Significant Net Impact of Aerosols on Cloud & Precipitation Revealed by the Long-term ARM Measurements

Introducing New Aerosol Forcing Indices

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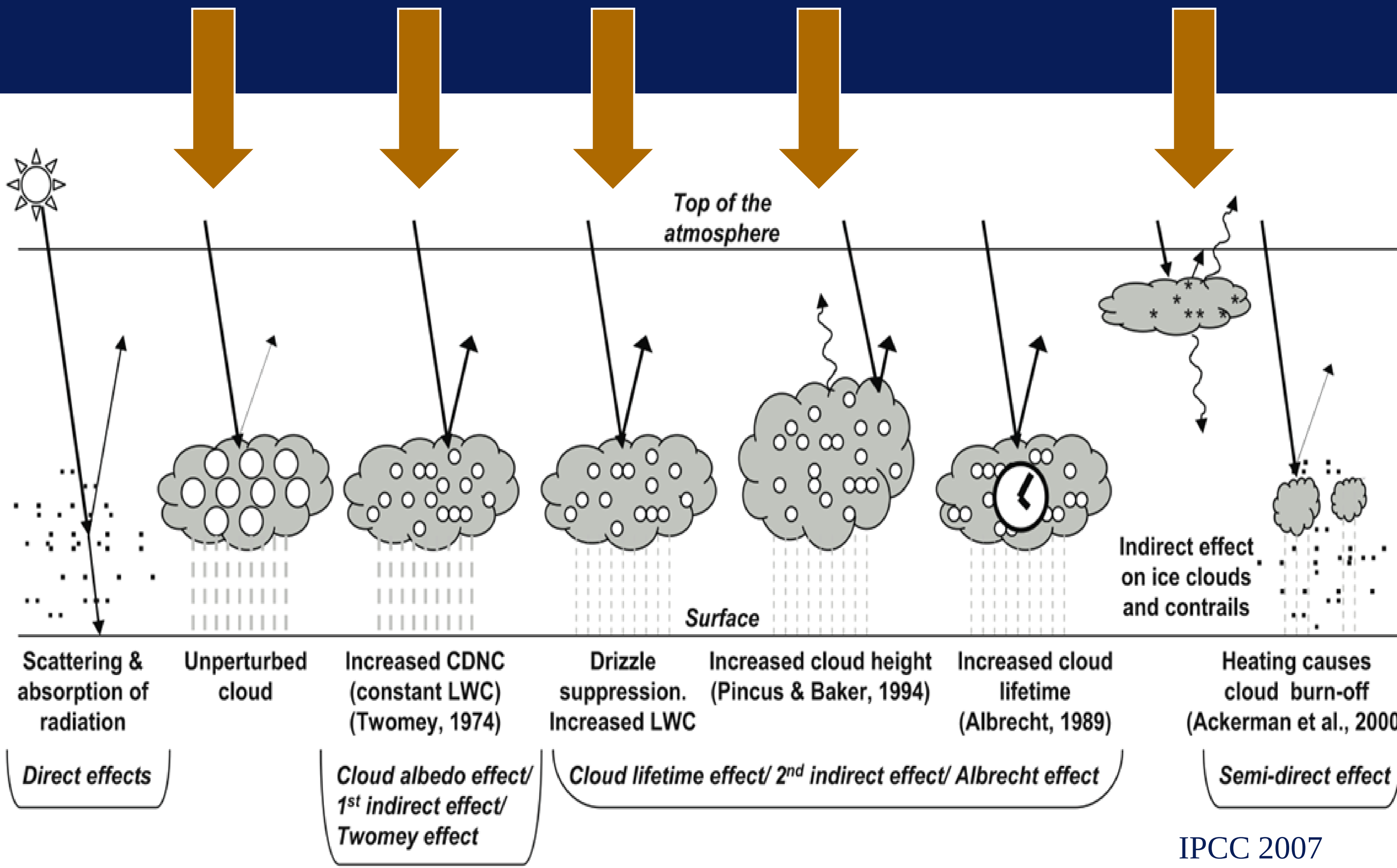
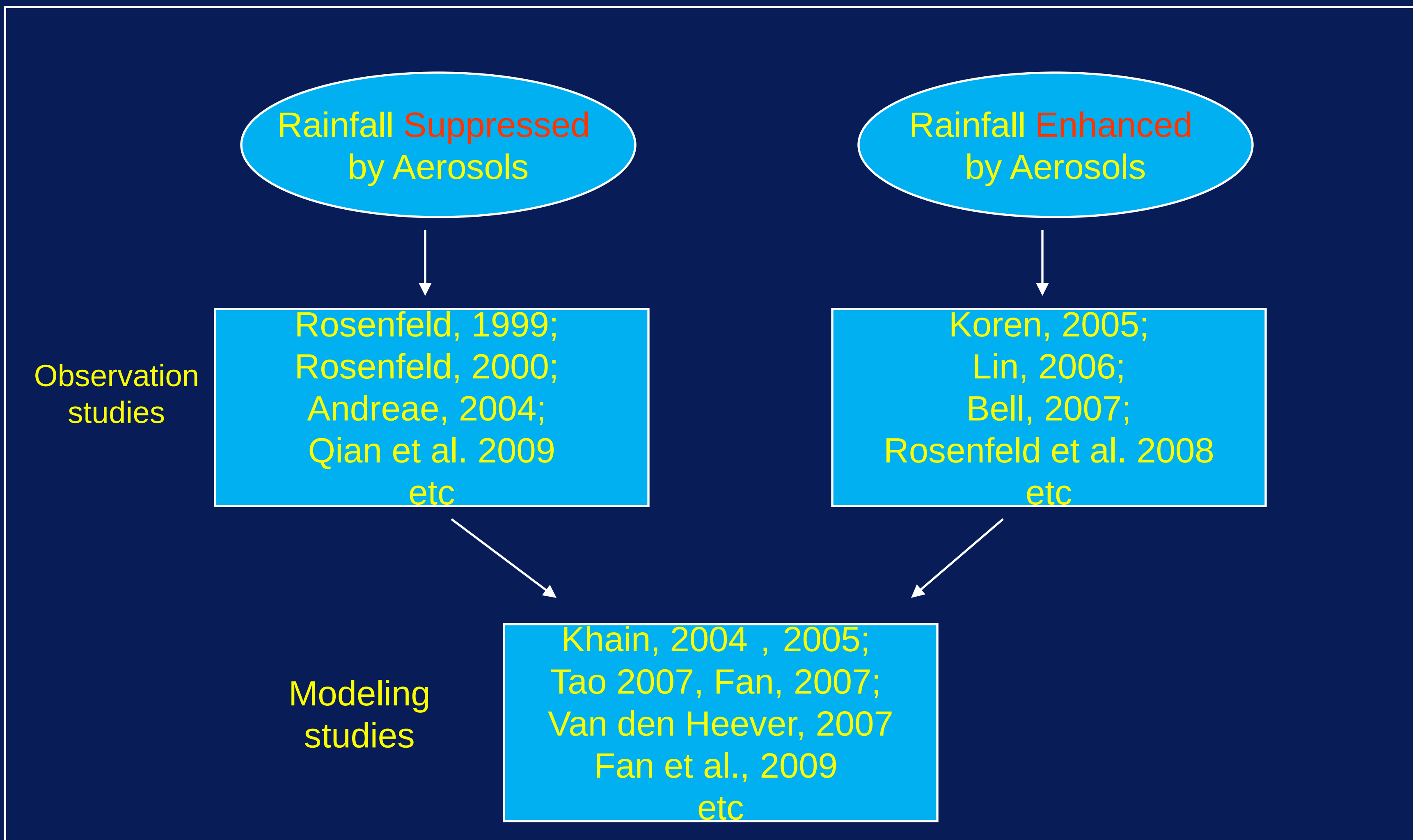
What is on earth the net impact of aerosol & precipitation?



IPCC 2007

A lot have been done concerning aerosol's impact on rainfall, but little is known about the NET IMPACT



Primary Theoretical Mechanisms of Aerosol's Impact on Cloud & Precipitation

- Aerosol microphysical effect (e.g. Twomey):

- Aerosol thermodynamic effect (e.g. Invigoration)

- What is the net, long-term, effect, if any ?
- What are their determining factors ?
- Are ARM data suited to address these questions ?

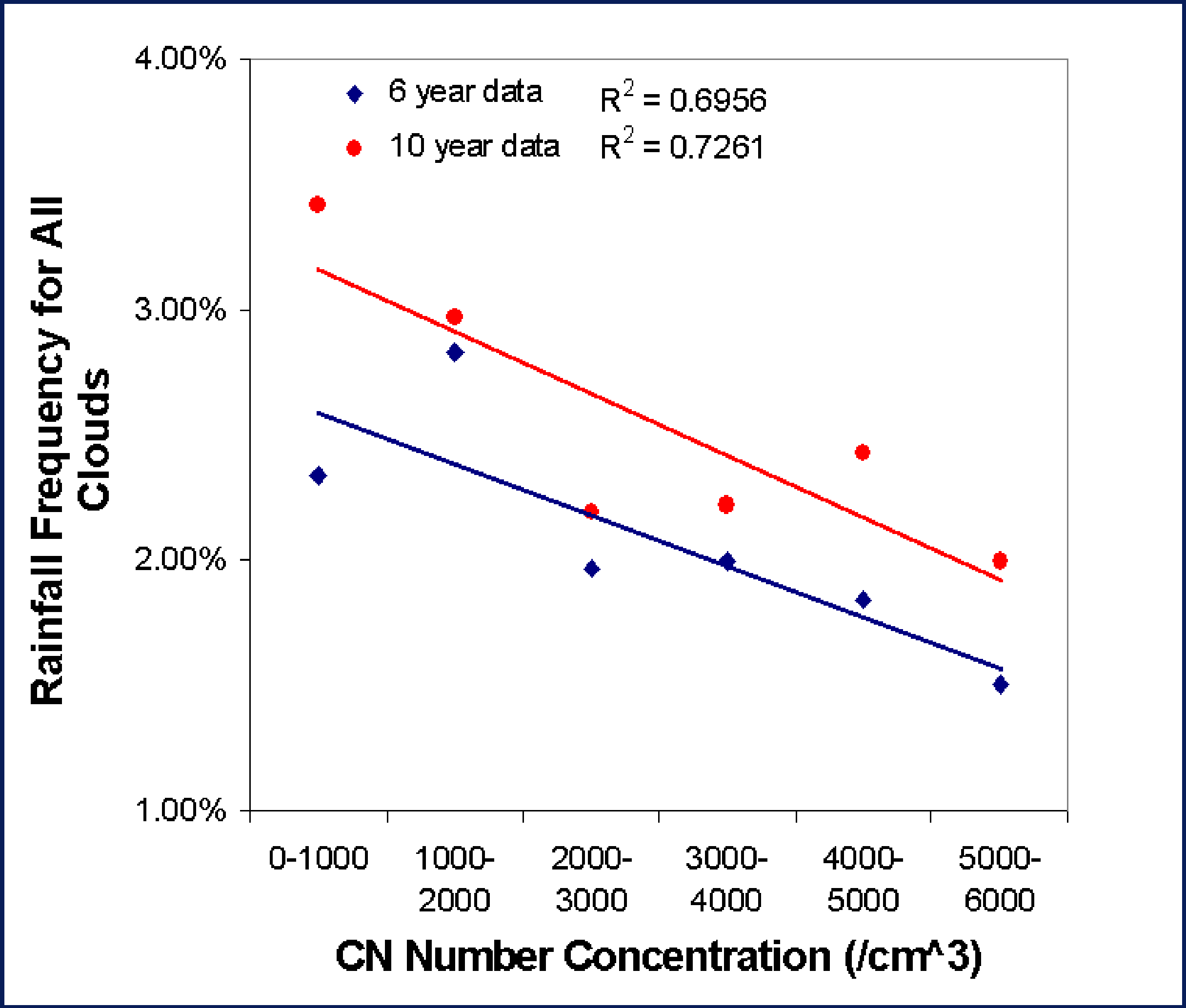
ARM Datasets Used

- Rain gauge (CO2Flx: Carbon Dioxide Flux Measurement System)
  - 6 year data rain data.
  - Resolution: 0.1mm
- Rain gauge (SMOS: Surface Meteorological Observation System)
  - 10 year data rain data
  - Resolution: 0.25mm
- Microwave Radiometer:
  - Liquid water path
  - Column water vapor
- ARSCL: Active Remote Sensing of Clouds
  - Cloud bases and tops
- TSI condensation particle counter
  - condensation nuclear (CN) number concentration, use the measurements made priori to rain to avoid rain contamination due to washout effect

A new paradigm to study the AIE: Top-down approach

- Challenge: atmospheric dynamic thermodynamic dictate cloud development and precipitation that readily overshadow the subtle effect of aerosols.
- Assumption: Dynamic/thermodynamic is a fast process (white noise?) whose influences may be ***washout*** for large enough samples
- Tests: Examine all known physics from the data to see if the signals stand out of noises
- Bottom-line: If aerosols have no discernible effect for a large ensemble of data, why should we be bothered ?

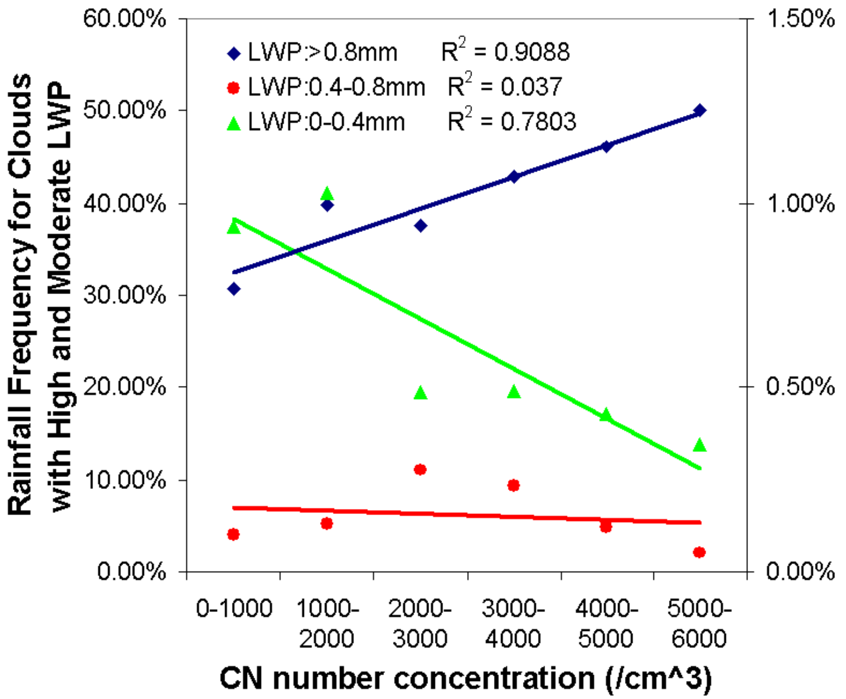
Overall Impact on Rainfall Frequency



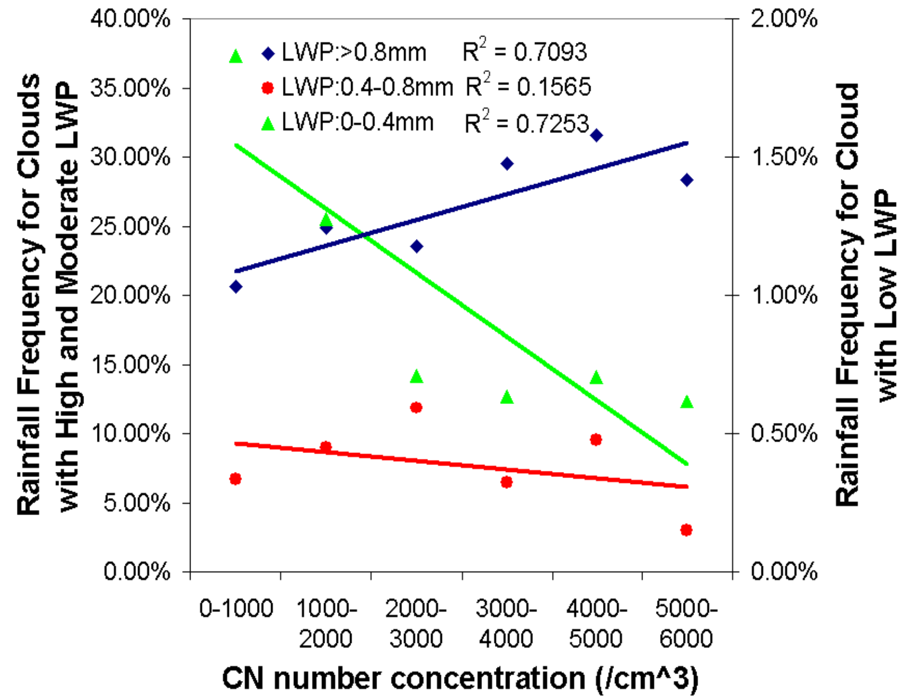
Overall, aerosol reduces the number of rainfall events by up to 50%

The Effect of Cloud Liquid Water Path

6 years



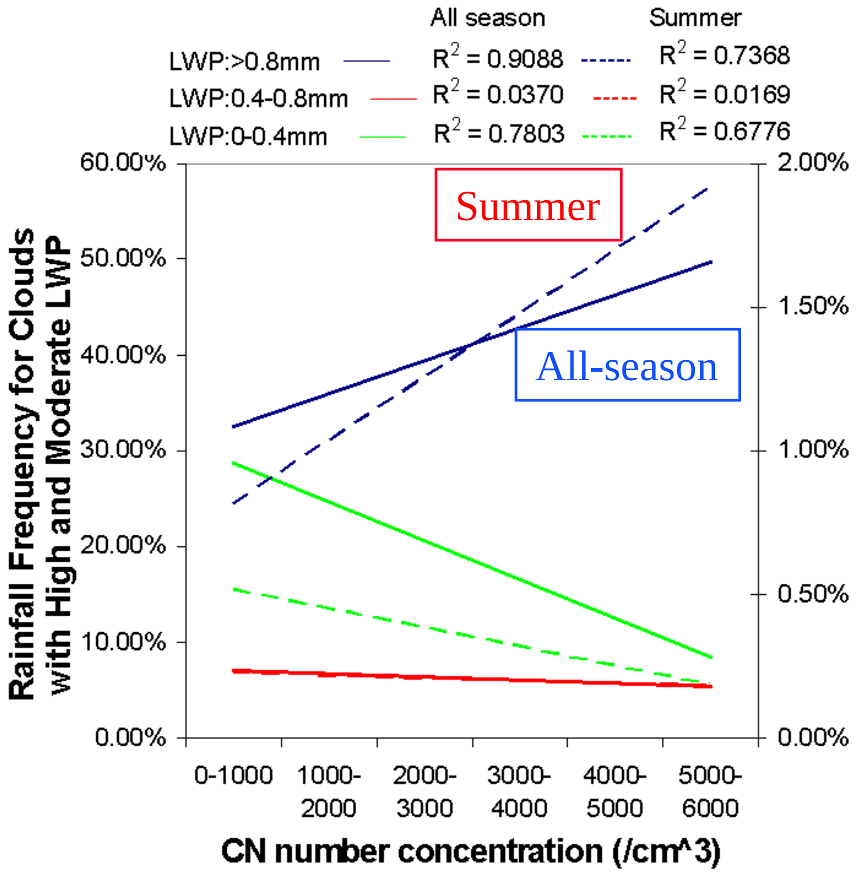
10 years



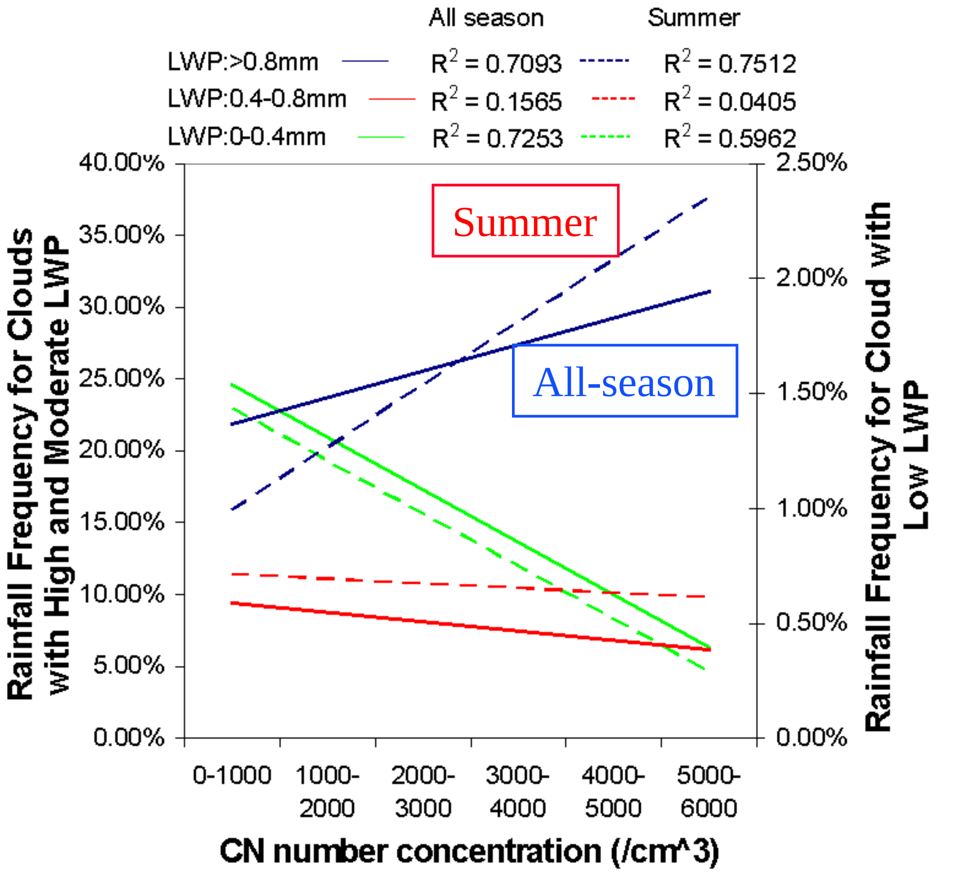
1. For low LWP, rainfall occurrence is suppressed by aerosols (30-50%)
2. For large LWP, rainfall frequency is increased by aerosols (50%)
3. For moderate LWP, aerosols have little impact

The Effect of Convection

6 years



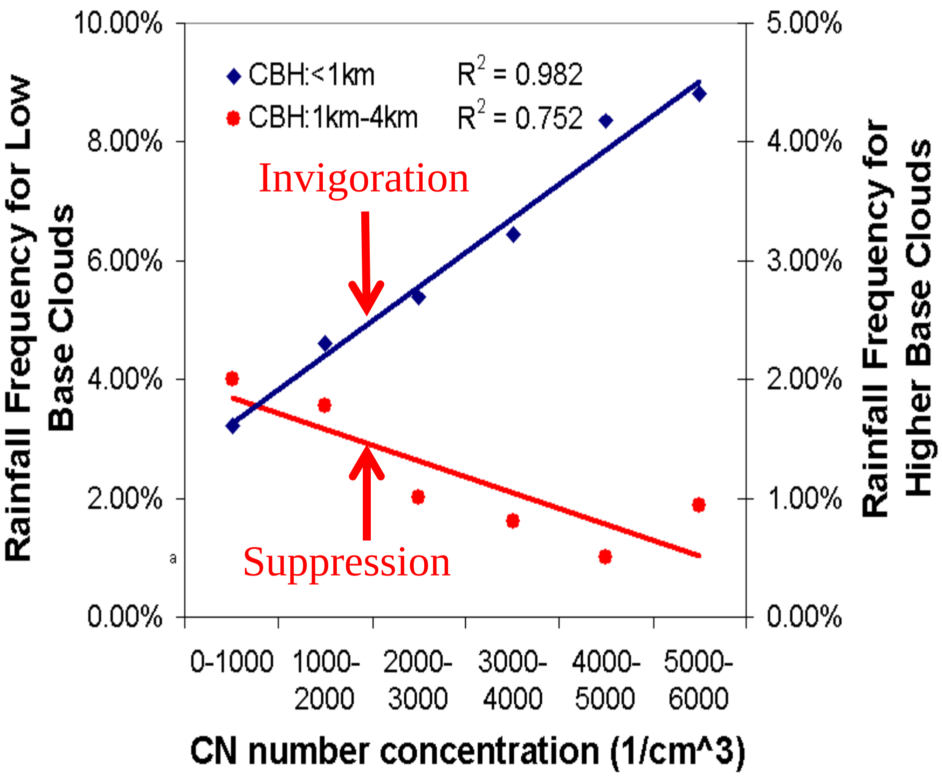
10 years



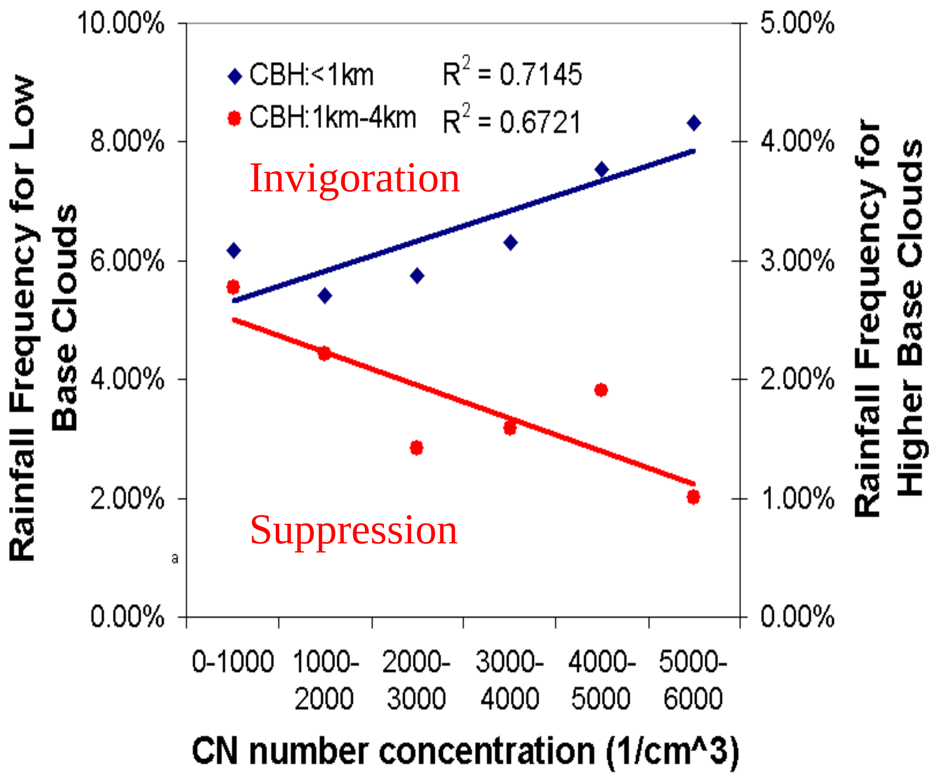
Aerosols have the strongest impact on convective clouds, especially for the invigorated clouds!

The Effect of Cloud Base Height (CBH) On Rainfall Frequency

6 years



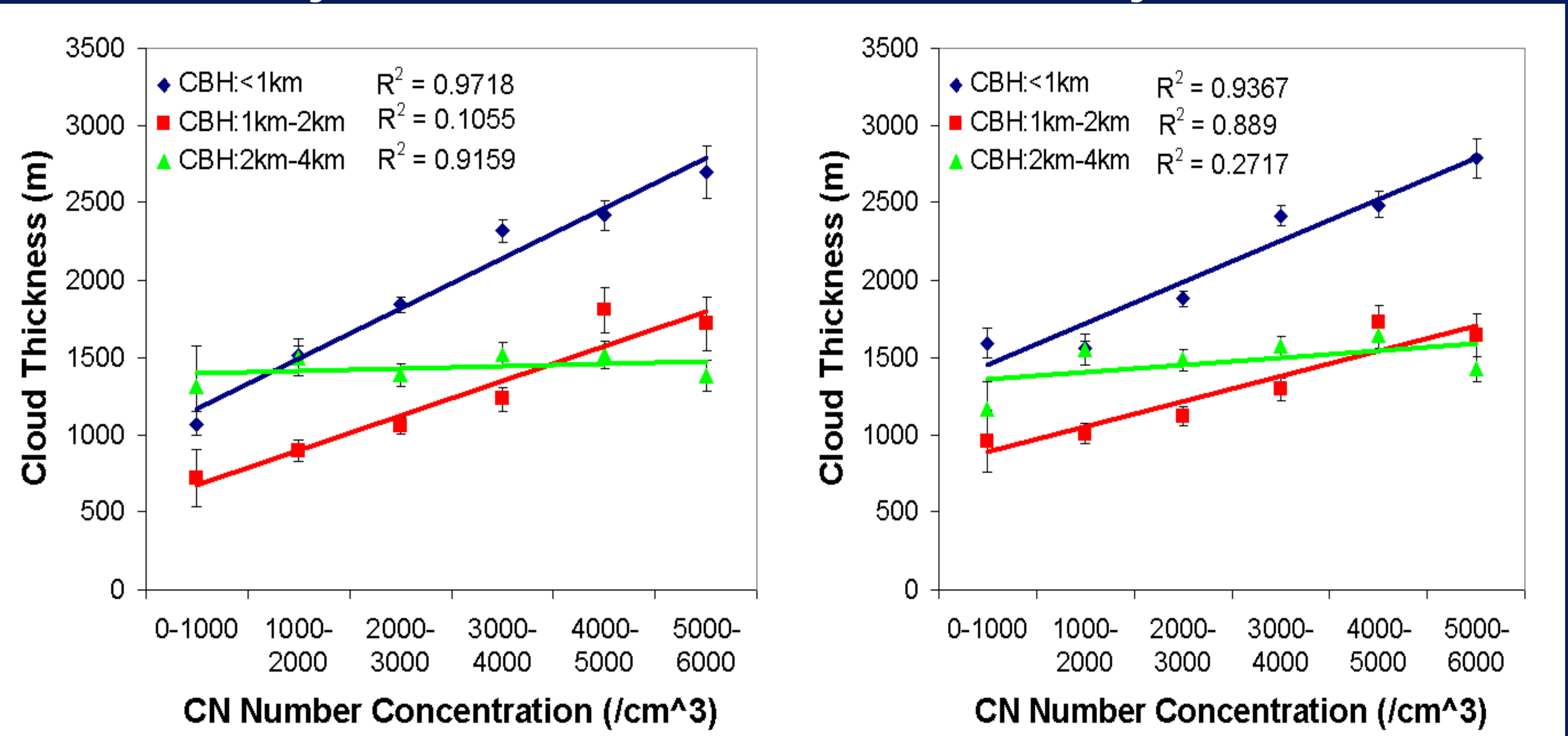
10 years



The invigoration effect depends critically on cloud base height!

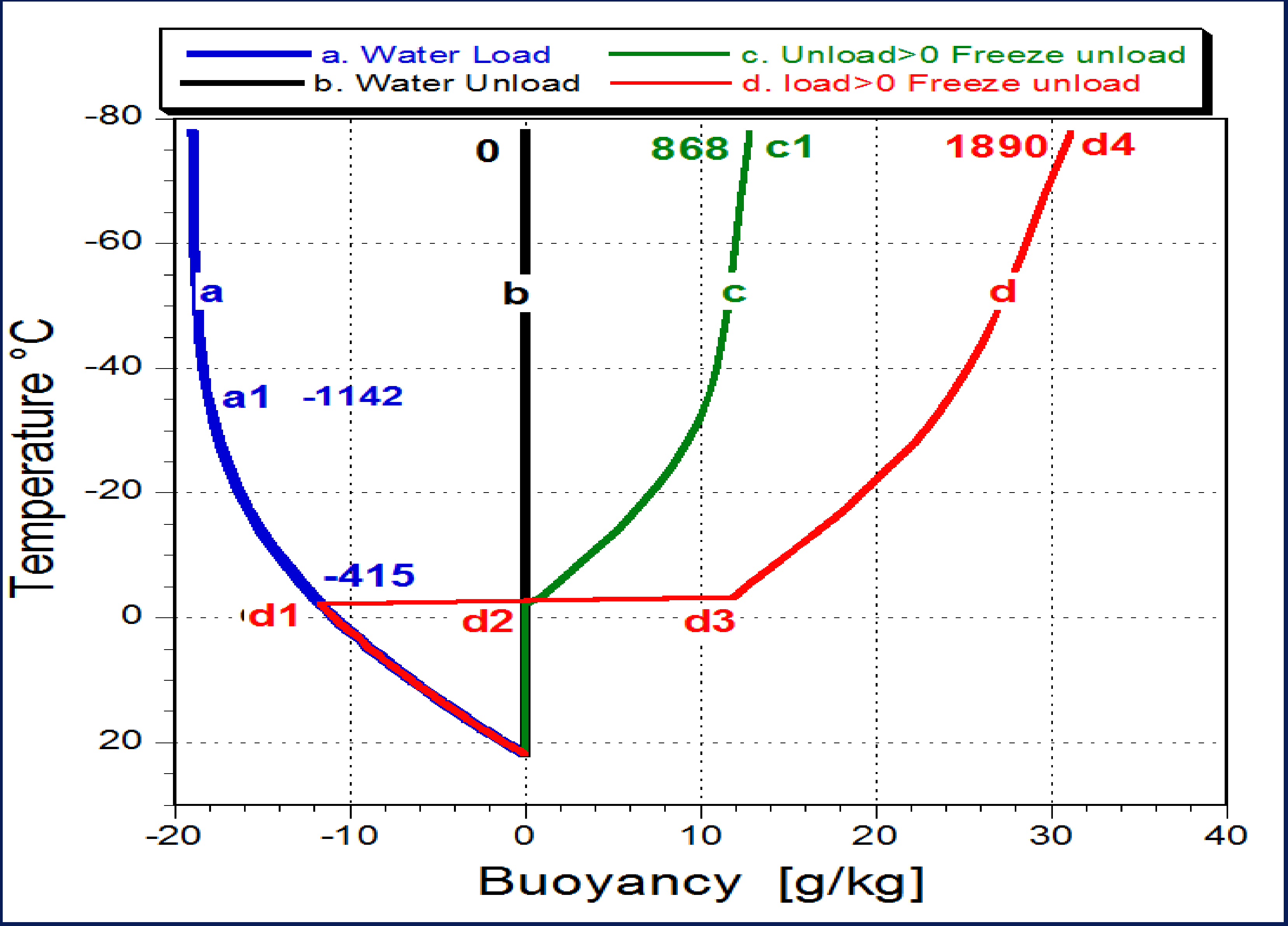
The Effect of Cloud Base Height (CBH) On Cloud Thickness

6 years 10 years



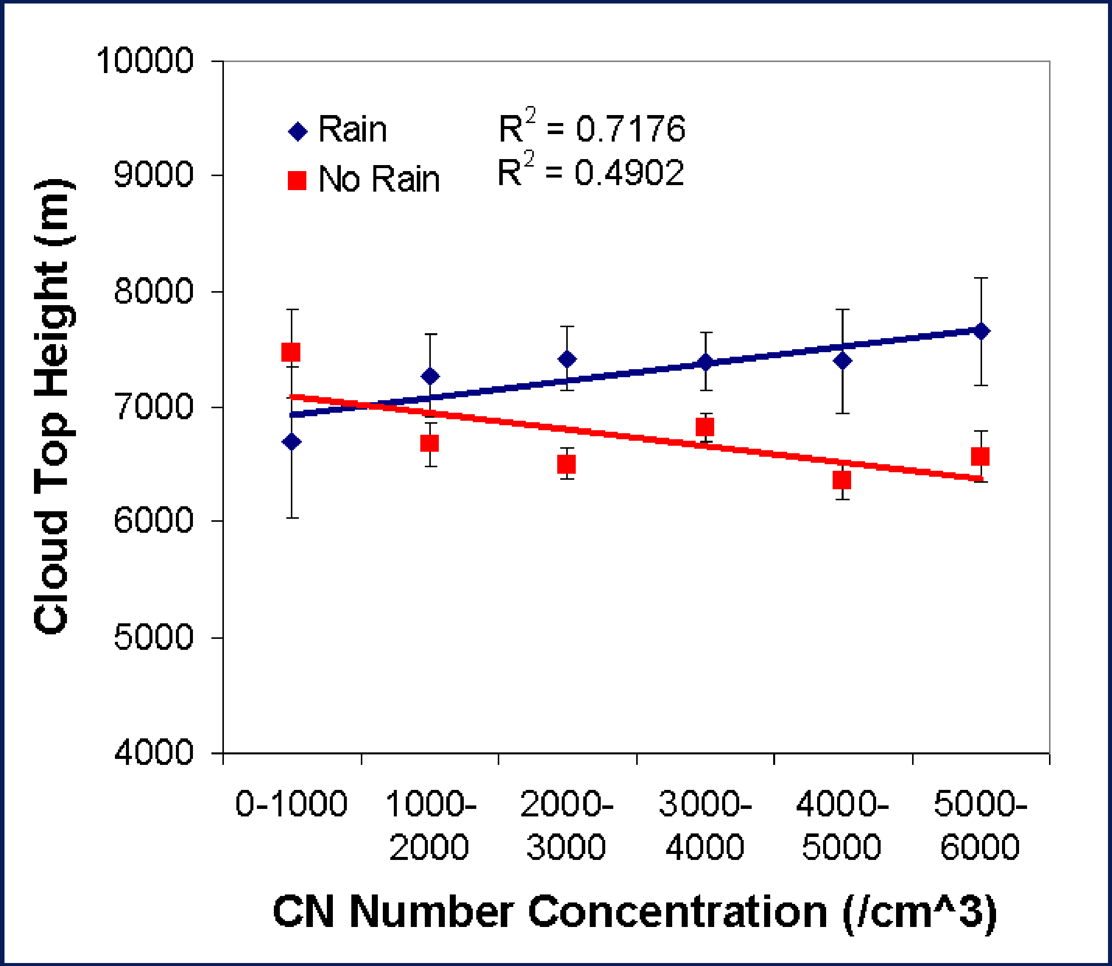
For low clouds (<1km), cloud thickness increases by a factor of 2!
For high clouds (>2km), cloud thickness is not affected at all!.

Hypothesis of aerosol's effects on cloud development due to phase change and water load/unload



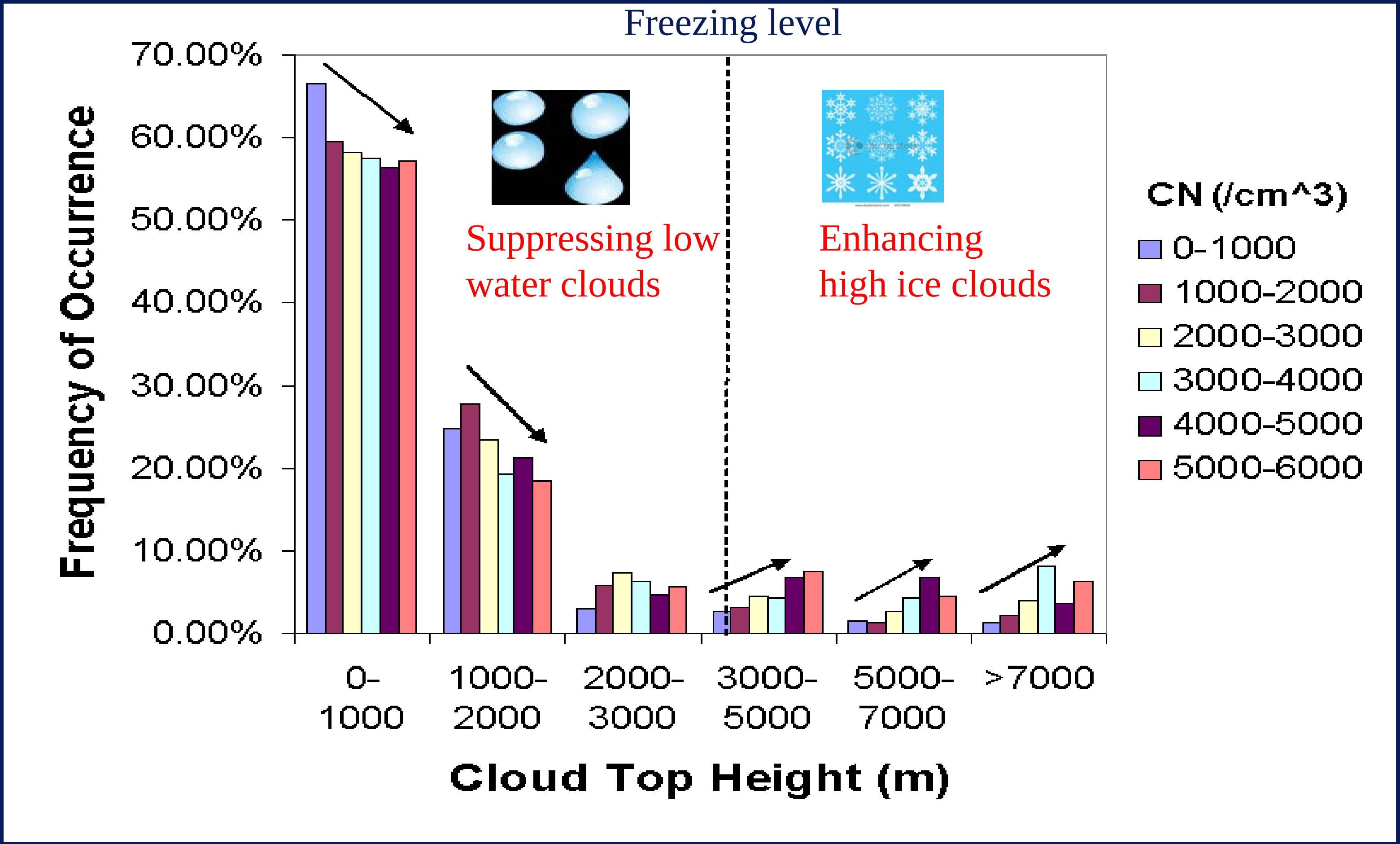
Rosenfeld et al. (2008, Science)

Effects of Dropout of Rain Drops



As raindrops fall out of cloud, buoyancy is increased to fuel the cloud to grow further

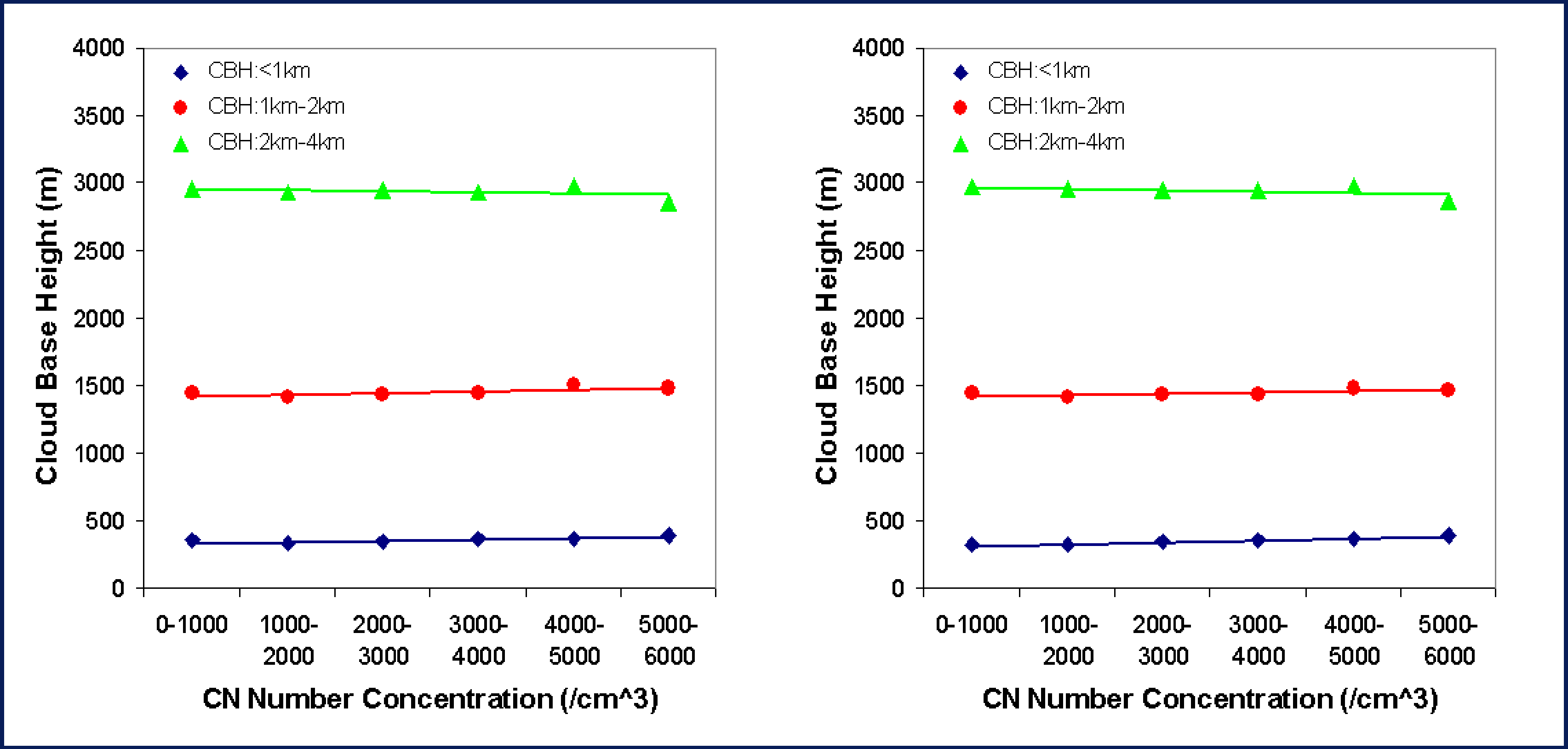
Effects of Cloud Phase
Frequency of Occurrence of Cloud Top Height:



As CN increases, high clouds occurred more frequently but low clouds occurred less frequently

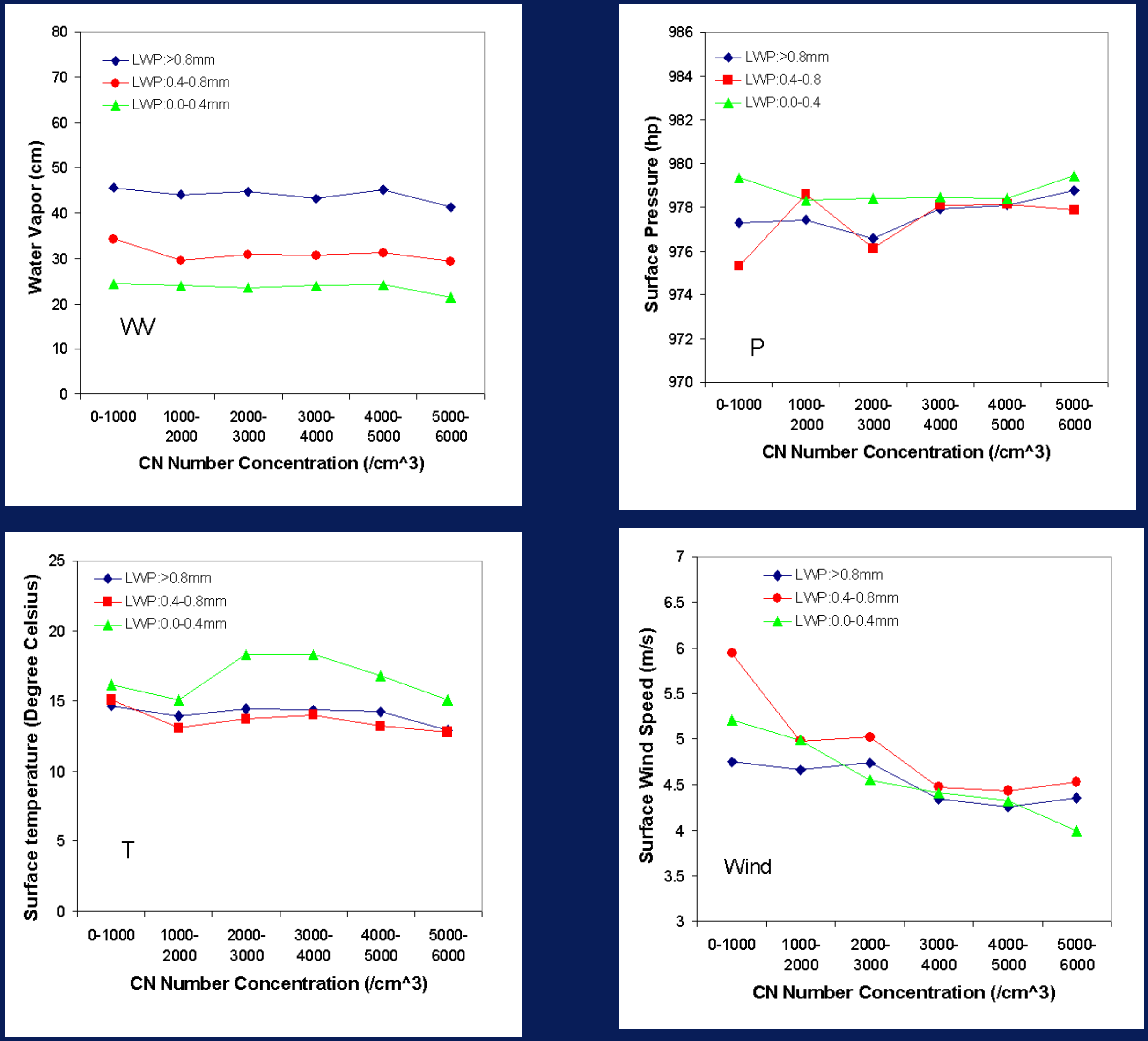
Does Aerosol Affect Cloud Base Height ?

6 years — 10 years



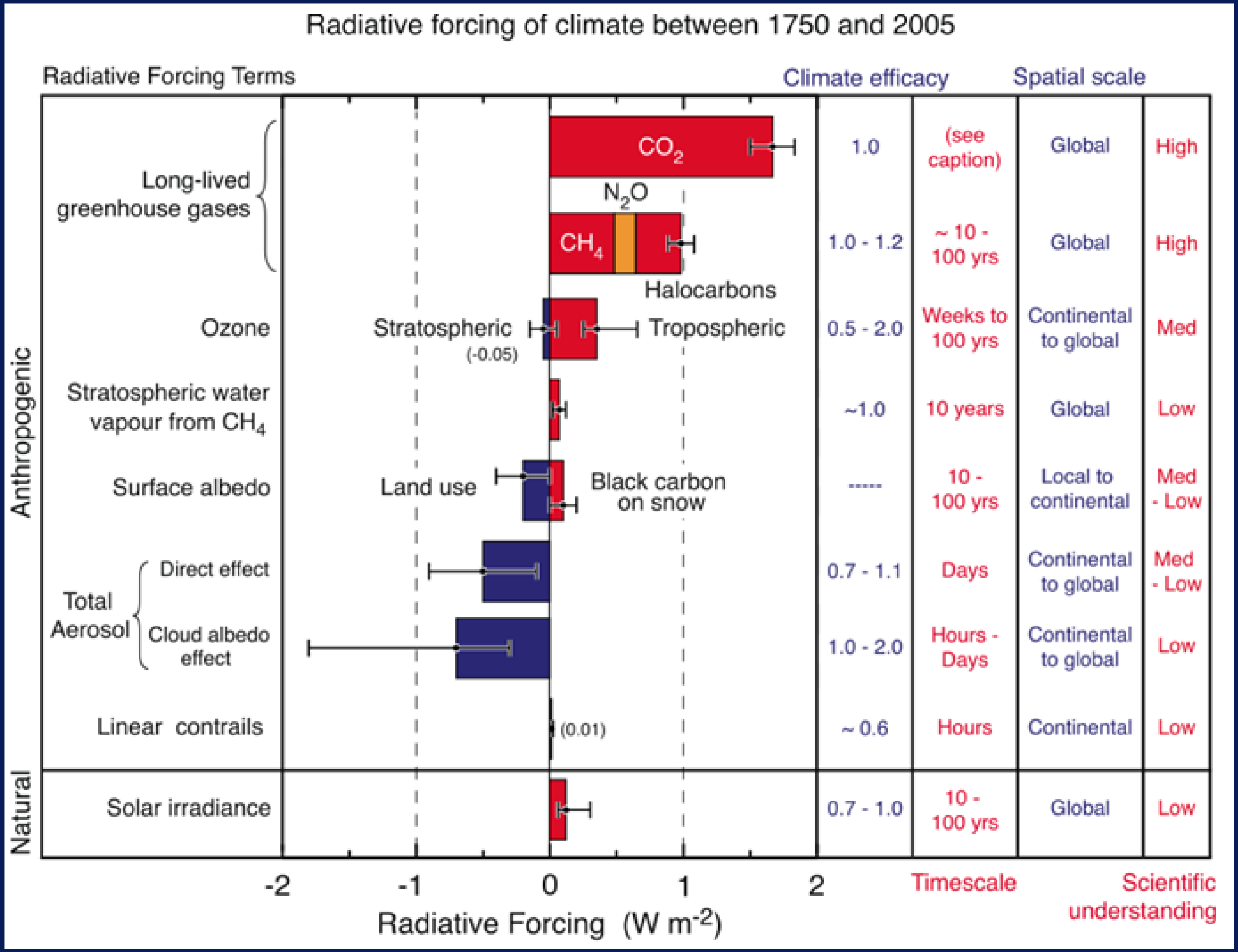
Aerosols have absolutely no effect on cloud base height ! The ubiquitous flat lines attest to that the dynamic effects are filtered out to help single out the aerosol effects :-) :-)

Can we find any other casual relation indicating CN as a proxy of other factors/effects ?

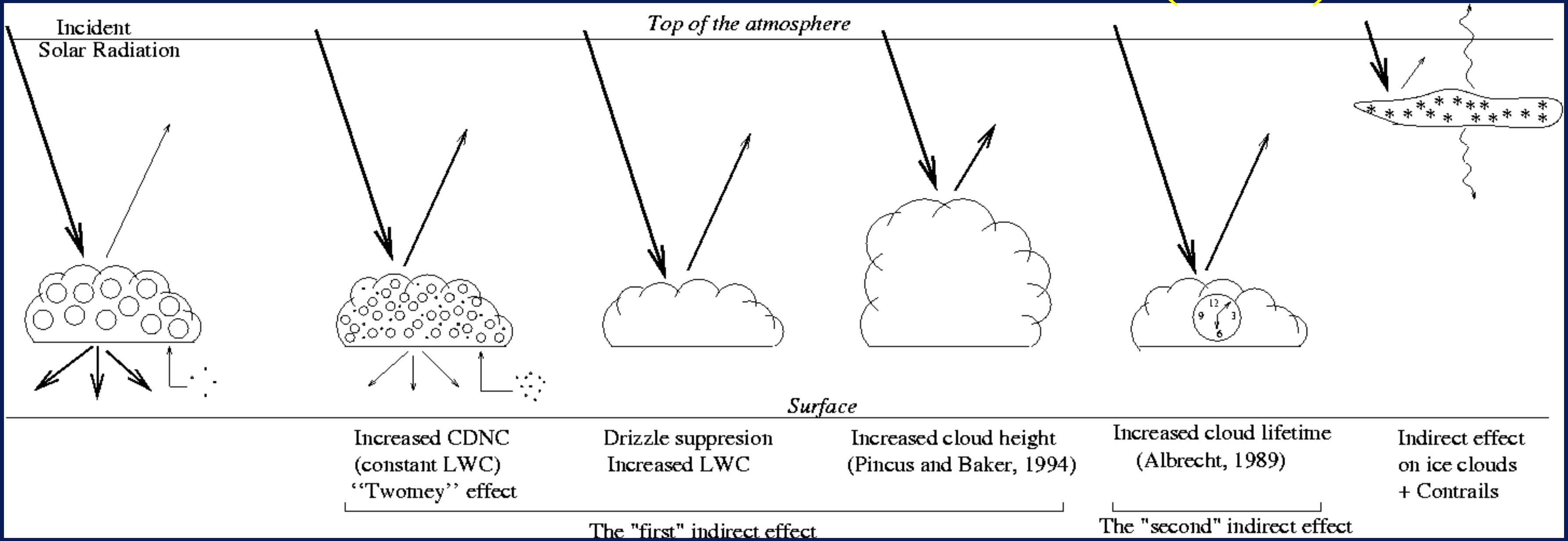


- Introducing “Aerosol Cloud Forcing Efficiency” and “Aerosol Rain Forcing Efficiency” to gauge among observations and models about the net effects of aerosols on hydrology, just as we use “cloud radiative forcing” or “aerosol radiative forcing to gauge their net effects on energy

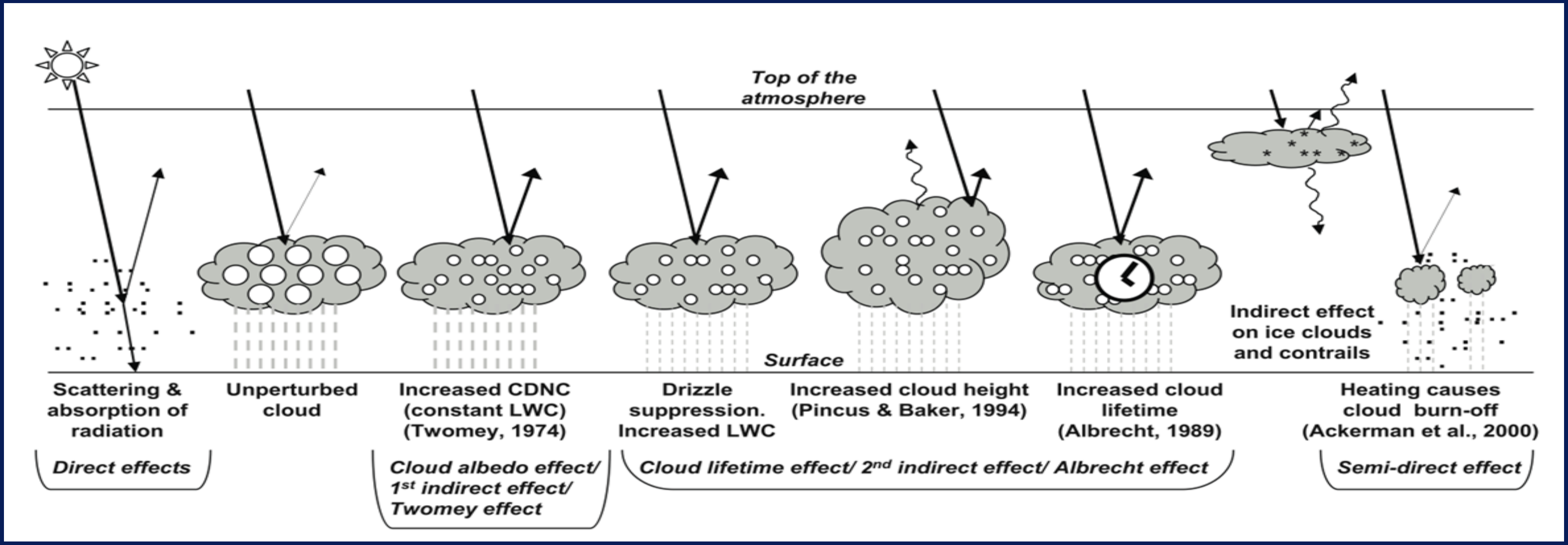
Argument : Aerosol Raditive Forcing (energy) is well-suited for describing its impact on energy cycle, but it is ill-suited to describe aerosol's effect on the hydrology cycle. So, we need to introduce new index



5 Aerosol Indirect Effects in IPCC(2001)



7 Aerosol Indirect Effects in IPCC(2007)



Thinking inside the box (by scientists)

In theory, we may find *indefinite* number of "aerosol indirect effects", as each effect represent a response of *un-limitied* number of meteorological variables to changes in aerosol, under *unlimited constraints* in a *continuous* spectrum of atmospheric variability.

Caring outside the box (by the public)

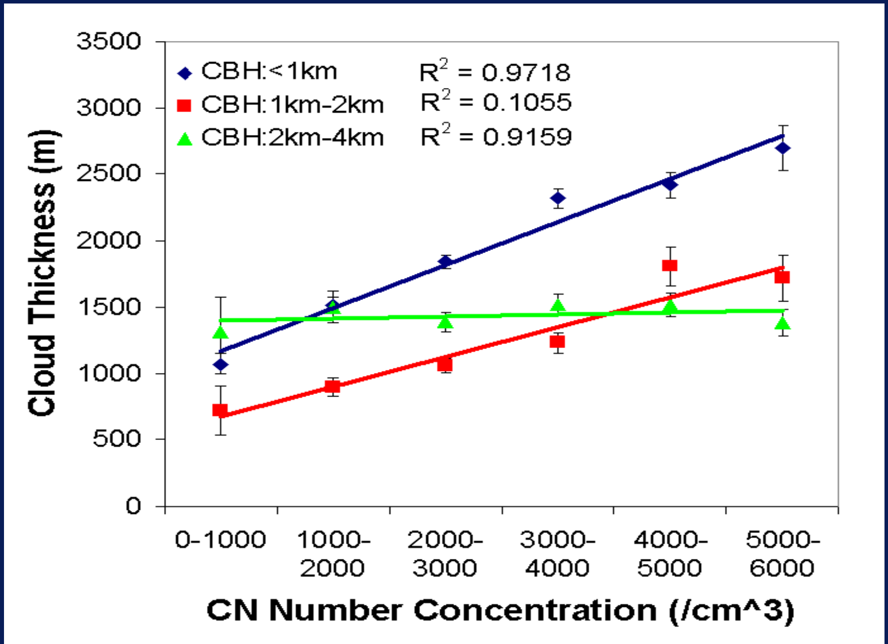
1. What changes to the box – Forcing (greenhouse gases, aersosol, land cover). Aerosol has only TWO forcing mechanisms: *Radiative and Microphysical Forcing*
2. How does the box state variables response – Effect (temperature, precipitation, cloud, etc.)

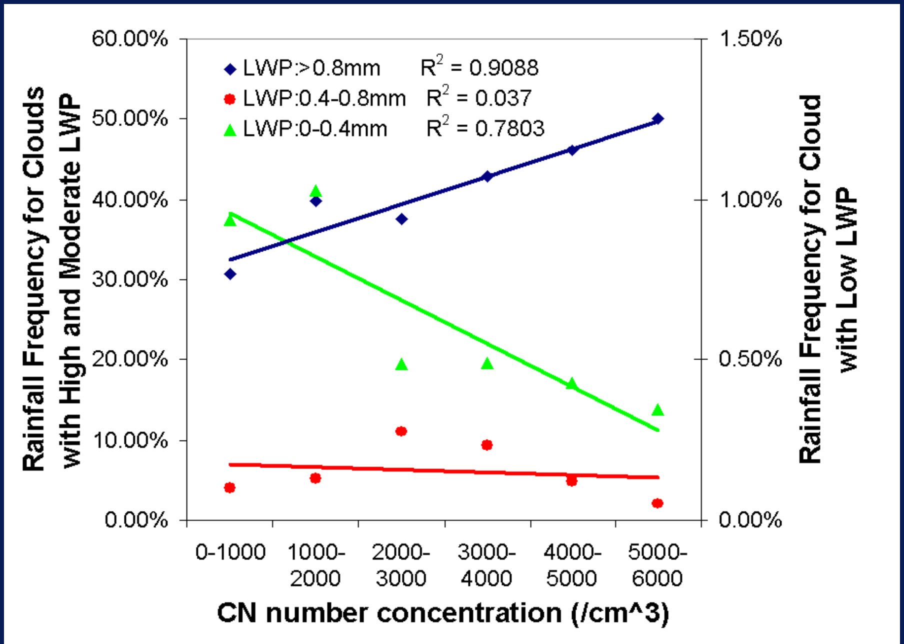
Indices Measuring Forcing-Effect

1. Energy – Aerosol Radiative Forcing and Forcing Efficiency
2. Hydrology – *Aerosol Cloud Forcing (ACF), Aerosol Rain Forcing (ARF) and Forcing Effiency (ACFE, ARFE)*

Aerosol Cloud Forcing Efficiency ΔH/ΔCN, or ΔH/ΔCCN, ΔH/ΔAOD

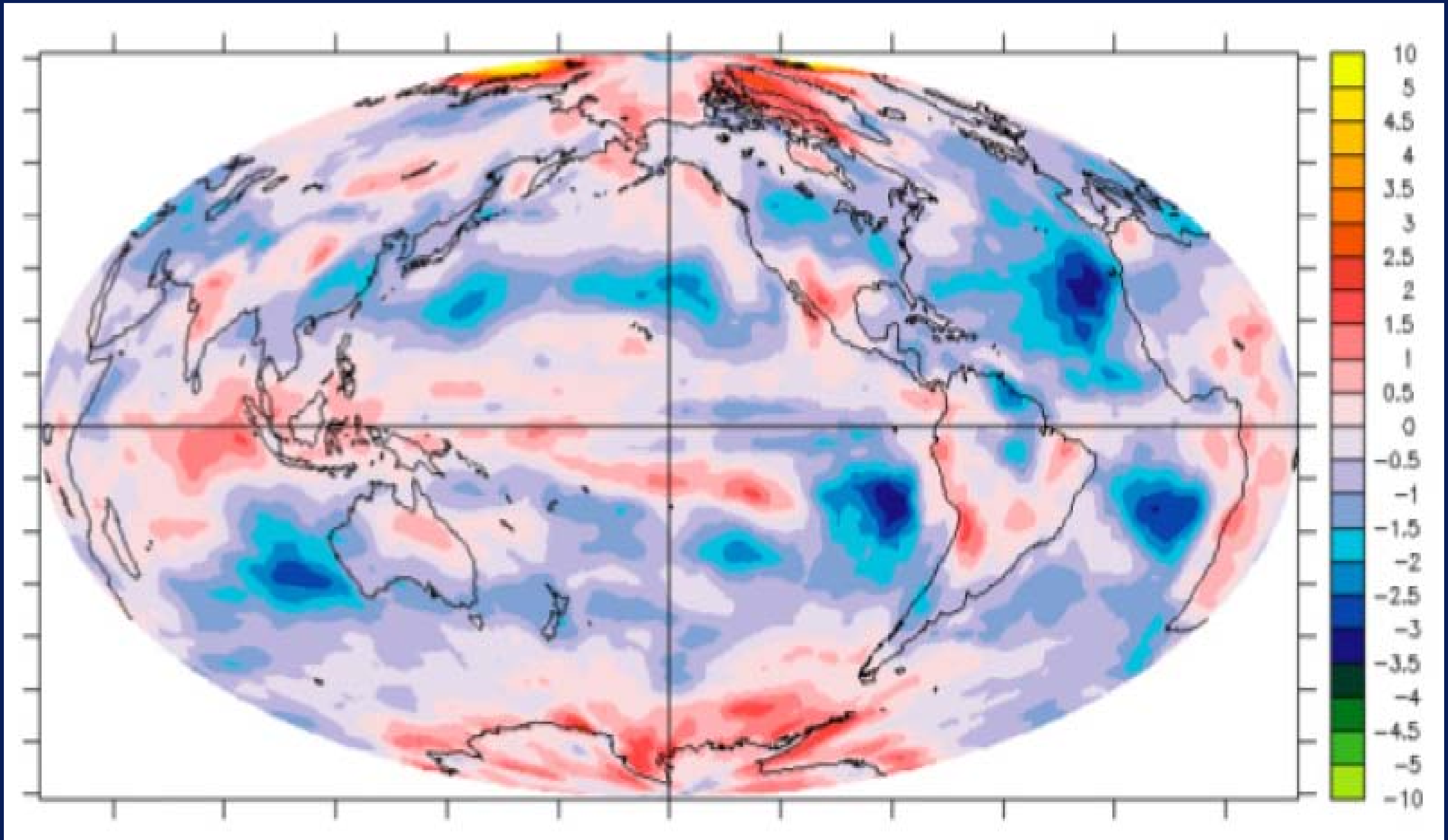
Aerosol Rain Forcing Efficiency ΔR/ΔCN, or ΔR/ΔCCN, ΔR/ΔAOD

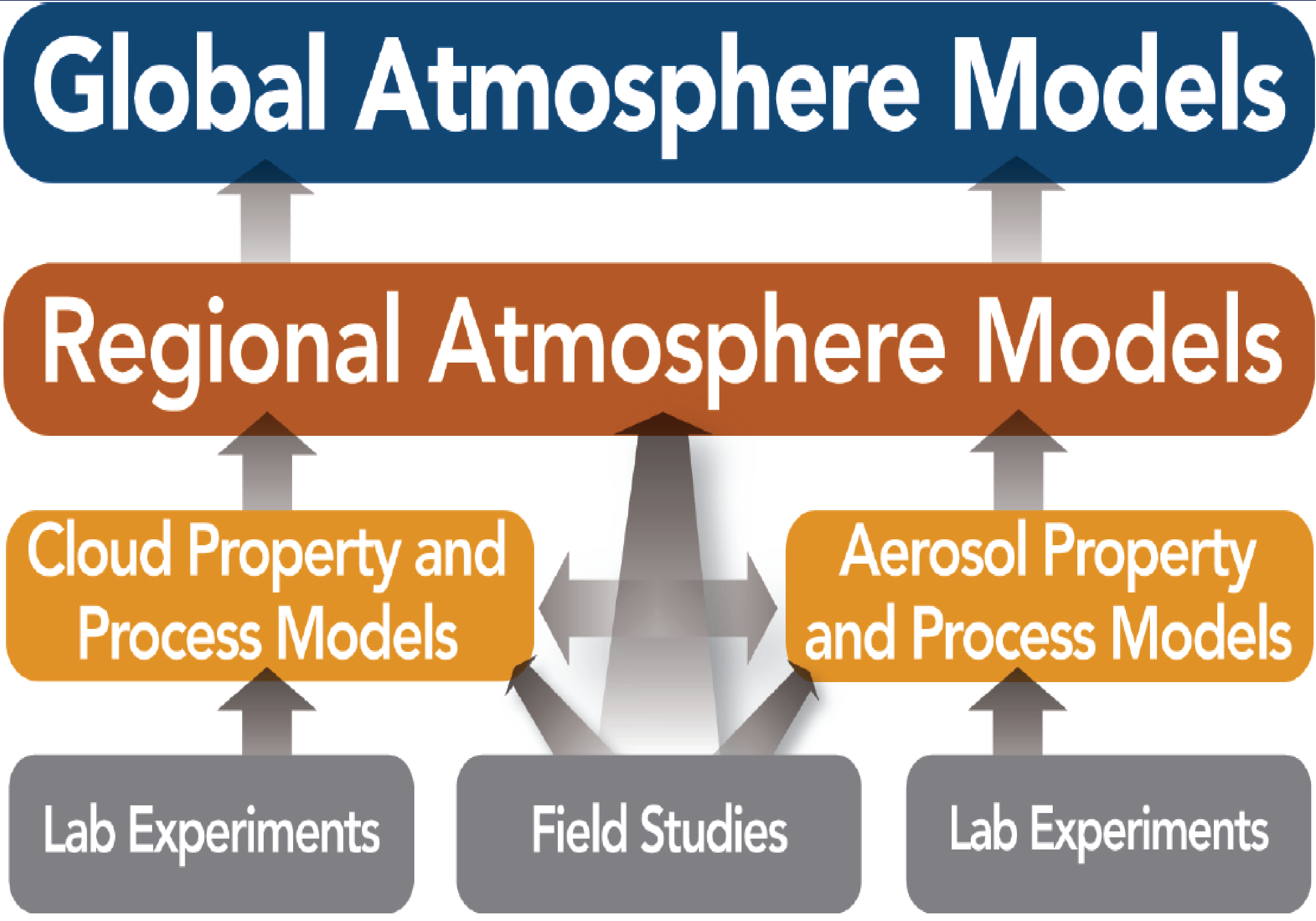




ARFE (ACFE) provides a common ground to compare the net effect of aerosol on precipitation (cloud) between observations and models & among models. ARFE can be determined from observations of long duration, just as model can be run till convergence. Both may vary with location/season, etc.

I have a dream to see the map of the ACFE/ARFE from observations and models and compare them. Their regional & seasonal variations reveal not only the NET impact of aerosols on cloud and precipitation, but also dominance of underlying physics.

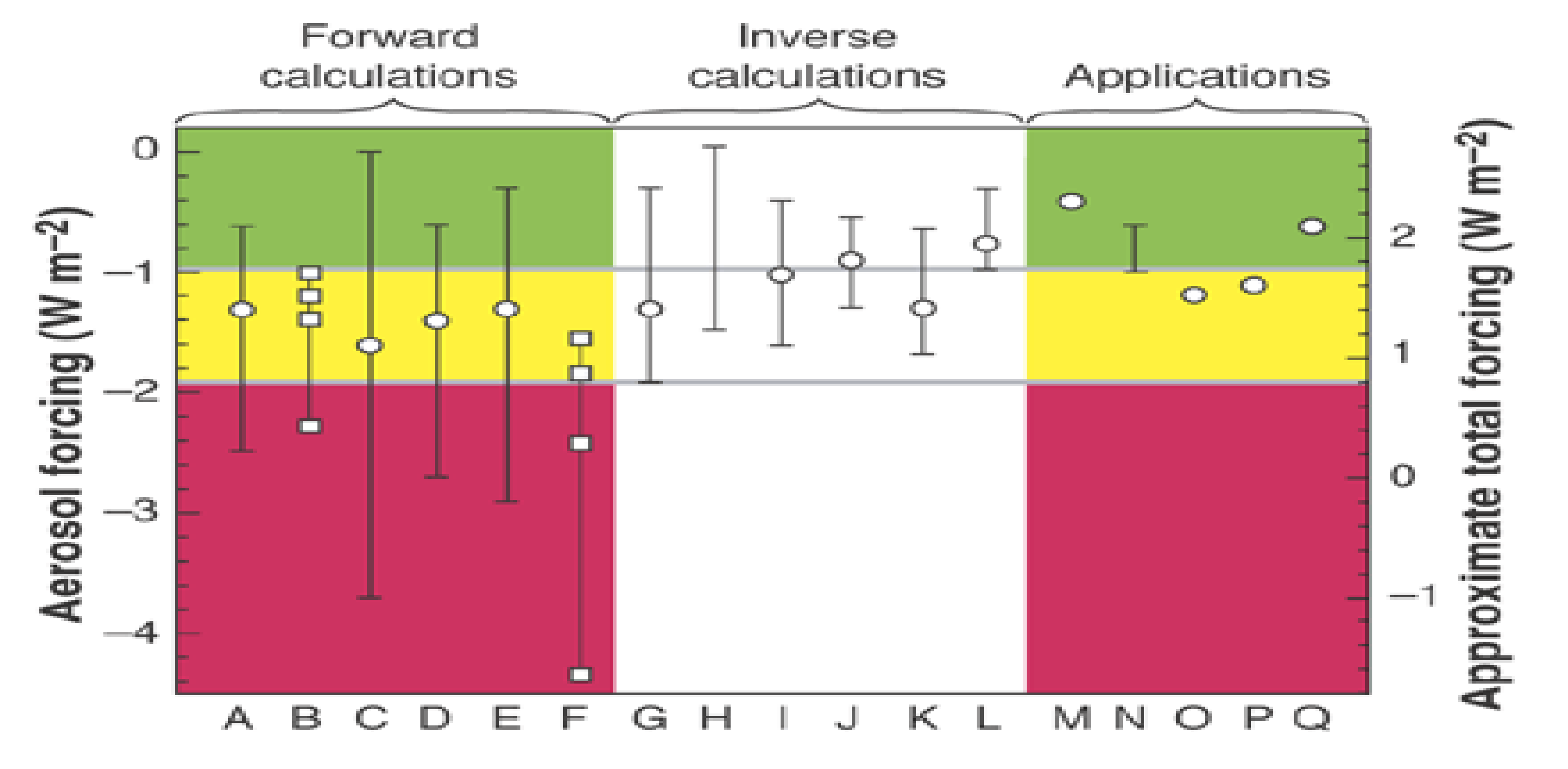



Global Atmosphere Models
Regional Atmosphere Models
Cloud Property and Process Models
Aerosol Property and Process Models
Lab Experiments
Field Studies
Lab Experiments

Conclusions

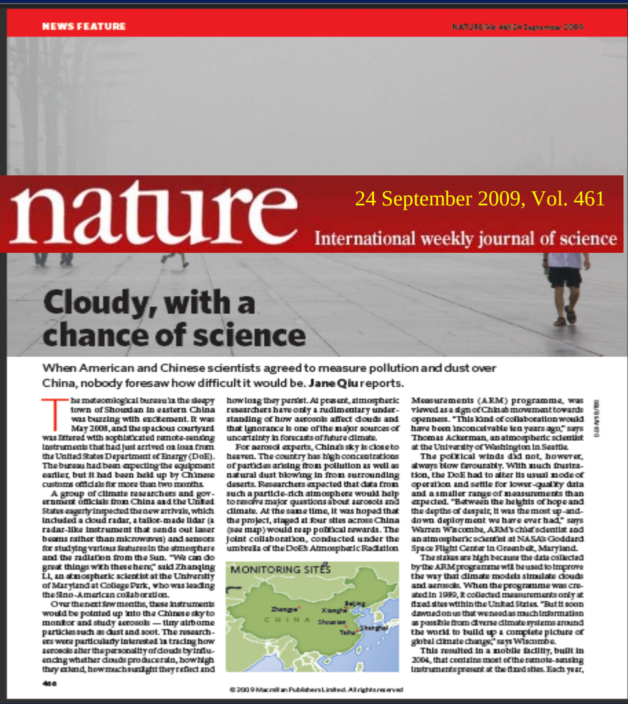
- The long-term, HQ and extensive measurements help reveal the long-term net impact of aerosols on cloud & precipitation for the first time.
- Provide observational evidence of the aerosol invigoration effect, and microphysical effects.
- Both aerosol microphysical & thermodynamic effects are at work whose strength depends on LWP, cloud height, cloud phase, precipitation, convection, etc
- If these findings are true, the total aerosol indirect effect should be less than current estimate, narrowing the gap in our knowledge.

Can the finding of the impact of aerosol on cloud help resolve an Outstanding Issue in Estimation of Global Aerosol Indirect Forcing ?



Anderson et al. (2003, Science)

AMF-China Breakout Session 1:30-3:30 pm


NEWS FEATURE

nature

24 September 2009, Vol. 461

International weekly journal of science

Cloudy, with a chance of science

When American and Chinese scientists agreed to measure pollution and dust over China, nobody foresaw how difficult it would be. Jane Qiu reports.


NEWS FEATURE

"We now have cloud data from China nobody has ever had before." — Mark Miller

Highlight of Major Findings from >20 papers in JGR Special Sections (>40 papers submitted to date)

Li, Z., K.-H. Lee, J. Xin, Y. Wang, 2010, First observation-based estimates of aerosol radiative forcing at the top, bottom and inside of the atmosphere, *J. Geophy. Res.*, revised.

Li, C., N. A. Krotkov, R. R. Dickerson, Z. Li, K. Yang, and M. Chin (2009), Transport and evolution of a pollution plume from northern China: A satellite-based case study, J. Geophys. Res., doi:10.1029/2009JD012245, in press.

Li, C. et al., Anthropogenic Air Pollution Observed near Dust Source Regions in Northwestern China during Springtime 2008

Guo, Z., Z. Li, J. Farquhar, A. J. Kaufman, N. Wu, C. Li, R. R. Dickerson, and P. Wang (2009), Identification of Sources and Formation Processes of Atmospheric Sulfate by Sulfur Isotope and SEM Measurements, *J. Geophys. Res.*, doi:10.1029/2009JD012893, in press.

Lee, K. H., Z. Li, M.C. Cribb, J. Liu, L. Wang, Y. Zheng, X. Xia, H. Chen, and B. Li (2009), Aerosol optical depth measurements in Eastern China and a new calibration method, *J. Geophys. Res.*, doi:10.1029/2009JD012812, 2009, in press.

Zhang, J. H. Chen, Z. Li, X. Fan, L. Peng, Y. Yu, M. Cribb, Analysis of cloud layer structure in Shouxian, China using RS92 radiosonde data, *J. Geophys. Res.* Submitted.

Li, C., N. A. Krotkov, R. R. Dickerson, Z. Li, K. Yang, and M. Chin (2010), Transport and evolution of a pollution plume from northern China: A satellite-based case study.

Qian, Y., D. Gong, J. Fan, L. R. Leung, R. Bennartz, D. Chen, and W. Wang (2009), Heavy pollution suppresses light rain in China: Observations and modeling.

Lee, K. H., Z. Li, M.C. Cribb, J. Liu, L. Wang, Y. Zheng, X. Xia, H. Chen, and B. Li (2010), Aerosol optical depth measurements in Eastern China and a new calibration method.

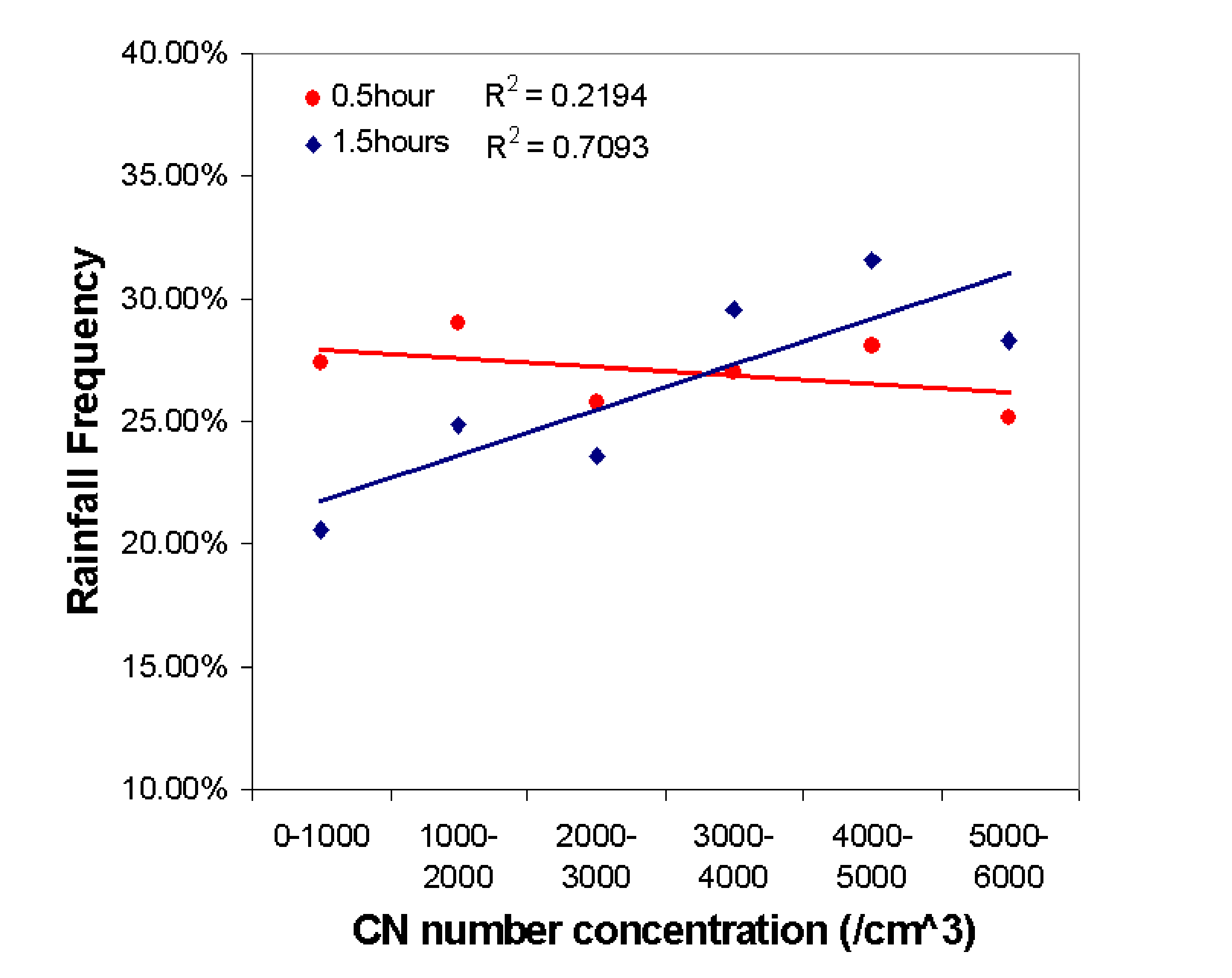
Ge, J. M., J. Su, T.P. Ackerman, Q. Fu, J.P. Huang, and J.S. Shi (2010), Dust Aerosol Optical Properties Retrieval and Radiative Forcing over Northwestern China during the 2008 China-US Joint Field Experiment.

Huang, K., G. Zhuang, J. Li, Q. Wang, Y. Sun, Y. Lin, and J. S. Fu (2010), The mixing of Asian dust with pollution aerosol and the transformation of aerosol components during the dust storm over China in spring, 2007.

Zhuang. G. (corresponding author) et al., Relation between optical and chemical properties of dust aerosol over Beijing, China

Liu, Y., D. Yang, W. Chen, and H. Zhang (2010), Measurements of Asian dust optical properties over the Yellow Sea of China by shipboard and ground-based photometers, along with Satellite remote sensing: a case study of the passage of a frontal system during April 2006.

The Effect of Rain Washout on Aerosol



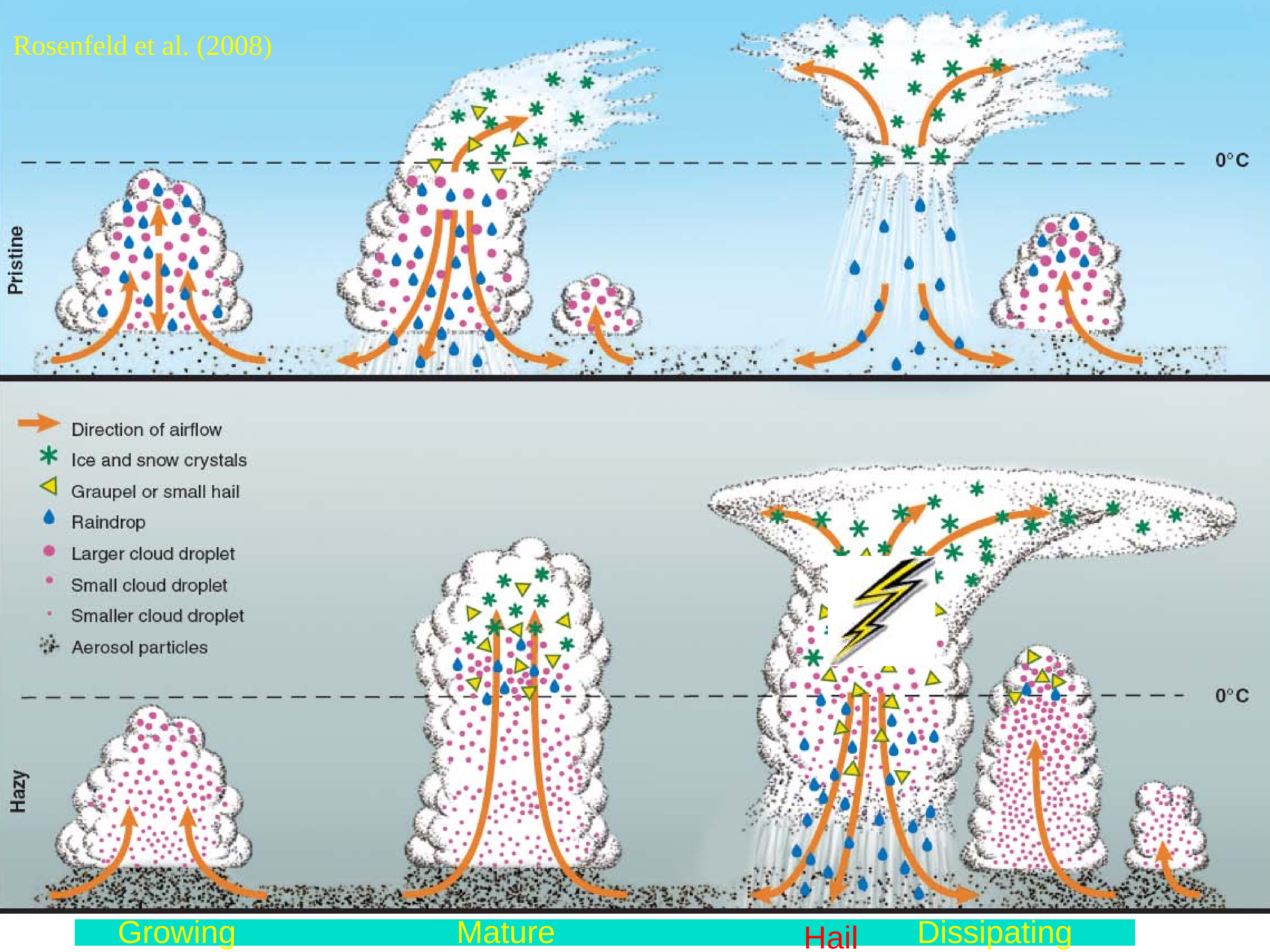
1. Ground-level CN is washout by rain
2. Use of simultaneous or semi-simultaneous CN misleads aerosol effects

Theoretical Interpretation

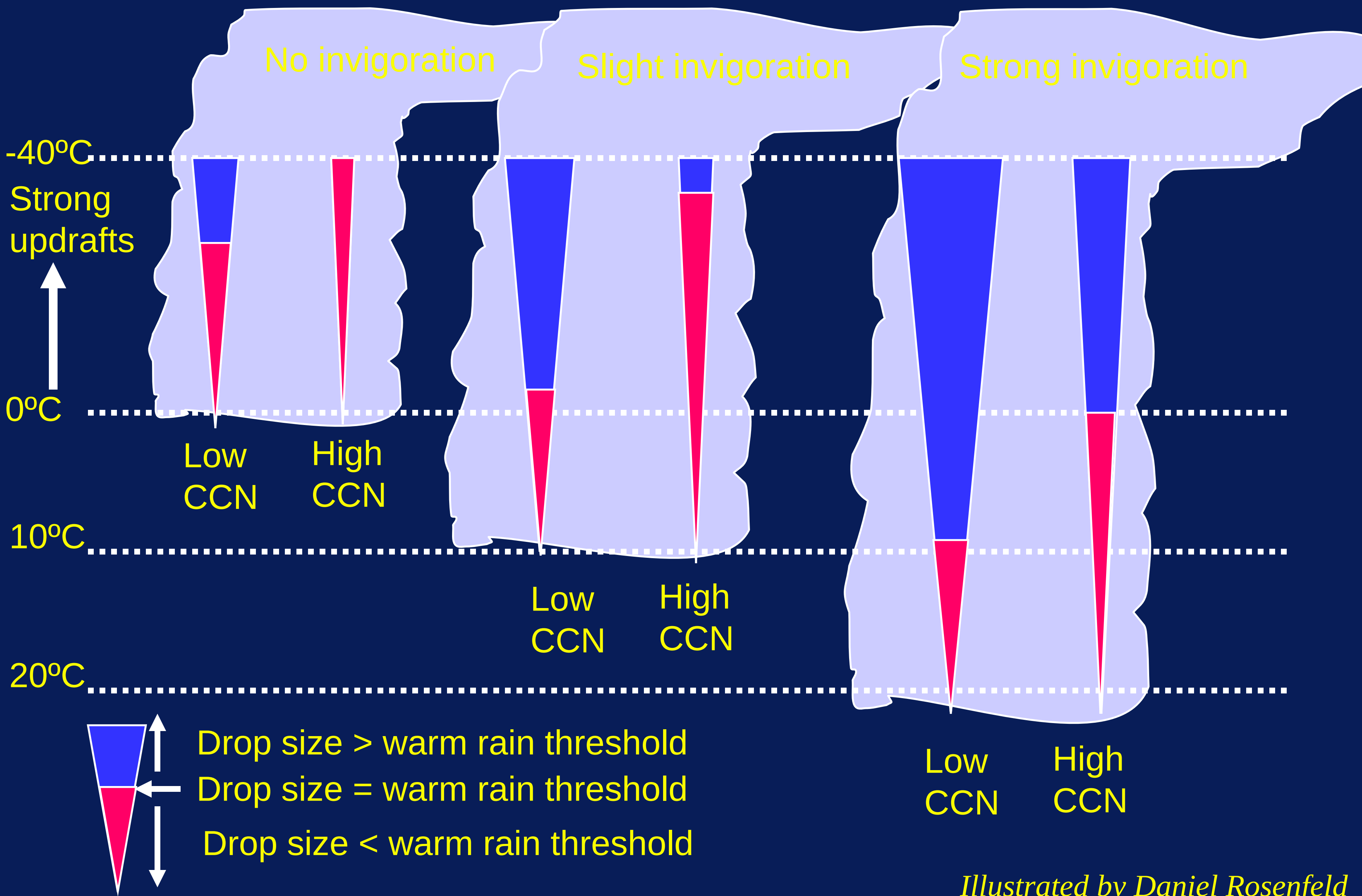
- The cloud thickness for the onset of precipitation H* is a critical parameter (*Rosenfeld et al*., 2008)

- $H^*=C (N_a)^{ß}$ generally increases with aerosol number concentration.

- The relation between H*, the freezing level, and cloud top H determines whether clouds are invigorated or suppressed.


Rosenfeld et al. (2008)
0°C
Pristine
Direction of airflow
Ice and snow crystals
Graupel or small hail
Raindrop
Larger cloud droplet
Small cloud droplet
Smaller cloud droplet
Aerosol particles
0°C
Hazy
Growing
Mature
Hail
Dissipating

Conceptual model for aerosol invigoration effect:



Illustrated by Daniel Rosenfeld

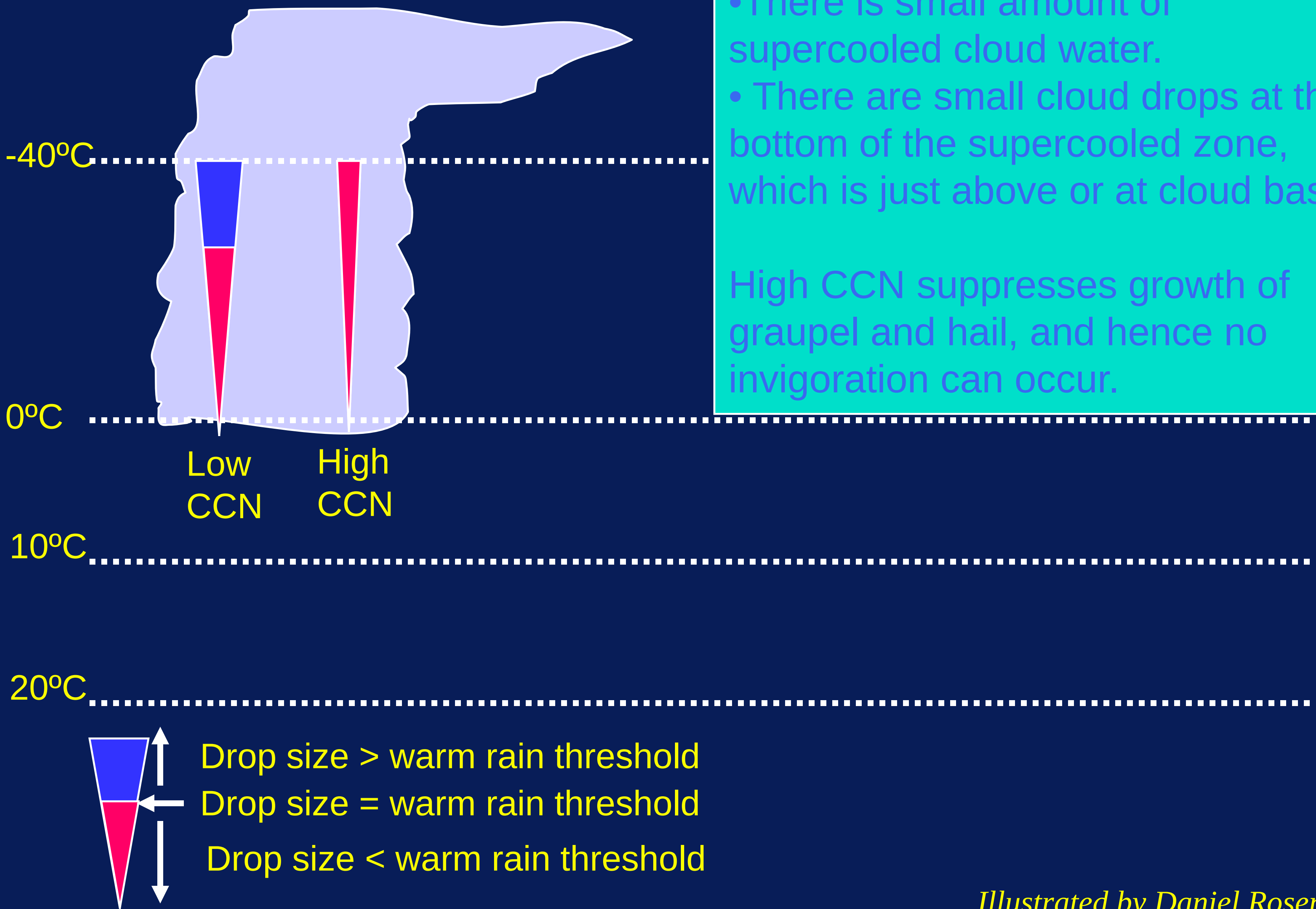
Conceptual model:

Cold base clouds:

Even in small CCN concentrations:

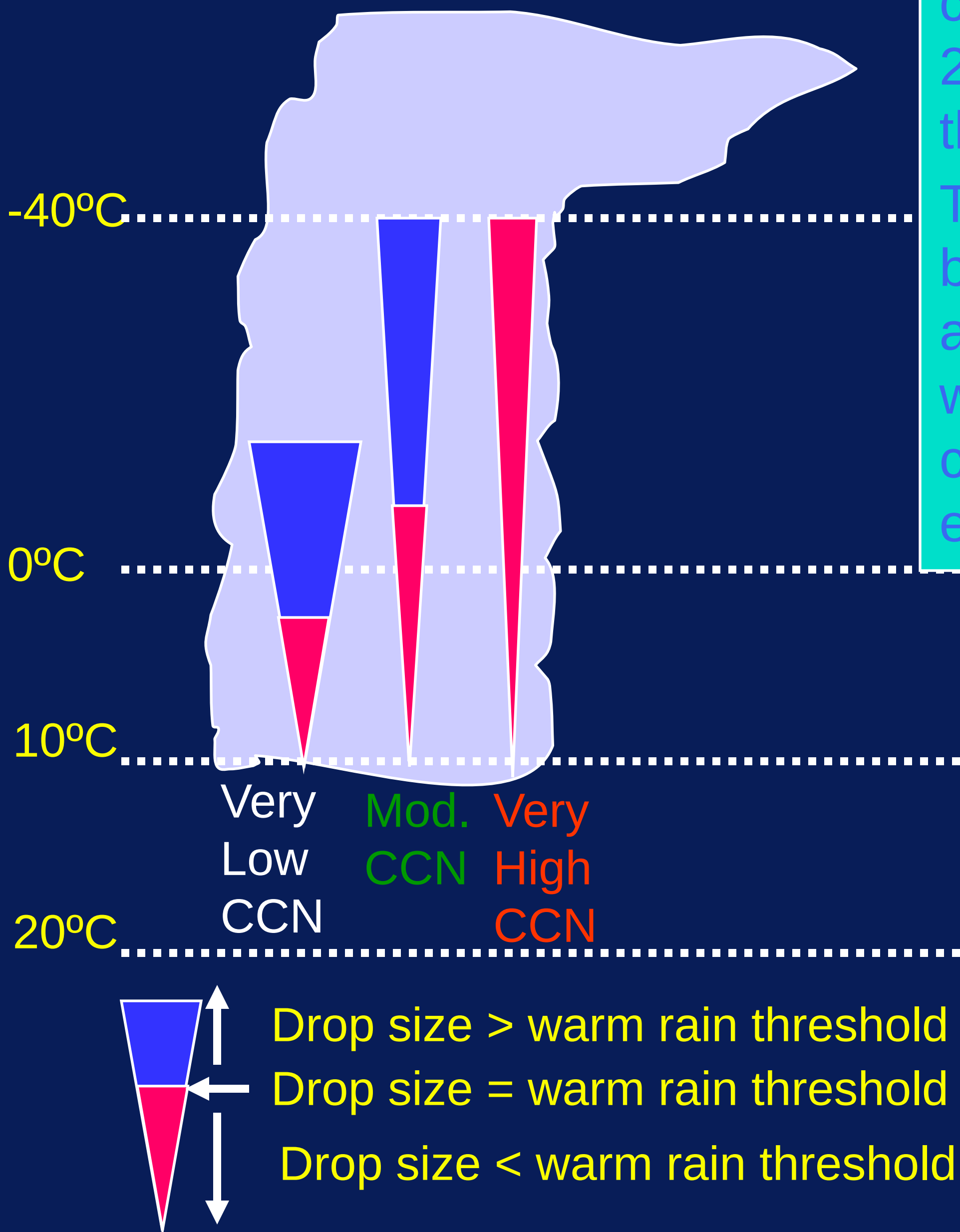
- There is small amount of supercooled cloud water.
- There are small cloud drops at the bottom of the supercooled zone, which is just above or at cloud base.

High CCN suppresses growth of graupel and hail, and hence no invigoration can occur.



Illustrated by Daniel Rosenfeld

Conceptual model:

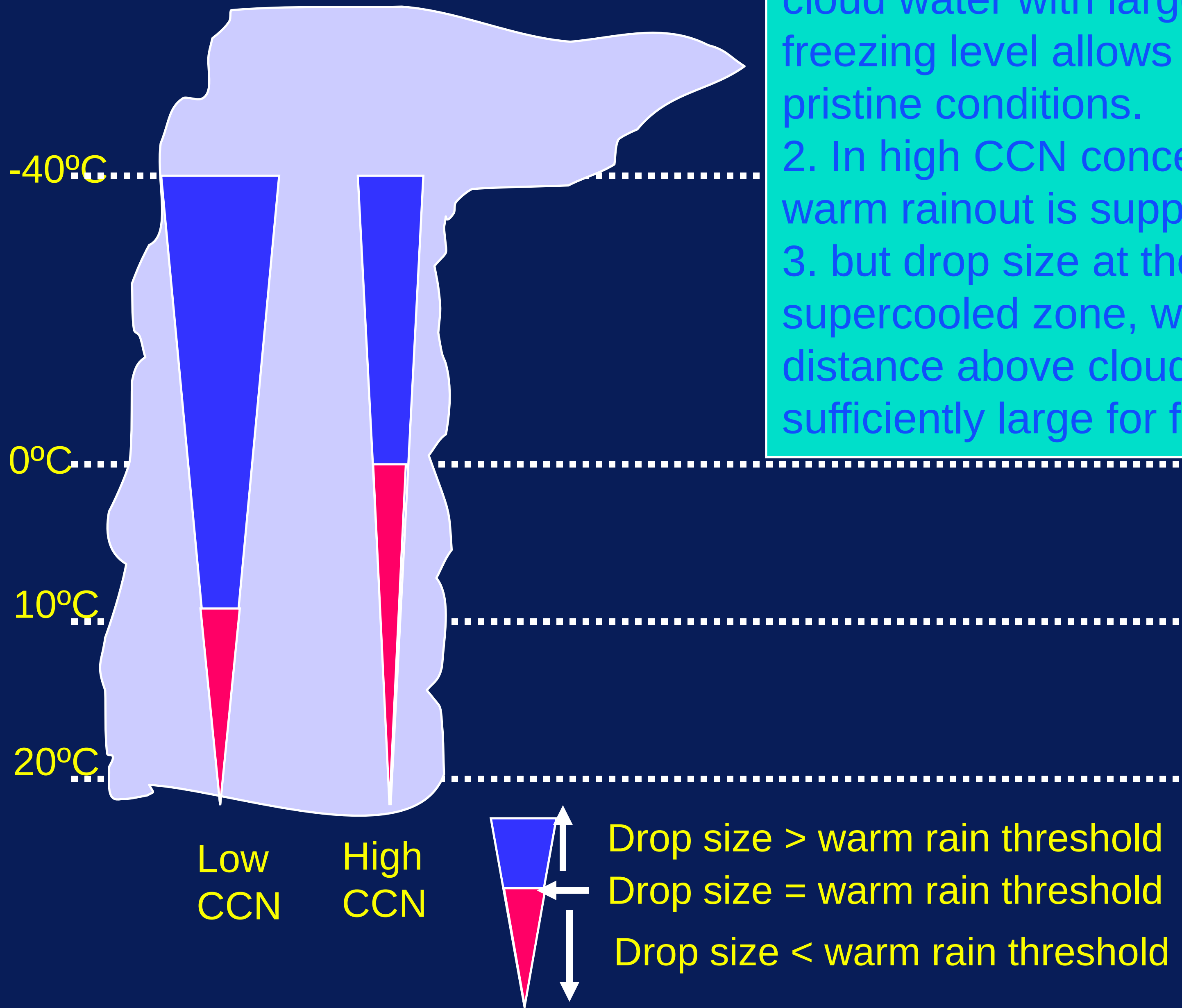


Mild base clouds:

1. Medium amount of supercooled cloud water.
2. Medium drop size at the bottom of the supercooled zone.

The small distance between cloud base and the freezing level does not allow much room for development of warm rain and its rainout in pristine clouds. Therefore, adding CCN is not expected to cause much invigoration.

Conceptual model:

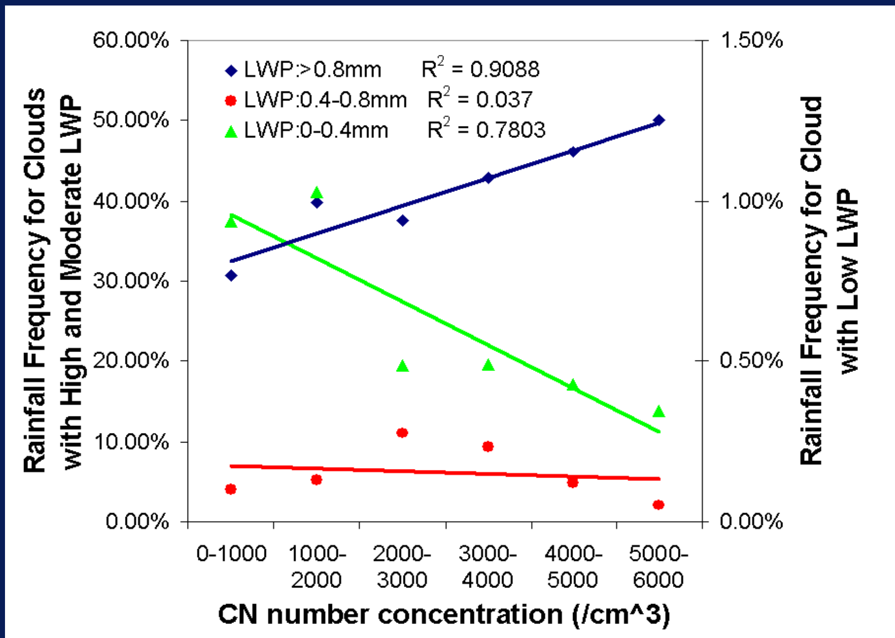


Warm base clouds:

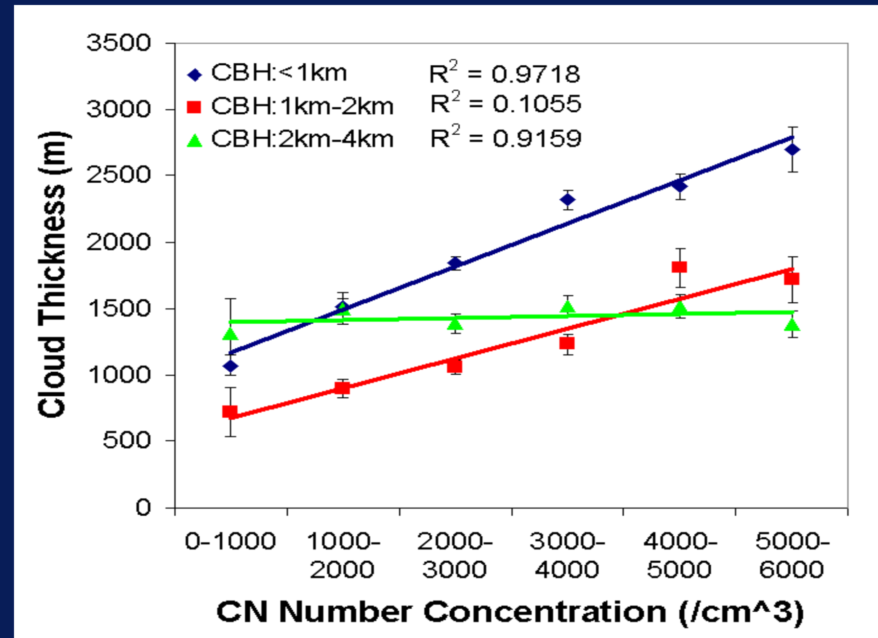
1. Large amount of supercooled cloud water with large distance to freezing level allows rainout in pristine conditions.
2. In high CCN concentrations early warm rainout is suppressed,
3. but drop size at the bottom of the supercooled zone, which is large distance above cloud base, is sufficiently large for fast freezing.

Strongest Long-term Net Impact of Aerosols on Cloud & Precipitation is Revealed by the ARM Data

Rainfall Frequency



Cloud Thickness



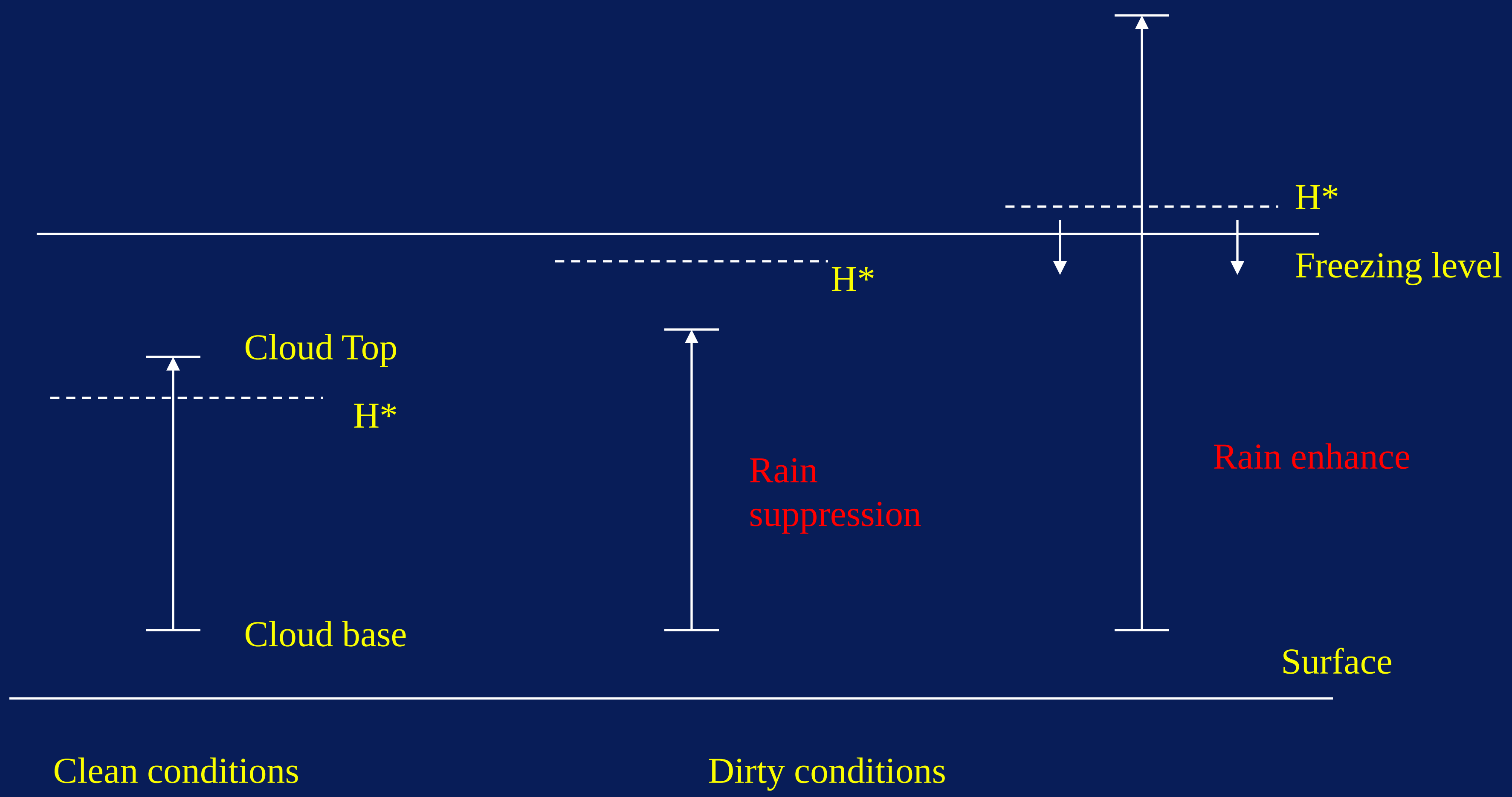
Rainfall frequency is reduced by aerosols for low liquid water parth (LWP), but increased for large LWP.

Cloud thickness/top increases with aerosol concentration for low cloud height (CBH), but nil for high.

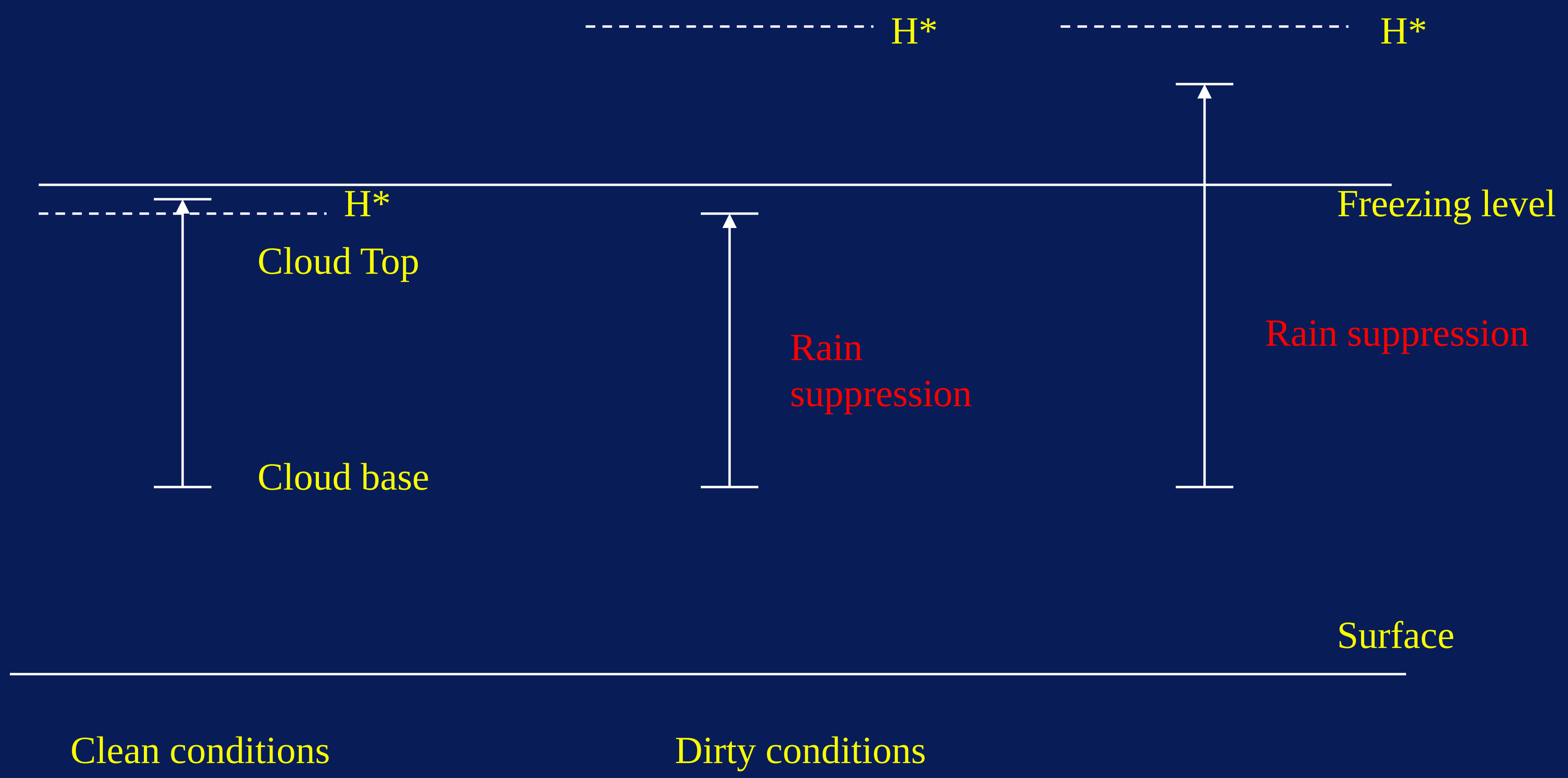
The Twomey Effect and Invigoration Effect are both at work !

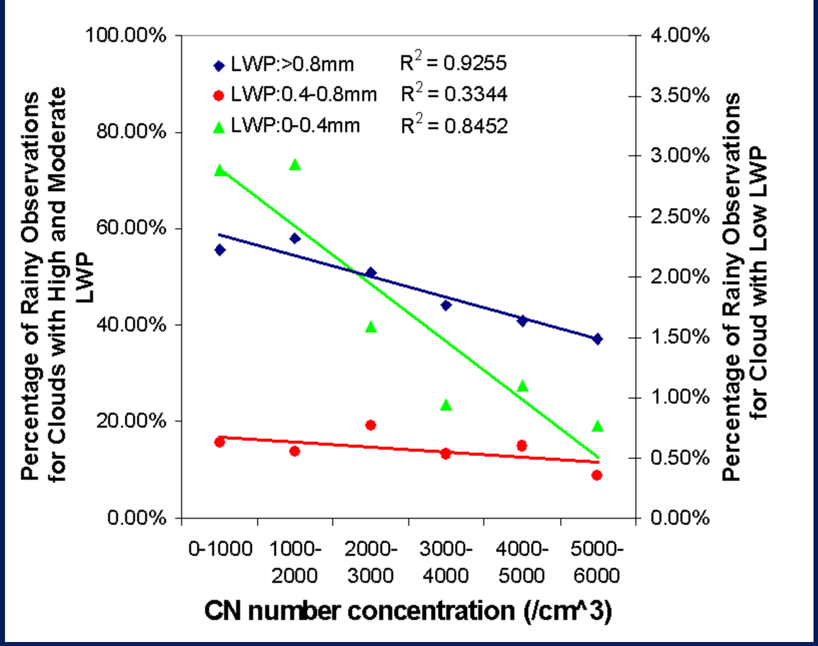
Z. Li (University of Maryland)

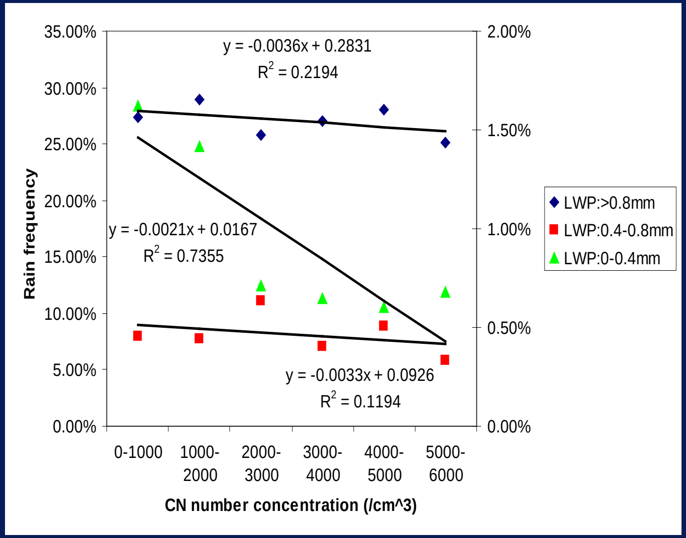
Low-base Clouds

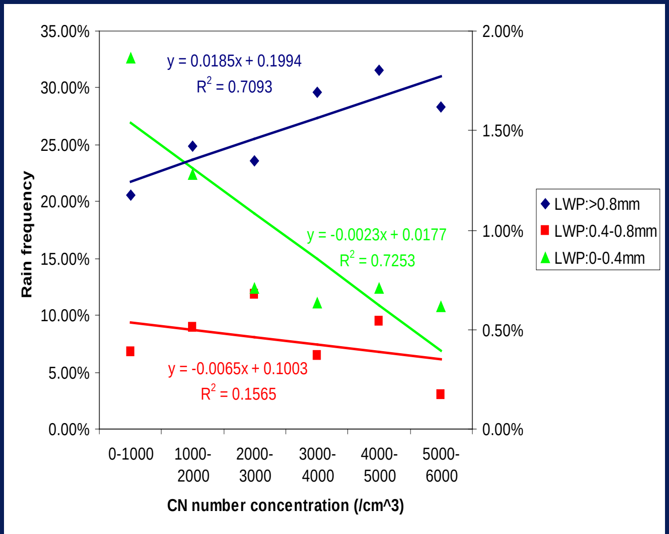


High base clouds









10 year dat

CN number concentration half an hour before rain is used to remove washout effect of rain. Late rain detection causes incomplete removal of it.