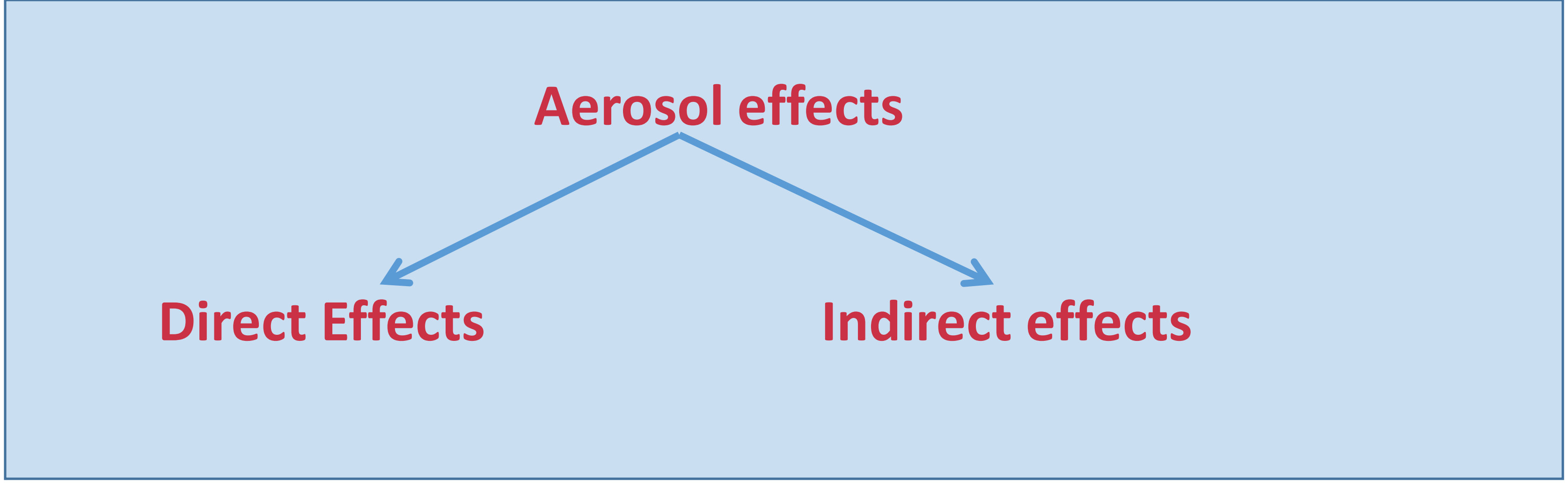
Cloud Aerosol Interaction research and weather modification

Thara Prabhakaran

Indian Institute of Tropical Meteorology Pune, India

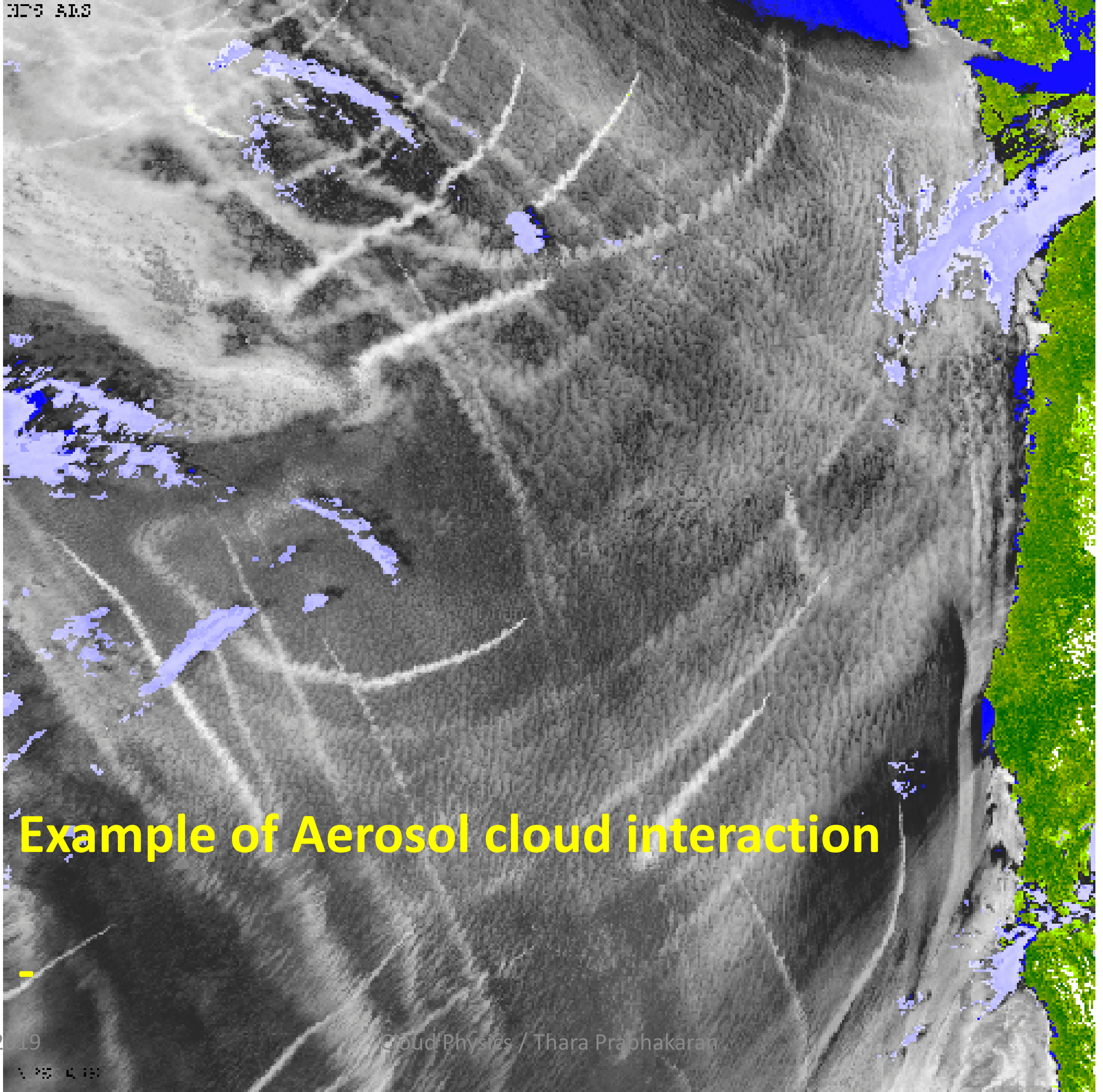


Direct Forcing

- ***Direct*** refers to the interaction between solar and terrestrial infrared radiation with aerosol particles before they become cloud particles.

- This magnitude of the interaction depends on the particle concentration, size, shape, and composition of the particles.

- This produces a net cooling effect due to the solar radiation that is scattered back to space. However, aerosol particles like black carbon can produce net warming

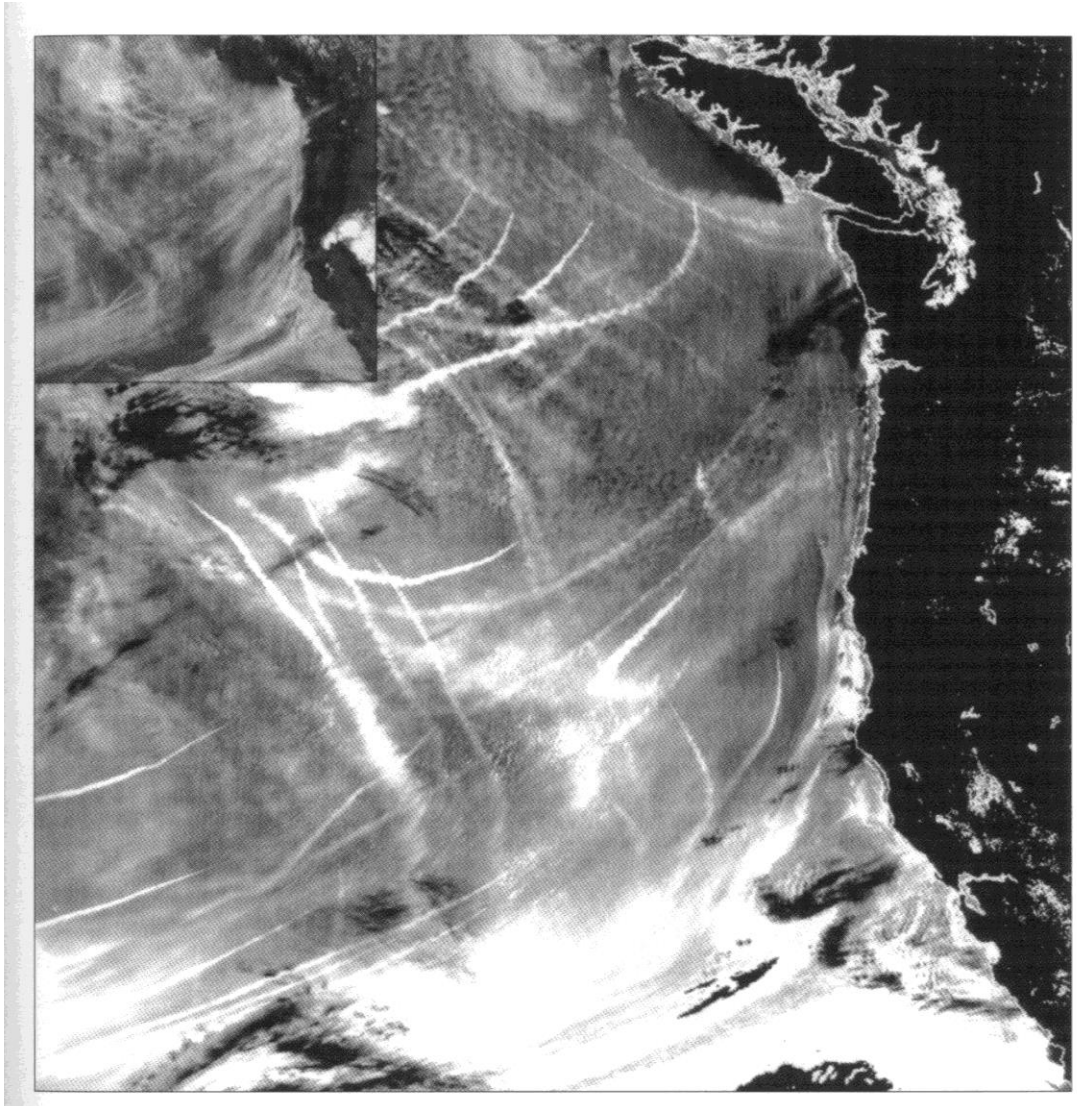


Example of Aerosol cloud interaction

-

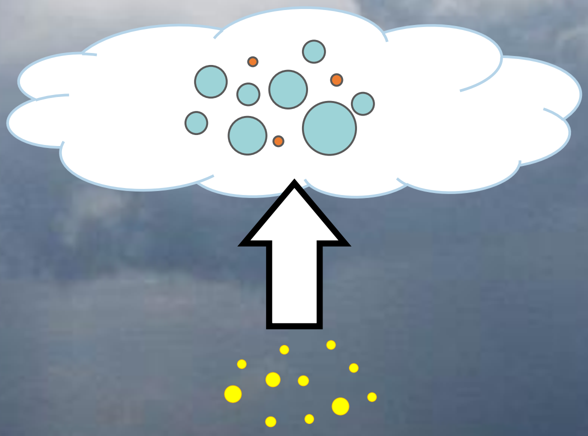
Evidence for the indirect "Twomey" effect in this satellite image of clouds off the coast of California.

The ship tracks are a result of high reflectivity regions in the marine stratus clouds formed by increased concentrations of small droplets formed on the sulfate particles from emissions by ships.



Cloud Condensation Nuclei (CCN)

The “seeds” upon which cloud droplets form



Cloud Condensation Nuclei (CCN)

The “seeds” upon which cloud droplets form

More CCN

More Cloud Droplets

Smaller Droplets

Cloud Condensation Nuclei (CCN)

The “seeds” upon which cloud droplets form

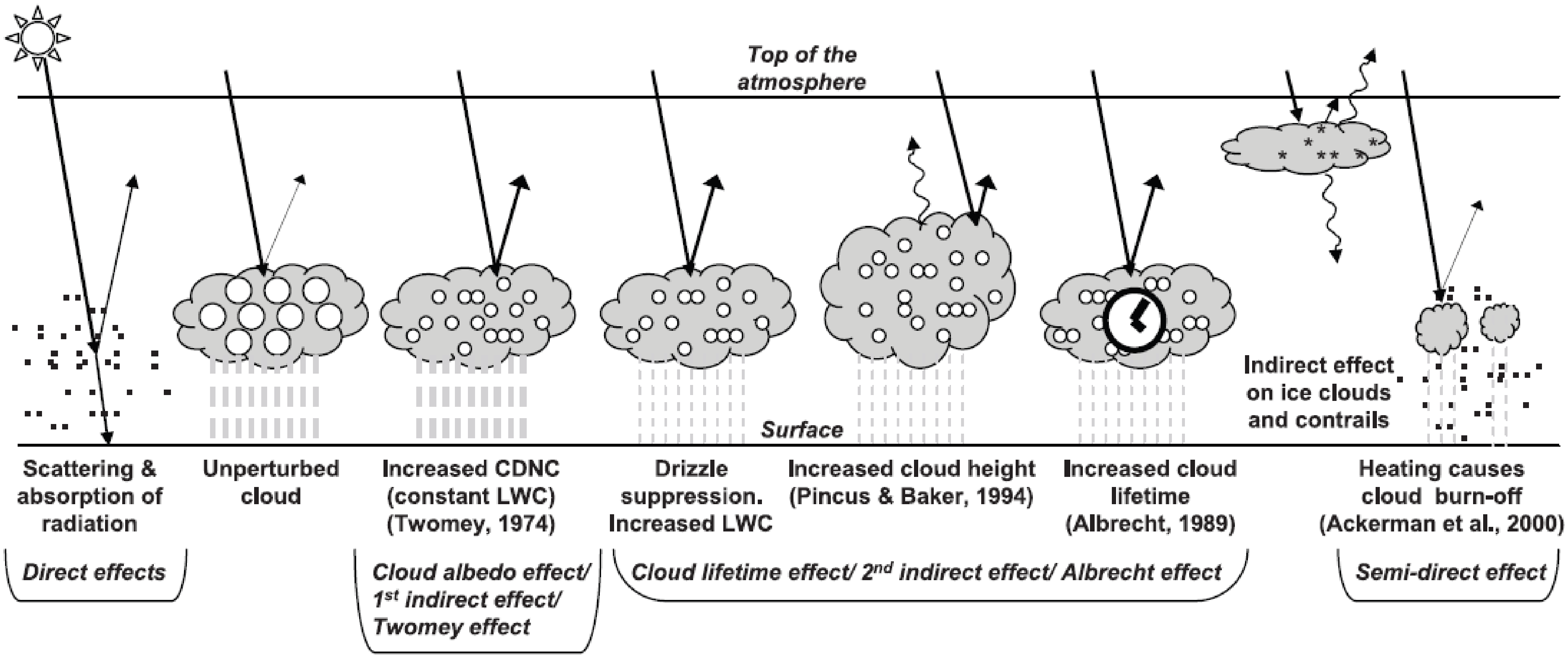
Measurements of CCN provide a direct link between aerosol and cloud microphysics.

More CCN

More Cloud Droplets

Smaller Droplets

Aerosol Cloud Interaction



Source IPCC AR4 Report

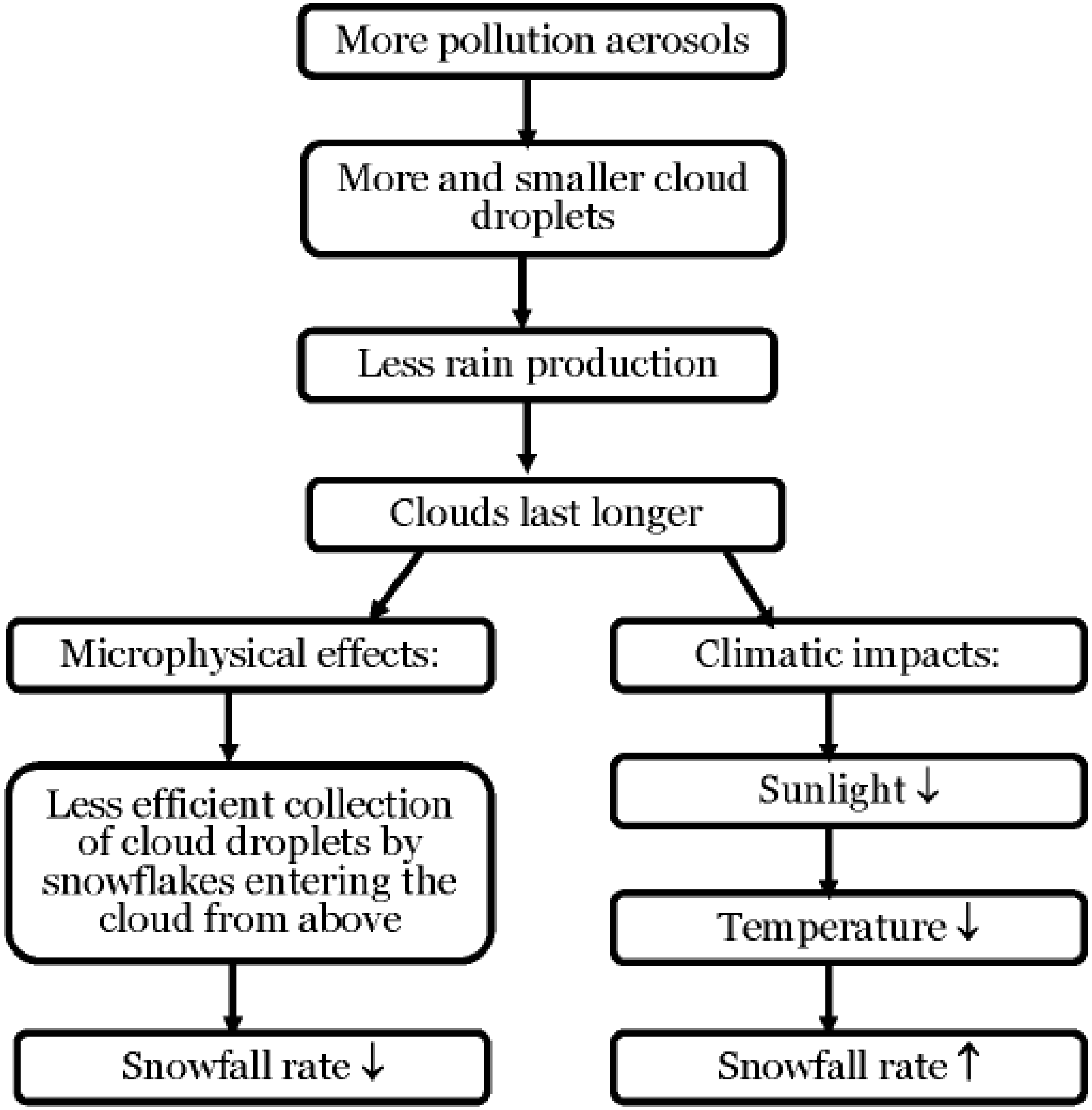
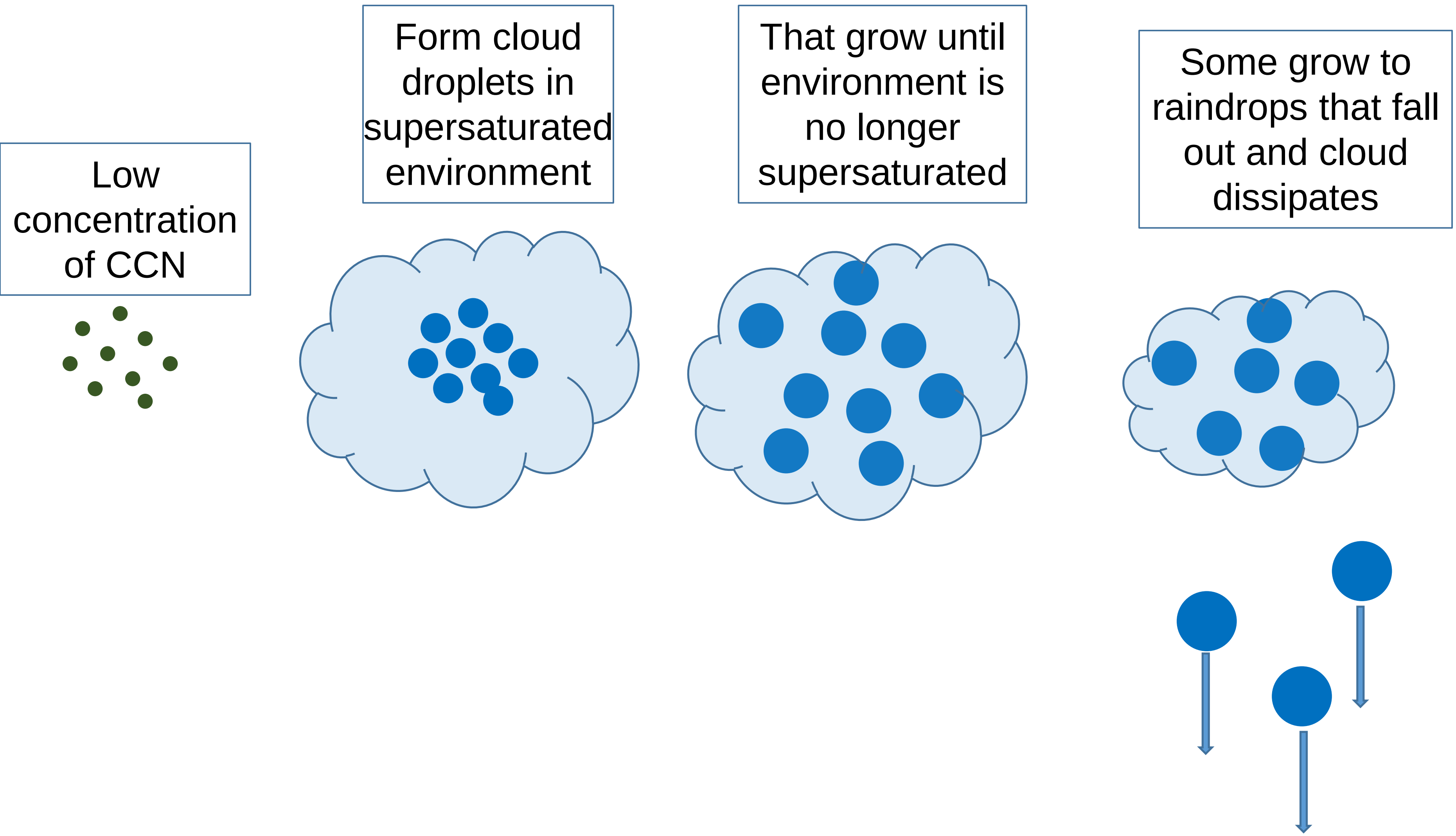


Fig. 5. Schematic diagram of the effect of pollution on snow showing the microphysical and climatic implications (adapted from Lohmann, 2004).

Why adding more CCN decreases average droplet size and increases cloud lifetime



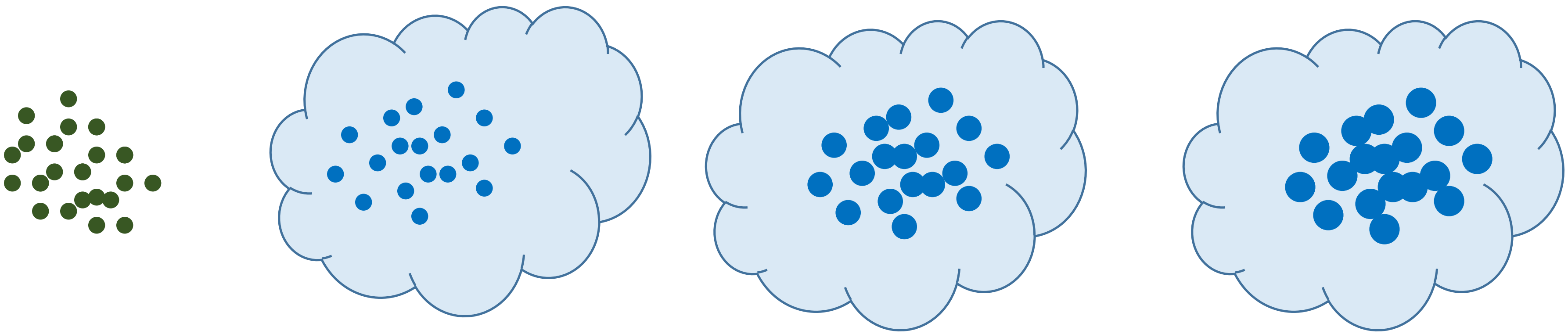
Why adding more CCN decreases average droplet size and increases cloud lifetime

High concentration of CCN

Form cloud droplets in supersaturated environment

That grow much slower as they compete for available vapor

No rain forms, cloud lasts longer



Aerosols, Climate, and the Hydrological Cycle

V. Ramanathan,[1*] P. J. Crutzen,[1,2] J. T. Kiehl,[3] D. Rosenfeld[4]

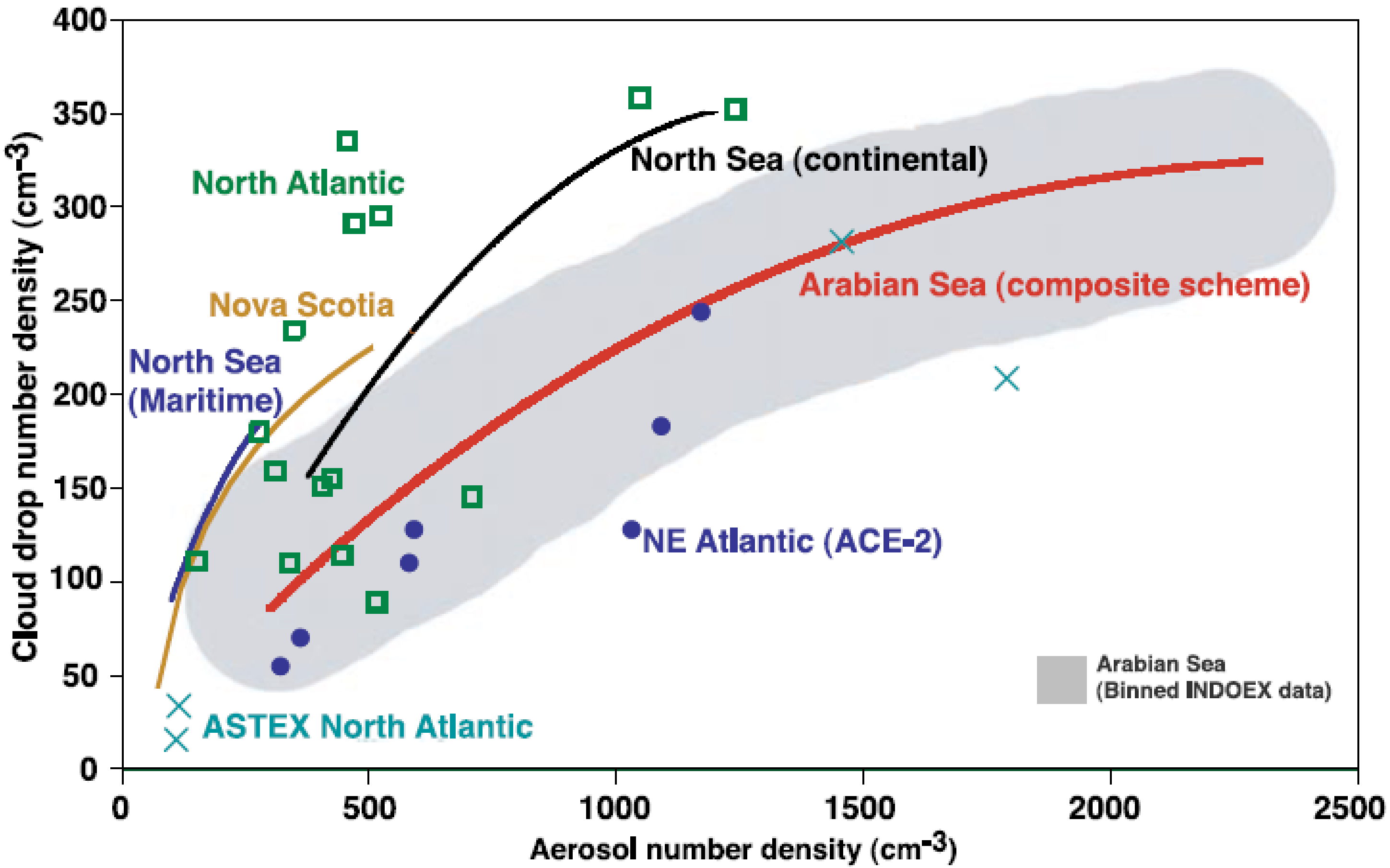
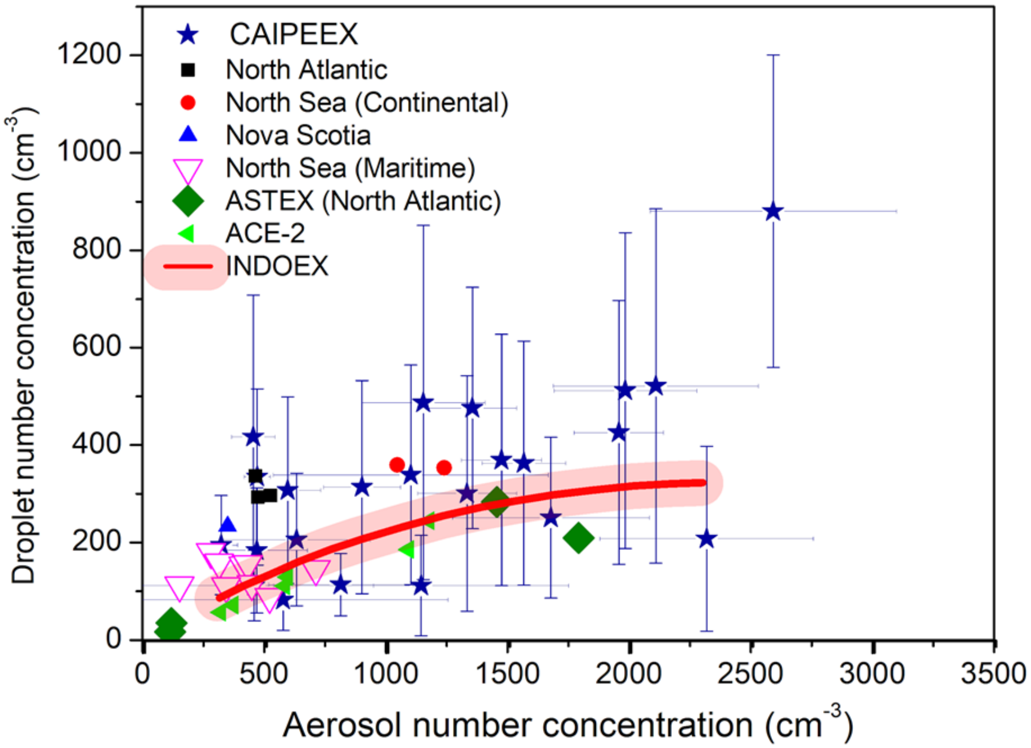
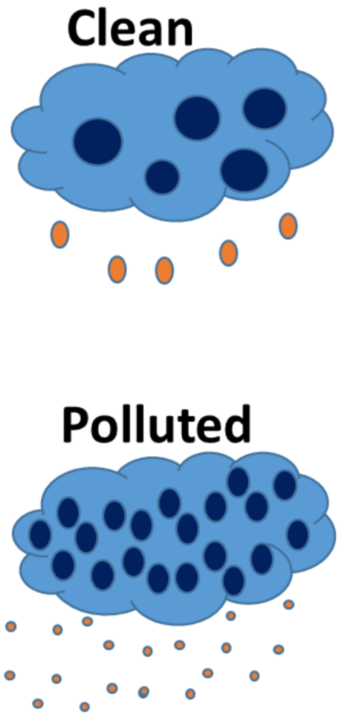


Fig. 5. Aircraft data illustrating the increase in cloud drops with aerosol number concentration. References for the data are as follows: North Sea (*28*), Nova Scotia and North Atlantic (*29*), ACE-2 (*30*), Astex (*31*), the thick red line is obtained from a composite theoretical parameterization that fits the INDOEX aircraft data for the Arabian Sea (*23*). The gray-shaded region is the INDOEX aircraft data for the Arabian Sea (*32*).

Human activ
human-made
produce brig
lead to large
correspondin
temperature
These aeroso
to availabilit
century.

Aerosol cloud interaction in liquid clouds



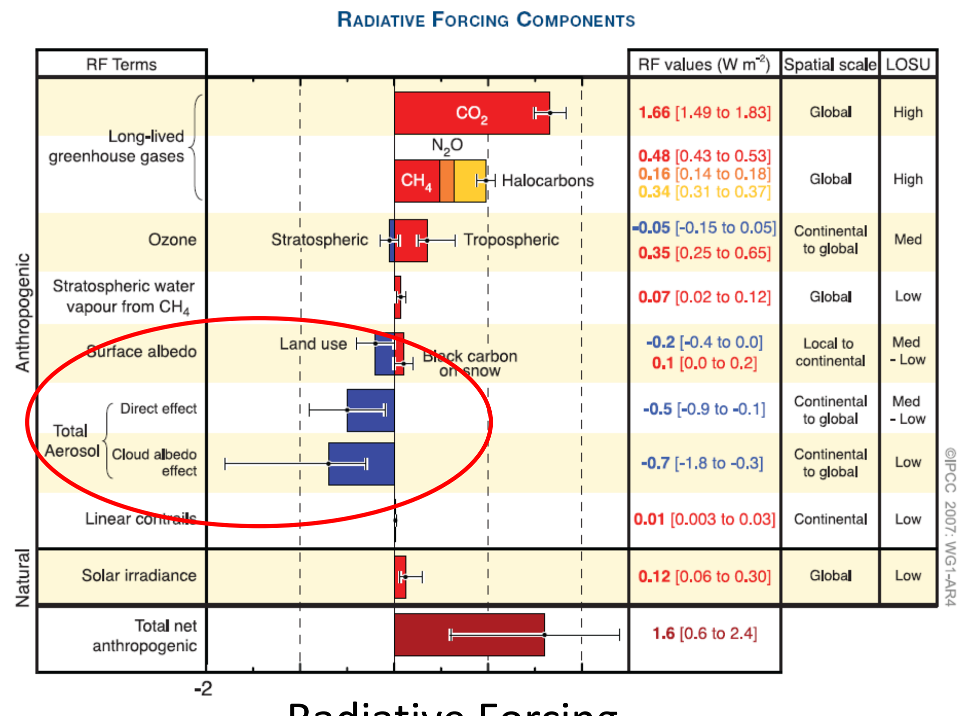


Source: Chapter in Encyclopedia of Water, Wiley publishers: Prabha and Khain (in press)

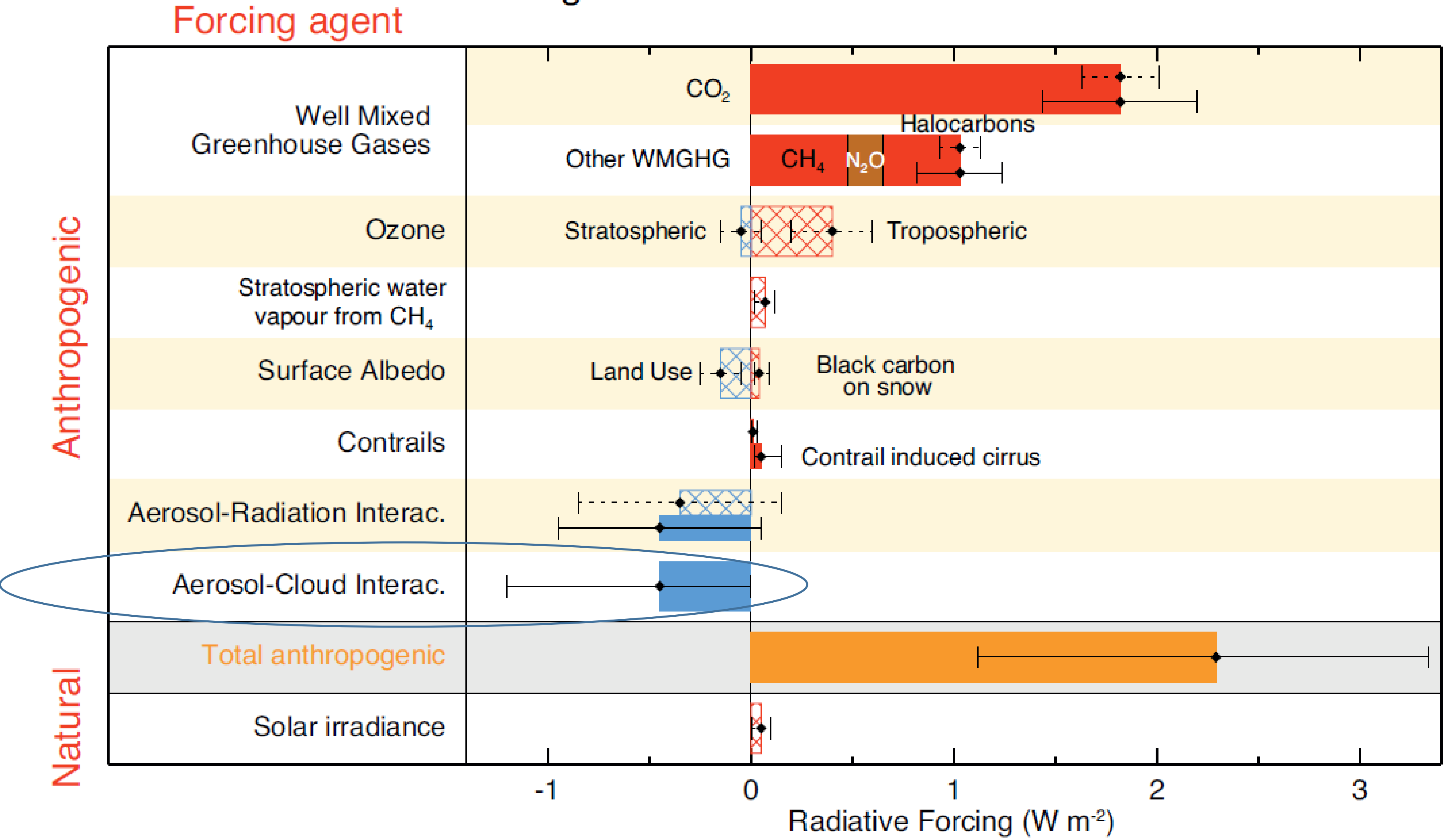
INDIAN INSTITUTE OF TROPICAL METEOROLOGY PUNE

Why do we care about aerosol-cloud interactions?

- Planetary albedo is strongly affected by clouds
- <u>Large</u> uncertainty in aerosol effects on albedo and radiative forcing
- <u>Larger</u> uncertainty in aerosol effects on <u>cloud</u> albedo and radiative forcing

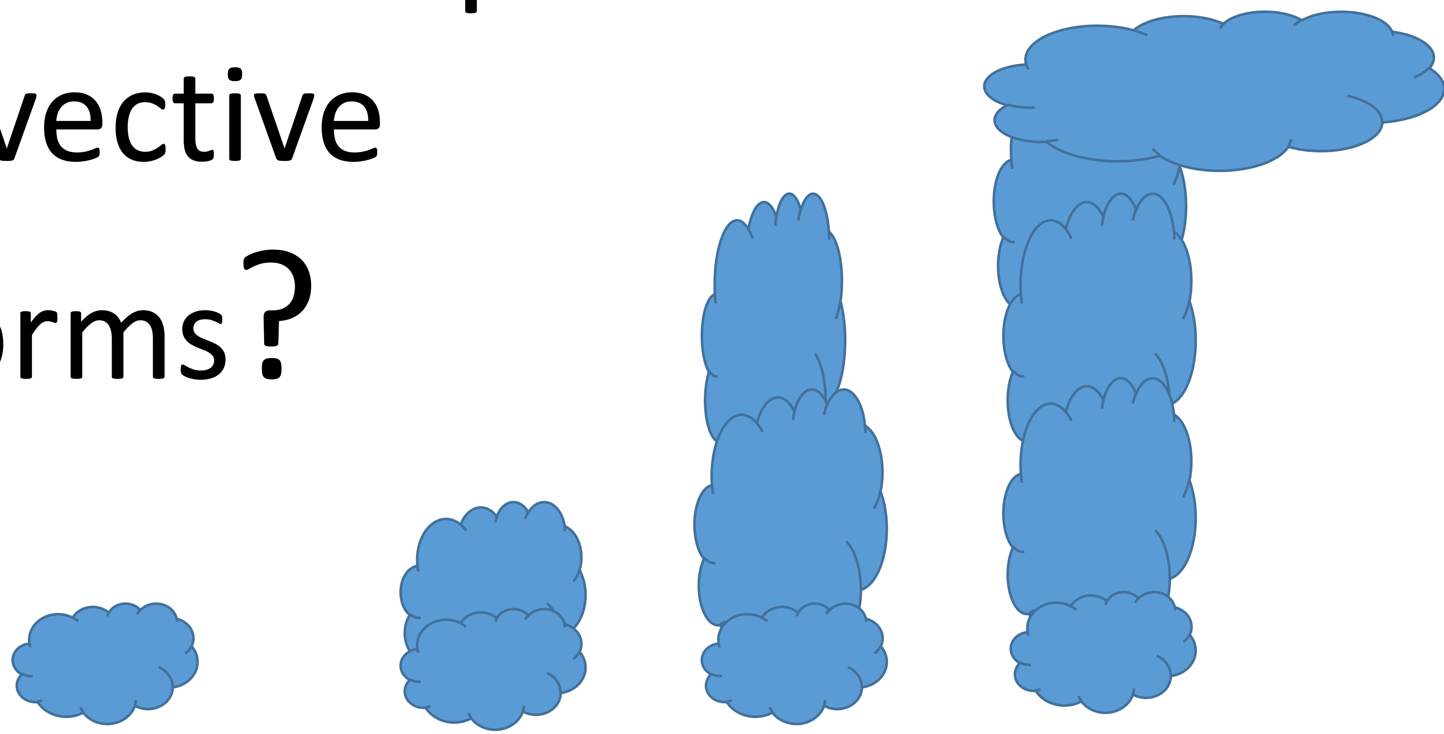


Radiative forcing of climate between 1750 and 2011

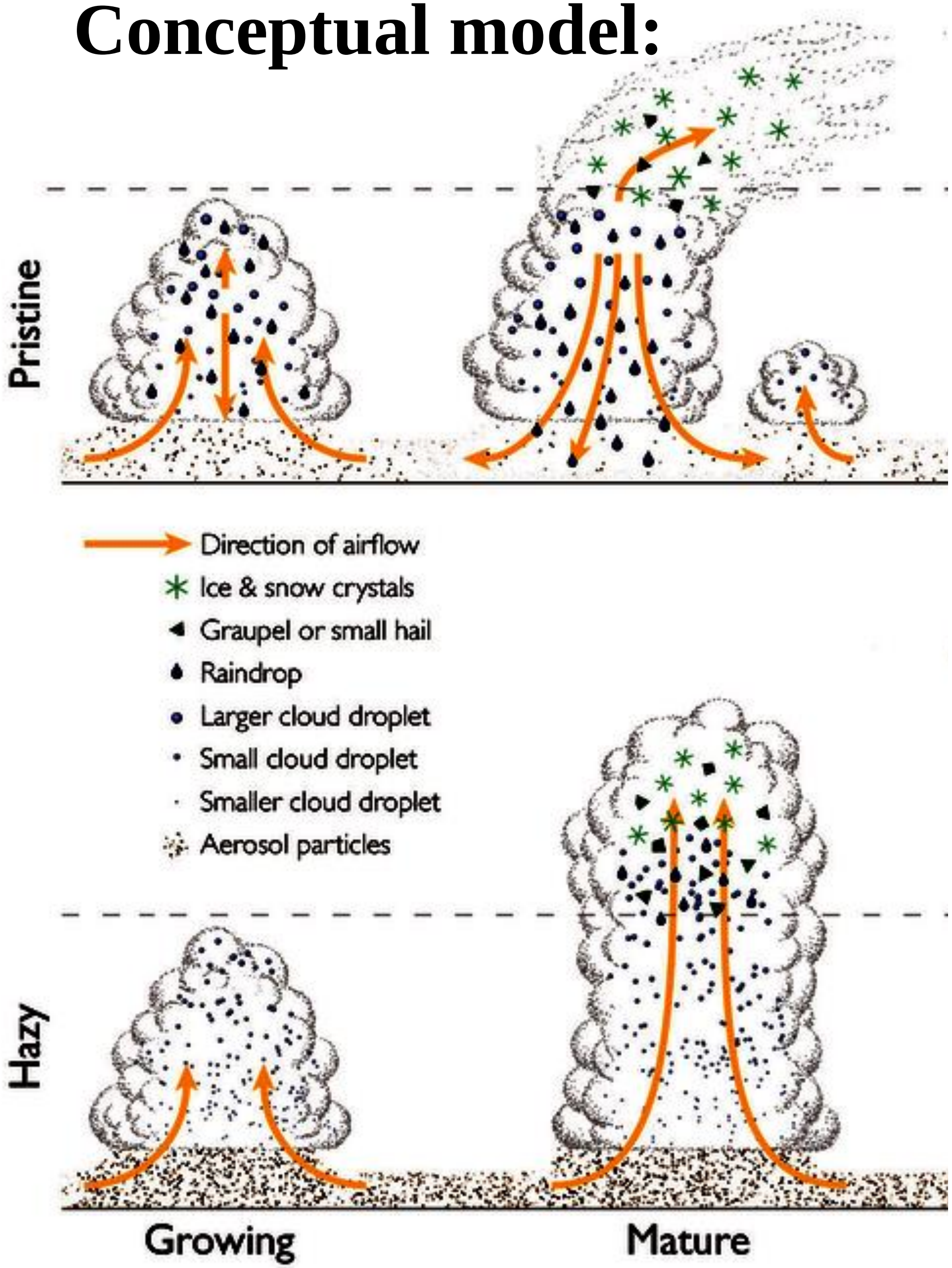


The net change in the energy balance of earth system due to an imposed change (**IPCC AR5**)

Do aerosols invigorate deep convective storms?

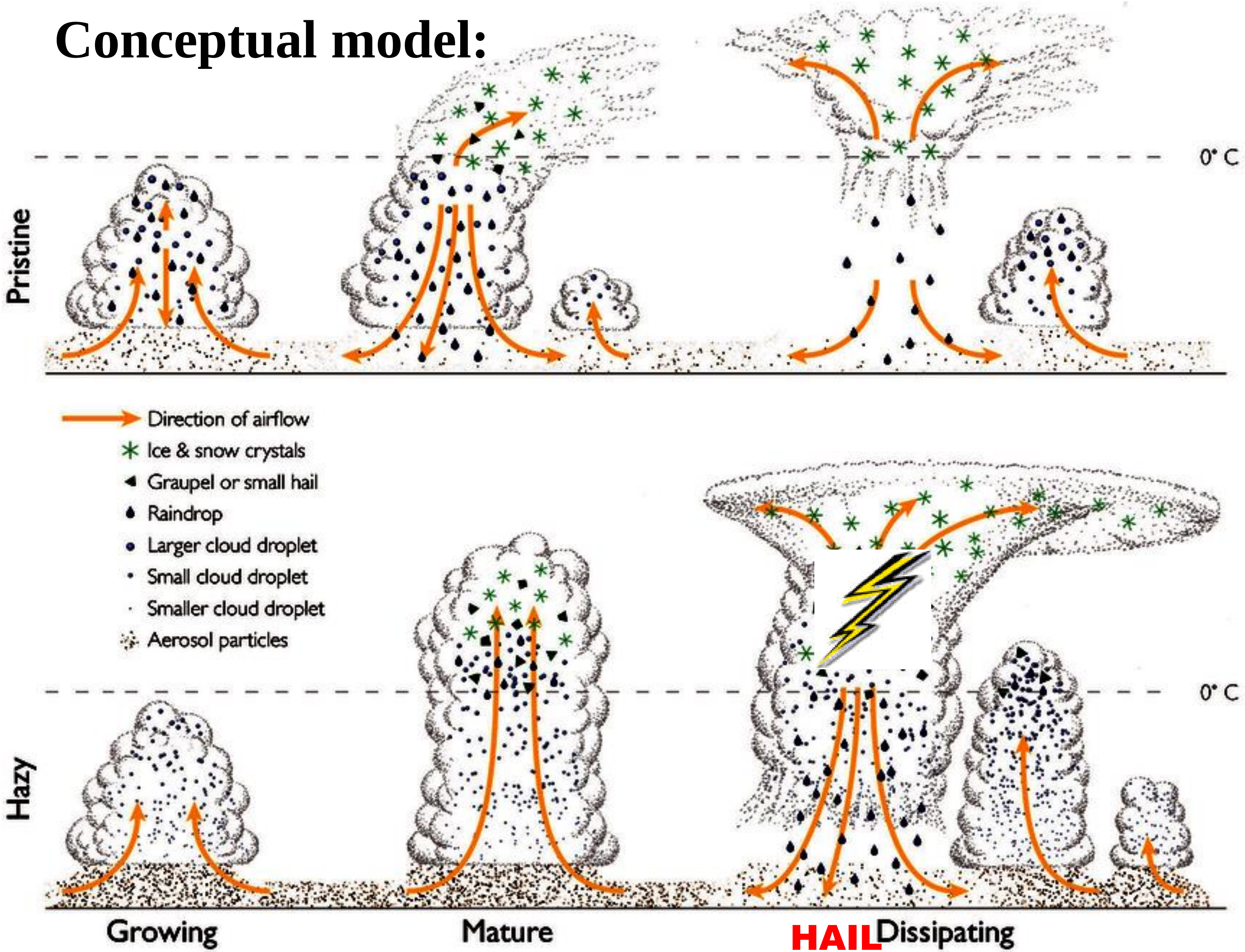


Conceptual model:



Graphics by Robert Simmon, NASA

Conceptual model:



Graphics by Robert Simmon, NASA

Increase in CCN

Small and numerous cloud droplets, suppress collision coalescence, delays raindrops and the ice formation (Khain et al., 2005).

Review on Invigoration (Altaratz et al, 2014)

Invigoration of convective storms

a) **Thermodynamic invigoration: latent heating and convective updrafts (Andreae et al., 2004; Tao et al., 2012)**

b) **Greater lightning activity, but with a large sensitivity to ice multiplication (Mansell and Ziegler 2013)**

c) **Weak winds (Koren et al., 2005; Khain et al., 2005; Tao et al., 2007; Storer and van den Heever, 2013)**

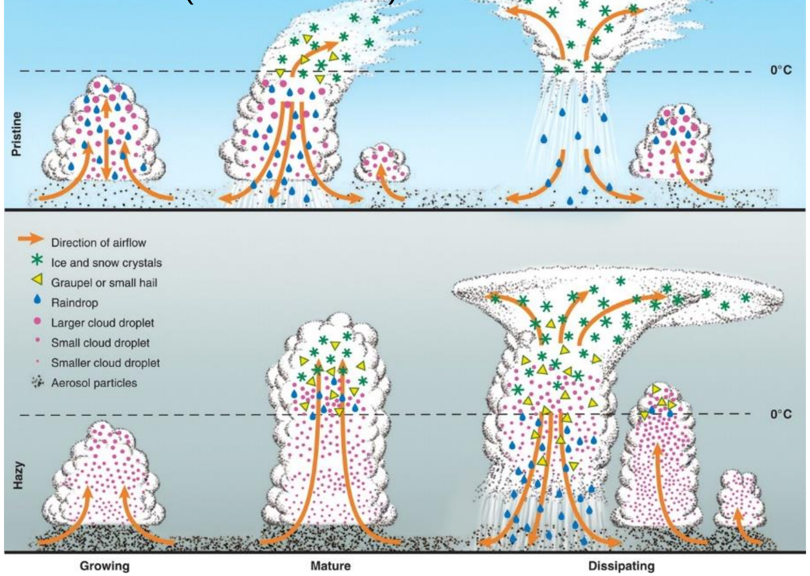
d) **Microphysical invigoration Fan et al., (2013, 2016).**

e) **Increased cloud fraction and cloud top height (Grabowski and Morrison 2016)**

f) **Anthropogenic aerosol may invigorate storms (Fan et al., 2018)**

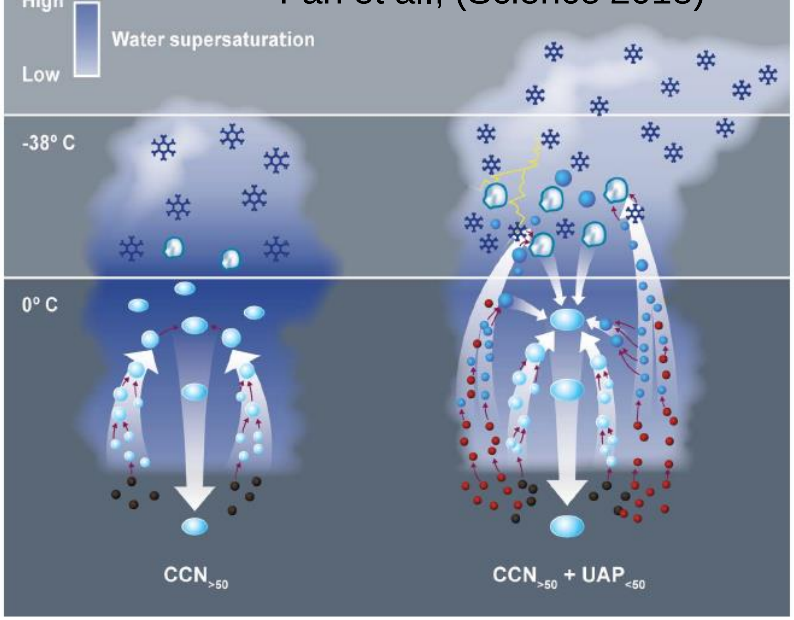
Pollution invigorate clouds ?

Rosenfeld (Science 2008)



Ultrafine particles make stronger storms ?

Fan et al., (Science 2018)



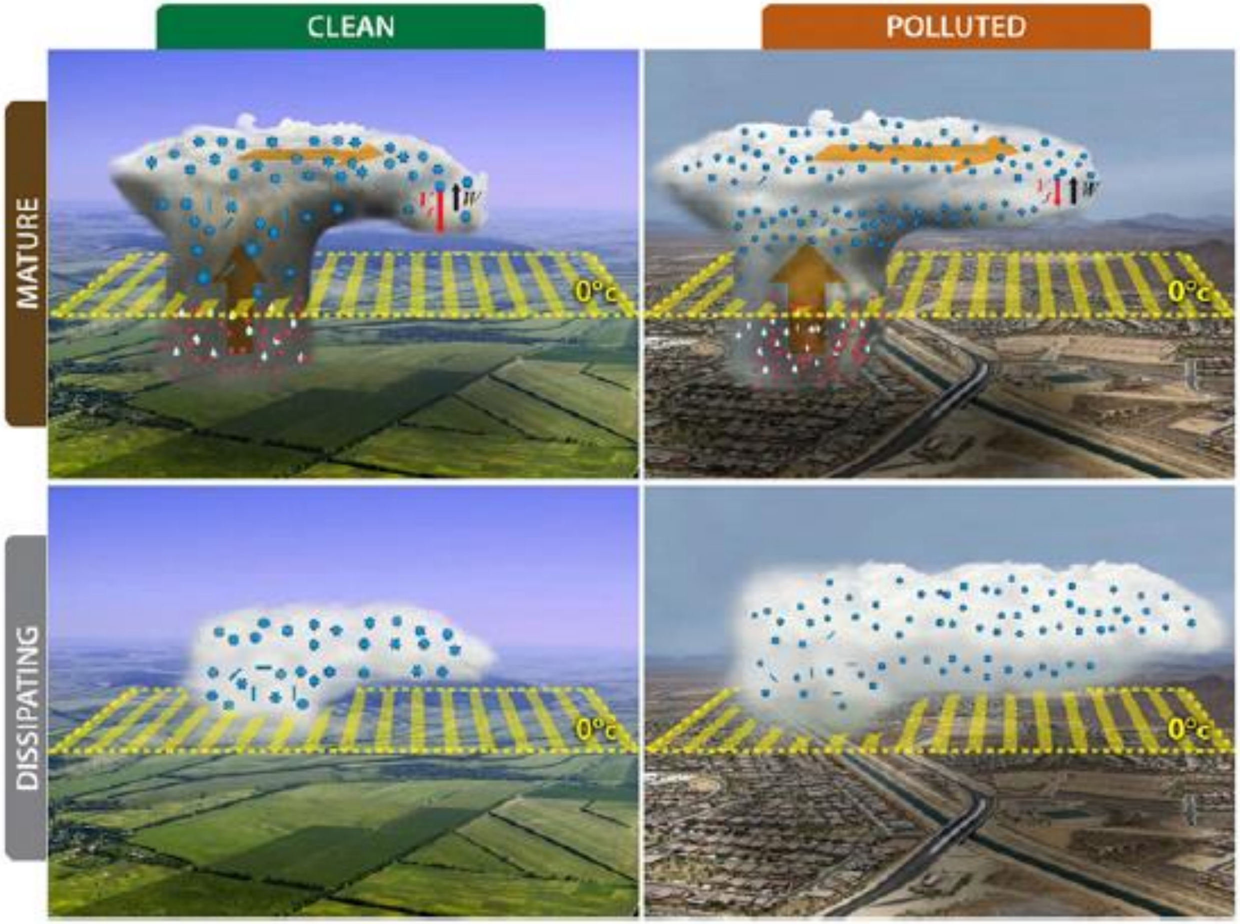
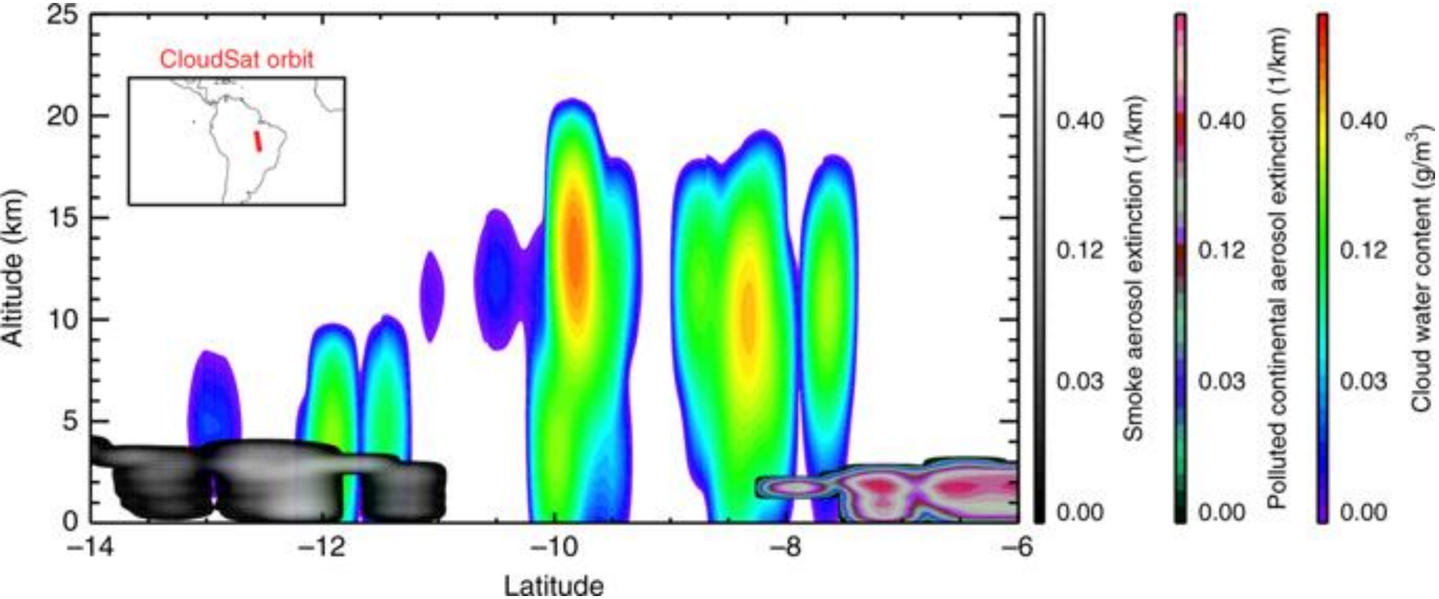
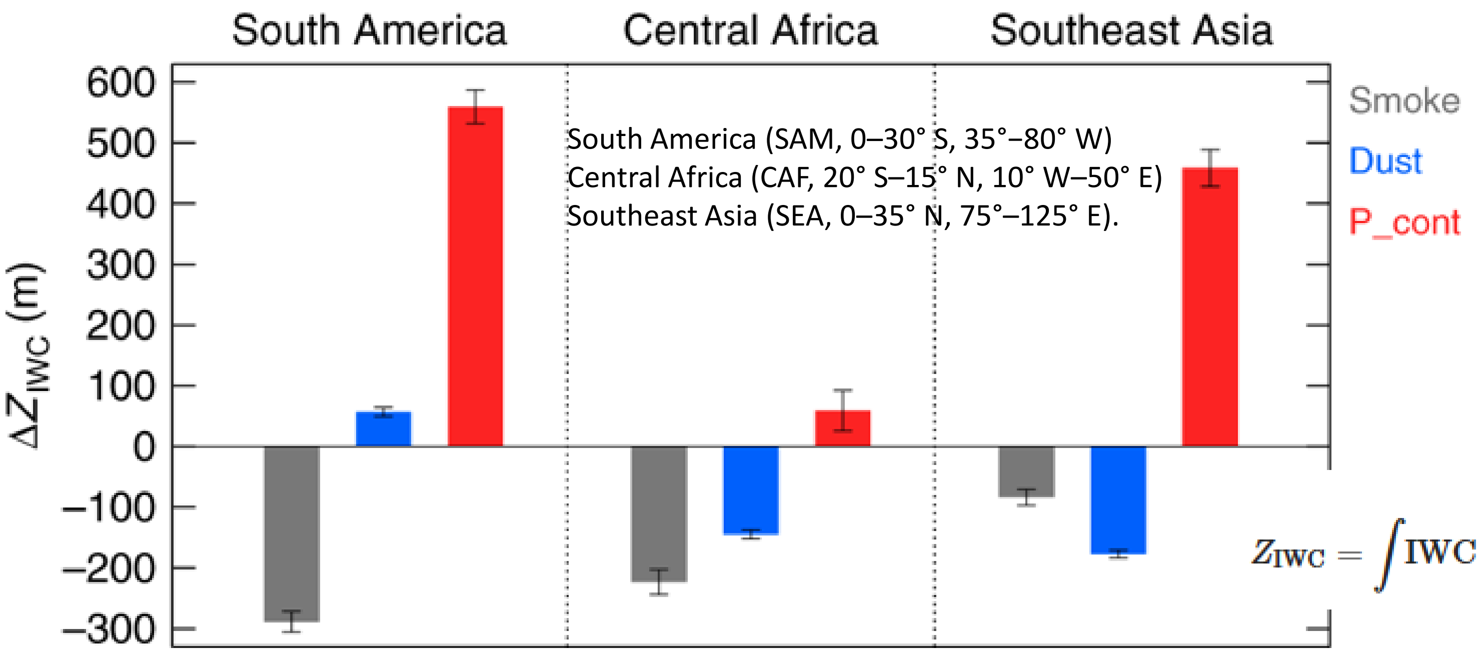


Fig. 9. Schematic illustration of the differences in CTH, cloud fractions, and cloud thickness for the storms in clean and polluted environments. Red dots denote cloud droplets, light blue dots represent raindrops, and blue shapes are ice particles. In the polluted environment, convective cores detrain larger amounts of cloud hydrometeors of much smaller size, leading to larger expansion and much slower dissipation of stratiform/anvil clouds resulting from smaller fall velocities of ice particles because of much reduced sizes. Therefore, the larger cloud cover, higher CTHs, and thicker clouds are seen in the polluted storm after the mature stage.

The microphysical effects induced by aerosols are a fundamental reason for the observed increases in cloud fraction, cloud top height, and cloud thickness in the polluted environment, even when invigoration is absent.

Observational study based on Calipso data





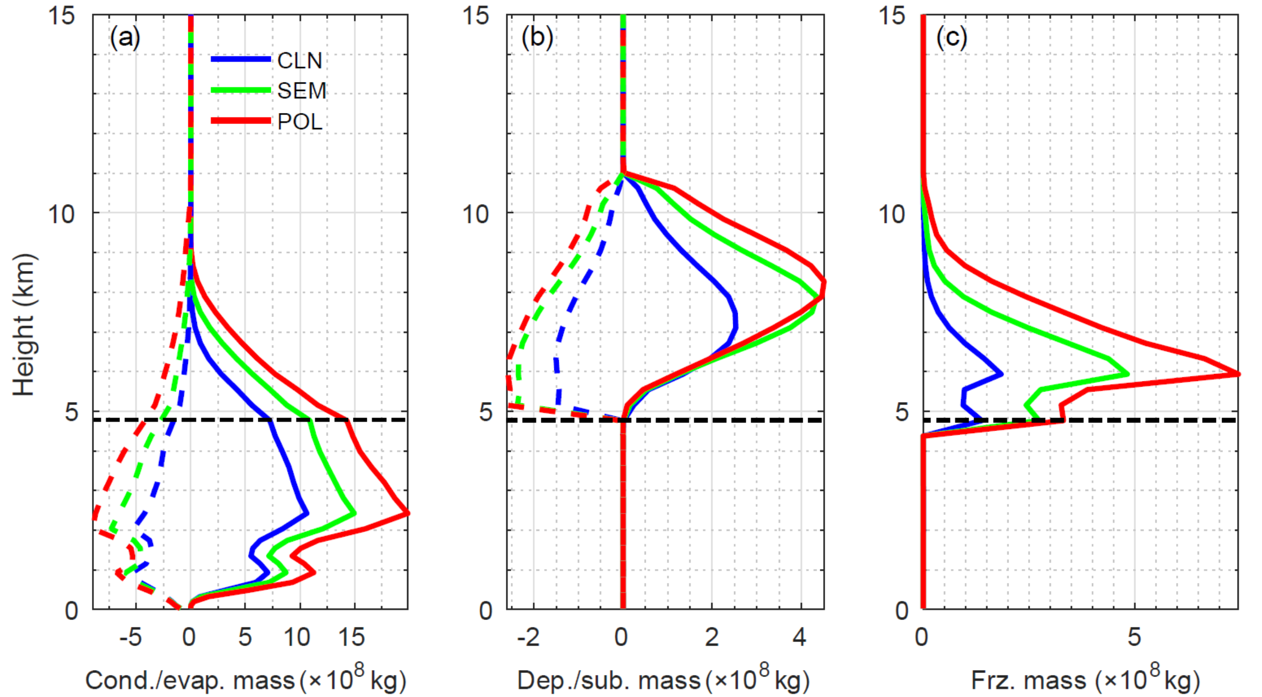
$$Z_{\mathrm{IWC}} = \int \mathrm{IWC} \cdot z \cdot \mathrm{d}z \Big/ \int \mathrm{IWC} \cdot \mathrm{d}z,$$

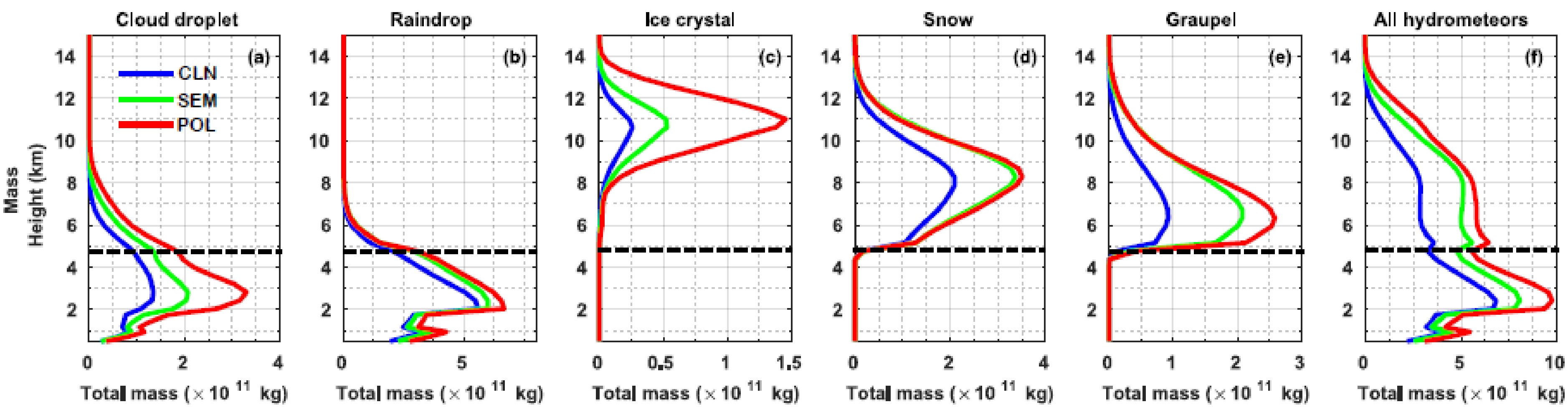
smoke, dust and polluted continental aerosol

Jiang et al, 2018

Liquid phase influences the mixed phase processes in deep convective cloud

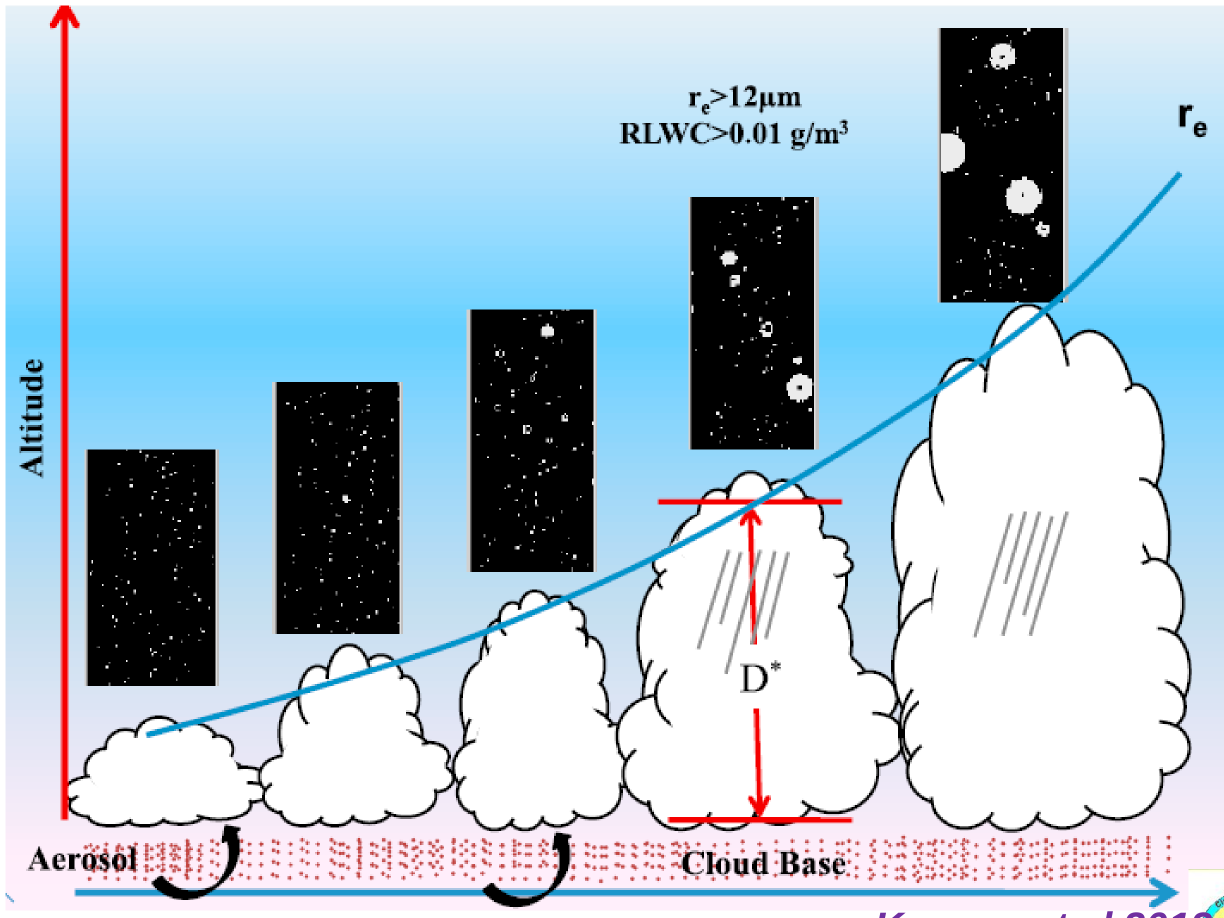
Clean to polluted conditions



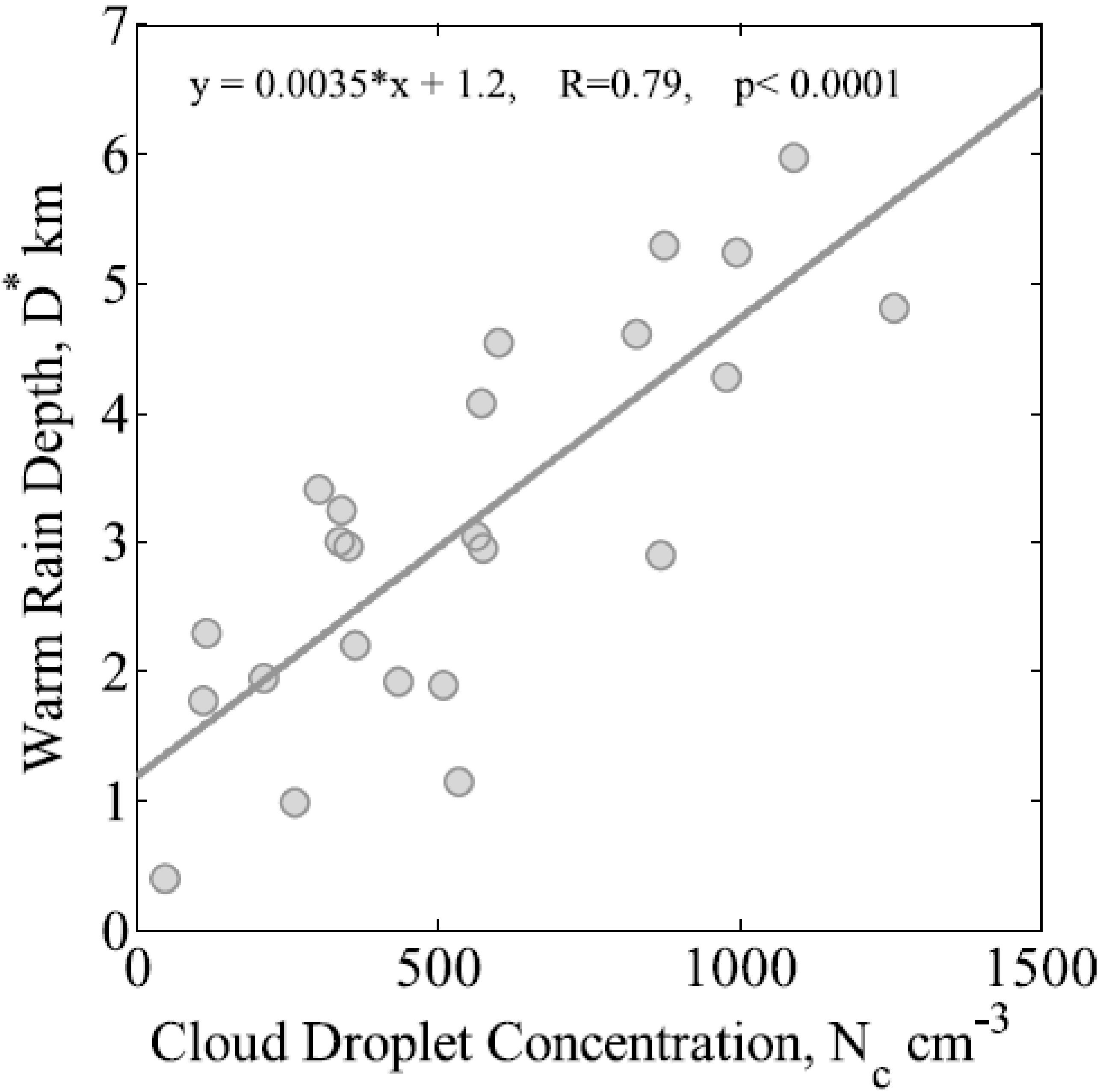


Chen et al., 2017

Pollution elevates the level of rain drop formation



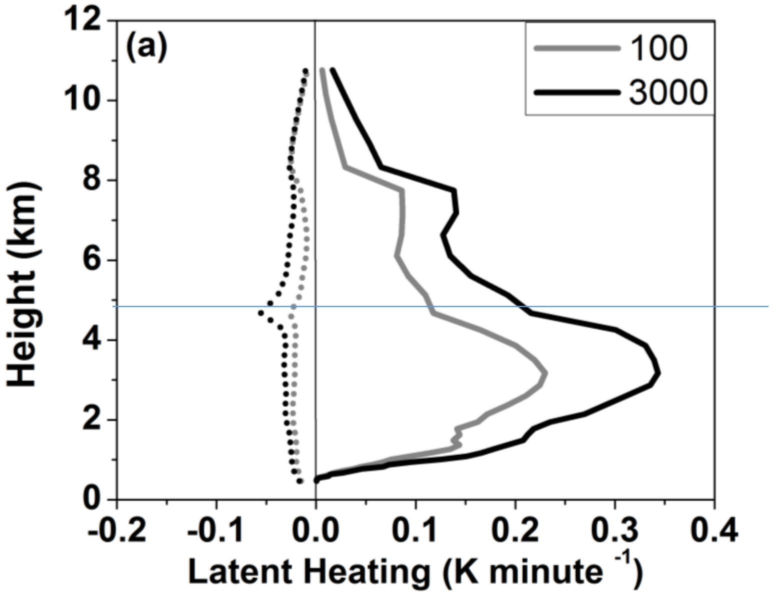
Konwar et al 2012

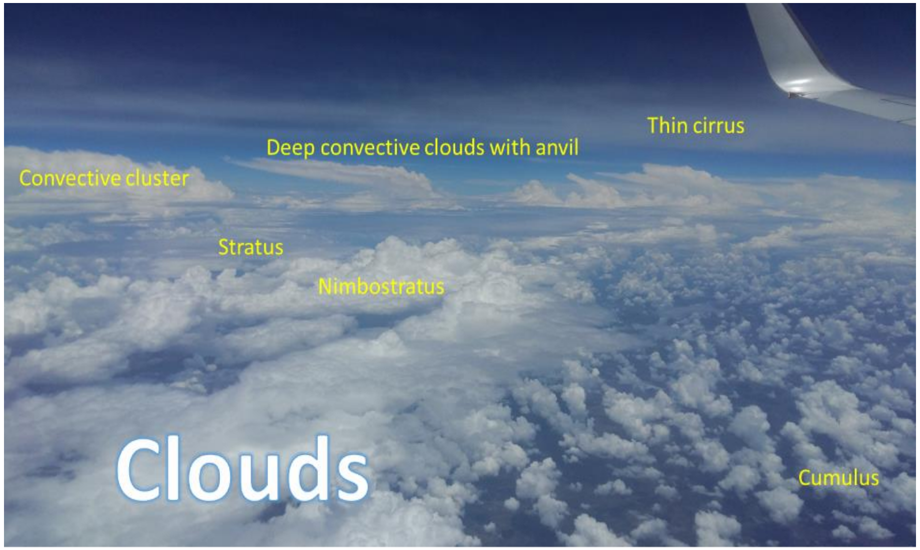


Konwar et al., Aerosol control on** depth of warm rain in convective clouds**,** **Journal of Geophysical Research, 117, 2012, D13204

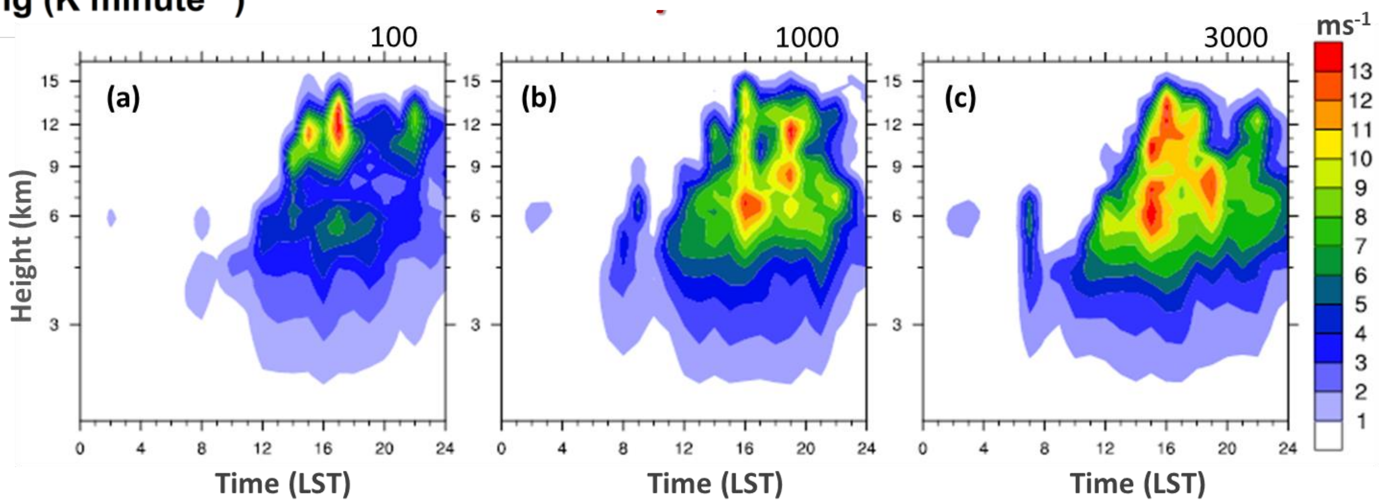
Aerosol impact on congestus/ deep cumulus clouds:

Invigoration of warm phase : More warm clouds will cross the freezing level to regions where mixed phase processes become important



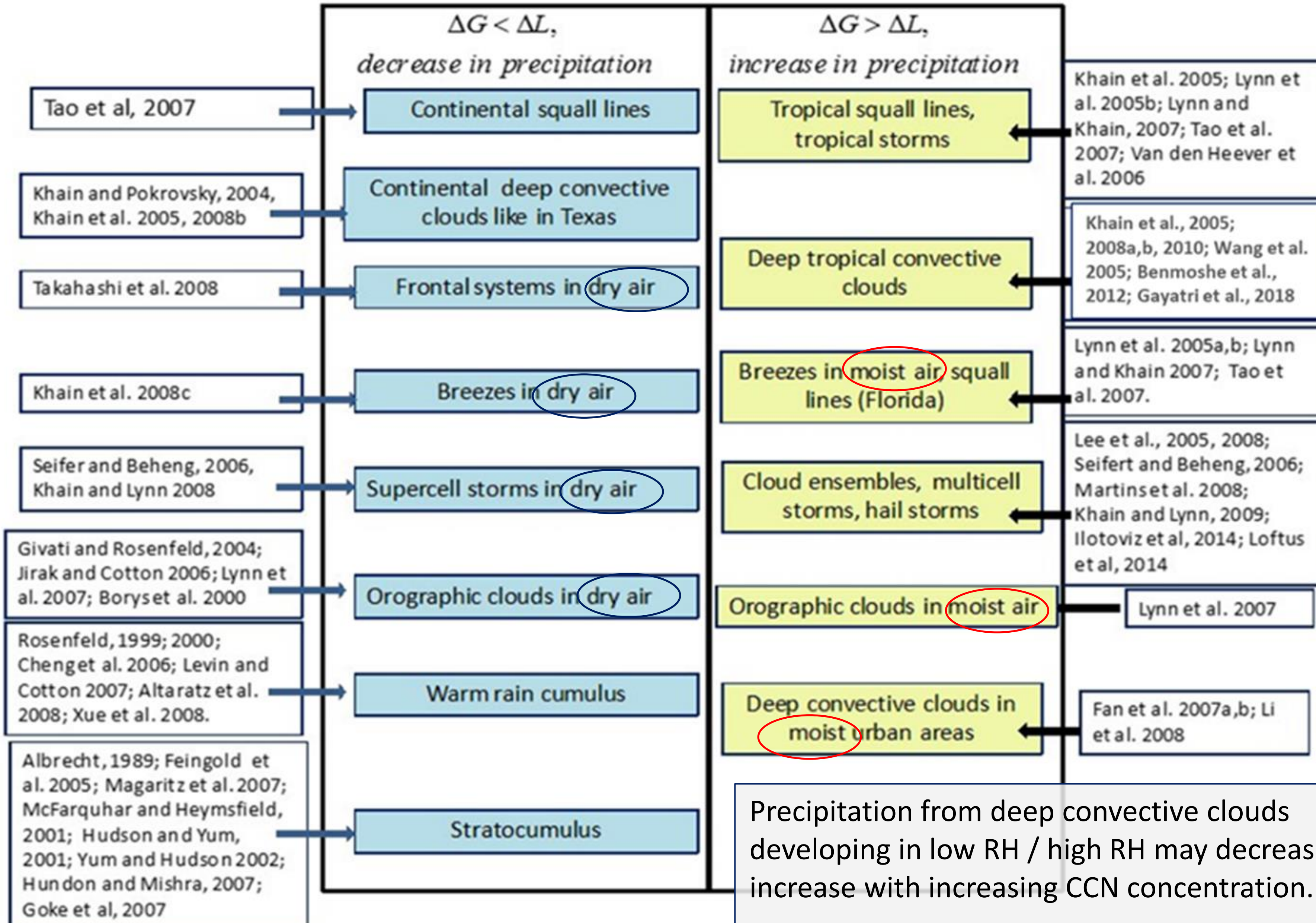


Increase in cloud core updrafts



Gayatri et al., 2017

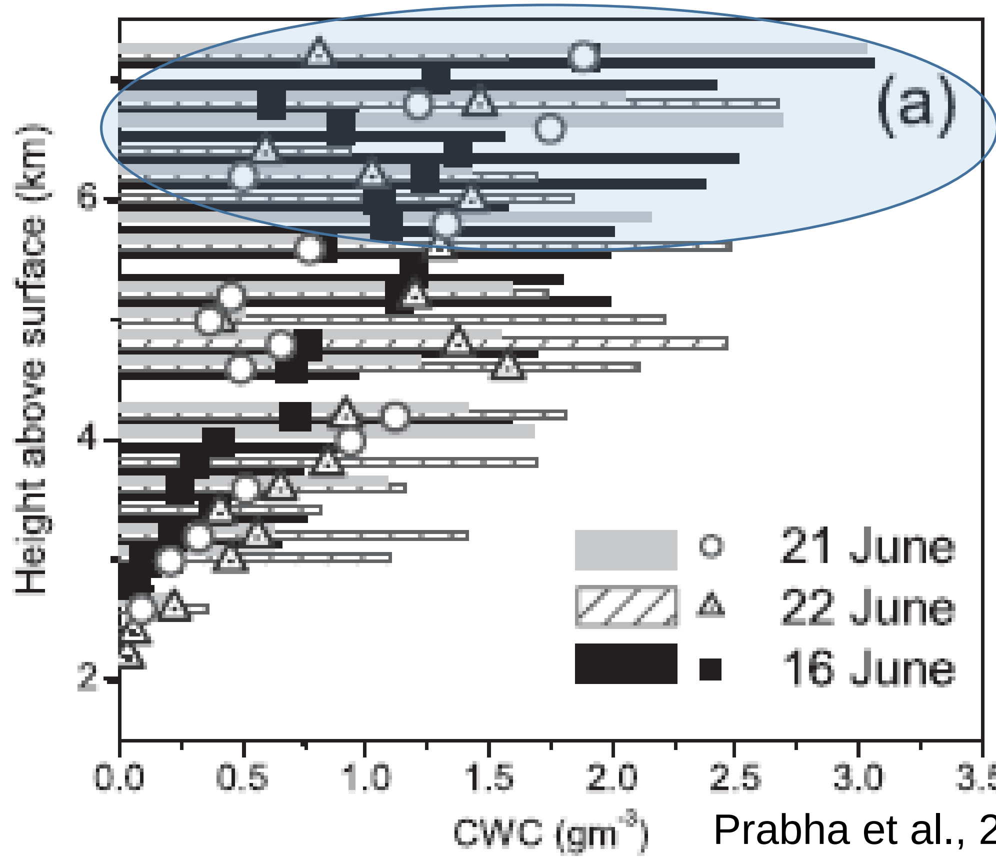
Decrease ⇦ Precipitation ➡ Increase



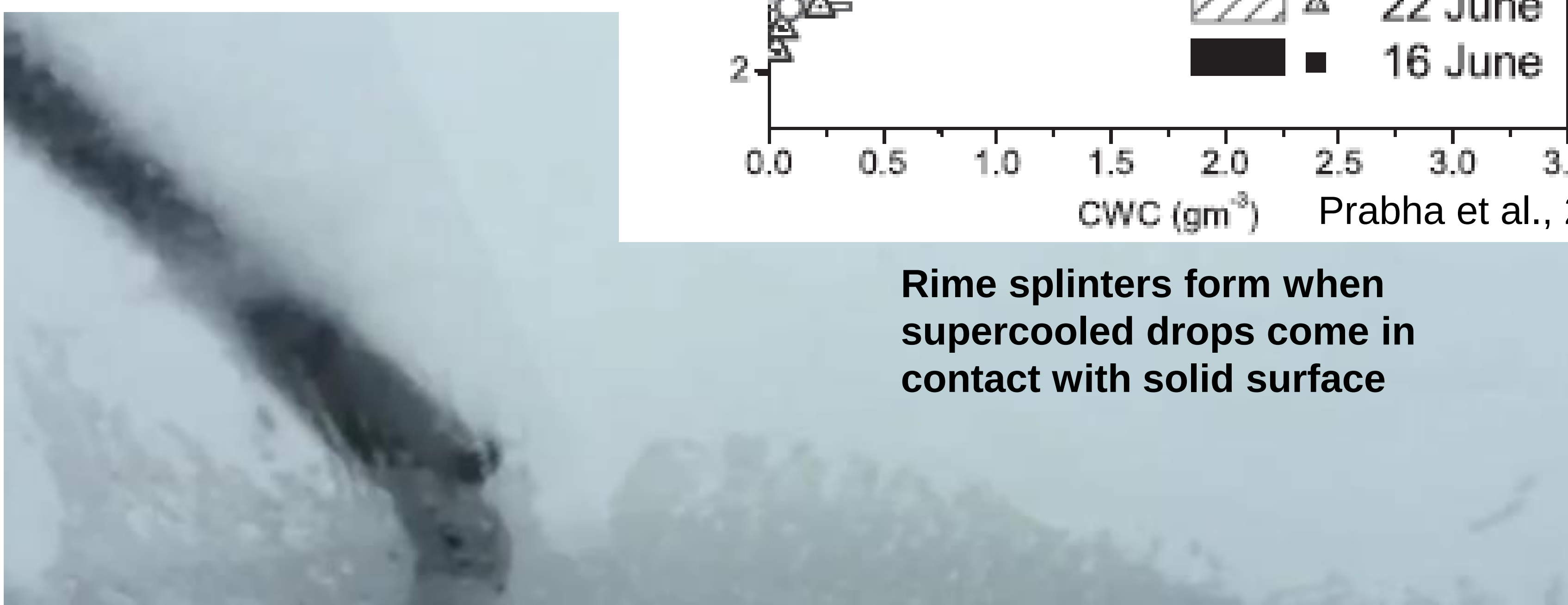
Precipitation from deep convective clouds developing in low RH / high RH may decrease / increase with increasing CCN concentration.

Cloud liquid water (CWC) profile from in situ measurements

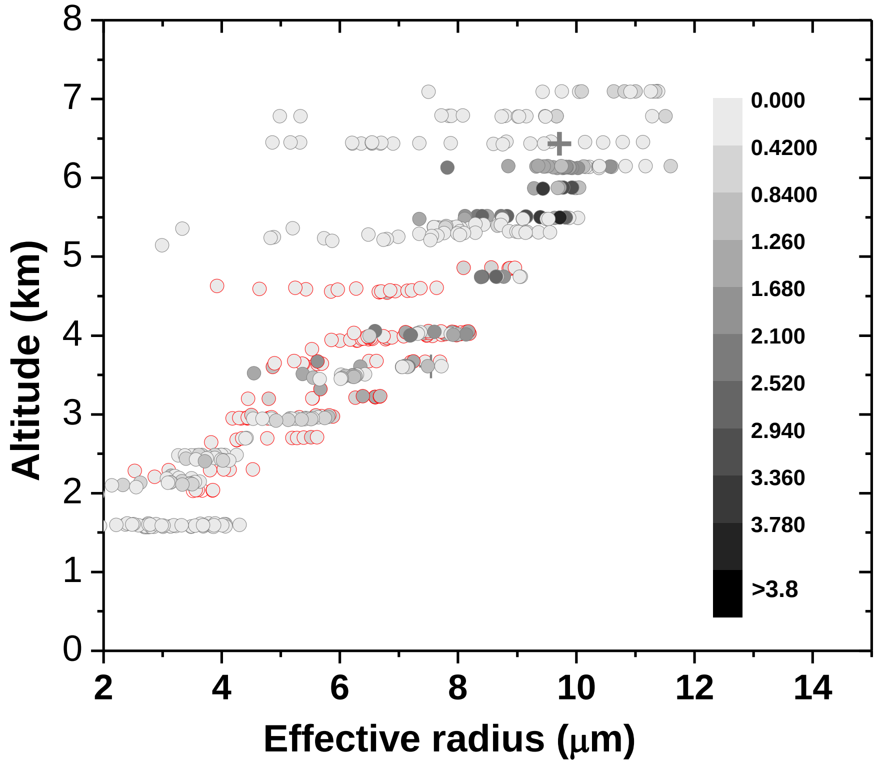
- Maximum Liquid water content at higher elevation
- High supercooled liquid water content

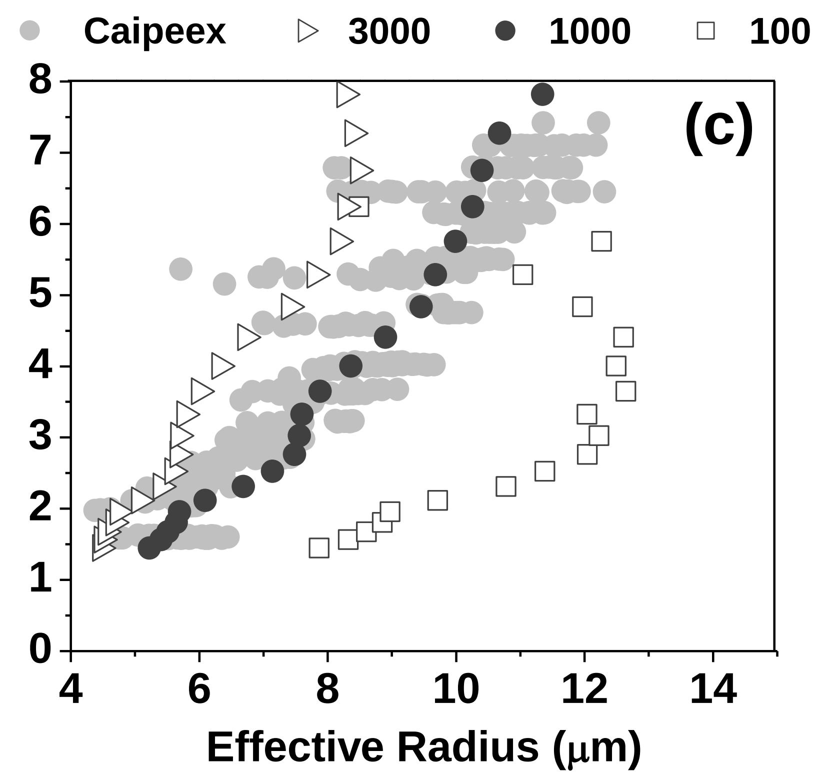


Prabha et al., 2011



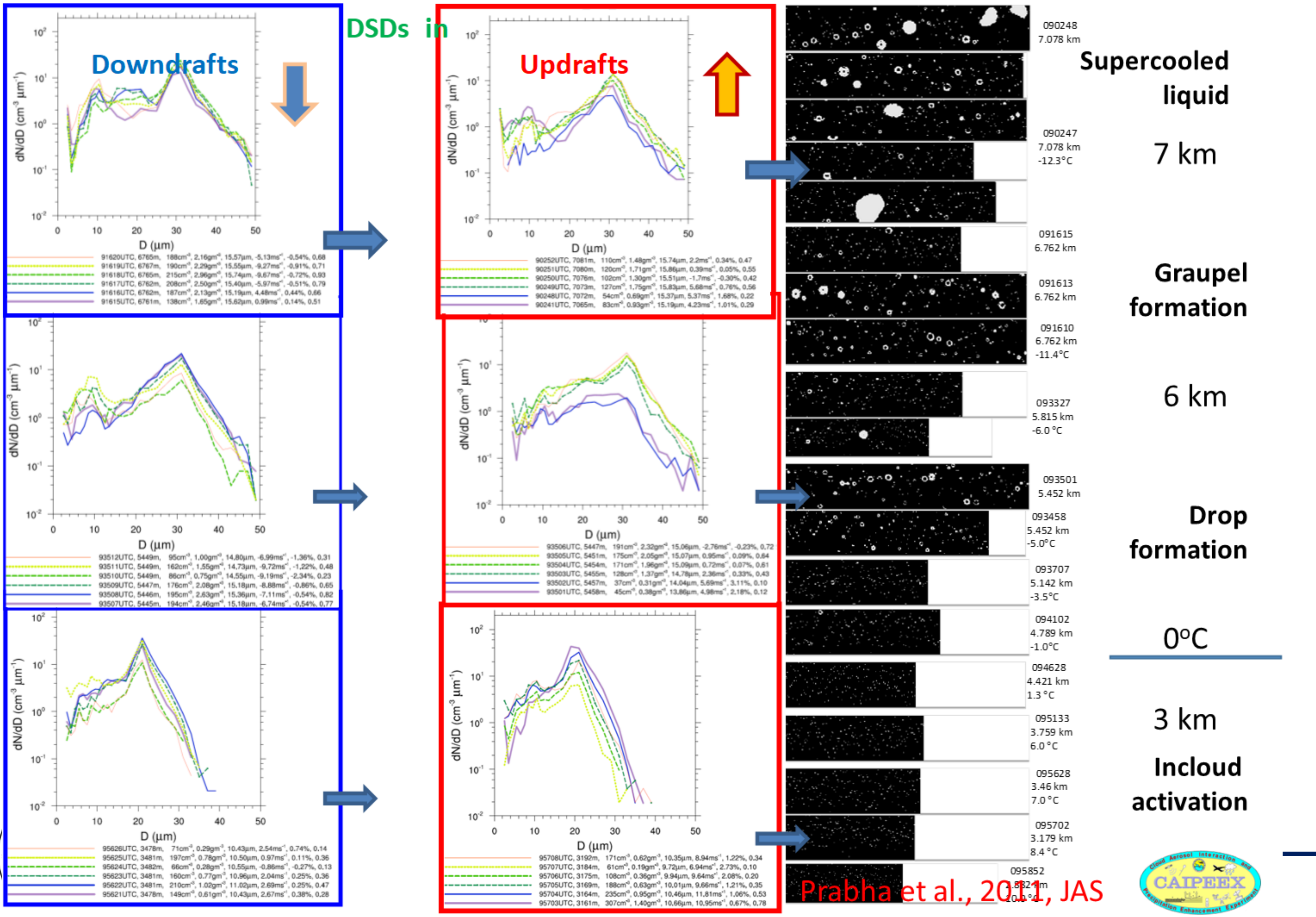
Vertical variation of cloud effective radius from CAIPEEX observations and bin simulations



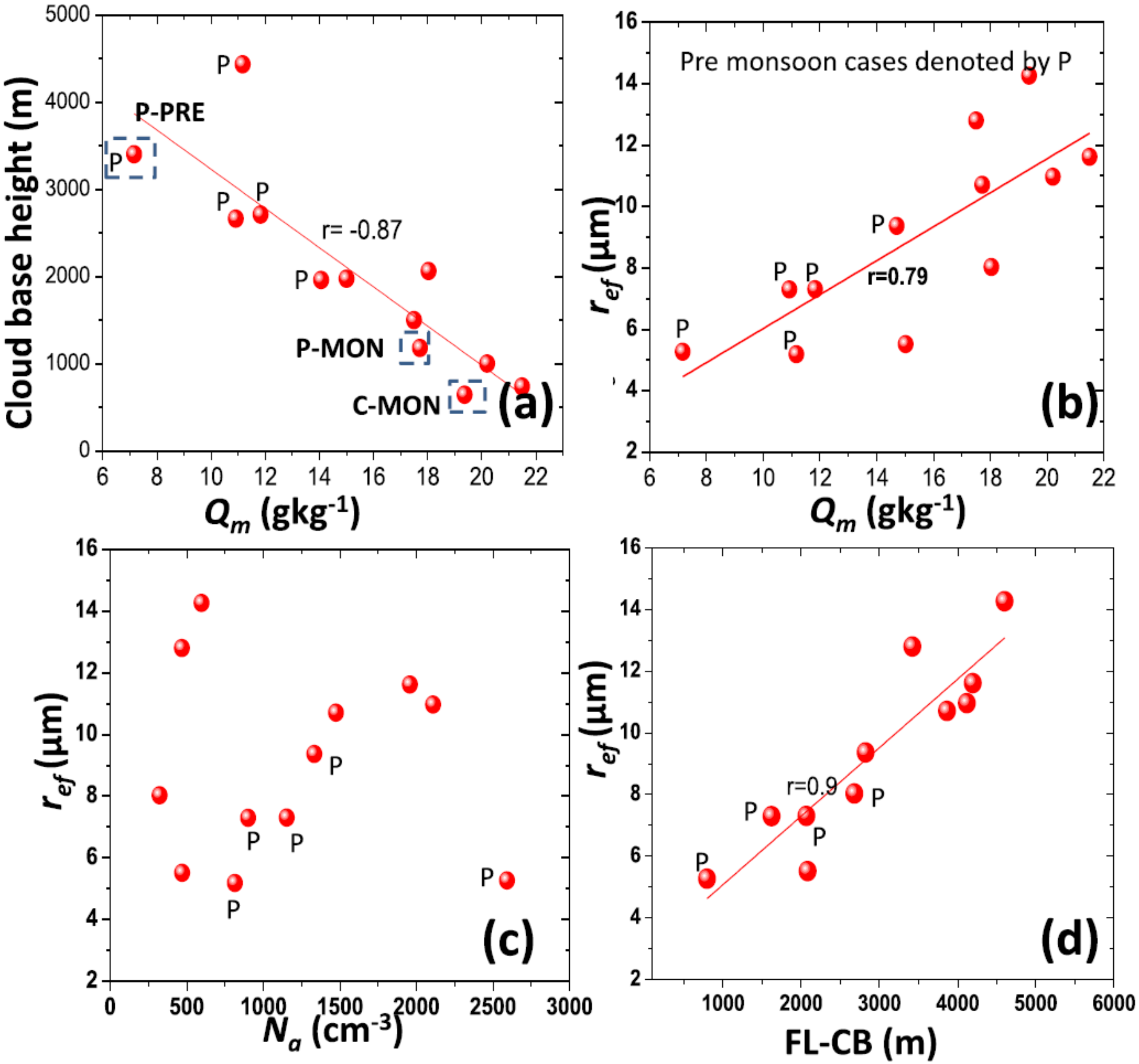


Gayatri K., S. Patade and T. V. Prabha. Aerosol cloud interaction in deep convective clouds over the Indian peninsula using Spectral (bin) Microphysics, 2017, *Journal of Atmospheric Science*,10.1175/JAS-D-17-0034.1

Vertical structure of microphysics of monsoon clouds: mixed phase



Effective radius at freezing level increases with subcloud moisture content and aerosol number concentration

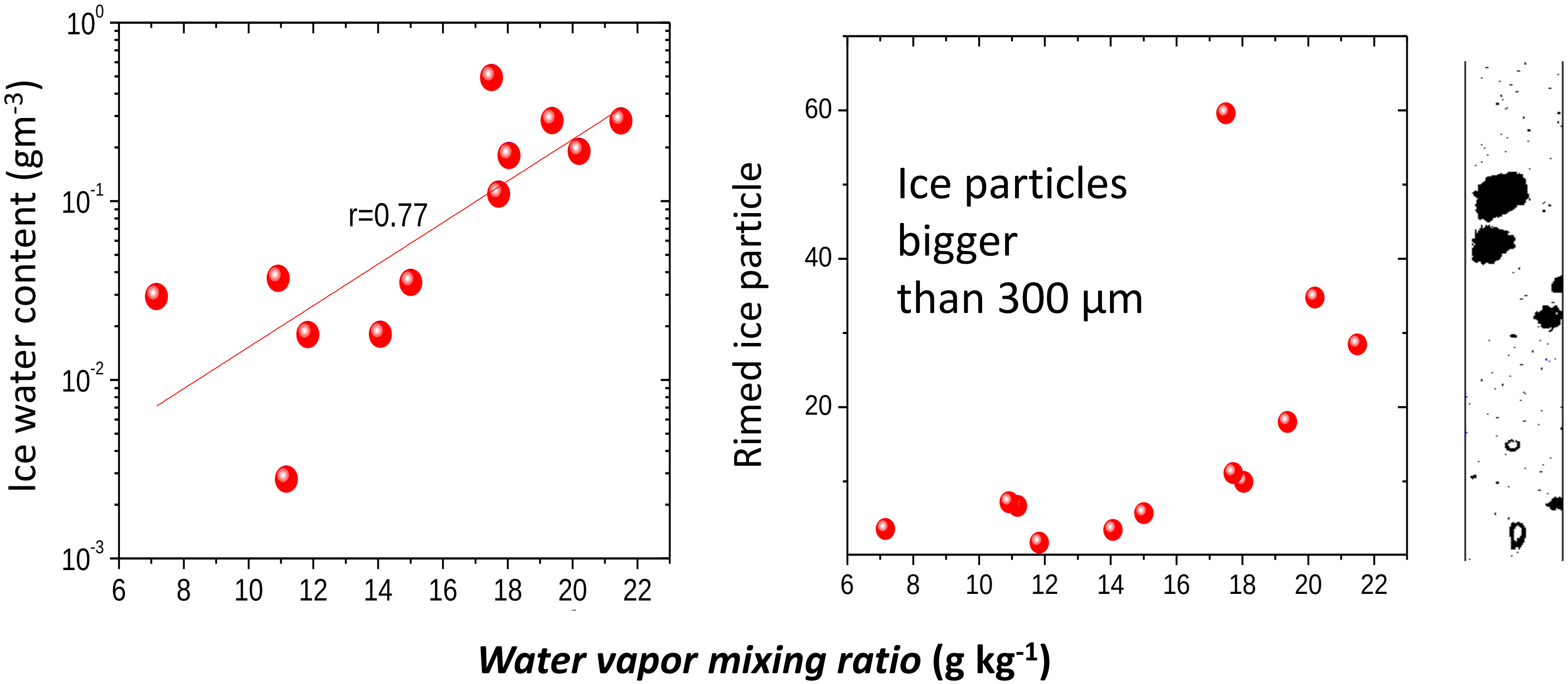


Patade et al., 2019)

Each point correspond to a Deep convective cloud observation from CAIPEEX flight

Effect moisture on ice microphysics is complex from observations alone
Especially in understanding the processes

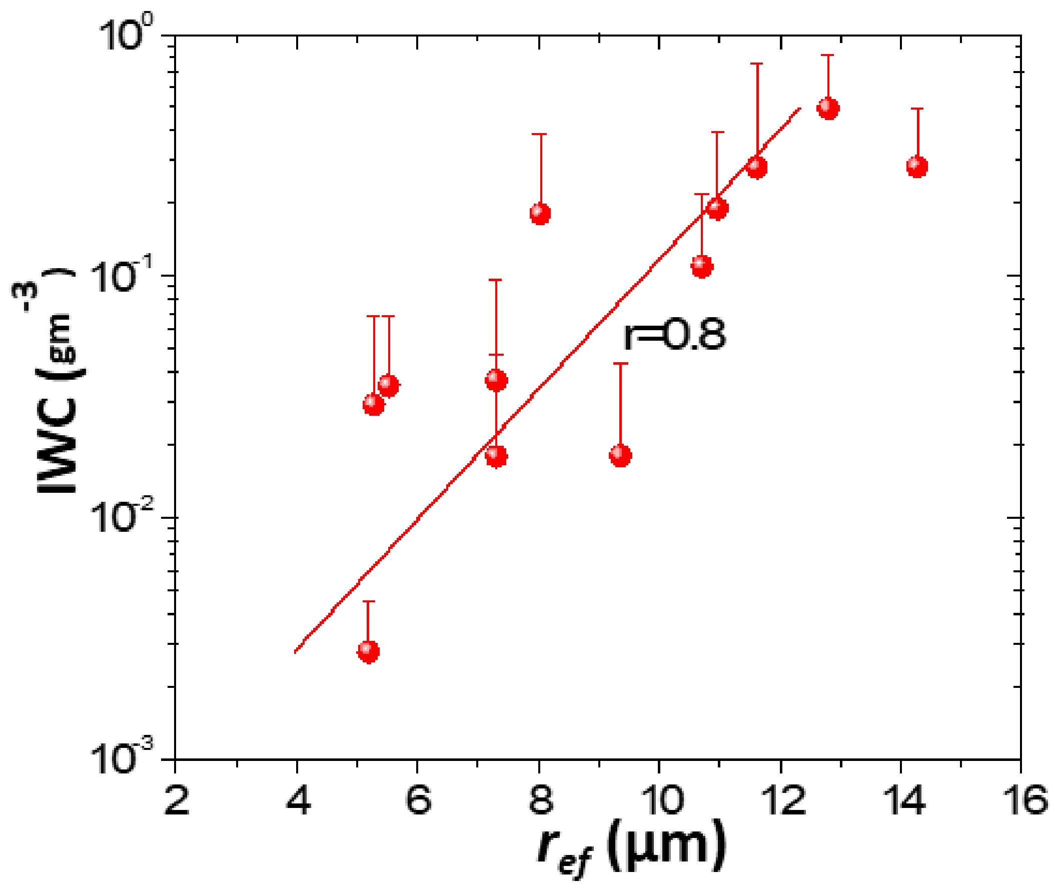
Ice water content and rimed ice particle number concentration



- Higher ice mass in clouds growing over moist boundary layer
- Ice particle growth by riming increases with increase in moisture contribute to Broader spectra

Patade et al., 2019)

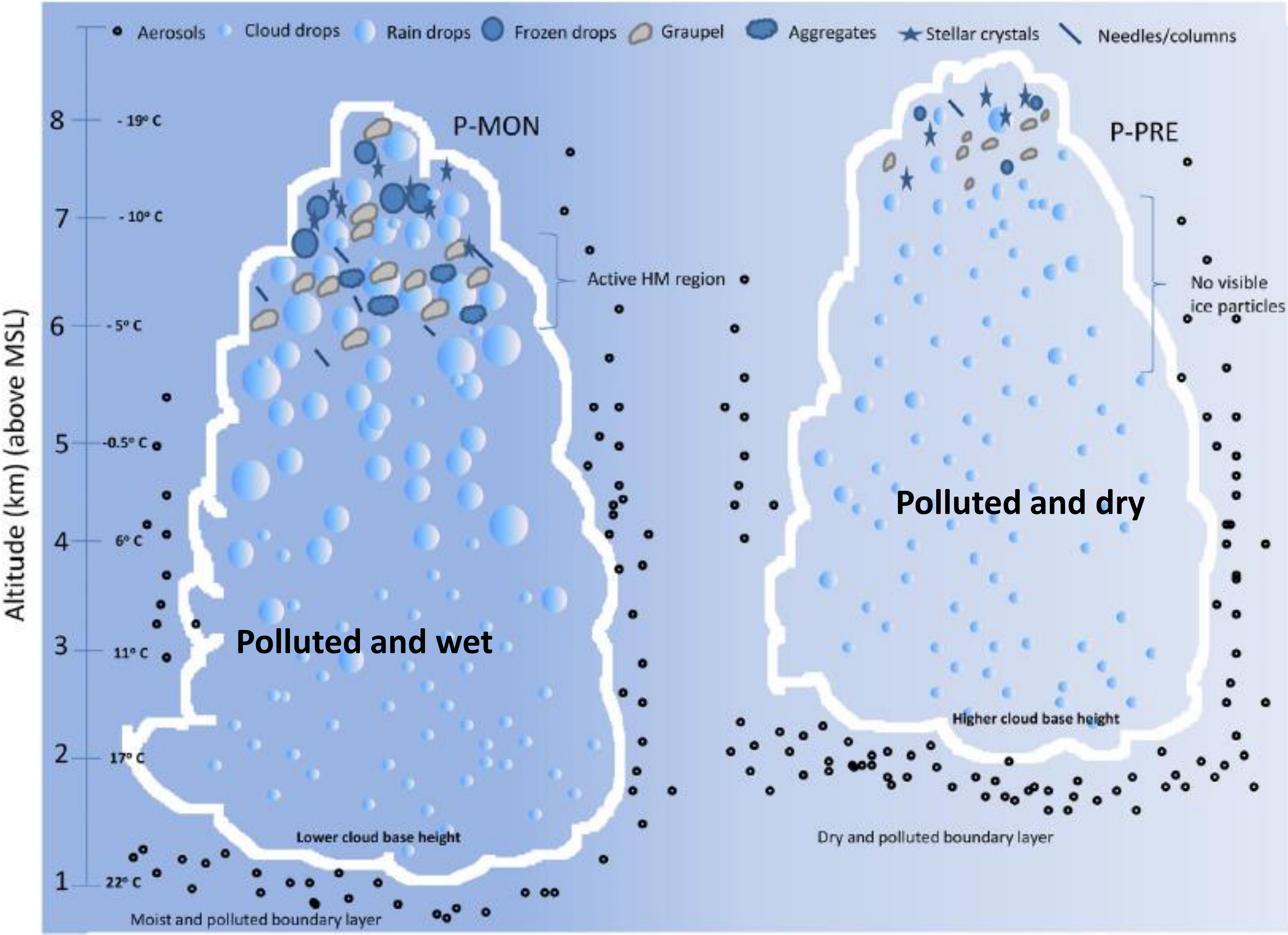
Liquid and ice processes in a mixed phase cloud



Each point correspond to a Deep convective cloud observation from CAIPEEX flight

7 Monsoon and 5 pre-monsoon

Patade et al., 2019)


Aerosols
Cloud drops
Rain drops
Frozen drops
Graupel
Aggregates
Stellar crystals
Needles/columns
Altitude (km) (above MSL)
8
7
6
5
4
3
2
1
- 19° C
- 10° C
- 5° C
-0.5° C
6° C
11° C
17° C
22° C
P-MON
Active HM region
Polluted and wet
Lower cloud base height
Moist and polluted boundary layer
P-PRE
No visible ice particles
Polluted and dry
Higher cloud base height
Dry and polluted boundary layer

Cloud albedo effect

- More aerosols compete for uptake of water vapor, cloud droplet does not grow
- As a result more numerous, smaller cloud droplets – have larger surface area than few large cloud droplets
- The polluted cloud reflect more solar radiation back to space- negative radiative forcing (cloud albedo effect)
- - does not cause a change in precipitation

Cloud albedo and lifetime effect (negative radiative effect for warm clouds at TOA; less precipitation and less solar radiation at the surface)

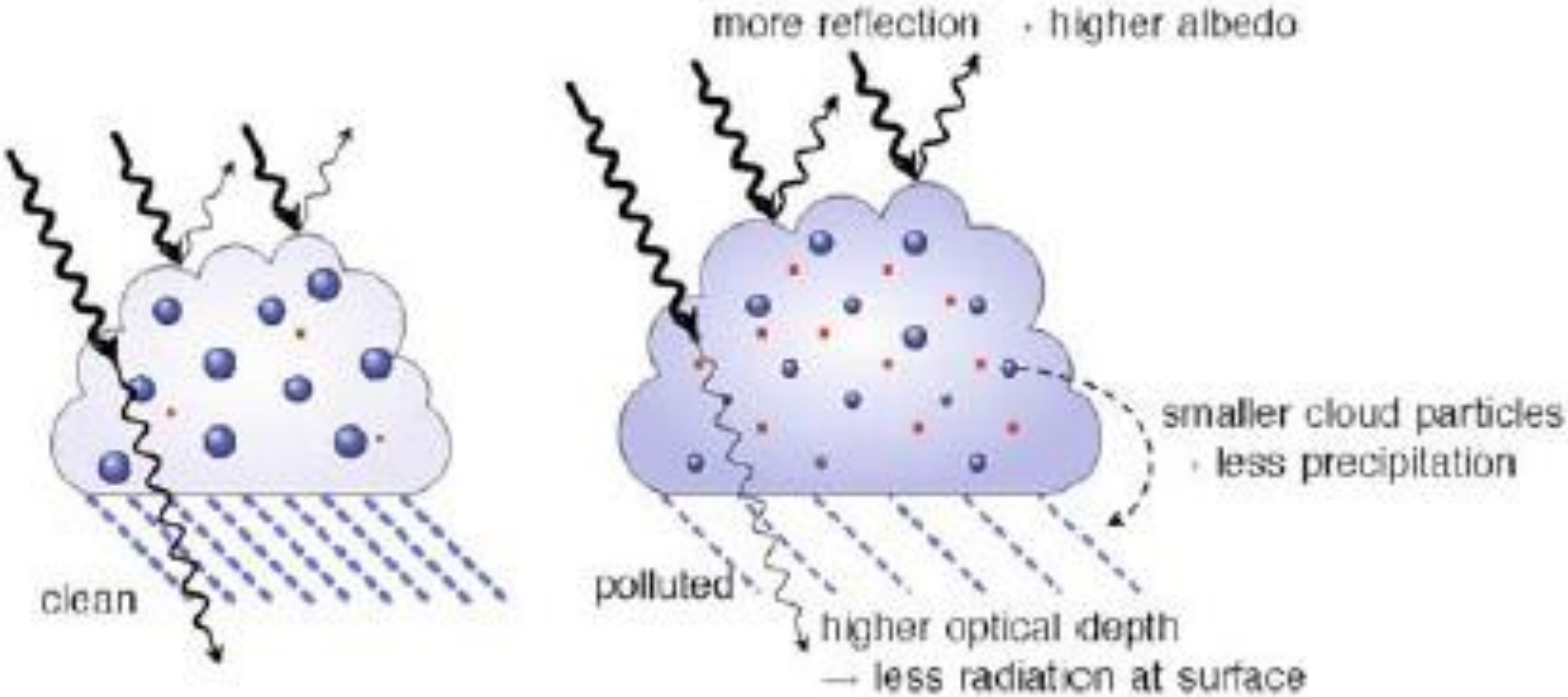


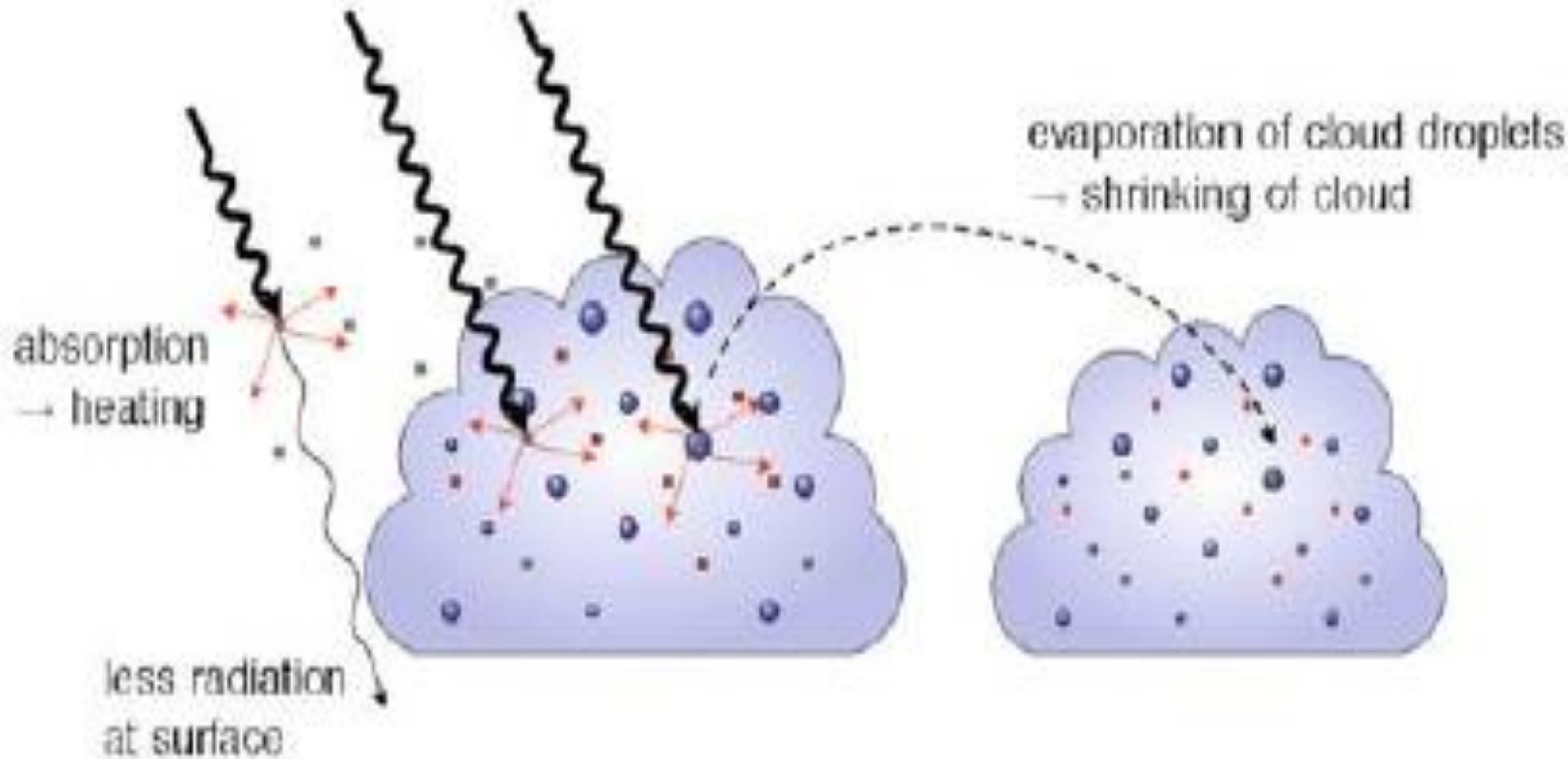
Table 1 Overview of the different aerosol indirect effects and their sign of the change in surfa
precipitation

Effect	Cloud types affected	Process	Sign of change in surface precipitation	Potentia magnitu
Cloud albedo effect	All clouds	For the same cloud water or ice content more but smaller cloud particles reflect more solar radiation	n/a	n/a
Cloud lifetime effect	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby presumably prolonging cloud lifetime	Negative	Small
Glaciation indirect effect	Mixed-phase clouds	An increase in ice nuclei increases the precipitation efficiency	Positive	Medium
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay freezing causing super-cooled clouds to extend to colder temperatures	Positive or negative	Medium
Semidirect effect	All clouds	Absorption of solar radiation	Negative	Large

Table 1. Overview of the different aerosol indirect effects and range of the radiative budget perturbation at the top-of-the atmosphere (F_{TOA}) [$\mathrm{W\,m^{-2}}$], at the surface (F_{SFC}) and the likely sign of the change in global mean surface precipitation (P) as estimated from Fig. 2 and from the literature cited in the text.

Effect	Cloud type	Description	F_{TOA}	F_{SFC}	P
Indirect aerosol effect for clouds with fixed water amounts (cloud albedo or Twomey effect)	All clouds	The more numerous smaller cloud particles reflect more solar radiation	−0.5 to −1.9	similar to F_{TOA}	n/a
Indirect aerosol effect with varying water amounts (cloud lifetime effect)	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime	−0.3 to −1.4	similar to F_{TOA}	decrease
Semi-direct effect	All clouds	Absorption of solar radiation by soot may cause evaporation of cloud particles	+0.1 to −0.5	larger than F_{TOA}	decrease
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay the onset of freezing	?	?	increase or decrease
Glaciation indirect effect	Mixed-phase clouds	More ice nuclei increase the precipitation efficiency	?	?	increase
Riming indirect effect	Mixed-phase clouds	Smaller cloud droplets decrease the riming efficiency	?	?	decrease
Surface energy budget effect	All clouds	Increased aerosol and cloud optical thickness decrease the net surface solar radiation	n/a	−1.8 to −4	decrease

Semi-direct effect (positive radiative effect at TOA for soot inside clouds, negative for soot above clouds)



Semi direct effect

- Light-absorbing aerosol generate local heating and they can modify the atmospheric stability and suppress vertical motion and cloud formation (Hansen et al. 1997)
- Reduced downwelling solar radiation at the surface.
- net surface radiation, surface sensible and latent heat fluxes are reduced.
- Over land, where surface heating is a primary driver
- for convective clouds, this can have a significant impact on cloud fraction and cloud depth.
- This process links aerosol–cloud interactions to land surface type

What about deep clouds ?

- Elevated levels of aerosols - suppress precipitation formation in the warm region – elevates the level of rain formation- mixed phase and ice microphysics- changes the dynamical response of clouds to microphysics-larger spatial scales

All these process are also highly dependent on the "**type of cloud and the environment**"

"Deep convection is the heat engine of the tropics: latent heating left in the atmosphere when precipitation reaches the surface drives large-scale atmospheric circulations"(Grabowski)

Deep clouds and aerosol

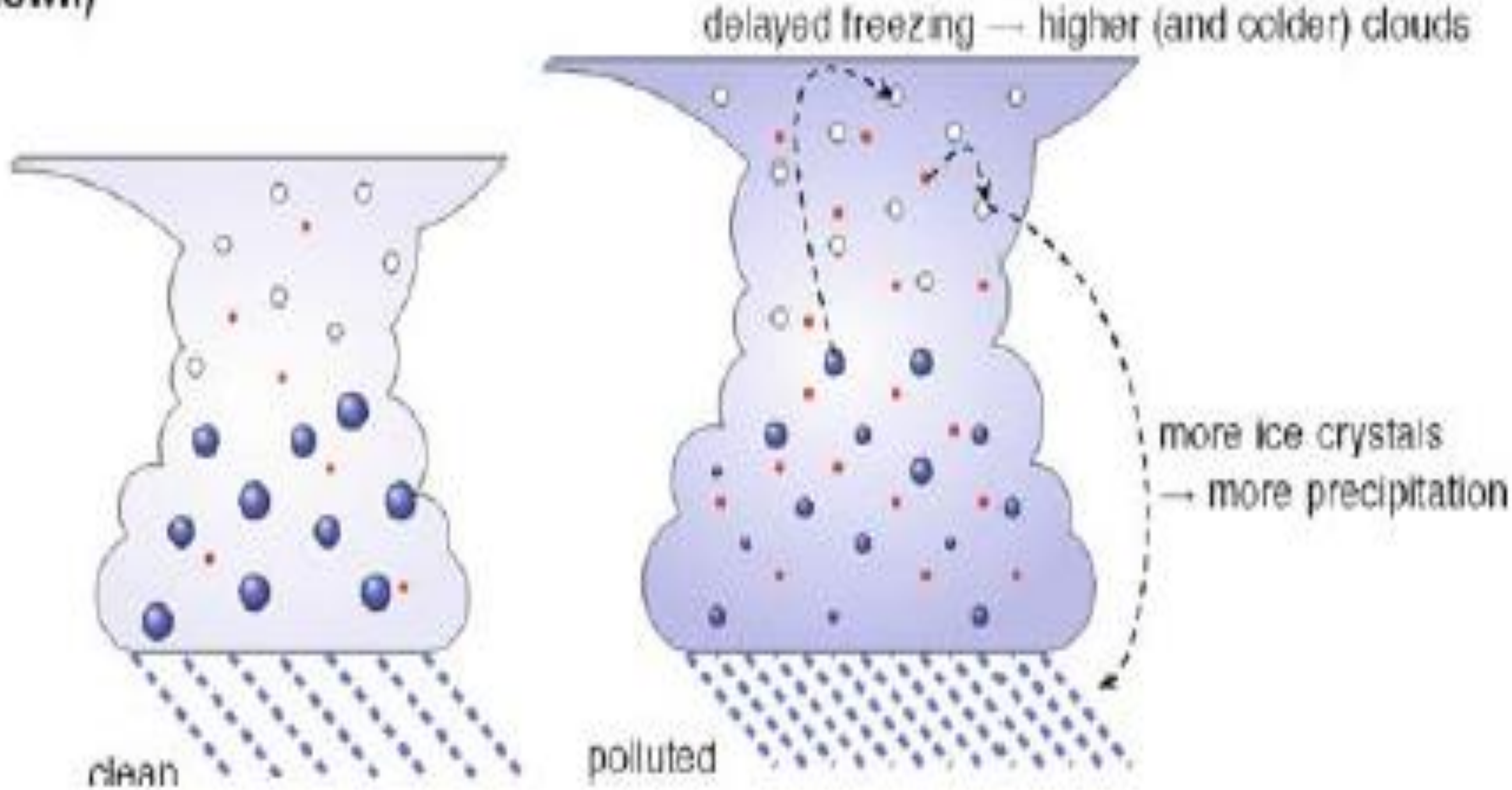
- Polluted clouds have higher freezing level and invigoration due to latent heat of freezing, resulting in an increase in the mass of condensed or frozen hydrometeors, which assists in generating precipitation via accretion processes
- Moderate pollution Clouds precipitate less
- Low pollution, assisted by warm rain process it precipitates

Aerosol effect in mixed phase clouds

- ➢Depends on cloud type
- ➢Small convective storms: increase in CCN decreases precipitation
- ➢Multi cellular storms: increase in CCN has opposite effects – promote secondary convection and increase updrafts and precipitation

- ➢Pathway for microphysics-dynamics: release of latent heat freezing
- ➢Marine airmass clouds precipitated sooner compared to the continental airmass clouds

Glaciation effect (positive radiative effect at TOA and more precipitation), thermodynamic effect (sign of radiative effect and change in precipitation not yet known)



Invigoration of convective clouds with a warm base – Theoretical chain of events

↑ aerosol loading

→ ↑ CCN amount

→ ↑ number of droplets & ↓ droplets size & ↓ droplets size variance

→ ↓ growth by collision-coalescence & ↑ drops growth by diffusion

→ ↑ condensation latent heat release & ↓ droplets terminal velocities

→ ↑ level and time of rain onset (warm rain may be suppressed)

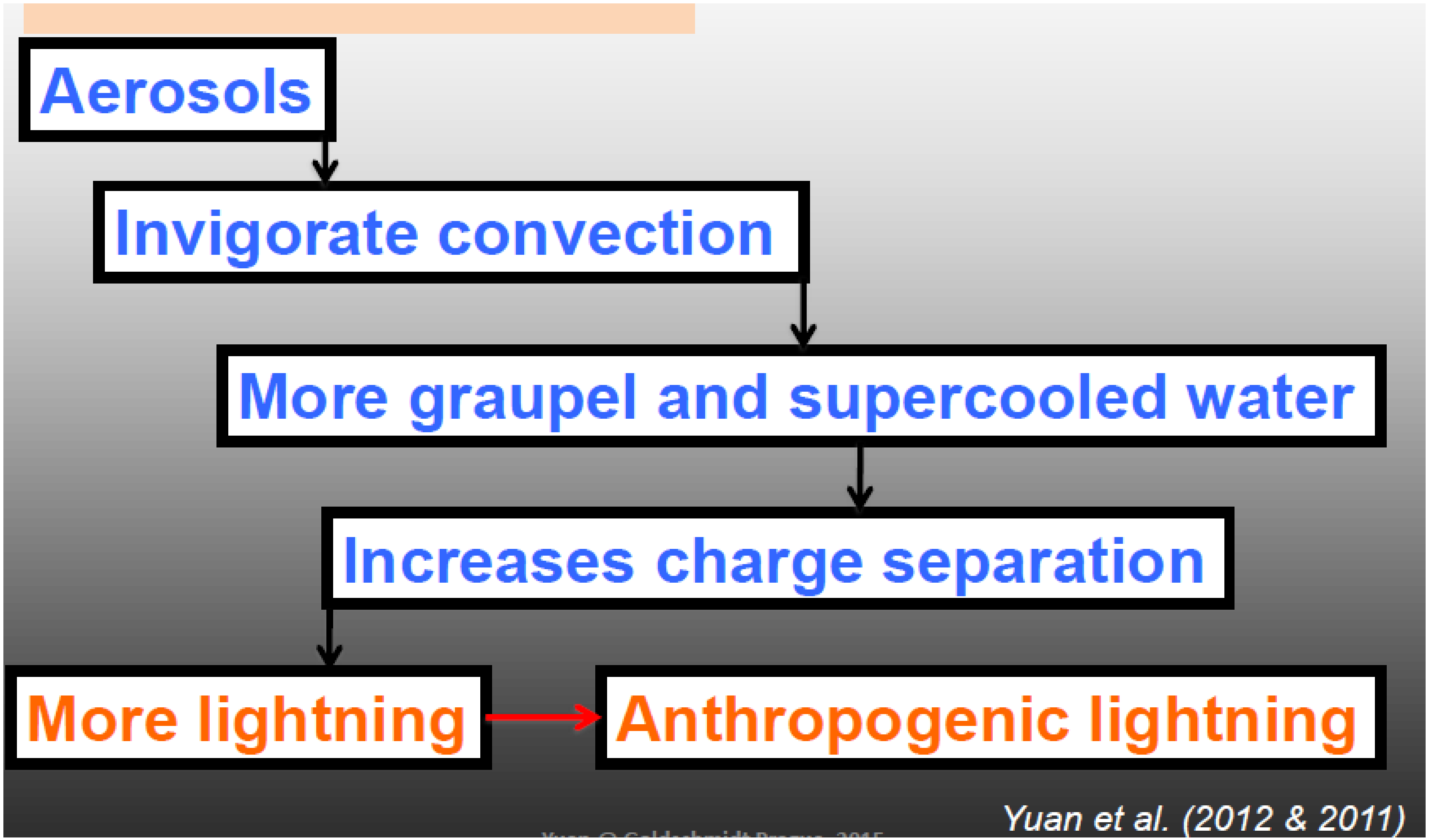
→ ↑ water mass passing up the 0°c level & ↑ freezing level

→ ↑ freezing latent heat release

→ ↑ clouds depth & ↑ cloud area

Review: Cloud invigoration by aerosols—Coupling between microphysics and dynamics

O. Altaratz [a,*], I. Koren [a], L.A. Remer [b], E. Hirsch [a]


Aerosols
Invigorate convection
More graupel and supercooled water
Increases charge separation
More lightning
Anthropogenic lightning
Yuan et al. (2012 & 2011)

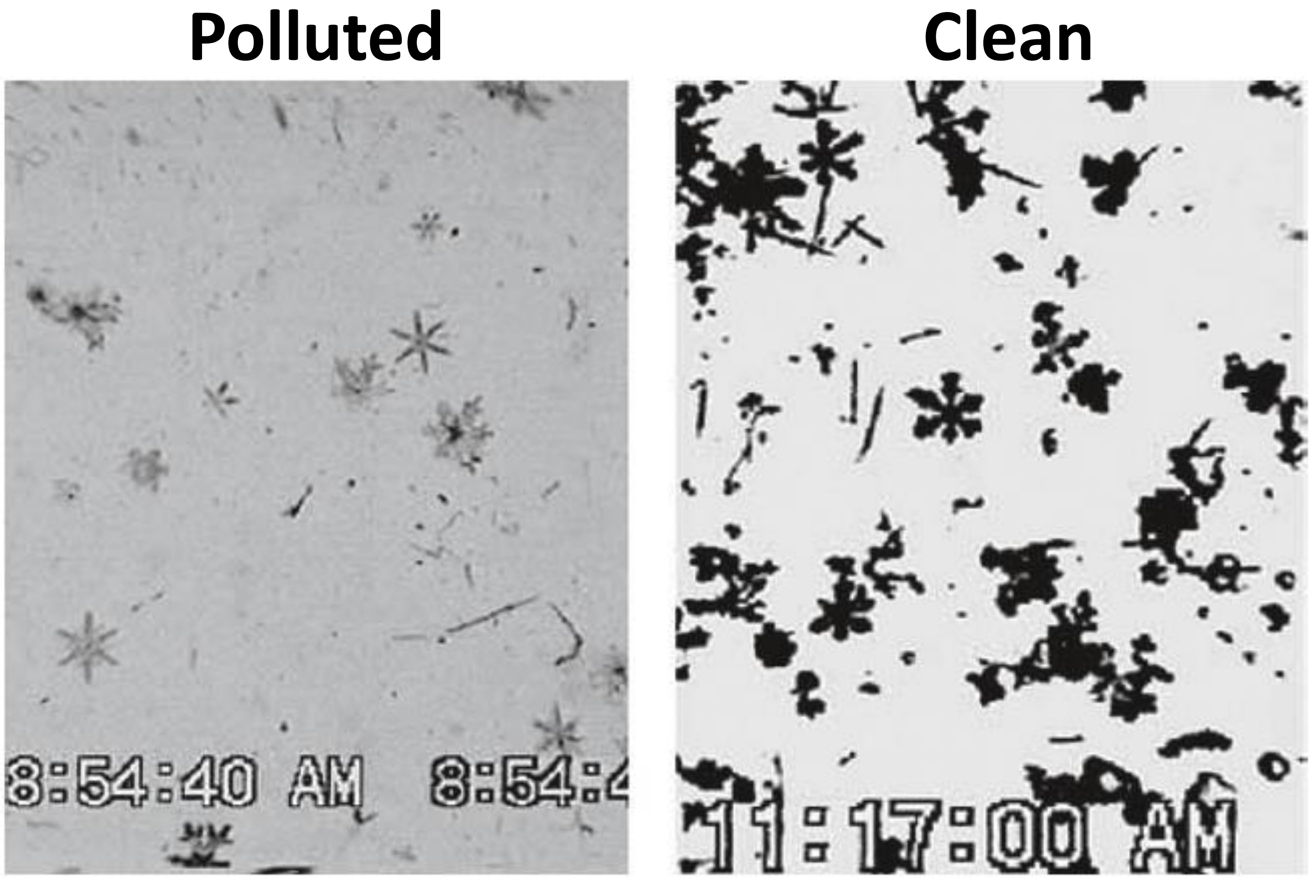
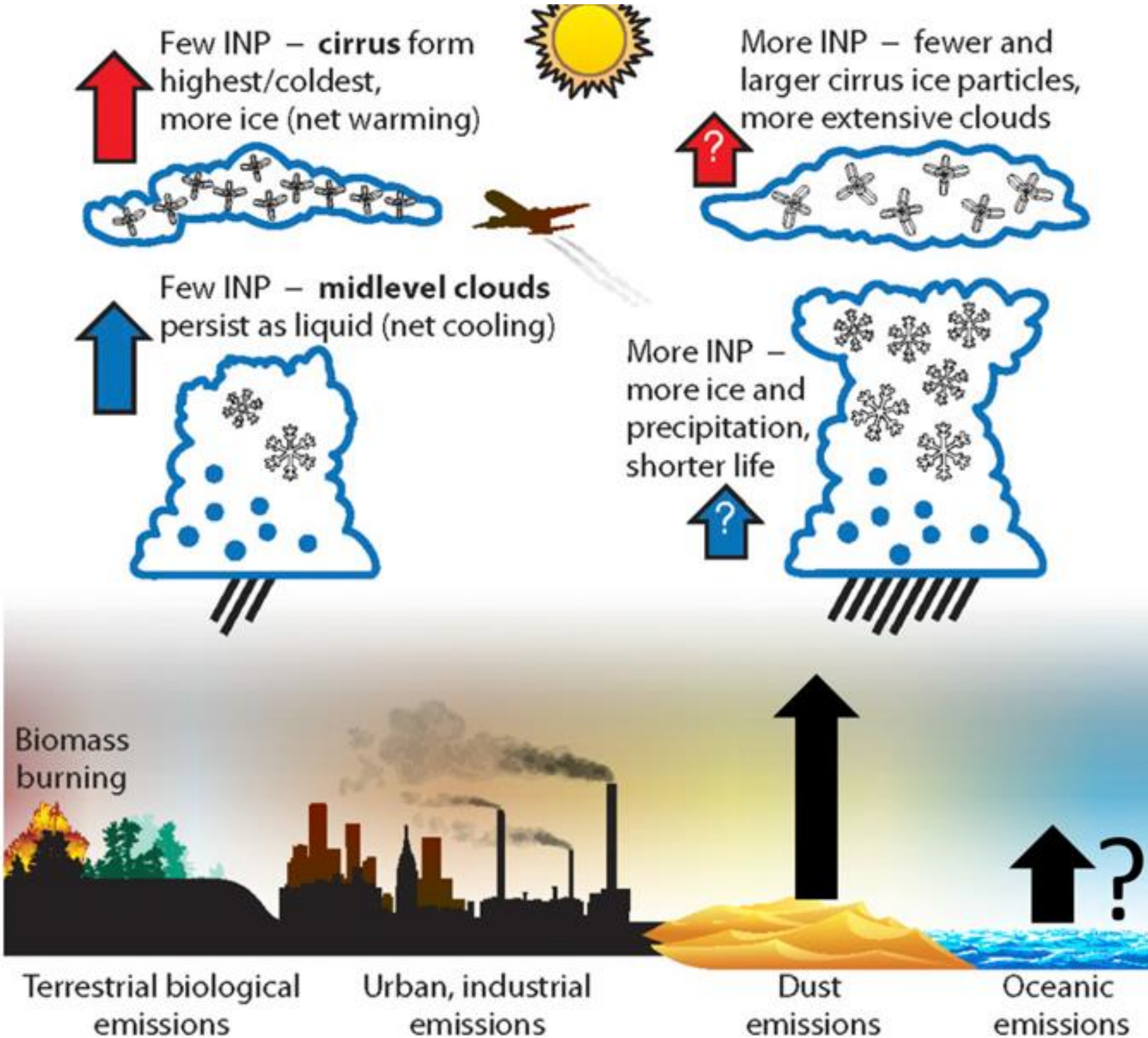
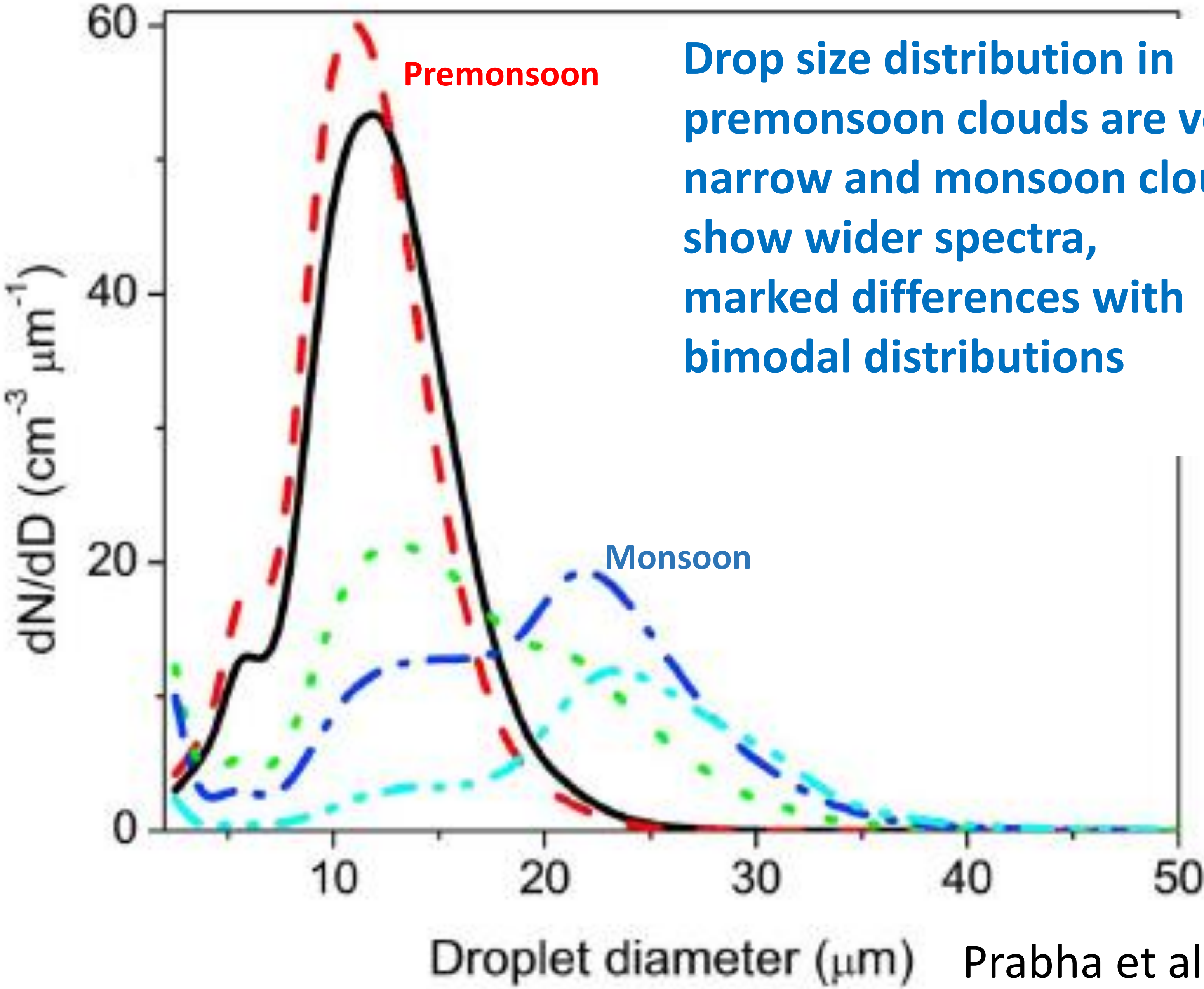


Fig. 6.21 Light riming of ice crystals in clouds affected by pollution (*left*) compared to heavier riming in non-polluted clouds (*right*). From Borys et al. (2003) with permission of the American Geophysical Union



Few INP – **cirrus** form highest/coldest, more ice (net warming)
More INP – fewer and larger cirrus ice particles, more extensive clouds
?
Few INP – **midlevel clouds** persist as liquid (net cooling)
More INP – more ice and precipitation, shorter life
?
Biomass burning
?
Terrestrial biological emissions
Urban, industrial emissions
Dust emissions
Oceanic emissions

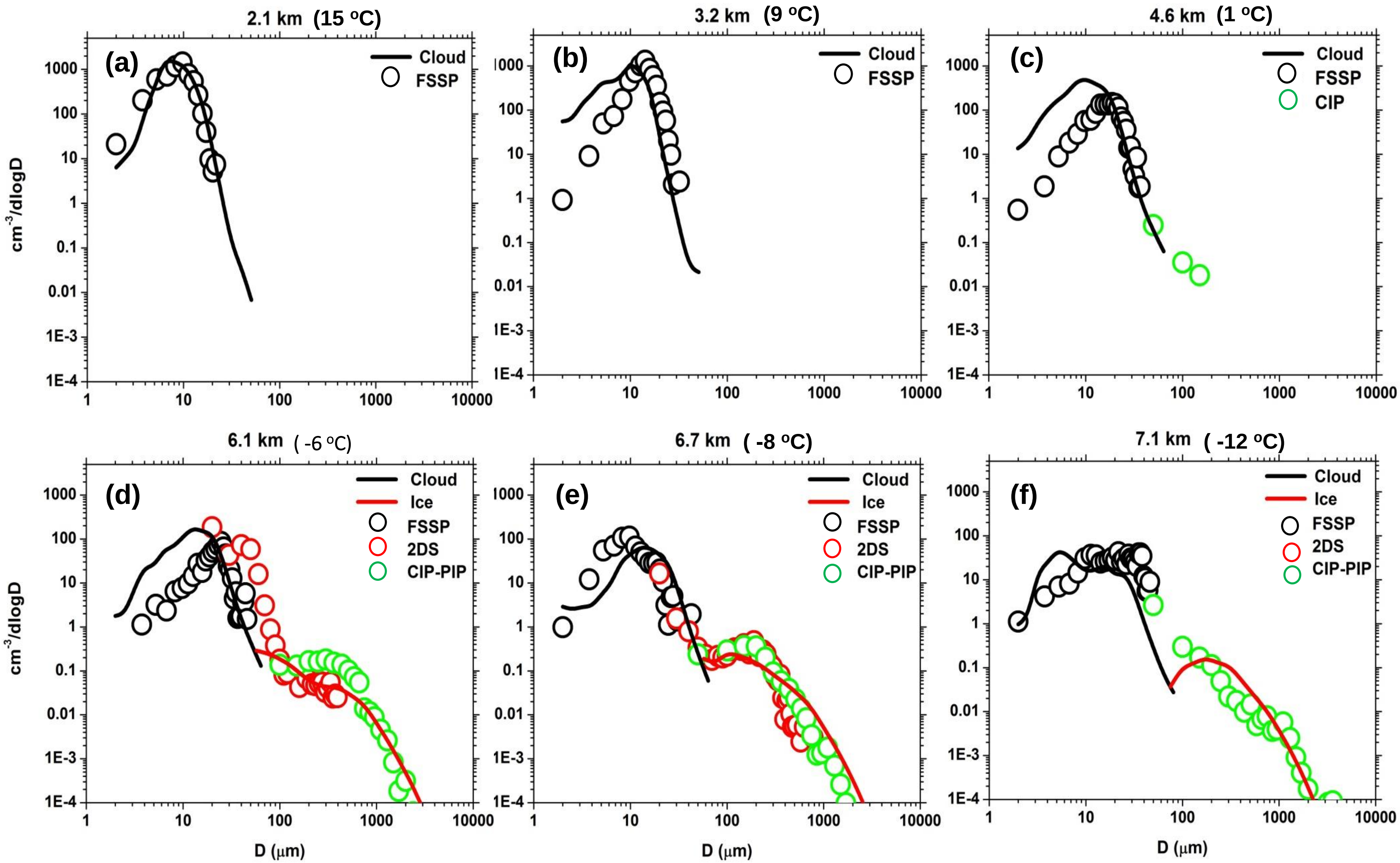
Droplet size distribution in the PREmonsoon and MONsoon clouds



Drop size distribution in premonsoon clouds are very narrow and monsoon clouds show wider spectra, marked differences with bimodal distributions

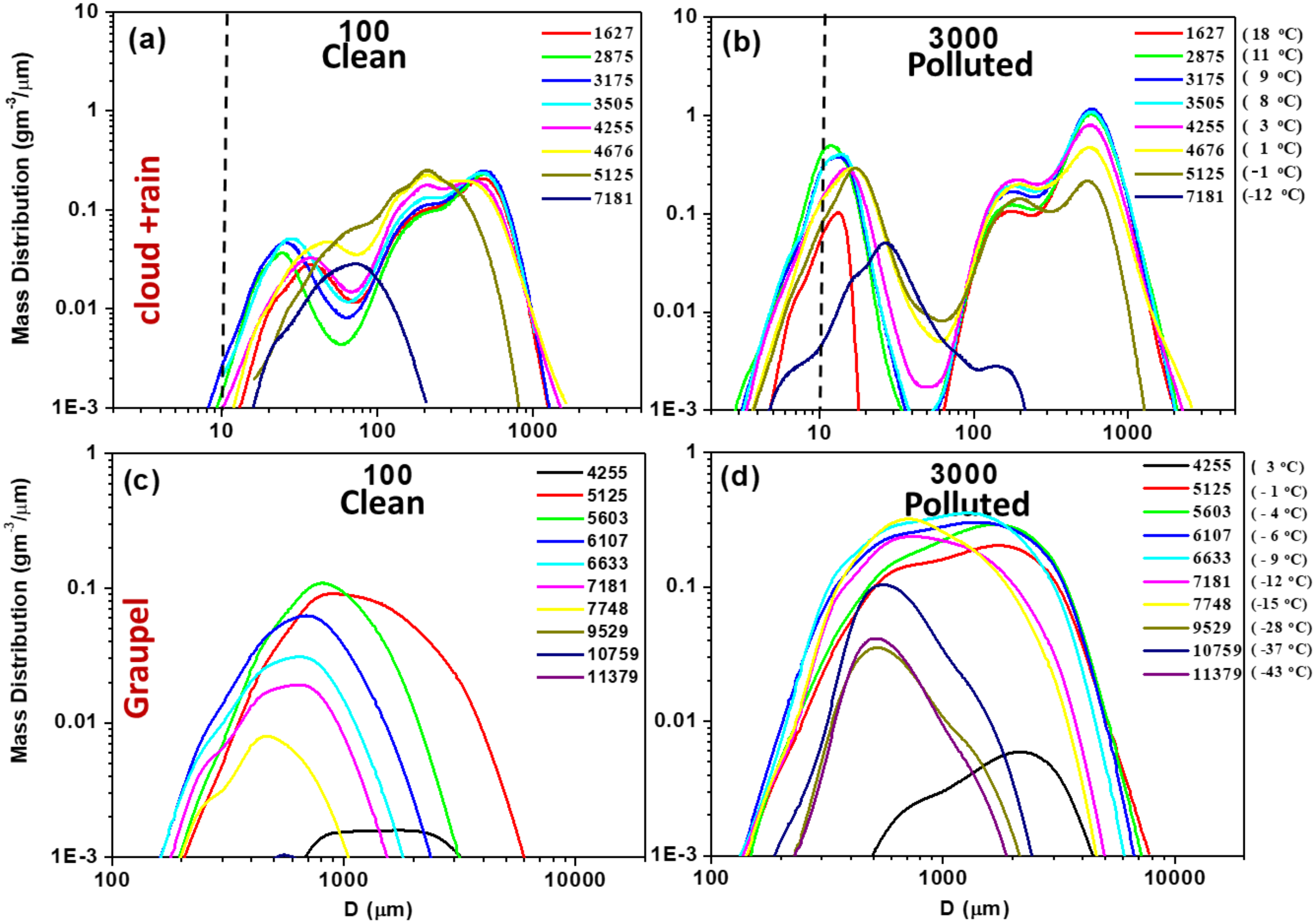
Prabha et al., 2012), JGR

Evaluation of bin microphysics simulations with CAIPEEX observations



Gayatri K., S. Patade and T. V. Prabha. Aerosol cloud interaction in deep convective clouds over the Indian peninsula using Spectral (bin) Microphysics, 2017, *Journal of Atmospheric Science*,10.1175/JAS-D-17-0034.1

Cloud+ Rain and Graupel particle spectra in the clean and polluted cloud

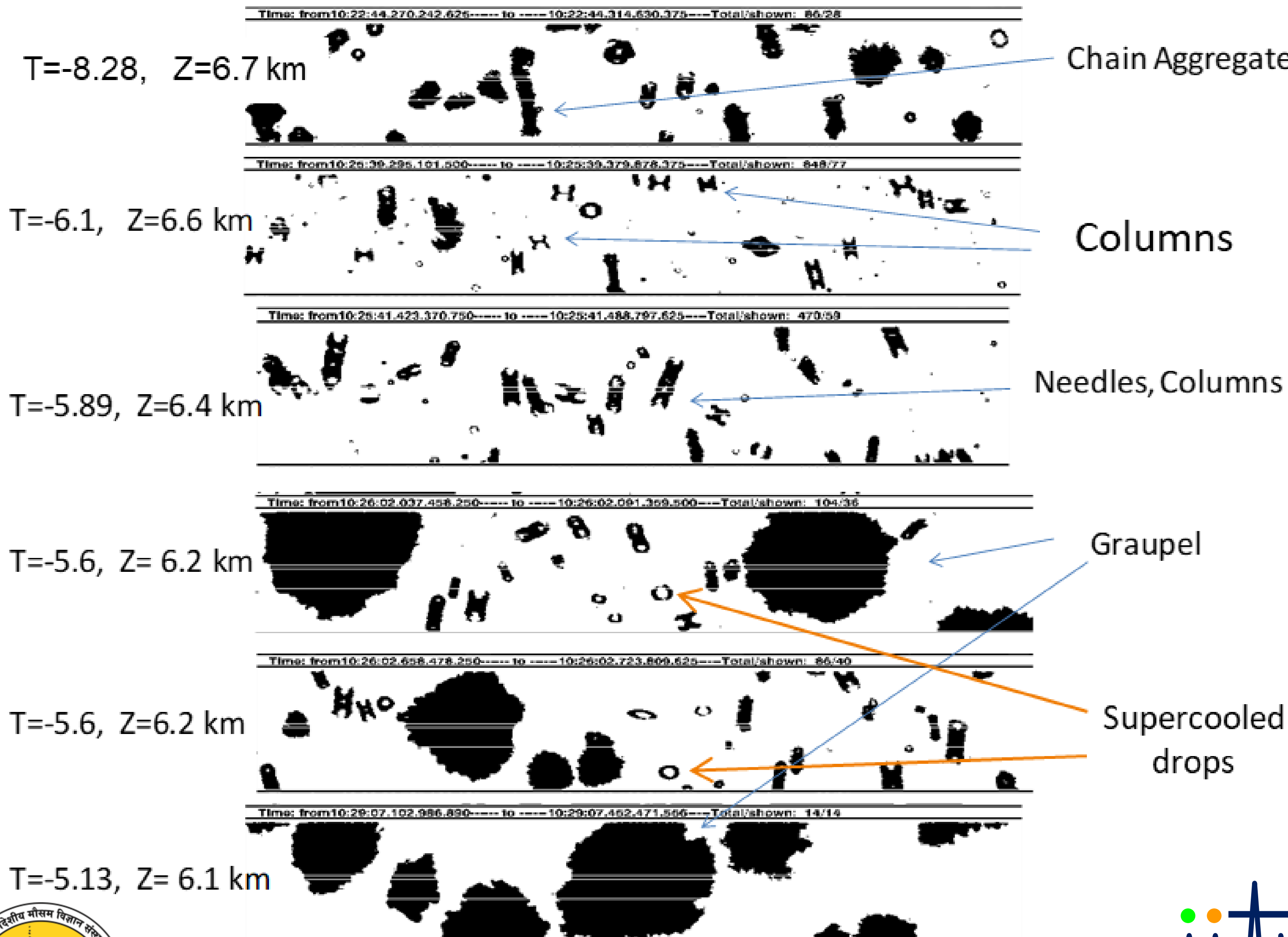


- Supercooled drops between 10 - 40 μm attributed to activation and diffusional growth
- The melting of large amount of snow and graupel contributed to larger drops (greater than 400 μm), and further promoted collision coalescence

INDIAN INSTITUTE OF TROPICAL METEOROLOGY PUNE

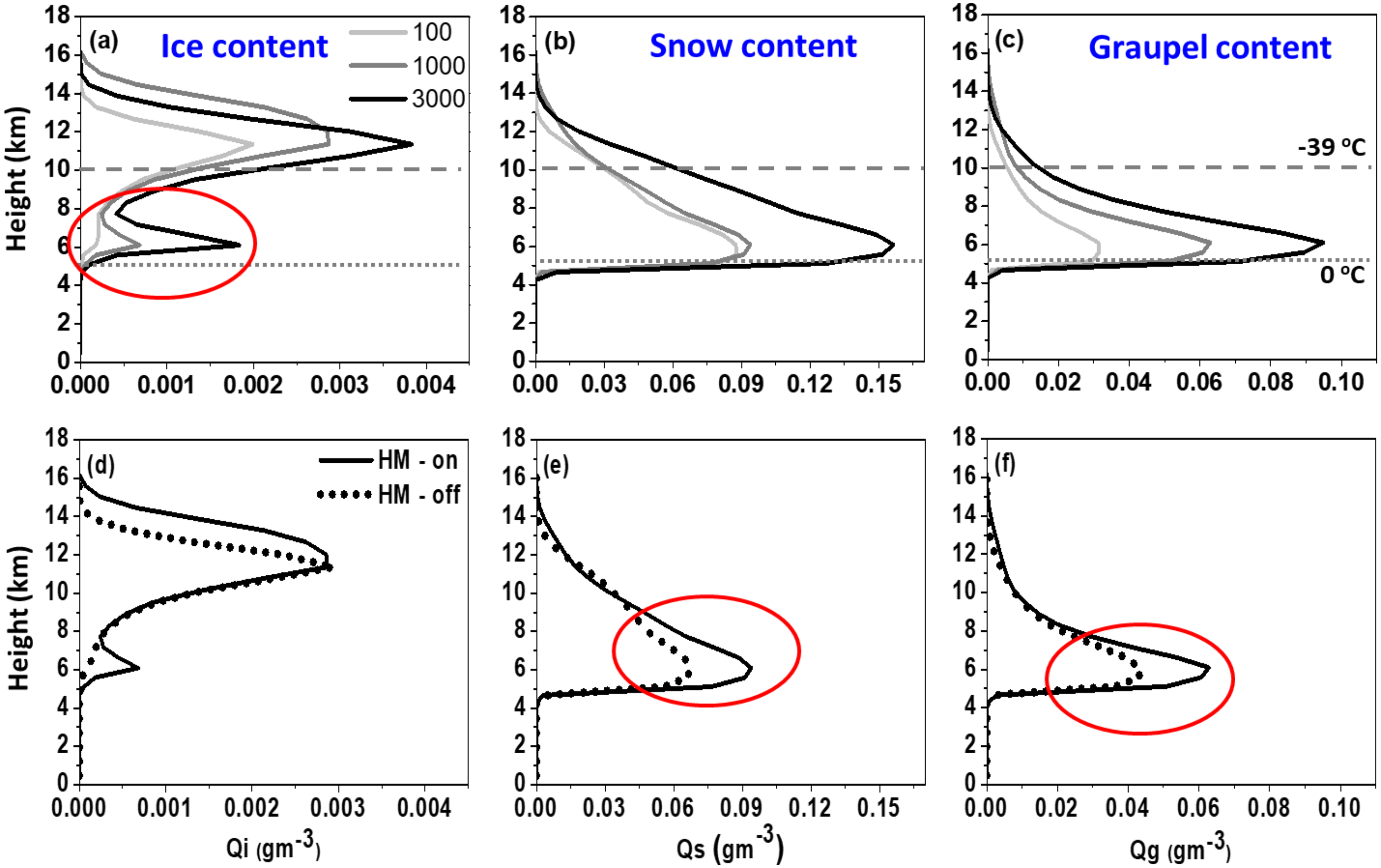
Identifying HM process from CAIPEEX observations

Particle images from 2DS



Gayatri K., S. Patade and T. V. Prabha. Aerosol cloud interaction in deep convective clouds over the Indian peninsula using Spectral (bin) Microphysics, 2017, *Journal of Atmospheric Science*, 10.1175/JAS-D-17-0034.1

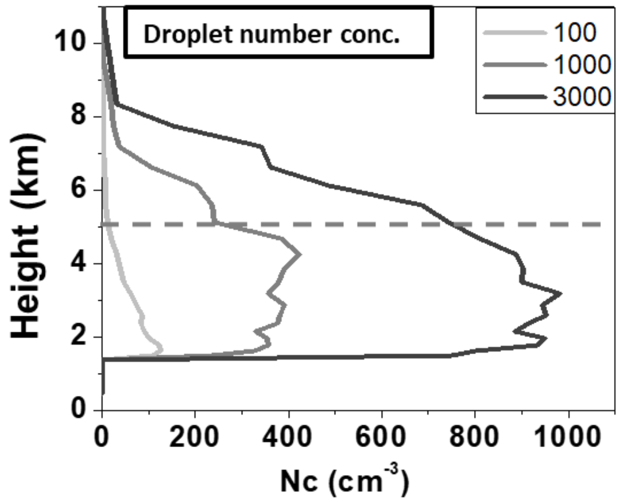
Vertical structure of ice microphysics from different CCN simulations

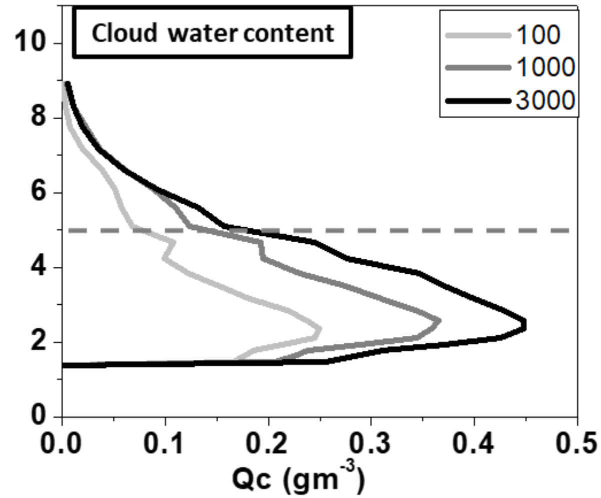


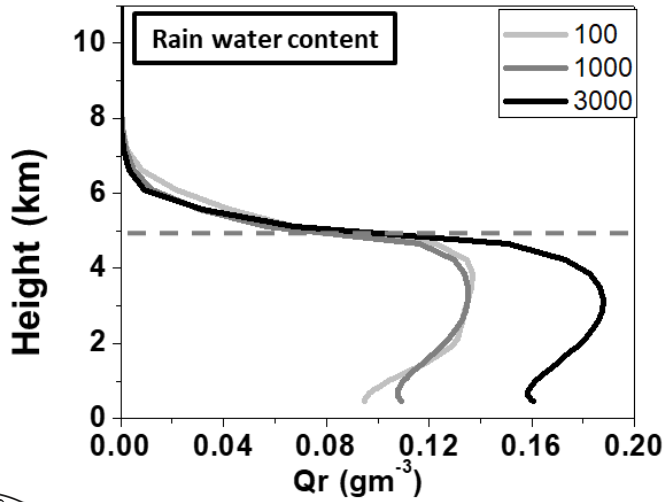
The lower peak in Qi is from the secondary ice production by Hallet Mossop Process, which is seen to be active in CAIPEEX observation

Gayatri K., S. Patade and T. V. Prabha. Aerosol cloud interaction in deep convective clouds over the Indian peninsula using Spectral (bin) Microphysics, 2017, *Journal of Atmospheric Science*,10.1175/JAS-D-17-0034.1

Single cloud analysis: Vertical variation of cloud microphysical parameters for different CCN simulations



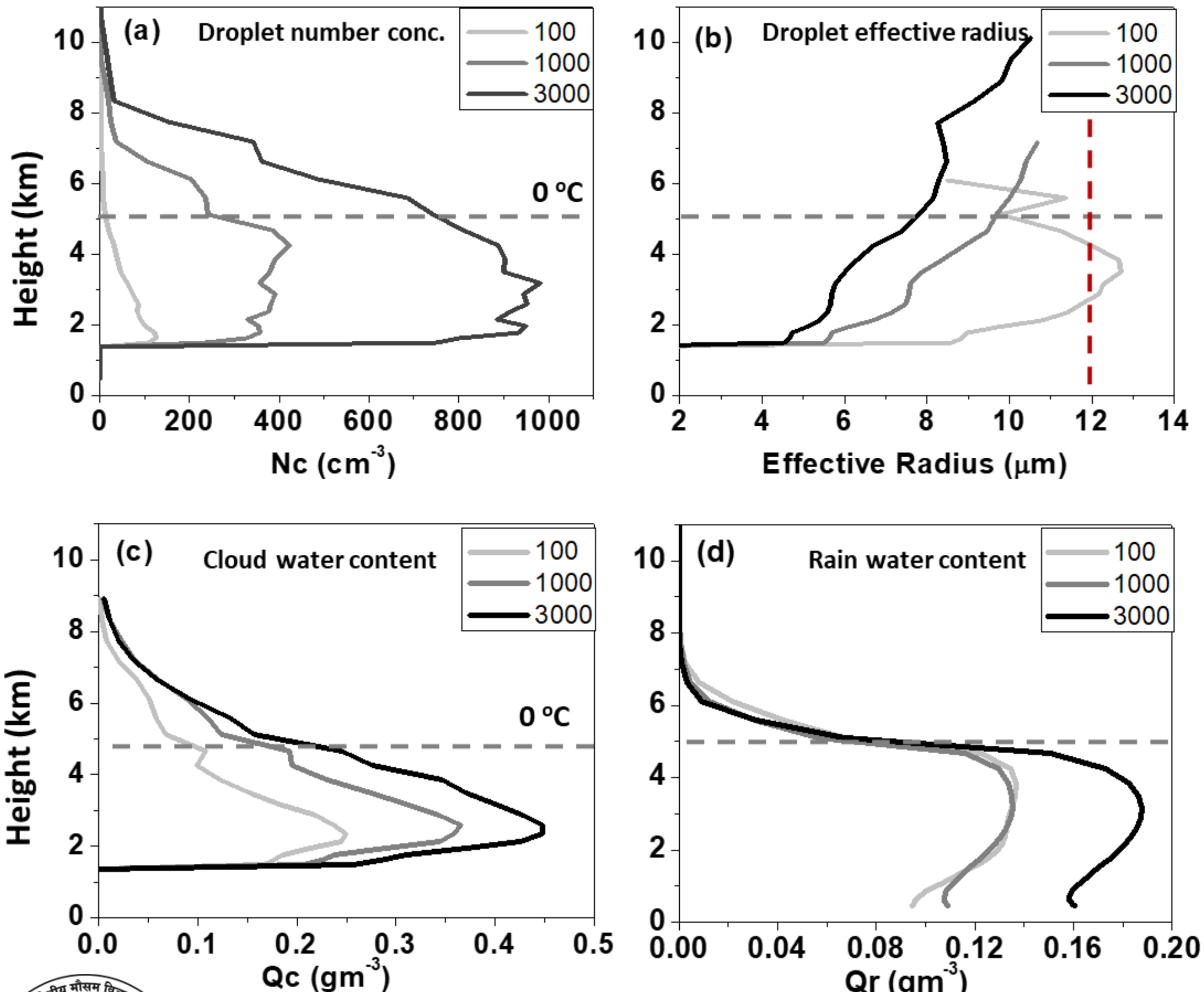




Both first indirect effect (smaller cloud drops with high CCN) and second indirect effect (more cloud water retained in the clouds) are simulated by the model.

Gayatri K., S. Patade and T. V. Prabha. Aerosol cloud interaction in deep convective clouds over the Indian peninsula using Spectral (bin) Microphysics, 2017, *Journal of Atmospheric Science*,10.1175/JAS-D-17-0034.1

Single cloud analysis: Vertical variation of cloud microphysical parameters for different CCN simulations

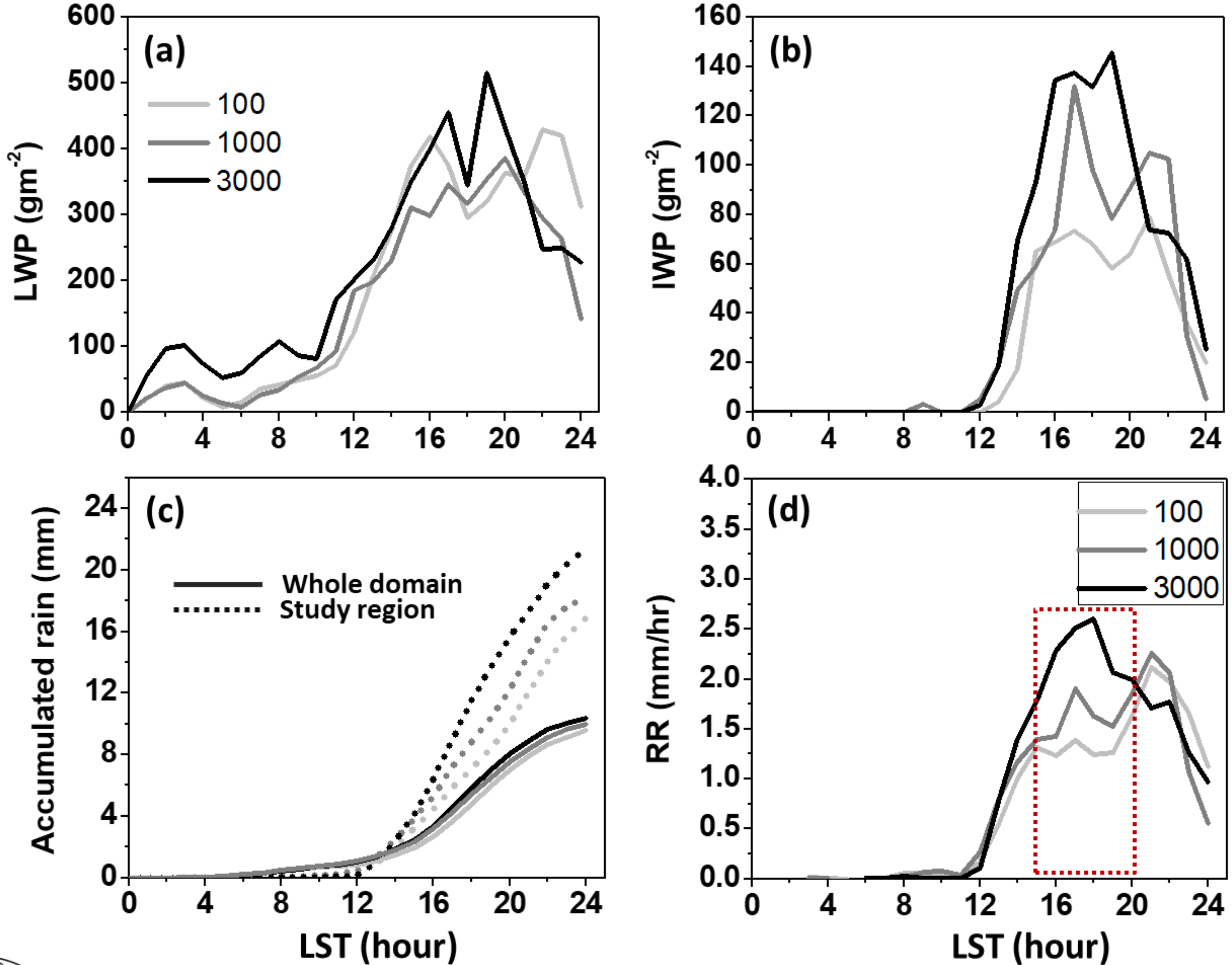


Both first indirect effect (smaller cloud drops with high CCN) and second indirect effect (more cloud water retained in the clouds) are simulated by the model.

Gayatri K., S. Patade and T. V. Prabha. Aerosol cloud interaction in deep convective clouds over the Indian peninsula using Spectral (bin) Microphysics, 2017, *Journal of Atmospheric Science*,10.1175/JAS-D-17-0034.1

INDIAN INSTITUTE OF TROPICAL METEOROLOGY PUNE

Single cloud analysis: With increase in CCN concentration LWP, IWP and precipitation was increased. The precipitation increased by 20%



Gayatri K., S. Patade and T. V. Prabha. Aerosol cloud interaction in deep convective clouds over the Indian peninsula using Spectral (bin) Microphysics, 2017, *Journal of Atmospheric Science*, 10.1175/JAS-D-17-0034.1

Advertisement

Olympics of Cloud Physics coming to Pune in 2020

Indian Institute of Tropical Meteorology (IITM)

and

International Commission on Clouds and Precipitation http://www.iccp-iamas.org/

Will be hosting

International Conference on Clouds and Precipitation ICCP 2020

Thank you

The Indirect Effect of Aerosol Particles

- The concentration of water droplets depends directly on the concentration of aerosol particles that can form these droplet, cloud condensation nuclei (CCN) and the vapor pressure of water with respect to the equilibrium saturation vapor pressure.

- An increase in anthropogenic sources of CCN can increase the reflection (albedo) of clouds, by increasing the droplet concentration while decreasing the average diameter.

- This effect was named the indirect effect of aerosols by Twomey (1974)

Effect of Giant nuclei

- Effect is negligible in clean clouds which already have an active warm-rain process
- More significant in polluted clouds
- Most important in moderately polluted conditions.

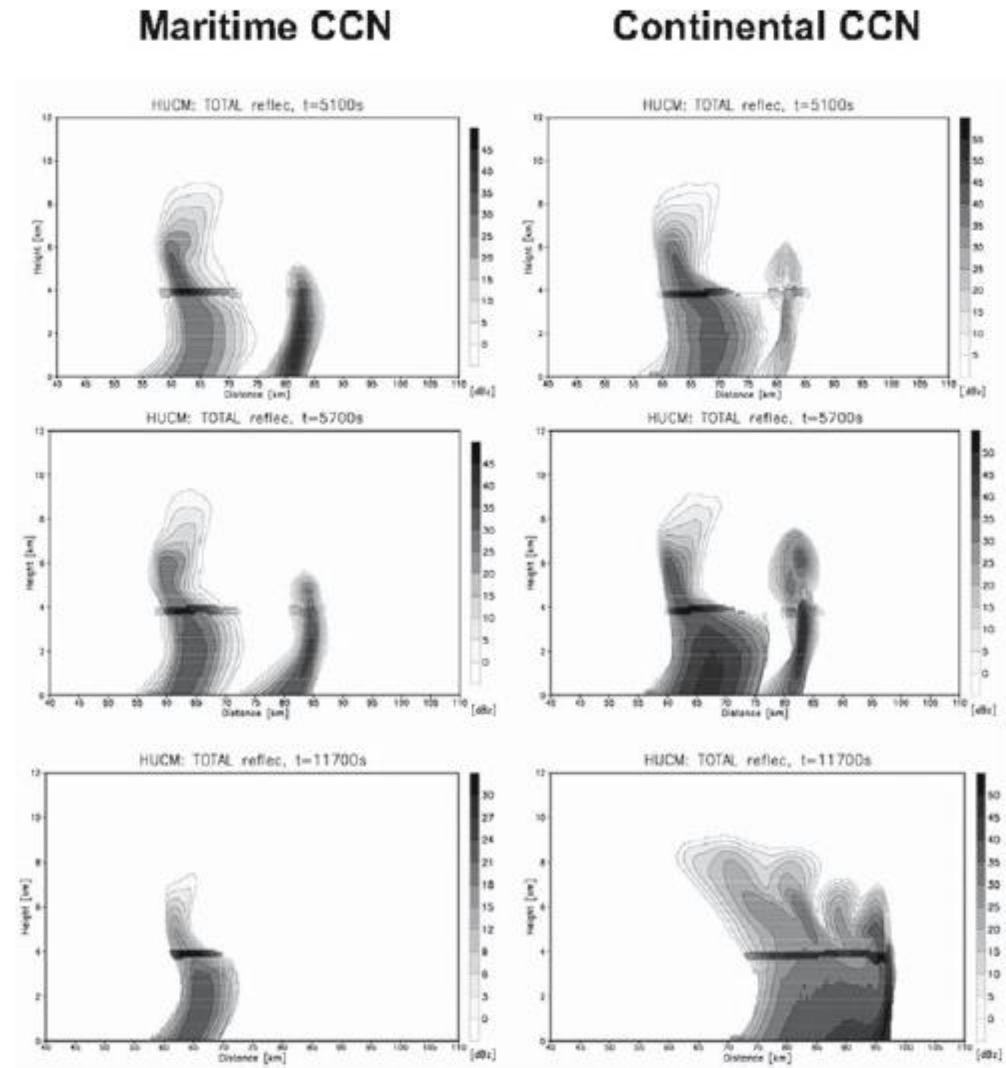


Fig. 2 Time evolution of radar reflectivity in the microphysically maritime conditions (left panels) and in the microphysically continental conditions (right panels). The formation of a squall line in the microphysically continental conditions is seen (reproduced from Khain et al. 2005, with permission).

Aerosol effects on LWP and cloud fraction:

An increase in aerosol

- -to slow collision–coalescence
- -to enhance evaporation
- -reduce drop fall velocities.

Xue et al. (2008) identified two regimes:

(a) at low aerosol concentrations, aerosol and LWP are positively correlated;

(b) at high aerosol concentrations, aerosol and LWP are negatively correlated.

Clouds respond to aerosol depending on meteorology.

Clouds are dynamic entities influenced by meteorological factors which control convection.

Aerosol particles needed for cloud droplet formation, are not the primary driver for clouds.

Feedbacks have the potential to make aerosol effects on clouds of major climatic and hydrological importance

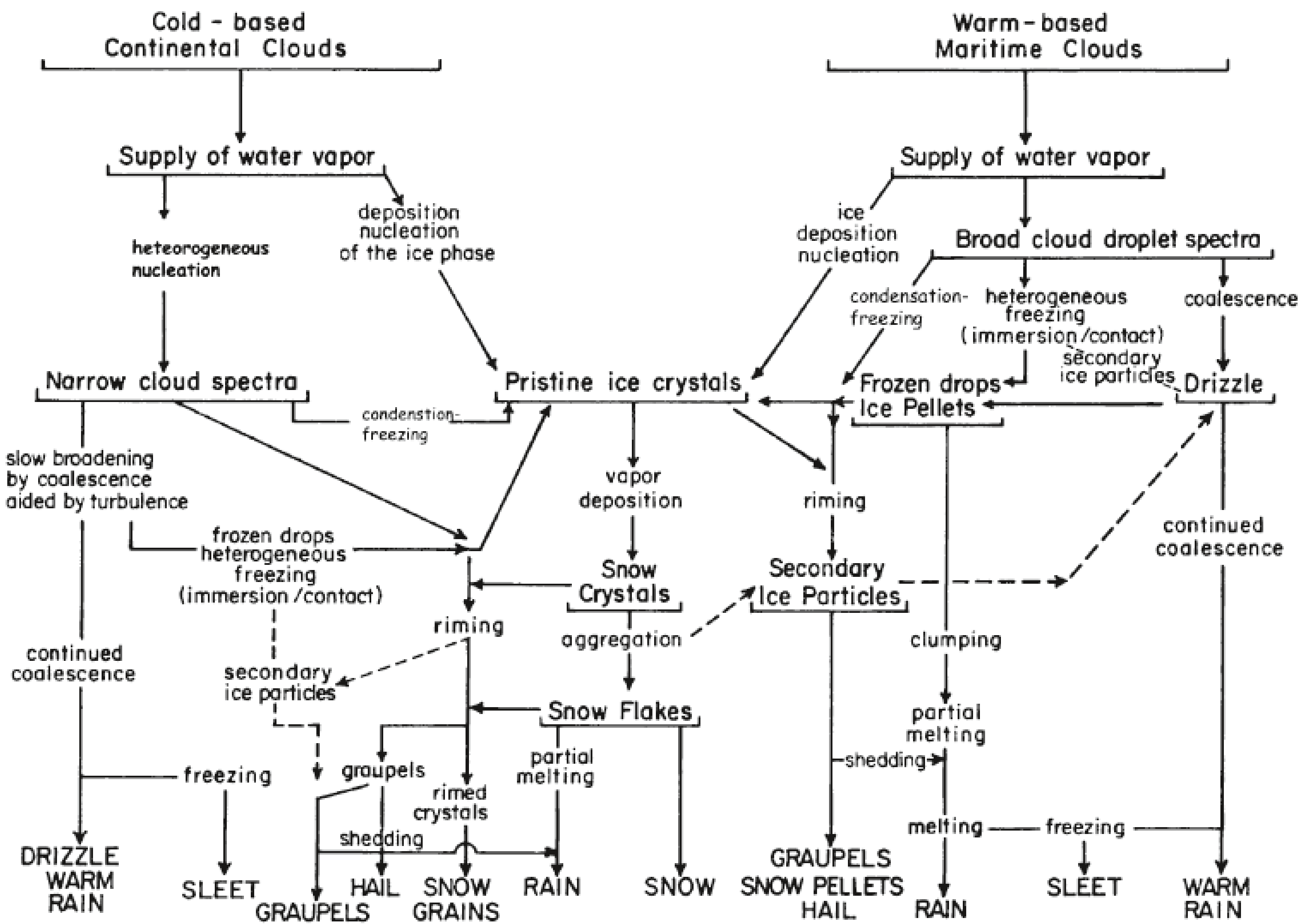
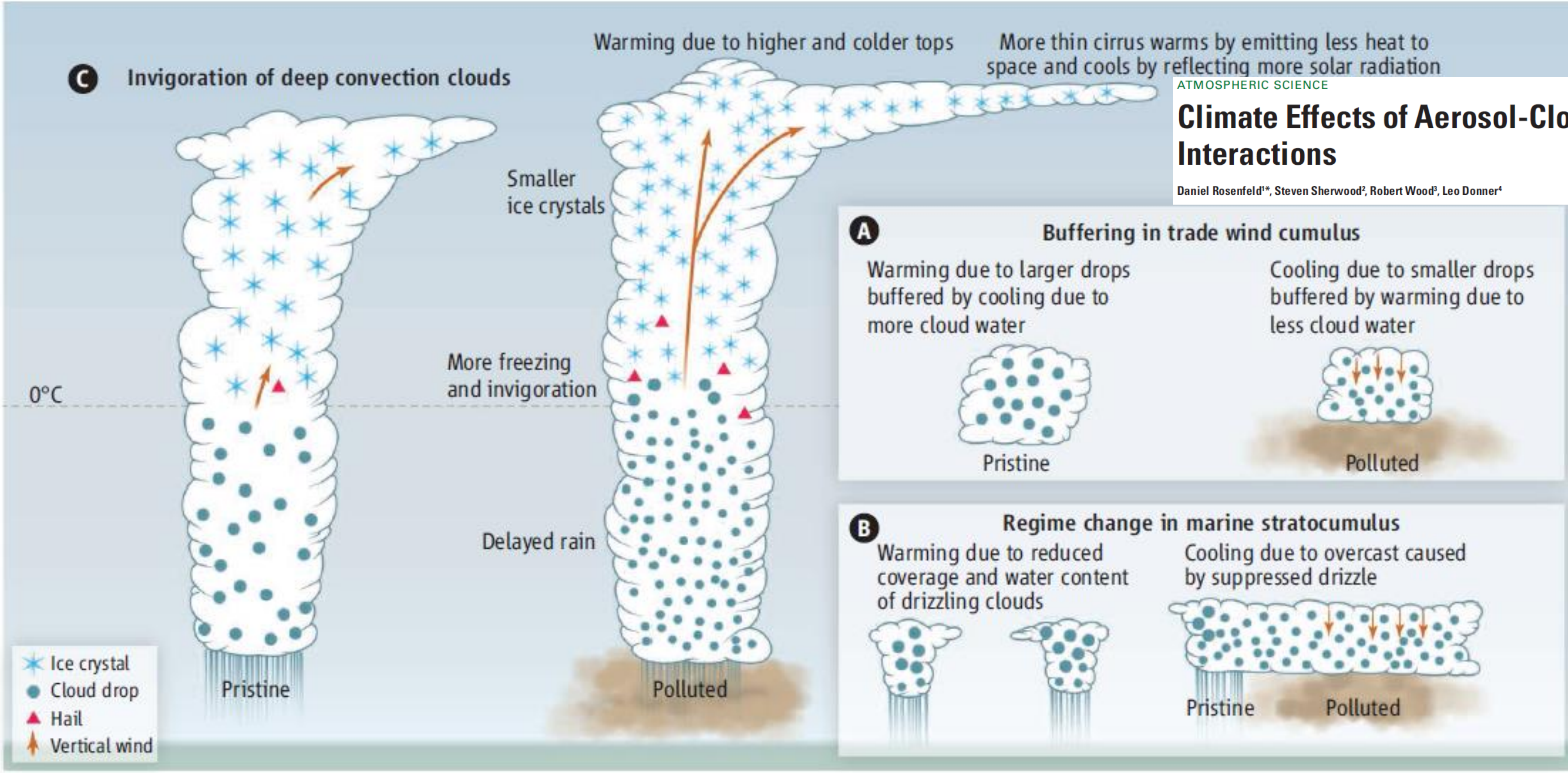


Fig. 2.14 Flow diagram describing microphysical processes, including different paths for precipitation formation. From Cotton and Anthes (1989) with permission of W.R. Cotton

ATMOSPHERIC SCIENCE

Climate Effects of Aerosol-Cloud Interactions

Daniel Rosenfeld[1]*, Steven Sherwood[2], Robert Wood[3], Leo Donner[4]



How aerosols affect the radiative properties of clouds. By nucleating a larger number of smaller cloud drops, aerosols affect cloud radiative forcing in various ways. (**A**) Buffering in nonprecipitating clouds. The smaller drops evaporate faster and cause more mixing of ambient air into the cloud top, which further enhances evaporation. (**B**) Strong cooling. Pristine cloud cover breaks up by losing water to rain that further cleanses the air in a positive feedback loop. Aerosols suppressing precipitation prevent the breakup. (**C**) Larger and longer-lasting cirrus clouds. By delaying precipitation, aerosols can invigorate deep convective clouds and cause colder cloud tops that emit less thermal radiation. The smaller ice particles induced by the pollution aerosols precipitate more slowly from the anvils. This can cause larger and longer-lasting cirrus clouds, with opposite effects in the thermal and solar radiation. The net effect depends on the relative magnitudes.

- buffering mechanisms: result in compensation between different cloud responses to aerosols
- aerosols have become extremely depleted by precipitation
- addition of aerosols can dramatically increase cloud cover, causing large cooling
- aerosol-induced invigoration of deep convective clouds may transport larger quantities of smaller ice particles to the anvils
- The higher, colder, and more expansive anvils can lead to warming by emitting less thermal radiation to space

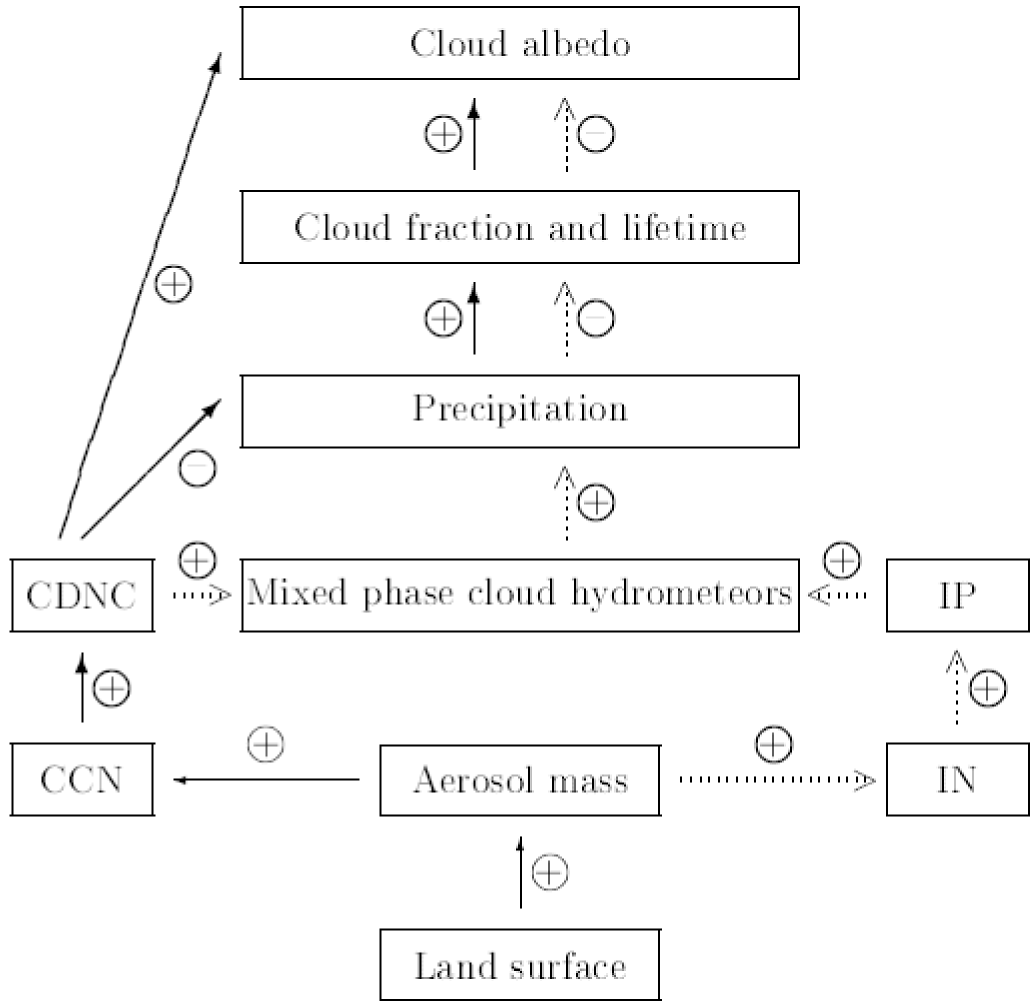
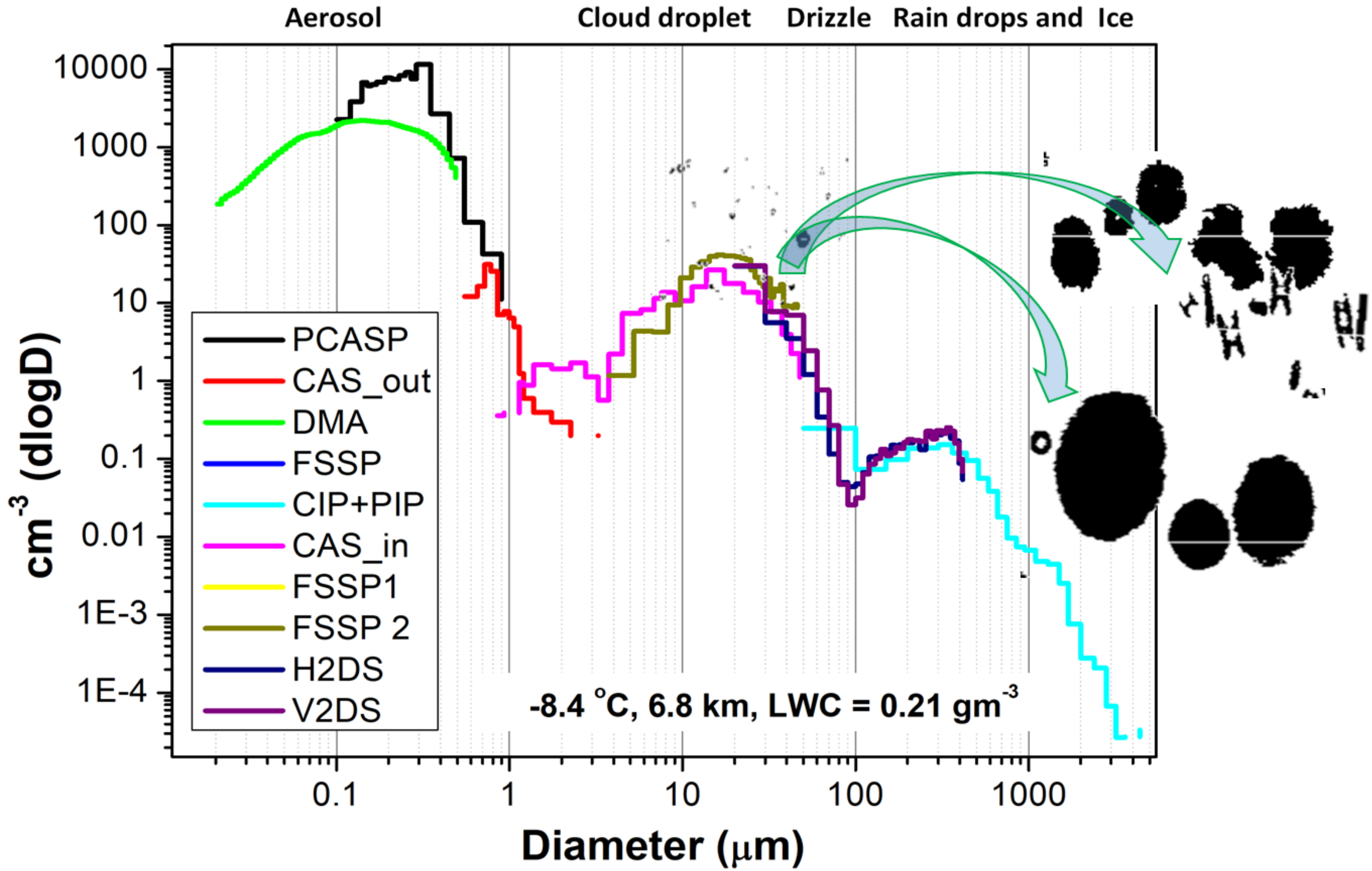


Fig. 4. Schematic diagram of the warm indirect aerosol effect (solid arrows) and glaciation indirect aerosol effect (dotted arrows) (adapted from Lohmann, 2002a). CDNC denotes the cloud droplet number concentration and IP the number concentration of ice particles.

Particle/droplet size distribution from different probes



Source: Chapter in Encyclopedia of Water, Wiley publishers: Prabha and Khain (in press)