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

Daniel Rosenfeld
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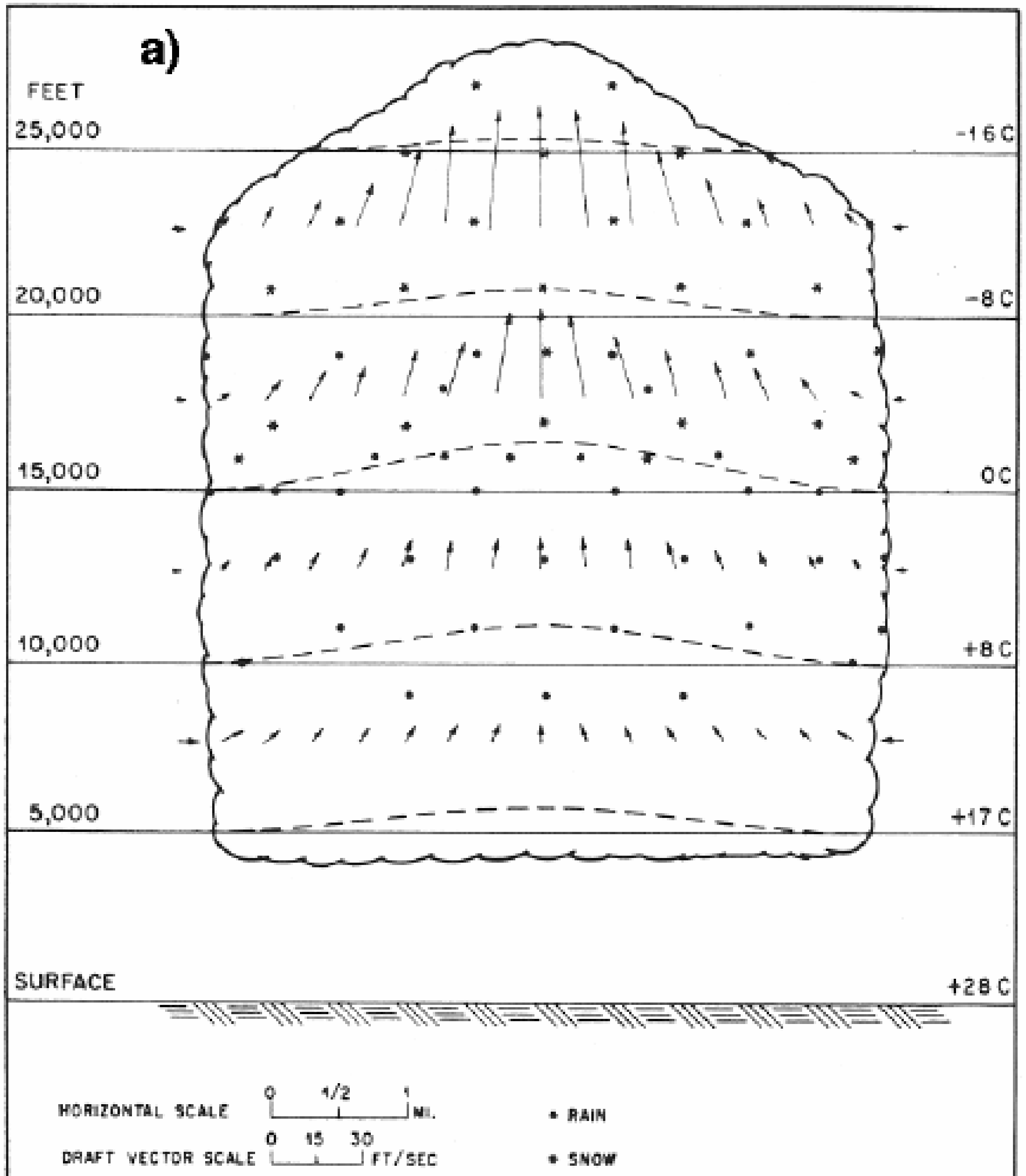
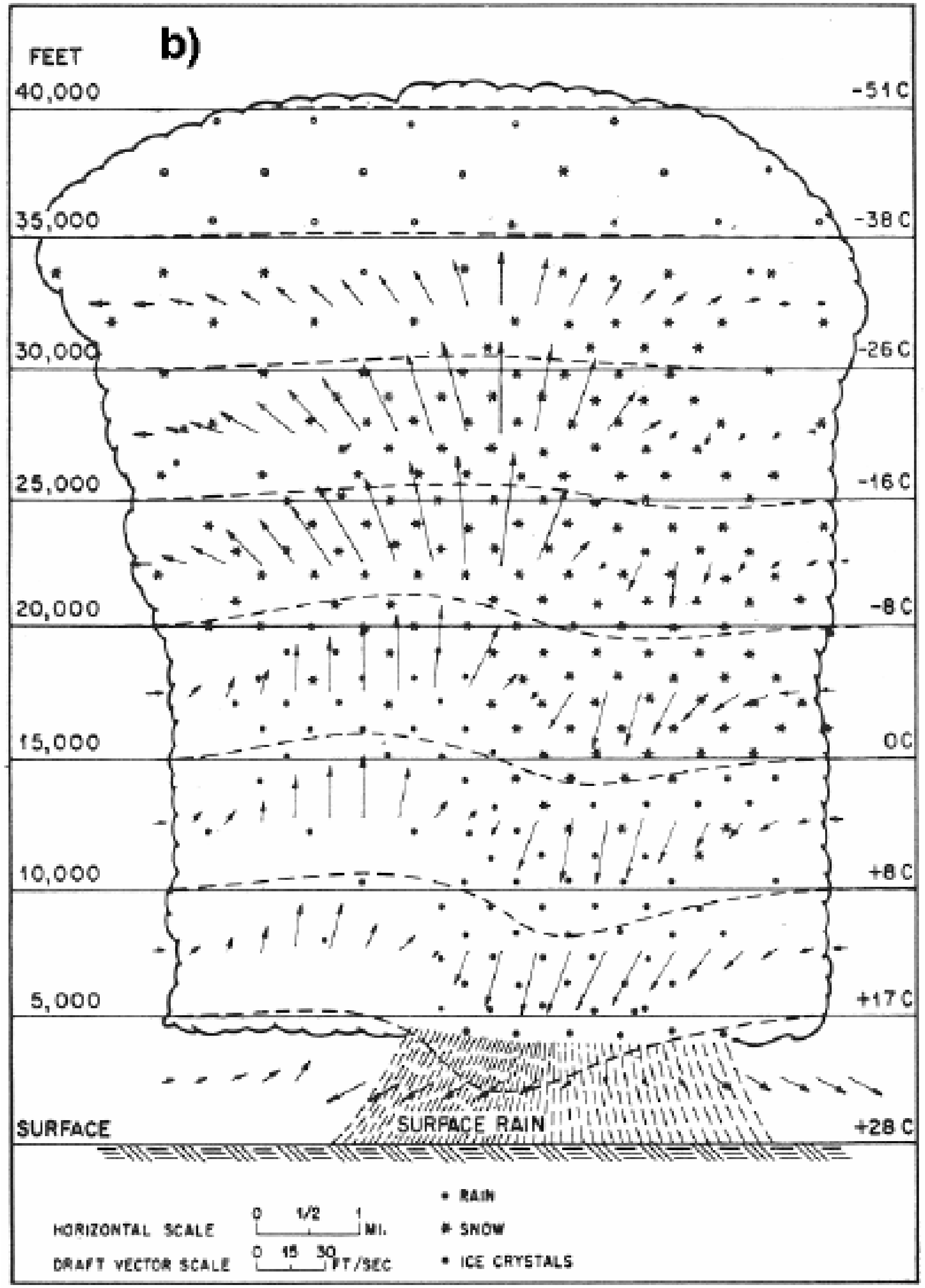
Thanks to Dr. Kulkarni et al.,
Indian Institute of Tropical Meteorology



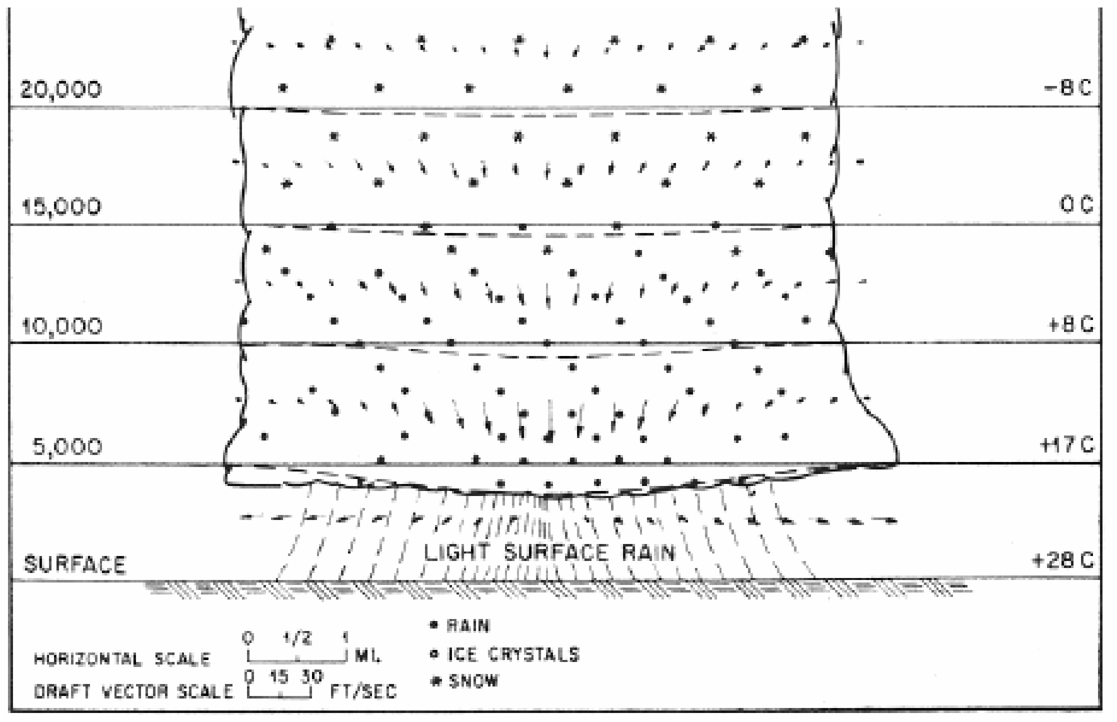
Schematic of a **growing** storm cell (From Byers and Braham. 1949)



Schematic of a **mature** storm cell (From Byers and Braham. 1949)

Slower (faster) formation of precipitation would respectively delay (advance) the formation of the downdraft and lengthen (shorten) the cloud lifetime and cloud time-area coverage.

This can be caused by added (less) aerosols.

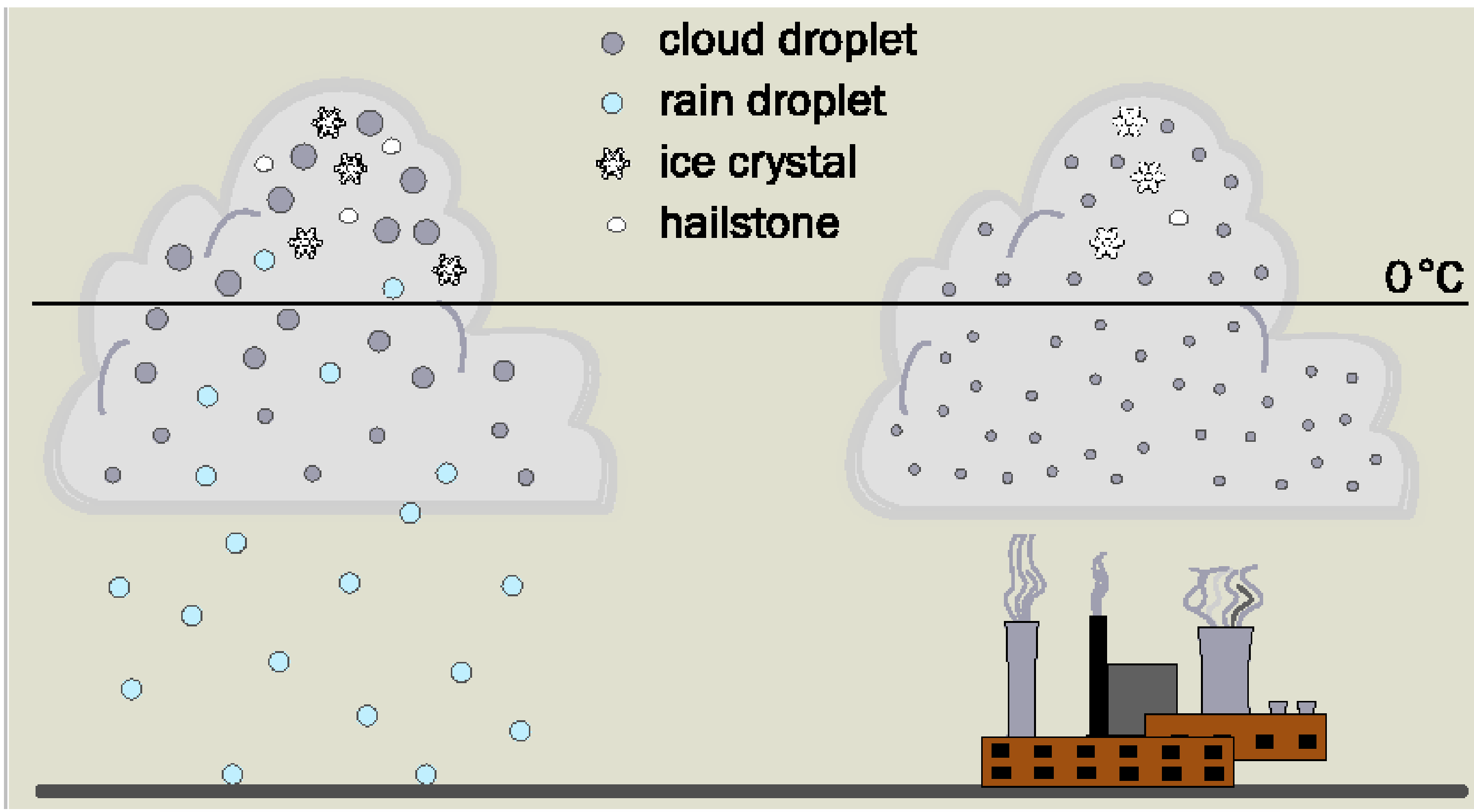


A **dissipating** storm cell (From Byers and Braham. 1949)

Small CCN aerosols have been known for 50 years to slow down the conversion of cloud water to precipitation.

An experimental investigation of the effect of air pollution on the initiation of rain

Gunn and Phillips, 1957: Journal of the Atmospheric Sciences, 14, 272-280



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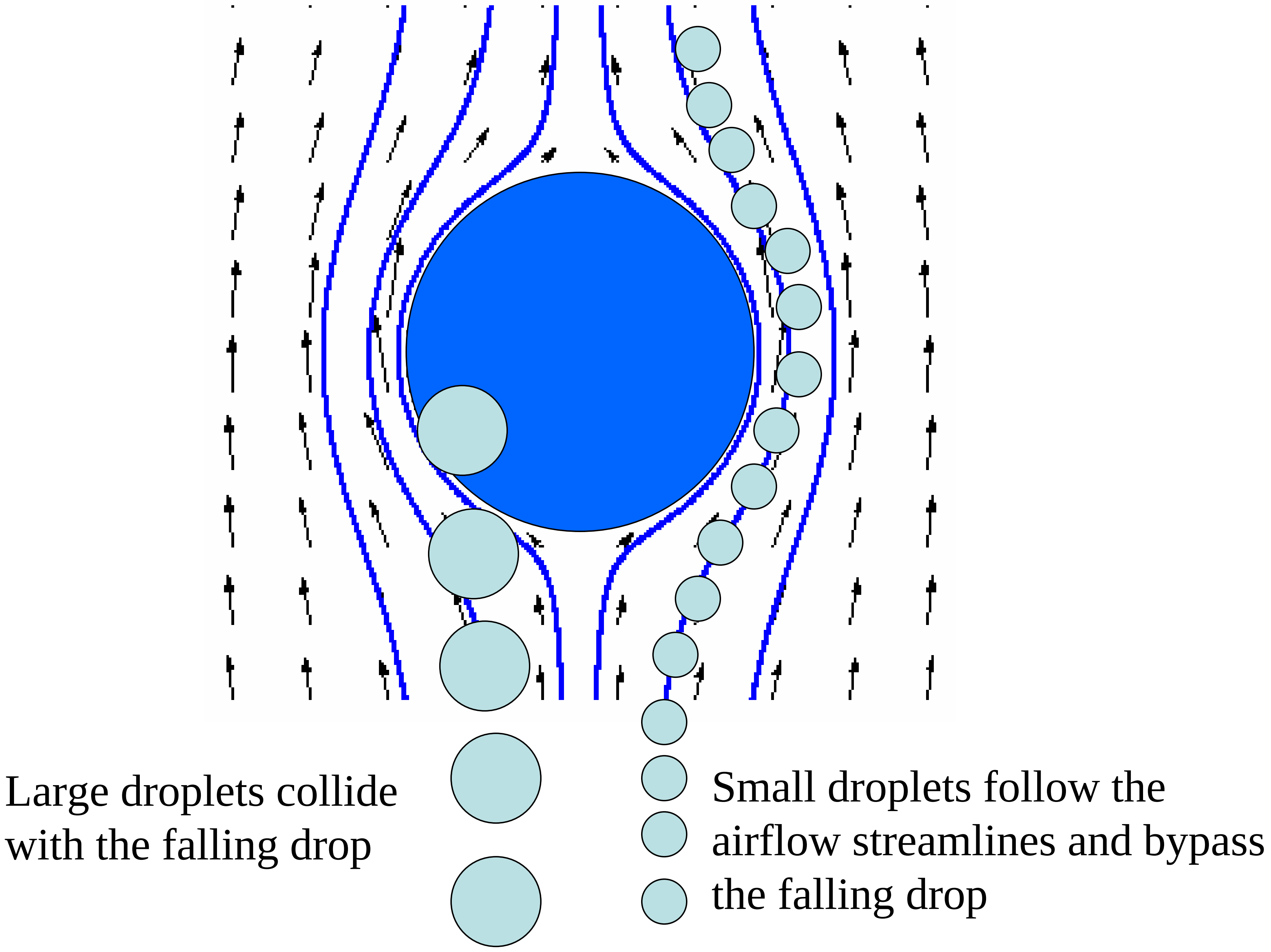
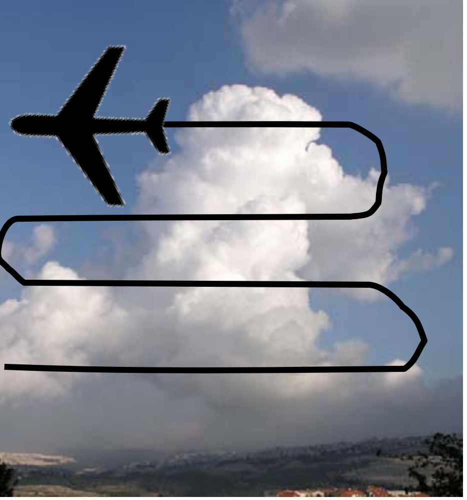
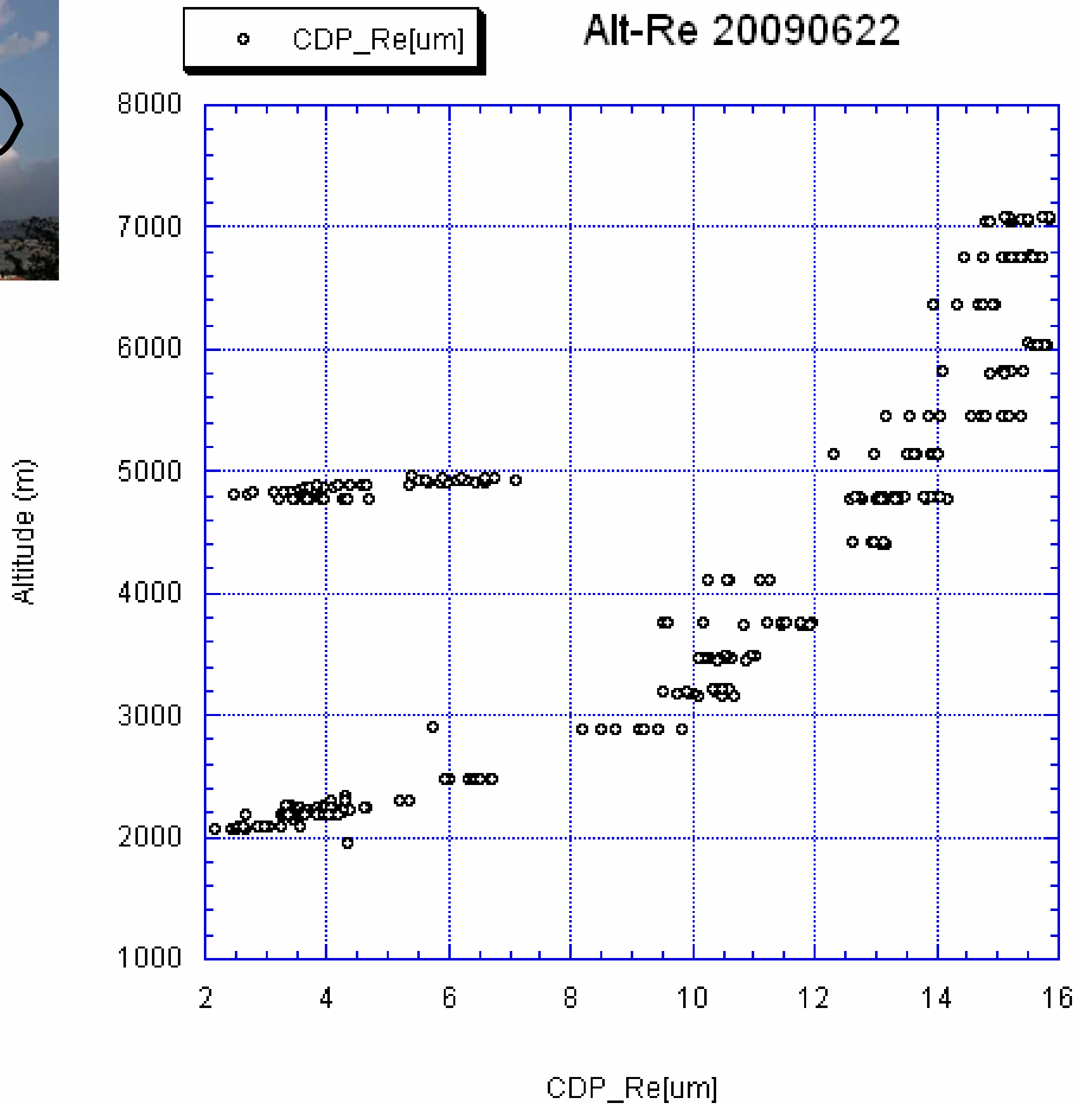
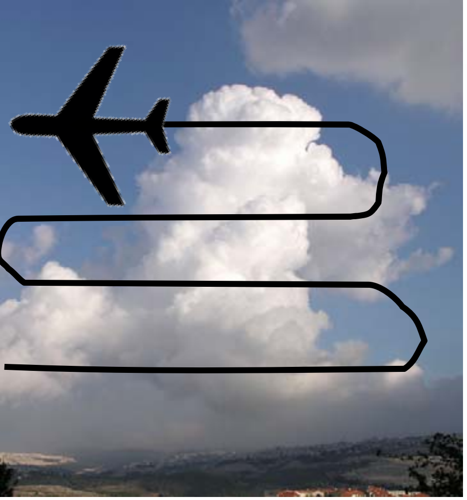

Large droplets collide
with the falling drop
Small droplets follow the
airflow streamlines and bypass
the falling drop



Hyderabad, India
22 June 2009

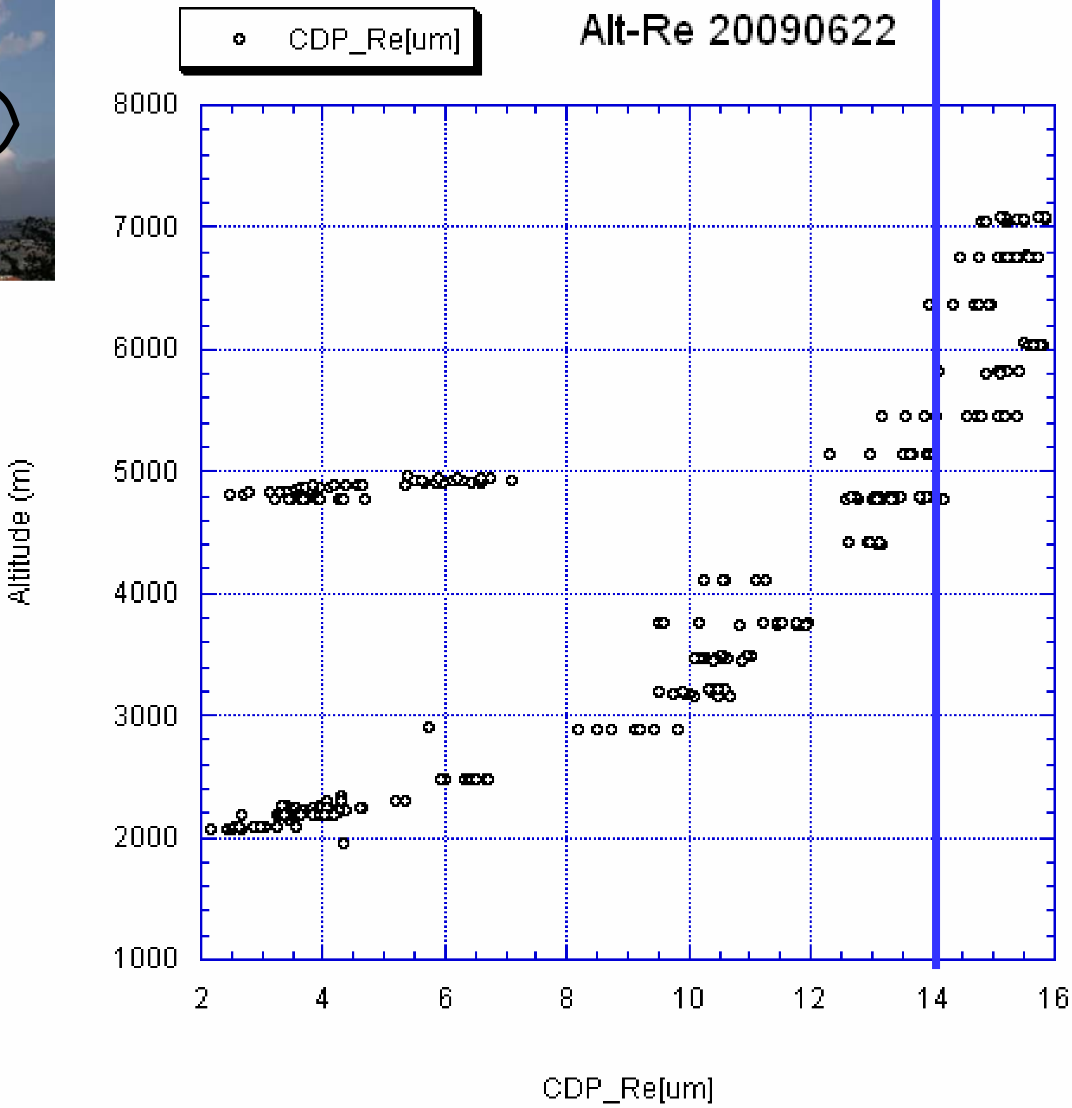


Cloud base temperature = 18.7ºC

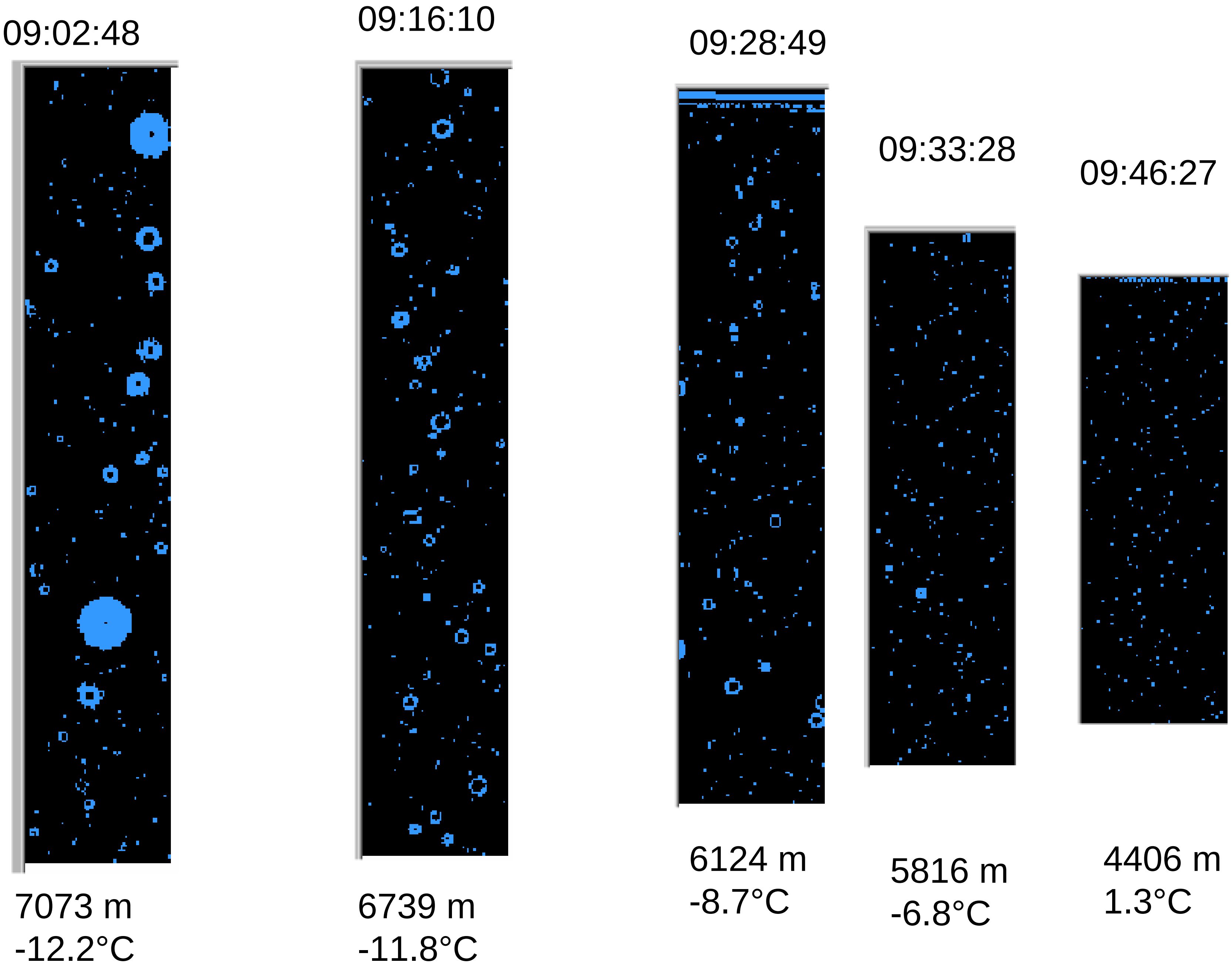


Hyderabad, India
22 June 2009

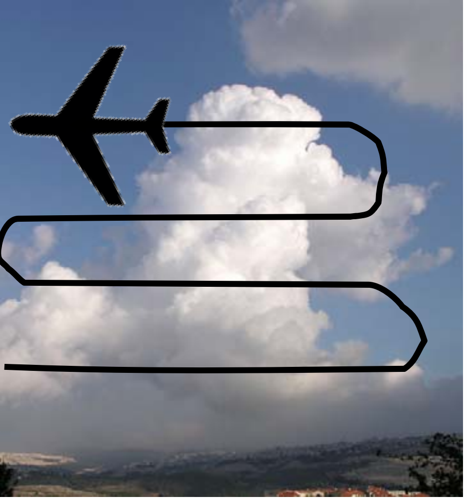
Rain onset at Re=14 μm



Cloud base temperature = 18.7ºC

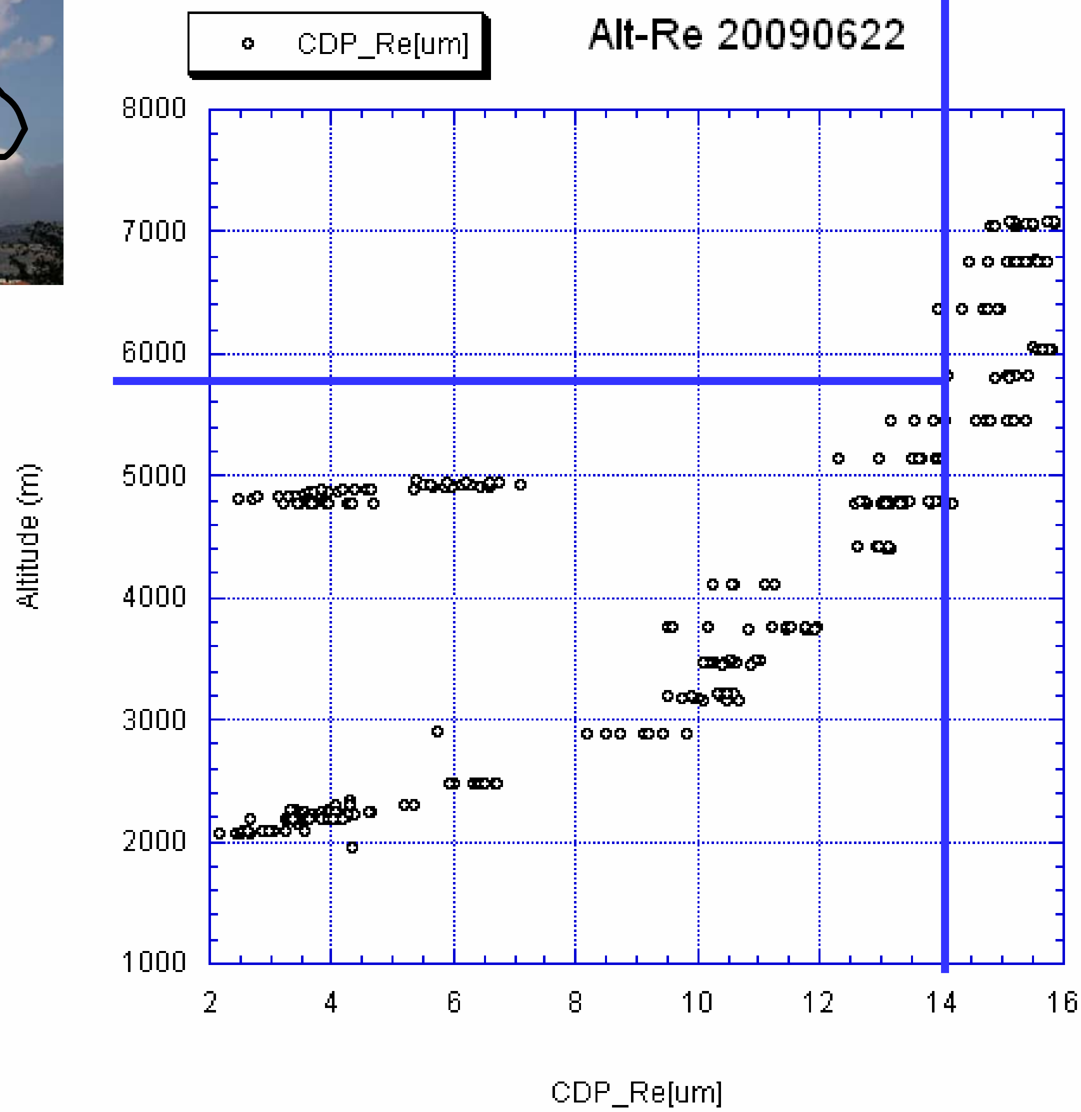


09:02:48
09:16:10
09:28:49
09:33:28
09:46:27
7073 m
-12.2°C
6739 m
-11.8°C
6124 m
-8.7°C
5816 m
-6.8°C
4406 m
1.3°C



Hyderabad, India
22 June 2009

Rain onset at Re=14 µm

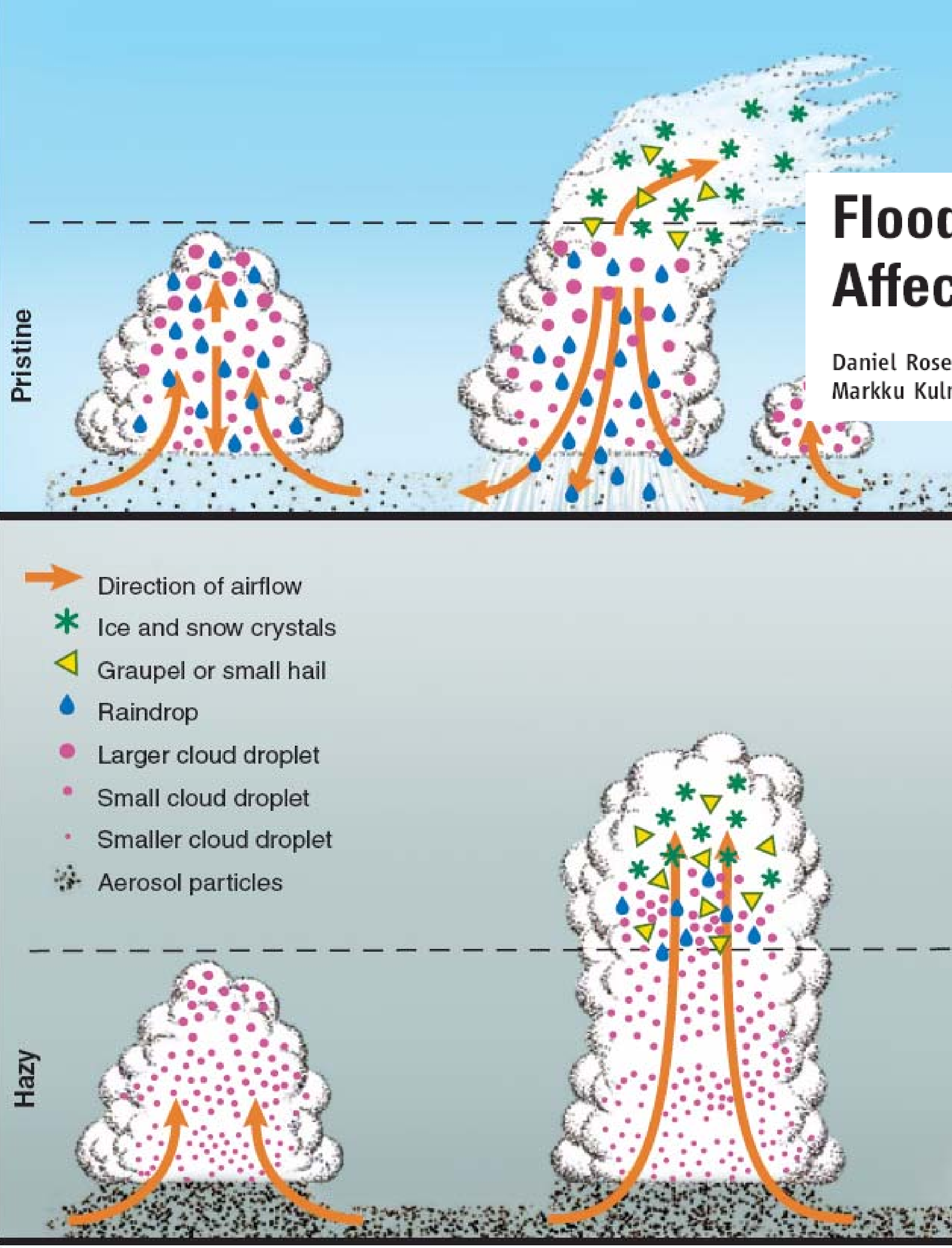


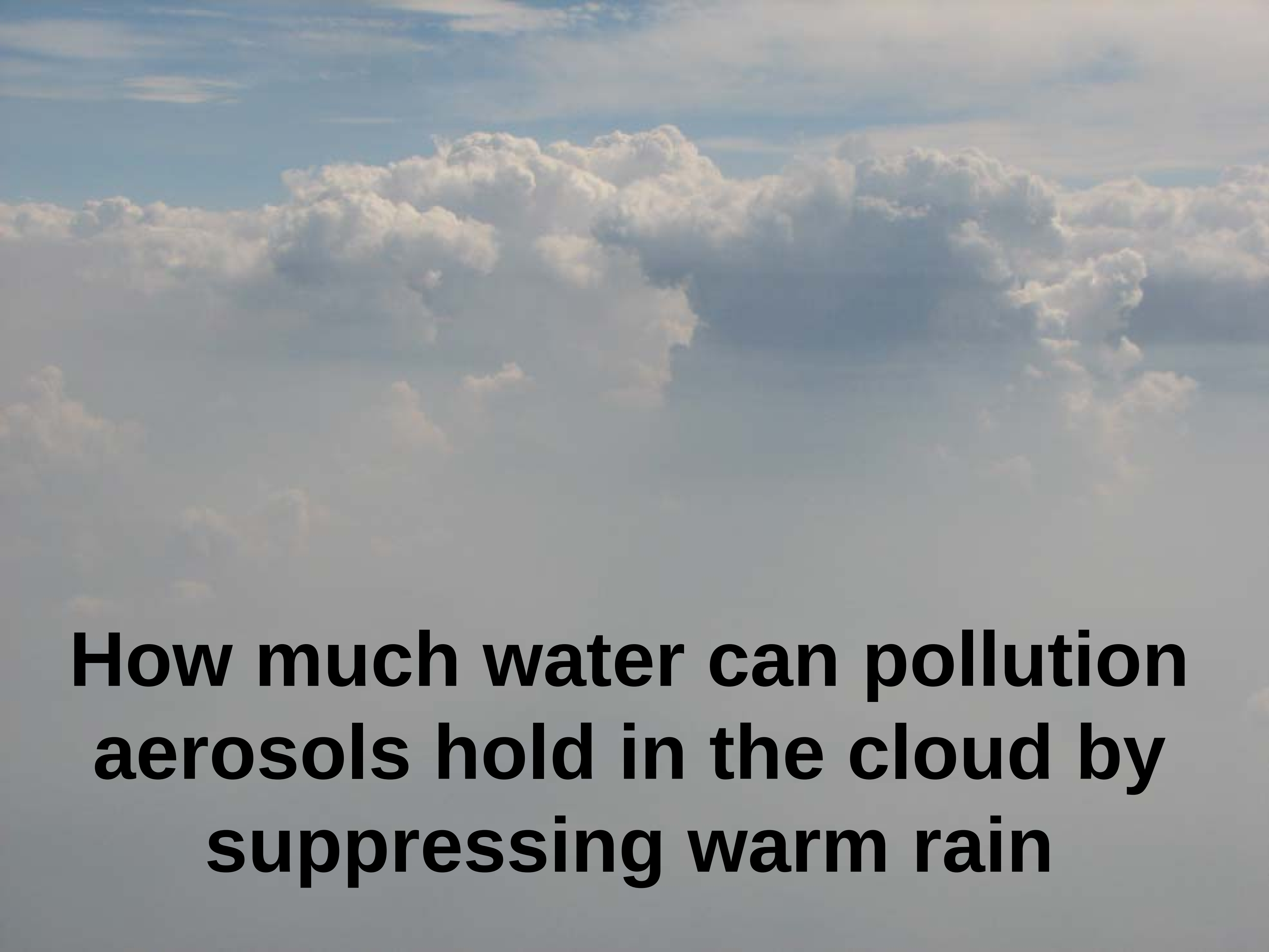
Cloud base temperature = 18.7ºC

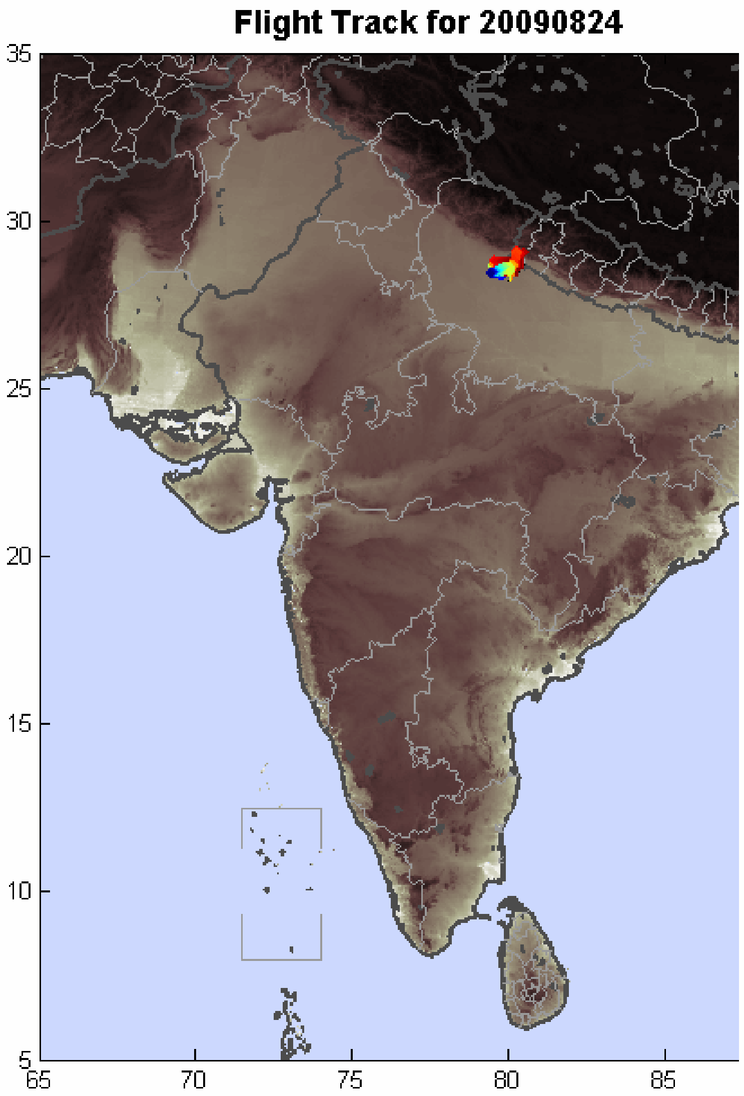
SCIENCE VOL 321 5 SEPTEMBER 2008

Flood or Drought: How Do Aerosols Affect Precipitation?

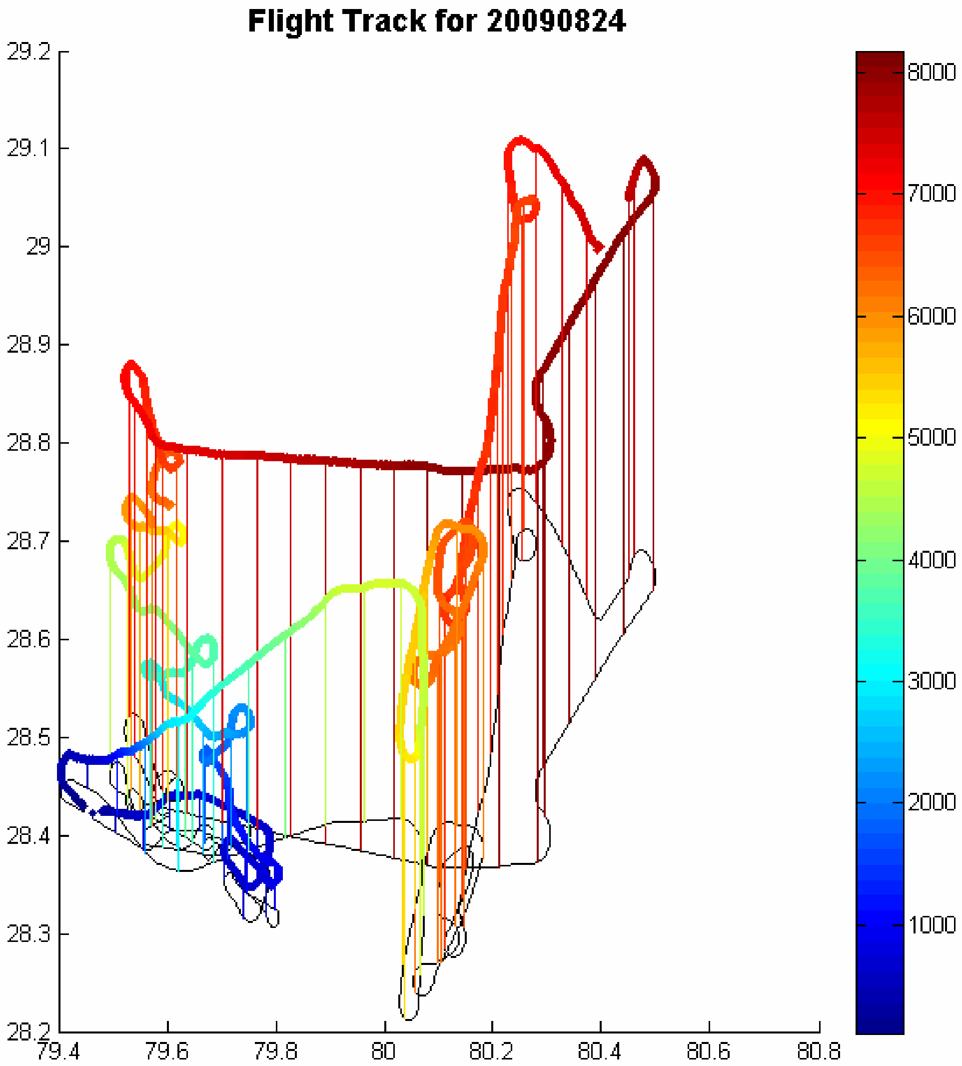
Daniel Rosenfeld,[1]* Ulrike Lohmann,[2] Graciela B. Raga,[3] Colin D. O'Dowd,[4] Markku Kulmala,[5] Sandro Fuzzi,[6] Anni Reissell,[5] Meinrat O. Andreae[7]



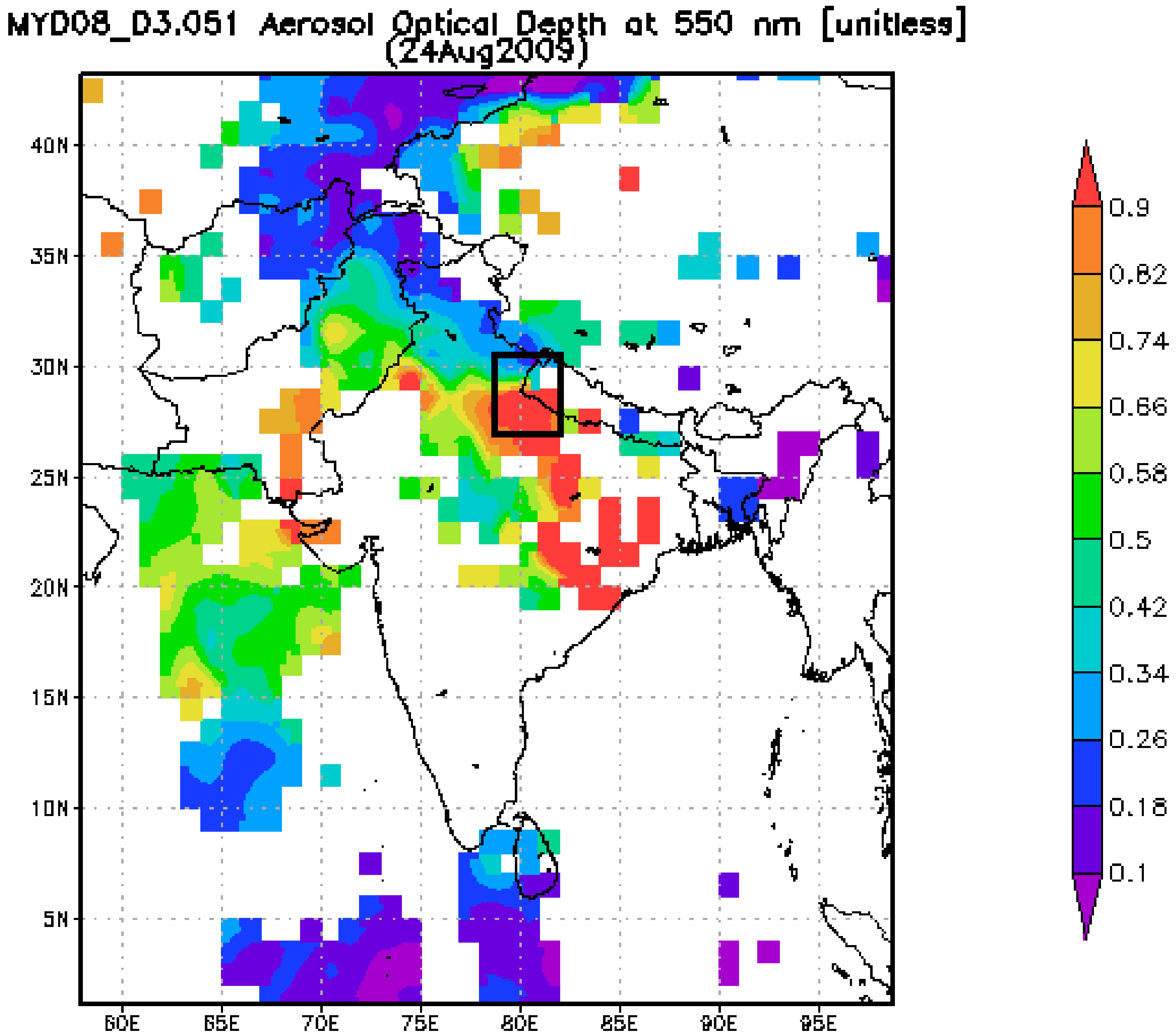

How much water can pollution aerosols hold in the cloud by suppressing warm rain



Flight Track for 20090824
35
30
25
20
15
10
5
65
70
75
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
80.6
80.8
8000
7000
6000
5000
4000
3000
2000
1000


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.

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.

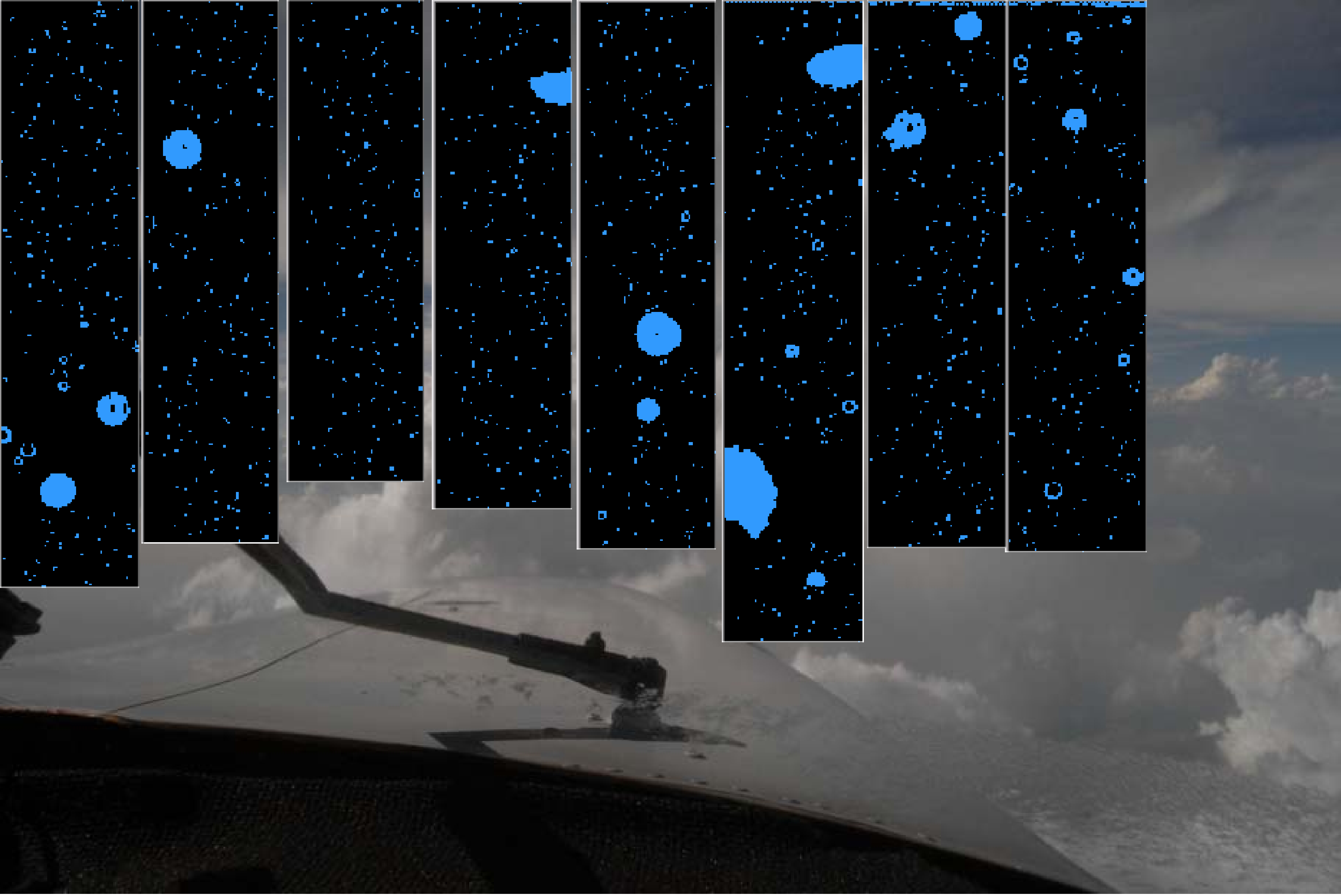
2009 08 24, 10:31 UT, 4700 m, 3.2ºC. Max HWLWC=2.45 gm-3. N of Bareilly.
No rain.

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.

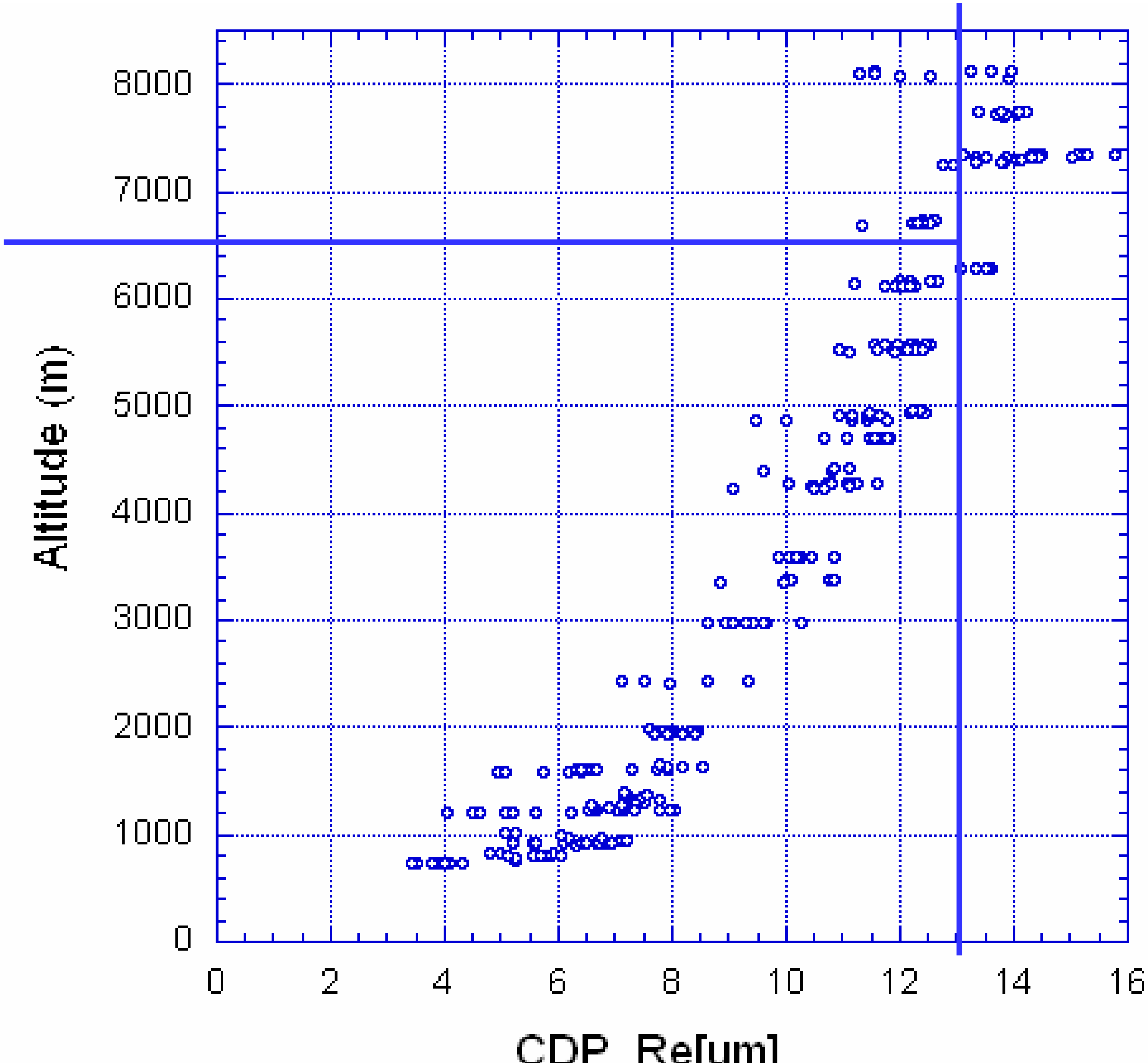


2009 08 24, 10:03 UT, 7350 m, -11.8ºC. Max HWLWC=0.87 gm-3. N of Bareilly.
The cloud has small raindrops and larger freezing rain drops.

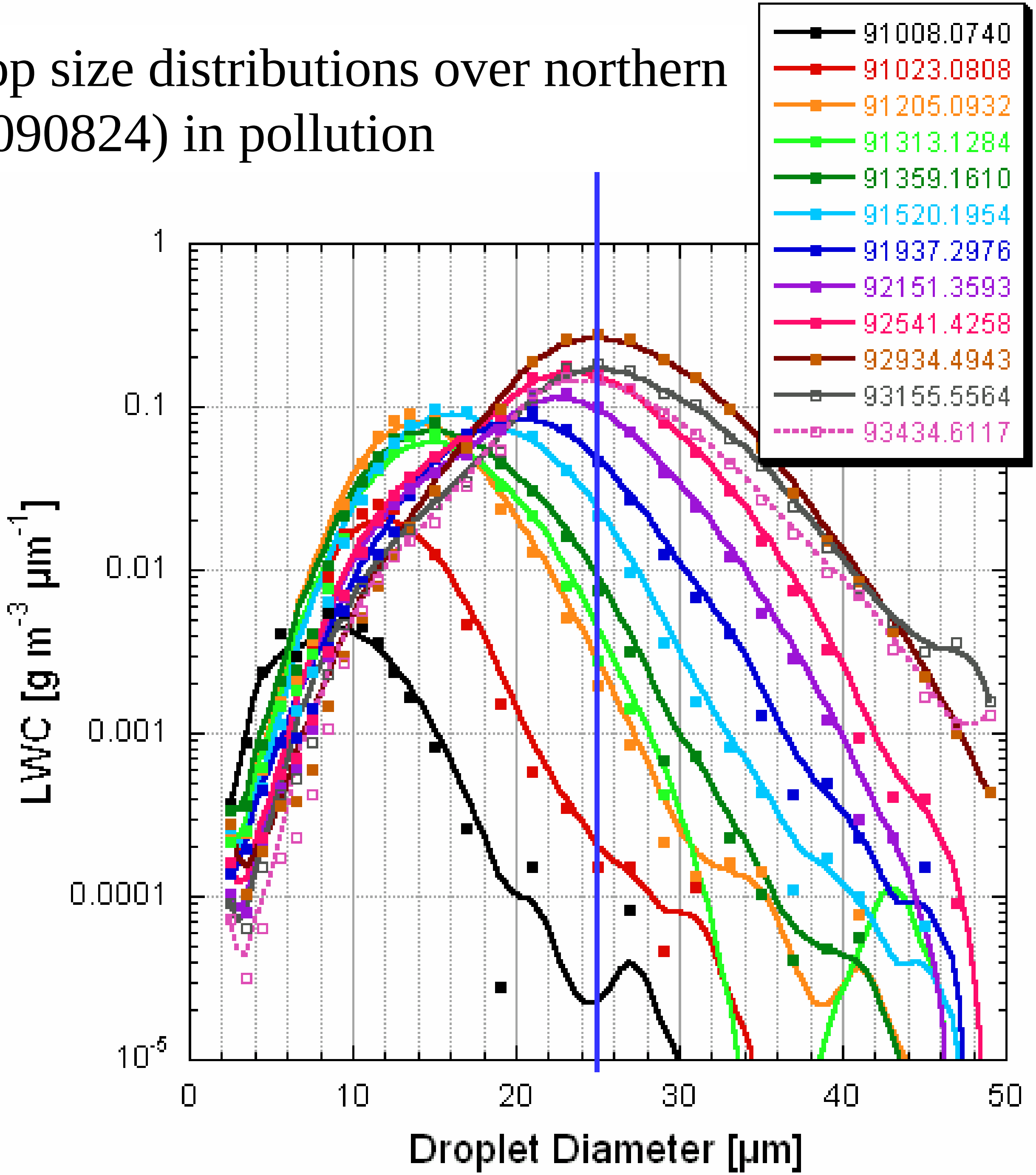
2009 08 24, 10:00 UT, 7700 m, -14.7ºC. Max HWLWC=1.45 gm-3. N of Bareilly.
The cloud has small rain drops, large freezing rain drops and small graupel.

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.

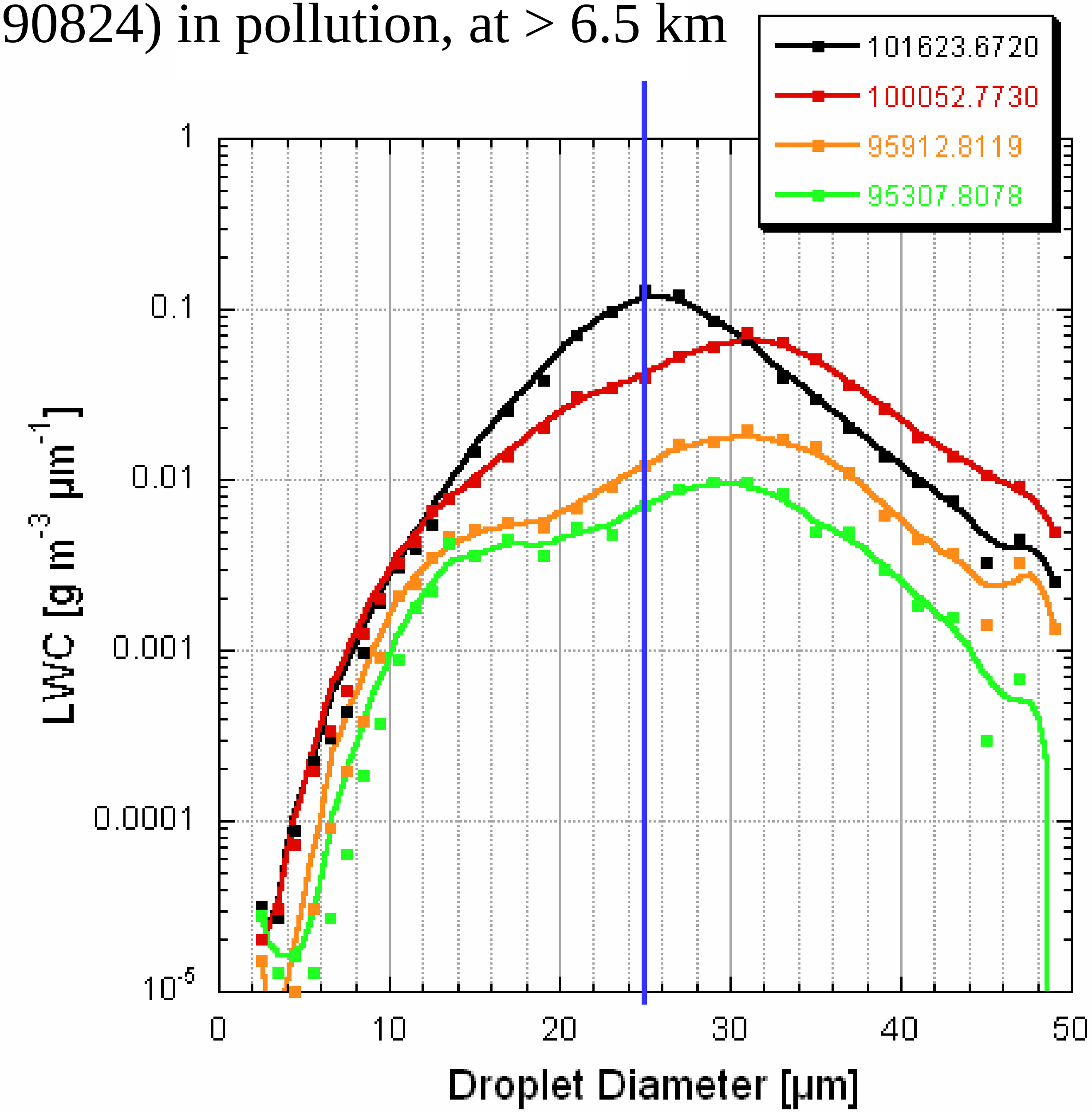
Vertical development of cloud drop effective radius in highly polluted conditions in extremely moist conditions over the flooded Indo-Gangetic plains on 24 August 2009. Rain starts at height of 6.5 km



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



Cloud drop size distributions over northern India (20090824) in pollution, at > 6.5 km



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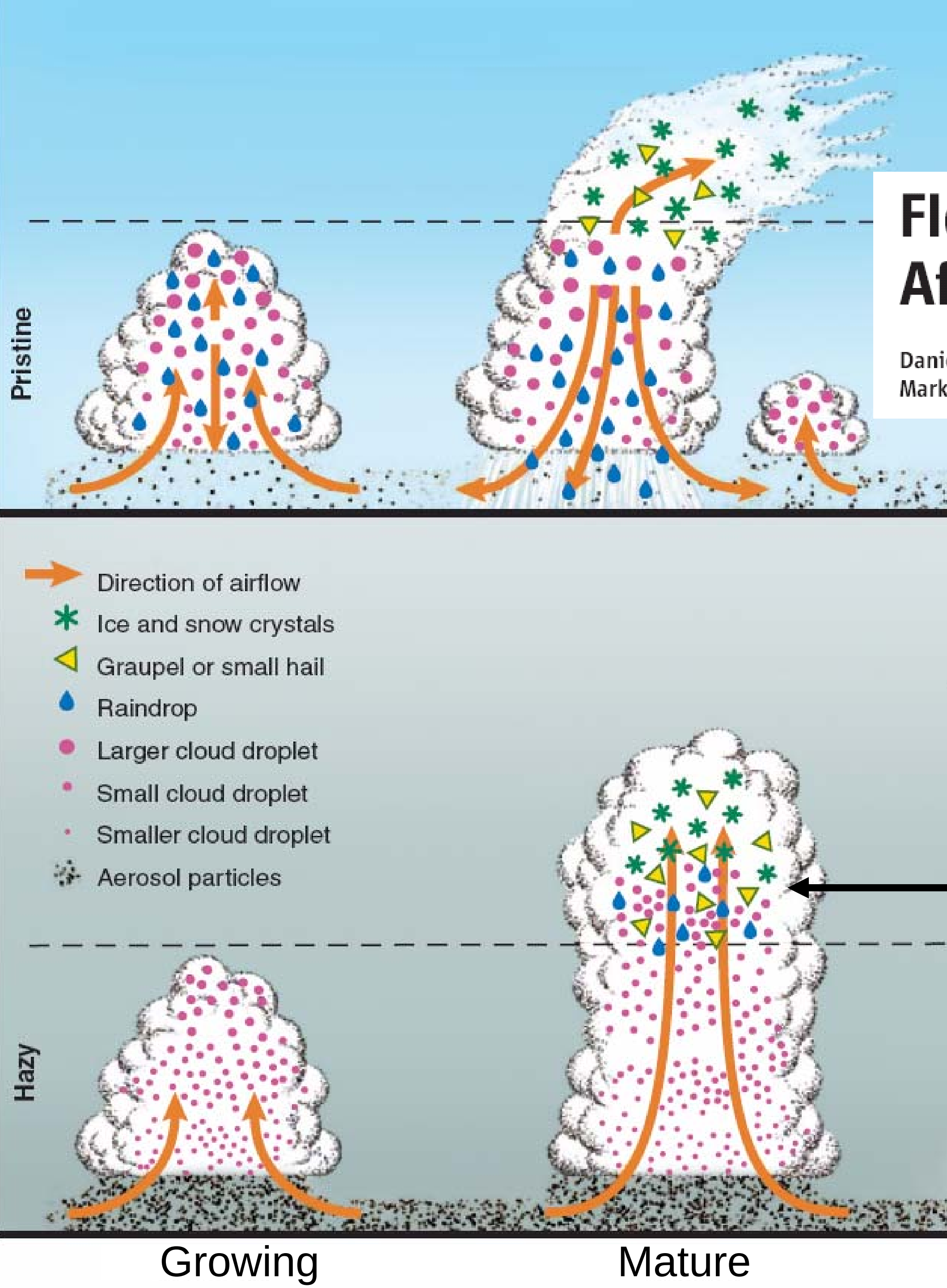
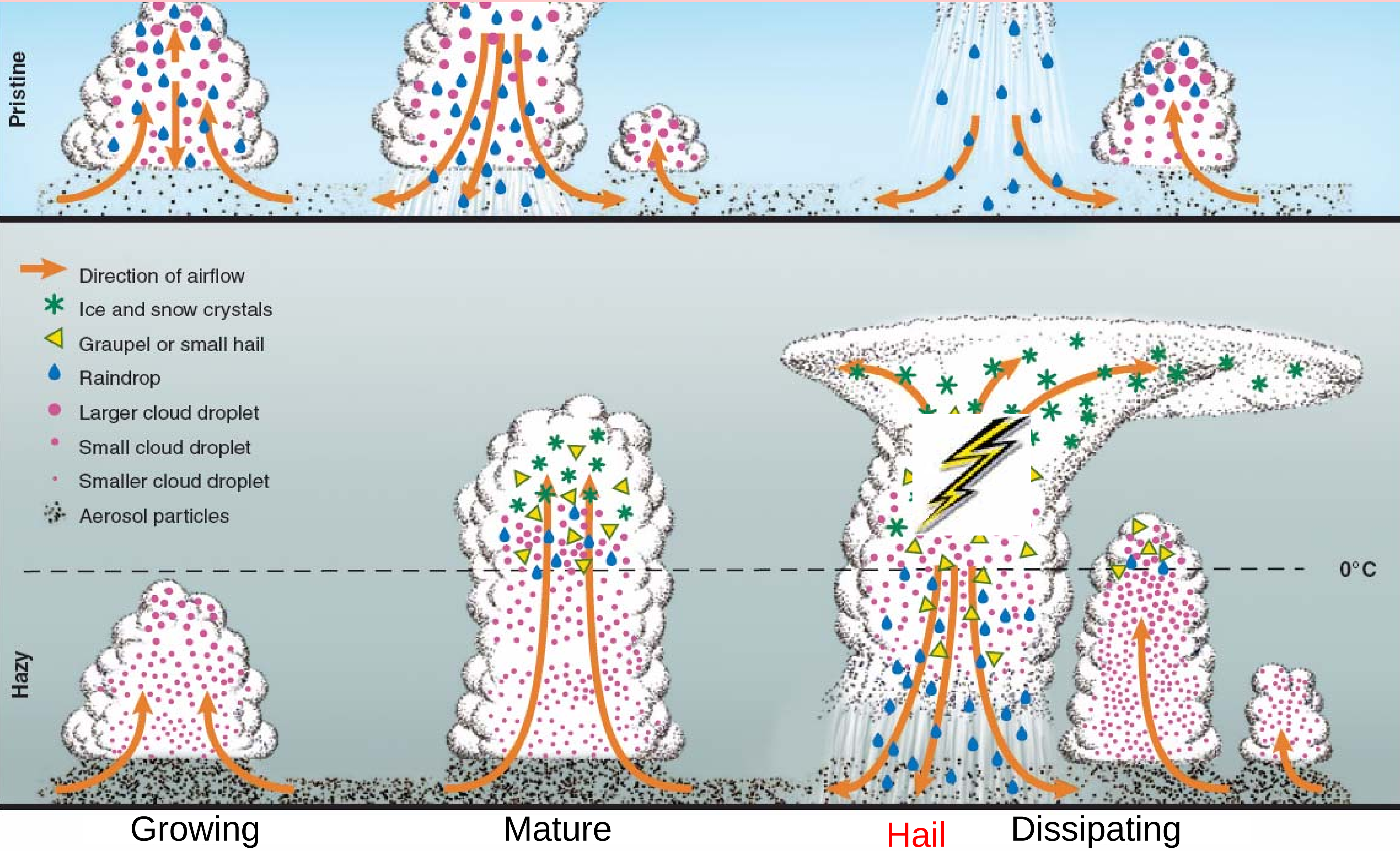
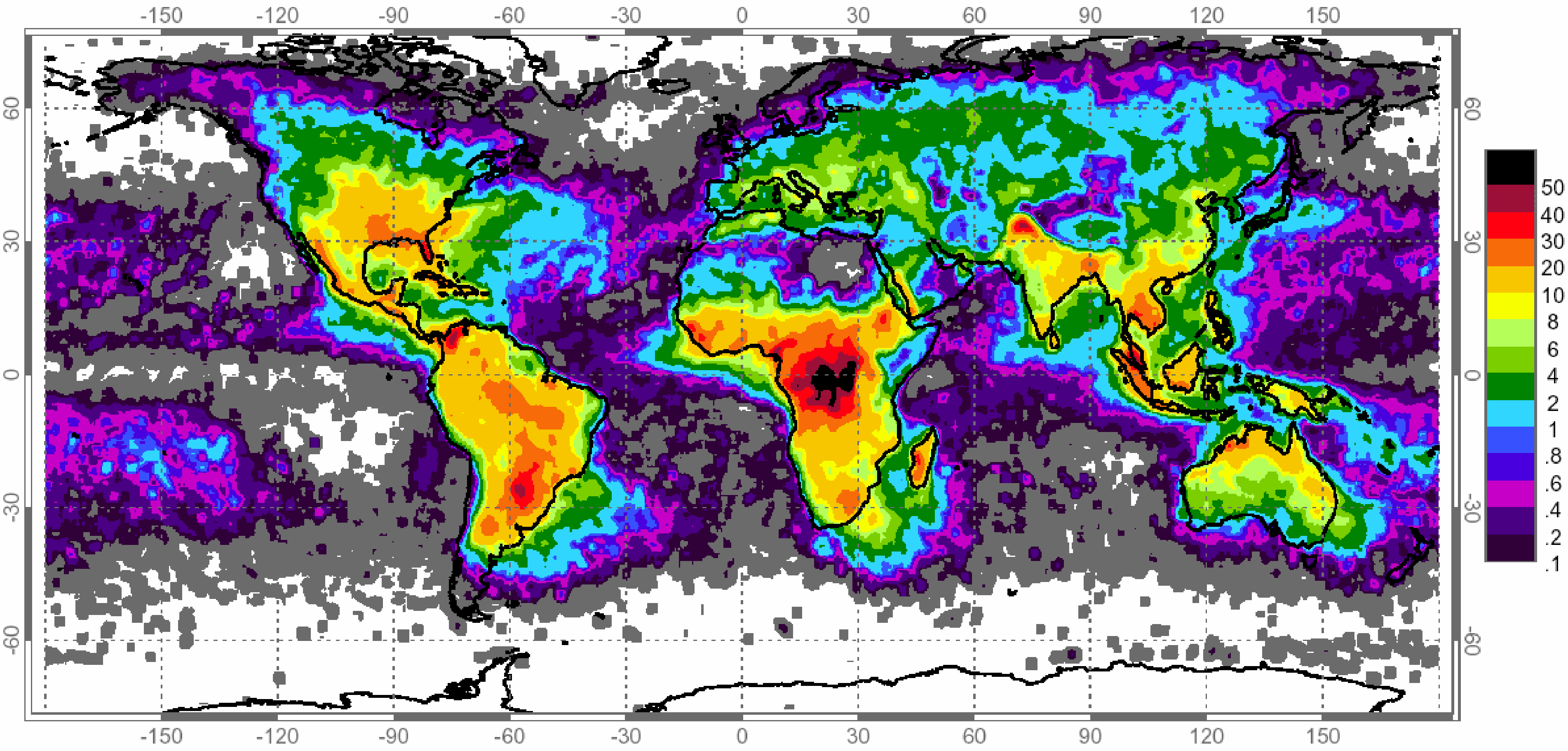


The evaporative cooling of downdrafts may b even more important than the added latent heat of freezing.

Lee S.S., L.J. Donner, J.E. Penner, 2010: Thunderstorm and stratocumulus: how does their contrasting morphology affect their interactions with aerosols? *Atmos. Chem. Phys. Discuss.*, 10, 4305–4343

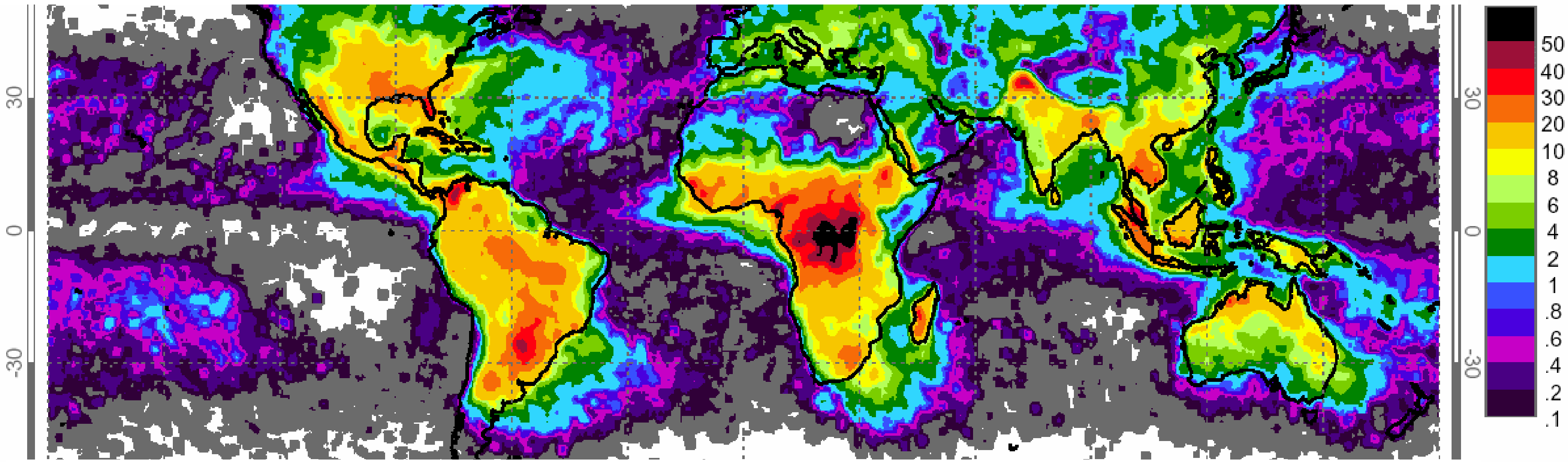


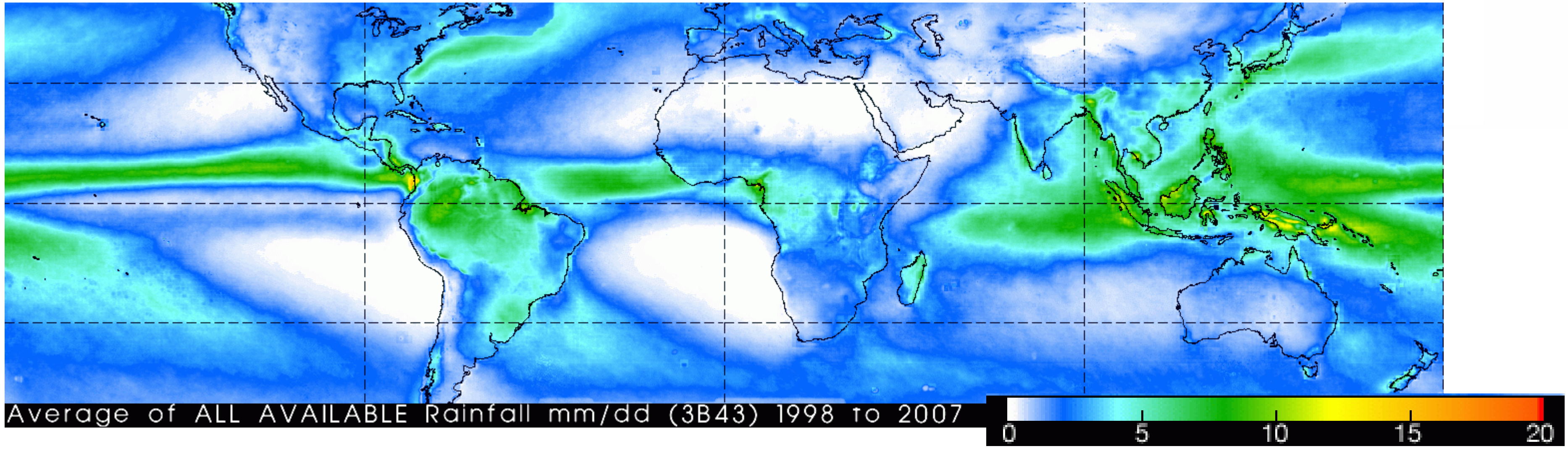
Most lightning is over land, but most rainfall is over ocean



Annual average lightning density [flashes km^{-2}]

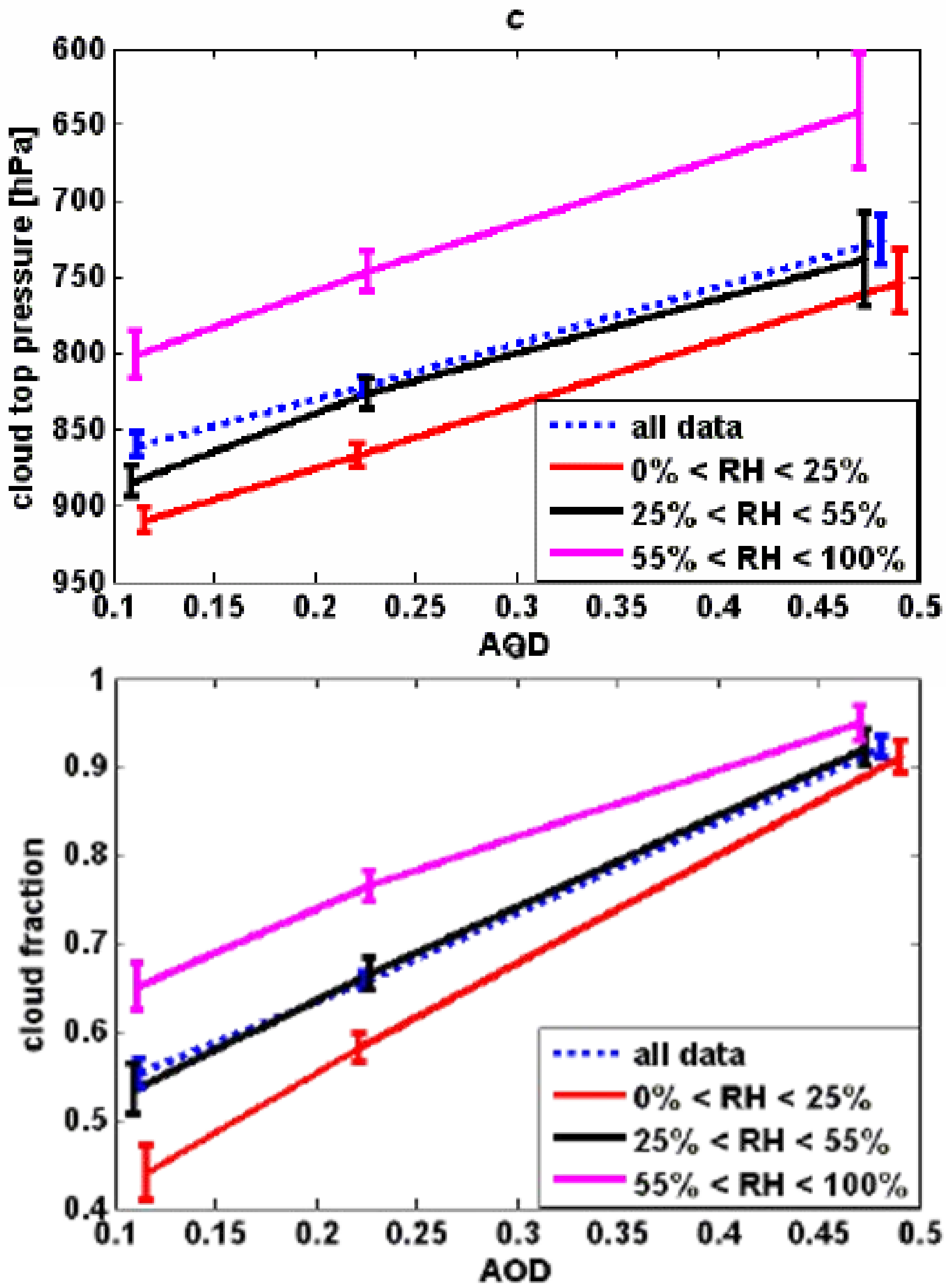
Lightning prevail mostly over land, whereas rainfall is similar over land and ocean, indicates fundamental differences between continental and maritime rainfall.





TRMM annual average rainfall amount [mm / day]

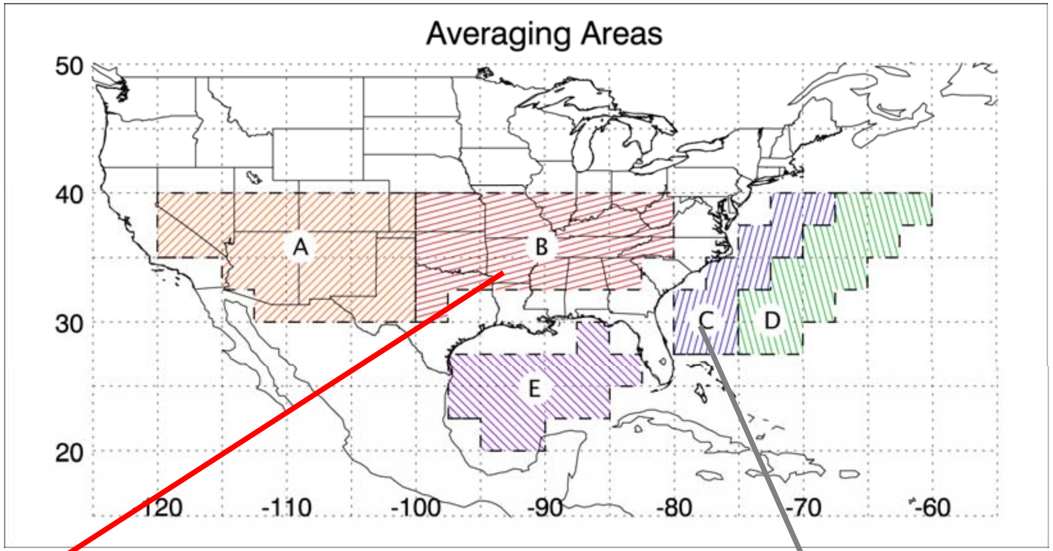
There is little relation between lightning and rainfall amount

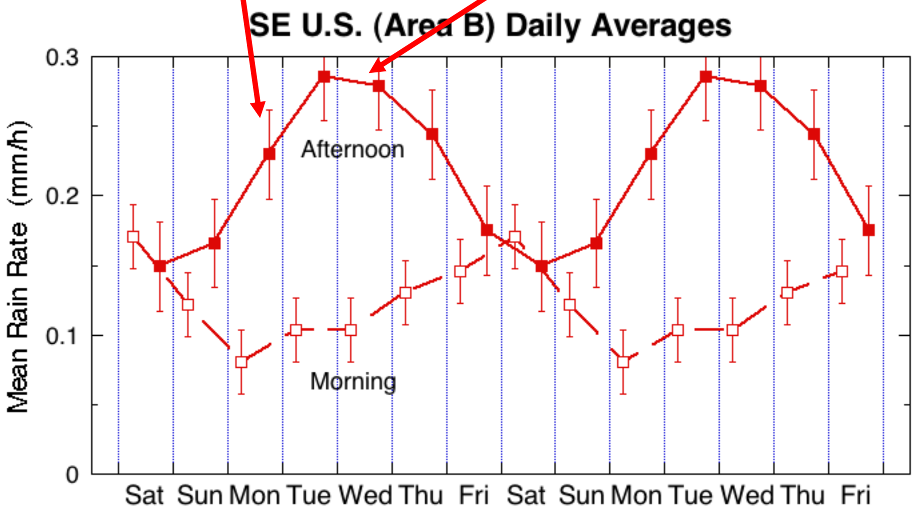


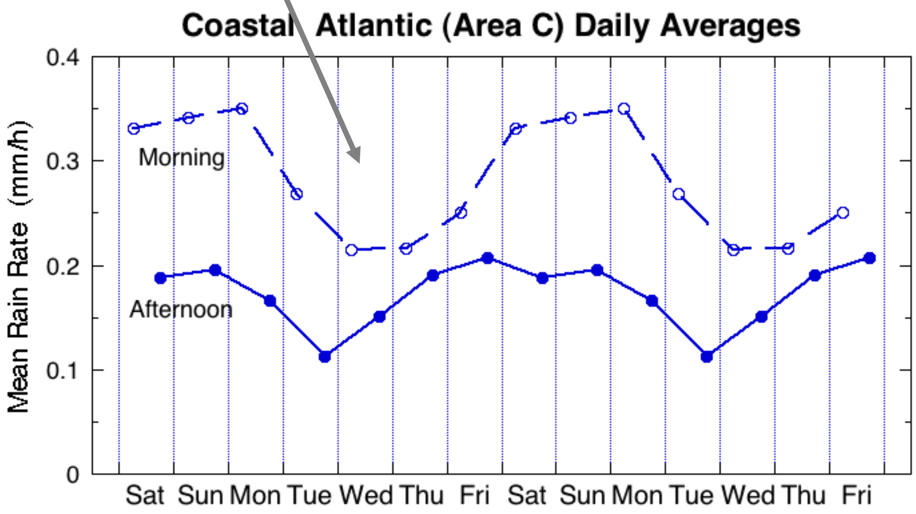
MODIS measured cloud top heights and fraction increases with GOCART aerosol optical depth over the Equatorial Atlantic Ocean (From Koren et al., ACPD 2010), in agreement with the invigoration hypothesis (Rosenfeld et al., Science 2008)

Weekly Cycle of Large-Scale Averages

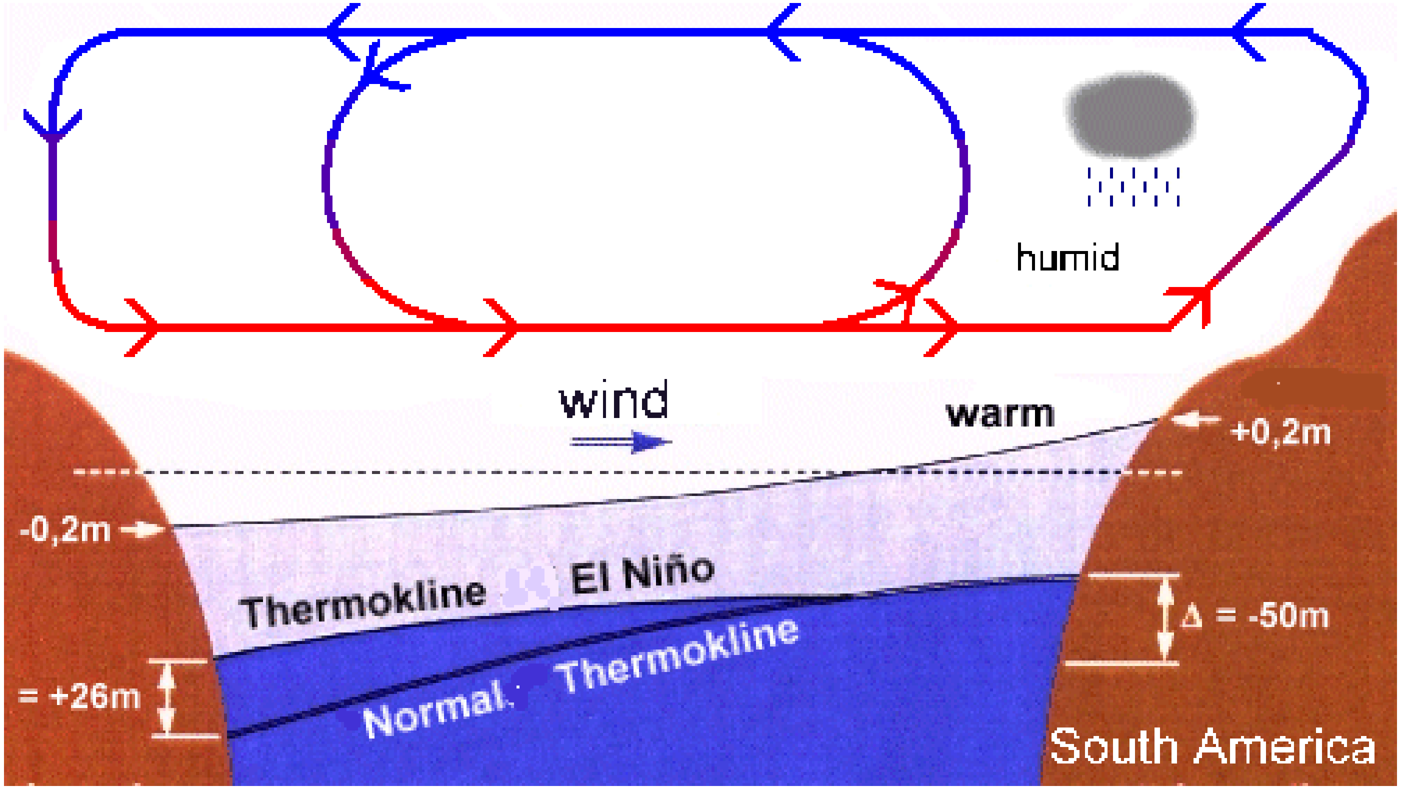
Cycle of <u>afternoon</u> TRMM rain significant at $p = 0.1\%$ level.







T.L. Bell, D. Rosenfeld, K.M. Kim, J.M. Yoo, M.I. Lee, M. Hahnenberger, 2007: Midweek Increase in U.S. Summer Rain and Storm Heights Suggests Air Pollution Invigorates Rainstorms. JGR.



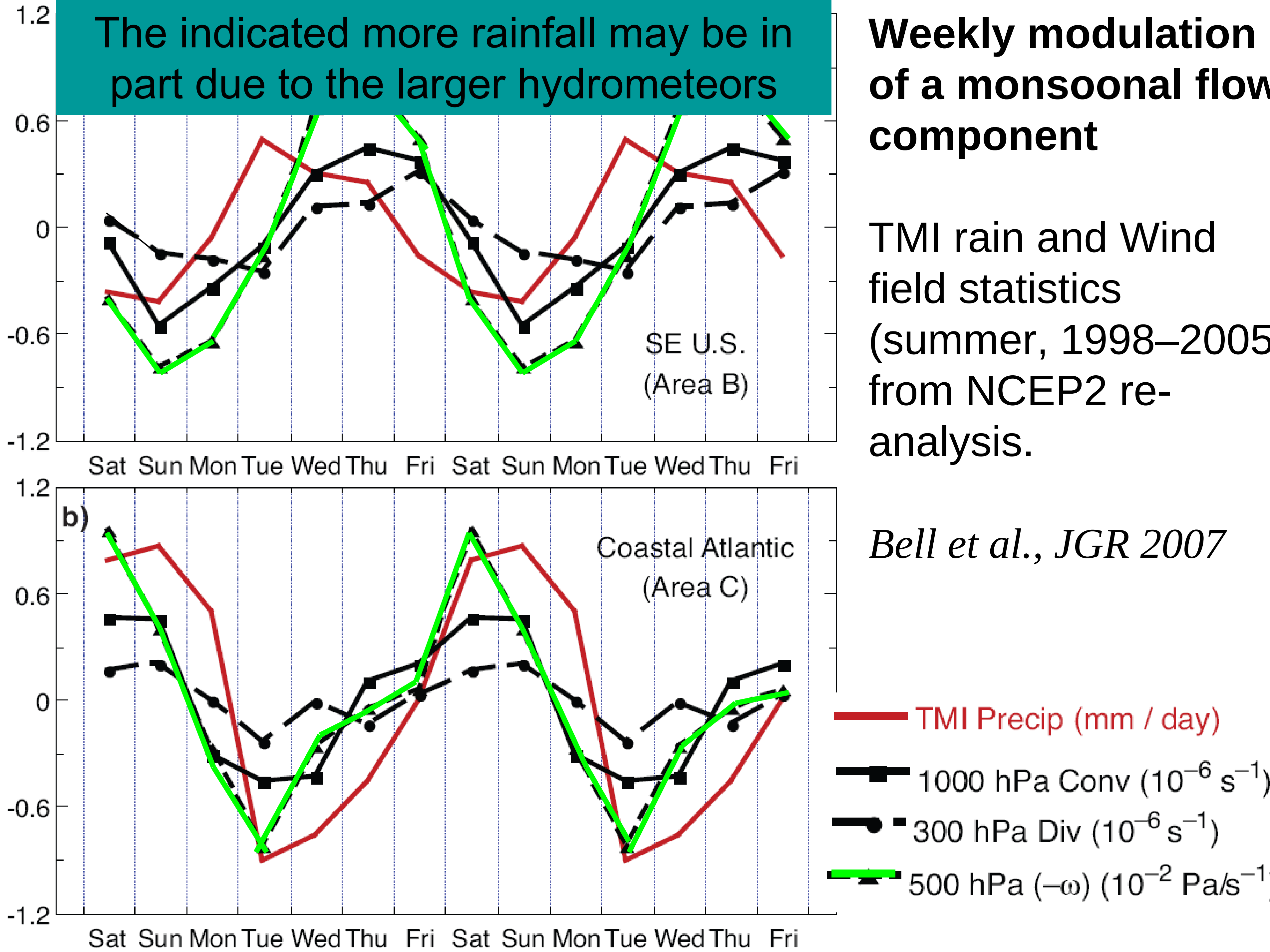
humid
wind
warm
+0,2m
-0,2m
Thermokline
El Niño
Δ = -50m
= +26m
Normal Thermokline
South America

The indicated more rainfall may be in part due to the larger hydrometeors

Weekly modulation of a monsoonal flow component

TMI rain and Wind field statistics (summer, 1998–2005) from NCEP2 re-analysis.

Bell et al., JGR 2007



Conclusions (1/2)

- The convective lifecycle is dominated by the precipitation and resultant downdrafts. Precipitation start forming above certain height in the cloud (D).
- Aerosols control the cloud depth for onset of warm rain in convective elements by determining the dependence of cloud drop size (Re) on cloud depth (D).
- The requirement of Re> ~12-14 μm for onset of warm rain implies a well defined D for a given cloud base drop concentration, which is determined by CCN concentration and updraft speed.
- Height for onset of warm rain can vary from D of few hundred m in pristine air to D>5 km in heavily polluted air, which occurs well above the freezing level, even in extremely moist tropical air mass.

Conclusions (2/2)

- Therefore, CCN concentrations affect the convective regime (intensity, cloud cover and precipitation) in all convectively driven systems, from marine stratocumulus to deep convection, even at its most organized form as tropical cyclones.
- This means that aerosols have profound impacts on Earth energy budget by redistribution of precipitation and latent heat release in shallow Sc to deep convective clouds both in the tropics and mid-latitudes.
- We must understand and quantify these processes before we can make believable GCMs for IPPC type climate predictions.