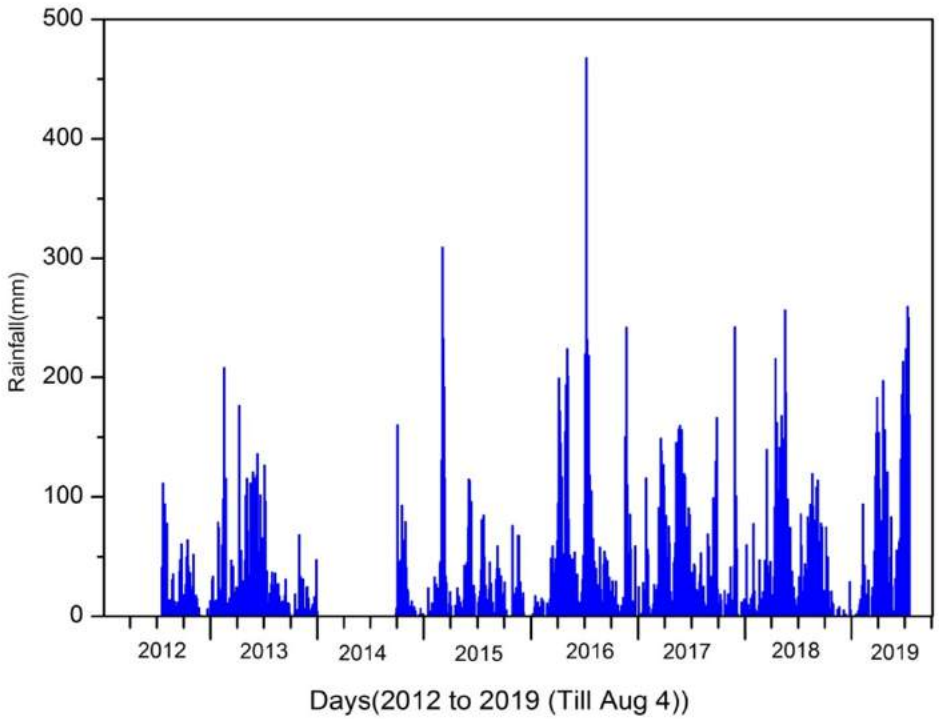
Background

- High Altitude Cloud Physics Laboratory (HACPL) at Mahabaleshwar [17.92°N, 73.66°E, and 1378 m above mean sea level (AMSL)], situated in Western Ghats, India.

- The HACPL building is surrounded by rural settlements on one side and dense vegetation on another side. Approximately 80% of the land in this region is covered with dense forest.

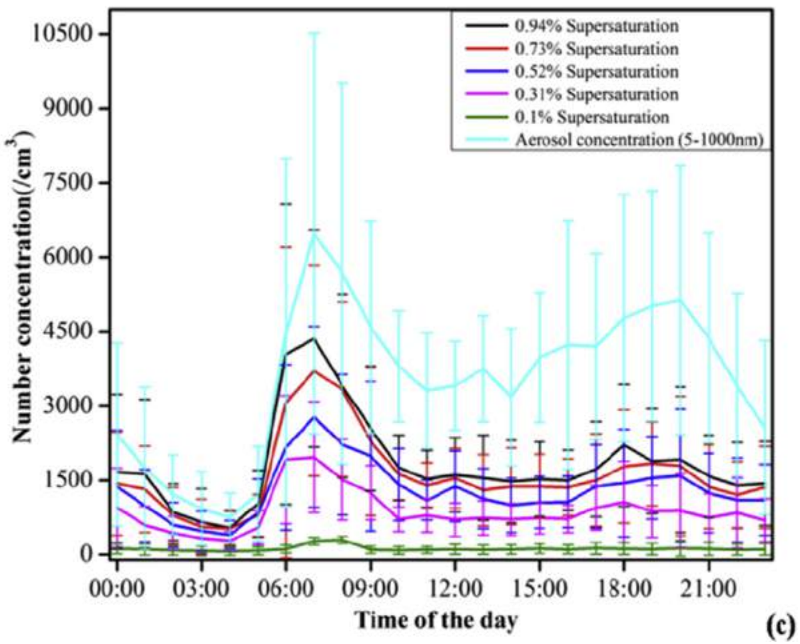
- HACPL has various ground based observations to study about aerosol particles-chemical composition, cloud condensation nuclei (CCN), cloud microphysics, precipitation and other meteorological parameters.

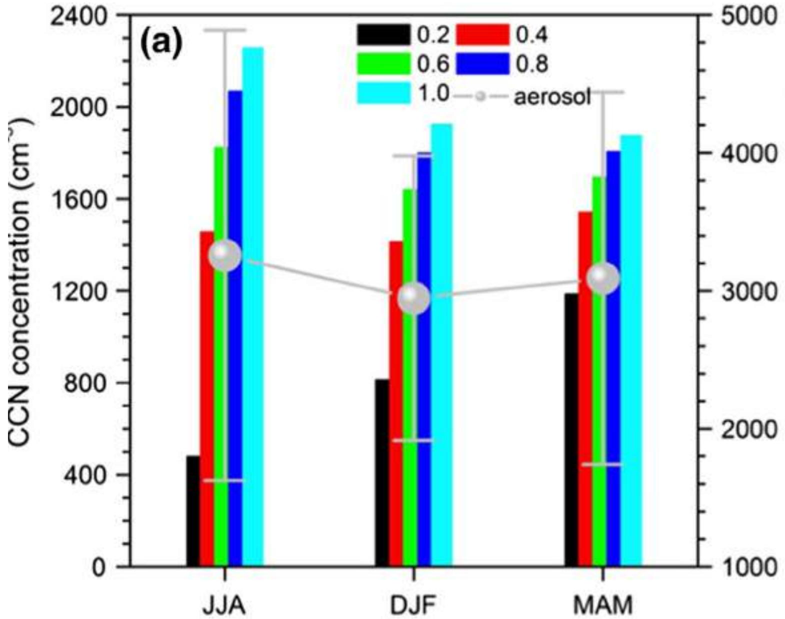




Rainfall measured from Impact disdrometer

Aerosol-CCN variability



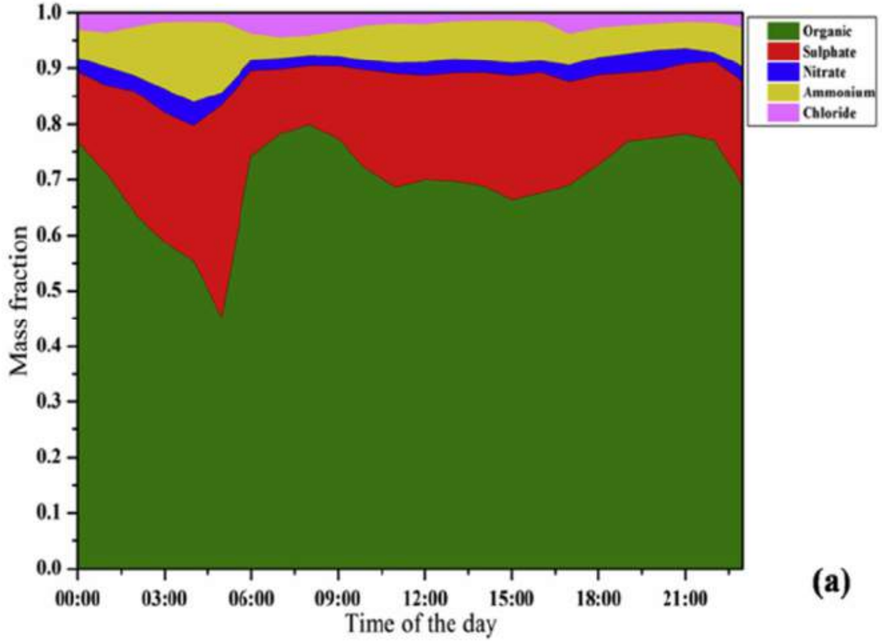


Leena et al., 2016; Singla et al., 2017

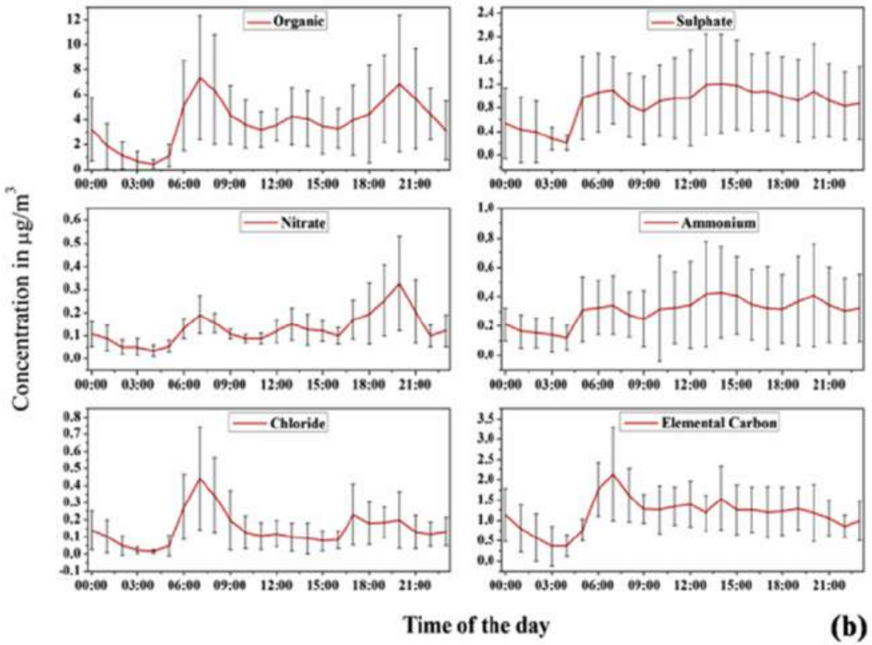
- **Aerosol number concentration obtained by wide range aerosol spectrometer (WRAS) (5 nm - 1000 nm) showed that during monsoon season there is a significant enhancement in finer sized aerosol concentration over HACPL.**

- **CCN measurements obtained by CCN counter also showed increase during monsoon which suggested that there can be an increase in number of cloud droplets.**

Chemical composition of the aerosol



(a)



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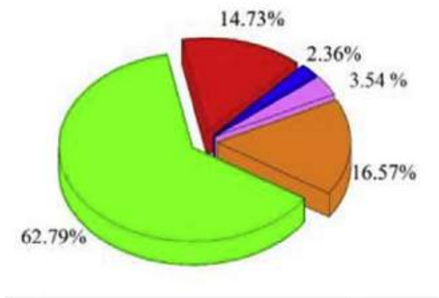
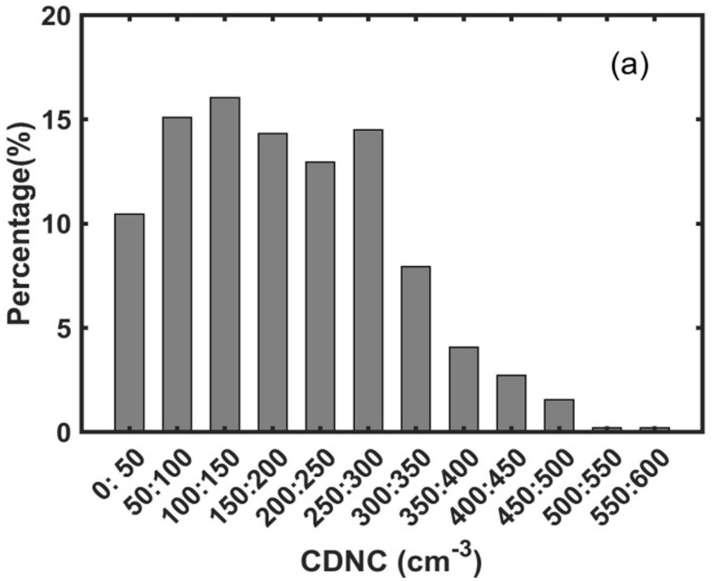


- Mass fraction of organics, ammonium, chloride, nitrate and sulphate as measured by Aerosol Chemical Speciation Monitor (ACSM).
- Organics and sulphate contributed most abundantly to the total aerosol mass concentration.

Singla et al., 2017; S. Mukherjee et al., 2018

Microphysical properties of monsoon clouds

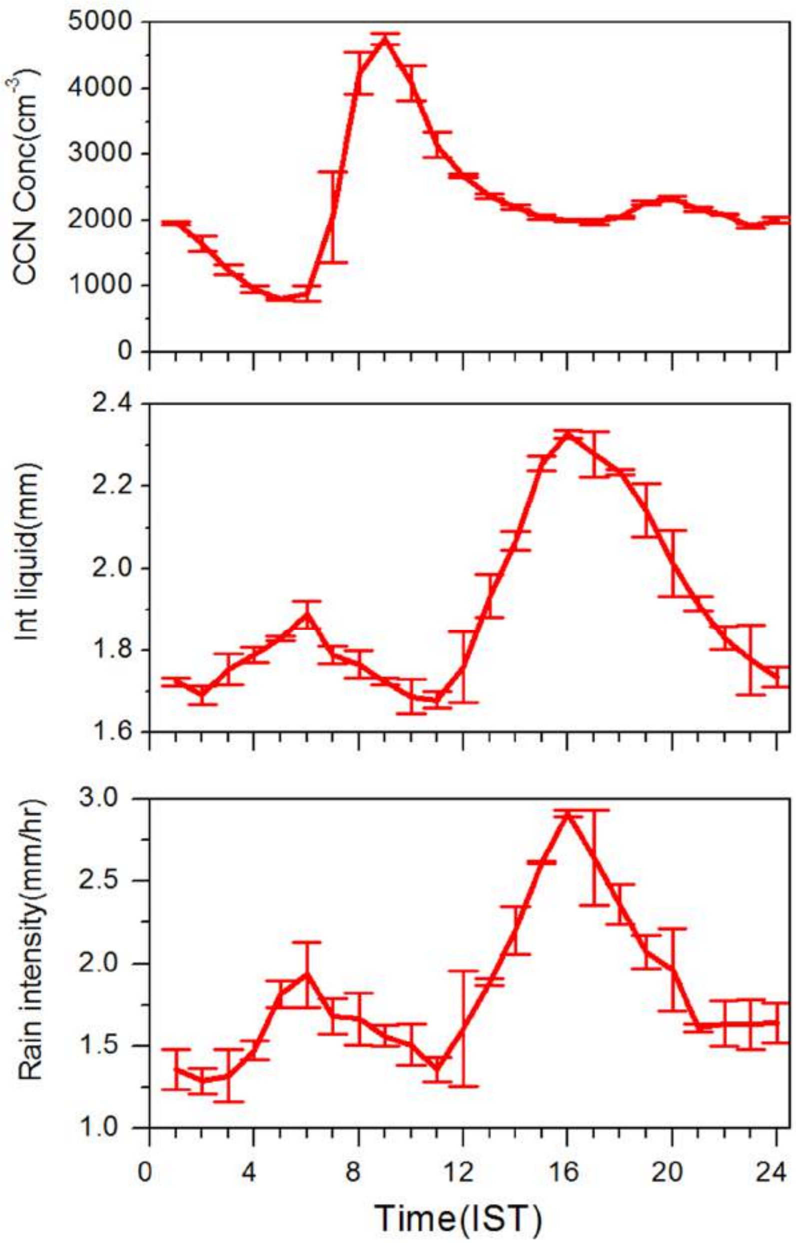
Cloud microphysical properties i.e. cloud droplet number concentration (CDNC) measured using cloud droplet probe (3um to 50 um) showed bimodal distribution during monsoon season.



Leena et al., 2019 (submitted)

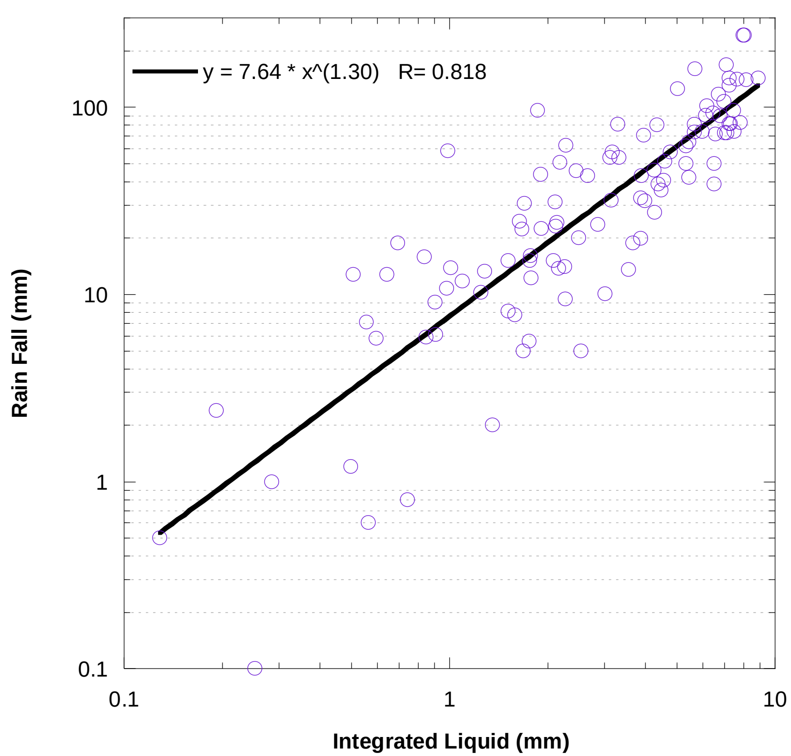
- **Robustness of ground based observations in the aerosol-cloud –precipitation related studies.**
- **Aerosol and CCN concentration was higher over this high altitude site despite of dominant sink processes such as cloud scavenging and washout mechanisms indicating local emissions and biogenic Volatile Organic Compounds (BVOC) emissions from wet forest as major sources.**
- **Also suggest possibility of effect of aerosol on precipitation.**

CCN, Integrated liquid and rain intensity variation



- Diurnal variation of CCN concentration, integrated liquid and rain intensity indicates , there are two peaks .
- CCN concentration is higher in morning and less in the evening hours vice versa in other two.
- Positive relation (R=0.81) is seen between rainfall and integrated liquid.
- Thus, it is required to determine the magnitude of the effect of pollution particles/aerosols on precipitation.

Integrated Liquid and Rain Fall



Summary of precipitation susceptibility studies over different locations

Studies by Feingold and Siebert (2009) and Sorooshian et al. (2009) introduced a new method to quantify the sensitivity of precipitation to changes in aerosol or in other words to quantify the precipitation susceptibility (S_0). The precipitation susceptibility is defined as

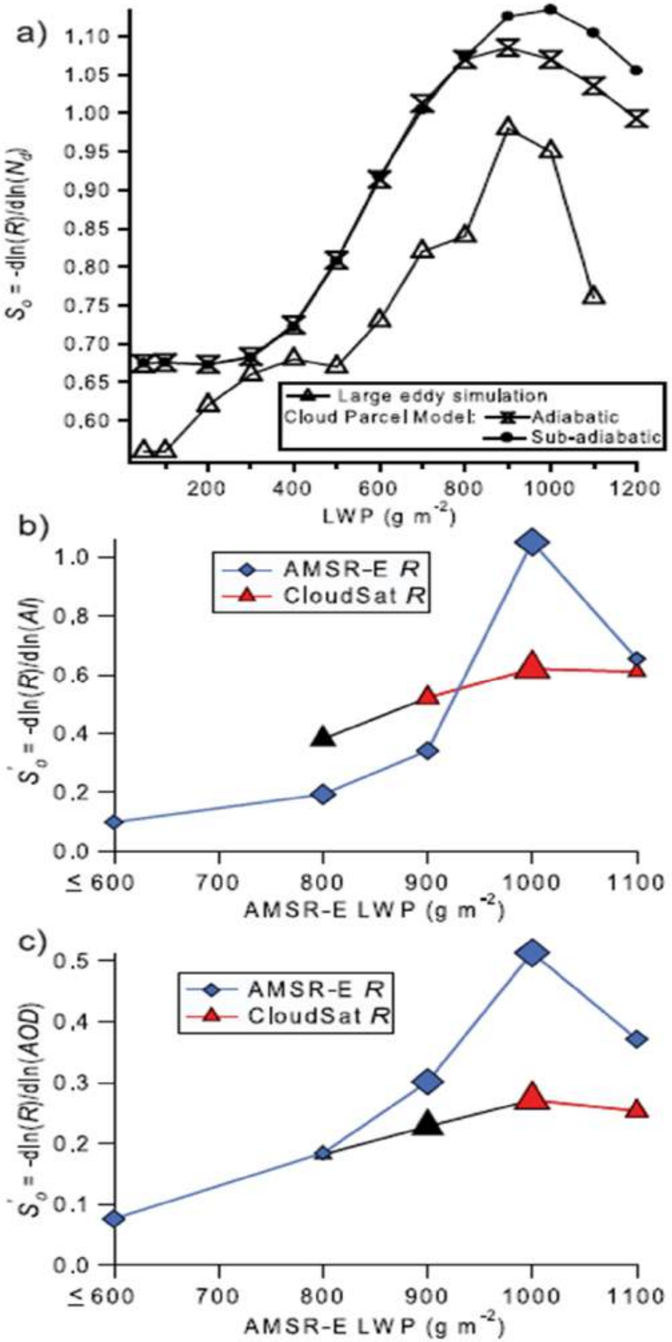
$$S_0 = -\frac{d\ lnR}{d \ln N_d}$$

Where R is the precipitation or rain rate, N_d is the cloud drop number concentration which can even be replaced with an aerosol measurement.

- Analysis carried out by considering potential controlling factors such as LWP and lower tropospheric static stability [Klein and Hartmann, 1993] (LTSS = potential temperature difference between 700 hPa and 1000 hPa), which is an indicator of the thermodynamic state of the atmosphere.

- Focused on shallow cumulus clouds in unstable atmospheric conditions (LTSS < 15C; R > 1 mm h1), and the region was tropics (15N, 15S; 180W, 180E)

- Three susceptibility regimes are identified: (i) clouds with low liquid water path (LWP) generate very little rain and are least susceptible to aerosol; (ii) clouds with intermediate LWP where aerosol most effectively suppress precipitation; and (iii) clouds with high LWP, where the susceptibility begins to decrease because the precipitation process is efficient owing to abundant liquid water.



- *The first regime is at low LWP (<500 g m^{-2}), where S_o is small because clouds cannot generate much precipitation, regardless of aerosol amount.*

- *The second regime is at intermediate LWP (~500–1000 g m^{-2}), where S_o increases steadily with increasing LWP. The increase in S_o shows that the ability of clouds in this regime to generate precipitation is no longer limited by LWP, but rather that higher N_d, and consequently less collision-coalescence amongst droplets, suppresses precipitation.*

- *Finally, in the third regime (LWP > 1000 g m^{-2}) S_o becomes progressively smaller as the increasing LWP dominates precipitation formation, regardless of Nd.*

Sorooshian et al., 2009

- **More studies on precipitation susceptibility including the initial one was carried out using model simulation or satellite observations (e.g. Lu et al., 2009; Sorooshian et al., 2010; Wang et al., 2012; Hill et al., 2015).**

- **A few studies (e.g. Sorooshian et al., 2010; Terai et al., 2012; Jung et al., 2016) on precipitation susceptibility using aircraft observations and other one using ARM (Atmospheric Radiation Measurements) mobile facility (AMF) deployments (Mann et al. (2014)) but the observations were not continuous.**

- **Studies explicitly using ground observations are sparse.**

- **It is observed that Sorooshian et al. (2009) has reported for the tropical region i.e. from 15° N-15° S, 180° W-180°E.**

- **Gettelmann et al. (2013) has reported for entire globe and Wang et al. (2012) for the latitudinal band 60° N to 60° S**

- **Studies over oceanic region were more concentrated on different sectors of Pacific Ocean (e.g. Lu et al., 2009; Sorooshian et al., 2010; Gettelmann et al., 2013; Terai et al., 2015; Jung et al., 2016) and then on Atlantic Ocean (Sorooshian et al., 2010; Gettelmann et al., 2013).**

- **Sorooshian et al. (2010) showed results over Tropical Indian Ocean, Terai et al. (2015) showed over Asian Coast, Gulf of Mexico etc.**

- **Study by Mann et al. (2014) only showed results from Black forest, Germany and Azores.**

- **Overall reports showed that**
  - **(a) LWP range where the precipitation is getting suppressed broadly varied from 400 to 1000 gm^{-2} for most of regions around the world.**
  - ***(b)* Noticed that there is no reports from Indian subcontinent.**

Data used

- Utilising the observations from this laboratory we have made an attempt to estimate the precipitation susceptibility of monsoon clouds.
- This study has been carried out using both ground based and satellite observations.
- Cloud condensation nuclei (CCN) concentration, rain intensity (RI) and integrated liquid (IL) from co-located ground based instruments
- Aerosol Optical Depth (AOD), rain rate (RR) and liquid water path (LWP) has been used from various satellite observations

Observations used	Year	Parameter	Resolution
CCN counter	2012,2013,2016	CCN concentration at 05 super saturation	Sampling interval at 01 sec
Impact disdrometer	2012,2013,2016	Rain intensity	Sampling interval at 30 sec
PARSIVAL disdrometer	2012	Rain intensity	Sampling interval at 30 sec
Microwave radiometer	2012,2013,2016	Integrated liquid	Sampling interval at 02 mint
MODIS Terra MYD04_3K	2011 to 2016	Aerosol products (AOD) Cloud products (LWP)	03 km×03 km 01 km×01 km
TRMM (TRMM-3B42)	2011 to 2016	Rain rate	0.25 deg×025 deg

Methodology

The precipitation susceptibility is defined as

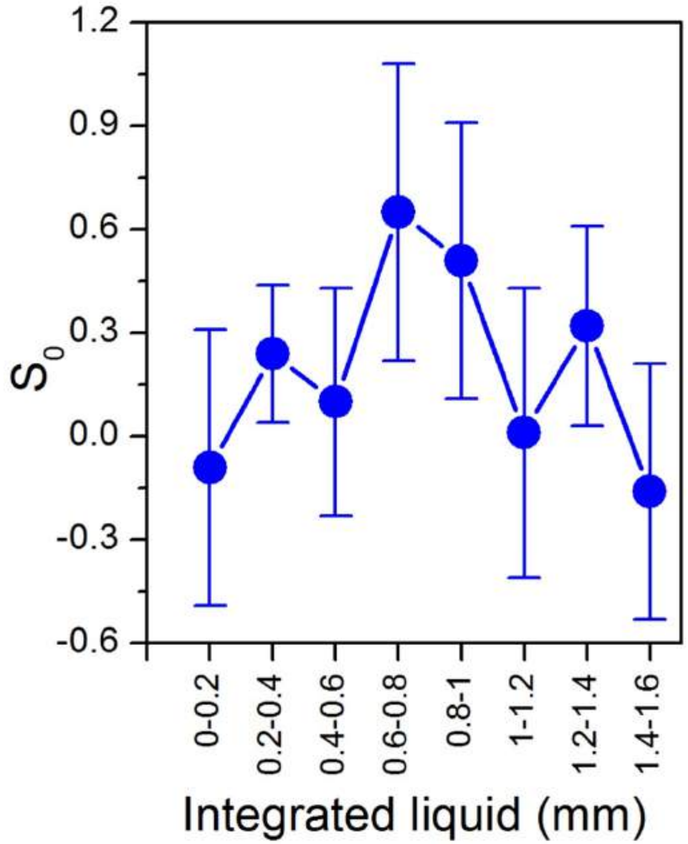
$$S_0 = -\frac{d\ lnR}{d\ \ln N_d}$$

Where R is the precipitation or rain rate, N_d is the cloud drop number concentration which can even be replaced with an aerosol measurement.

- CCN (AOD) was used as aerosol proxy for finding S_0 using ground based instruments (satellite observations).
- We have used 30 minute averaged CCN concentration, IL and RI observations and grouped the CCN and rain intensity for different integrated liquid bins.
- A correlation analysis between log (RI) and log (CCN) for each IL bin has been carried out and the negative value of slope along with the standard error of the slope obtained was later represented as precipitation susceptibility i.e.S_0.
- Area averaged (02×01 degree i.e. 16.5 to 18.5^0 N and 73.5 to 74.5^0 E) AOD, LWP and RR obtained from satellite observations was used for the comparison.
- For finding S_0, the correlation analysis was carried out between log (RR) and log (AOD) for each LWP bin.

CCN-rain intensity relationship for various IL bins

- **The condition applied was rain intensity greater than 1 mm/hr and CCN concentration from 500 to 5000 cm^{-3}.**
- **There is a clear variation of negative value of slope (or S_0) with respect to IL bins.**
- **Below 0.6 mm of integrated liquid, the value is small which shows that low water content clouds are not much susceptible to aerosols.**
- **From 0.6 to 1 mm of liquid, S_0 is higher and above 1 mm, it is seen that S_0 is decreasing.**
- **The precipitation is getting suppressed in the bin 0.6 to 1 mm due to more number of smaller cloud droplets and associated suppression of collision-coalescence efficiency and above 1mm shows increase in CCN does not further increase precipitation rate.**



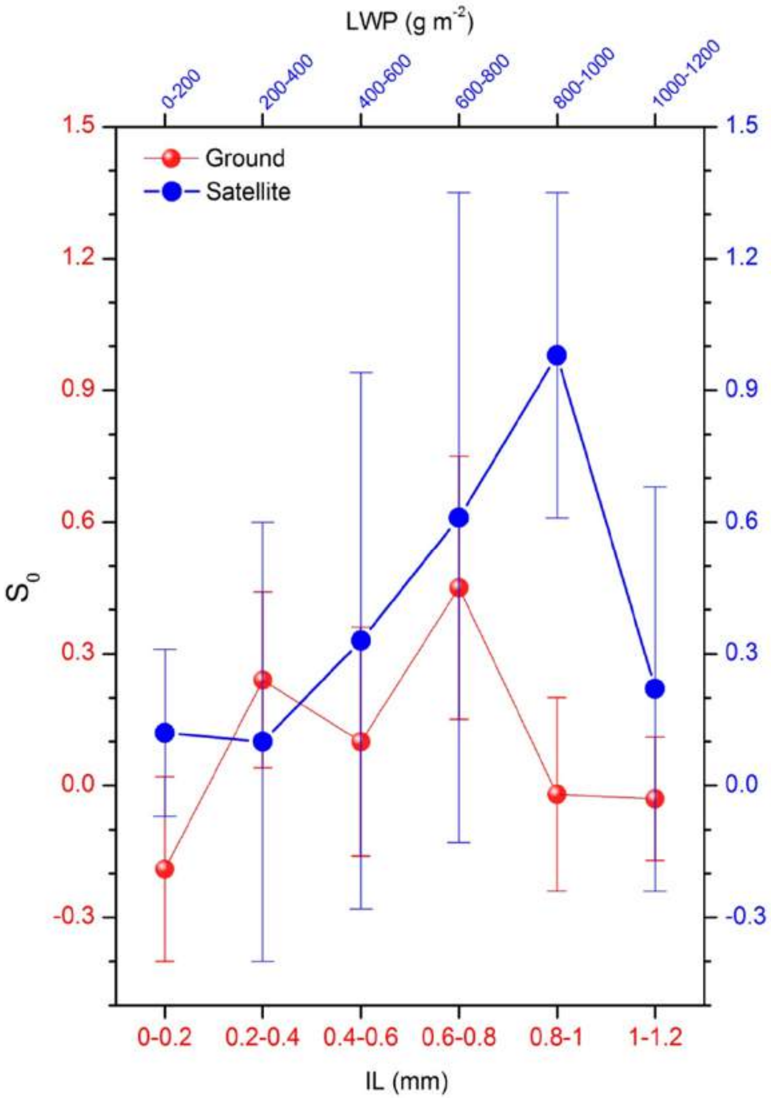
Variation of negative of slope (S_0) w.r.t integrated liquid bins for the year 2012.

S. No	Conditions applied	S_0 maximum value	IL range (mm)	n
1	CCN 500-5000 cm^{-3}; RI> 1mm/hr; IL 0.2 mm bins	0.65	0.6-0.8	09
2	CCN 500-5000 cm^{-3} ; 1mm/hr<RI<10mm/hr; IL 0.2 mm bins	0.65	0.6-0.8	09
3	CCN 500-10,000 cm^{-3}; RI> 1mm/hr; IL 0.2 mm bins	0.61	0.6-0.8	11
4	CCN 500-5000 cm^{-3} ;RI> 1mm/hr; IL 0.3 mm bins	0.63	0.6-0.9	18
5	CCN 500-5000 cm^{-3}; 0.5 < RI < 10 mm/hr; IL 0.2 mm bins	0.62	1.2-1.4	13
6	CCN 500-5000 cm^{-3} ; RI >0.2 mm/hr; IL 0.2 mm bins	0.46	0.6-0.8	19
7	CCN 500-5000 cm^{-3}; RI no threshold applied; IL 0.2 mm bins	0.44	0.4-0.6	114
8	CCN 500-5000 cm^{-3}; 0.2 < RI < 1 mm/hr; IL 0.2 mm bins	0.30	0.8-1.0	28
9	CCN no threshold applied; RI> 1mm/hr; IL 0.2 mm bins	0.61	0.6-0.8	11
10	no threshold applied to CCN and RI; IL 0.2 mm bins	-0.10	0.4-0.6	132

Summary of various conditions applied

- Precipitation susceptibility has been calculated by applying various thresholds to CCN, RI and even by changing the bin size of IL.
- Precipitation susceptibility value is varying from 0.10 to 0.65
- Change in the threshold of CCN concentration does not affect the integrated liquid range where the precipitation is getting suppressed.
- Precipitation susceptibility is partially affected by changing the threshold of rain intensity.
- Overall analysis showed that maximum value of slope (S_0) is obtained mainly for integrated liquid range 0.6–0.8 mm

Comparison with satellite observations



IL (mm(LWP (g m^{-2}))bins	n	S_0 value
0.0-0.2 (0-200)	14(108)	-0.19(0.12)
0.2-0.4 (200-400)	13(33)	0.24(0.10)
0.4-0.6 (400-600)	14(18)	0.10(0.33)
0.6-0.8 (600-800)	19(06)	0.45(0.61)
0.8-1.0 (800-1000)	36(05)	-0.02(0.98)
1.0-1.2 (1000-1200)	50(02)	-0.10(0.22)

- **Compared the results obtained from ground observation with satellite observation.**
- **(a)Below 600 gm^{-2}, S_0 showed a smaller value but a negative relationship between AOD and RR , (b) 600 to 1000 gm^{-2}, S_0 increases steadily with LWP where a negative relationship between AOD and RR , (c) for LWP greater than 1000 gm^{-2}, the value of S_0 reduced.**

Conclusions

- Precipitation susceptibility of monsoon clouds to changes in aerosols has been studied by utilizing ground based observations from a High Altitude Cloud Physics Laboratory (HACPL), Mahabaleshwar, India collected during monsoon seasons and later compared with the results obtained from satellite observations.

- Precipitation susceptibility estimated using ground observation i.e. using CCN as aerosol proxy showed S_0 (S_0 = 0.65) is higher for the integrated liquid water ranging from 0.6 to 0.8 mm.

- Satellite observations showed that S_0 estimated using AOD as aerosol proxy is higher (S_0 = 0.98) for liquid water path ranging from 800 to 1000 gm^{-2}.

- Analysis showed that the precipitation is getting suppressed at medium range of integrated liquid/liquid water path.

- On comparing the present analysis, it is seen that our study was comparable with Sorooshian et al. (2009) which reported for tropical region.

Thank You