CLOUD MODELS
RELATED TO WEATHER MODIFICATION

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INTRODUCTION

- It is well known that a large number of samples are required in order to evaluate seeding effects on surface precipitation using statistical methods due to the large variability of natural precipitation (Dennis, 1980).
- Along with recent advances in computer technology and performance of numerical models, quantitative evaluation of seeding effects using numerical models is gradually becoming realistic and effective. Numerical models are also becoming an indispensable tool for developing various technologies related to precipitation enhancement
  - Assessment of seedability,
  - Development of an optimum seeding method
  - Development of effficient statistical evaluation method with physical predictors of precipitation in target area.
- We review recent research trends using numerical models in precipitation enhancement field.

NUMERICAL MODELS USED IN WEATHER MODIFICATION

- Types of model frameworks
  - Zero, one, two and three-dimensional
    - Zero- dimensional; called parcel or box model & Lagrangian in nature: most accurately express cloud particle generation processes from aerosol particles
  - Time-dependent or steady-state
  - Coupled and uncoupled (kinematic model) between cloud microphysics and dynamics
- Cloud microphysics Parameterizations
  - Bulk cloud microphysics parameterization (Qc, Qr, Qi, Qs, Qg, Qh)
  - Bin (spectral) microphysics parameterization (drops, ice, snow, graupel, hail)
  - New bulk microphysics scheme (Qc, Qr, Ice (Mtotal, Mrime, Vrime, and number)
- Seeding schemes (Classification is proposed by Orville 1996)
  - 1st generation; changing supercooled cloud liquid to ice at some arbitrarily predetermined temperature
  - 2nd generation; creating more ice by arbitrarily adding ice crystals to the domain
  - 3rd generation; simulating a seeding agent field

Multi-Dimensional Bin Microphysics Model

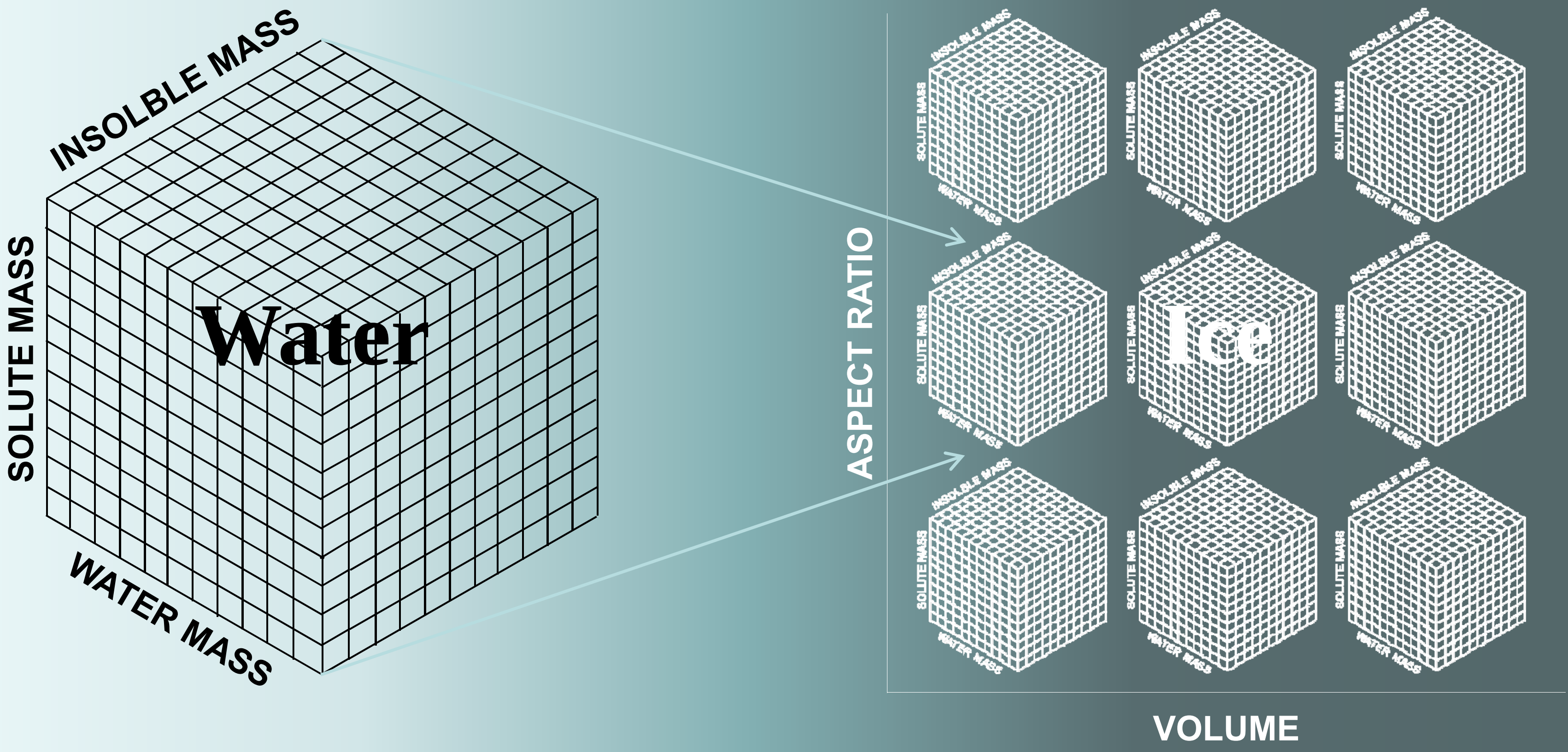
The microphysical parcel model developed by Chen and Lamb (1994) divides the categories of droplet and ice particle into multi-dimensional bin components to express a variety of properties of hydrometeors. Based on their model, we have developed a new parcel model with detailed cloud microphysics. The mass of insoluble material (ice nuclei) is introduced as another variable of droplet and ice particle categories to investigate both CCN and IN abilities of aerosol particles and their effect on microphysical structure of clouds. For ice particle category, the volume of particle is also introduced to simulate the successive change in the bulk density of ice particle in its growth processes (Misumi *et al.*, 2010). We call this "reference model" or "truth model" and use it for comparison with cloud chamber experiments and microphysics parameterizations for 3D-NHM.

Multi-dimensional Bin Microphysics

For discrete expression of hydrometeors

Three-dimensional bin

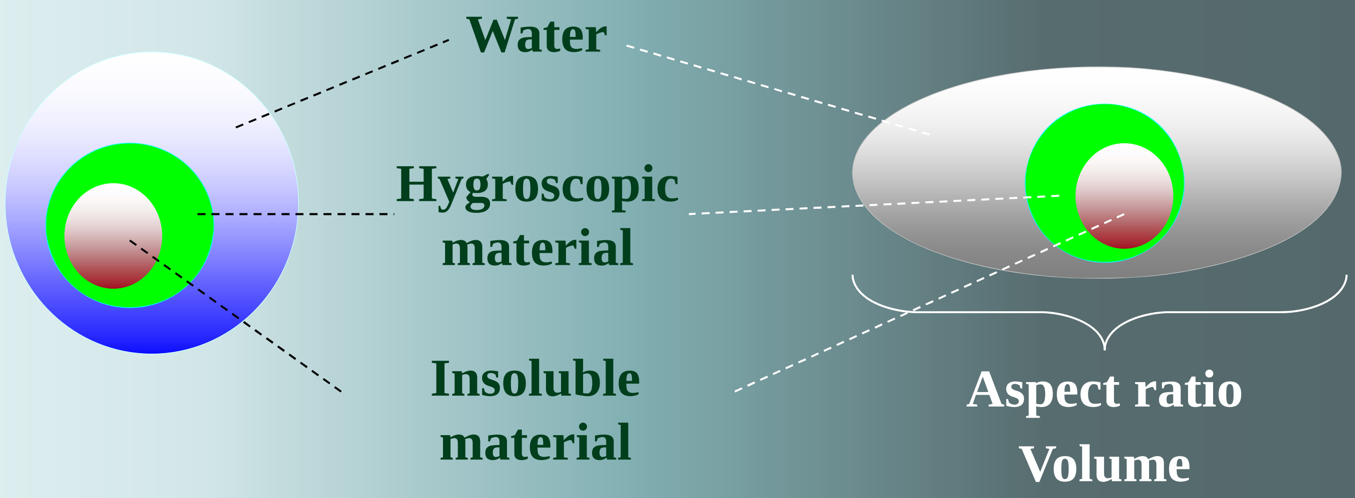
Five-dimensional bin



Multi-dimensional Bin Microphysics

Description of hydrometeors

Water | **Ice**



Three properties

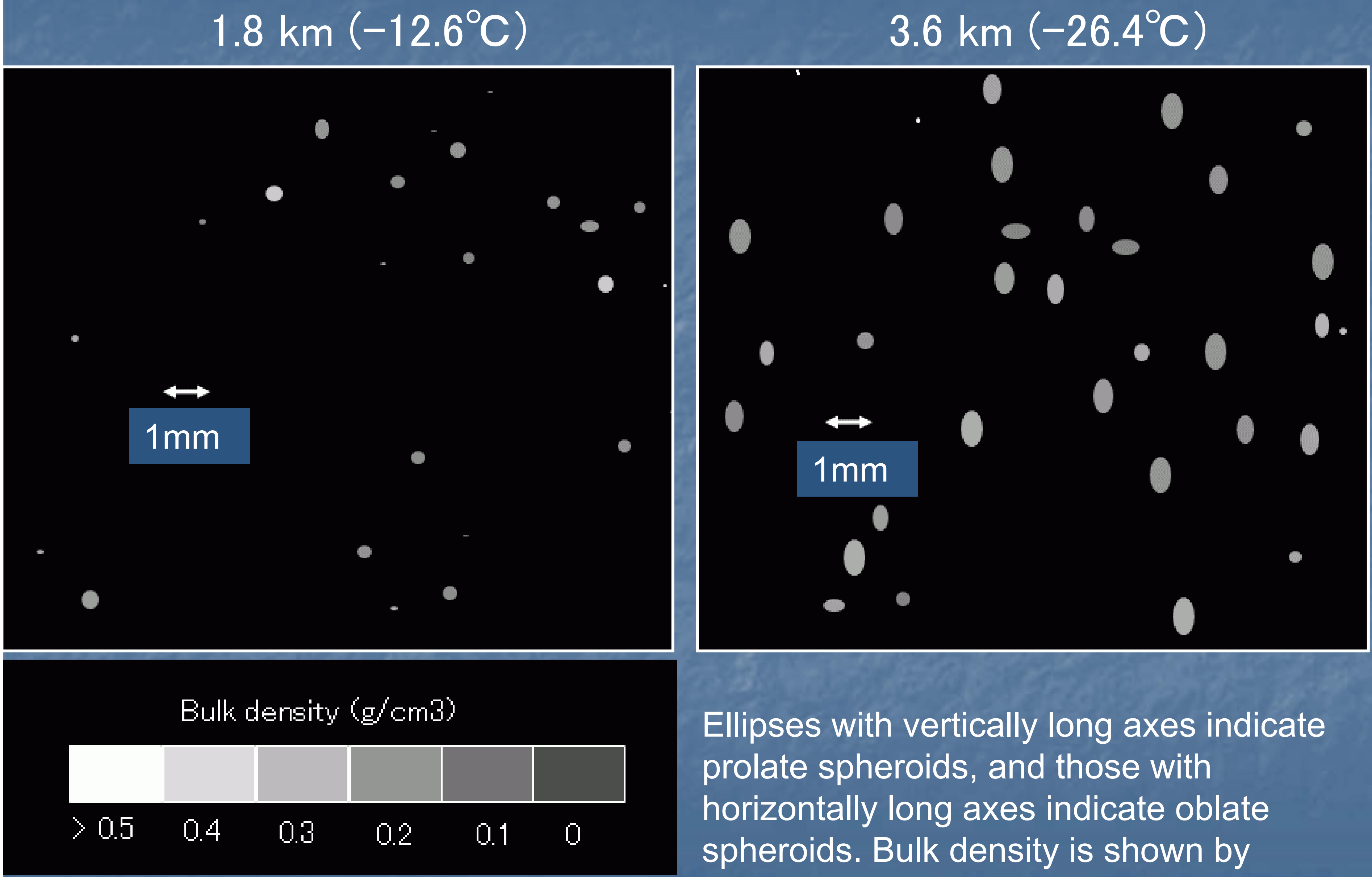
Only two in the original model

Five properties

Only three in the original model

Still so simple compared to the nature, but more sophisticated than the other current SBMs

Solid Hydrometeors Formed in the Model



Ellipses with vertically long axes indicate prolate spheroids, and those with horizontally long axes indicate oblate spheroids. Bulk density is shown by brightness of particles.

Equation of κ-Köhler Theory and Classical Ice Nucleation Theory(CNT)

Developed

Droplet activation

κ-Köhler theory (Yamashita et al. 2011)

$$S = a_w \cdot \exp\left(\frac{4\sigma M_w}{RT\rho_w D}\right)$$

$$\frac{1}{a_w} = 1 + \kappa \frac{V_s}{V_w}$$

Ice nucleation

(condensation/immersion freezing)

CNT (Chen et al. 2008)

$$J = A' \cdot r_N^2 \cdot \sqrt{f} \cdot \exp(B)$$

$$B = \frac{\left(-\Delta g^{\#} - f \cdot \Delta g_g^0\right)}{kT}$$

Original

Köhler theory

(treat soluble particle)

$$\frac{1}{a_w} = 1 + i \frac{M_w m_s}{M_s m_w}$$

Emperical equation based on Danielsen et al.(1972)

(don't include IN imformation)

$$\frac{dn_i}{dt} = -\gamma \cdot \exp(-\gamma(7+T)) \cdot \frac{dT}{dt}$$

CCN & IN Parameters for Arizona Test Dust (ATD)

CCN parameter

Hygroscopicity : 0.017

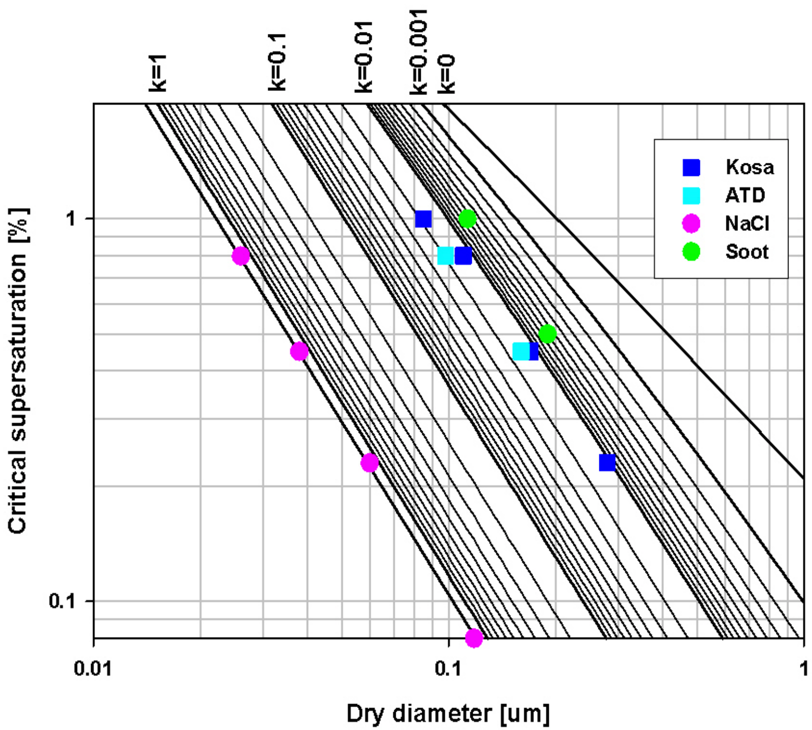
＝＞κ−Köhler theory

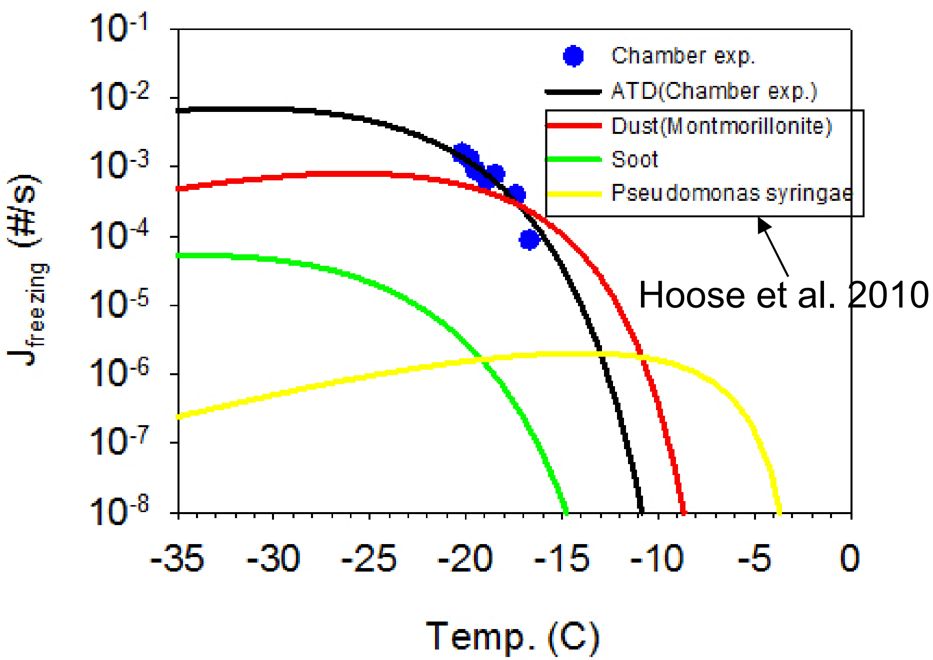
IN parameter

Activation energy : 1.4×10^{-19} J

Contact angle : 37°

＝＞**Classical nucleation theory**





Adiabatic Expansion Simulation Using Parcel Model

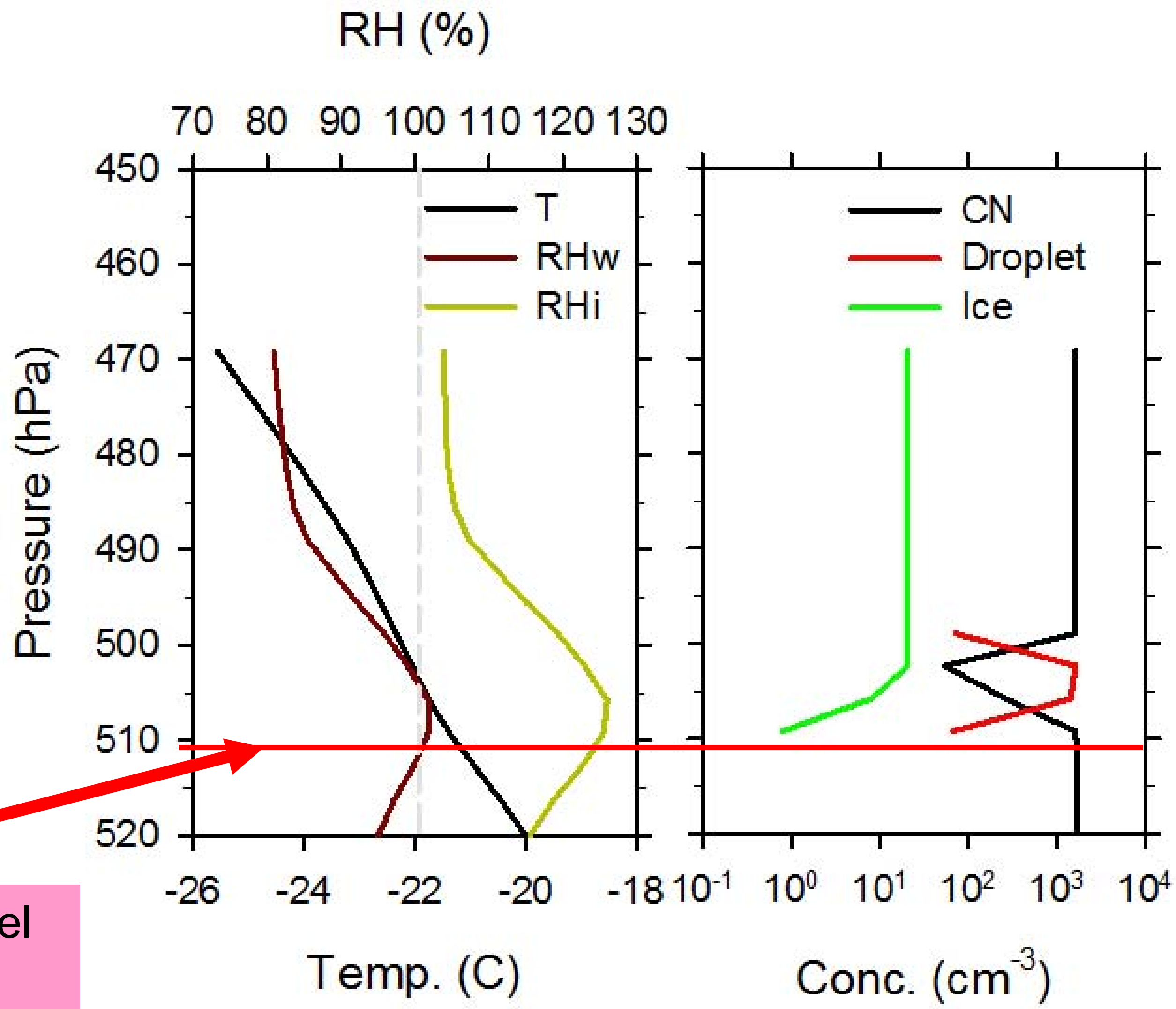
CCN/IN : ATD

Tinitial : -20℃

Pinitial : 520hPa

RHinitial : 95%

Ascent rate : 1m/s



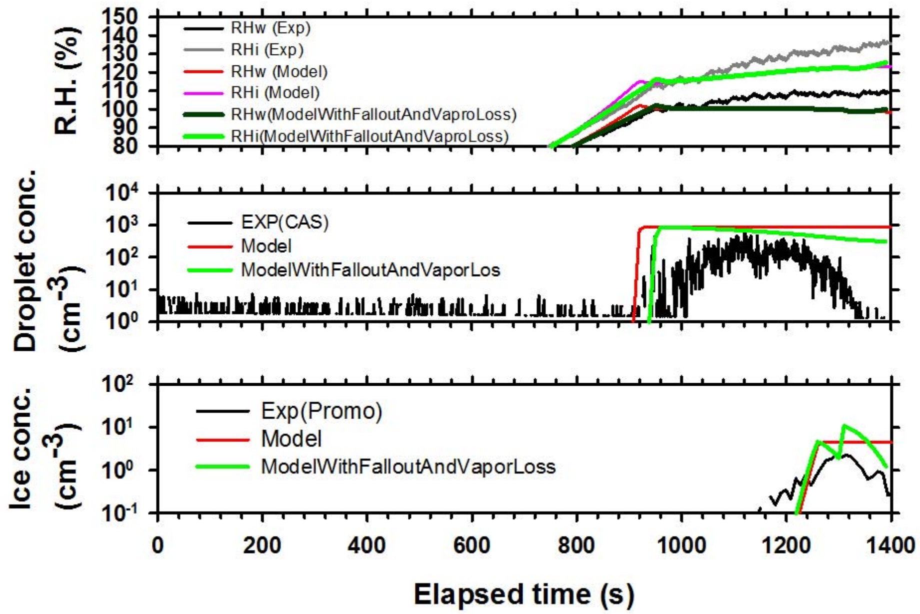
Cloud Condensation Level

(RHw=100%)

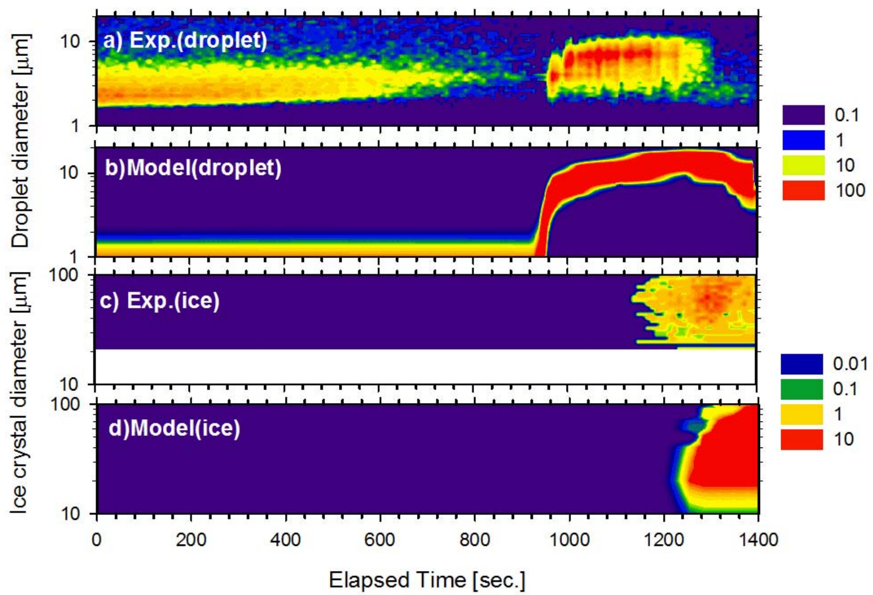
Comparison between Numerical Exp. and Cloud Chamber Exp.

(adiabatic expansion at 3m/s ascent speed)

Time evolution of RH, Droplet concentration, and ice crystal concentration

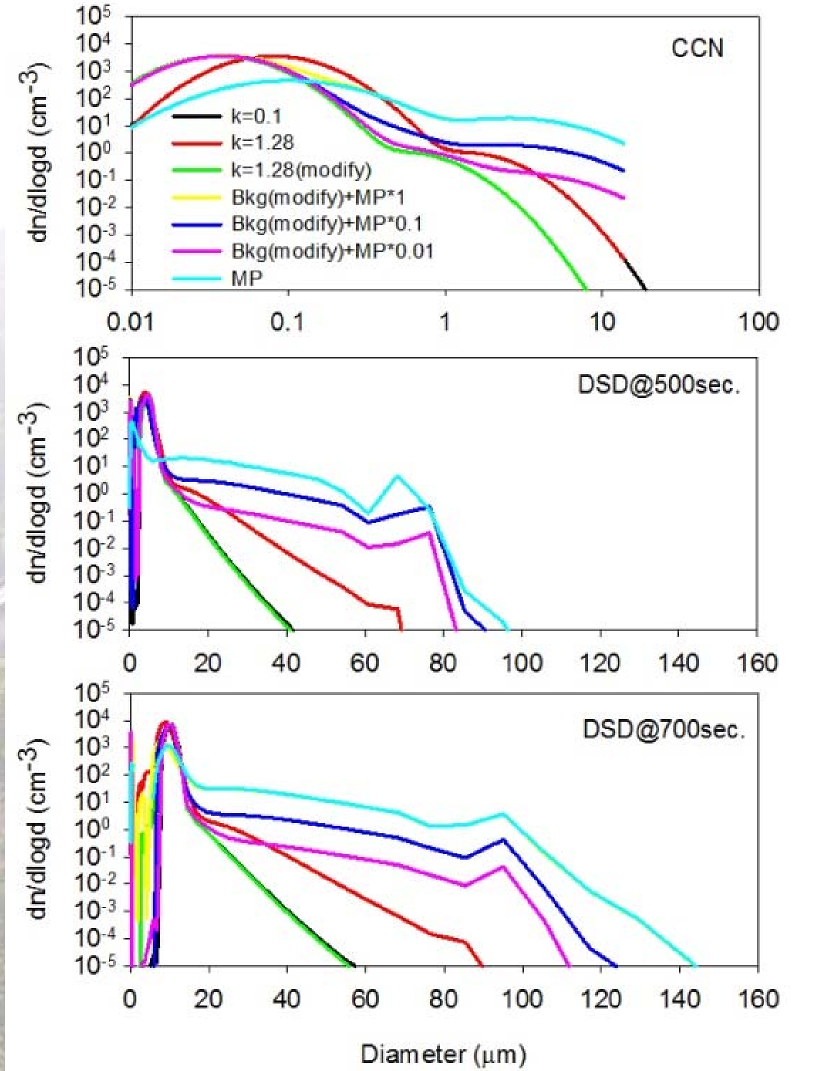


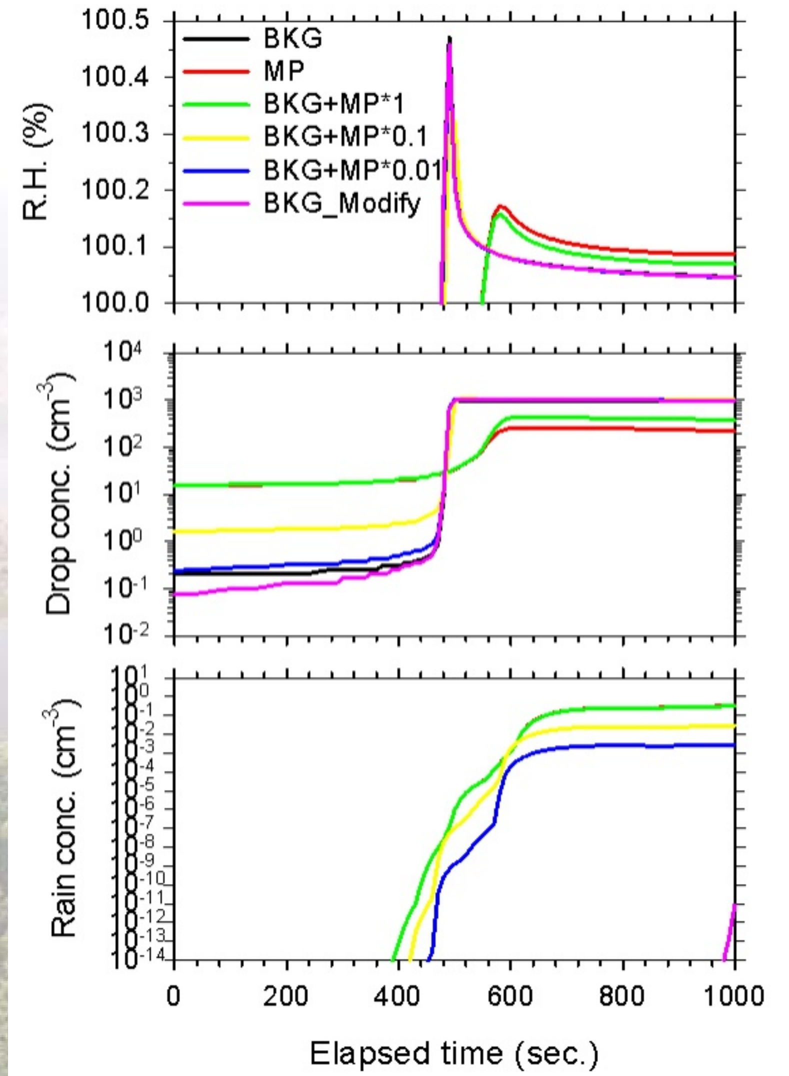
Time evolution of droplet and ice crystal size distribution



Salt Micro-Powder Seeding

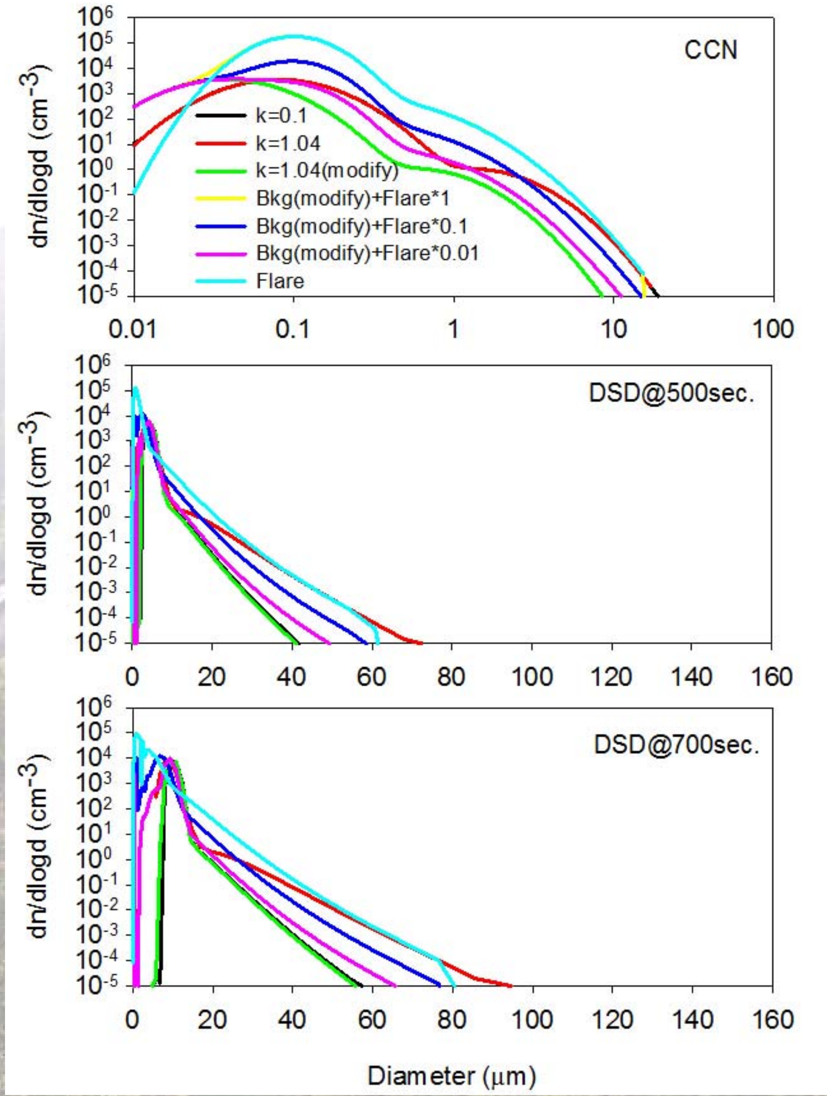
Reference (Parcel) Model

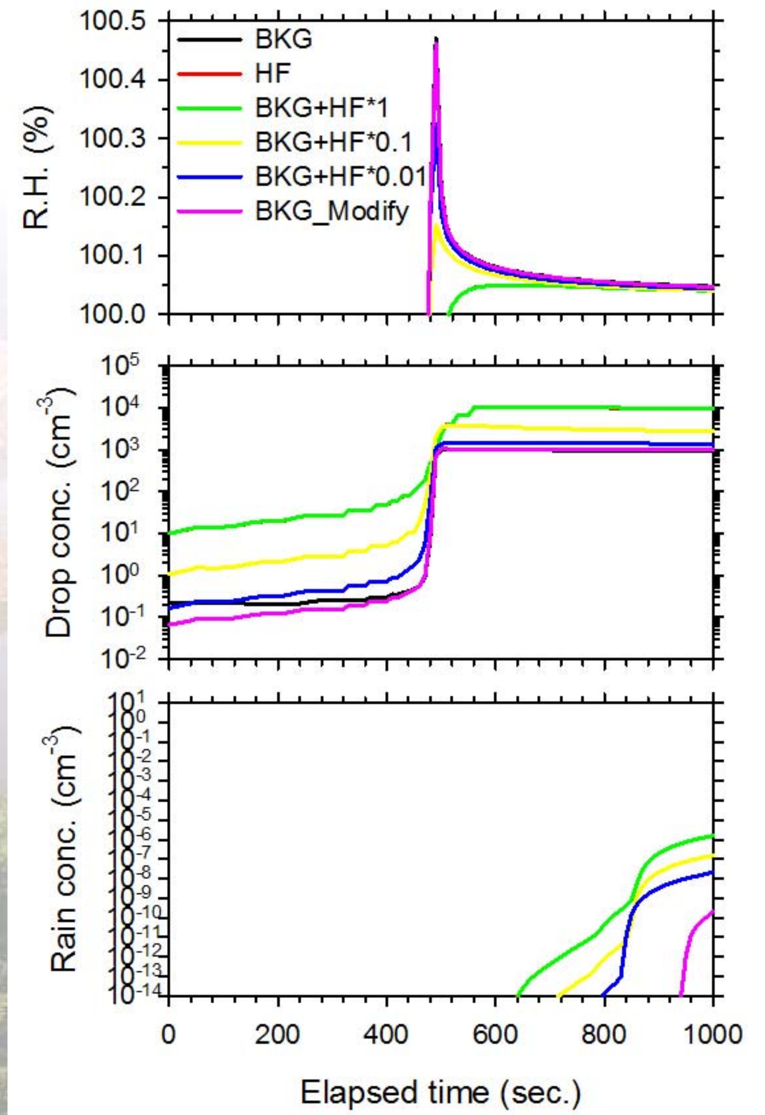




Hygroscopic Flare Seeding

Reference (Parcel) Model



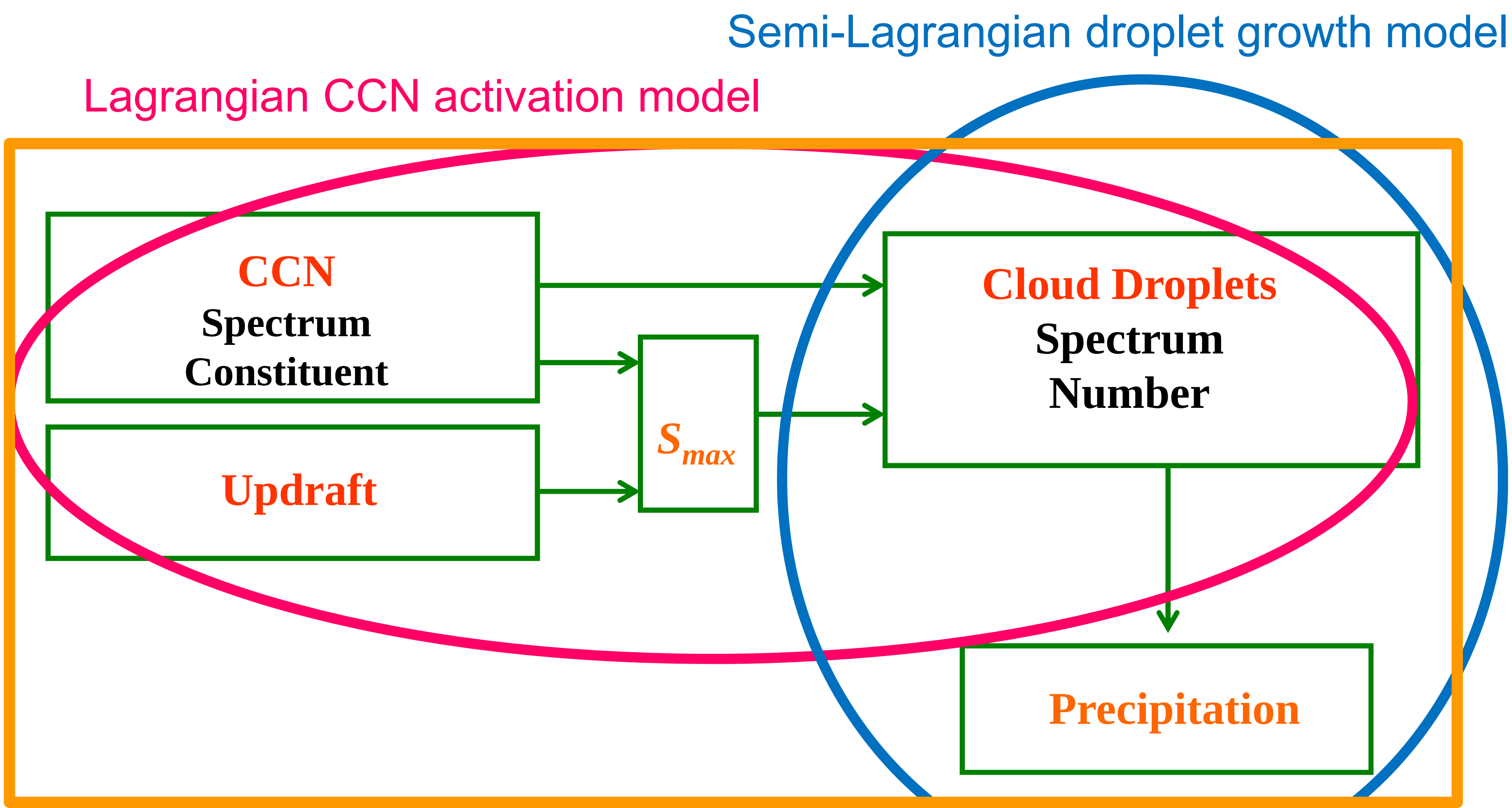


HYGROSCOPIC SEEDING

- Model studies using simplified dynamical frameworks
  - Parcel models (Cooper et al. 1997, Segal et al. 2004, Yamashita et al. 2015)
  - Axisymmetric NHM (Tzivion et al. 1994, Reisin et al. 1996)
  - 2D kinematic models (Caro et al. 2002, Kuba & Murakami 2010)
- Two- and three- dimensional NHM
  - 2D NHM (Yin et al. 2000)
- Competitive condensation growth (swelling and activation of hygroscopic particles as CCN and diffusion growth immediately thereafter) among seeding aerosols and background aerosols acting as CCN could be accurately investigated using parcel models and some kinematic models.
- All the numerical simulations suggest that the seeding effects to promote raindrop formation of hygroscopic particles with submicron sizes are weak or negative as compared to those of hygroscopic particles with micron sizes.

Numerical Experiment on Hygroscopic Seeding

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



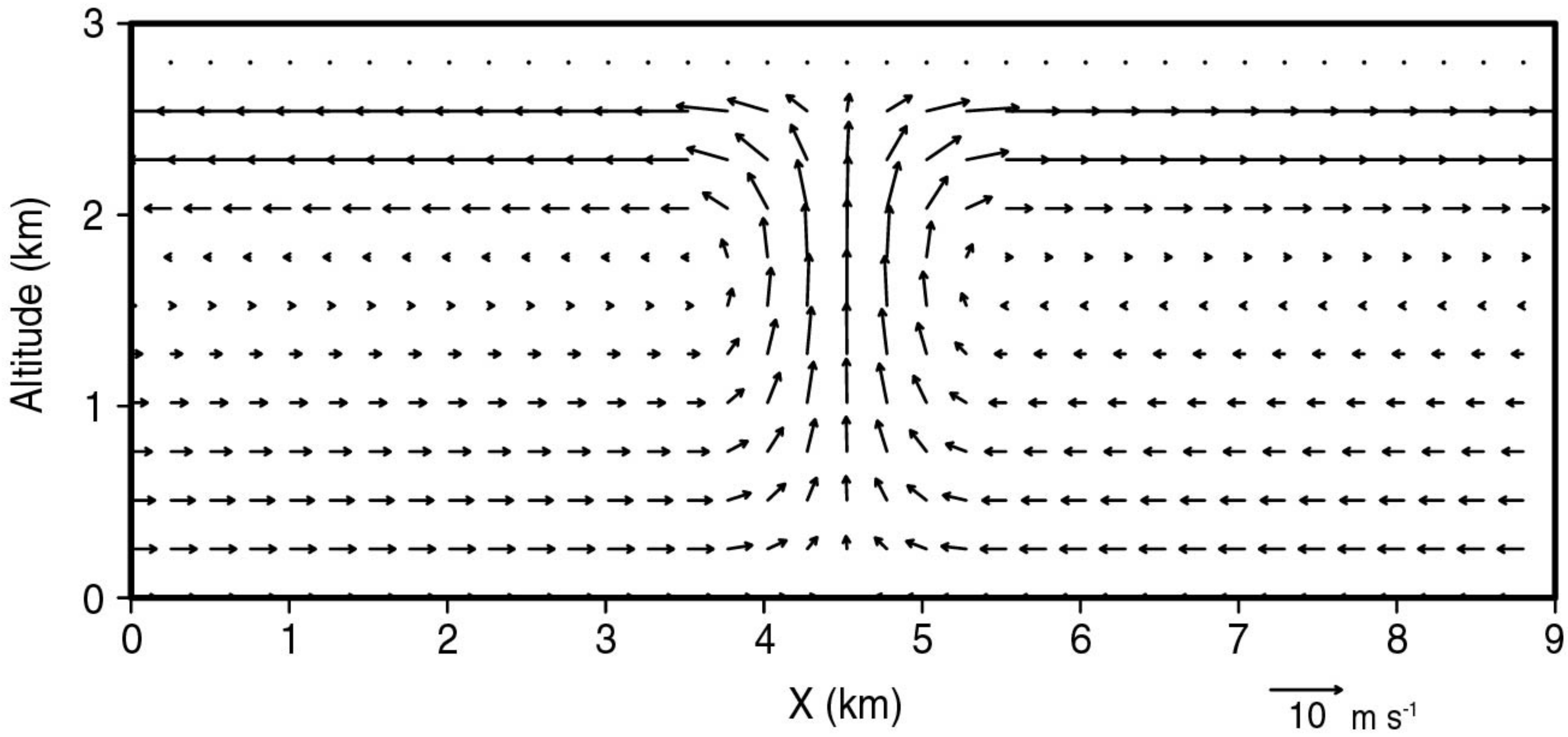
This model can simulate the activation process of CCN, including giant CCN precisely although dynamic frame

Eulerian spatial model for advection and

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

Wind Field (25 min)

Shallow cumulus cloud

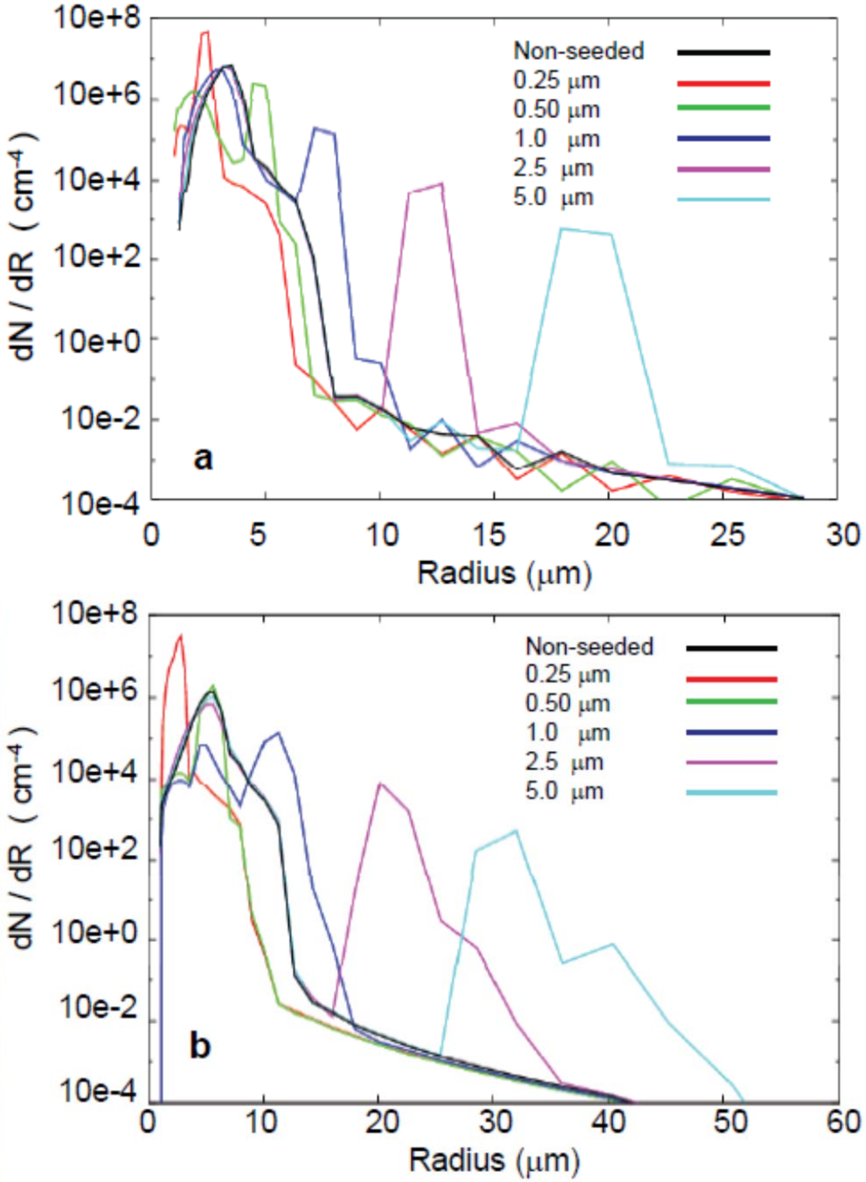


Initial Cloud Droplet Size Distribution

(Mono-disperse, 100 m above cloud base)

Shallow convective cloud

Stratiform cloud

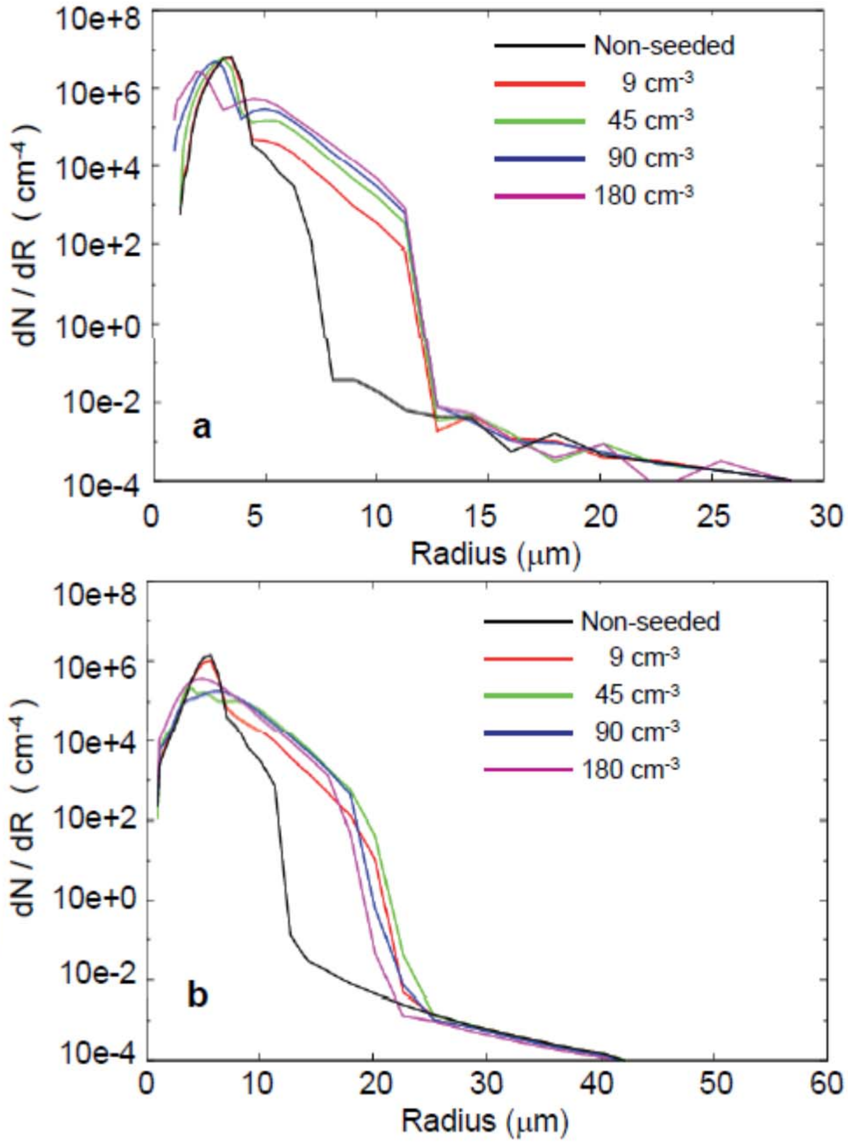


Initial Cloud Droplet Size Distribution

(MP Seeding, 100 m above cloud base)

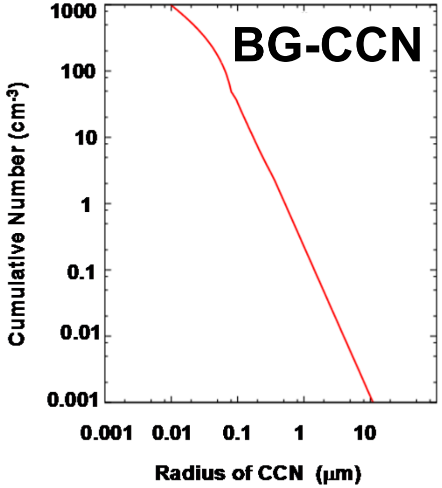
Shallow convective cloud

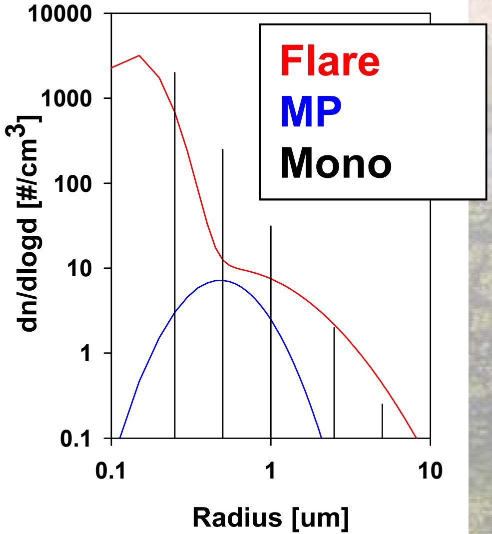
Stratiform cloud



Numerical Experiment on Hygroscopic Seeding

(Hybrid Cloud-Microphysics Model)





Mono-disperse NaCl Particles
(Polluted Maritime, Shallow Cumulus)

Total Mass Ratio(Standard:280μg/m^3)

Radius[um]	0.1	0.5	1	10
0.25	**1.0**(1.1)	**0.7**(1.7)	**0.2**(3.1)	**0.1**(25.2)
0.50	**1.0**(1.0)	**1.0**(0.9)	**1.2**(0.6)	**0.2**(3.2)
1.00	**1.0**(1.0)	**1.0**(0.9)	**1.1**(0.9)	**1.3**(0.4)
2.50	**1.0**(1.0)	**1.0**(1.0)	**1.1**(1.0)	**1.5**(0.4)
5.00	**1.0**(1.0)	**1.0**(1.0)	**1.1**(1.1)	**1.3**(0.9)

- **Positive seeding effect for particles > 0.5um**
- Optimum size and seeding effect increase with increasing the total amount of seeding particles
- Reasonable sizes are 1.0~2.0 from cost benefit and environmental consideration

GLACIOGENIC SEEDING

- AgI seeding
  - 2D-NHM with AgI as prognostic variable (Hsie et al. 1980,)
  - 3D-NHM with AgI (Farley et al. 1994, Meyers et al. 1995, etc.)
  - 3D-NHM with AgI in air and hydrometeors (Hashimoto et al. 2008, Xue et al. 20013, etc.)
- Dry ice seeding
  - 2D-NHM with dry-ice as prognostic variable (Kopp et al. 1983)
  - 3D-NHM with simplified dry-ice seeding scheme (Murakami et al. 2007)
  - 3D-NHM with with dry-ice as prognostic variable (Hashimoto et al. 2008)
- Liquid carbon dioxide seeding
  - 3D-NHM with simplified liquid CO2 seeding scheme (Guo et al. 2006, Seto et al. 2011)
  - Need to re-examine the number of ice crystals generated from the unit mass of liquid CO2 because liquid CO2 boils and vaporizes quickly (on the order of 1 second) before being dispersed over a wide area.
  - Liquid CO2 seeding is never superior to dry ice seeding (Hashimoto & Murakami, 2016).

Glaciogenic Seeding Scheme for MRI-NHM

Seeding Materials

$$\frac{\partial Q_{sd}}{\partial t} + ADV(Q_{sd}) + DIF(Q_{sd}) = \left(\frac{dQ_{sd}}{dt}\right)_{sd} + \left(\frac{dQ_{sd}}{dt}\right)_{sub} + \left(\frac{dQ_{sd}}{dt}\right)_{fall} + \left(\frac{dQ_{sd}}{dt}\right)_{scv}$$

$$\frac{\partial N_{sd}}{\partial t} + ADV(N_{sd}) + DIF(N_{sd}) = \left(\frac{dN_{sd}}{dt}\right)_{sd} + \left(\frac{dN_{sd}}{dt}\right)_{sub} + \left(\frac{dN_{sd}}{dt}\right)_{fall} + \left(\frac{dN_{sd}}{dt}\right)_{scv}$$

Cloud Ice

$$\frac{\partial Q_i}{\partial t} + ADV(Q_{sd}) + DIF(Q_i) = PRD(Q_i) + \left(\frac{dQ_i}{dt}\right)_{sd}$$

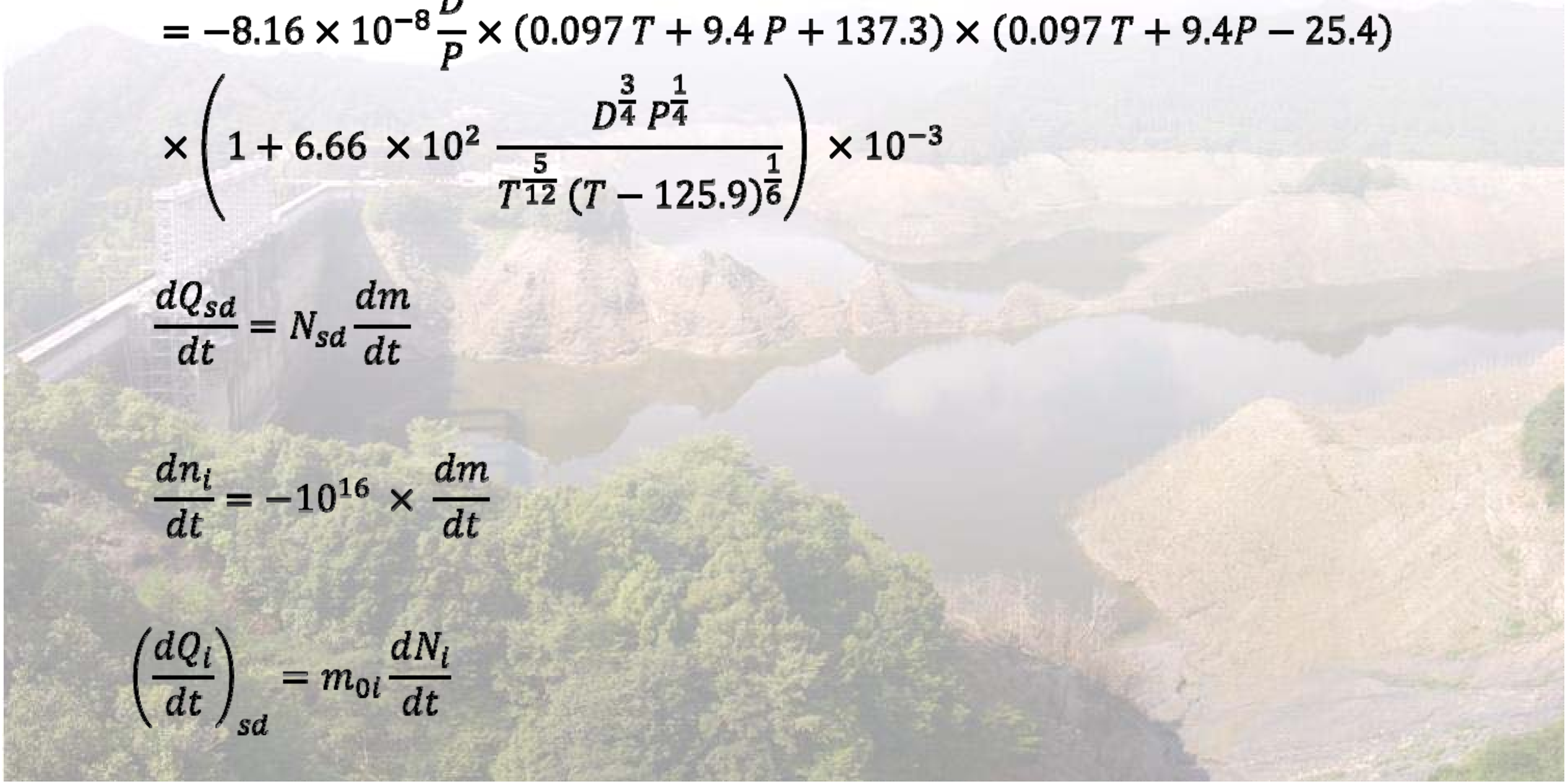
$$\frac{\partial N_i}{\partial t} + ADV(N_i) + DIF(N_i) = PRD(N_i) + \left(\frac{dN_i}{dt}\right)_{sd}$$

$$\frac{\partial \theta}{\partial t} + ADV(\theta) + DIF(\theta) = PRD(\theta) + \frac{L_s}{c_p\,\pi}\left(\frac{dQ_i}{dt}\right)_{sd}$$

$$\left(\frac{dQ_i}{dt}\right)_{sd} = m_{0i}\left(\frac{dN_i}{dt}\right)_{sd}$$

Dry-Ice Pellet Seeding

Evaporation rate of dry-ice pellet



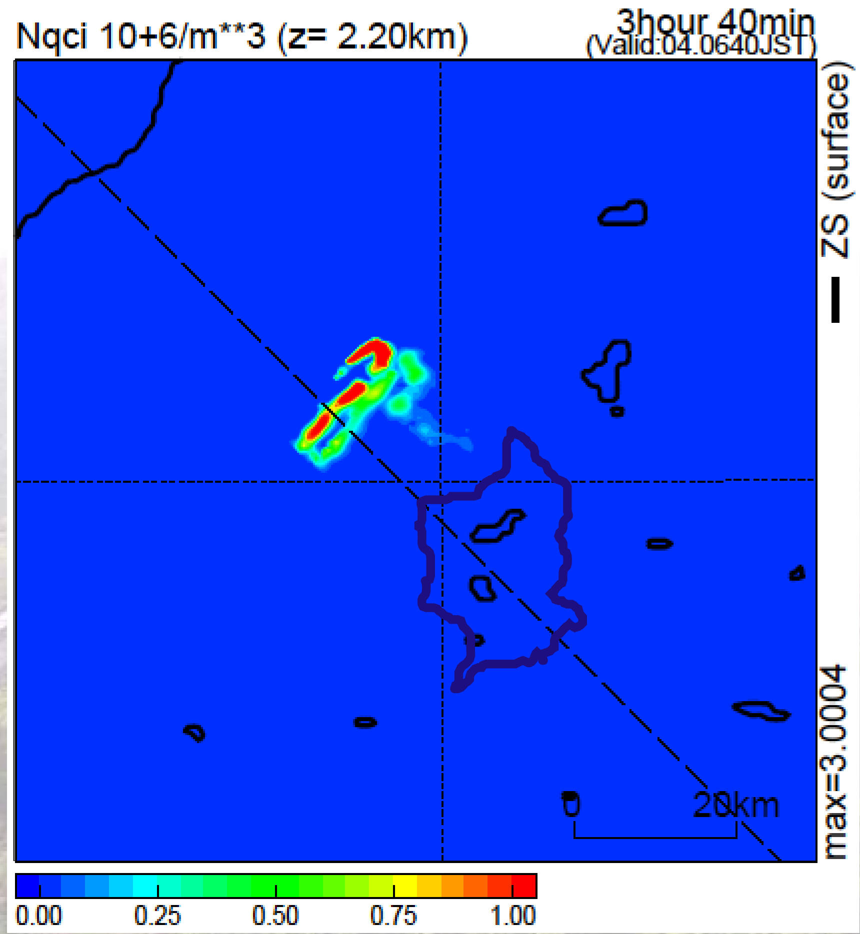
$$\frac{dm}{dt} = -8.16 \times 10^{-8} \frac{D}{P} \times (0.097\,T + 9.4\,P + 137.3) \times (0.097\,T + 9.4P - 25.4) \times \left(1 + 6.66 \times 10^{2} \frac{D^{\frac{3}{4}}\,P^{\frac{1}{4}}}{T^{\frac{5}{12}}\,(T - 125.9)^{\frac{1}{6}}}\right) \times 10^{-3}$$

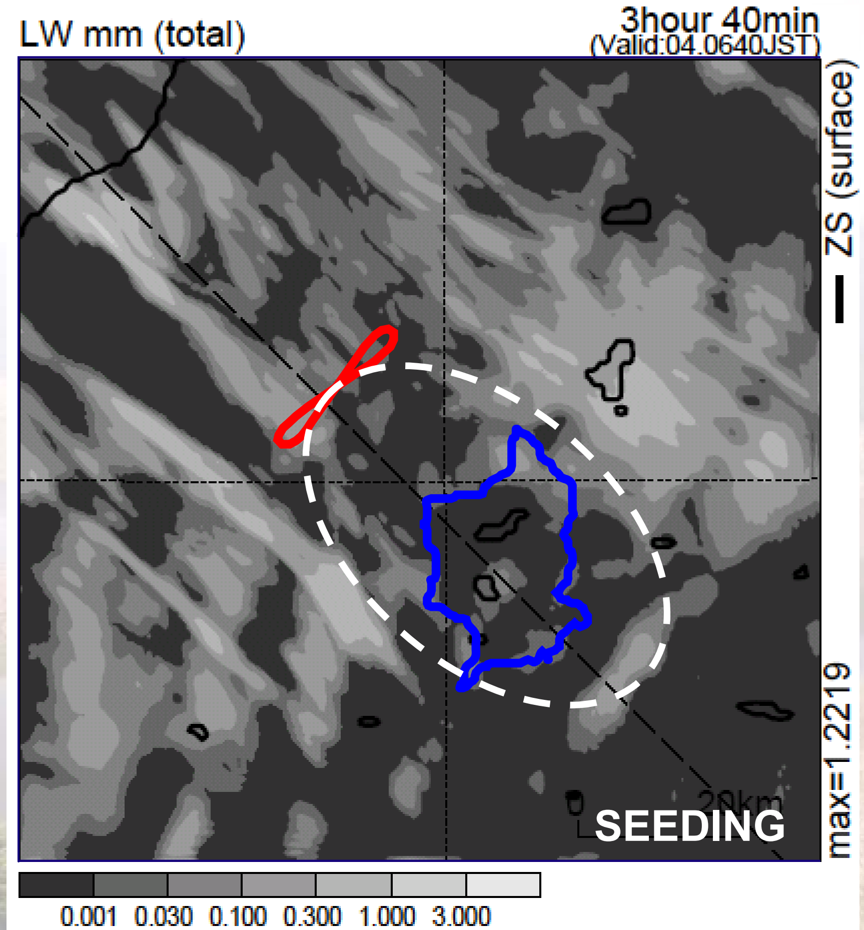
$$\frac{dQ_{sd}}{dt} = N_{sd} \frac{dm}{dt}$$

$$\frac{dn_i}{dt} = -10^{16} \times \frac{dm}{dt}$$

$$\left(\frac{dQ_i}{dt}\right)_{sd} = m_{0i} \frac{dN_i}{dt}$$

Dry Ice Pellet Seeding in NHM

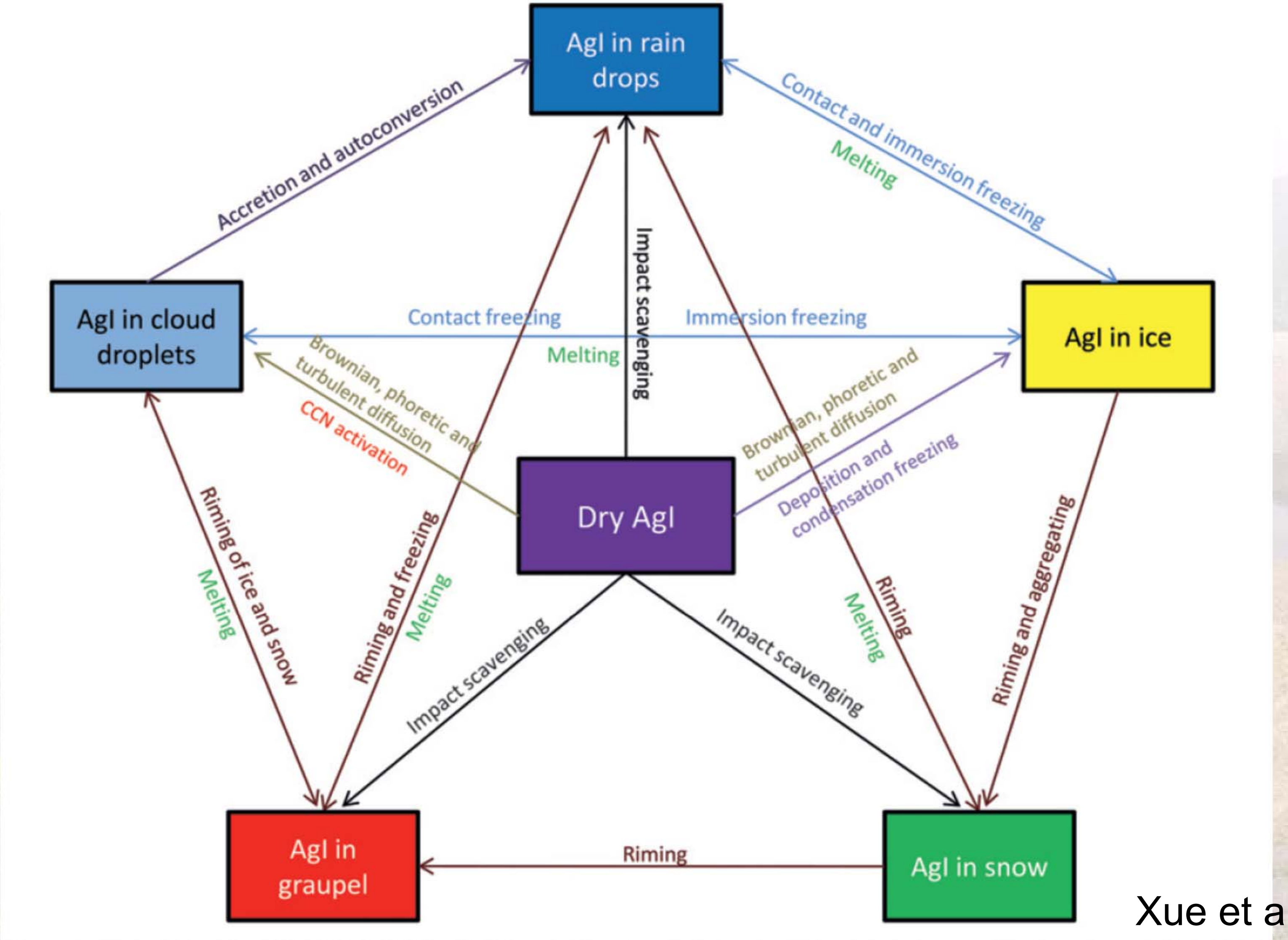




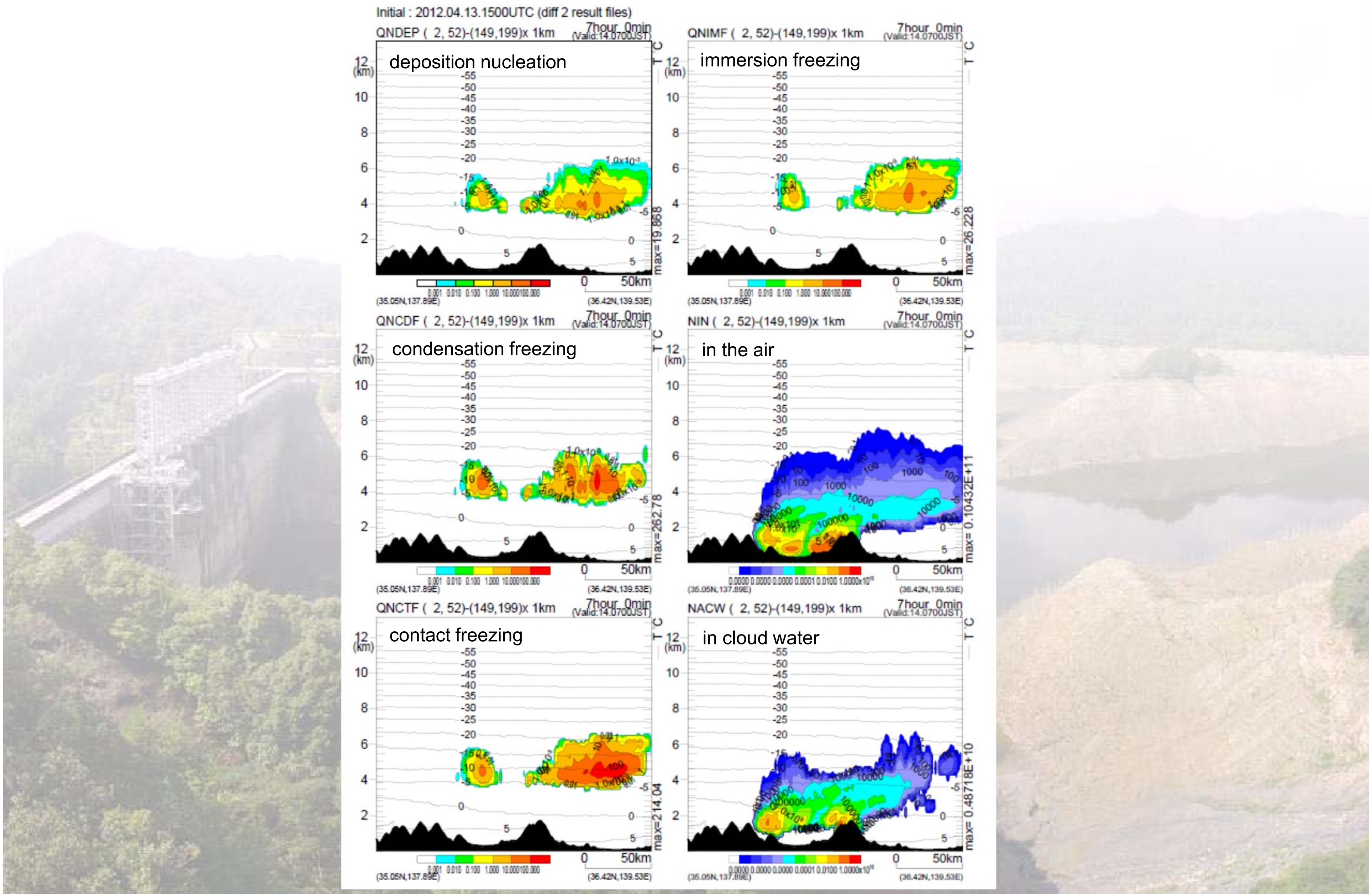
Number conc. of cloud ice produced by dry ice pellet seeding

Depositional growth of ice & snow crystals
↓
Depletion of cloud water

AgI Seeding Scheme



Xue et al. 2013



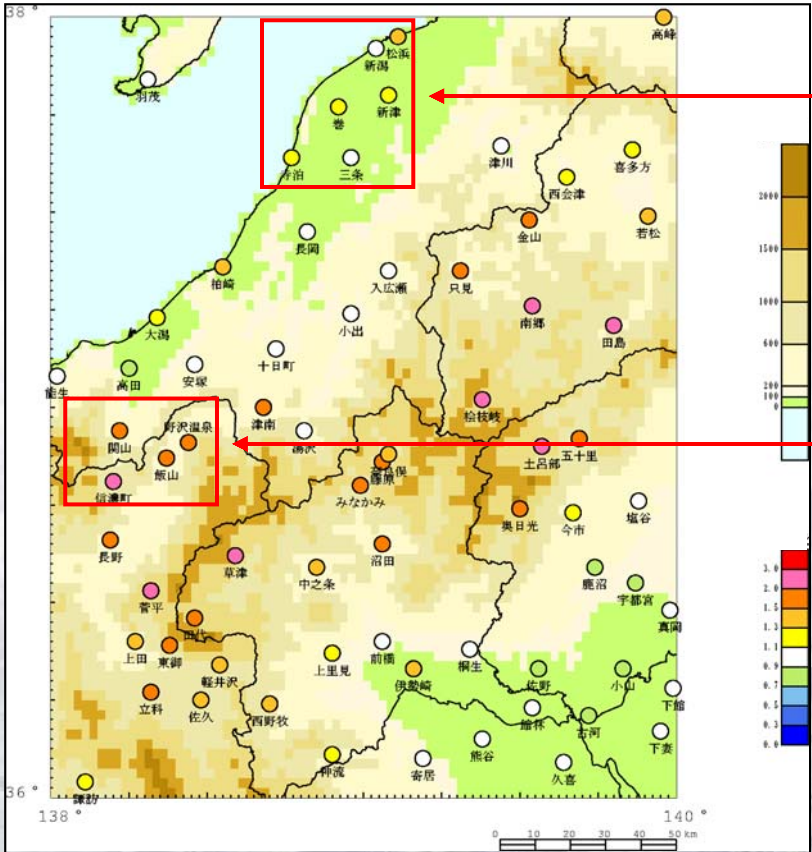
Initial : 2012.04.13.1500UTC (diff 2 result files)
QNDEP (2, 52)-(149,199)x 1km
7hour 0min
deposition nucleation
QNIMF (2, 52)-(149,199)x 1km
immersion freezing
QNCDF (2, 52)-(149,199)x 1km
condensation freezing
NIN (2, 52)-(149,199)x 1km
in the air
QNCTF (2, 52)-(149,199)x 1km
contact freezing
NACW (2, 52)-(149,199)x 1km
in cloud water
(35.05N,137.89E)
(36.42N,139.53E)
50km
max=19.858
max=26.228
max=262.78
max= 0.10432E+11
max=214.04
max= 0.48718E+10

MODEL VALIDATION AND IMPROVEMENT

- Not only models used for precipitation enhancement research, but also models used for numerical forecasting and general atmospheric research are required to have high accuracy and high reproducibility of simulated phenomena. Simulation results such as seeding effects will be trusted by using such a model.
- Regarding airflow structures, thermodynamic structures, and cloud microphysical structures simulated by the models, it is necessary to verify the reproducibility of the models against the observations and to improve them.
- For the models used in precipitation enhancement research, it is also essential to verify and improve seeding schemes against observation results on responses of clouds and precipitation due to seeding.

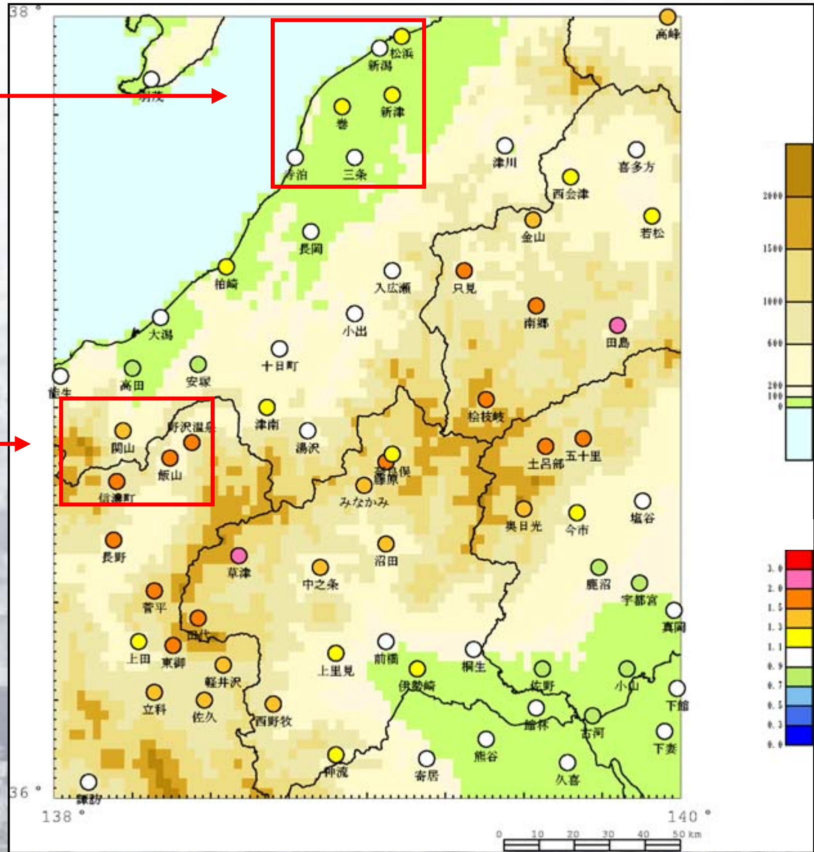
Comparison of Surface Precipitation from 1km_NHM and Raingauges

Before correction for collection efficiency



Ratio of total precipitation amount (model / observation)

After correction for collection efficiency

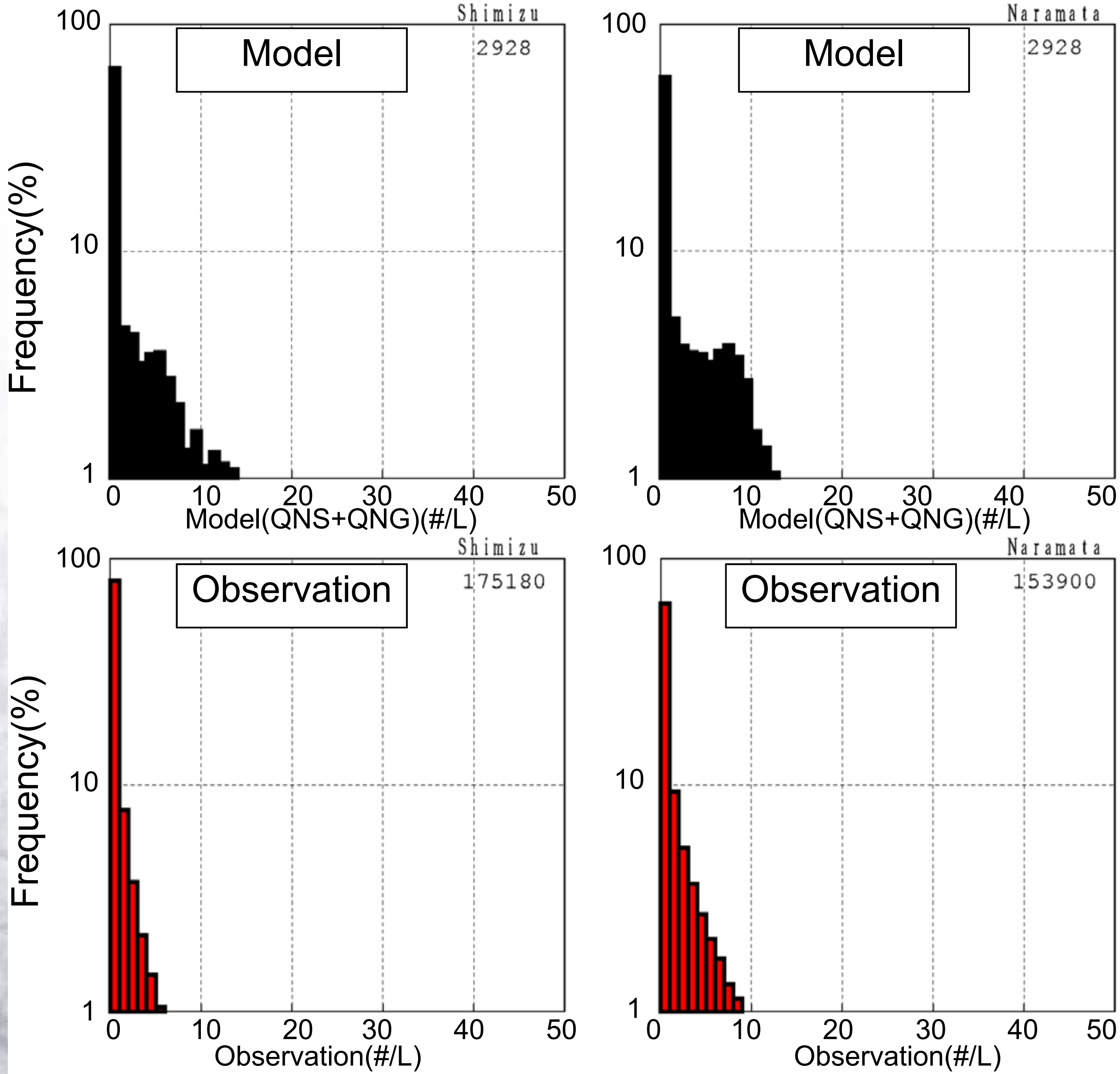


Ratio of total precipitation amount (model / observation)

(Analytical period: Dec.2007~Mar.2008)

Japanese cloud seeding Experiment for Precipitation Augmentation

Comparison of Solid Precip. Number Conc.

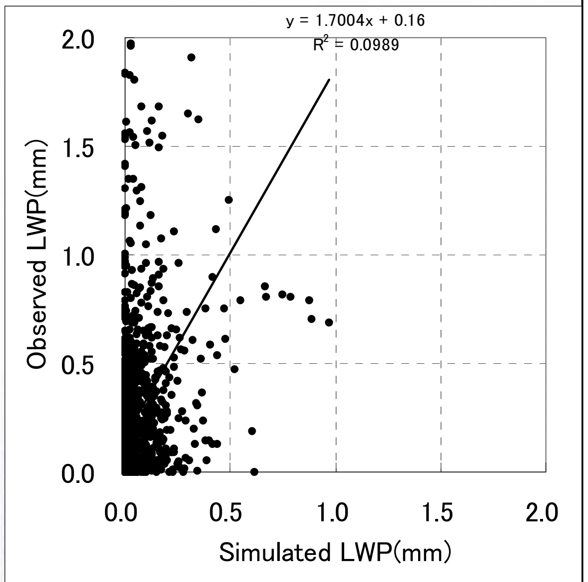


(Optical disdrometer measurements at Shimizu and Naramata sites
Dec. 2007~Mar. 2008)

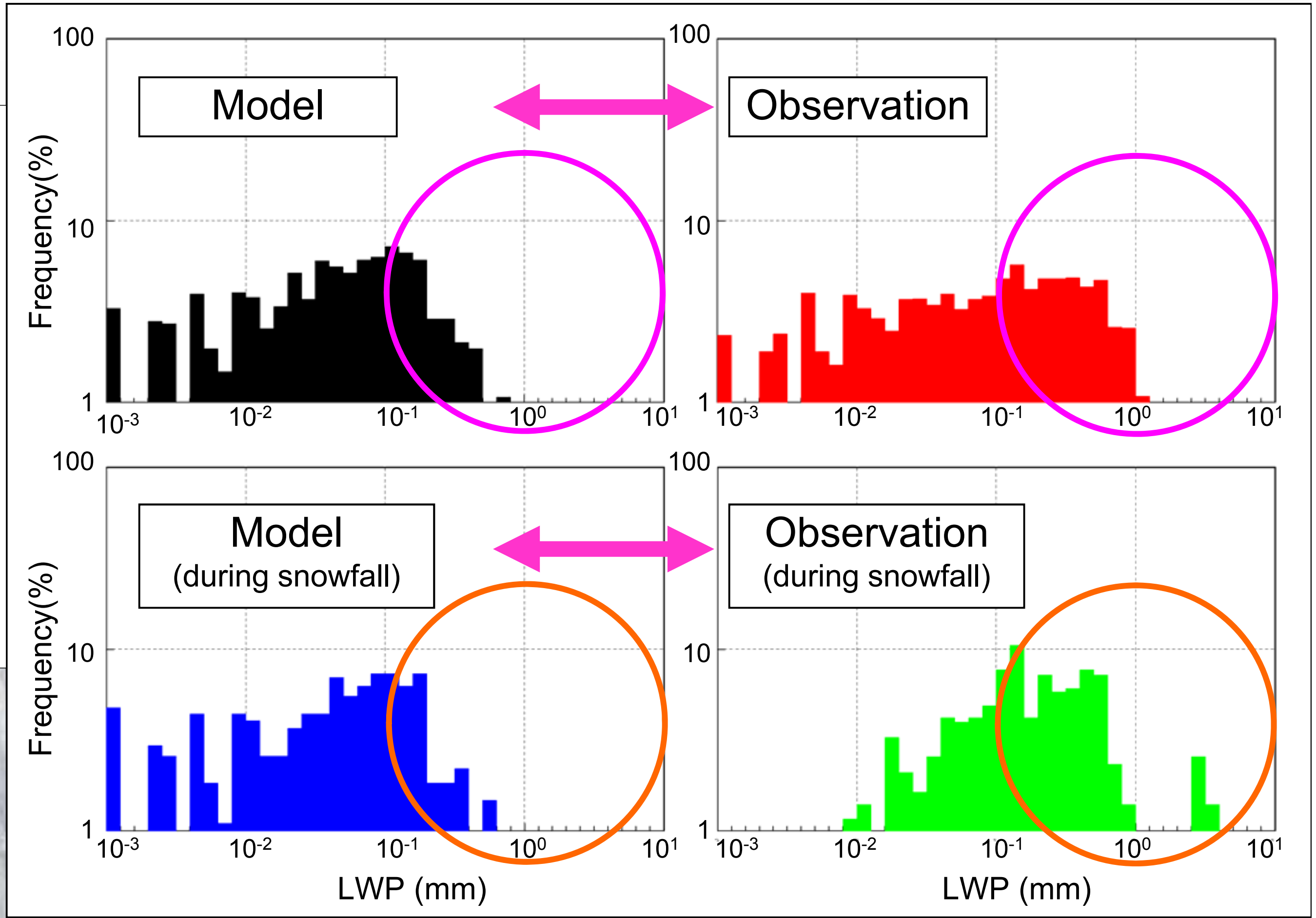
Japanese cloud seeding Experiment for Precipitation Augmentation

Comparison of LWP

(Microwave radiometer; Dec. 2007~Mar. 2008)



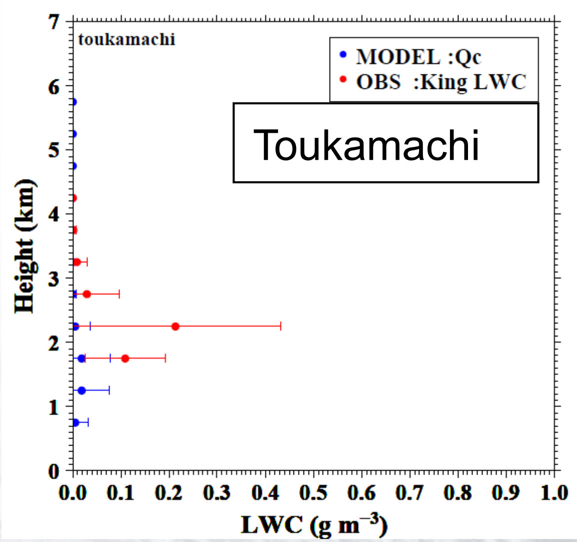
Scatter diagram

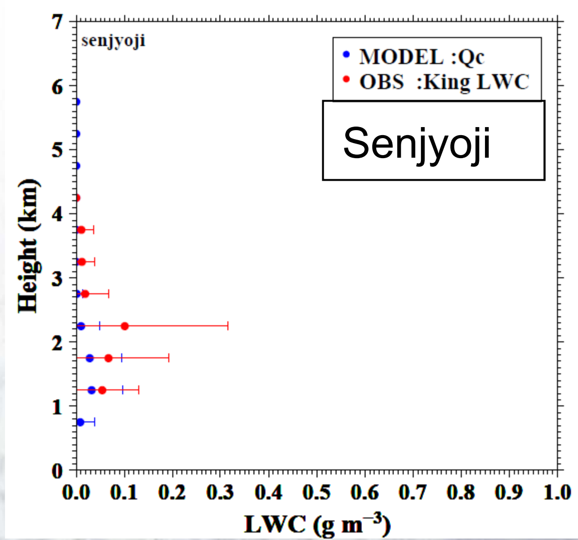


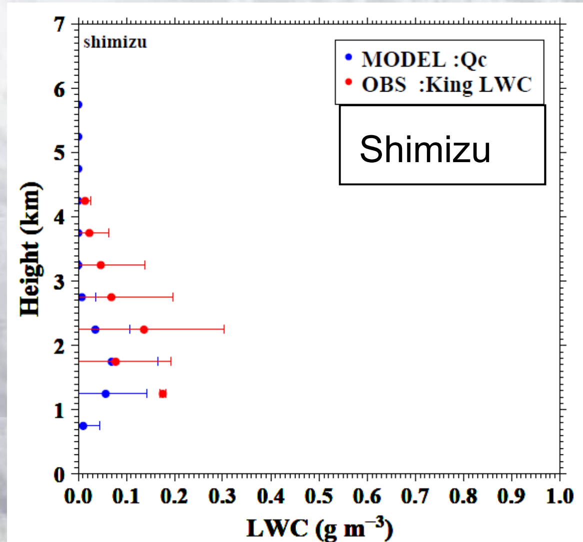
Japanese cloud seeding Experiment for Precipitation Augmentation

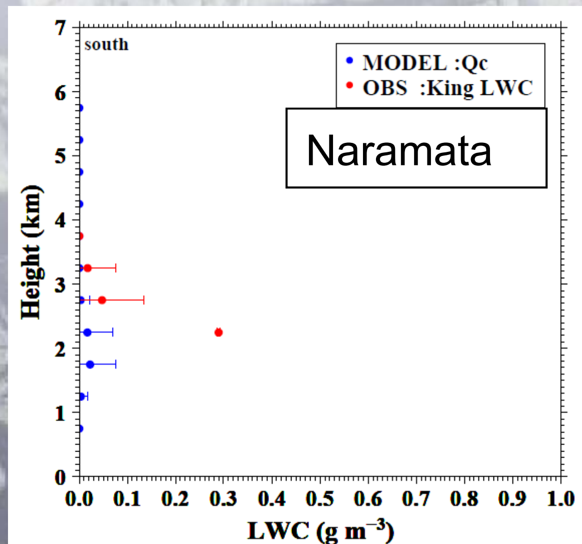
Comparison of LWC

(Obs.; King or Nevzorov LWC)





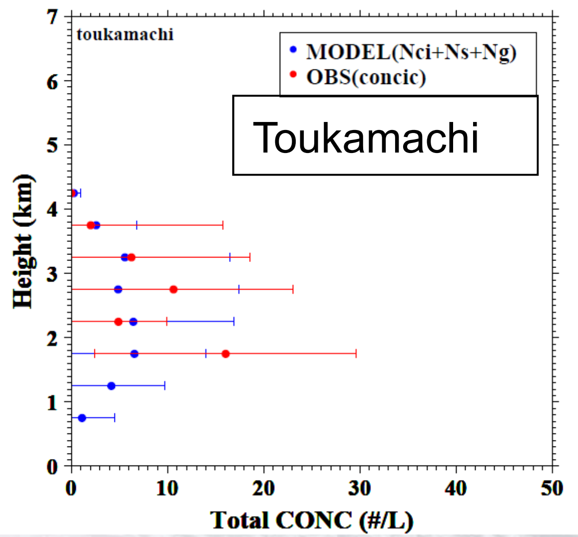


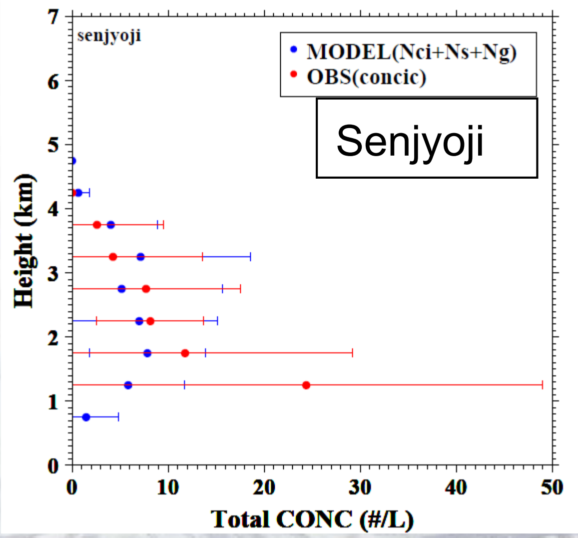


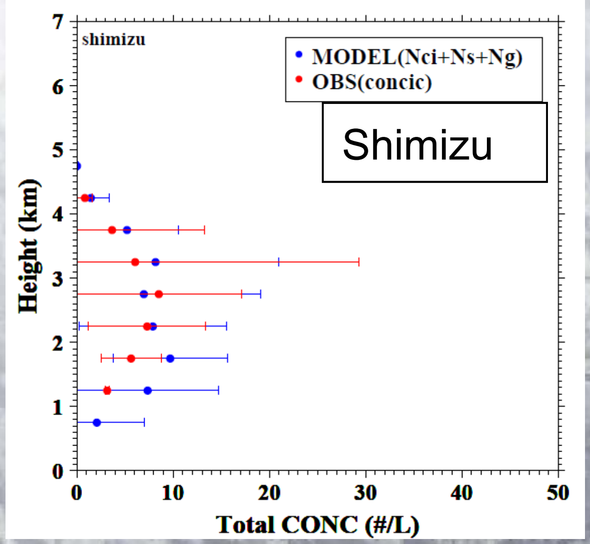
Japanese cloud seeding Experiment for Precipitation Augmentation

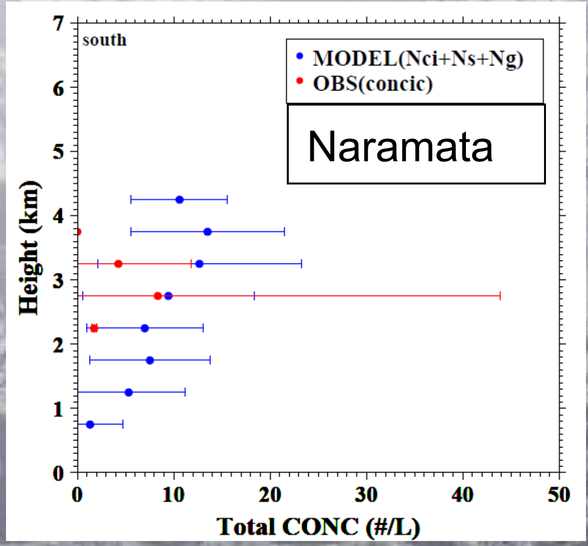
Comparison of Total Conc. (Ni+Ns+Ng)

(Obs.; 2DC concentration)



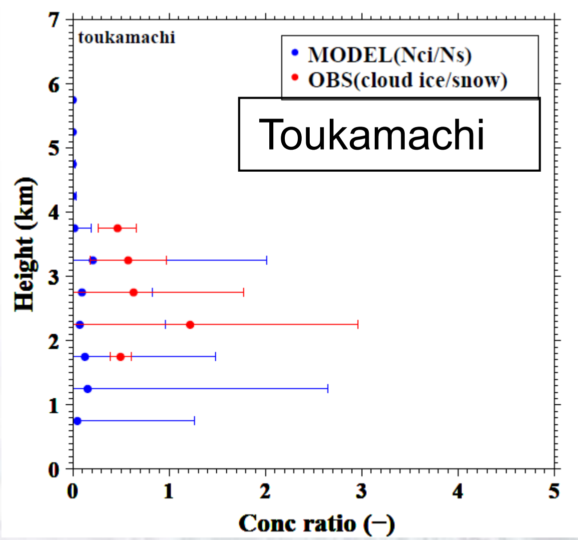


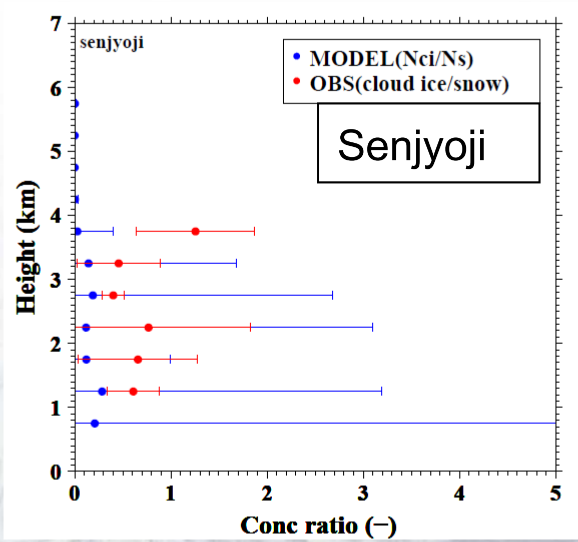


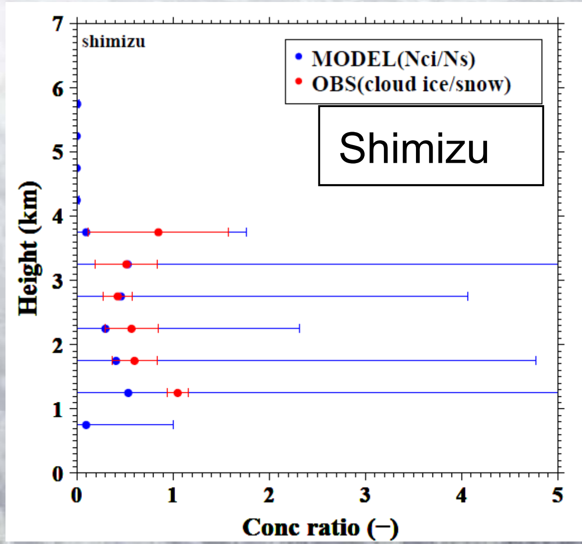


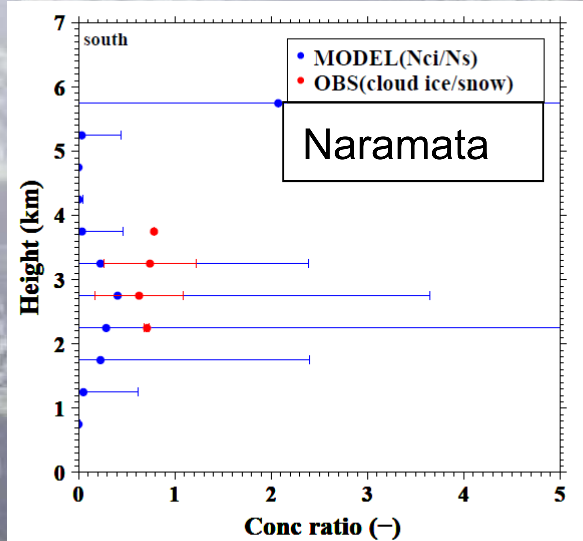
Japanese cloud seeding Experiment for Precipitation Augmentation

Comparison of Ni/Ns ratio





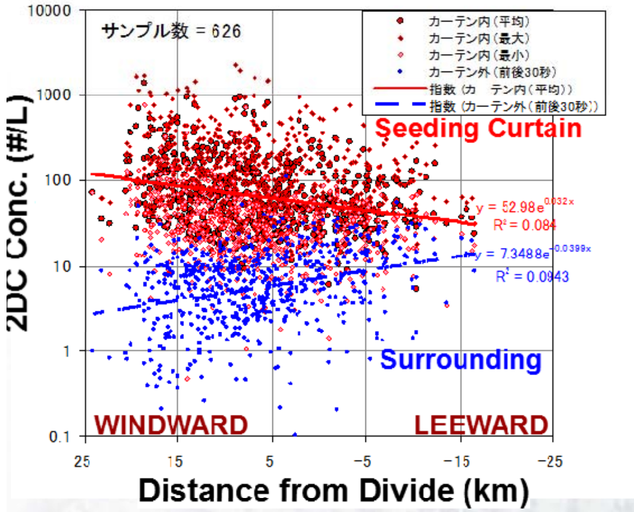


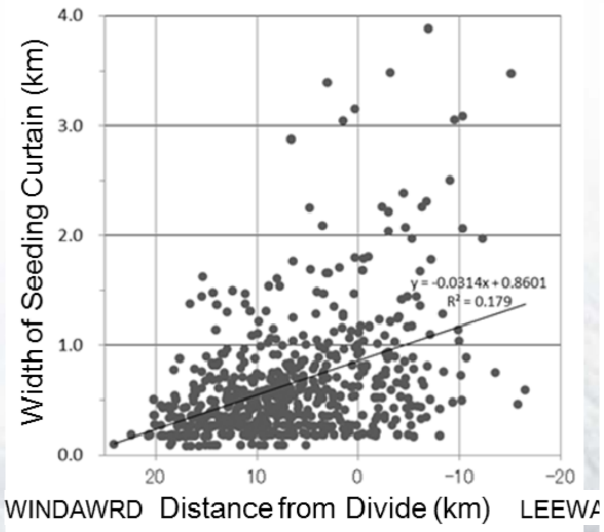


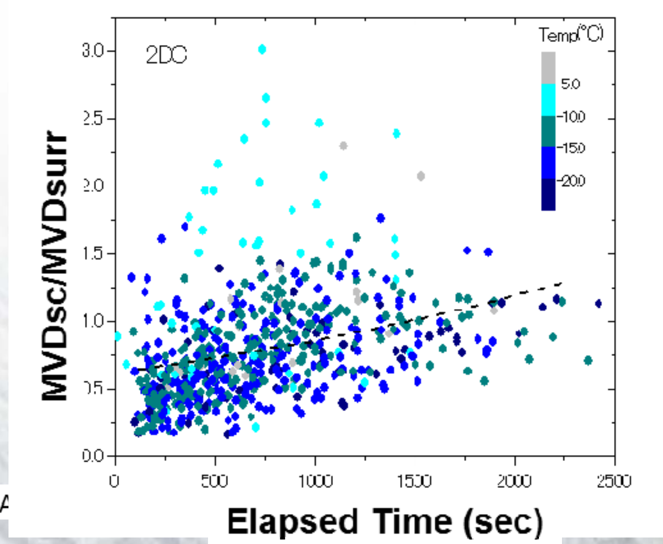
Japanese cloud seeding Experiment for Precipitation Augmentation

Comparison of Seeding Signature

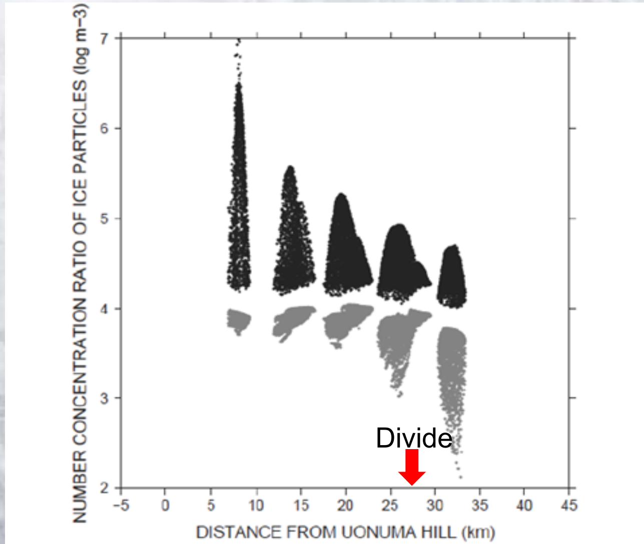
Aircraft Observations

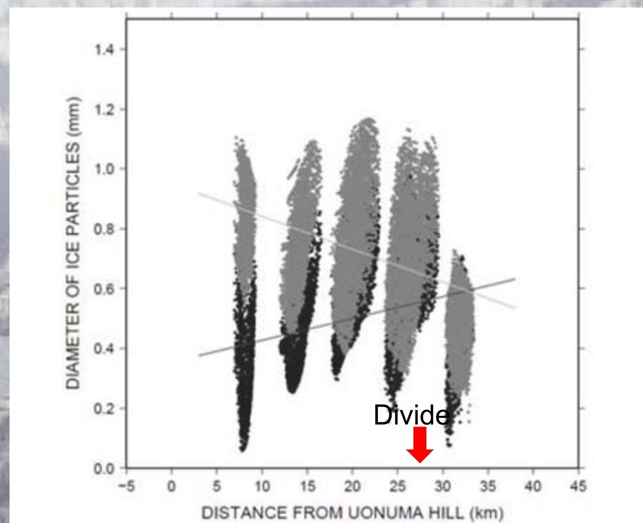






Model





DATA ASSIMILATION

- To reduce spatio-temporal forecast (prediction) errors due to the error contained in the initial, major forecast centres around the world assimilate
  - surface observation data, aerological observation data, meteorological satellite data, etc. to create global analysis data
  - wind profiler, radar and surface meso-net observation data to create regional analysis data.
- When running the regional non-hydrostatic models with such global or regional analysis data as initial/boundary conditions, the reproducibility by the models of the synoptic scale/mesoscale phenomena generally does not indicate any serious problem.
- Many challenges remain to accurately reproduce the spatio-temporal development of individual clouds and cloud systems.

UNCERTAINTY OF FORECAST RESULTS

Numerical simulations have rapidly improved in accuracy with the remarkable progress of computer technology. However, there are still many model uncertainties in order to accurately reproduce the actually seeded cloud system and its response to cloud.

Apart from systematic uncertainties due to model parameterisations, there are chaotic uncertainties associated with observational errors and variations in known parameters. Both of these sources of uncertainty are currently managed through the use of ensembles.

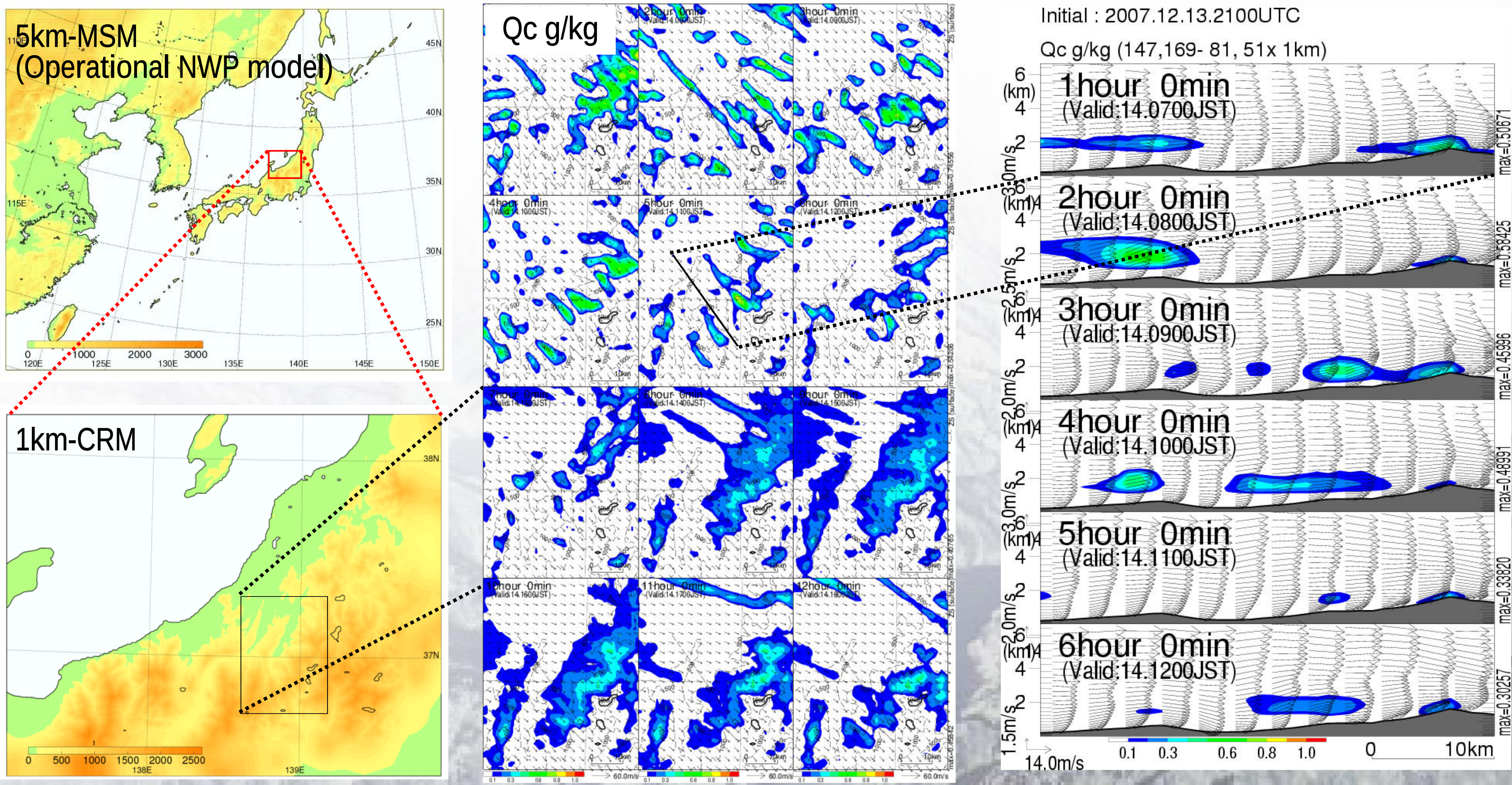
- Initial data ensemble
  - Ensemble forecast (simulation) method, which runs the model with initial condition perturbations, has been used at the major forecast centres.
- Model ensemble
  - Different cloud microphysical parameterizations and seeding schemes among the models cause a large difference in the performance of the models, so that it is thought that the multi model ensemble simulation using several different models may increase the reliability of simulation results.

USAGE OF NUMERICAL MODELS IN WEATHER MODIFICATION RESEARCH

- Before field projects
  - Seeding hypothesis development
  - Assessment of seedability
  - Experimental design
- During field projects
  - Operational decision (guidance)
- After field projects
  - Project evaluation
  - Understanding of seeding effects

Guidance for field experiment

Forecast of seedable clouds, twice a day

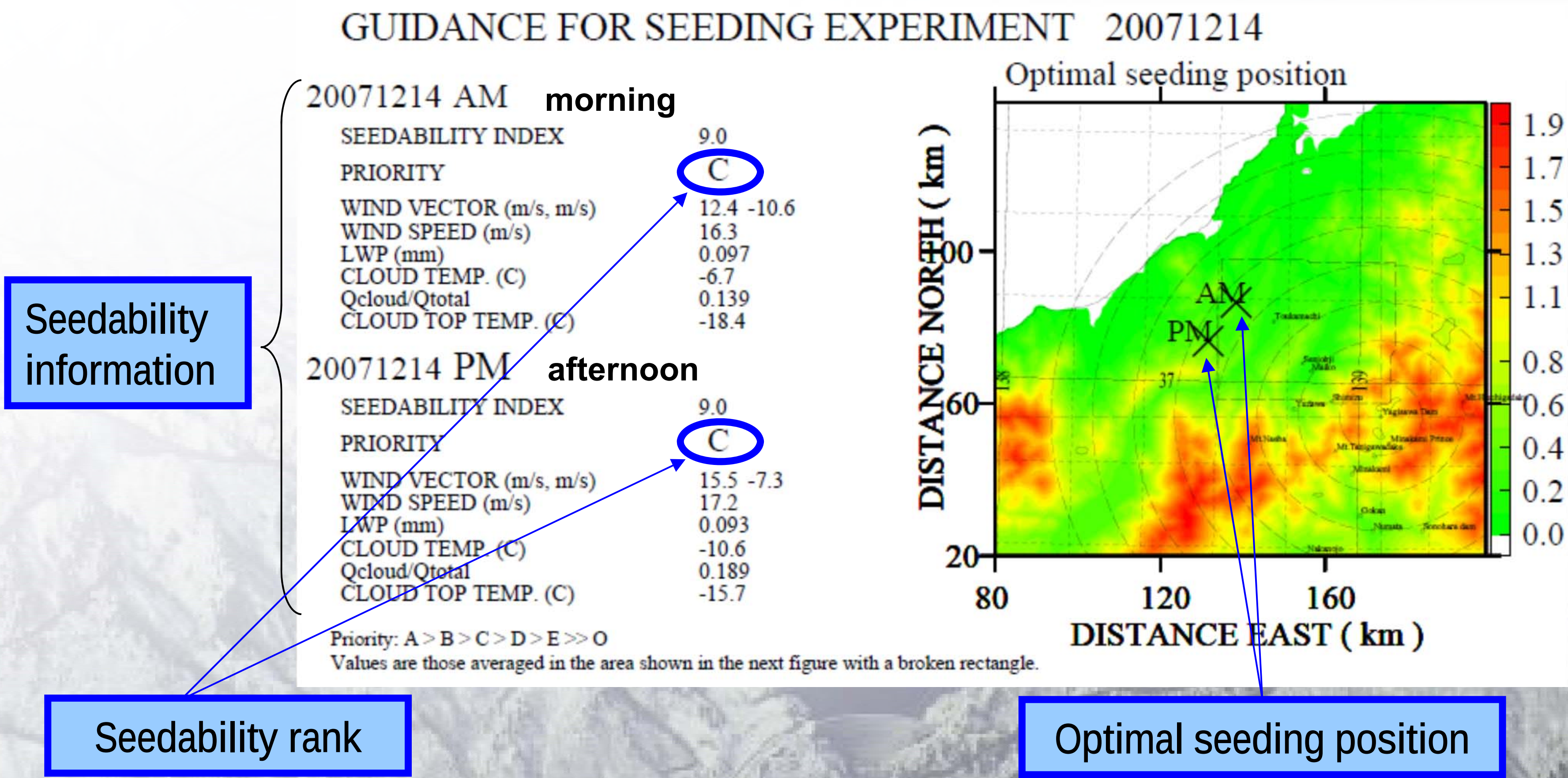


Prediction of cloud water distribution

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

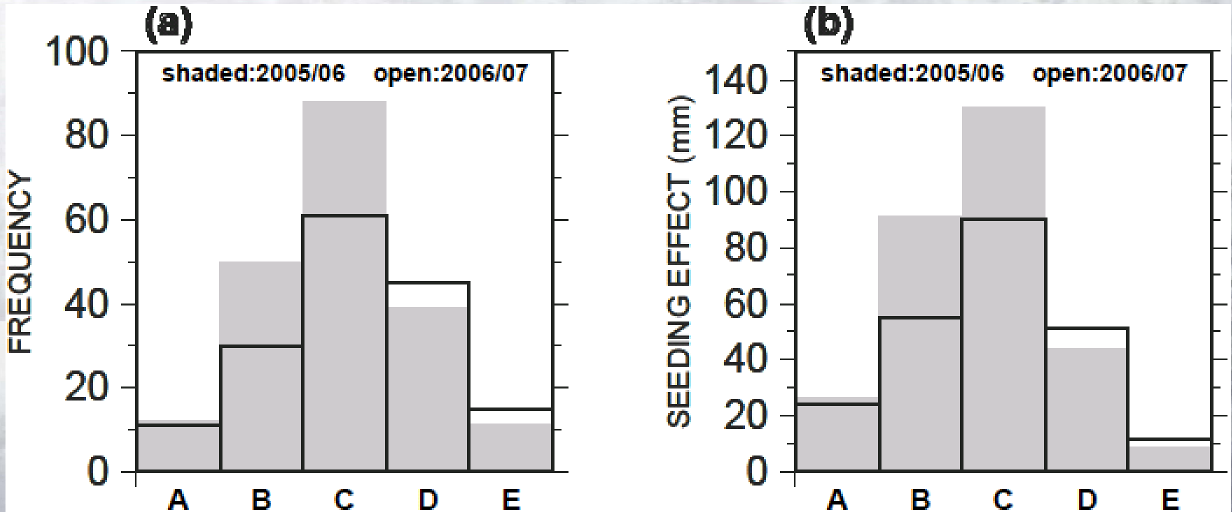


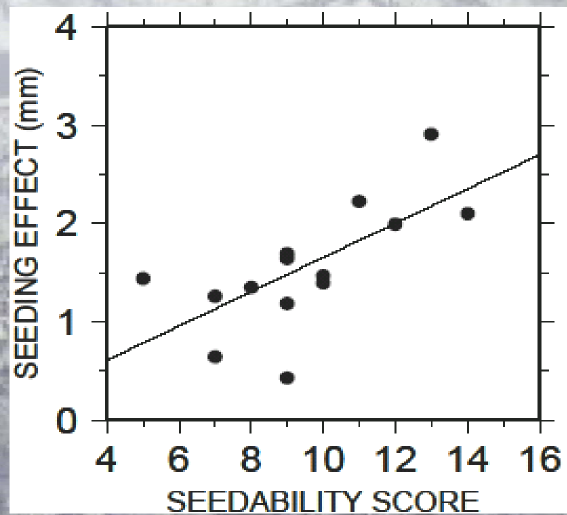
Assessment of seedability

Winter of 2005/2006 and 2006/2007

Score	0	1	2	3	4
WD	the others	N to W			
WS ($m\ s^{-1}$)	< 8	8 - 13	13 - 18	18 - 23	> 23
LWP (mm)	< 0.05	0.05-0.10	0.10-0.15	0.15-0.20	> 0.20
$T_{Q_c}(^oC)$	> 0	-6 - 0	-6 - -11	-11 - -16	< -16
Q_c/Q_t	< 0.01	0.01 - 0.1	0.1 - 0.3	0.3 - 0.5	> 0.5

Priority	A	B	C	D	E
Score	> 12	10 - 12	8 - 10	6 - 8	4 - 6





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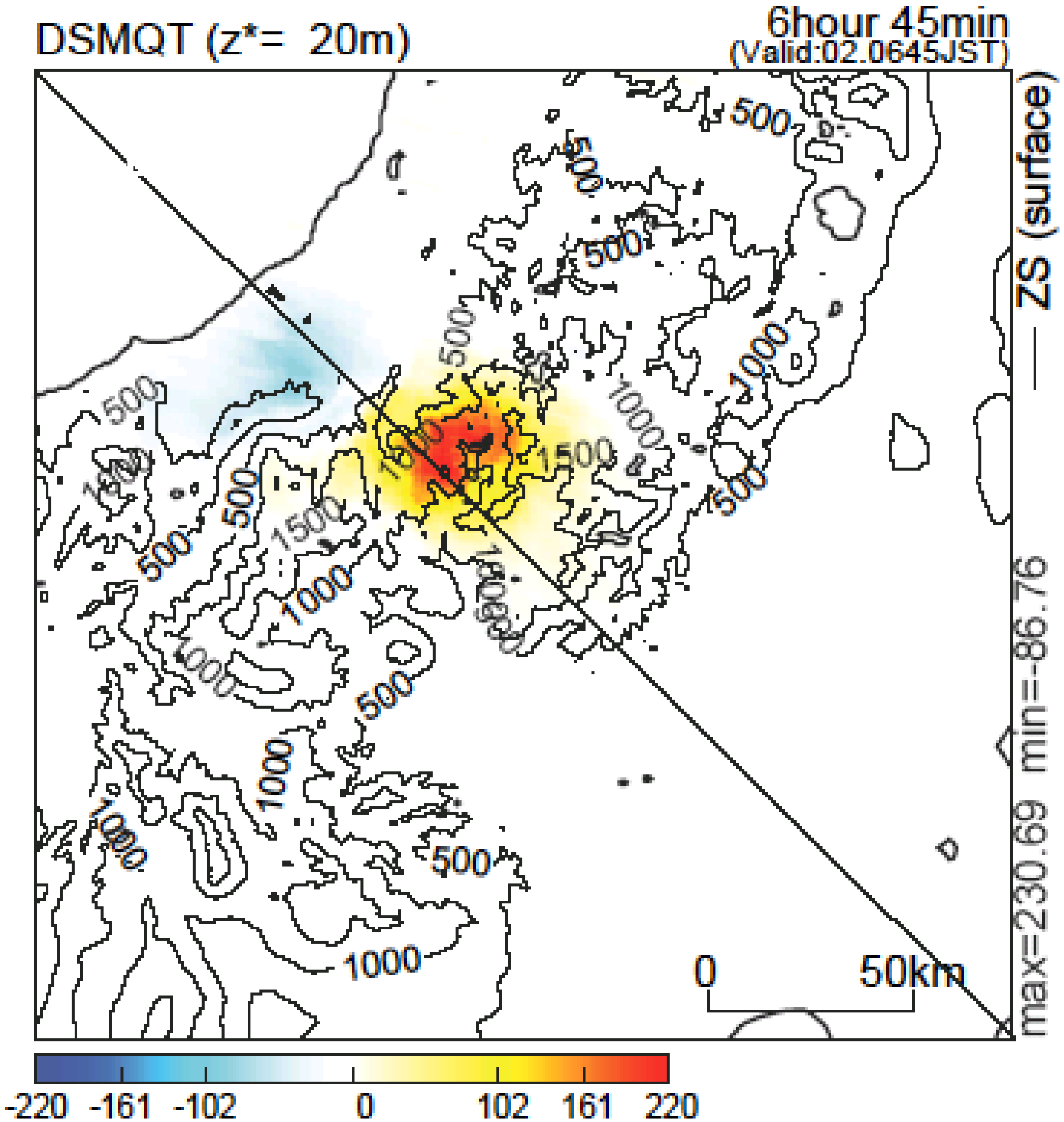
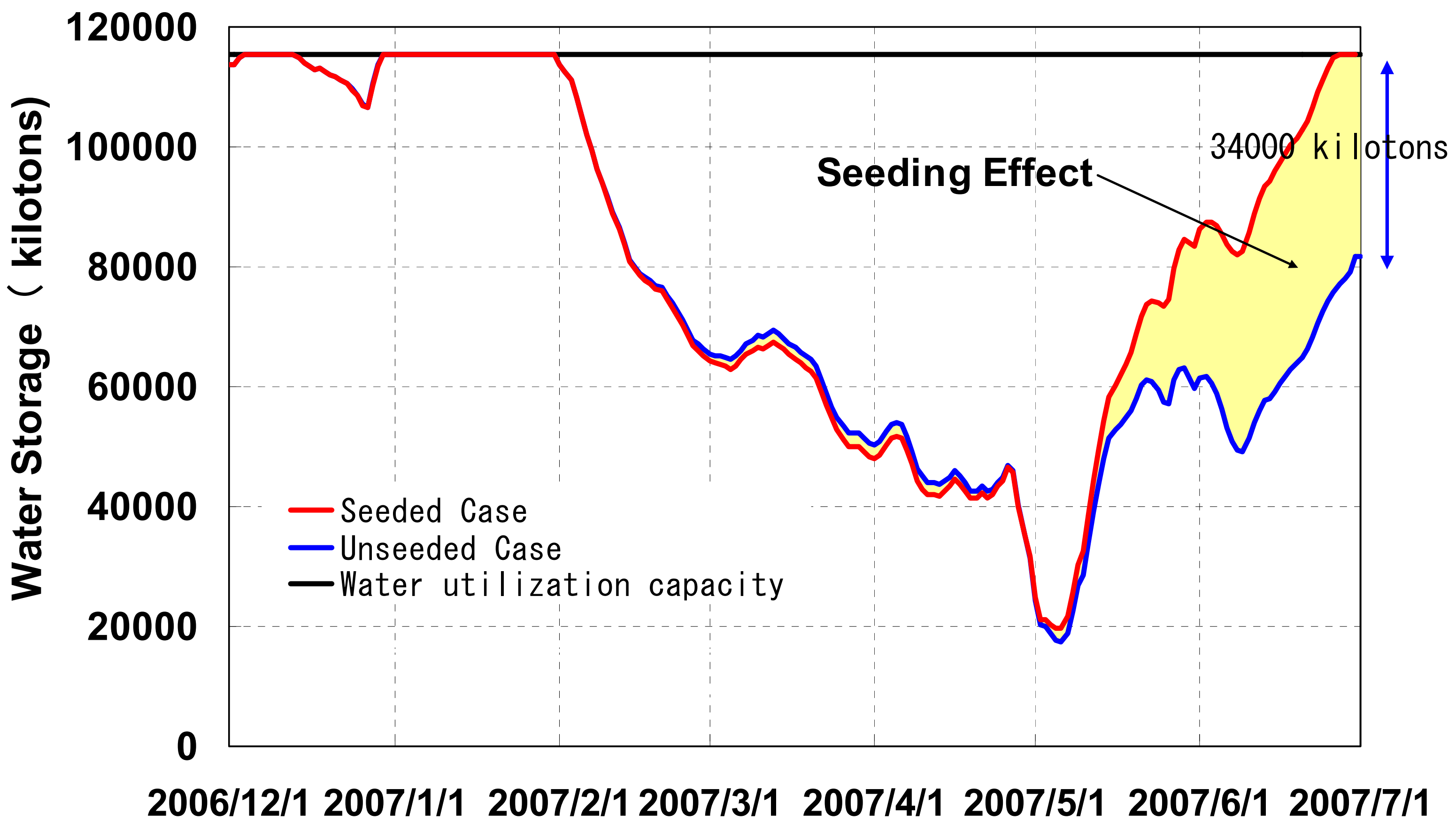
Seeding Effects on Seasonal Precip.(163 cases)

（NHM simulation: Under winter monsoon conditions: Dec. 2006-Mar. 2007）



Seeding Effect on Dam Water Storage



CONCLUSIONS AND RECOMMENDATION

- Three-dimensional mesoscale modelling of entire cloud systems has become a new standard
  - driven by the output of NWP models
  - nesting capabilities to zoom into a region of interest
  - LES resolutions
  - multi-moment or bin resolved schemes
- Outstanding source of uncertainty is sensitivity of weather prediction models to variations in cloud microphysics and boundary layer parameterizations
- To improve the uncertainty through validation against observation and model comparison
- Current rain predictions are fairly good over scales of tens of km and days but there is large uncertainty in the exact timing, location and intensity of rainfall.
  - apart from special cases in which external forcing (such as orographic barrier) tends to fix the cloud location,

CONCLUSIONS AND RECOMMENDATION

- Regarding glaciogenic seeding, numerical modelling of dry ice seeding and AgI seeding has come to a level that is of practical use while numerical modelling of liquid CO2 seeding still has uncertainty.
- Almost all the model simulations show that the seeding effects of hygroscopic particles with submicron sizes are weak or negative when compared with those of hygroscopic particles with micron sizes. However, there is little research on realistic hygroscopic seeding using three-dimensional NHMs.
- For both glaciogenic and hygroscopic seeding, typical spatial resolutions of 1 km or several hundreds of metres for 3D NHMs are too coarse compared with the initial spatial extent (10 m) of seeding materials, and the advection/diffusion of seeding materials tends to be over-estimated.

CONCLUSIONS AND RECOMMENDATION

- Development and improvement of numerical models, which include not only seeding aerosol particles but also atmospheric aerosol particles acting as CCN and INP as prognostic variables are required.
  - Current AgI seeding schemes are based on experimental results from the 1990s. There has been remarkable progress in research on the CCN and INP capabilities of aerosols since that time. Recent experimental results should be reflected in AgI seeding schemes, which recognise that AgI can also serve as a CCN
  - for hygroscopic seeding, it is necessary to take into consideration the CCN and INP capabilities of particles generated from the combustion agent of hygroscopic flares and of particles included in salt micro-powder as anti-caking agents

Thank you for your attention !