Design of weather modification research

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AMS statement on weather modification

There remain limits to the certainty with which desired changes in cloud behavior can be brought about using current cloud seeding techniques. Continued effort is needed toward improved understanding of the risks and benefits of planned modification through well-designed and well-supported research programs.

1) **Efforts should continue to improve understanding** of the targeted cloud and precipitation processes in planned modification.

2) Because predictability is a limiting factor in the assessment of weather modification efforts, **well-designed (randomized) and well-supported research programs should be conducted** that improve the predictability of the undisturbed weather and the magnitude of weather modification effects.

3) It is necessary to **comprehensively address the risks, benefits and ethical issues** associated with planned weather modification and to develop policy approaches that can help the implementation and conduct of future experiments and operations.

4) Research into **modification of extreme weather systems**, such as tornadic thunderstorms, tropical cyclones, etc., **should be limited to numerical simulations** until such time as there is sufficient knowledge to lay the foundation for safe experimentation in the atmosphere.

WMO statement on the randomized hygroscopic seeding

“Measurements of the key steps in the chain of physical events associated with hygroscopic particle seeding are needed to confirm the seeding conceptual models and the range of effectiveness of these techniques in increasing precipitation from warm and mixed-phase convective clouds. “

Recommendations

- The comparisons are required **not only on the amount of precipitation in seeded and unseeded events**, but also on a range of **properties that identify the sequence of physical processes that lead to any enhanced precipitation**.
- The capabilities of observing systems at all scales from microphysical to synoptic are now very substantial, so that it is feasible to **employ ground-based, aircraft-based and satellite-based instruments to systematically observe these physical (and chemical) properties**.
- One aspect of the protocols is the **accurate and consistent measurement of key variables such as the precipitation across the region of interest**. Particularly for convective cloud, these measurements will involve radars, which must be routinely and consistently calibrated throughout the experiment.
- Supporting modelling studies for the seeded clouds

WMO guidelines say that

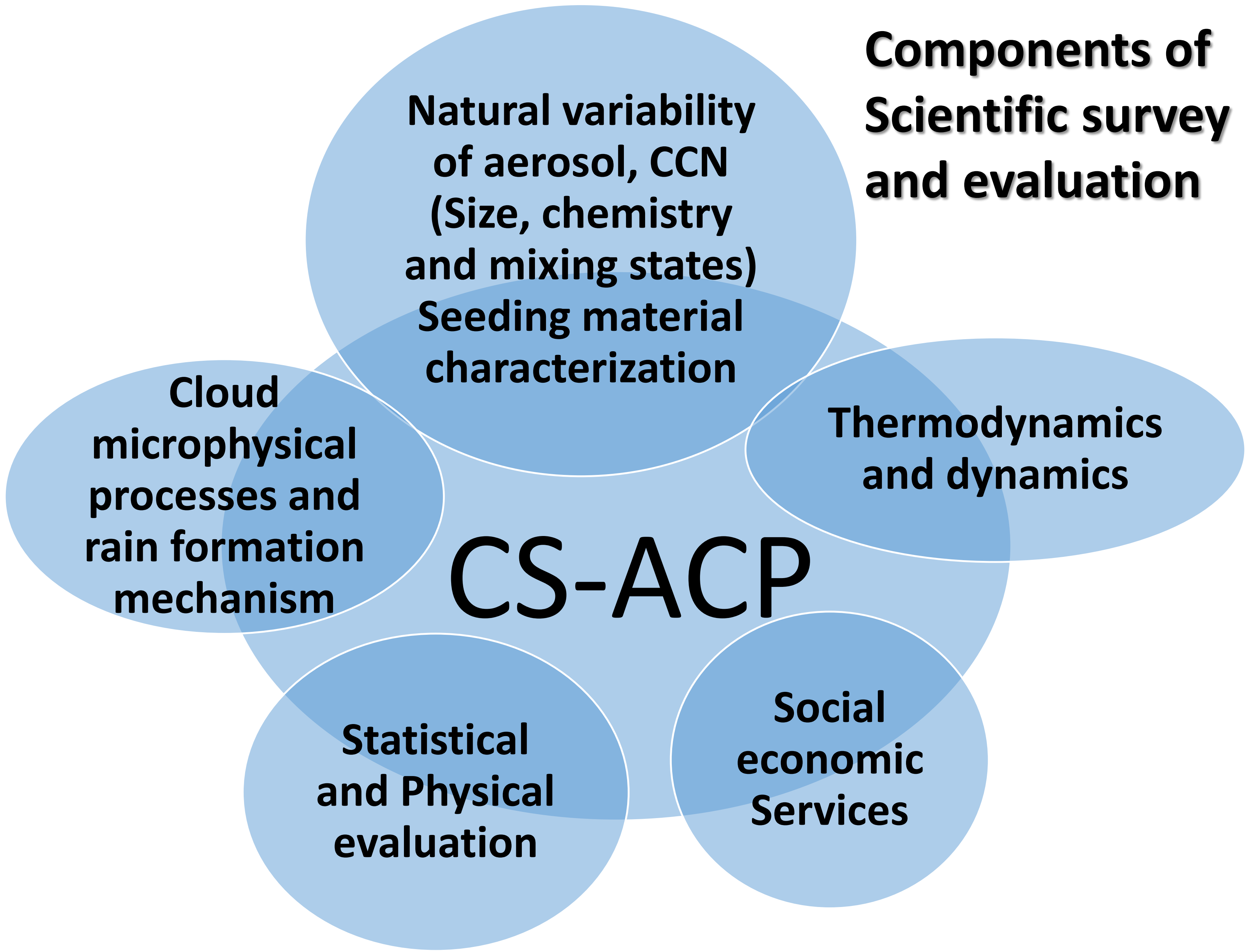
- ❖Conduct randomized experiments
- ❖Evaluation of randomized experiments through statistical methods.
- ❖Rainfall at the ground to be documented
- ❖Statistical experiment must be supported with physical experiment
- ❖Experiment has to be repeated at different locations

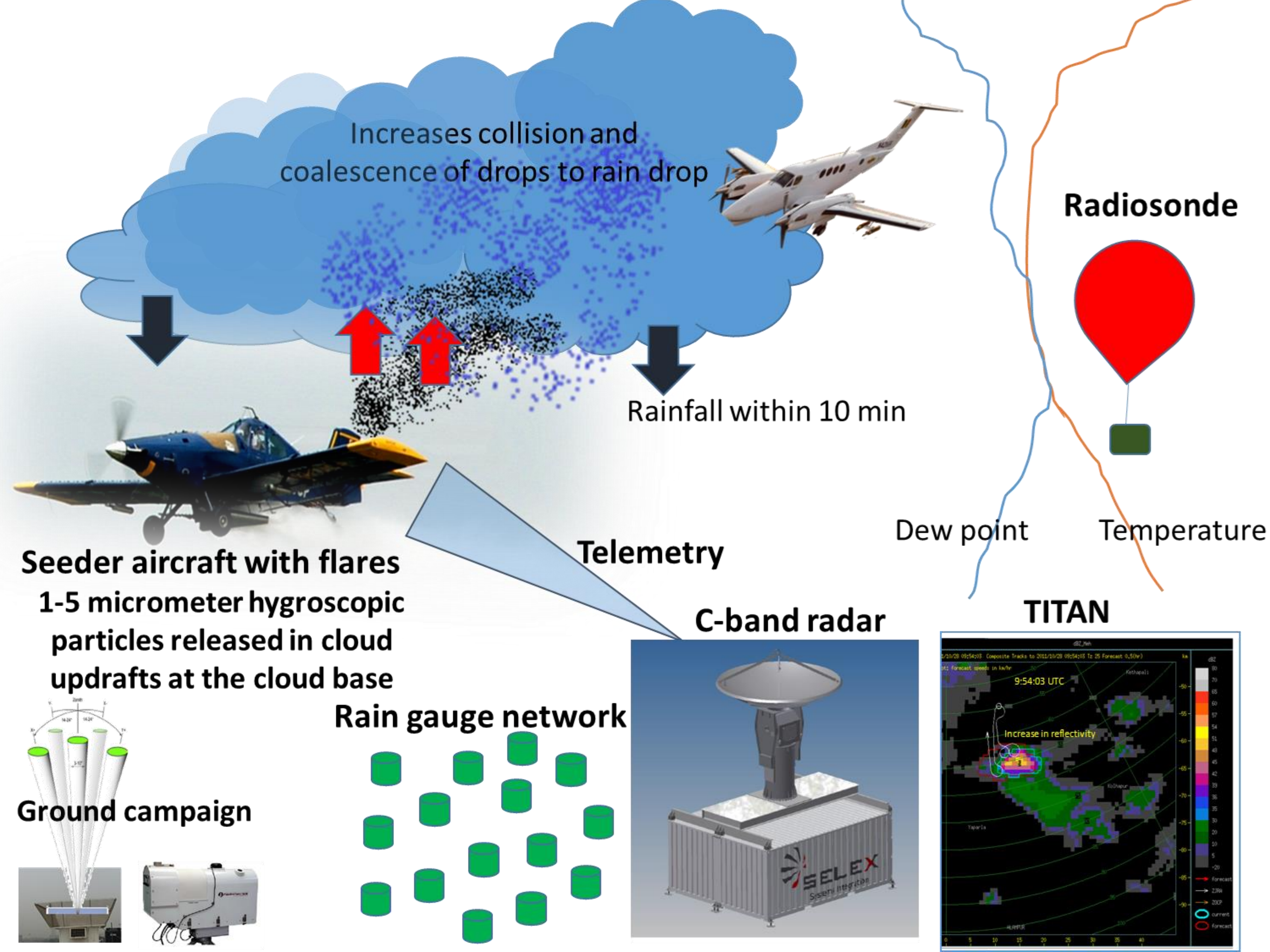
Evidence for the following from physical experiment is sought:

a. Seeding material in the cloud
b. Broader droplet spectra in seeded clouds
c. High droplet number concentration in Seeded clouds, higher LWC
d. Documentation of chains of processes in the seeding hypothesis
d. Increase in rainfall on the ground.

Components of research

- ✓Seeding Hypothesis and criteria for seeding
- ✓Background data: Aerosol, cloud, and rainfall climatology and aerosol-cloud-precipitation interactions, modelling studies, airborne observations
- ✓Tested/characterized Flares/ lab for testing flares
- ✓Strategy for flare application
- ✓Evaluation criteria (physical and statistical – randomization ?)
- ✓Understanding on the dynamical aspects
- ✓Guidelines/protocols minimum requirements /standards


Components of
Scientific survey
and evaluation
Natural variability
of aerosol, CCN
(Size, chemistry
and mixing states)
Seeding material
characterization
Cloud
microphysical
processes and
rain formation
mechanism
Thermodynamics
and dynamics
CS-ACP
Statistical
and Physical
evaluation
Social
economic
Services


Increases collision and coalescence of drops to rain drop
Radiosonde
Rainfall within 10 min
Dew point
Temperature
Seeder aircraft with flares
1-5 micrometer hygroscopic particles released in cloud updrafts at the cloud base
Telemetry
C-band radar
TITAN
9:54:03 UTC
Increase in reflectivity
Rain gauge network
Ground campaign
SELEX

Preliminary study needed

- the use of **historical data** to document the **variability of precipitation**
- to **estimate the time required to detect a statistically significant enhancement of the natural precipitation** across the target area on a seasonal time scale
- natural variability of cloud processes, including precipitation on the ground, is very large, **careful design and management are needed to optimize the probability of detecting and confirming the physical basis** of enhanced precipitation from cloud seeding
- Numerical modelling study of clouds

Research Questions

- In which clouds is hygroscopic seeding beneficial?
- What is the optimal size and concentration of hygroscopic particles (e.g. flare seeding, powder seeding, seeding intense updraft)
- Mechanisms: competition effect vs. tail effect
- How to identify a seeding effect and seeding signature ?
- How does hygroscopic seeding affect ice-phase precipitation?
- How the chains of reactions in the seeding hypothesis be validated ?
- What is the background CCN and its hygroscopicity ?

Natural Cloud Systems and Variability

- Focus on dynamical features and the natural microphysical processes from aerosol particles to surface precipitation
- Major gaps
  - The formation and growth of solid hydrometeors.
  - Secondary ice multiplication processes
- Interactions between these processes as well as with the dynamics on all scales needs to be improved
- Orographic clouds have a well constraint dynamics and convective clouds have more variability

Observations of Aerosols Clouds and Precipitation

- Success of a precipitation enhancement project is evaluated by the observation of increased precipitation on the ground, above the naturally expected level.
- Detection of increased precipitation is a major challenge
- Especially difficult for convective cloud systems, where both spatial and temporal variability are high
- Progress in remote sensing and *in situ* observations with aircraft probes

CCN from the flare is the key

The principle of flare seeding is to have the flares produce effective CCN (usually salts such as sodium chloride, potassium chloride, or calcium chloride) particles in larger sizes (large or giant nuclei) than occur in the natural environment.

- The chemistry (hygroscopicity), size and concentrations of the particles (CCN) produced from the flares or large particle salt seeding.
- The effectiveness of seeding will depend on the natural background particles and their characteristics with regard to the same parameters.

Evaluation of experiments

“The evaluation of a cloud seeding experiment needs to be based on **a scientific understanding of the chain of dynamical and microphysical processes leading to enhanced precipitation on the ground**. While the **chain of processes for wintertime orographic cloud is now reasonably well understood**, there remain **substantial uncertainties in the processes associated with the enhancement of precipitation in mixed-phase convective cloud**. “

Techniques for evaluation

- Use tracer as a tag for seeded region for understanding of dispersion and transport of seeding material.
- Chaff and SF6 are released from an aircraft or at the surface. The dispersion and transport of the chaff is monitored by radar while the detection of the SF6 with aircraft equipped to detect this gas at very low concentrations.
- Use of special insitu observations to document the particle chemistry and particle scattering
- Lidars with 3D scanning
- Use of sophisticated numerical models

Key points to ponder

- Understanding of the natural and modified precipitation formation processes to support the statistical results
- Better characterization of the particles produced by the flares (using aircraft or using a laboratory)
- The necessity to extend the single-cloud, radar-evaluated results to area rainfall at the ground with associated hydrological impacts

Need for randomized experiments

- Small “signal” of enhanced precipitation against the large “noise” of natural variability on large time and space scales
- Properties of specified seeded events to be compared with those of similar but unseeded events.
- A detailed protocol is to be prepared for the selection of events as seedable and for the seeding of randomized events.
- Protocols to be followed precisely and consistently throughout the experiment
- The accurate and consistent measurement of key variables such as the precipitation across the region of interest.
- Involve well calibrated radars throughout the experiment

Randomization procedure

- Two sets of decision envelopes were made, one at the radar and one in the aircraft. This procedure was followed to ensure that none of the project personnel has prior knowledge of the contents of the envelopes. The radar envelopes contain either a ‘seed’ or a ‘no-seed’ decision. The aircraft envelopes contain either a ‘yes’ or a ‘no’ decision.
- Once the pilot has declared a ‘case’, both the radar operator and the pilot open the next envelope in each sequence. The radar operator communicates the result from the radar envelope to the pilot, who then decides whether to seed or not based upon the following decision table:

Radar	Aircraft	Action
seed	no	no-seed
seed	yes	seed
no-seed	yes	no-seed
no-seed	no	seed

- The pilot will not tell the radar operator whether the decision is to seed or not, and the pilot and radar operator will not communicate on issues related to the effects of seeding or lack thereof.

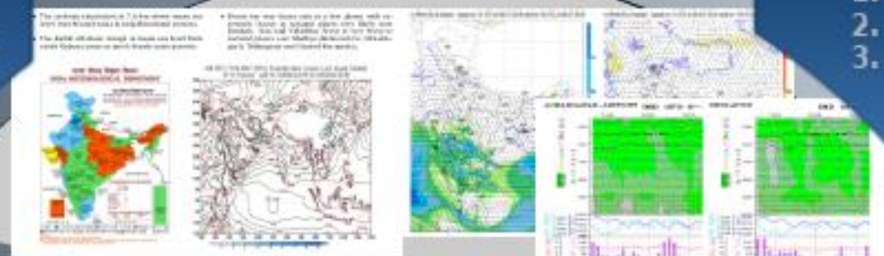
Operational procedure

- ✓ Daily meteorological briefing based on synoptic and mesoscale weather parameters, convection forecast, thermodynamics based on sounding, radar images, diurnal cycle of convection etc.
- ✓ Discussion on previous days seeding and evaluation of radar images and data
- ✓ Performance check on the aircraft instruments
- ✓ Briefing to Pilots
- ✓ Decision on the flight
- ✓ Documentation of flight, data summary
- ✓ Radar daily report on seeded clouds
- ✓ Ground observations summary
- ✓ Rainguage data evaluation
- ✓ Data quality checks and actions; calibration if needed
- ✓ Dissemination of base data to decision support system

Making of Daily Meteorological Briefing for CAIPEEX Phase IV

Monsoon Features based on 05:30 IST Analysis

1. IMD monsoon status analysis and outlook.
2. Satellite bulletin
   - Current Progress of monsoon
   - Position of monsoon trough.
   - Off-shore trough
   - Upper level wind shear
   - Monsoon depression
   - Cloudiness

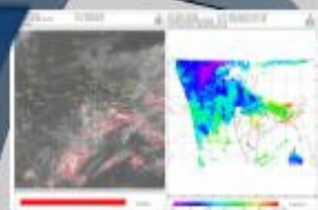


IMD & NCMRWF Forecasts

1. Local circulation features
2. 10 day Meteogram.
3. Expected convection and stratiform fraction.

Sattelite Inference

1. IR cloud-top BT image.
2. RAPID mid-level moisture
   - Cloudiness in the region
   - Availability of Moisture

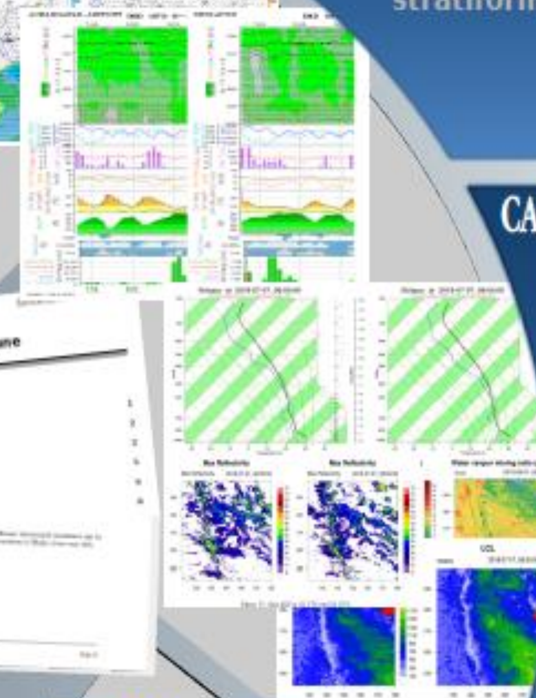


CAIPEEX Phase IV:
Meteorological briefing from Pune

CAIPEEX Forecasts

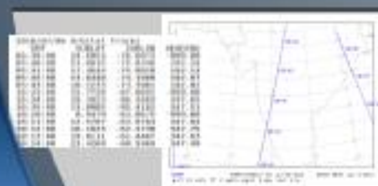
1. Skew-T plot at 6-8 UTC
2. CAPE & CINE
3. LCL & Warm Layer Depth
4. Max Reflectivity forecast
5. Precipitation tendency
6. WV mixing ratio
7. Precipitable Water
8. Effective Radius
9. Liquid Water Path
10. Ice Water Path

- Height and strength of inversion layer
- BL instability and cloud-base height
- Expected time and place of initiation of convection
- Expected intensity & type (isolated or embedded) convection.



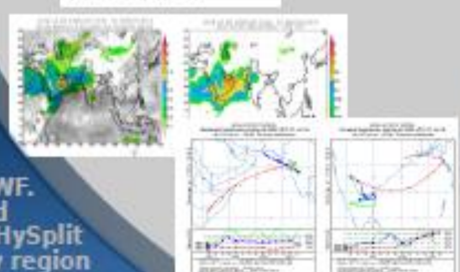
Satellite overpasses

1. Lat-Lon-Time of CloudSat overpass.
2. Time of GPM and other satellite overpass



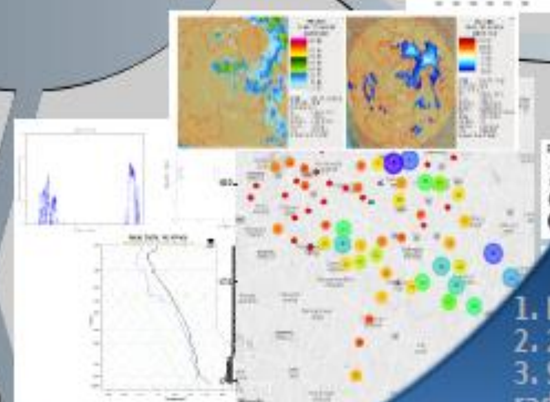
Aerosols and Trajectories

1. Aerosole concentration & optical depth forecast from NCMRWF.
2. 72 hours Backward and Foreward trajectories at 3 levels from NOAA HySplit
   - Origin of airmass over the study region
   - Expected aerosole types (continental or marine) at various heights (1-3 km).



Radar & other observations

1. Latest radar image.
2. 24-hour rainfall in rain-gauges
3. Skew-T from evening radiosonde flight
4. Radiometer and Wind profiler.



Cloud seeding criterion

- Visual criterion by Pilots : solid base with 1-2 ms-1 updraft , growing cloud turrets
- Aircraft climb to a higher altitude to identify the actively growing clouds
- Liquid water content near cloud base approx. 0.5 gm-3
- Make passes below cloud base to monitor the updraft areas and aerosol and CCN concentration
- At the updraft areas 2 flares at a time (it takes 4 min each), one on each wing is burned, 8 flares (16 min) are burned per cloud
- Upto 3 seeding events per flight

Catchment scale experiments

- to provide **evidence that the chain of physical processes can lead to enhanced precipitation** over catchment-scale areas and time scales of seasons
- carry out a range of **preliminary studies that demonstrate the suitability** of the meteorological environment of the proposed site for sustained precipitation enhancement.
- the conditions for effective cloud seeding are quite demanding, and so **suitable sites are limited geographically** and by season.

Catchment-scale experiments

- Requires a strict protocol
- Demonstrating an economic benefit of cloud seeding is difficult
- Large variability of natural precipitation
- Scaling up of seeding in mixed phase clouds is a challenge
- Need to investigate environmental risks through careful planning/monitoring
- Historical data analysis to determine duration

Environmental effects

- Seeding agents such as **silver iodide are toxic**
- **External chemicals used in cloud seeding are generally too low** to cause the levels of these chemicals in the environment to approach ‘trigger’ levels for health concerns.
- It is important for any large-scale experiment to include **careful monitoring and assessment of environmental risks**.
- The **redistribution of precipitation at the ground** in both space and time. While some cloud seeding activities are specifically aimed at redistributing precipitation (in particular, at reducing precipitation in some urban areas),
- **Extra area effect**: There is little evidence that precipitation enhancement activities at a specific site lead to discernible changes in precipitation at downwind sites at the time of seeding or at later times.

Glaciogeneic seeding

- Documented seeding effect in observations with radars and airborne observations
- Recent experimental results promising with AgI
- To consider AgI also as a CCN
- CCN and INP capabilities of particles from the combustion agent
- Spatial resolution of models are too coarse

Hygroscopic seeding

- type of clouds
- type of seeding materials
- Execution of seeding (aircraft, ground based, etc.)
- Results are not consistent
- There is little research on hygroscopic seeding using three-dimensional models
- Seeding schemes used in models need to be improved.

Convective clouds: outstanding challenges

- The extreme variability of convective clouds in space and time
- Scaling-up of the effects of seeding mixed-phase convective clouds
- The uncertainties in the physical basis of the methodology
- Orographic clouds have encouraging results in experimental campaigns (enhancements < 20% seems feasible)

Outlook

The resolution of the substantial uncertainties that currently limit the scientific framework for cloud seeding, especially for mixed-phase convective clouds

Queensland: 2008 - 2009

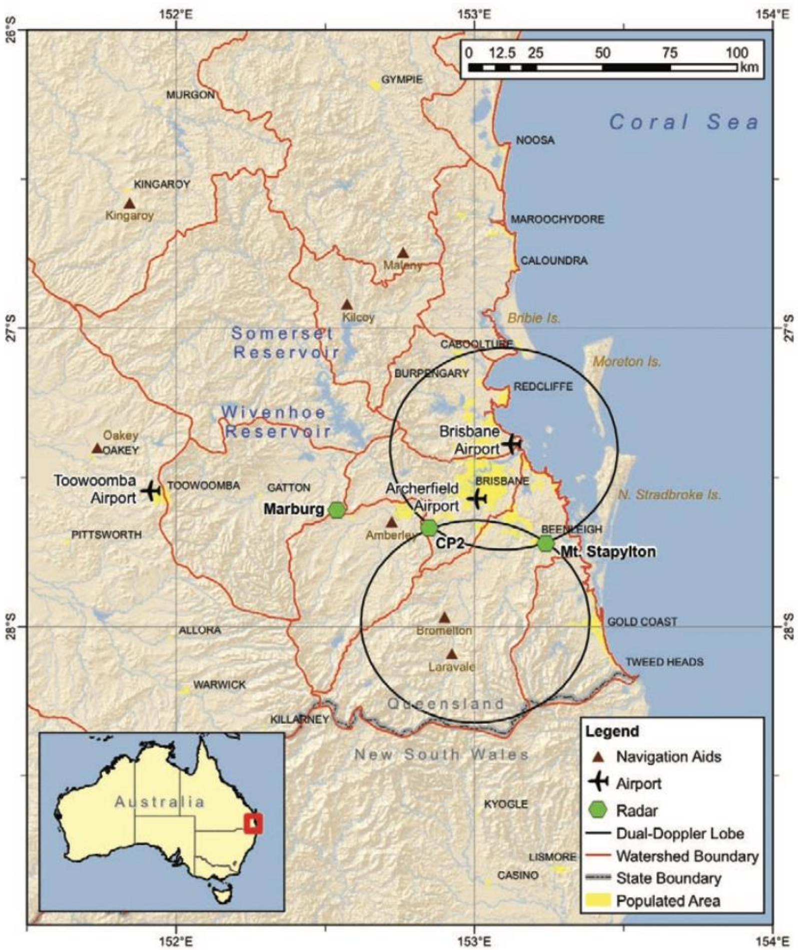


FIG. 1. Map of southeast Queensland region targeted for the QCSRP field effort and associated facilities and landmarks. The 30° beam crossing angle dual-Doppler lobes are overlaid in black. [Courtesy of Kevin Sampson, NCAR.]

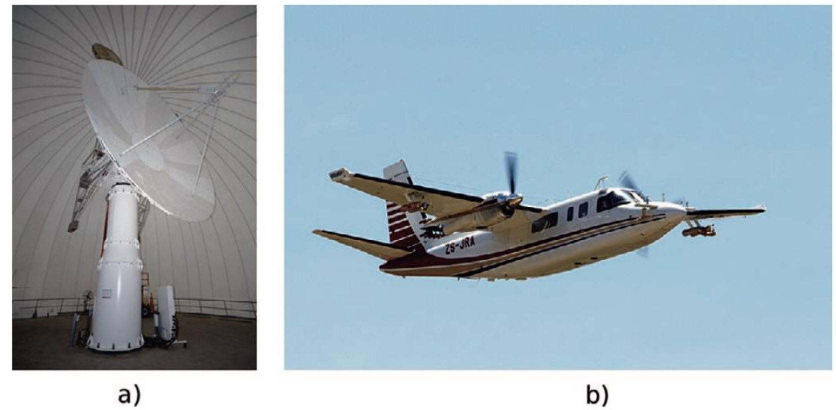
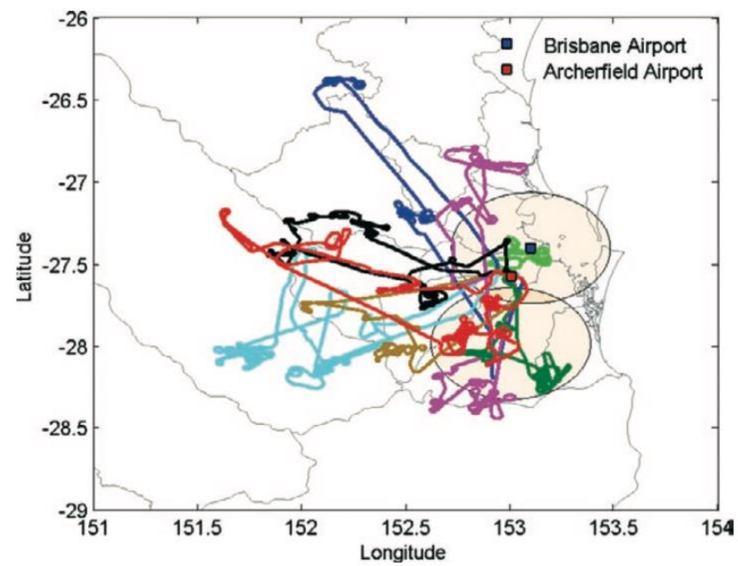
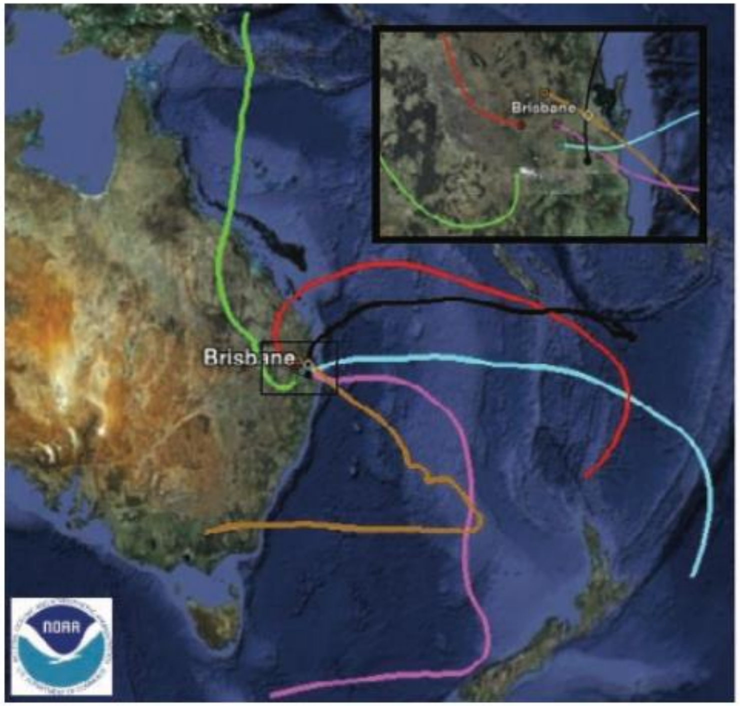


FIG. 2. Facilities operated during the QCSRP included (a) the CP2 radar (photo depicts the S-band and X-band antennae), and (b) the SAWS Aero Commander research/seeding aircraft depicted in flight on a research mission. [Photos courtesy Scott Collis, CAWCR.]



Queensland: 2008 - 2009



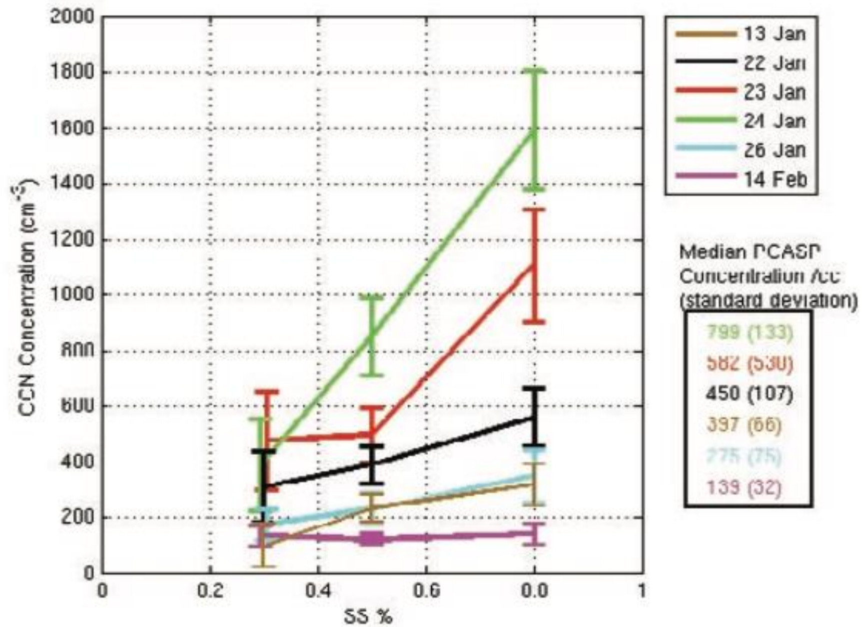


FIG. 4. (left) Map of 120-h HYSPLIT back trajectories for six sampling days in 2009 (13, 22–24, and 26 Jan, and 14 Feb) and (right) associated color-coded CCN concentration measurements at three supersaturations (0.3%, 0.5%, 0.8%) with whiskers indicating plus/minus one standard deviation for each filter sampling measurement (see legend). The median (and standard deviation in parentheses) PCASP aerosol concentration for each measurement is also noted by color for each day in the legend. An inset map is included to provide a zoomed-in view of the trajectory paths relative to the city of Brisbane.

Aerosol size distribution to be monitored and characterized

Eg: Queensland: 2008 - 2009

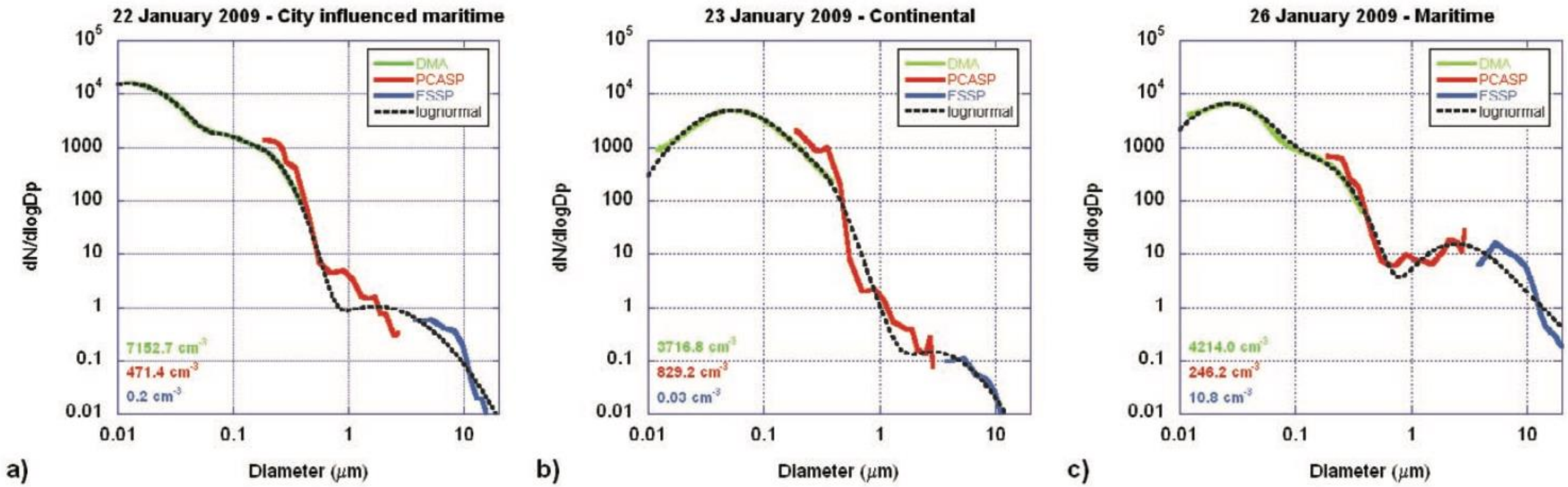


FIG. 5. Aerosol size distributions created from the DMA (green), PCASP (red), and FSSP (blue) measurements for (a) 22 Jan 2009, (b) 23 Jan 2009, and (c) 26 Jan 2009. A lognormal fit has been applied to the combined dataset based on methods in Hussein et al. (2005) and is overlaid as a black dashed line. The mean total concentration per probe (same color as distribution line) is indicated in the lower left corner.

Queensland: 2008 - 2009

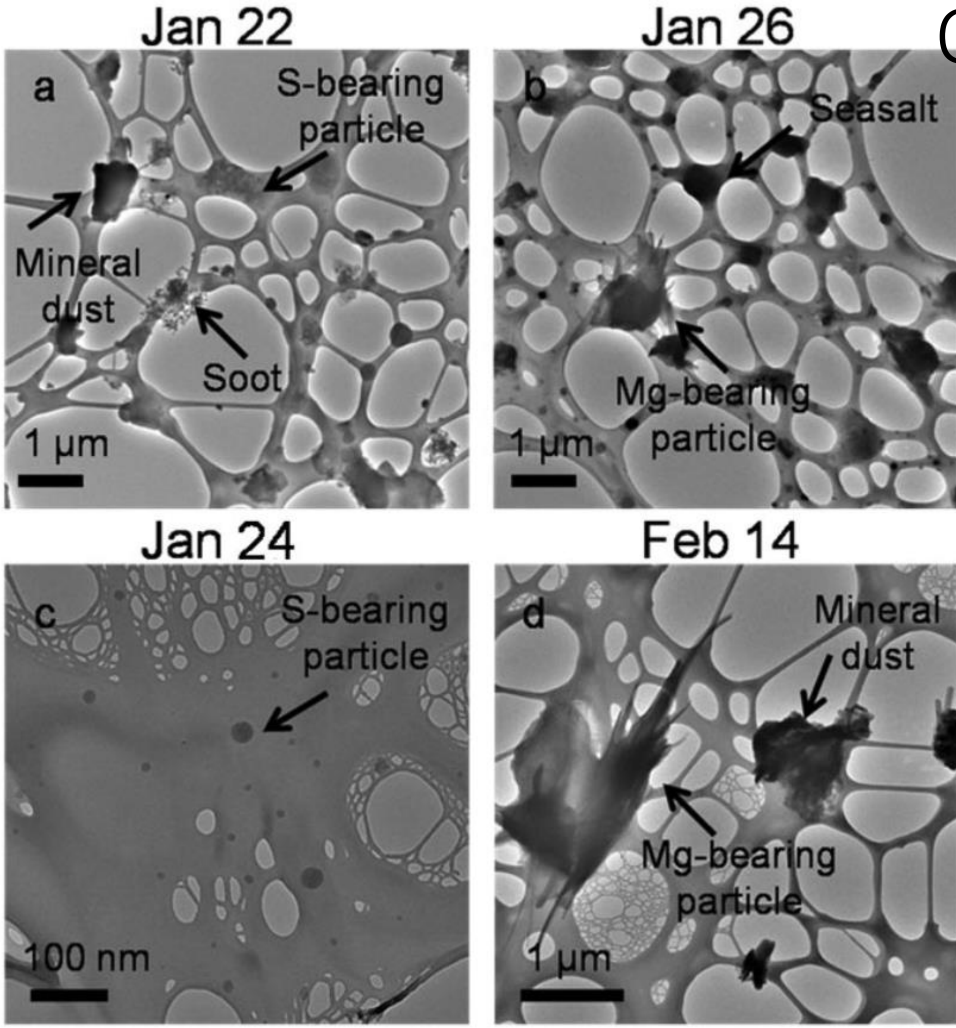


FIG. 6. Examples of particles collected during selected research flights. "S bearing" particles are sulfur bearing, and "Mg bearing" are magnesium-bearing particles. The fibrous, spider web-like material is the lacy-carbon substrate on which the particles were collected. The date on which particles were sampled is shown above each image, all of which occurred in 2009. Note the different scale for the 24 Jan image.

JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 2858–2871, doi:10.1002/jgrd.50274, 2013

Aerosol characteristics observed in southeast Queensland and implications for cloud microphysics

Sarah A. Tessendorf,[1] Courtney E. Weeks,[1] Duncan Axisa,[1] and Roelof T. Bruintjes[1]

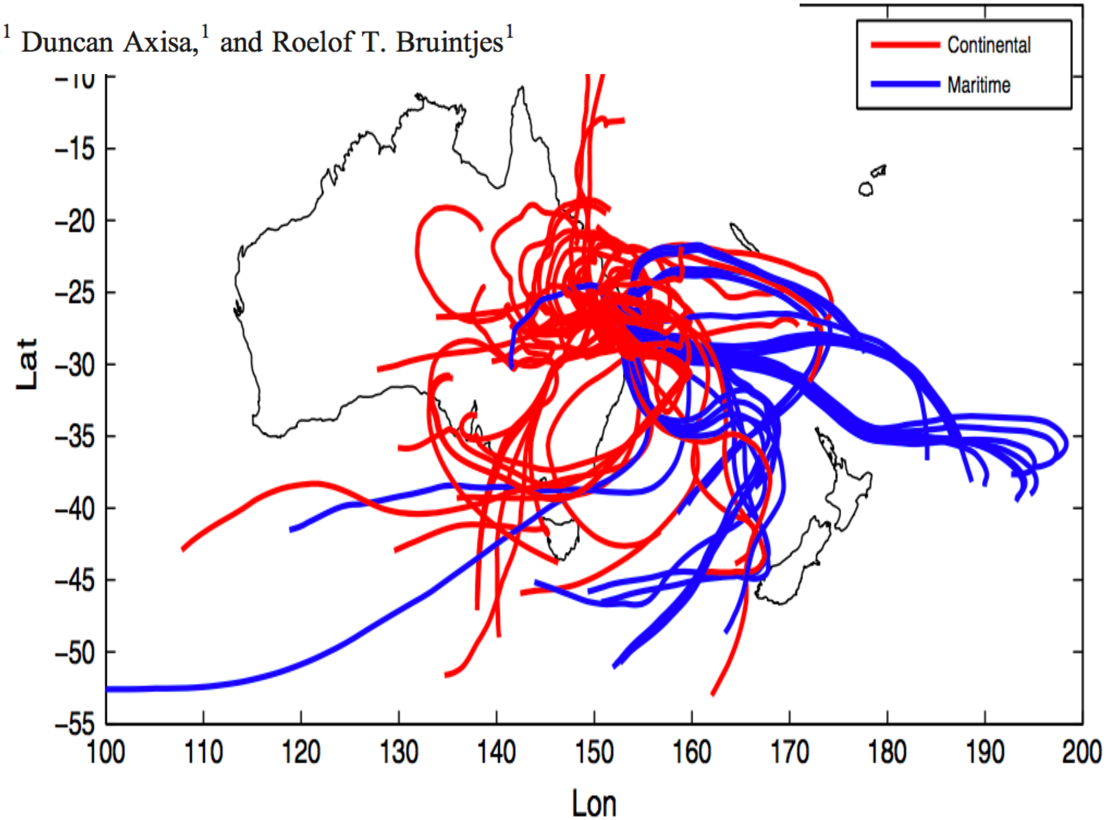


Figure 1. 120 h HYSPLIT back trajectories for each cloud base aerosol measurement color-coded into two regimes based on how much time each trajectory spent over land below 2 km: (blue) maritime regime ≤ 12 h and (red) continental regime > 12 h.

Queensland: 2008 - 2009

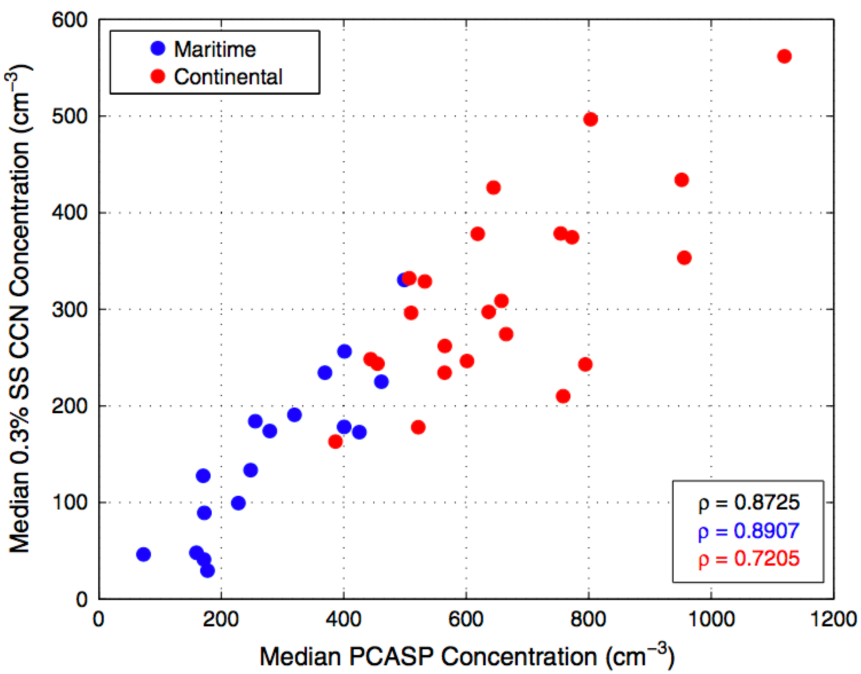


Figure 5. Scatter plot of the median PCASP concentration and 0.3% SS CCN concentration for each cloud base aerosol measurement, colored by (blue) maritime and (red) continental regimes. [Note that not all of the PCASP measurements used in the regime analysis had corresponding CCN measurements, given that the CCN instrument was not available on every flight. Thus, in this analysis with CCN measurements, the maritime (continental) regime had 21 (24) samples.] The correlation coefficient (ρ) is noted for each regime (color) and for all points combined (black).

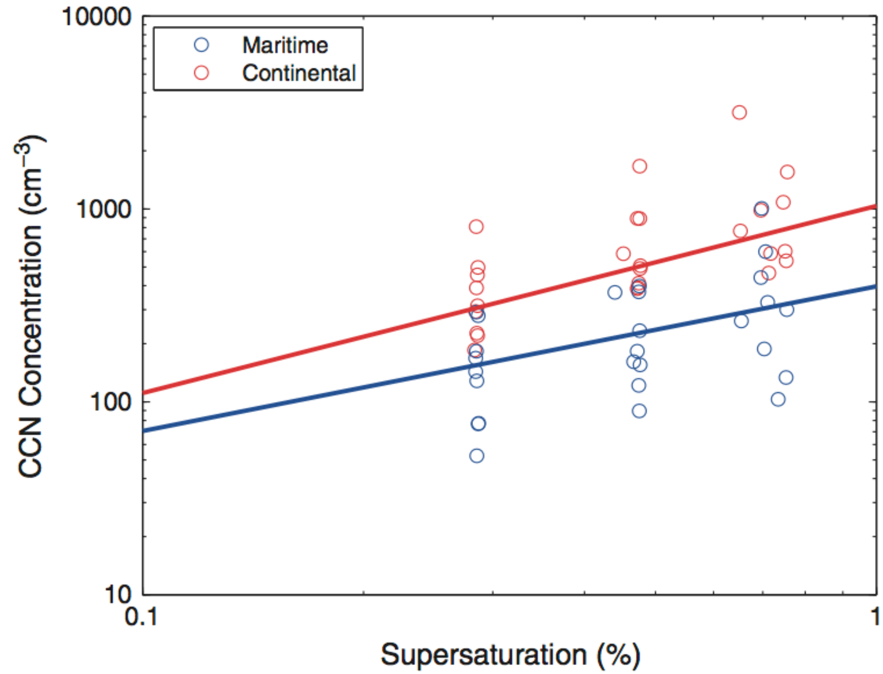
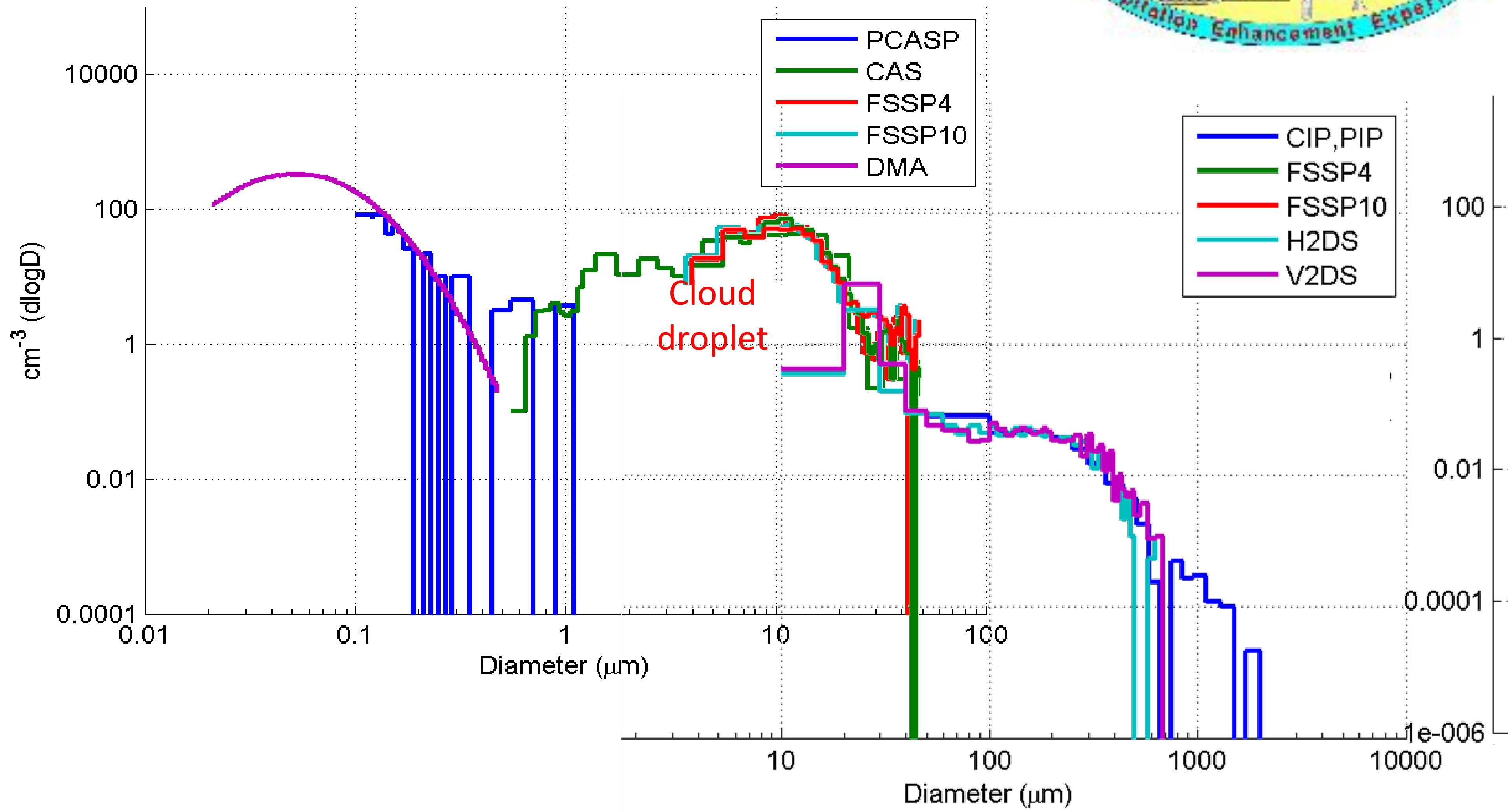
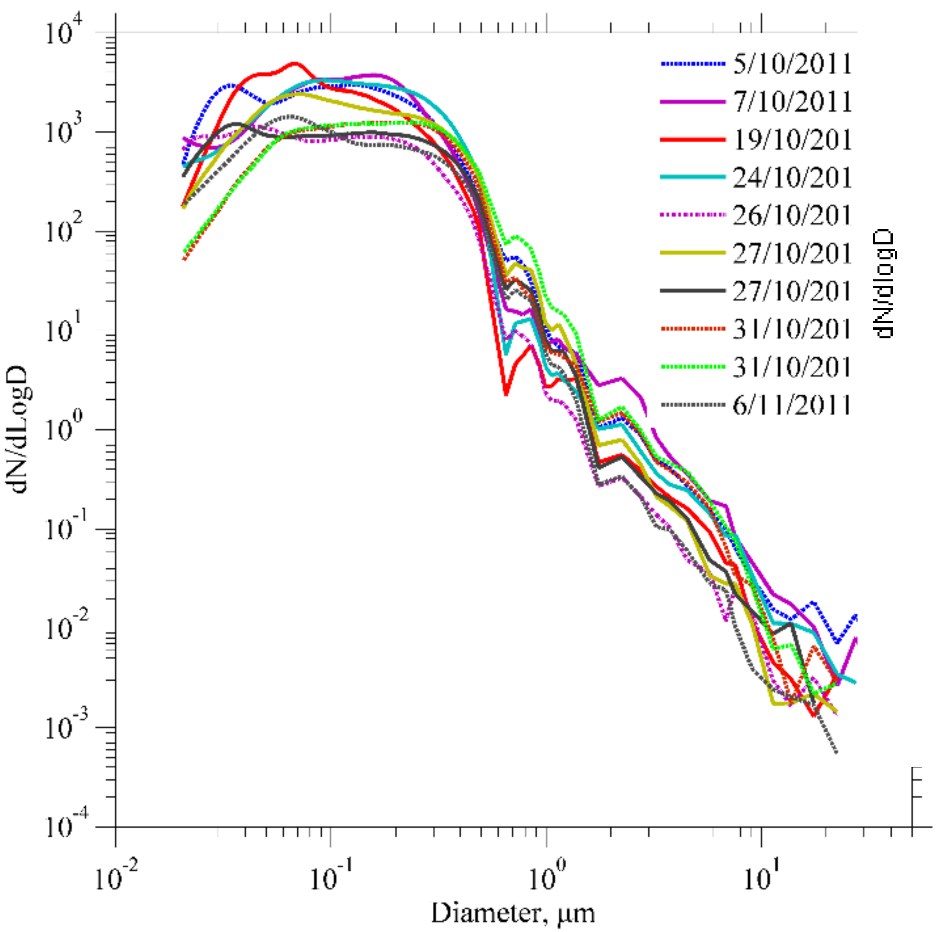


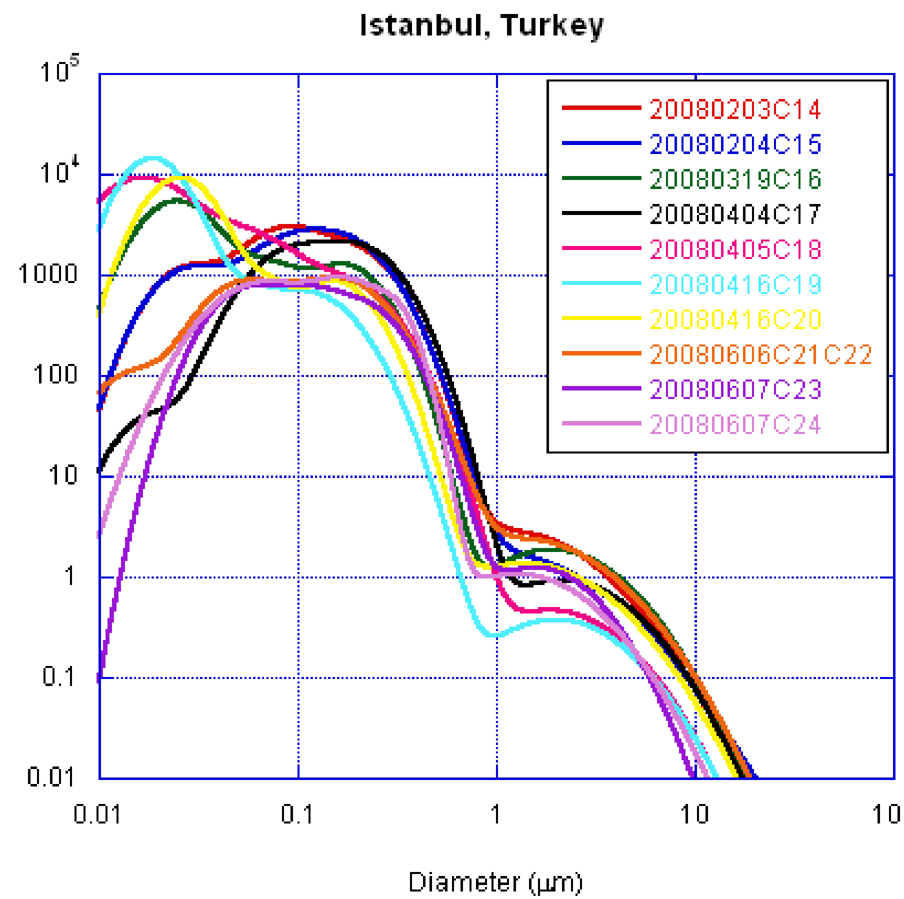
Figure 4. CCN concentrations at varying supersaturations measured during cloud base supersaturation cycles, colored by maritime (blue) and continental (red) regimes. The solid line represents the power law fit (based on equation (4)) for each regime. There is some scatter about the set supersaturation values, most notably around 0.8%, because temperatures did not actually stabilize in every cycle to achieve the specified supersaturation. Therefore, the temperature difference within the column was used to calculate the actual supersaturation for each measurement.

Particle/droplet size distribution from different probes

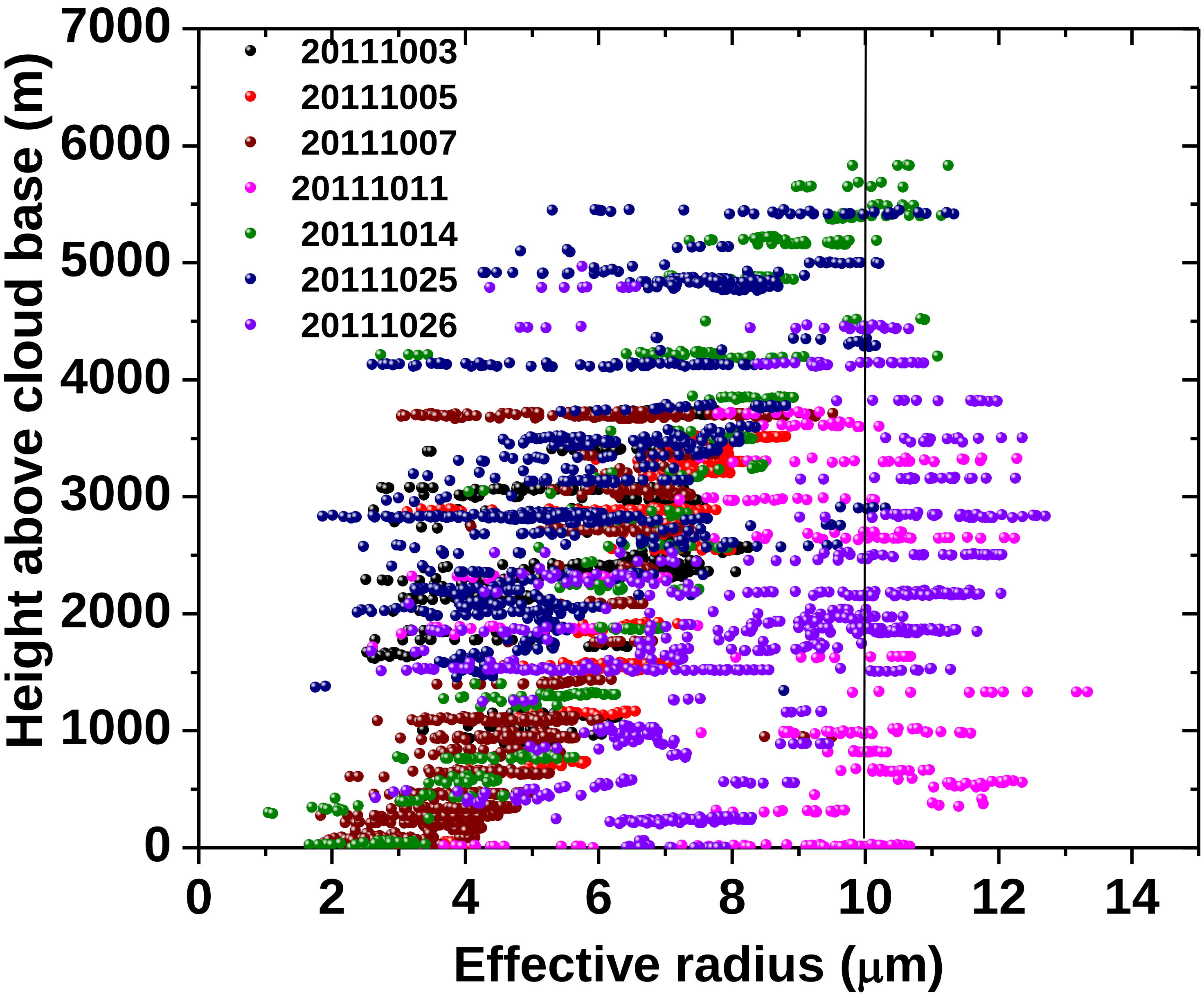


Background cloud base ASD and activation characteristics associated with size are important





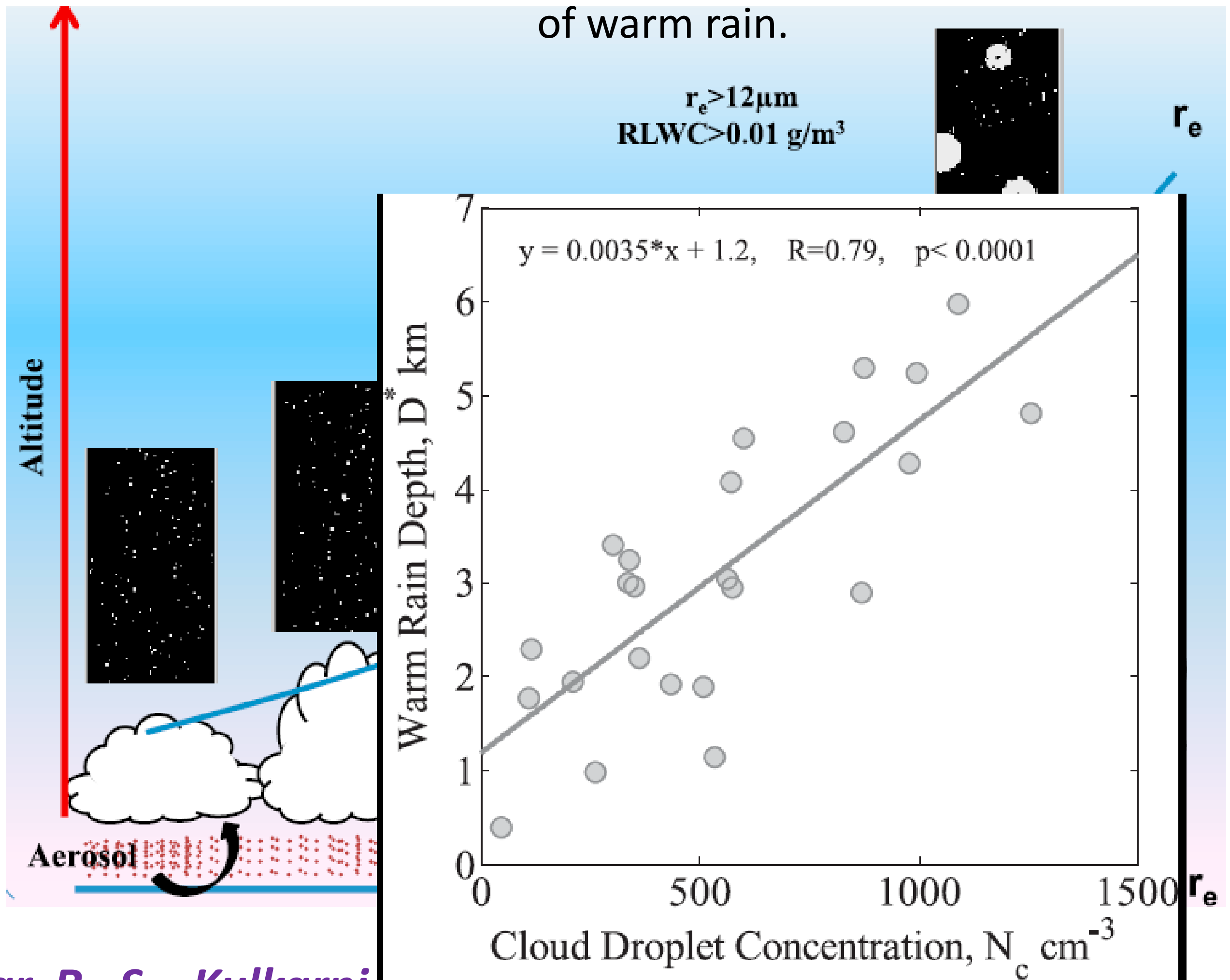
Knowing cloud vertical microstructure is important



Aerosol control on depth of warm rain

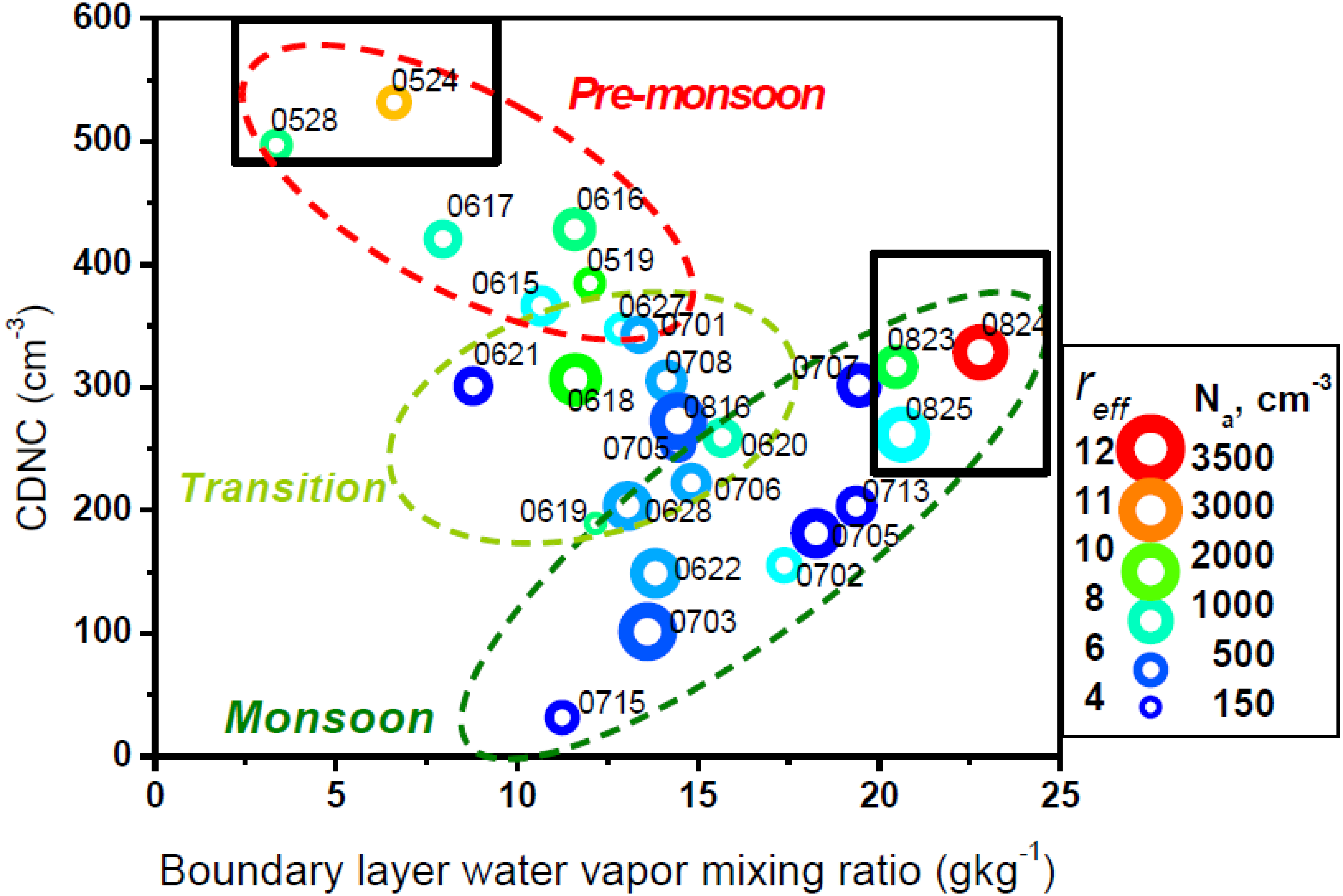
Schematic diagram of aerosol's influence on depth for onset of warm rain.

The hydrometeor images are from Cloud Image Probe; rain starts when effective radius of cloud > 12 micron and rain LWC> 0.01 g/m^3. D* is the distance from the cloud base.



Konwar M., Maheskumar R. S., Kulkarni J. R.,. Freud E, Goswami B. N., Rosenfeld D., Aerosol control on depth of warm rain in convective clouds, Journal of Geophysical Research, 117, 2012, D13204

Knowing cloud microstructure in different conditions

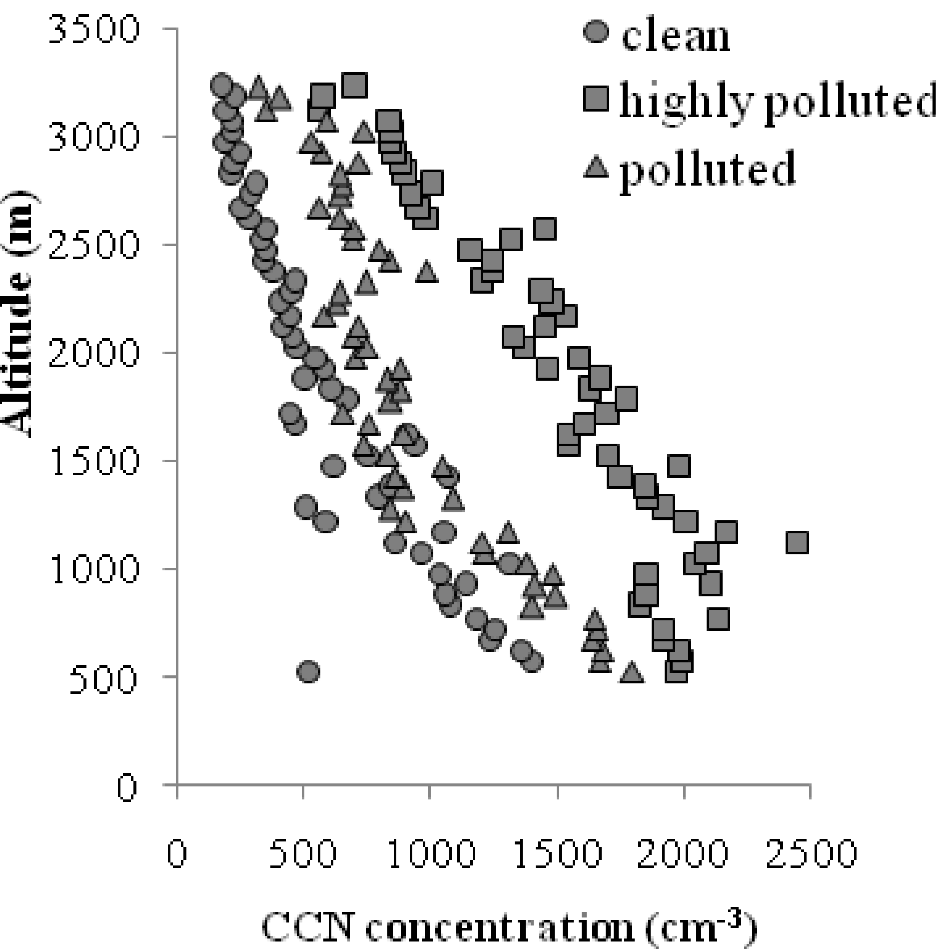


Prabha, T. V., S. Patade, G. Pandithurai, A. Khain, D. Axisa, P. Pradeep-Kumar, R. S. Maheshkumar, J. R. Kulkarni and B. N. Goswami, 2012: Spectral width of premonsoon and monsoon clouds over Indo-Gangetic valley, J. Geophys. Res., 117, D20205, doi:10.1029/2011JD016837.

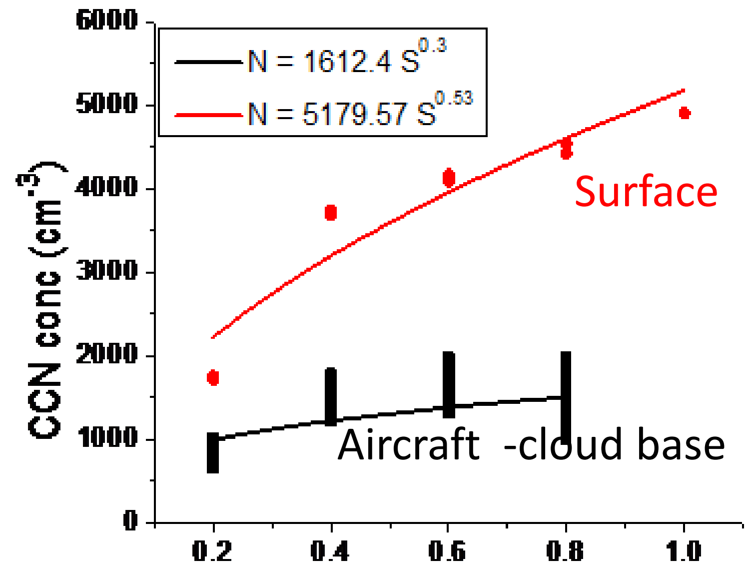
CAIPEEX Background CCN

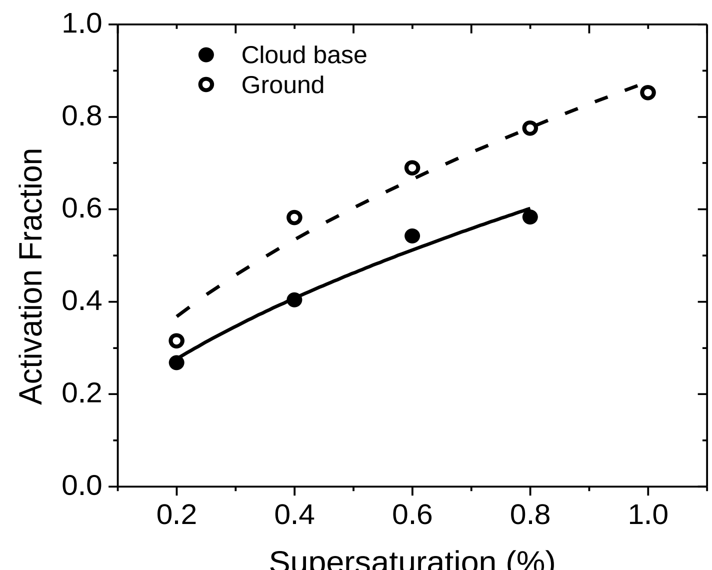
CCN observations airborne and ground based

Vertical profile of CCN



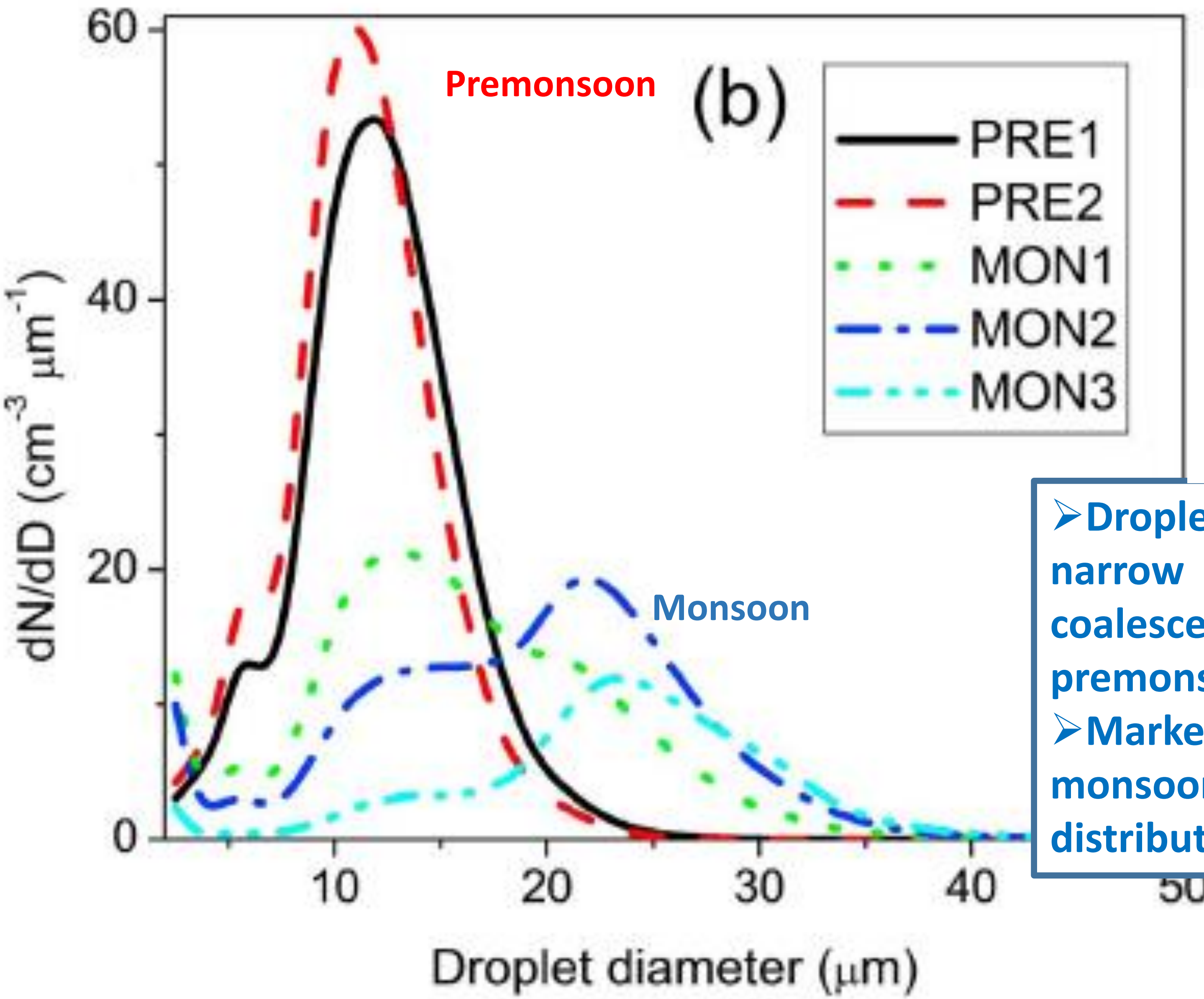
CCN activation spectra





Varghese et al., (Atmospheric Environment, 2015)

Droplet size distribution in the PREmonsoon and MONsoon clouds

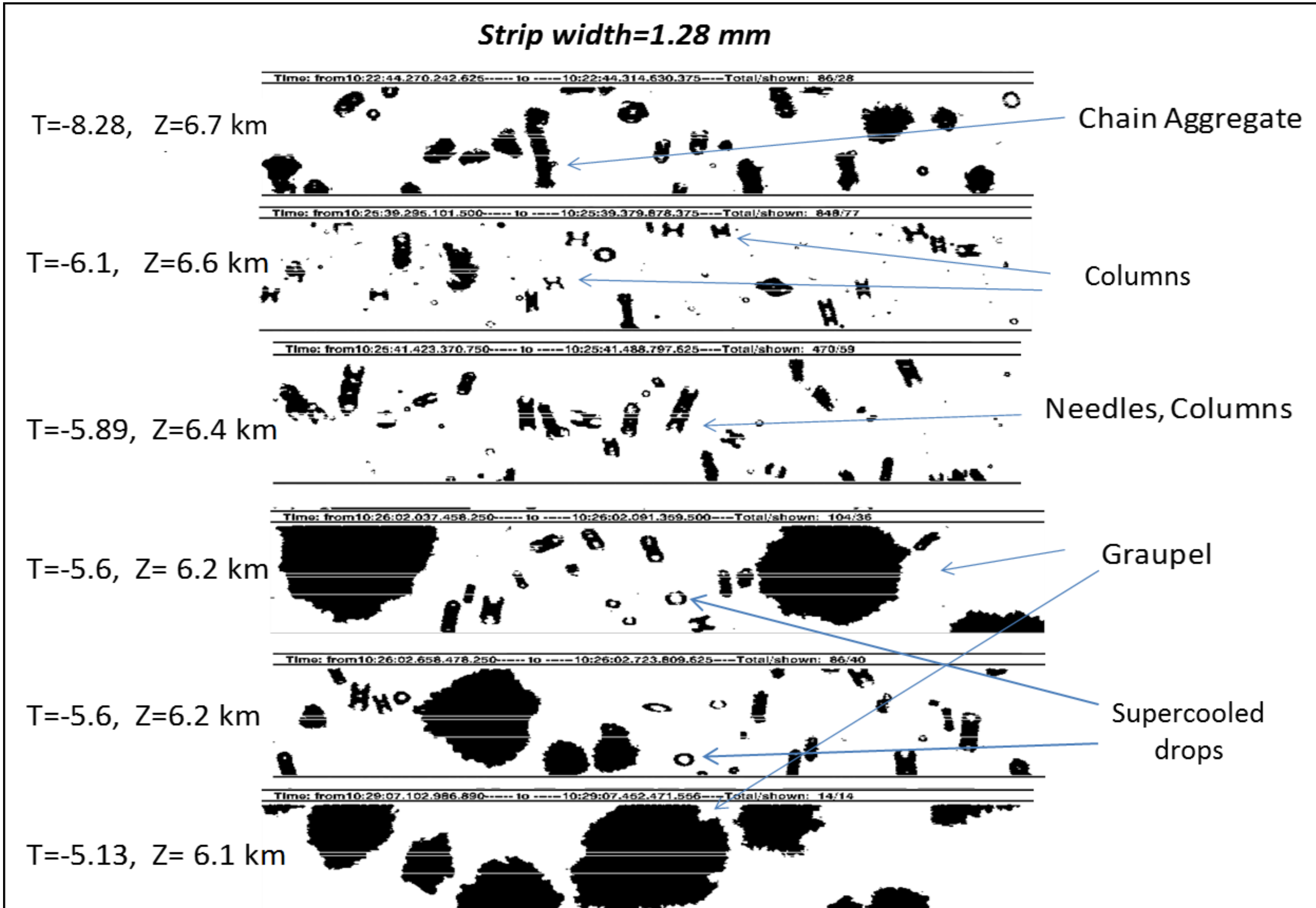


High
High
Moderate
High
Low aerosol

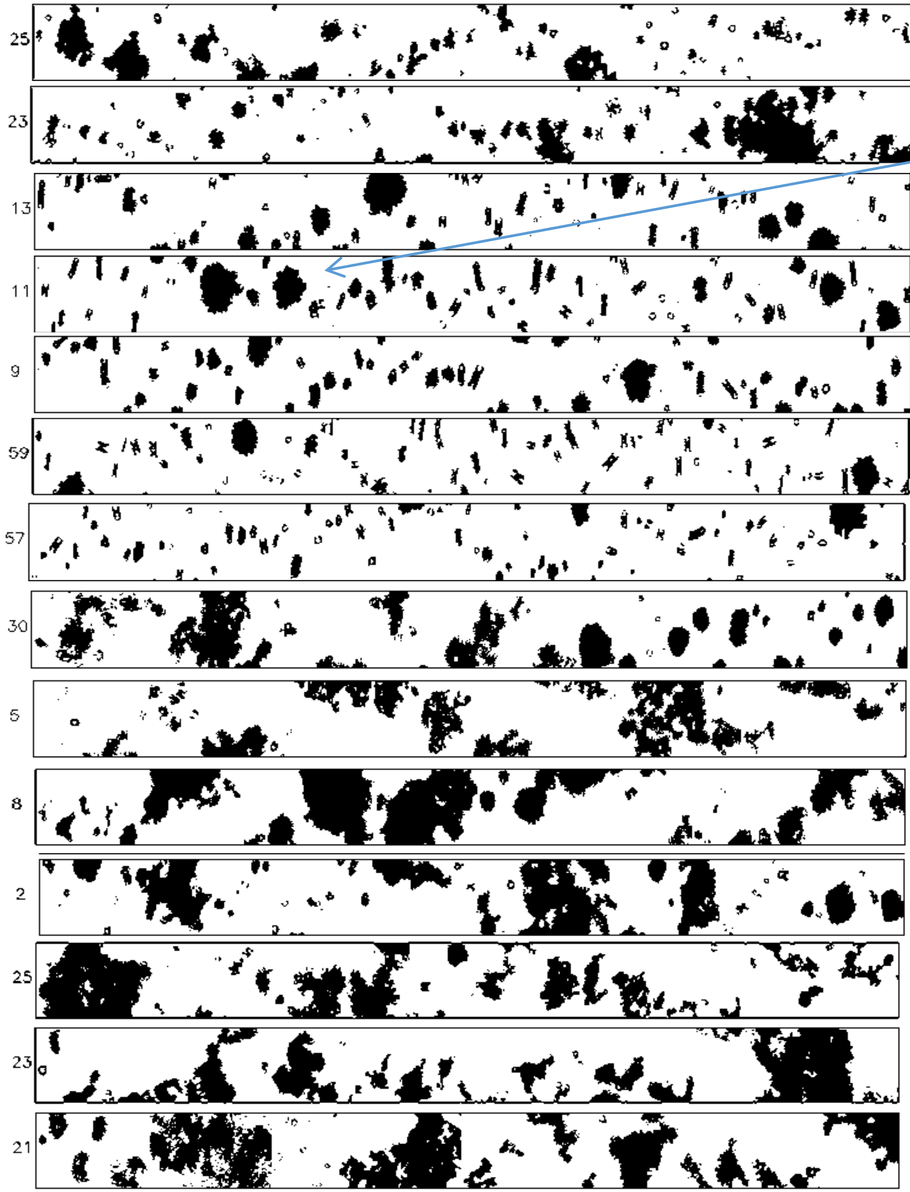
- **Droplet spectrum is narrow and Collision-coalescence is absent in premonsoon clouds**
- **Marked differences in monsoon with bimodal distributions**

Prabha et al., 2012), JGR

Clear evidence of large graupel and ice multiplication process



Width of strip=1600 μm



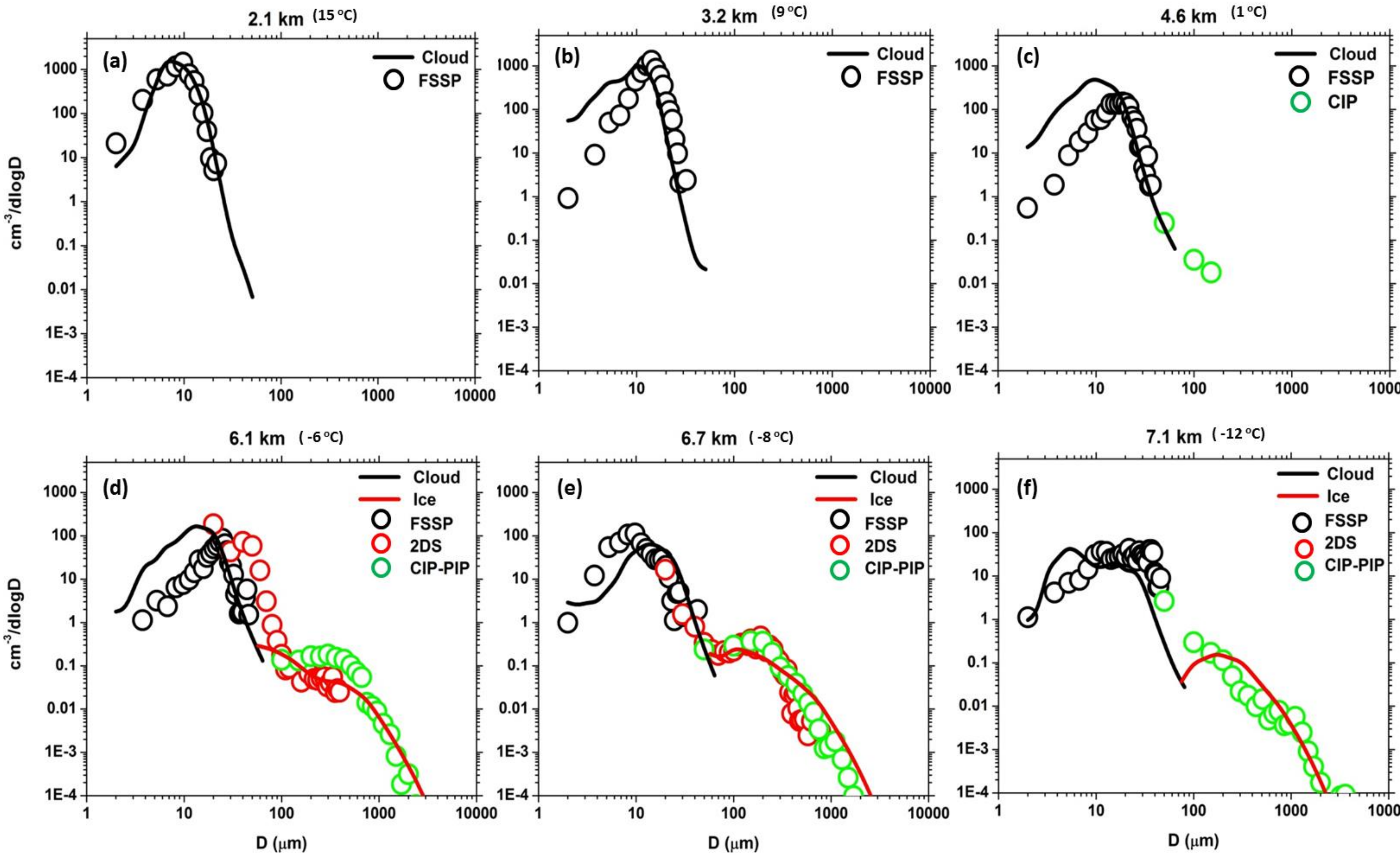
Time (UTC)	Temp (^{o}C)
095025	-8.59
095023	-8.60
094713	-7.22
094711	-7.11
094709	-7.16
094659	-6.59
094657	-6.59
094430	-4.49
094305	-4.58
094208	-3.38
094202	-3.67
094125	-2.54
094123	-2.49
094121	-2.74

Needles and graupel

Active Hallet Mossop Zone

From Sachin Patade et al., 2015, Atmospheric research

Seeding in numerical simulations and evaluations
Comparing particle size distribution from bin microphysics simulation and CAIPEEX observations at different altitudes



[Gayatri et al., under revision, JAS]

Modelling requirements

- Model intercomparison projects
- Modern approaches like the "piggybacking" method
- To take ambient background aerosol population for the simulation of drop and ice particle nucleation. (competition between the two populations needs to be simulated)
- Seeding/natural aerosol particles acting as CCN and INP as prognostic variables
- Parameterize ice nucleation capabilities of various atmospheric aerosol particles
- Ice multiplication processes.
- Model skill in synoptic scale could not be translated to cloud scale dynamics, microphysics and thermodynamics and to precipitation production.

Precipitation formation from orographic cloud seeding

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- **Scientific evidence confirming physical hypothesis for glaciogenic seeding where AgI is introduced into clouds with supercooled liquid**

- Hypothesis: Introduction of AgI aerosol in to clouds lead to nucleation of ice crystals and further ice particle growth to large size and that falls as snow at the ground
- Direct evidence using radar and aircraft cloud physics observations
- Cloud seeding efficacy is not addressed