Proposed flight strategies based on experience, scientific insights and lessons gained from previous cloud physics and aerosols aircraft campaigns in the Amazon and elsewhere

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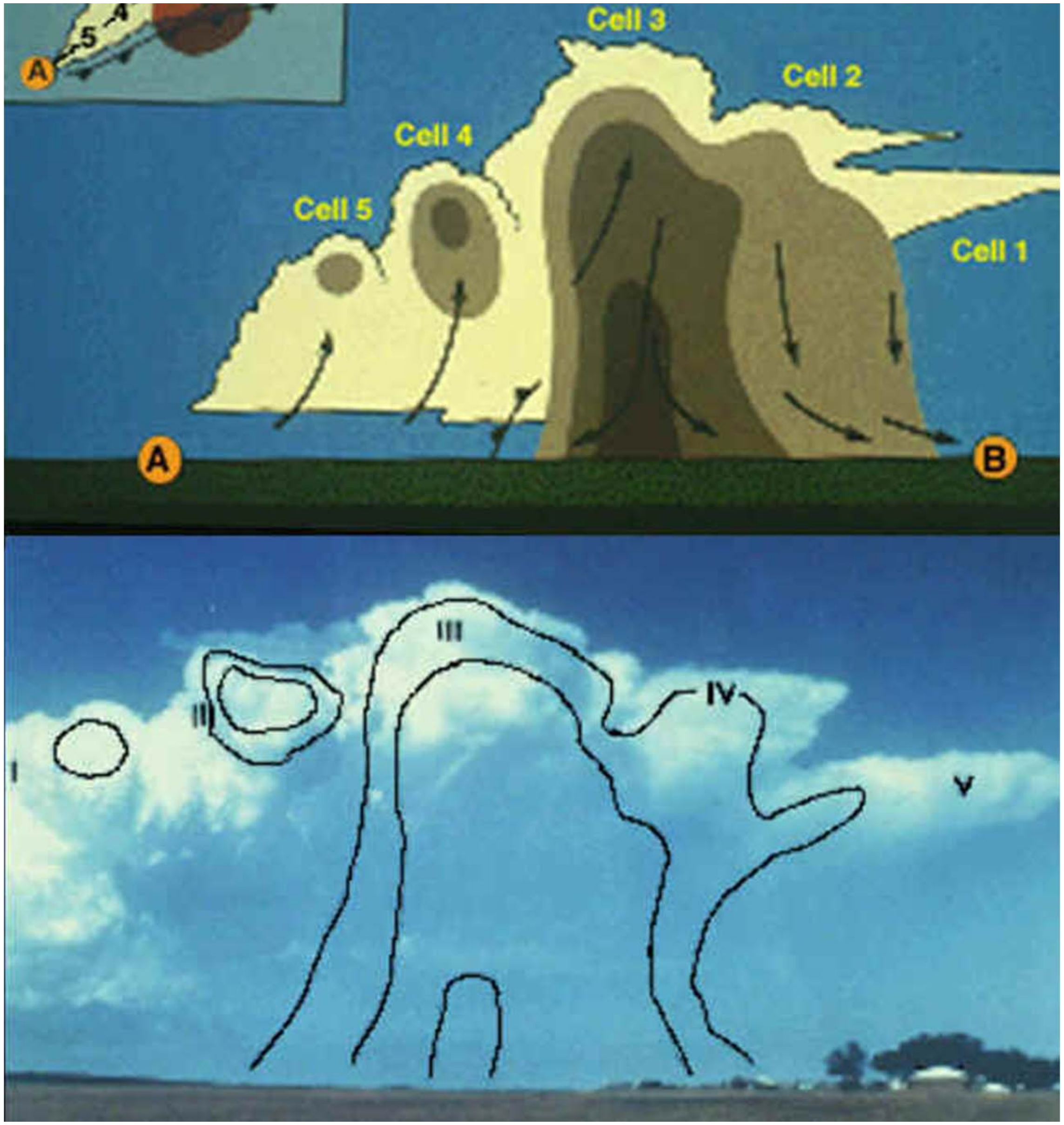
The Hebrew University of Jerusalem

Understanding the precipitation structure requires understanding precipitation initiation. This, in turn, depends on aerosol and their interactions with cloud microstructure and dynamics (e.g., cloud invigoration, alteration of DSD and cold pools).



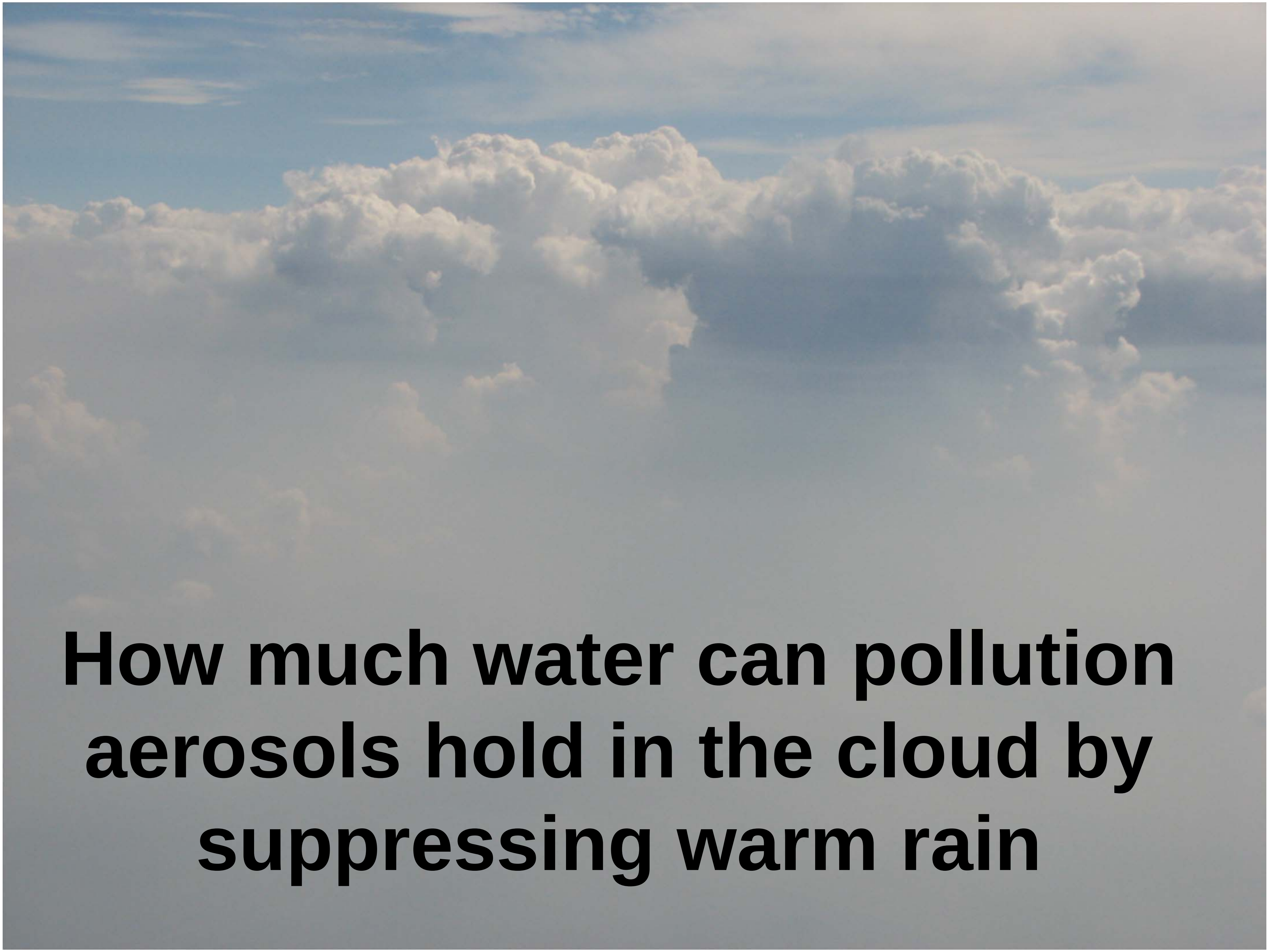
Outline

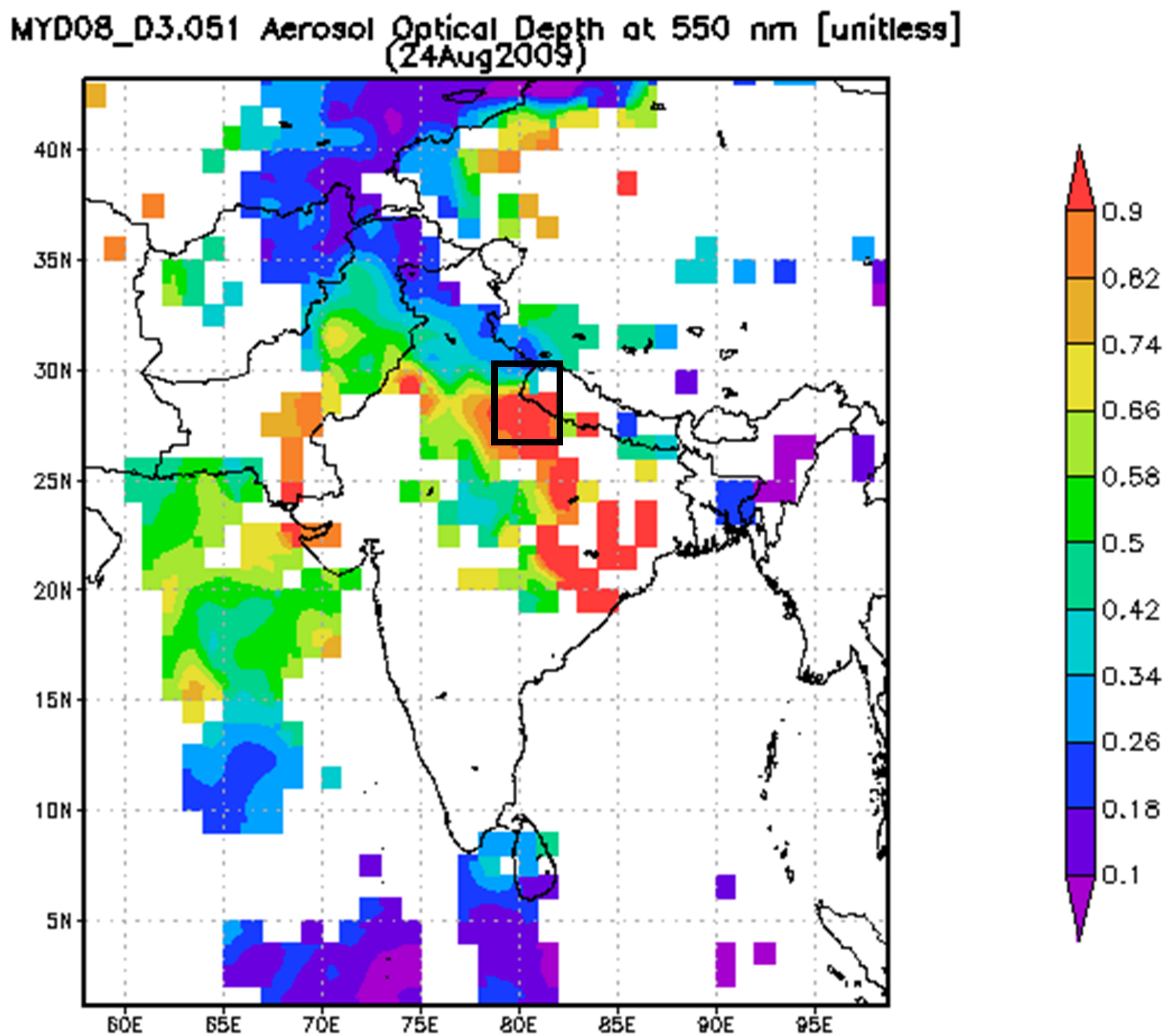
- Vertical profiles of r_e and precipitation in different campaigns.
- Relations between D-r_e and Na and CCN.
- Validate relations of CCN-Na-Dc in the Amazon.

How high should we climb in smoky clouds for start precipitation?

How is the precipitation initiated? Supercooled rain or mixed phase?


01 10 2002 19:51


How much water can pollution aerosols hold in the cloud by suppressing warm rain


MYD08_D3.051 Aerosol Optical Depth at 550 nm [unitless]
(24Aug2009)
40N
35N
30N
25N
20N
15N
10N
5N
60E
65E
70E
75E
80E
85E
90E
95E
0.9
0.82
0.74
0.66
0.58
0.5
0.42
0.34
0.26
0.18
0.1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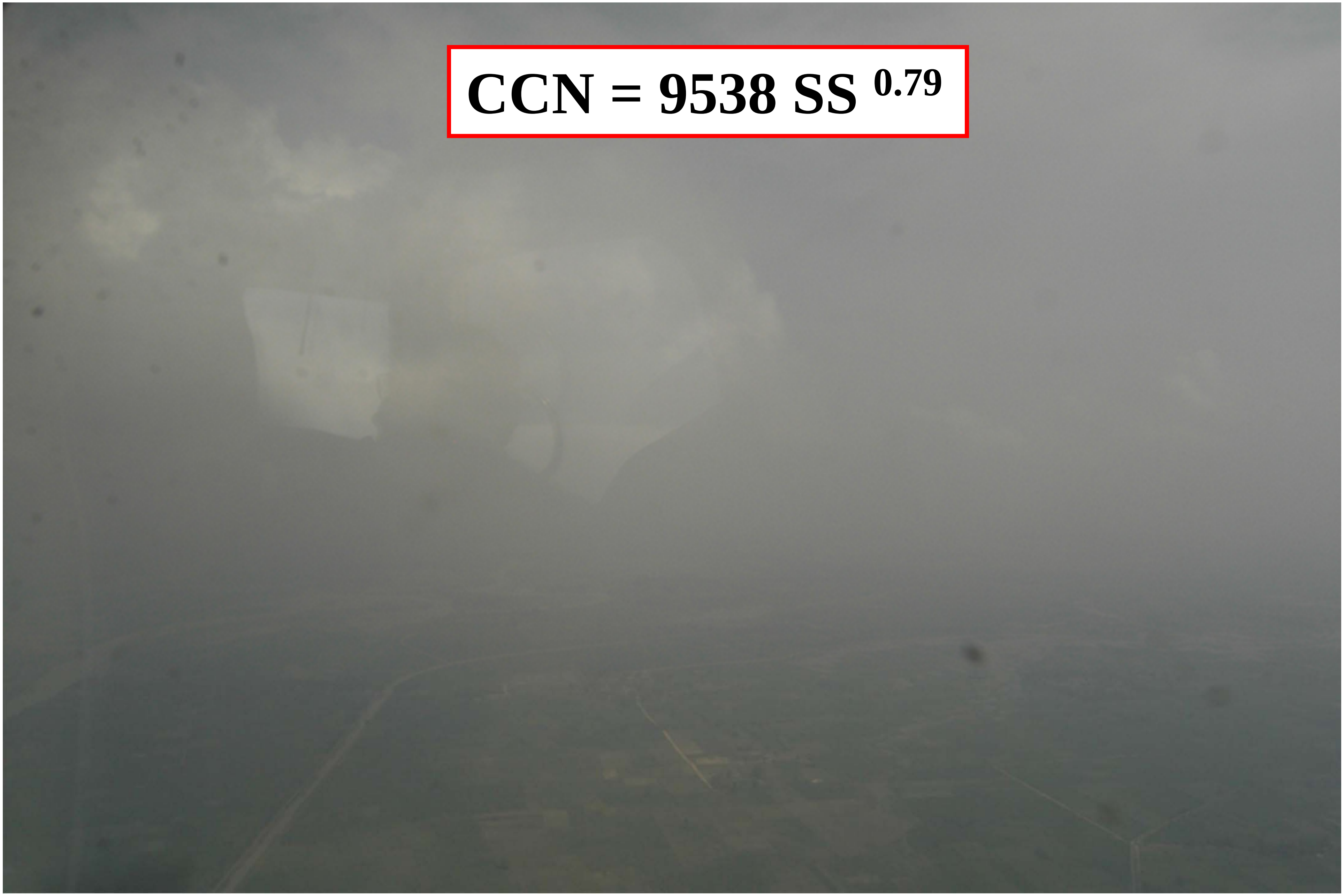
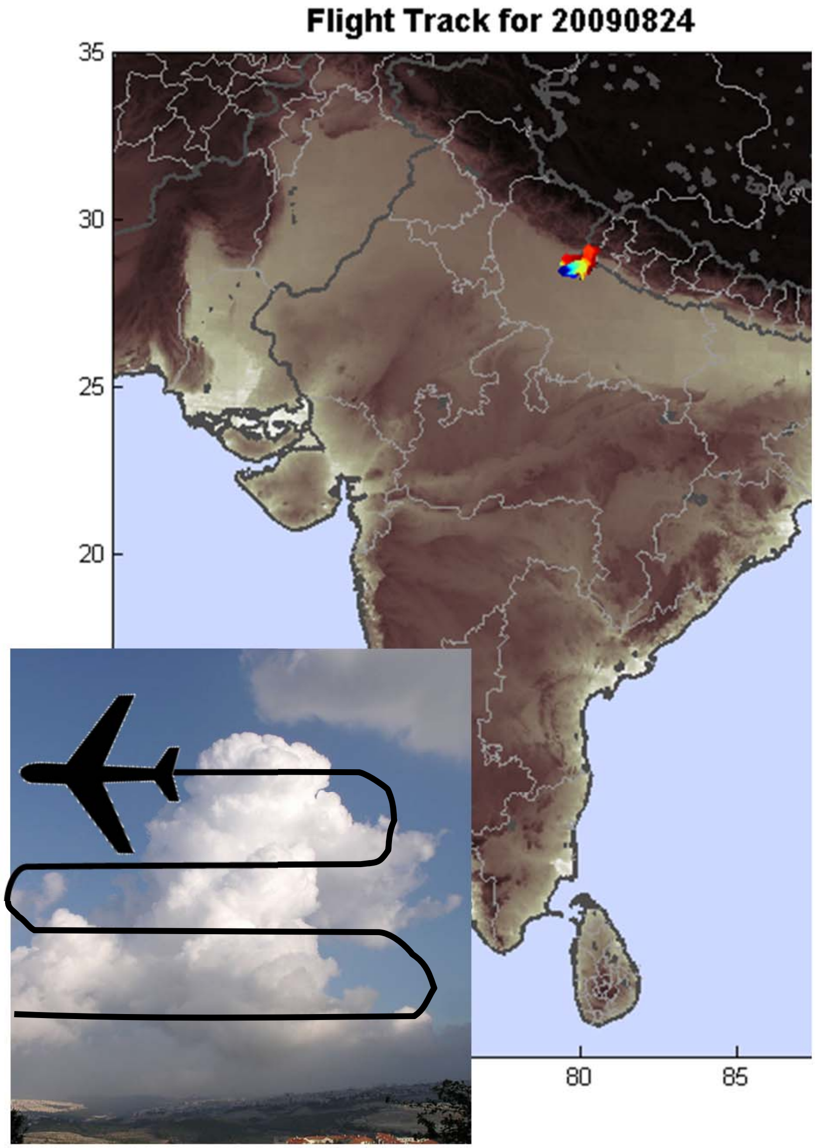
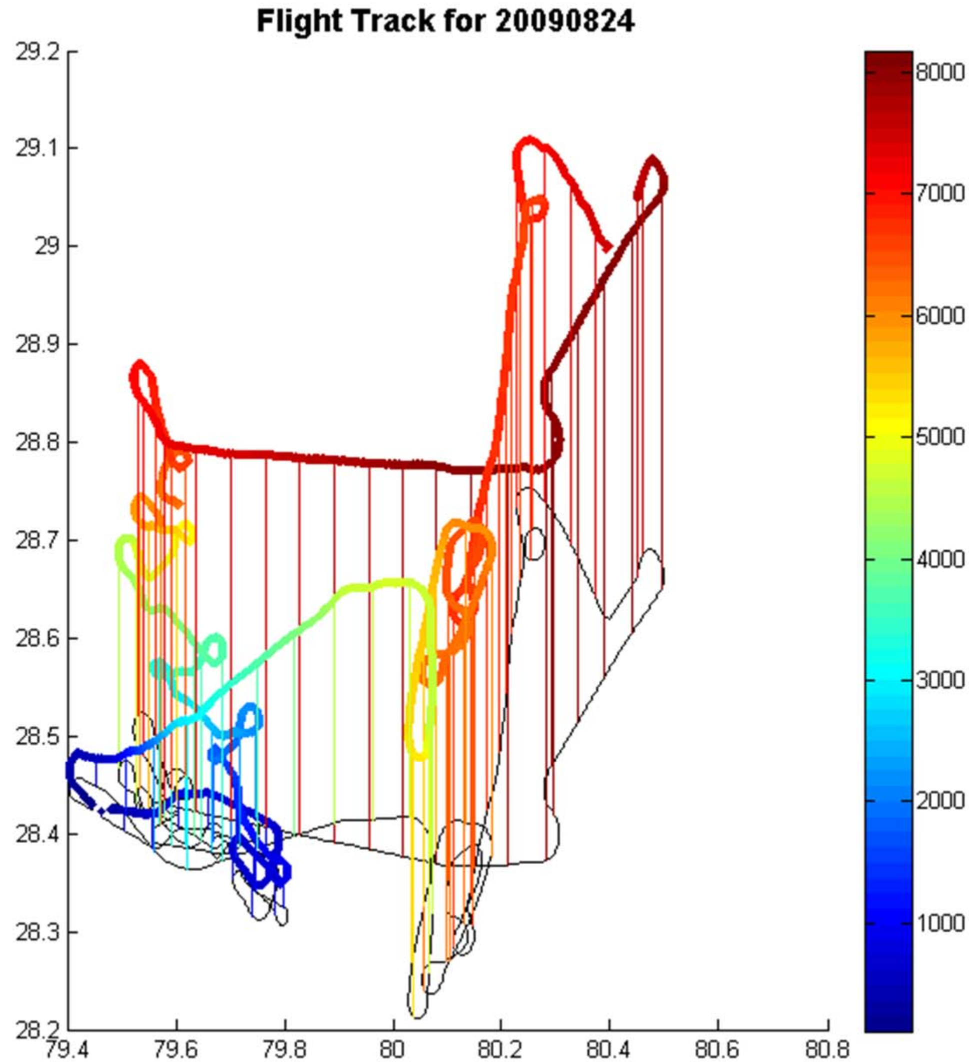
Anthropogenic Aerosols



2009 08 24, 9:06 UT, **690 m, 25.3ºC**. Just east of Bareilly.
Cloud base in heavy haze of air pollution.


Flight Track for 20090824
35
30
25
20
80
85


Flight Track for 20090824
29.2
29.1
29
28.9
28.8
28.7
28.6
28.5
28.4
28.3
28.2
79.4
79.6
79.8
80
80.2
80.4
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80.8
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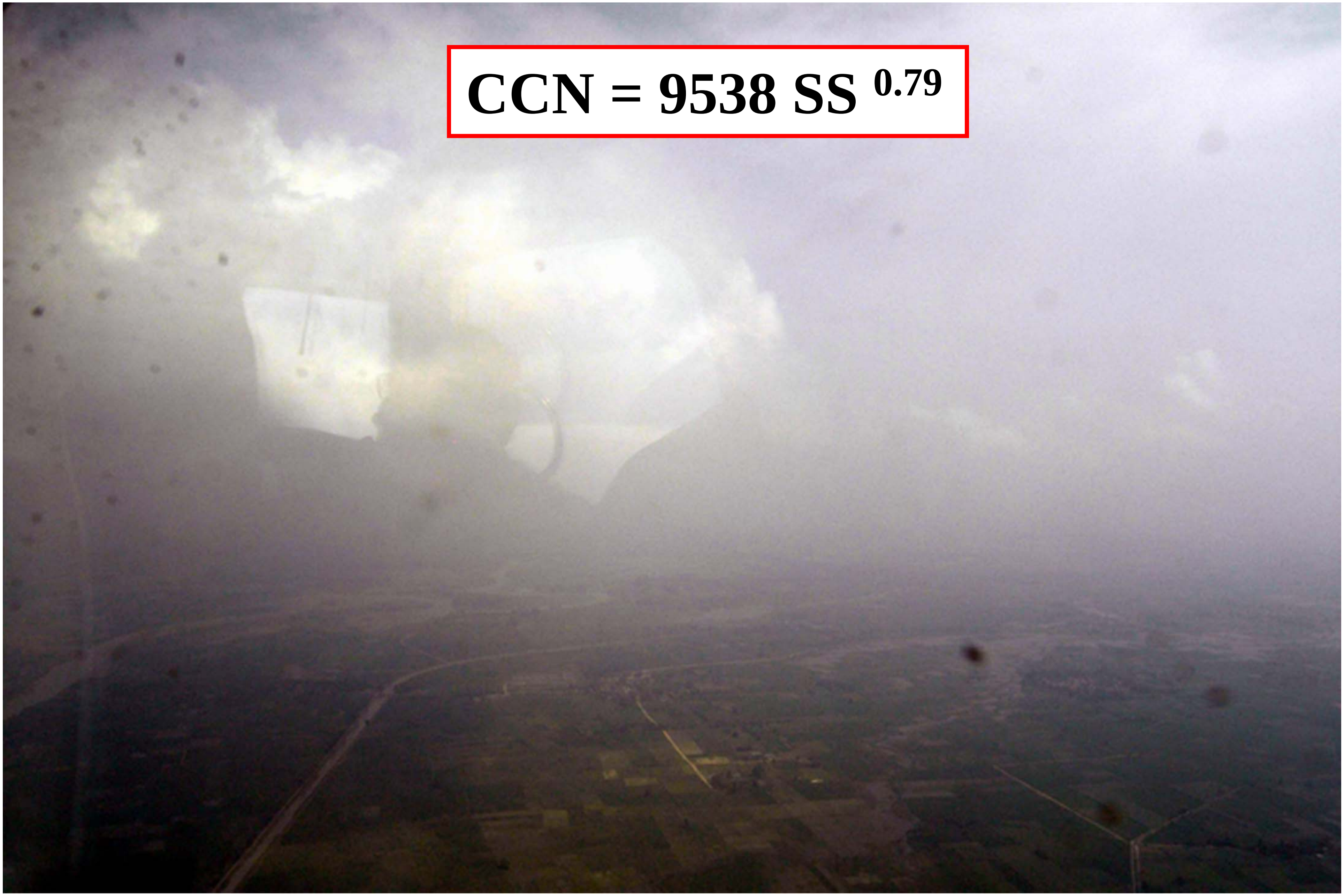
7000
6000
5000
4000
3000
2000
1000

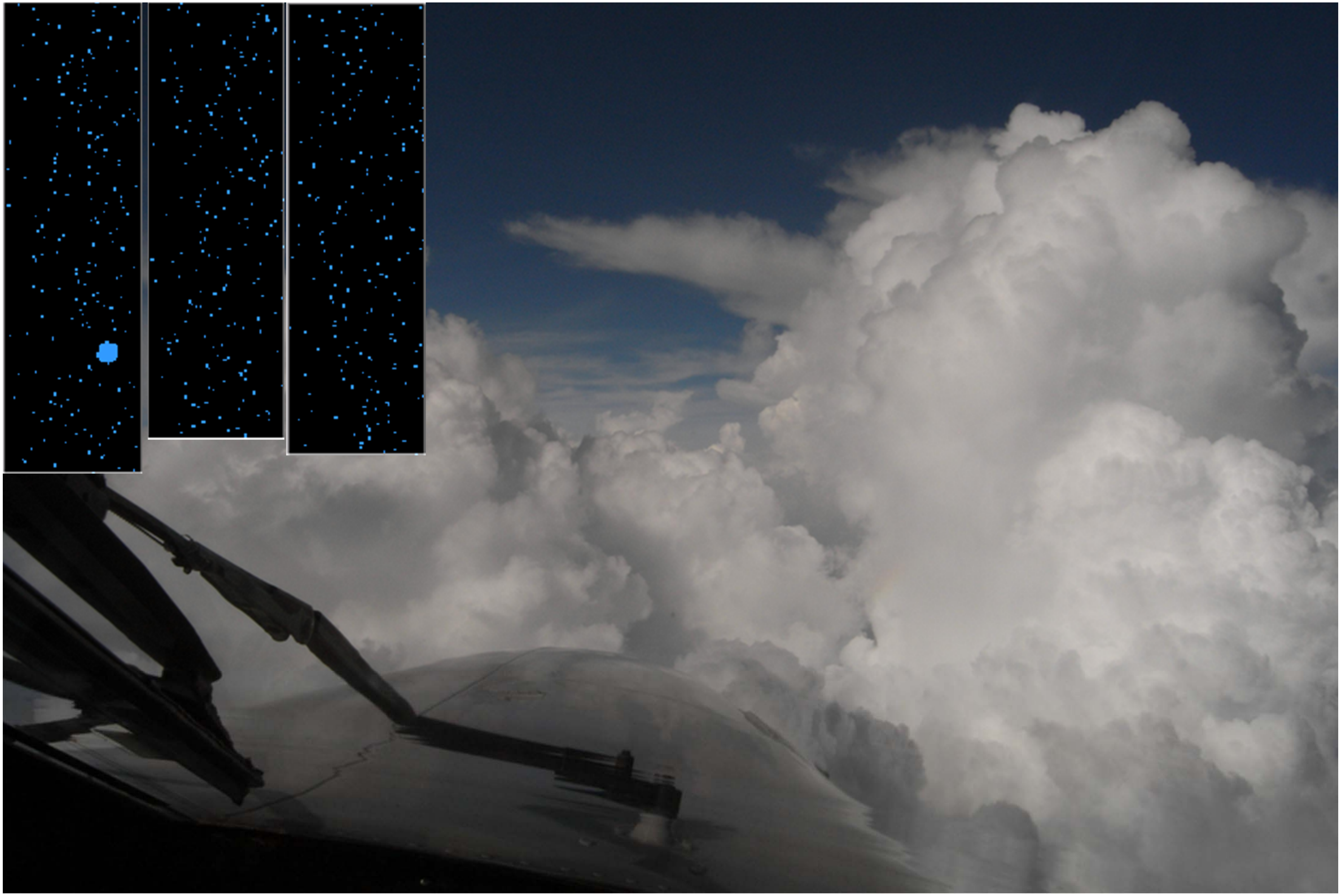


2009 08 24, 9:06 UT, 690 m, 25.3ºC. Just east of Bareilly. Contrast enhanced.
Cloud base in haze. **The ground is flooded, so that sensible heat flux is low.**

2009 08 24, 10:38 UT, 3400 m, 10.0ºC. Max HWLWC=1.90 gm^{-3}.
Approaching Bareilly. Note the thick haze.

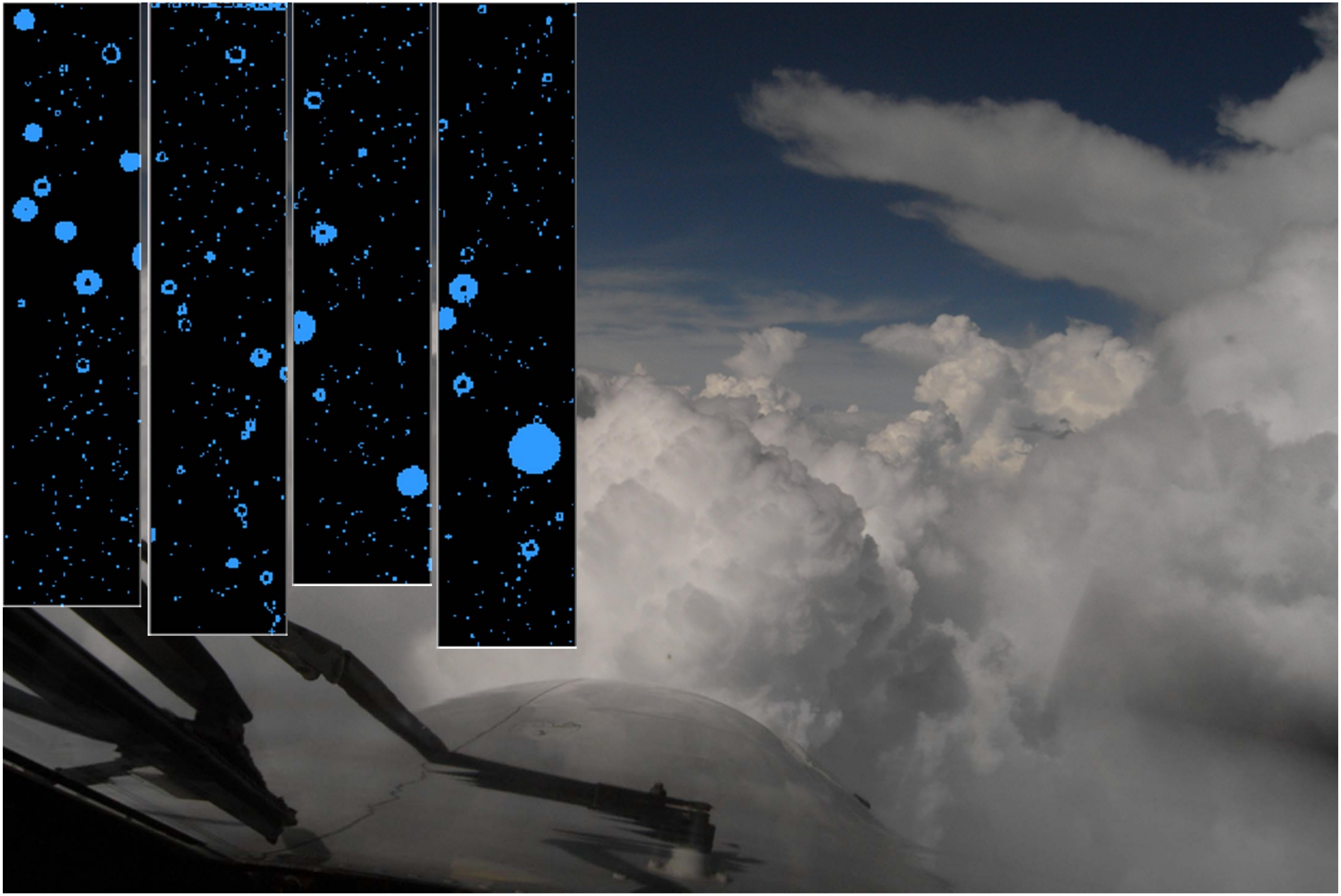
2009 08 24, 10:31 UT, 4700 m, 3.2ºC. Max HWLWC=2.45 gm^{-3}. N of Bareilly.
No rain.

2009 08 24, 10:29 UT, 5530 m, -1.6ºC. Max HWLWC=2.91 gm^{-3}. N of Bareilly.
The cloud had isolated small rain drops.

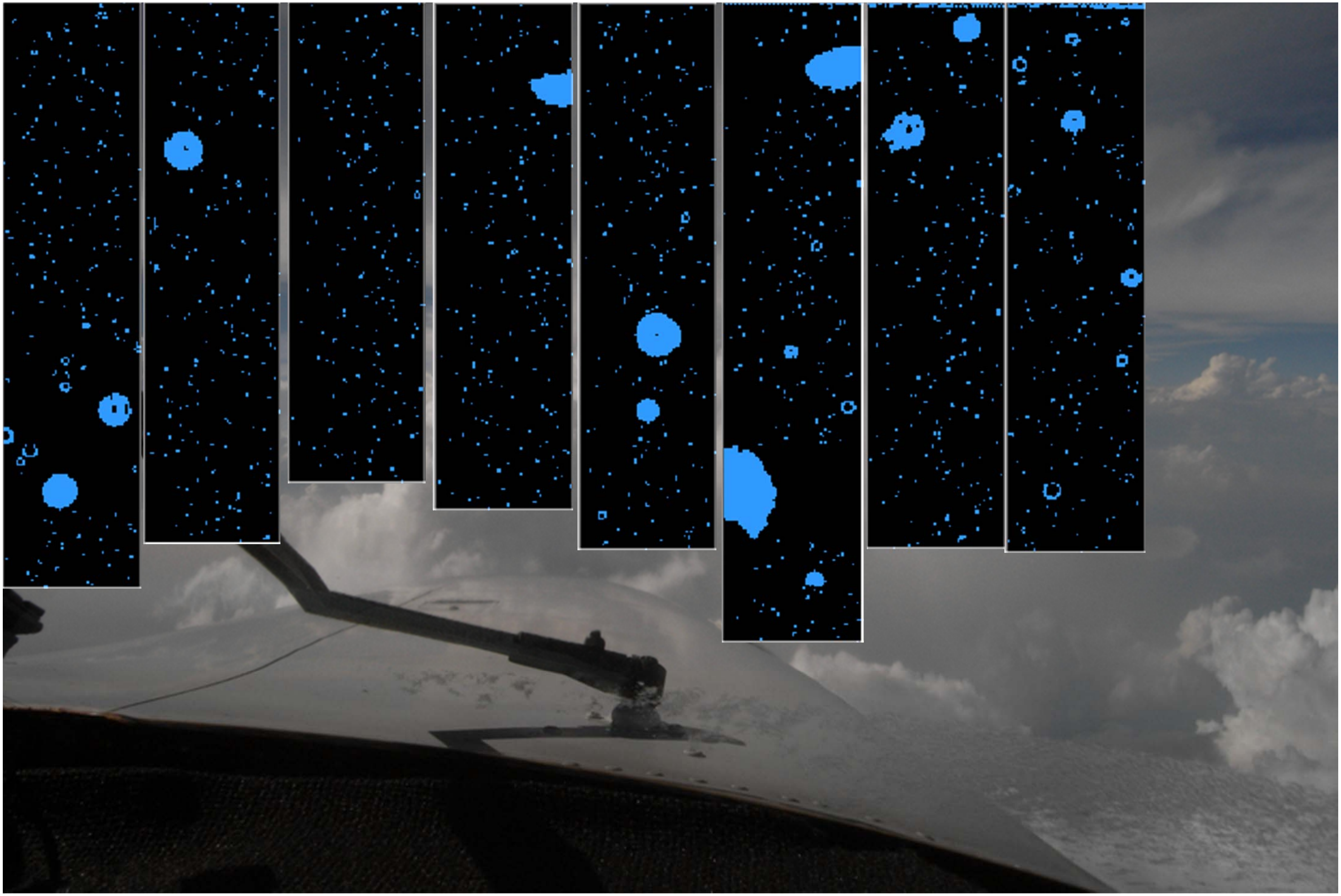


2009 08 24, 10:24 UT, 6270 m, -4.8ºC. Max HWLWC=1.05 gm^{-3}. N of Bareilly.
Some small rain drops were at the edge of the cloud.

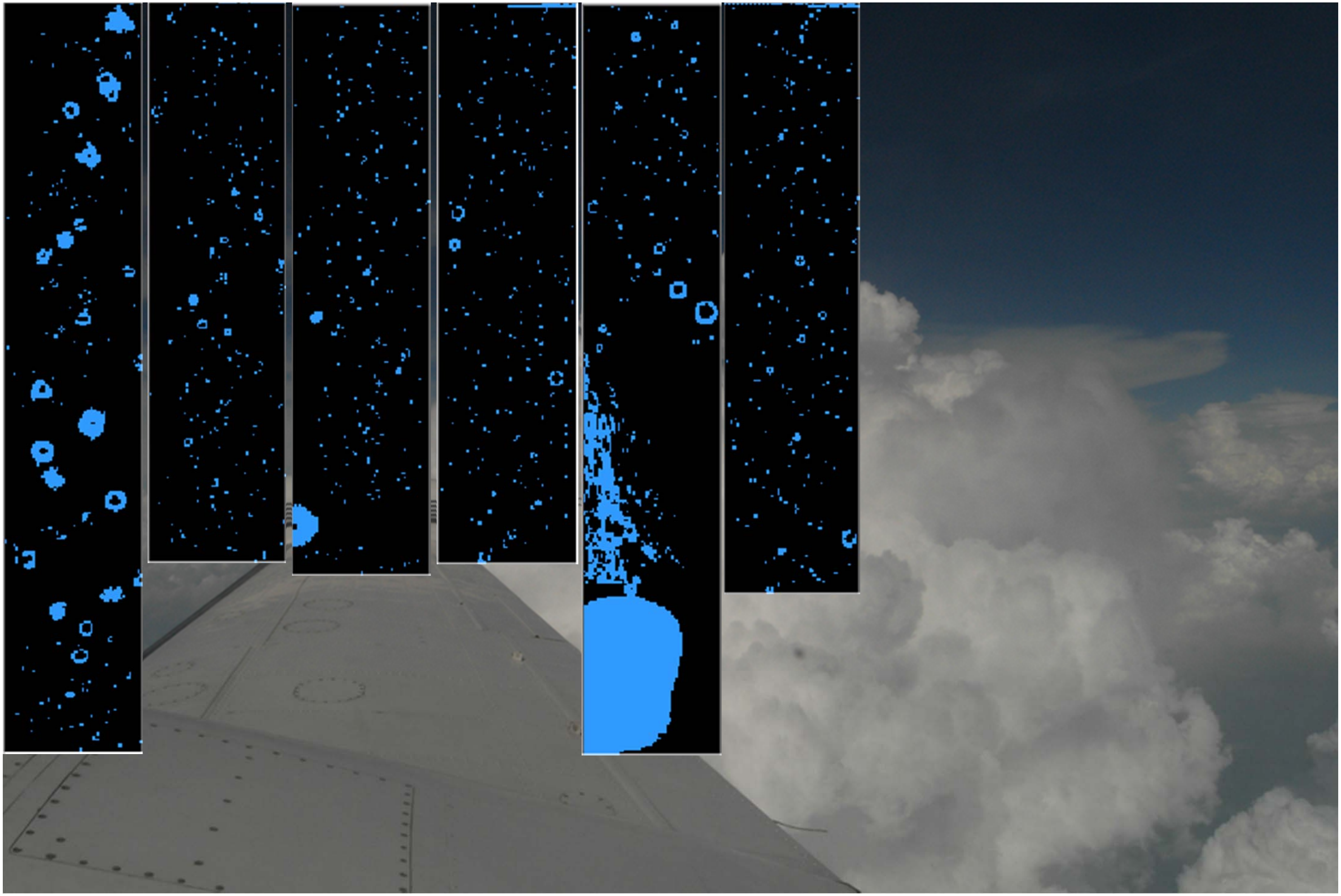
2009 08 24, 10:19 UT, 6500 m, -8.3ºC. N of Bareilly.
Cloud top precipitating. Haze.



2009 08 24, 10:14 UT, 6720 m, -8.1ºC. Max HWLWC=1.66 gm^{-3}. N of Bareilly.
The cloud has supercooled rain drops.



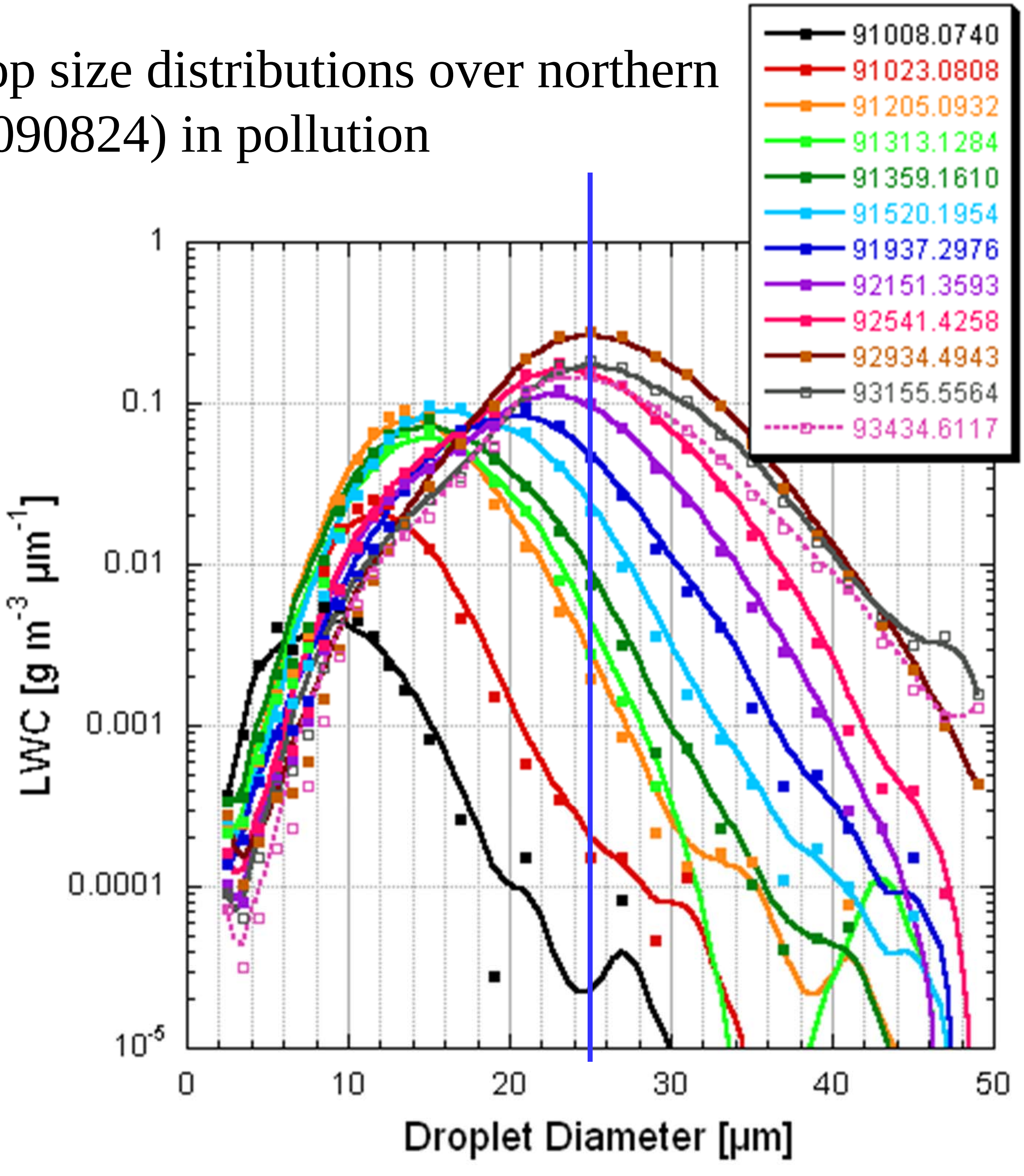
2009 08 24, 10:03 UT, 7350 m, -11.8ºC. Max HWLWC=0.87 gm^{-3}. N of Bareilly.
The cloud has small raindrops and larger freezing rain drops.



2009 08 24, 10:00 UT, 7700 m, -14.7ºC. Max HWLWC=1.45 gm^{-3}. N of Bareilly.
The cloud has small rain drops, large freezing rain drops and small graupel.

2009 08 24, 9:57 UT, 8130 m, -17.1ºC. Max HWLWC=0.49 gm^{-3}. N of Bareilly.
The cloud is glaciating, with frozen rain drops, small graupel and ice crystals.

Cloud drop size distributions over northern India (20090824) in pollution

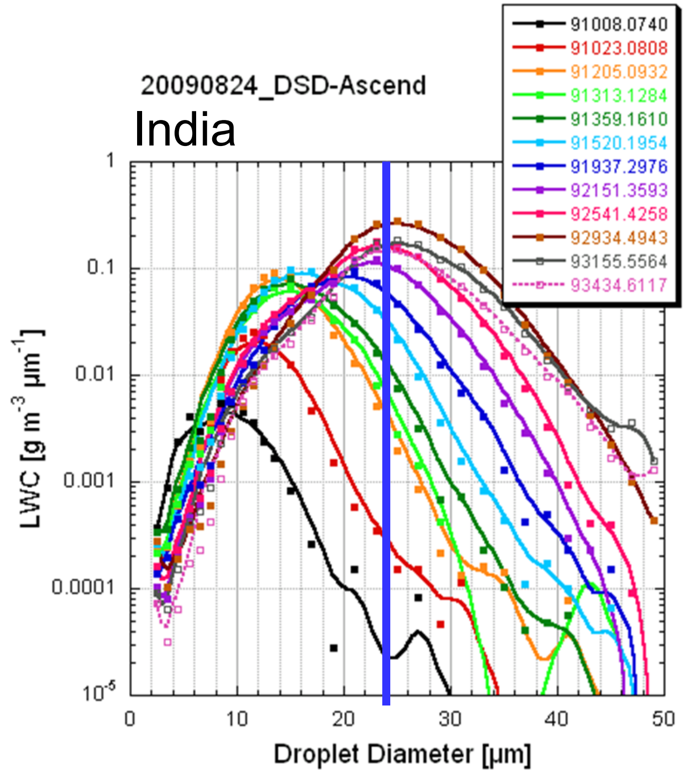


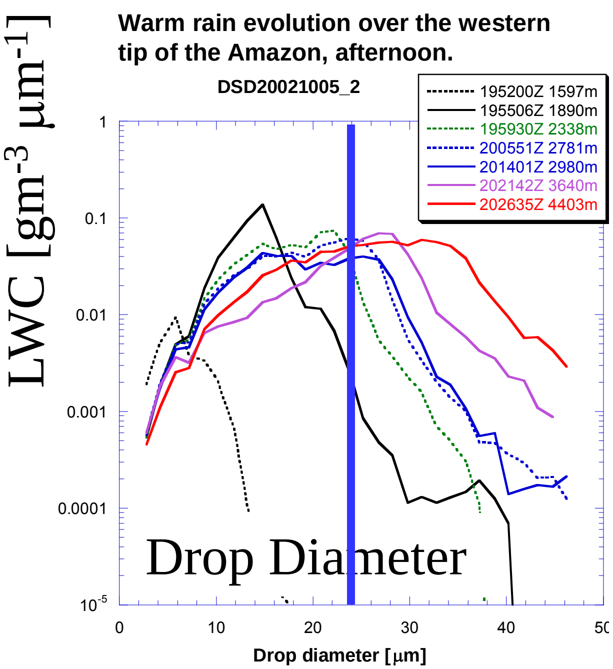

RESEARCH ARTICLE SCIENCE VOL

Smoking Rain Cl[...] the Amaz[...]

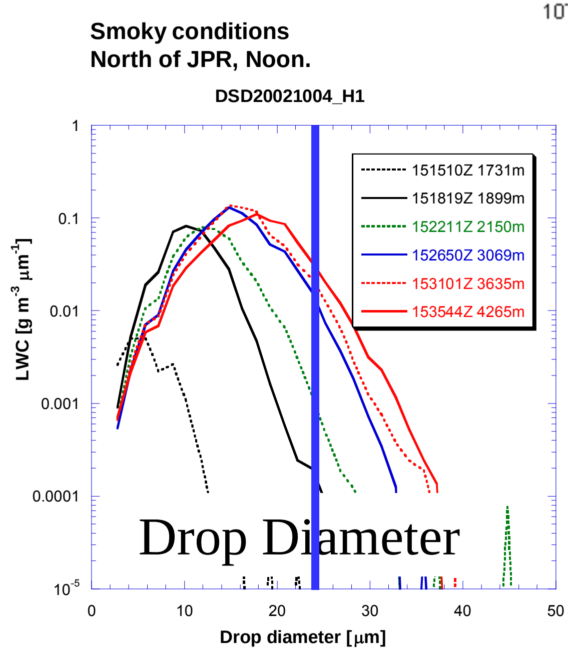
M. O. Andreae,[1]* D. Rosenfeld,[2]* P.
G. P. Frank,[1] K. M. Longo,[5] M.

Heavy smoke from forest fires in the Amazon
droplet size and so delay the onset of precipitat

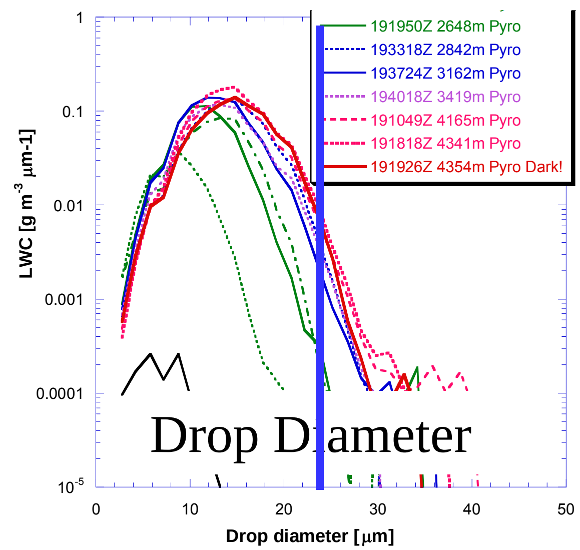




Pristine

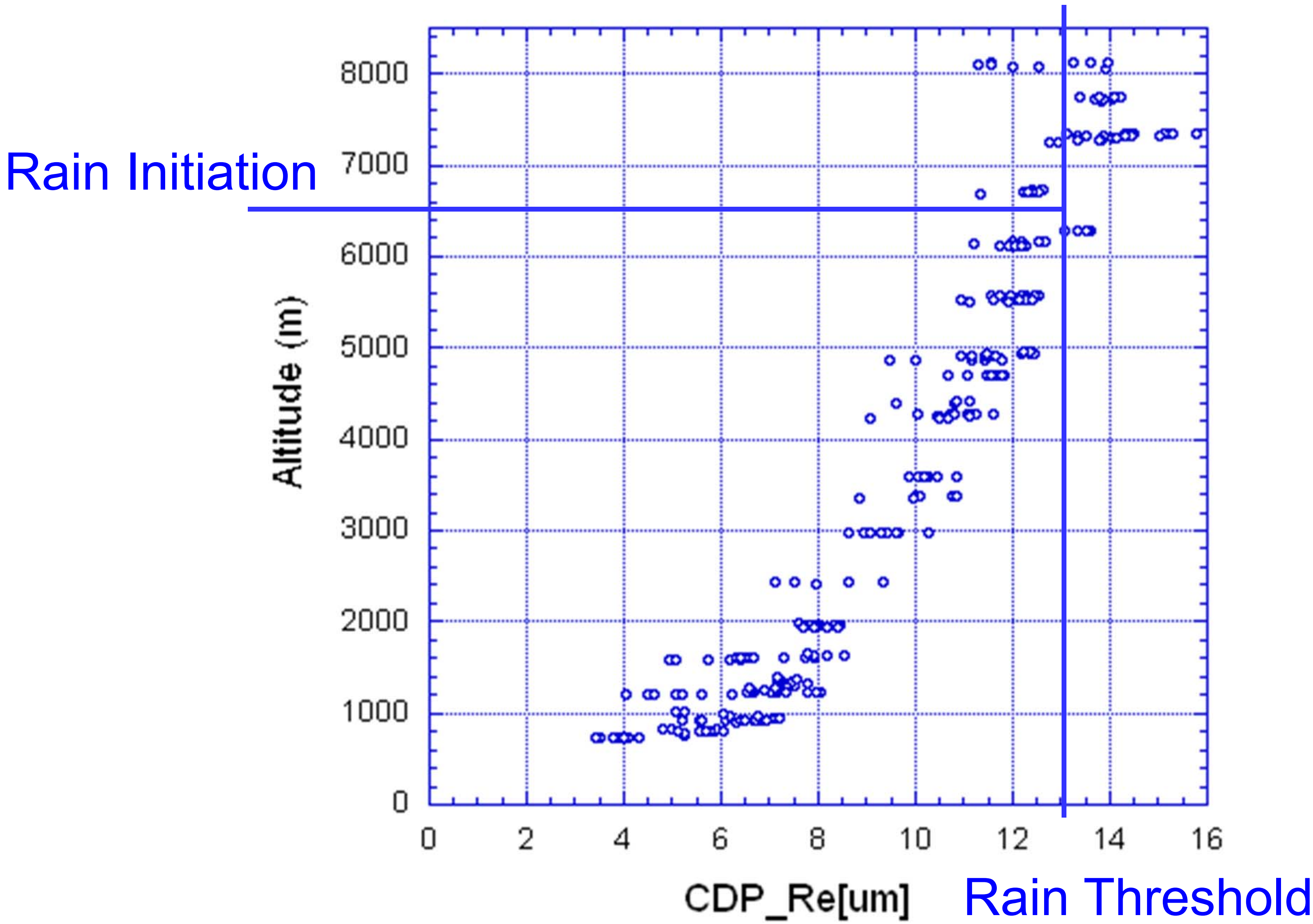


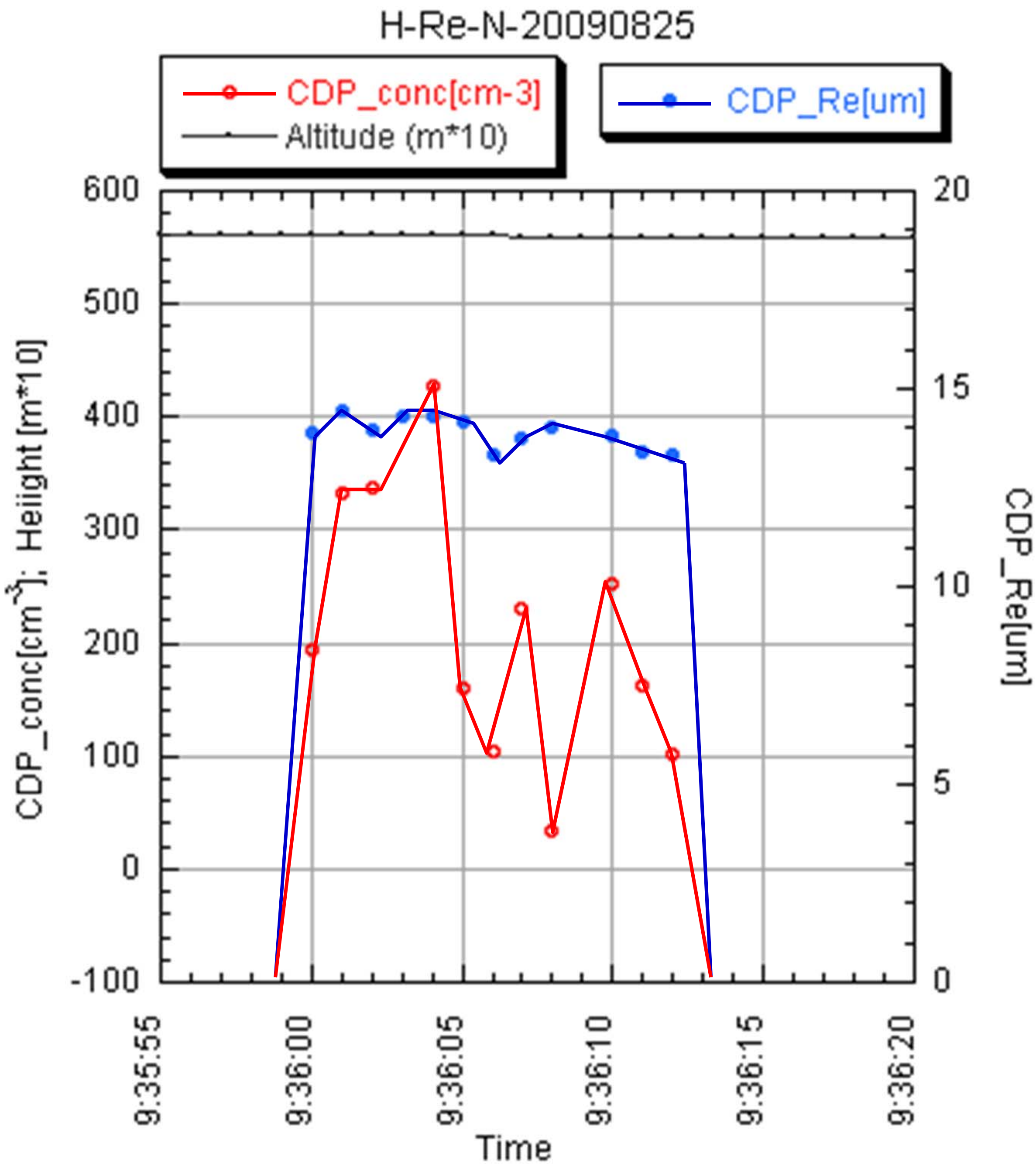
Smoky



Pyro

Vertical development of cloud drop effective radius in highly polluted conditions in extremely moist conditions over the flooded Indo-Gangetic plains on 24 August 2009. Rain starts at height of 6.5 km

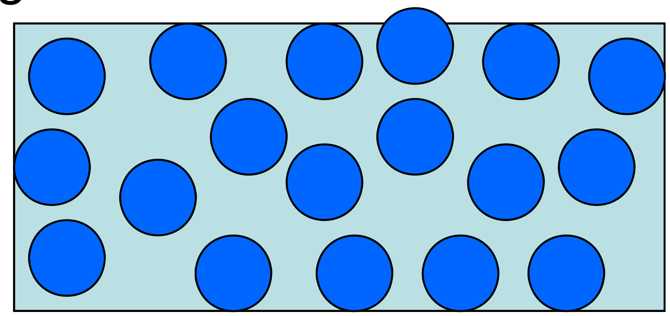




H-Re-N-20090825
CDP_conc[cm-3]
Altitude (m*10)
CDP_Re[um]
CDP_conc[cm-3]; Heiight [m*10]
CDP_Re[um]
600
500
400
300
200
100
0
-100
20
15
10
5
0
9:35:55
9:36:00
9:36:05
9:36:10
9:36:15
9:36:20
Time

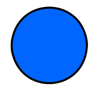
Extreme _homogeneous mixing

1. Original unmixed cloud



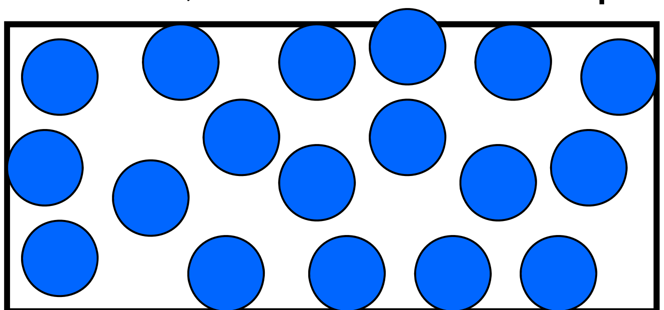
Saturated cloudy air parcel

Sub-saturated mix of cloud with entrained air

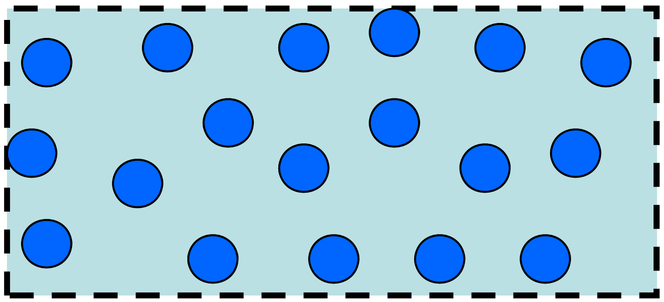


Cloud drop

2. The cloud mixes homogeneously with dry air and becomes sub saturated, before cloud drops had time to evaporate.

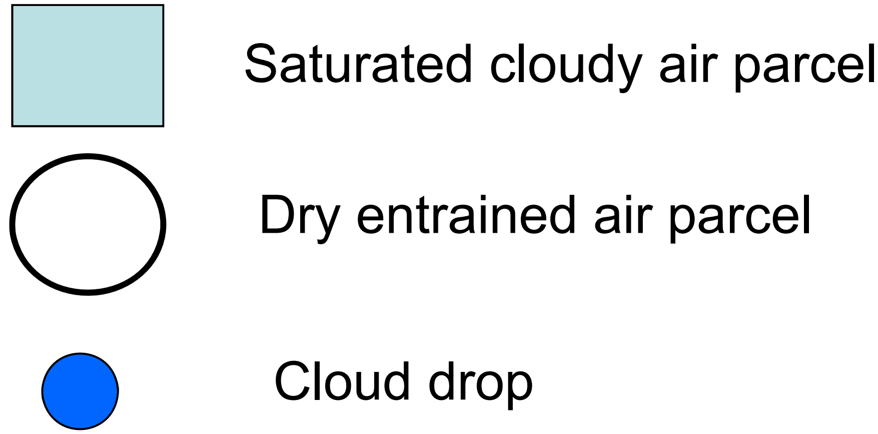


3. The cloud drops evaporate partially and reduce their size until the cloudy air saturates again.

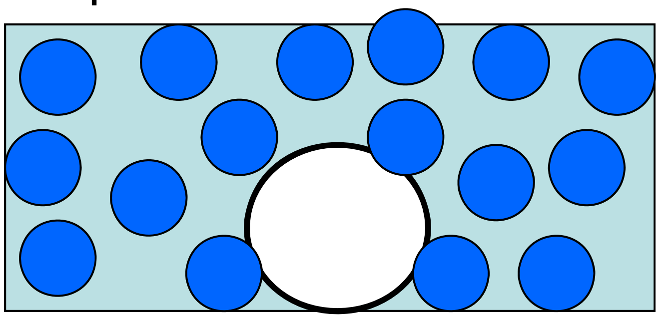


Results:
Drop concentration slightly decreased
Droplet size decreased

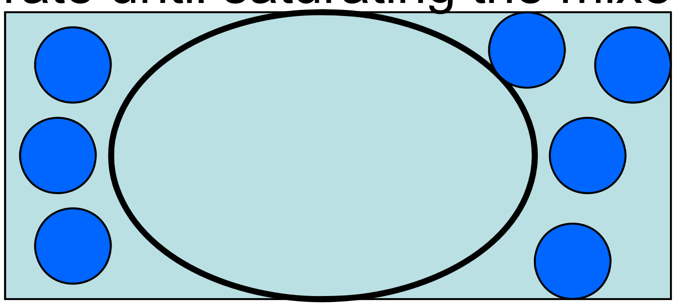
Extreme inhomogeneous mixing



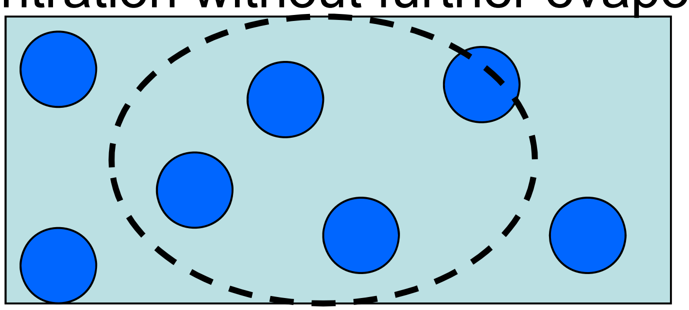
1. Dry air penetrates



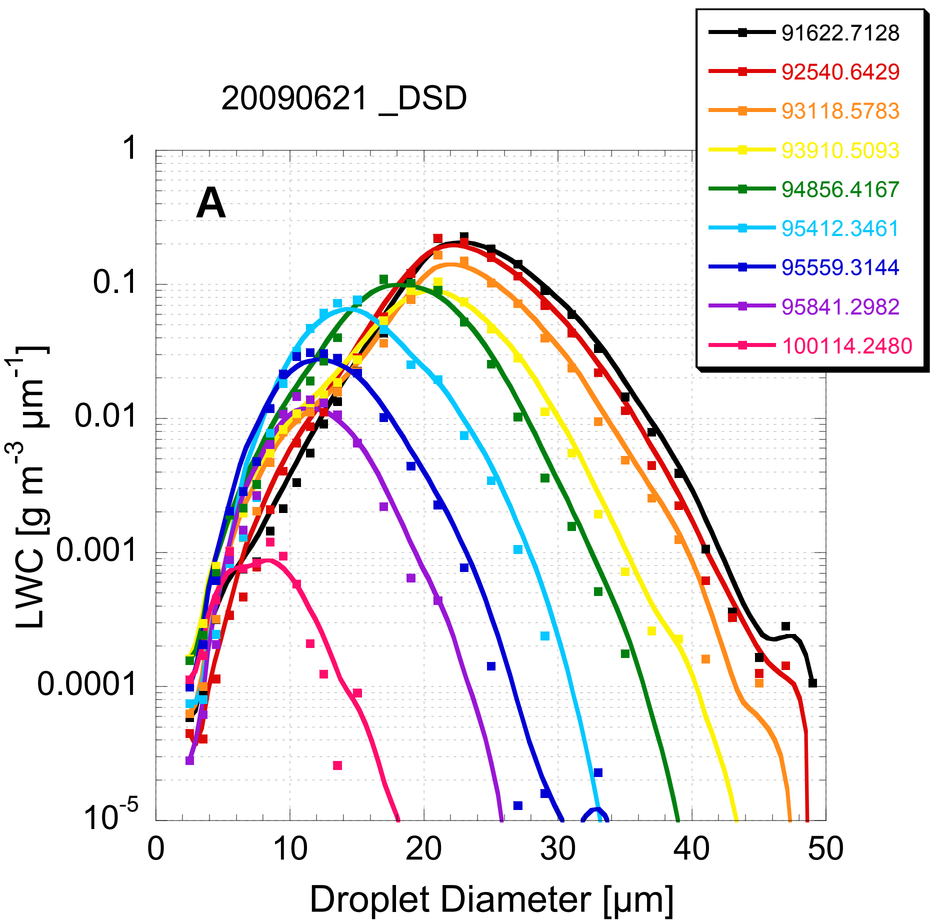
2. Drops at the border of the dry parcel completely evaporate until saturating the mixed parcel.

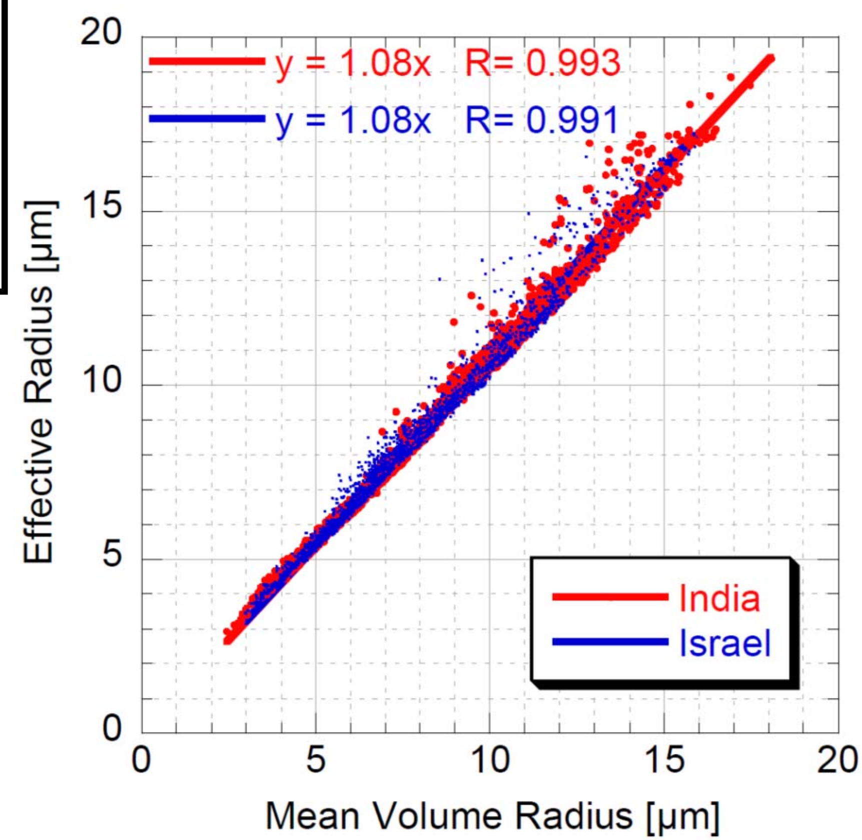


3. The saturated parcel mixes and dilutes the drop concentration without further evaporating them.



Results:
Drop concentration decreased
Drop size conserved

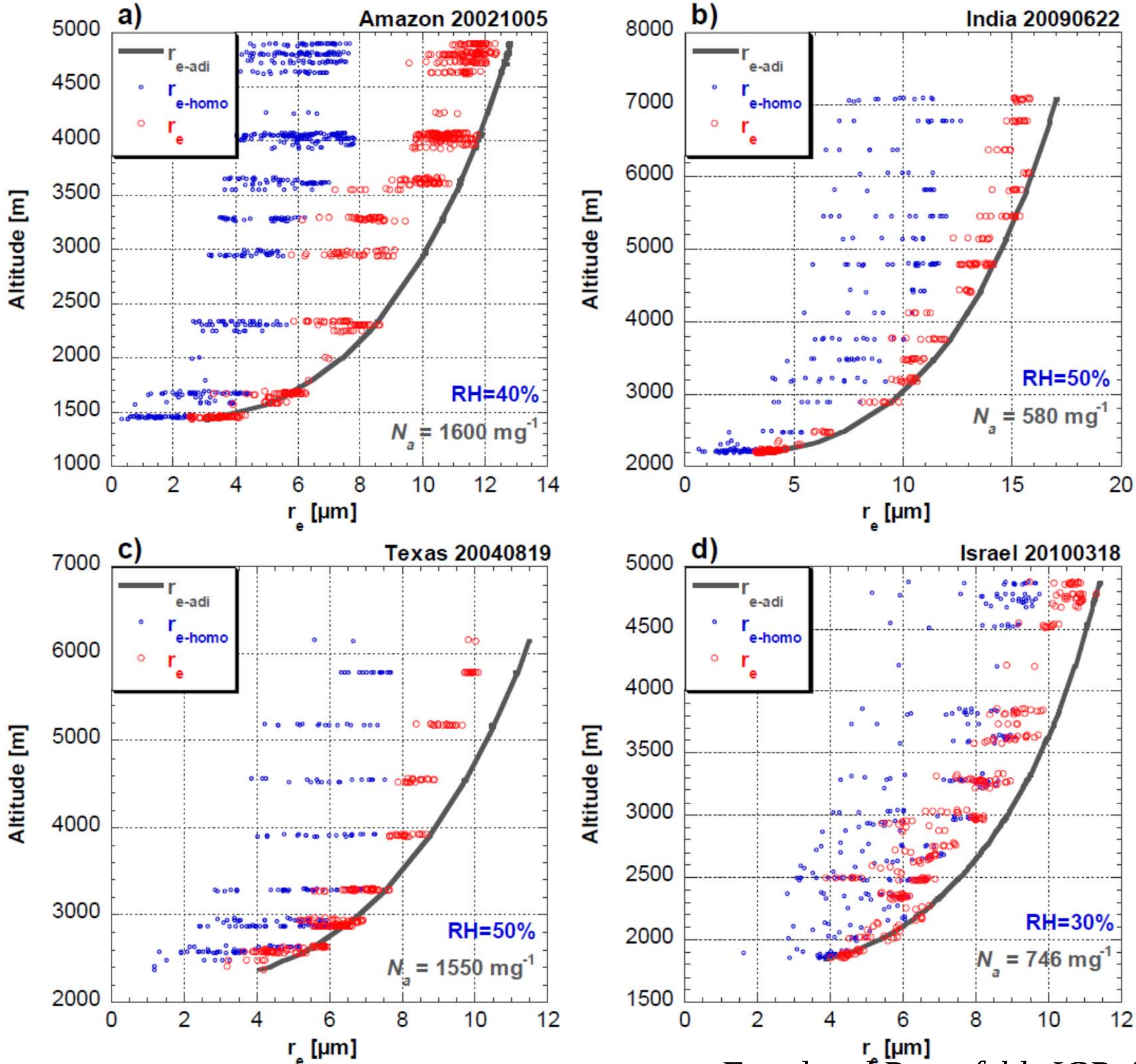




$$r_e = 1.08\ r_v$$

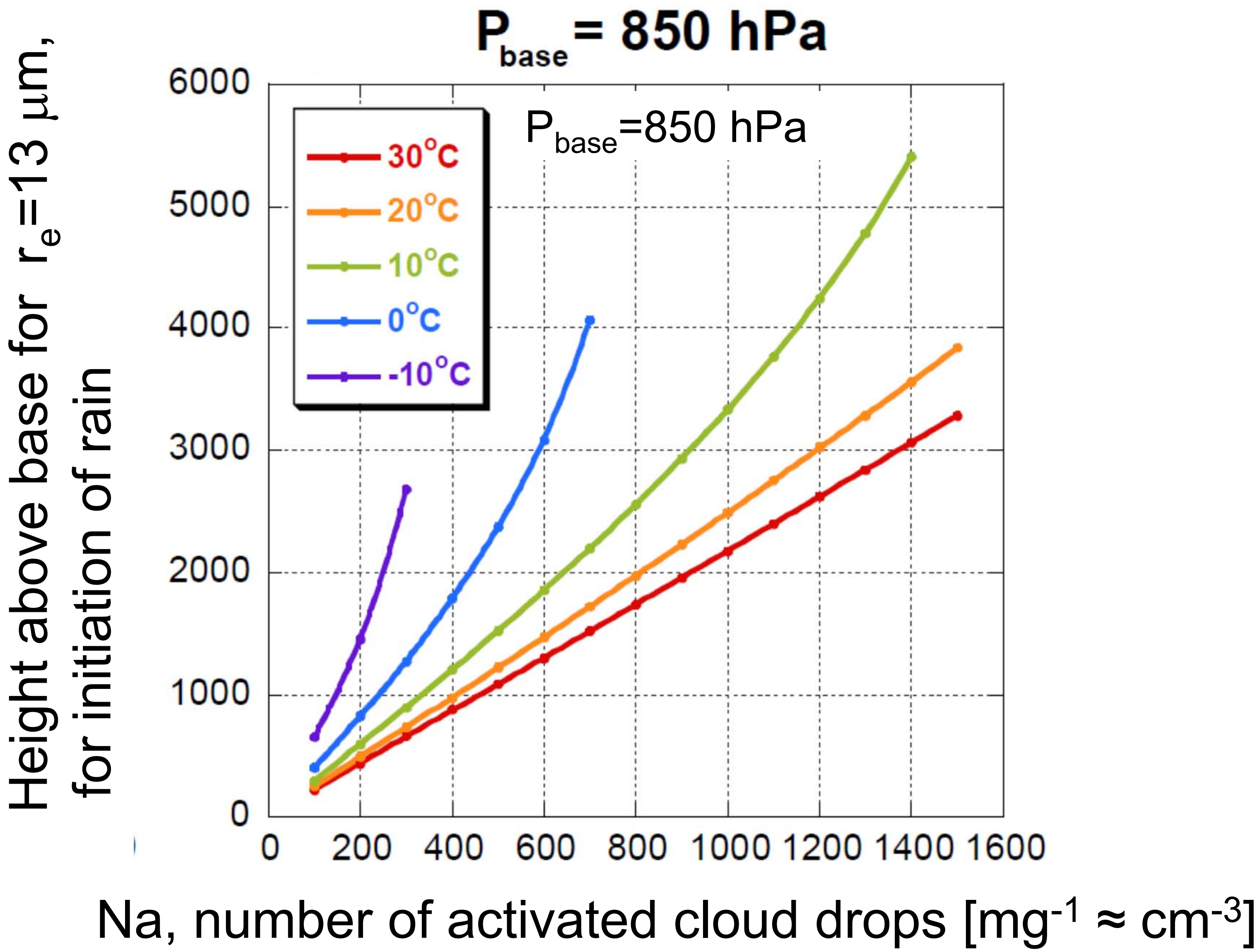
The similar shapes of convective DSDs causes a fixed relation between r_v and r_e.

Freud et al. ACPD 2011



Freud and Rosenfeld, JGR, in review

Converting Na to CCN requires measuring cloud base updraft. This is a major challenge!



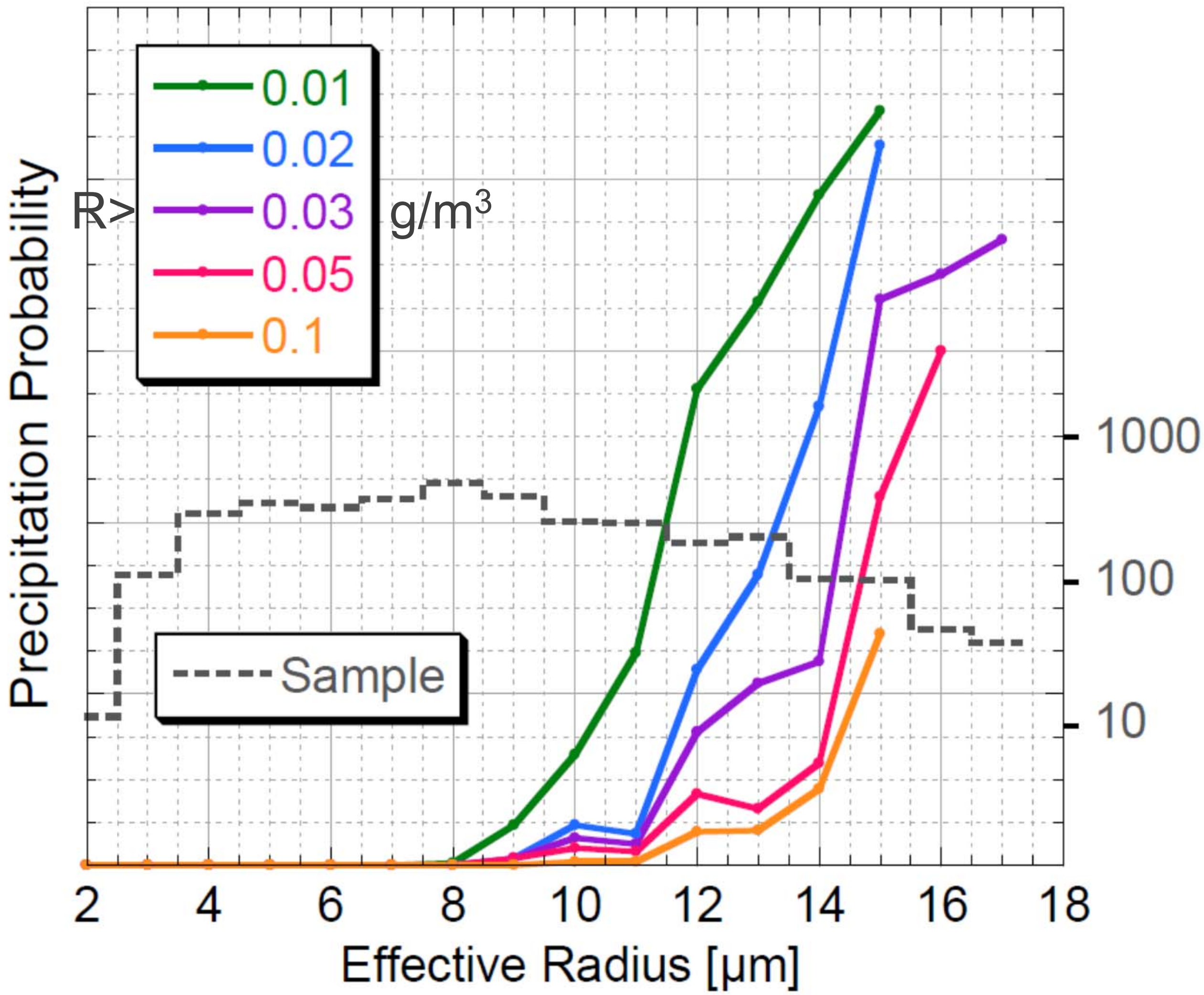
How sensitive is the threshold value?

Rain initiates at 10-12 μm, but accelerates strongly above 14 μm.

$$r_{e_c} \approx 14\mu m$$

R is rain water content in drops with diameters of 0.1-0.25 mm, as measured by the Cloud Imaging Probe (CIP).

R> 0.01 – 0.1 g/m^3 raises the precipitation flag.



Freud and Rosenfeld, submitted.

Questions to be addressed

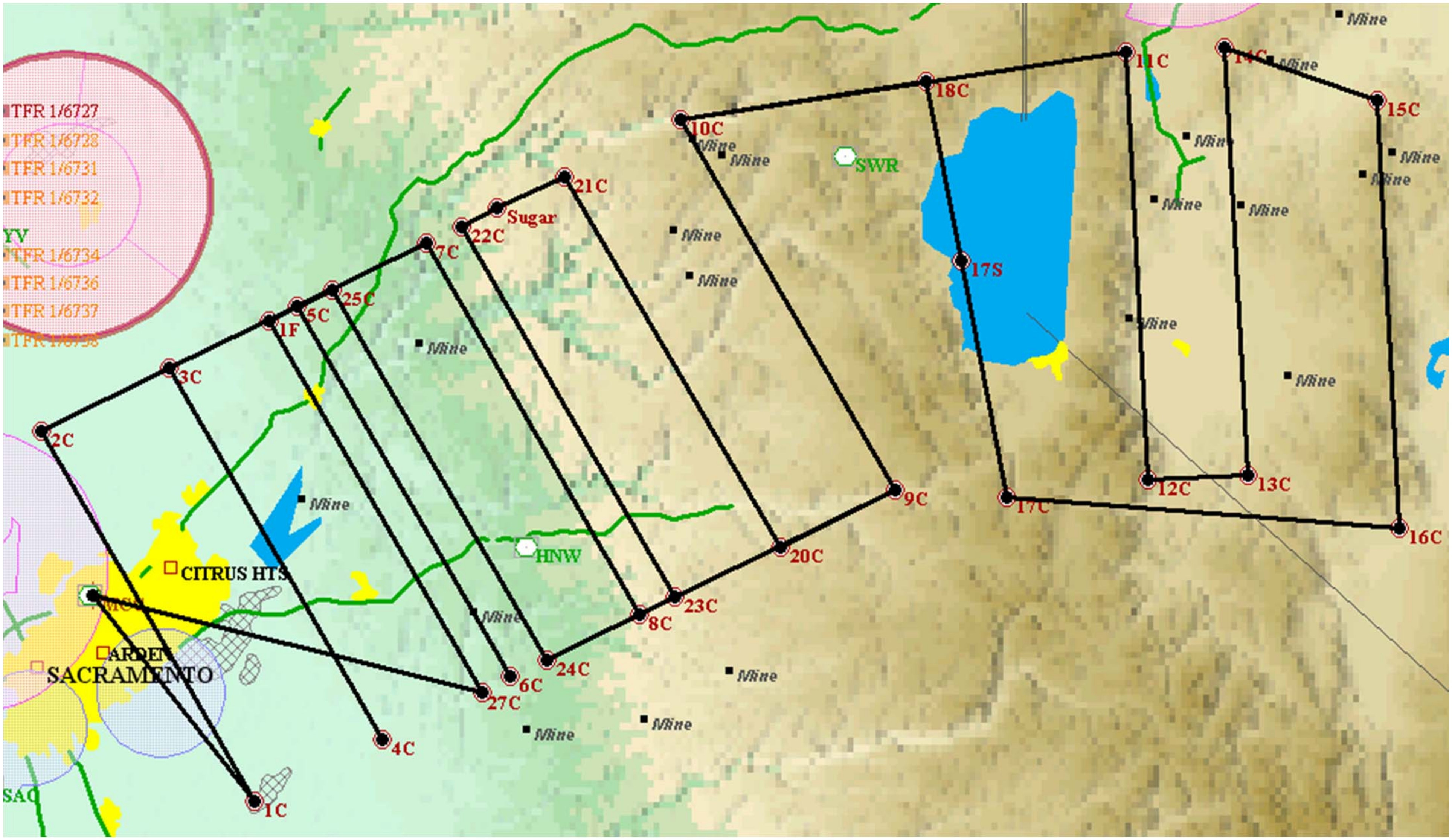
- Vertical profiles of r_e, initiation of precipitation and hydrometeor types in different aerosols.
- Partitioning of convective/stratiform rain and its dependence on the aerosols and D-r_e relations.
- Explain relations between Na and CCN by aerosol size dependent composition and cloud base updrafts. Na can be obtained by D-r_e.
- How high should we climb in smoky clouds for start precipitation?
- How is the precipitation initiated in the heavily smoky clouds? Supercooled rain as in India, or mixed phase?

G1 instrumentation at CALWATER

Platform Pos/Vel/Attitude		
Trimble DSM	position/velocity @ ~10Hz	PNNL
Trimble TANS 10Hz	pitch/roll/azimuth	PNNL
C-MIGITS	inertial GPS	PNNL
Atmospheric State		
Rosemount 102 probe	temperature	PNNL
Rosemount 1201F1	static pressure	PNNL
Rosemount 1221F2 (3x)	differential pressure (dynamic, alpha, beta)	PNNL
GE-1011B chilled-mirror hygrometer	dew-point temperature	PNNL
AIMMS-20	wind and turbulence	PNNL
Liquid and Total Water Content		
Gerber PVM-100	liquid water content	PNNL/CIRPAS
CAPS-hotwire	liquid water content	PNNL/CIRPAS
DMT Cloud Spectrometer and Impactor (CSI)	total water content	PNNL
SEA total water WCM-2000	liquid water concent, total water content	PNNL/CIRPAS
Cloud Microphysics		
HVPS-3	cloud droplets size distribution (400-50,000 μm)	PNNL
2DS	cloud droplets size distribution (10 3,000 – μm)	PNNL
CIP (part of CAPS)	cloud droplet size distribution (25-1500 μm)	PNNL/CIRPAS
CDP (part of CSI)	large aerosol and cloud droplets (2-50 μm)	PNNL/CIRPAS
CAS (part of CAPS)	large aerosol and cloud droplets (0.5-50 μm)	PNNL/CIRPAS

Aerosol		
UCPC TSI 3025	total particle concentration (> 3 nm)	PNNL
CPC TSI 3010	total particle concentration (> 10 nm)	PNNL
PCASP	aerosol size distribution (100-3000 nm)	PNNL/CIRPAS
UHSAS-A	aerosol size distribution (55-1000 nm)	PNNL
DMT Cloud Condensation Nuclei (CCN) counter (dual SS(	CCN concentration	PNNL/CIRPAS
ATOF-MS	single-particle mass spectrometer	UCSD-Prather
Radiance Particle/Soot Absorption Photometer (PSAP)	aerosol absorption	PNNL
Nephelometer (TSI 3563)	aerosol scattering	PNNL
CFDC	ice nuclei concentration	CSU-DeMott
Aerosol Sample Collection		
isokinetic inlet	sample stream of dry aerosol, sizes < 2.5um	PNNL
pumps for aerosol flow	maintains flow through aerosol inlet and internal plumbing.	PNNL
Counter-flow Virtual Impactor (CVI)	sample stream of cloud-droplet residuals	PNNL
Gases		
Thermo Electron 48C	Carbon Monoxide	PNNL
Thermo Electron 49	Ozone	PNNL

Other		
Weather radar	cockpit display of precipitation returns	PNNL
SEA Data System	Central Data System	PNNL
Iridium Satellite Modem	Limited data link to ground station	PNNL
Radar Altimeter	Altitude above surface	PNNL
TCAS	Traffic Collision and Avoidance System	PNNL
TAWS	Terrain Awareness and Warning System	PNNL
nose video camera	forward video images out wind screen	PNNL



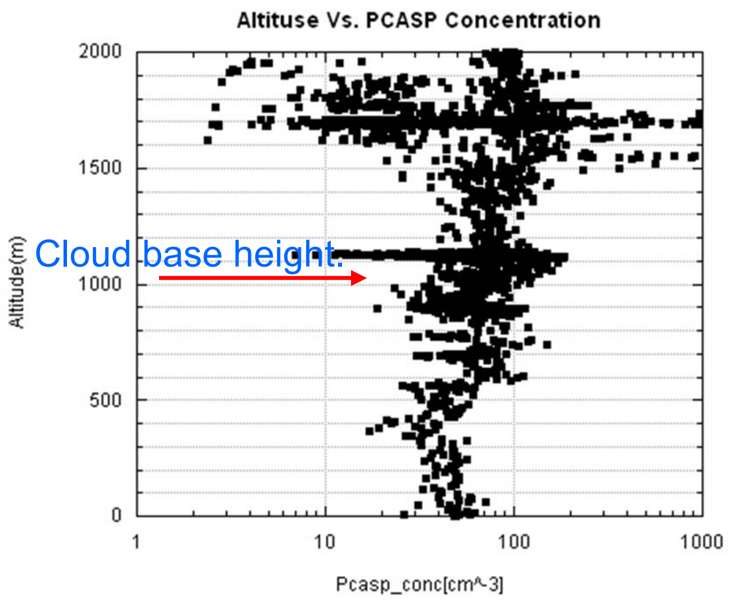
16 February – 0900L/1700Z Takeoff: 4:10 enroute

We can see from the PCASP that the aerosol concentration has changed from the morning.

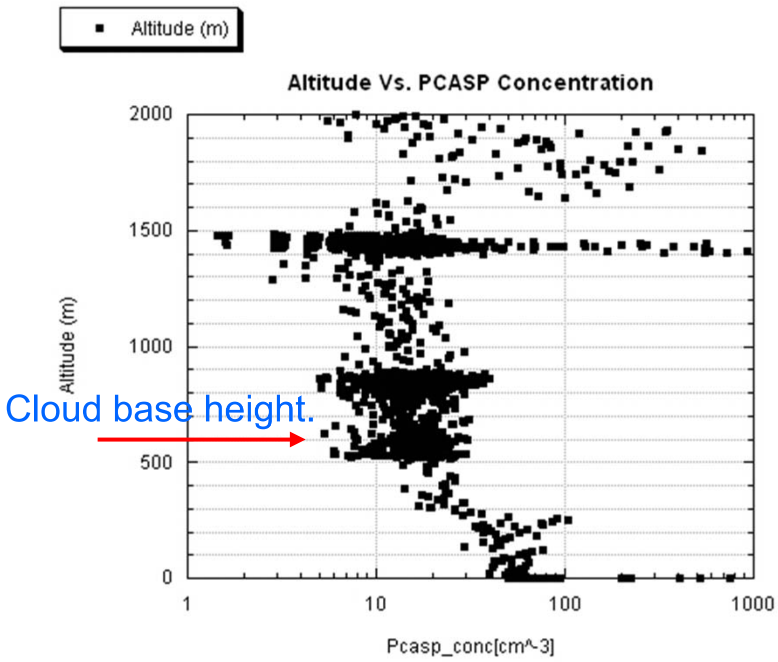
Now, since the morning the aerosol inversion vanished and the air from the boundary layer is not decoupled any more from the air at clouds base.

We can see high concentration at the ground and at the cloud base ,around 1000 meters, of 100 cm^{-3}.

In slide 17 we saw that the aerosols chemistry ,of the air mass at these heights, is the same as the aerosols chemistry at the boundary layer.



PCASP Concentration from 11 LT



PCASP Concentration from 9 LT

Another parameter that shows us the change in the cloud droplets, is the CDP concentration.

We clearly see the change of the values between 09:00 and 11:00.

In the morning the values reach 70 cm^{-3} maximum, but it more than doubles at noon.

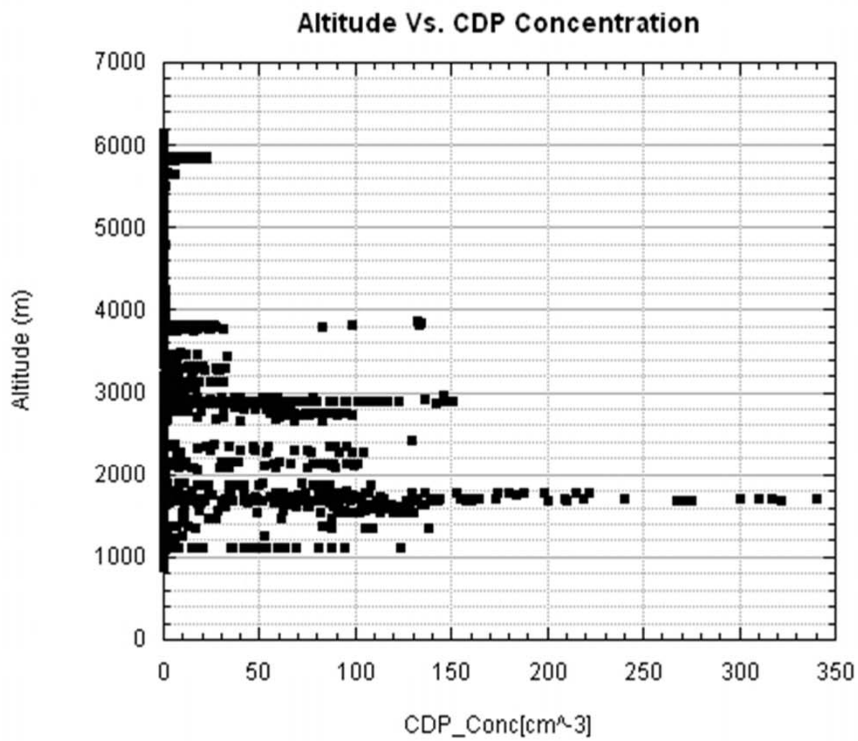
That is why these clouds could have warm rain at lower heights and almost no graupel at all.

Unlike around noon when we saw that these clouds tend to have more graupel and warm rain only in greater heights.

This could also explain the narrowness in the LWC-CDP graphs at slide 12. Higher CDP concentration leads to smaller cloud droplets.

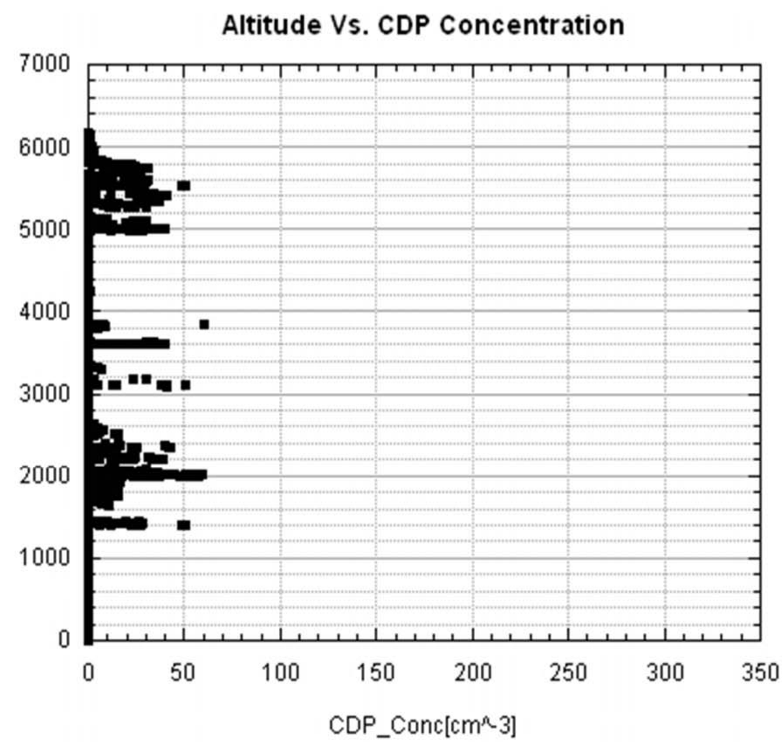
CDP Concentration around noon

11 LT



CDP Concentration in the morning

9 LT

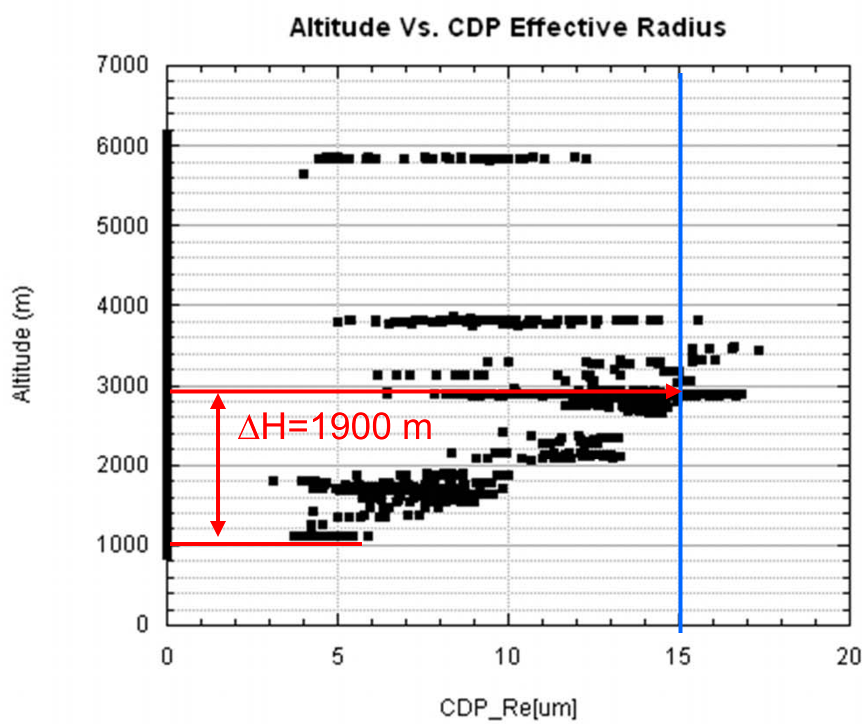


This means that also the CDP effective radius should changed from the morning until noon.

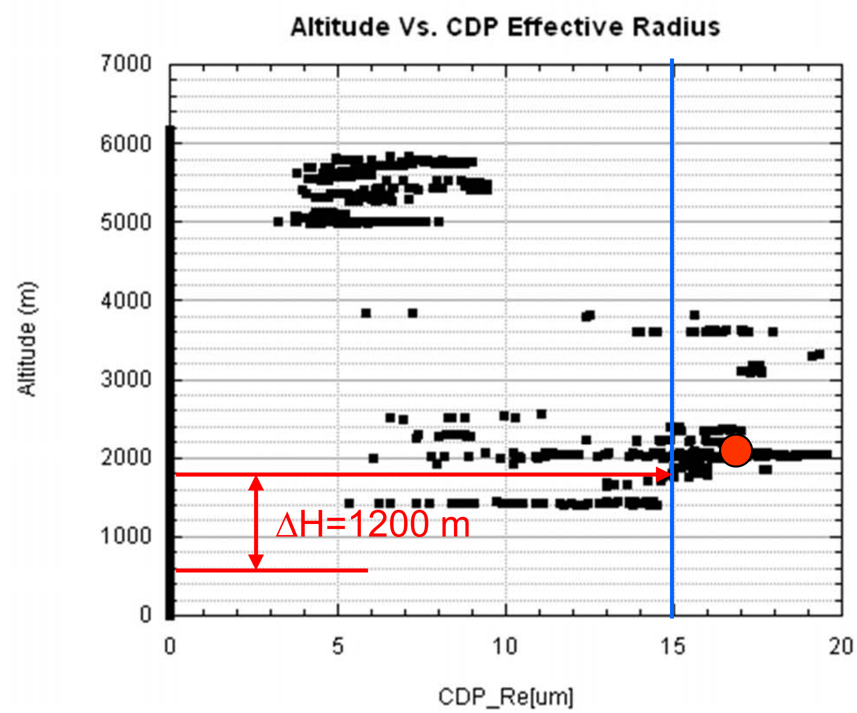
We can see how in the morning ,when the boundary layer was decoupled, We reach Re of 15 micron at 1800 meters.

As the more continental air reach up to the cloud base, we achieve Re of 15 micron only at 3000 meters!

We can see how the slope of the Re Vs. height became less steep as the chemistry of the aerosols changed from the morning decoupled until noon when it became coupled with the boundary layer.



CDP Effective Radius from 11 LT



CDP Effective Radius from 9 LT

At 17:41:04 we can see on the nose camera rain drops.

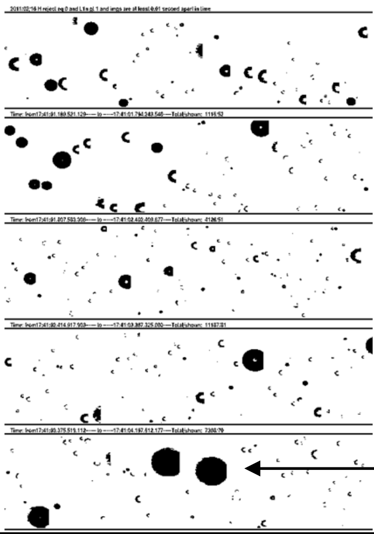
We confirm these drops with 2D-S pictures and its LWC graph.

At this time the plain is at 2050 meters and -12.3 Cº! These are supercooled rain drops!

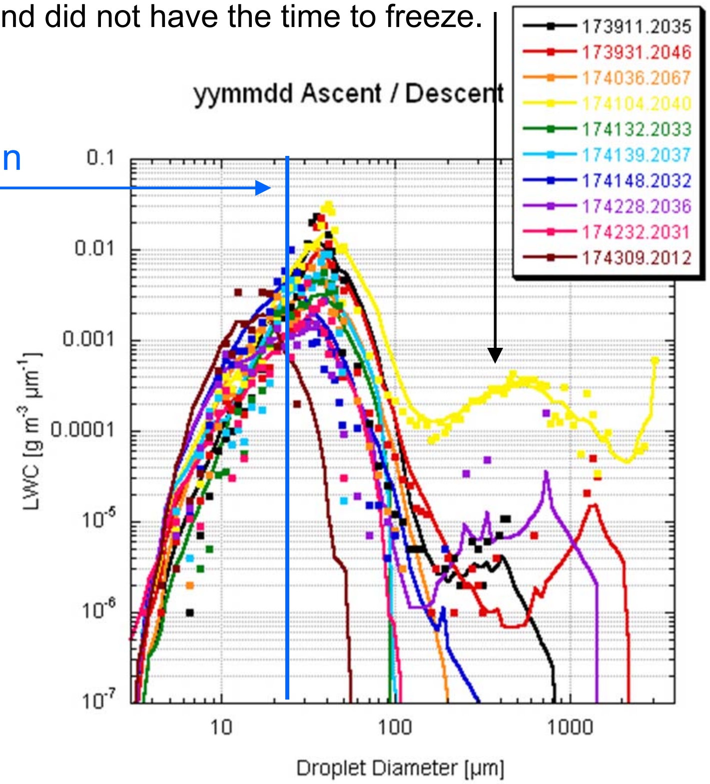
In order to achieve warm rain at this temperature we must have large effective radius of the cloud drops.

The drops will grew up ,rapidly enough, to rain drops by collisions, and did not have the time to freeze.

2D-S image at 17:41:01, 2036 m, -12.3°C



Modal LWC diameter rain threshold of 25 µm

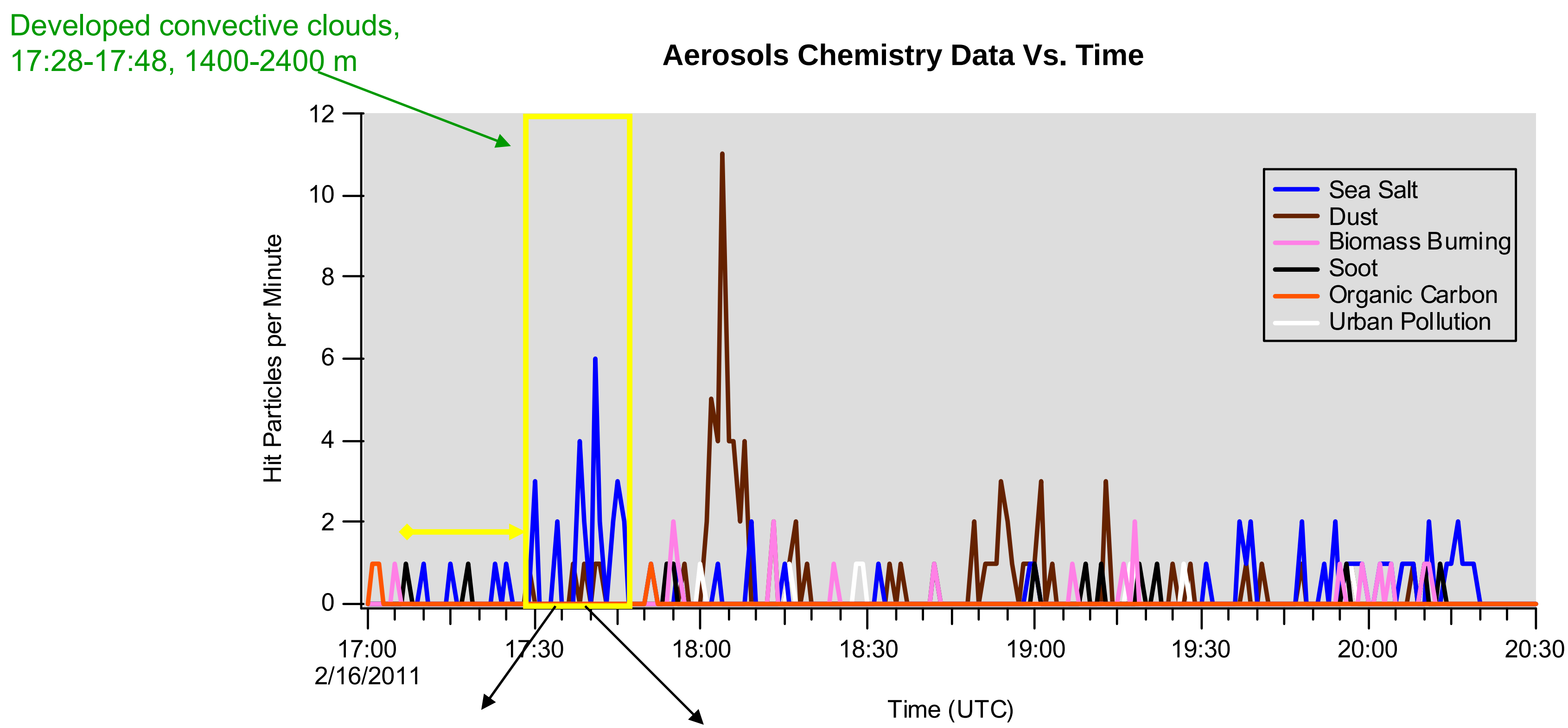


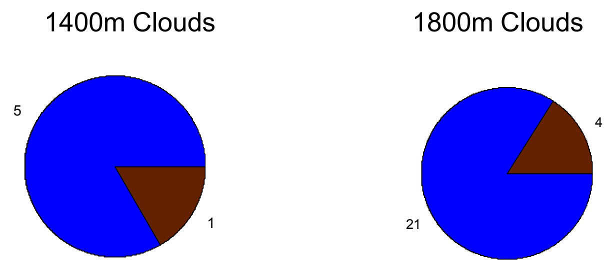
Large (>1 mm) supercooled rain drops

Nose camera at 17:41:21, 2036 m, -12.3°C.

The supercooled rain washed away the ice sheet from the wind shield

We can see from the aerosols chemistry data below ,at these times 17:30-17:48 the air contains not only the sea salts that form the convective clouds, but also some dust from long range transport aloft. This agrees with the highly maritime microstructure of the clouds.





*The number labels on the pie charts are the number of particles per type.

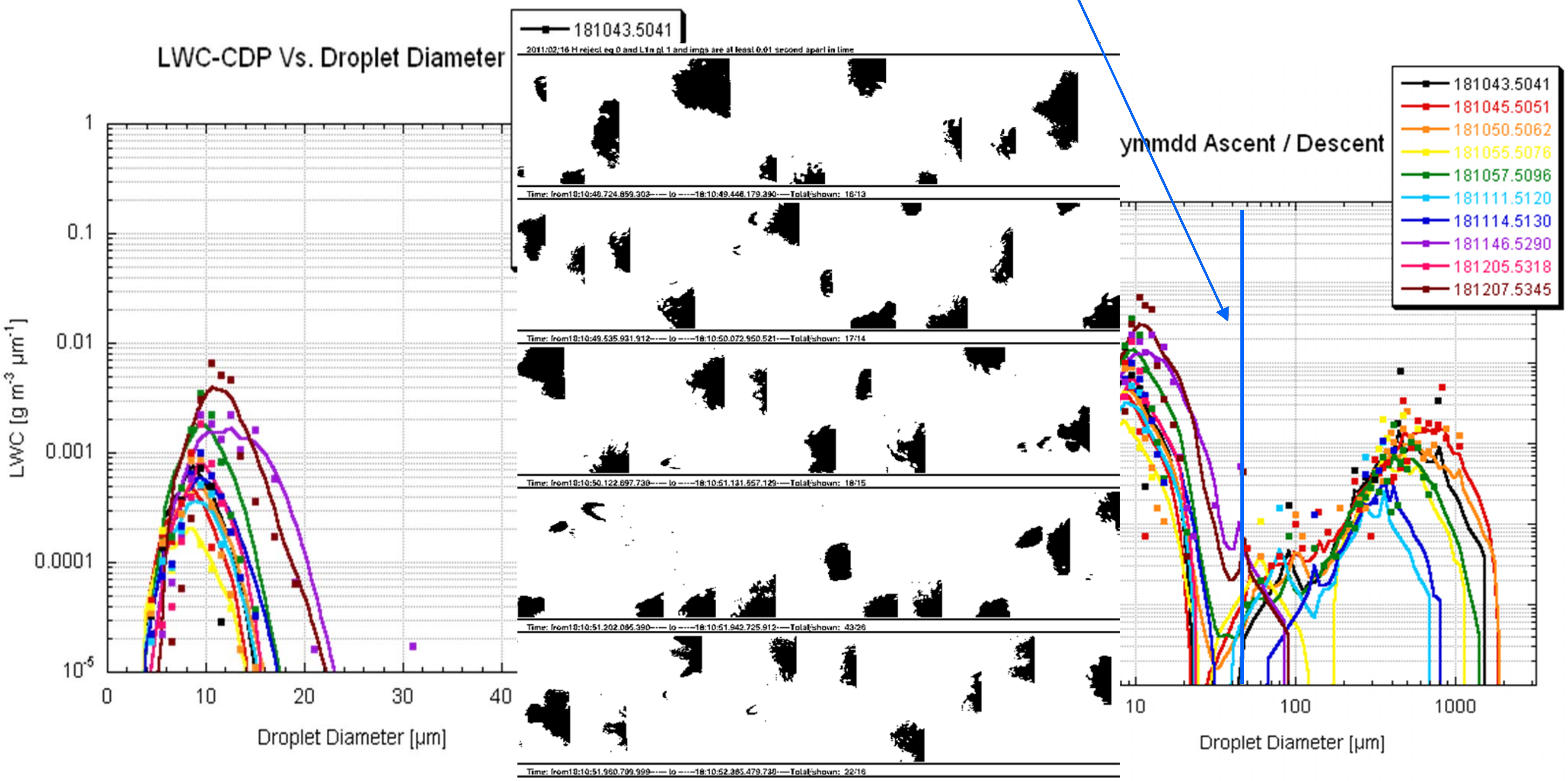
At 18:00 we are entering the high stratiform clouds with temperature of -21.8 Cº at 3800 meters. As we climb through these clouds the CDP spectra become more narrow with mode around 10 micron and we can see from the 2D-S and the nose camera that we have only ice precipitation, mostly graupel.

The CDP spectra become narrow and with small mode because:

- The depth of the clouds above their base is small. These stratiform clouds are not deep enough in order to develop large cloud droplets.

We can see the lack of the continuity between the CDP and the 2D-S spectra around 50 micron, that shows us that there is ice precipitations that fall from above, unlike the CDP-2DS graphs of the convective clouds with warm rain.

2D-S image, 18:10:48 5055 m, -21.8°C

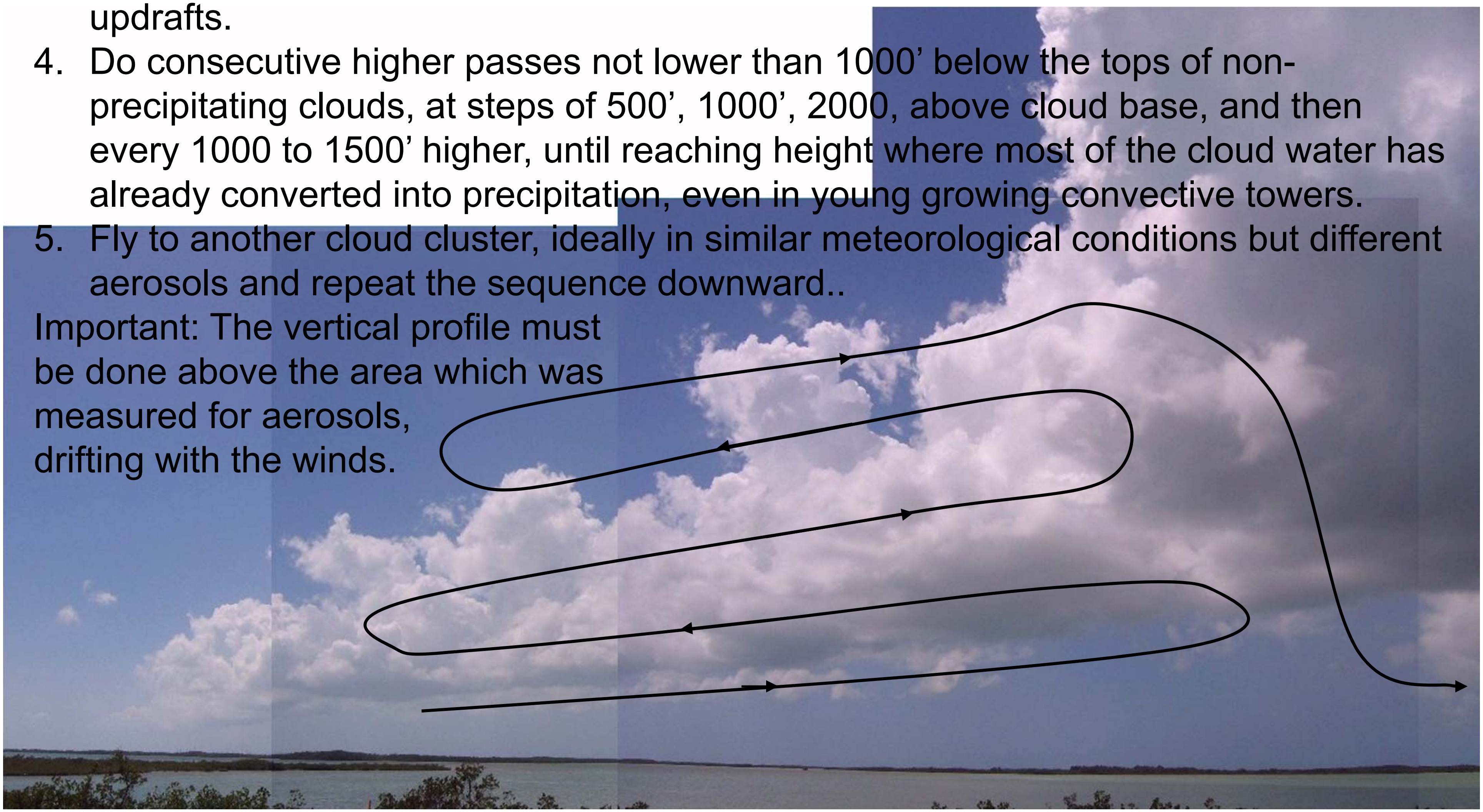



04 10 2002 18:39

The measurements of the aerosols and clouds convective clouds:

1. Select a segment with new growth of convective clouds with tops at varying heights, that are not under higher precipitating clouds.
2. Measure the aerosols and CCN spectrum below the cloud bases, but not in rain.
3. Measure non precipitating well defined lowest cloud base, such that the surface is barely visible, for at least 20 seconds cumulative time in cloud. Get the best updrafts.
4. Do consecutive higher passes not lower than 1000’ below the tops of non-precipitating clouds, at steps of 500’, 1000’, 2000, above cloud base, and then every 1000 to 1500’ higher, until reaching height where most of the cloud water has already converted into precipitation, even in young growing convective towers.
5. Fly to another cloud cluster, ideally in similar meteorological conditions but different aerosols and repeat the sequence downward..

Important: The vertical profile must be done above the area which was measured for aerosols, drifting with the winds.



Flight Patterns for Measuring Cloud-Aerosol Interactions

- These flights must be conducted visually, therefore only during daylight time.
- Preference should be given to events with high smoke, pollution or dust aerosols, because the majority of the situations are with relatively clean maritime air.
- Flights will be conducted at the upshear feeders of the storm clouds near their tops.
- Do not enter a cloud that you do not see where you go out of it.