Advancing the Representation of Cloud Microphysical Processes in a Snow Growth Model

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Photo by Ehsan Erfani

Motivation

- A single Mass-dimension (m-D) power law ($m=\alpha D^{\beta}$) is not valid for the whole range of particle size distribution. So, it produces uncertainty in modeling the ice cloud microphysics.

- Riming effect on particle dimension is small, but it considerably changes the mass and projected area.

Science Question

How can ice particle mass- and area-dimension (m-D & A-D) relationships be expressed as a function of riming?

Approach for m-D and A-D Laws

$$m = \alpha D^{\beta} \qquad , \qquad A = \gamma D^{\delta}$$

α, β γ, and δ size-dependent:

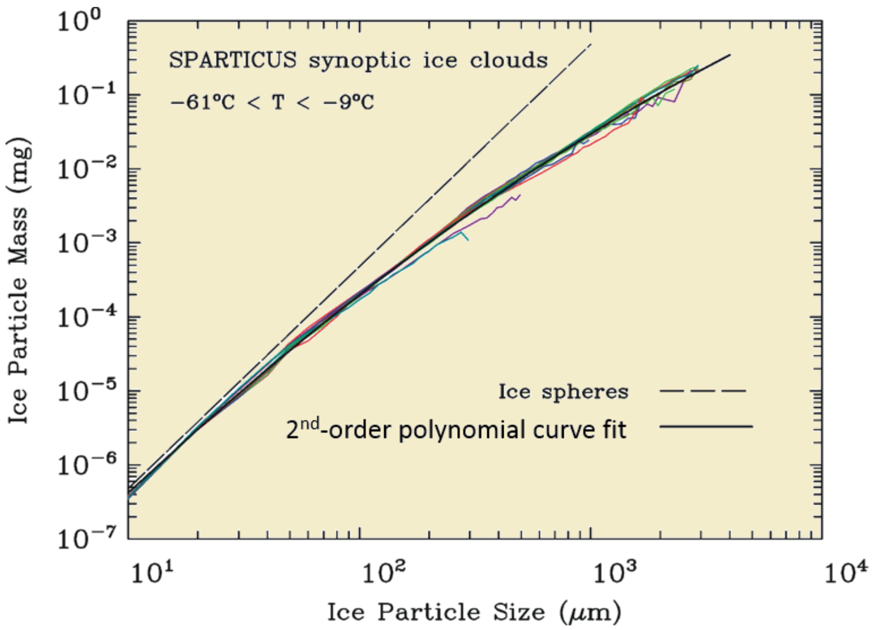
$$\beta = a_1 + 2a_2 \ln(D)$$

$$\alpha = \frac{exp\{a_0 + a_1 \ln(D) + a_1[\ln(D)]^2\}}{D^{\beta}}$$

2nd-order polynomial fit in log-log space:

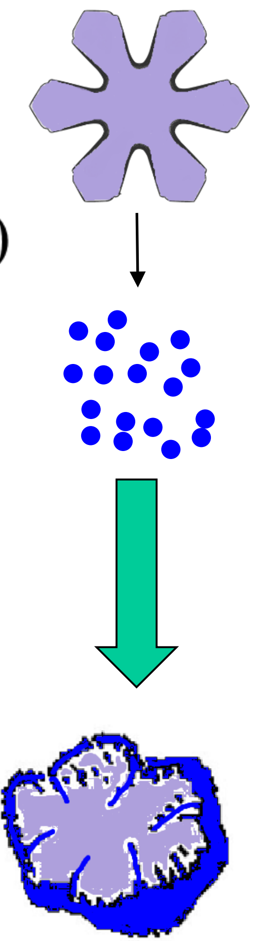
$$\ln(m) = a_0 + a_1 \ln(D) + a_2[\ln(D)]^2$$

Mass vs. Dimension



Observations: SCPP data
Mitchell *et al.* (2015)

Approach for Treatment of Riming



- **Rimed Mass:**

$$\frac{\alpha}{\alpha_u} = \frac{IWC}{IWC_u} \quad , \quad \beta = \beta_u \quad \text{(empirical result), (D > 150 µm)}$$

- **Max Mass and Max Projected Area:**

$$A_{max} = k\frac{\pi}{4}D^2 \quad , \quad m_{max} = 3.5\, m_u \quad \text{(empirical result)}$$

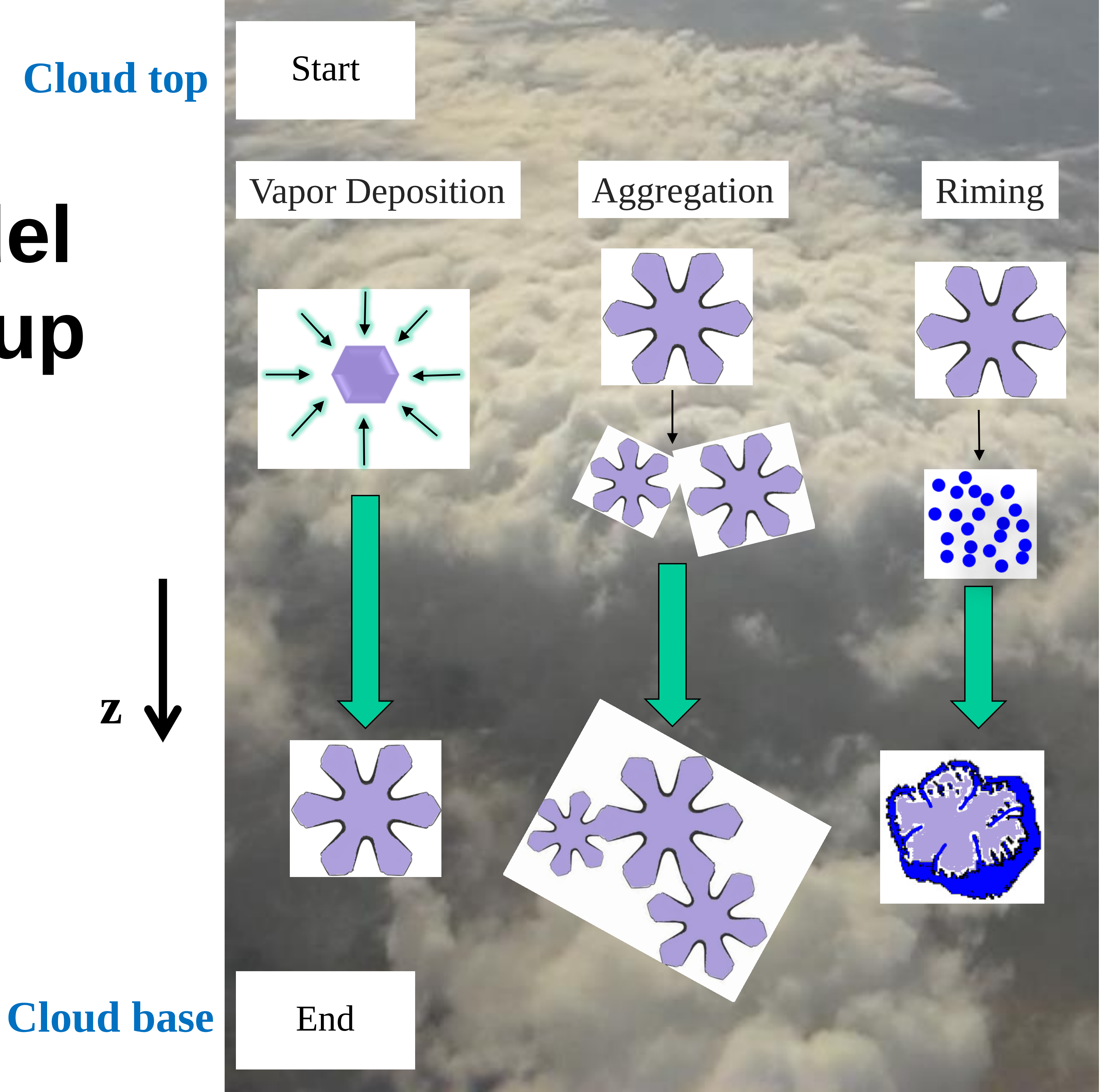
- **Rimed Projected Area:**

$$R = \frac{m - m_u}{m_{max} - m_u} \quad , \quad A = (A_{max} - A_u)R + A_u$$

$$\gamma = \frac{A}{D^{\delta}} \quad , \quad \delta = \delta_u$$

R: riming factor (0<*R*<1)

Model Setup


Cloud top
Start
Vapor Deposition
Aggregation
Riming
z
Cloud base
End

Model Setup

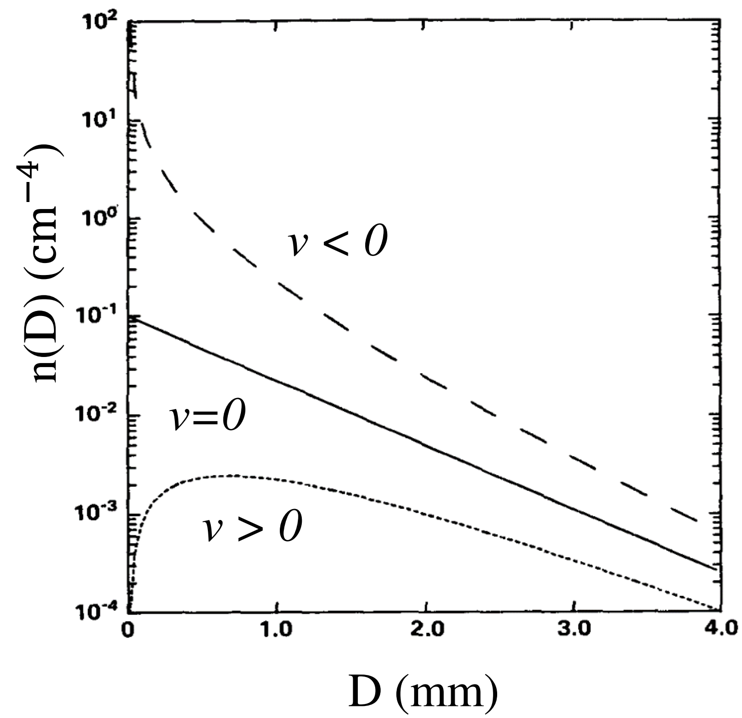
- **Gamma** size distribution:

$$n(D) = n_o D^{\nu} \exp(-\lambda D)$$

λ: slope parameter,

ν: dispersion parameter.
In this study: ν = -0.6
(super exponential distribution)

Size Distribution



Mitchell (1991, JAS)

Basic Equations

- **0th moment eq.:** height dependence of **number concentration**:

$$\frac{\partial N}{\partial z} = \frac{bN}{\lambda}\frac{\partial \lambda}{\partial z} - \frac{1}{V_{Nf}}\left[kCS^{k-1}\frac{dS}{dt} + \frac{\partial (wN)}{\partial z}\right] - \frac{\pi E I(\nu, b) N^2}{8\Gamma(b+\nu+1)\Gamma(\nu+1)\lambda^2}$$

fallout nucleation updraft aggregation

- **2nd moment eq.:** height dependence of **slope parameter**:

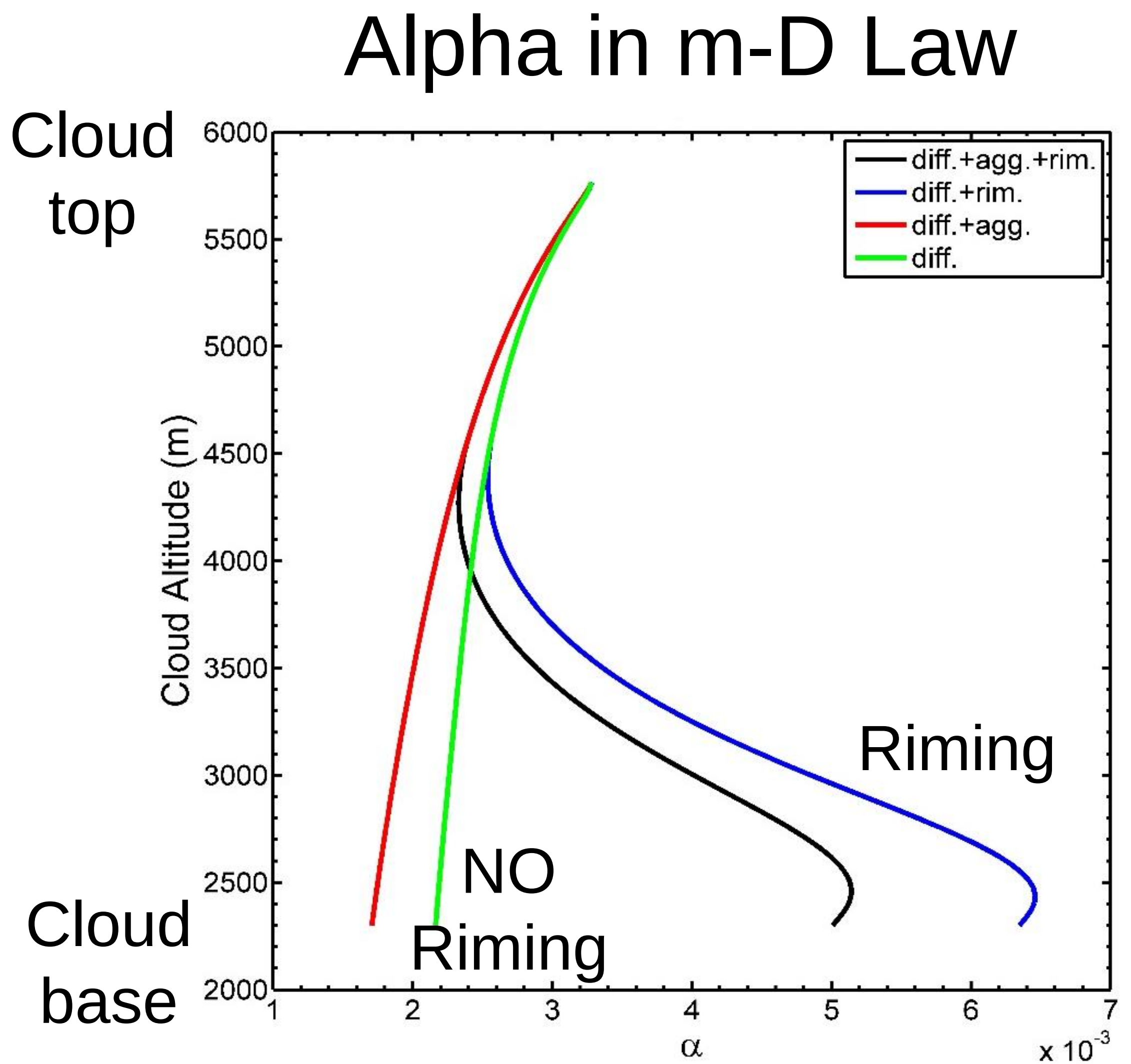
$$\frac{\partial \lambda}{\partial z} = \frac{\lambda}{(2\beta+b)N}\frac{\partial N}{\partial z} - \frac{1}{V_{Zf}}\frac{f(T,p,S)\lambda^{\beta} 2\Gamma(\beta+\nu+2)}{\alpha(2\beta+b)\Gamma(2\beta+\nu+1)}$$

sedimentation vapor diffusion

$$-\frac{\pi E I(\beta,\nu,b)N}{4(2\beta+b)\Gamma(2\beta+b+\nu+1)\Gamma(\nu+1)\lambda} - \frac{2\gamma\overline{E_d}\, Q\, \Gamma(\beta+b+\delta+\upsilon+1)}{\alpha(2\beta+b)\Gamma(2\beta+b+\upsilon+1)\lambda^{\delta-\beta-1}}$$

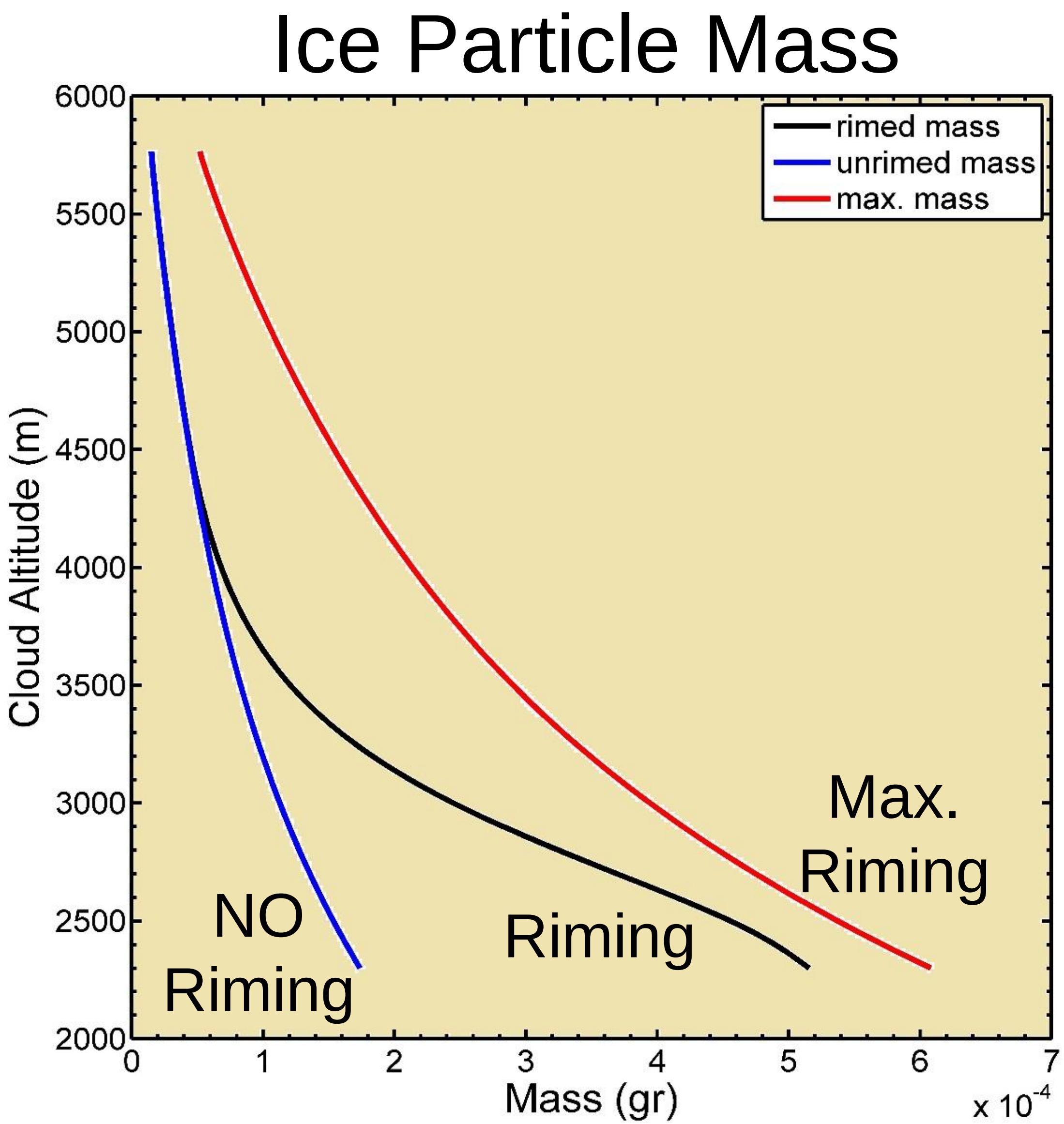
aggregation riming

Testing the Riming Process

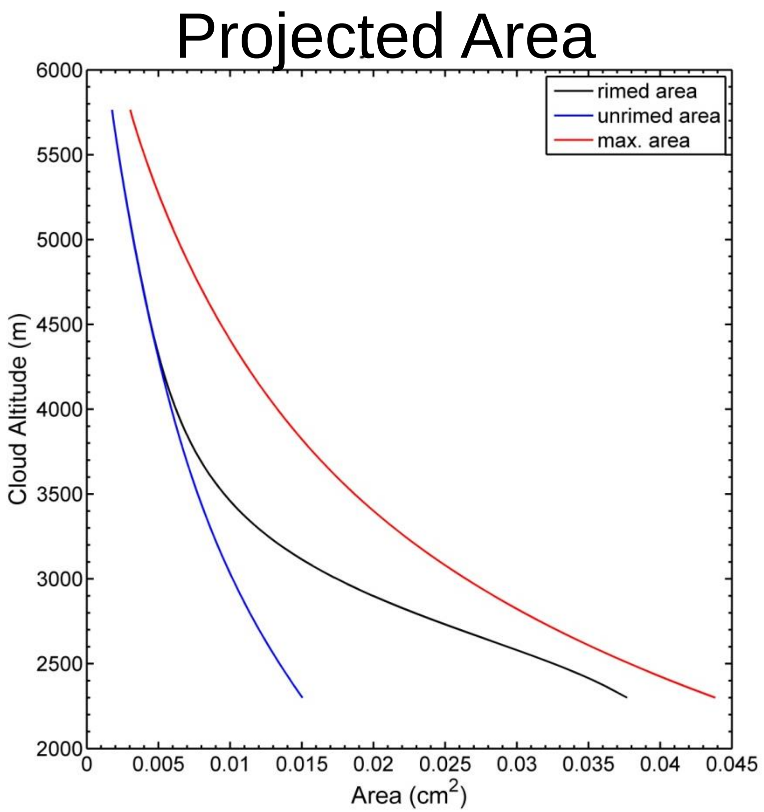


- α, β, γ and δ: constant in most models (not real), but variable in our model
- In the absence of riming, particles are more compact at cloud top and become more branched during the decent due to aggregation and diffusion.
- Riming produces more compact particles with greater α

Testing the Riming Process

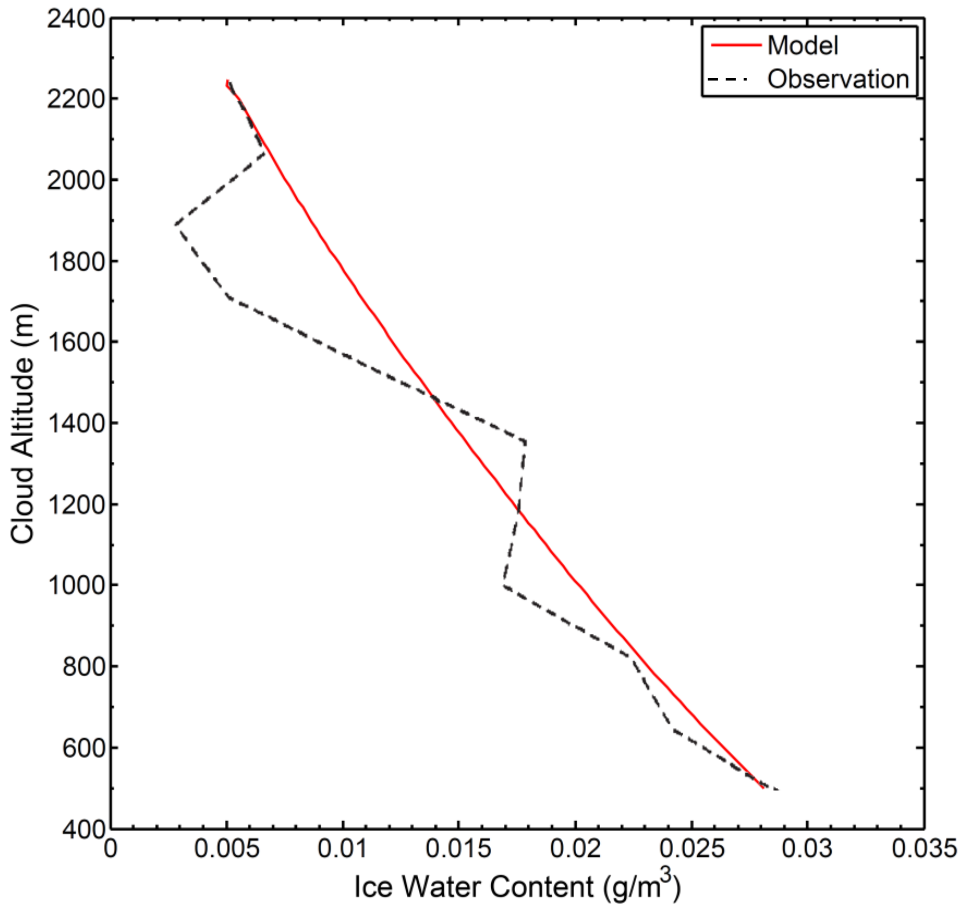


- Increase in mass and projected area by riming, associated with increase in α



Comparing Model & Observation

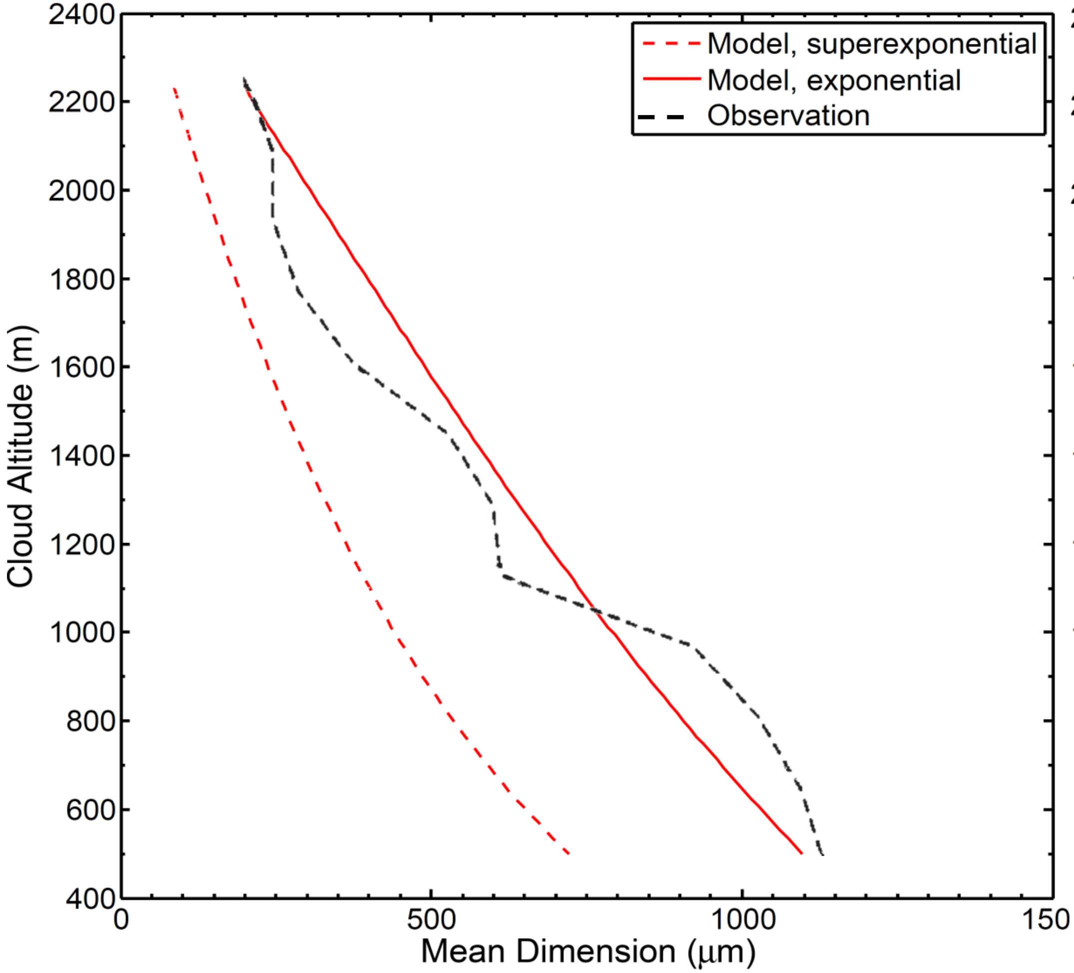
Ice Water Content



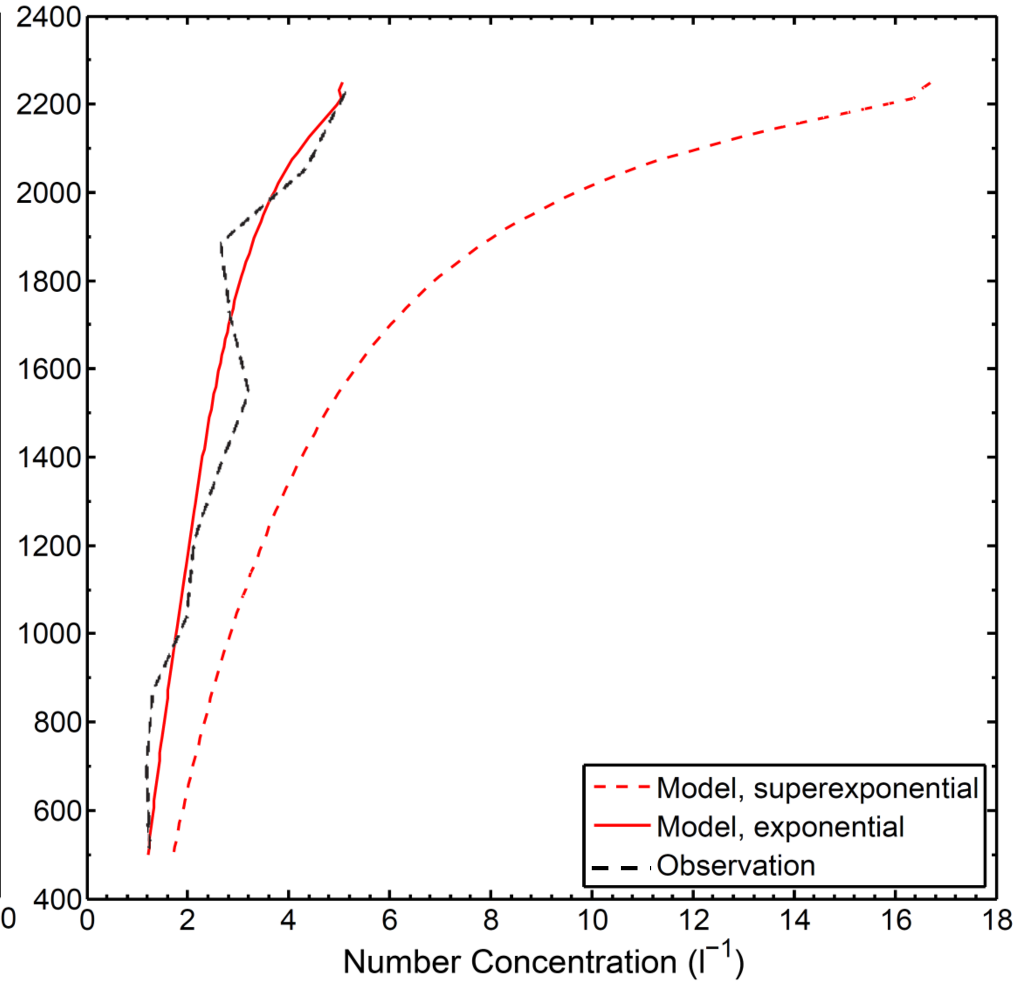
- Observation: Lagrangian spiral descent, off the coast of NH, 8 Mar. 1980.
- Consistency between observed and predicted variables: microphysical processes modeled correctly (Observation: *D > 200 μm*).

Comparing Model & Observation

Mean Dimension ($\bar{D}$)

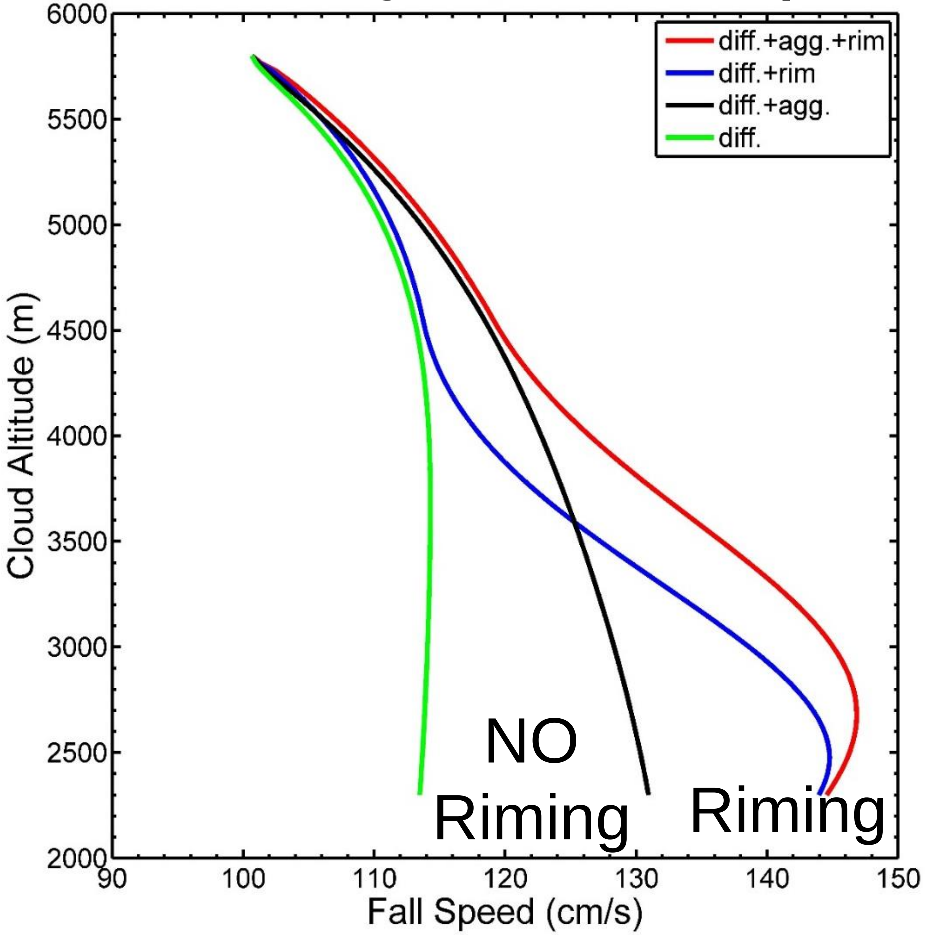


Number Concentration (N)

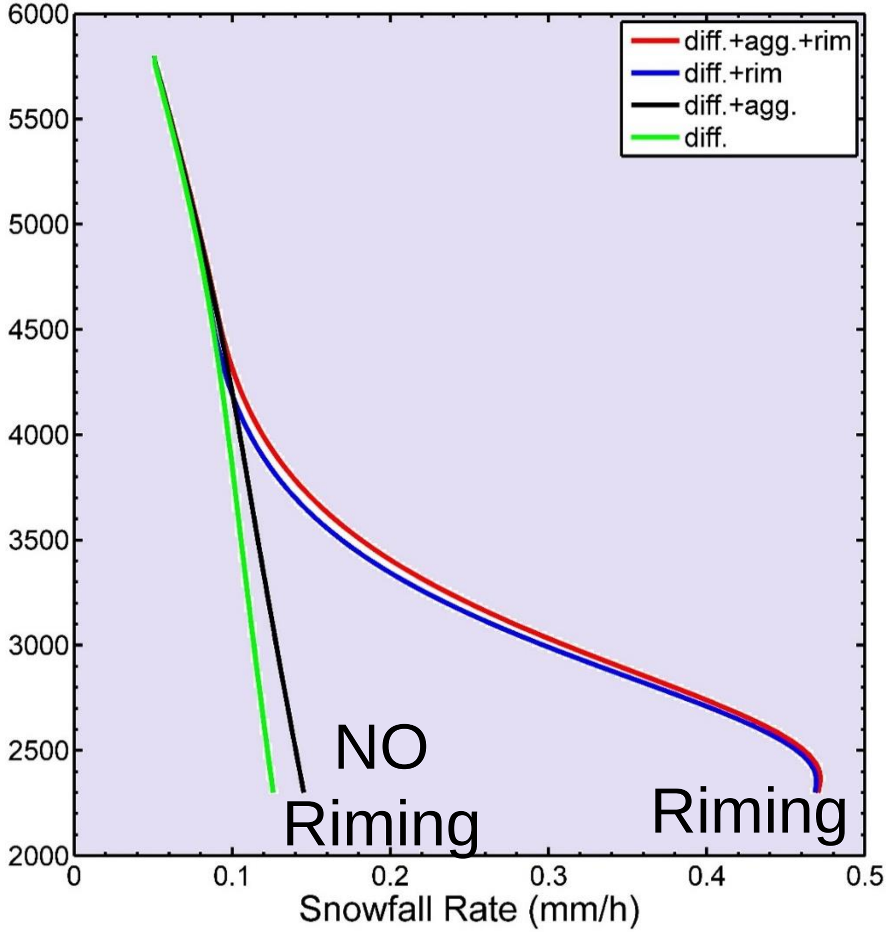


Comparing Deposition, Aggregation & Riming

Mass weighted fall speed



Snowfall rate



Conclusions

- By using new m-D and A-D relationships, the model characteristics are represented more accurately and realistically.
- The size spectra predicted by the model are in good agreement with those observed from aircraft measurement during Lagrangian spiral descents in frontal clouds.
- Riming seems to play an important role in the evolution of snowfall rates.

Thank you!

Question?

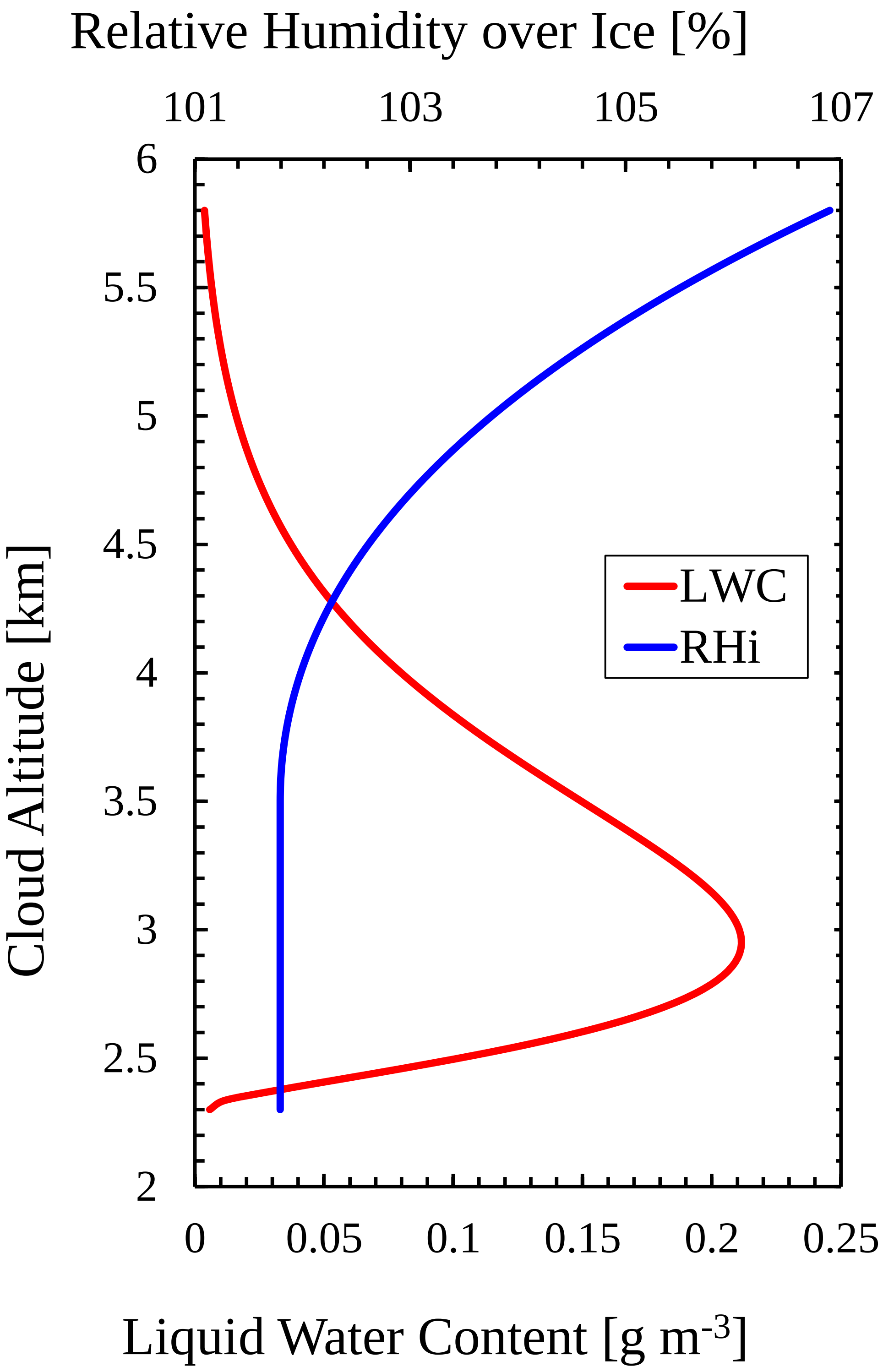
Photo by Ehsan Erfani

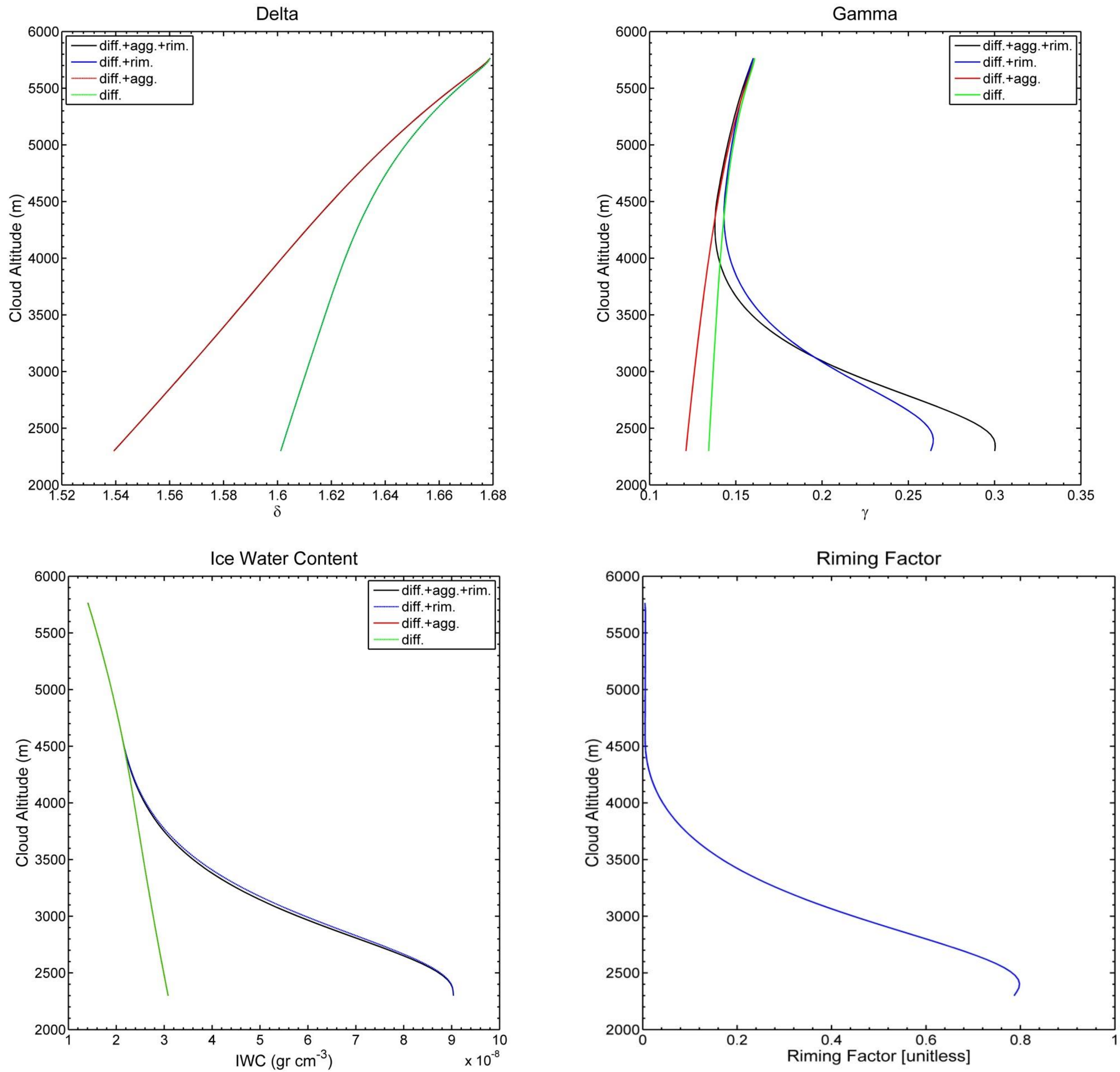
Contents

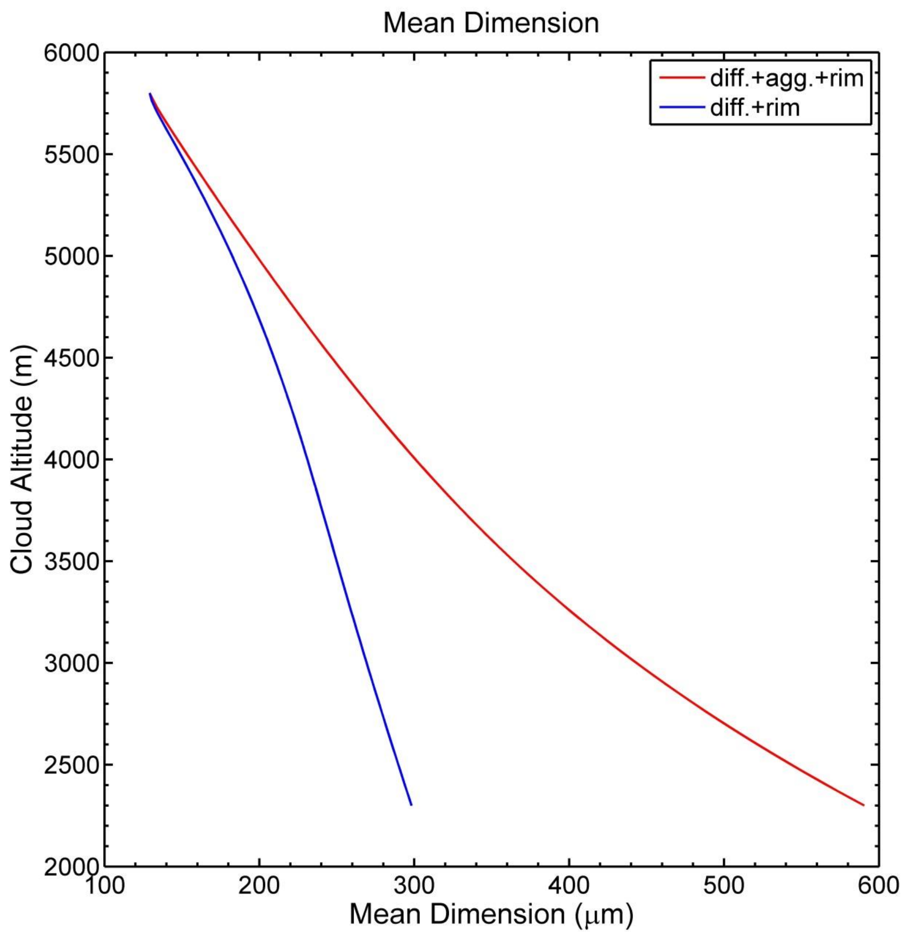
Approach for Treatment of Riming

$$\frac{\Delta IWC}{\Delta z} = \int_{150}^{D_{max}} A(D)N(D)\overline{E_d}Q dD$$

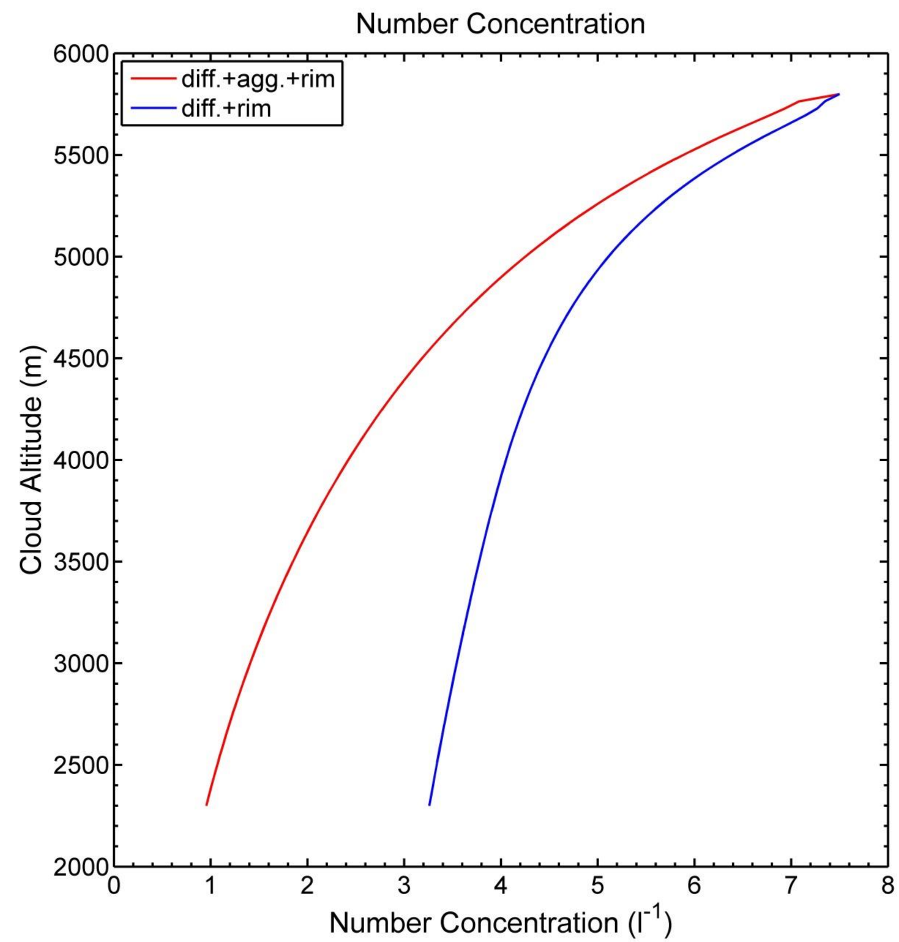
$$= \int_{150}^{D_{max}} \gamma D^{\delta} N_0 D^{\upsilon} e^{-\lambda D} dD \int_{0}^{d_{max}} E_d \frac{\pi}{6} \rho_w d^3 n_d(d) dd$$


Relative Humidity over Ice [%]
101
103
105
107
6
5.5
5
4.5
4
3.5
3
2.5
2
Cloud Altitude [km]
LWC
RHi
0
0.05
0.1
0.15
0.2
0.25
Liquid Water Content [g m-3]


Delta
Cloud Altitude (m)
δ
diff.+agg.+rim.
diff.+rim.
diff.+agg.
diff.
Gamma
Cloud Altitude (m)
γ
diff.+agg.+rim.
diff.+rim.
diff.+agg.
diff.
Ice Water Content
Cloud Altitude (m)
IWC (gr cm^{-3})
x 10^{-8}
diff.+agg.+rim.
diff.+rim.
diff.+agg.
diff.
Riming Factor
Cloud Altitude (m)
Riming Factor [unitless]

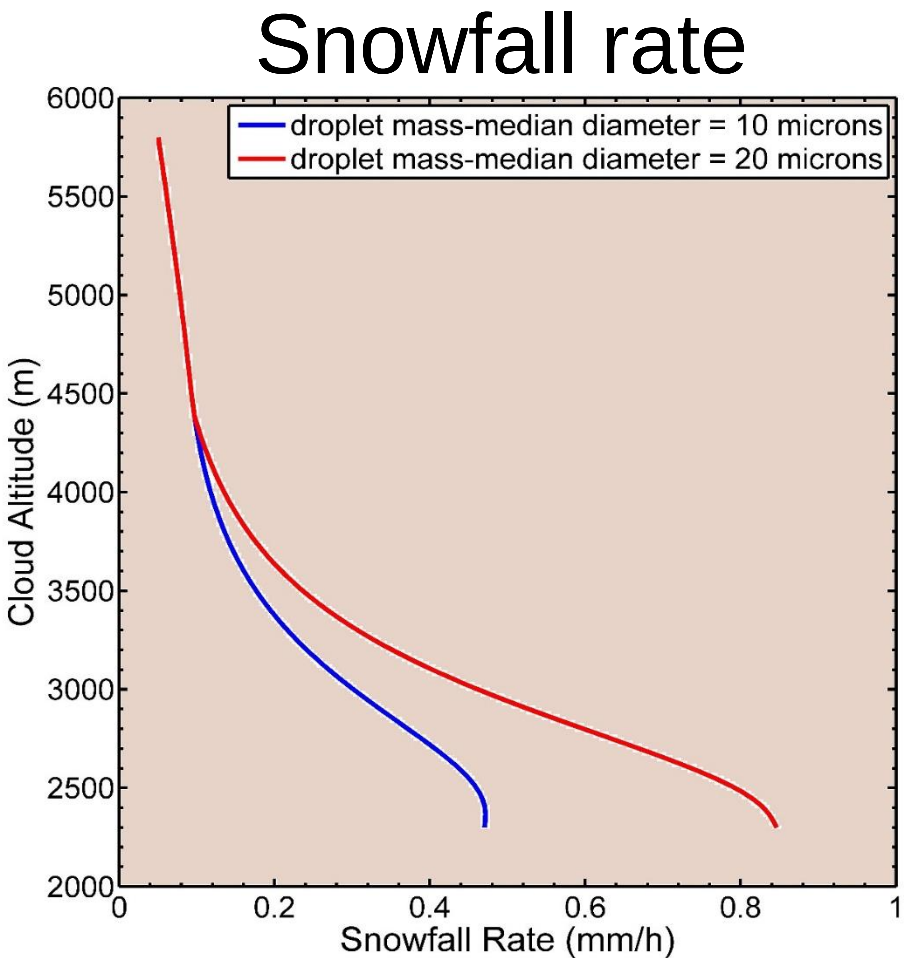


Mean Dimension
diff.+agg.+rim
diff.+rim
Cloud Altitude (m)
Mean Dimension (μm)
6000
5500
5000
4500
4000
3500
3000
2500
2000
100
200
300
400
500
600

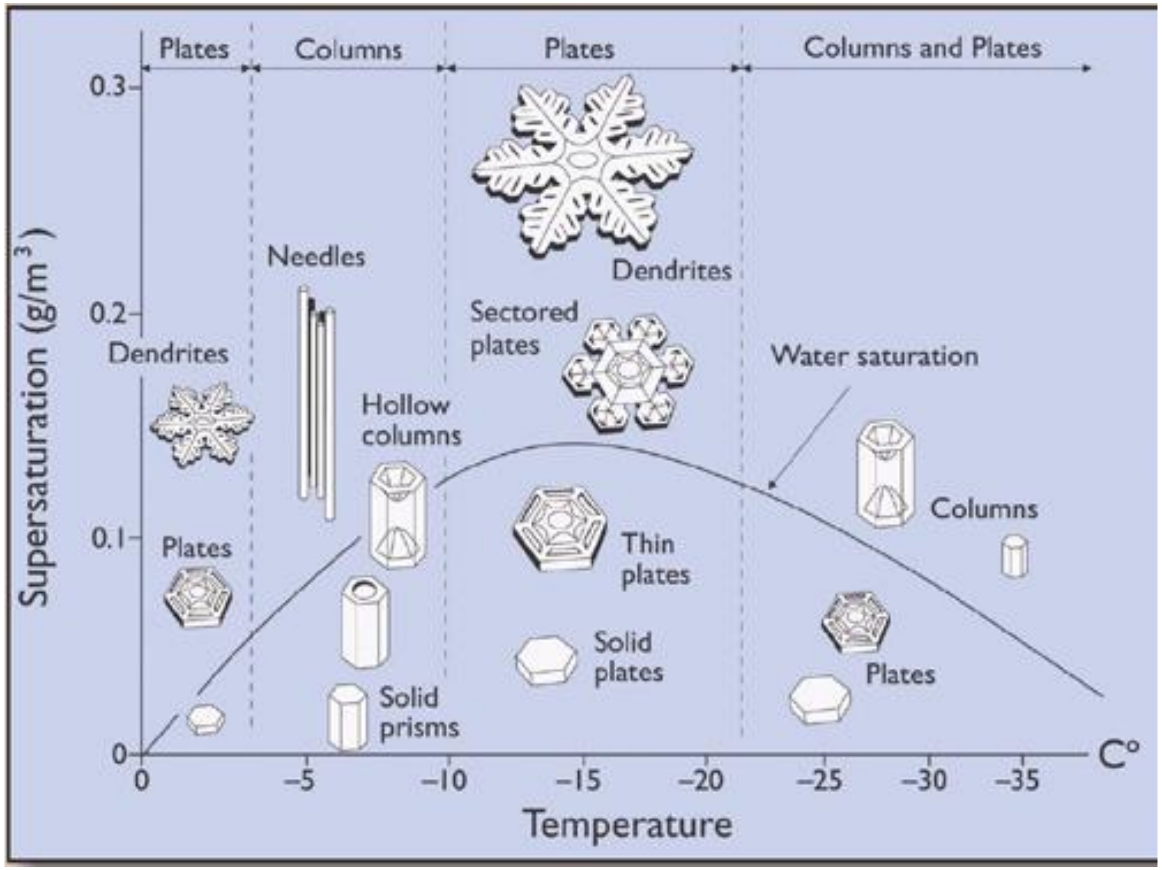


Number Concentration
diff.+agg.+rim
diff.+rim
Cloud Altitude (m)
Number Concentration (l-1)
6000
5500
5000
4500
4000
3500
3000
2500
2000
0
1
2
3
4
5
6
7
8

Aerosol-Cloud Interaction



- Increase in CCN, due to aerosols, modifies cloud droplet size distribution and decreases water droplet mass-median diameter.
- Smaller water droplets have smaller collision efficiency, so riming is less important and snowfall rate decreases.



Ken Libbrecht's (Voyager Press, 2006)
After Ukichiro Nakaya

References

- Mitchell, D. L., A. Huggins, and V. Grubisic, 2006: A new snow growth model with application to radar precipitation estimates. *Atmos. Res.*, **82,** 2–18
- Mitchell, D. L., Erfani, E., Mishra, M., 2014. Developing and Bounding Ice Particle Mass- and Area-dimension Expressions. Submitted to *J. Geophys. Res*.