

**Significant Net Impact of Aerosols on Cloud &
Precipitation Revealed by the Long-term
ARM Measurements**
Introducing New Aerosol Forcing Indices

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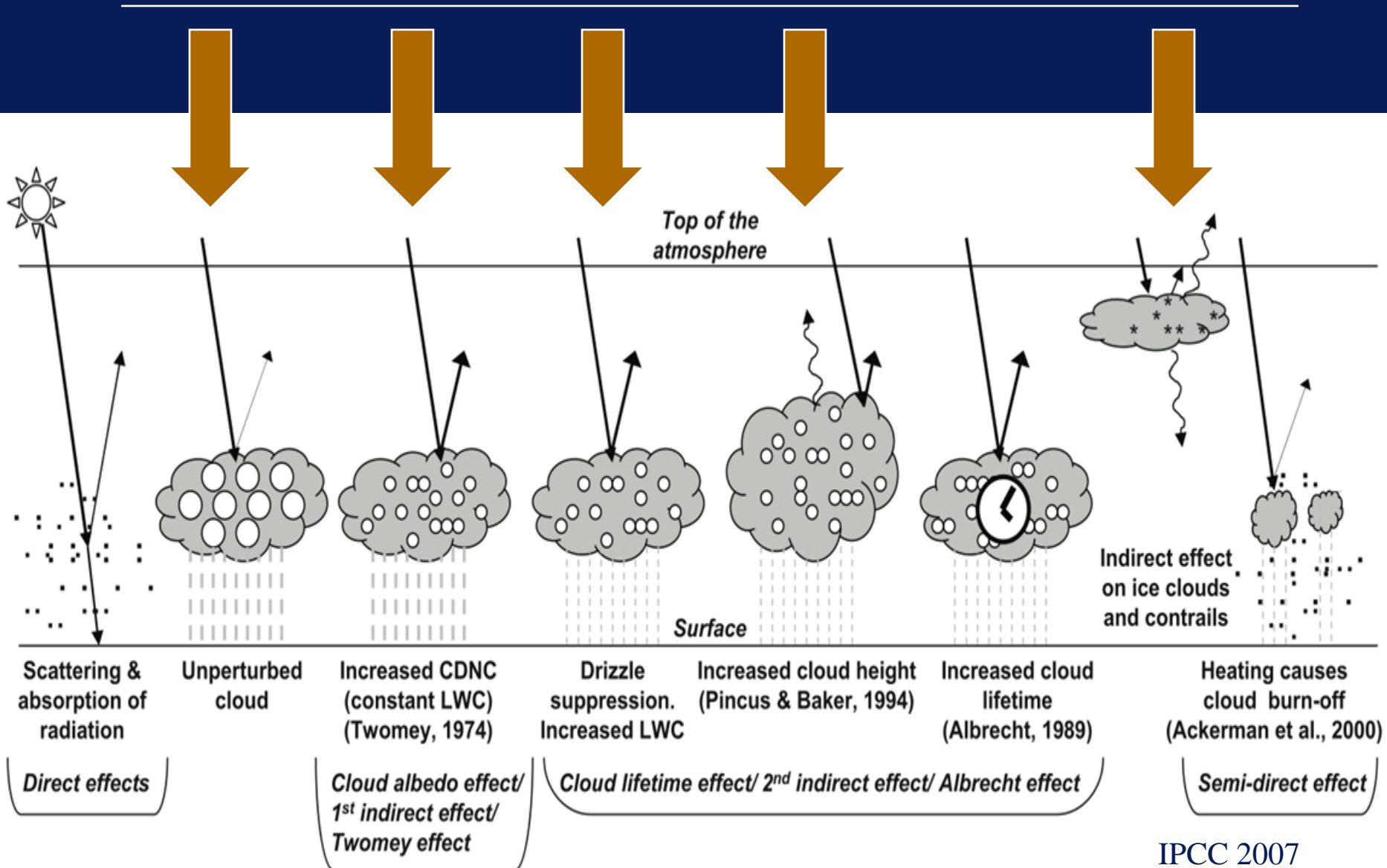
Daniel Rosenfeld², Yangang Liu³, Jiwen Fan⁴

2. The Hebrew University of Jerusalem

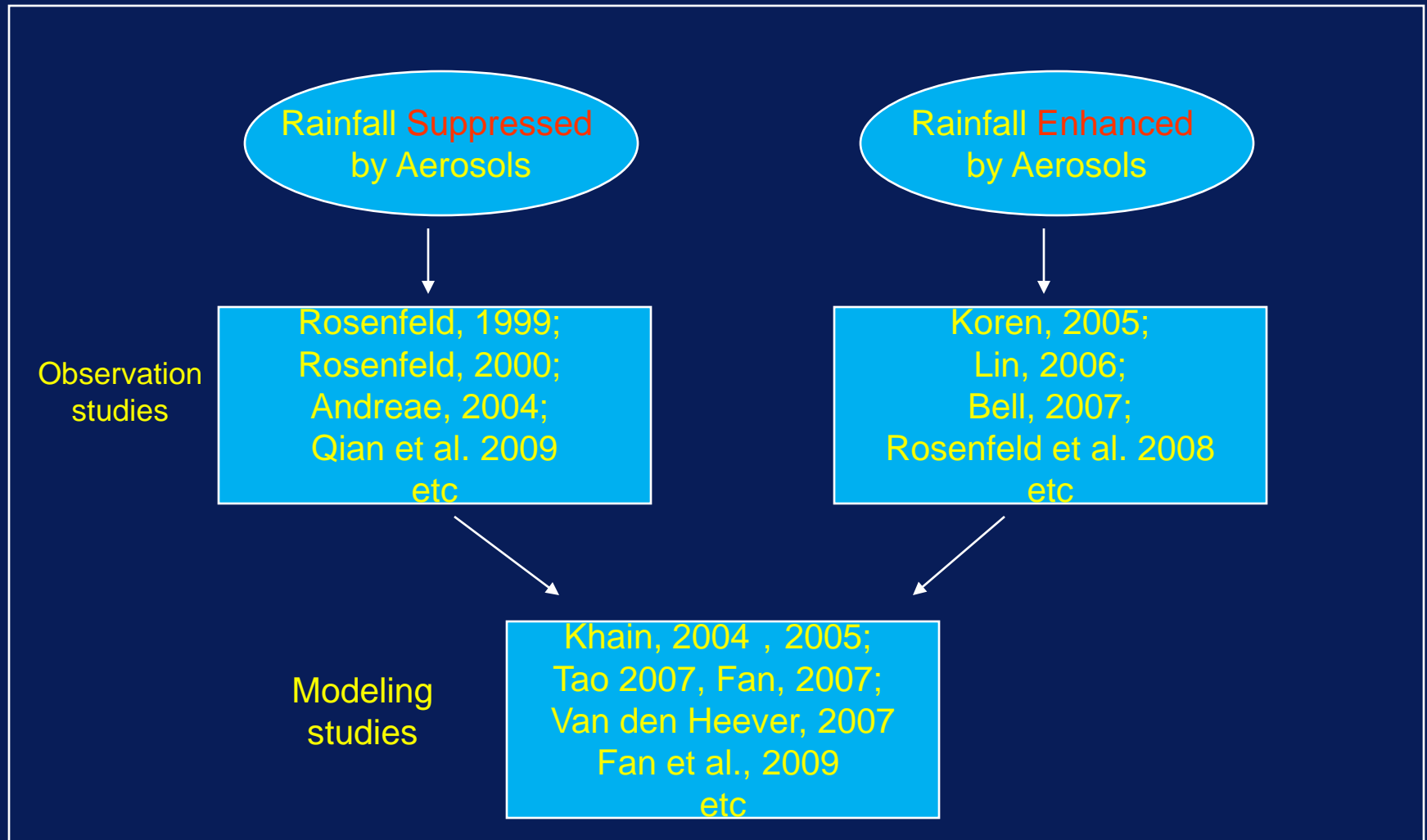
3. Brookhaven National Laboratory

4. Pacific Northwest National Laboratory, Richland, WA

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



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

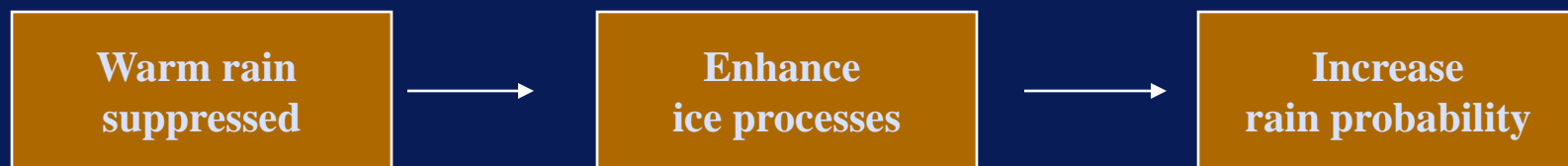


Primary Theoretical Mechanisms of Aerosol's Impact on Cloud & Precipitation

➤ 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 ?

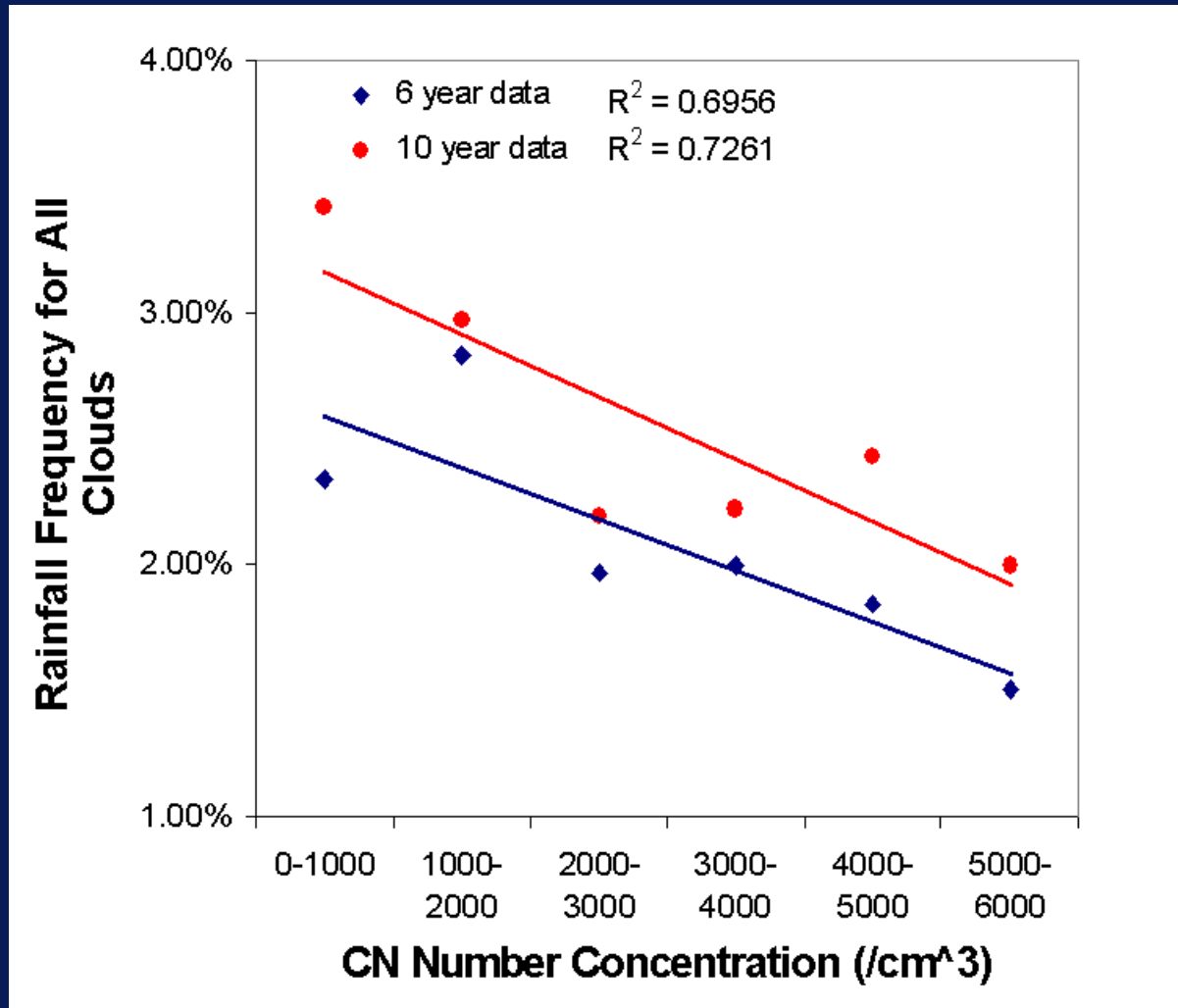
ARM Datasets Used

- **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

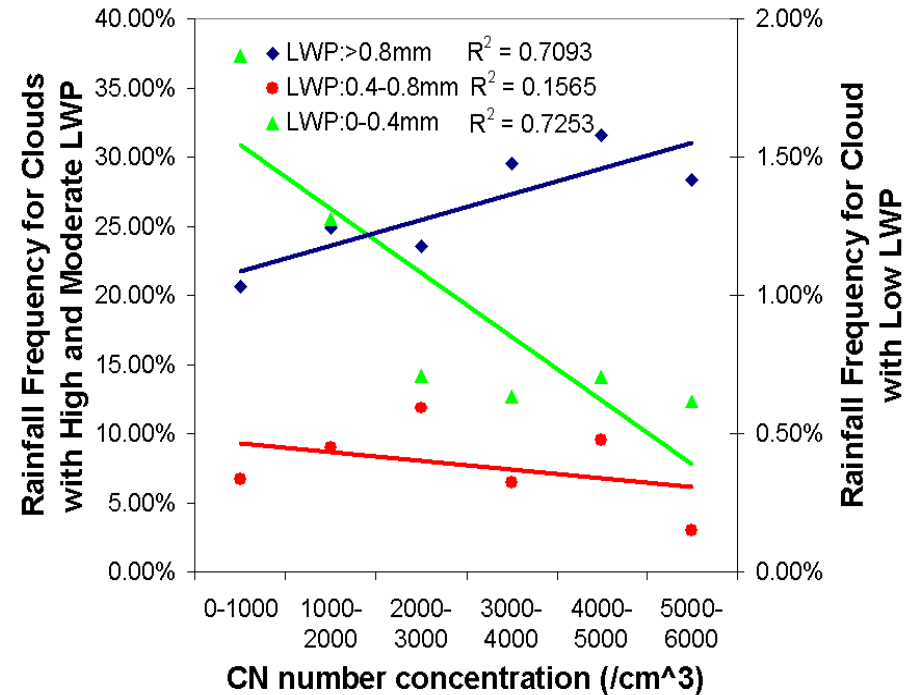
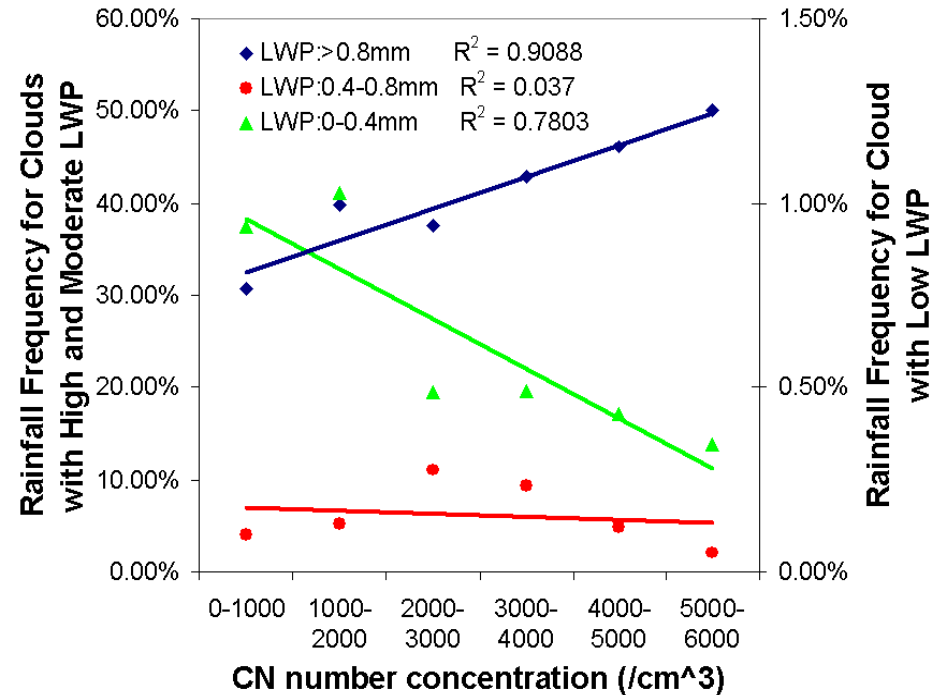


Overall, aerosol reduces the number of rainfall events by up to 50%

The Effect of Cloud Liquid Water Path

6 years

10 years

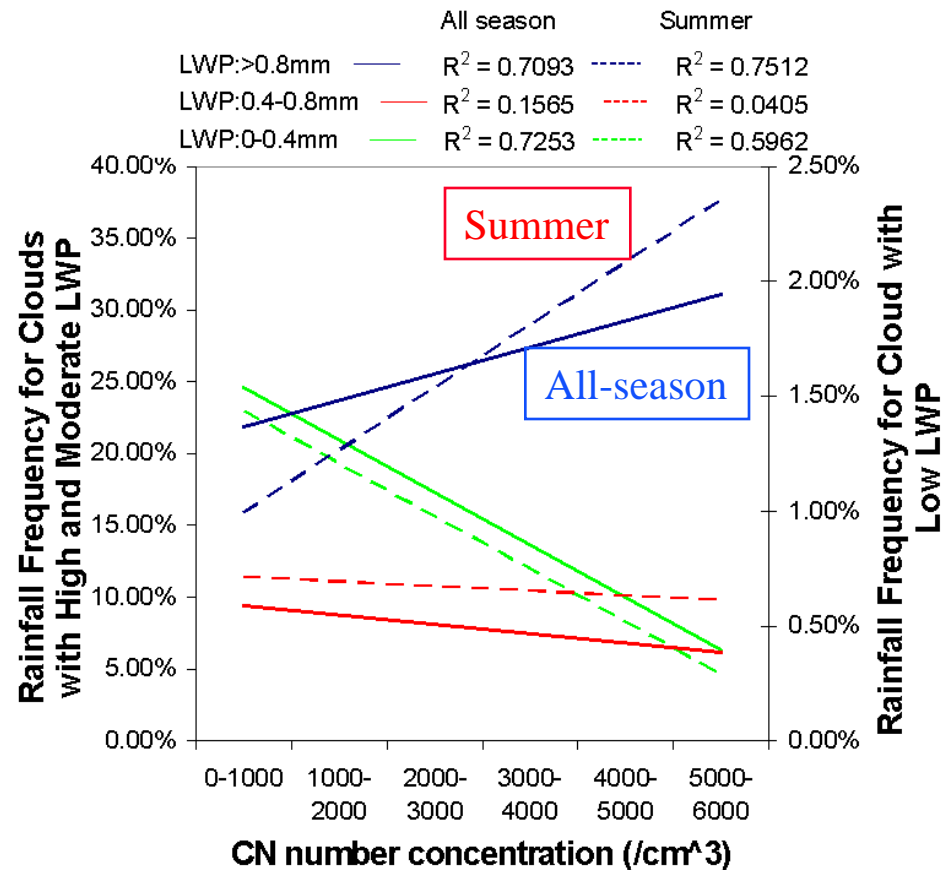
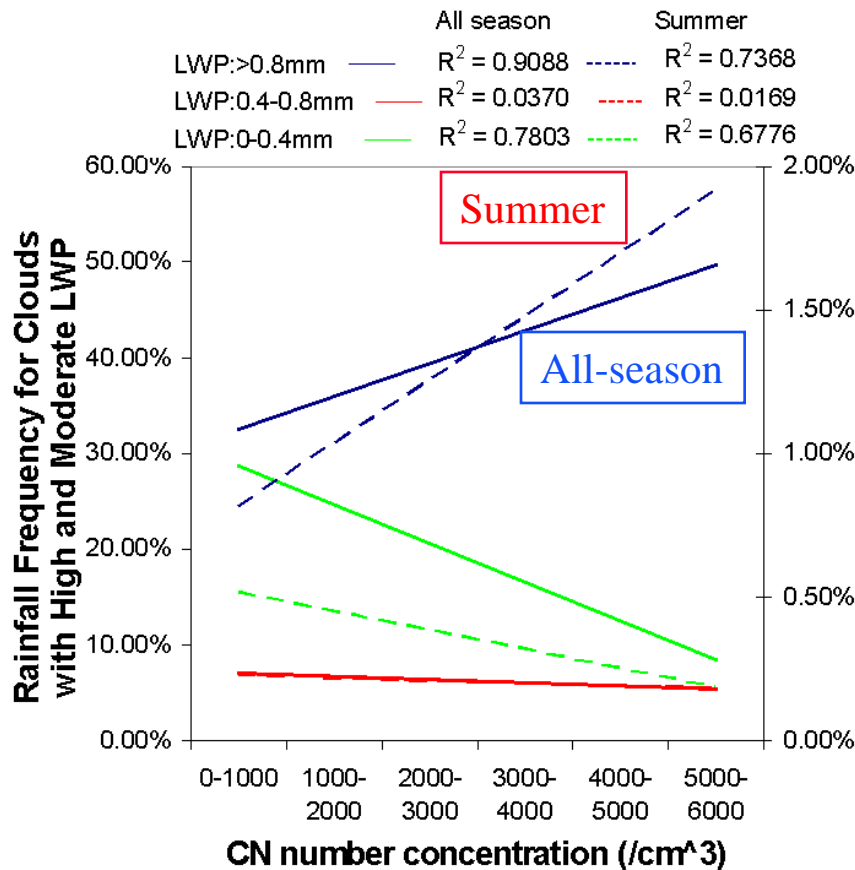


1. For low LWP, rainfall occurrence is suppressed by aerosols (30-50%)
2. For large LWP, rainfall frequency is increased by aerosols (50%)
3. For moderate LWP, aerosols have little impact

The Effect of Convection

6 years

10 years

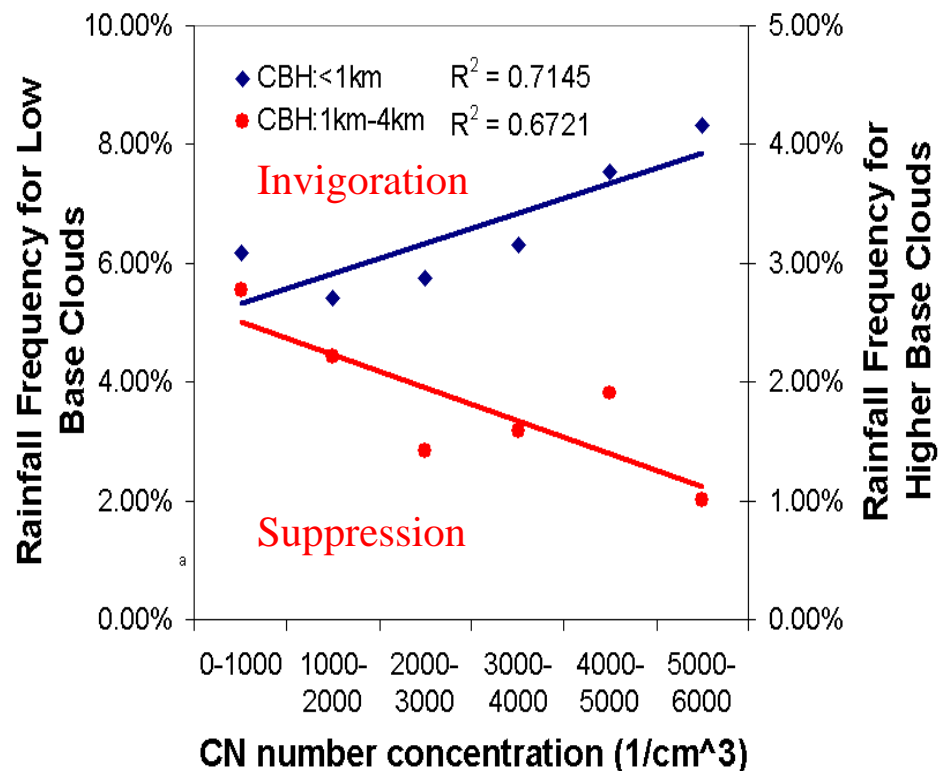
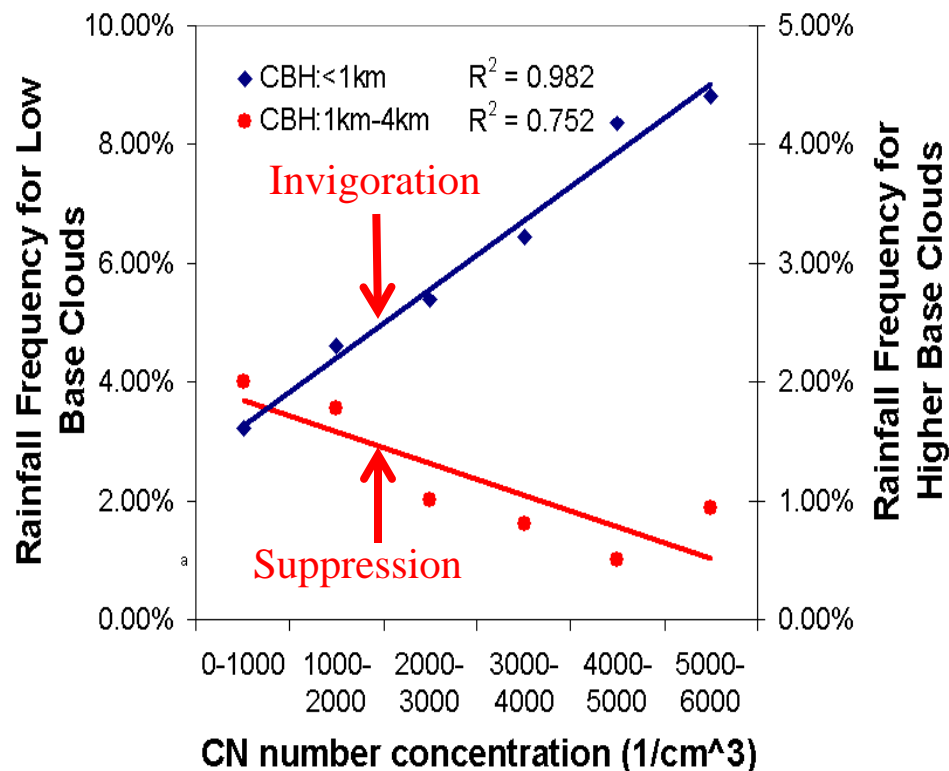


Aerosols have the strongest impact on convective clouds, especially for the invigorated clouds!

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

6 years

10 years

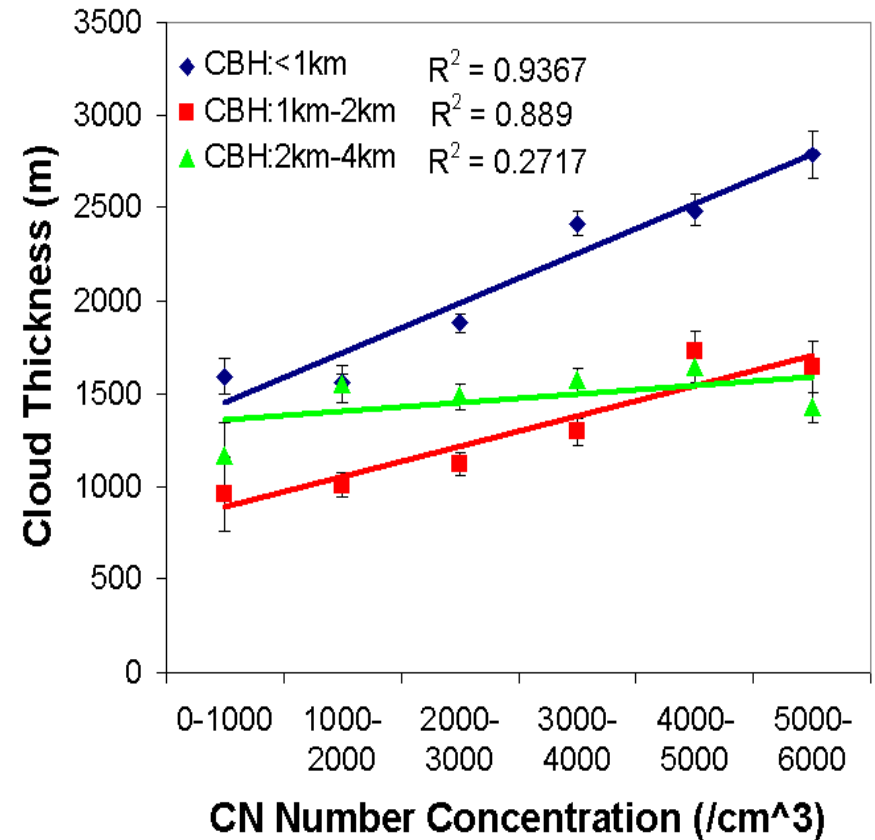
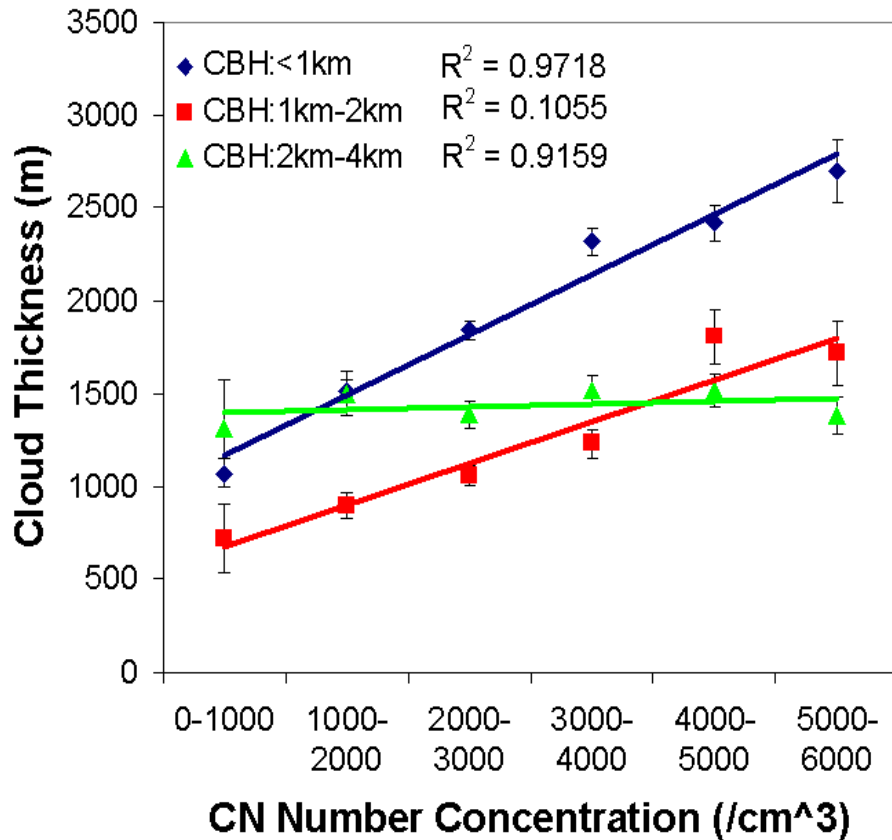


The invigoration effect depends critically on cloud base height!

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

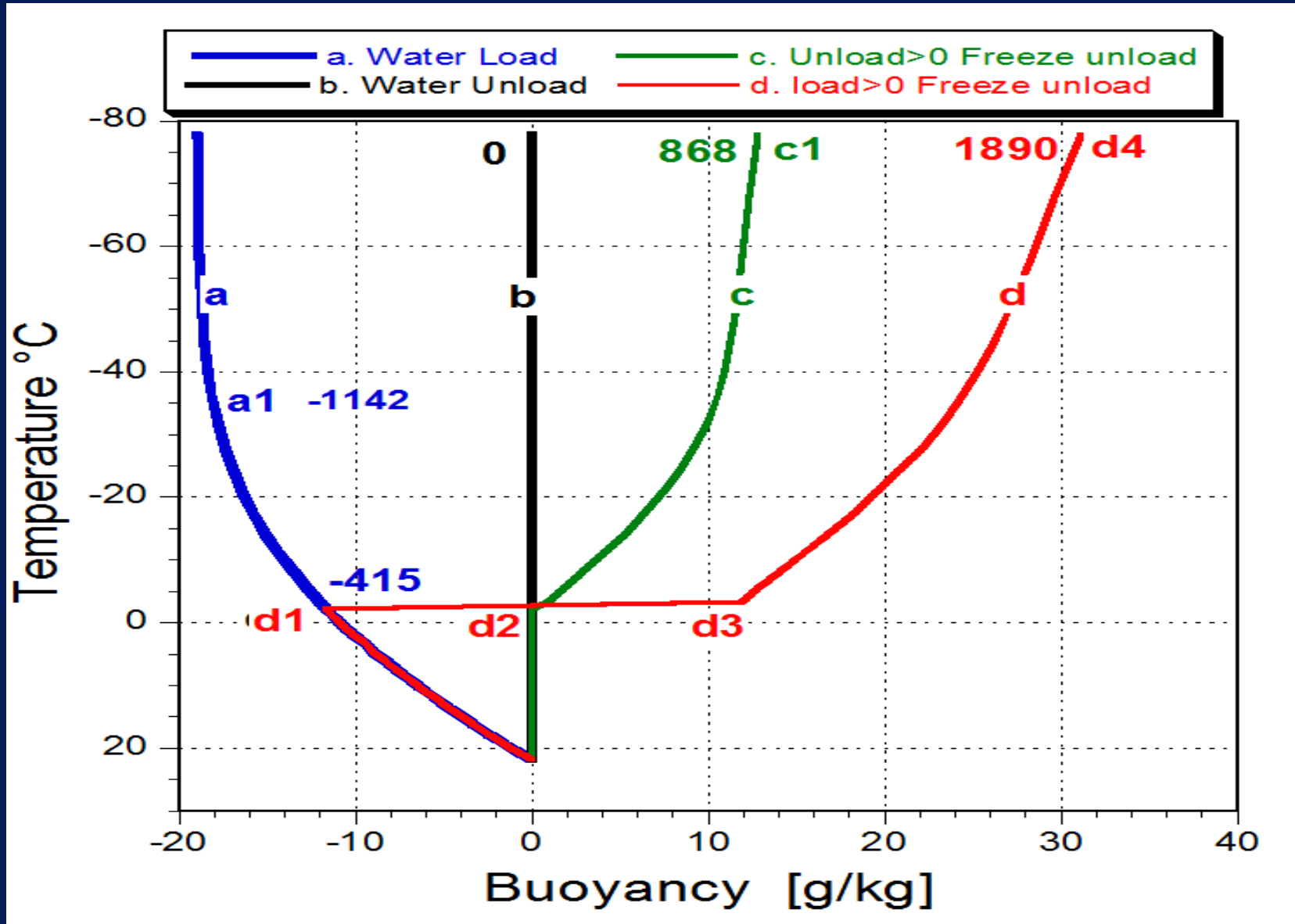
6 years

10 years

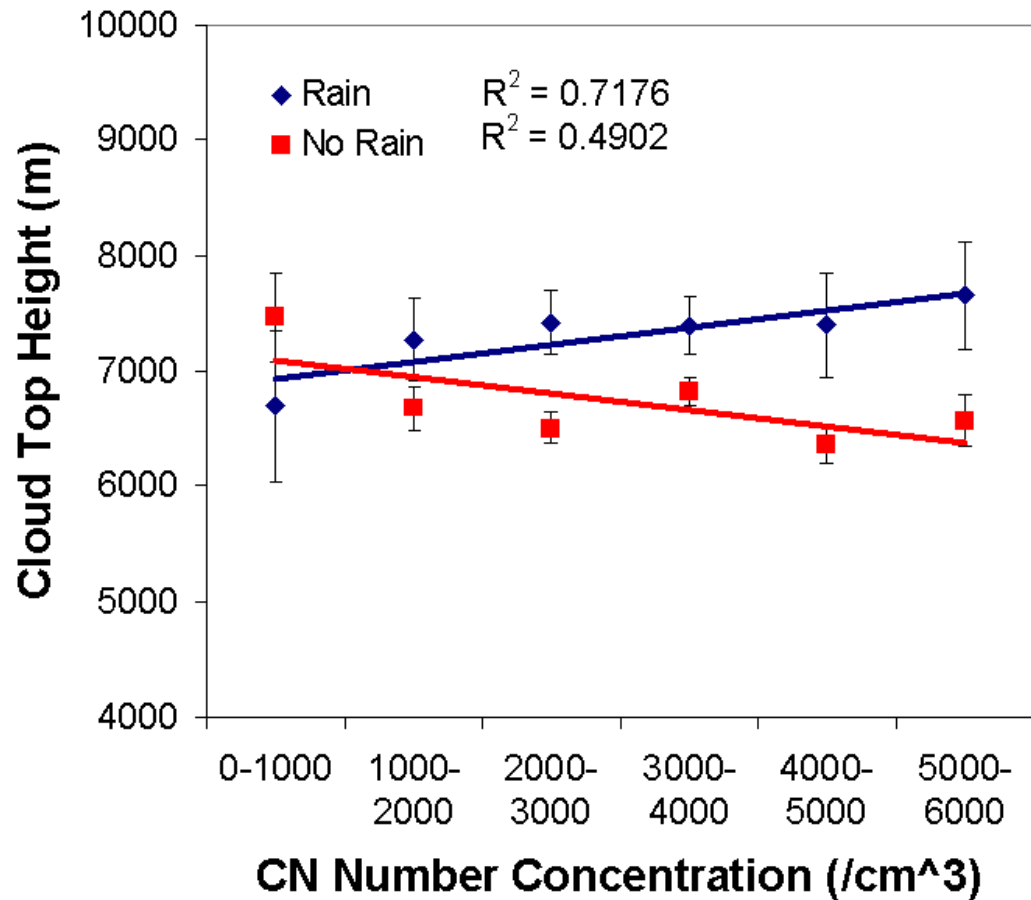


For low clouds (<1km), cloud thickness increases by a factor of 2!
For high clouds (>2km), cloud thickness is not affected at all!.

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



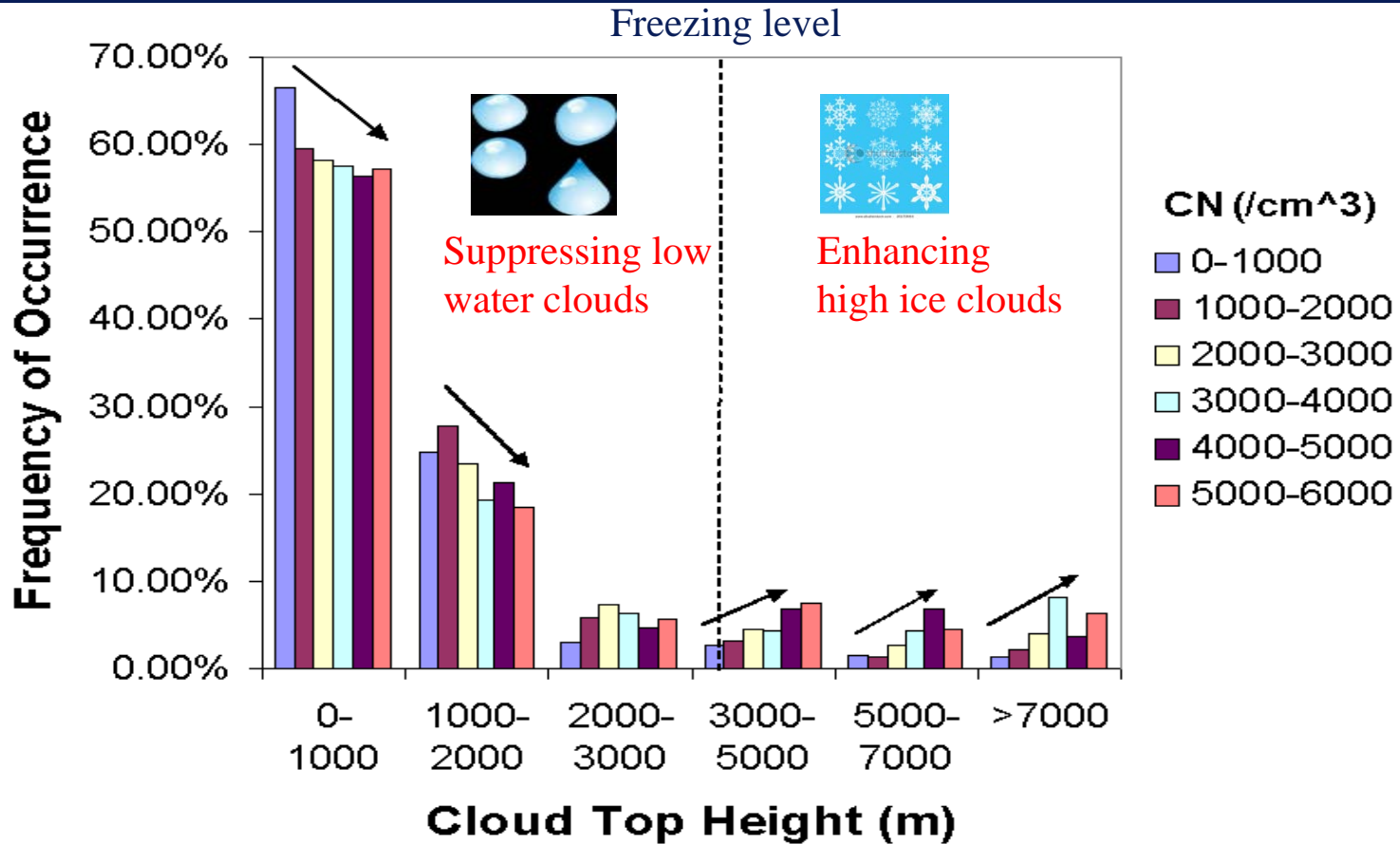
Effects of Dropout of Rain Drops



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:

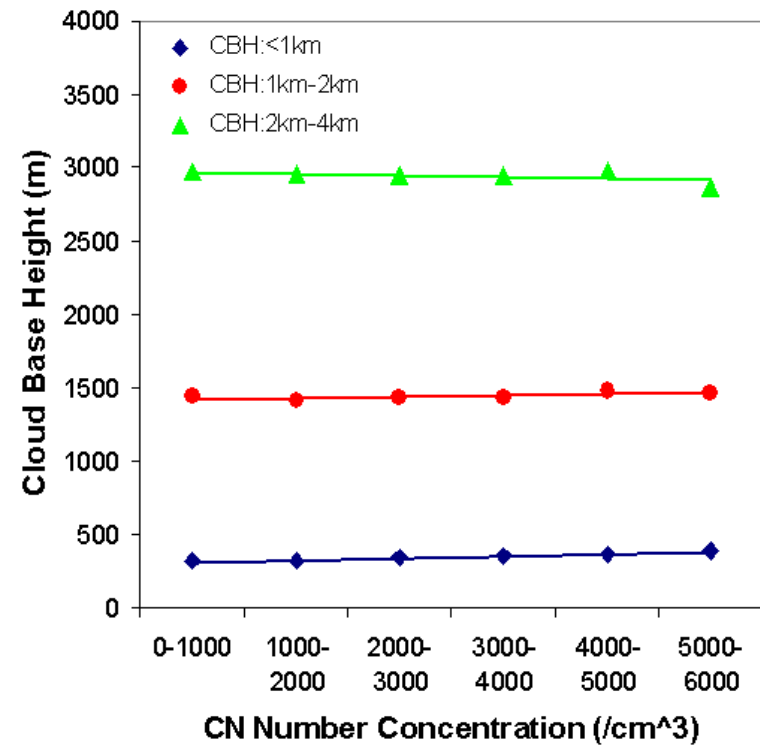
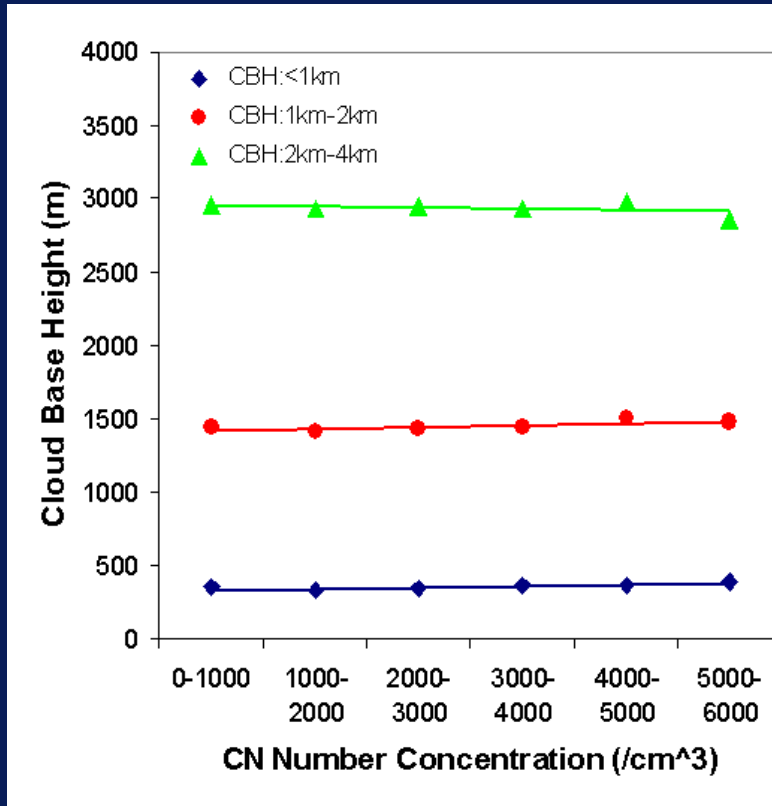


As CN increases, high clouds occurred more frequently but low clouds occurred less frequently

Does Aerosol Affect Cloud Base Height ?

6 years

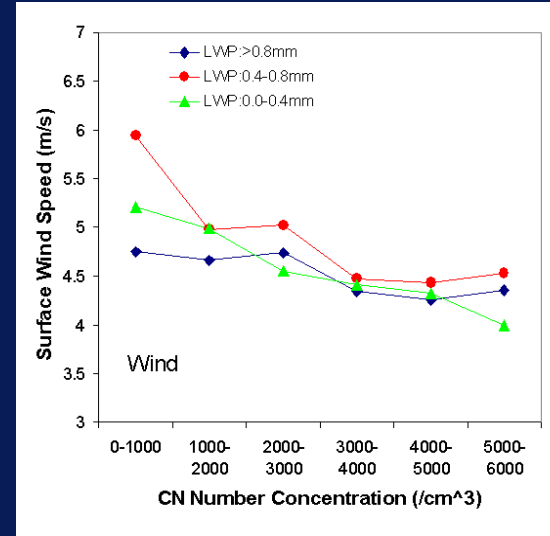
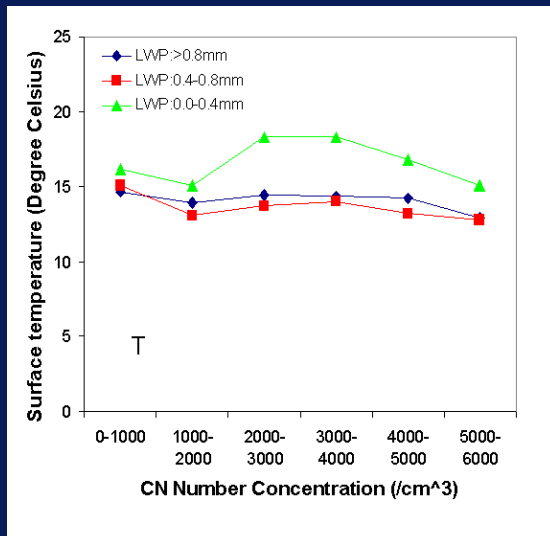
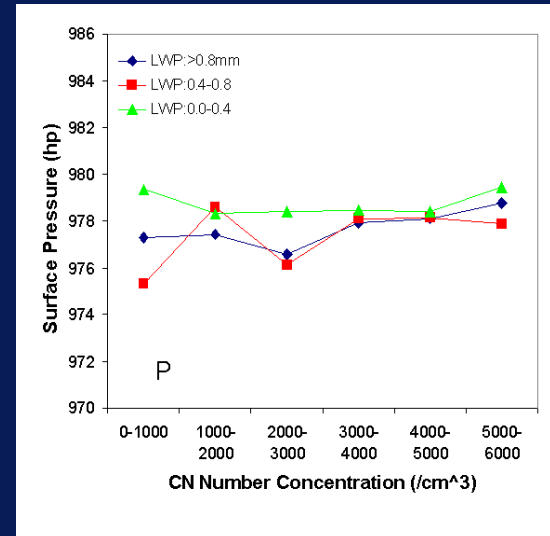
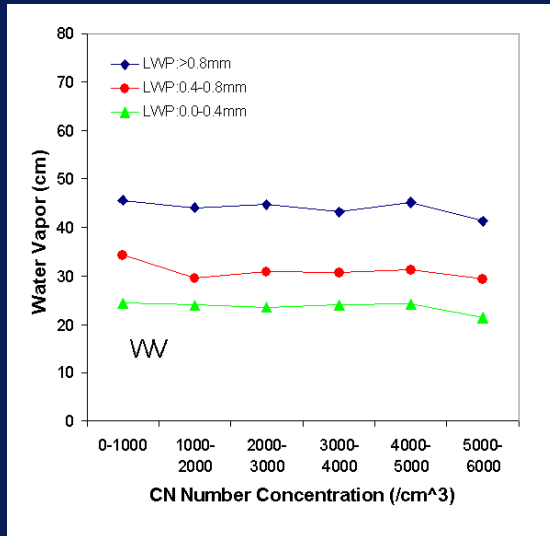
10 years



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 :-)

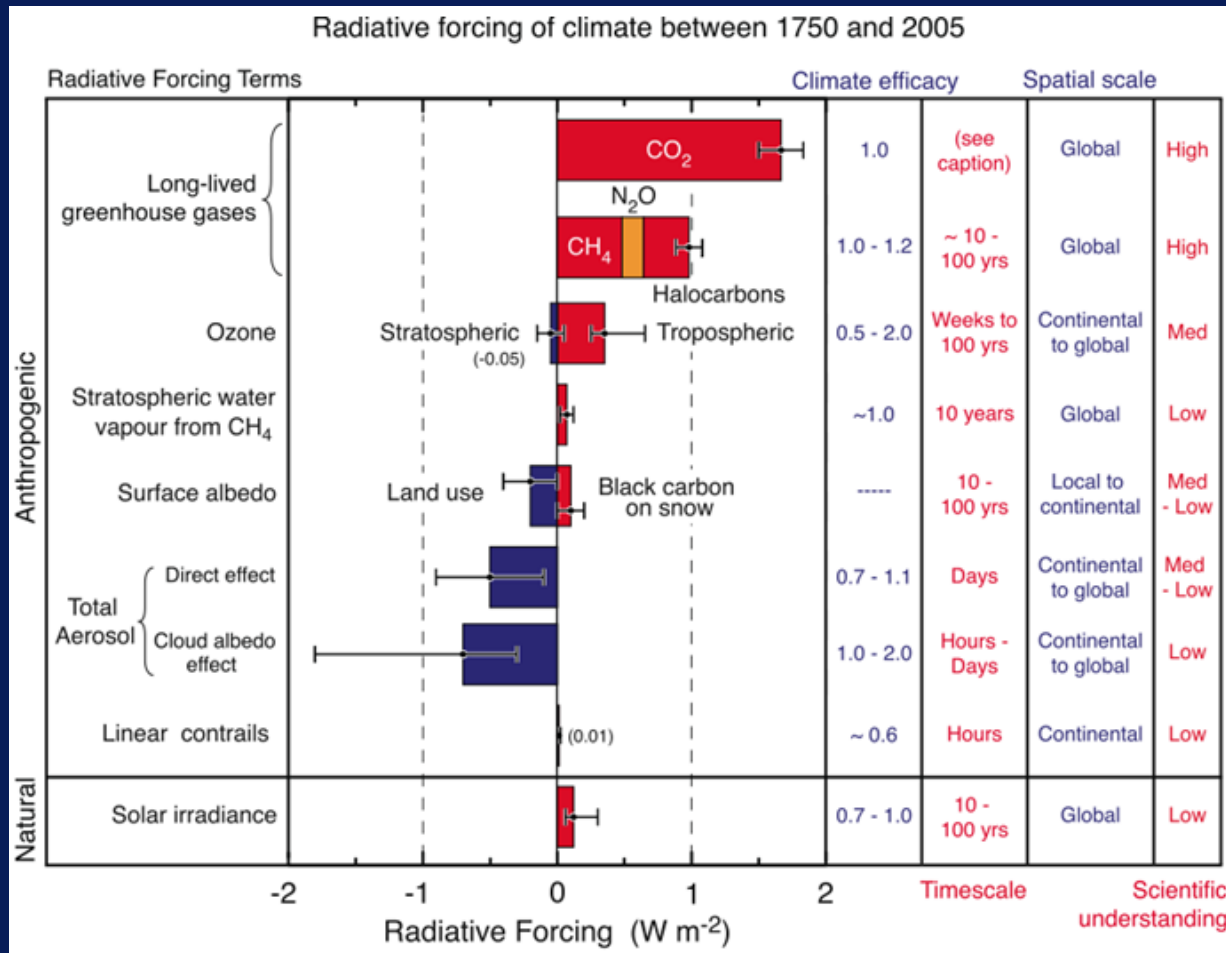


Can we find any other casual relation indicating CN as a proxy of other factors/effects ?

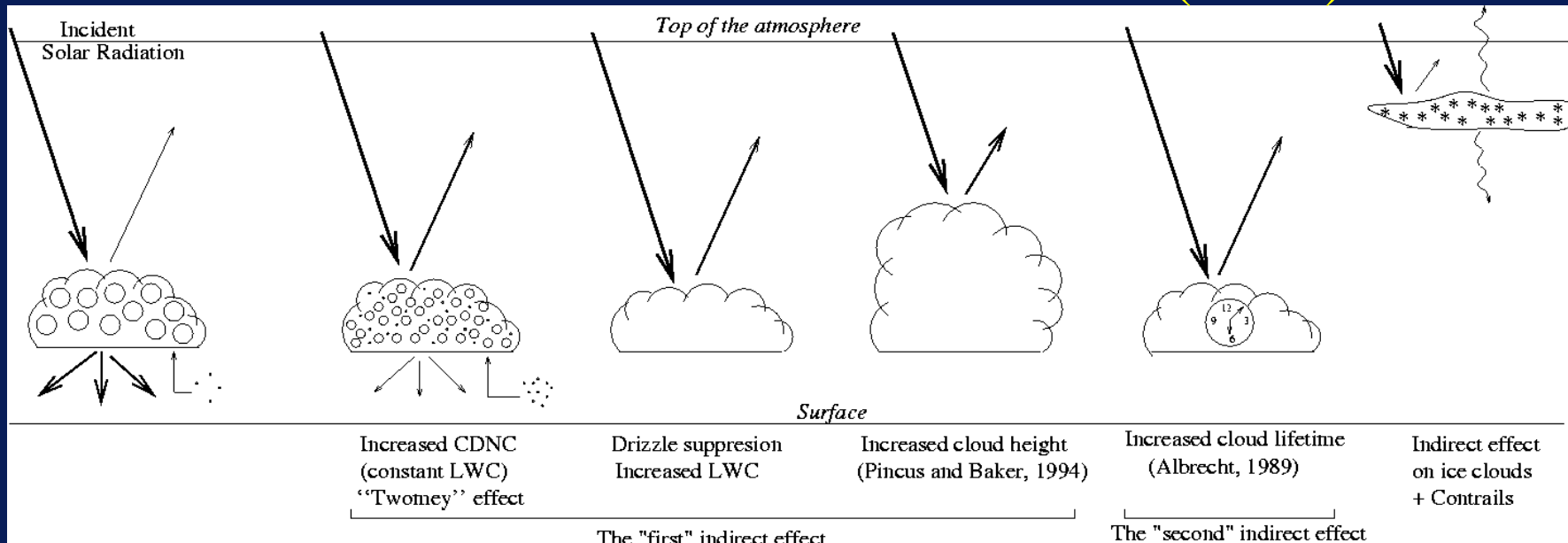


- Introducing “Aerosol Cloud Forcing Efficiency” and “Aerosol Rain Forcing Efficiency” to gauge among observations and models about the net effects of aerosols on hydrology, just as we use “cloud radiative forcing” or “aerosol radiative forcing to gauge their net effects on energy

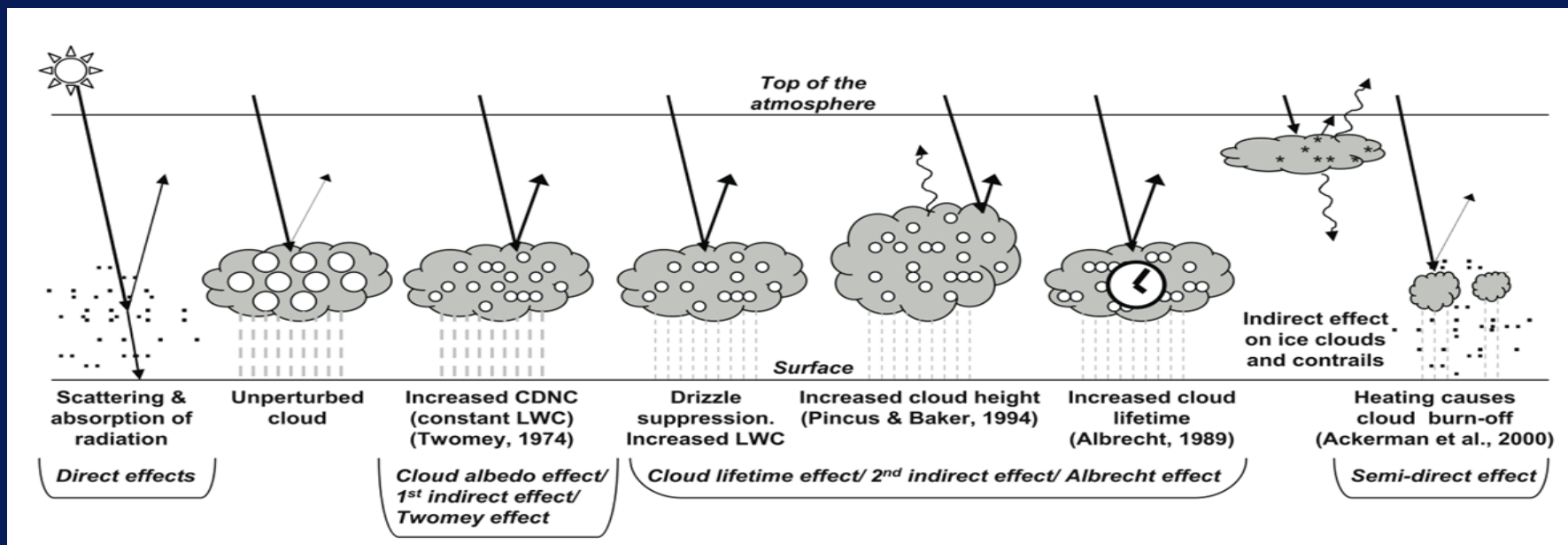
Argument : Aerosol Raditive Forcing (energy) is well-suited for describing its impact on energy cycle, but it is ill-suited to describe aerosol's effect on the hydrology cycle. So, we need to introduce new index



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-limited* number of meteorological variables to changes in aerosol, under *unlimited constraints* in a *continuous* spectrum of atmospheric variability.

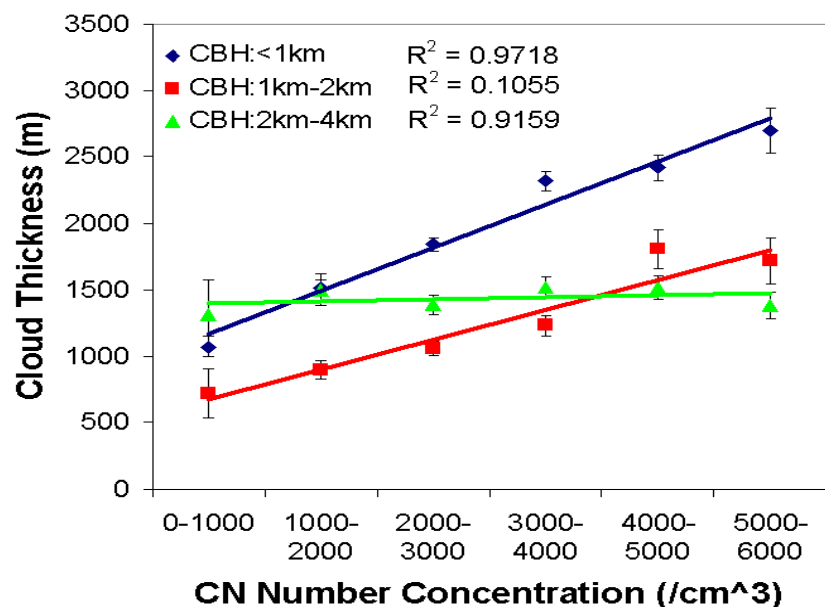
Caring outside the box (by the public)

1. What changes to the box – **Forcing** (greenhouse gases, aerosol, 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.)

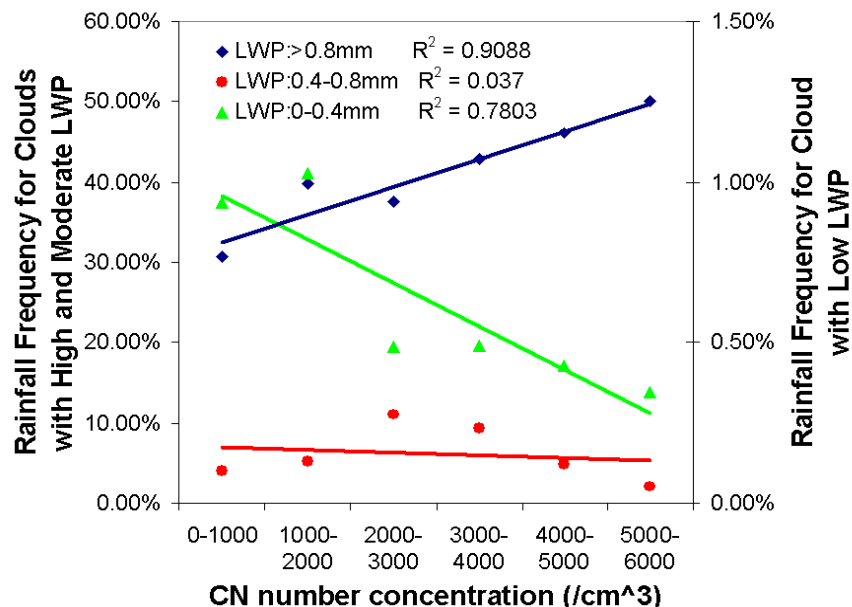
Indices Measuring Forcing-Effect

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

Aerosol Cloud Forcing Efficiency $\Delta H/\Delta CN$, or $\Delta H/\Delta CCN$, $\Delta H/\Delta AOD$

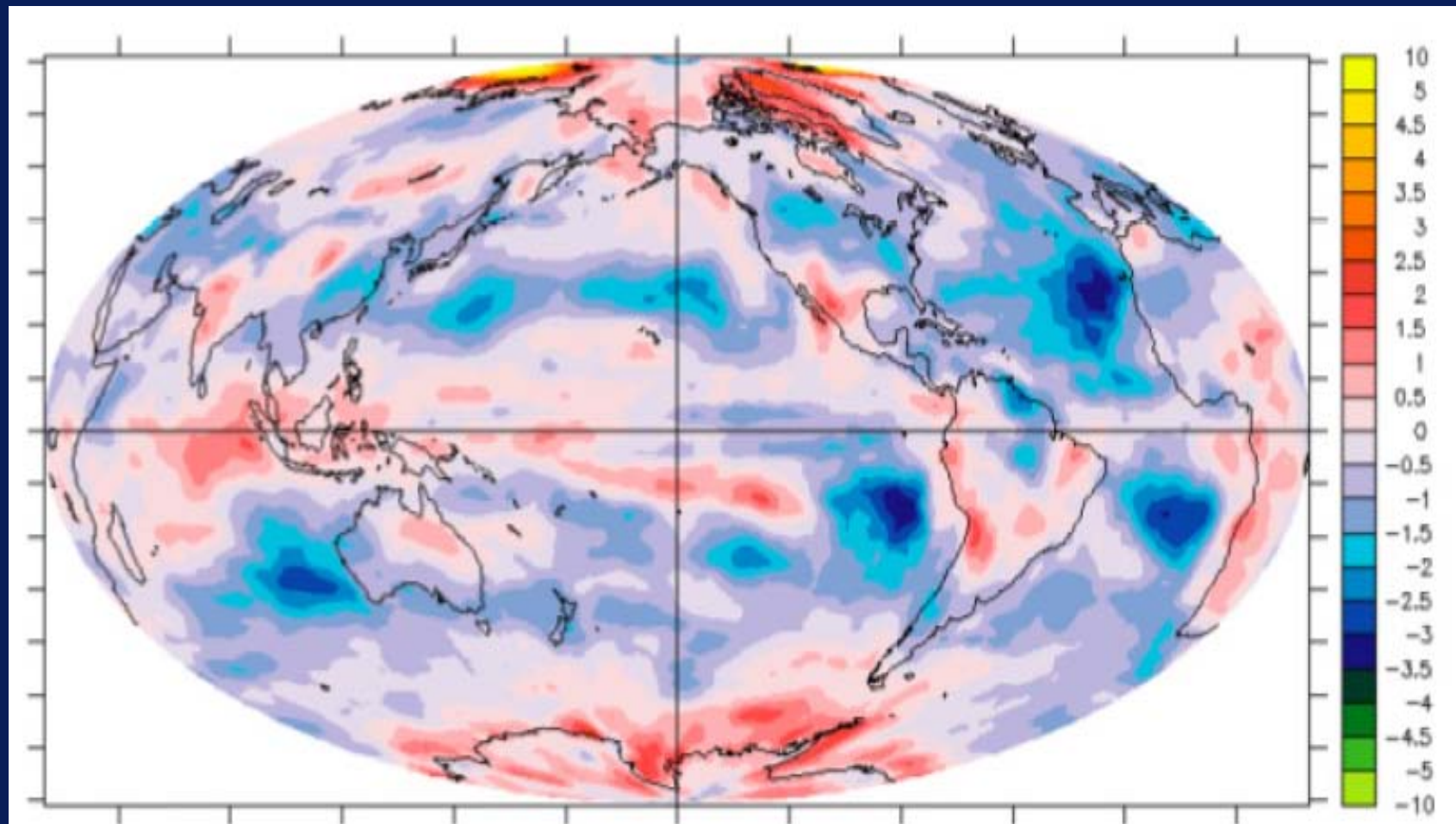


Aerosol Rain Forcing Efficiency $\Delta R/\Delta CN$, or $\Delta R/\Delta CCN$, $\Delta R/\Delta AOD$



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

```
graph BT; L1[Lab Experiments] --> C[Cloud Property and Process Models]; L2[Field Studies] --> C; L2 --> A[Aerosol Property and Process Models]; L3[Lab Experiments] --> A; C --> R[Regional Atmosphere Models]; A --> R; R --> G[Global Atmosphere Models];
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The diagram illustrates the flow of information and model development. At the base, three boxes represent data sources: 'Lab Experiments' on the left, 'Field Studies' in the center, and 'Lab Experiments' on the right. Arrows point from these sources to two intermediate model categories: 'Cloud Property and Process Models' (receiving input from the left and center) and 'Aerosol Property and Process Models' (receiving input from the center and right). A double-headed arrow connects these two intermediate models. Arrows from both intermediate models point to 'Regional Atmosphere Models'. Finally, an arrow from 'Regional Atmosphere Models' points to the top level, 'Global Atmosphere Models'.

Regional Atmosphere Models

Cloud Property and Process Models

Aerosol Property and Process Models

Lab Experiments

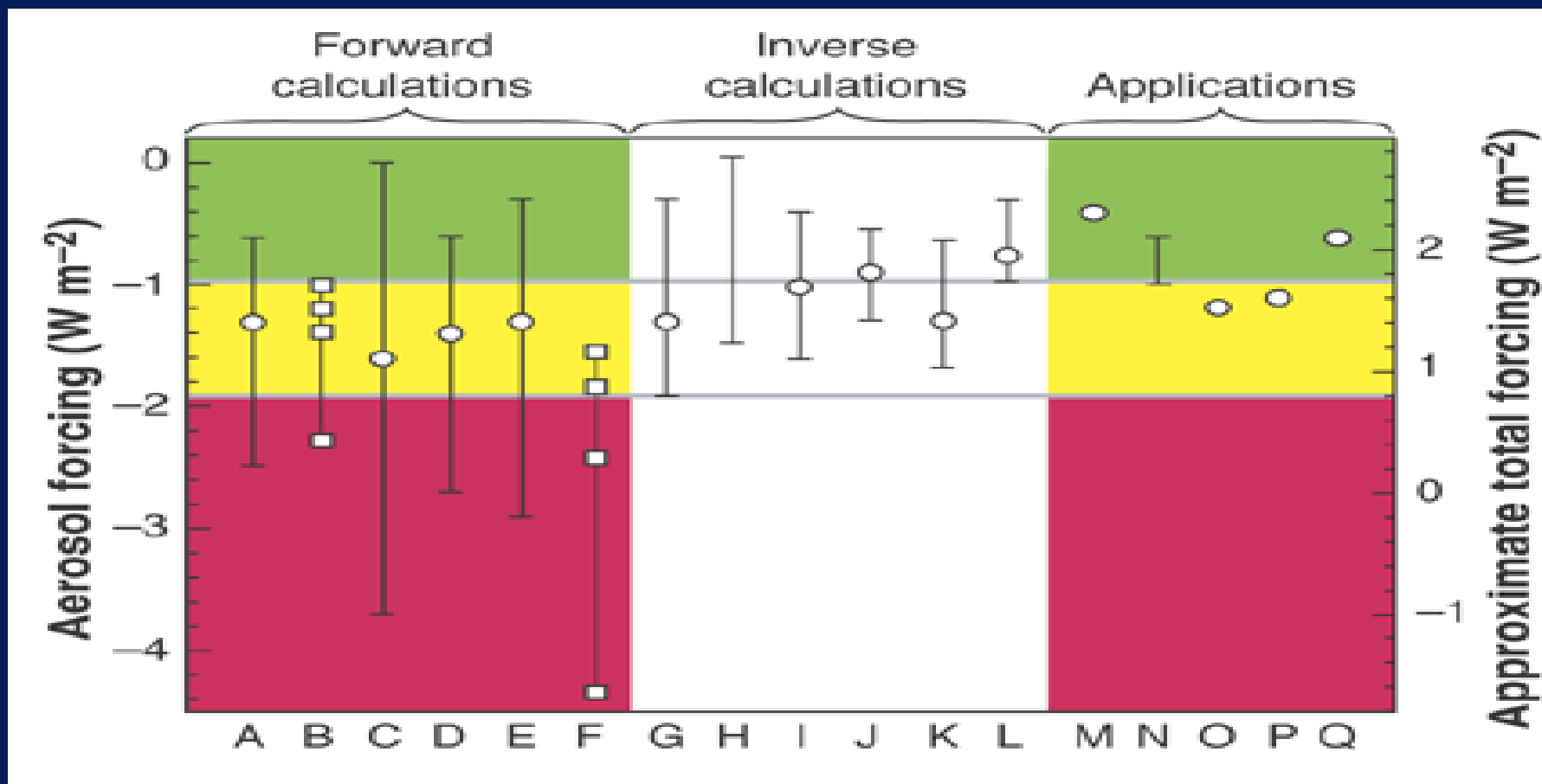
Field Studies

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 461 24 September 2009

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.

In meteorological terms, the dusty towns of Shouyan in eastern China was buzzing with excitement. It was May 2008, and the packed courtyard was filled with sophisticated remote-sensing instruments that had just arrived on loan from the United States Department of Energy (DOE). The bureau had been expecting the equipment earlier, but it had been held up by Chinese customs officials for the more than two months. A group of climate researchers and government officials from China and the United States eagerly inspected the new arrivals, which included a cloud radar, a tailor-made lidar (a radar-like instrument that sends out laser beams rather than microwave) and sensors for studying various features in the atmosphere and the radiation from the Sun. "We can do great things with these here," said Zhuang Li, an atmospheric scientist at the University of Maryland at College Park, who was leading the Sino-American collaboration.

Over the next few months, these instruments would be pointed up into the Chinese sky to monitor dust and other aerosols. They are designed to measure the number of particles such as dust and soot. The researchers were particularly interested in tracing how aerosols alter the transparency of clouds by reflecting whether clouds produce rain, how long they extend, how much sunlight they reflect and how long they persist. At present, atmospheric researchers have only a rudimentary understanding of how aerosols affect clouds and that ignorance is one of the major sources of uncertainty in forecasts of future climate.

For aerosol experts, China's sky is chock-a-bow. The country has high concentrations of particles arising from pollution as well as natural dust blowing in from surrounding deserts. Researchers expected that data from such a particle-rich atmosphere would help to resolve major questions about aerosols and climate. At the same time, it was hoped that the project, staged at four sites across China (see map), would set up political towards. The joint collaboration, conducted under the umbrella of the DOE's Atmospheric Radiation Service, was high because the data collected by the ARM programme will be used to improve the way that climate models simulate clouds and aerosols. When the programme was created in 1989, it collected measurements only at fixed sites within the United States. "But we decided on it that we needed a much instrument as possible from diverse climate systems around the world to build up a complete picture of global climate change," says Whitcomb.

His resulted in a mobile facility built in 2004, that contains most of the remote-sensing instruments present at the fixed sites. Each year,

Monitors (ARM) programme, was viewed as a sign of China's movement towards openness. "This kind of collaboration would have been inconceivable ten years ago," says Thomas Ackerman, an atmospheric scientist at the University of Washington in Seattle.

The political winds did not, however, always blow favourably. With much frustration, the DOE had to alter its usual mode of operation and settle for lower-quality data than a smaller range of measurements than expected. "Between the heights of hope and the depths of despair, it was the most eye-and-down deployment we have ever had," says Warren Whitcomb, ARM's chief scientist and an atmospheric scientist at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

The stakes are high because the data collected by the ARM programme will be used to improve the way that climate models simulate clouds and aerosols. When the programme was created in 1989, it collected measurements only at fixed sites within the United States. "But we decided on it that we needed a much instrument as possible from diverse climate systems around the world to build up a complete picture of global climate change," says Whitcomb.

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Primary Site
Supplemental Site
Auxiliary Site

The arrival of the equipment in Shouyan was a cause for celebration.

The difficulties began right at the start, when the instruments became stuck in Chinese customs because of tightened regulations due to the Olympics. "We were not sure of some of the Chinese in-

the DOE and Chinese science ministry. Under that compact, the two countries are committed to sharing data and collaborating on joint field campaigns, climate modelling and strategies for adapting to climate change.

Cloud pearls
One aim of deploying the ARM mobile facility in China was to investigate an observation that had puzzled atmospheric scientists for some time. Microwave-sensing instruments on the Jetix US-100e (see Tropical Rainfall Measuring Mission satellite) detect large amounts of liquid water in clouds over the coastal region of eastern China, yet the satellite radar shows that there is very little rain.

"The two satellite instruments disagree with one another, which is very unusual," says Chris Kummerow, an atmospheric scientist at Colorado State University in Fort Collins, who discovered the discrepancy.

spite of problems created their hopes. "At some points we thought we wouldn't be able to get anything out of it," says Whitcomb. "I had all the data with me on a portable hard drive, but wasn't sure whether I would manage to get them out of China or if the Chinese government would let us make them publicly available."

The CMAA did give the green light, and the original data from Shouyan and Zhangye are now available to ARM's archive. Many researchers are philosophical about the difficulties encountered by ARM's China deployment. "China is going through a transitional phase," says Daniel Rosenfeld, an atmospheric scientist at the Hebrew University in Jerusalem, Israel. Although the country's sky still set up as people would like it to be, the collaboration clearly signals a move away from the old ways, he says. "The process is not complete yet, but I hope the issues of openness will be sitting of the past soon." Wei-Chyung Chang, a climate scientist at the State University of New York at Albany, and the United States' chief scientist managing the climate-science agreement, says that the project is "by far the most successful collaborations under the agreement." He adds that "this unique experience has really opened up the dialogue and will stimulate more interest in similar collaborations."

Data feast
Participants in the project say they are happy with what they were able to collect. "We now have cloud data from China nobody has ever had before," says Miller. Since the data are now at Shouyan and Zhangye, machine-readable studies show that this can be explained by

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NATURE 461 24 September 2009

and Zhangye sites that were measuring particles of black carbon, a major component of soot. Interestingly, the CMAA did not request measurements at other observing sites, possibly because it was being jointly operated with Chinese universities.

At one point in July last year, the DOE threatened to renege the ARM project in China, but it decided to stay on, in consideration of the other already-invested. Eventually, after lengthy negotiations, the American researchers were granted a two-week window in October 2008. Starting which they could connect with the instruments remotely from the United States for about four hours each day. Only then were they able to fix the broken cloud radar, enabling it to collect data during the last two months of the project.

Political problems caused headaches up to the final days of the year-long stay in China. "Even at the end of the deployment, we were not sure whether we would be able to get anything out of it," says Whitcomb. "I had all the data with me on a portable hard drive, but wasn't sure whether I would manage to get them out of China or if the Chinese government would let us make them publicly available."

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increased aerosol concentrations in the region (Y. Qian et al. *J. Geophys. Res.* 114, D19002, 2009). What's more, data collected at Shouyan and Taihu show that aerosols apparently affect the thickness of clouds and the altitudes at which they form. "If this proves to be the case, the implications for aerosols for climate change will be tremendous," he says.

But the Chinese data have not solved all the cloud conundrums. Using a computer simulation, Kummerow and his colleagues have ping-ponged a very complex and pattern in how aerosols affect clouds. "They seem to increase precipitation in some places and decrease rainfall in others," he says. For example, the cloud radar and radiometer data from Shouyan indicated that, on days with comparable aerosol amounts and cloud liquid water, sometimes it rained and sometimes it didn't.

These preliminary passes through the ARM data collected in China show how much remains to be learned there. And the scientific results so far are the only dividends the project has yielded. To Chinese researchers such as Huang Hanyang, an atmospheric scientist at Lanzhou University in China, providing the ARM collaboration helped strengthen China's capability to run long-term field campaigns. Since 2005, Huang has been building up an observational site 40 kilometers east of Zhangye, focusing on climate research of semi-arid regions. "The ARM deployment to Zhangye has allowed us to work alongside the best people in the field," says Huang. And that experience has helped spur Chinese scientists to set up their own climate research programmes, studies show that this can be explained by

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. Geophys. Res.*, revised.

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

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

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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.

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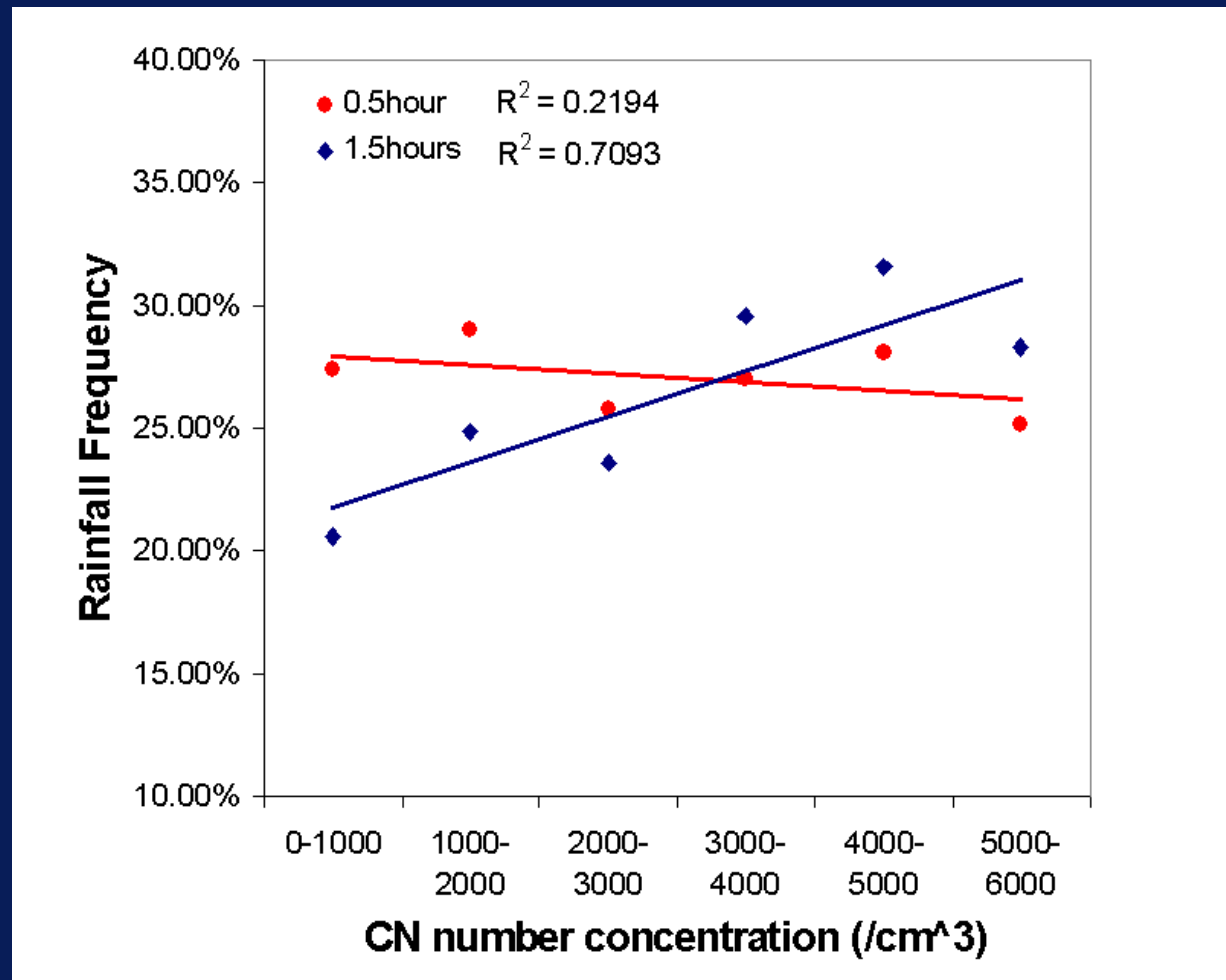
Ge, J. M., J. Su, T.P. Ackerman, Q. Fu, J.P. Huang, and J.S. Shi (2010), Dust Aerosol Optical Properties Retrieval and Radiative Forcing over Northwestern China during the 2008 China-US Joint Field Experiment.

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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.

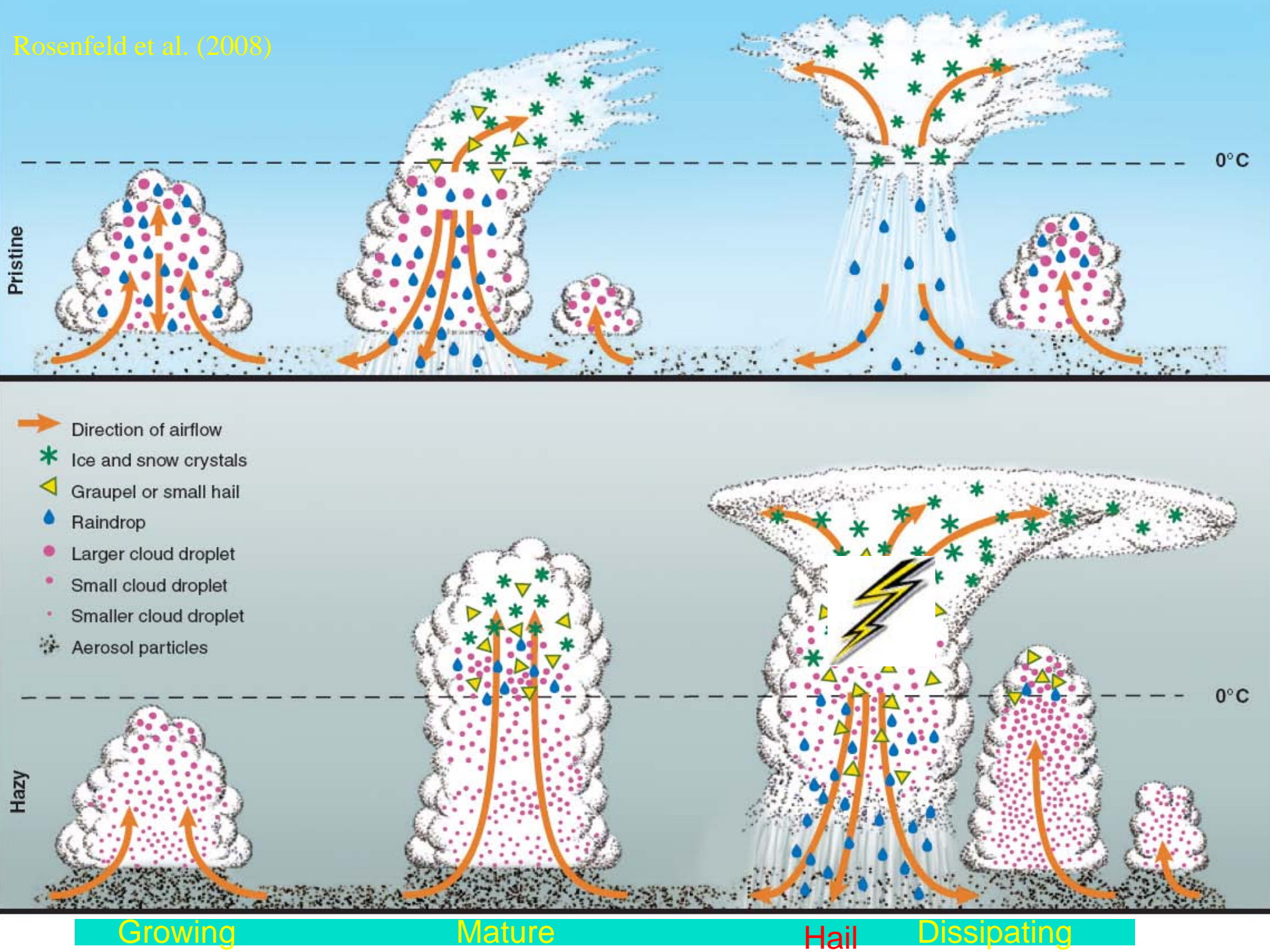
The Effect of Rain Washout on Aerosol



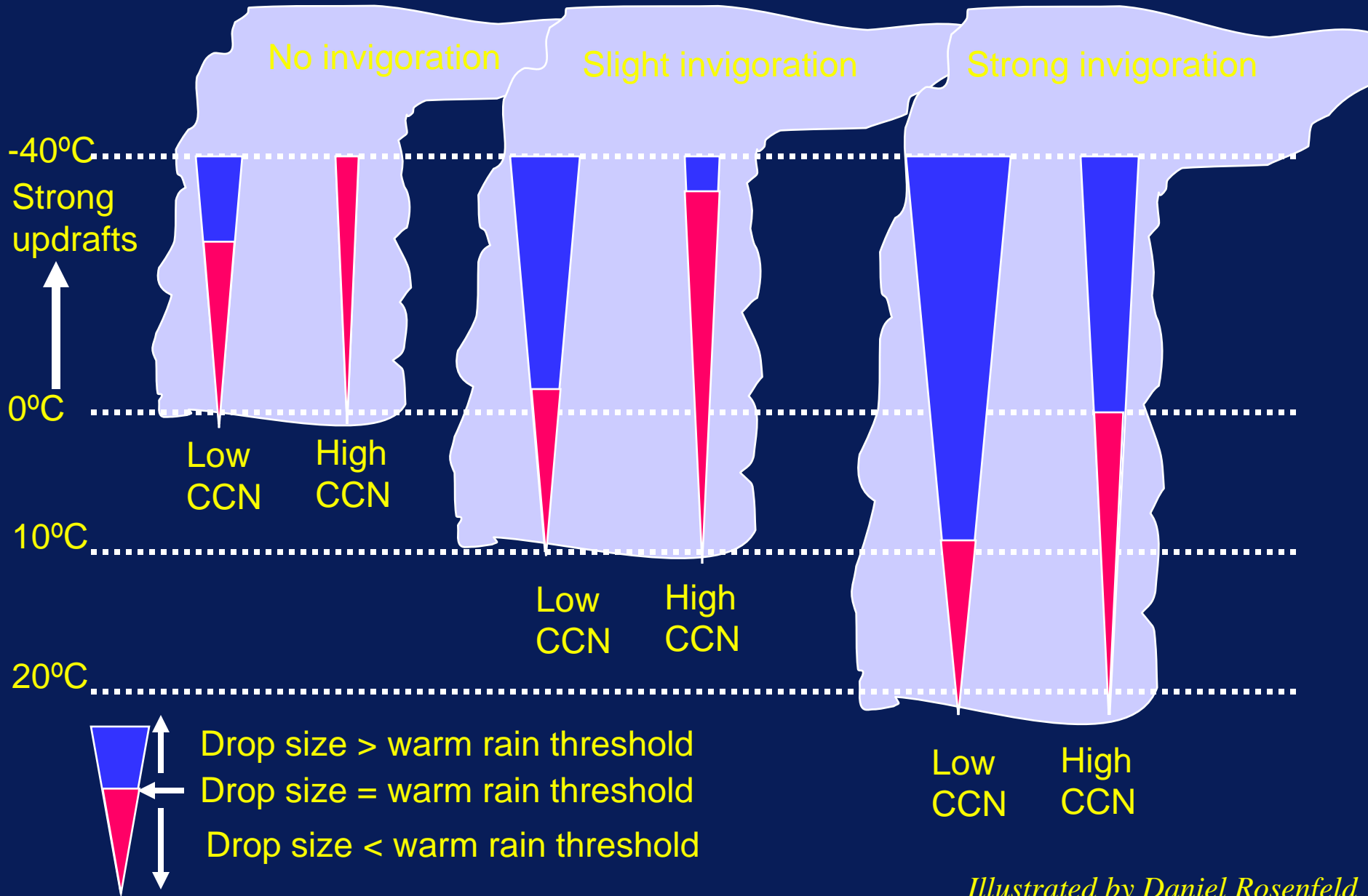
1. Ground-level CN is washout by rain
2. Use of simultaneous or semi-simultaneous CN misleads aerosol effects

Theoretical Interpretation

- The cloud thickness for the onset of precipitation H^* is a critical parameter (*Rosenfeld et al., 2008*)
- $H^* = C (N_a)^\beta$ generally increases with aerosol number concentration.
- The relation between H^* , the freezing level, and cloud top H determines whether clouds are invigorated or suppressed.

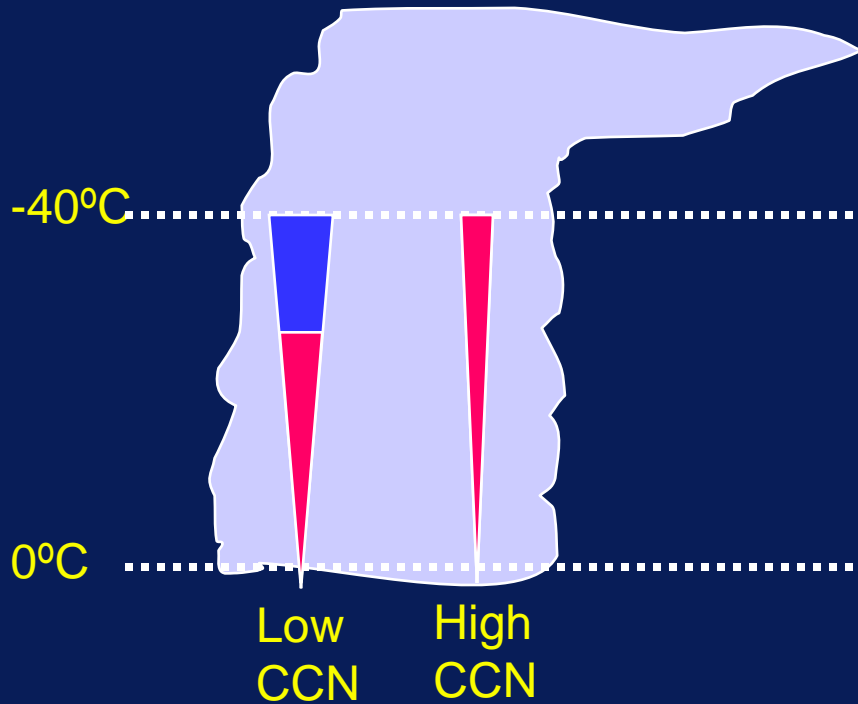


Conceptual model for aerosol invigoration effect:



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.

10°C

20°C

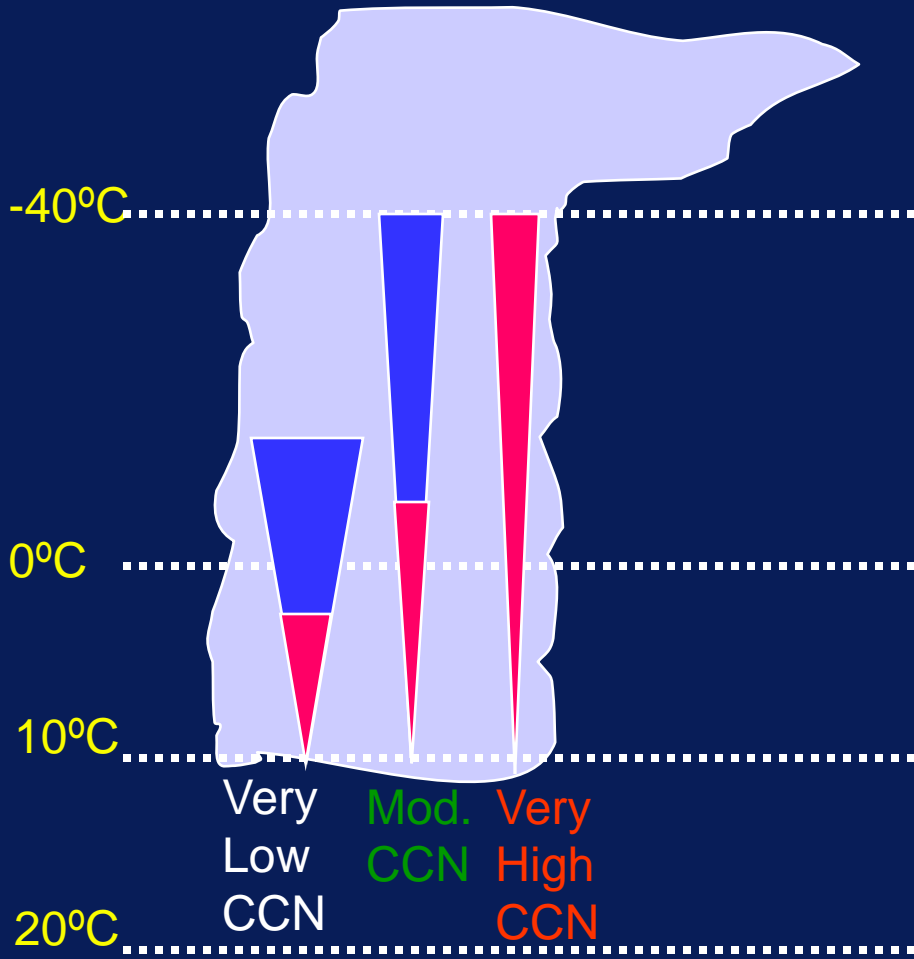


Drop size > warm rain threshold

Drop size = warm rain threshold

Drop size < warm rain threshold

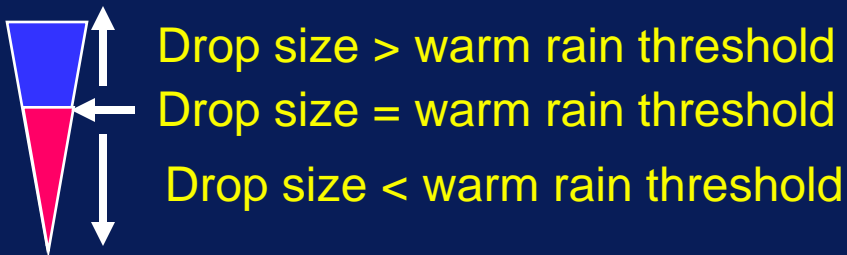
Conceptual model:



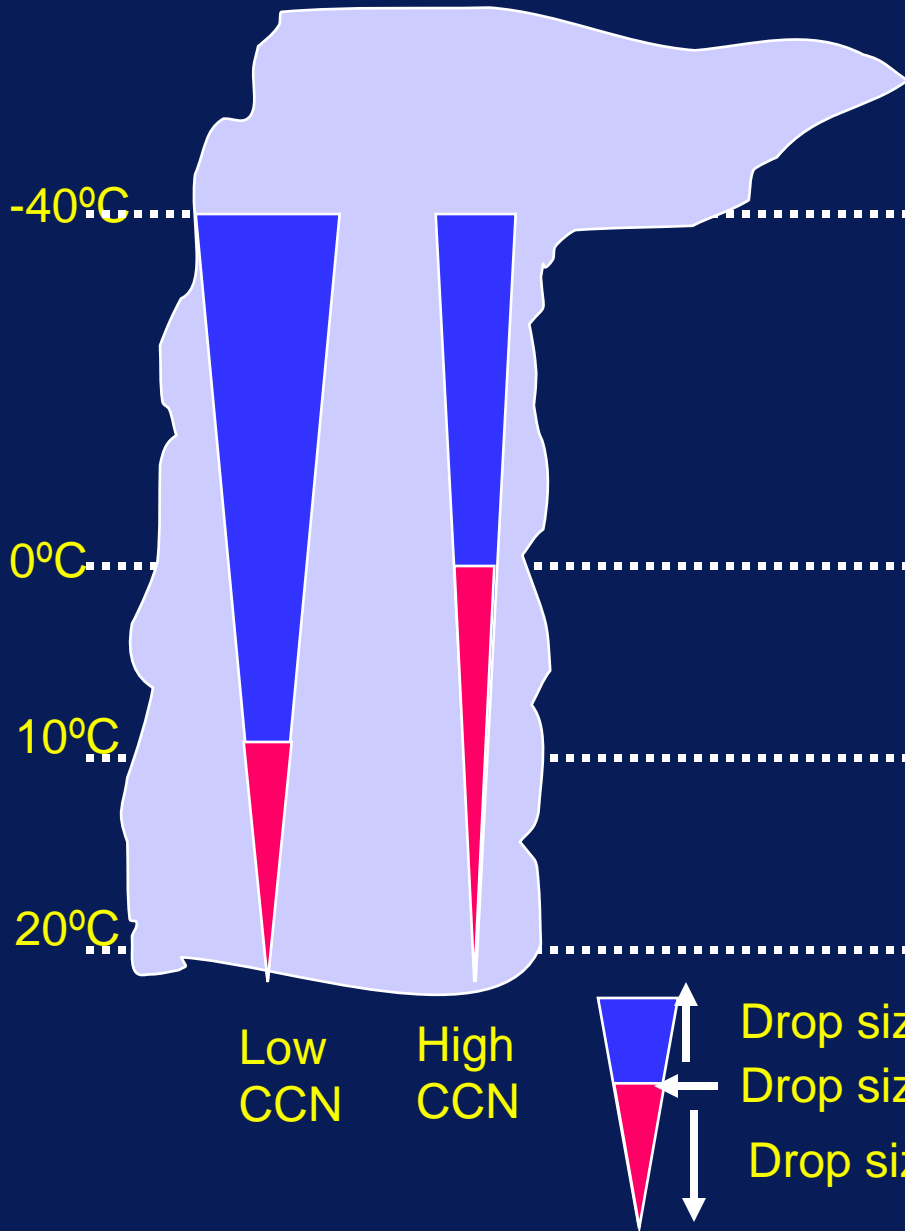
Mild base clouds:

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:



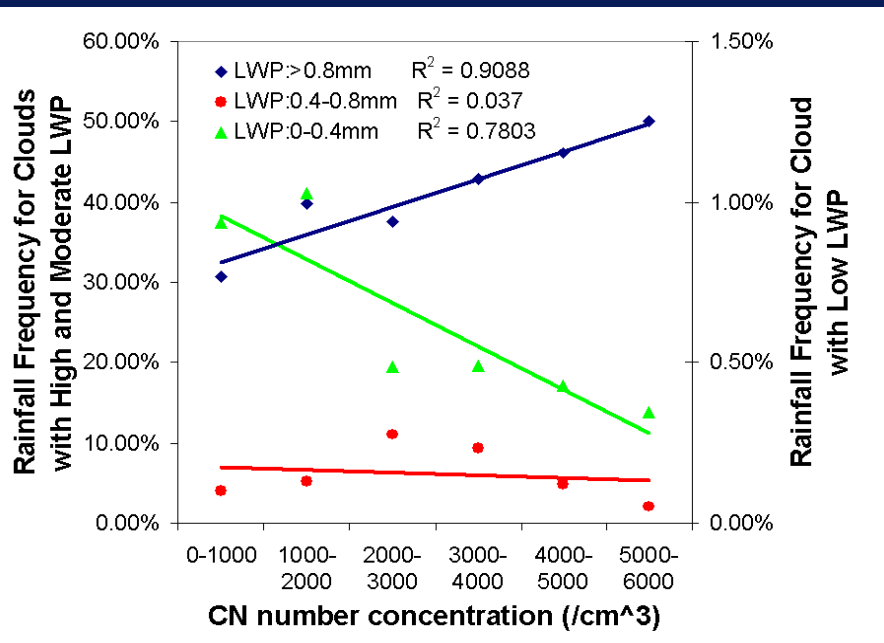
Warm base clouds:

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.

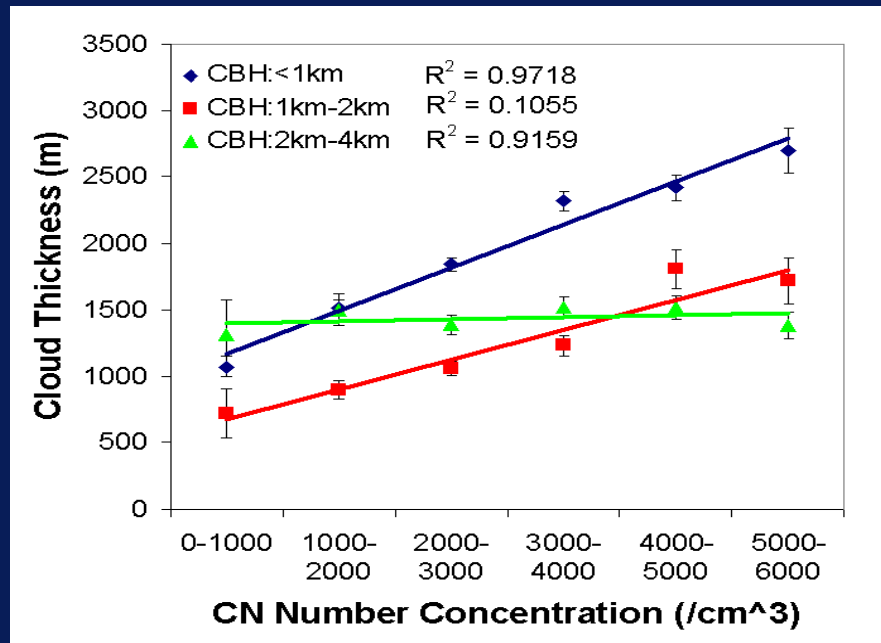
Drop size > warm rain threshold
Drop size = warm rain threshold
Drop size < warm rain threshold

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

Rainfall Frequency



Cloud Thickness

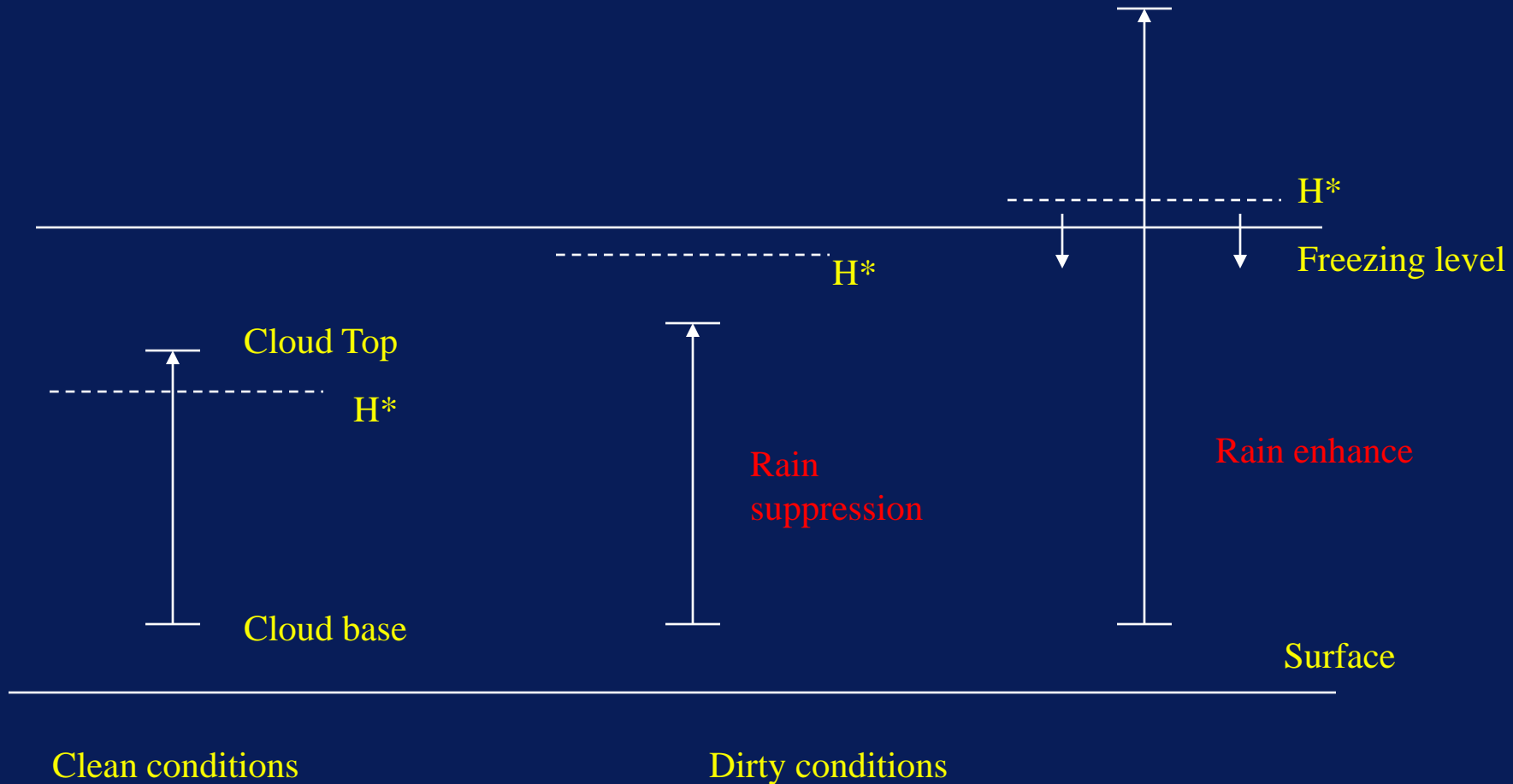


Rainfall frequency is reduced by aerosols for low liquid water path (LWP), but increased for large LWP.

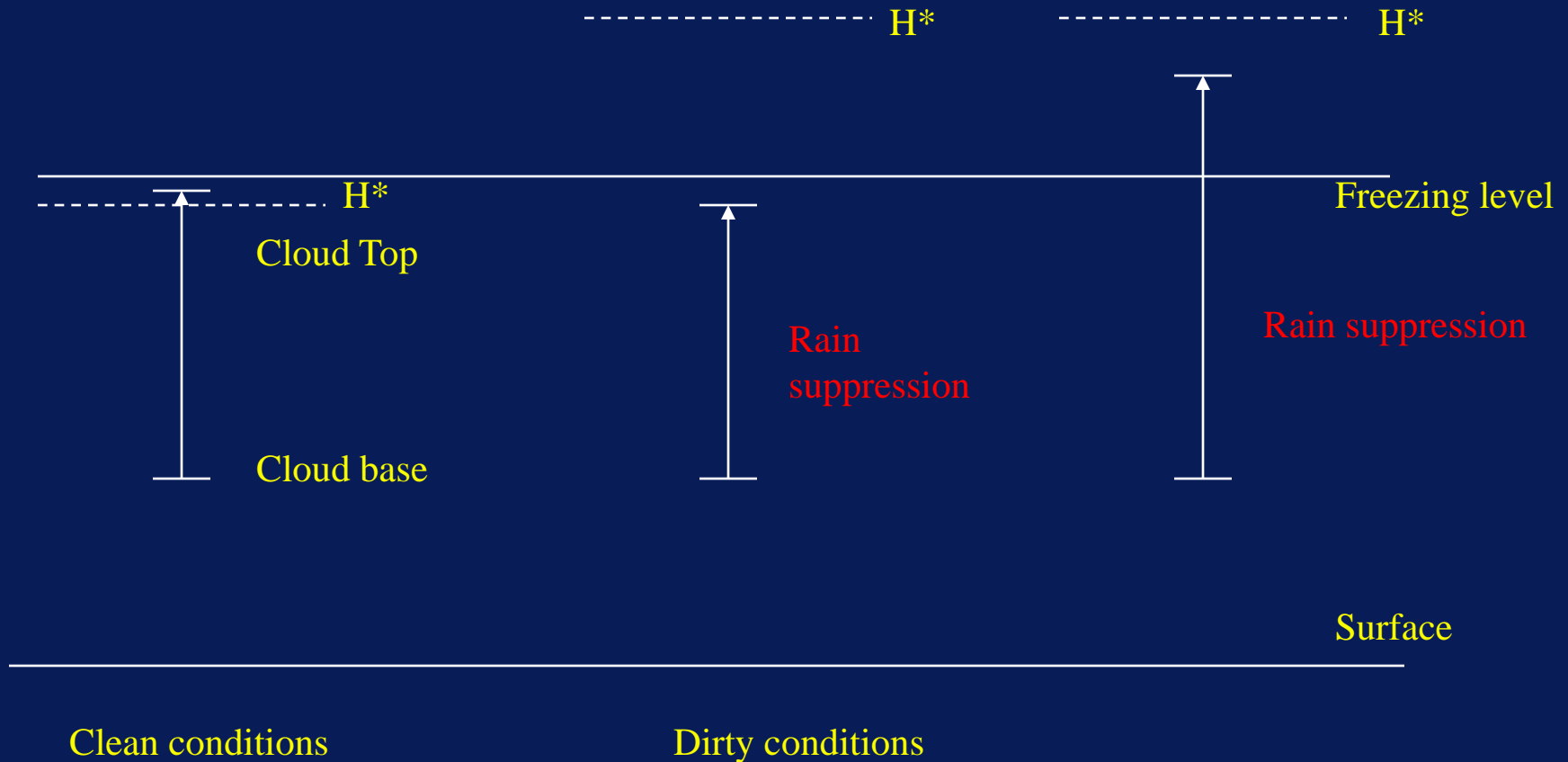
Cloud thickness/top increases with aerosol concentration for low cloud height (CBH), but nil for high.

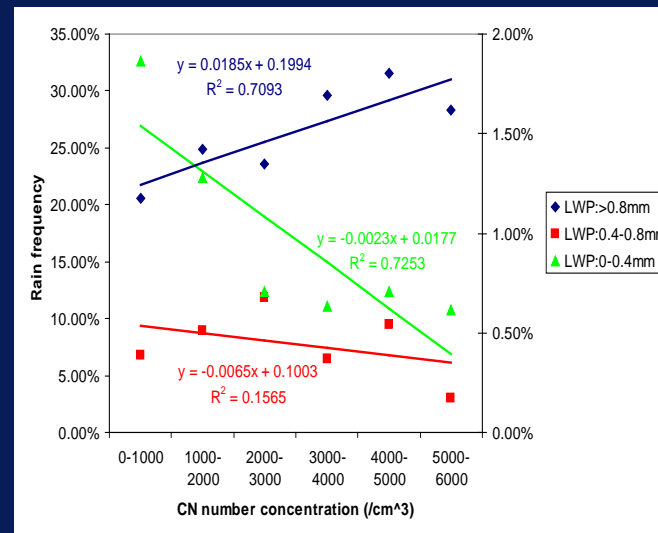
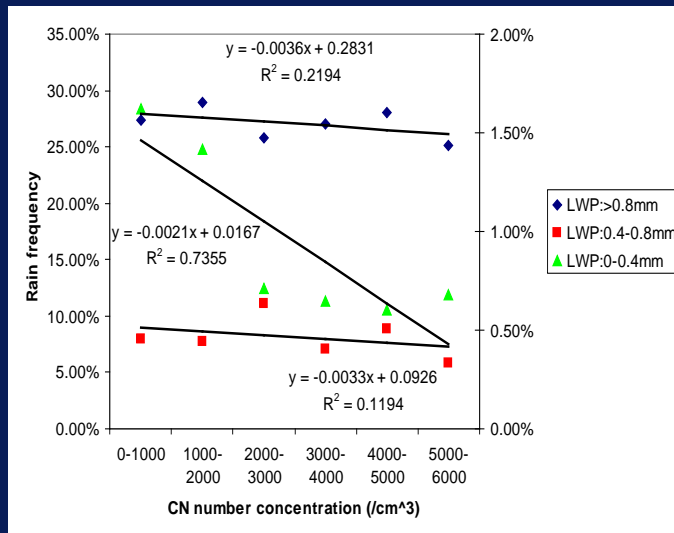
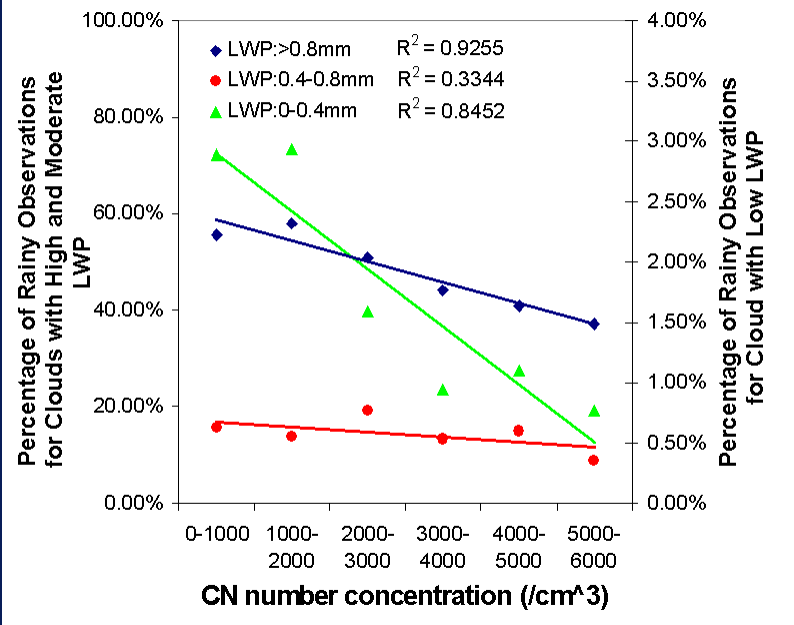
The Twomey Effect and Invigoration Effect are both at work !

Low-base Clouds



High base clouds





10 year data

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