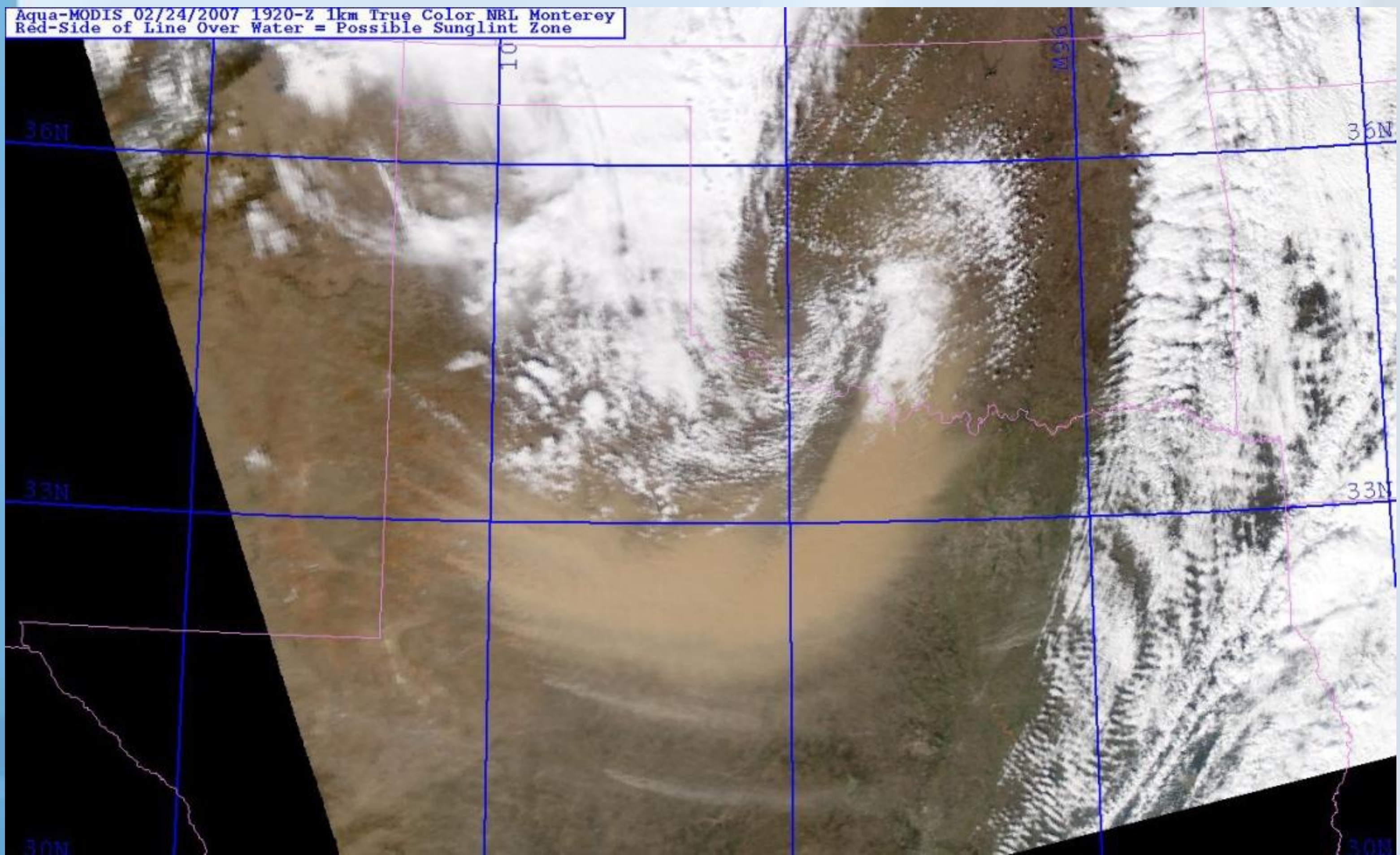
Incorporating Aerosol Effects on Clouds and Precipitation into WRF

Roy Rasmussen, Trude Eidhammer, Greg Thompson and Lulin Xue
NCAR

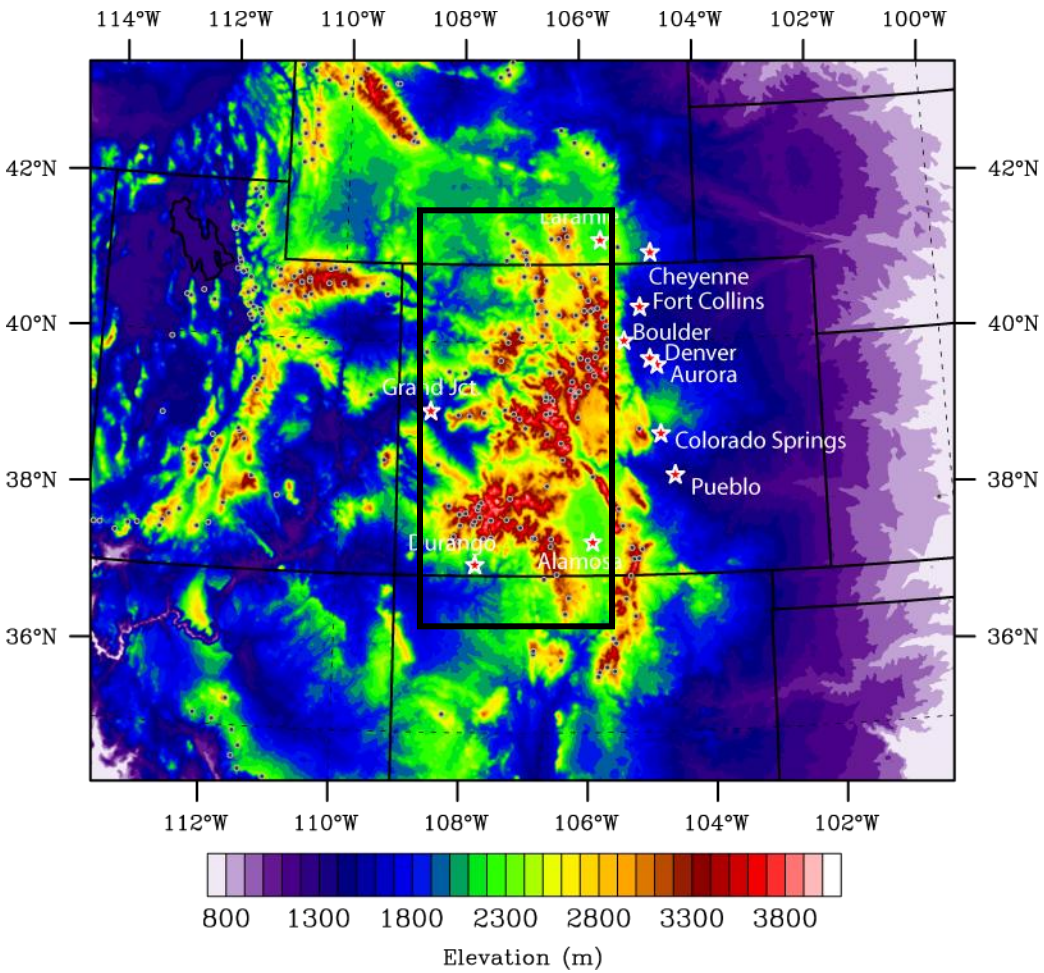


Outline

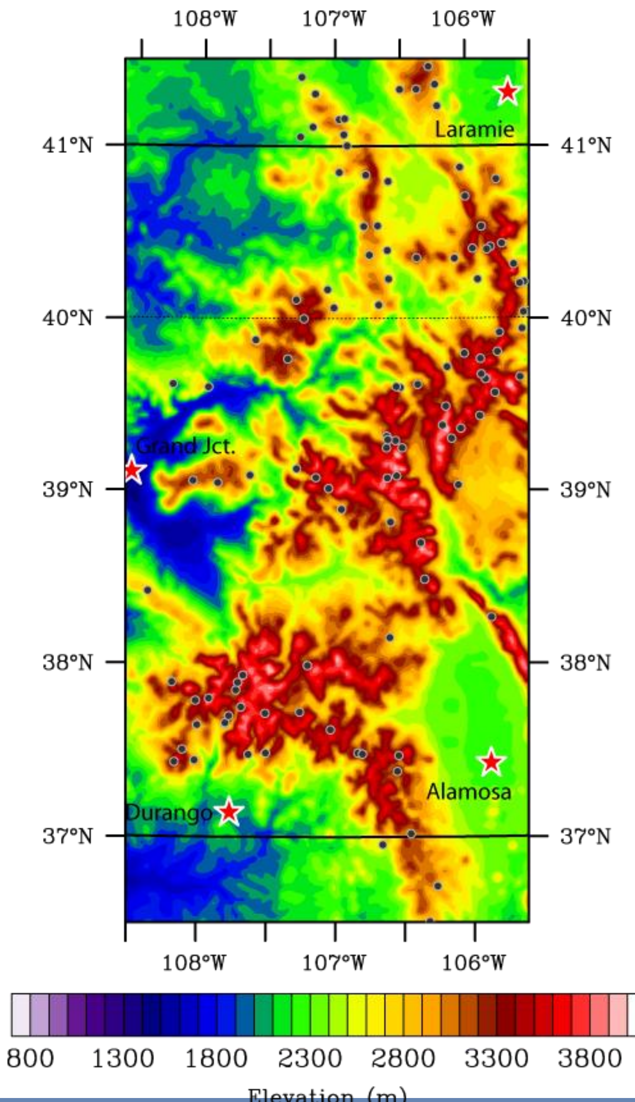
1. Motivation and Background
2. Initiation of cloud droplets by aerosols
3. Cloud processing of aerosols
4. Ice Initiation by Aerosols
5. Perspective

Colorado Headwaters simulations of snowfall (2 km resolution)

Full Domain

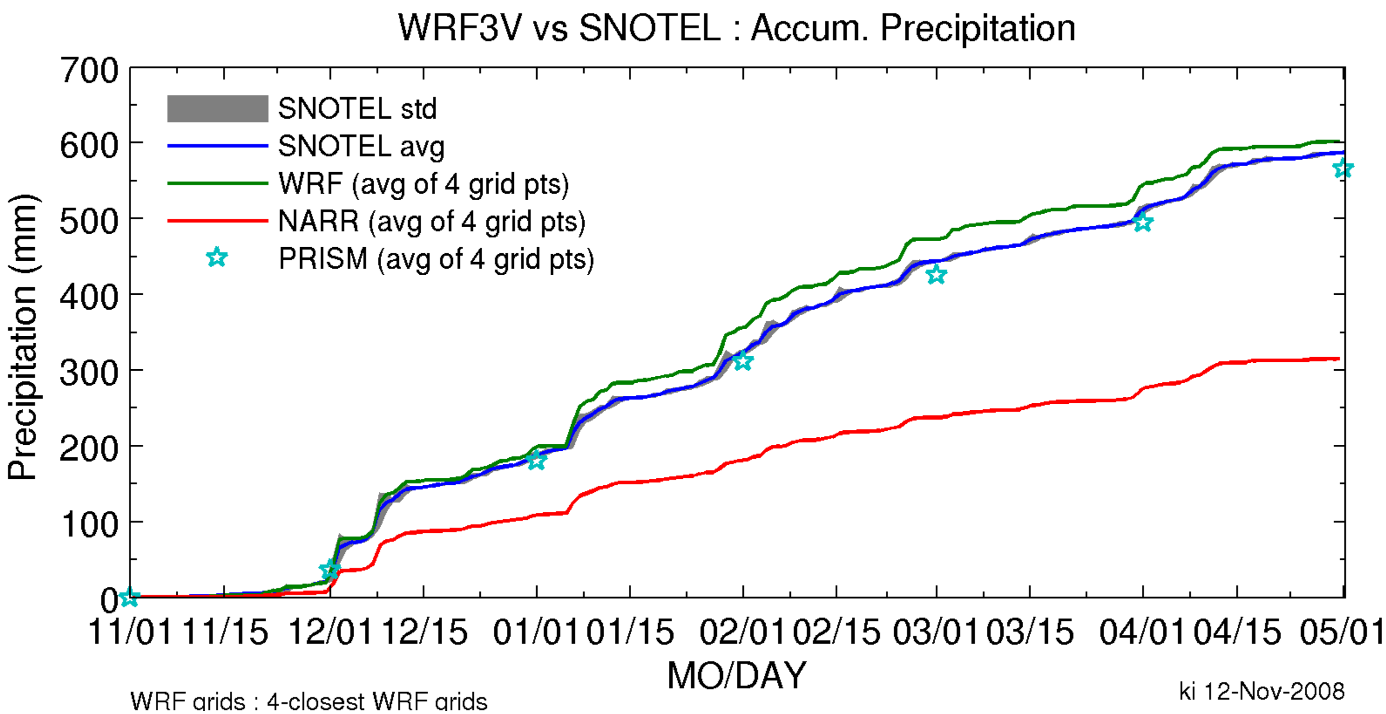


Sub-domain



Full Water Year Simulation

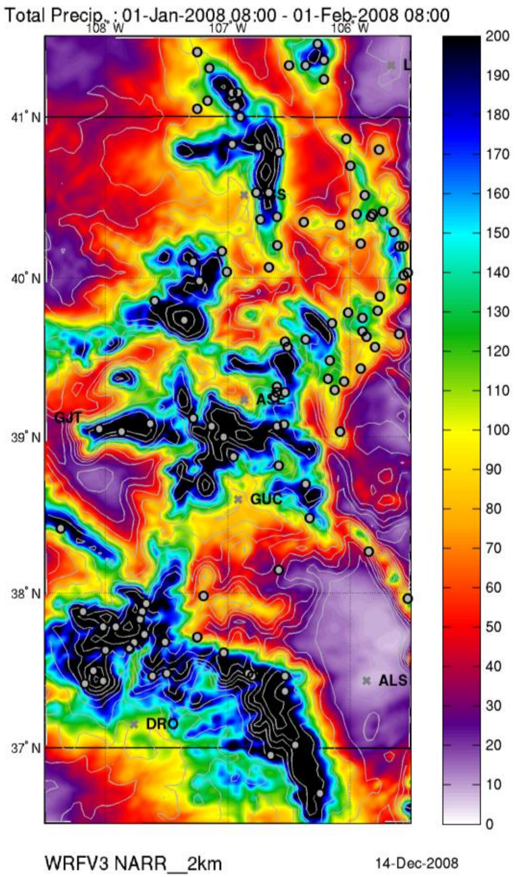
Nov. 2007-May 2008



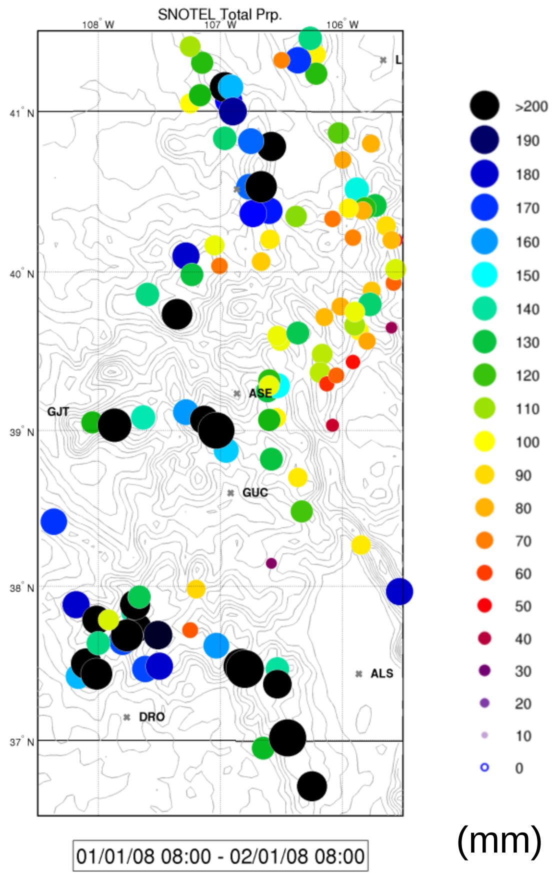
		Monthly						Sim. Period
		November	December	January	February	March	April	11/1-5/1
Difference in accumulative precipitation between WRF and OBS (WRF-SNOTEL)	Mean of 4-grid points	-1.70	7.10	23.43	-1.44	4.24	-18.32	14.76
	Inverse distance weighted mean of 4-grid points	-1.66	7.48	23.90	-1.15	4.29	-18.27	16.16
Absolute difference in accumulative precipitation between WRF and OBS (WRF-SNOTEL)	Mean of 4-grid points	6.82	27.54	30.43	21.57	16.11	21.75	88.95
	Inverse distance weighted mean of 4-grid points	6.82	27.39	30.26	21.51	16.03	21.72	87.67

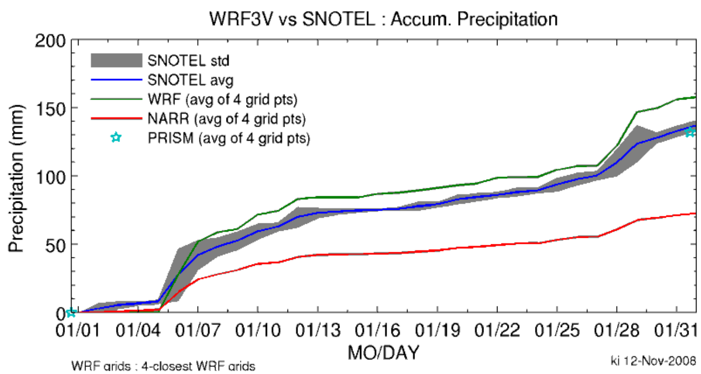
Total Precipitation: January 2008

WRF simulation

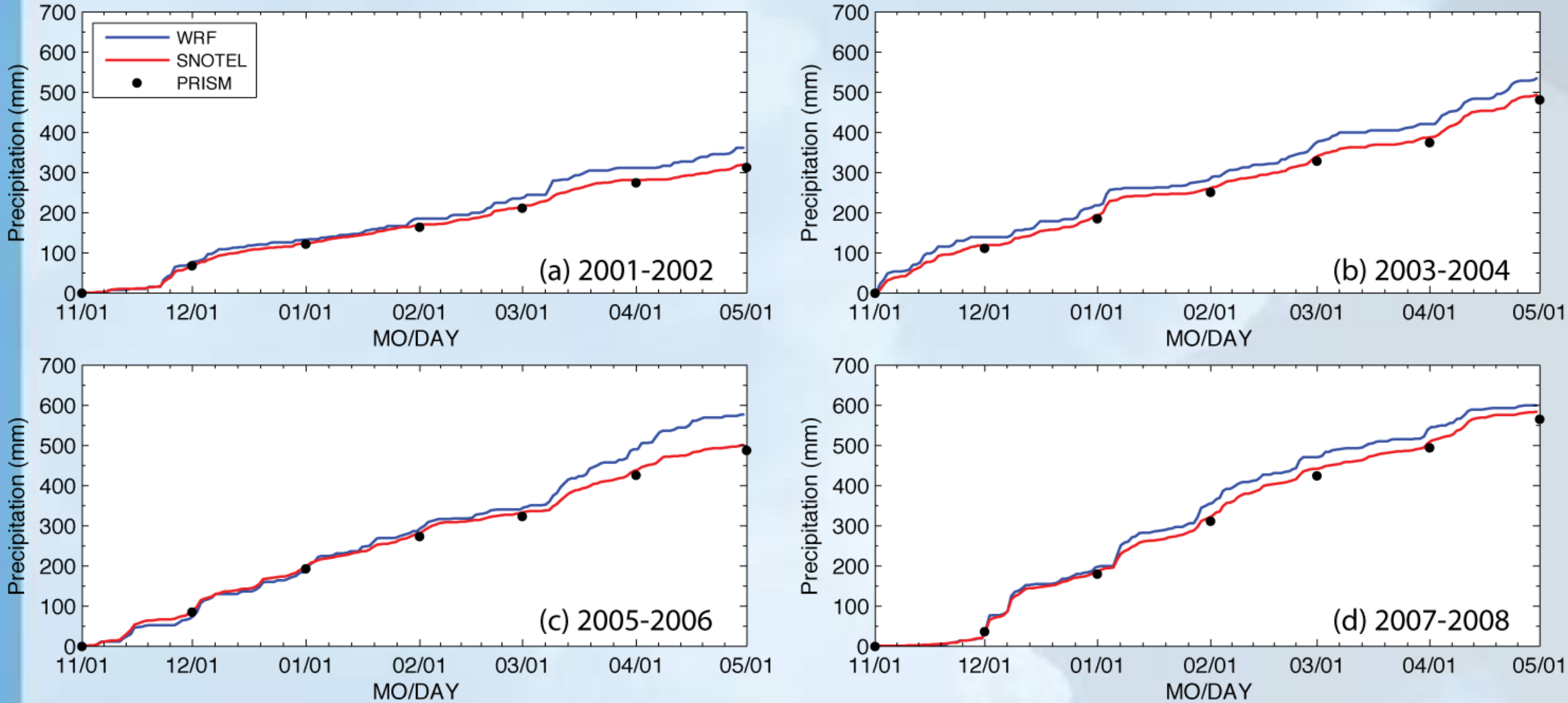


SNOTEL observations





4-Year Comparison between average SNOTEL and PRISM observations and WRF Simulations

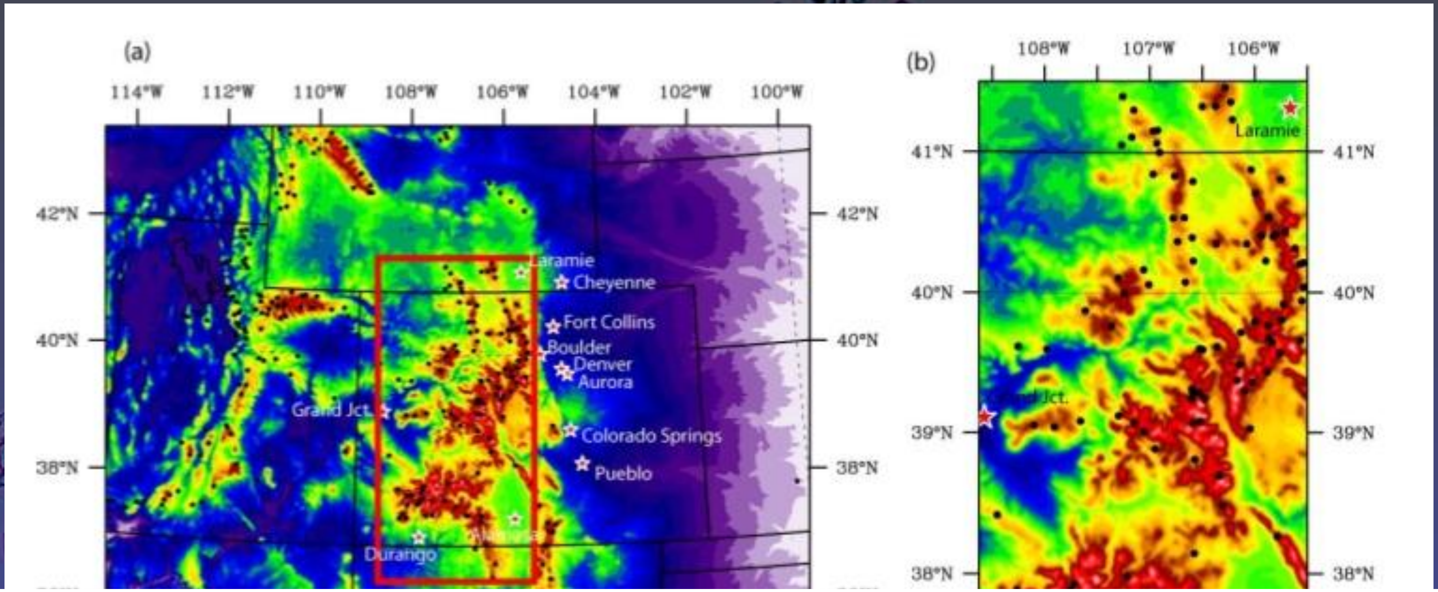


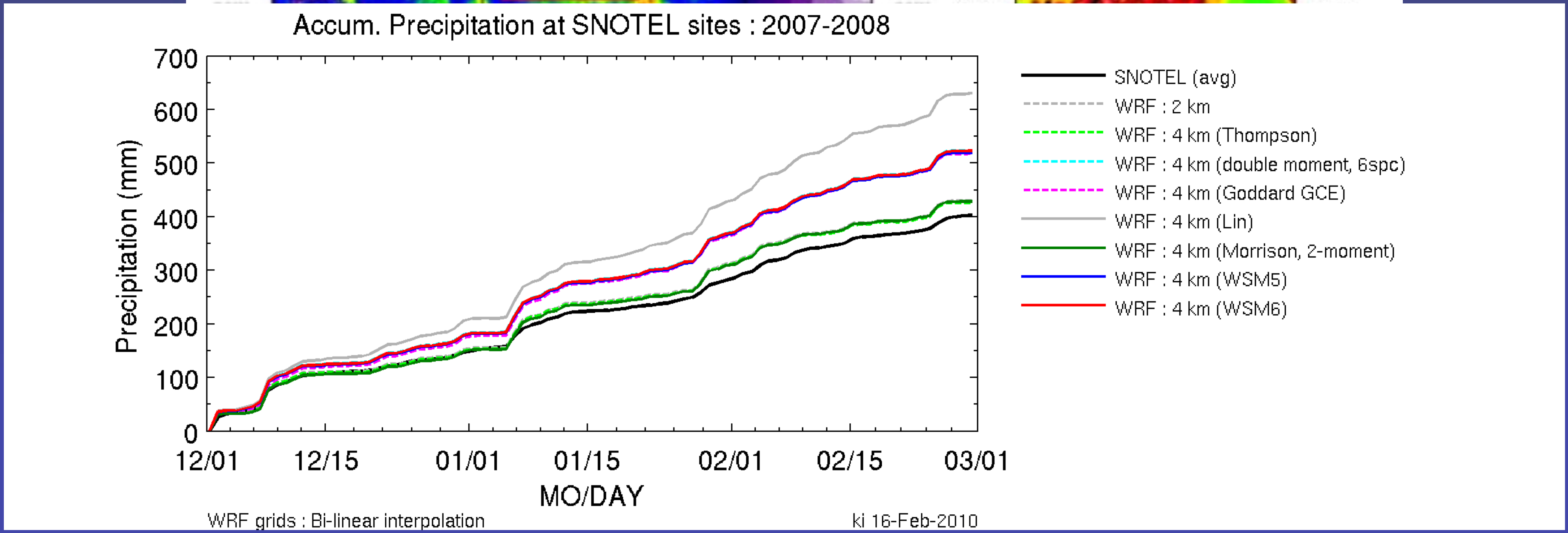
Percent Difference : (model – obs)/obs

	NOV	DEC	JAN	FEB	MAR	APR	6-mo.
2001-2002	13.7	-1.1	17.8	12.0	11.4	34.4	13.4
2003-2004	17.4	4.5	3.5	10.3	-3.7	8.2	8.4
2005-2006	-15.1	6.6	20.4	1.9	37.3	39.7	15.1
2007-2008	7.8	5.2	15.0	-1.6	6.1	-24.8	2.7

ESSL NCAR

CO Headwaters: microphysics sensitivity





The next frontier: “aerosol impacts”

The bulk scheme now appears to match observations relatively well, so we proceed on a “journey to aerosol impacts”

Crawl:

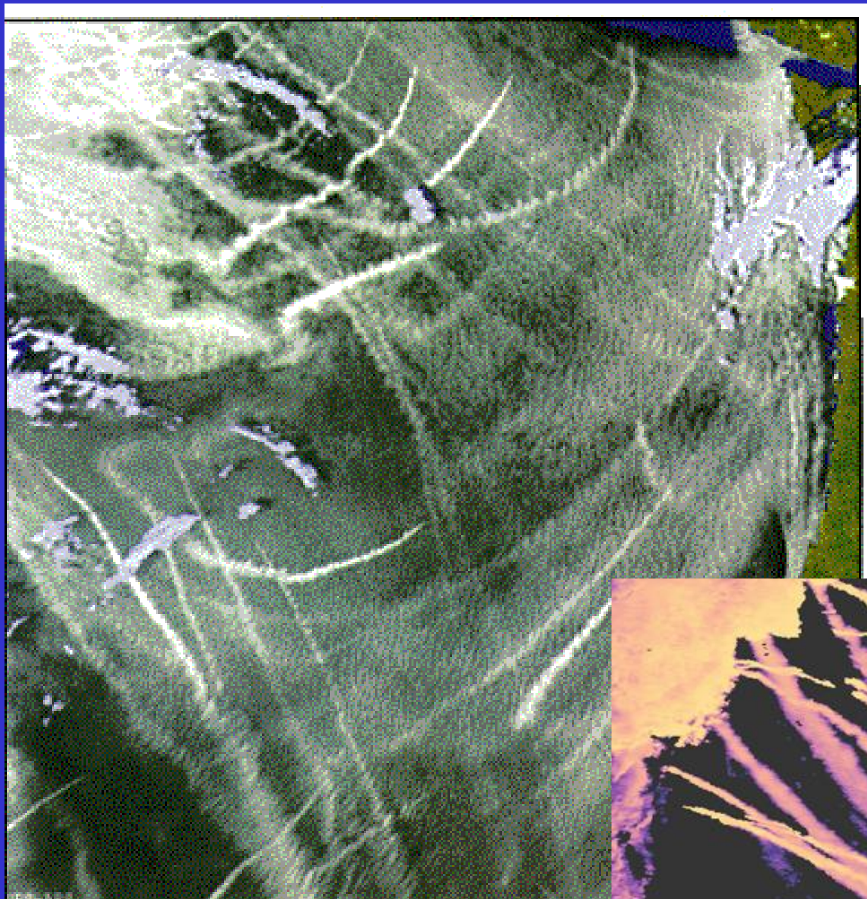
- Constant cloud droplet number that influences precipitation
- Ice formation depends on temperature and/or ice supersaturation (not aerosols)

Walk:

- Creating ice and droplet number based on simple, but realistic aerosols

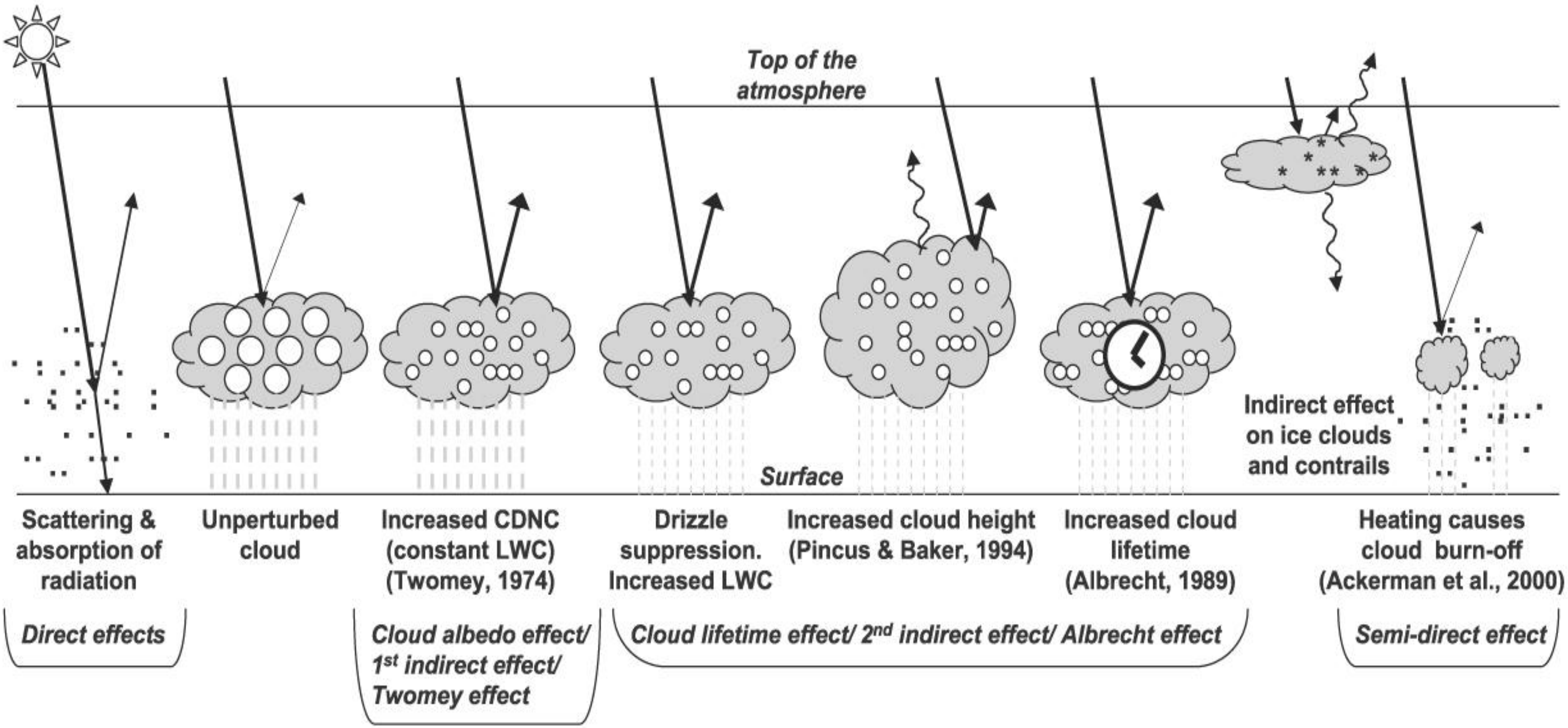
Run:

- Full integration with WRF-Chem and multiple aerosol species



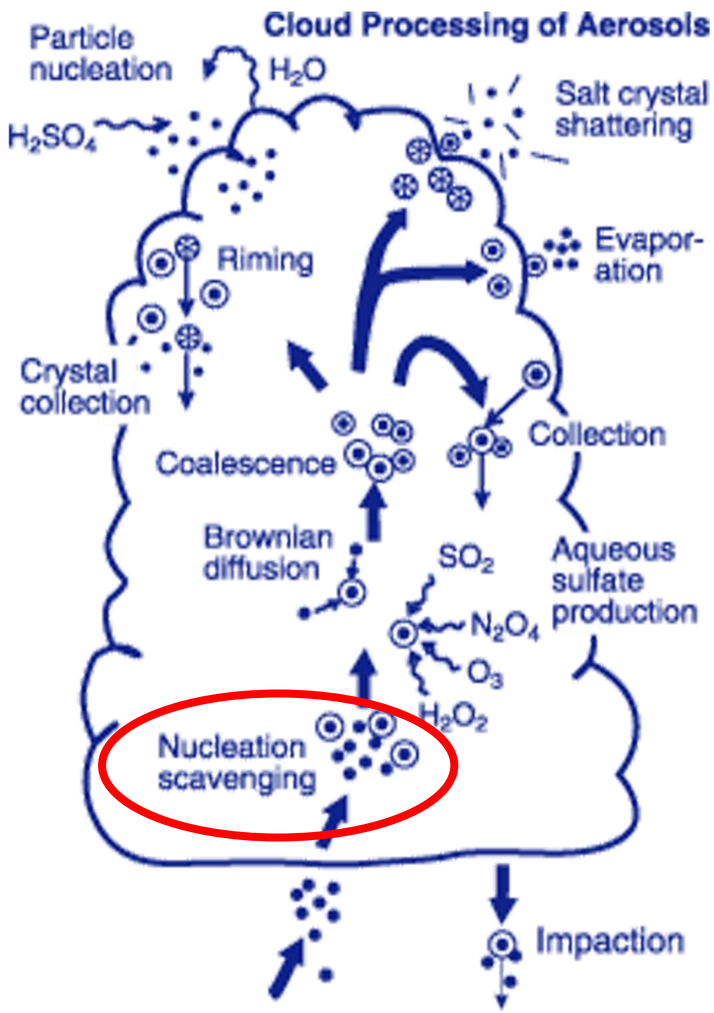
Ship tracks: spectacular example of indirect effects caused by ship exhausts acting as CCN
(long-lasting, feedback on cloud dynamics?)

Aerosol Direct and Indirect Effects on Clouds , Precipitation and Raddiation



IPCC 2008

Introduction



- Observations showed that aerosol chemical and hygroscopic features are modified by clouds.

- Cloud-processed aerosol particles affect the radiation.

- Cloud-processed aerosol particles impact secondary cloud/precipitation development.

- Numerical representation of the cloud processing of aerosol particles is difficult.

Those aerosol particles forming cloud droplets are called Cloud Condentation Nuclei (CCN)

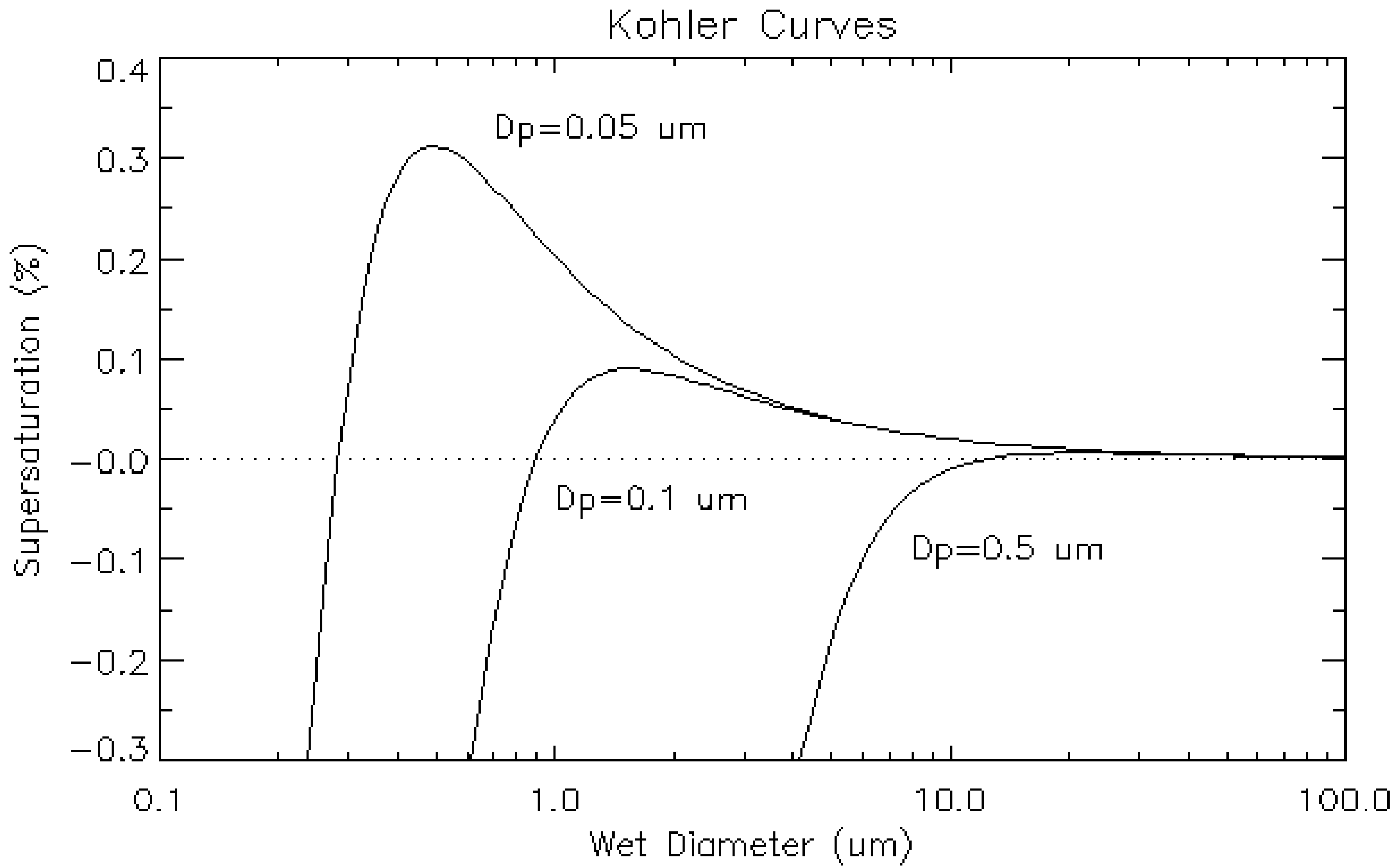
... END

Model

$$\frac{dm}{dt} = 4\pi r_d \frac{\left[s - \dfrac{2\sigma_{wa}}{R_v T \rho_w r_d} + \dfrac{\varepsilon \upsilon \Phi_s M_w m_a}{M_s(m - \rho_w m_d/\rho_s)} \right] f_v}{\dfrac{L_v}{k_a^* T}\left(\dfrac{L_v}{R_v T} - 1\right) + \dfrac{R_v}{e_{\mathrm{sat},w} D_v^*}}$$

Curvature and solute effects are considered in diffusional growth.

Geresdi and Rasmussen, 2005, JAS



Kohler Curves
Dp=0.05 um
Dp=0.1 um
Dp=0.5 um
Supersaturation (%)
0.4
0.3
0.2
0.1
−0.0
−0.1
−0.2
−0.3
0.1
1.0
10.0
100.0
Wet Diameter (um)

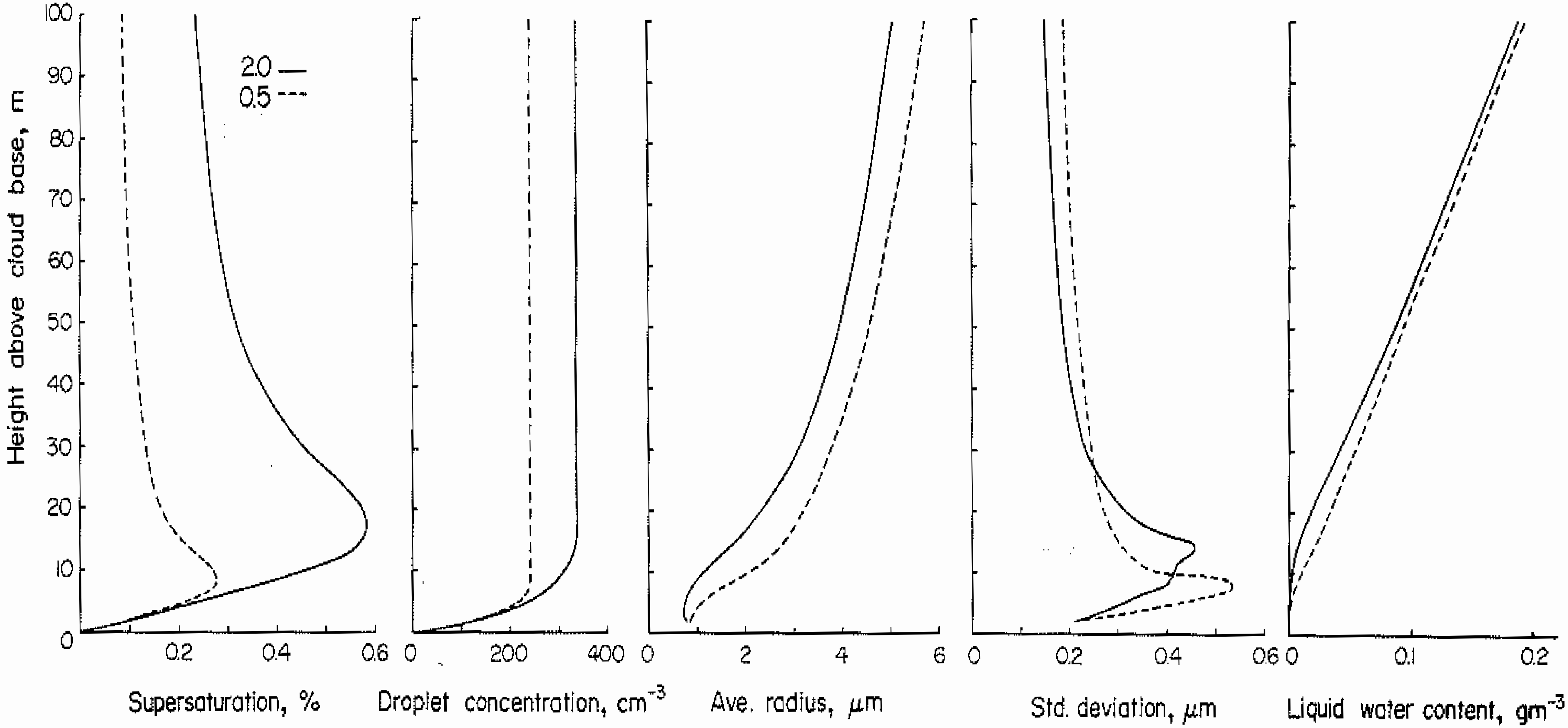
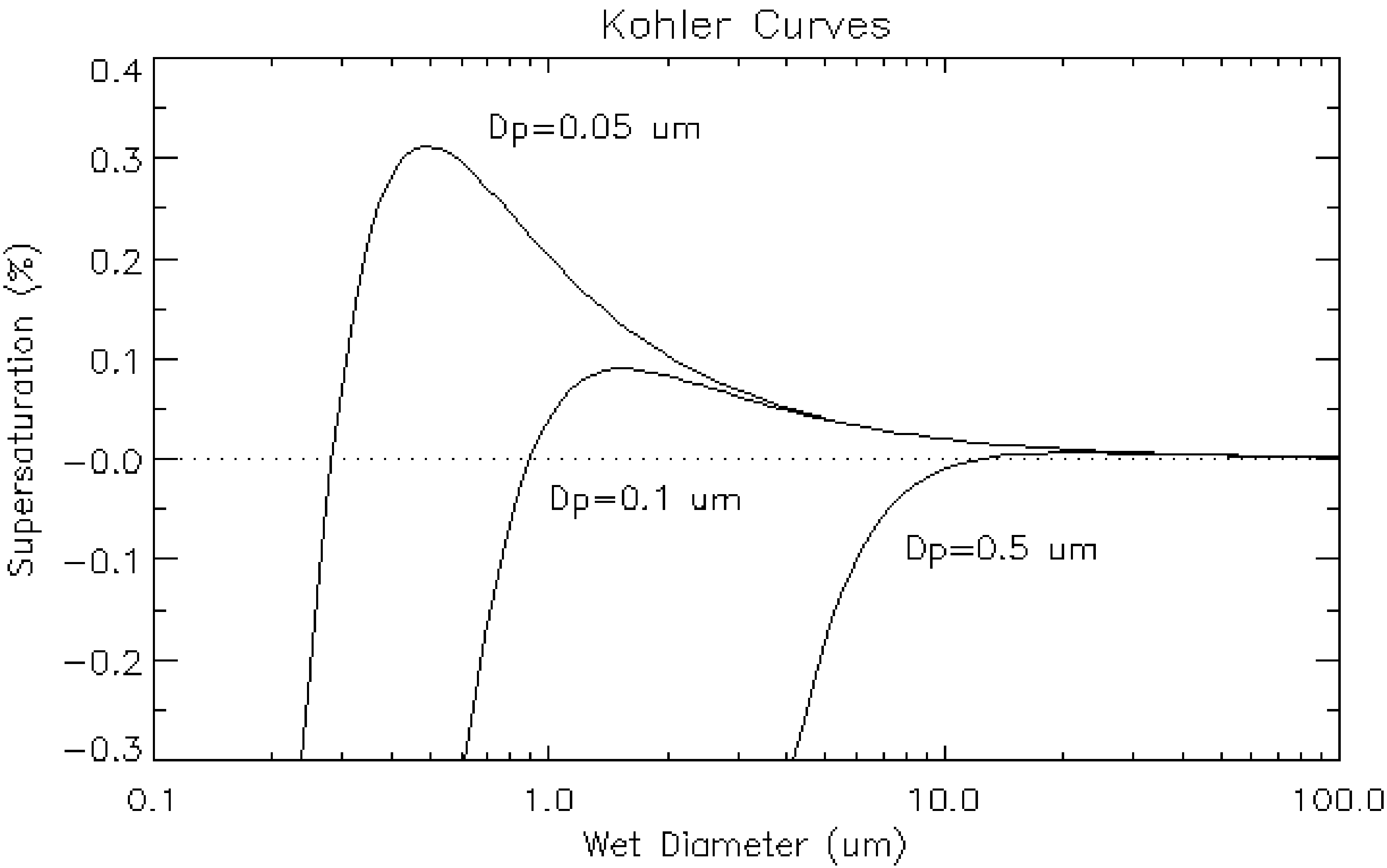


FIG. 7.4. Early development of cloud properties in air ascending at constant velocity of 0.5 m/s or 2 m/s.



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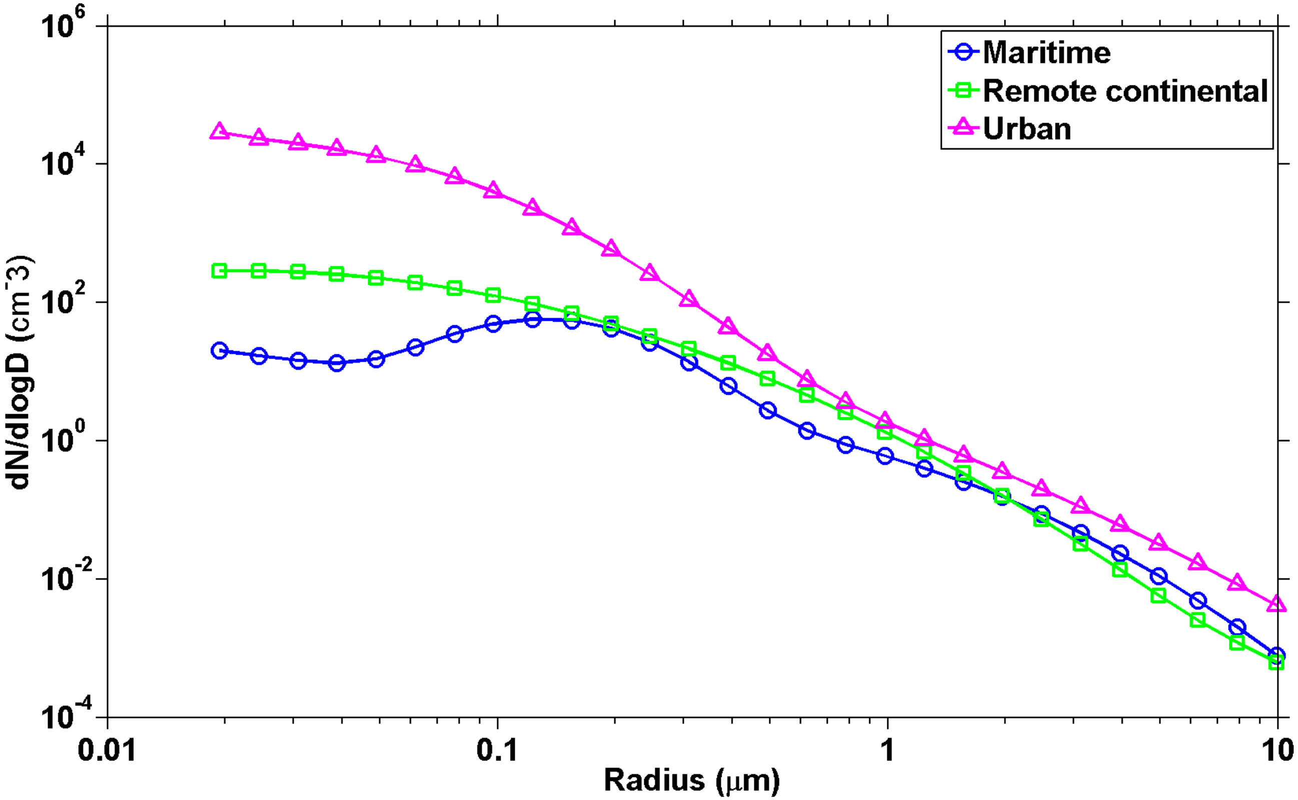
0.1
1.0
10.0
100.0
Wet Diameter (um)

Typical Aerosol Size Distributions



Maritime, remote continental and urban backgrounds

Internal mixture of $(NH_4)_2SO_4$ and SiO_2

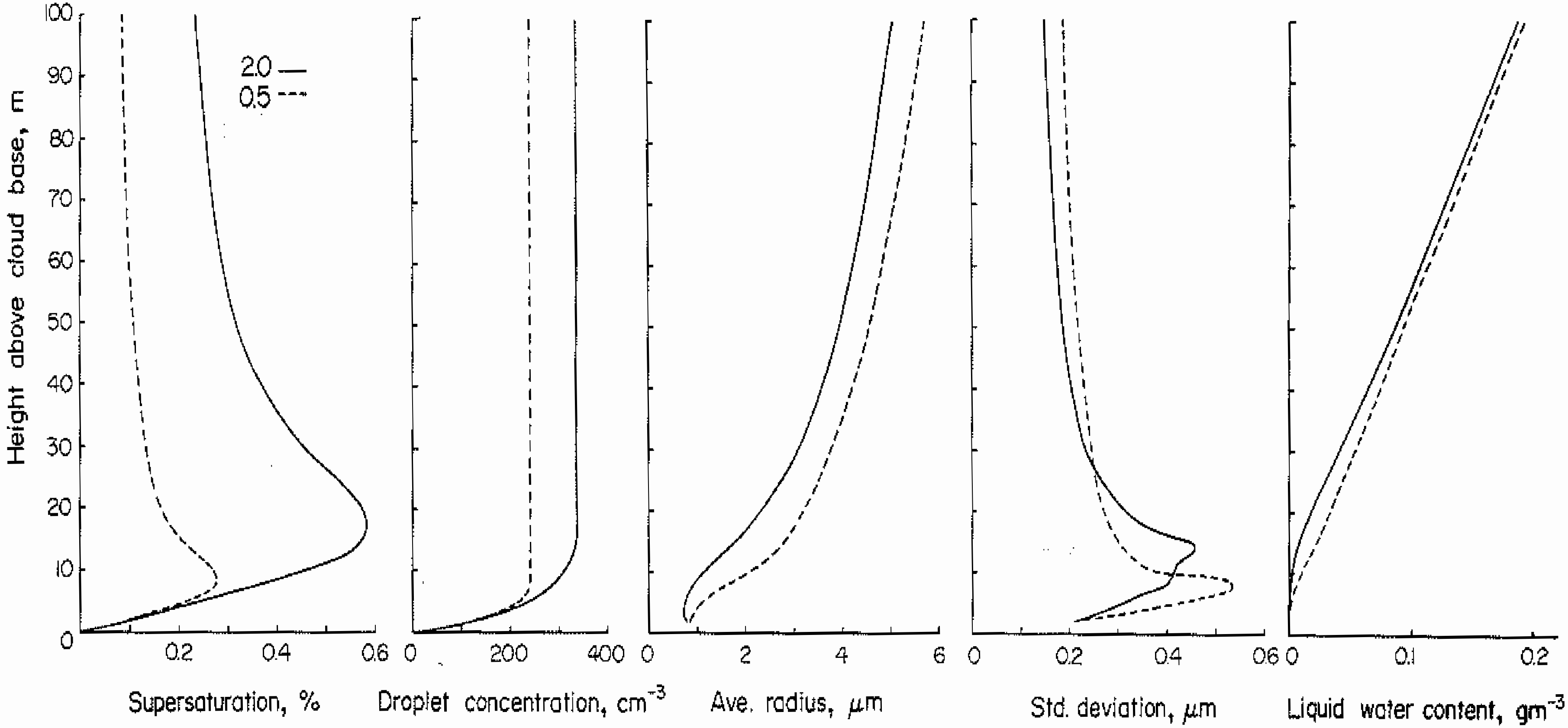
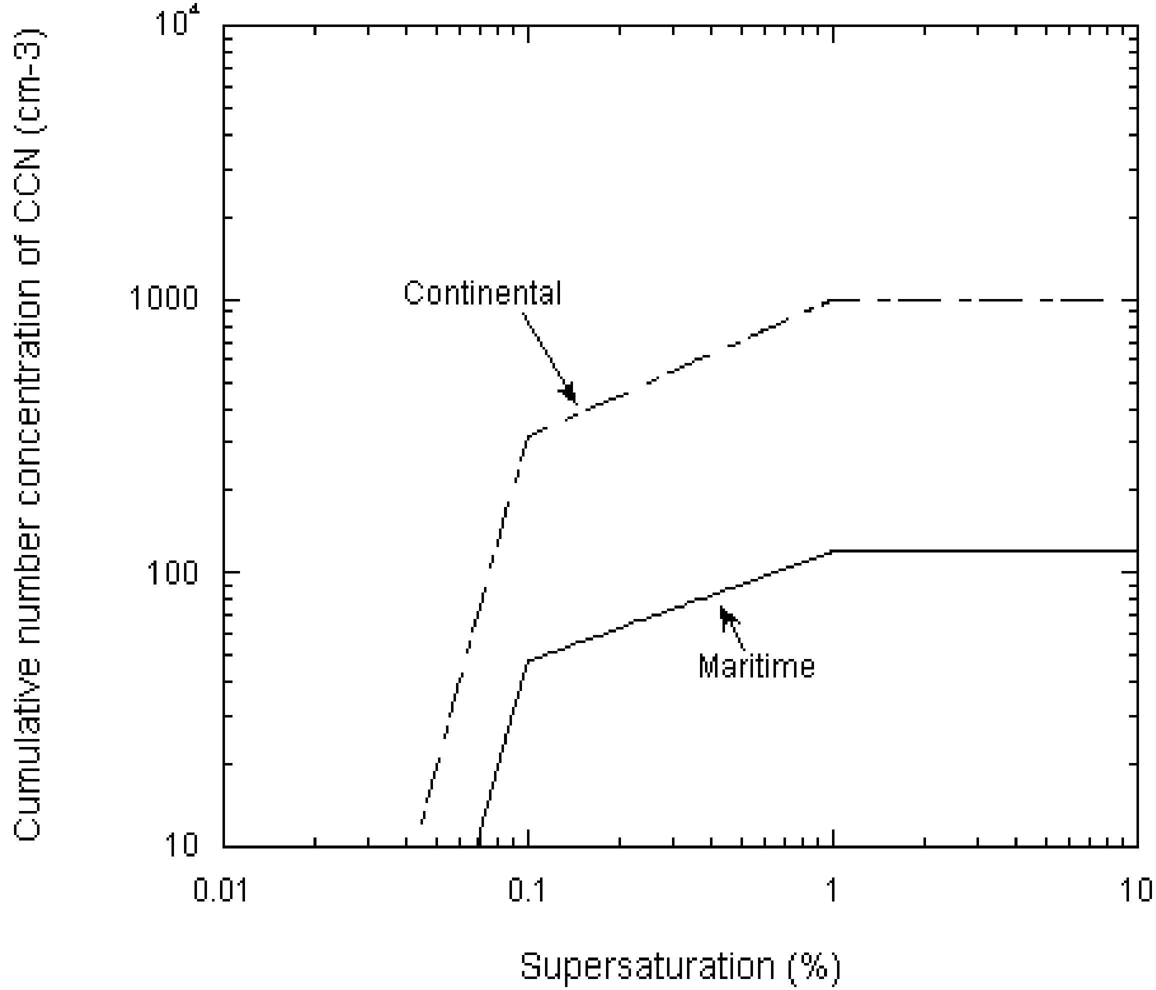


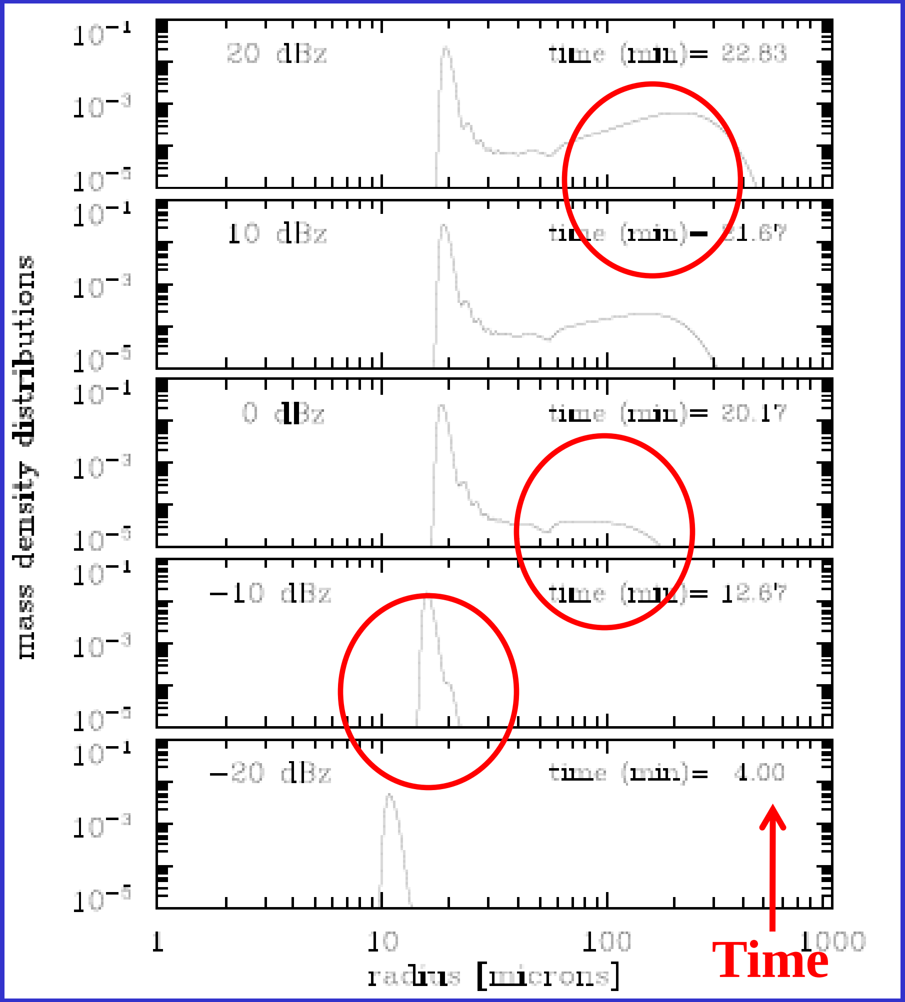
FIG. 7.4. Early development of cloud properties in air ascending at constant velocity of 0.5 m/s or 2 m/s.



Cumulative number concentration of CCN (cm-3)
10^4
1000
100
10
0.01
0.1
1
10
Supersaturation (%)
Continental
Maritime

Liquid microphysics – Kessler (1969)

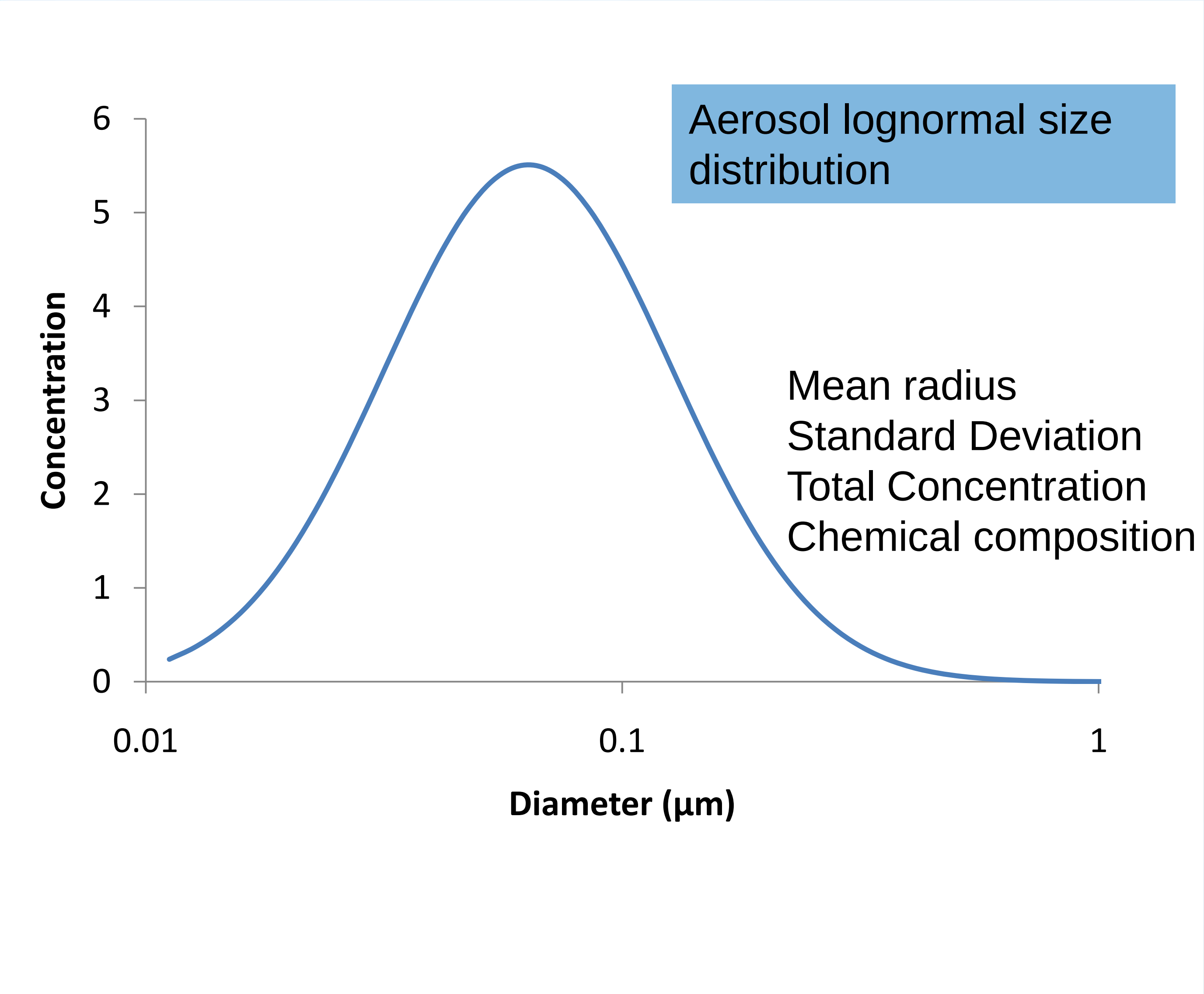
• **Separate liquid into cloud water and rain**



Droplet mass distribution evolution during rain formation using a detailed bin model.

Grabowski and Wang 2009

Integration of Aerosols into WRF Microphysics

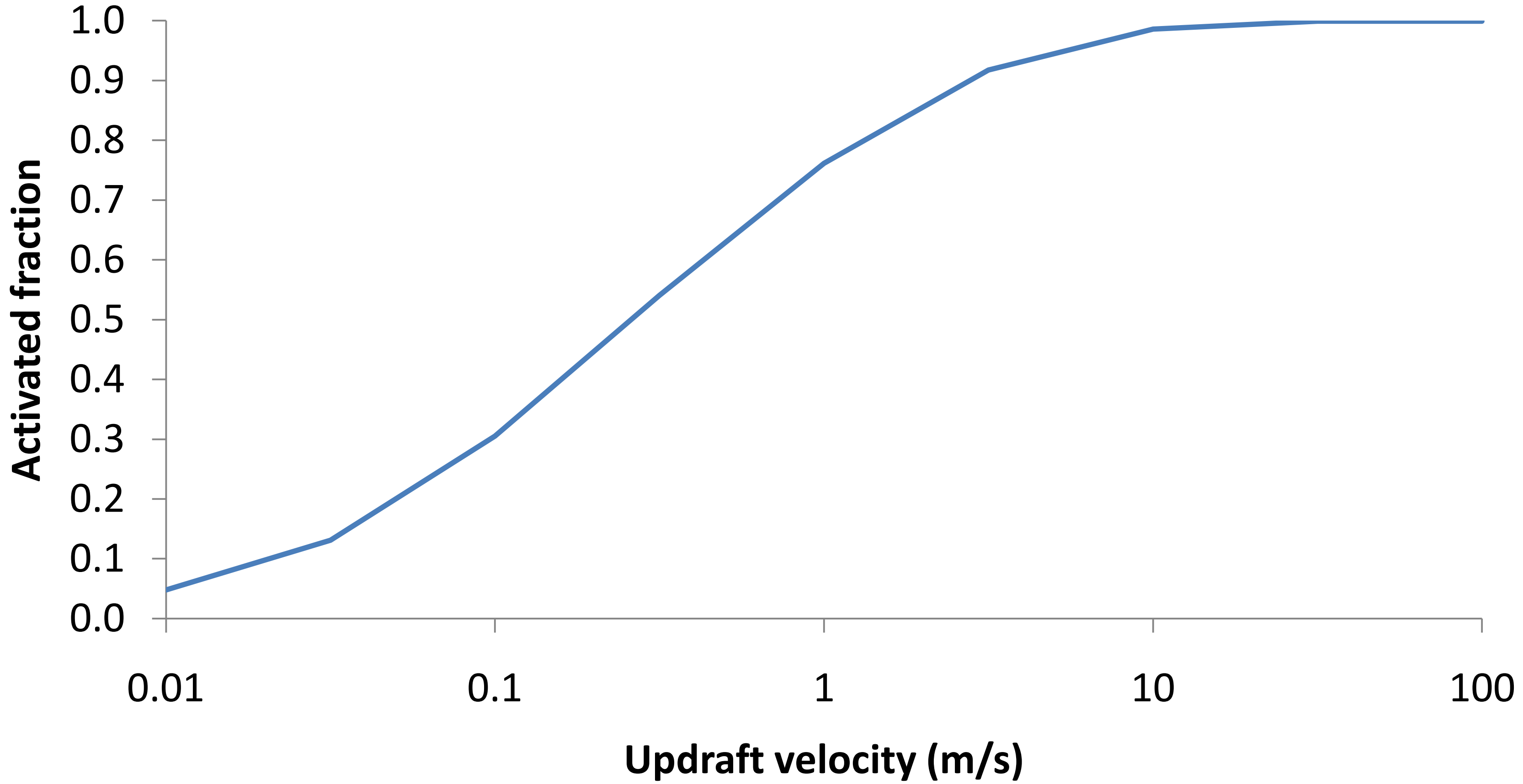


Motivation for the Use of Lookup Tables

Could use:

$$N_{CCN} = aS^b$$

- **Supersaturation difficult to accurately estimate in bulk model simulations**
- **Does not explicitly account for aerosol concentration**
- **Parcel model simulations easy to run with bin microphysics and create look up table**
- **Vertical velocity now the most important model calculated variable that needs to be estimated accurately**



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Activated fraction
0.01
0.1
1
10
100
Updraft velocity (m/s)

Two-moment cloud water number sources/sinks currently being implemented in the Thompson et al. Scheme

"Autoconversion" (collision/coalescence to form rain)

number loss calculated from a characteristic diameter

Freezing into cloud ice

consistent with mass – volume/temp dependence from Bigg, 1953

number from lookup table created using 5 to 3000 droplets per cm^3

Collection by rain, snow, graupel (accretion)

proper collection equation for number done similar to mass including variable collection efficiency

Evaporation/Condensation

number evaporated determined from all drops small enough to evap in single timestep (lookup table)

condensation on aerosols the main source of cloud droplets. Next Thompson scheme update uses parcel model lookup table to calculate the cloud droplet number concentration depending on updraft speed, aerosol concentration, temperature, mean aerosol size, and hygroscopicity

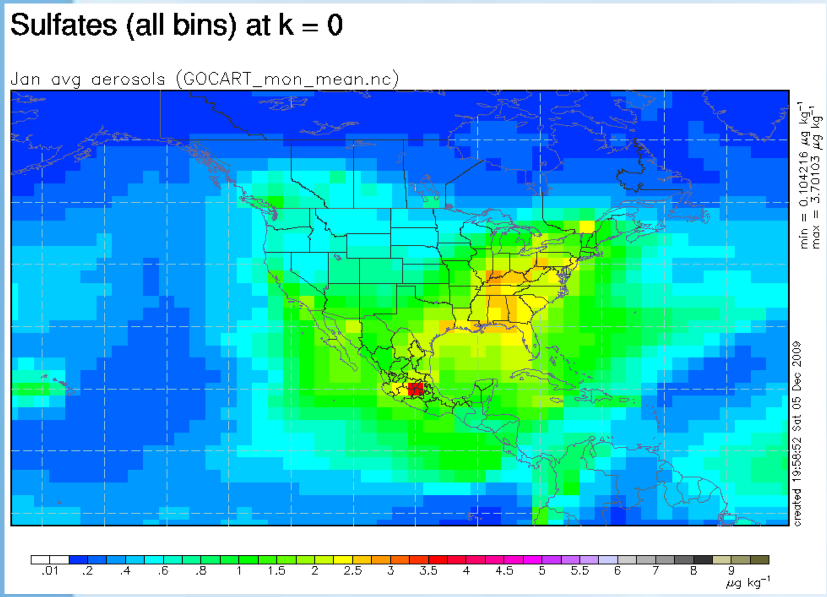
Sedimentation of mass and number

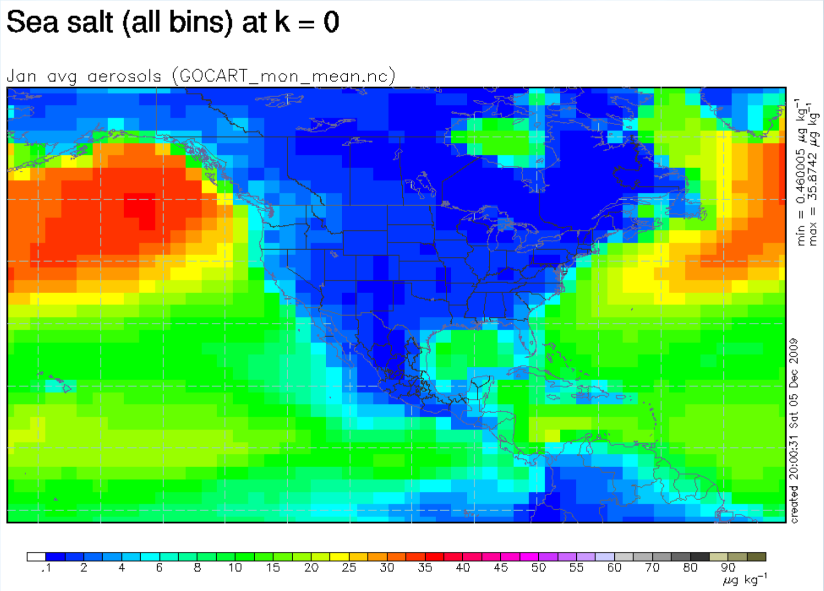
only lowest 500 m (for fog applications)

Aerosol number sink:

Impaction scavenging by rain/snow/graupel and Brownian diffusion capture by cloud droplets neglected, but coming soon.

Aerosols in Thompson microphysics scheme: Droplet activation





- GOCART 2.5^o (lon) x 2.0^o (lat) global monthly avg data, 20 sigma levels
- Will update to 1.5^o (lon) x 1.0^o (lat)

Input Aerosols: Sulfates and Sea salt

Sulfates:

- Mass content in 6 size bins provided
- Converted to number concentration per kg

Sea salts:

- Mass content in 4 size bins provided
- Converted to number concentration per kg
- Currently added to sulfates, not treated separately

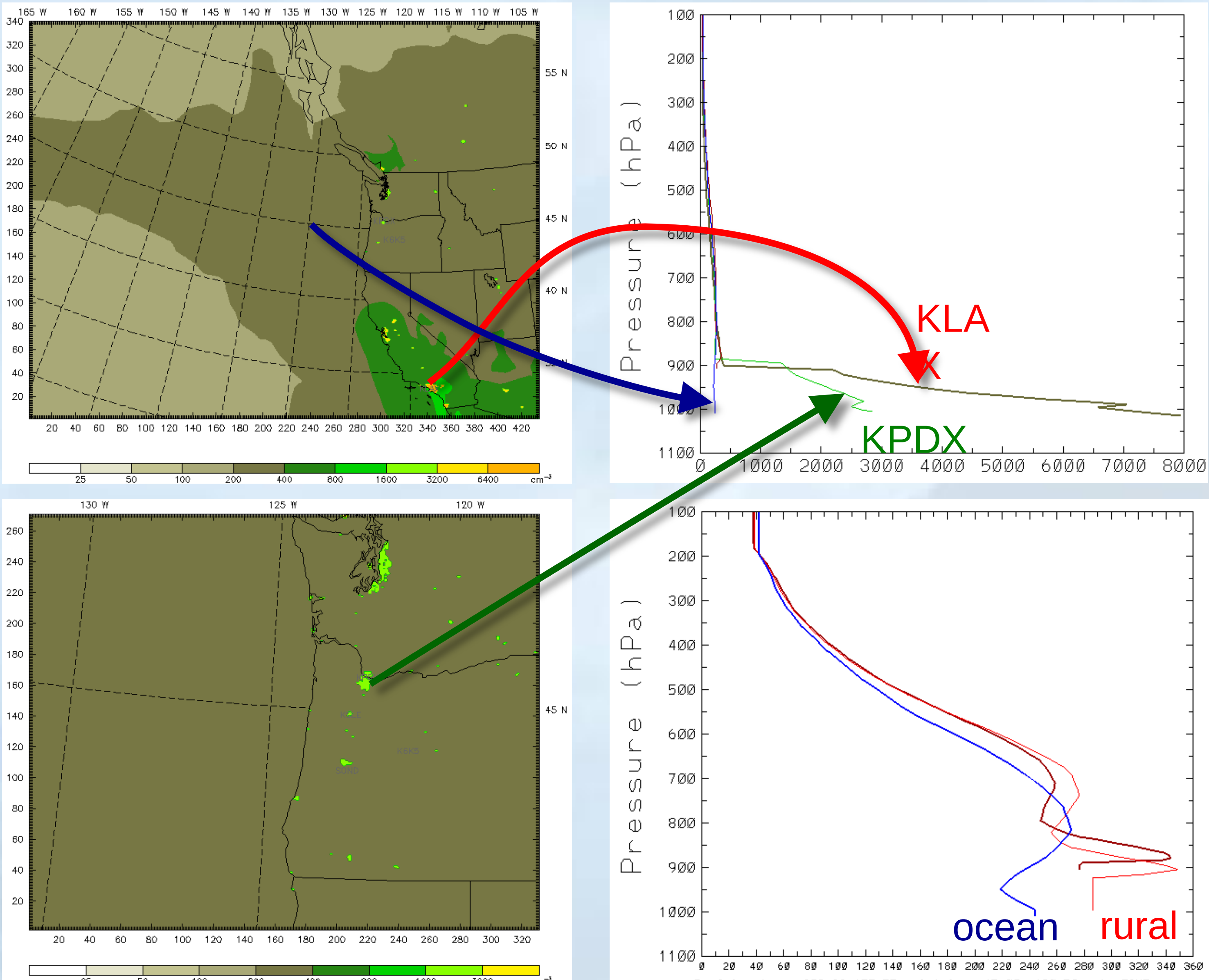
Dust:

- Mass content in 7 size bins provided
- Converted to number concentration per kg

We use an external WRF-Chem program (mozbc) to modify wrfinput_d*n* and wrfbdy files

We increase aerosols at WRF-designated “urban” land use by factor of 10 at lowest level decreasing exponentially to 1 km AGL.

Sample columns of aerosol: ocean, rural, urban



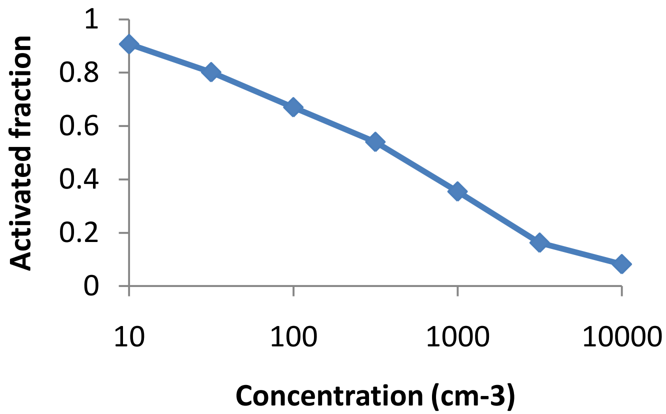
Droplet activation look-up table

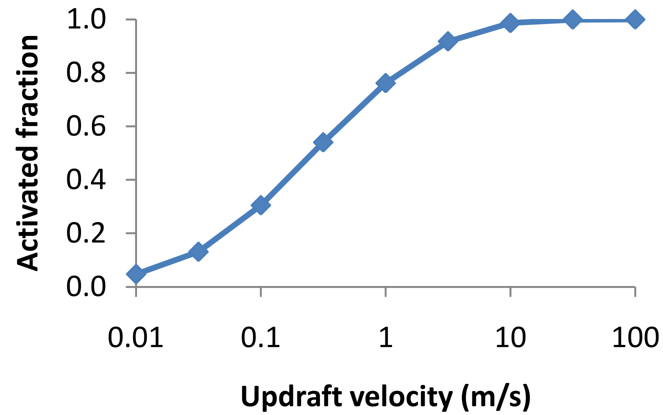
1) aerosol concentration
2) updraft velocity
3) temperature
4) hygroscopicity (kappa)
5) aerosol mean radius
6) Standard deviation of size distribution
7) Condensation coefficient

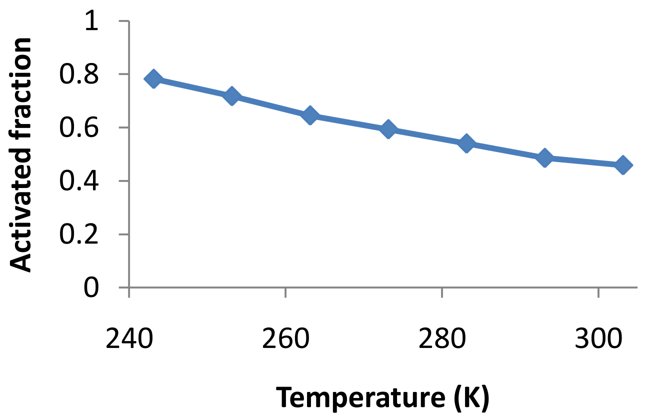
Look-up table of activated fraction of aerosols created using parcel model by Feingold and Heymsfield (1992) and changes by T. Eidhammer & S. Kreidenweis

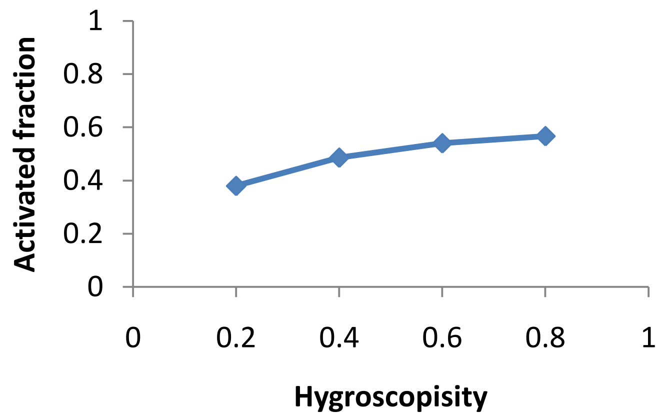
N_a (cm^{-3})	w (m/s)	T (^oC)	k	r (µm)
10	0.01	−30	0.2	0.01
31.6	0.0316	−20	0.4	0.02
100	0.1	−10	0.6	0.04
316	0.316	0	0.8	0.08
1000	1	10		0.16
3160	3.16	20		
10000	10	30		
	31.6			
	100			

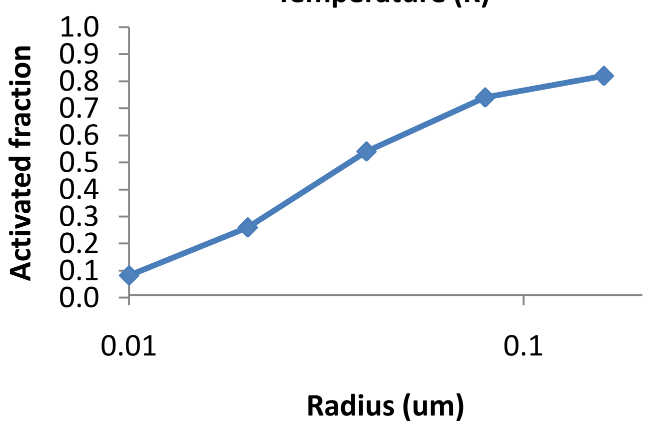
Droplet activation look-up table











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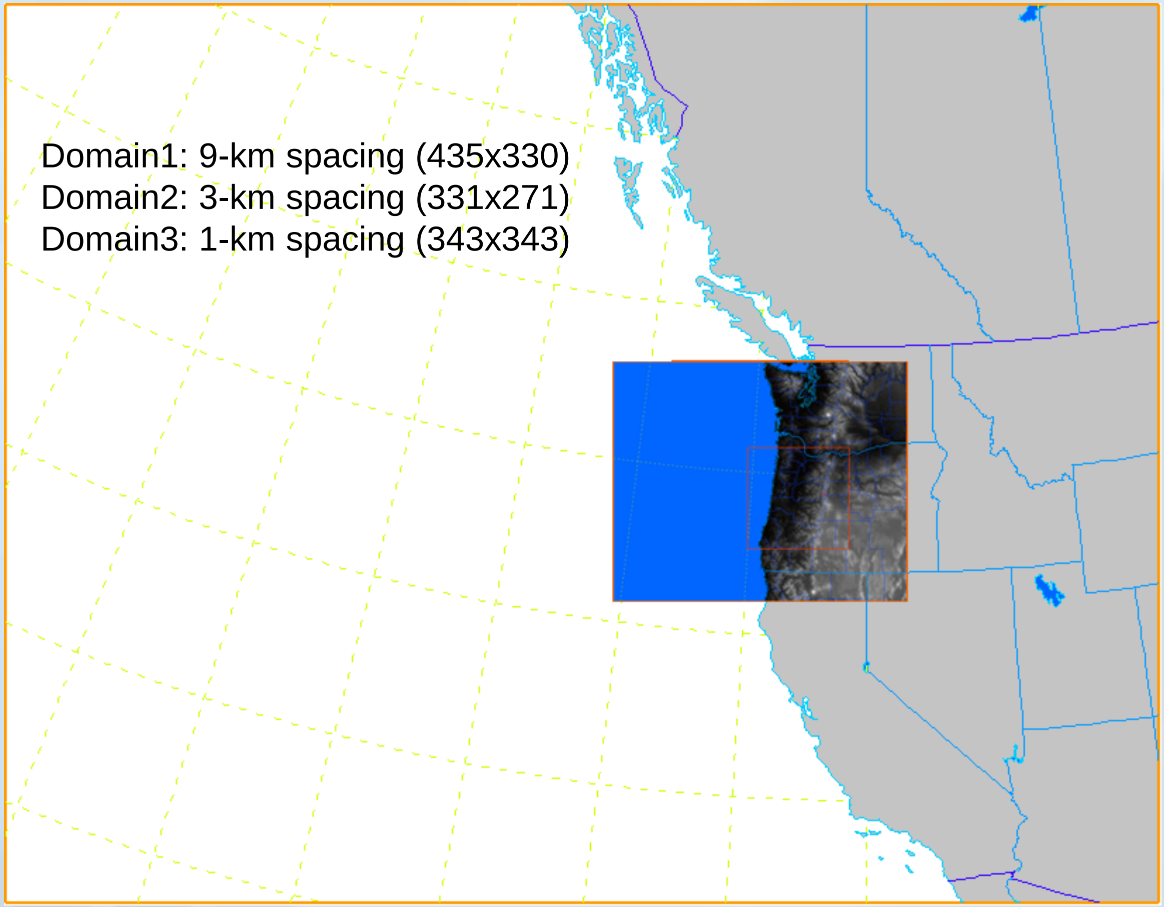
3160	3.16	20		
10000	10	30		
	31.6			
	100			

Prelim Results: 2001Dec13 (IMPROVE-2)

High-res (9, 3, 1-km spacing), 71 levels, 36-hour forecast

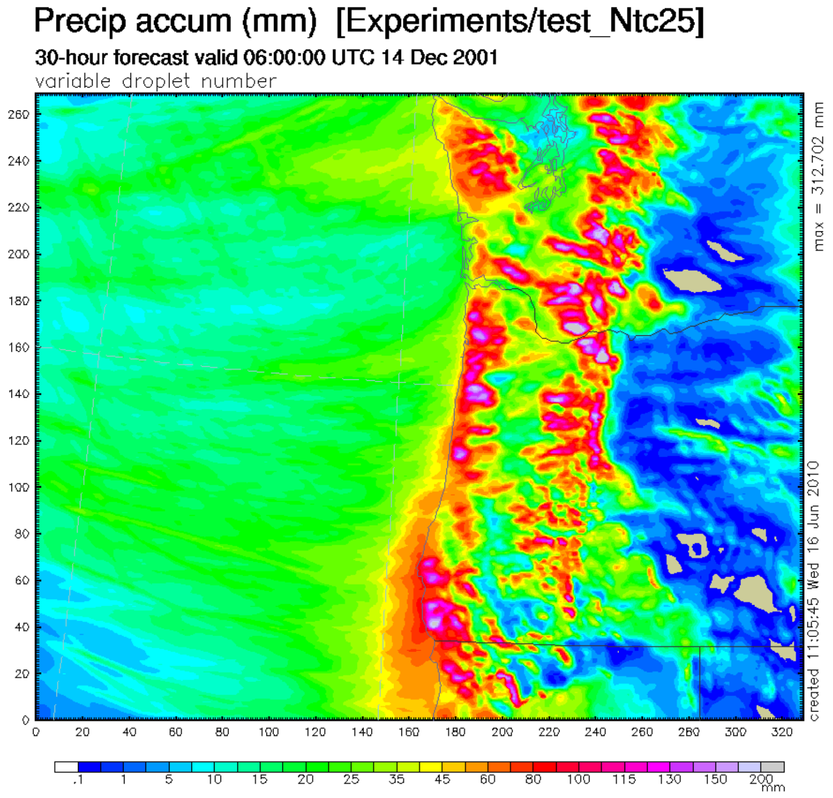
- Constant cloud droplet concentration (1-moment cloud): N_c=750 & 25 cm^{-3}
- Low (control) versus high (polluted) variable aerosols (w/ 2-moment cloud)

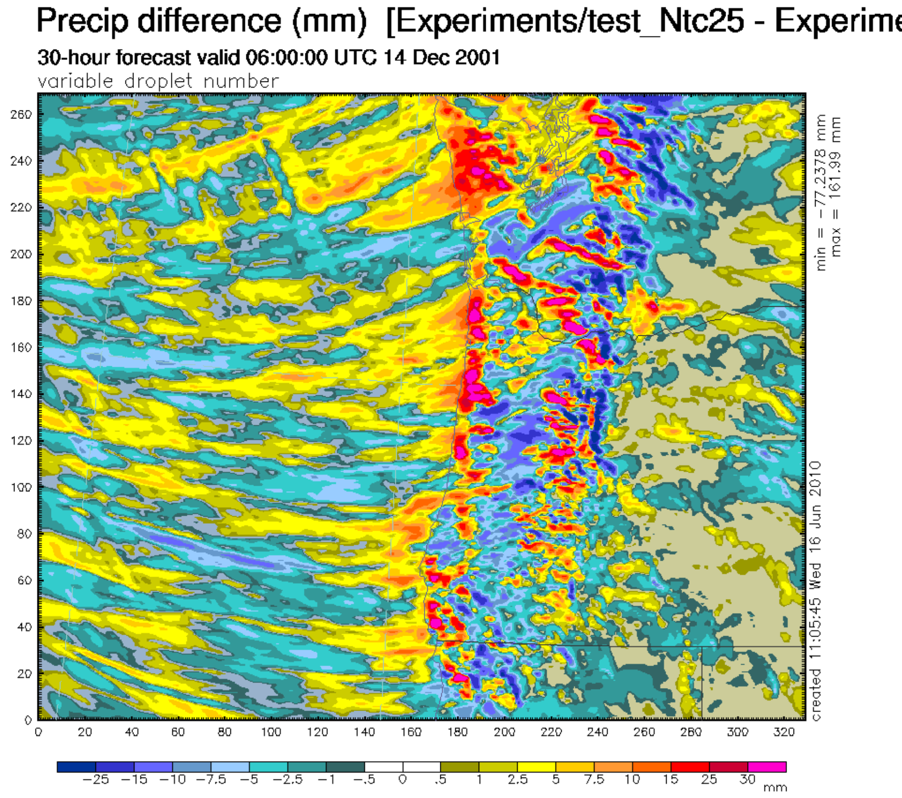


Prelim Results: 2001Dec13 (IMPROVE-2)

Constant cloud droplet concentration (1-moment cloud): N_c=750 & 25 cm^{-3}

30-hour precip accumulation (mm) and difference (clean minus polluted)

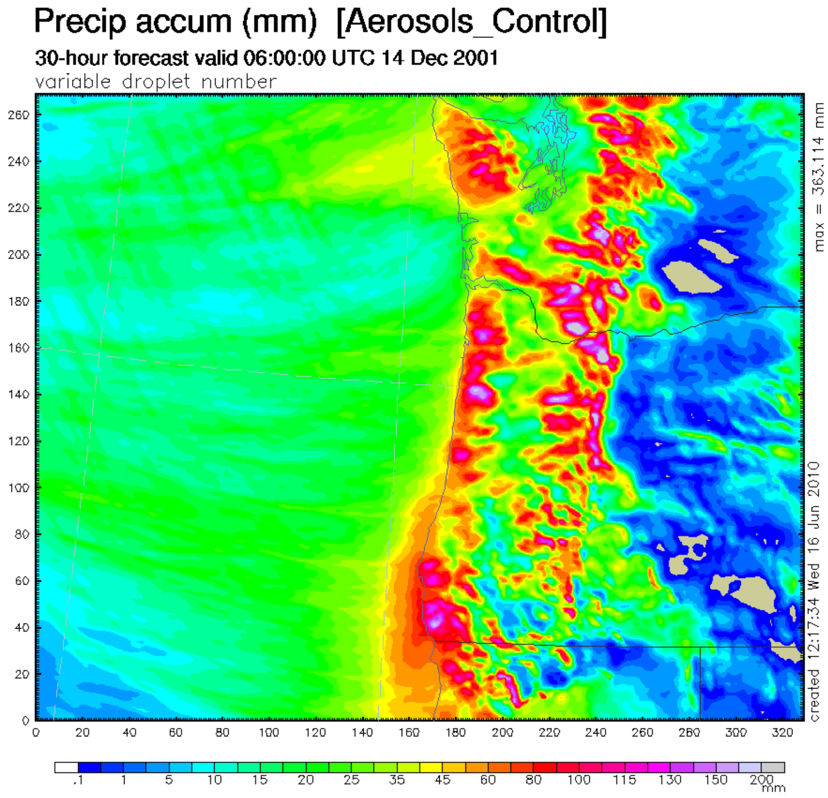


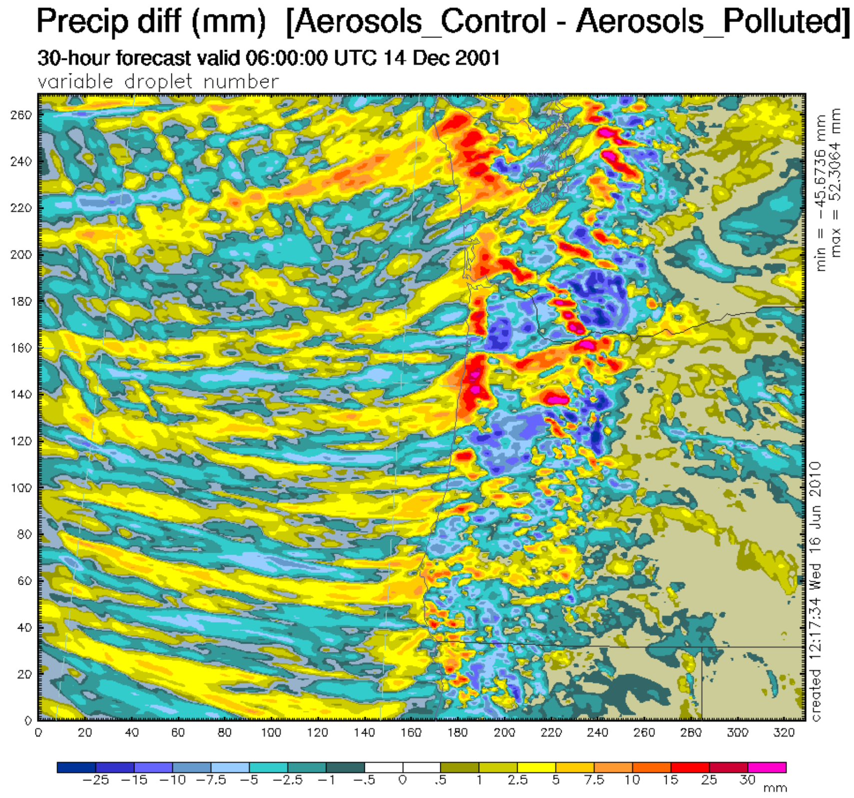


Prelim Results: 2001Dec13 (IMPROVE-2)

Variable droplet concentration from aerosols

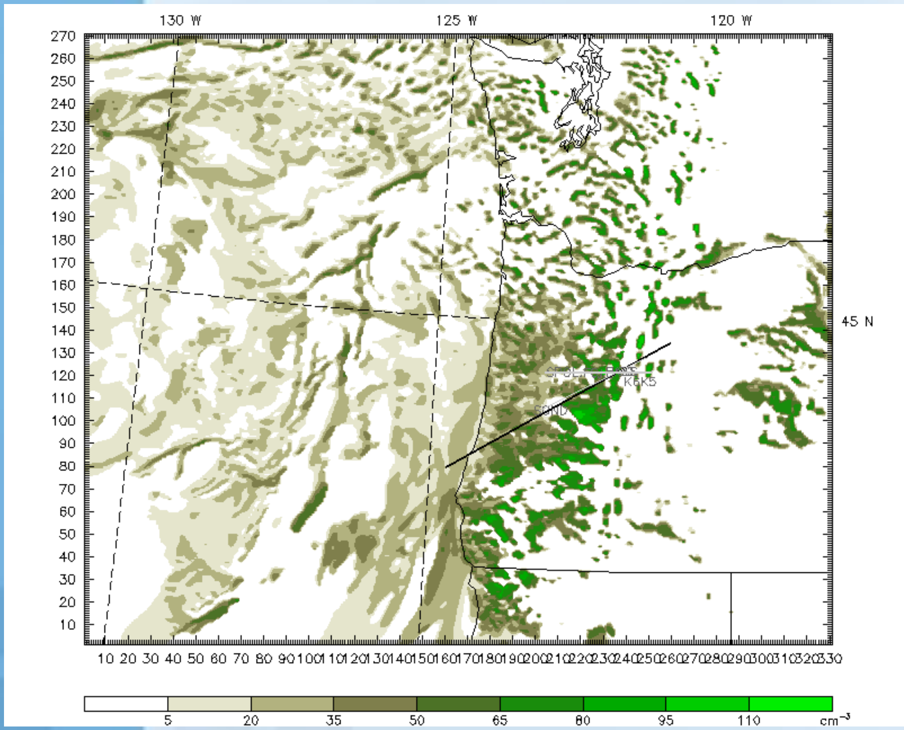
30-hour precip accumulation (mm) and difference (clean minus polluted)

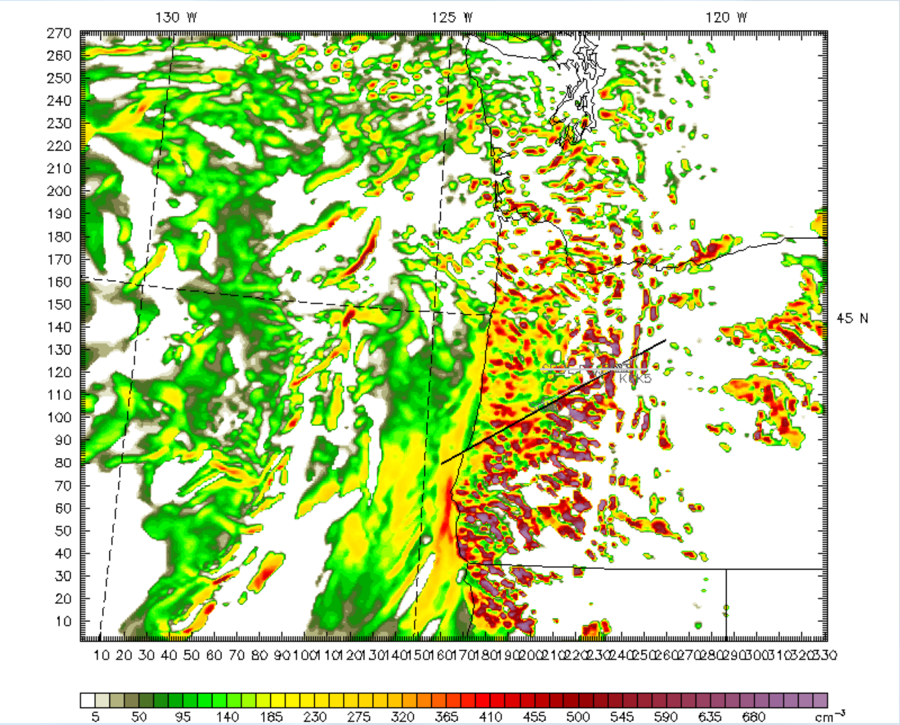




Example aerosol and droplet concentration

clean versus polluted generally less extreme than the constant droplet values



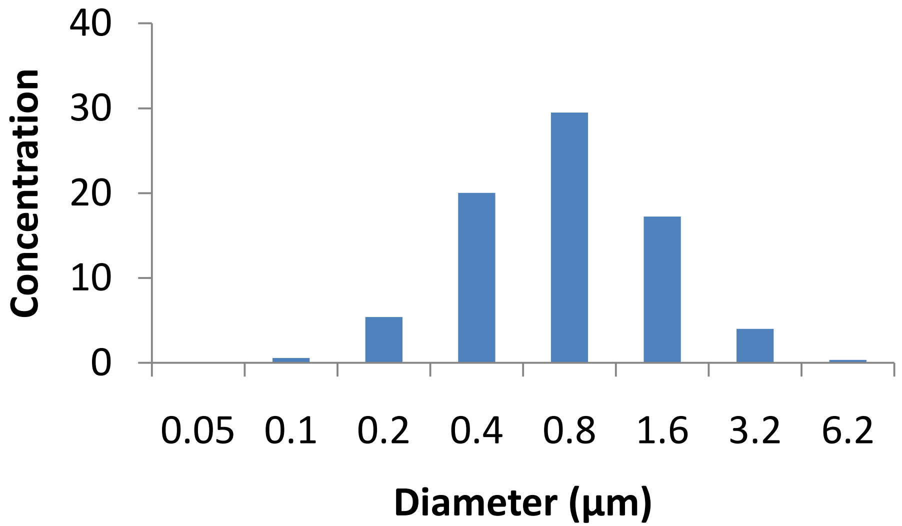


Aerosol – droplet activation link in WRFchem

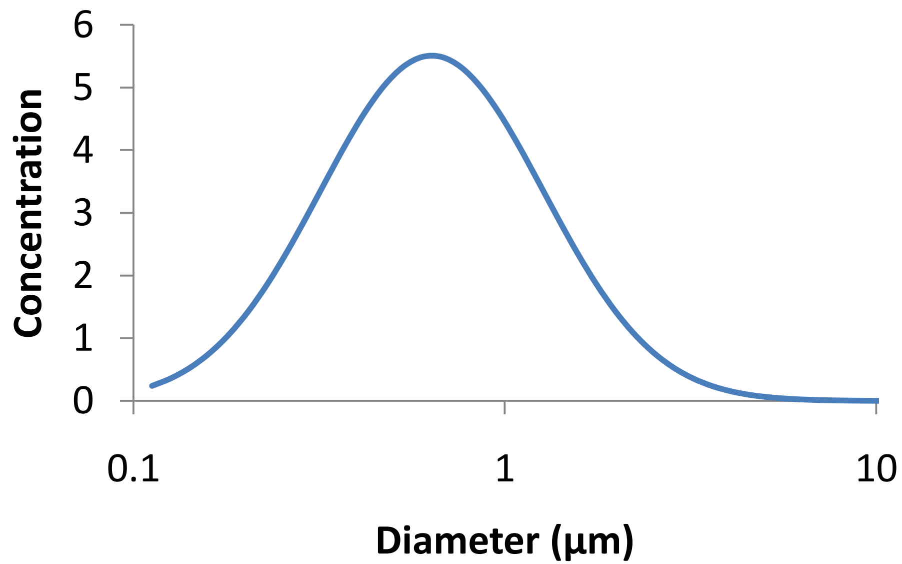
- Developed by the Pacific Northwest National Laboratory (PNNL). (see Chapman et al 2009)
- Link to Lin microphysics scheme implemented.
    - Two different aerosol schemes can be used:

        Aerosol bin approach (MOSAIC) 4 or 8 size bins.

        Aerosol modal approach (SORGAM). Use 3 lognormal modes (Aitken, accumulation and coarse mode). Predicts the median size, but keep the with (standard deviation) constant.



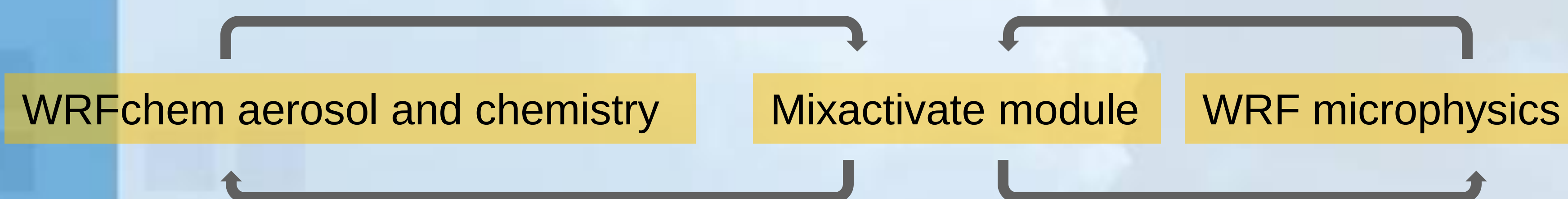
Bin approach
MOSAIC
- Predicts mass and number concentration in each bin



Modal approach
SORGAM
- Predict geometric diameter and mass concentration
- Standard deviation is constant

Aerosol – droplet activation link in WRFchem

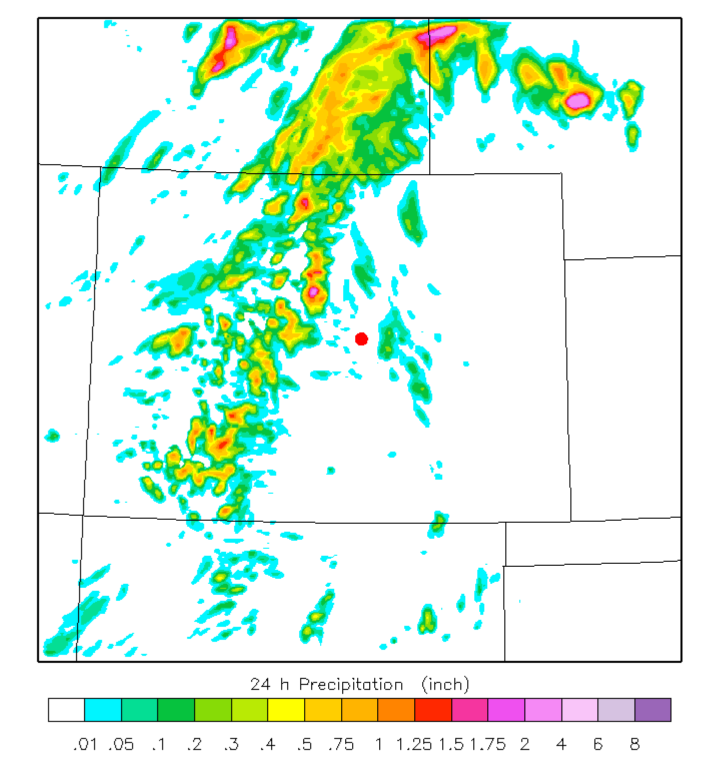
•Developed by the Pacific Northwest National Laboratory (PNNL). (Chapman 2009)
•Link to Lin microphysics scheme implemented.
•PNNL working on Thompson and Morrison microphysics schemes.
•No ice nucleation dependent on aerosols included.



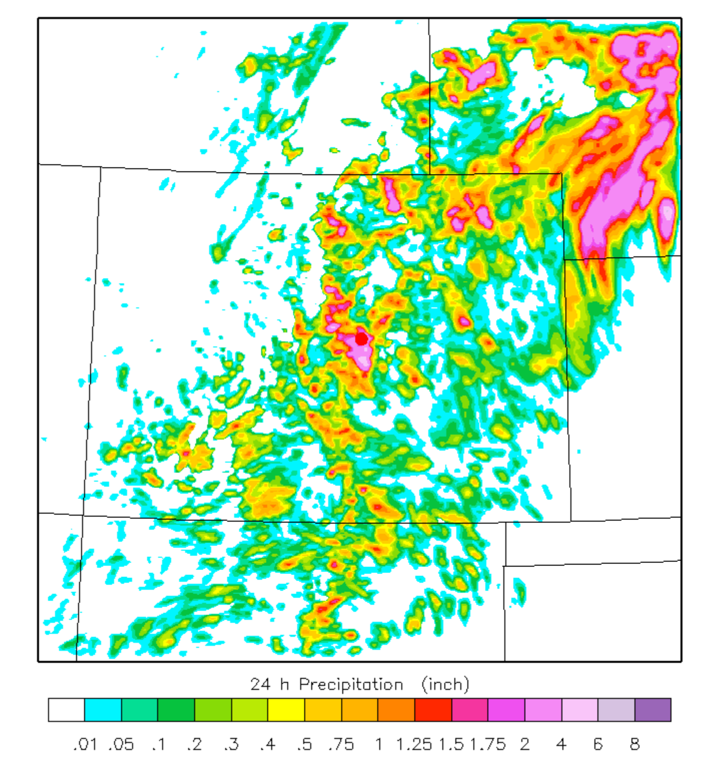
Droplet activation follow parameterization by Abdul-Razzak and Ghan (2000)

Aerosol cloud interaction studies in the Colorado area (BEACHON)

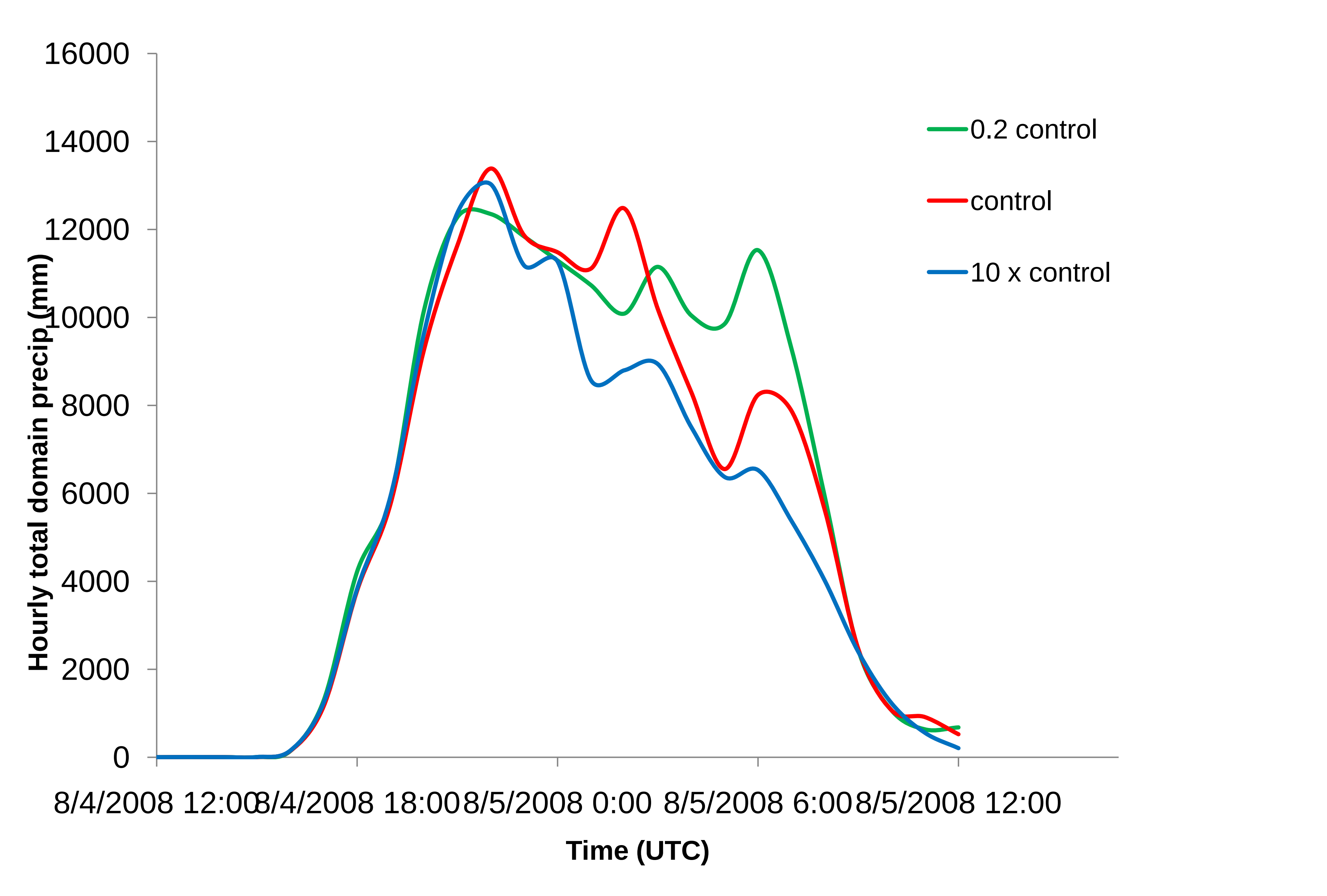
4 August 2008



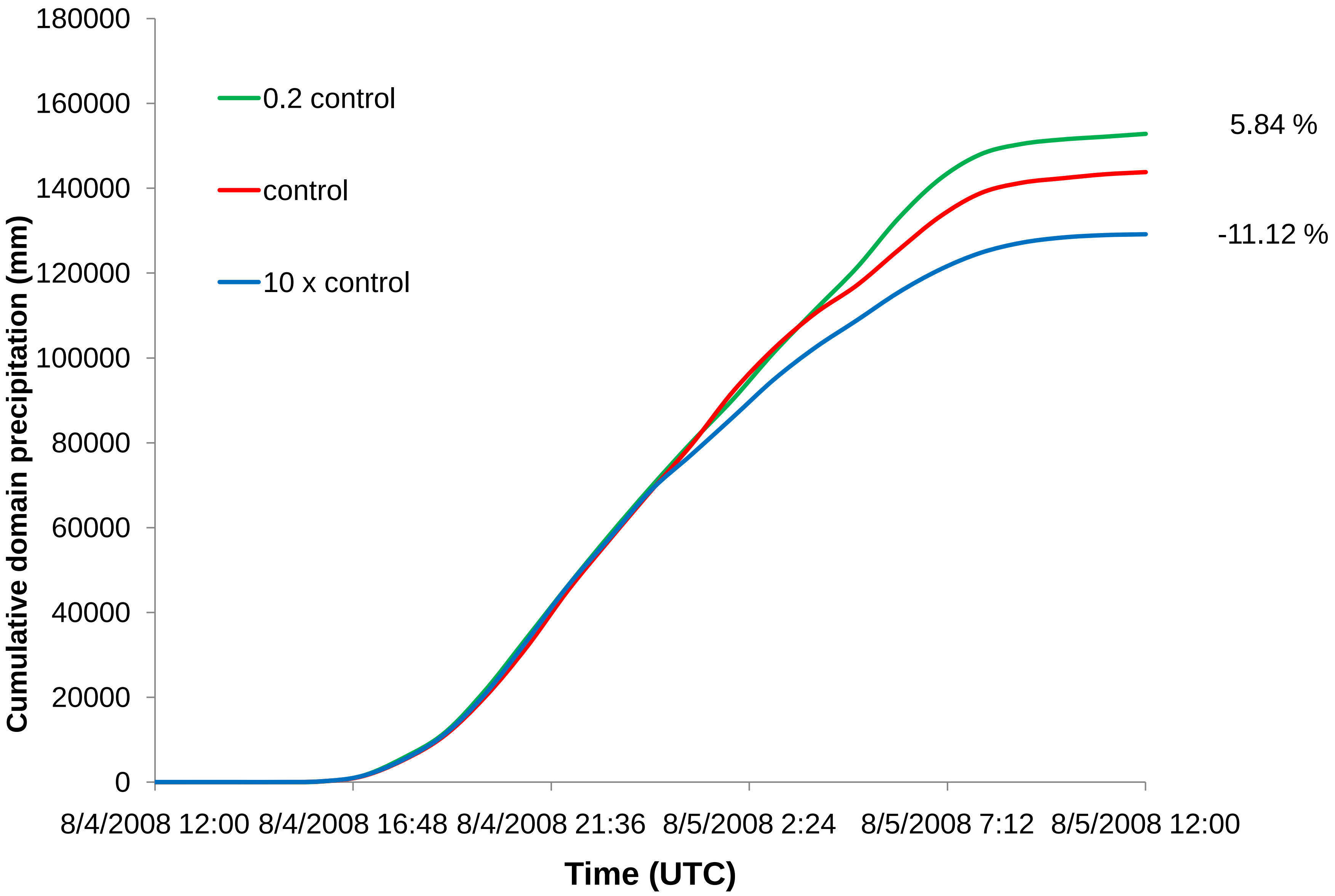
5 August 2008

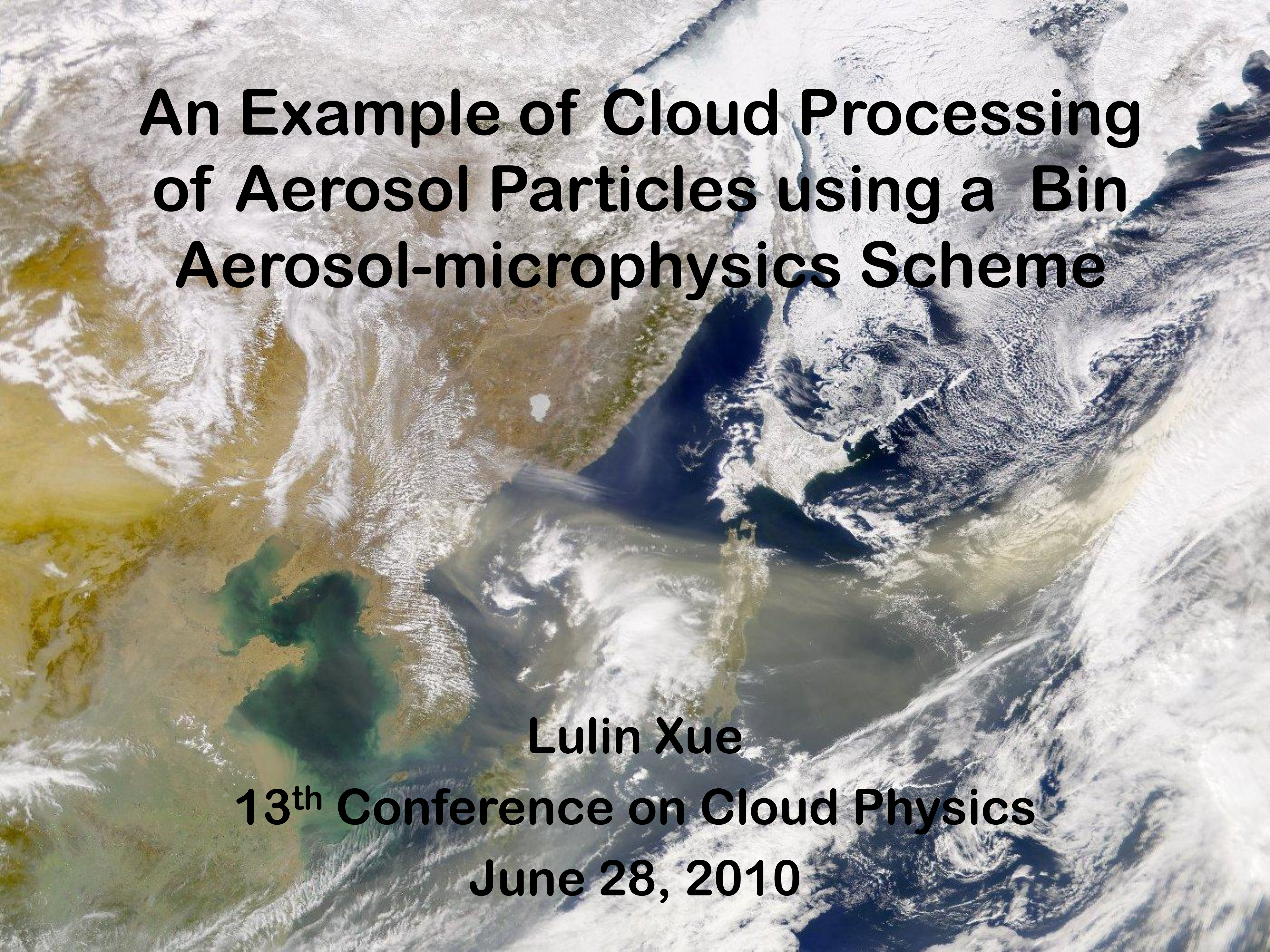


Domain wide total precipitation



Cumulative precipitation in domain





An Example of Cloud Processing of Aerosol Particles using a Bin Aerosol-microphysics Scheme

Lulin Xue

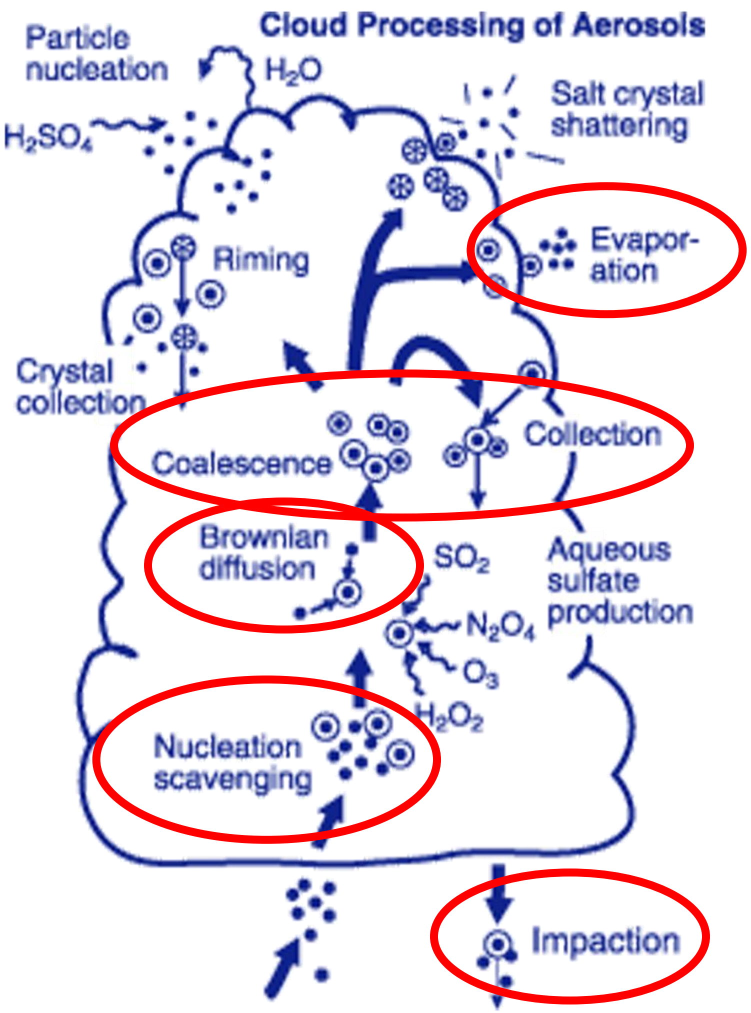
13th Conference on Cloud Physics

June 28, 2010

Detailed Bin microphysical model

The detailed microphysical model of Geresdi (1998) was implemented into the MM5/WRF mesoscale model to conduct two-dimensional simulations of drizzle formation in a stably stratified cloud (Rasmussen et al. 2002, JAS)

Introduction



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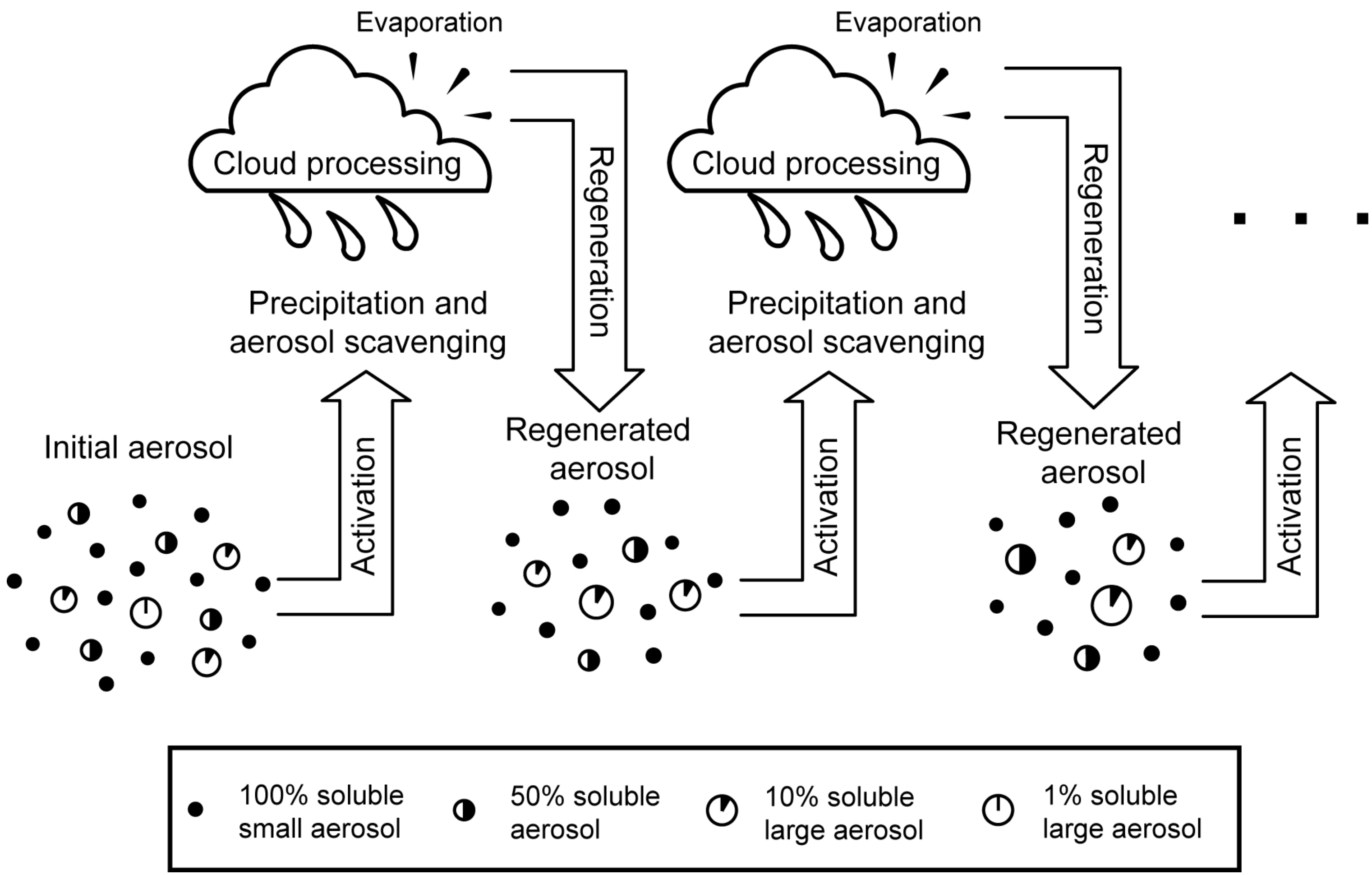
- Numerical representation of the cloud processing of aerosol particles is difficult.

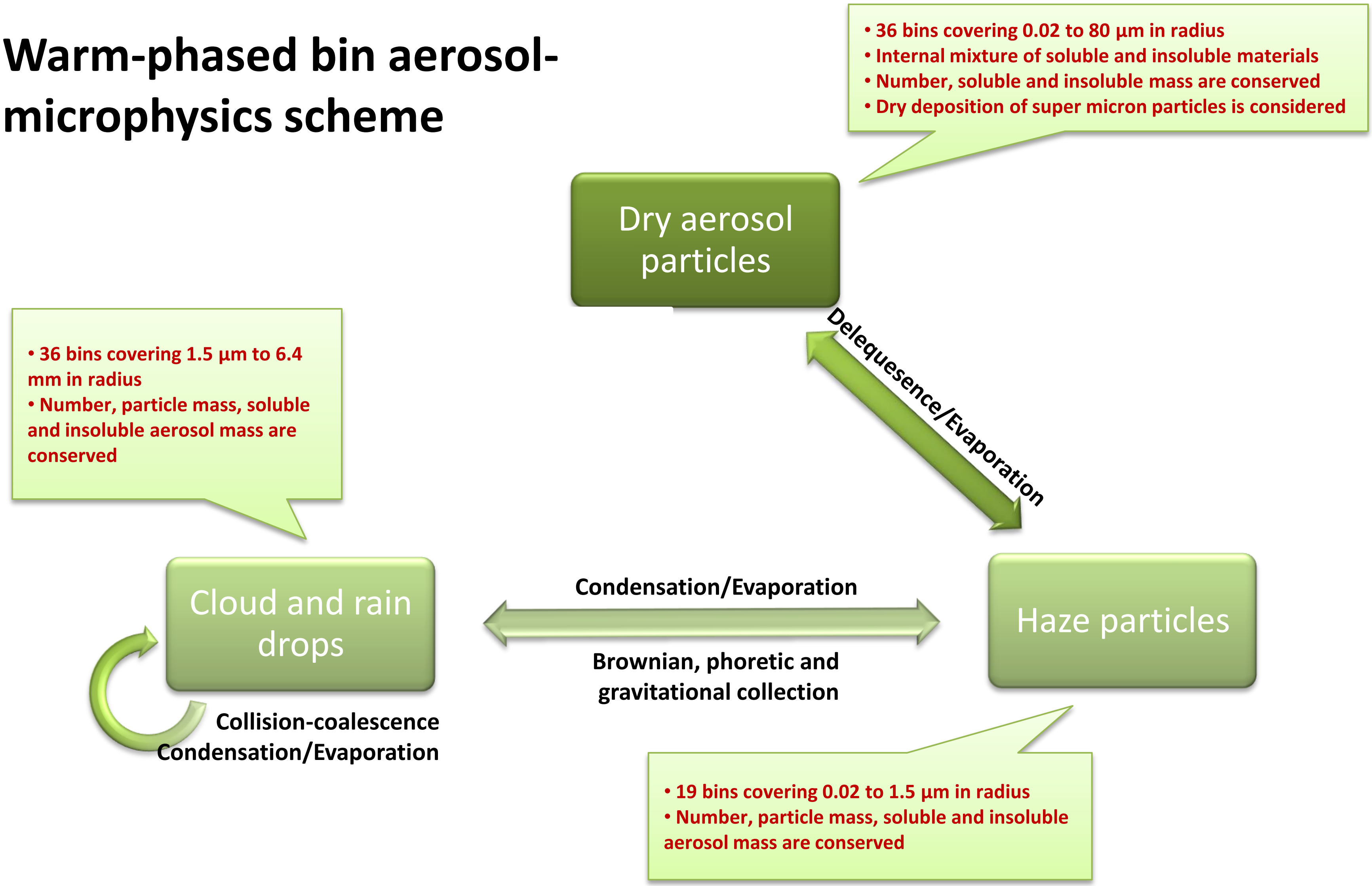
Introduction



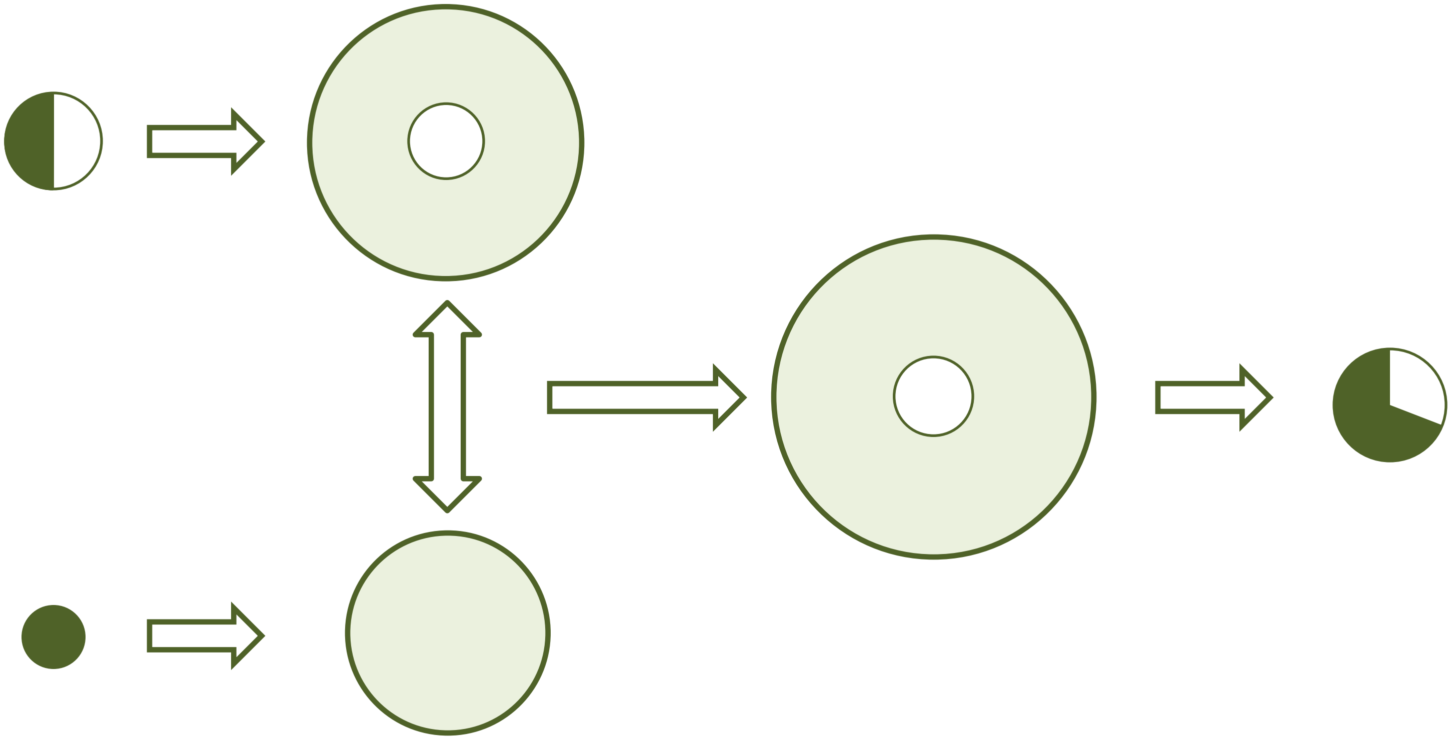
Xue, L., A. Teller, R. Rasmussen, I. Geresdi and Z. Pan, 2010, JAS, in press

Model

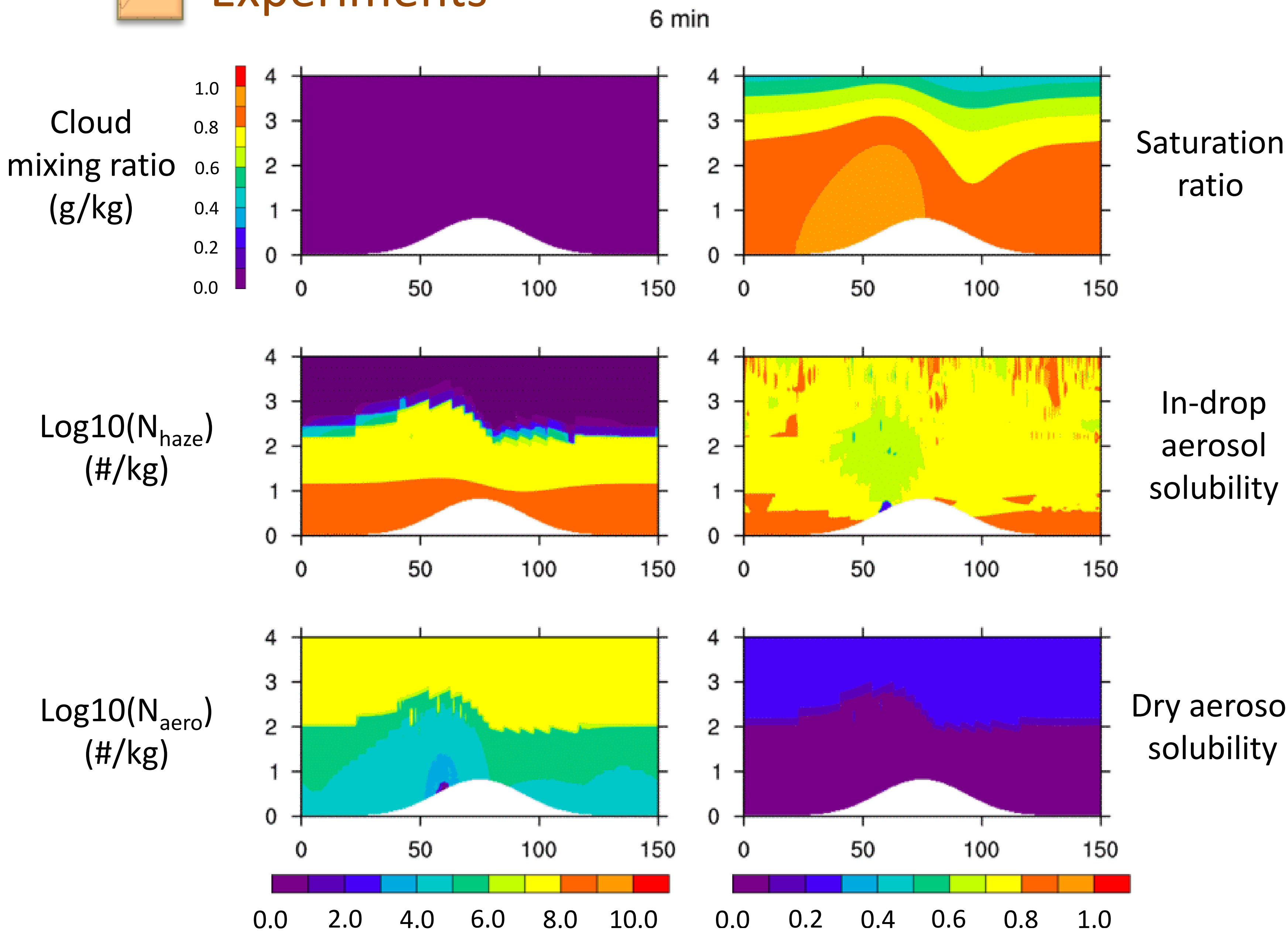
Warm-phased bin aerosol-microphysics scheme



Model



Experiments



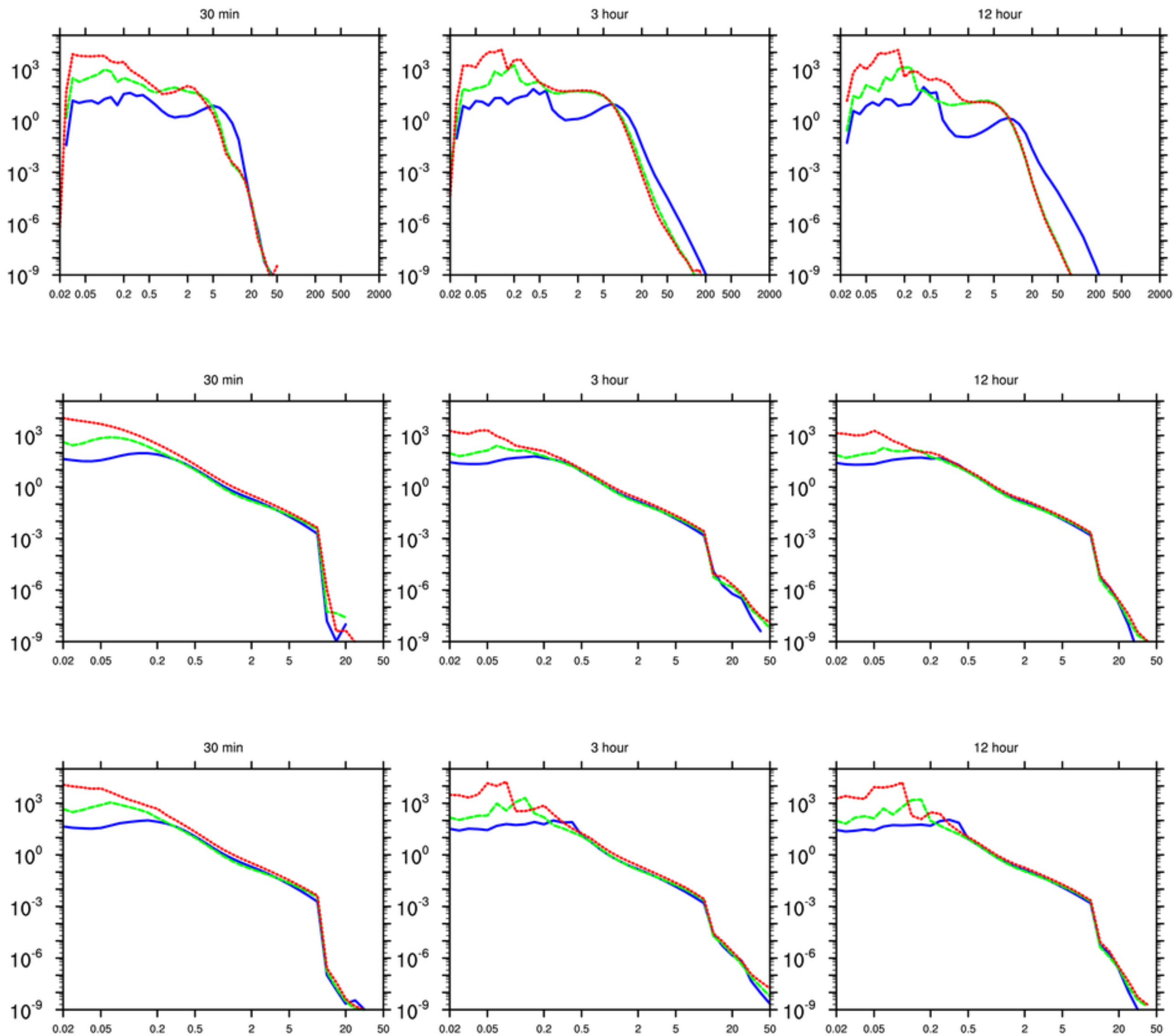
Loop of contour plots of various variable for remote continental when RH=90%

Experiments

Drop size distribution

Dry aerosol distribution

Combined aerosol distribution



dN/dlogR (cm^-3)

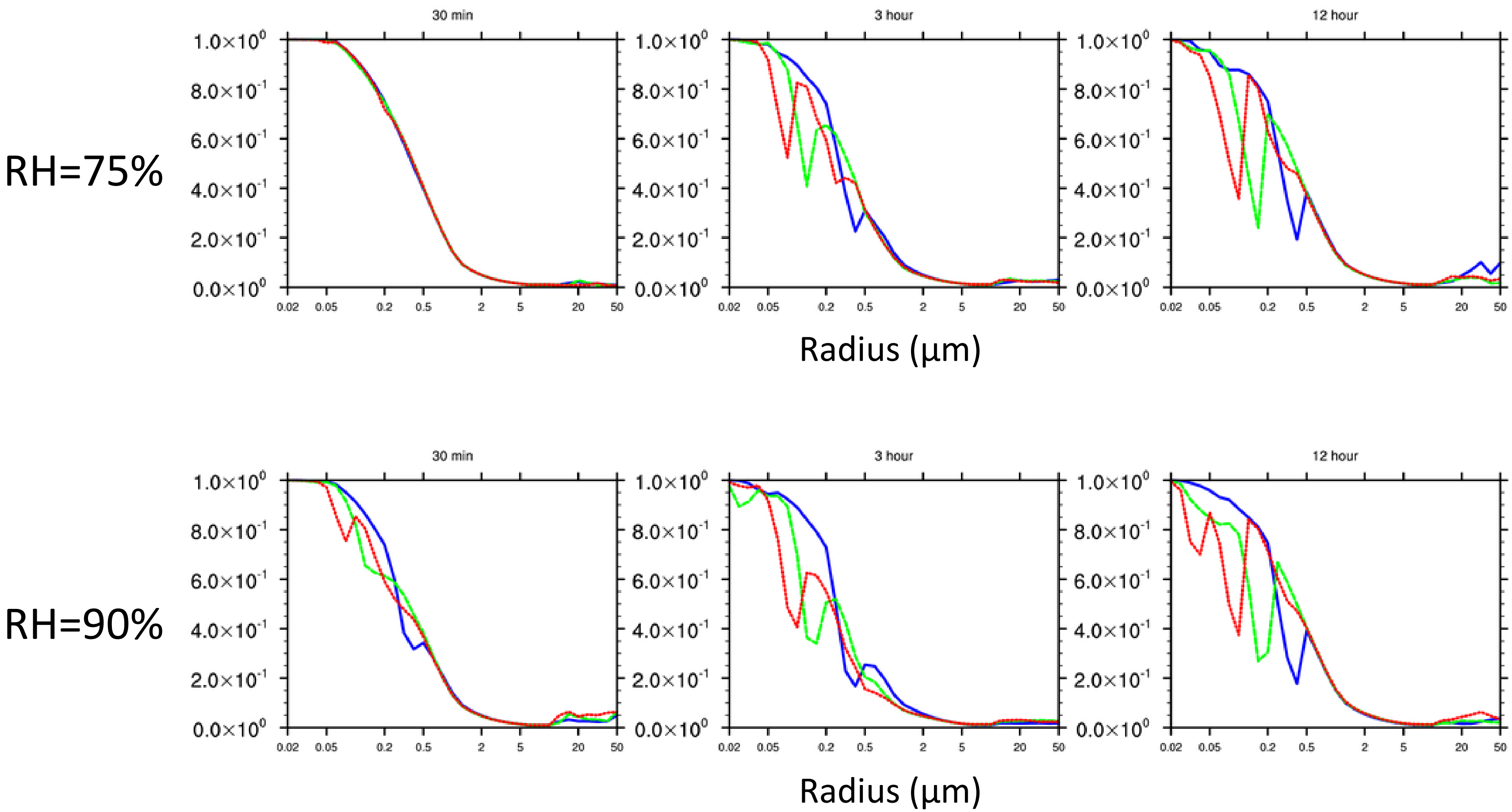
dN/dlogR (cm^-3)

dN/dlogR (cm^-3)

Radius (µm)

Domain averaged (below 4km) size distributions for Maritime, Remote Continental, Urban when RH=75%

Experiments



Domain averaged (below 4km) combined solubility distributions for Maritime, Remote Continental, Urban when RH=75% and 90%

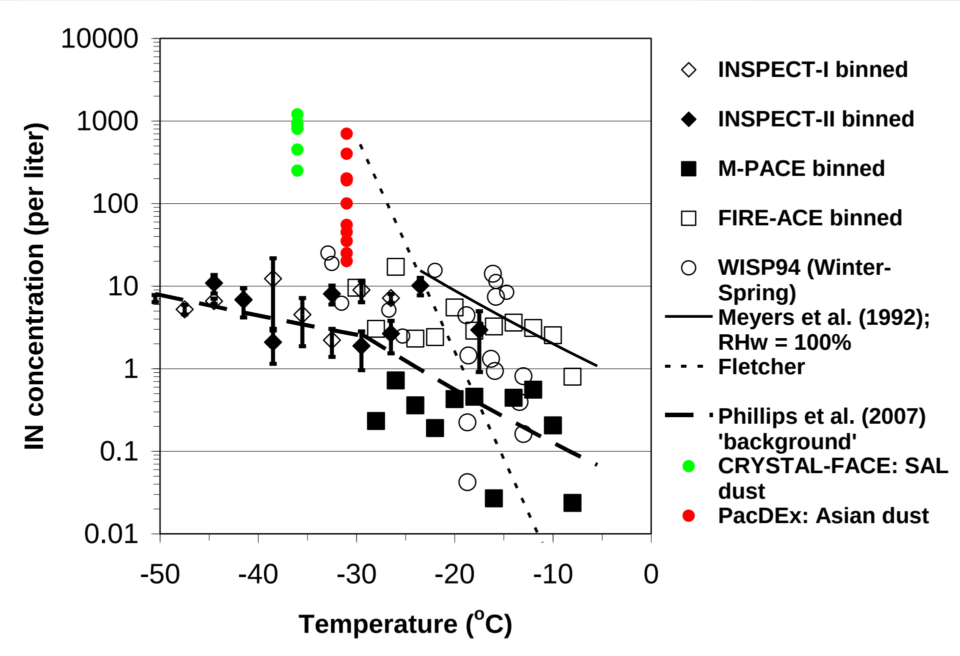
Cloud Processing Summary

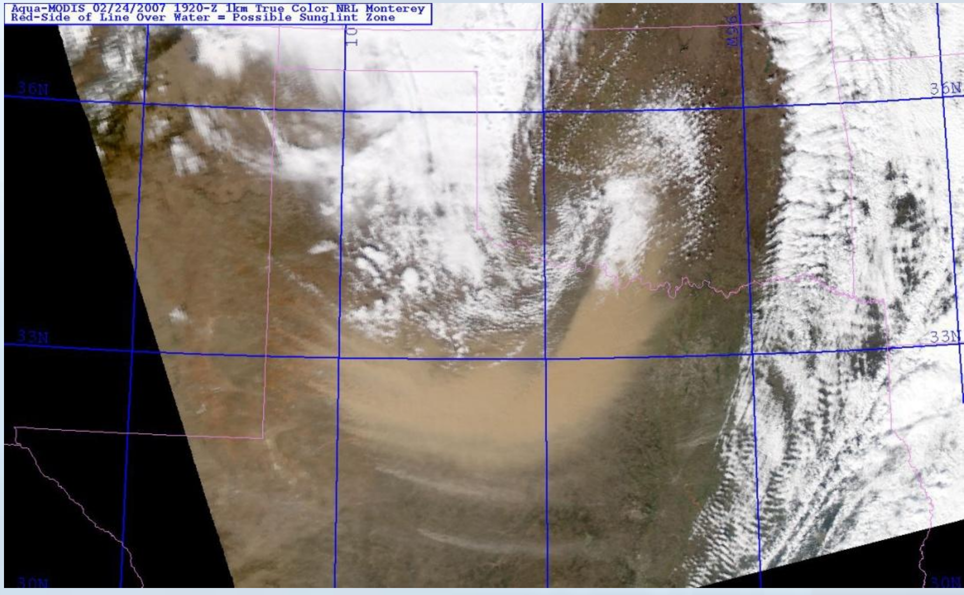
Given an aerosol background size and solubility distribution, an equilibrium state of aerosol exists after cloud processing.

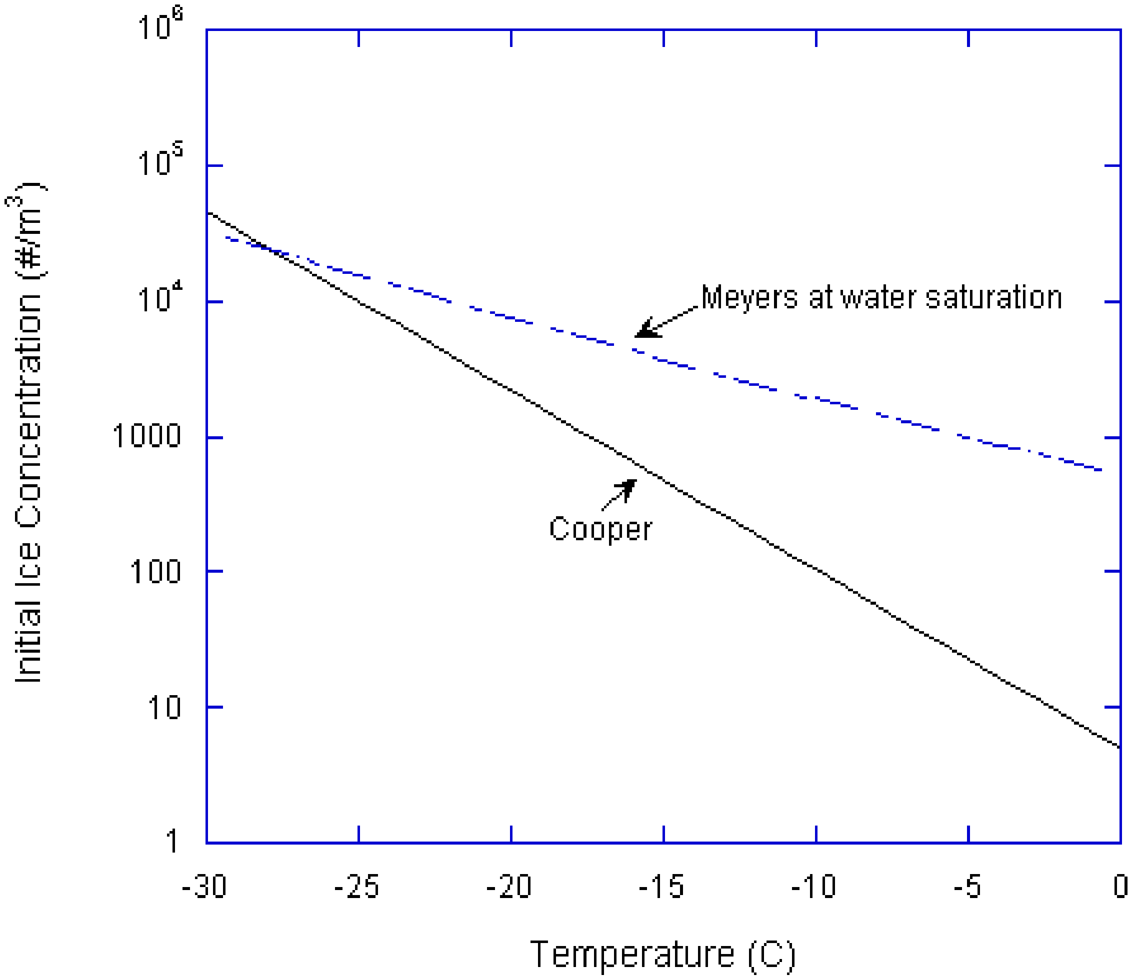
Cloud processing generates larger and more hygroscopic aerosols.

Initiation of Ice

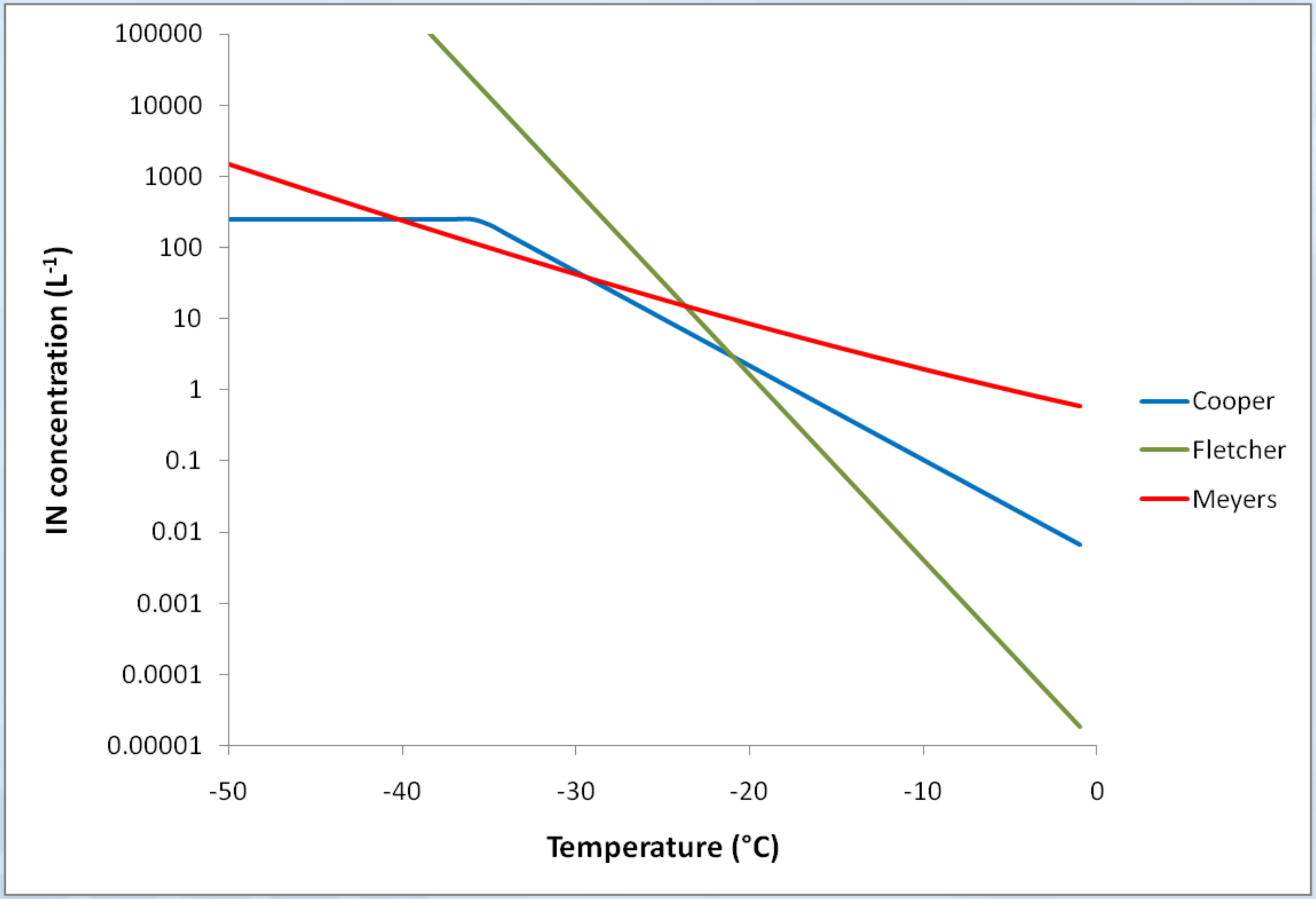
- **Adding aerosols into the microphysics scheme: dust/ice nuclei**
  - incorporate dust/mineral category and influence ice nucleation
  - ICE-L case studies



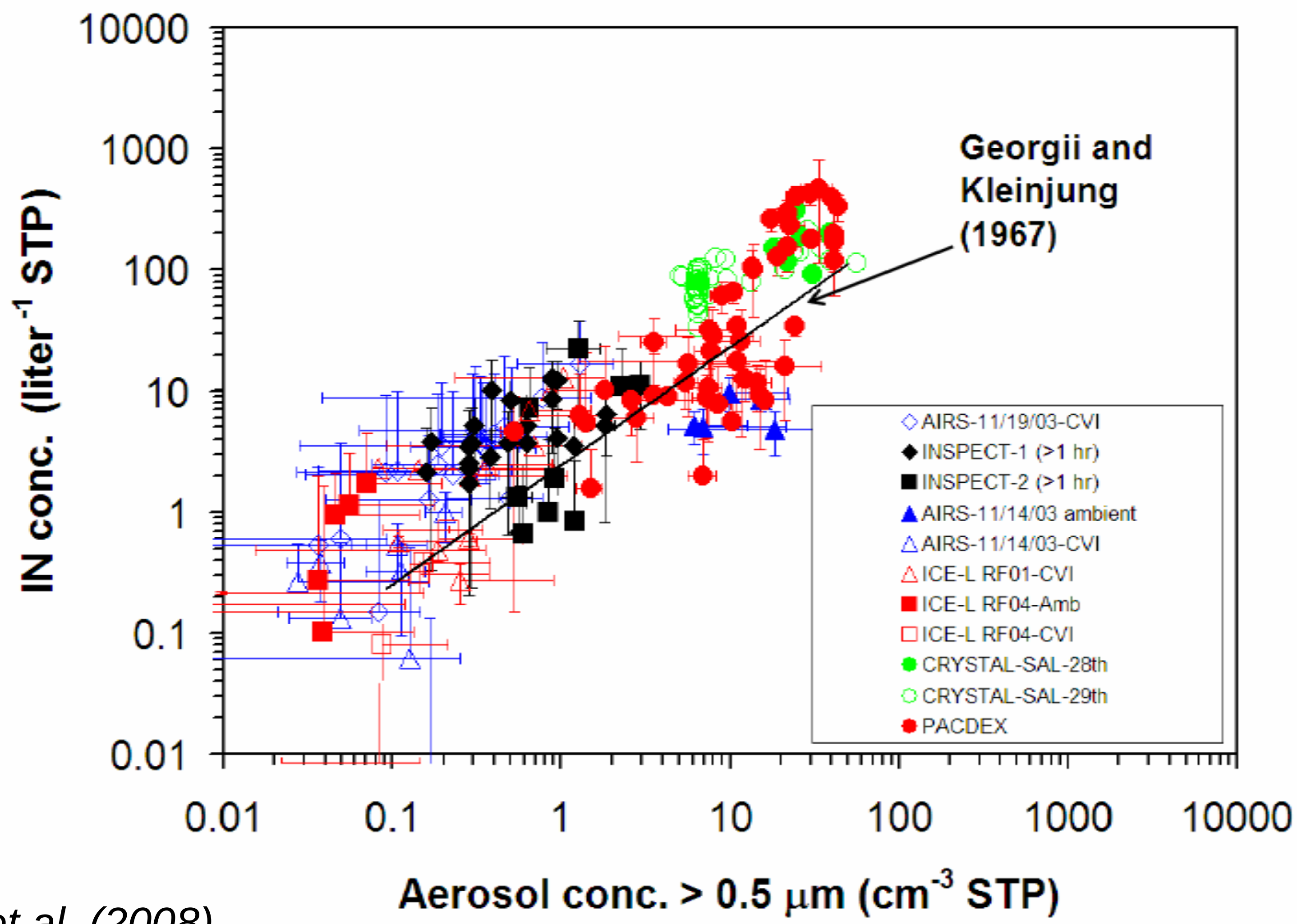



Initial Ice Concentration (#/m³)
10⁶
10⁵
10⁴
1000
100
10
1
-30
-25
-20
-15
-10
-5
0
Temperature (C)
Meyers at water saturation
Cooper

Ice nucleation parameterizations in models

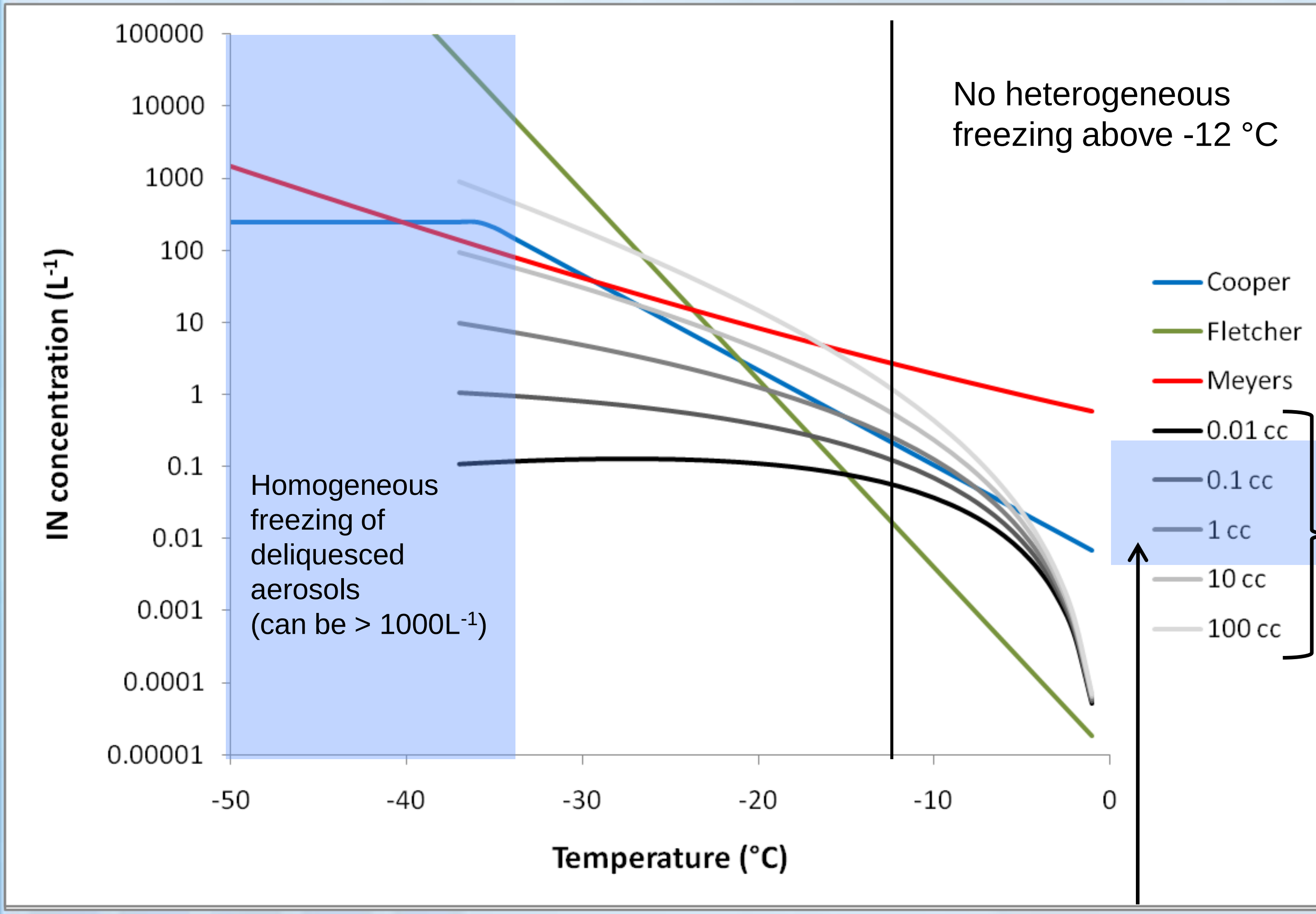


Relationship between aerosol concentration and ice nuclei (IN) concentration



DeMott et al. (2008)

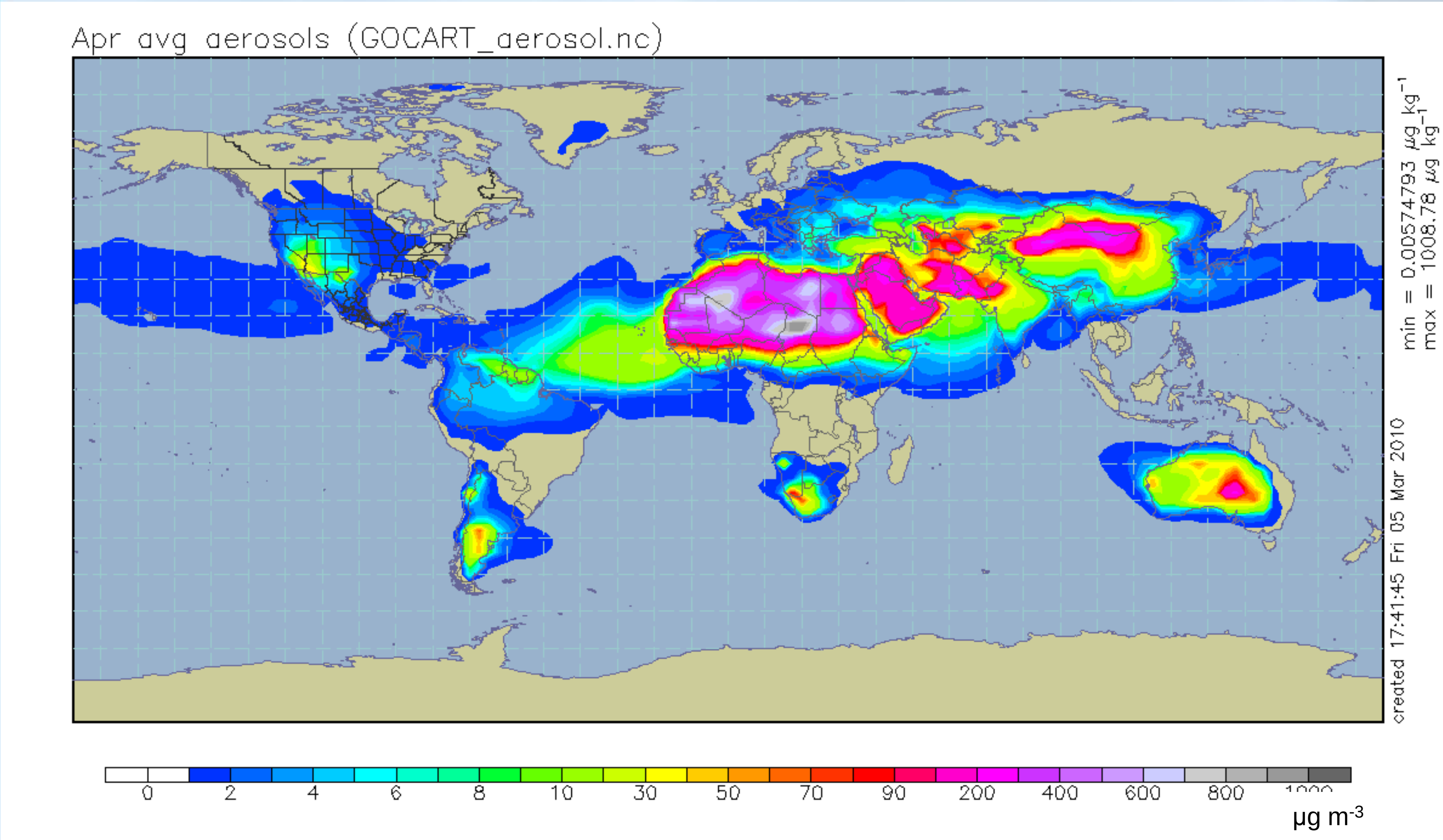
Ice nucleation parameterization scheme



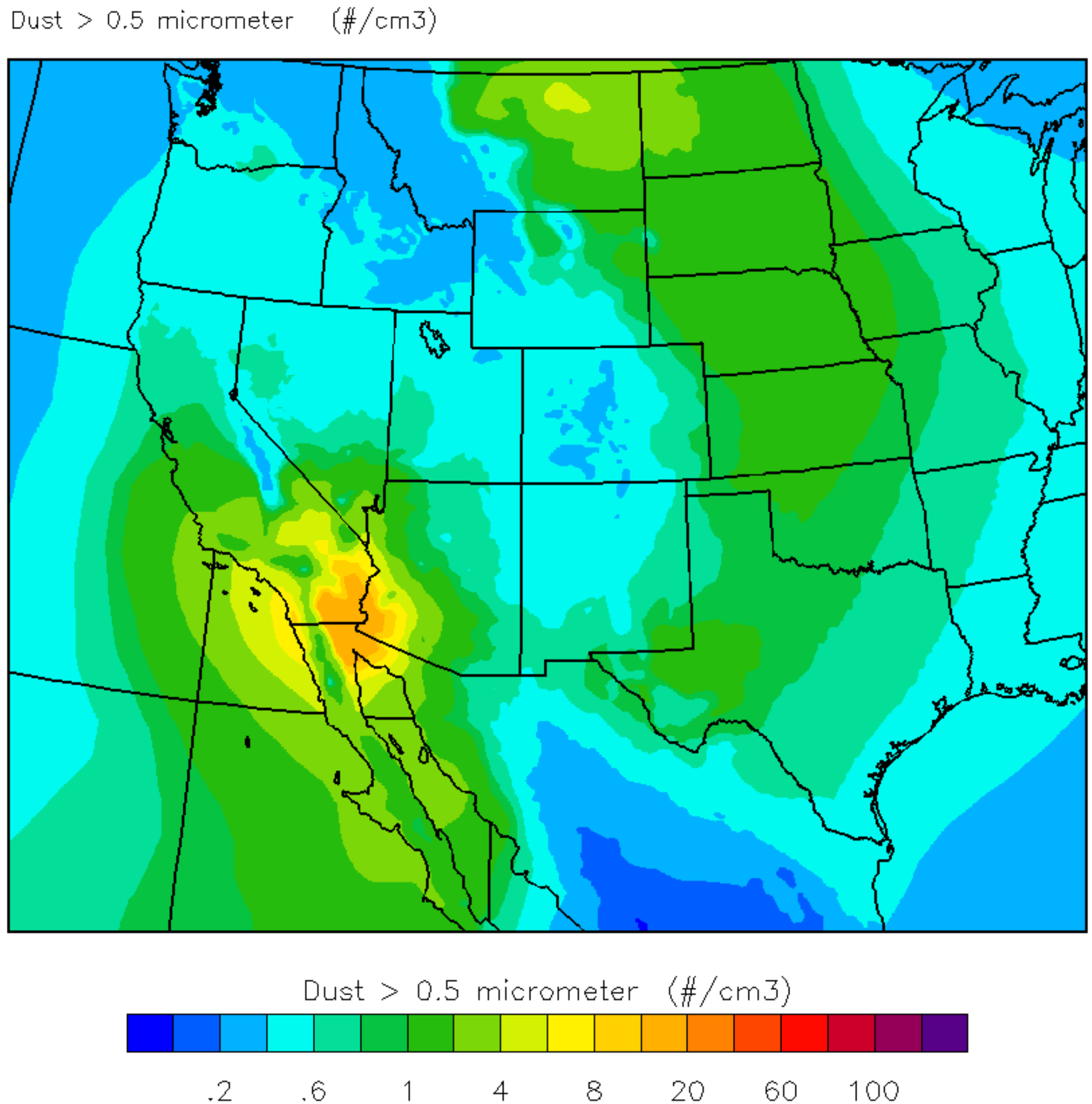
DeMott et al 2010. IN dependent on aerosols > 0.5 μm.

Typical aerosol > 0.5 μm background concentration values

Aerosols in Thompson microphysics scheme: Ice nucleation from Dust particles



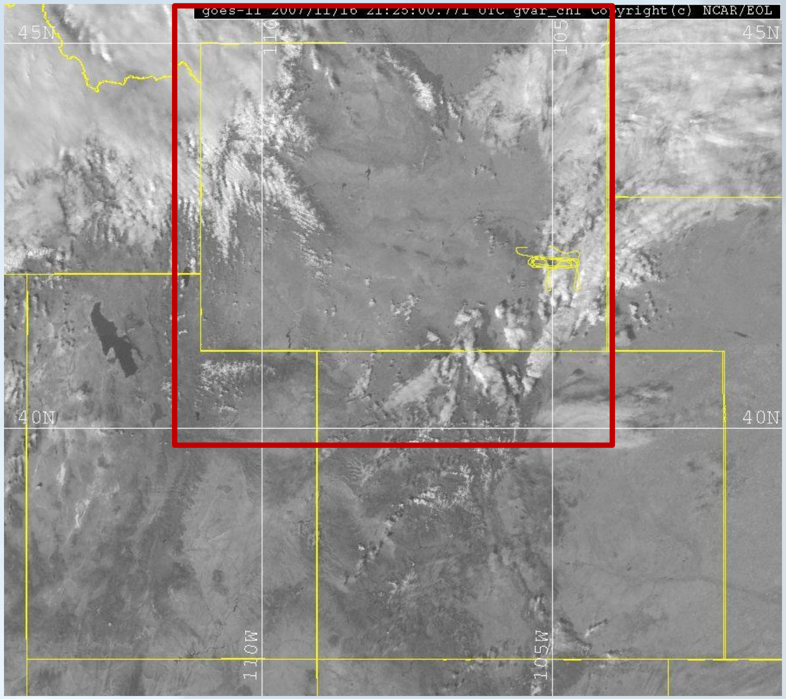
GOCART 1.5° (lon) x 1.0° (lat) global monthly avg data, 20 sigma levels


Dust > 0.5 micrometer (#/cm3)
Dust > 0.5 micrometer (#/cm3)
.2
.6
1
4
8
20
60
100

Dust Module in the Thompson Scheme

- Assume constant dust distribution shape (D = 0.8 μm and σ = 2 (standard deviation))
- Emission of dust is included. Dependent on land surface, soil moisture and wind speed (need evaluation).
- Main source of deposition for dust sizes important for ice nucleation is wet deposition.

Ice in Clouds Experiment – Layer clouds (ICE-L)



- In situ measurements of wave clouds in Wyoming and Colorado, November/December 2007.
- Focus on primary heterogeneous nucleation, in clouds where this type of nucleation can be distinguished from other types of ice nucleation.
- Mixed phased clouds

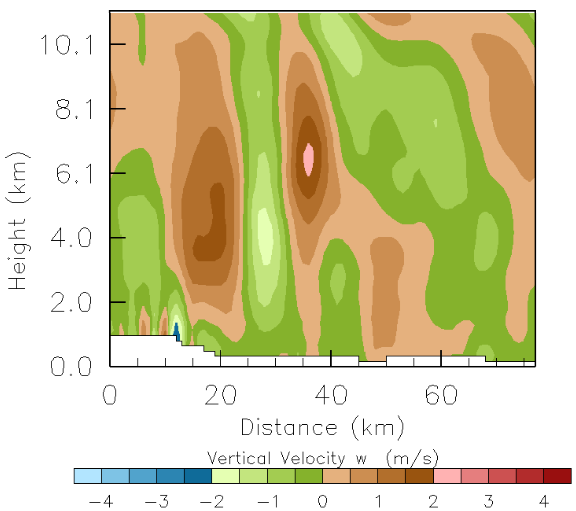
Original Thompson version (Cooper curve)

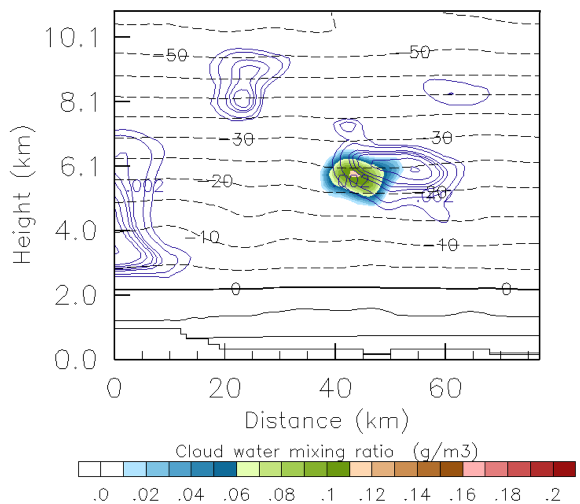
New version Dust dependent

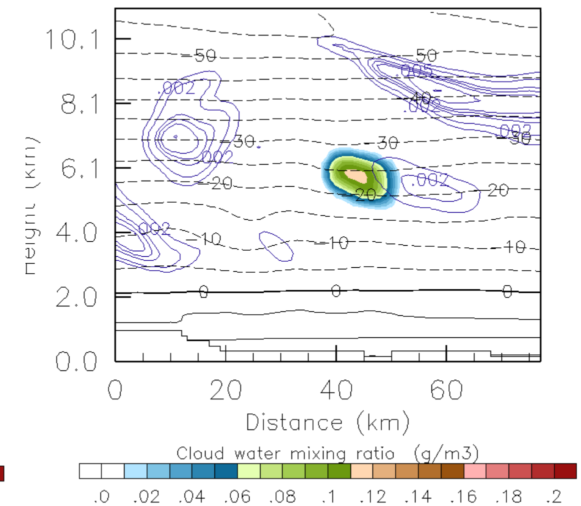
Vertical velocity

Water content

Ice and snow water content (g/m³)

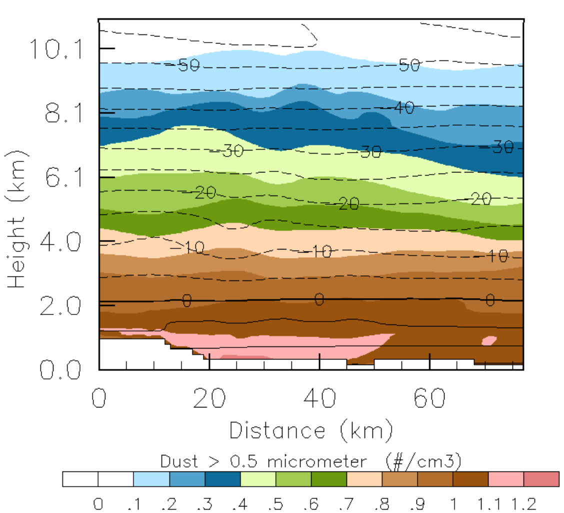


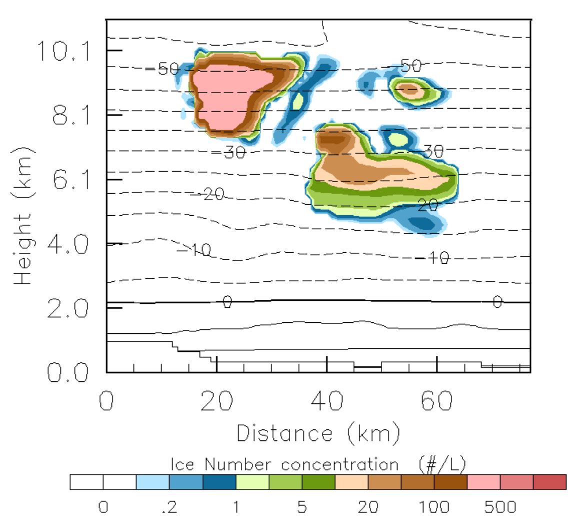


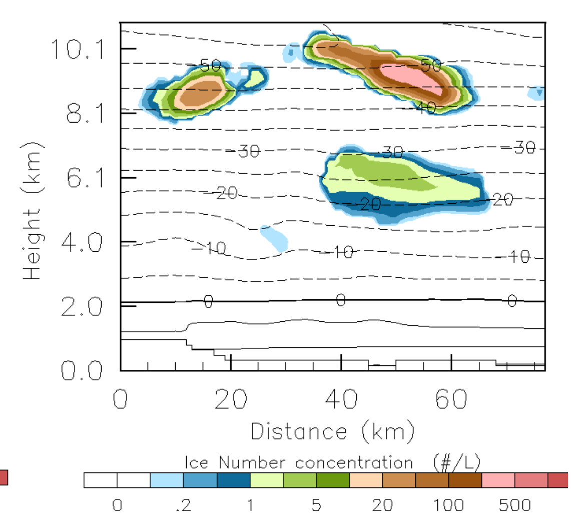


Dust concentration for sizes > 0.5 µm

Ice crystal concentration



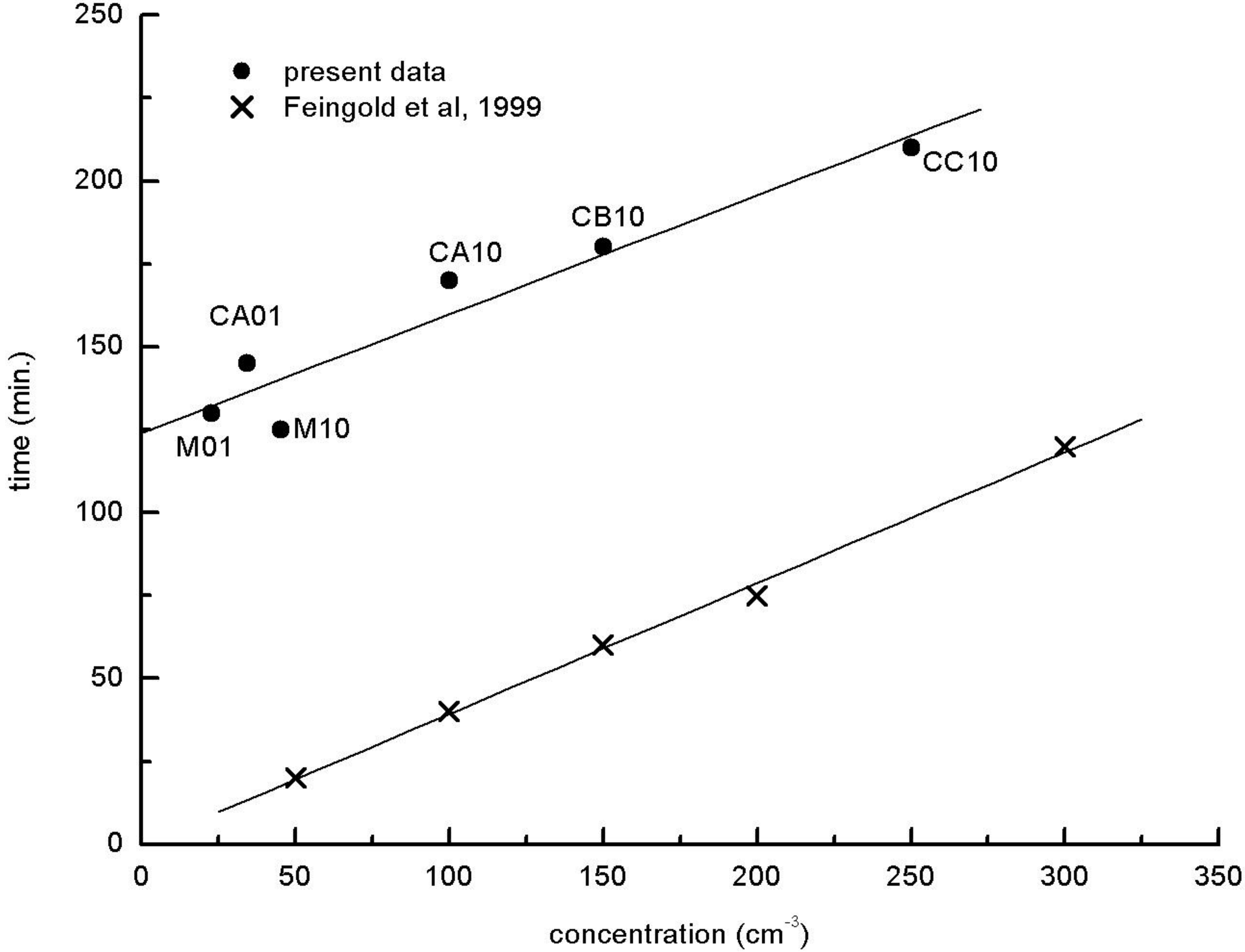




History and Plans for the Thompson et al. scheme

Model/ System	Horizontal Resolution	Number levels	Assimilation Frequency	Implemented at NCEP	Microphysics
RUC1	60 km	25	3 hr	Sept. 1994	
RUC2	40 km	40	1 hr	April 1998	Reisner 1998
RUC20	20 km	50	1 hr	April 2002	Thompson 2004
RUC13	13 km		1 hr	2005	Thompson 2004
RR	13 km		1 hr	mid- 2010	Thompson 2008
HRR	3 km			mid-2011	Aerosols in Thompson scheme

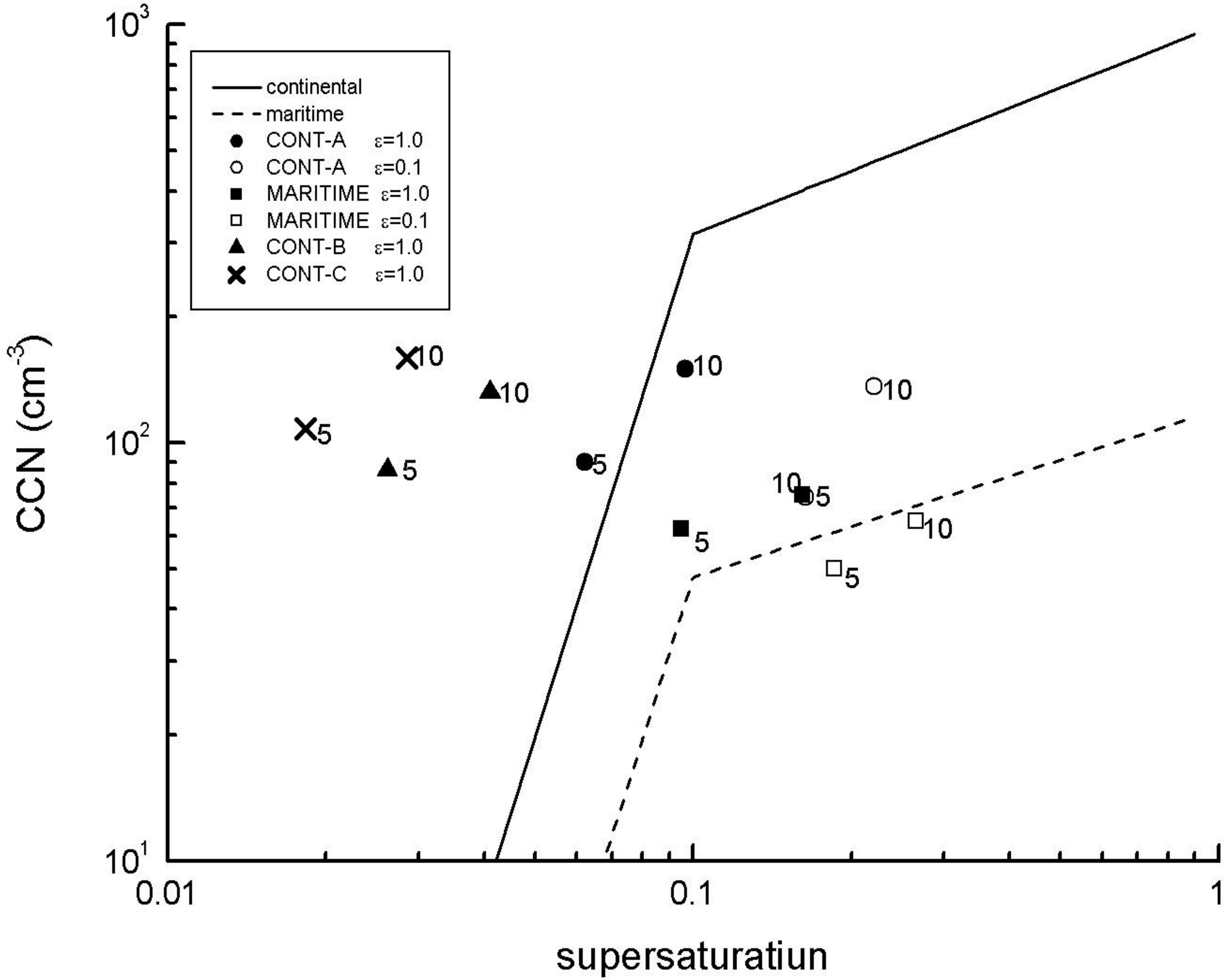
Questions?



present data
Feingold et al, 1999
time (min.)
concentration (cm^{-3})
M01
CA01
M10
CA10
CB10
CC10
0
50
100
150
200
250
300
350

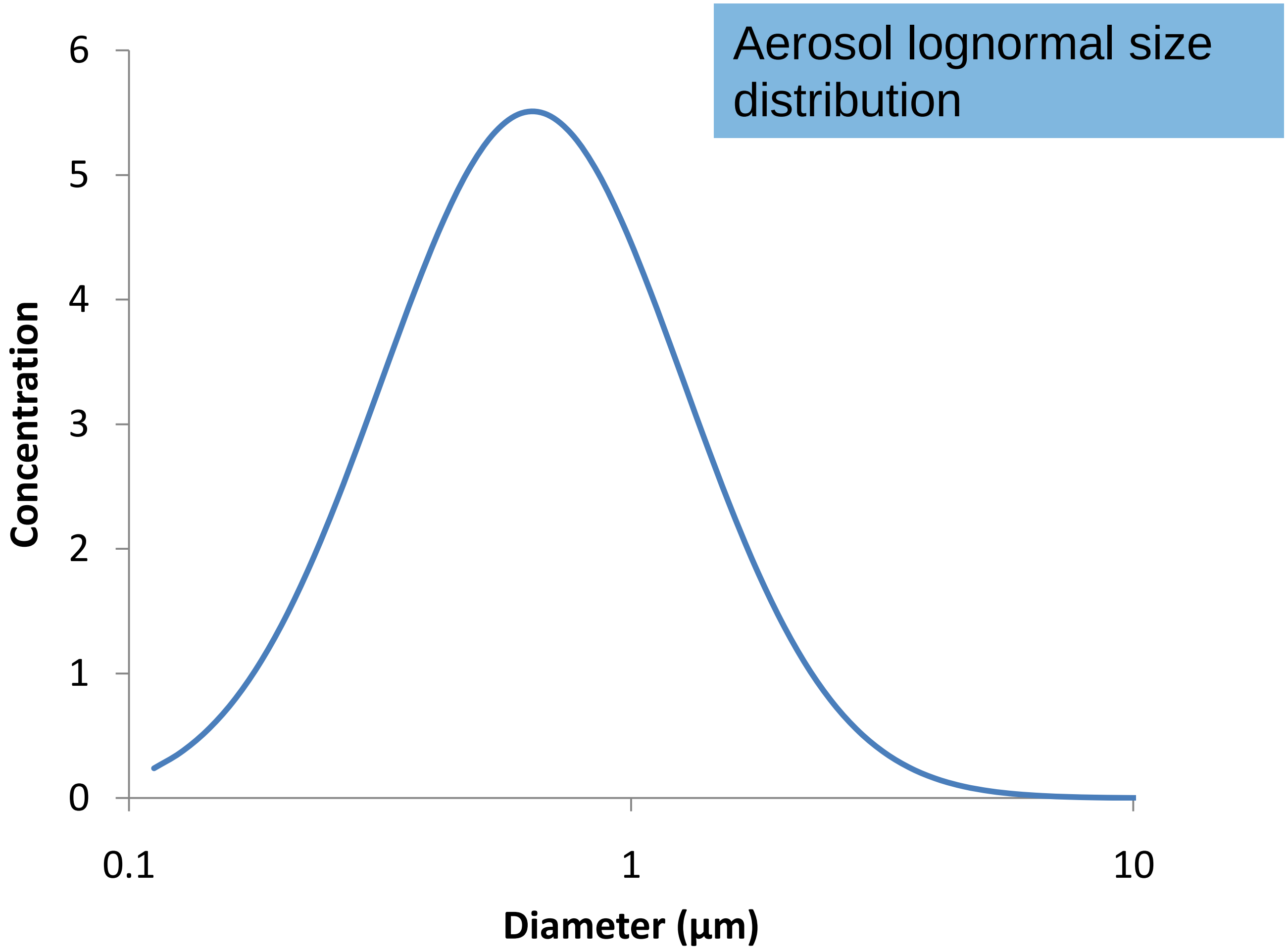
Questions?

Questions?



continental
maritime
CONT-A ε=1.0
CONT-A ε=0.1
MARITIME ε=1.0
MARITIME ε=0.1
CONT-B ε=1.0
CONT-C ε=1.0
CCN (cm-3)
supersaturatiun
0.01
0.1
1
10
5

Example of aerosol scheme in Thompson et al. microphysics



Droplet activation; function of at least 12 parameters

AEROSOL SIZE DISTRIBUTION (diameter[1] (D), number concentration[2] (N_t) and standard deviation[3] (σ_g))

THERMODYNAMIC STATE OF ENVIRONMENT (temperature[4] (T) and pressure[5] (P))

CLOUD DYNAMICS (updraft[6] (w))

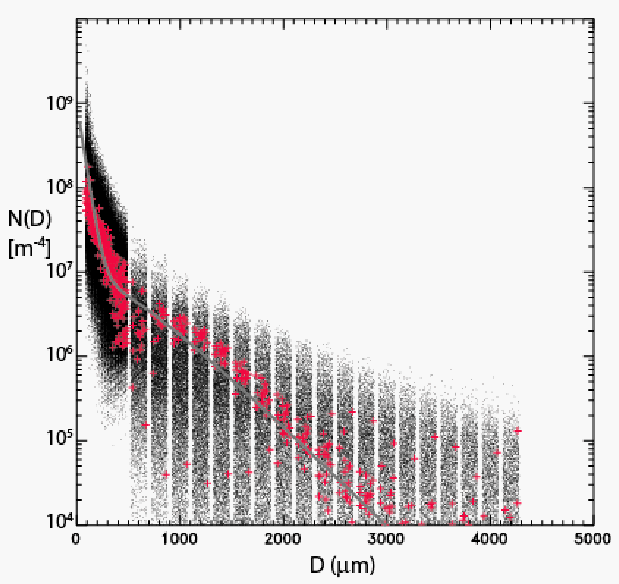
DROPLET GROWTH KINETICS (condensation coefficient[7] (α))

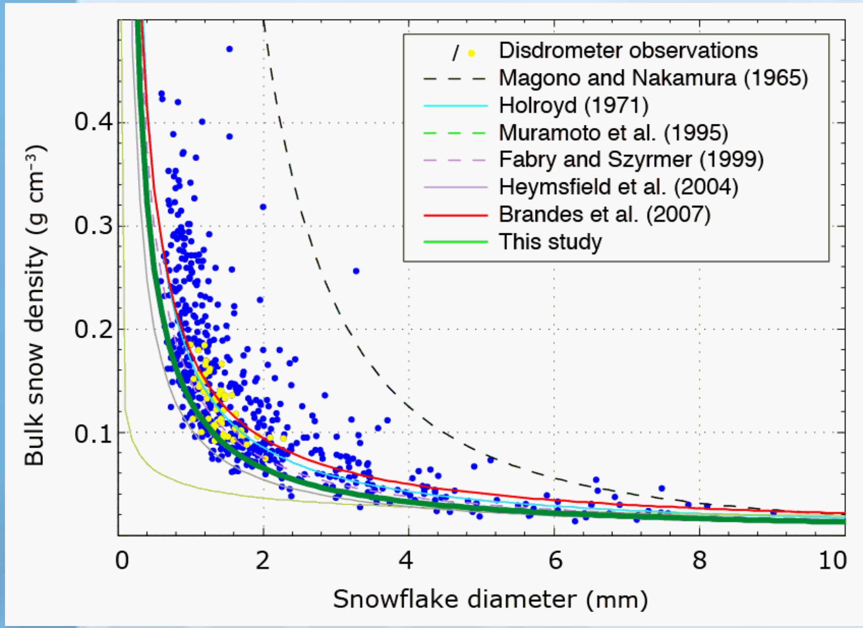
AEROSOL CHEMICAL PROPERTIES (solute molecular weight[8], bulk solute density[9], surface tension[10] ($\sigma_{s/a}$), number of dissociating species in solution[11], practical osmotic coefficient[12])

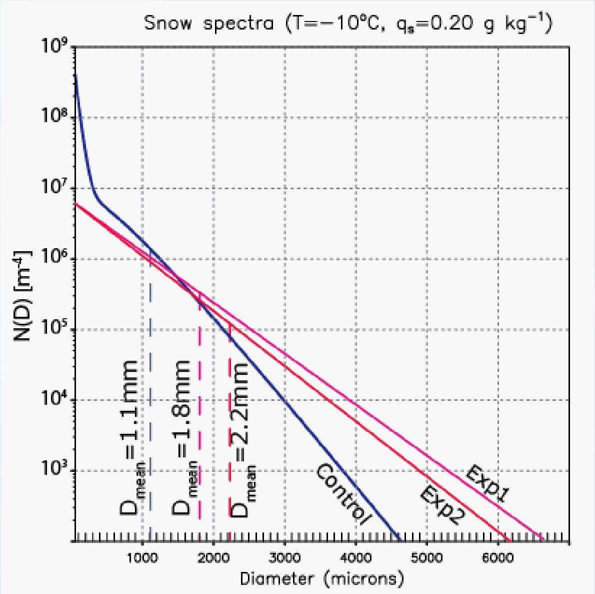
Thompson et al. 2008 MWR

- **Non-dimensional snow size distribution added with more realistic snow particle shapes**
  - More realistic diffusional growth (less than before), resulting in more SLW.
  - Improved conversion of snow to graupel (less graupel)

(Thompson et al., 2008, MWR)







Bulk schemes predict one or more bulk quantities (e.g., mixing ratio) and assume some functional form for the particle size distribution, e.g., gamma distribution:

$$n(D) = N_0\, D^{\mu}\, e^{-\lambda D}$$

If N_0 and μ are specified, then λ can be obtained from the predicted mixing ratio q:

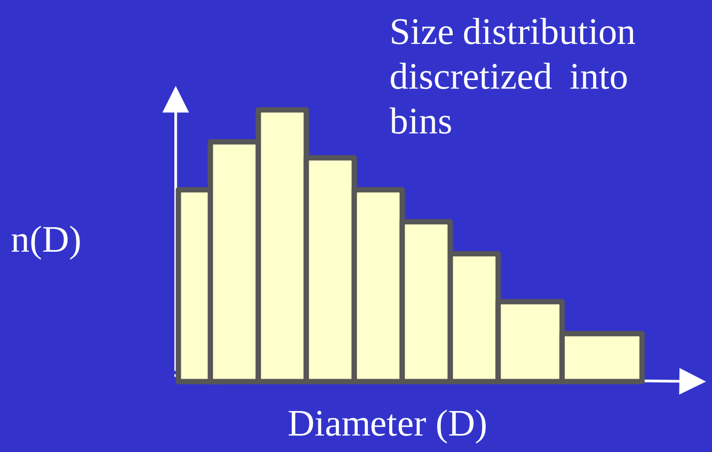
$$q = \int_0^{\infty} \frac{\pi}{6} \rho_w N_0 D^{3+\mu} e^{-\lambda D} dD$$

$$\lambda = \left[\frac{\pi \rho_w N_0 \Gamma(\mu + 4)}{6q} \right]^{\frac{1}{\mu+4}}$$

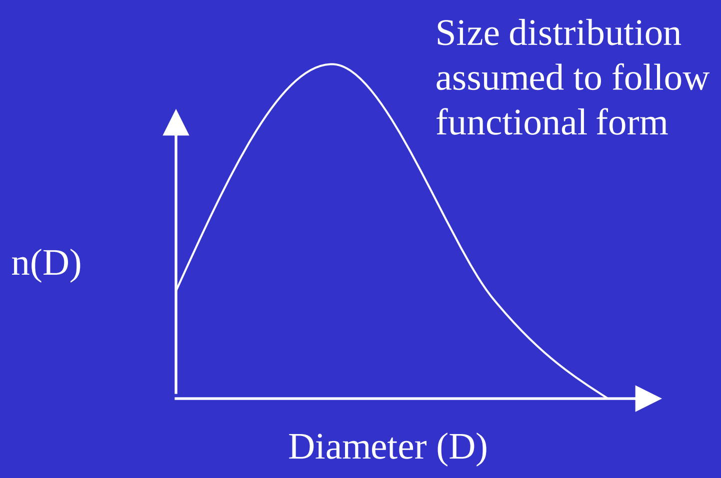
Equations for spherical drops

Microphysics schemes can be broadly categorized into two types:

Detailed (bin)



bulk



Representation of particle size distribution

Integration of Aerosols into WRF Microphysics Schemes

Crawl:

- Constant cloud droplet number that influences precipitation. Ice nucleation only dependent on temperature or saturation.

Walk:

- Creating ice and droplet number based on simple, but realistic aerosols

Run:

- Full integration with WRF-Chem and multiple aerosol species