The Abdus Salam
International Centre for Theoretical Physics

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2256-16

Workshop on Aerosol Impact in the Environment: from Air Pollution to Climate Change

8 - 12 August 2011

Aerosols and Weather Modification including Geo-Engineering principles

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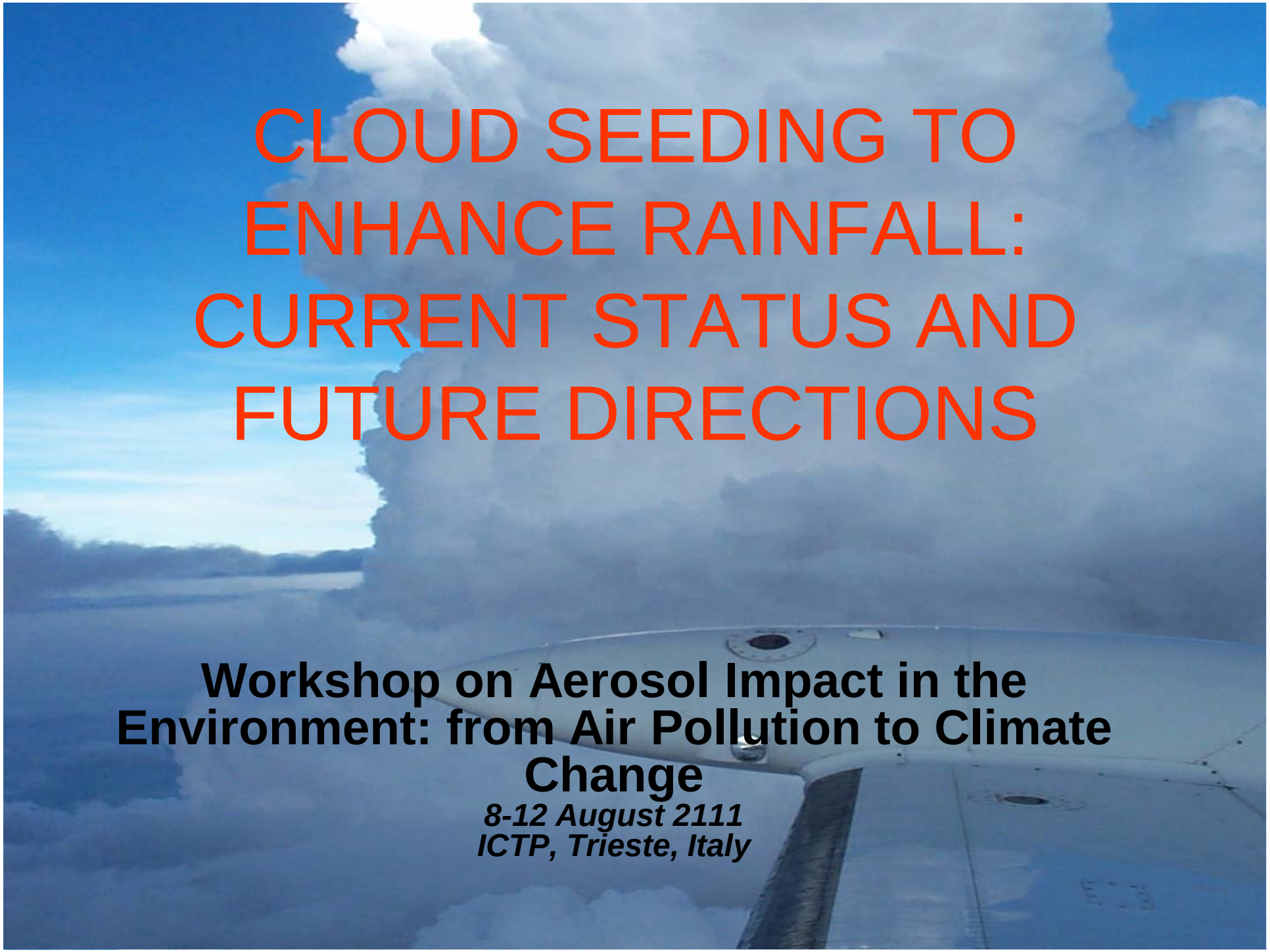


CLOUD SEEDING TO ENHANCE RAINFALL: CURRENT STATUS AND FUTURE DIRECTIONS

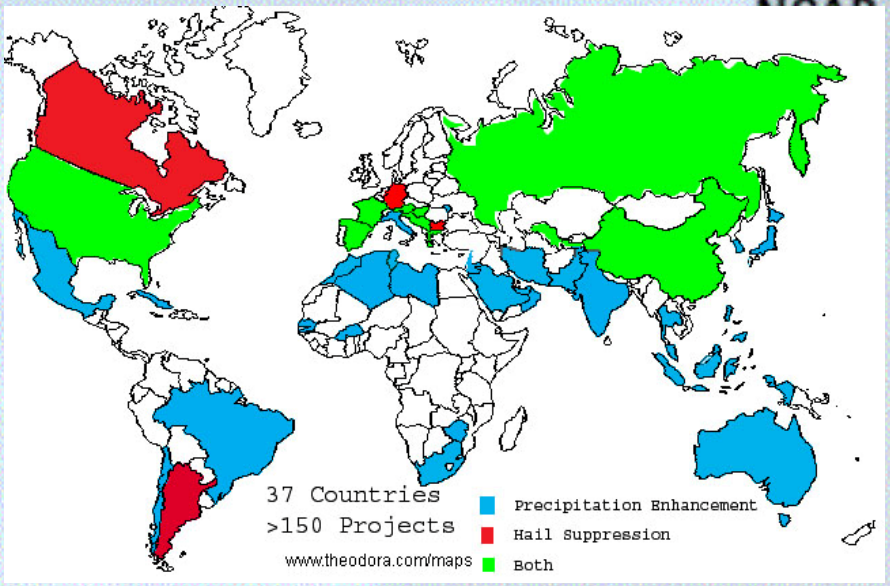
Workshop on Aerosol Impact in the Environment: from Air Pollution to Climate Change

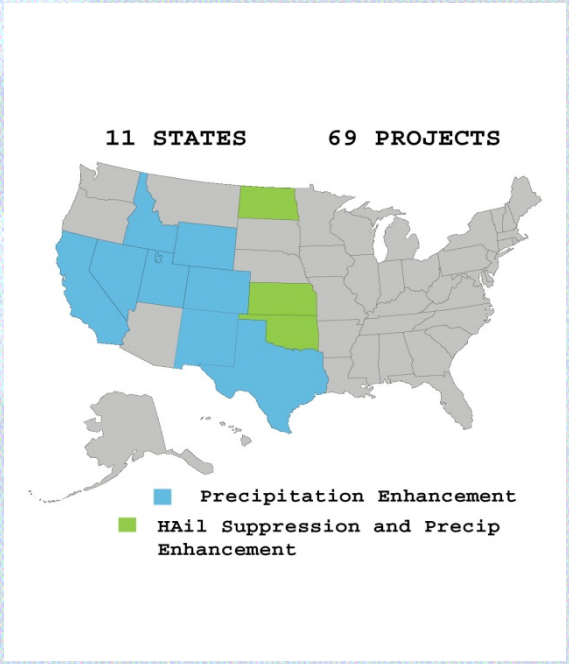
8-12 August 2111

ICTP, Trieste, Italy

The Paradox

- Operational programs in more than 37 countries worldwide
- At least 69 programs in 11 U.S. states in 2005





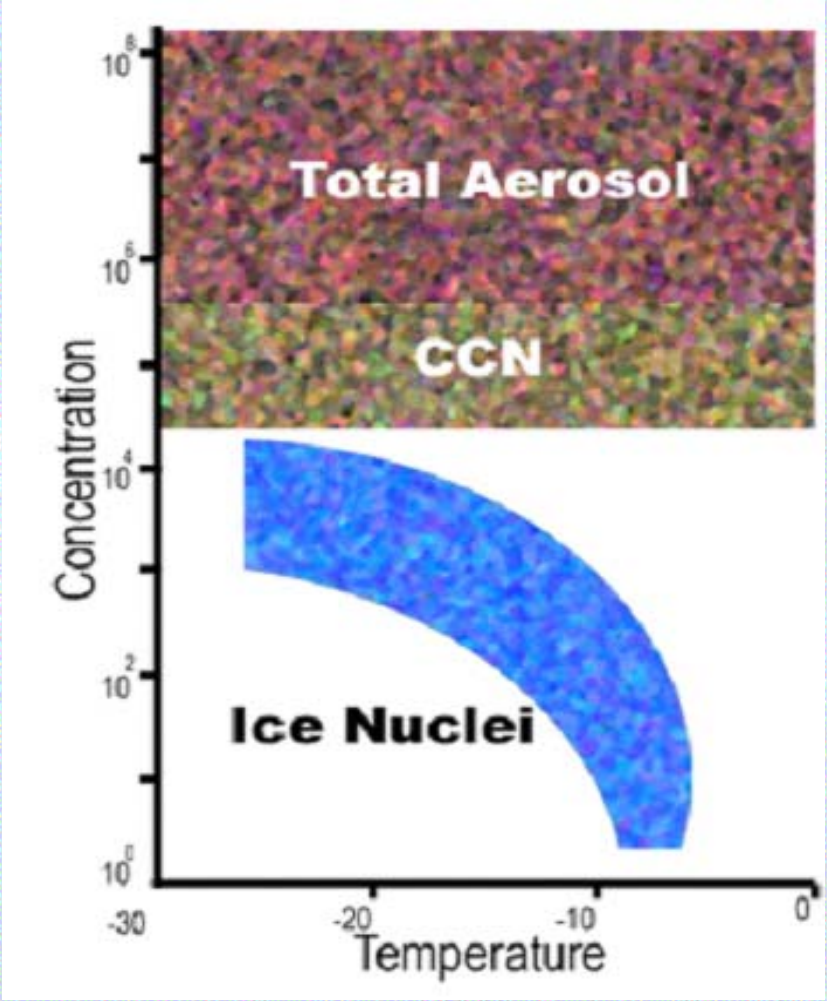
- Limited funding supporting research as part of operational programs
- Impact of human activity on weather and climate recognized and heavily funded

Questions

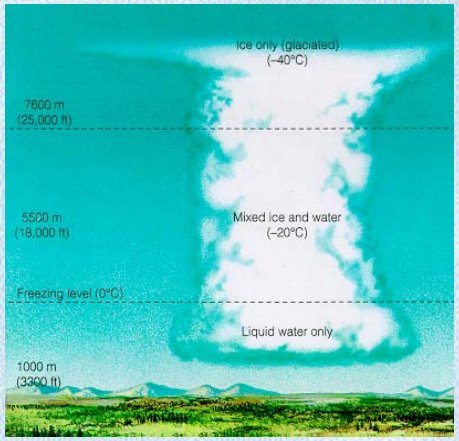
- What role does aerosols play in warm and mixed phase processes in deep convective clouds?
- How does aerosol effects compare with other effects such as thermodynamics (stable layers and updraft speed) and cloud base temperature?
- What are the implications for cloud seeding experiments?

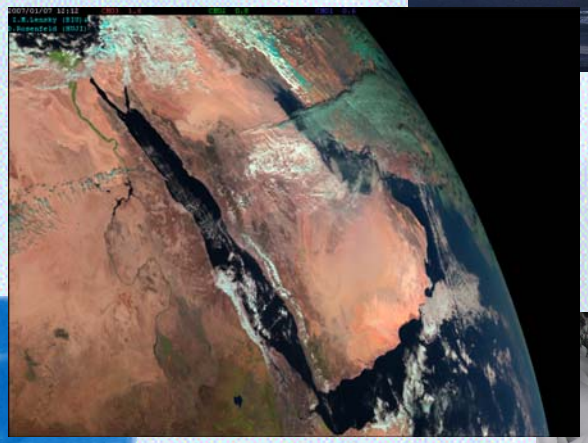
Total aerosol, cloud condensation nuclei (CCN), and ice nuclei (IN) concentrations as a function of temperature.

- In order to enhance precipitation the concept of seeding is to seed with appropriate CCN or IN to make precipitation develop more efficiently.

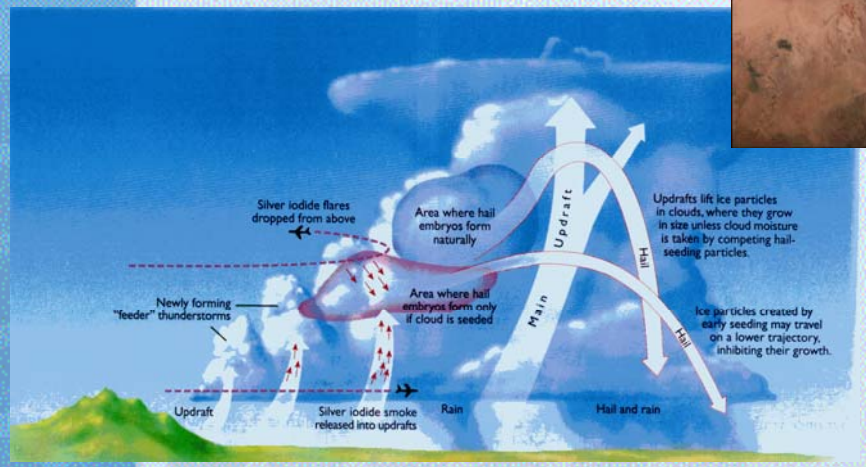


Cloud characteristics changes





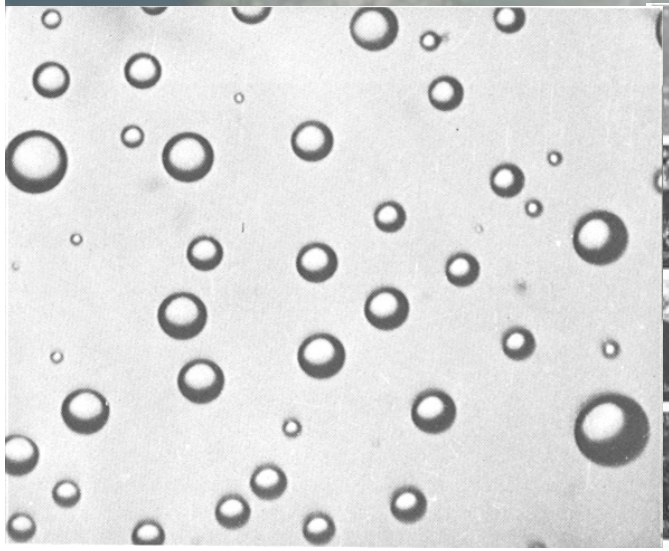
Convective storms

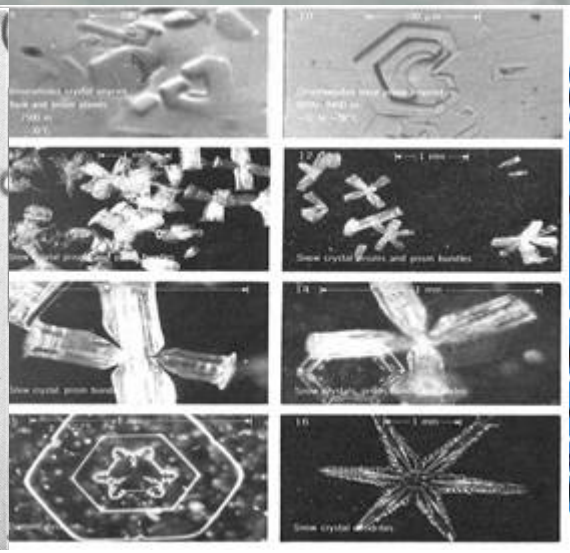


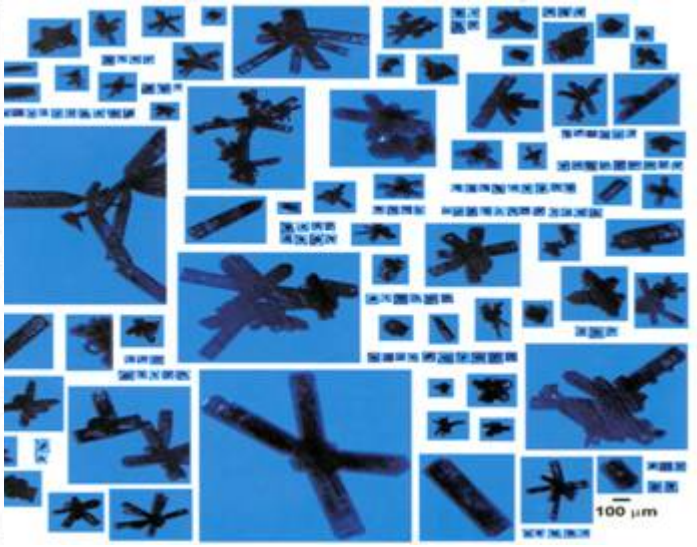
Frontal and orographic clouds

Fundamentals

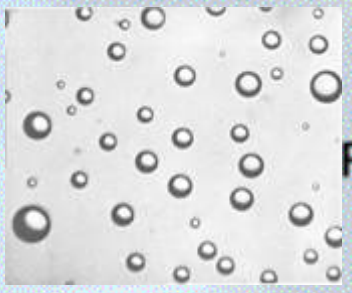
What are clouds made of?







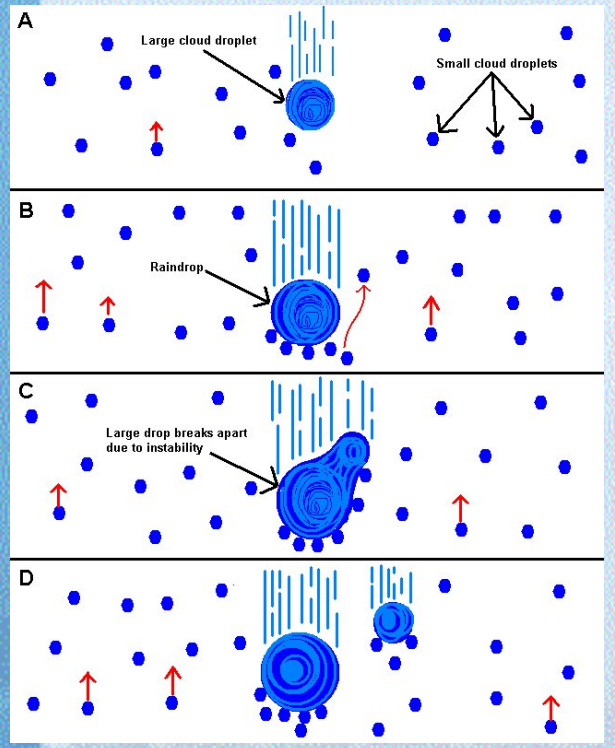
Cloud droplets



- Condensation on hygroscopic particles (a specific kind of water-soluble aerosol)
- Droplet growth by condensation
  - Condensation occurs through diffusion of water vapor
  - Cloud droplets are typically in the size range of 5-25 μm (i.e., very small)
  - They have a very small terminal velocity
- Result: No precipitation from only cloud droplets. The water stays in the cloud

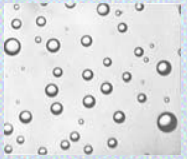
Warm rain process

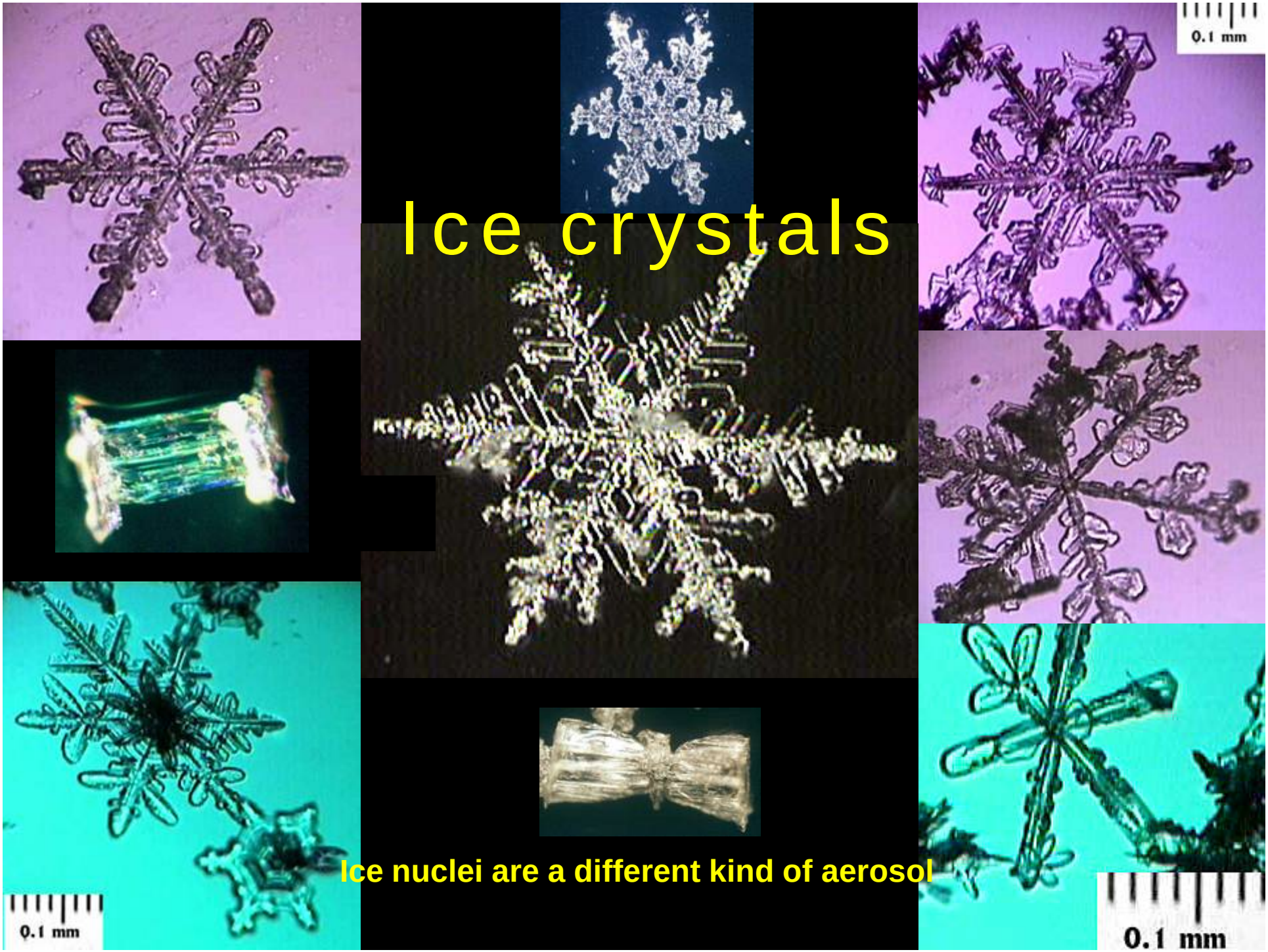
- Collision and coalescence of droplets falling at different terminal velocities leads to raindrop formation



Raindrops are millimeters in size

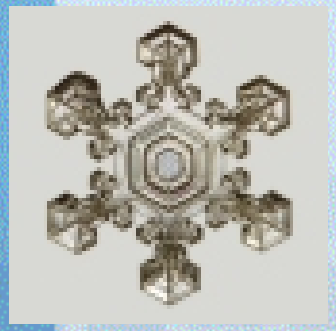
Cloud droplets are 100 times smaller in diameter

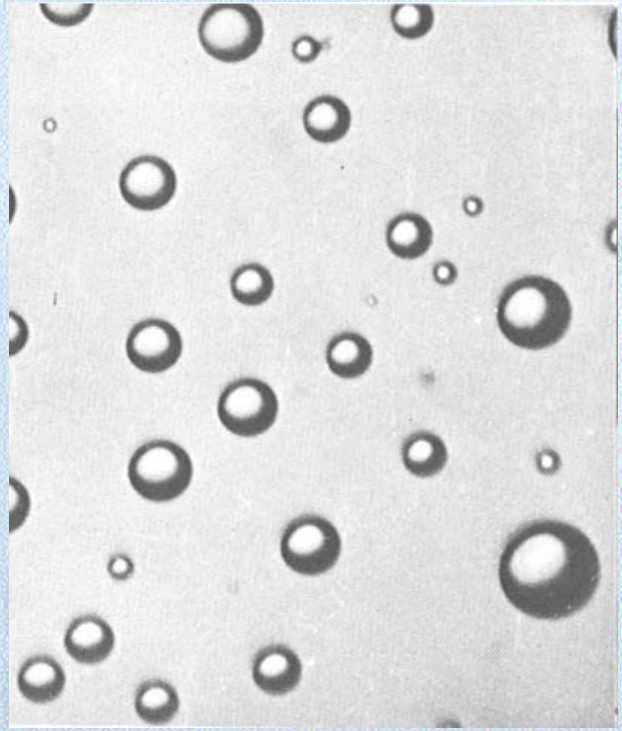


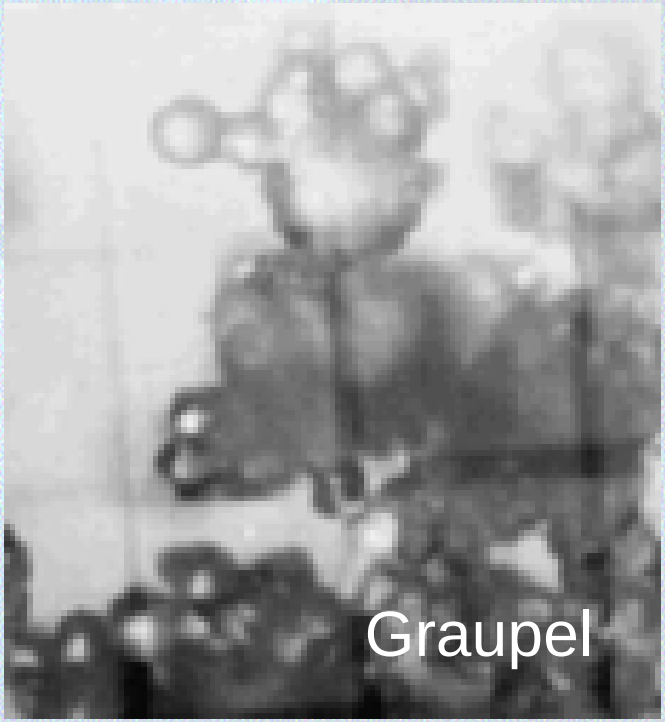

Ice crystals
0.1 mm
0.1 mm
0.1 mm
Ice nuclei are a different kind of aerosol

The cold rain process

- Co-existence of ice crystals and supercooled droplets leads to rapid vapor growth of crystals, followed in suitable convective clouds by accretional growth (riming), fall-out, and melting as rain

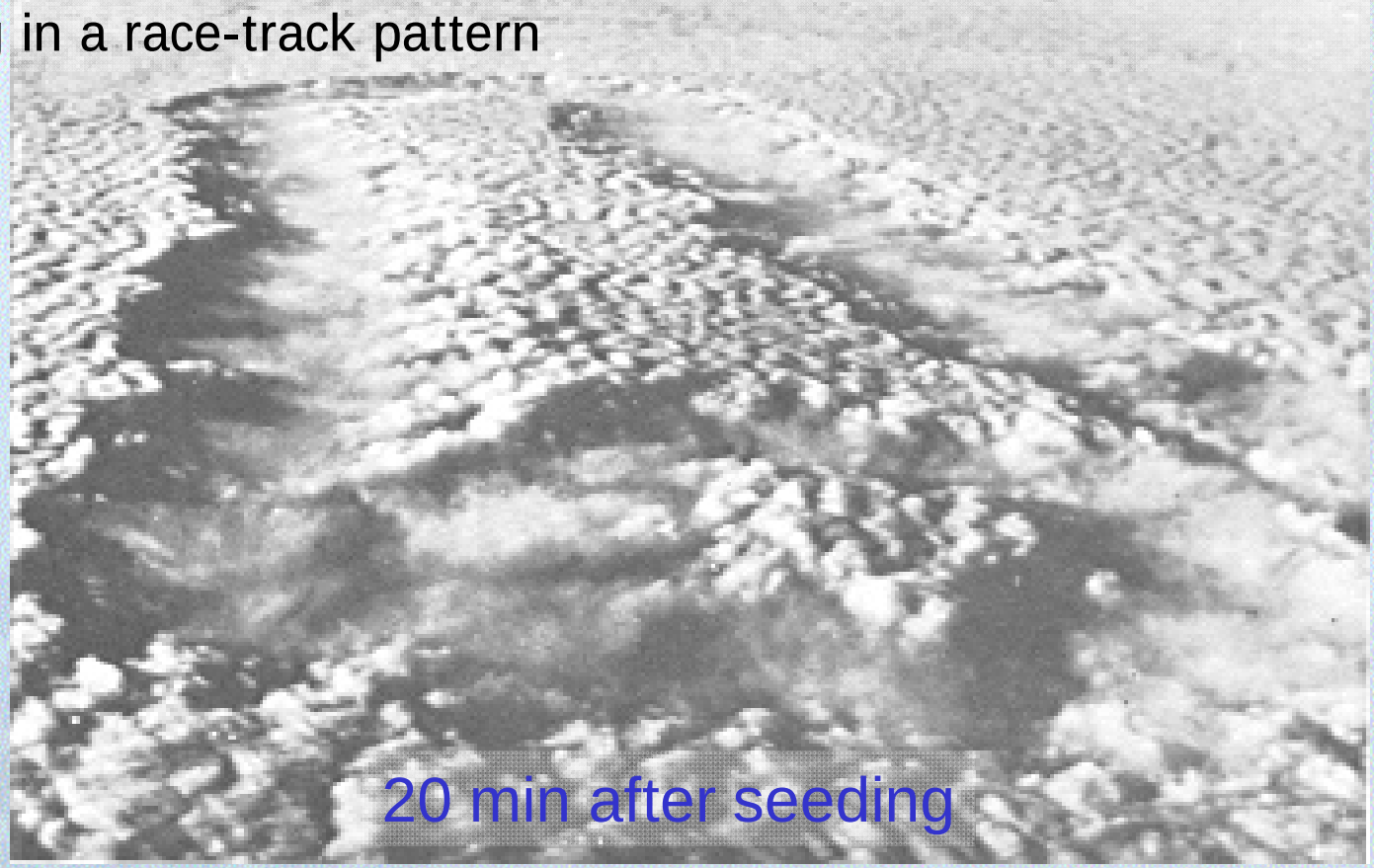






The origins of cloud seeding...

- Freeze supercooled droplets by introducing artificial “seeds”
- Langmuir and Schaeffer, Schenectady, NY, Nov 13, 1946: Dropped 3 pounds of dry ice pellets into a stratus deck at 14,000 ft, -20C, flying in a race-track pattern



20 min after seeding

WEATHER MODIFICATION

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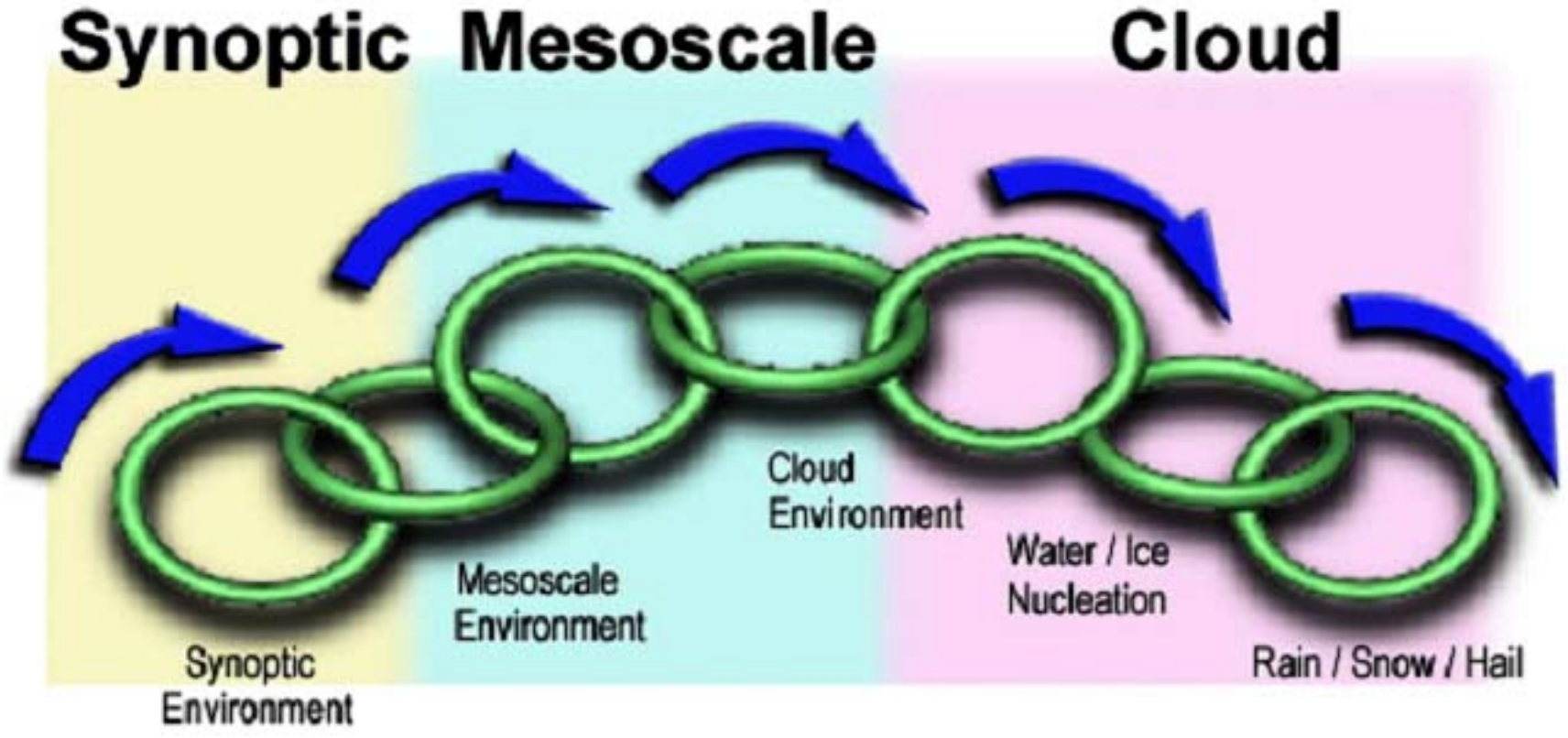
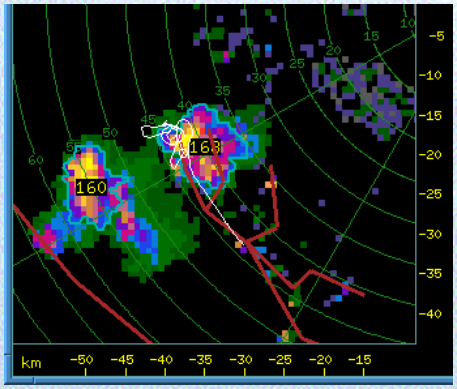
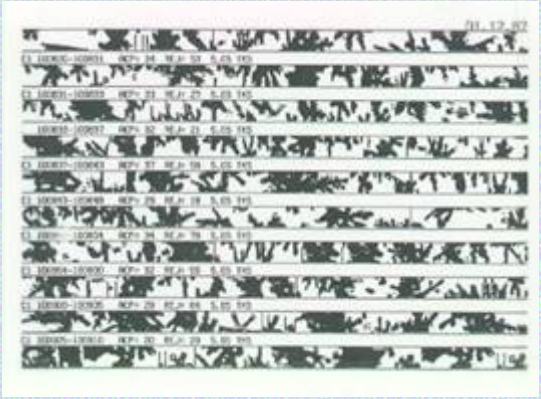


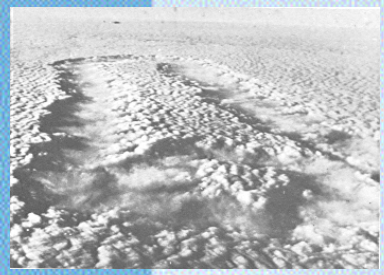
- **The Initial Age**
  - **Spectacular claims (rain, hail, hurricanes, snow, etc)**
  - **Problems with scientific evaluation**
    - **How to detect seeding effect (10-50%) against a background of natural variability some 10-100 times greater?**
  - **Emergence of the professional statistician into the field**
  - **Physical hypotheses stated; almost none actually checked**

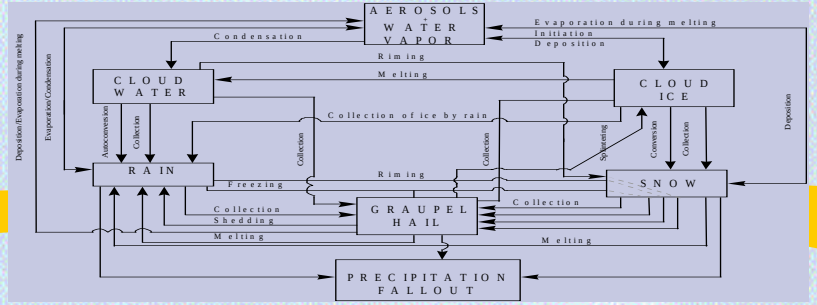
- **New Age: starting in the 1970s with direct measurements and advanced computer models**
  - Airborne instruments, digital data
  - Doppler radar
  - Coordinated experiments
  - 3D cloud modeling
  - Radiometers





So where are we?





- **Much has been learned about natural rainfall and seeding**
  - Warm vs cold rain
- **The fundamental weather mod result: AgI seeding produces lots of ice crystals**
- **The effects of seeding on precipitation are essentially never as clear-cut as in the stratus cloud photo. Clouds are complex.**
- **Controversial results regarding AgI seeding for rain increase from convective clouds**
  - Re-analysis of experiments; effects less clear-cut
- **Better progress with continued efforts studying winter orographic snowfall enhancement and hygroscopic seeding of convective clouds**
- **Greatly decreased funding since the ’80s**

Principal Conclusion (NAS 2003)

Advances in atmospheric sciences positions us to mount **concerted** and sustained **effort** to delineate **scope** and **expectations** of future weather modification research

- Must be directed at answering **fundamental** scientific questions
- Will yield results that go **beyond** application to weather modification (e.g., NWP, QPF)
- Emphasis be on **understanding** processes and results

Scientific approach

- Preliminary study (needs, area, clouds, rainfall, tools, human resources)
- Design (infrastructure, training, tools, conceptual model, operations, evaluation)
- Execution (operations plan, data gathering, processing and archival, quality control, analyses, evaluation)
- Evaluation (assessment, hydrological, economical and social impacts and cost/benefit assessment)

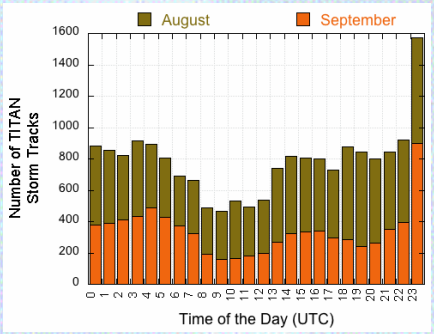
ALL STEPS ARE CRITICAL IN THE EXECUTION OF A SCIENTIFICALLY BASED PROGRAM TO QUANTIFY THE RESULTS

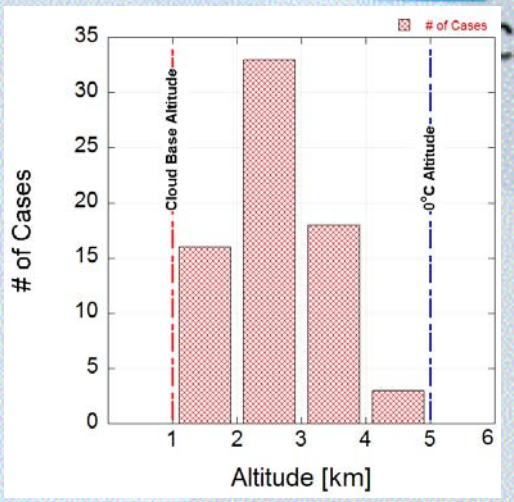
PRELIMINARY STUDIES

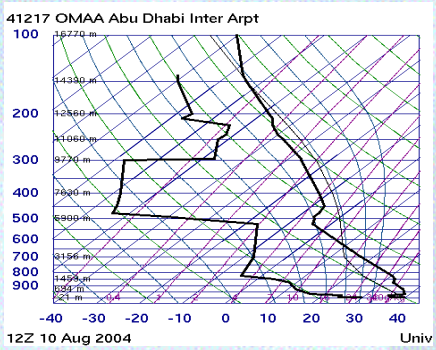
WHY?

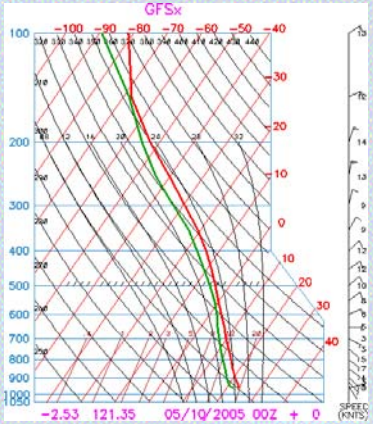
TEMPORAL AND SPATIAL VARIATIONS IN:

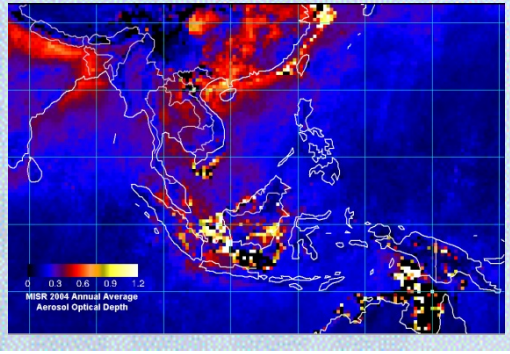
- Climatology of clouds and precipitation in a region
- Thermodynamic structure
- of the atmosphere
- Aerosol and associated
- microphysical variations

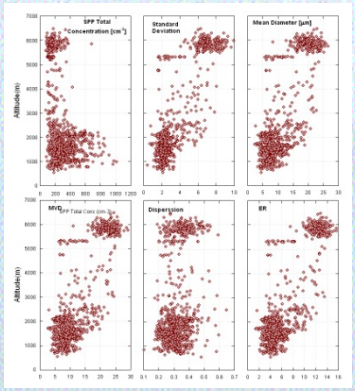


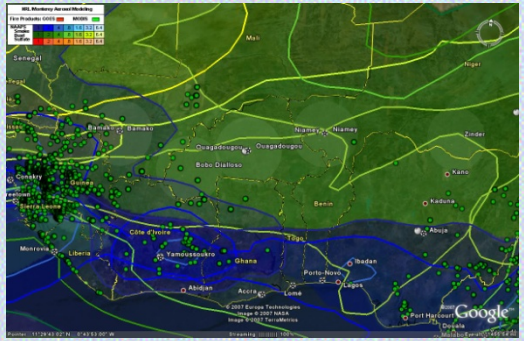












Key Uncertainties

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Cloud and precipitation microphysics issues

- Background concentration, sizes, and chemical composition of aerosols participating in cloud processes

Cloud dynamics issues

- Cloud-to-cloud and mesoscale interactions relating to updraft and downdraft structures and cloud evolution and lifetimes

Cloud modeling issues

- Combination of best cloud models with advanced observing systems in carefully designed field tests and experiments

Seeding-related issues

- Targeting of seeding agents, diffusion and transport of seeding material, and spread of seeding effects throughout the cloud volume
- Measurement capabilities and limitations of cell-tracking software, radar, and technologies to observe seeding effects

DESIGN

- Infrastructure
- Conceptual model
- Operations
- Evaluation
- Training

Conceptual Models

Hygroscopic Conceptual Model

Hygroscopic Seeding with Flares

Broadens cloud droplet spectra near cloud base

Destabilizes narrow droplet spectra & enhances drizzle production

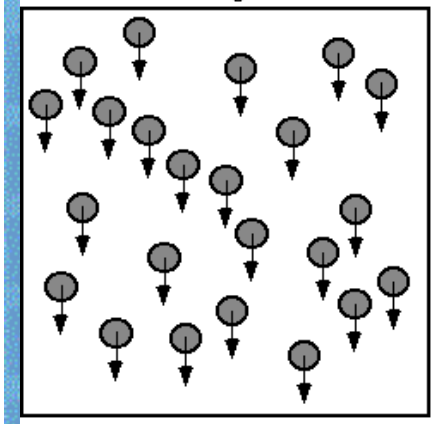
Recirculation helps drizzle enter growth area and spread to other turrets

Updrafts helps loft drizzle above freezing level

May form primary graupel embryos
Riming rates higher
Potential increased secondary ice generation

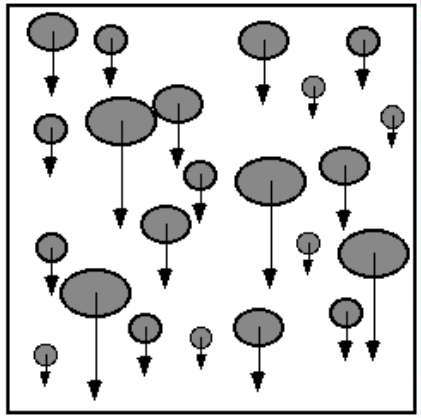
Increases precipitation at cloud base

Distribución de gotas uniforme



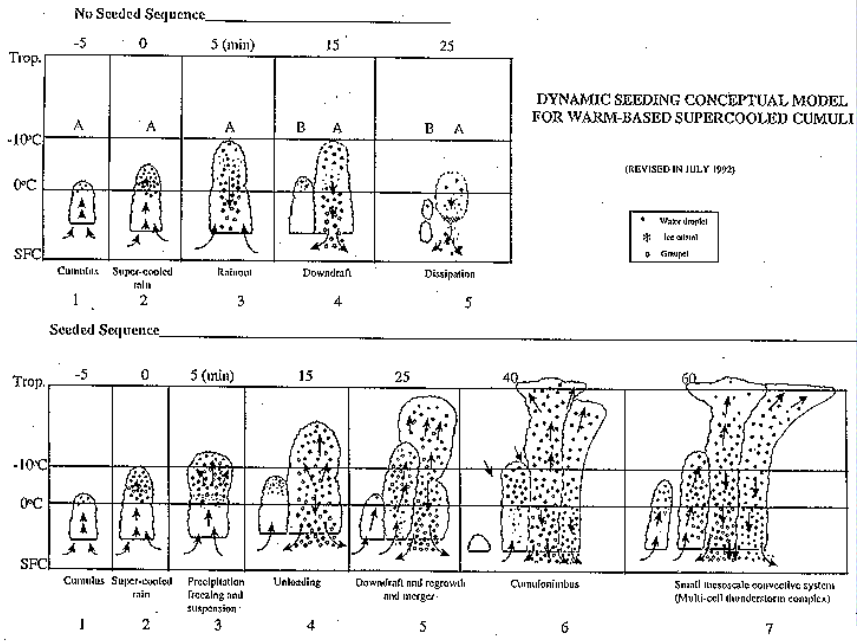
Colisión/coalescencia mínima

Distribución de gotas no uniforme

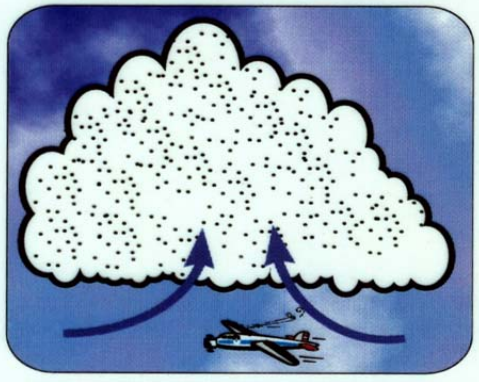


Colisión/coalescencia vigorosa

Dynamic seeding conceptual model



Good Candidate Clouds



Cumulus Congestus

Or larger… Cumulus clouds deep enough to allow for precipitation development (>2km vertical depth

Narrow Cloud Base Spectra

Formed on a continental aerosol population. Spectra will exhibit high concentration, small mean diameter, and no drops larger than 20 μm

Sustained Updraft

At least 100-300 feet per min

Aerosol, thermodynamic and Cloud base temperature effects

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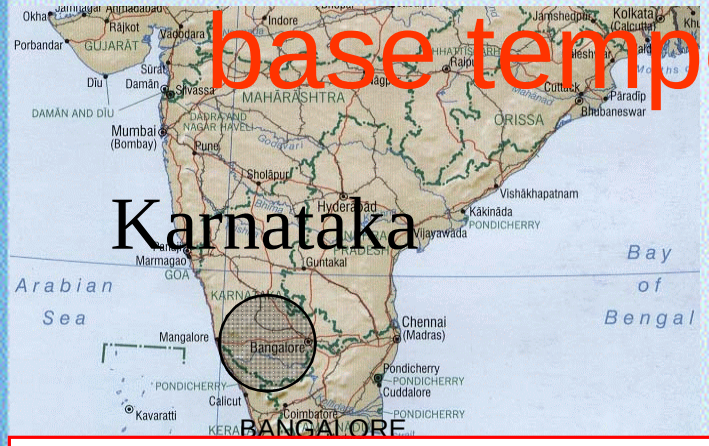

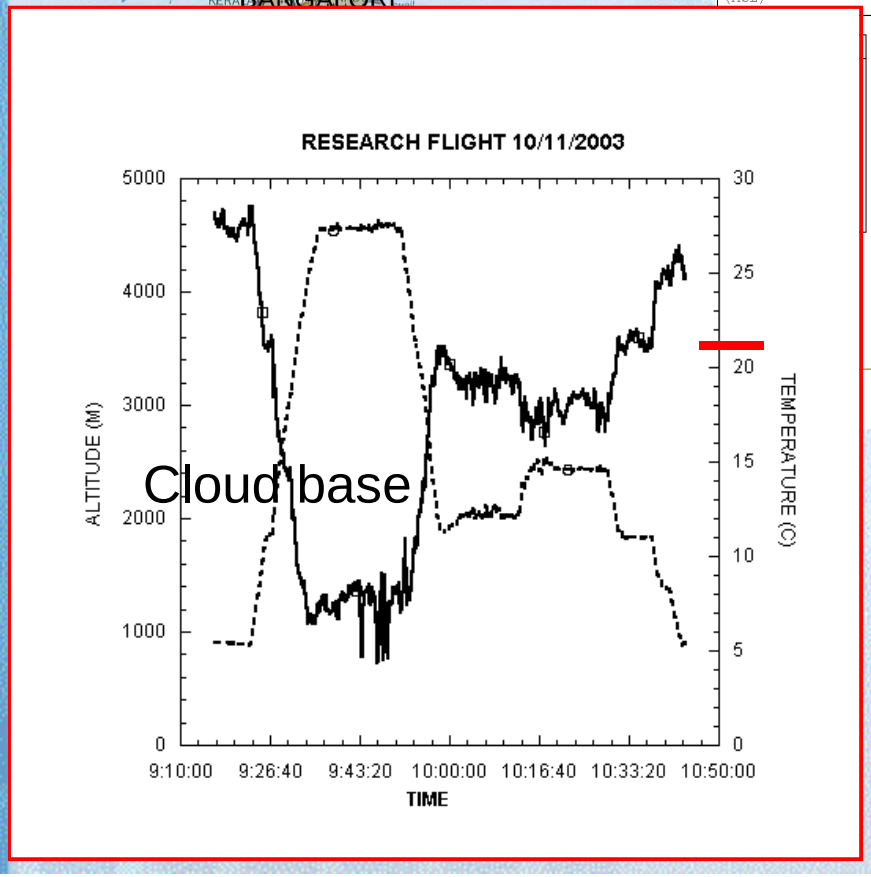

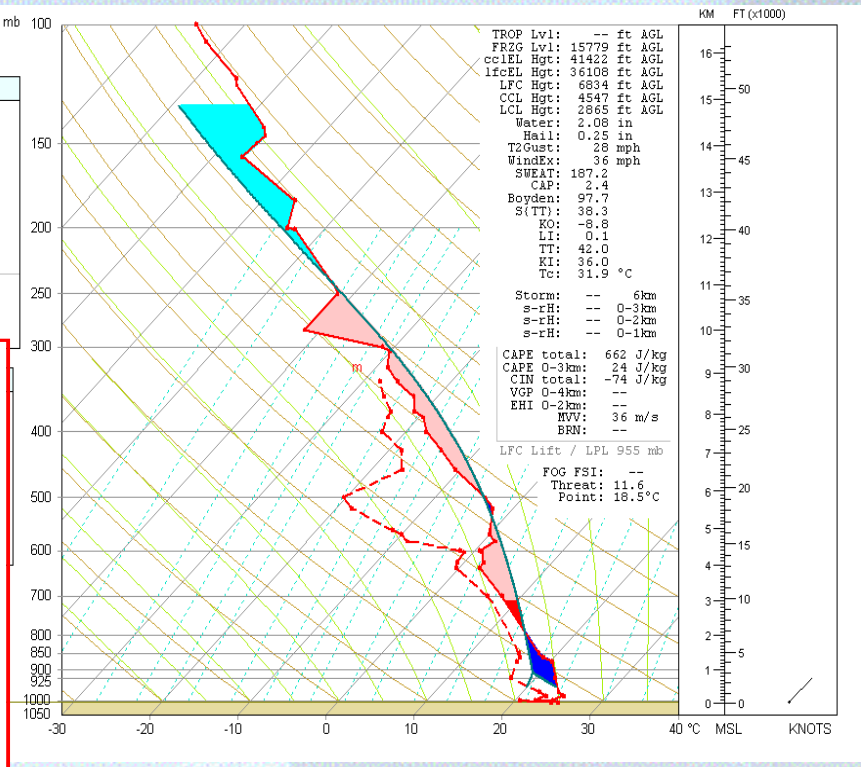

Aerosols, CCN and Cloud droplet concentrations (India)

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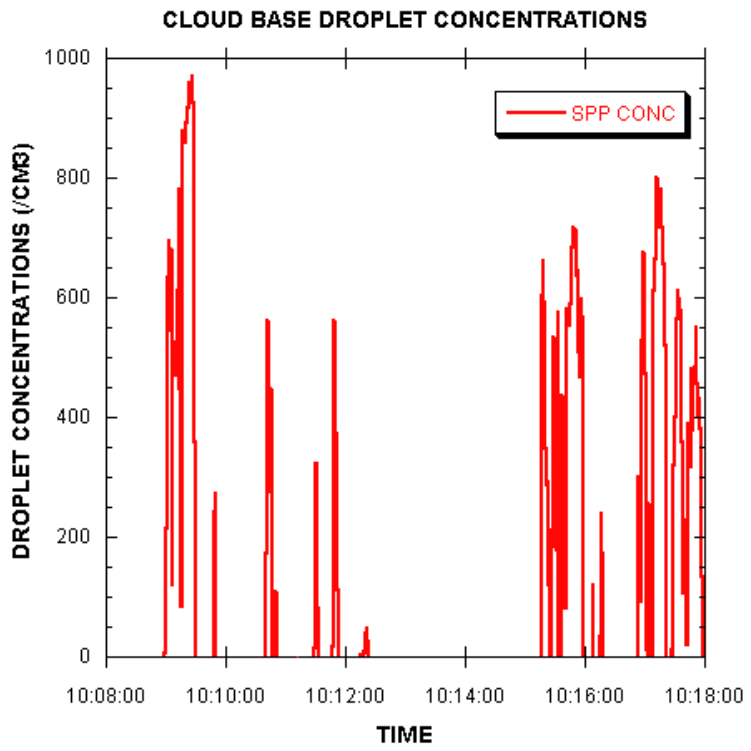
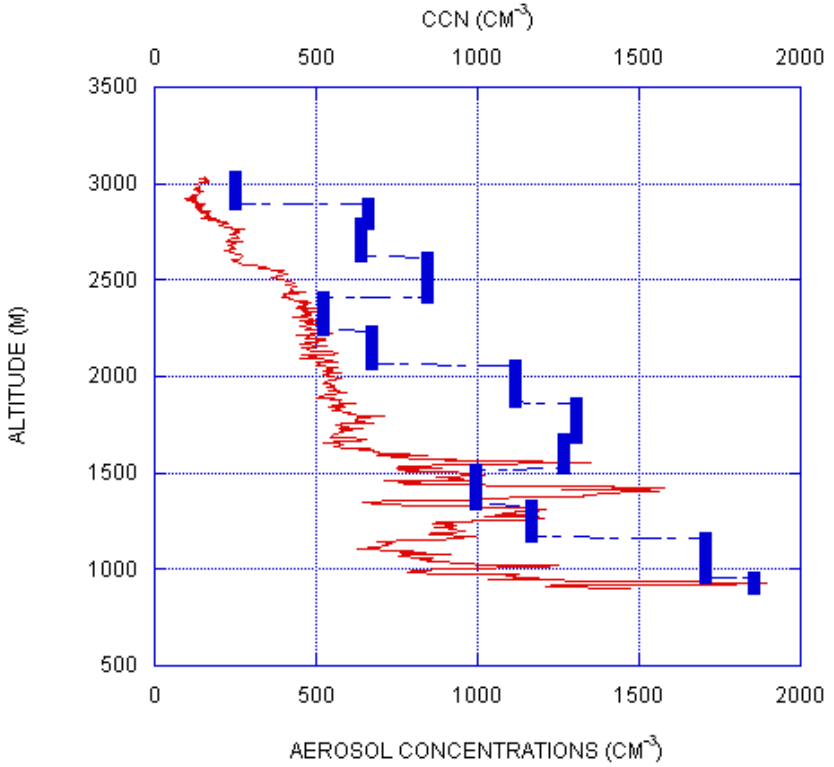
High concentrations of droplets due to pollution



CCN and aerosol conc.



Broadening of cloud droplet spectra by re-circulation

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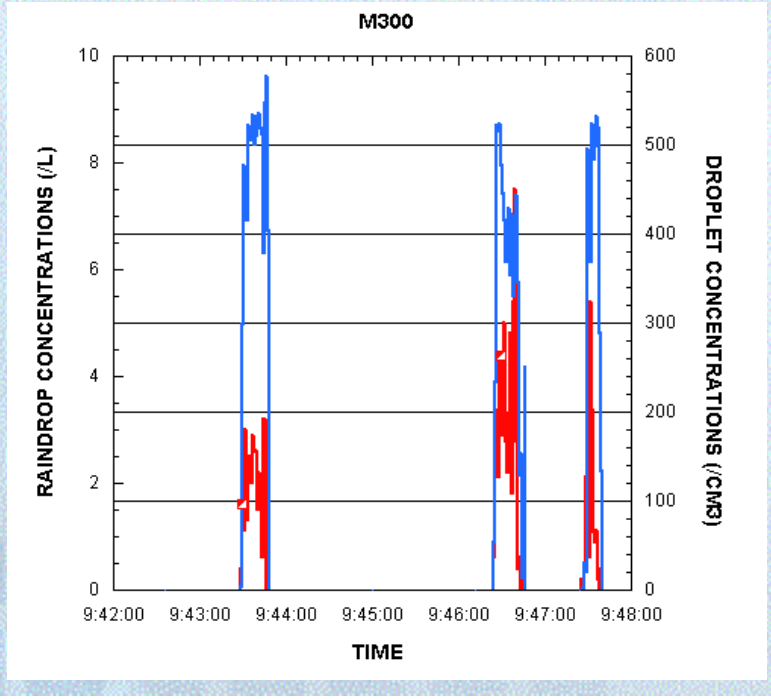
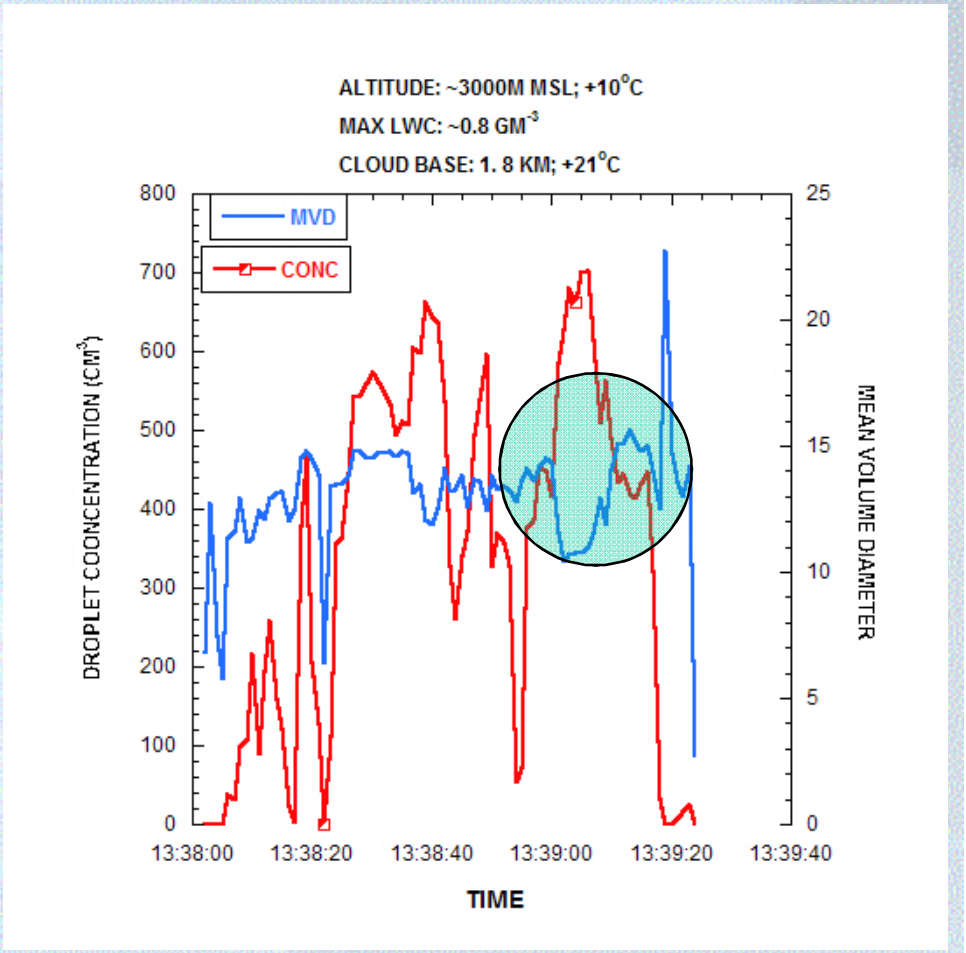


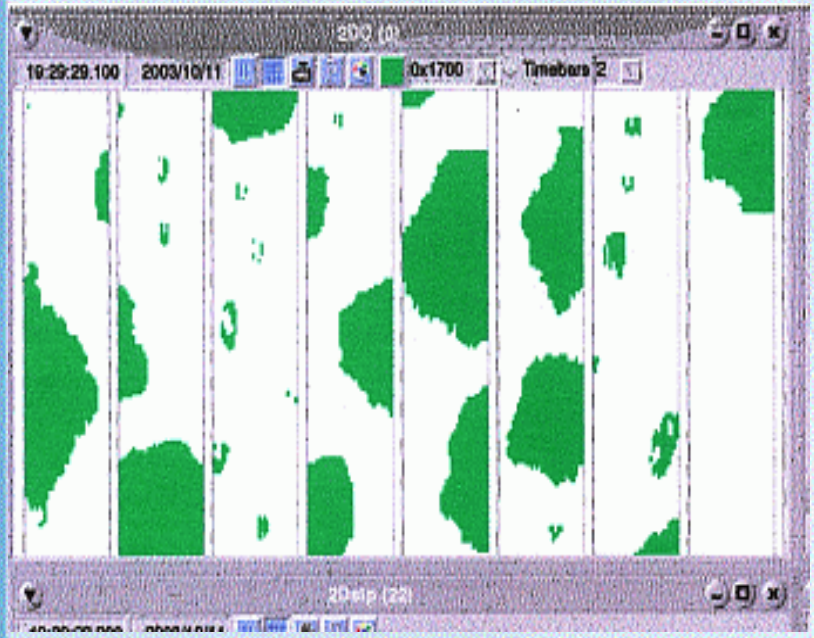


CCN effect: Difficult to form rain in clouds

Effects on Ice Processes

NCAR

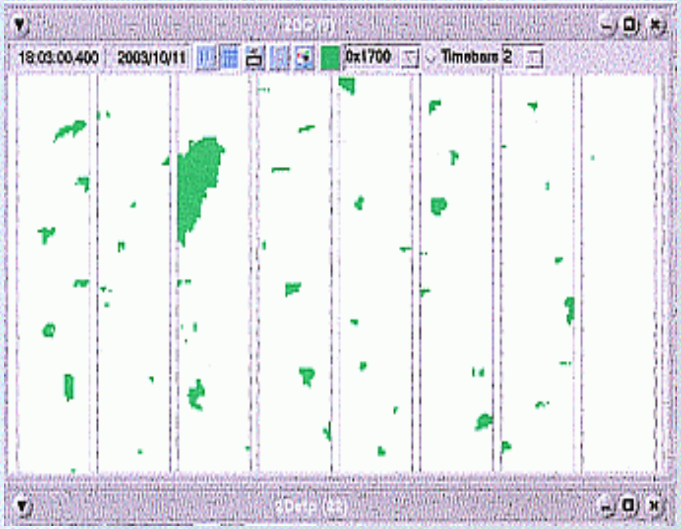
Large drops freezing



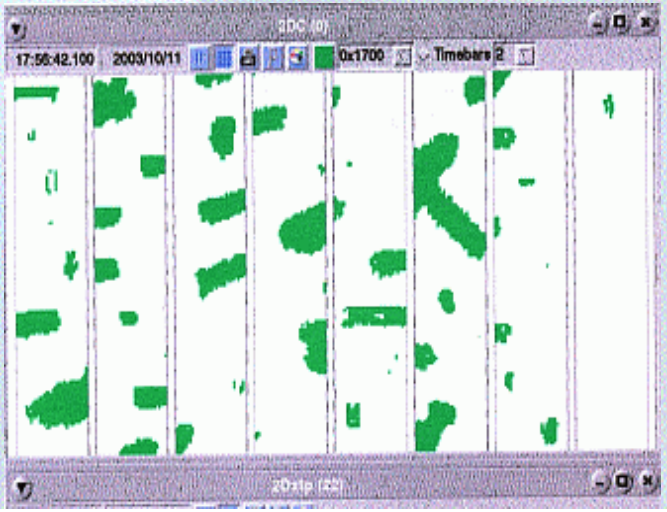
Concentrations: ~5-10L^{-1}
Similar to concentrations of observed large drops

POTENTIAL INVIGORATION OF CLOUD GROWTH DUE TO LATENT HEAT OF FREEZING

Secondary Ice Formation

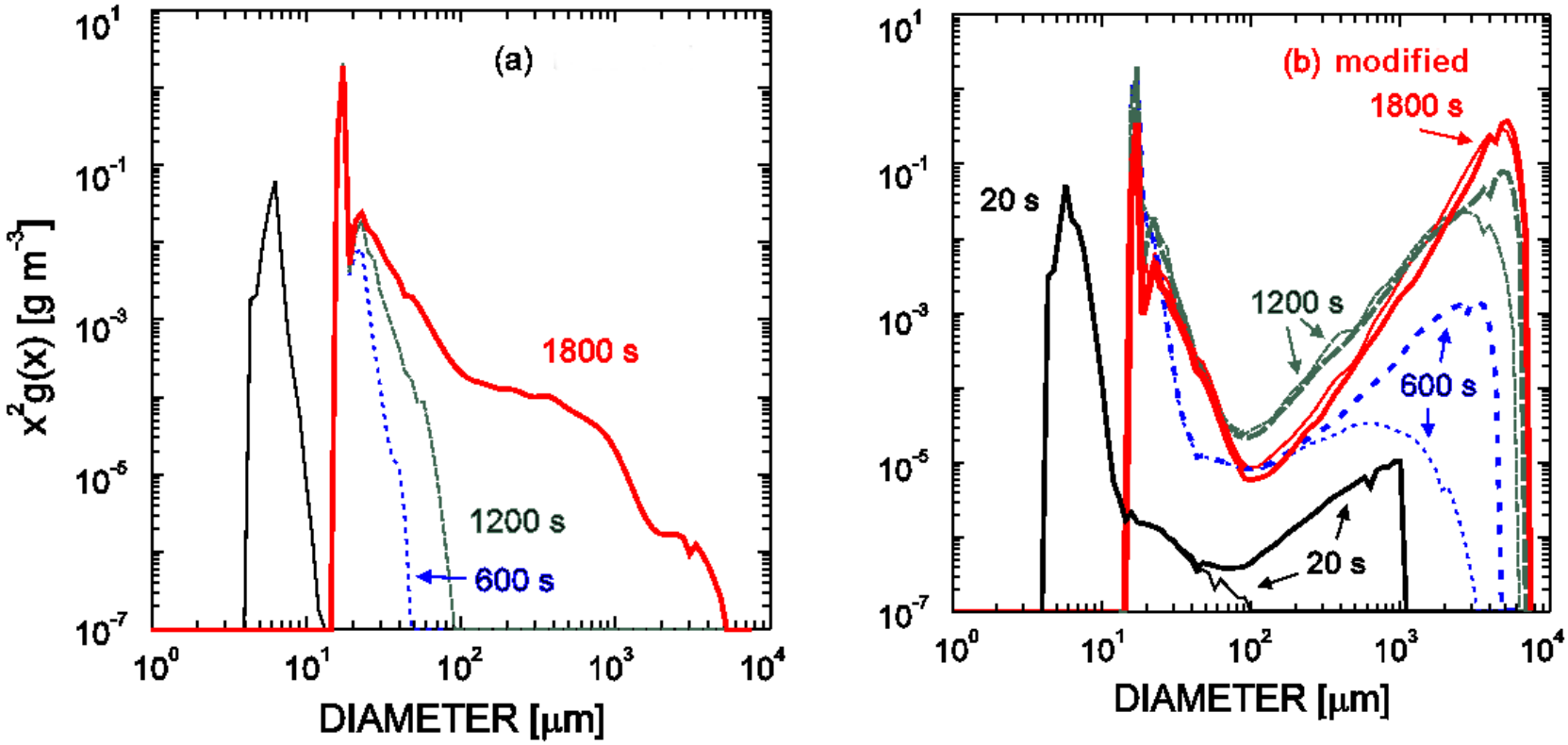


Concentrations between 200 to 400L^{-1}



Comparison of “special” natural and “seeded” cases:

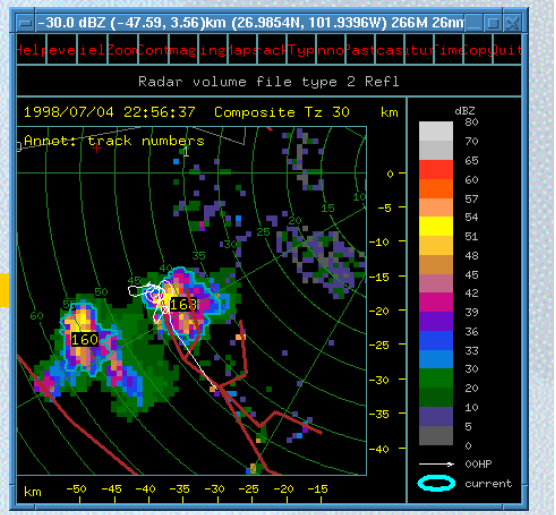
Condensate after 30 min: 0.02 % in raindrops vs 82% or 85% in raindrops



Significant acceleration of the precipitation process results.

Cooper et al., 1997

Radar estimate of rainfall within the TITAN framework



The storm

The TITAN experimental unit

30

45

55

TITAN identifies and tracks individual storms based on a specified reflectivity threshold

Objective radar estimate of rainfall

Evaluation approaches

- Physical observations
  - Numerical models, observations, theory
- Statistical evaluations
- Radar tracking
- Precipitation gauge stations
- Indirect evaluations
  - Hail: crop damage
  - Rain: River flows, dam levels, etc

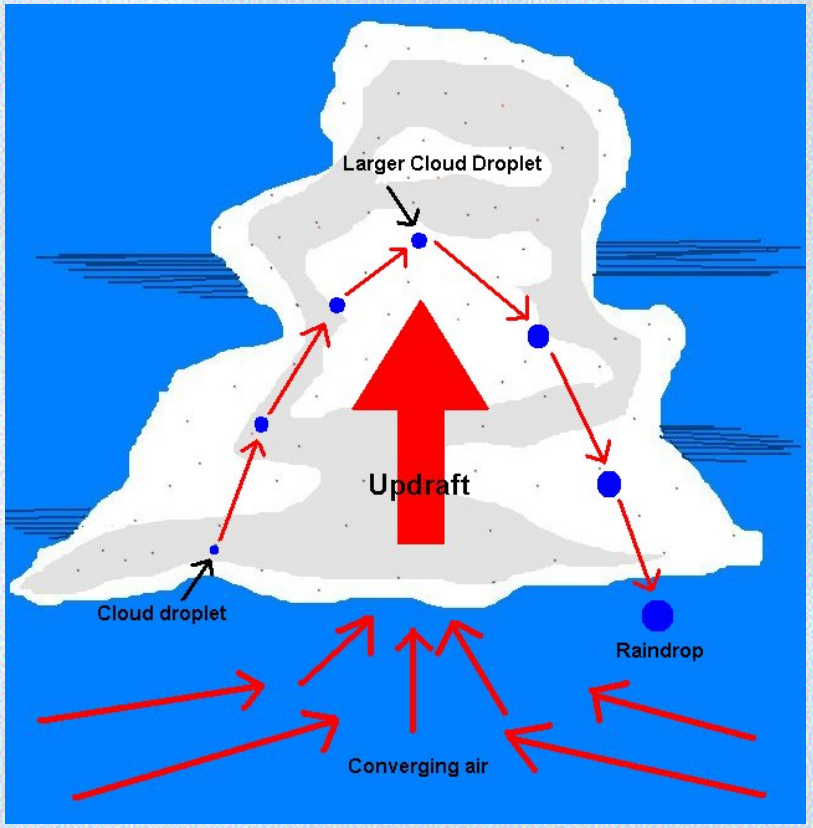
Evaluation Issues

- Inadvertent weather modification
- Geographical meteorological differences
- Natural variability
- Inadequate understanding of physical processes
- Controversy: Unsubstantiated claims
- Independent assessment and evaluation
- Old technology

Operation and Execution South African program (1990's)

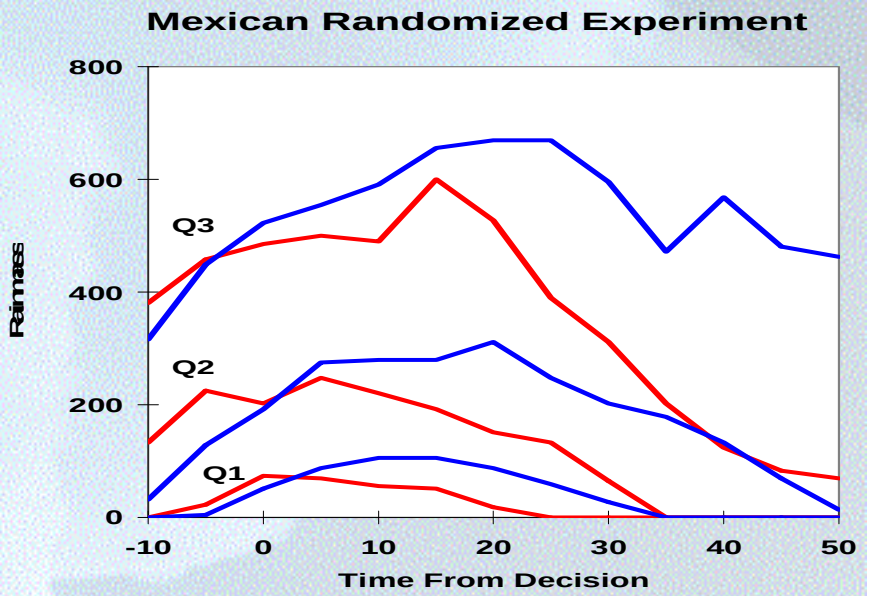
NCAR

- Initiated a randomized experiment using hygroscopic flares
- Some aircraft measurements
- New evaluation methods
  - Used the "storm" as the experimental unit
    - Radar estimated rainfall
  - Many more experimental cases
  - Objective storm-tracking software (TITAN)
  - Allowed for study of time-resolved response to seeding

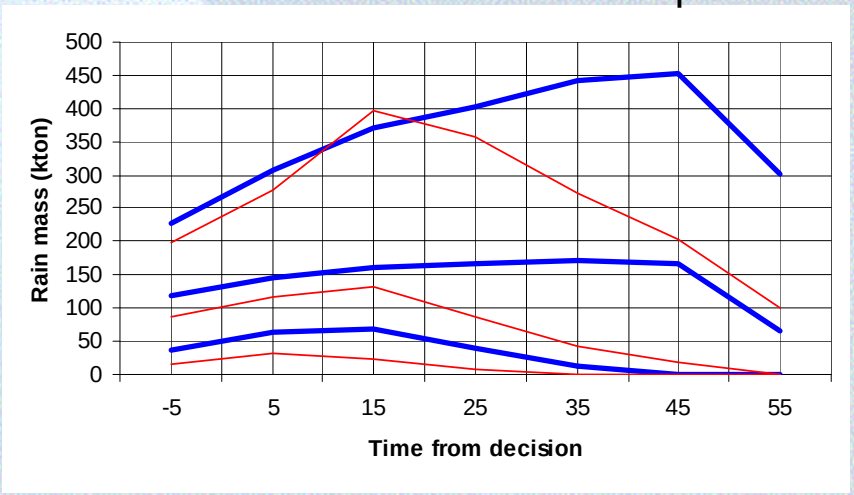


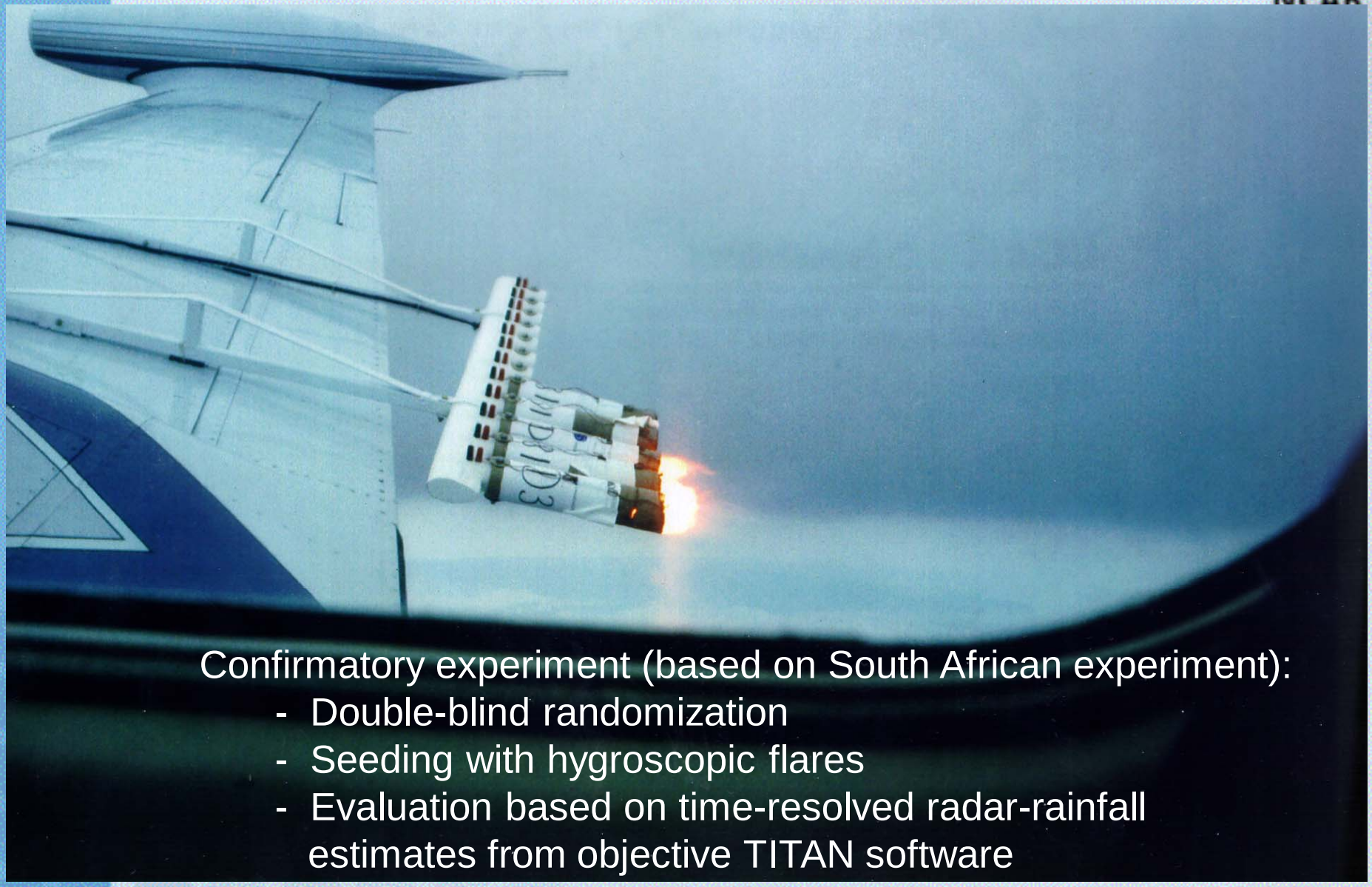
Results and Questions

- To what **extent** would weather modification operations be **dependent** on these background concentrations? (e.g. South African and Mexico experiments)



South African Randomized Experiment





Confirmatory experiment (based on South African experiment):

- Double-blind randomization
- Seeding with hygroscopic flares
- Evaluation based on time-resolved radar-rainfall estimates from objective TITAN software

Response Variables

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TIME-SERIES VARIABLES

Radar-estimated precipitation flux ($m^3 s^{-1}$), using the Marshall-Palmer Z-R relationship.
Total storm mass (in kilotons).
Storm mass above 6 km MSL (in kilotons).
Storm area (km^2).
(Height of maximum reflectivity) - (Z-weighted vertical centroid).

STORM (time-integrated) VARIABLES

- Total case precipitation in kilotons from decision time until 60 minutes after decision time.
- Area-time-integral (ATI) in km^2h from decision time until 60 minutes after decision time. (ATI is defined as the integral of storm area over time, computed using discreet volume-scantime intervals.)
- Duration of the experimental unit from decision time to 60 min after decision time.

(a) 7 min. before seeding

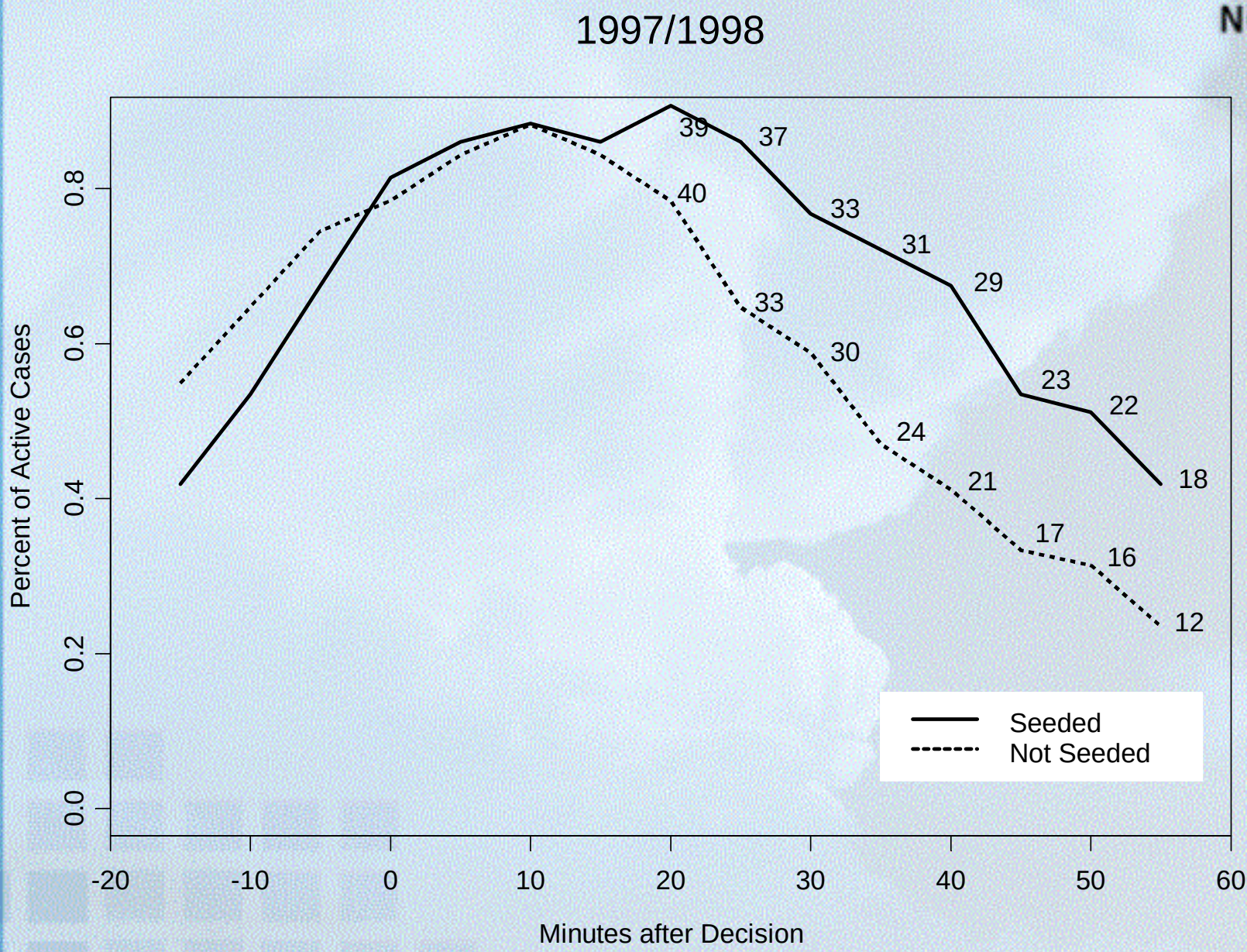
(b) 19 min. after seeding

(c) 44 min. after seeding

(d) 50 min. after seeding

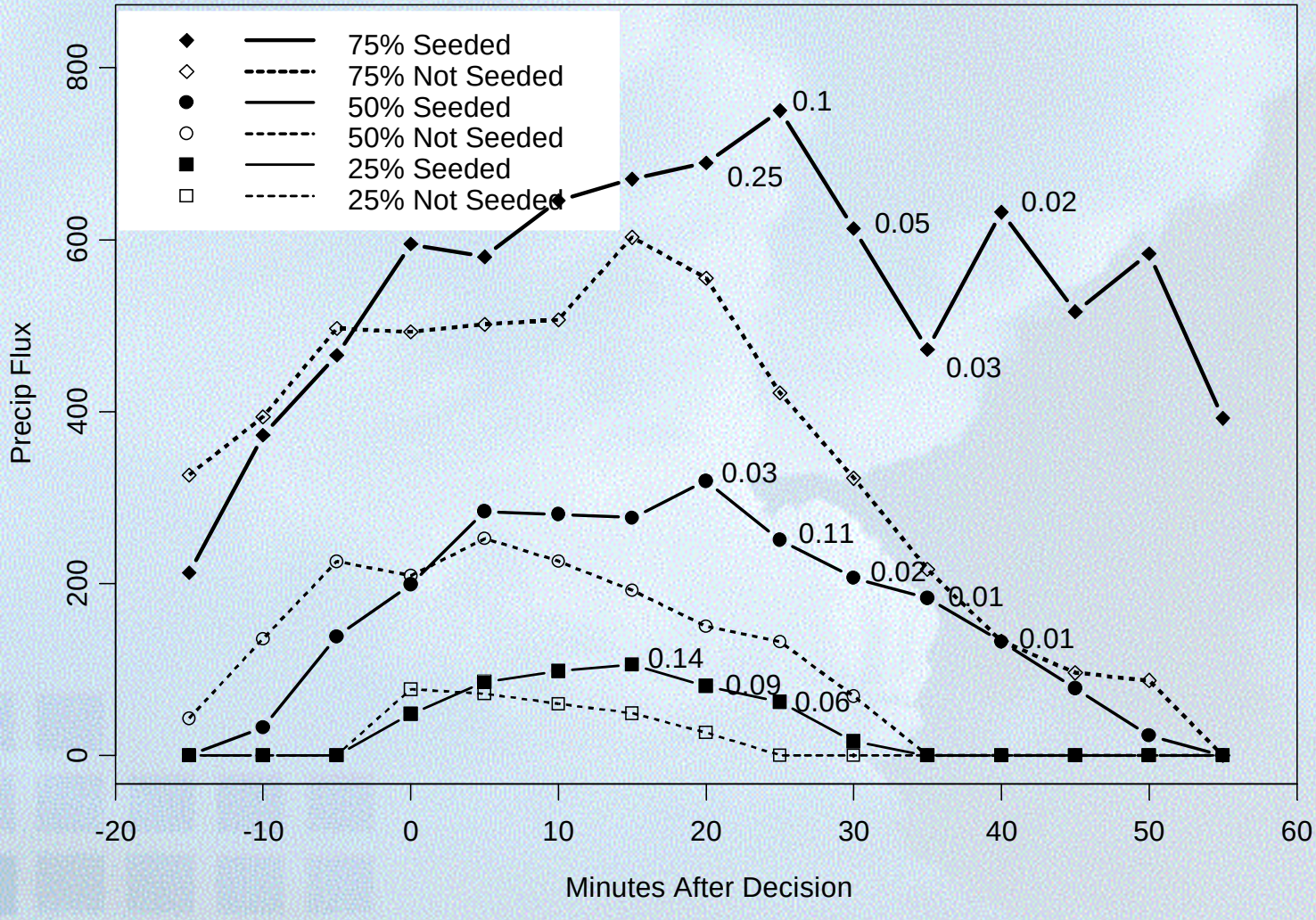
Evolution of the seeded cloud on July 23, 1996

STORM DURATION



Precipitation Flux (m^3/s)

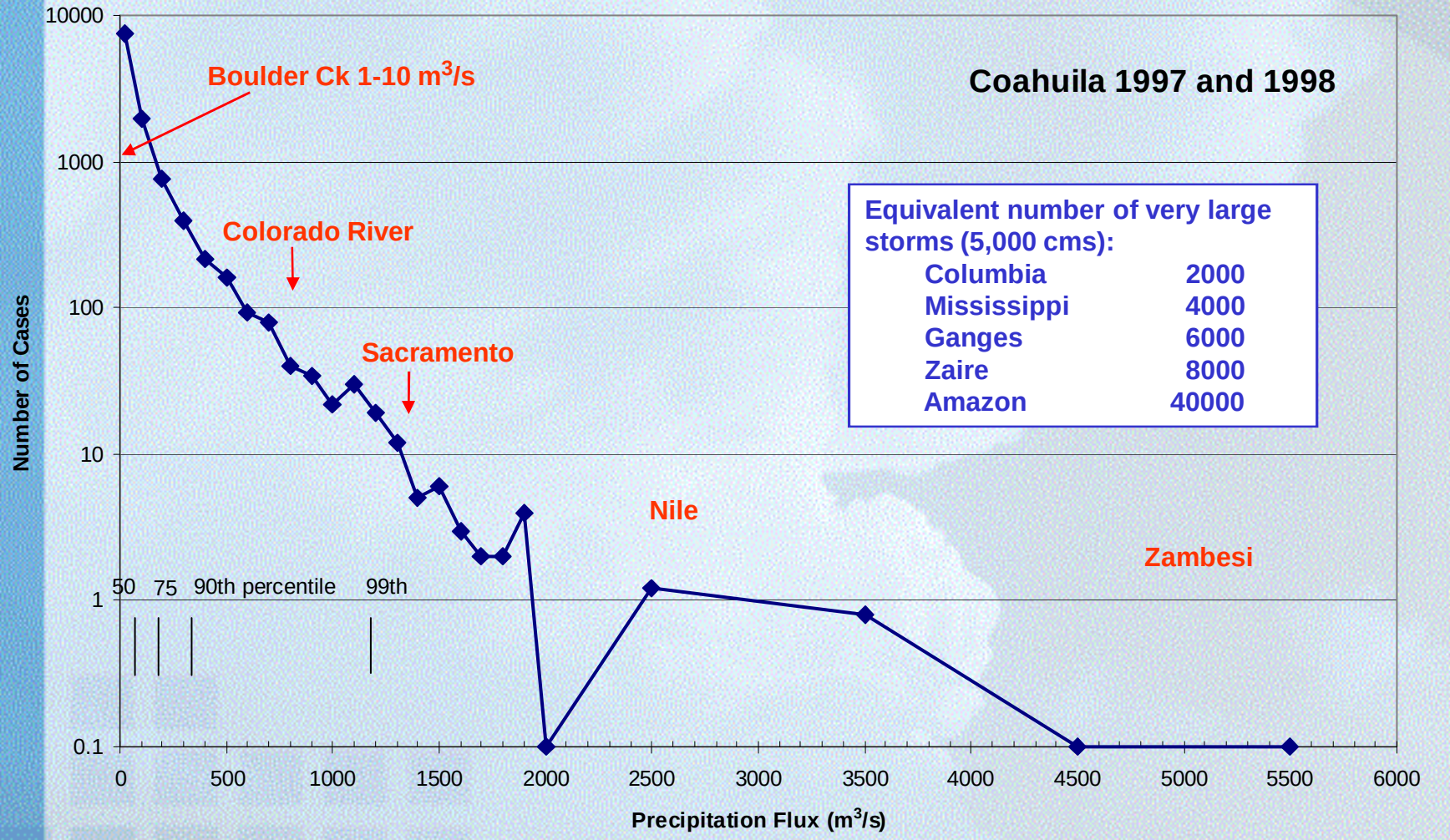
1997/1998



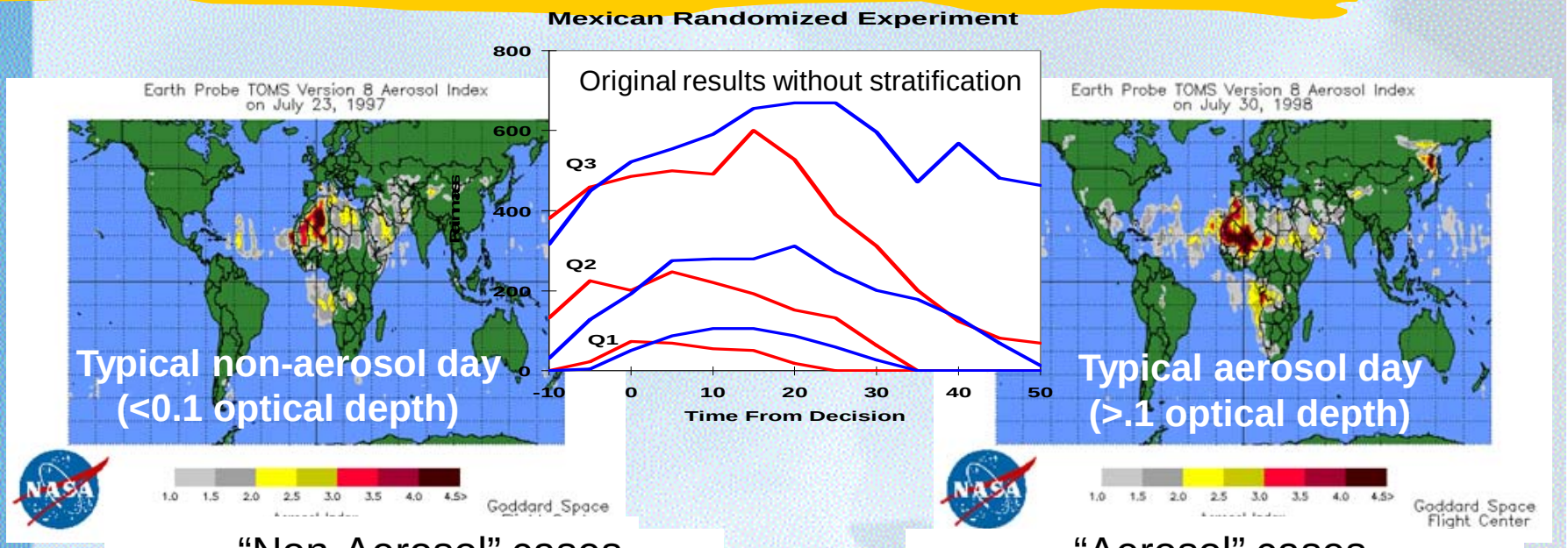
MEXICO EXPERIMENT EXAMPLE

NCAR

All Storms within Radar Coverage
Number of Cases in Each Rain-Out Size Category

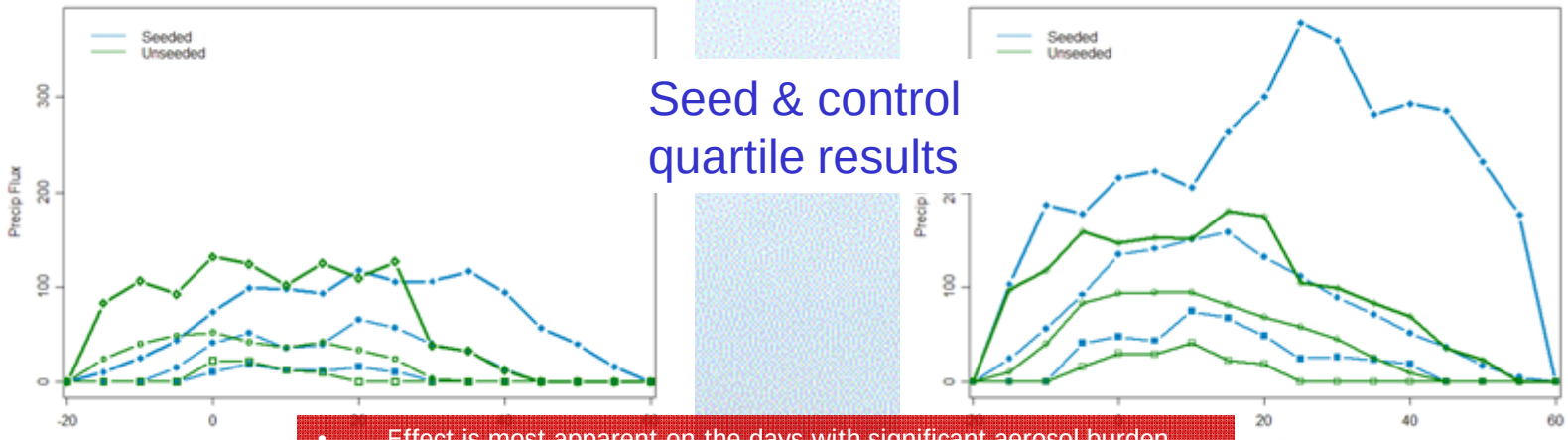


Classification of Mexico data using aerosol burden (satellite aerosol optical depth)



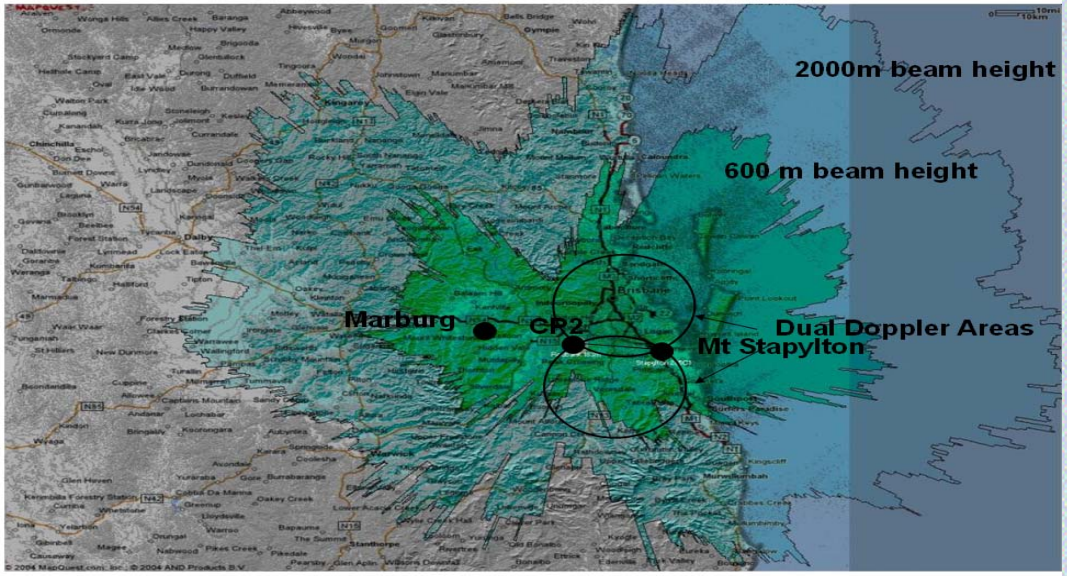
"Non-Aerosol" cases

"Aerosol" cases



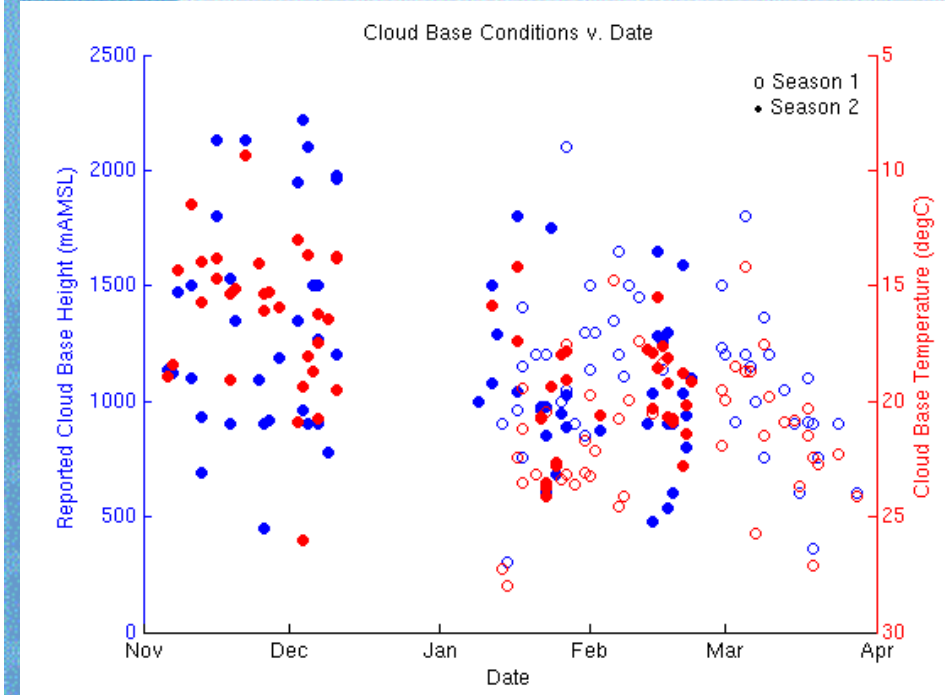
- Effect is most apparent on the days with significant aerosol burden
  - On cleaner, "non-aerosol" days, little effect

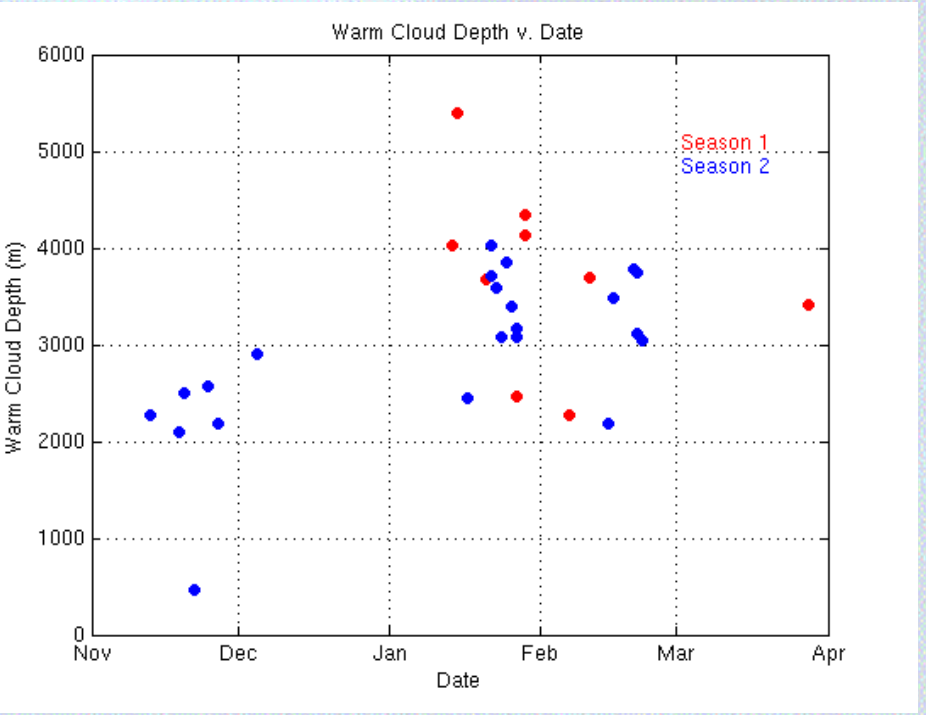
EXAMPLE: USE OF NEW TOOLS CLOUD SEEDING RESEARCH PROGRAM (CSRP) Queensland, AUSTRALIA



Cloud base heights

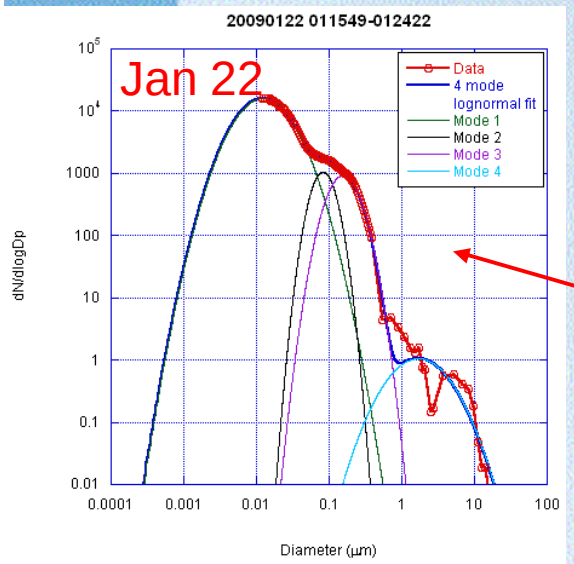
- Cloud base heights generally got lower as the wet season progressed, leading to deeper warm cloud depths in Feb compared to Nov
  - This may affect the mixed phase microphysics

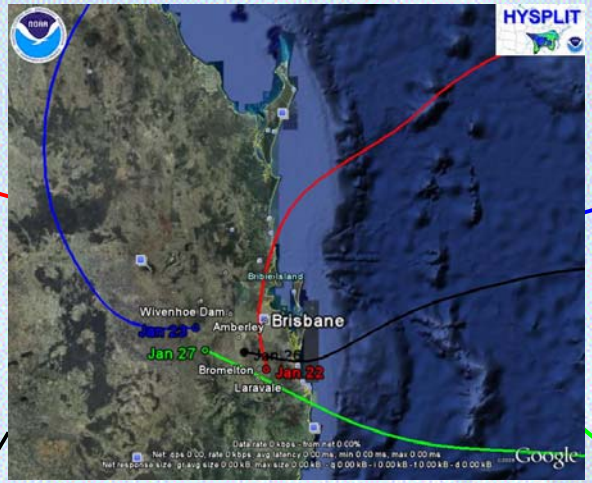


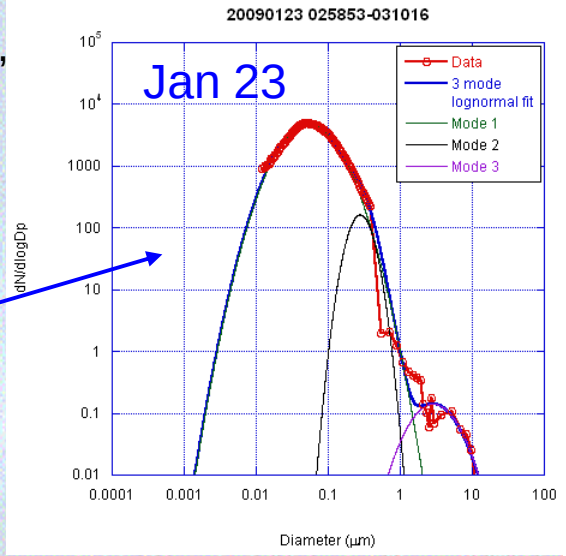


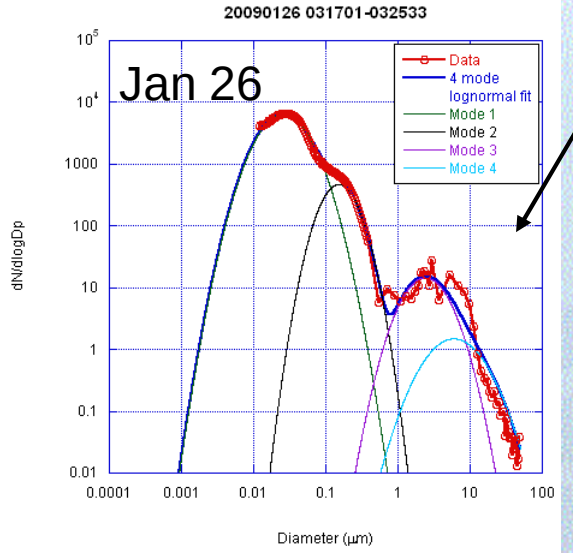
Aerosol/particles

Air mass source influences aerosol sizes, which affects initial cloud droplet sizes

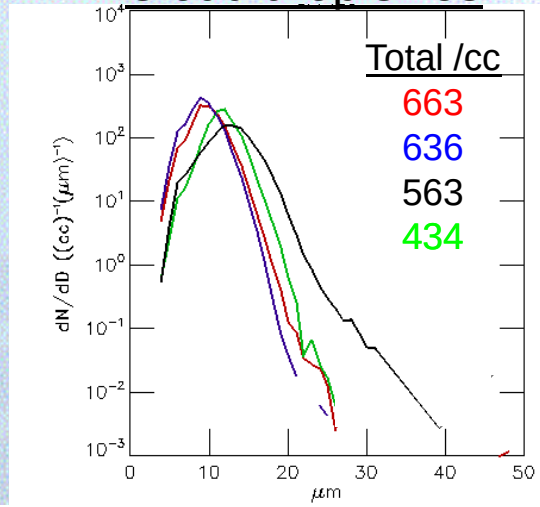


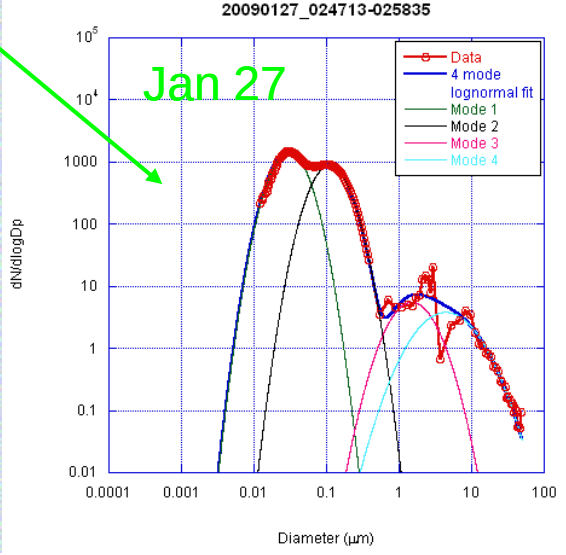






Cloud drop sizes



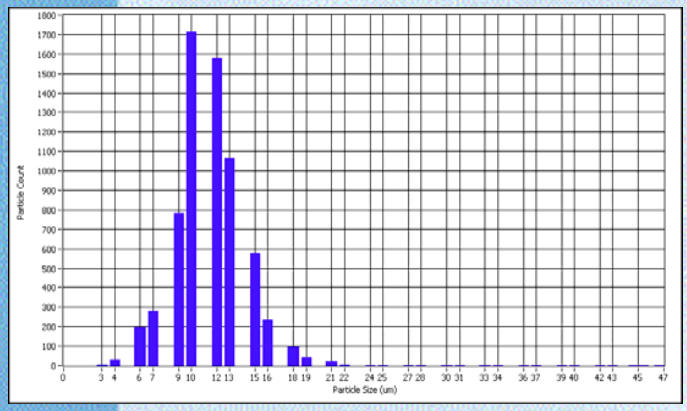


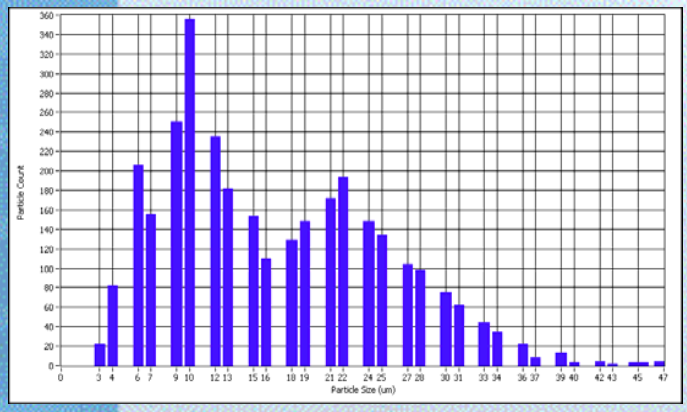
Rain formation: Warm rain process

(Typical in Southeast Queensland clouds)

NCAR

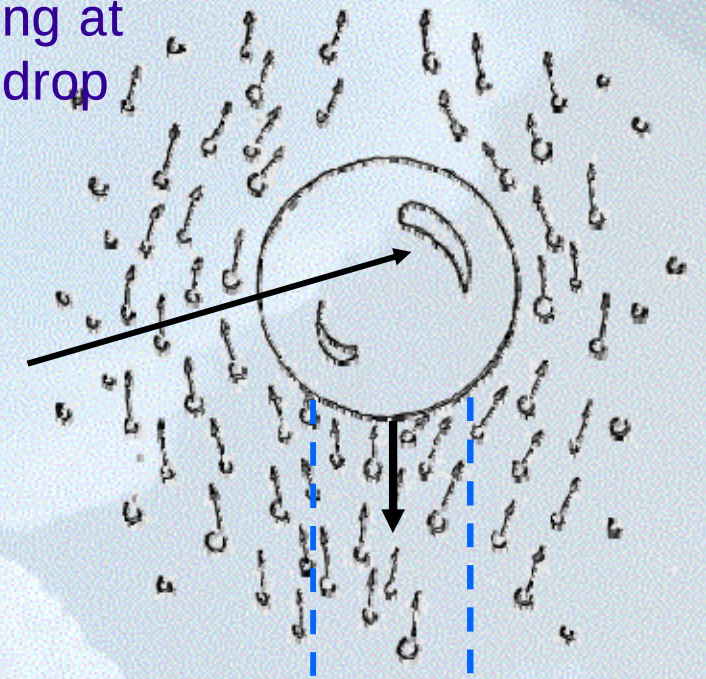
- Collision and coalescence of droplets falling at different terminal velocities leads to raindrop formation



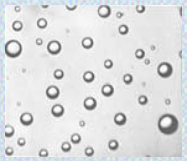


Drop size distributions in Southeast Queensland

Raindrops are millimeters in size



Cloud droplets are 100 times smaller in diameter

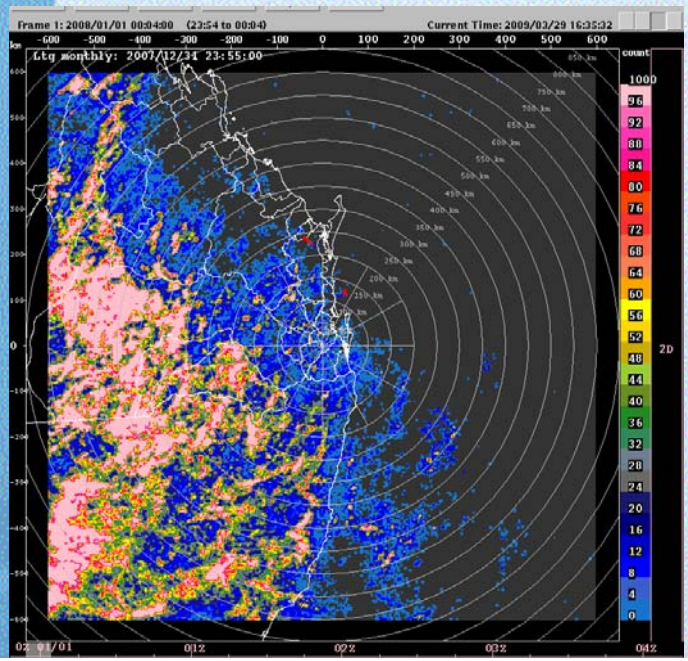


Rain formation: Ice process

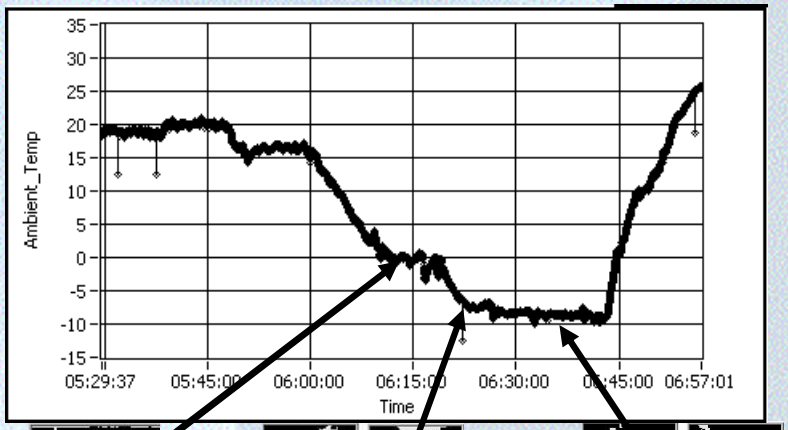
Ice processes are initiated by freezing of large drizzle/rain drops and subsequent initiation of natural seeding (ice splintering) process rapidly depleting cloud liquid water content

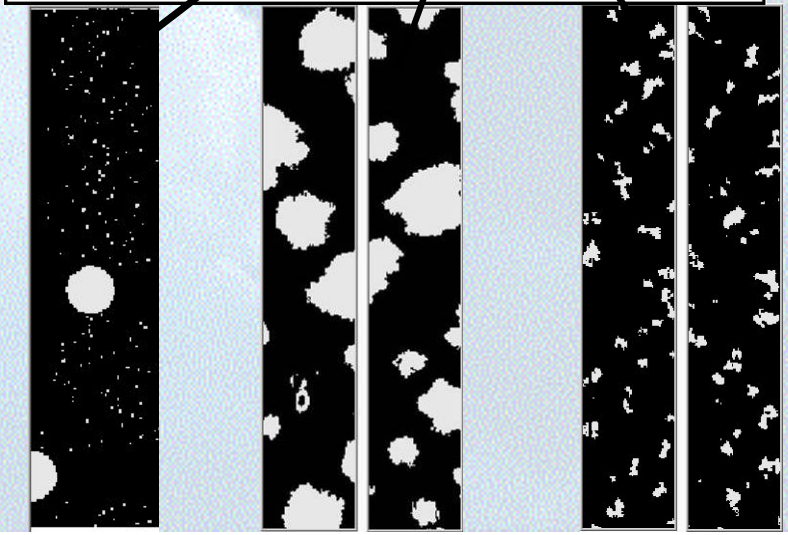
- Large drops freezing at ~-5°C
- Initiation of ice splintering process
- Rapid depletion of cloud water inhibiting lightning in these cases

Map of lightning



Temperature versus time
27 January 2009



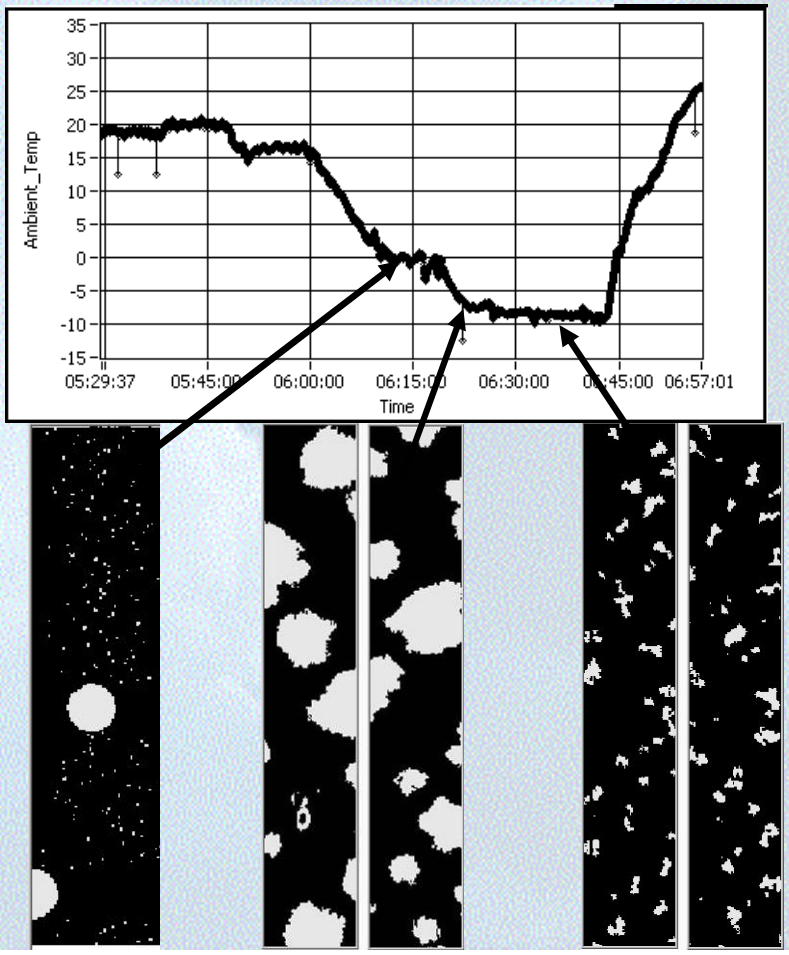


Precipitation Processes:

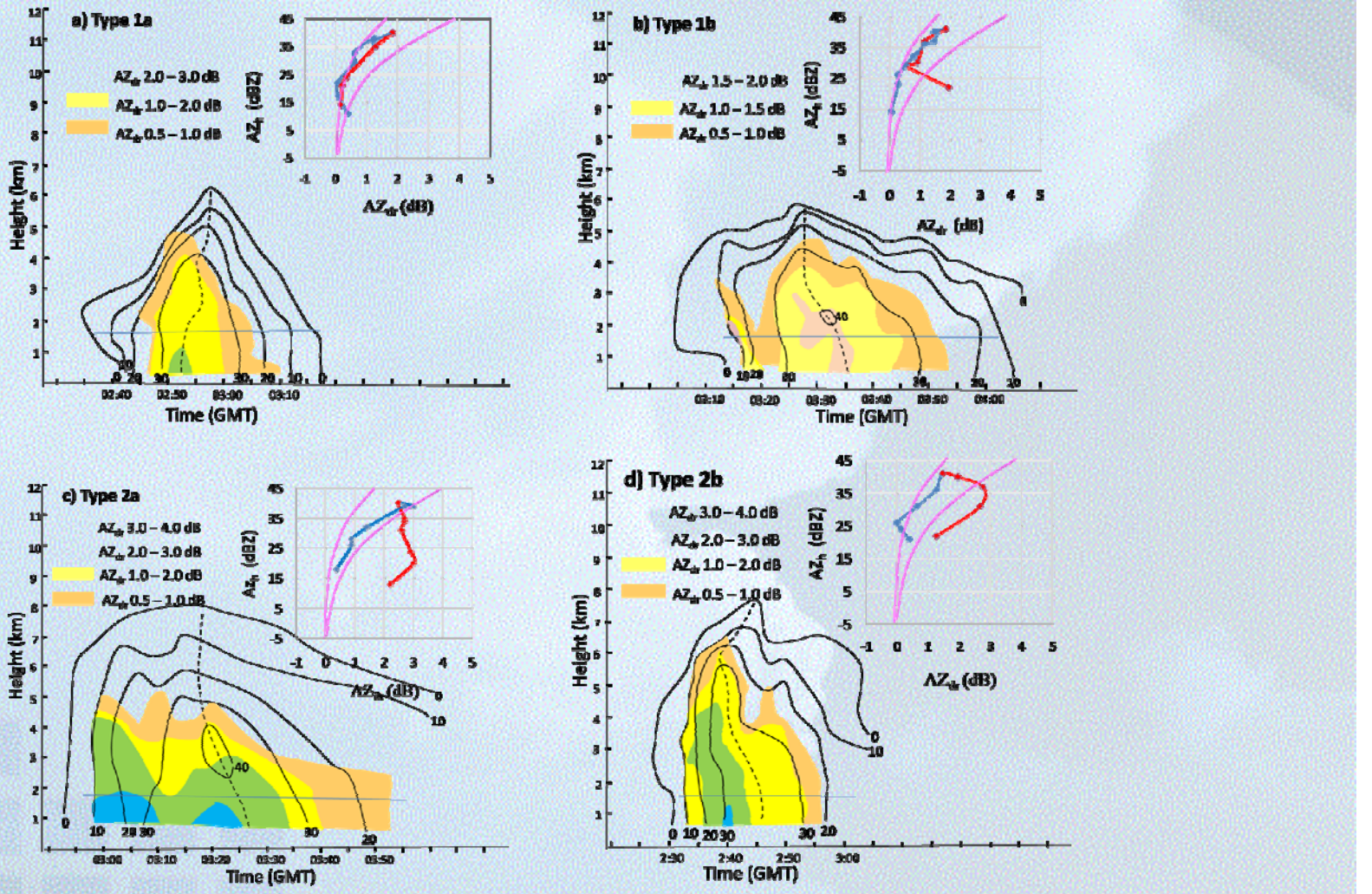
Mixed-phase/ice processes initiated by freezing of large drizzle/rain drops and subsequent initiation of natural seeding (ice splintering) process rapidly depleting cloud liquid water content

- Large drop freezing at ~-5ºC
- Initiation of ice splintering process
- Rapid conversion of LWC to ice
- Rapid depletion of LWC inhibiting lightning in these cases

Temperature versus time
27 January 2009

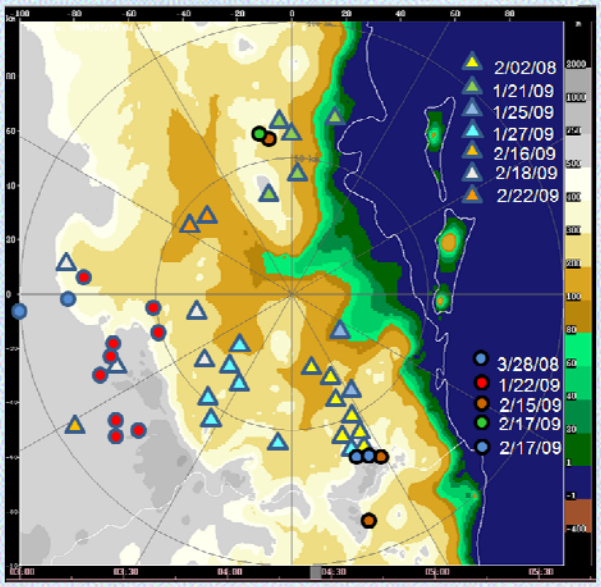


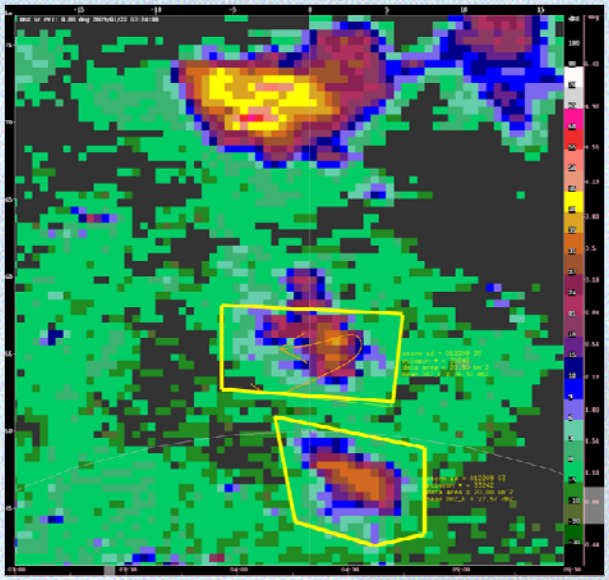
Dual Polarization Radar



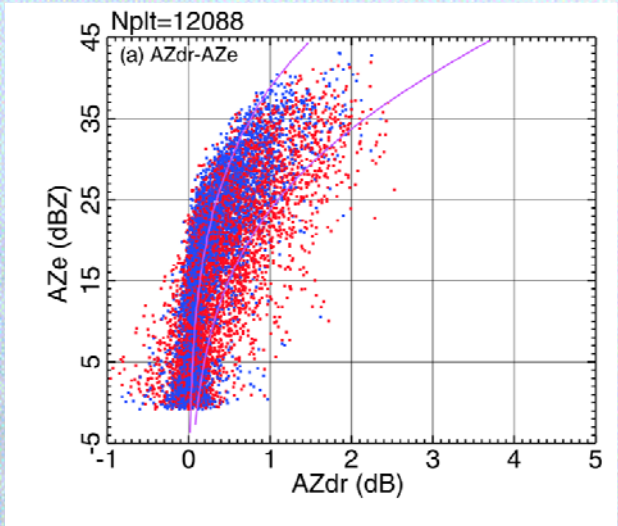
Time height diagrams of radar reflectivity and differential radar reflectivity

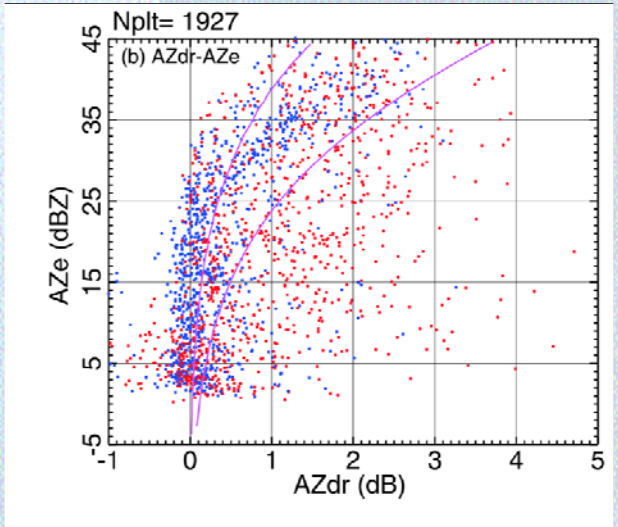
Dual Polarization Radar measurements



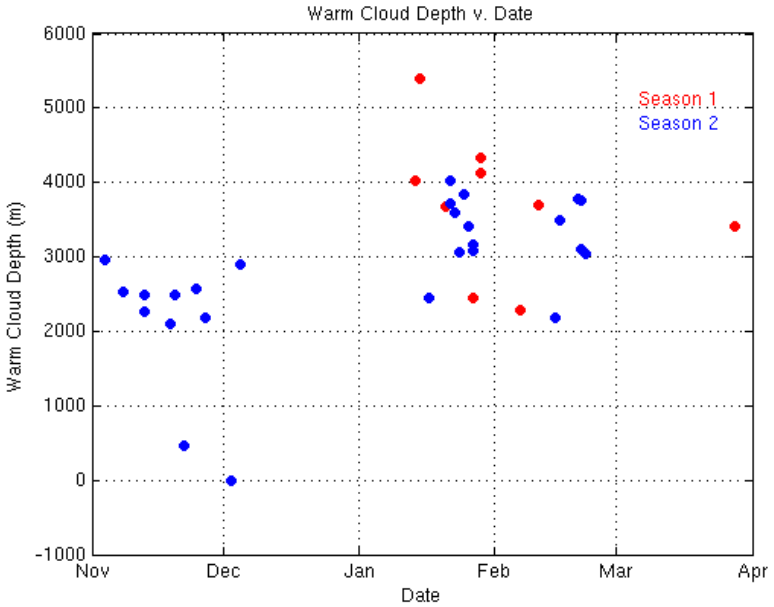


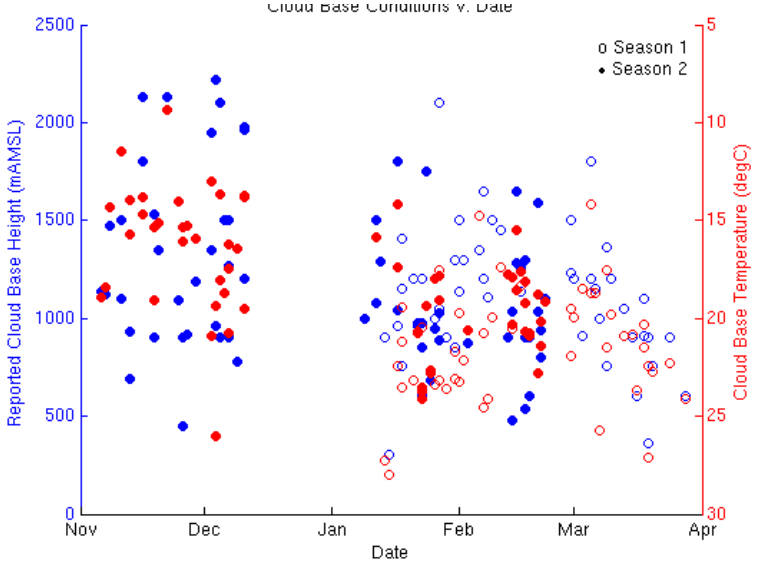
Rain drop size distributions

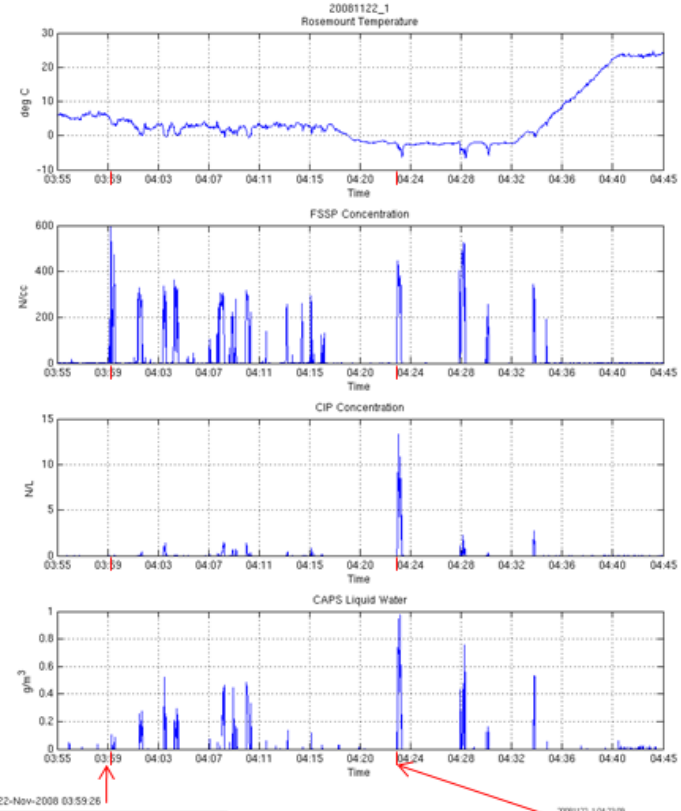


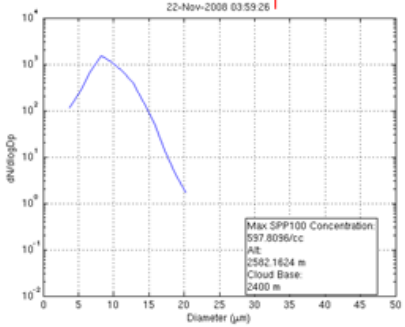


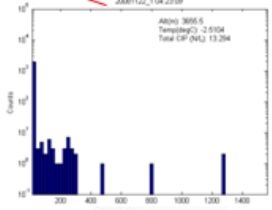
Cloud base heights and warm cloud depths during Queensland project







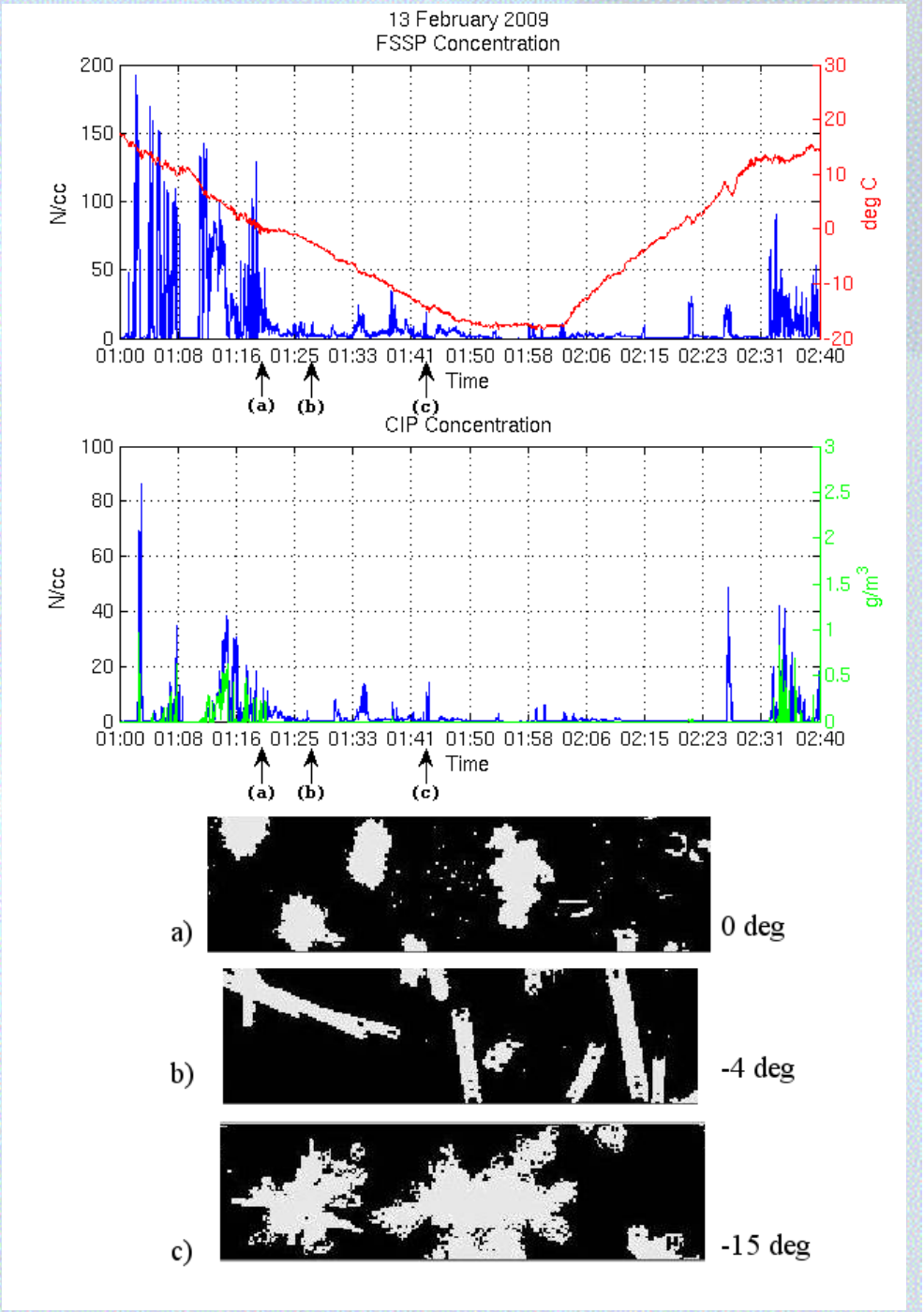




22 November 2008
High cloud base
No large drops at 0C
First ice below -12C

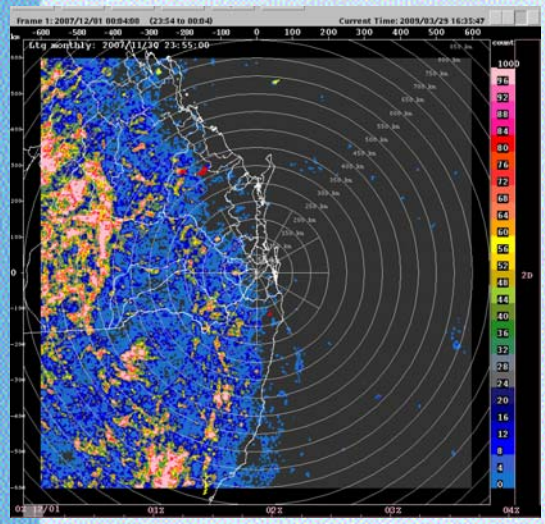
13 Feb 2009

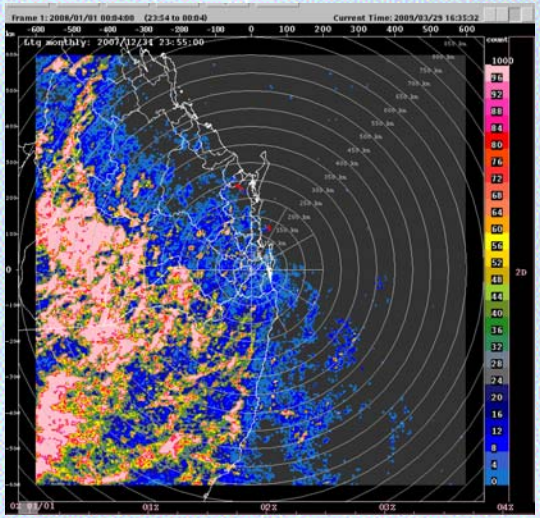
- Deep stratiform system
- Little supercooled liquid water
- Lots of ice
- Glaciogenic or hygroscopic seeding not recommended

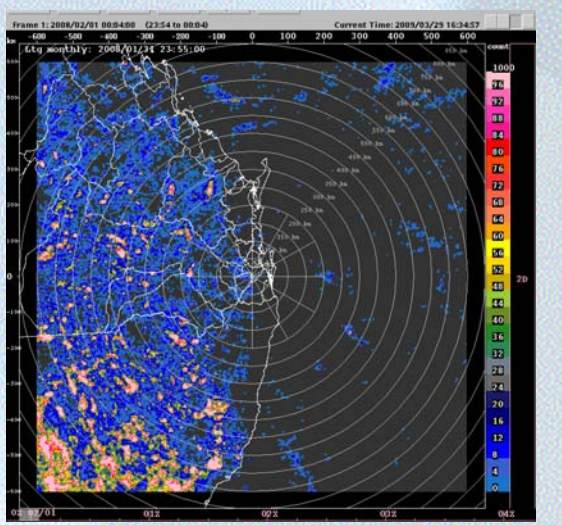


Monthly lightning maps

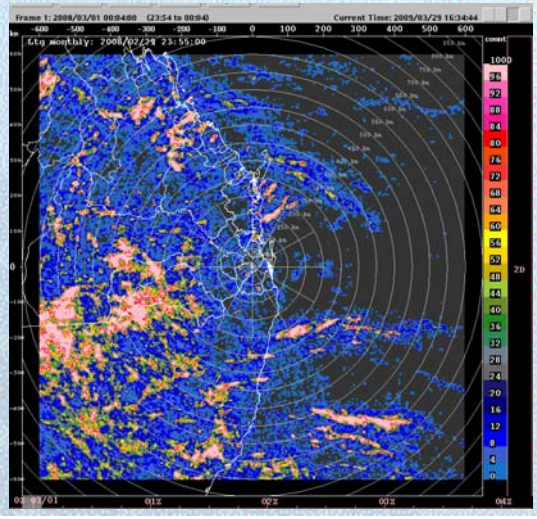
November 2007 to March 2008

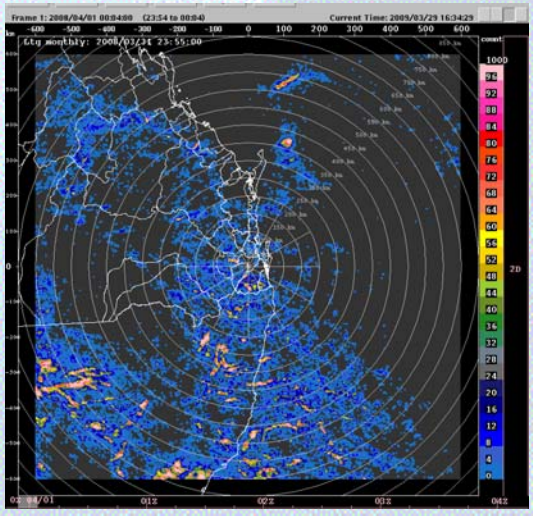




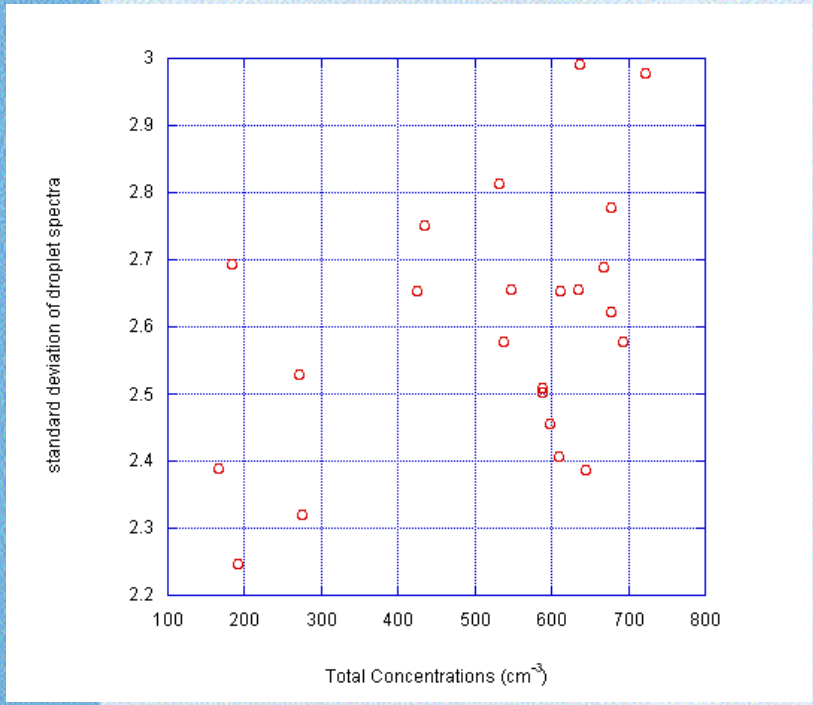


Lower frequency of lightning in coastal regions due to potentially less LWC between -10 and -20^{o}C where naturally most charge buildup occurs

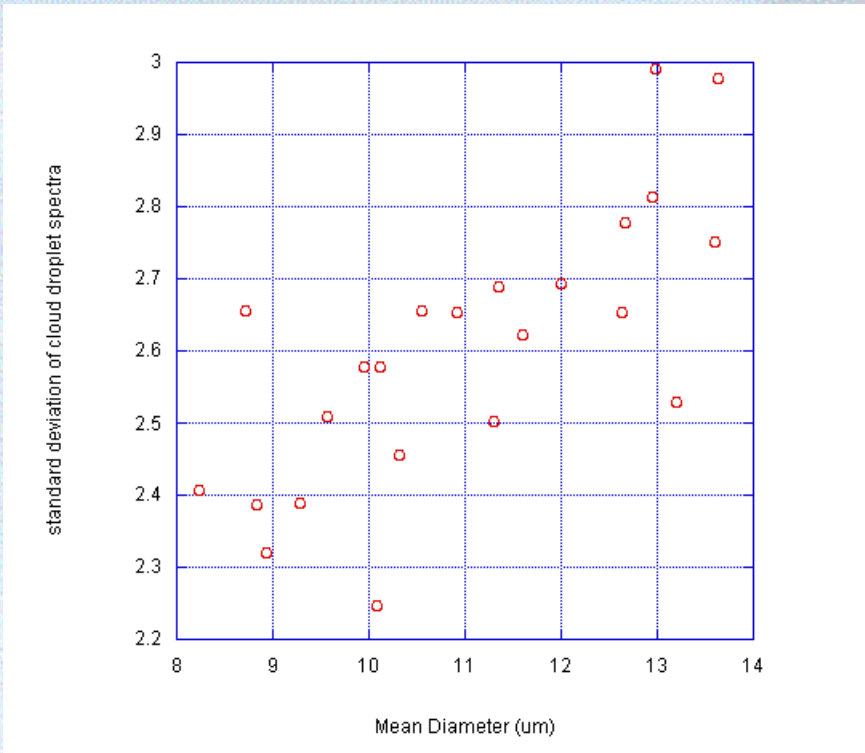




Microphysical relationships



Total peak droplet concentrations (cm^{-3}) as a function of standard deviation of the cloud droplet spectra for the 22 cases when penetrations were conducted in deep convection near cloud base in growing non-precipitating parts of the cloud.

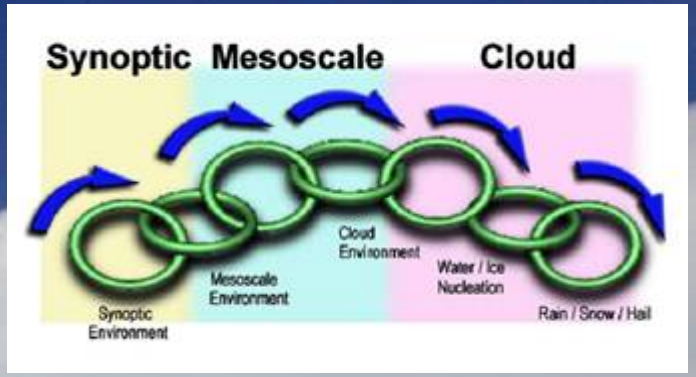


Mean diameter of the cloud base doplet spectra as a function of standard deviation of the cloud droplet spectra for the 22 cases when penetrations were conducted in deep convection near cloud base in growing non-precipitating parts of the cloud.

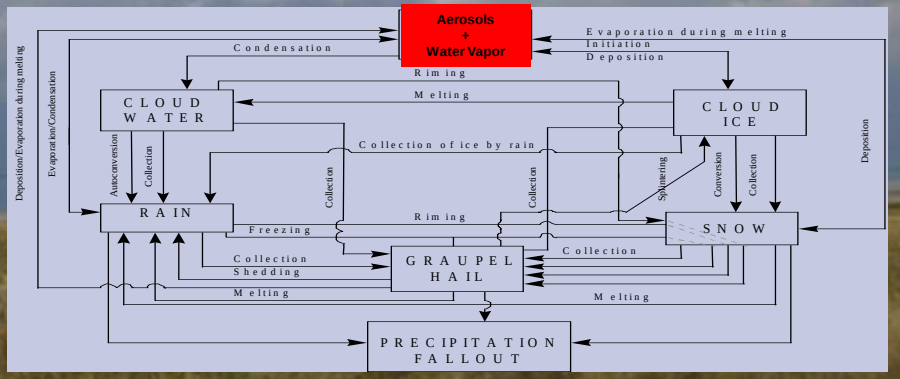
Summary

- Convective clouds produce large amounts of rain
  - Comparable to flow in major rivers
- AgI seeding of cumulus clouds for rain enhancement is a well used technology in many countries
  - However, it is not a well proven technology
- Based on experiments in S. Africa, Mexico, and Thailand, hygroscopic seeding seems promising under specific circumstances
  - Though promising, it is not well understood
- There are many new tools available to establish confidence in seeding technologies

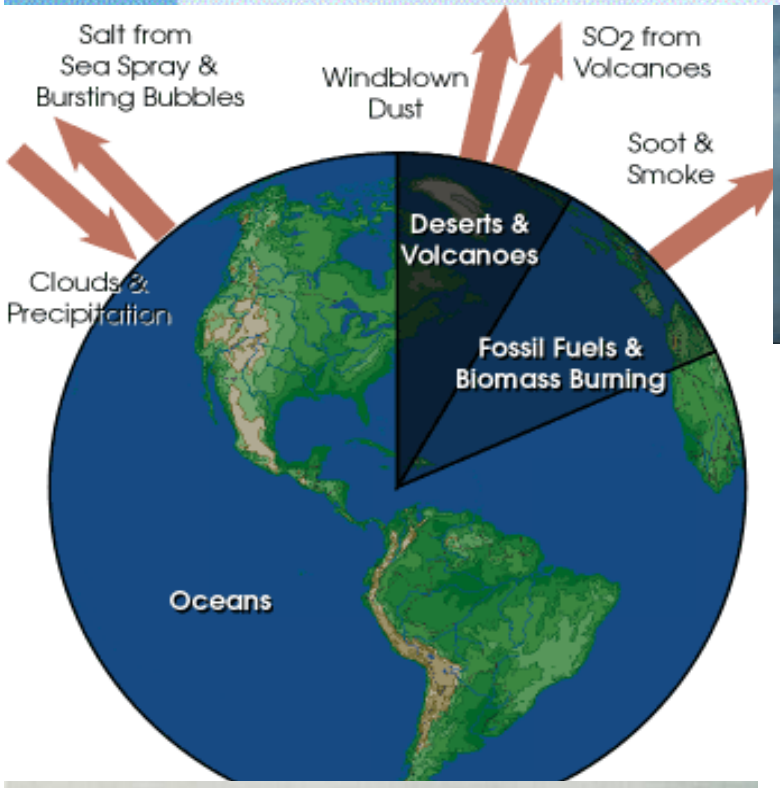
Summary

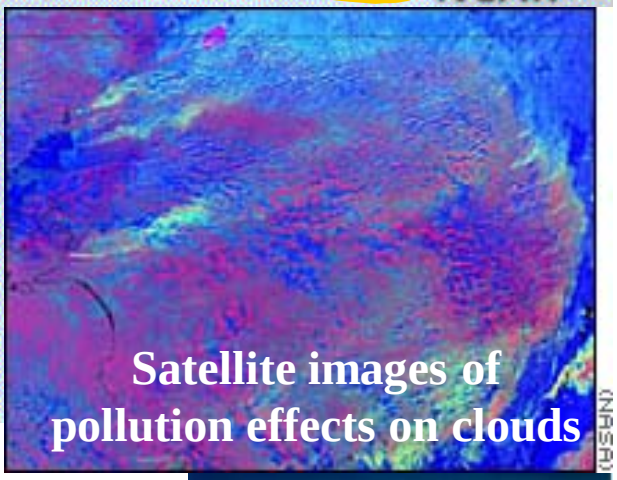


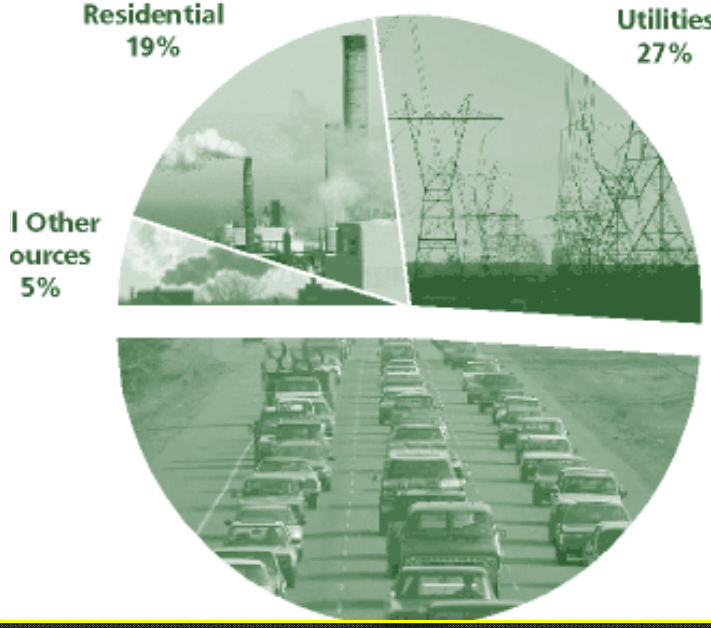
- **Many factors control the amount of rain from convective clouds**
- **Aerosols (both CCN and IN) clearly affect the cloud particle structure**
- **Very likely affect the rain also (but positively or negatively?)**
- **However, the exact relationship has proven difficult to establish**

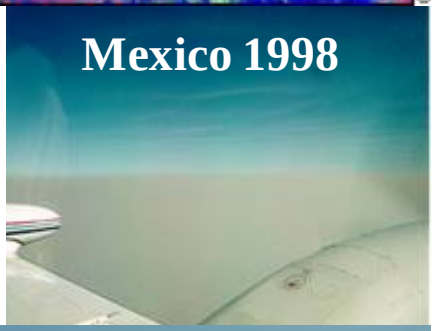


Aerosol change: natural and anthropogenic



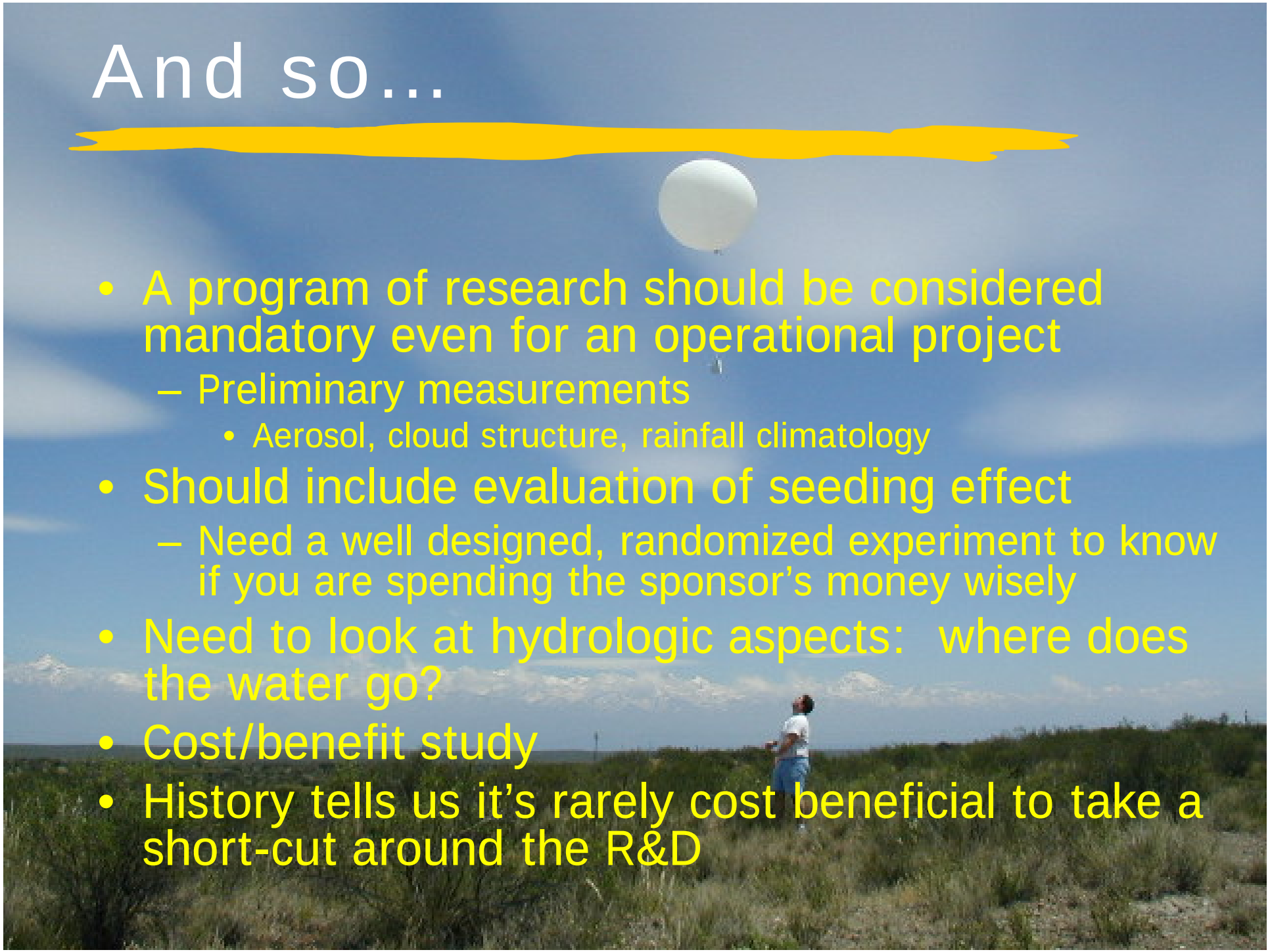






- Can mask seeding effects
- Older experiments may not be relevant today
- Transferring results from one region to another is very problematic

And so…



- A program of research should be considered mandatory even for an operational project
  - Preliminary measurements
    - Aerosol, cloud structure, rainfall climatology
- Should include evaluation of seeding effect
  - Need a well designed, randomized experiment to know if you are spending the sponsor's money wisely
- Need to look at hydrologic aspects: where does the water go?
- Cost/benefit study
- History tells us it's rarely cost beneficial to take a short-cut around the R&D