Current Status of Precipitation Enhancement Research

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Understanding of Cloud Nature and Weather Modification for Water Resources Management in ASEAN
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ISEE

UAE Research Program for Rain Enhancement Science

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   Glaciogenic Seeding

   (Dry ice, Yagisawa Dam; AgI, Ogouchi Dam)

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   Hygroscopic Seeding

   Glaciogenic Seeding

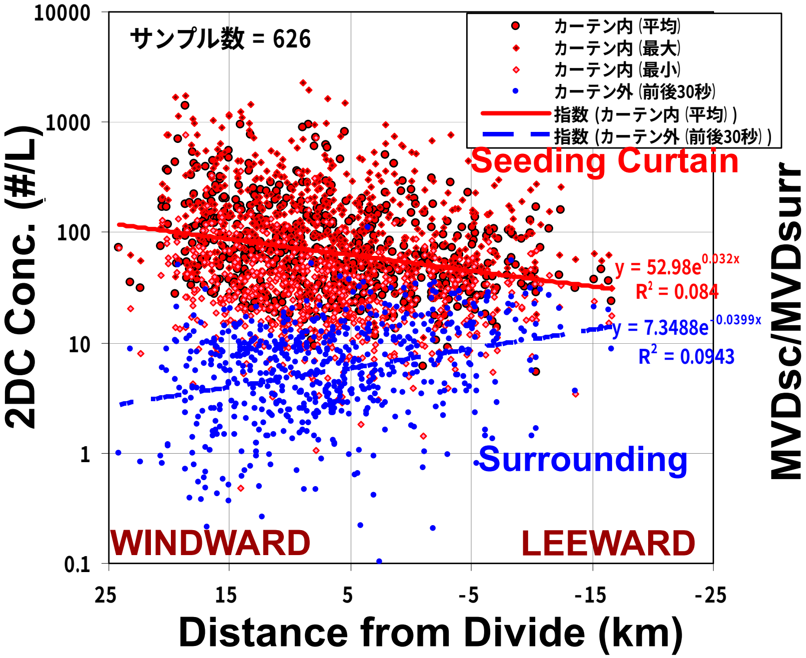
4. Conclusion & Recommendation

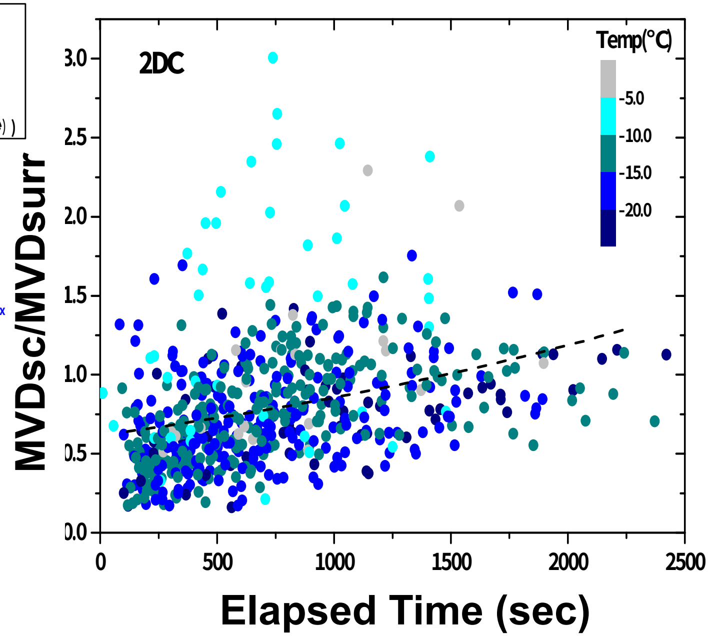
PART ONE

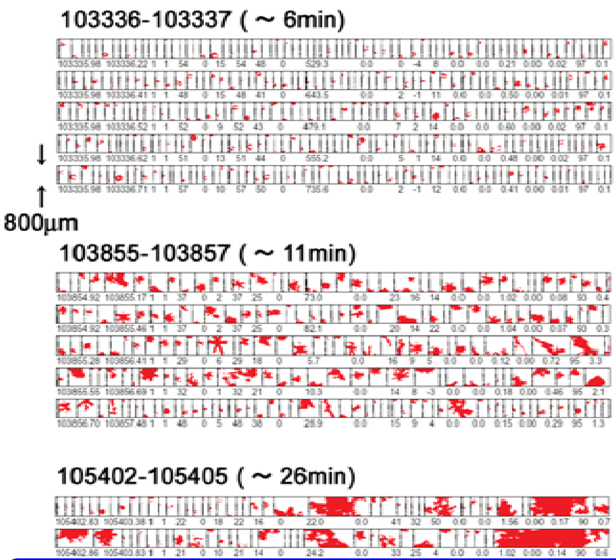
Wintertime Orographic Clouds

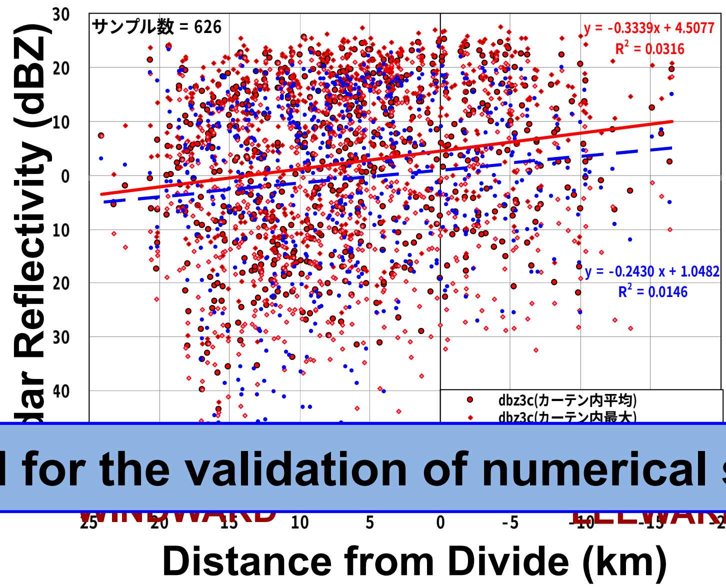
Physical Evaluation Techniques of Seeding Effects (A/C In-situ Measurements)

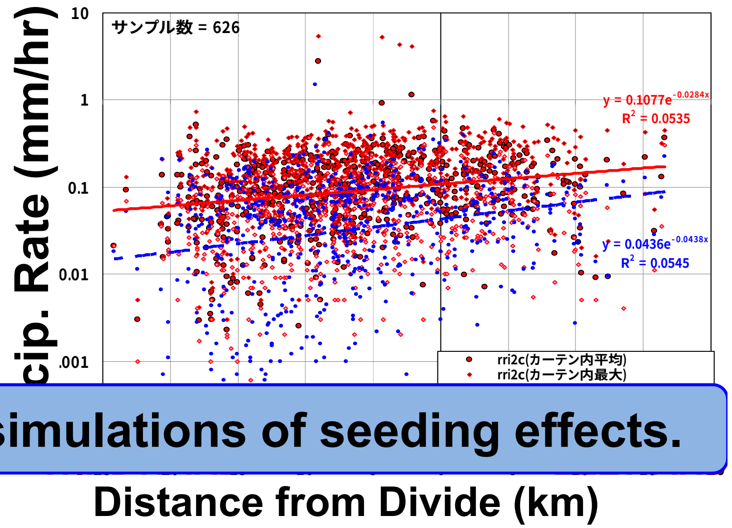
Instrumented aircraft (MU-2)







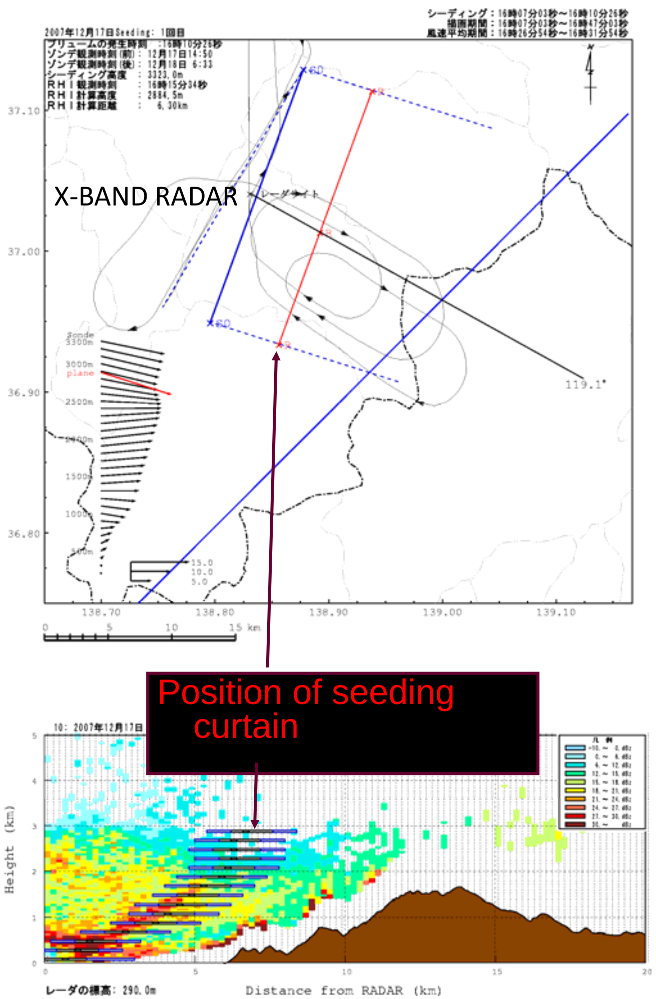




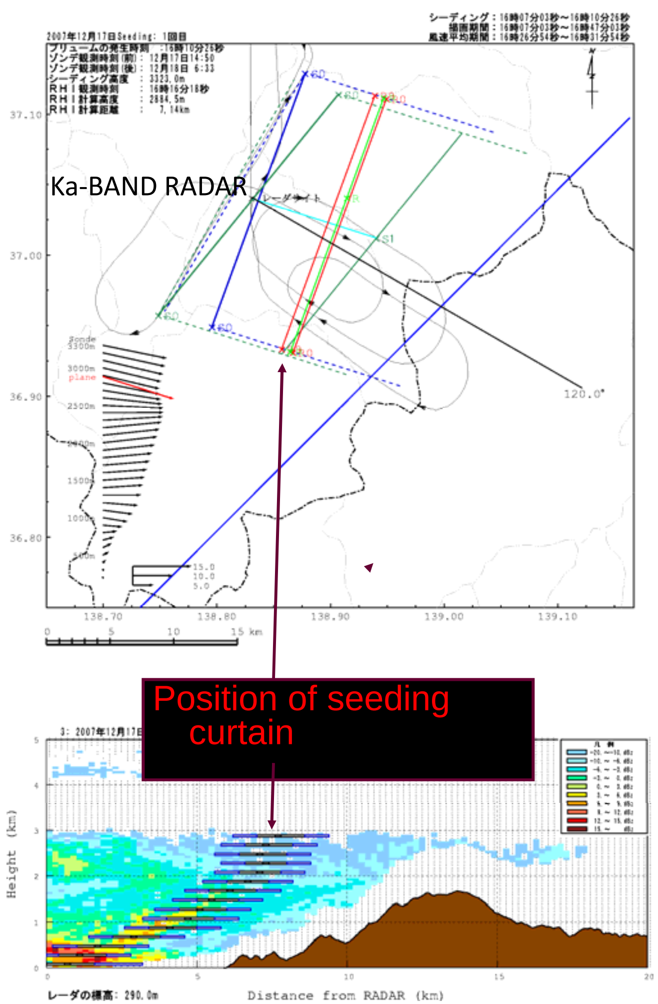
These data have been used for the validation of numerical simulations of seeding effects.

Physical Evaluation Techniques of Seeding Effects (cont.)

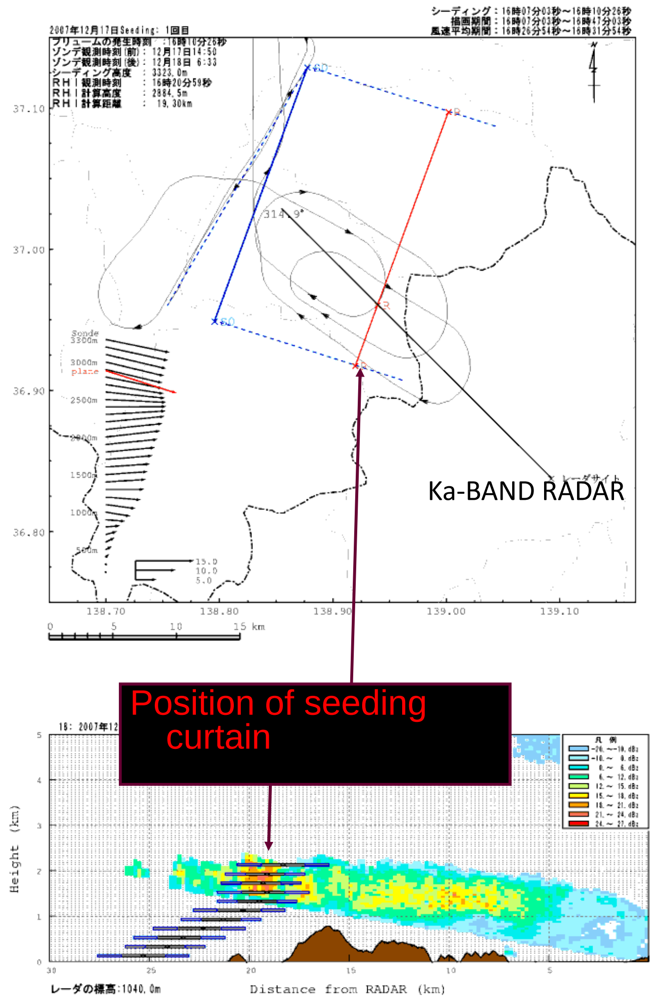
Simultaneous radar observations sometimes, but not so often, showed a significant increase in dBZ in seeding curtains.



WINDWARD (X-BAND)



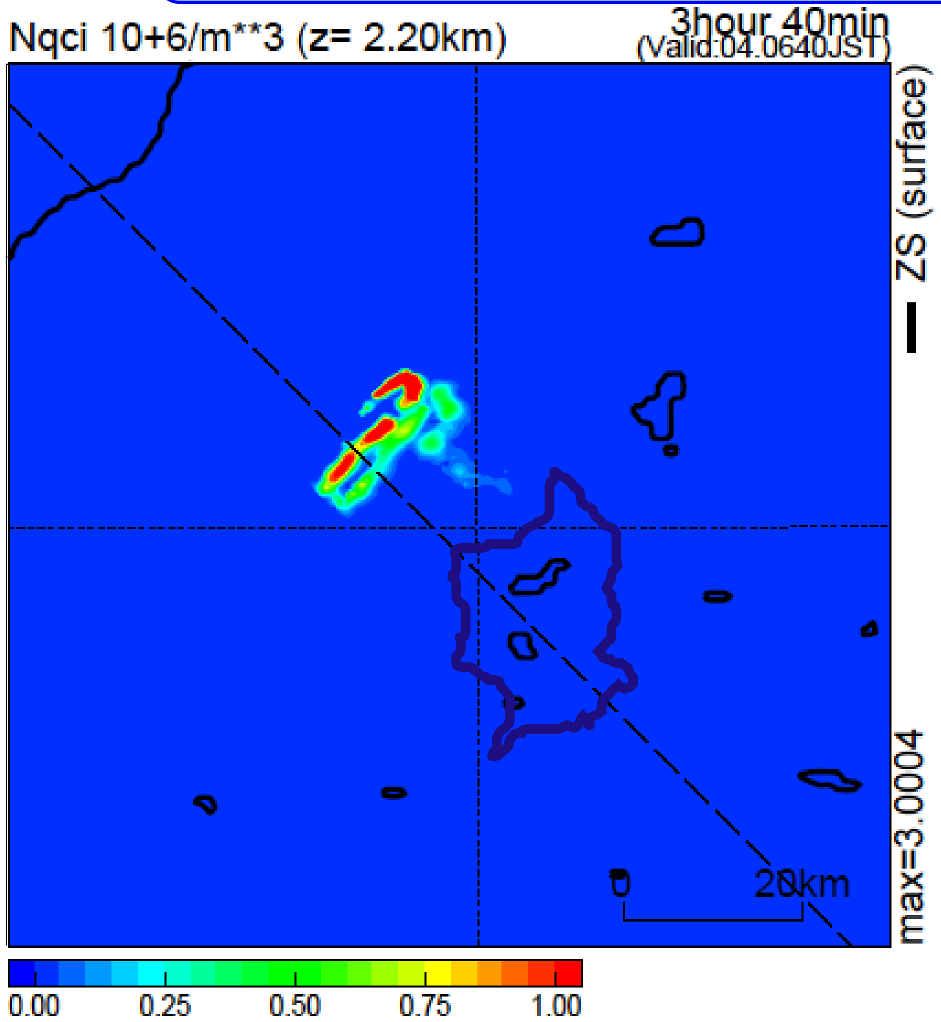
WINDWARD (Ka-BAND)



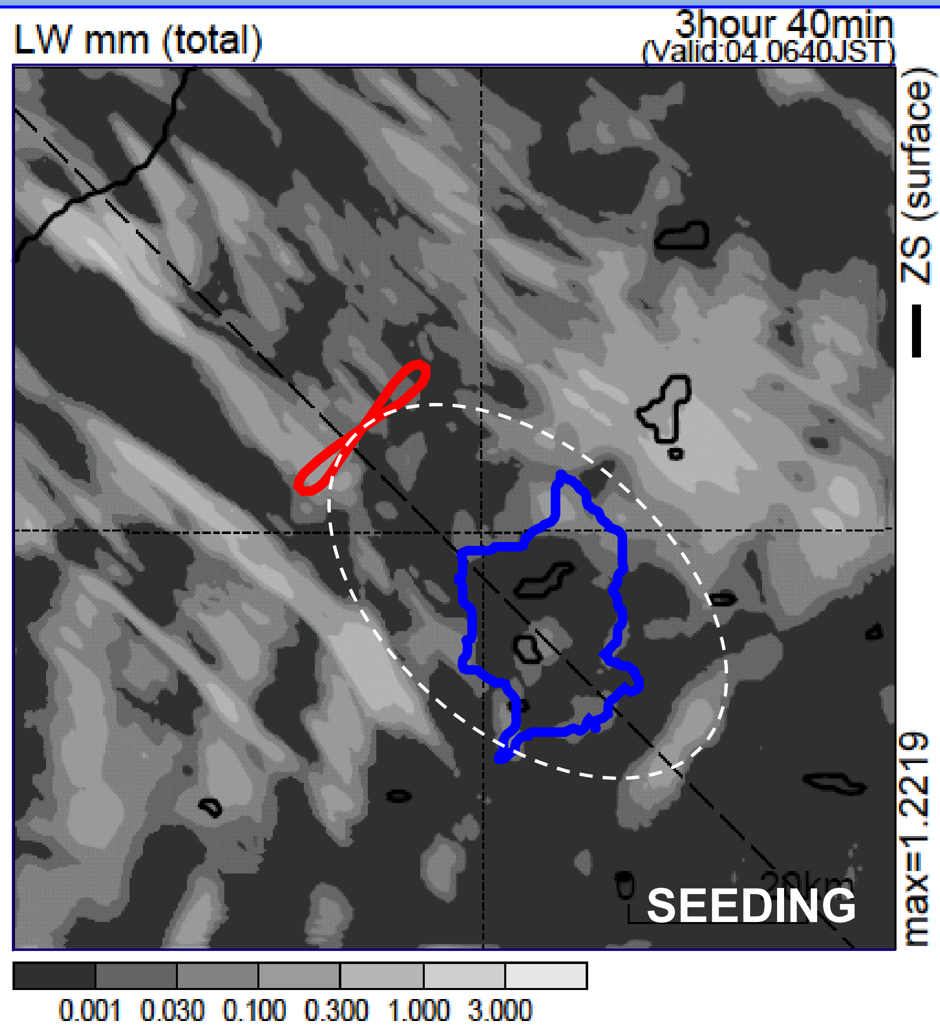
LEEWARD (Ka-BAND)

Dry Ice Pellet Seeding in NHM

These days we can simulate cloud seeding with dry ice pellets as well as AgI particles in a very realistic way.



Number conc. of cloud ice produced by dry ice pellet seeding



Depositional growth of ice & snow crystals

↓

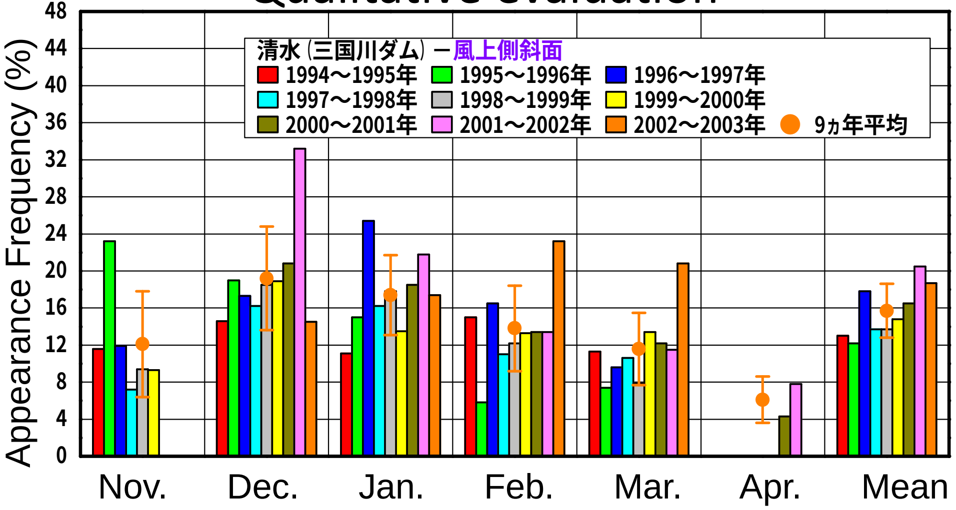
Depletion of cloud water

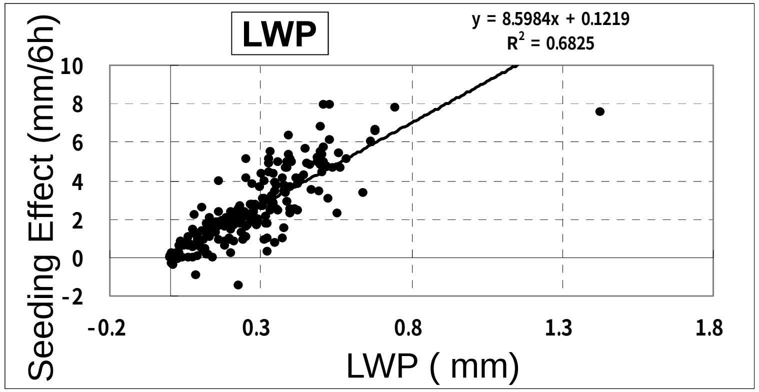
Quantitative Evaluation of Seedable Clouds

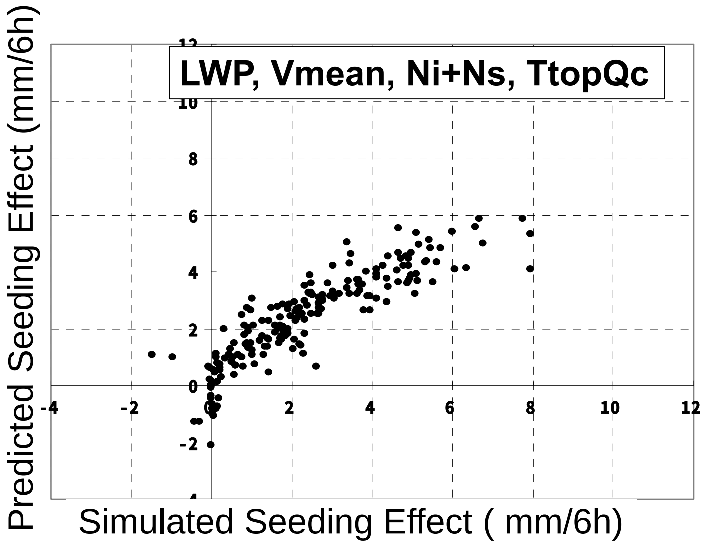
Ttop: −5～−25℃; Cloud amount > 9/10
1hr ave. LWP > 0.2mm; Htop > 2.5km

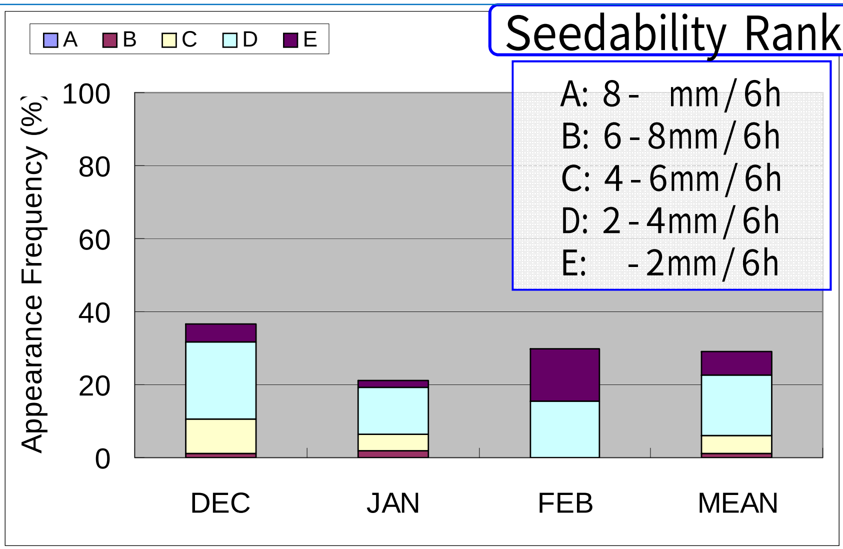
Microwave radiometer, Satellite IR data, Agrological data, AMeDAS

Qualitative evaluation

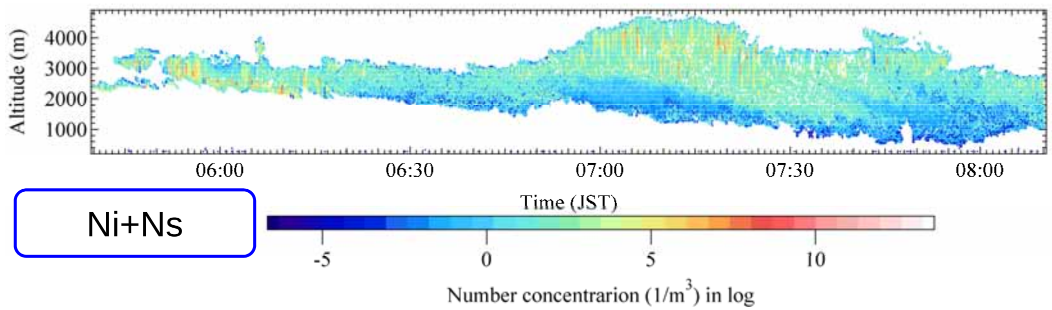








Synergy Observation

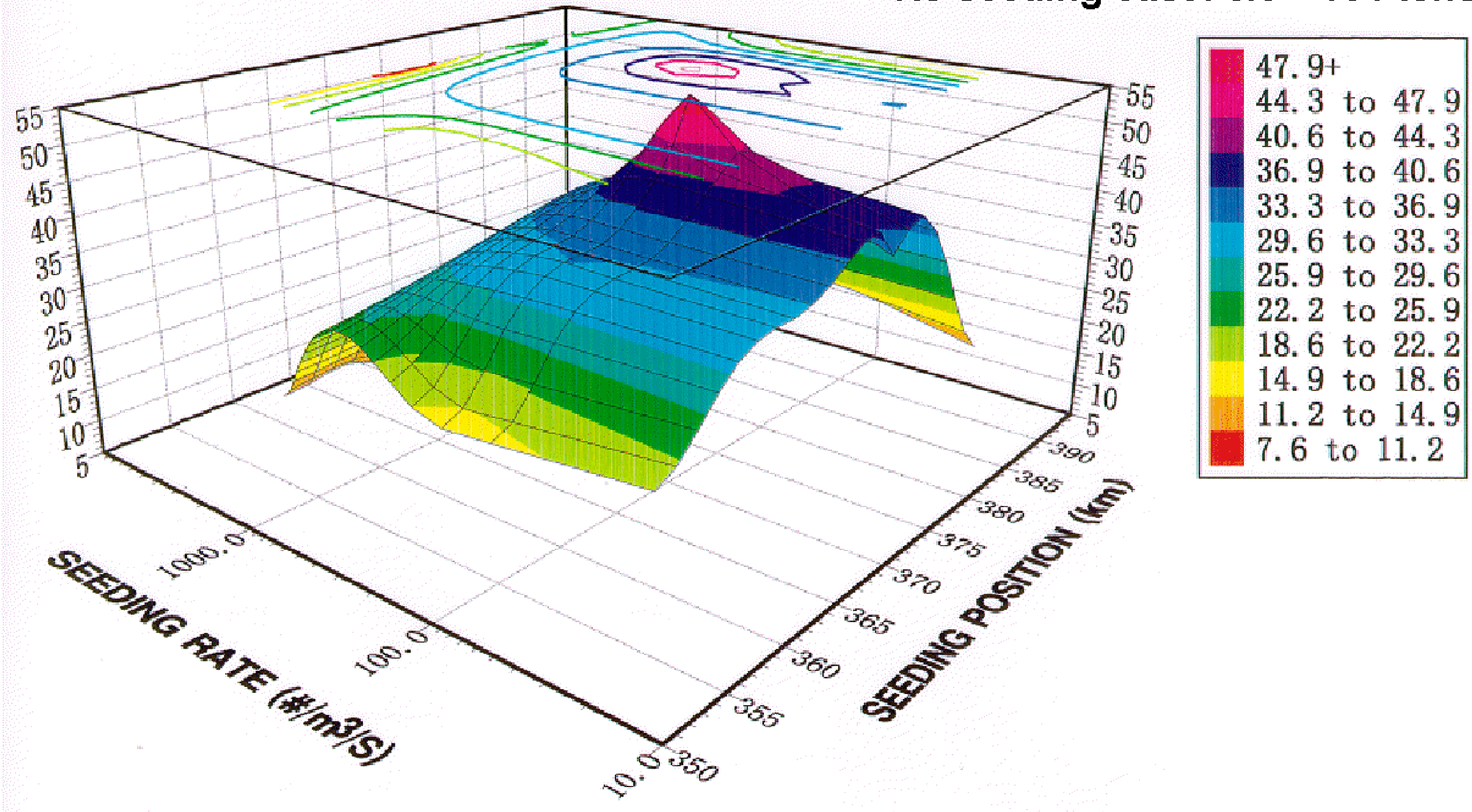


Sensitivity Experiments

PRECIPITATION AMOUNT ($\times 10^4$ tons/4hr)
OVER THE CATCHMENT (21 km$\times$10 km)

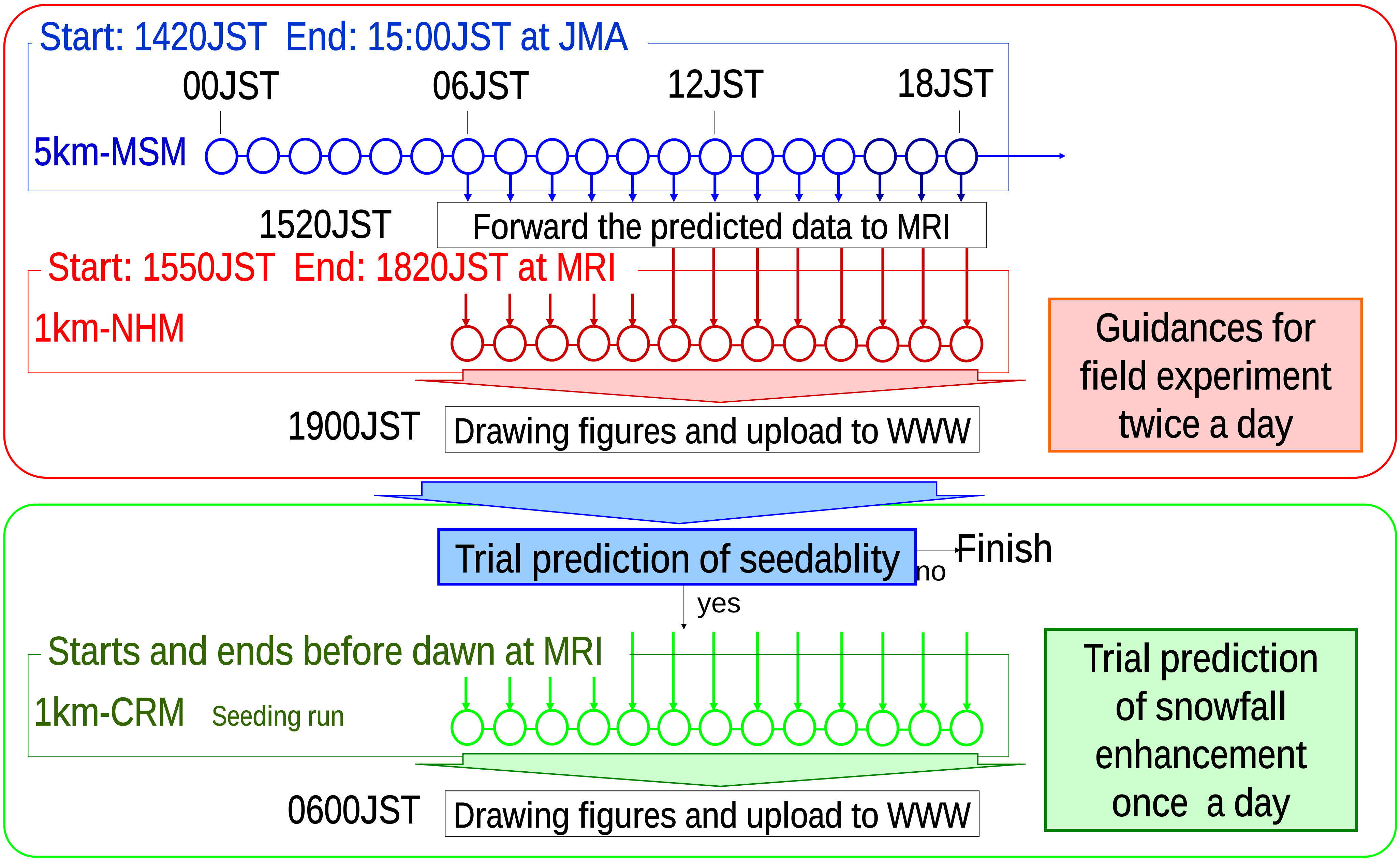
Optimum seeding condition
Y = 382.5 km
SR = 300 #/m^3/s

No seeding case: 6.6$\times$104 tons



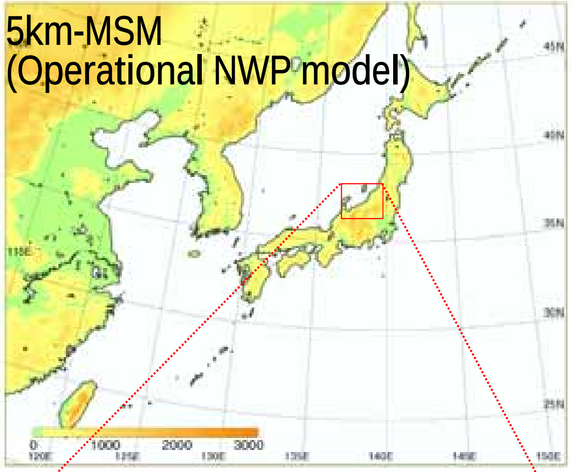
Guidance for field experiment and trial predictions of seedability and evaluation of seeding effect with 1km-NHM

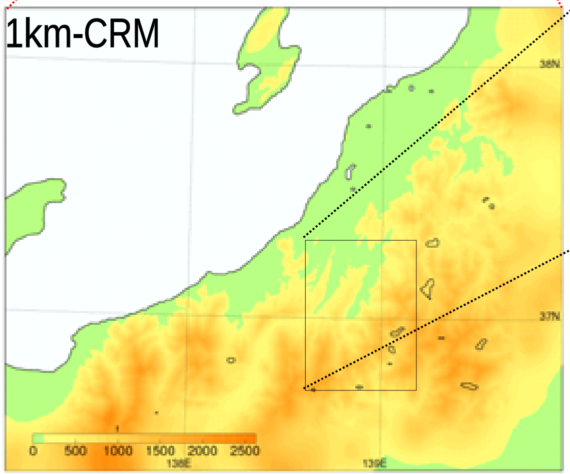
Time schedule

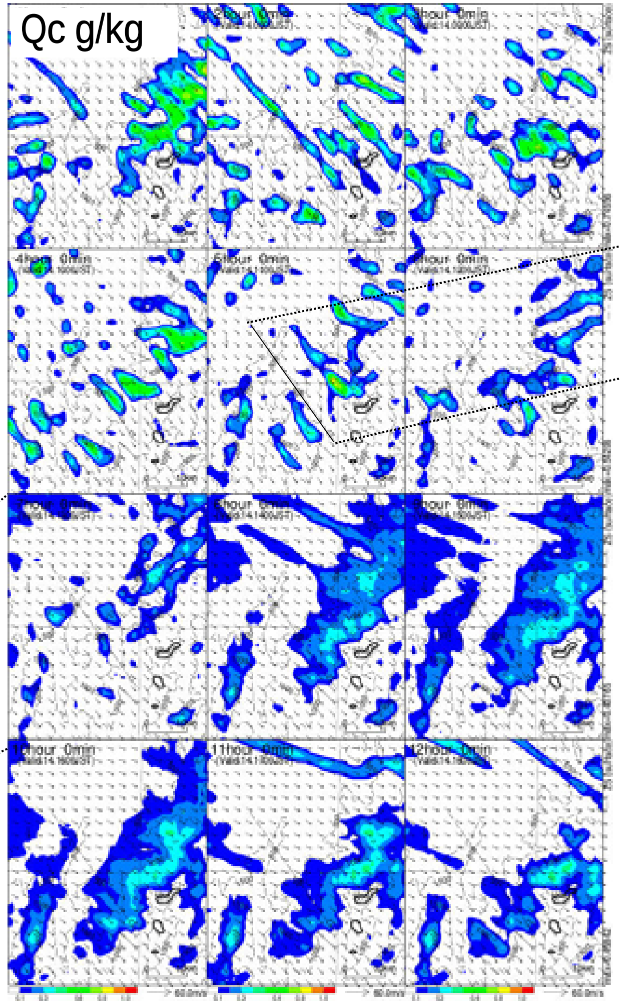


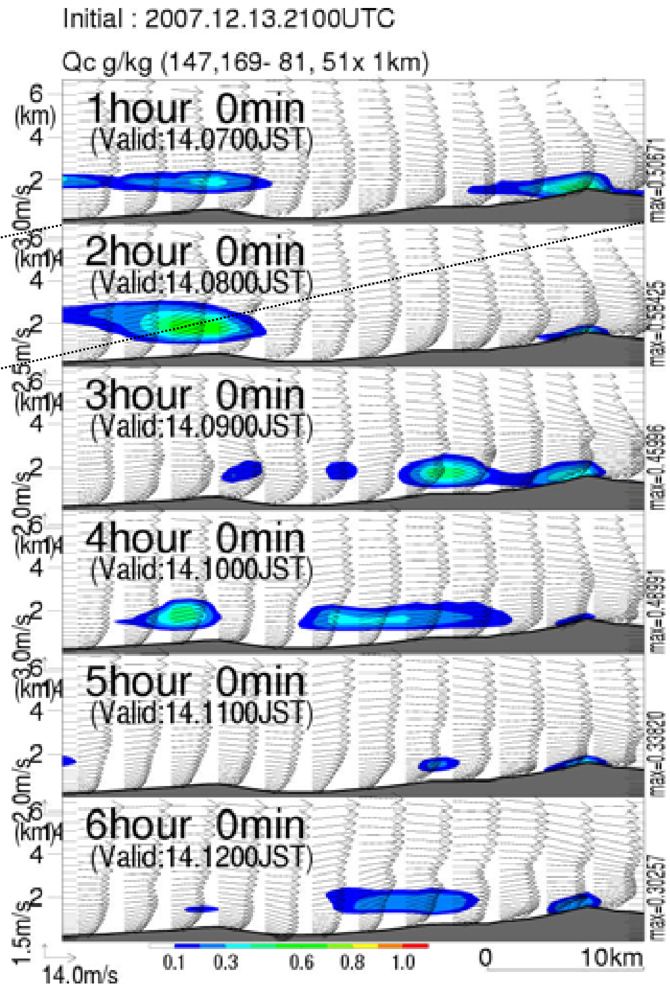
Guidance for field experiment

Forecast of seedable clouds, twice a day







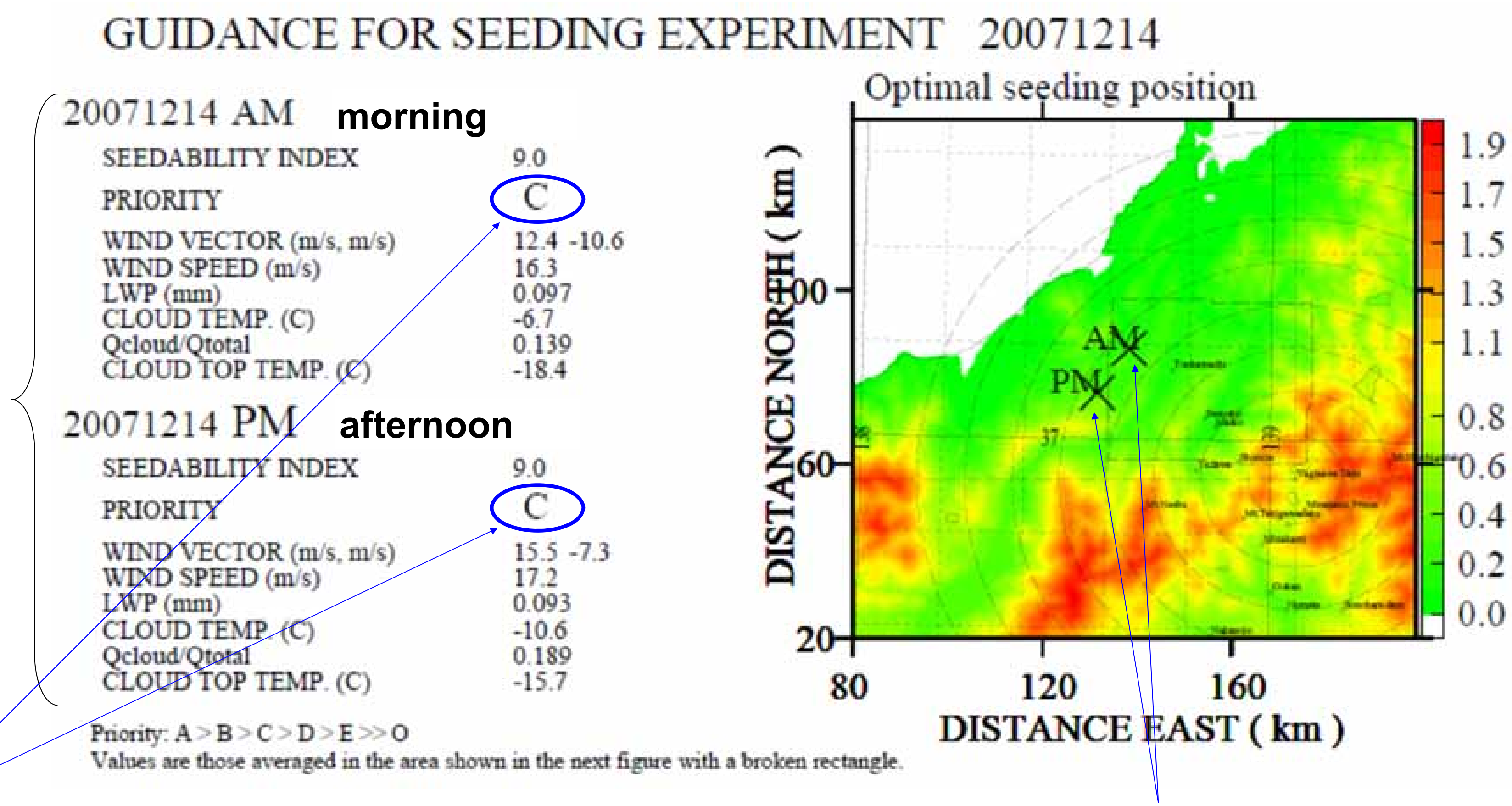


Prediction of cloud water distribution

Surface precipitation, LWP,IWP, mixing ratio and number concentration of liquid and solid hydrometeors, and wind field are also available.

Guidance for A/C seeding experiments

Trial of seedability prediction, twice a day

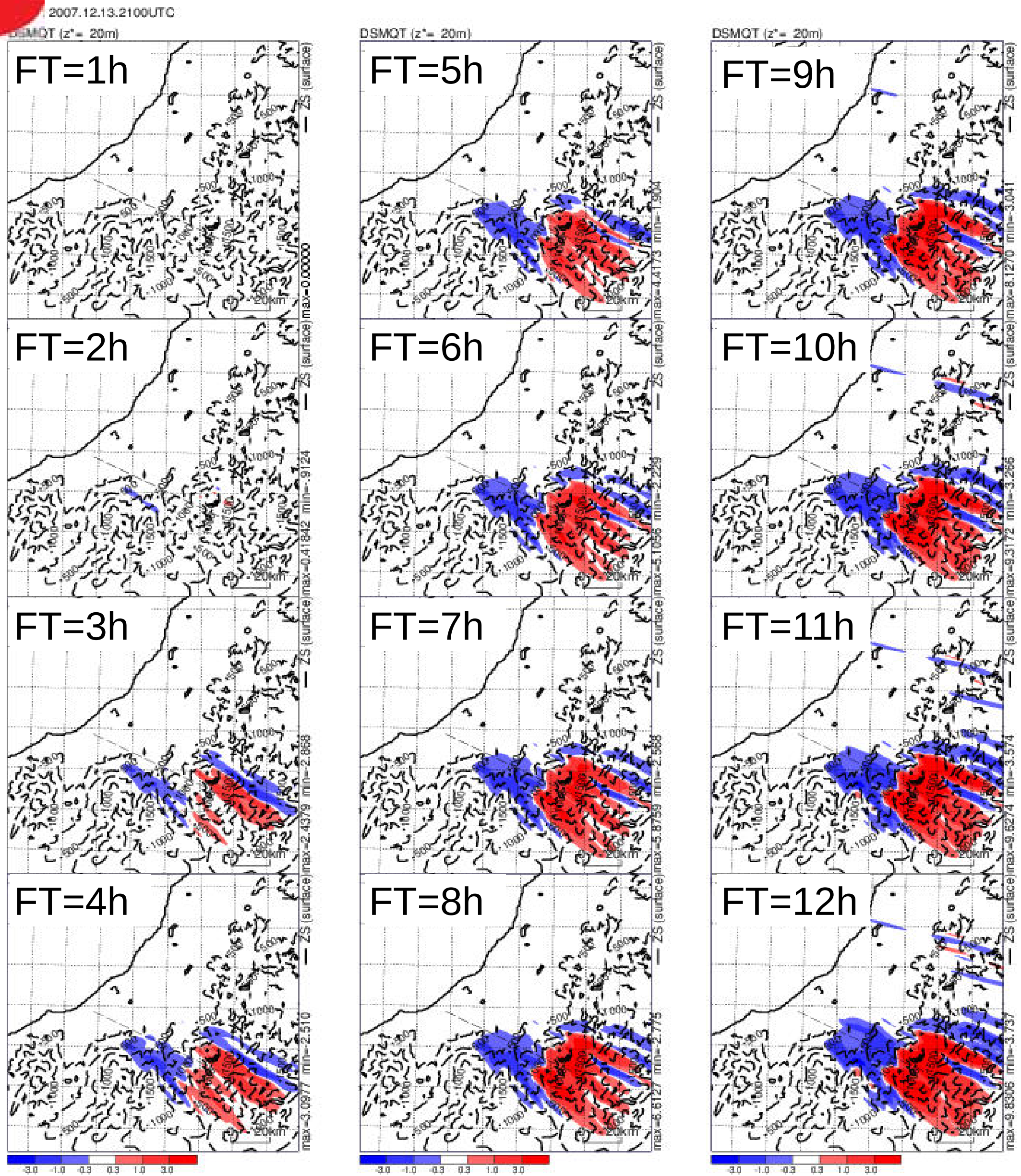


Seedability information

Seedability rank

Optimal seeding position

Guidance for A/C seeding experiments



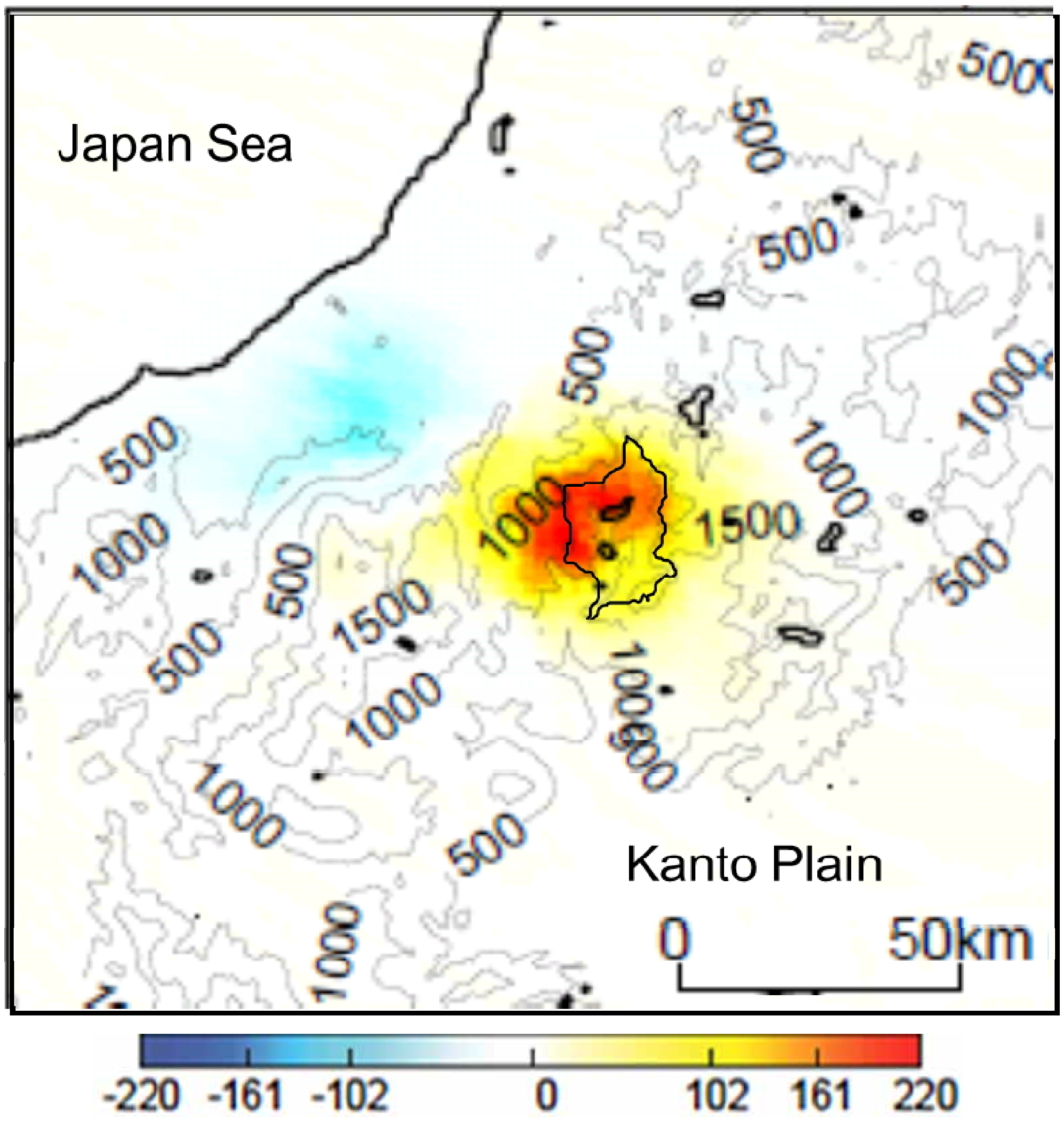
Trial prediction of seeding effects, once a day

Seeding rate : 3 kg/min
Seeding position : determined from meteorological parameters predicted in control run
Seeding material : dry ice pellet
Flight speed : 100 m/s
Flight level : 2600 m

Differences in accumulated surface precipitation (mm) (seeding run minus control run). Red and blue indicate the increase and decrease due to cloud seeding, respectively.

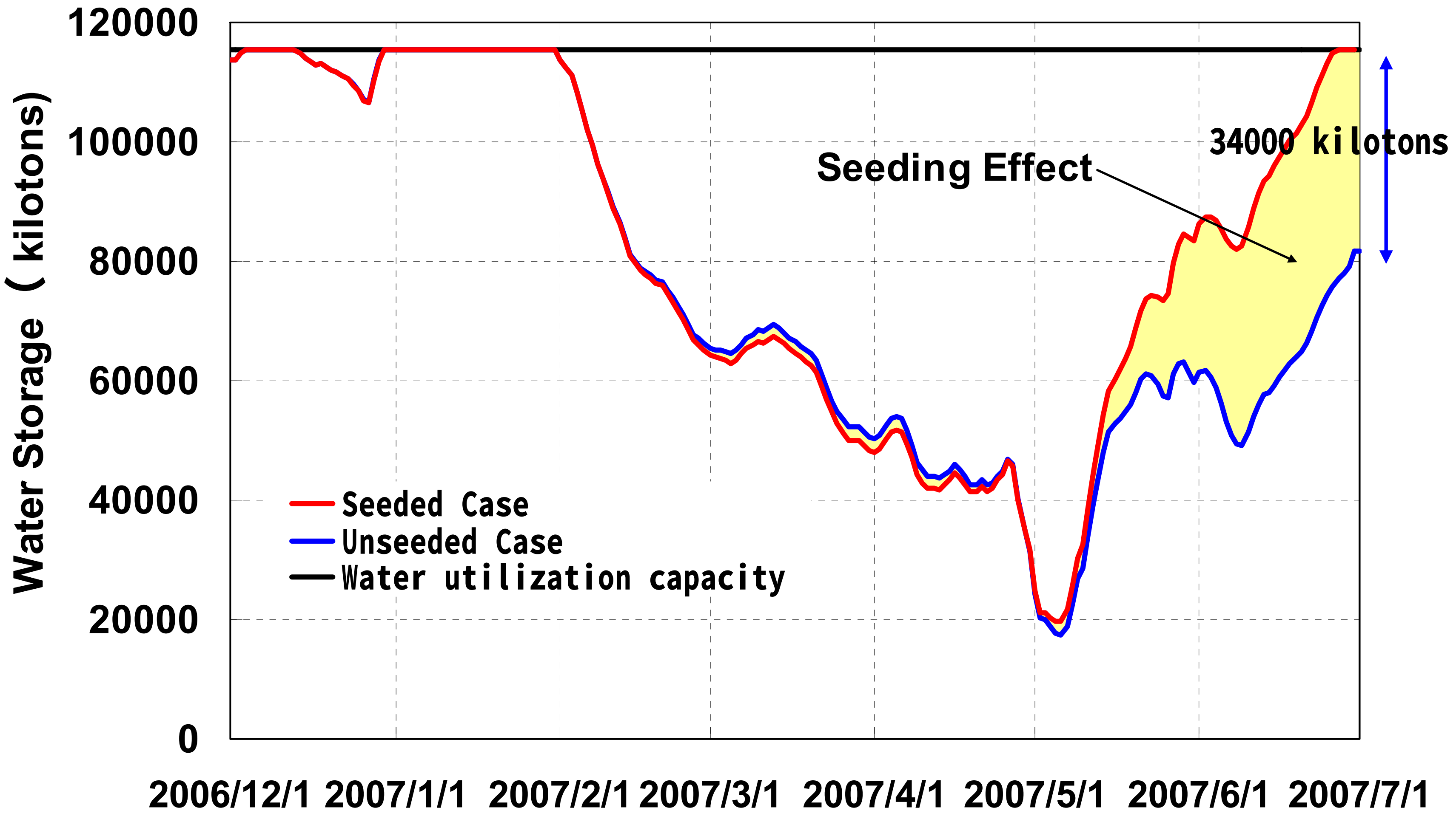
Seeding Effects on Seasonal Precip

(NHM simulations (163 cases):
Under winter monsoon conditions: Dec. 2006-Mar. 2007)

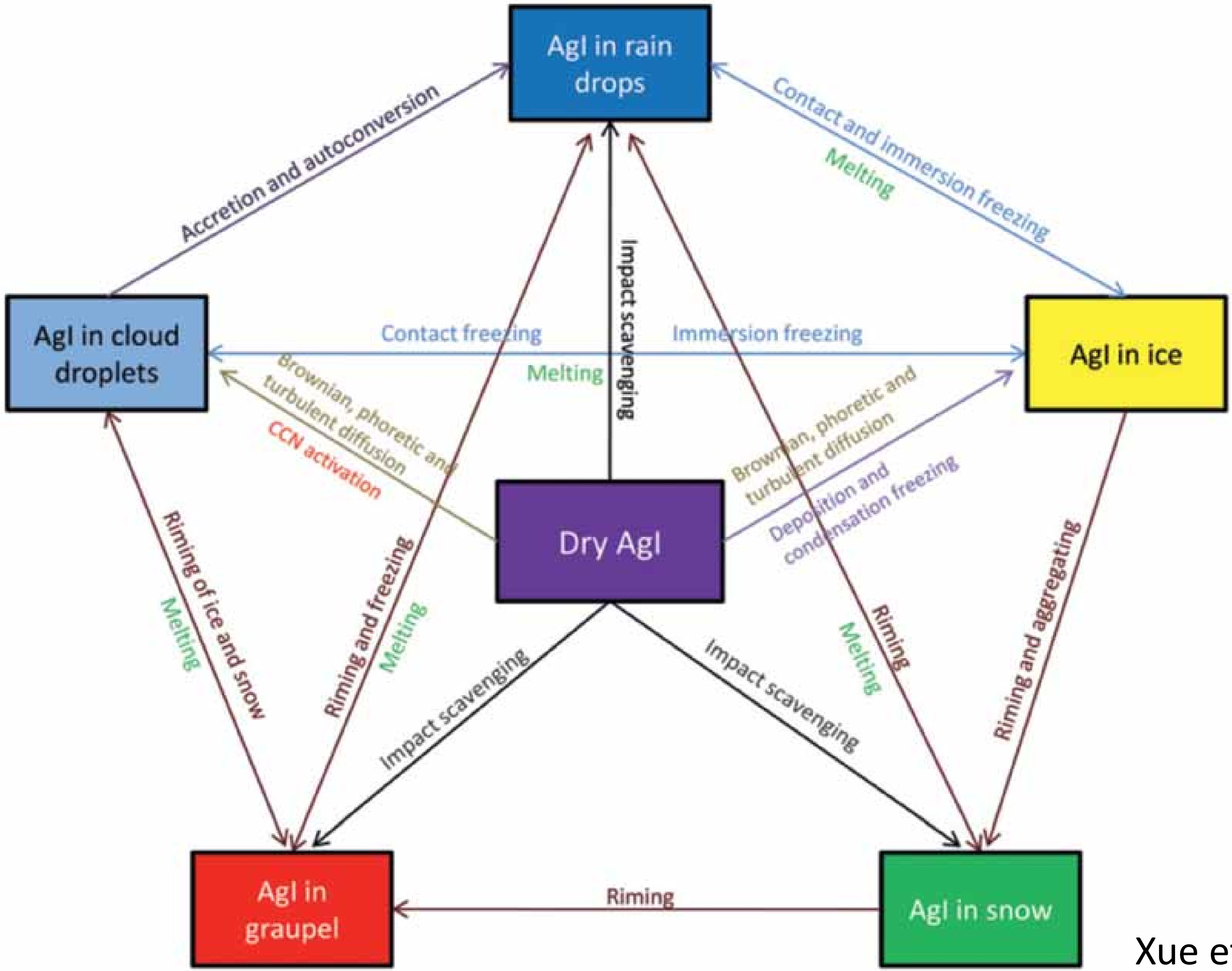


Seeding Effect on Dam Water Storage

(Numerical simulation with a combination of NHM and land surface model)

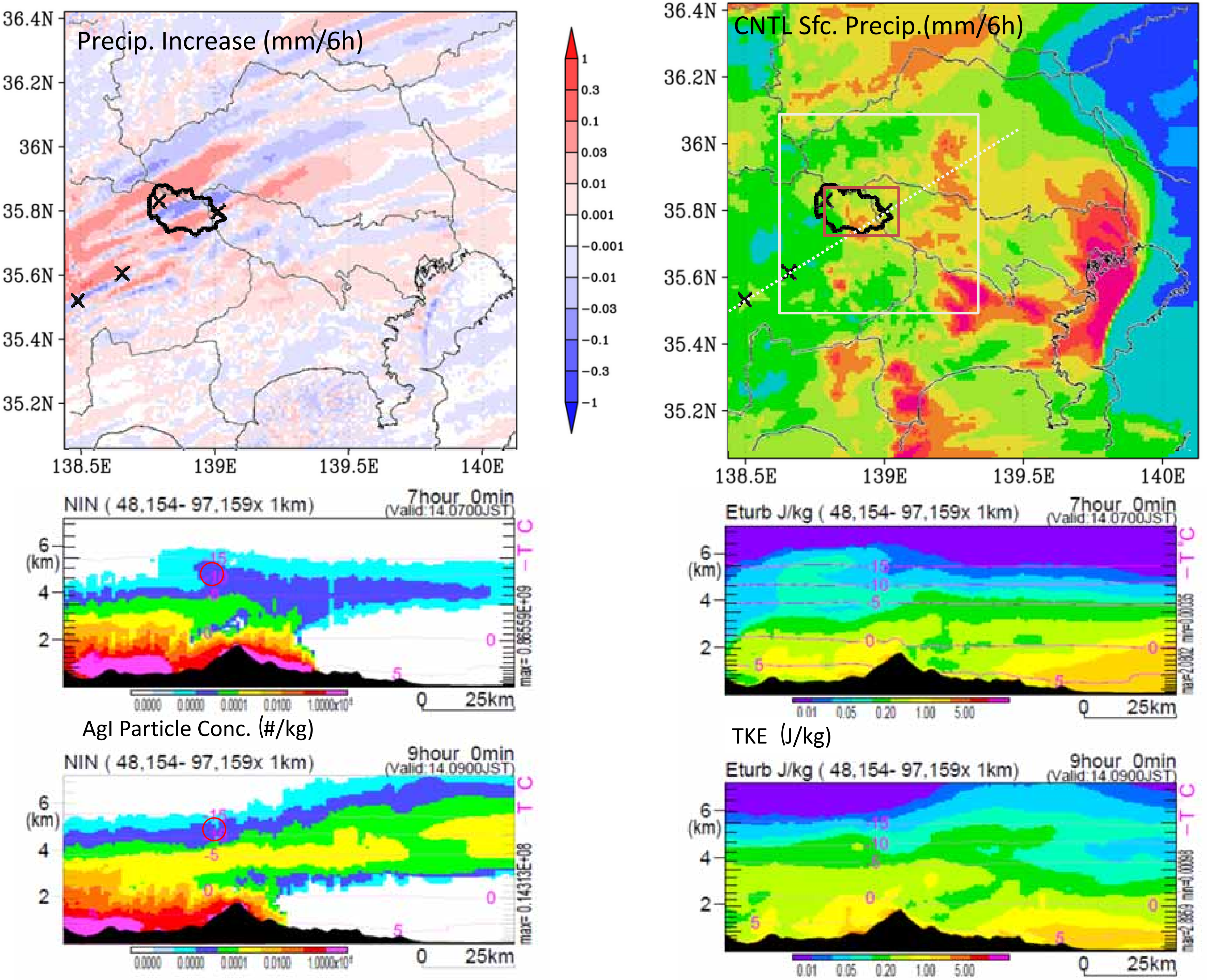


AgI Seeding Scheme

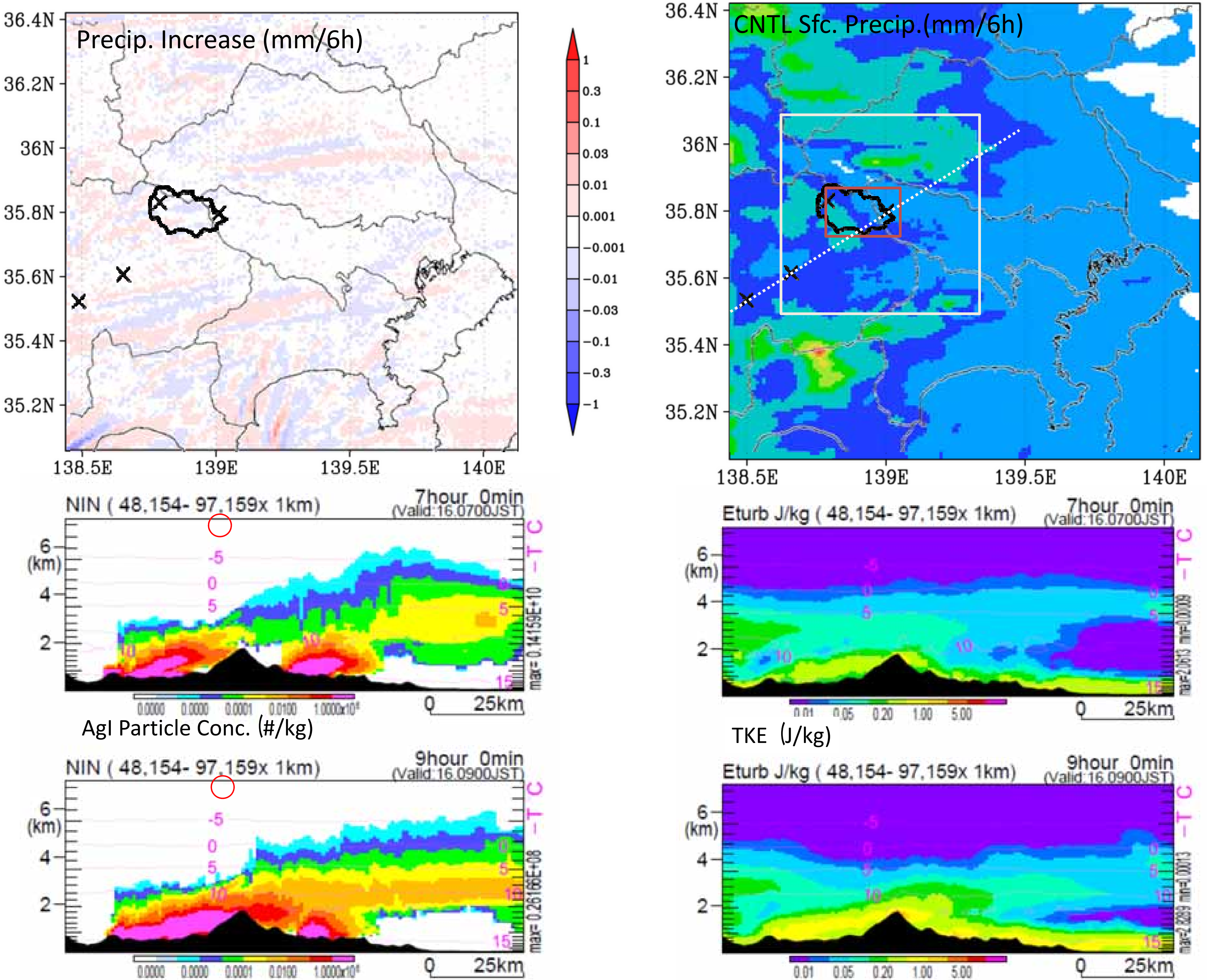


Xue et al. 2013

Effectiveness of G-B AgI Seeding (1km_NHM) (2012.04.13)



Effectiveness of G-B AgI Seeding (1km_NHM) (2012.06.15)

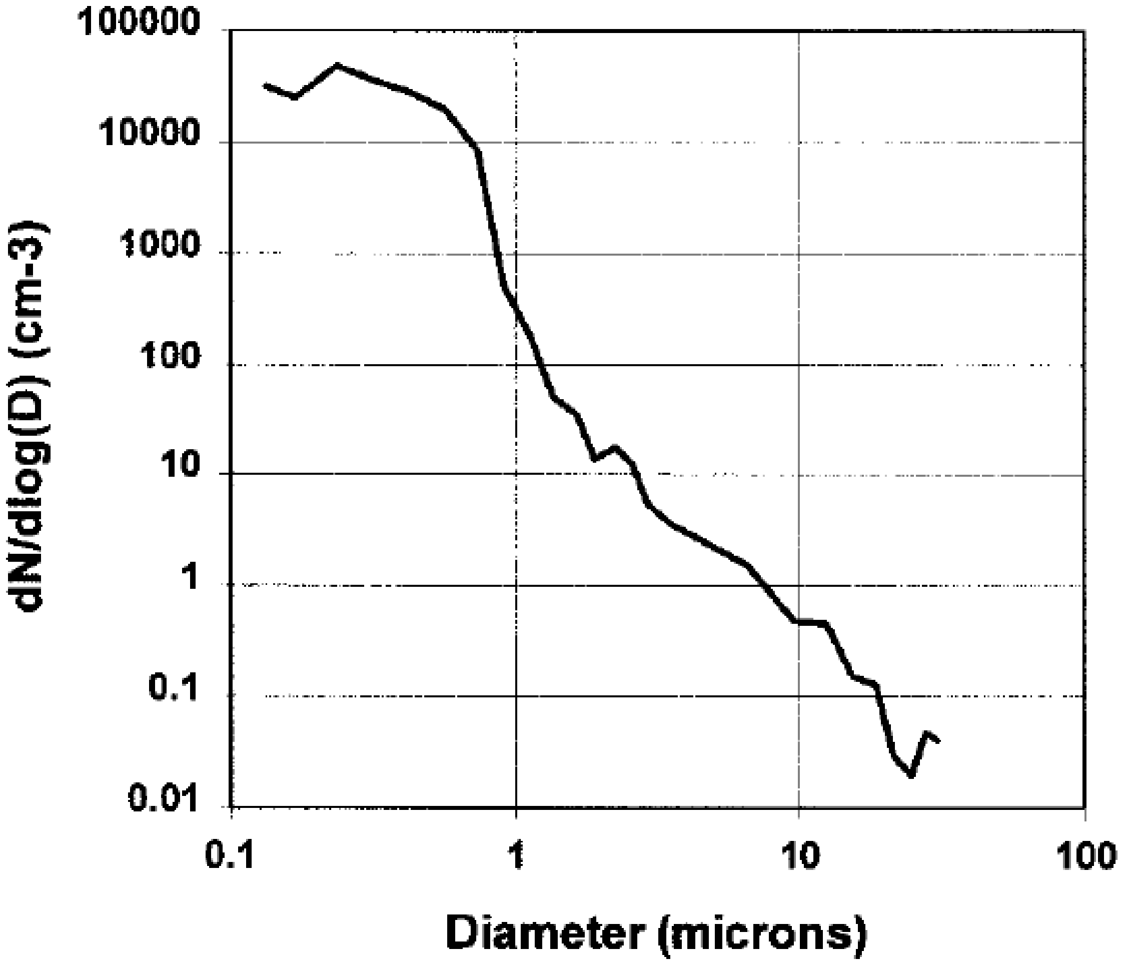


PART TWO

Warm Convective Clouds

Hygroscopic Flare Seeding

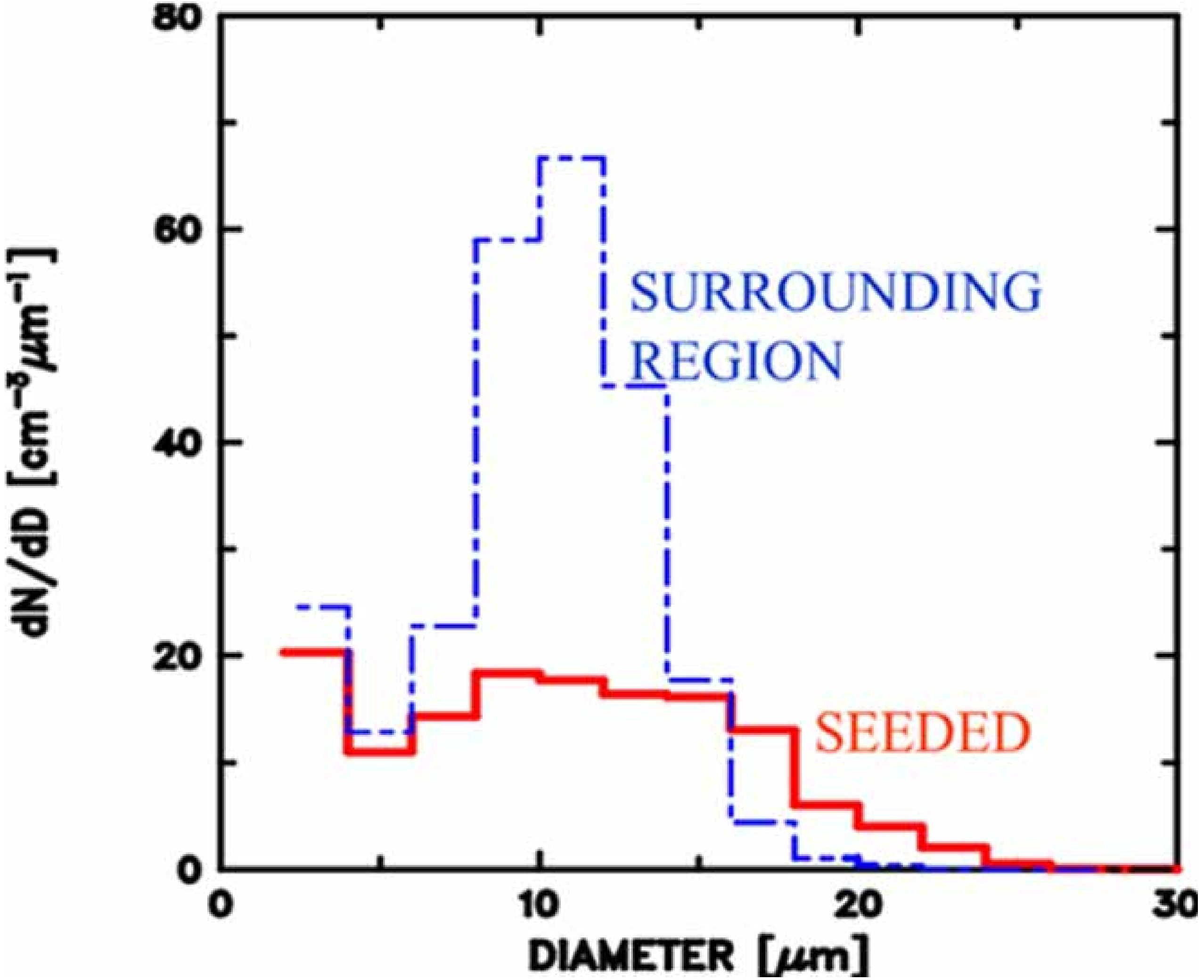
Dry Particle Spectrum



(Mather *et al.*. 1997)

Hygroscopic Flare Seeding

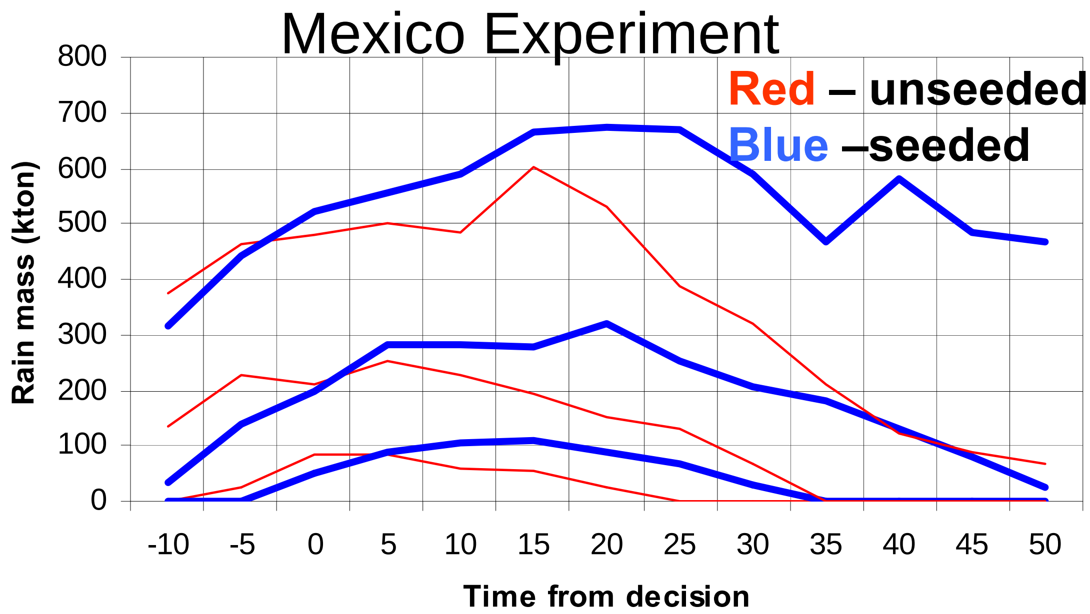
Change in Droplet size distribution

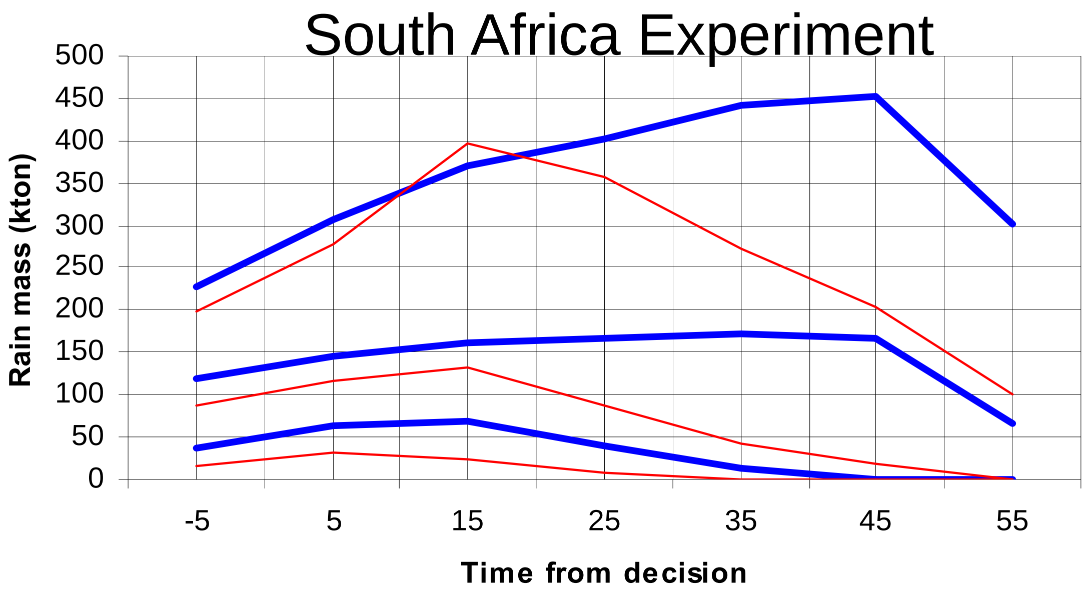


(Mather *et al*.. 1997)

Hygroscopic Flare Seeding

Rain Mass Results



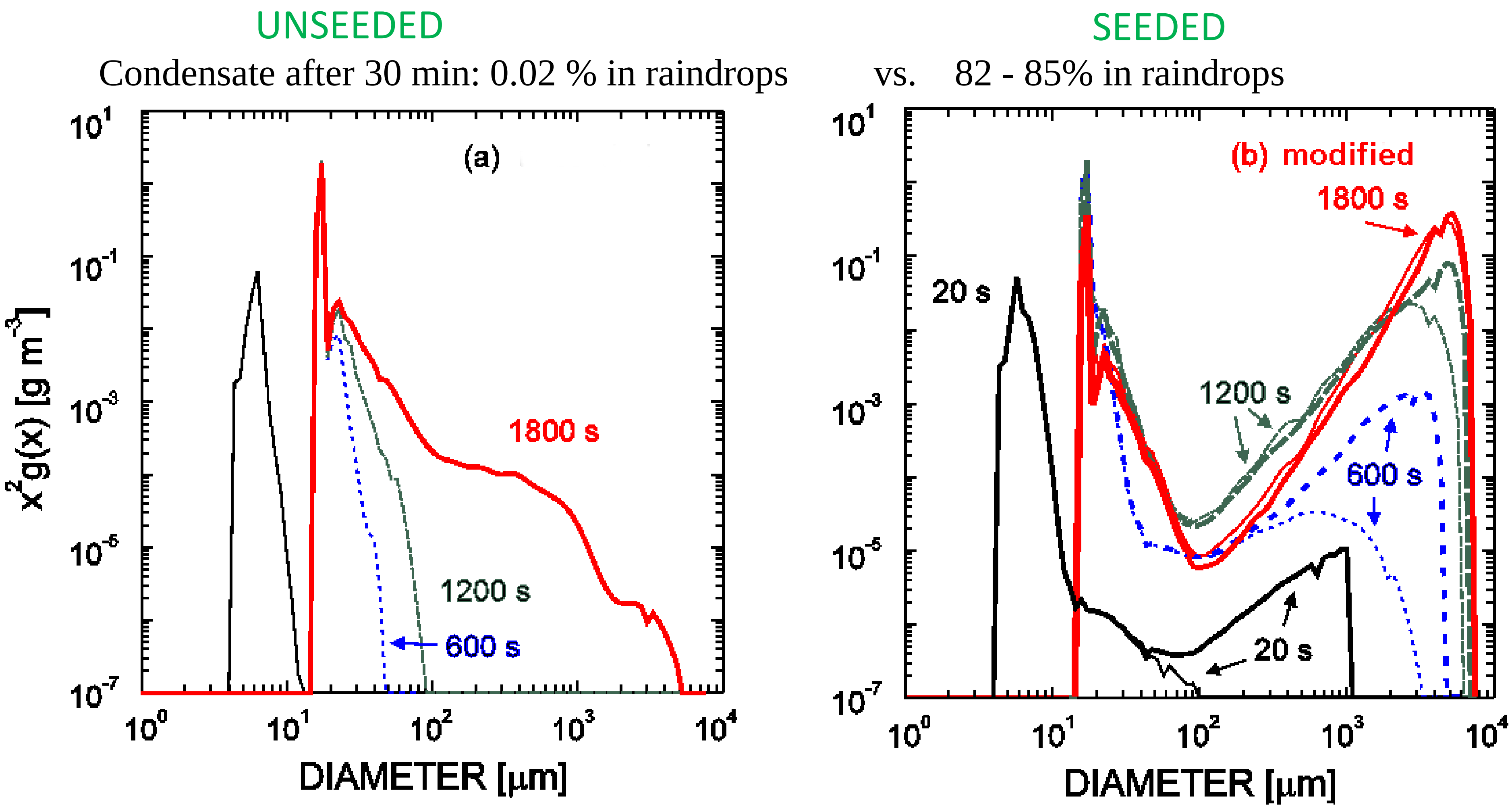


In recent years, the seeding of warm and cold convective clouds with hygroscopic chemicals to augment rainfall by enhancing warm rain processes has received renewed attention through model simulations and field experiments.
Recent randomized seeding experiments with flares that produce small (0.5 to 1.0 micrometers in diameter) hygroscopic particles in the updraft regions of continental, mixed-phase convective clouds have provided statistical evidence of increases in radar-estimated rainfall. Although the results are encouraging, the reasons for the observed seeding effects are not understood and some fundamental questions remain.

(Bruintjes 2010)

Hygroscopic Seeding (Parcel Model)

South African Hygroscopic Flare



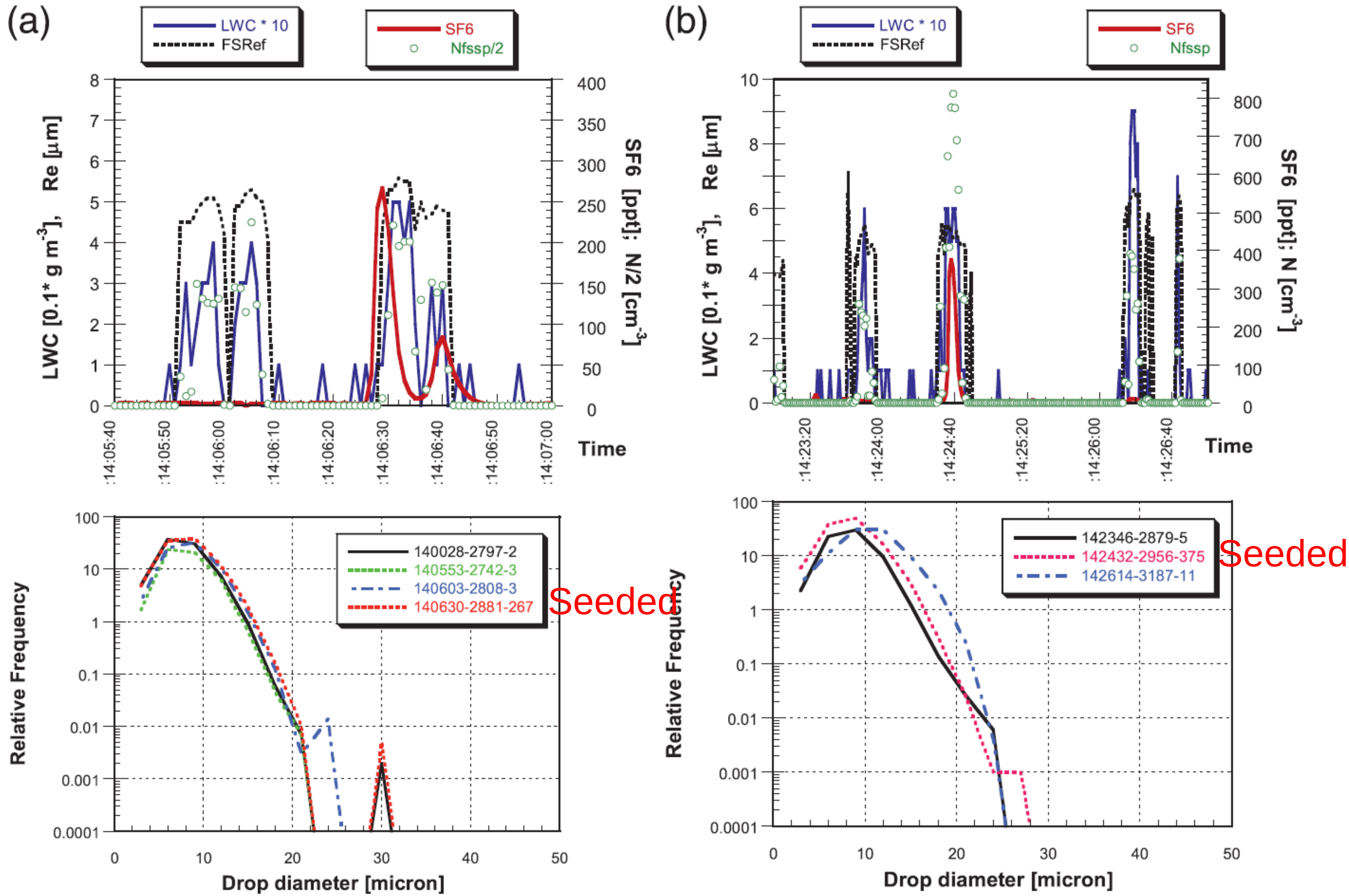
Model comparison: “natural” aerosols and seeded aerosols

(Cooper et al., 1997)

Hygroscopic Flare Seeding

(Texas, UAS; Rosenfeld et al. 2010)

Cloud base; 2.5 km, 15 C

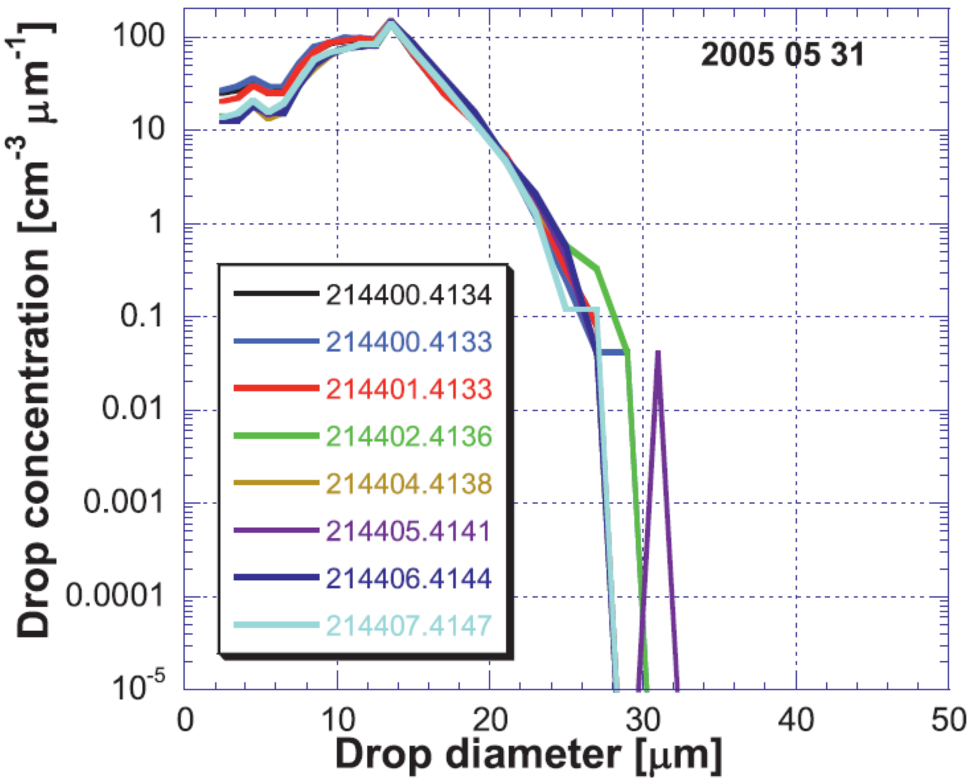


Salt Micro-Powder Seeding

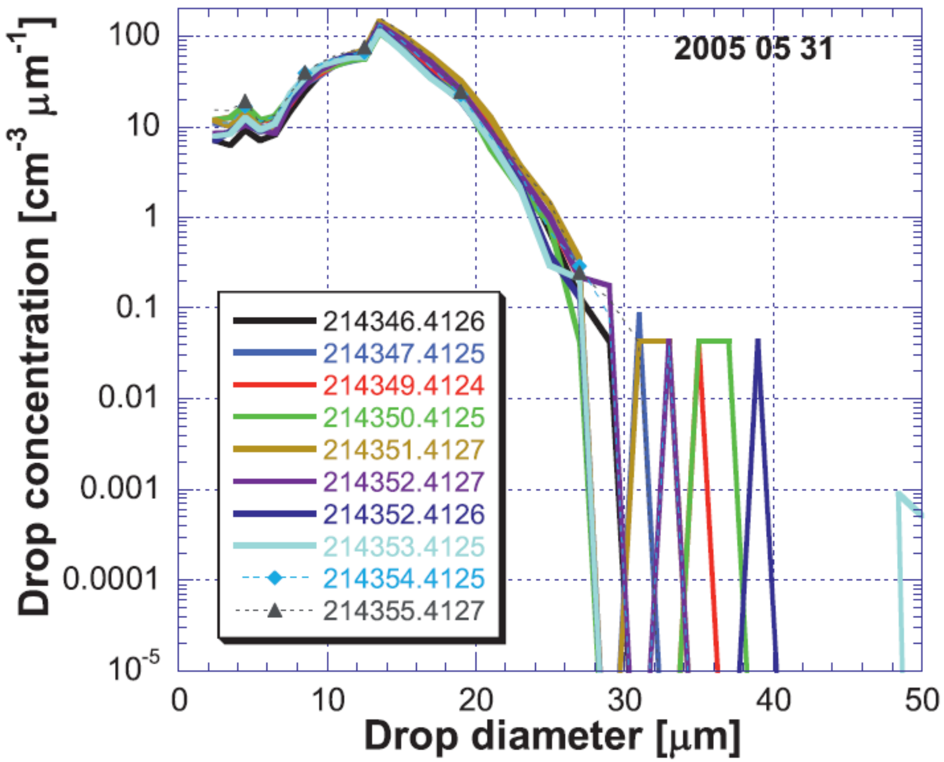
(Texas, UAS; Rosenfeld et al. 2010)

Cloud base; 3.1 km,

Unseeded



Seeded



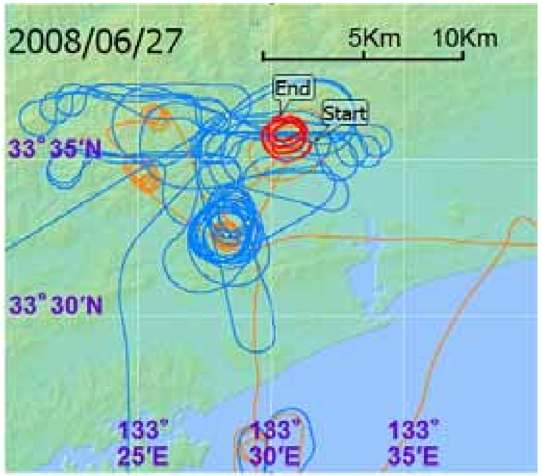
A/C Seeding Experiments (1)

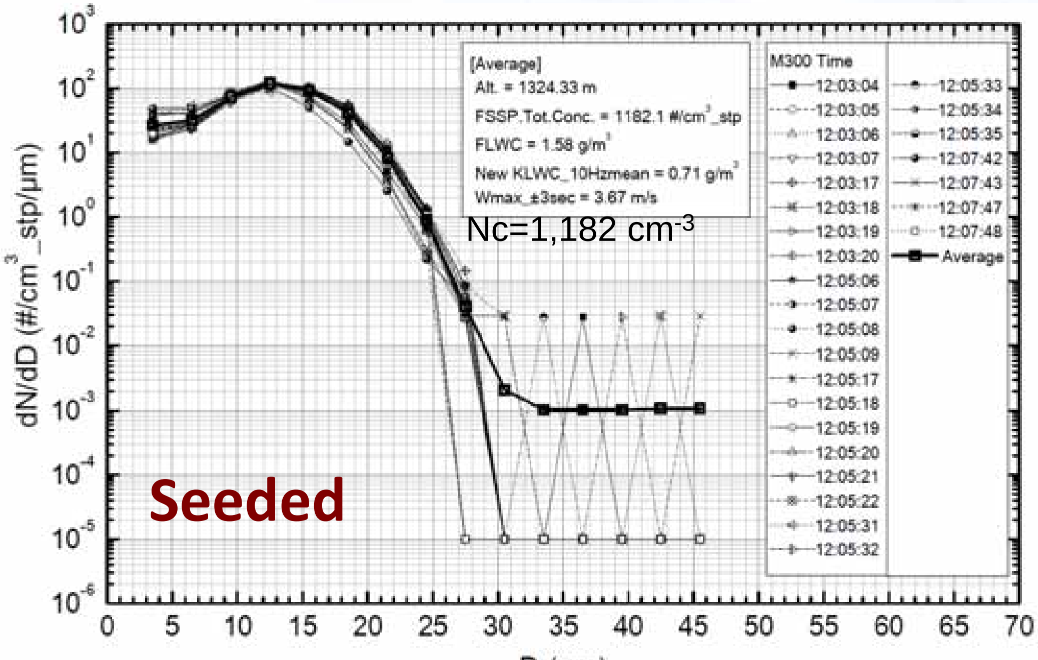
Hygroscopic Flare Seeding

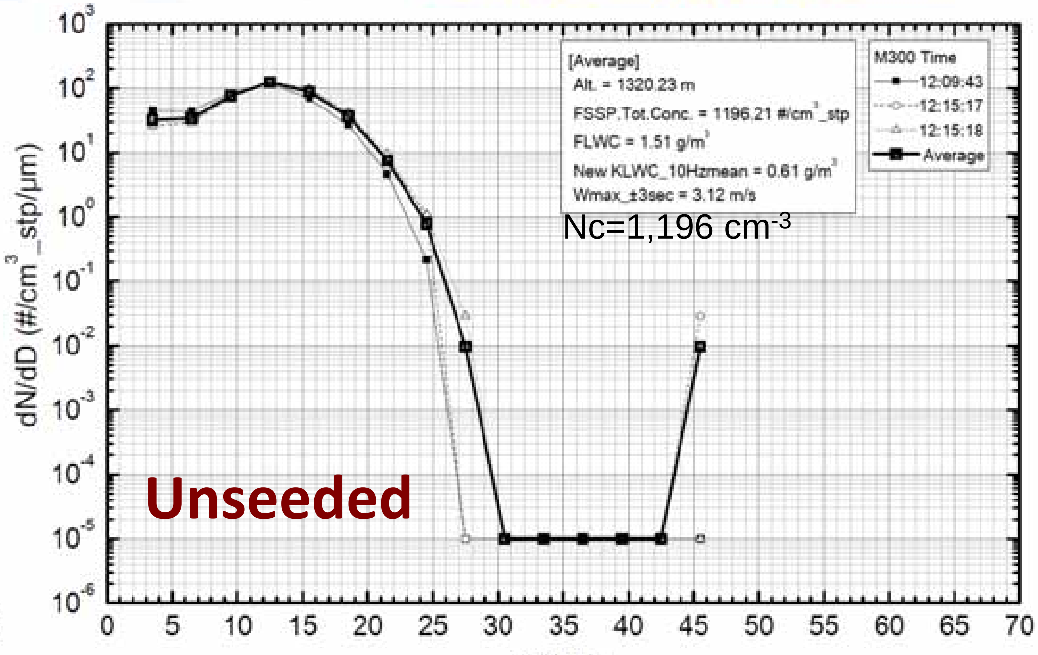
JCSEPA

Investigated hygroscopic seeding effect on droplet size distribution through in-situ aircraft measurements.

Track of KingAir
Track of Helicopter
Seeding track







This is the result from one case of hygroscopic flare seeding.
Size distributions of cloud droplets near cloud base, in seeded (left) and unseeded regions (right).
In this case, you can see that seeded regions have a broader distributions over the size ranges larger than about 30 microns.
But no significant change in total cloud droplet concentrations.
Clear difference was not always found.

A/C Seeding Experiments (2)

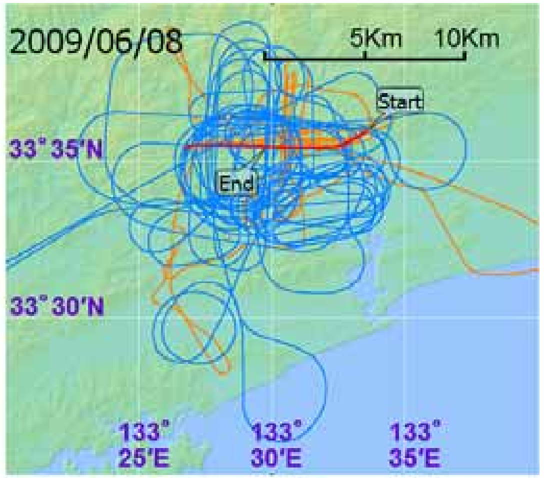
JCSEPA

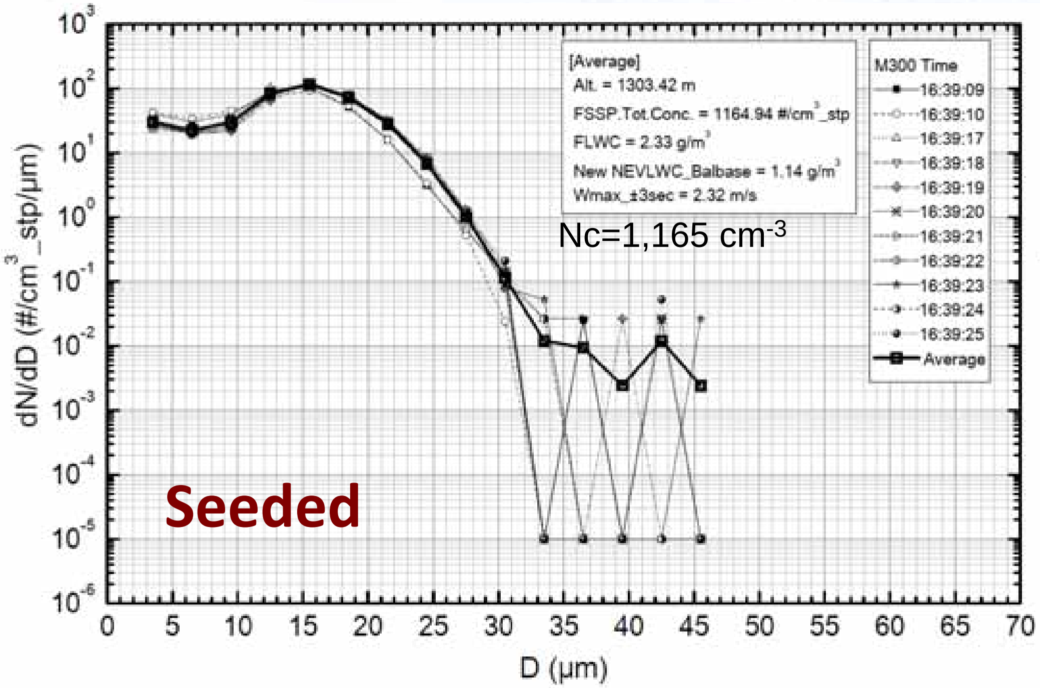
Salt Micro-powder Seeding

Track of KingAir

Track of Helicopter

Seeding track





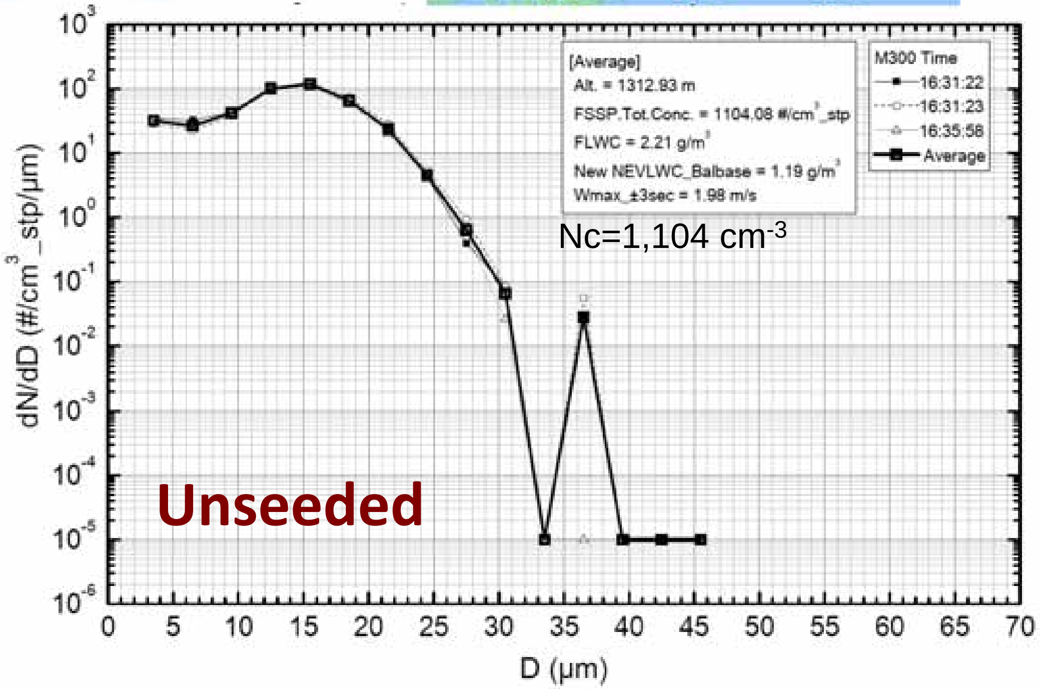
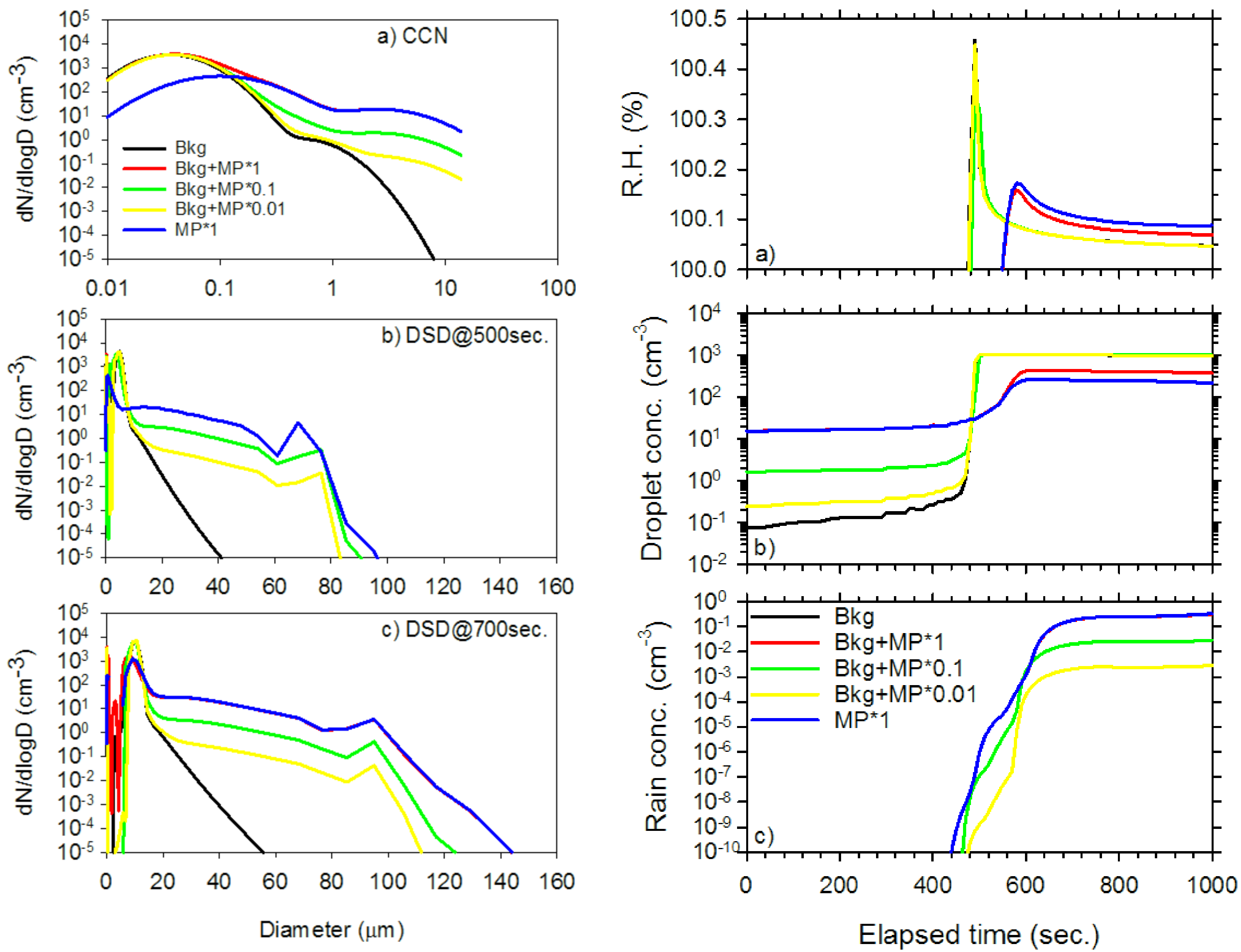


FIG. Size distributions of cloud droplets near cloud base, in case of salt micro-powder seeding on June 8, 2009. Thick line indicates the mean size distribution. Seeded cloud regions (left) versus unseeded regions (right). Concentration in a 3-

For salt micro-powder seeding.
The results were very similar to the hygroscopic flare seeding case.
Rosenfeld et al. (2010) reported similar results of hygroscopic seeding in Texas.

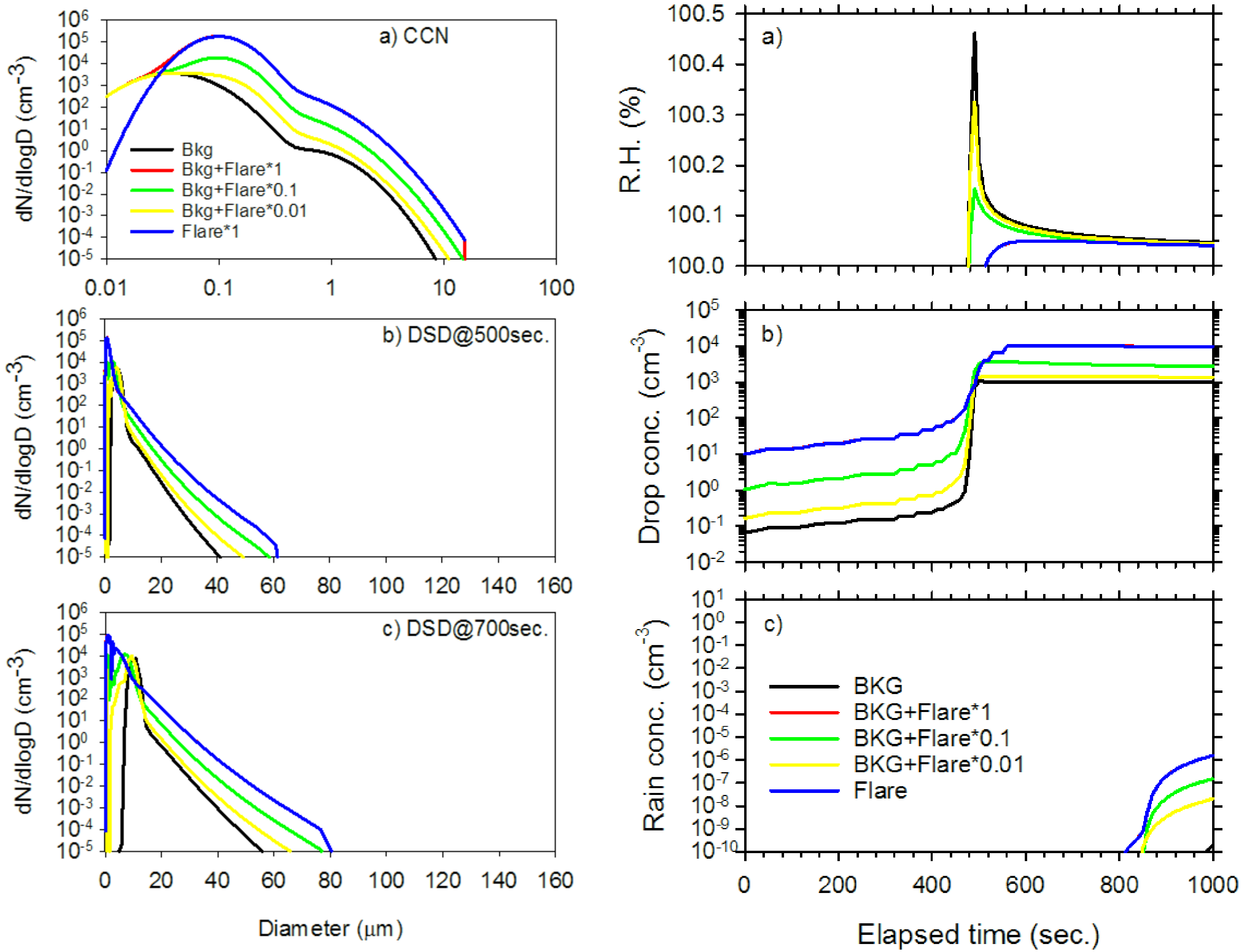
Salt Micro-Powder Seeding

Reference (Parcel) Model



Hygroscopic Flare Seeding

Reference (Parcel) Model



MRI CLOUD SIMULATION CHAMBER FACILITY

Cold Environment Simulator Building

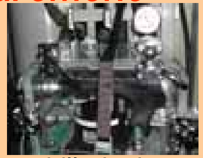
External Appearance

Control Panel

Air Conditioning & Measurement

View Laser (left)
Fan Agitator

Pressure Transducer



Chilled Mirror Hygrometers

Experimental Working Volume

Thermocouples Attached to The Chamber Wall

Cooling and Evacuation Air System

Unfreeze Fluid Circulation-pump

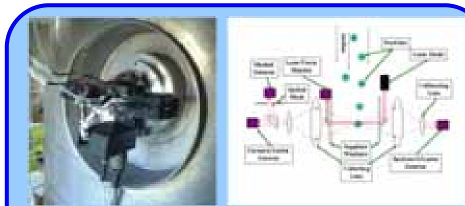
Refrigerators

Liquid Nitrogen Cylinder

Vacuum Pump

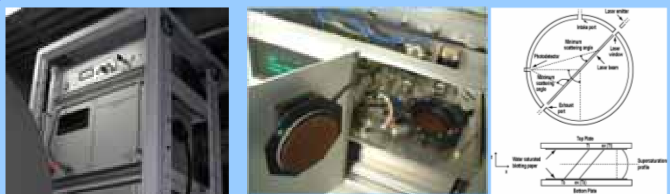
Devices for Particle Detection

Laser Sensor

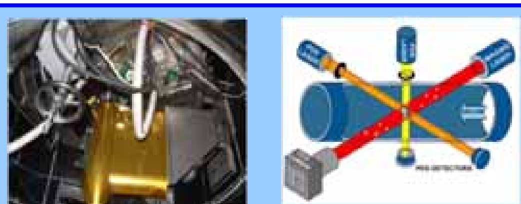


CAS

View Port

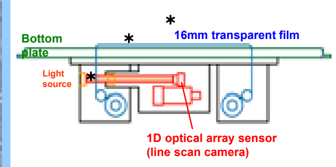


Wyoming CCN COUNTER

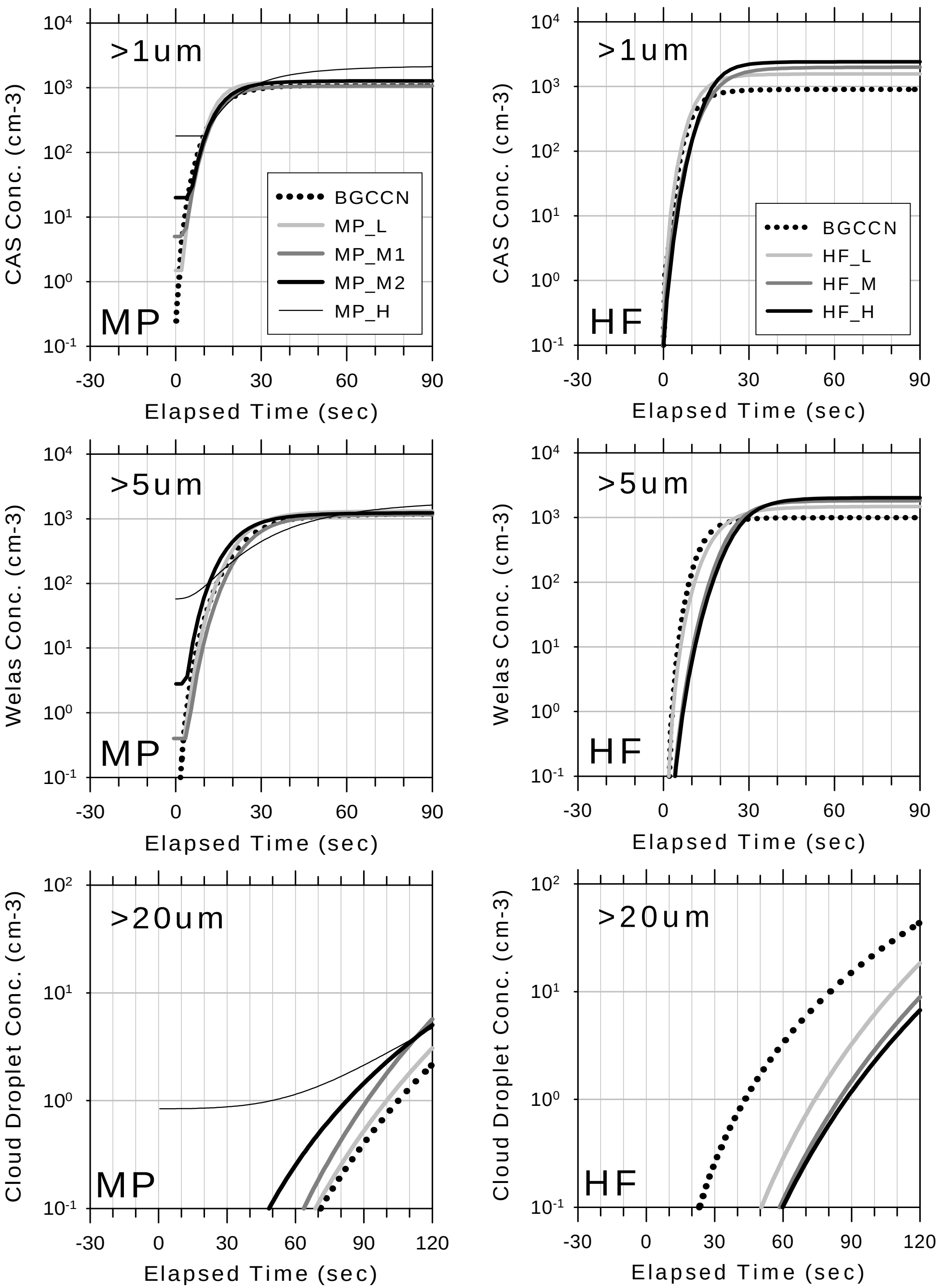


CPI

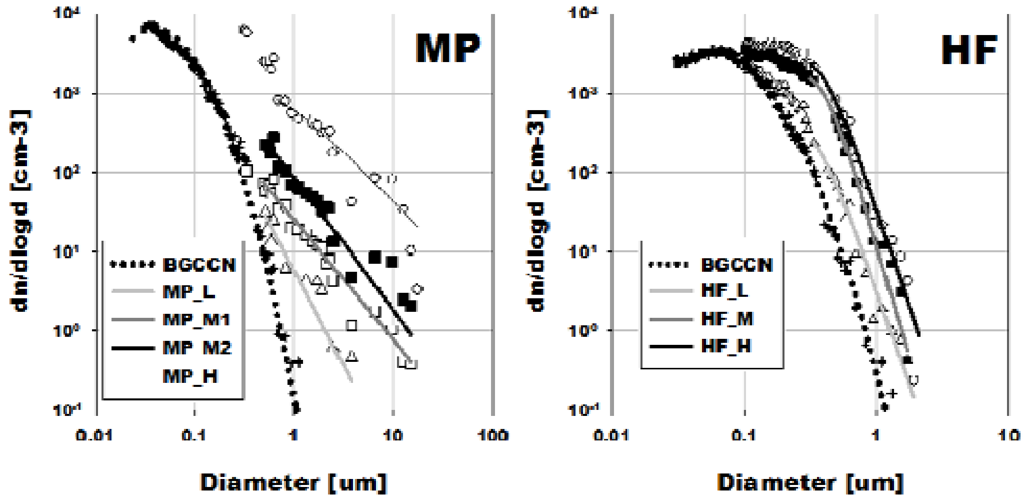
Microscopic Ice Crystal Detector



Chamber Experiment on Hygroscopic Seeding



Initial Aerosol Size Distributions

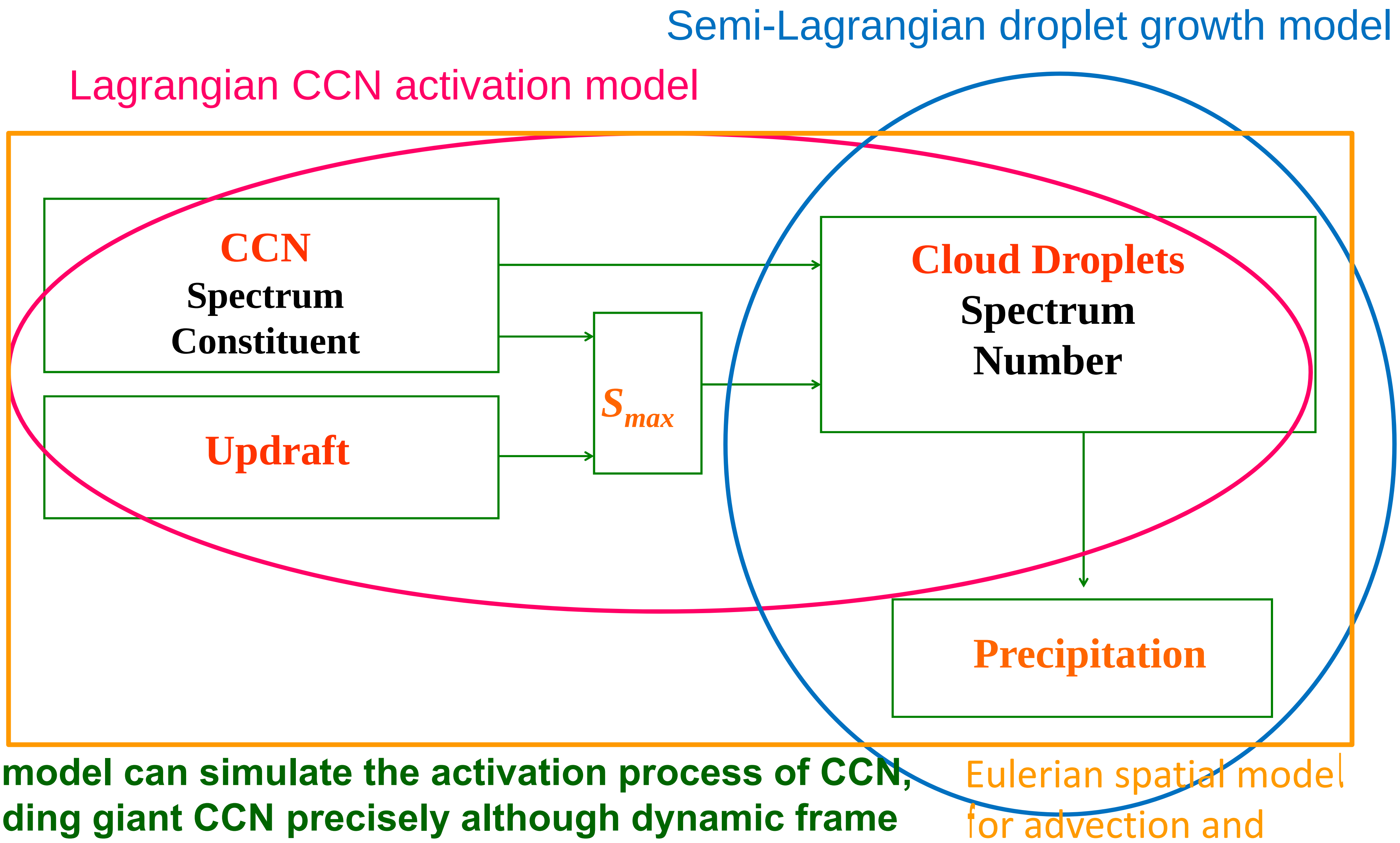


MP
Number of large droplets increases and total number of droplets slightly decreases with increasing the total mass of seeding materials.

Flare
Total droplet conc. increase and number of large droplets decrease.

Numerical Experiment on Hygroscopic Seeding

Hybrid Cloud-Microphysics Model ((Kuba and Murakami 2010, ACP)

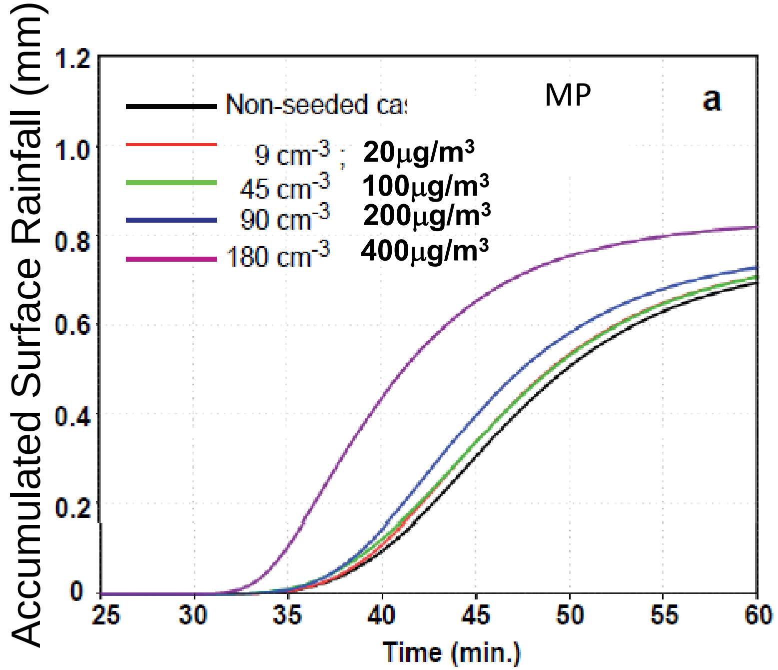


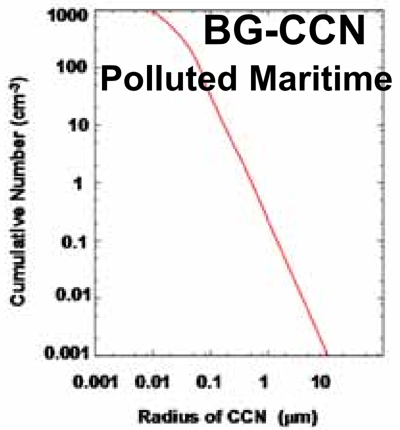
This model can simulate the activation process of CCN, including giant CCN precisely although dynamic frame

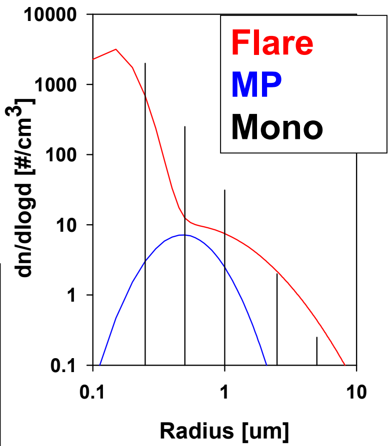
Interactions between microphysics and dynamics are not included, instead we look at seeding effect from the microphysical viewpoint.

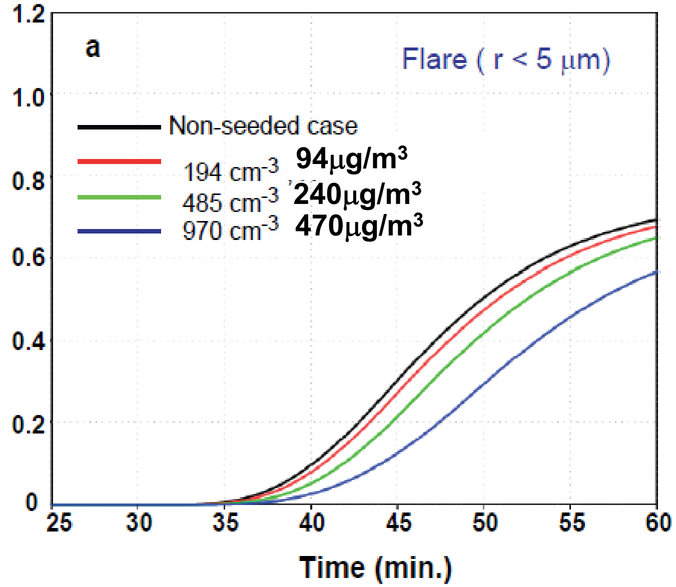
Numerical Experiment on Hygroscopic Seeding

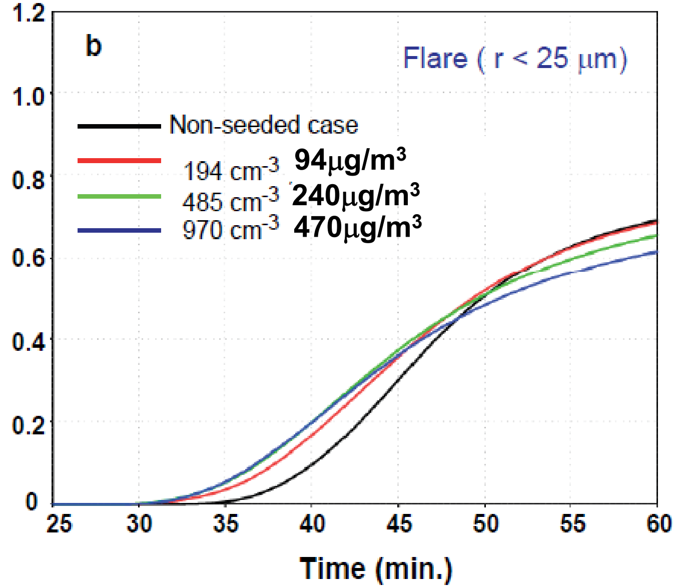
(Hybrid Cloud-Microphysics Model;
Shallow convective cloud in polluted maritime airmass)







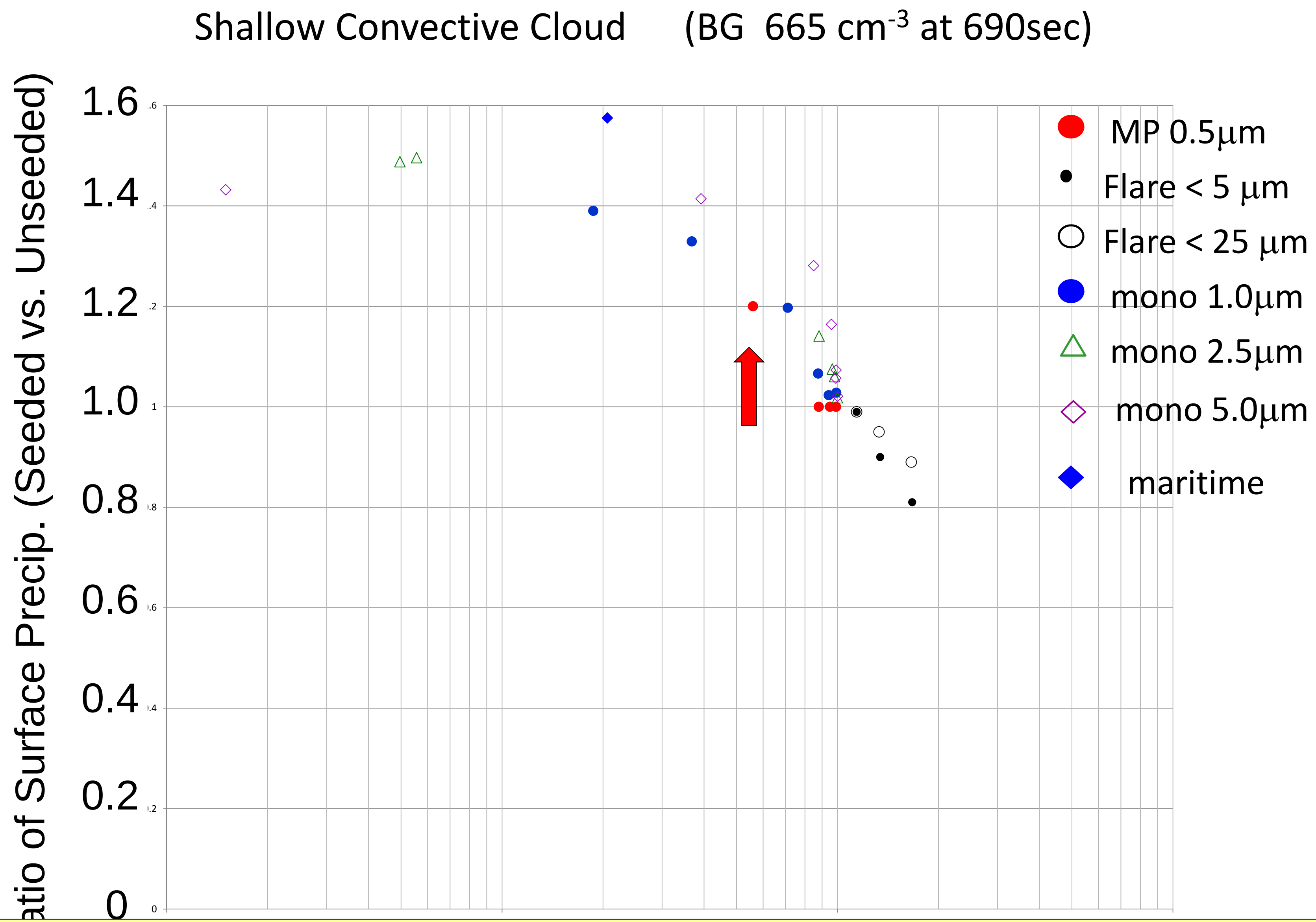




- Salt **Micro-powder**
  Positive effect (if total mass of seeding particles is large enough)
  due to increase in number of large droplets
  decrease in total number of cloud droplets

- **Hygroscopic Flare**
  Negative effect
  due to large increase in total number of cloud droplet
  Advance in onset of surface precipitation
  (due to increase in number of large droplets)

Seeding Effect on Accum. Surface Precip. vs. Ratio of Cloud Droplet Number Conc.

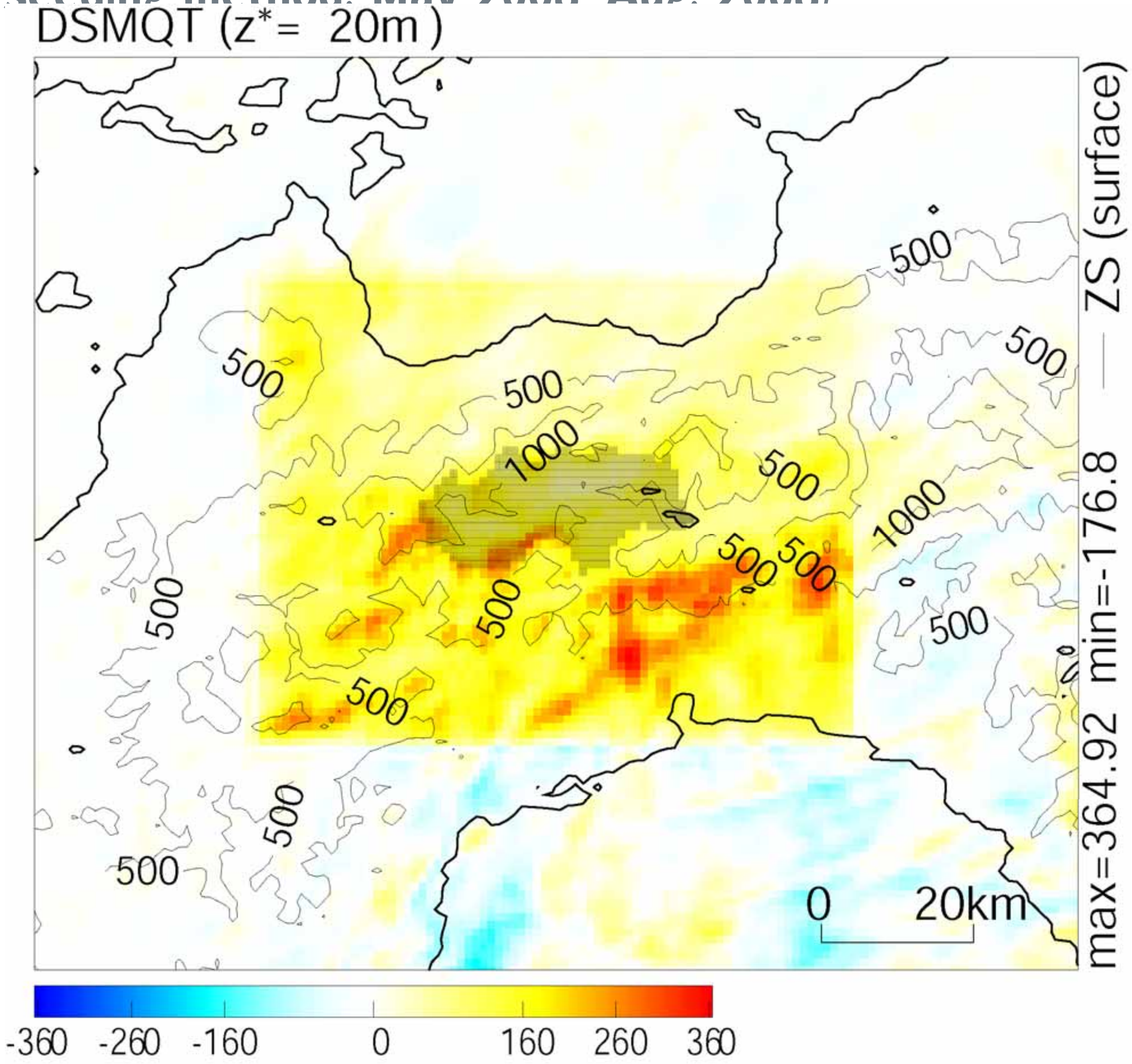


Seeding effect increase with decreasing number concentration ratio.
To increase precip. by 20%, we need to decrease droplet number conc. by 50%.

Seeding Effects on Seasonal Precip.

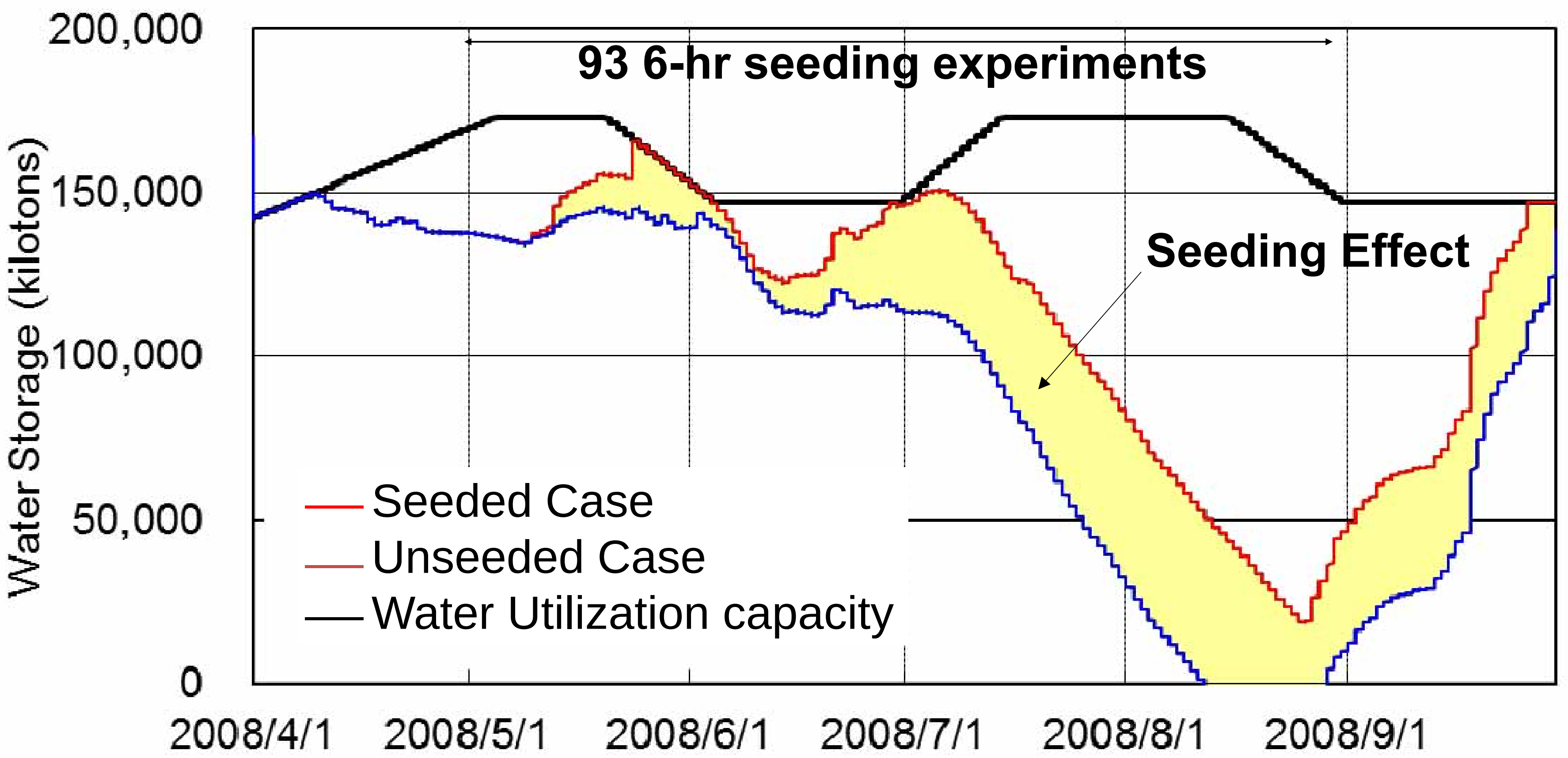
(93 6-hr MP seeding experiments)

Simplified seeding method: May 2008-Aug. 2008)



Seeding Effect on Dam Water Storage

(Numerical simulation with a combination of NHM and land surface model)



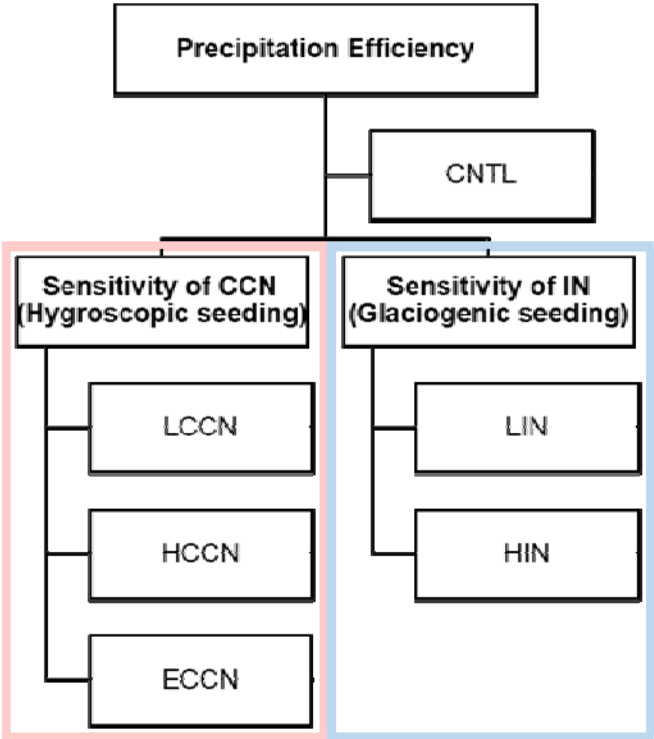
PART FOUR

Mixed-Phase Convective Clouds

Setups for Sensitivity Experiments

Hygroscopic seeding was originally designed to enhance warm rain.
But these days this technique has been used for mixed-phased convective clouds.
Questions are if hygroscopic seeding is really effective for mixed-phased convective clouds and which is more effective, hygroscopic or glaciogenic seeding?

To investigate possible maximum seeding effects by hygroscopic and glaciogenic seeding, sensitivity of surface precipitation to CCN and IN concentrations was investigated by using CReSS model.



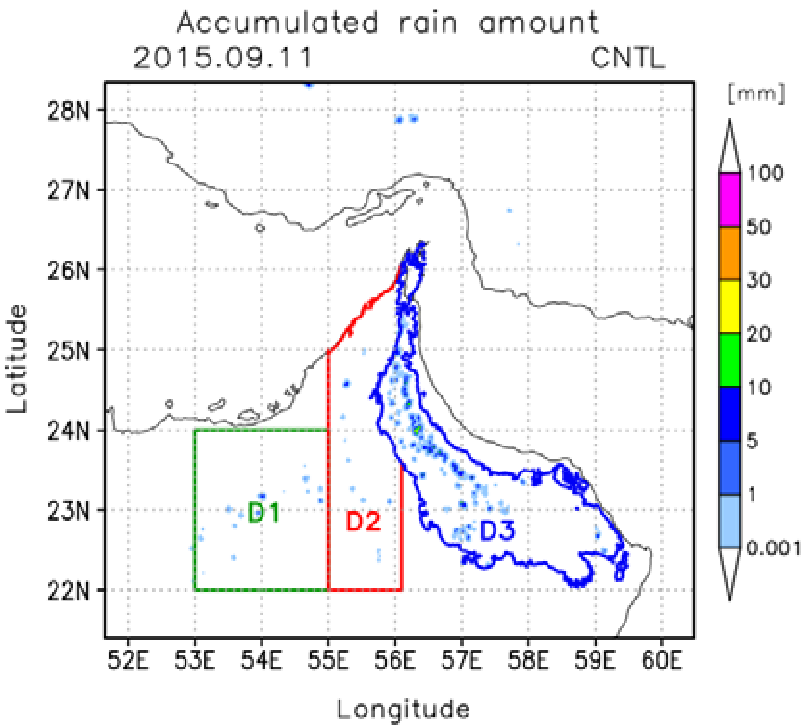
	CCN	IN
CNTL	500 cm^{-3}	Whole nucleation
LCCN	100 cm^{-3}	Whole nucleation
HCCN	1000 cm^{-3}	Whole nucleation
ECCN	2500 cm^{-3}	Whole nucleation
LIN	500 cm^{-3}	Heterogeneous nucleation/10
HIN	500 cm^{-3}	Heterogeneous nucleation*10

- Heterogeneous nucleation process in CReSS

: deposition nucleation, contact freezing, immersion freezing

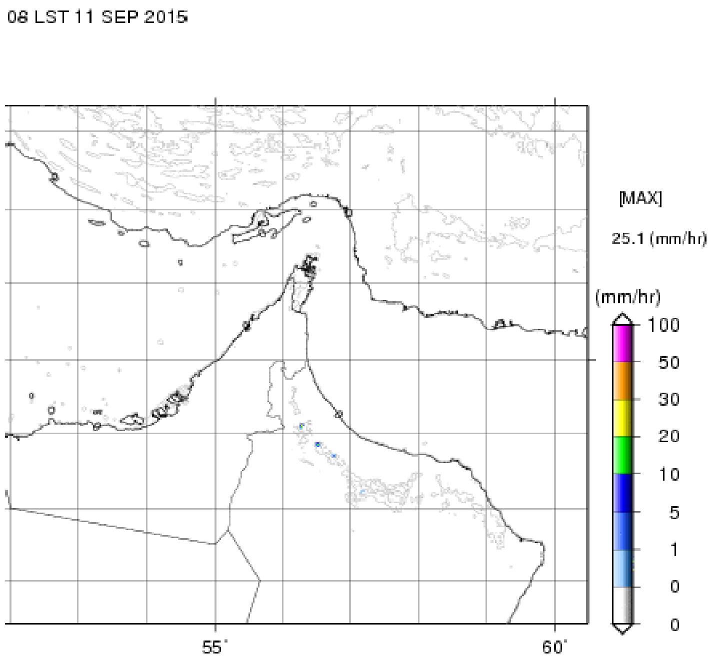
Horizontal distribution of precipitation in CNTL case

Accumulated rain amount



Rain intensity

(every 10min interval)



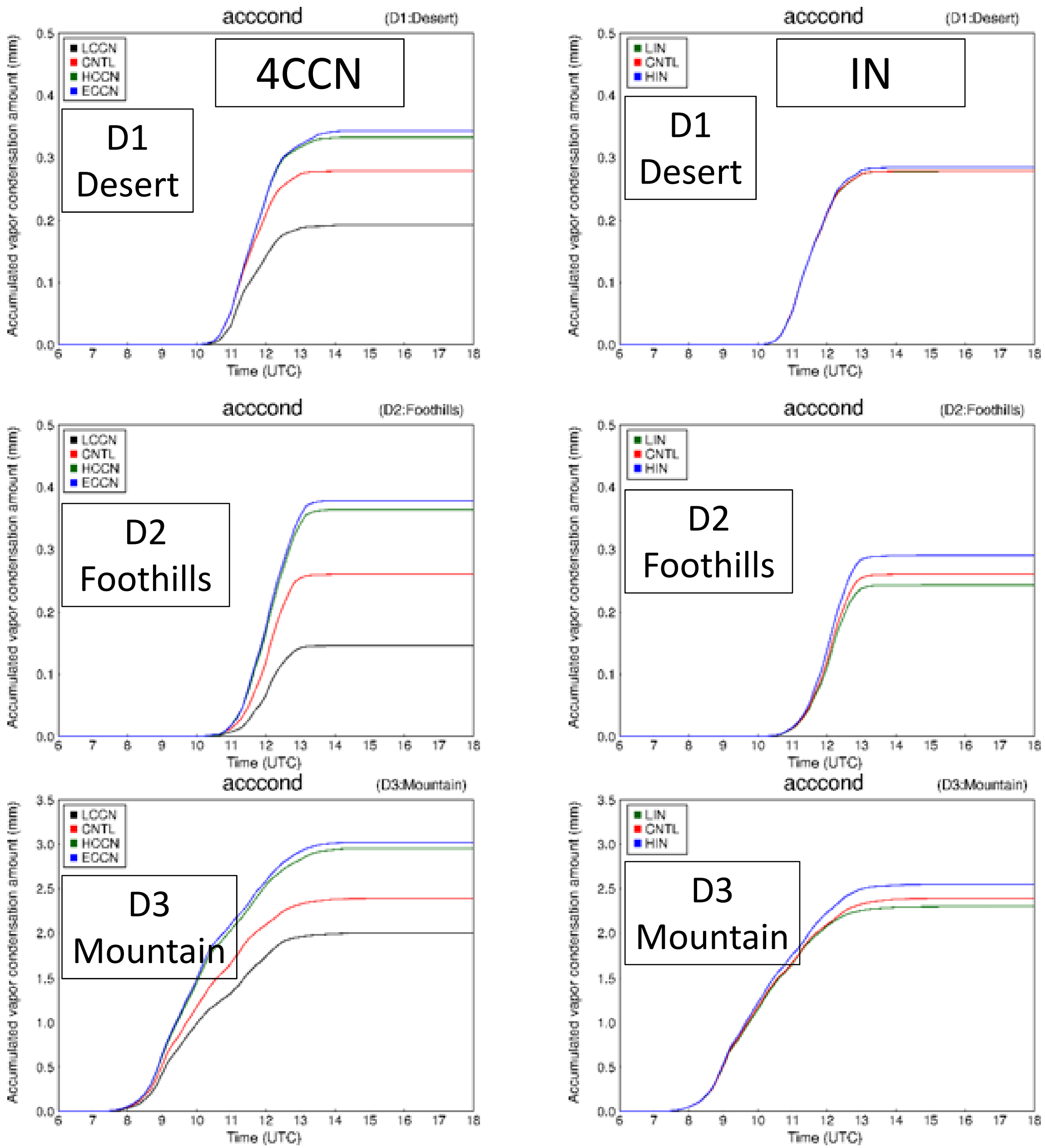
Diurnal convective clouds over mountain area include cumulonimbi and are more vigorous than those over foothill and desert areas. Htop_D3 > Htop_D2 > Htop_D1

Accumulated vapor condensation amount Case (2015.09.11)

CReSS_1 km

For HCCN and ECCN, almost 30 - 50 % increase due to dynamic seeding effect.
HCCN
> Increase droplet number conc. & reduce droplet size
> Weaken warm rain processes & carry up cloud water beyond freezing level
>Increase latent heat release due to droplet freezing (Riming & Freezing)
>Strengthen convection > Increase condensation amount

For HIN, 10 - 20 % increase over foothill and mountain due to static seeding effect.
HIN
> Increase solid hydrometer number conc.
> Enhance deposition growth
> Increase condensation/deposition amount



Domain-averaged accumulated rain amount (3km)

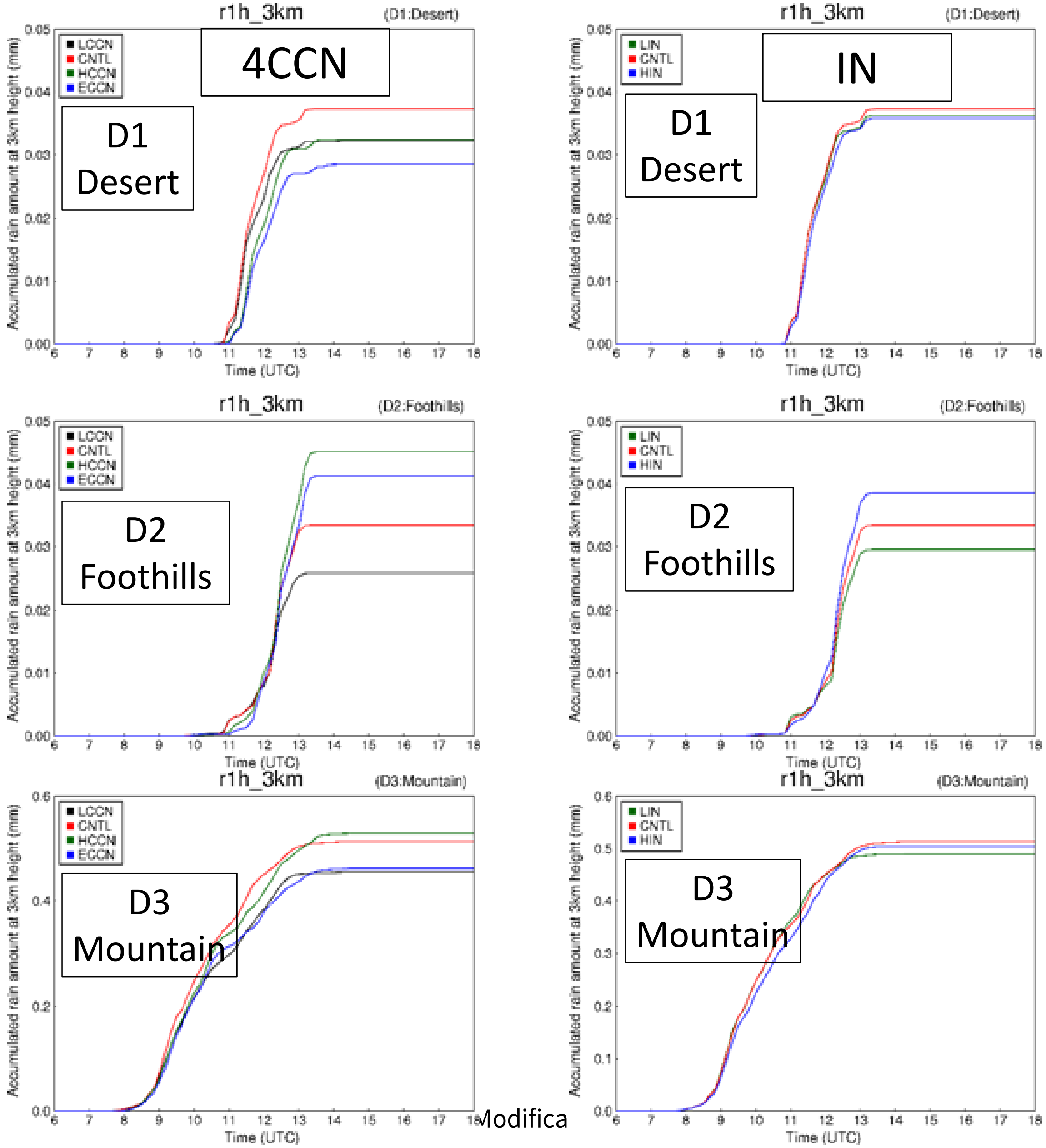
CReSS_1 km

More than 2/3 of precipitation amount at cloud base evaporates and obscures the seeding effects
> look at the precipitation at cloud base

For CCN sensitivity tests, the reduction of seeding effect over mountain is due to over-seeding effect; too many ice particles from homogeneous freezing of cloud droplets and additional heterogeneous freezing resulting from HCCN and ECCN

For IN sensitivity tests, the diminished or even negative seeding effect over mountain is again due to over-seeding effect.

For both CCN and IN sensitivity tests, the negative seeding effect over desert is due to less efficient warm rain processes resulting from reduced mean droplet size.



PART FOUR

Summary and Recommendations

SUMMARY

- Glaciogenic seeding techniques for mixed-phase orographic clouds, using dry-ice or AgI, are almost established and effective if the conditions meet.
  - ✓ Major question is if AgI particles from ground-based generators are effectively delivered in right places in clouds.
- Salt MP seeding of warm clouds may be effective under limited conditions but HF seeding may not.
  - ✓ Major question is if huge amount of seeding materials required is reasonable.
- Hygroscopic seeding of mixed-phase convective clouds not operating homogeneous freezing may be effective if it increases CDNC and decrease mean droplet size. Glaciogenic seeding is less effective.
  - ✓ Need more intensive study on cloud microphysics scheme dependency and cloud characteristics dependency

RECOMMENDATIONS

- Development of numerical models with aerosol / clouds / precipitation integrated microphysics scheme (a sophisticated seeding scheme, especially for hygroscopic seeding)
- Characterization of seeding materials as CCN and INP
- Development of the statistical evaluation method of seeding effects with help of physical predictors for precipitation
- Development of assessment techniques of seedable cloud occurrence frequency for warm and mixed-phase convective clouds
- Development of optimal seeding methods for warm and mixed-phase convective clouds
- Combination with hydrological models

Thank you very much for your attention