南京信息工程大学

Observational, Numerical and Theoretical Analysis of Entrainment/Detrainment Processes in Low-Level Clouds

Chunsong Lu[1], Xiaoqi Xu[1], Yangang Liu[2],

Lei Zhu[1], Shi Luo[1], Sinan Gao[1]

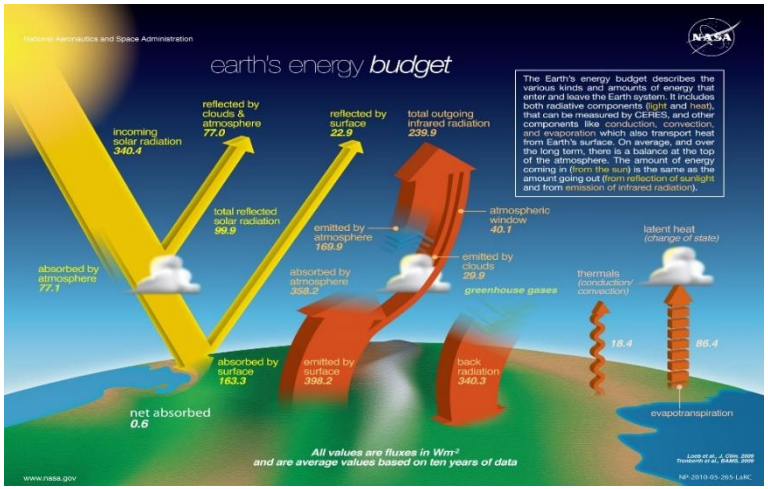
1. Nanjing University of Information Science and Technology, China

2. Brookhaven National Laboratory, US

2021.9

Importance of Clouds

https://giphy.com/search/cloud



https://en.wikipedia.org/wiki/Earth%27s_energy_budget

Clouds plays important roles in the earth-atmosphere system.

Entrainment/Detrainment

Cloud Lifetime
Small et al., 2009

Typhoon
Lim et al., 2007

ENSO
Kim et al., 2011

Radiative Transfer
Grabowski et al., 2006

MJO
Klingaman, 2013

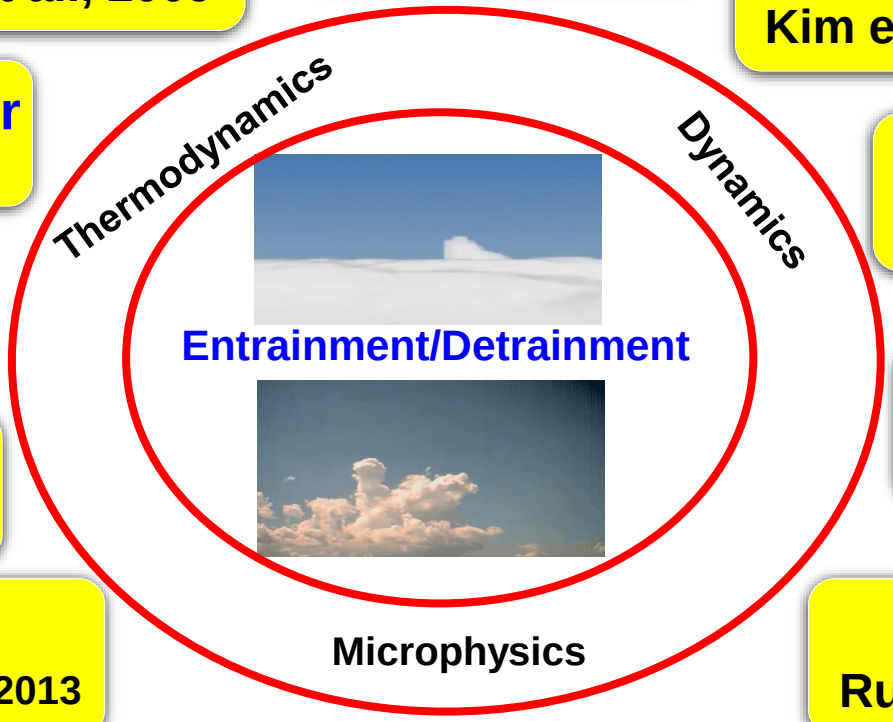
Precipitation
Wang et al., 2007

Kelvin Wave
Ruiz et al., 2013

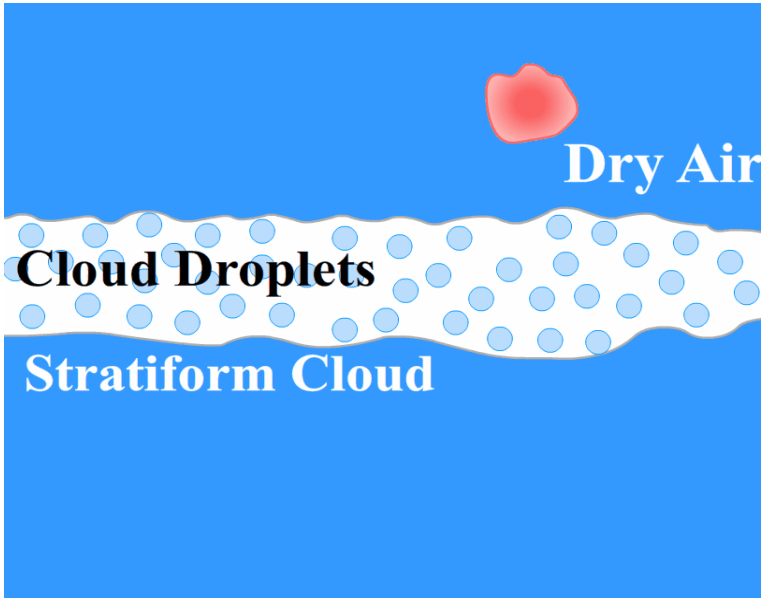
Aerosol-Cloud
Wang et al., 2007

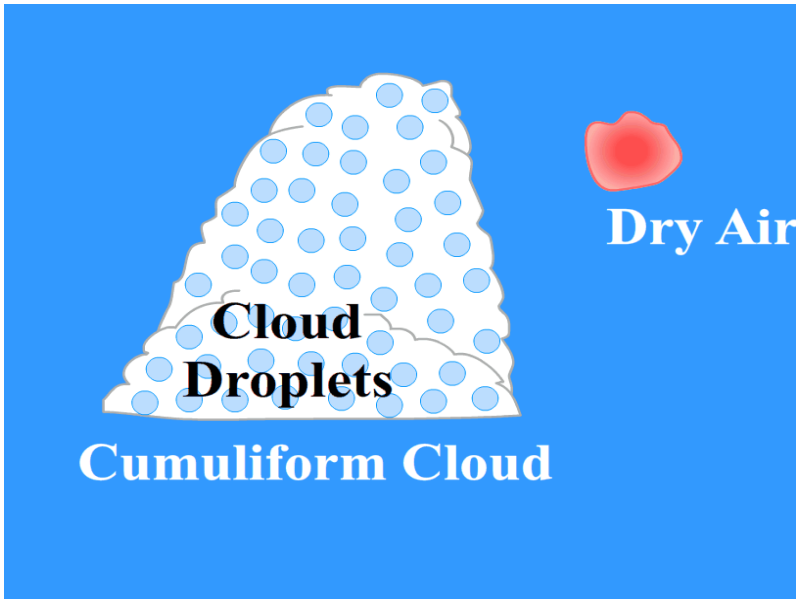
Lightning
Formenton et al., 2013

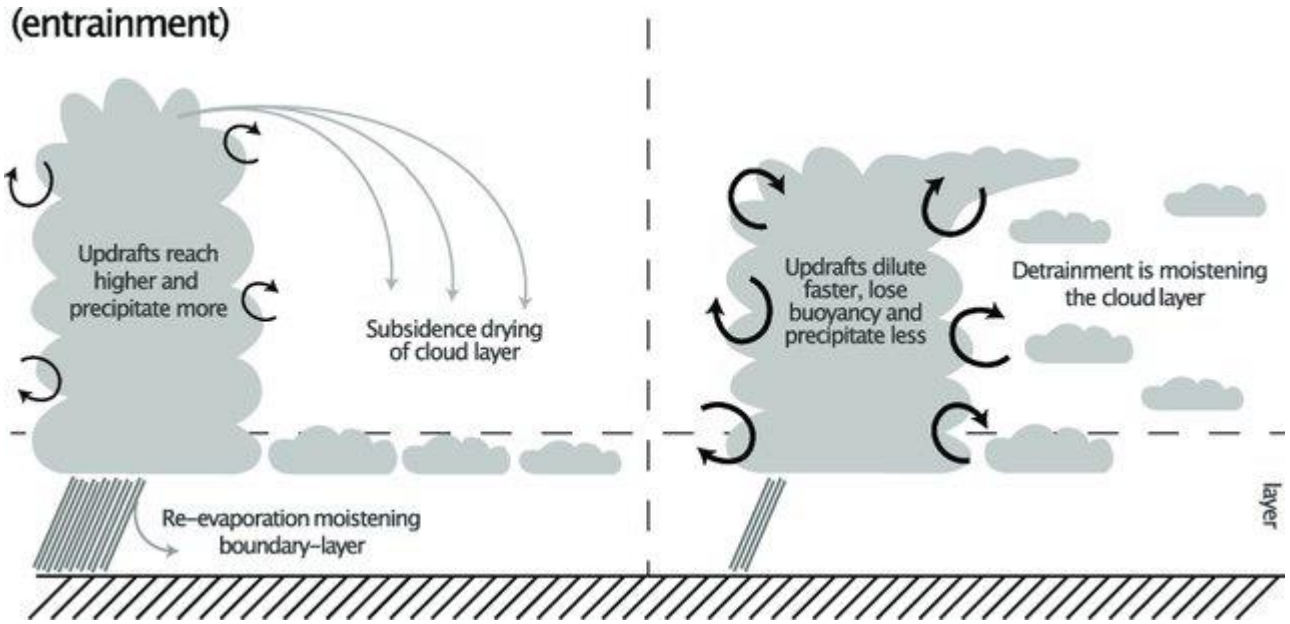
Monsoon
Ruiz et al., 2012



Entrainment/detrainment affects atmospheric phenomena of different scales.







Mauritsen and Roeckner, JAMES, 2020

Scientific Questions

Question One: Microphysics

How does cloud microphysics respond to entrained dry air?

Question Two: Dynamics

How fast is dry air entrained into cloud?

How fast is cloud detrained into environment?

Scientific Questions

Question One: Microphysics

How does cloud microphysics respond to entrained dry air?

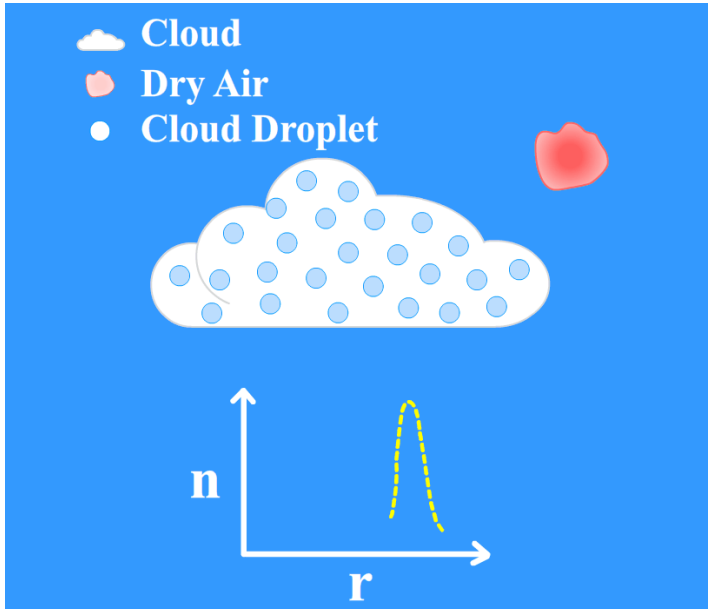
Question Two: Dynamics

How fast is dry air entrained into cloud?

How fast is cloud detrained into environment?

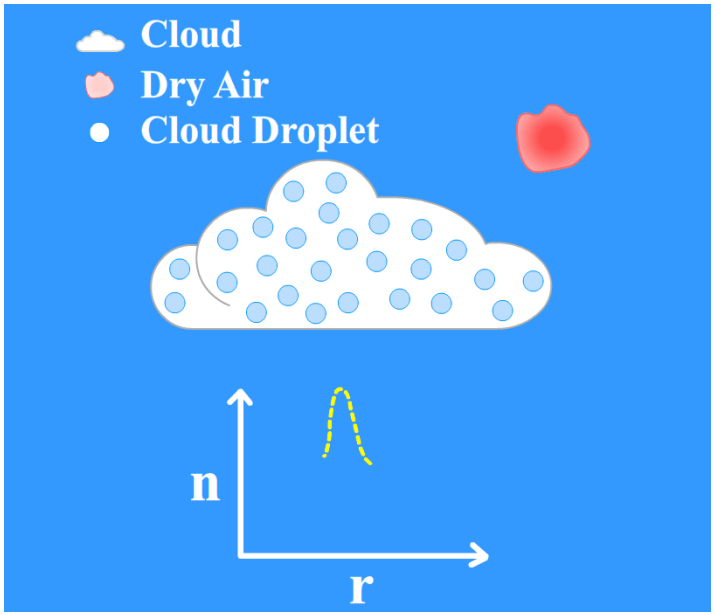
Entrainment-Mixing Mechanisms

Strong Turbulence



Homogeneous

Weak Turbulence

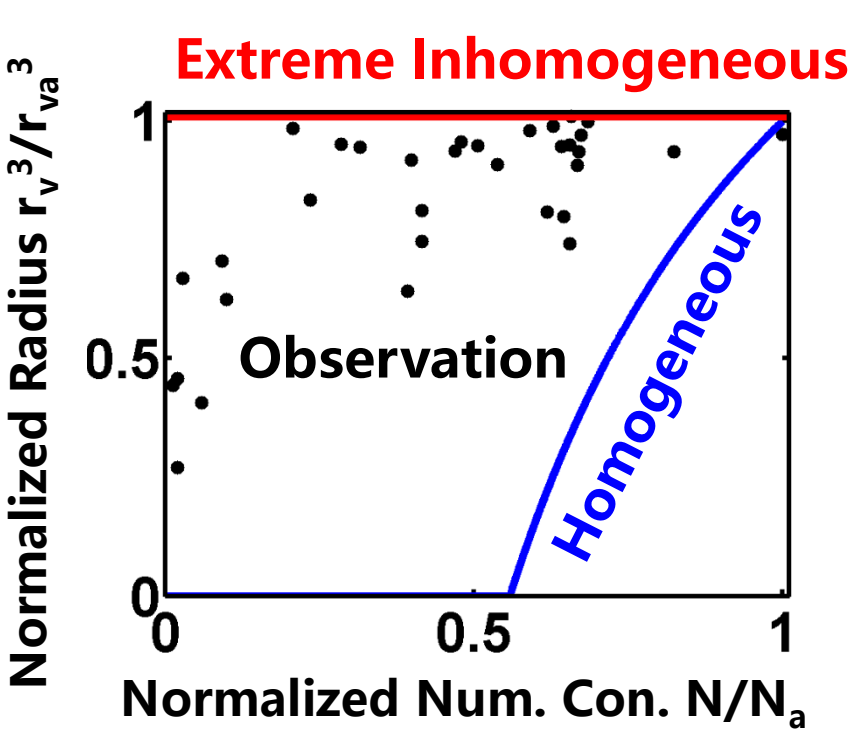


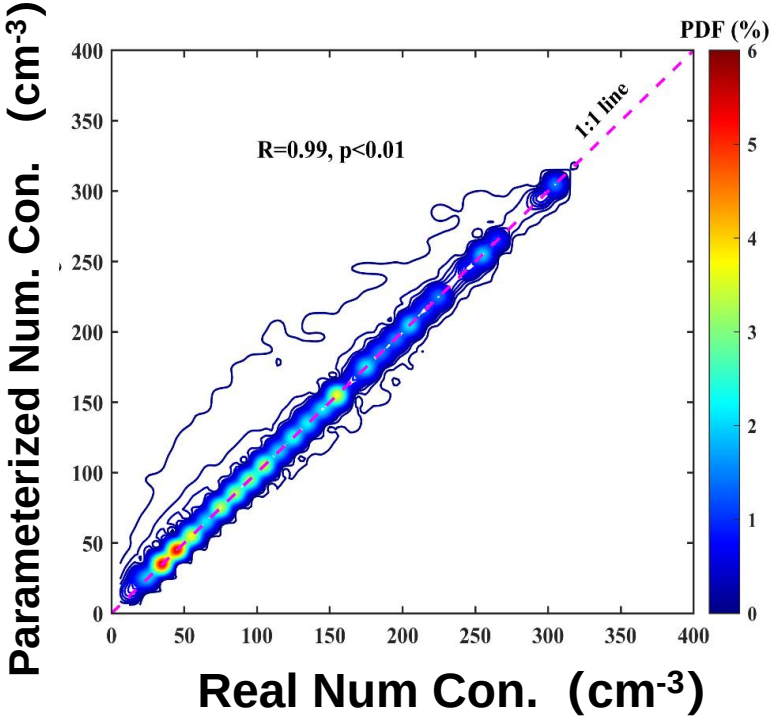
Extreme Inhomogeneous

Different mechanisms affect number concentration and radius.

Baker et al., 1984

Quantitative Description of Entrainment-Mixing





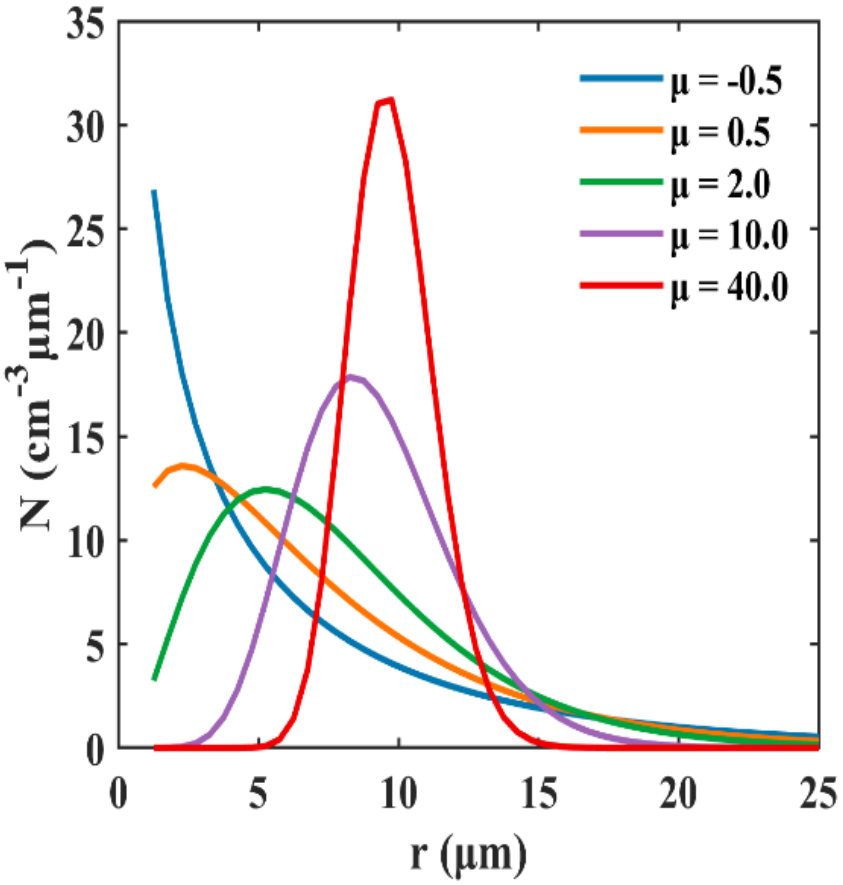
- **Quantitative description of entrainment-mixing mechanisms**

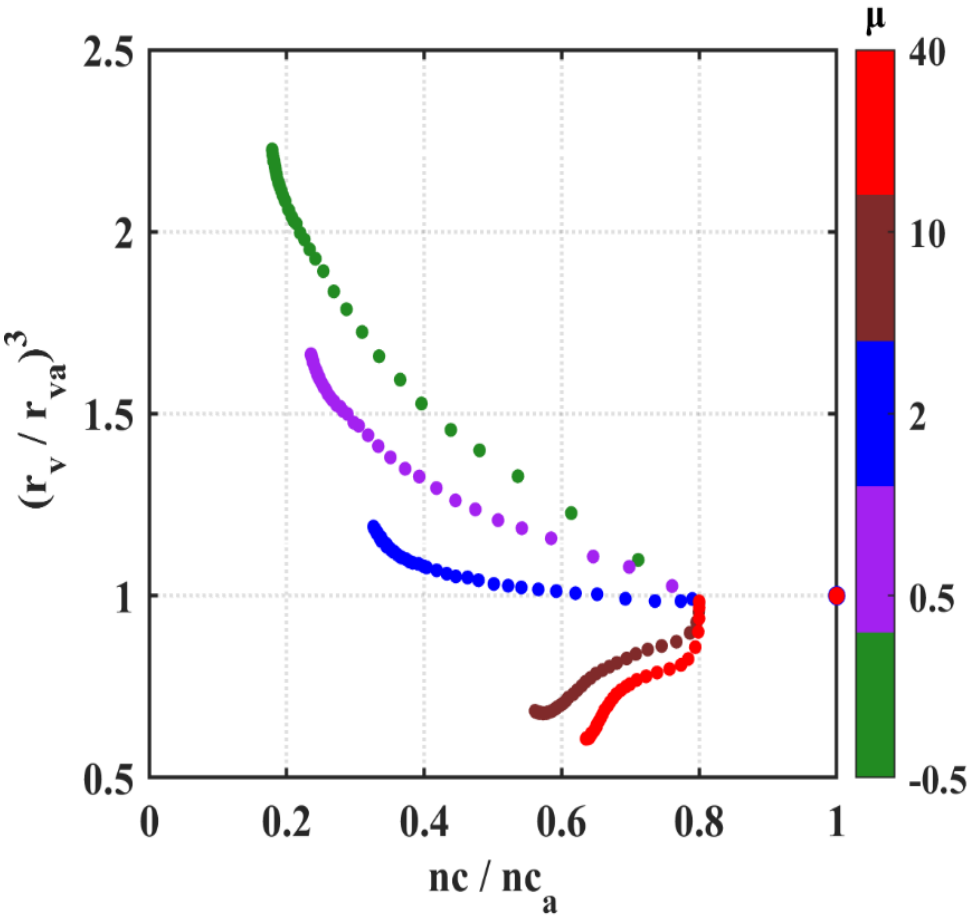
Lu et al., JGR, 2011, 2014, 2018, 2020;
Science Bulletin, 2012, 2013
Gao et al., GRL, 2020

- **Parameterization of entrainment-mixing mechanisms**

Lu et al., JGR, 2013; Science Bulletin, 2015
Luo et al., JGR, 2020
Gao et al., ACP, 2021

Effects of Different Cloud Droplet Spectra on Homogeneous Mixing Degree

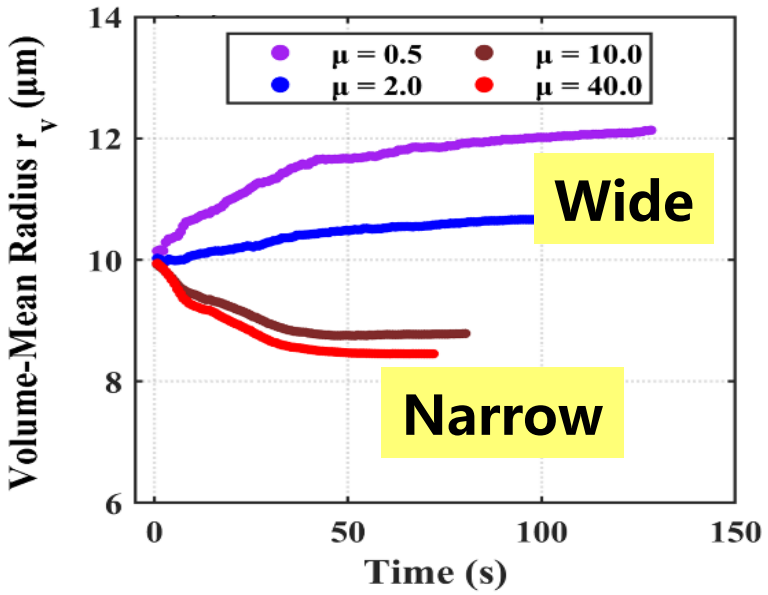


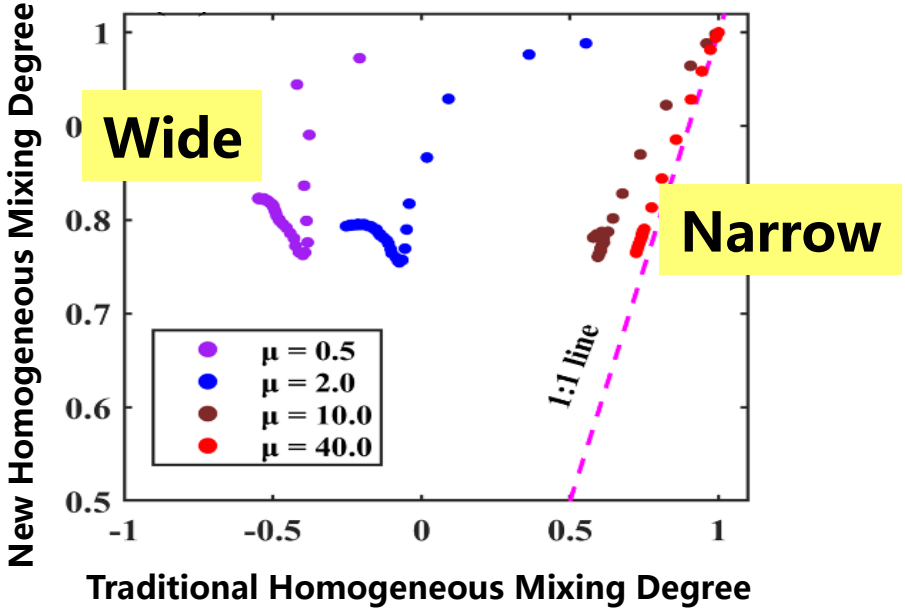


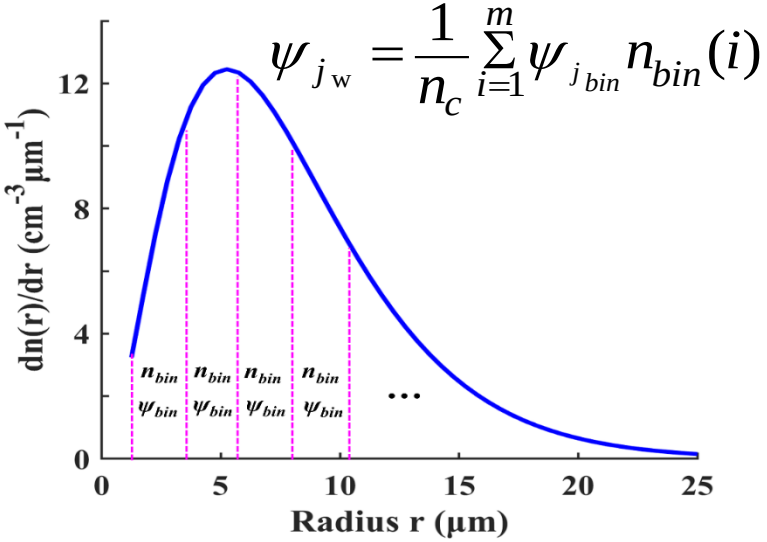
$$n(r) = N_0 r^{\mu} e^{-\lambda r}$$

Volume-mean radius and number concentration are unexpectedly negatively correlated.

Effects of Different Cloud Droplet Spectra on Homogeneous Mixing Degree







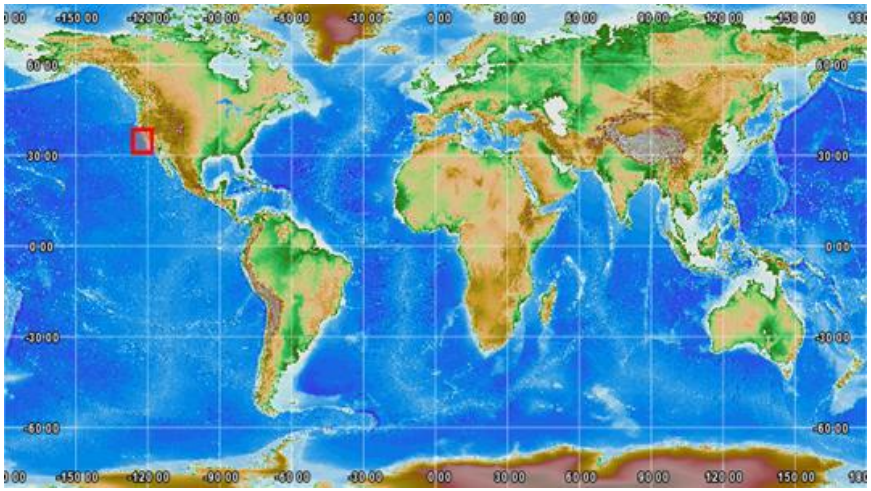
When initial cloud droplet spectra are wide, volume-mean radius increases during entrainment-mixing and traditional homogeneous mixing degree is negative.

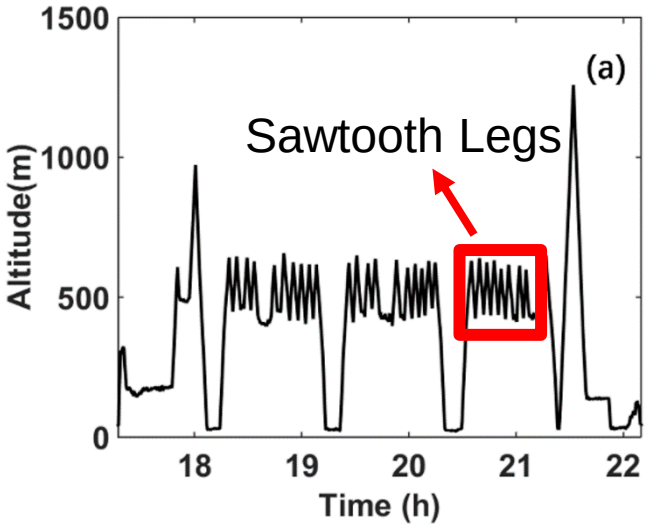
A new homogeneous mixing degree is defined, which works for both narrow and wide cloud spectra.

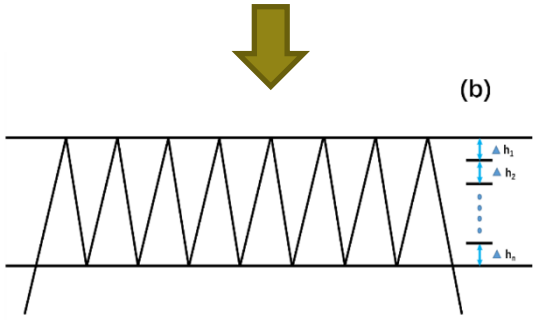
Luo, Lu, et al., JGR, 2021

Vertical Profile of Entrainment-Mixing Mechanisms

Project: Physics of Stratocumulus Top (POST)
Region: West coast of California
Type: Stratocumulus
Time: July to August of 2008



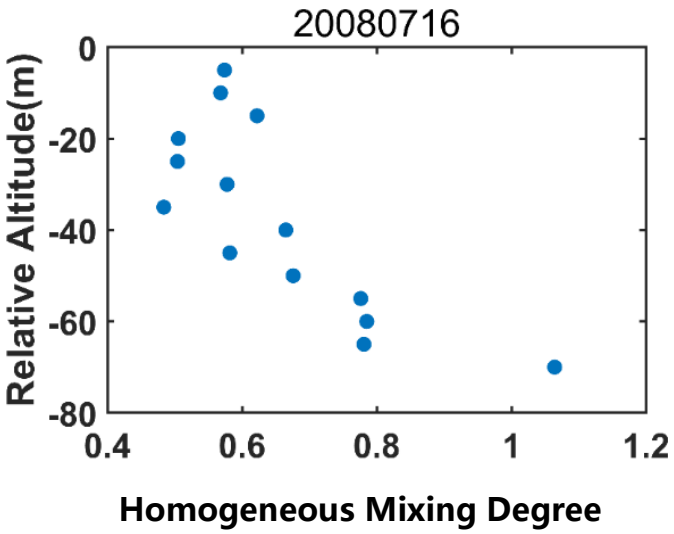


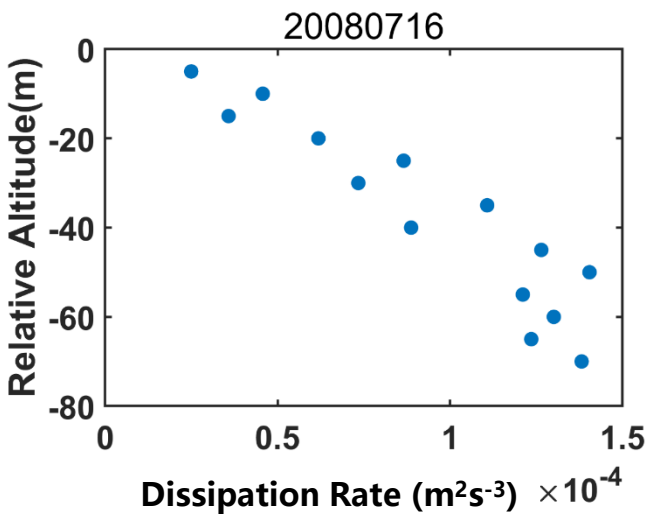


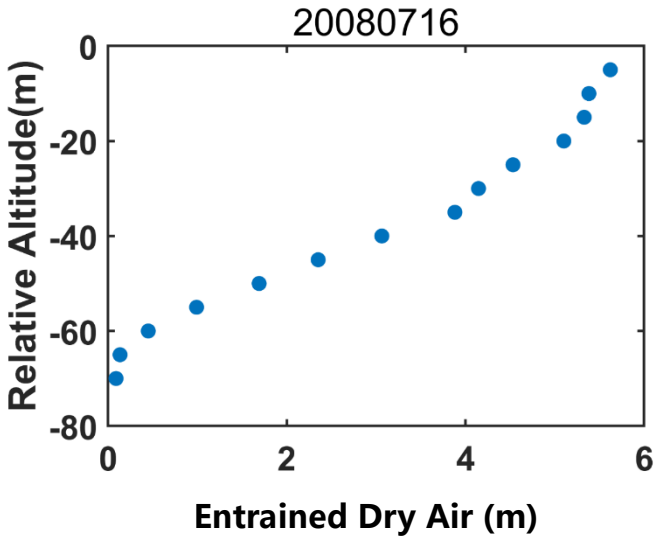
Δh=5m

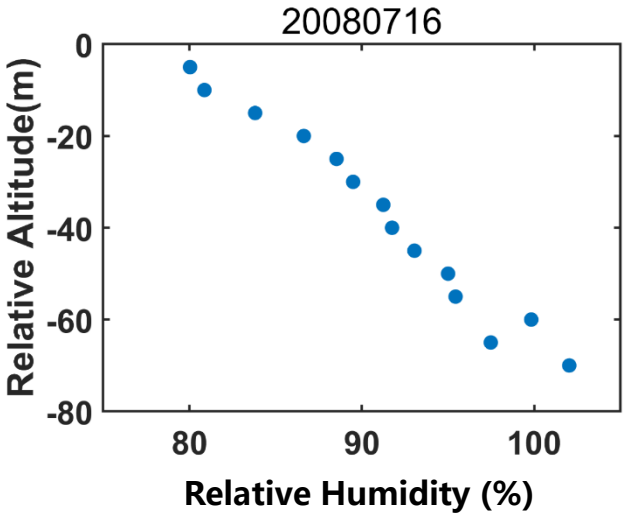
Gao, Lu, et al., ACP, 2021

Vertical Profile of Entrainment-Mixing Mechanisms









More inhomogeneous mixing near cloud top, because of smaller dissipation rate, larger entrained dry air and smaller relative humidity.

Gao, Lu, et al., ACP, 2021

Scientific Questions

Question One: Microphysics

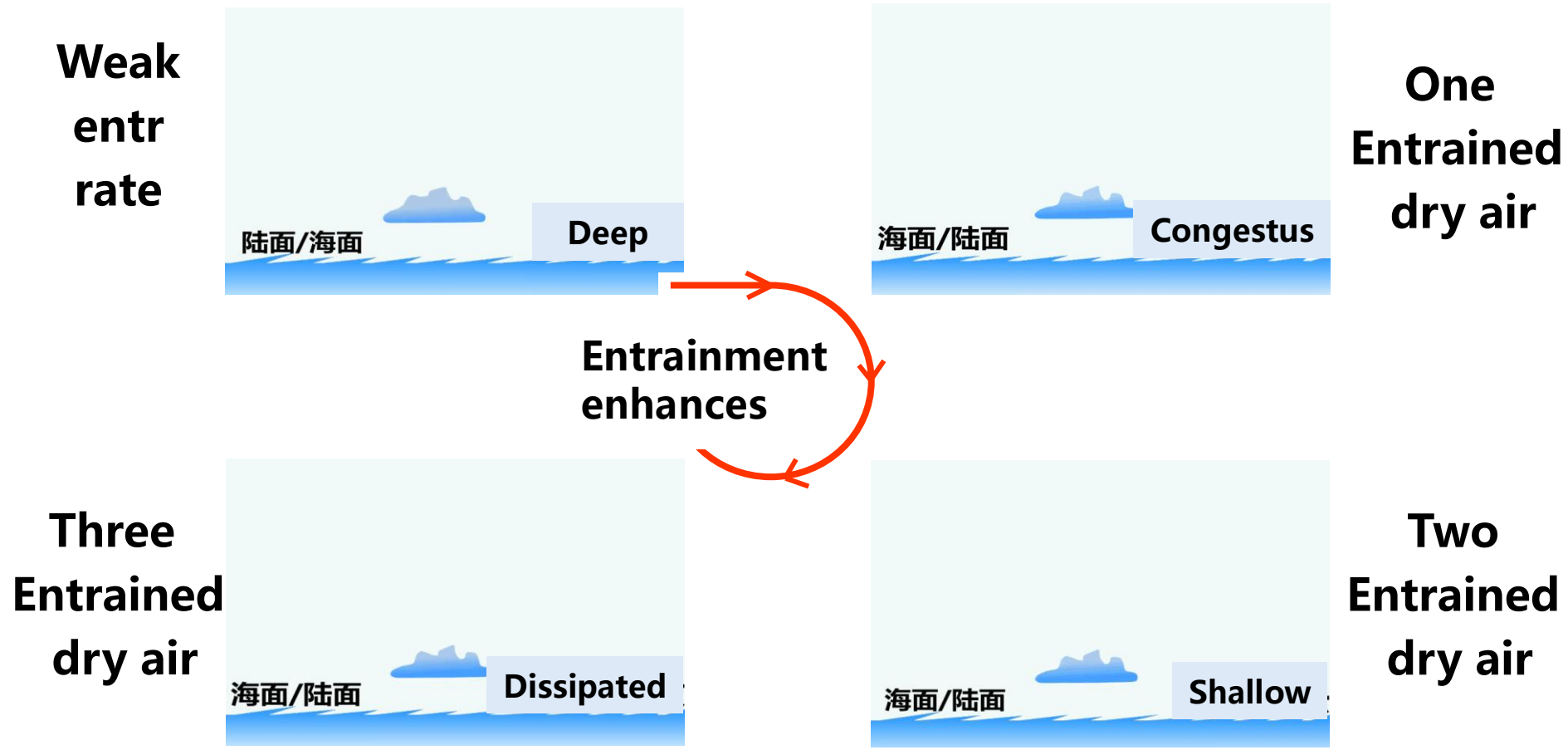
How does cloud microphysics respond to entrained dry air?

Question Two: Dynamics

How fast is dry air entrained into cloud?

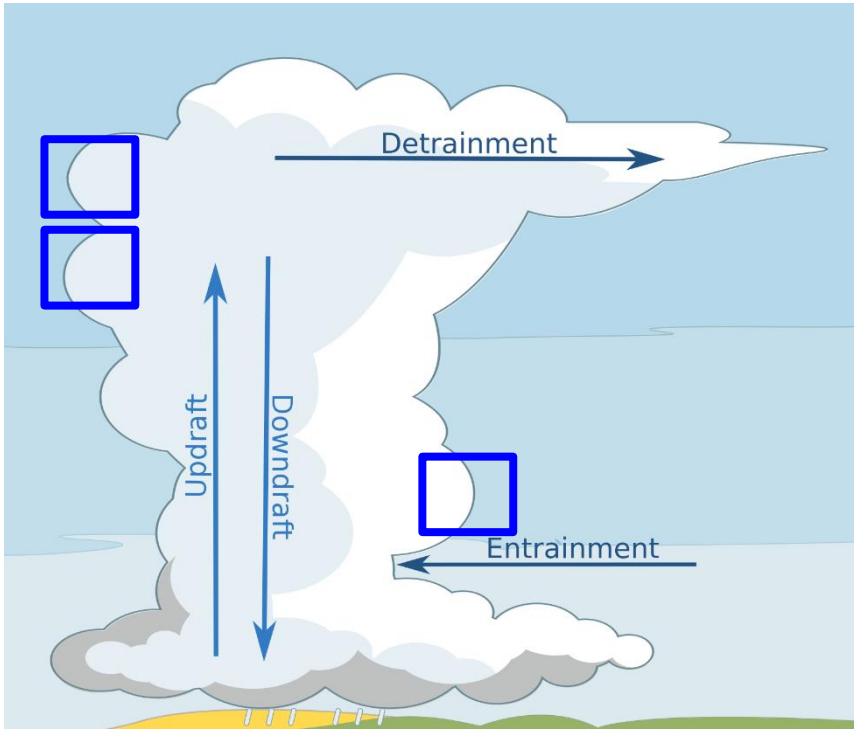
How fast is cloud detrained into environment?

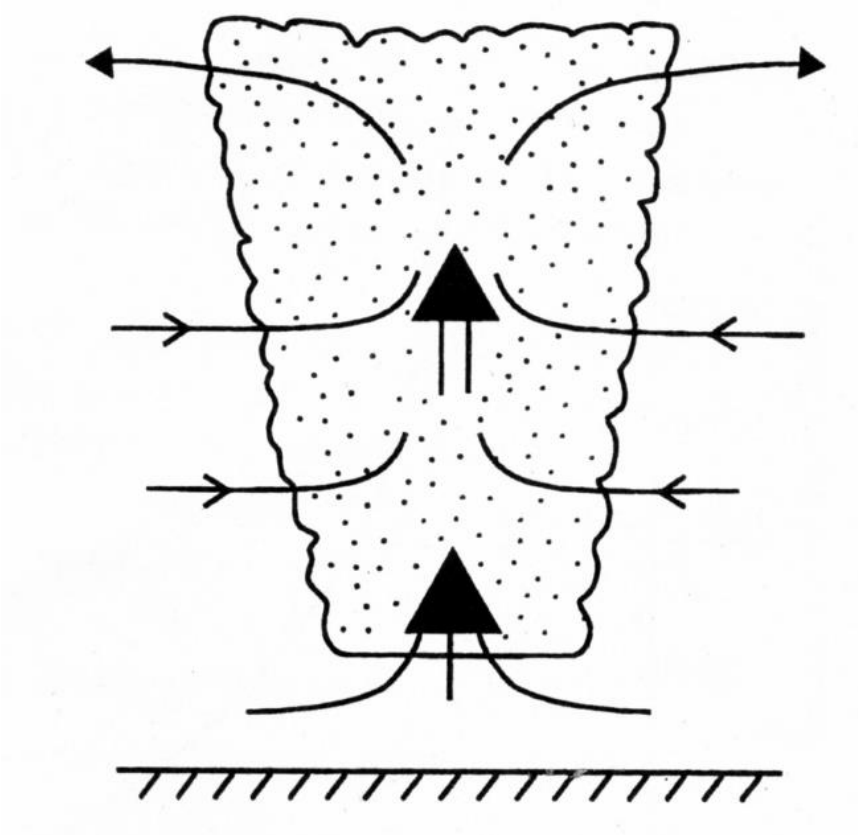
Importance of Entrainment Rate



Entrainment rate significantly affects cloud development and lifecycle.

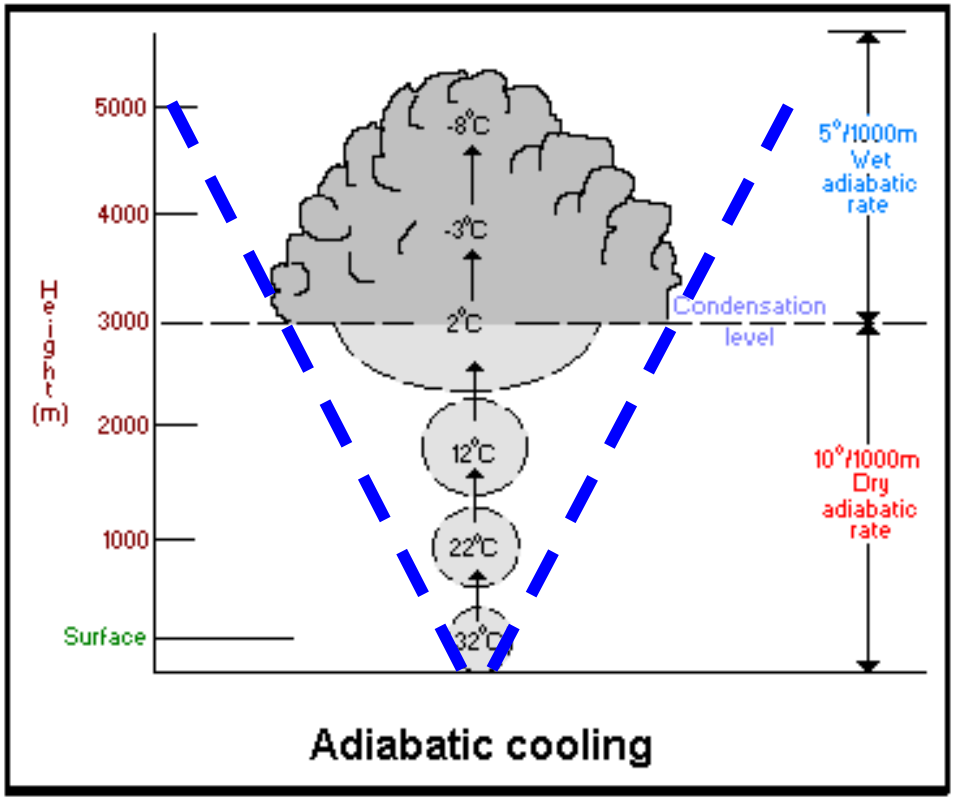
Importance of Detrainment Rate: Deep Convection





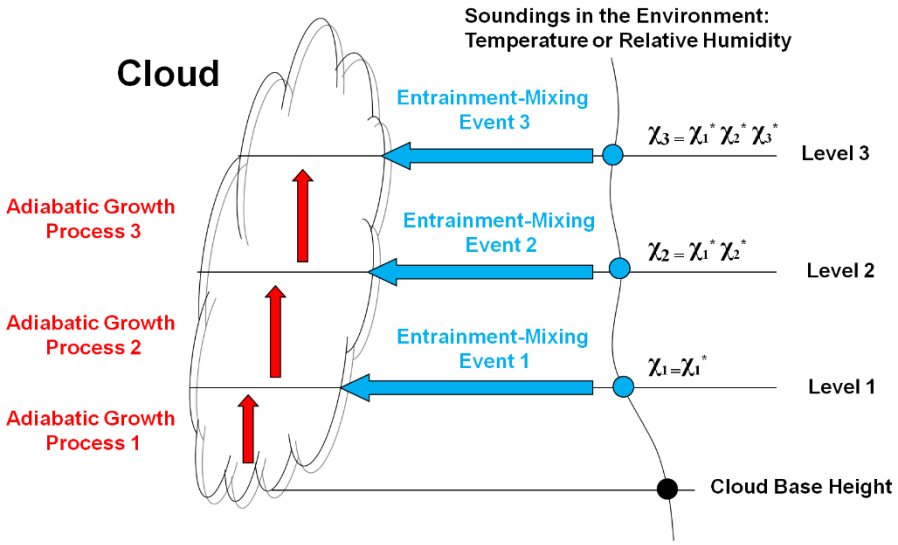
It is needed to consider the lateral detrainment, besides detrainment near the cloud top.

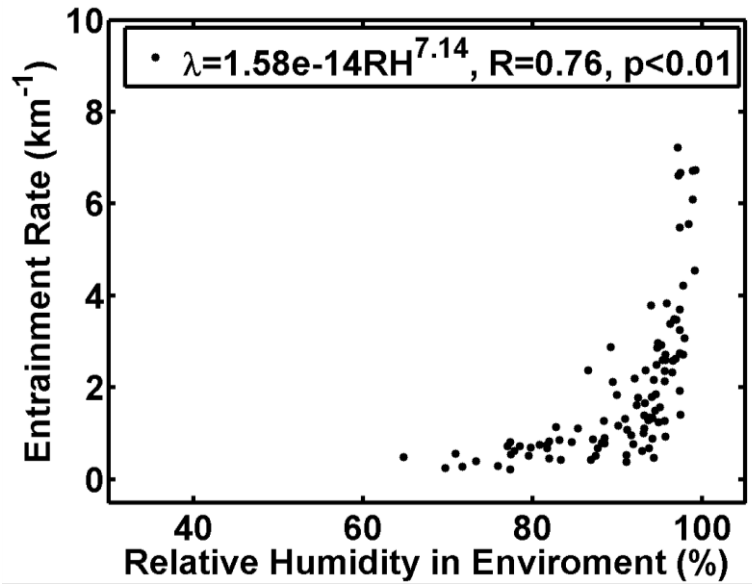
Importance of Detrainment Rate: Shallow Convection

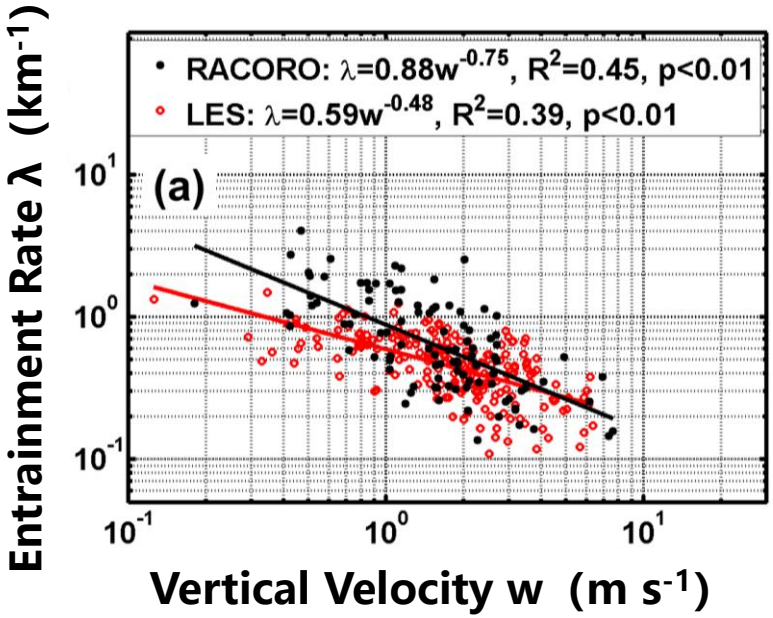


Detrainment is critical for cloud mass flux.

Estimation and Parameterization of Entrainment Rate







- **Method for estimating entrainment rate**

  Lu et al., GRL, 2012a, 2012b, 2013

- **Parameterization of entrainment rate**

  Lu et al., JAS, 2016, GRL, 2018

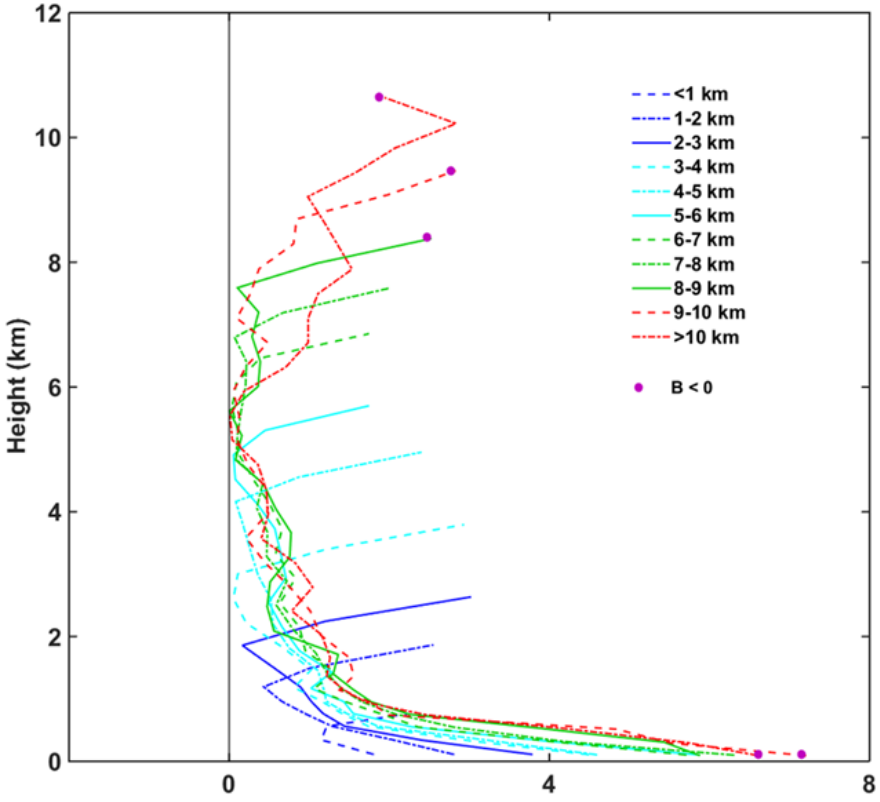
Parameterization of Entrainment Rate

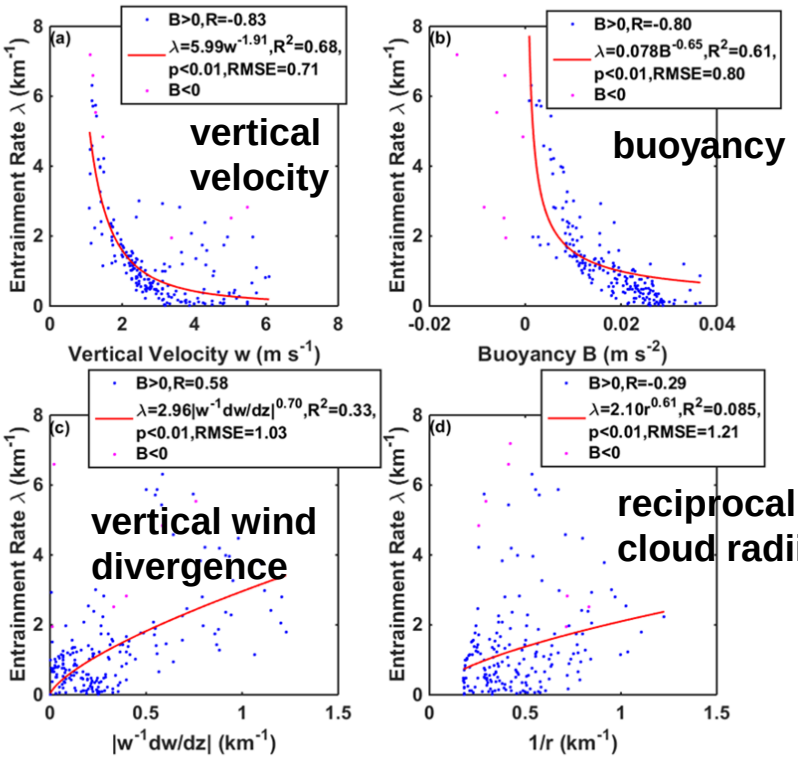
$$\lambda = \frac{-\frac{\partial M_c}{\partial z}(h_c - h_d) - M_c \frac{\partial h_c}{\partial z} + \sigma \rho S_c}{M_c (h_d - h_e)}.$$

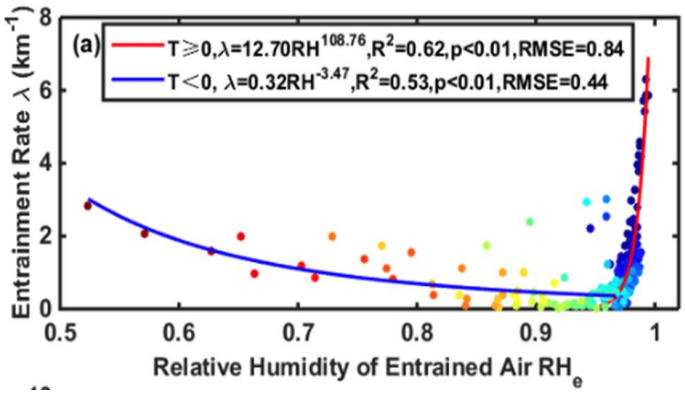
Zhang et al., 2015

***h*: moist energy** **σ: cloudy area**

M_c: cloud mass flux **S_c: source and sink for *h***

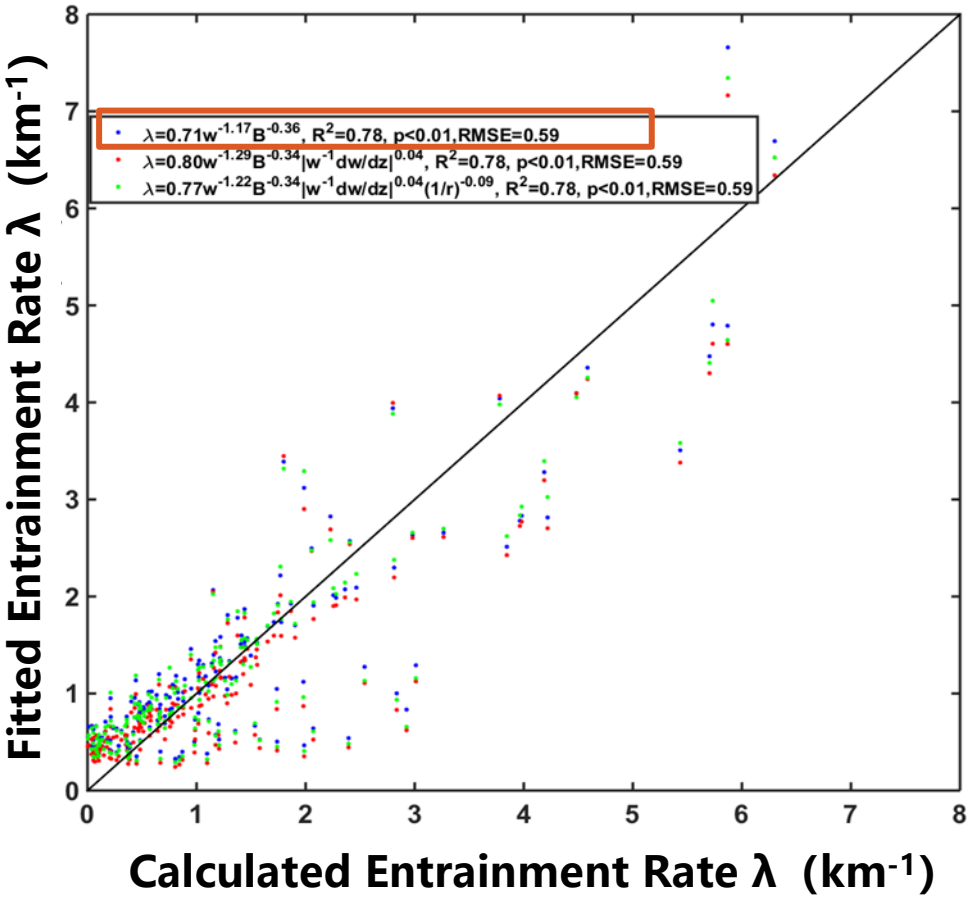


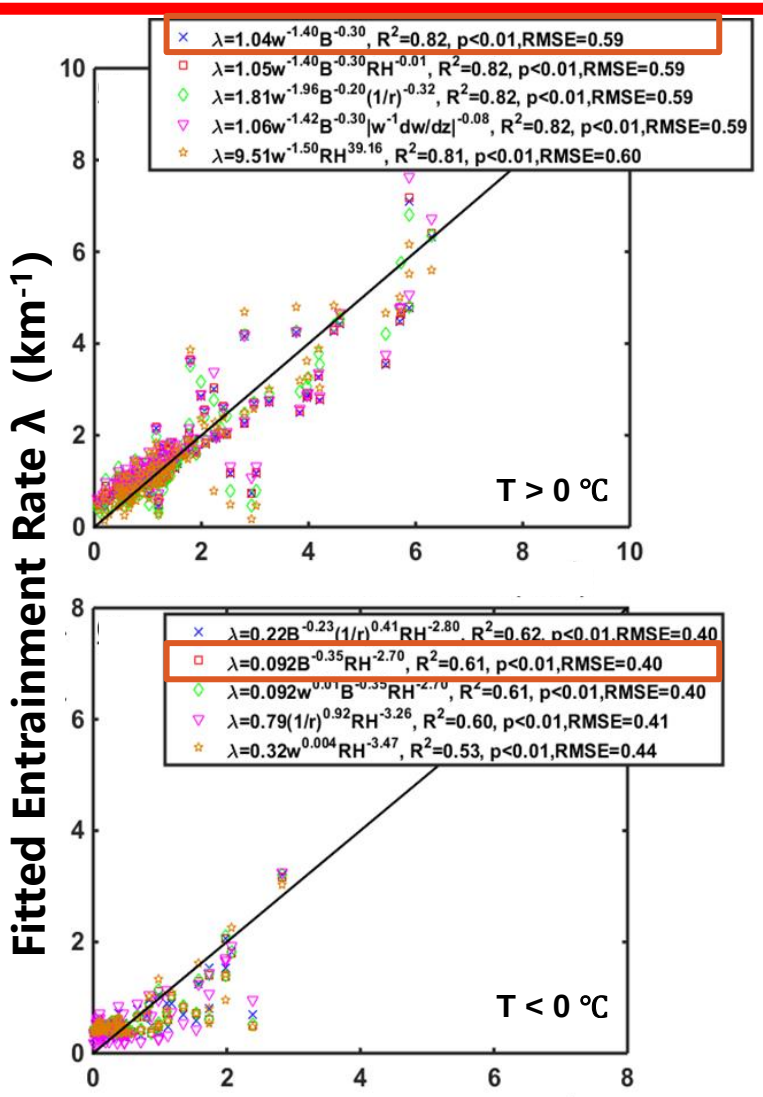




Xu, Lu, et al., JGR, 2021

Parameterization of Entrainment Rate

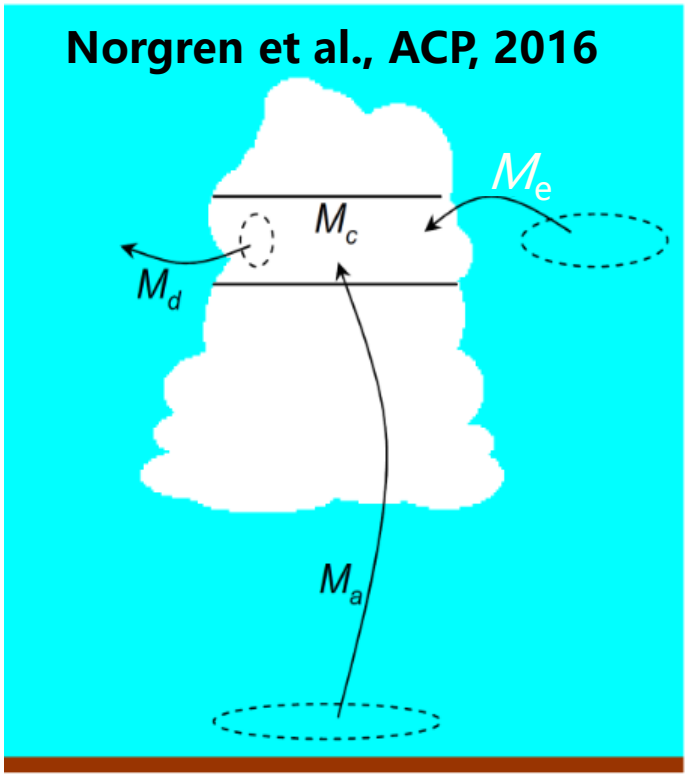




Two ways for parameterizing entrainment rate are recommended.

Xu, Lu, et al., JGR, 2021

A New Approach for Estimating Entr/Detr Rates



Norgren et al. (2016) can estimate gross entrainment/detrainment, but cannot estimate entrainment /detrainment rates.

$$\varepsilon = \frac{1}{M_c}\frac{dM_e}{dz} \qquad \delta = \frac{1}{M_c}\frac{dM_d}{dz}$$

Entr/Detr Rates Definitions + **Cloud Mass Total Water Energy**

Entr Rate

$$\varepsilon = \frac{m_e}{h(m_e - m_d)}\ln\frac{1}{m_a}$$

Detr Rate

$$\delta = \frac{m_d}{h(m_e - m_d)}\ln\frac{1}{m_a}$$

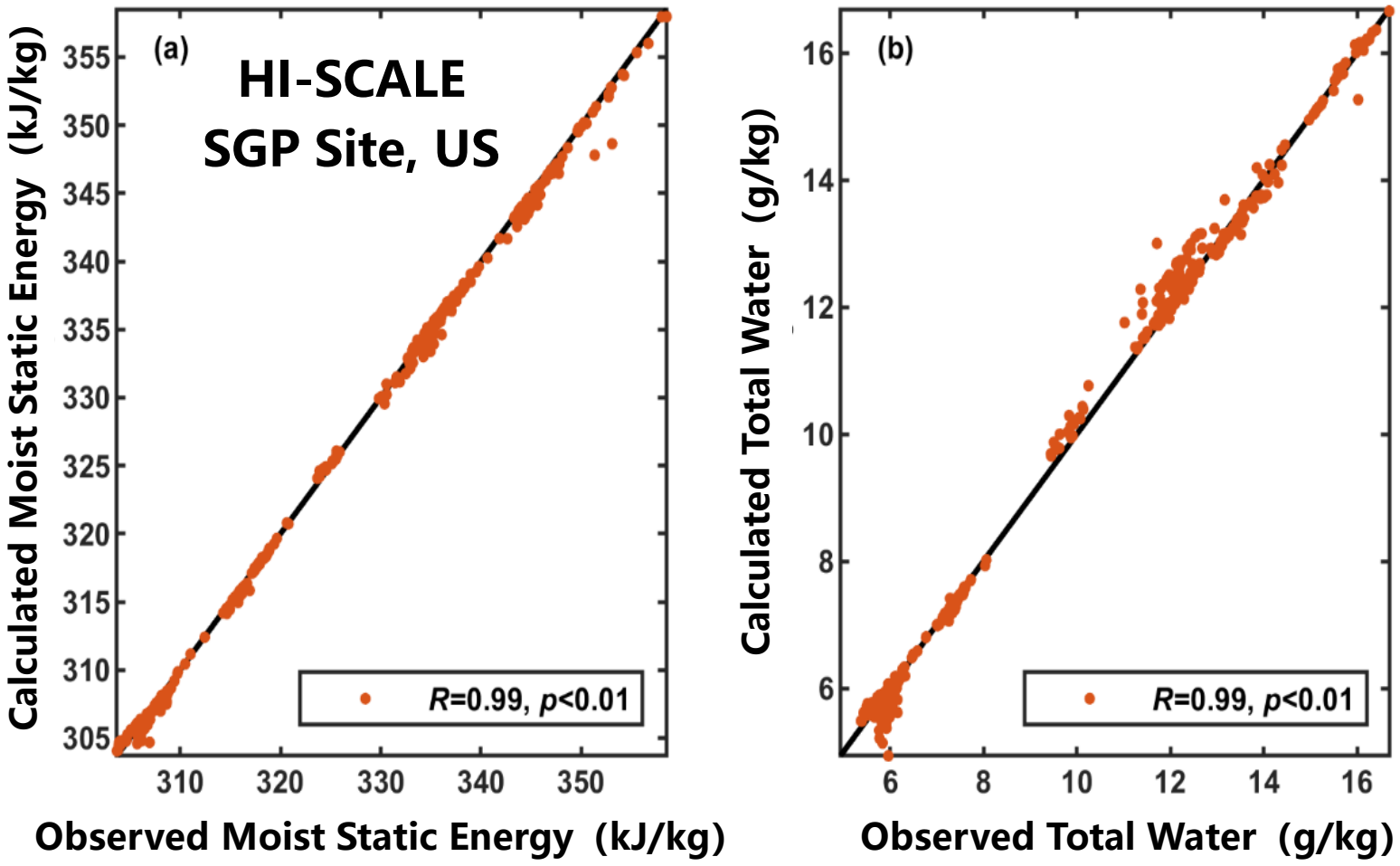
h: **Height above cloud base**

$m_a = M_a / M_c \quad m_e = M_e / M_c$

$m_d = M_d / M_c$

Zhu, Lu, et al., GRL, 2021

Validation of the New Approach



Entrainment/detrainment rates can reproduce the observed moist static energy and total water in cloud.

Zhu, Lu, et al., GRL, 2021

Summary

- **Question One: Microphysics**

(1) Entrainment-mixing mechanisms are quantitatively described and parameterized.

(2) A new homogeneous mixing degree is defined, which works for both narrow and wide cloud droplet spectra.

(3) Entrainment-mixing becomes more inhomogeneous with the increasing height near stratocumulus top

- **Question Two: Dynamics**

(1) Entrainment rate is estimated and parameterized.

(2) A new approach is developed for estimating entrainment/ detrainment rates in shallow cumulus clouds.

Thank you for your attention!

Email: clu@nuist.edu.cn