SCIENTIFIC BASIS OF WEATHER MODIFICATION

Masataka Murakami

Institute for Space-Earth Envionment Research,
Nagoya University, Nagoya, Japan

Meteorological Research Institute, Tsukuba, Japan

Training Programme
Understanding of Cloud Nature and Weather Modification
for Water Resources Management in ASEAN
Jul. 22, 2019
Amari Hua Hin Hotel, Prachuap Khiri Khan Province, Thailand

CONTENTS OF TODAY'S TALK

- Necessity of Weather Modification
- History of Weather Modification
- Weather Modification Projects in the World
- Scientific Basis of Weather Modification
- Weather Modification Technology
- Application of Weather Modification
- Problems of Weather Modification

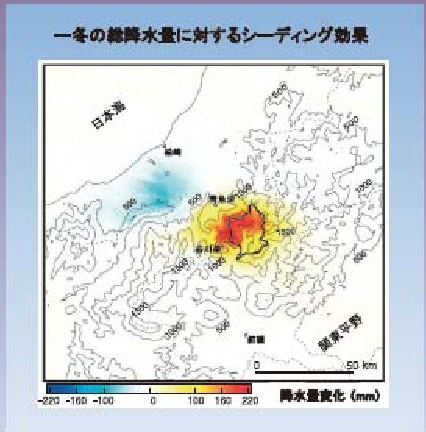
Meteorological Research Note

Frontier of Weather Modification Research

Japan Meteorological Society, Mar. 2015, 332pp (in Japanese)

Based on Japanese Cloud Seeding Experiments for Precipitation Augmentation (JCSEPA)

ISBN978-4-904129-14-2
定価　X,XXX円(消費税込み)



発行所
日本気象学会

気象研究ノート
人工降雨・降雪研究の最前線
第二三一号

人工降雨・降雪研究の最前線

気象研究ノート　第231号

編集　村上正隆・藤部文昭・石原正仁

日本気象学会

Contents of “Frontier of Weather Modification Research”

NECESSITY OF WEATHER MODIFICATION

（Mitigation of Severe Weather）

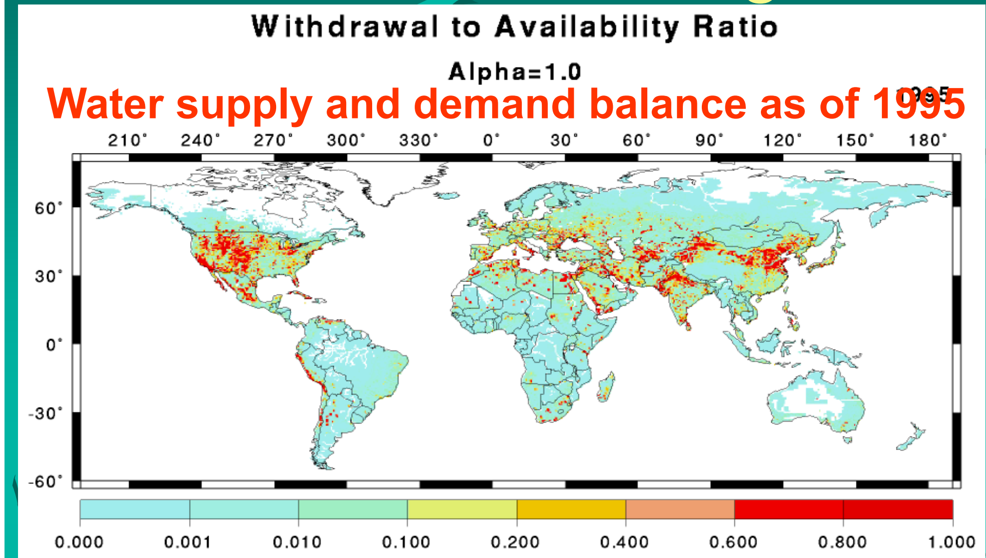
Heavy Snowfall in 1981

Flood in Summer of 1997

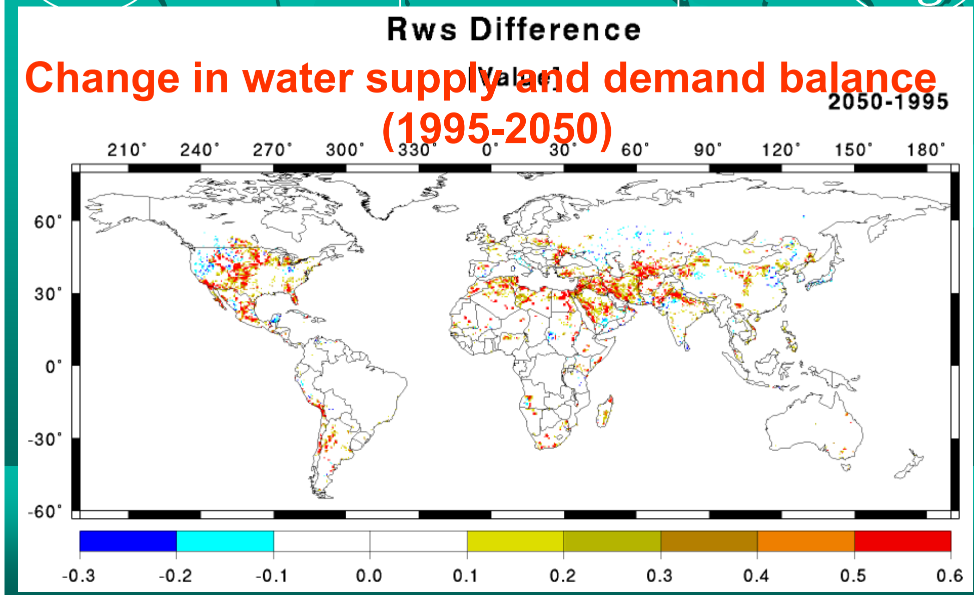
Water Shortage in Summer of 1994

NECESSITY OF WEATHER MODIFICATION

（Securing of Water Resource ）



Low ← Water Stress → High



Two-thirds of the ***world's*** population will face ***water*** shortages by ***2025***

World Water Forum (2003)

（Oki et al., 2003)

HISTORY OF WEATHER MODIFICATION

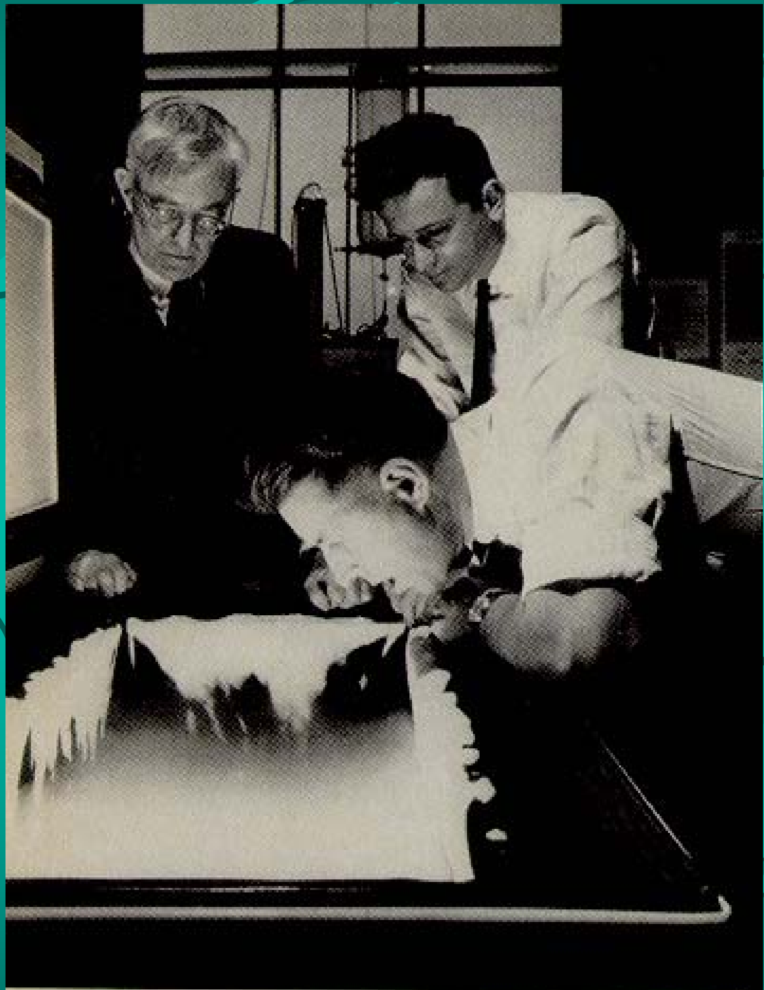
- Strong wish to rainmaking

↓

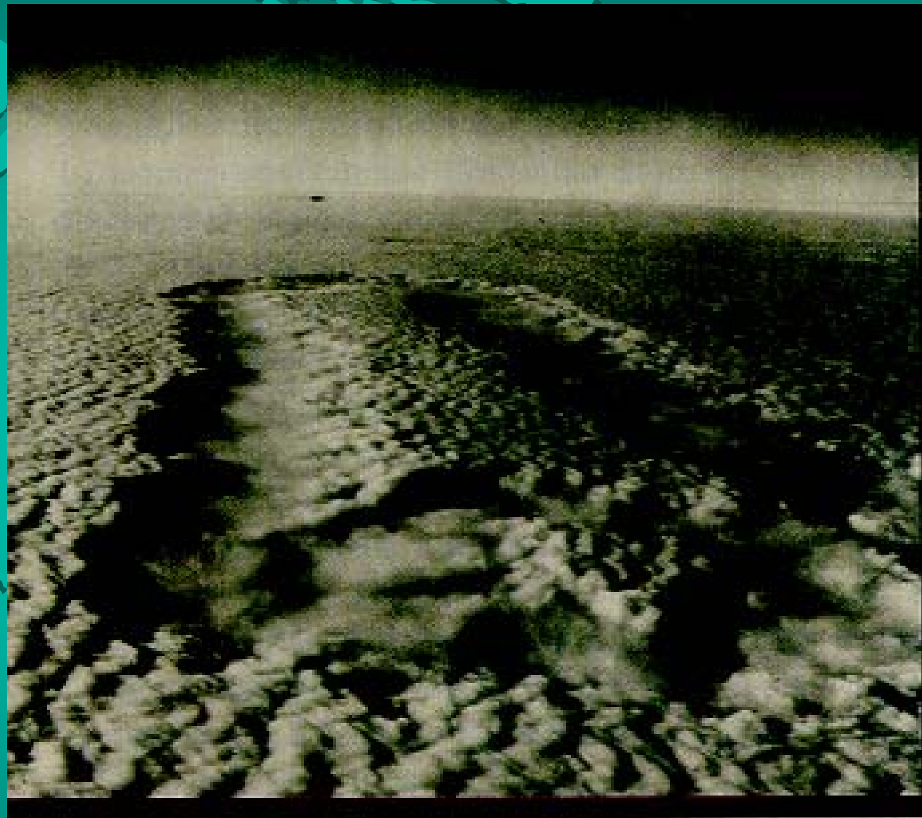
- Non-scientific methods
  - Praying for rain （ancient times ）
  - Cannon & Firework （early modern age ）

- Scientific methods
  - Introduction of artificially-generated ice crystals (late 1940s)

The First, Scientific Wea. Mod. Experiment

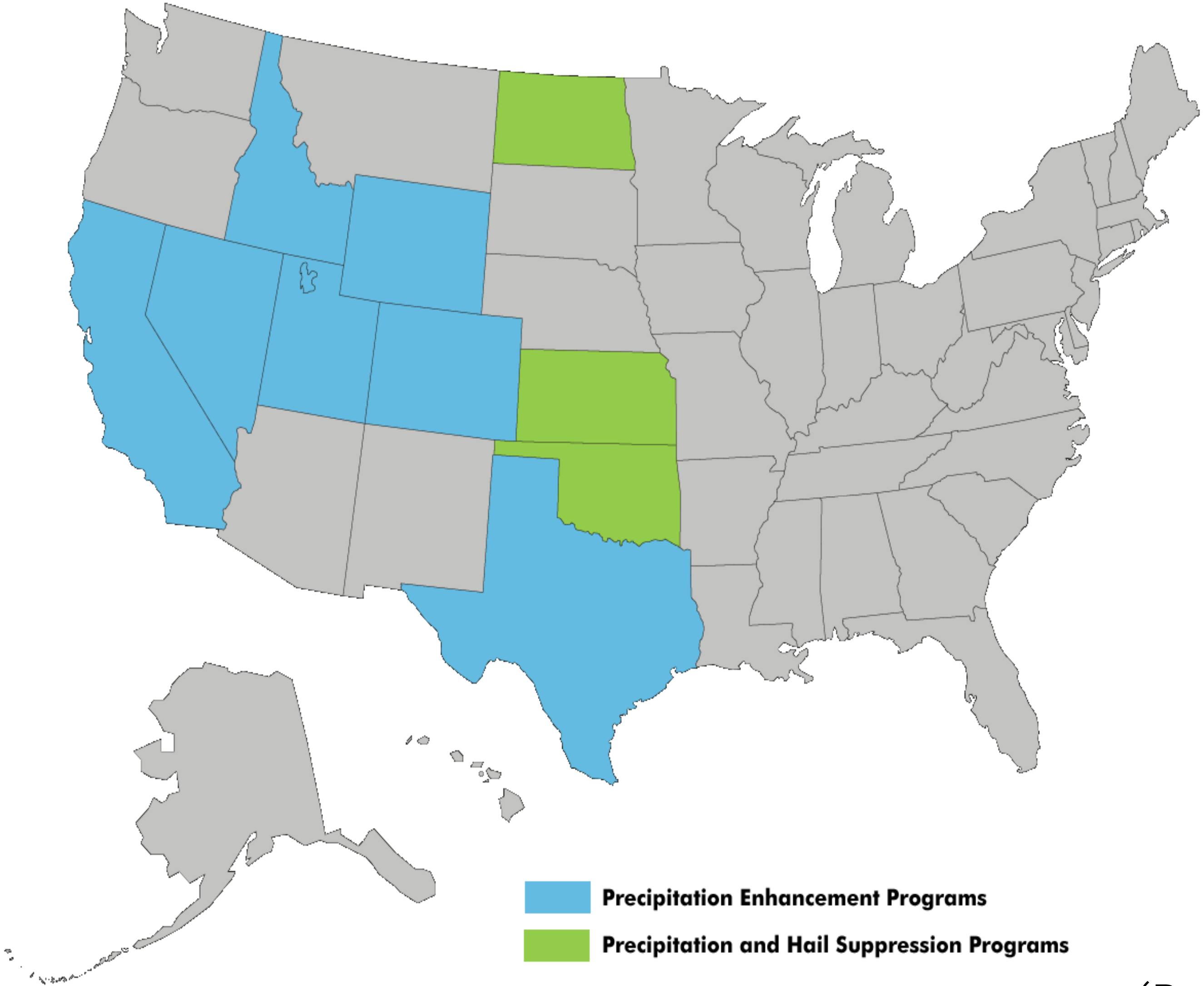


SNOWSTORM IN A BOX: General Electric scientists Irving Langmuir (*left*) and Bernard Vonnegut look on while Vincent J. Schaefer performs a snowmaking experiment. All three scientists were involved in developing the field of weather modification.



in Wilmington, Ohio, that showed seeding to be relatively ineffecti (*left*). Stratus clouds seeded with dry ice in another experiment displaye a characteristic racetrack pattern (*right*).

Weather Modification Projects in US



(Bruintjes, 2003)

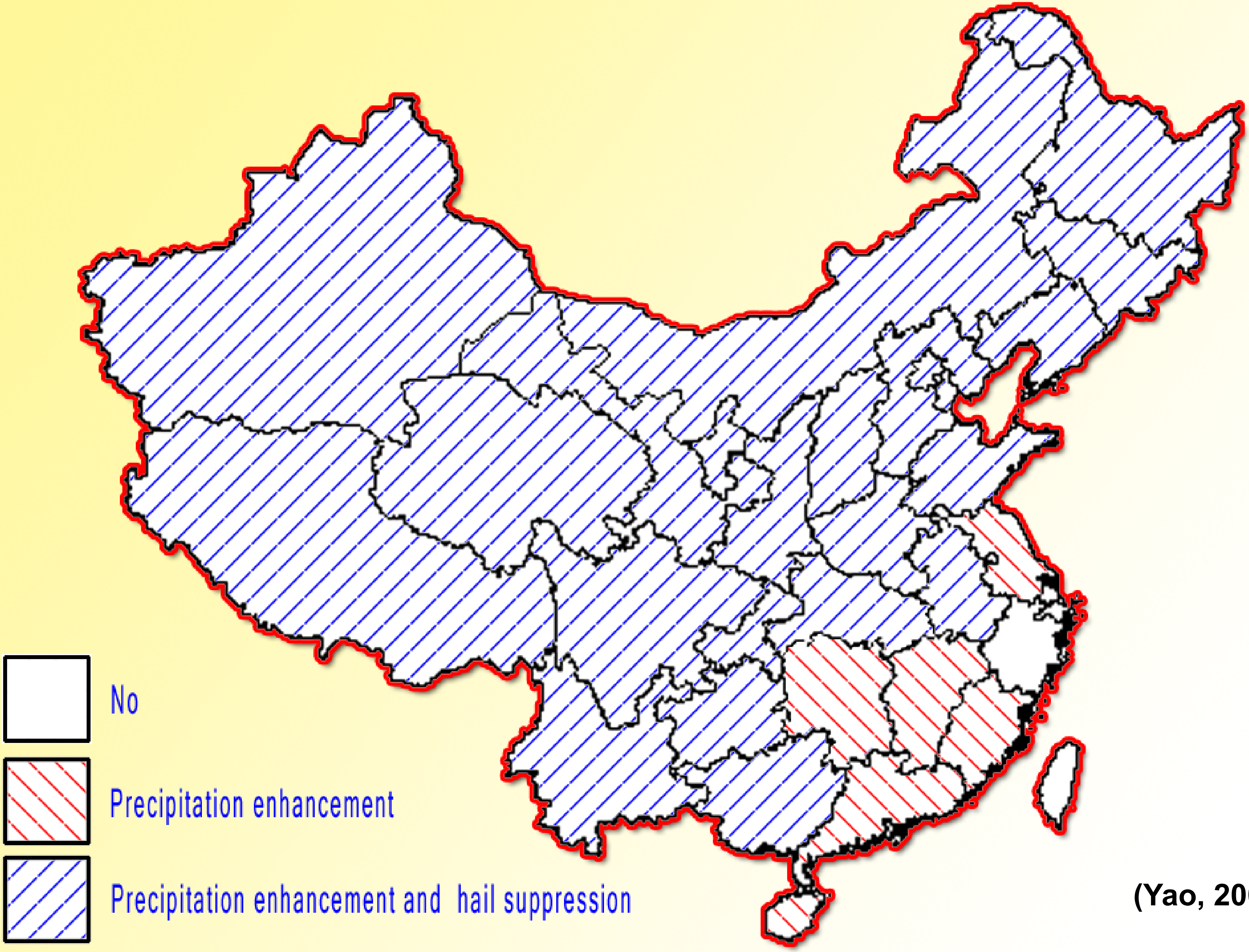
Private Wea. Mod. Company (US)

WEATHER MODIFICATION, INC.

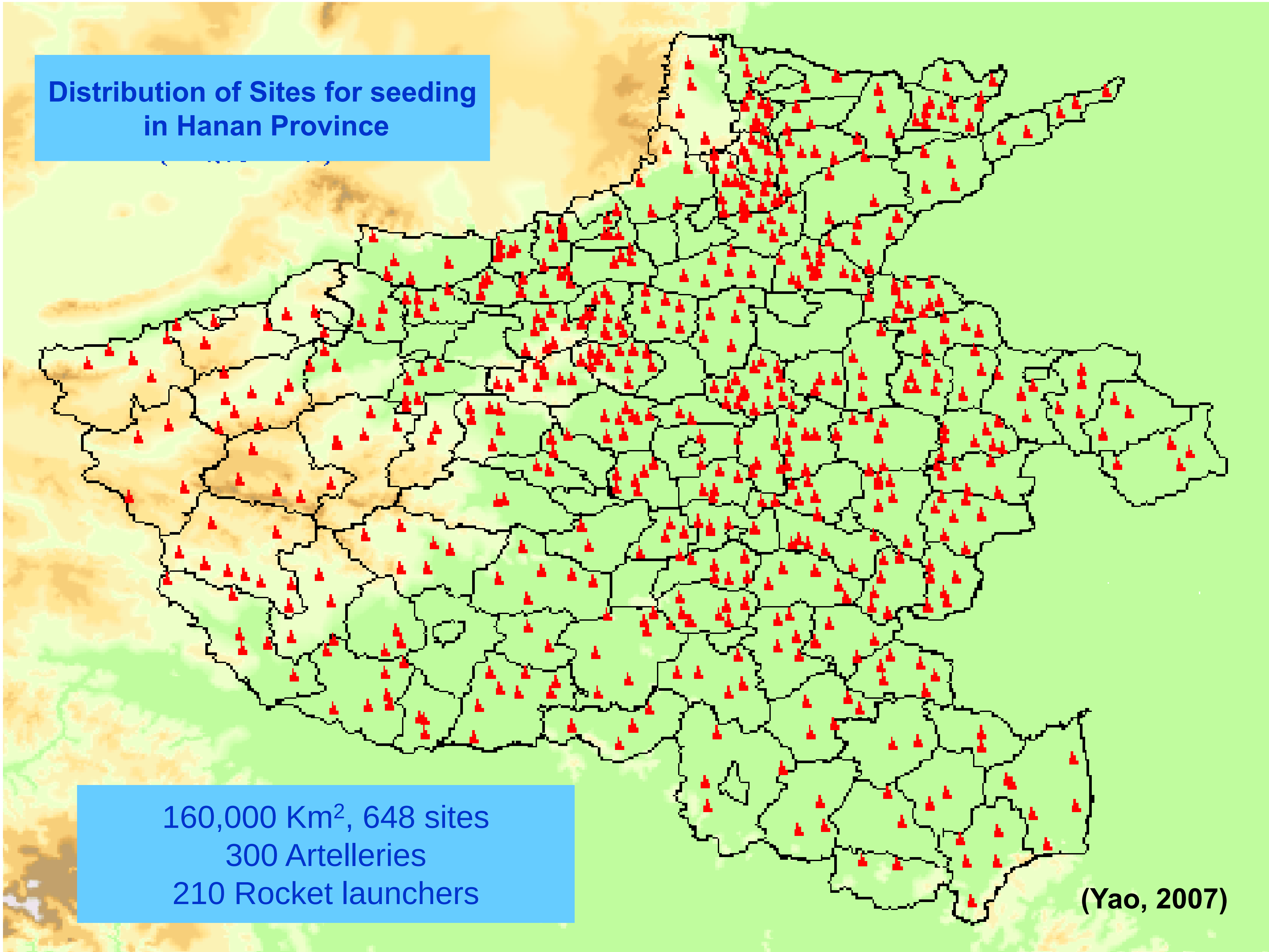
WMI Weather Modification Projects

- Alberta Hail Suppression Project
- Argentina Hail Suppression Project
- Greek Hail Suppression Program
- United Arab Emirates Program
- North Dakota Cloud Modification Program
- West Central Texas Rainfall Enhancement Program
- Oklahoma Weather Modification Program

Sketch Map of Weather Modification Operations in China in 2002



(Yao, 2007)


Distribution of Sites for seeding
in Hanan Province
160,000 Km², 648 sites
300 Artelleries
210 Rocket launchers
(Yao, 2007)

PRESENT STATUS

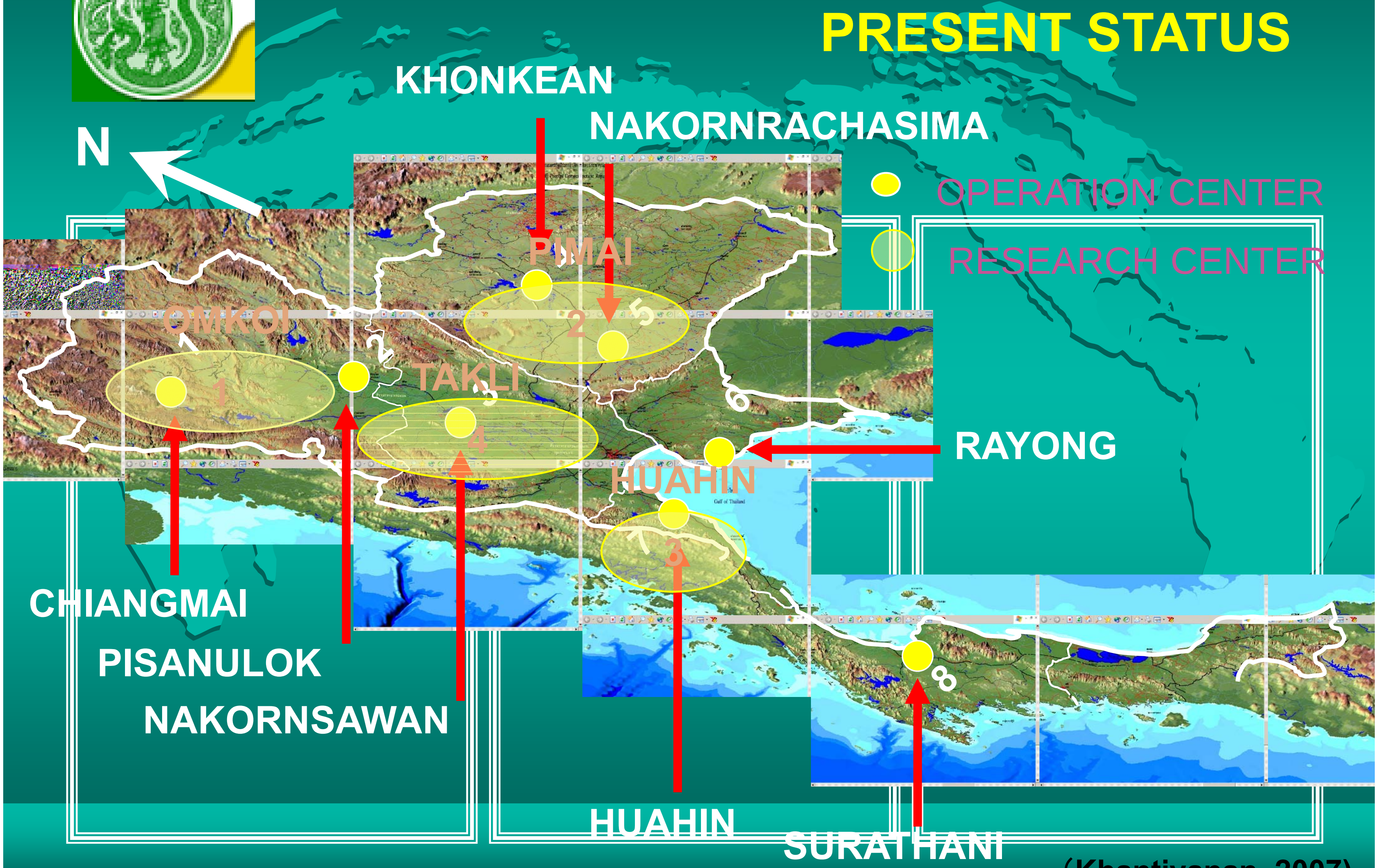
FACILITIES

Personnel:	500
Aircraft:	30
Operation Center:	8
Research Center:	4
Airfield:	3

(Khantiyanan, 2007)

50 YEARS OF THAILAND CLOUD SEEDING ACTIVITY

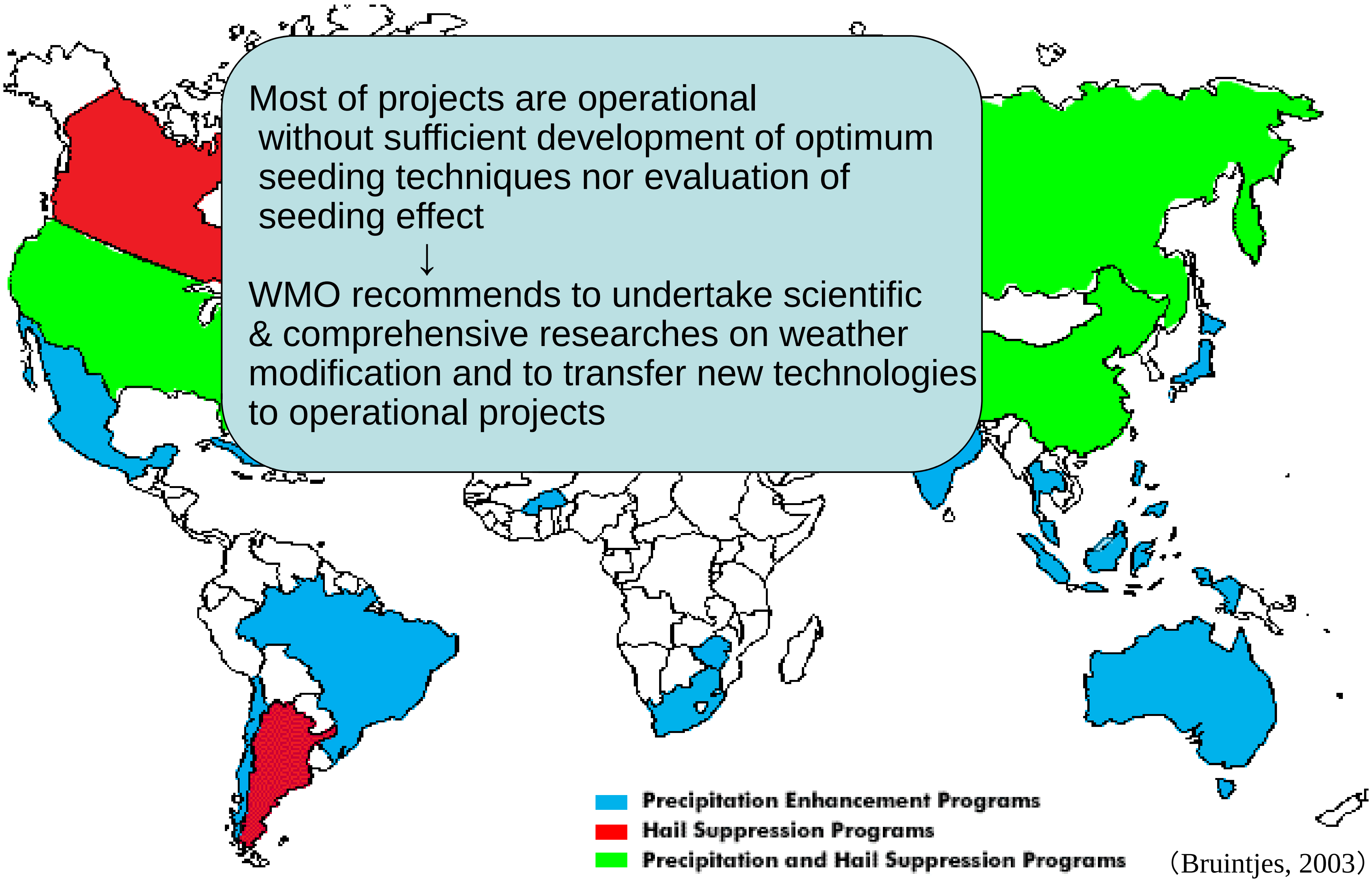
PRESENT STATUS



(Khantiyanan, 2007)

Wea. Mod. Projects in the World

Most of projects are operational
without sufficient development of optimum
seeding techniques nor evaluation of
seeding effect
↓
WMO recommends to undertake scientific
& comprehensive researches on weather
modification and to transfer new technologies
to operational projects



(Bruintjes, 2003)

IMPORTANCE OF CLOUD & PRECIPITATION PROCESSES

Small Scale

Microphysics :

Microphysical structure

↓

Precip. initiation & efficiency

↓

Timing, location & intensity

Dynamics

Latent heat and loading

↓

Vertical acceleration of air

↓

Dynamical structure

↓

Development/ Maintenance

↓

Forecast of Meso-scale Precip.

Large Scale

Water/Energy redistribution due to cloud /precip. processes

Radiative effect of cloud particles

↓

Water/Energy Cycle

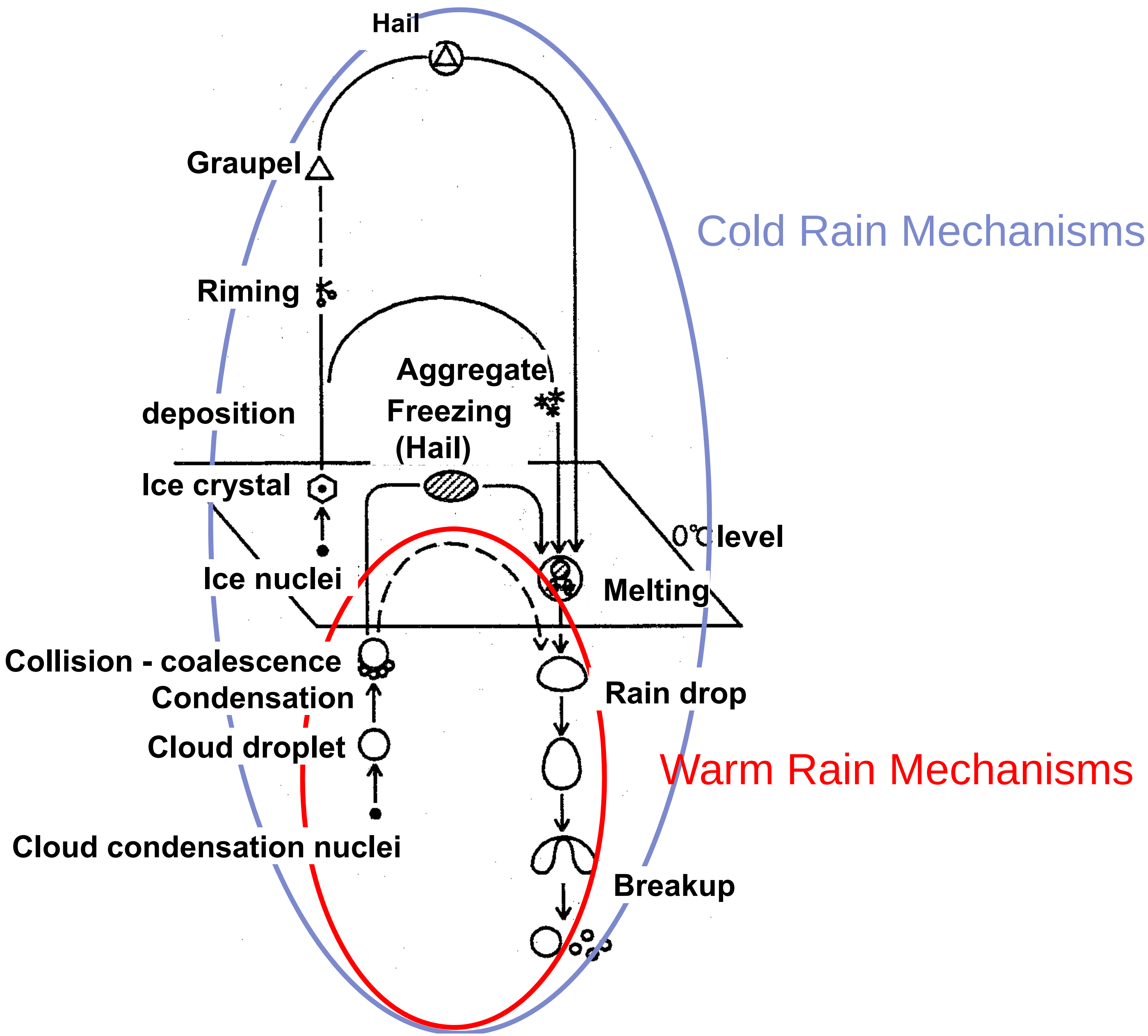
↓

Projection of Climate Change

First Indirect Effect of Aerosol

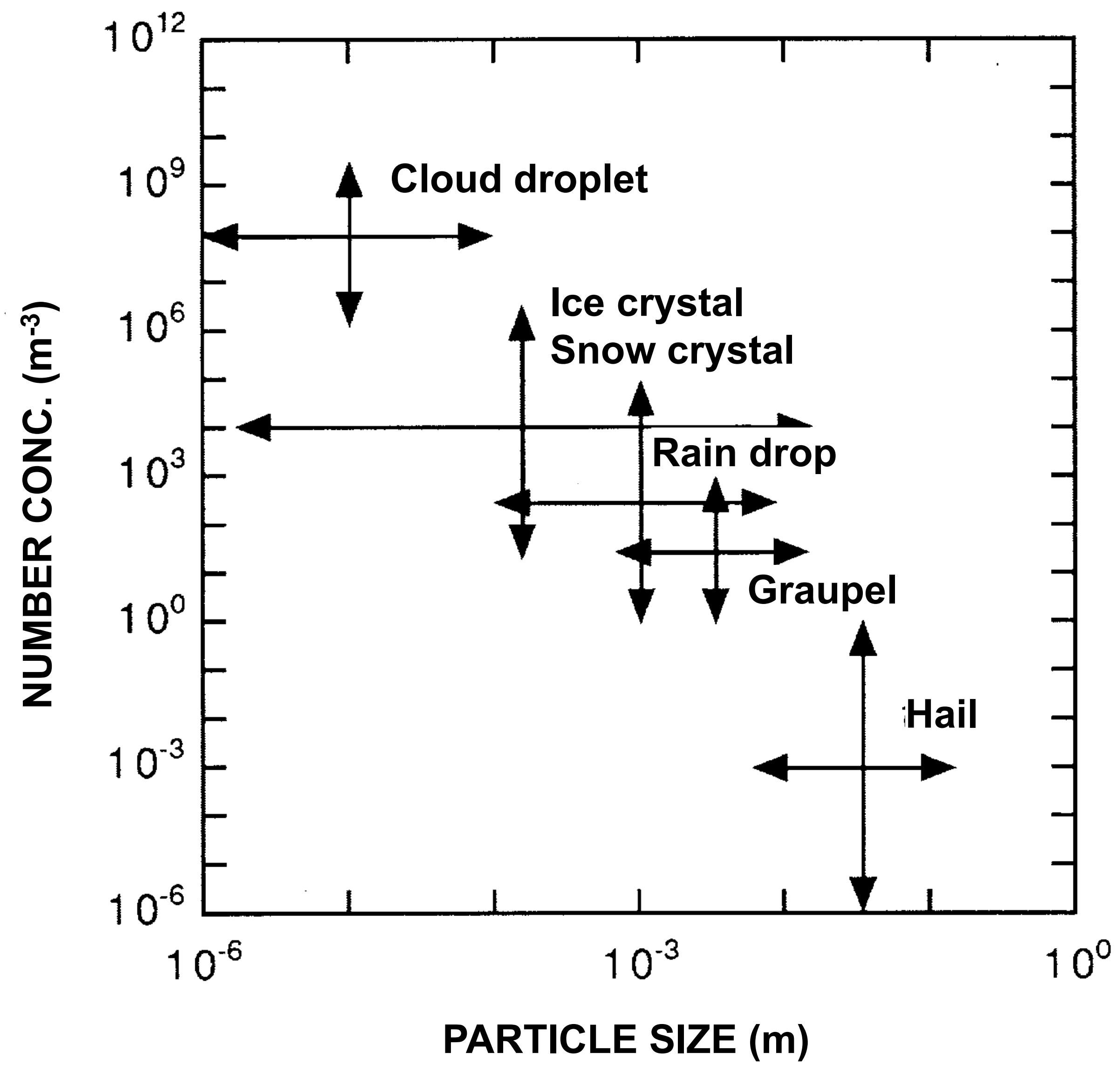
Second Indirect Effect of Aerosol

CLOUD & PRECIPITATION PROCESSES

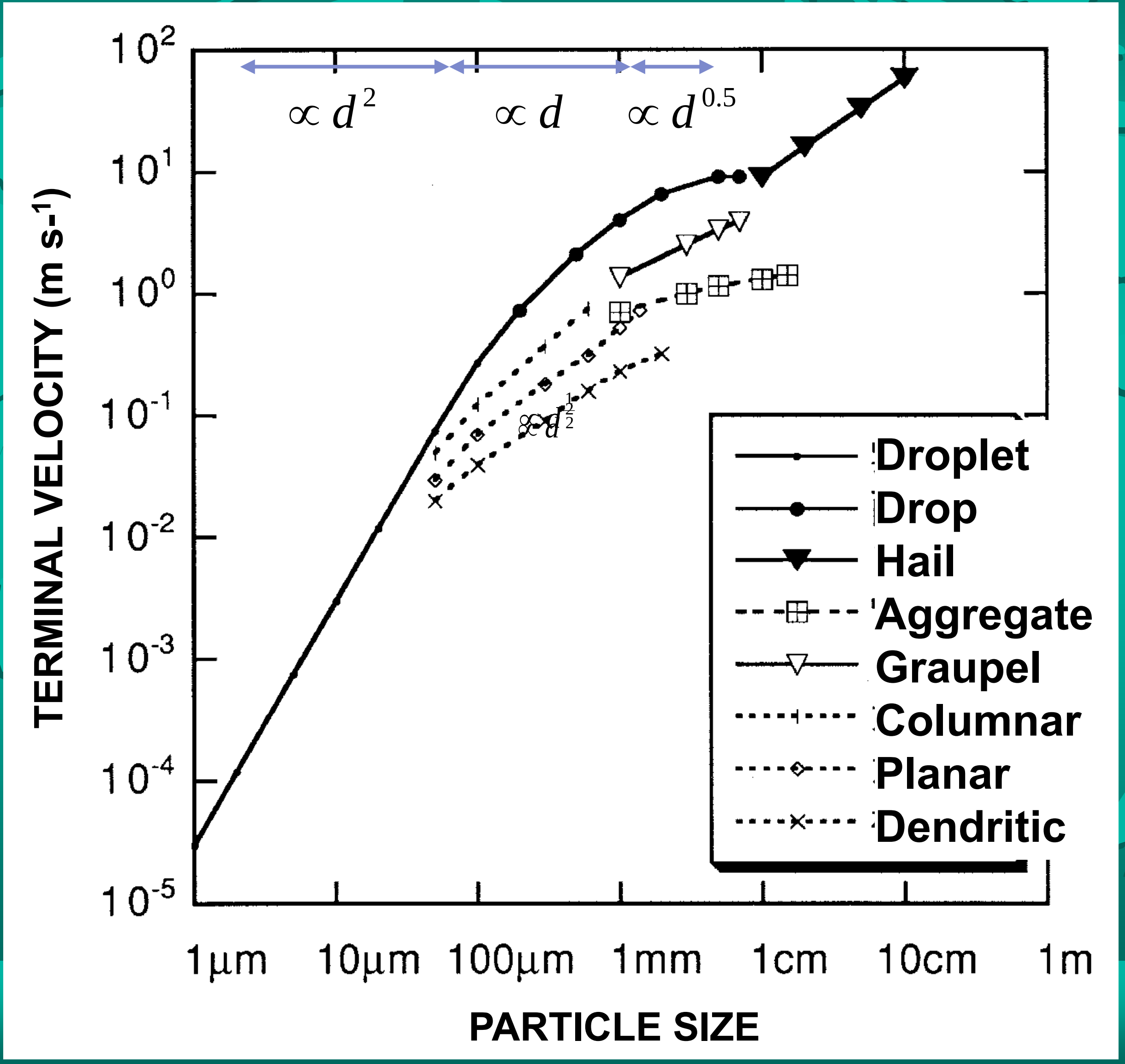


(Kawano, 1999)

SIZE vs. NUMBER CONC. of HYDROMETEORS



SIZE vs. FALL VELOCITY of HYDROMETEORS.



CLASSIFICATION OF CLOUD MICROPHYSICS PROCESSES

Nucleation： **Condensation･Deposition･Freezing**

Vapor ⇄ Water、 Vapor ⇄ Ice、 Water ⇄ Ice

Energy Barriers

Diffusion Growth： **Water drop･I ticle**

Kinetic effect (small par

Ventilation effect

Interaction: **Water ⟷ Wat**

Others： **Melting･Freezing**

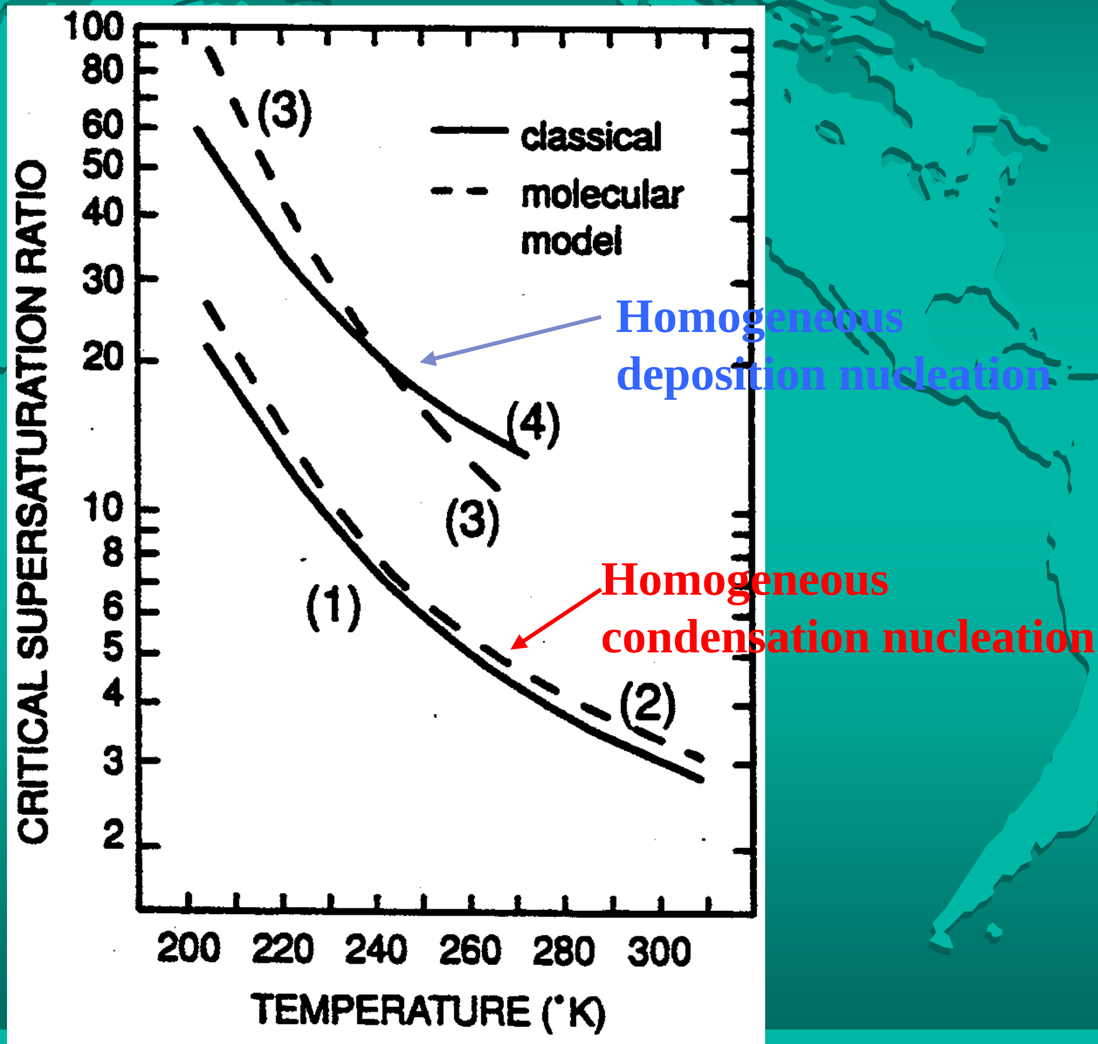
Breakup･ Sheddi

Phase changes of water species like these are basic to cloud microphysics. But the changes from left to right correspond to increasing molecular order and these transitions do not occur at thermodynamic equilibrium, but in the presence of a free energy barrier.

For new phase of water species to form from existing phase of pure water species, a strong energy barrier must be overcome. These processes are called homogeneous nucleation.

The processes by which a new phase of water species form on nuclei from existing phase of water species is called heterogeneous nucleation.

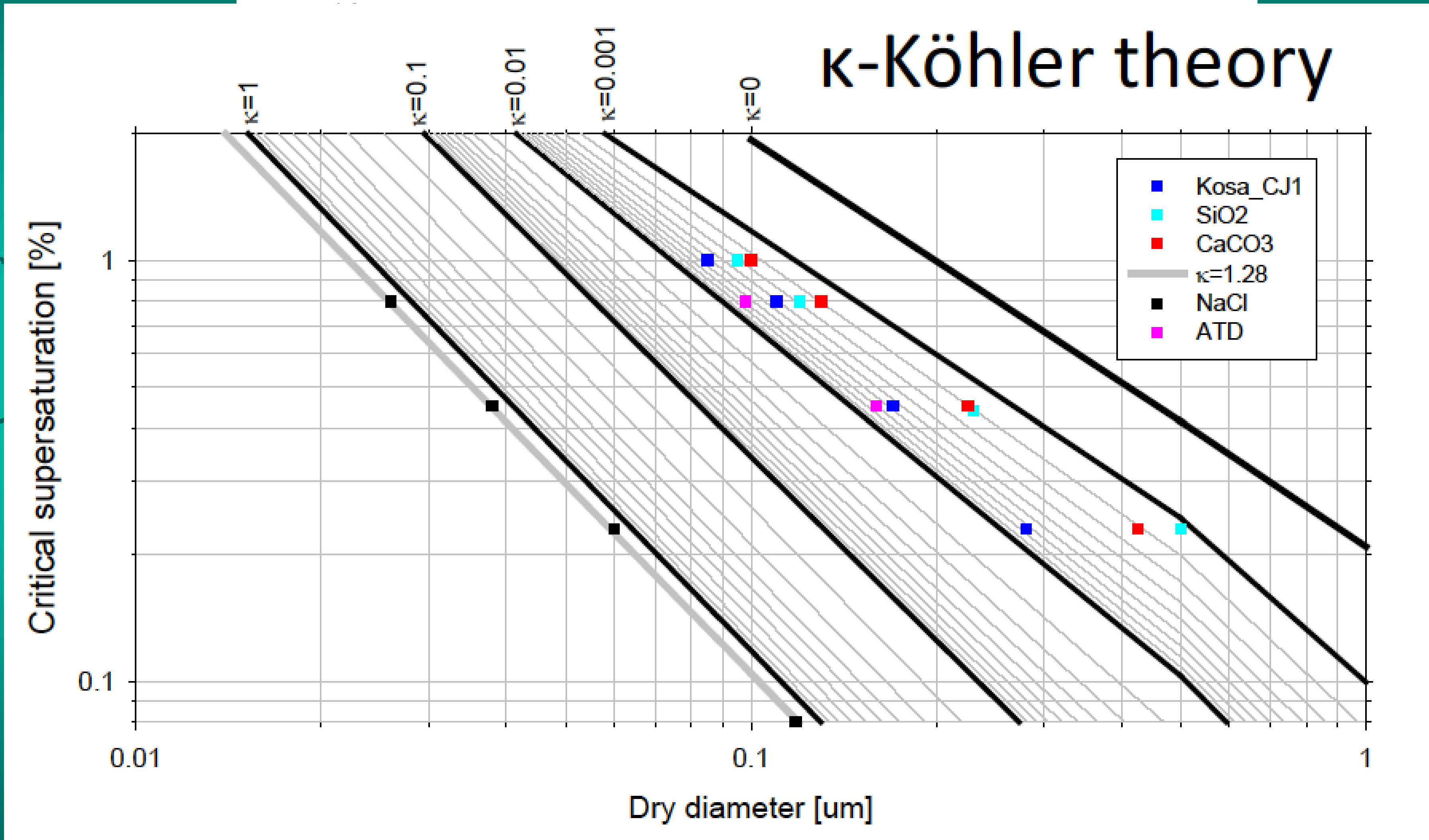
CRITICAL SUPERSATURATION FOR DROP AND ICE NUCLEATION



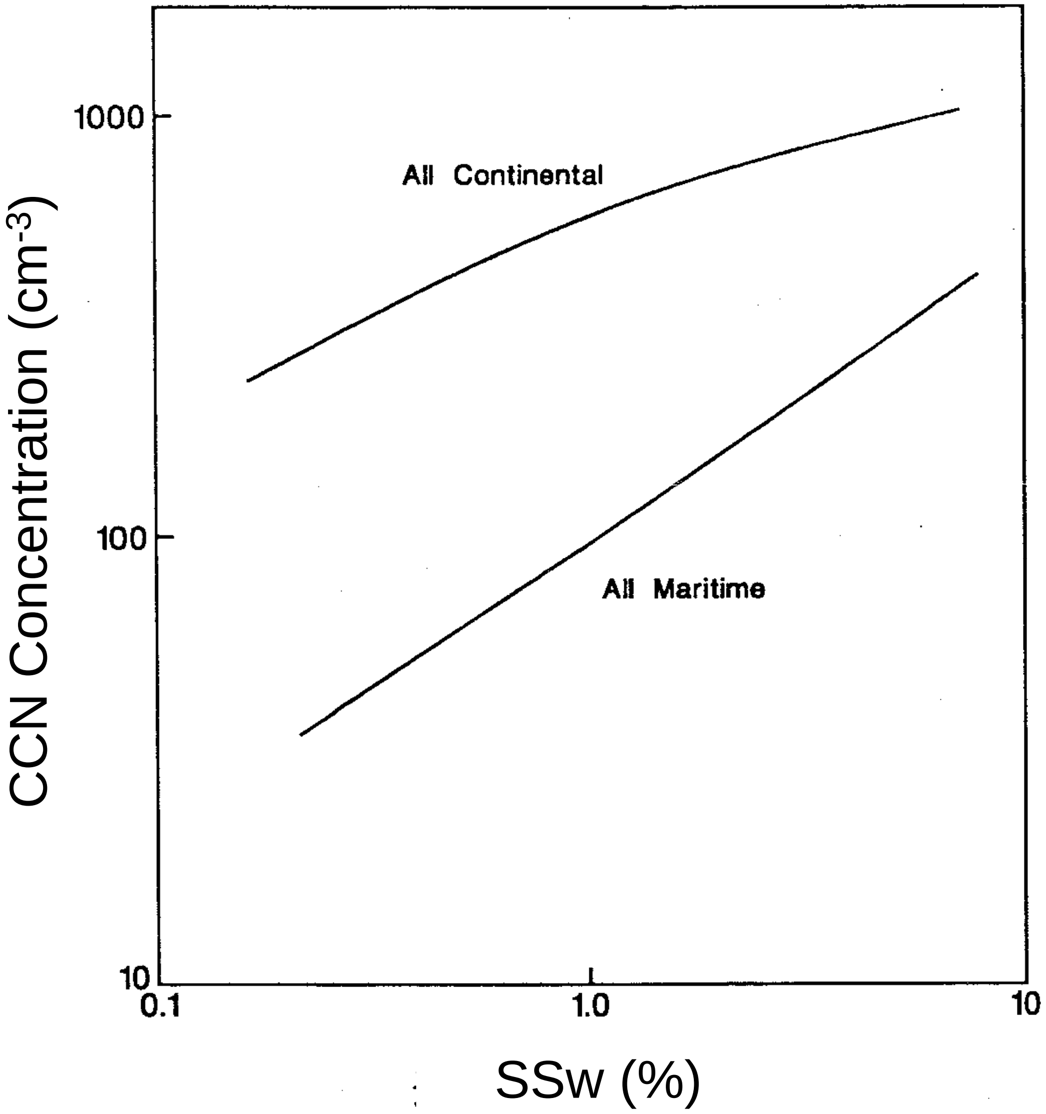
(Pruppacher & Klett, 1997)

Kohler Curve

Equilibrium saturation ratio over the surface of solution droplets as a function of droplet diameter

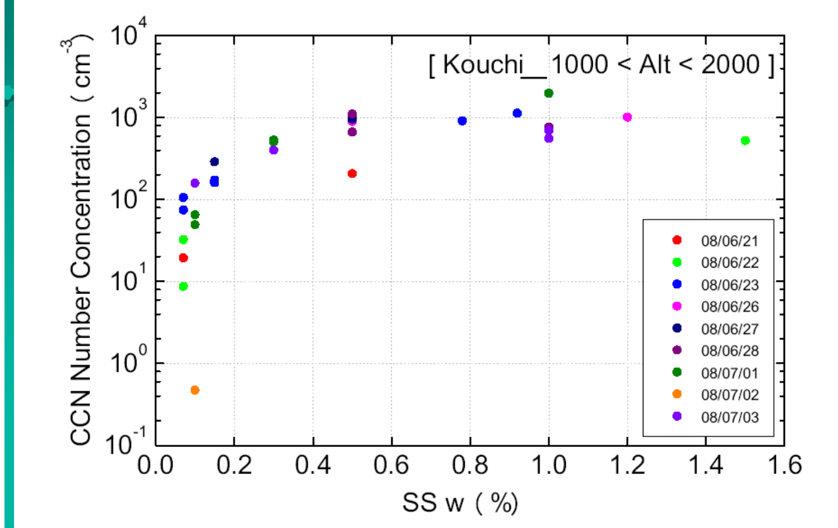


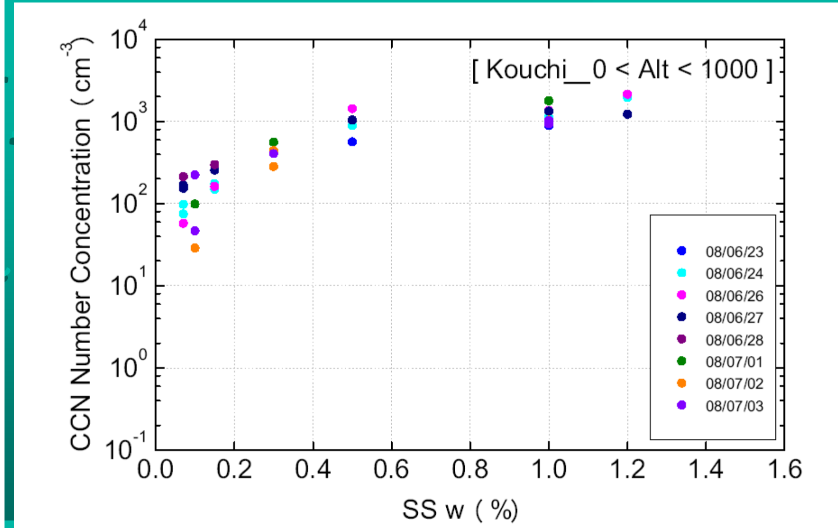
Supersaturation Spectra of CCN



(Twomey & Wojciechowski, 1969)

Shikoku District, summer of 2008



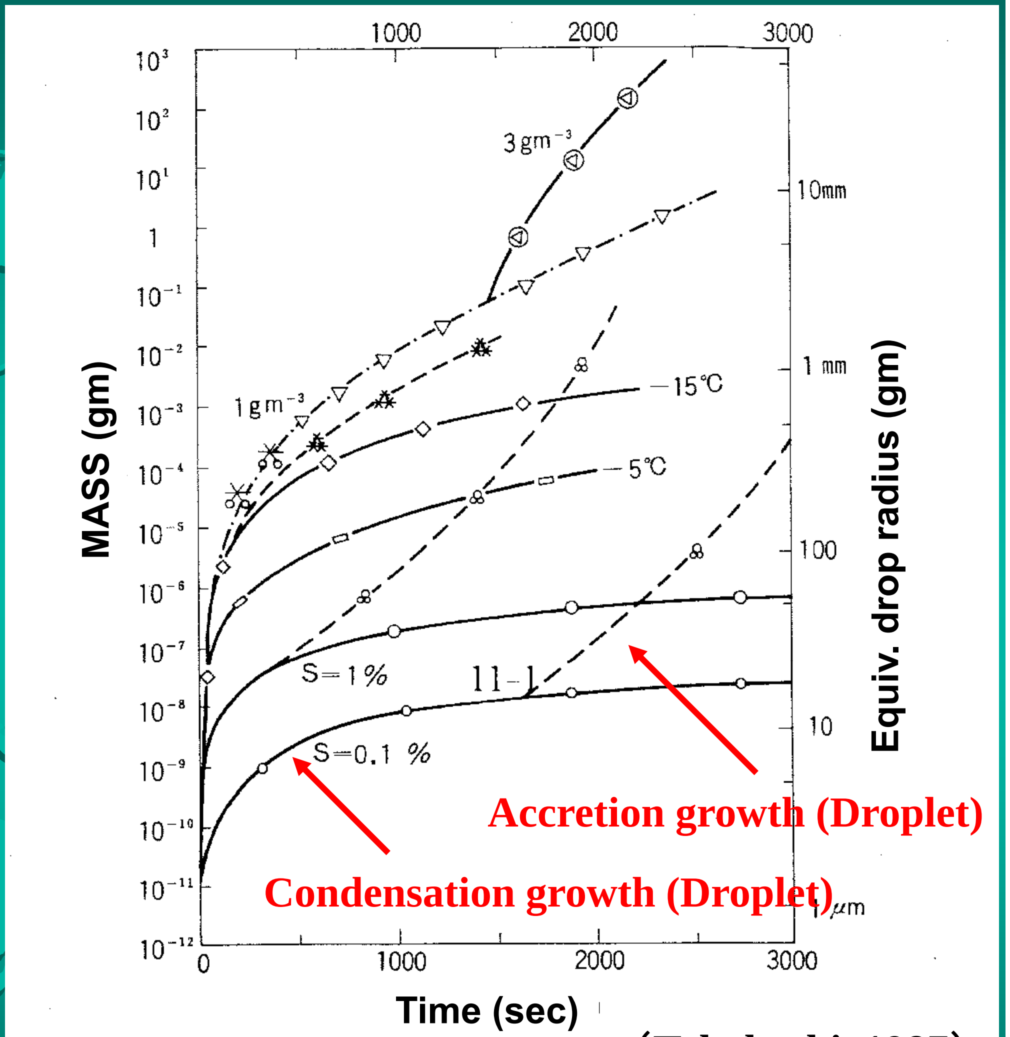


Condensation Growth

$$\frac{dm}{dt} = 4\pi r(s-1)\left(\frac{L^2}{KR_wT^2}+\frac{R_wT}{De_m}\right)^{-1},$$

$$\frac{dr}{dt}\propto\frac{1}{r}(S-1)$$

$$r\propto(S-1)^{\frac{1}{2}}t^{\frac{1}{2}}$$



（Takahashi, 1987）

図 11.1　種々の粒子の成長

○：水滴，過飽和S＝0.1％と1％の場合，

※：水滴の併合成長，1 gm⁻³ で濃度が 100 m⁻³ 番目の大きさ.

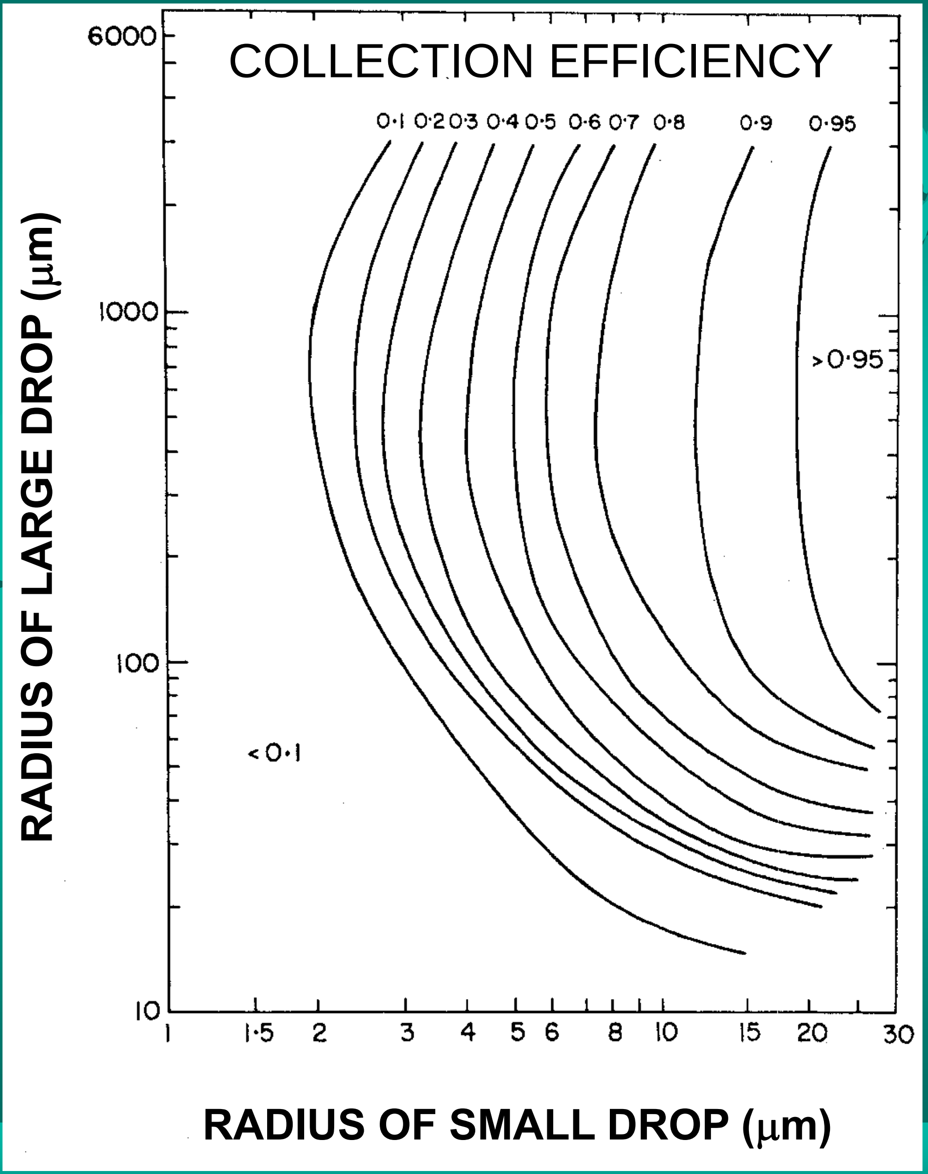
◇，▭：板状及び柱状結晶の −15°C 及び −5°C での水飽和状態での成長.

⁂：4/l の氷晶濃度での雲片形成．d＝1 mm で雪片形成開始とする.

✲ ▽：雲粒 1 gm⁻³ での着氷による霰の形成.

◬：雲粒 3 gm⁻³ での雹の形成，捕捉率はいづれも 1 と仮定している.

Collision-Coalescence Growth



(Rogers & Yaw, 1989)

$$\frac{dm(R)}{dt} = \pi E(R+r)^2 w_r (V_R - V_r),$$

$$\frac{dm(R)}{dt} = \pi R^2 w_r \bar{E} V_r$$

$$\frac{dR}{dt} = \frac{w_r \bar{E}}{4P_L} V_r, \qquad \text{or} \qquad dR = \frac{w_r \bar{E}}{4P_L} dZ,$$

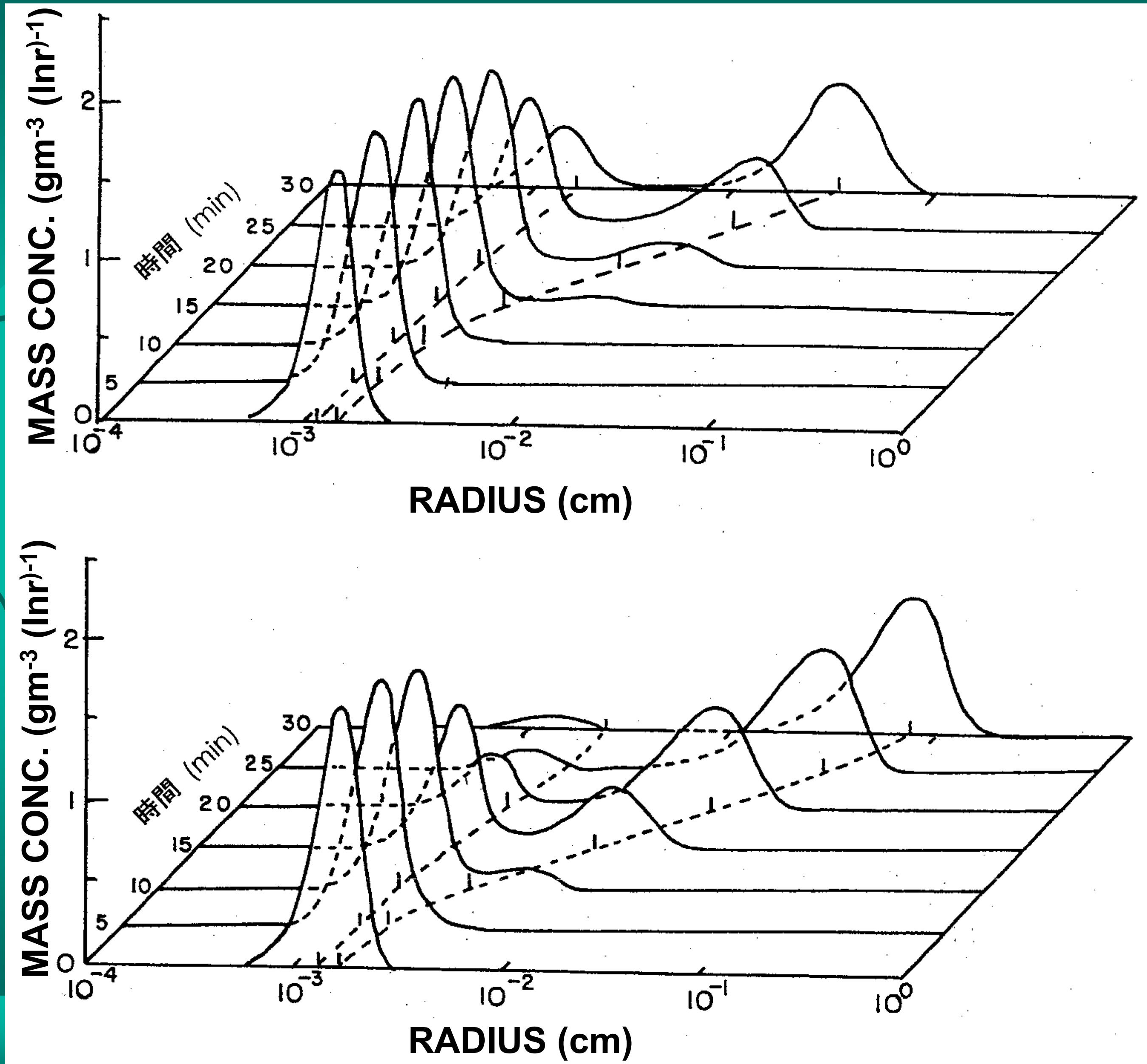
$$0.03mm < r \le 0.6mm$$

$$V_r \propto r$$

$$\frac{dr}{dt} \propto q_c E r$$

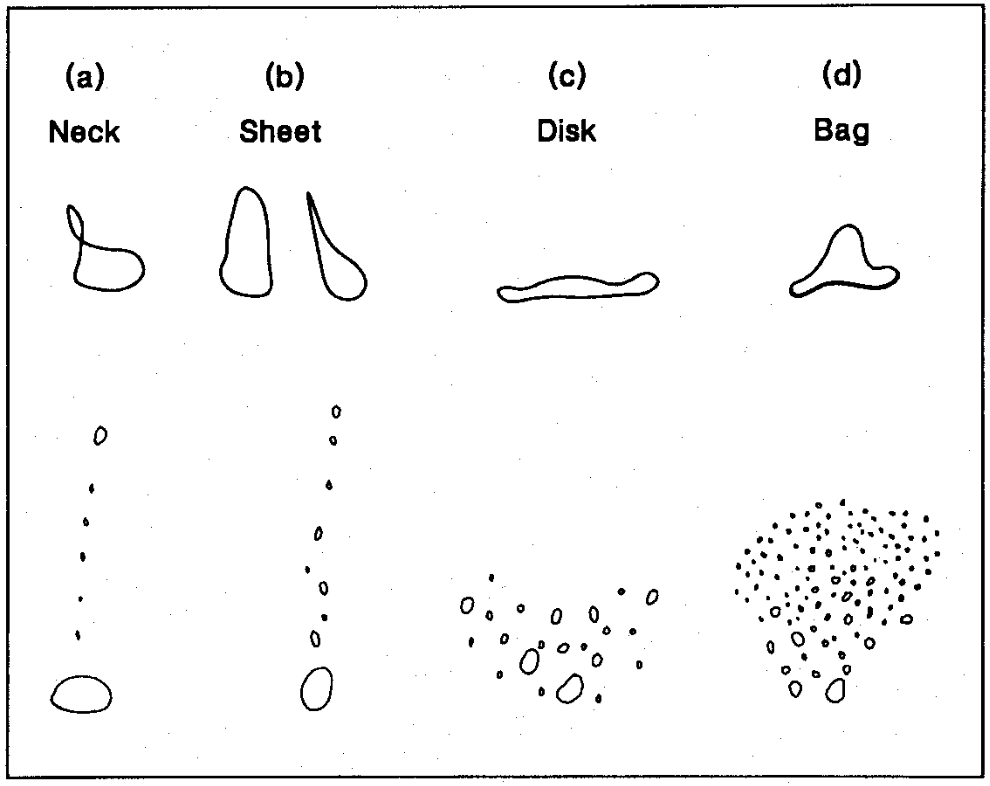
$$r \propto e^{q_c E t}$$

DEVELOPMENT OF DROPLET SPECTRUM

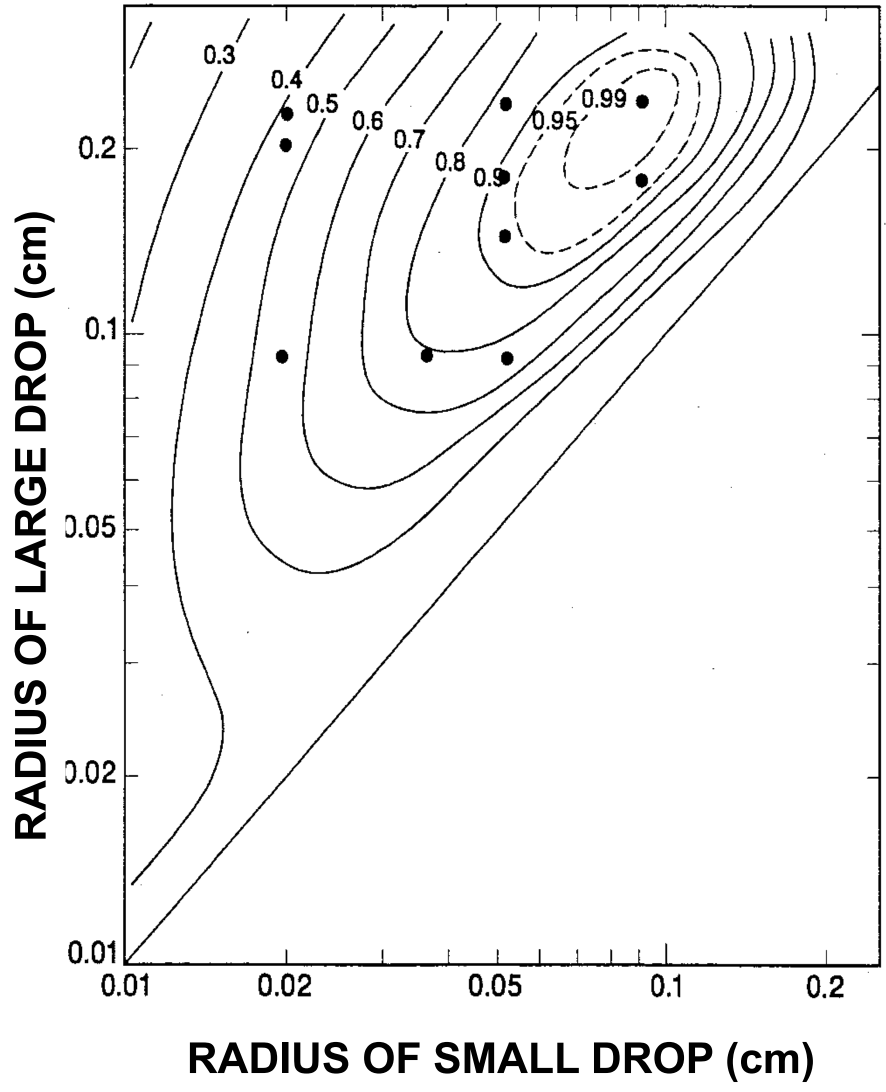


(Berry & Reinhardt, 1974)

BREAKUP MODES & PROBABILITY OF DROP

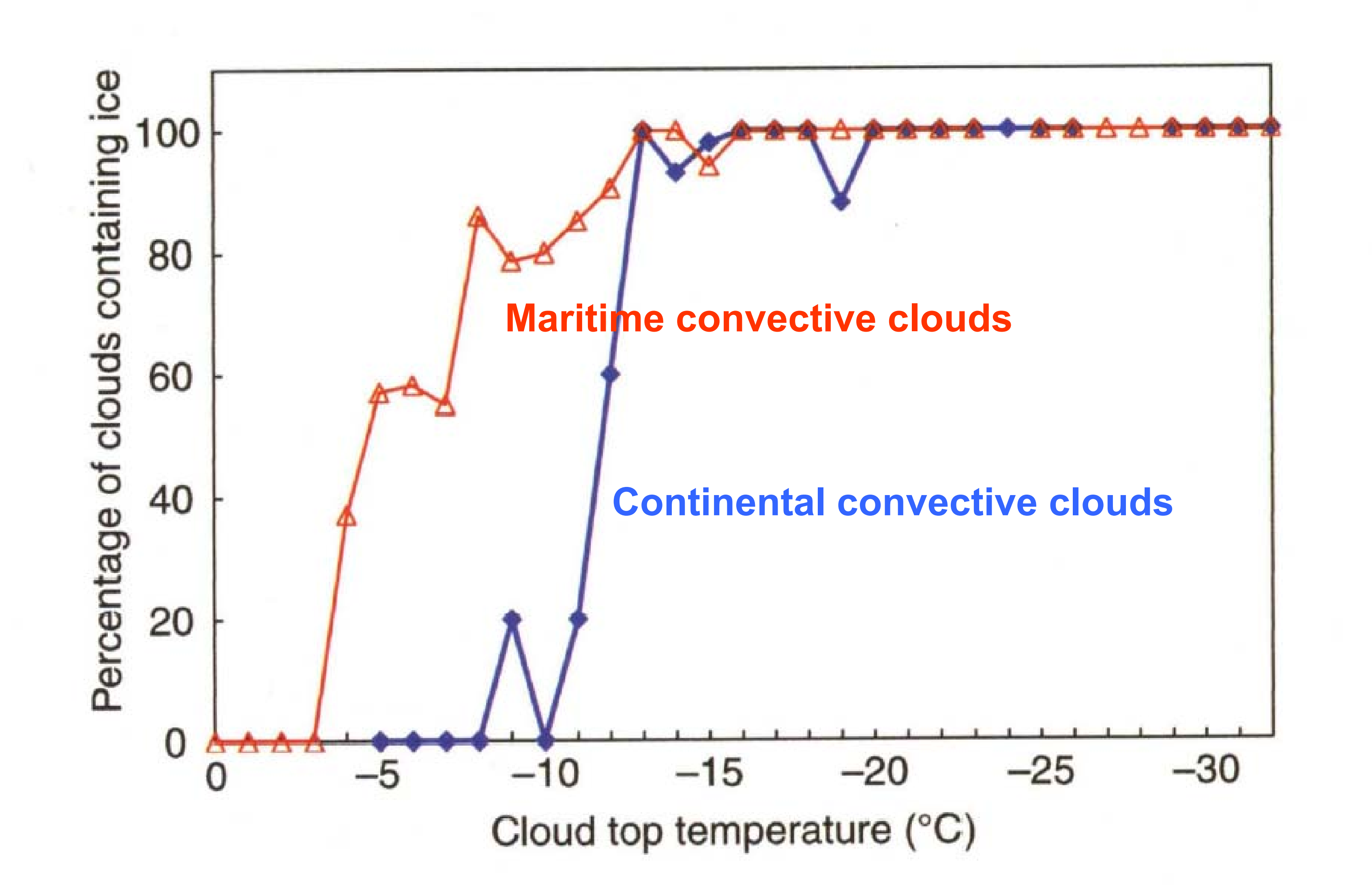


(Mctaggart-Cowan & List, 1975)



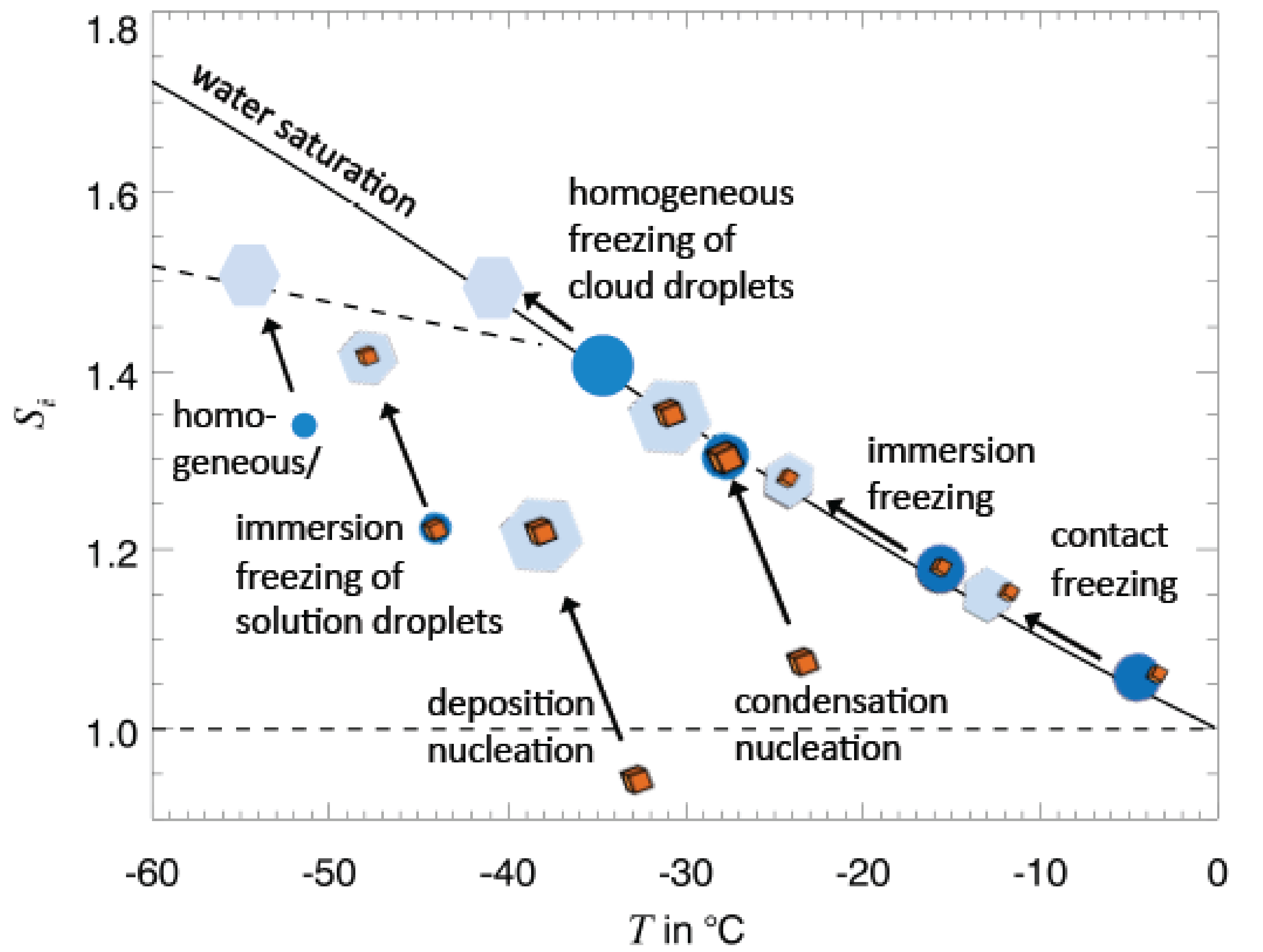
(Low & List, 1982)

Traction of clouds containing ice



(Wallece & Hobbs, 2006)

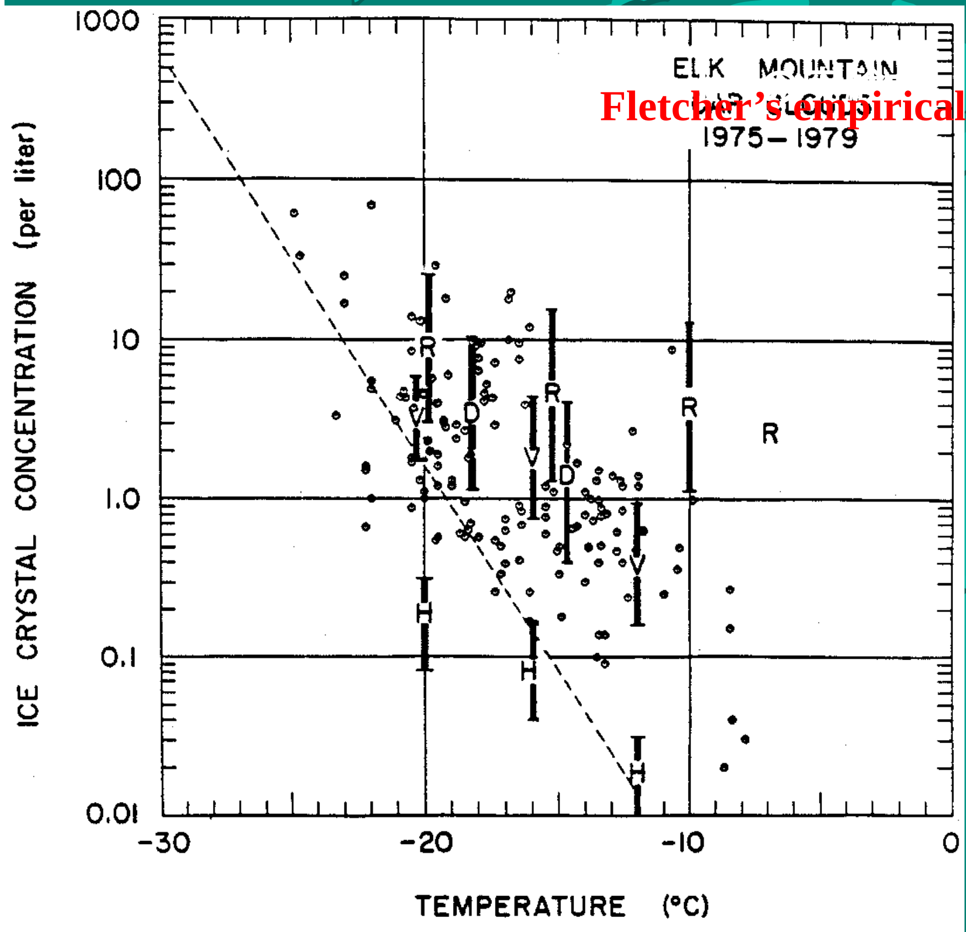
ICE NUCLEATION MECHANISMS

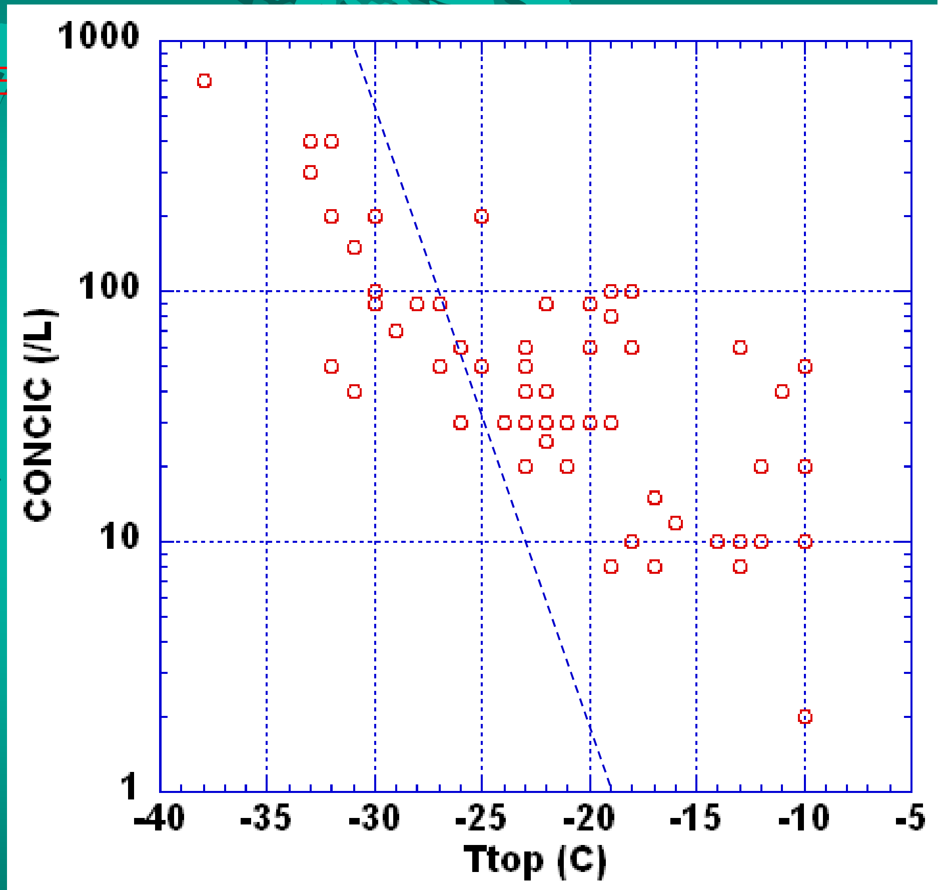


Hoose and Möhler 2012

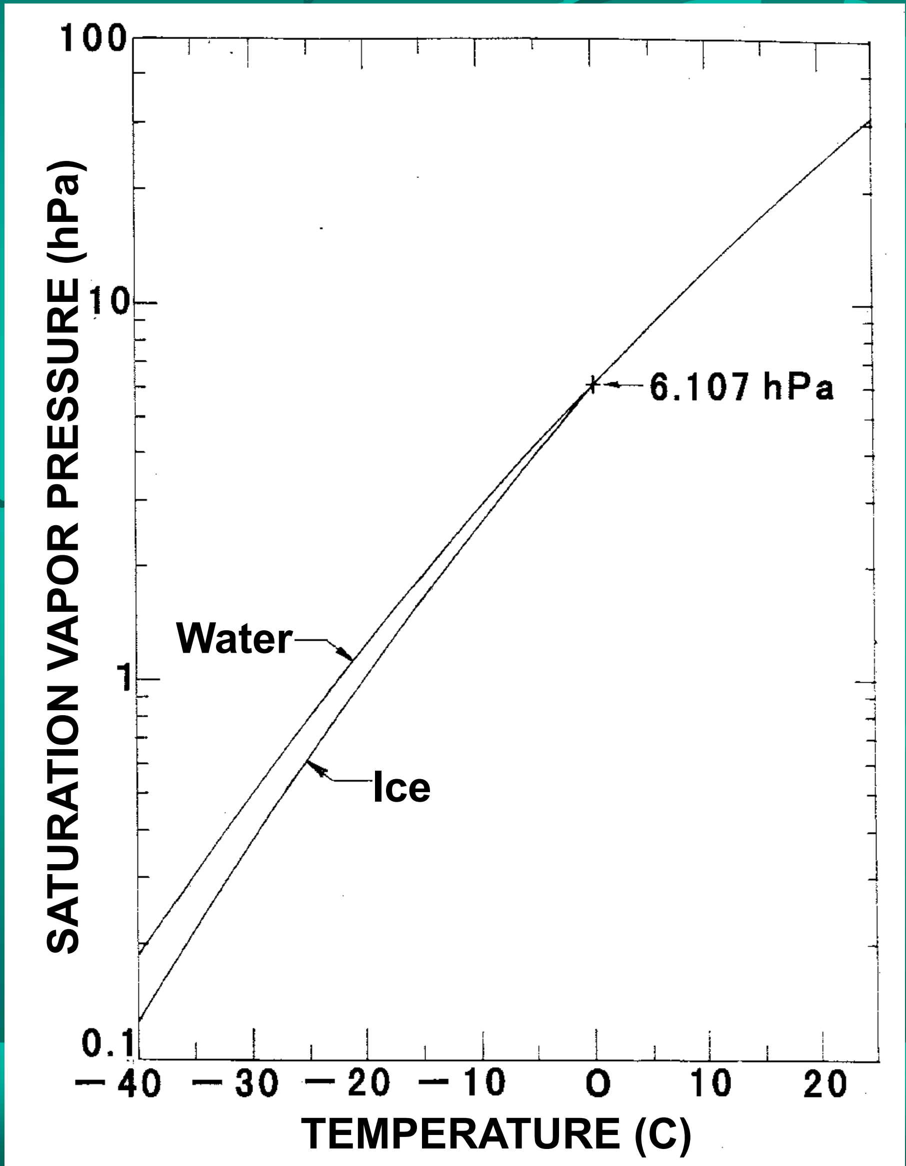
Ice Crystal Conc. vs. Cloud top Temp.

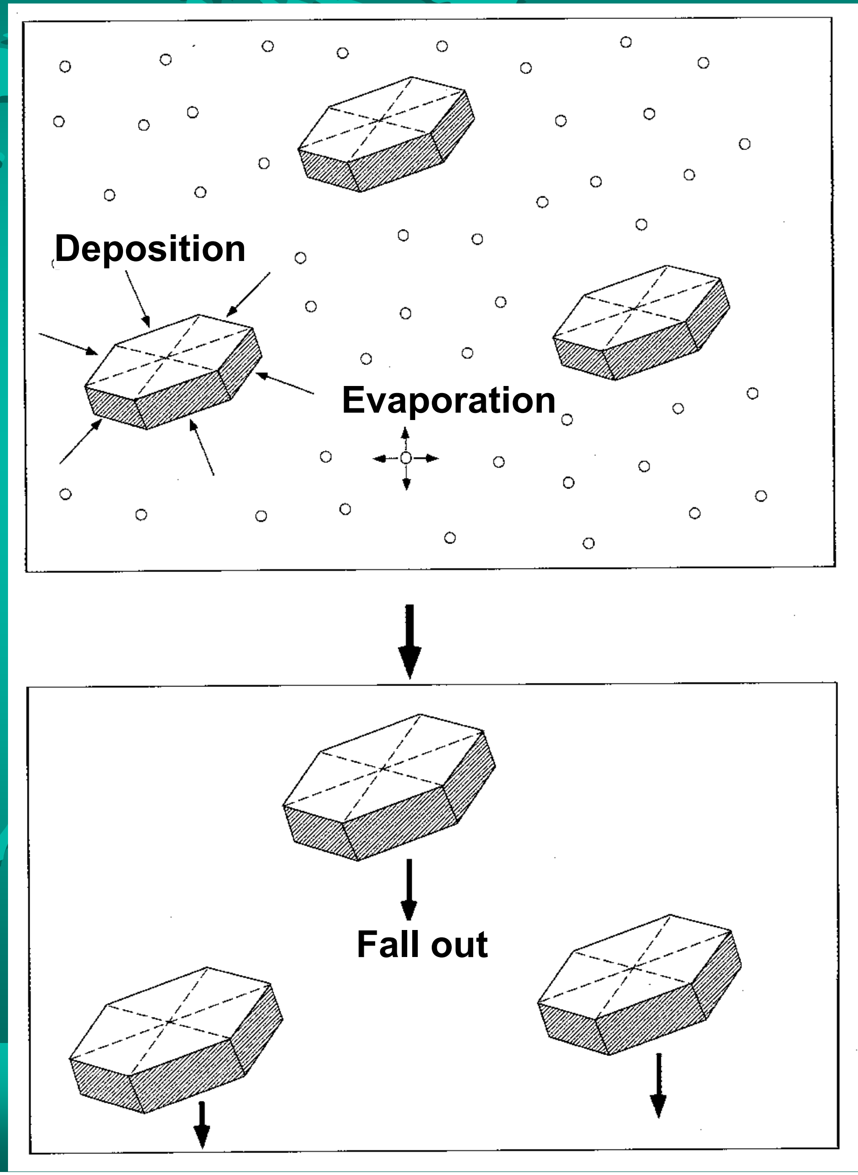
(Midwest of US) (Japan)





ICE CRYSTAL (BERGERON) PROCESS





GROWTH RATE OF HYDROMETEORS

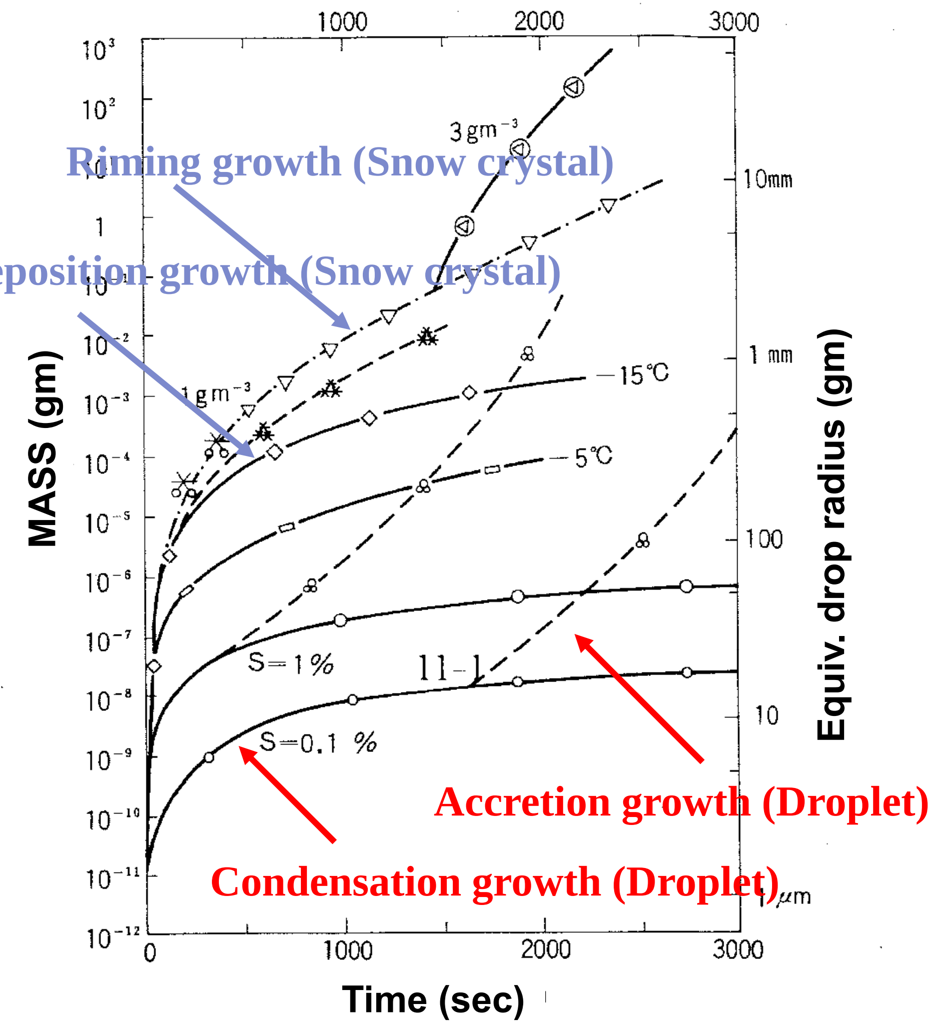


図 11.1　種々の粒子の成長

○：水滴，過飽和 S = 0.1% と 1% の場合，

ȣ：水滴の併合成長，1 gm^{-3} で濃度が 100 m^{-3} 番目の大きさ．

◇，▭：板状及び柱状結晶の −15°C 及び −5°C での水飽和状態での成長．

⁂：4/l の氷晶濃度での雪片形成．d = 1 mm で雪片形成開始とする．

✲　▽：雲粒 1 gm^{-3} での着氷による霰の形成．

◬：雲粒 3 gm^{-3} での雹の形成，捕捉率はいづれも 1 と仮定している．

（Takahashi, 1987）

CONCEPT OF WEATHER MODIFICATION

Basic Concept of Weather Modification

To bring out a potential ability of natural cloud to its maximum by a minimum artificial stimulation

Methods

Ice crystal	Coolant･Ice nuclei （Dry ice･AgI）	Cold cloud (fog) (Mixed-phased)
Droplet	Hygroscopic particle	
Raindrop embryo	Water spray	Warm cloud
	Heating Mixing with dry air Down drought	Fog dispersal

Cloud Seeding

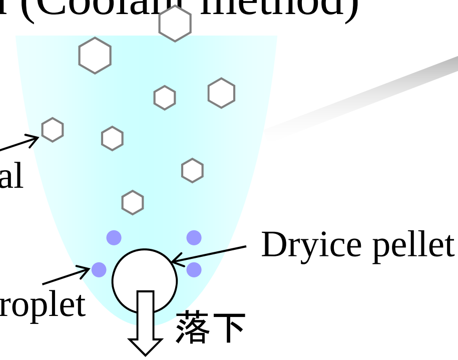
To introduce artificially-generated cloud droplets or ice crystals into clouds and alter its microphysical structure

Glaciogenic vs Hygroscopic; Static vs Dynamic

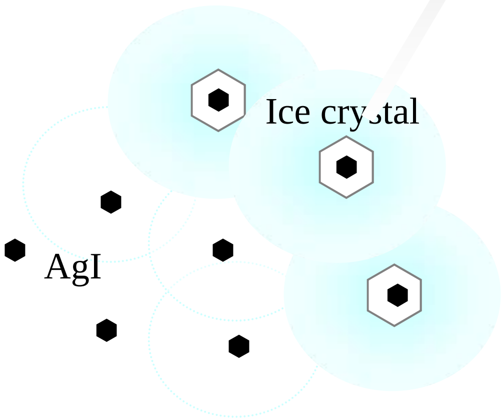
GLACIOGENIC SEEDING (ICE CRYSTAL)

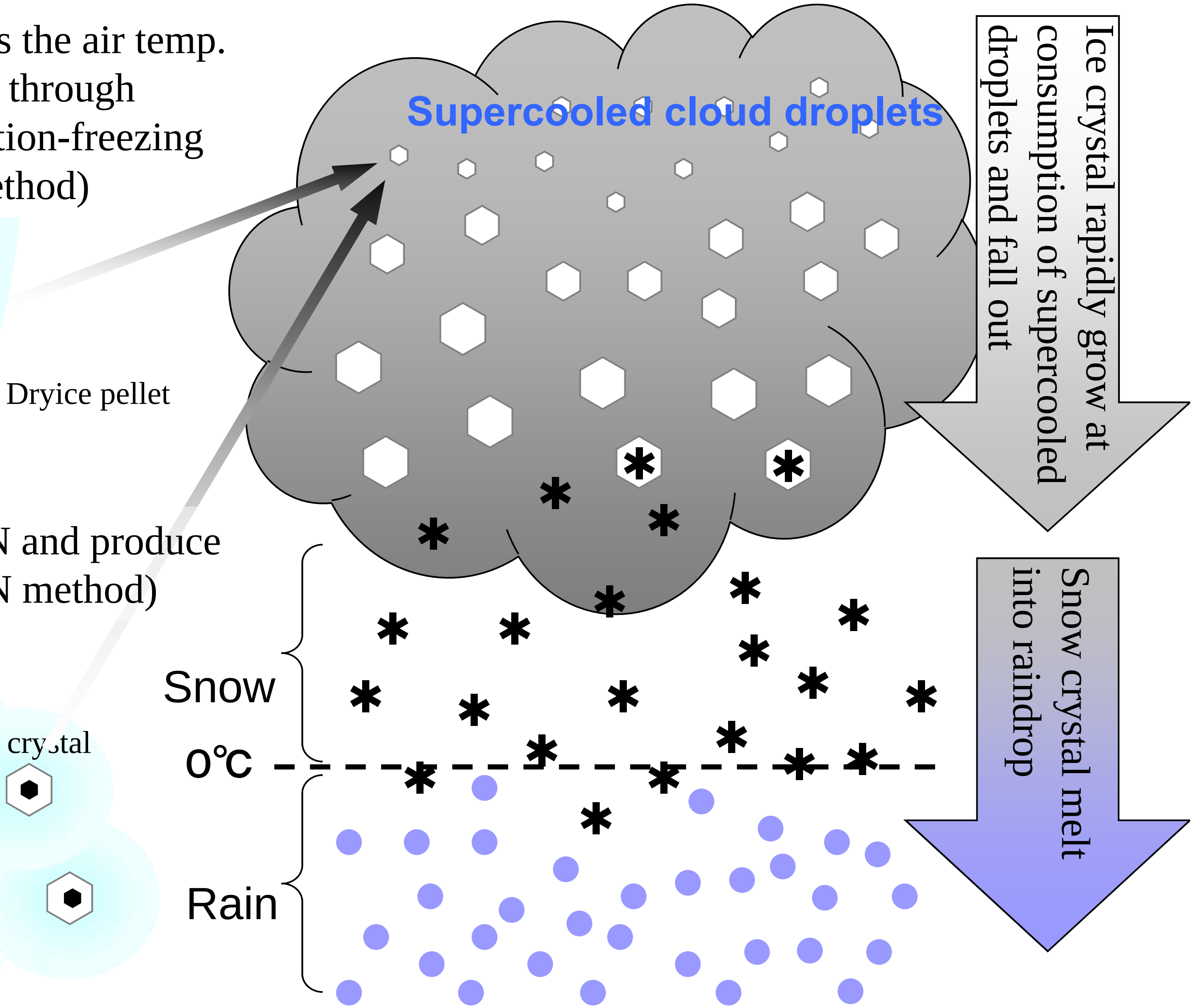
(Mixed-phase Cloud)

○Dryice/Liq. CO_2 cools the air temp. and produce ice crystals through homogeneous condensation-freezing mechanism (Coolant method)

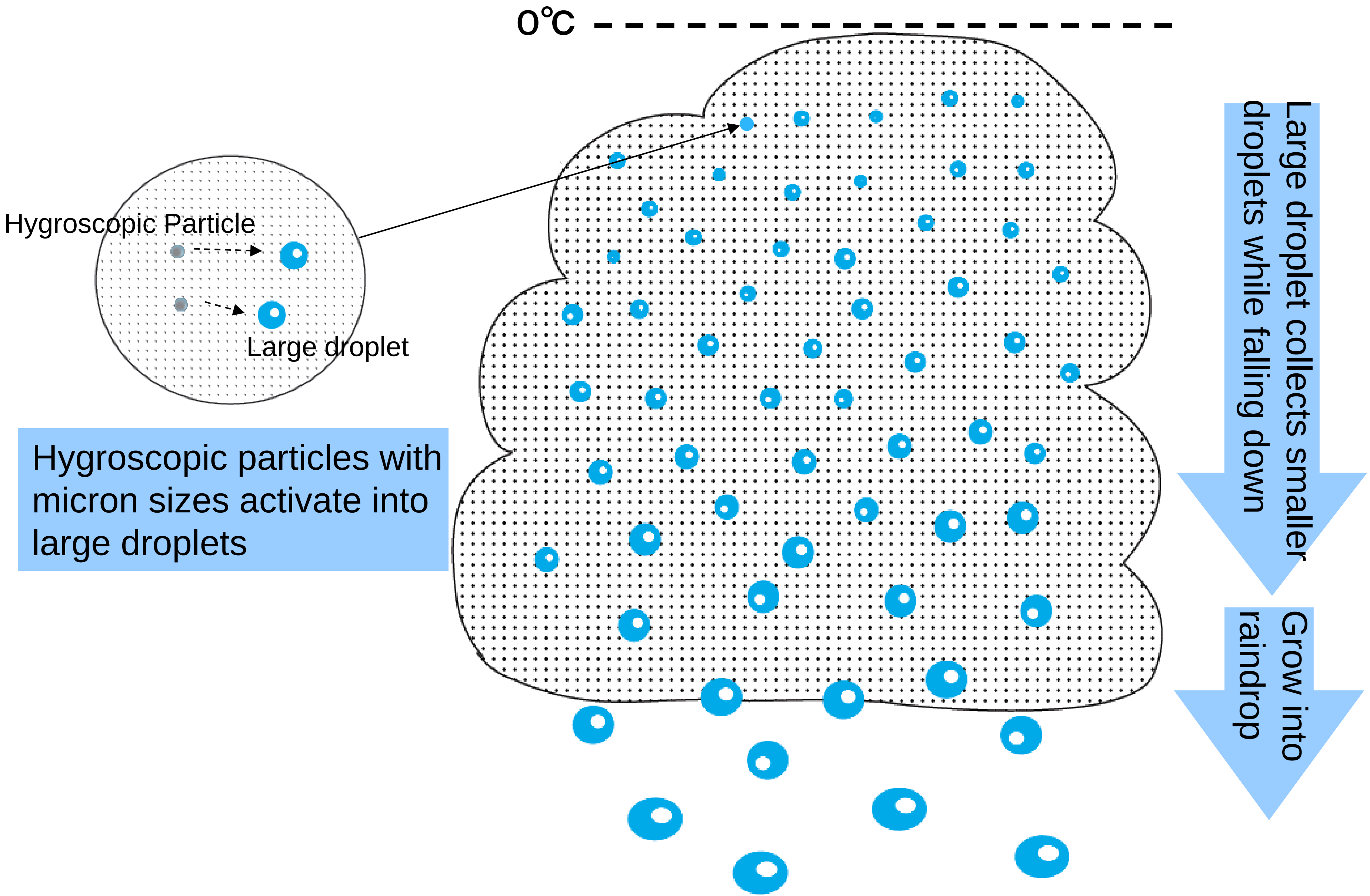


○AgI particles act as IN and produce ice crystals (Artificial IN method)





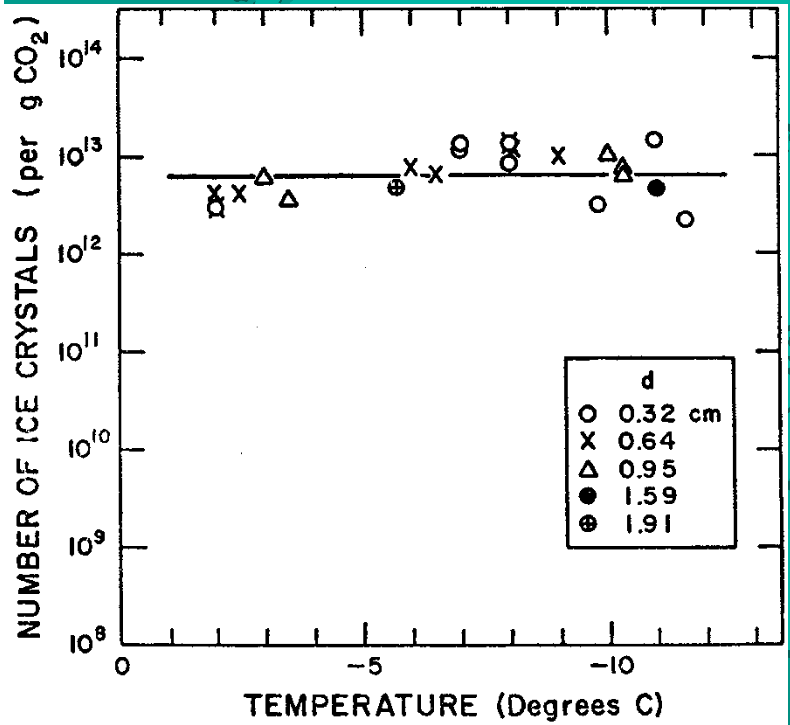
HYGROSCOPIC SEEDING (Large droplet)
(Warm cloud)

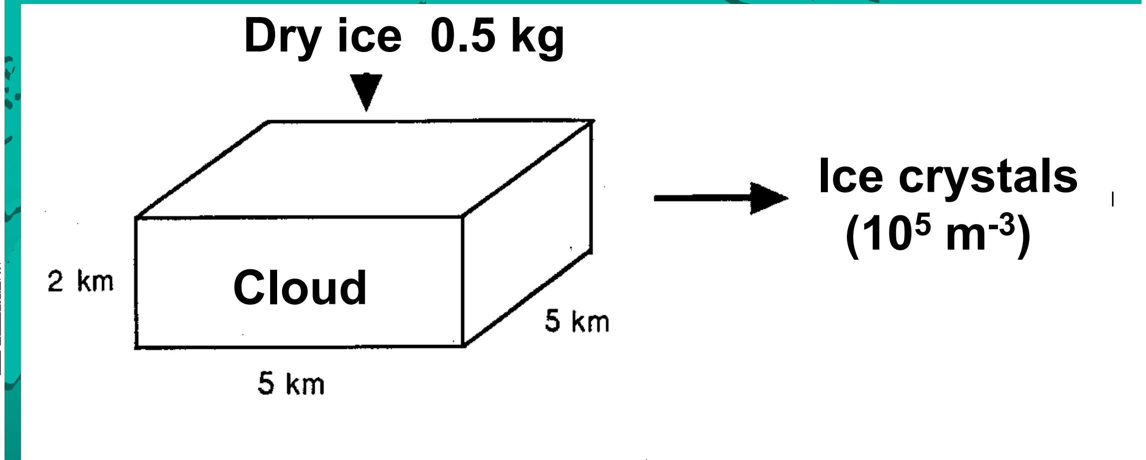


GLACIOGENIC SEEDING

(Coolant Method)

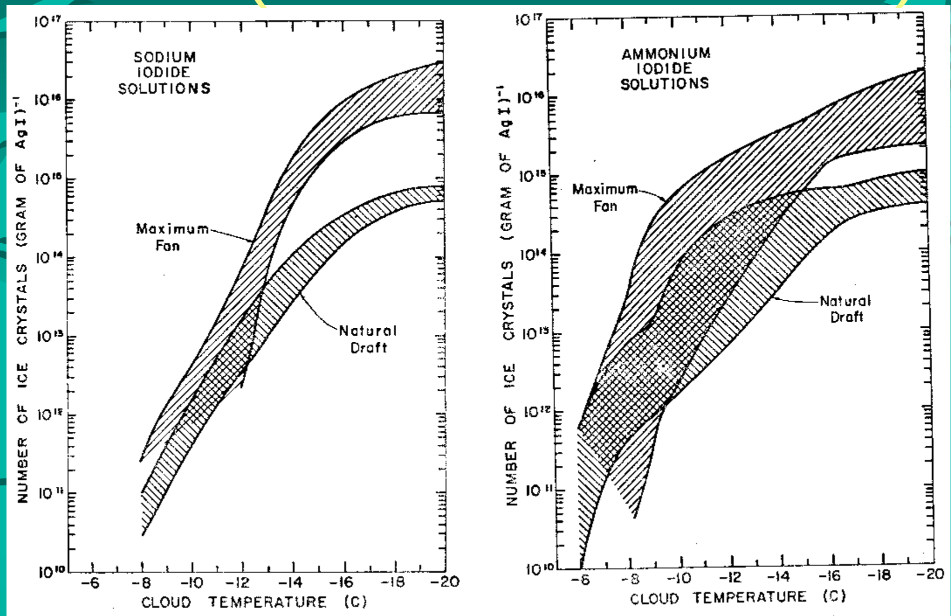
Dryice, Liq. CO_2, Liq. Propane



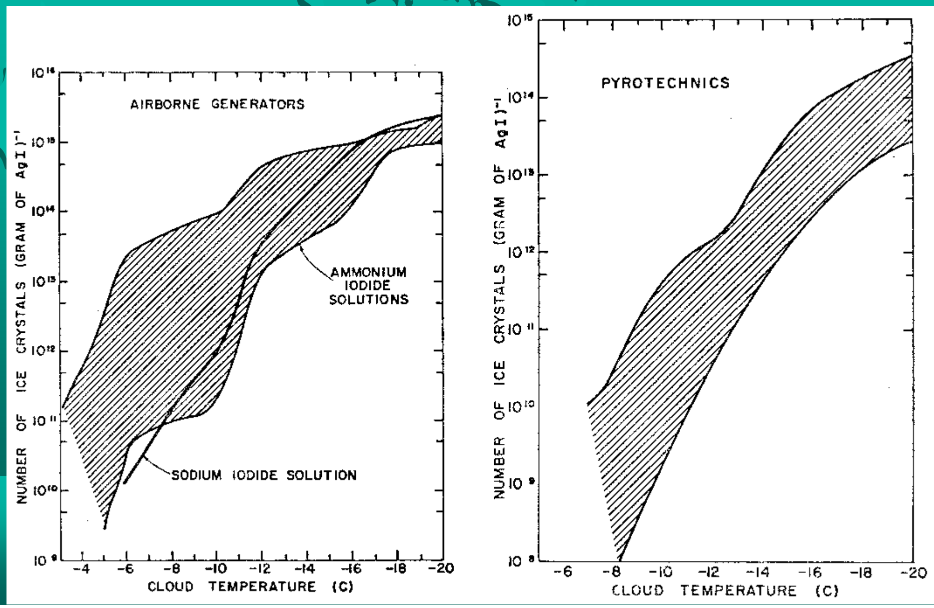


GLACIOGENIC SEEDING

(Artificial IN Method)



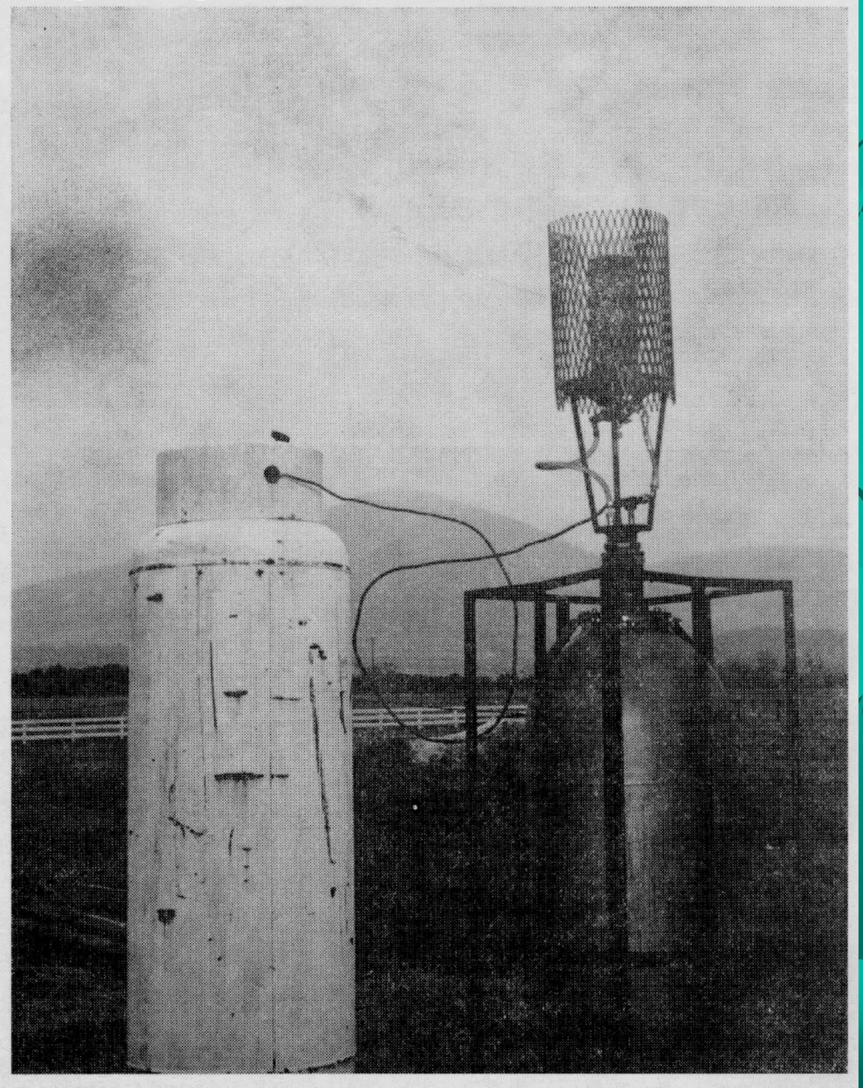
AgI, PbI_2,
Metaldehyde



AgI Generators

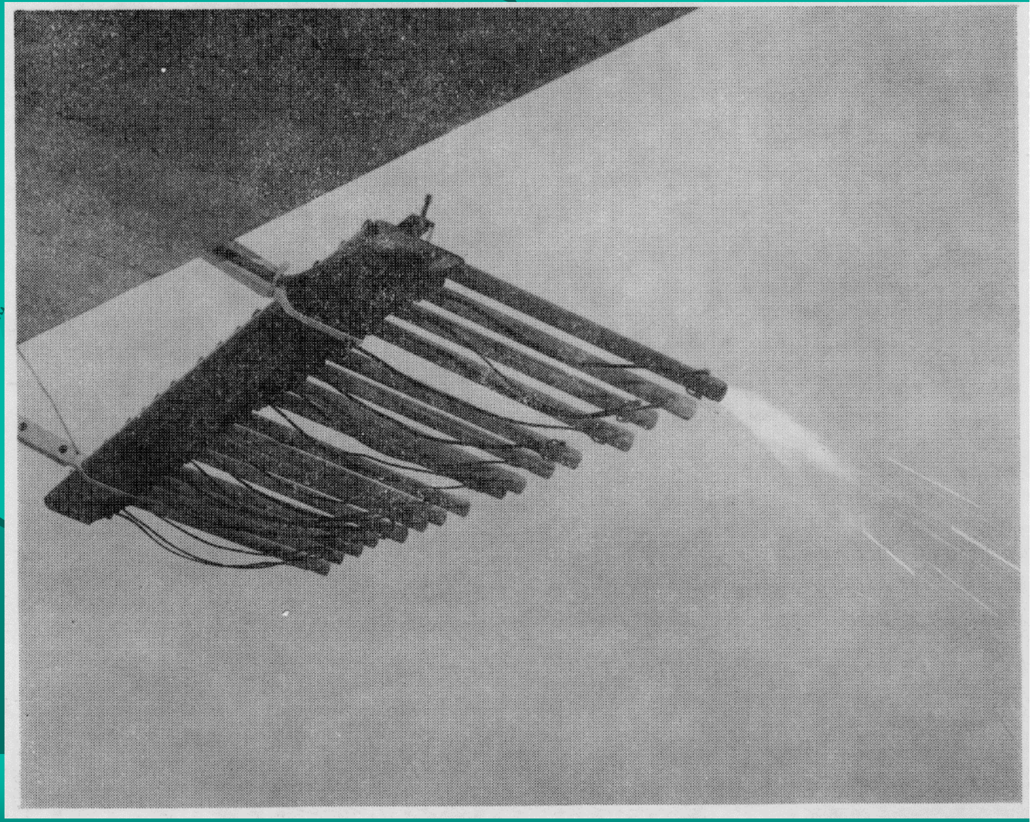
Acetone generator

AgI-AgCl-NaCl-acetone solution



Pyrotechnic

AgI burn-in-place flare



AgI Generators

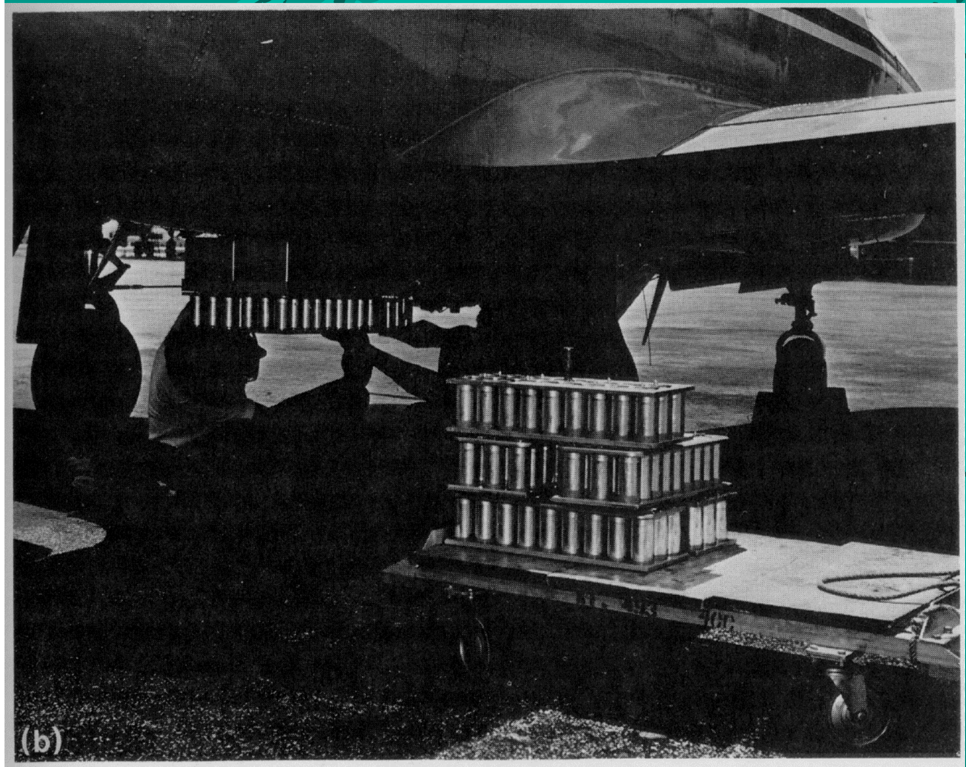
Portable Ground-based Generator

AgI-AgCl-NaCl-acetone solution

(**Snowy Hydro HP**)

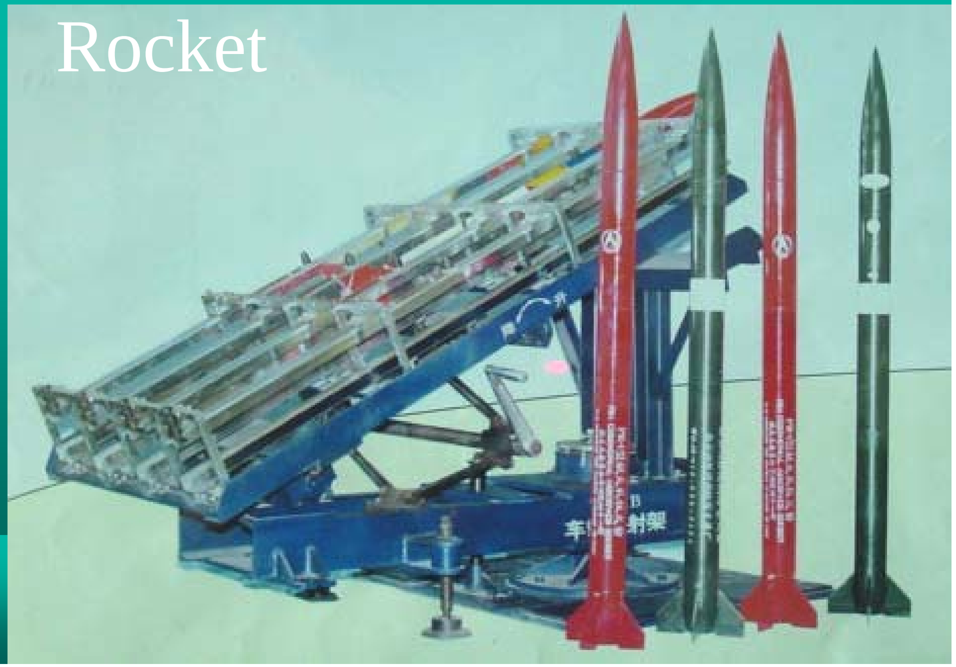
AgI Generators
(Pyrotechnic)

AgI ejectable flare



Artillery Shell

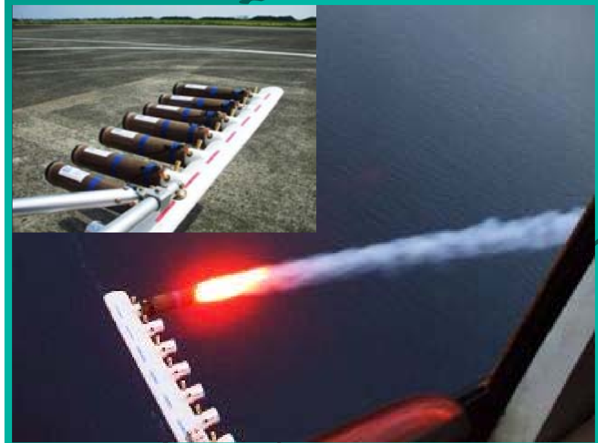
Rocket



Hygroscopic seeding

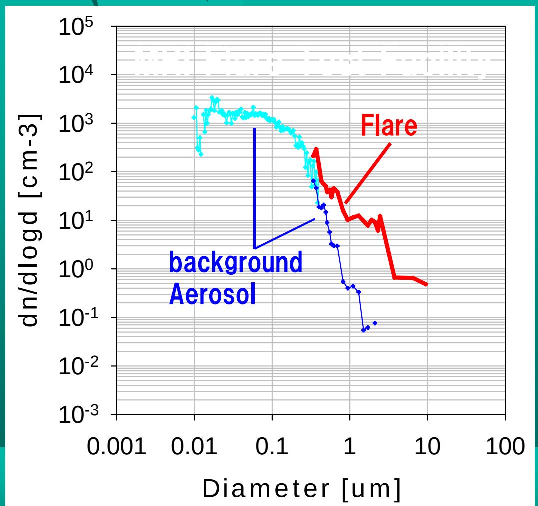
Hygroscopic flare seeding※

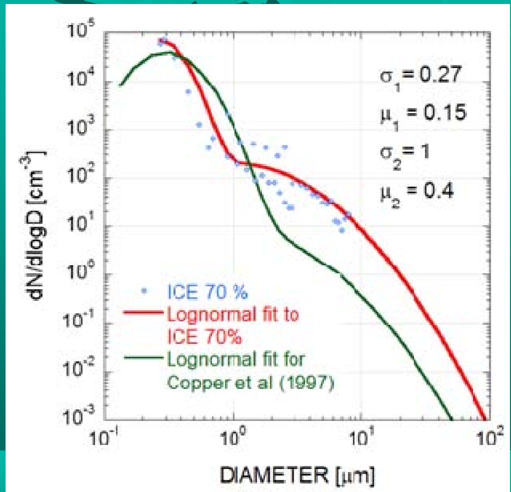
※Small salt particles produced from burning pyrotechnic flares are seeded in updraft region at cloud base and introduced into the clouds with help of updraft.



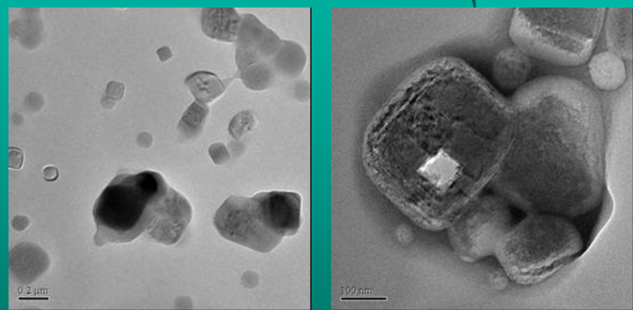
Elemental composition of the South African Flare

Chemical Components	Flare Composition	Small Particles (<10um)	Large Particles (>10um)
KCL ($KClO_4$)	0.54	0.58	0.42
Na Cl	0.20	0.23	0.25
MgO (Mg)	0.24	0.19	0.33
Li_2CO_3	0.03	Not detected	Not detected





Number size distributions of flare particles



TEM image of particles of $CaCl_2$ 70% flare (Ice Crystal Engineering Inc.)

Bruintjes et al. (2006)

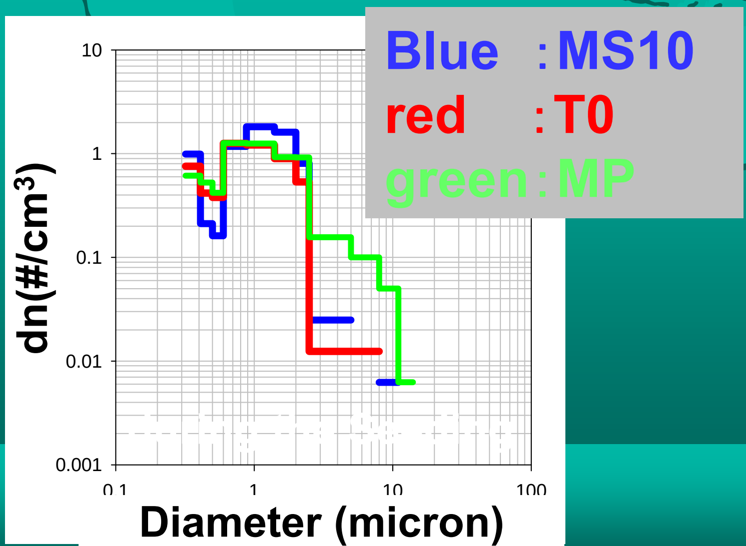
Hygroscopic Seeding

Salt Micro-Powder Seeding※

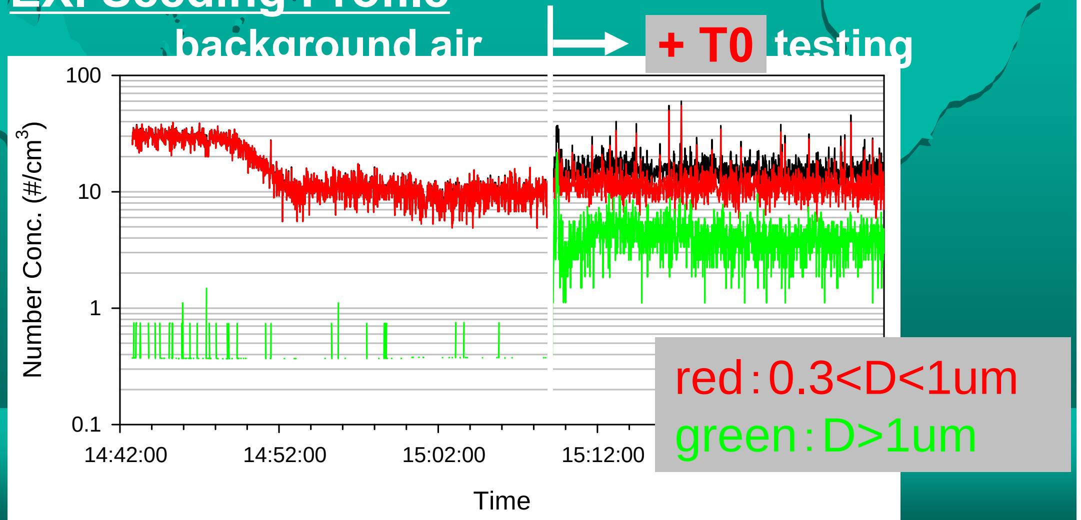
※Hygroscopic salt powder milled to the optimal size (a few microns in diameter) are seeded in updraft region at cloud base and introduced into the clouds with help of updraft

Different types of salt particles tested

	MS10 (AKO KASEI CO., LTD)	T0 (AKO KASEI CO., LTD)	MP (Israel)
Peak Size (spectrum width)	0.7um (0.3-5um)	1.5um (0.5-20um)	0.3,2,15um (-30um)
Chemical Components	NaCl	NaCl	NaCl` SiO2` Ca3(PO4)2?



EX. Seeding Profile



APPLICATION OF WEATHER MODIFICATION TECHNOLOGY

- PRECIPITATION ENHANCEMENT
- HAIL SUPPRESSION
- FOG DISPERSAL
- MITIGATION OF HEAVY PRECIPITATION
- HURRICANE MODIFICATION
- LIGHTNING SUPPRESSION
- OTHERS
  - CIRRUS MODIFICATION

PROBLEMS OF WEATHER MODIFICATION

- Statistical Evaluation of Seeding Effects
- Ecological Consideration
- Sociological Consideration

EVALUATION OF SEEDING EFFECTS

Before seeding

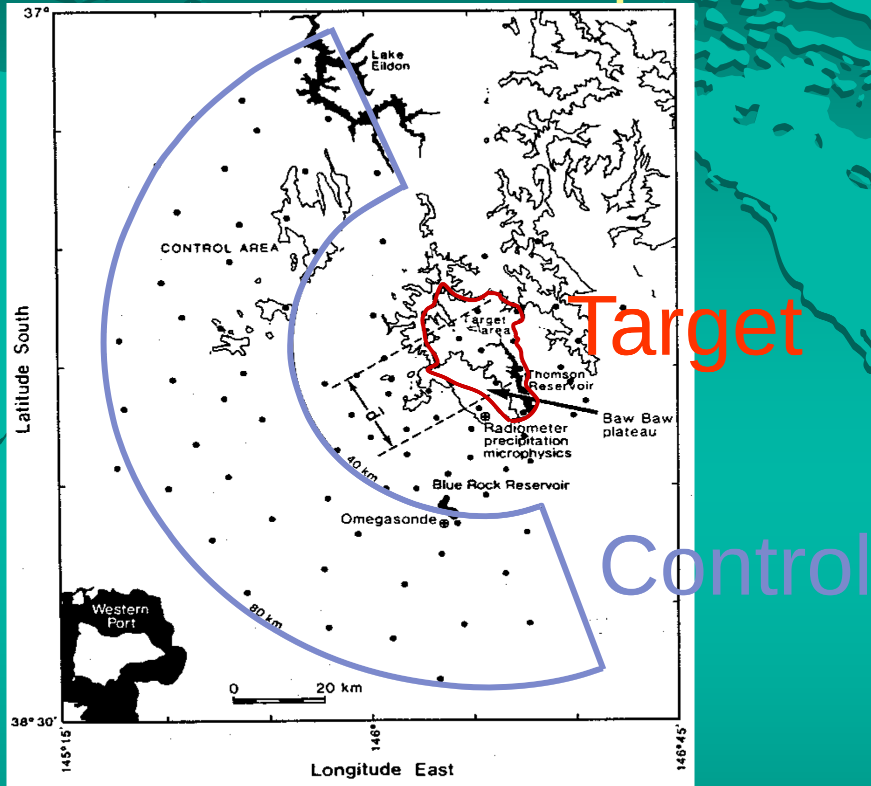
LET IT RAIN: Unseeded clouds (*top*) have less moisture conte than the same bank of clouds after seeding (*bottom*). The seed clouds managed to produce rain showers.

After seeding

What happened if we did not seed?

EVALUATION OF SEEDING EFFECTS

Statistical Techniques



Number of Experimental Units and Seasons Required to Detect a 40% Rainfall Increase under a Randomized Single-Area Design[a]

Experiment	No. of units	No. of units per season	Seasons
SCUD (Eastern U.S.)	178	19	9
Grossversuch IIIA (Swiss hail experiment)	390	15	26
Arizona I	460	22	21
East central Illinois (summer showers)	770	38	20

[a] Based on data from Neyman and Scott (1967a).


Thank you for your attention