Regime Dependence of Aerosol-Cloud Microphysical Interactions

Minghua Zhang[1,2]

Jingyi Chen[2], Yangang Liu[3,2], and Yiran Peng[4]

[1]Institute of Atmospheric Physics, Chinese Academy of Sciences

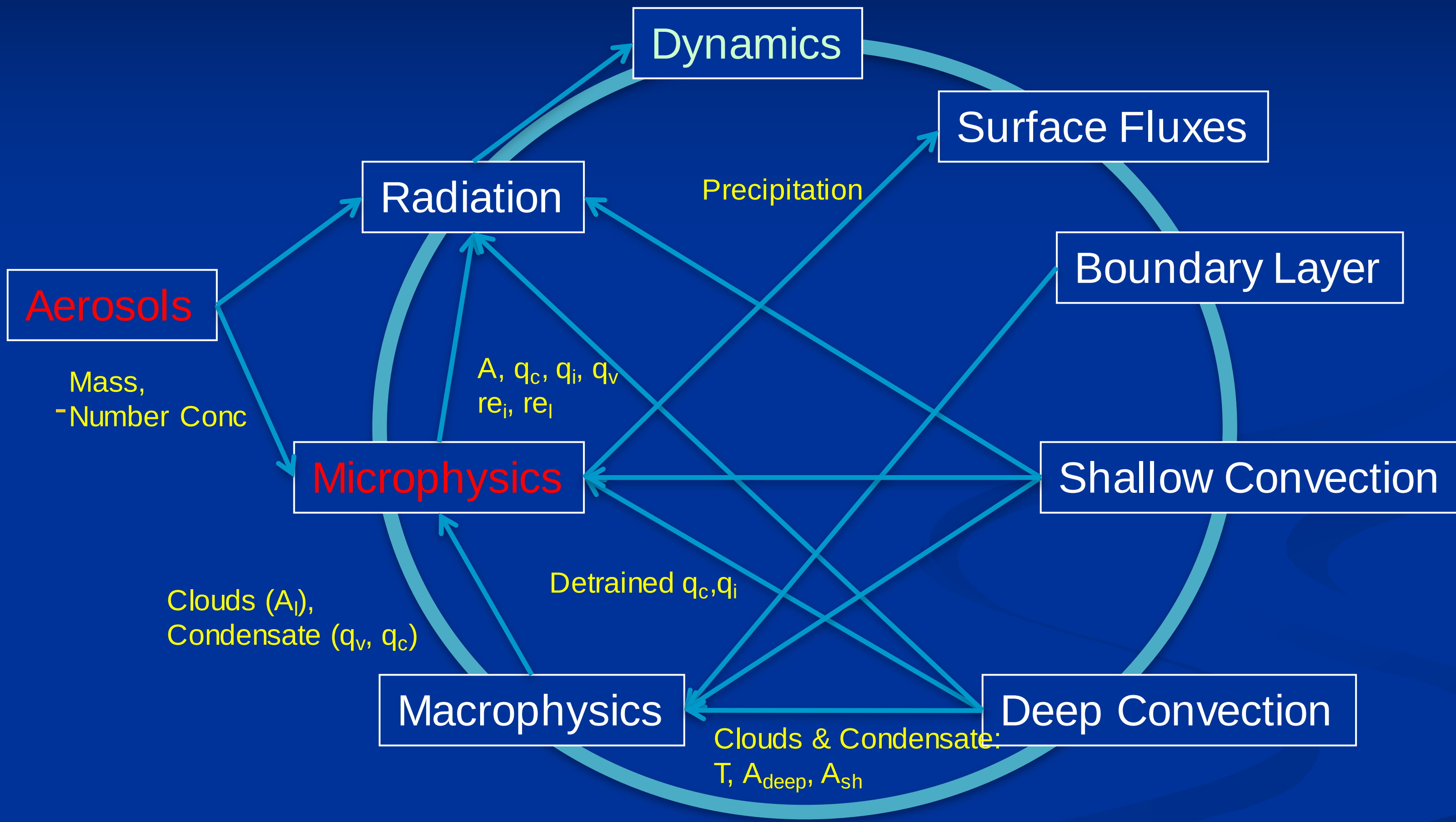
[2]Stony Brook University, Stony Brook, New York, USA

[3]Brookhaven National Laboratory, Upton, New York, USA

[4]Tsinghua University, China

1. Introduction
2. Model
3. Results about relative dispersion
4. Summary

Aerosol Coupling with Radiation and Clouds in a Climate Model (CAM5)



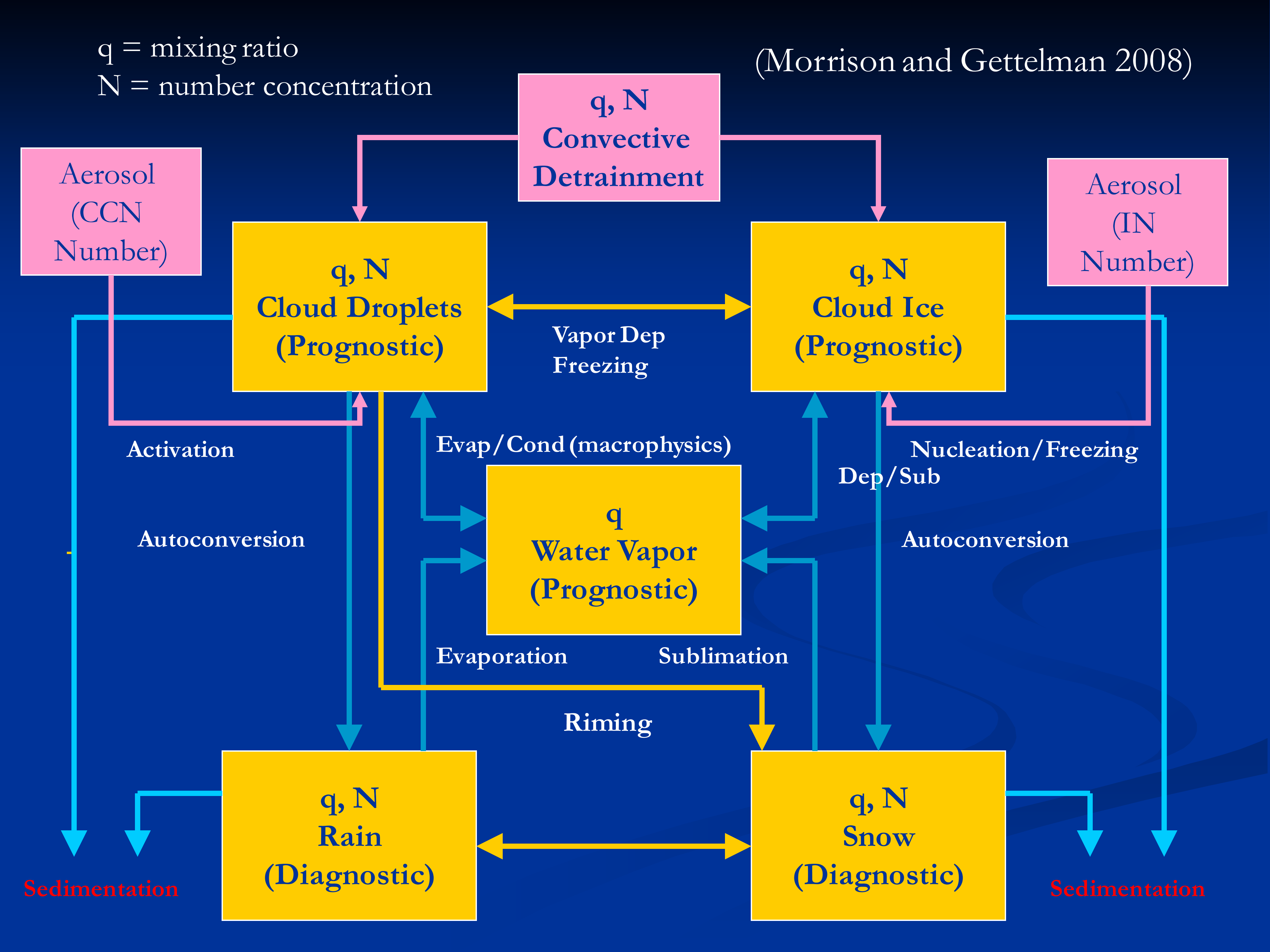
A = cloud fraction, $q=H_2O$, re=effective radius (size), T=temperature
(i)ce, (l)iquid, (v)apor

(Adapted from Hugh Morrison)

Impact of aerosols on cloud microphysics:

- Number concentration, mean radius
- Size distribution

Relative dispersion: $\varepsilon_d = \frac{\sigma}{r}$


q = mixing ratio
N = number concentration
(Morrison and Gettelman 2008)
q, N
Convective
Detrainment
Aerosol
(CCN
Number)
Aerosol
(IN
Number)
q, N
Cloud Droplets
(Prognostic)
q, N
Cloud Ice
(Prognostic)
Vapor Dep
Freezing
Activation
Evap/Cond (macrophysics)
Nucleation/Freezing
Dep/Sub
q
Water Vapor
(Prognostic)
Autoconversion
Autoconversion
Evaporation
Sublimation
Riming
q, N
Rain
(Diagnostic)
q, N
Snow
(Diagnostic)
Sedimentation
Sedimentation

Cloud and precipitation particle size distributions are represented by gamma functions:

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

- For cloud ice, snow, and rain, $\mu = 0$.

- For cloud droplets, μ varies from 2 to 15 as a function of droplet concentration following observations of Martin et al. (1994).

$$\mu = 1/\eta^2 - 1$$

$$\eta = 0.000\,571\,4 N_c'' + 0.2714$$

- Parameterization of μ can be important for prediction of effective radius and hence aerosol indirect effects (e.g., Rotstayn and Liu 2003, 2009)

(From Hugh Morrison)

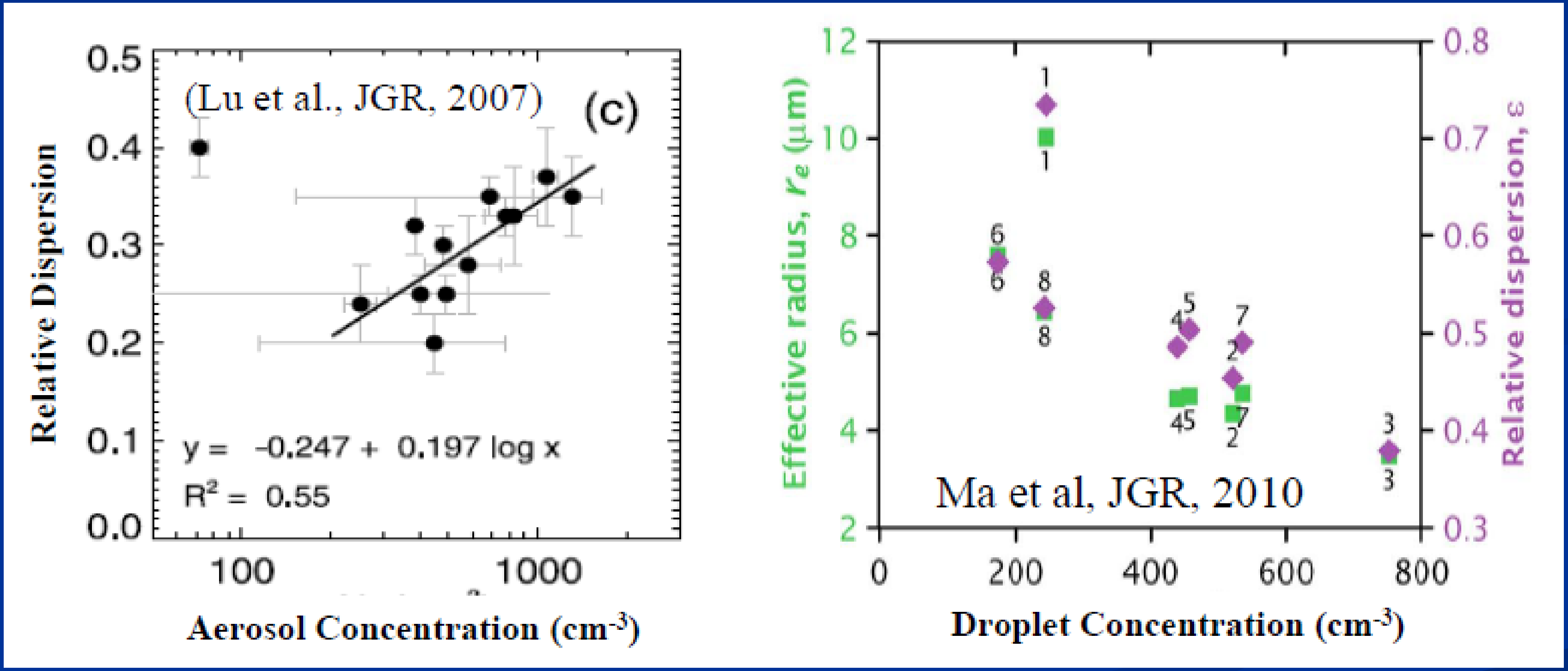
Impact of cloud spectral dispersion on radiation:

$$\tau = \frac{3}{2\rho_{\mathrm{w}}} \frac{W}{r_{\mathrm{e}}}.$$

$$r_e = \beta \cdot \bar{r} = \beta \cdot \left(\frac{LWC}{N} \cdot \frac{3}{4\pi\rho_w}\right)^{1/3}$$

$$\beta = \frac{\left(1 + 2{\varepsilon_d}^2\right)^{2/3}}{\left(1 + {\varepsilon_d}^2\right)^{1/3}}$$

Variation of dispersion with aerosol and cloud droplet concentration from observations



A modeling study of the aerosol impact on the relative dispersion of cloud droplet size distribution

CCN: Lognormal distribution

$$n(a_{ap}) = \frac{N_{ap}}{\sqrt{2\pi}\ln\sigma}\exp\left[-\frac{\ln^2(a_{ap}/a_m)}{2\ln^2\sigma}\right]$$

Geometric mean radius of 0.06 μm, geometric standard deviation of 1.5, sulfate ammonium with hygroscopicity (κ) 0.61 (Reutter et al., 2009).

A parcel model (Chen et al. 2016) with 200 size bins distributed logarithmically between 0.01 μm and 1 μm

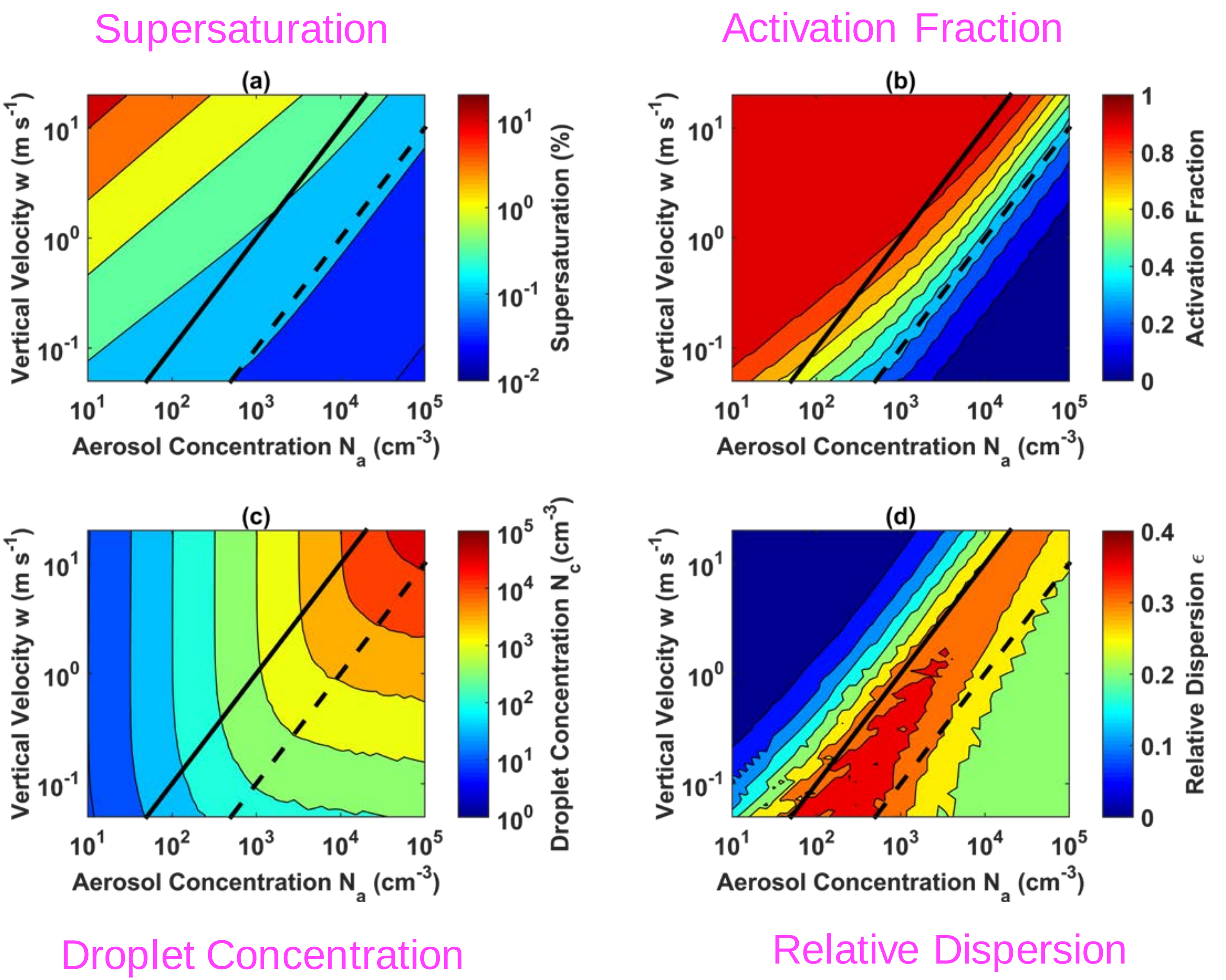
$$ln\frac{r_{bi}}{r_{min}} = \frac{i-1}{N_{bin}} * ln\frac{r_{max}}{r_{min}}.$$

$$\frac{\mathrm{dm_{p,i}}}{\mathrm{dt}} = 4\pi \mathrm{r_{d,i}} G \cdot (S - S_{k,i}),$$

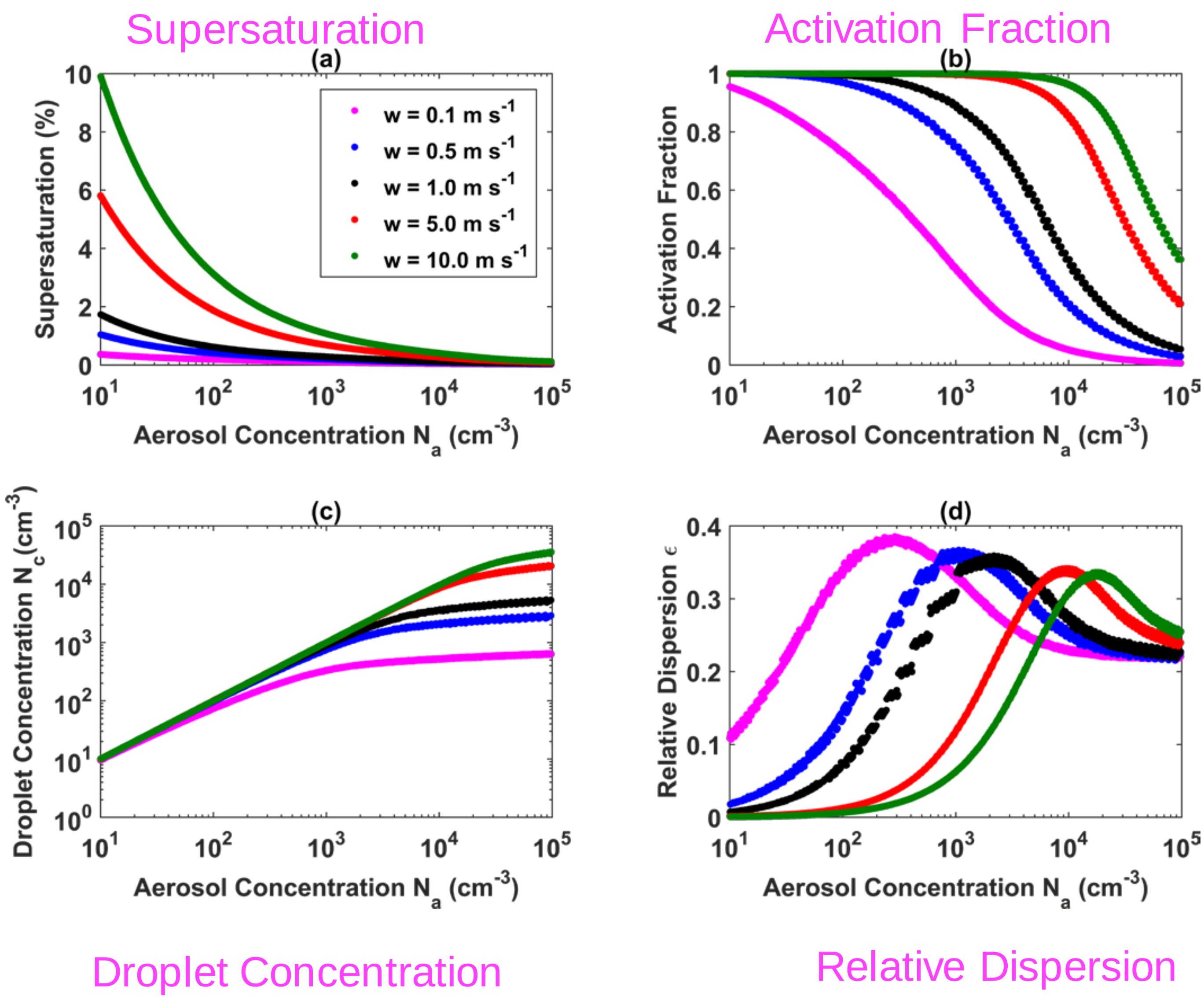
$$\frac{dq_v}{dt} = -\frac{1}{\rho_d}\sum_i\left(\frac{dm_{p,i}}{dt} \cdot N_i\right),$$

$$\frac{\mathrm{dT}}{\mathrm{dt}} = -\frac{\mathrm{g \cdot w}}{\mathrm{c_p}} + \frac{\mathrm{l_v}}{\mathrm{c_p}} \cdot \frac{\mathrm{dq_v}}{\mathrm{dt}},$$

The model is integrated at time steps of 0.01s to 1s for a wide range of aerosol number concentration and updraft velocity.

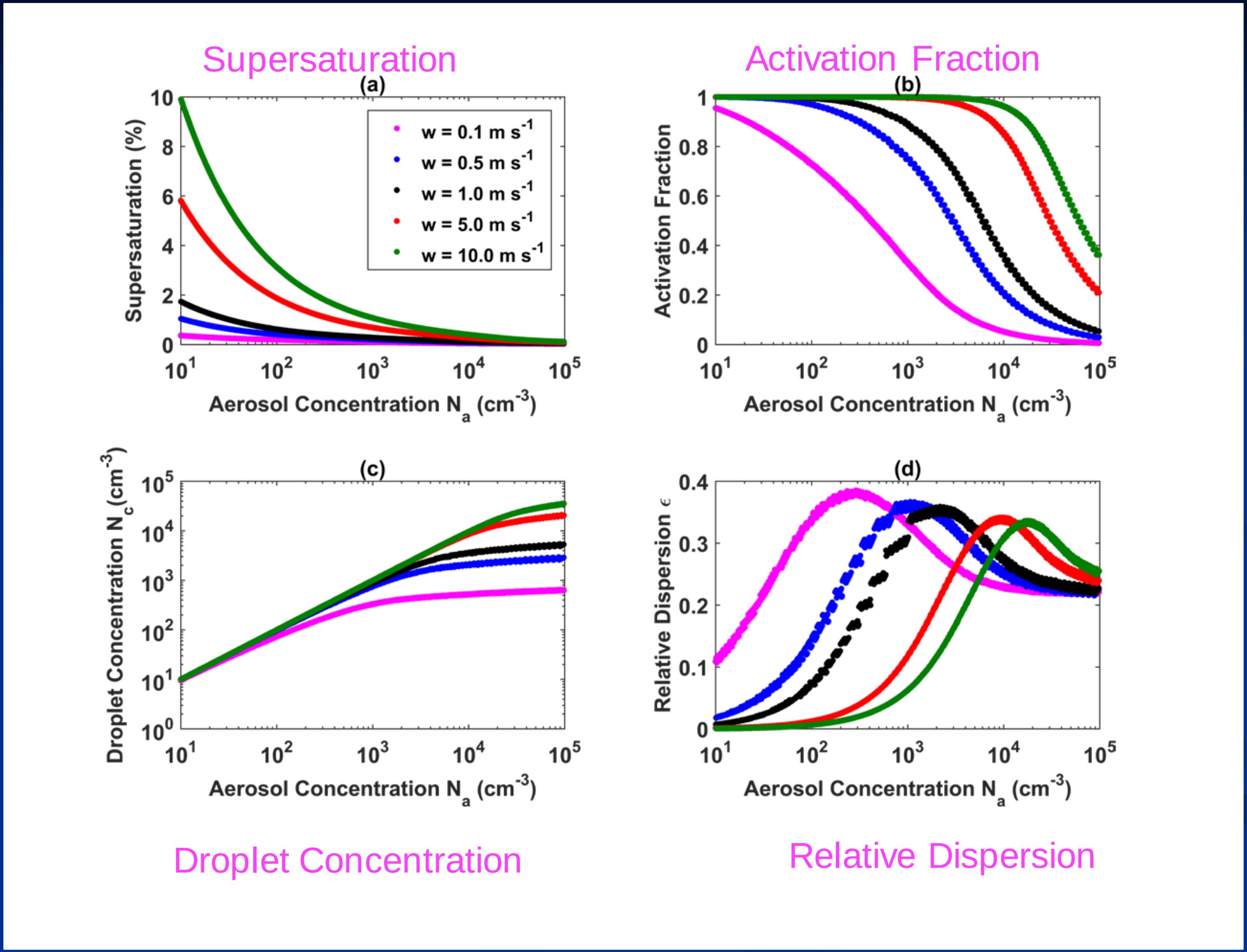


Reutter et al. [2009]; *Chen et al.* [2016]


Supersaturation
Activation Fraction
(a)
(b)
w = 0.1 m s-1
w = 0.5 m s-1
w = 1.0 m s-1
w = 5.0 m s-1
w = 10.0 m s-1
Supersaturation (%)
Activation Fraction
Aerosol Concentration Na (cm-3)
(c)
(d)
Droplet Concentration Nc (cm-3)
Relative Dispersion ε
Droplet Concentration
Relative Dispersion

$$\frac{dr}{dt} = \frac{1}{r}\frac{S - S_k}{G},$$

$$G = \left[\frac{RT\rho_w}{M_w D_v' e_s(T)} + \frac{l_v \rho_w}{M_w k_T' T}\left(\frac{l_v}{RT} - 1\right)(1 + S_k)\right]^{-1},$$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(a)
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Droplet Concentration Nc (cm-3)
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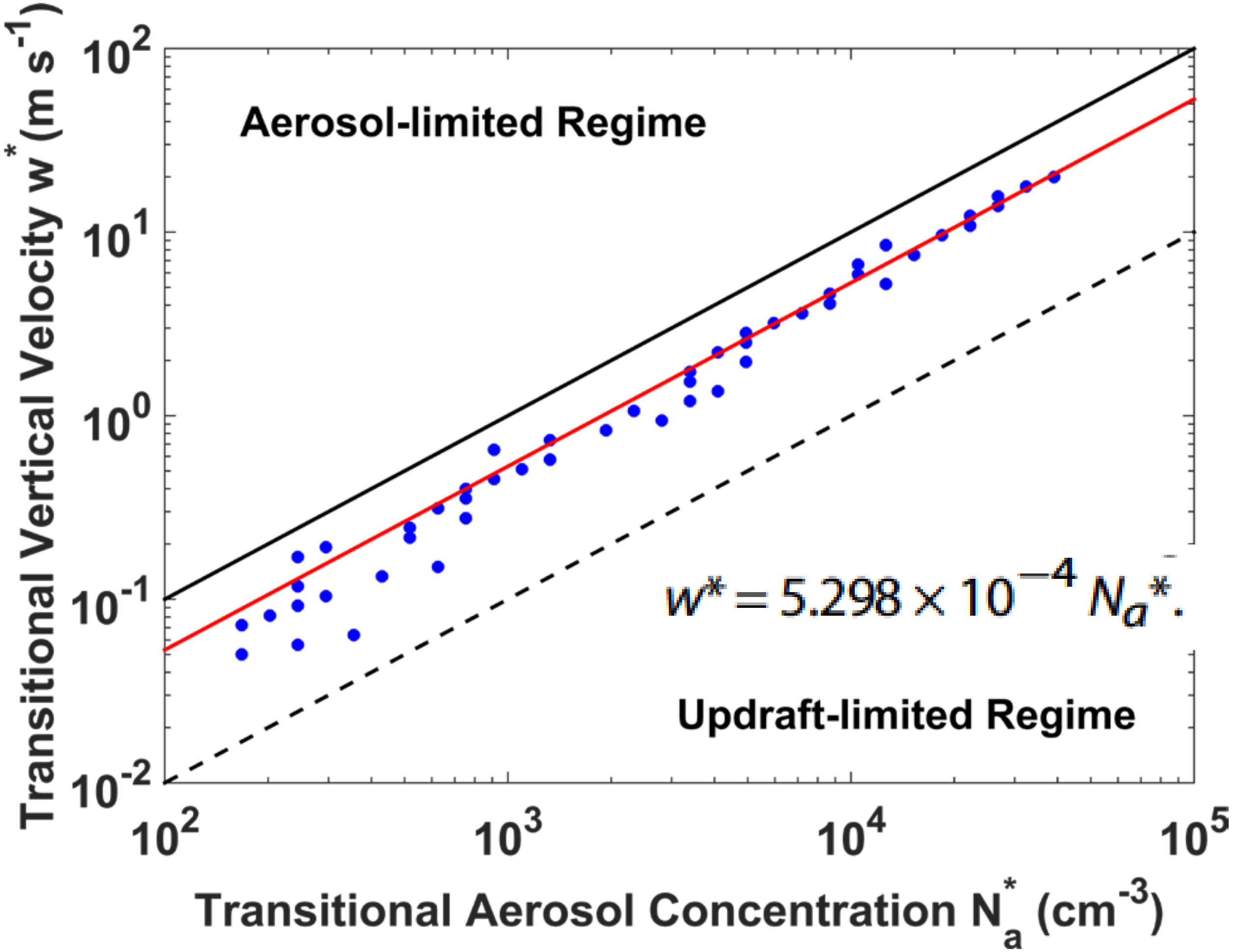
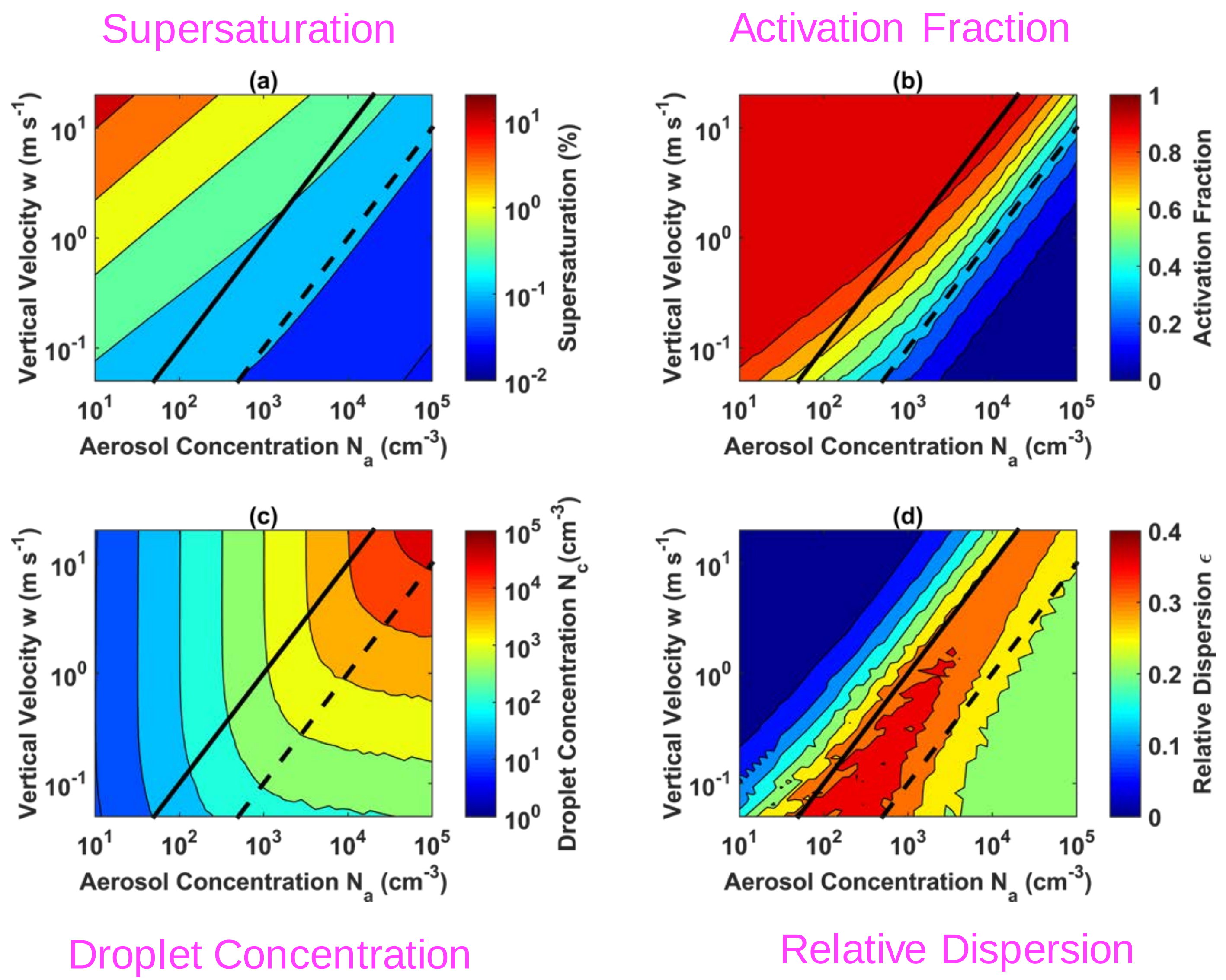
Droplet Concentration
Relative Dispersion



Aerosol-limited Regime
$w^* = 5.298 \times 10^{-4} N_a^*$.
Updraft-limited Regime
Transitional Vertical Velocity w^* (m s^{-1})
Transitional Aerosol Concentration N_a^* (cm^{-3})
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}



Chen et al. [2016]

Summary

1. Given updraft velocity, relative dispersion of cloud droplets from nucleation and condensation increases with increasing aerosol concentration in the aerosol-limited regime, peaks in the transitional regime, and decreases with further increasing aerosol concentration in the updraft-limited regime.

2. The contrasting behaviors of dispersion between the aerosol-limited and updraft-regimes can reconcile previous contradictory observational results on the dependence of cloud dispersion on aerosols.