Broadening of droplet spectra and stochastic activation in turbulent clouds

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Workshop on particle-based modeling of cloud microphysics 2018

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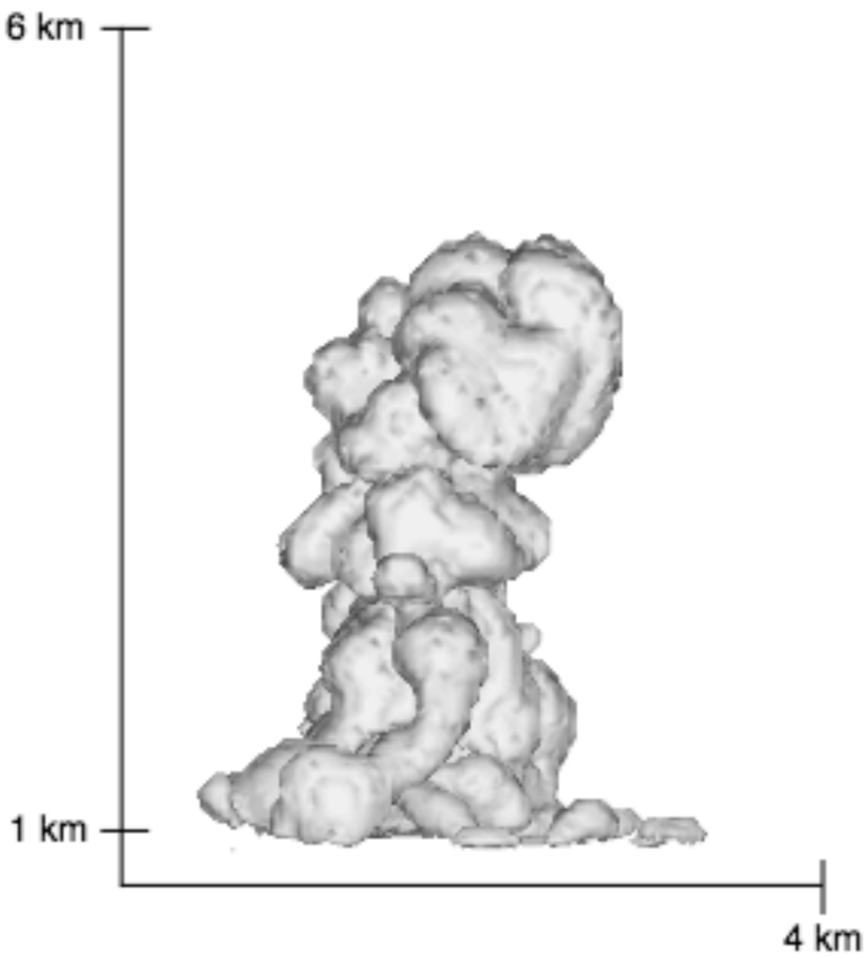
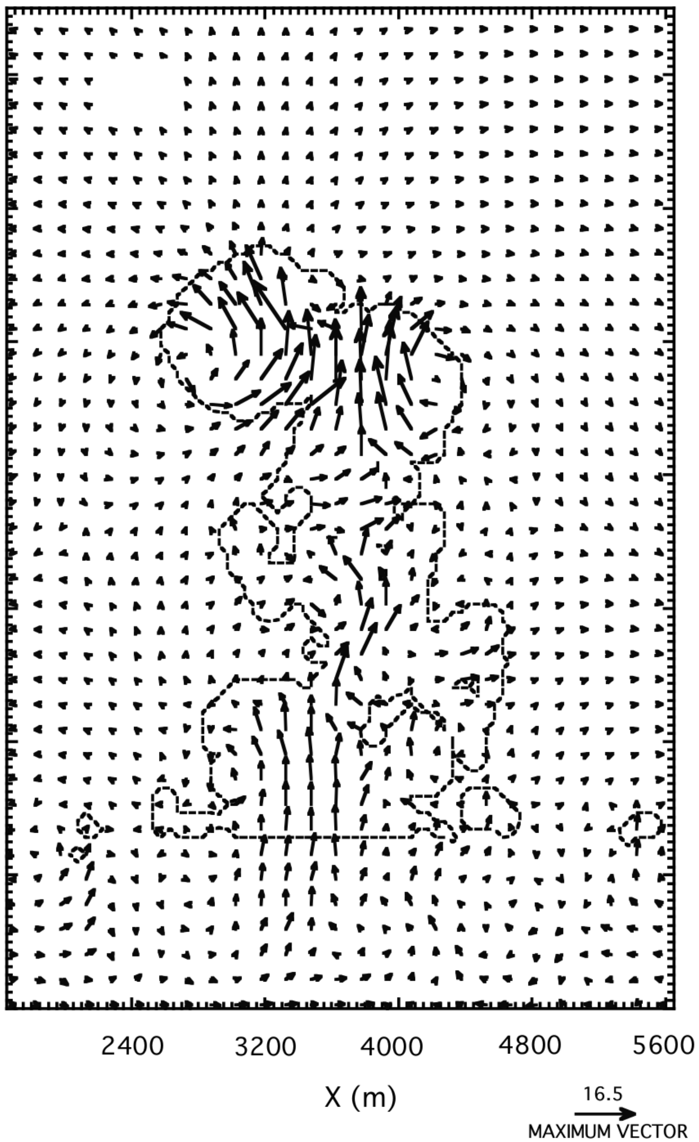
LES of cloud-scale flow

cloud updraft and interfacial instabilities (entraiment)





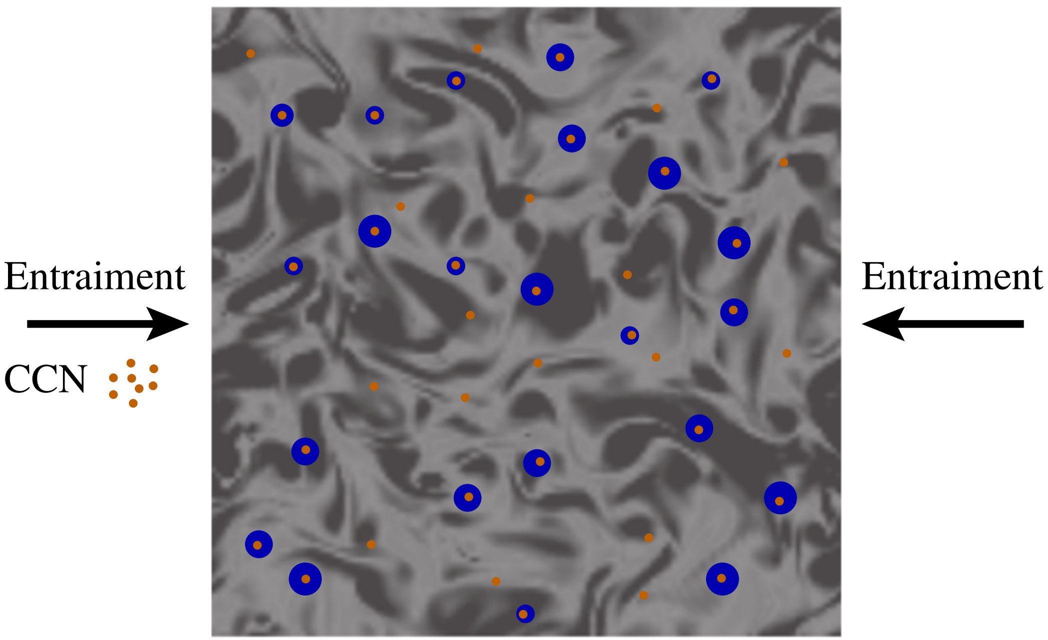
Lasher-Trapp *et al.*, QJRMS, **131** (2005)

Microphysical variability

at sub-grid scales (SGS)

- $S = \langle S \rangle + S'$
- Mixing
- Activation/deactivation
- Super-droplets

LES grid box



Köhler potential

Growth equation:

$$r \frac{\mathrm{d}r}{\mathrm{d}t} = D \left[\langle S \rangle \; - \frac{A}{r} + \frac{B}{r^3} \right]$$

$$x \equiv r^2$$

$$\frac{\mathrm{d}x}{\mathrm{d}t} = -\frac{\partial V}{\partial x}$$

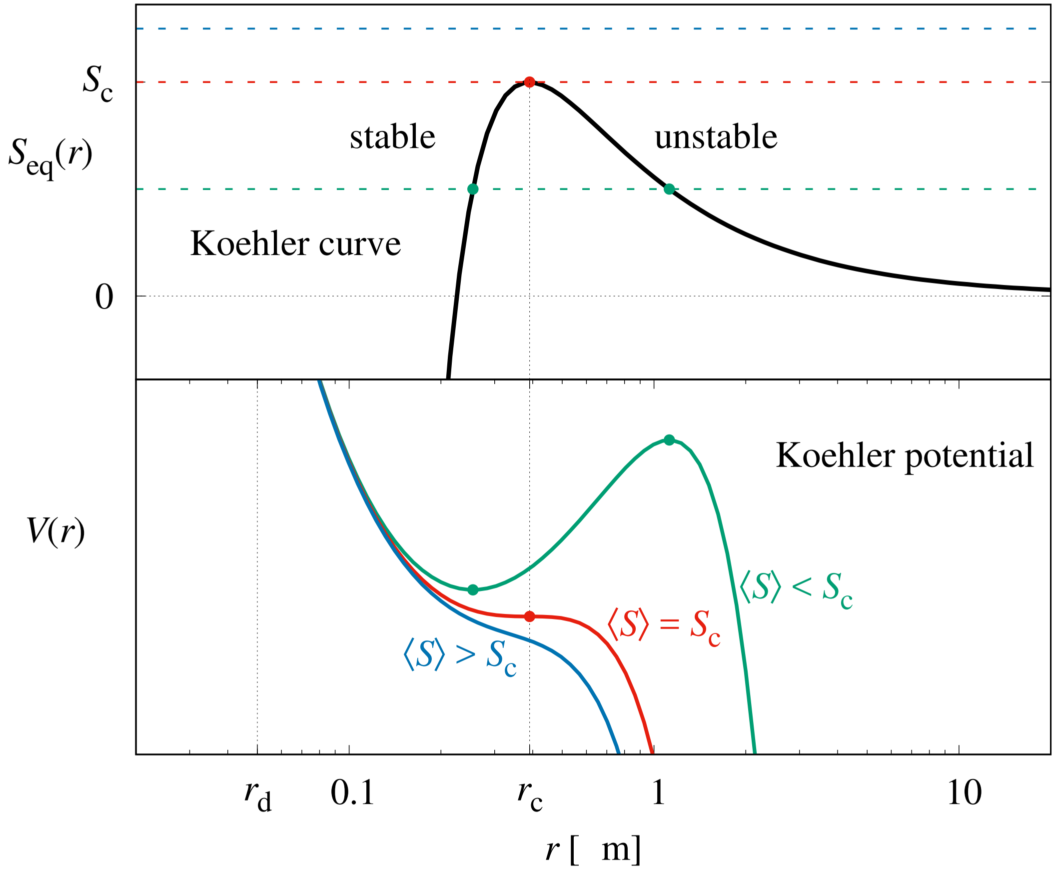
Köhler potential

Deterministic activation

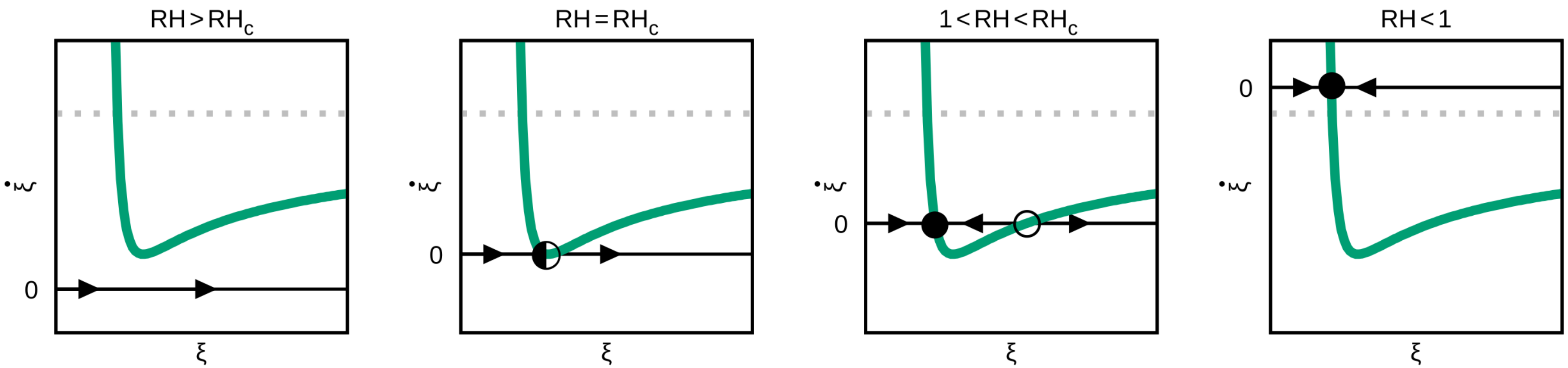
$$r\frac{\mathrm{d}r}{\mathrm{d}t} = D\left[\langle S\rangle - \frac{A}{r} + \frac{B}{r^3}\right]$$

$$x \equiv r^2$$

$$\frac{\mathrm{d}x}{\mathrm{d}t} = -\frac{\partial V}{\partial x}$$



Phase portraits



$$\mathrm{RH} = S + 1, \qquad \xi = x \equiv r^2$$

Stochastic activation

Köhler potential plus fluctuations

$$r\frac{\mathrm{d}r}{\mathrm{d}t} = D\left[\langle S\rangle + S' - \frac{A}{r} + \frac{B}{r^3}\right]$$

$$x \equiv r^2$$

$$\frac{\mathrm{d}x}{\mathrm{d}t} = -\frac{\partial V}{\partial x} + 2DS'$$

Abade, Grabowski and Pawlowska, JAS, **75** (2018)

Stochastic activation

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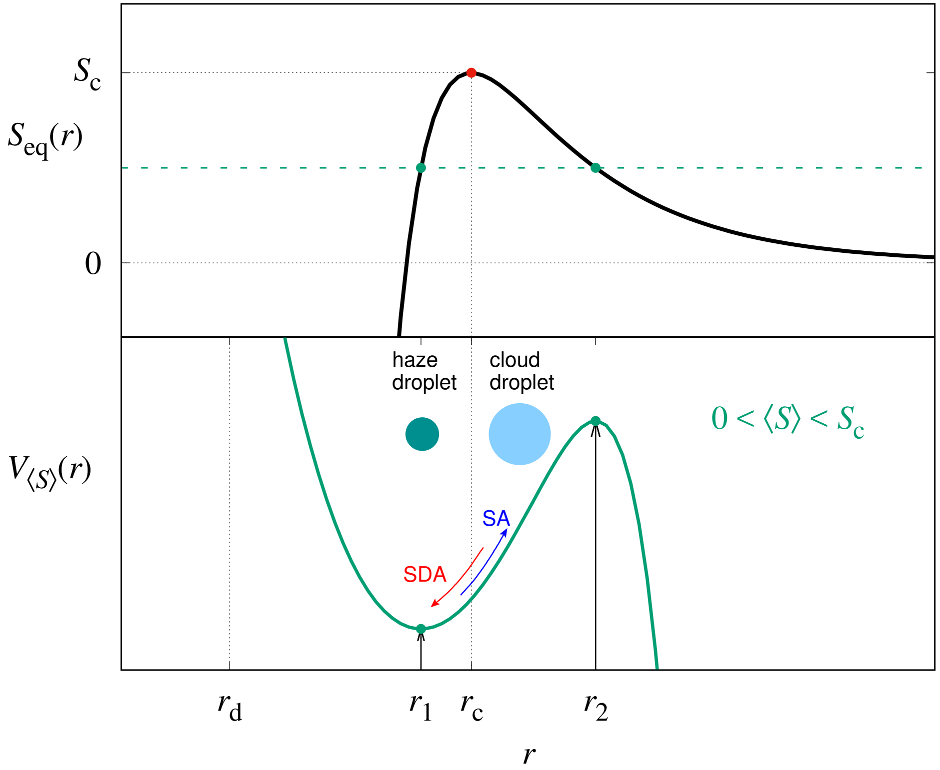
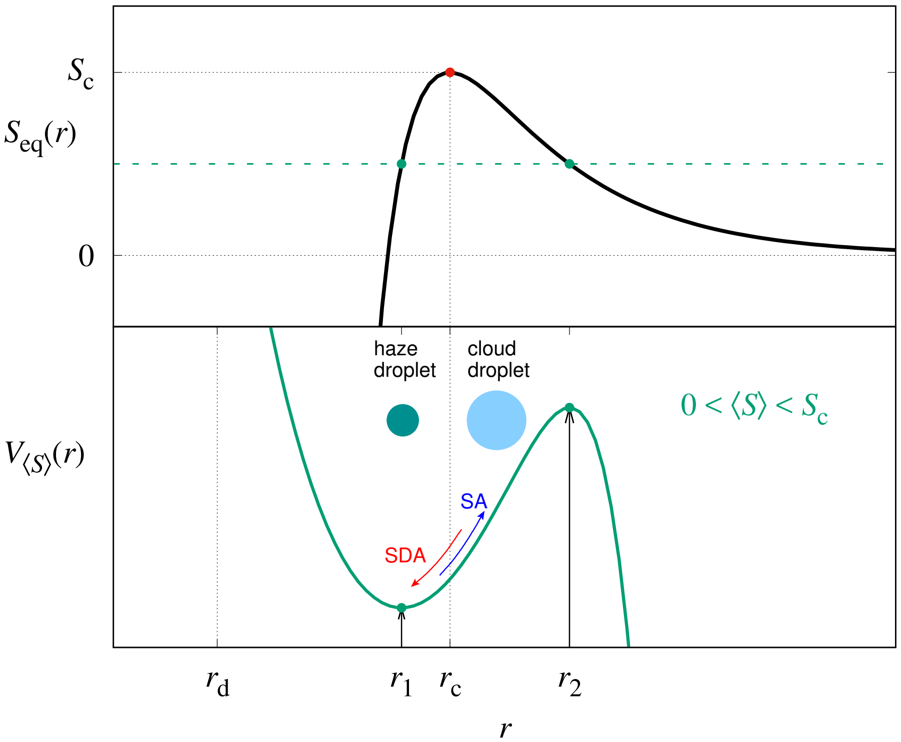


Abade, Grabowski and Pawlowska, JAS, **75** (2018)

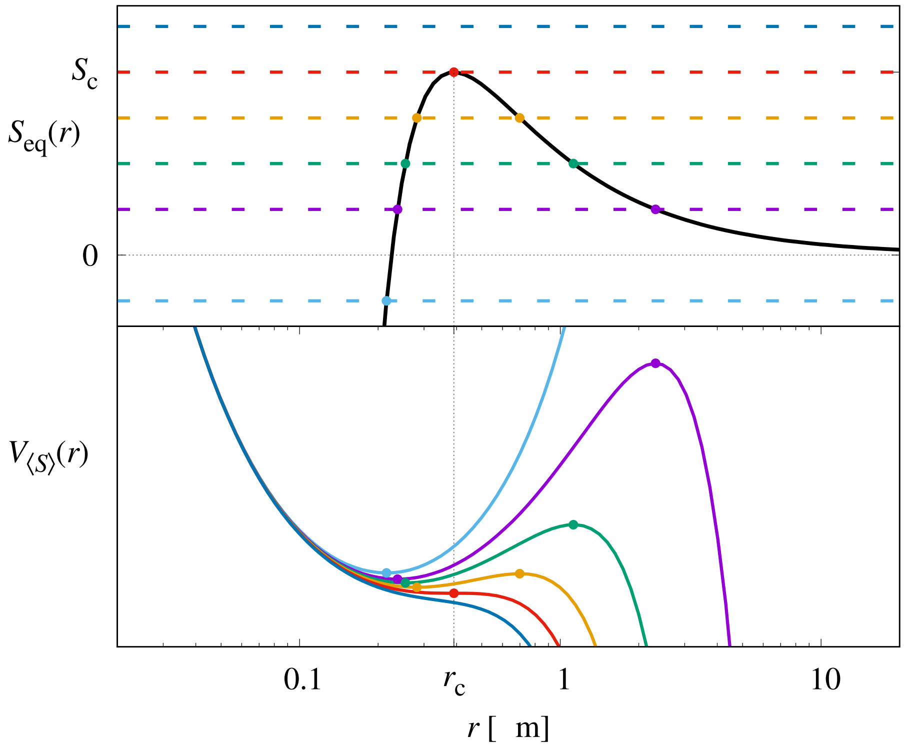
Stochastic activation

$S = \langle S \rangle + S'$

Köhler potential

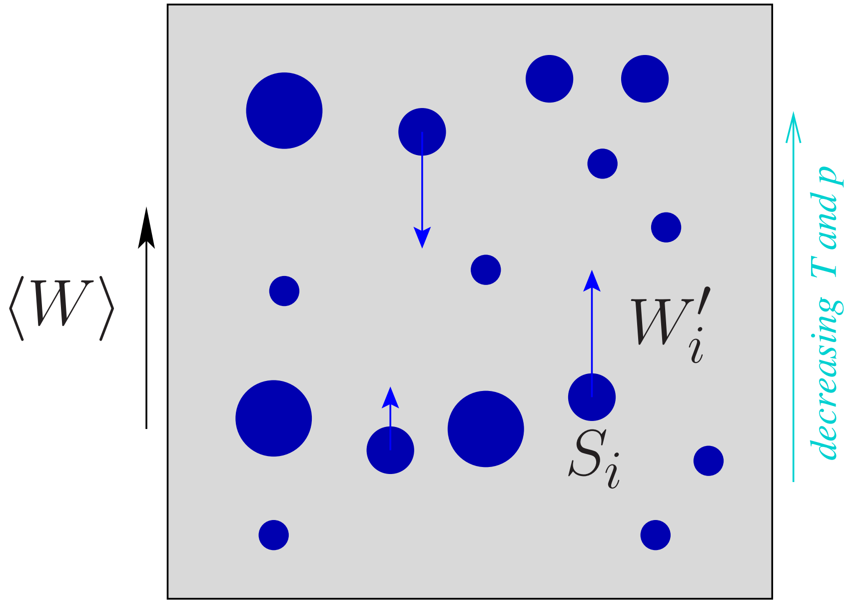


Feedback on $\langle S \rangle$



Abade, Grabowski and Pawlowska, JAS, **75** (2018)

Supersaturation and velocity fluctuations



$$\frac{\mathrm{d}S_i'}{\mathrm{d}t} = -\frac{S_i'}{\tau_\mathrm{c}} - \frac{S_i'}{\tau_\mathrm{m}} + aW_i'(t)$$

$$\tau_\mathrm{c} \sim \frac{1}{DN\langle r \rangle} \quad \text{(condensation)}$$

$\tau_\mathrm{m} \sim$ eddy turnover time (mixing)

- Statistical model for $W'(t)$

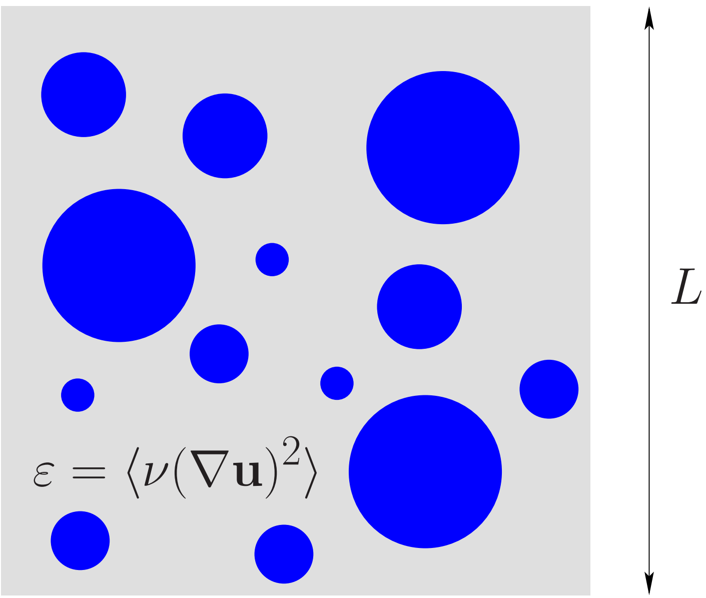
Celani *et al.*, EPL, **70** (2005); Grabowski and Abade, JAS, **74** (2017)

Vertical velocity fluctuations

Stationary homogeneous isotropic turbulence

$$\langle W'(t) \rangle = 0$$

$$\langle W'(0)W'(t) \rangle = \sigma_{W'}^2 \exp\left(-|t|/\tau_m\right)$$



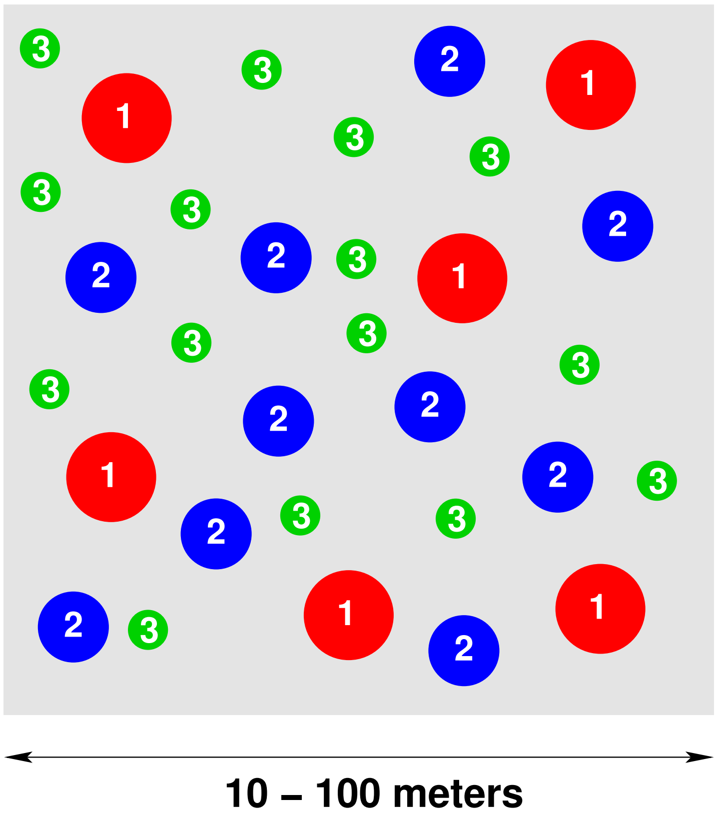
Kolmogorov scaling (inertial subrange)

$$\sigma_{W'}^2 \sim (L\varepsilon)^{2/3} \qquad \tau_m \sim \frac{L^{2/3}}{\varepsilon^{1/3}}$$

Super-droplets (SDs)

Shima *et al.* (2009), Arabas *et al.* (2015), Hoffmann *et al.* (2015)

$$N_{\text{droplets}} \sim 10^{11} - 10^{14}$$



- Multiplicities:

$$\xi_1 = 6, \quad \xi_2 = 10, \ldots$$

- SDs have the same attributes

$$(r, \ldots, S', W', \ldots)$$

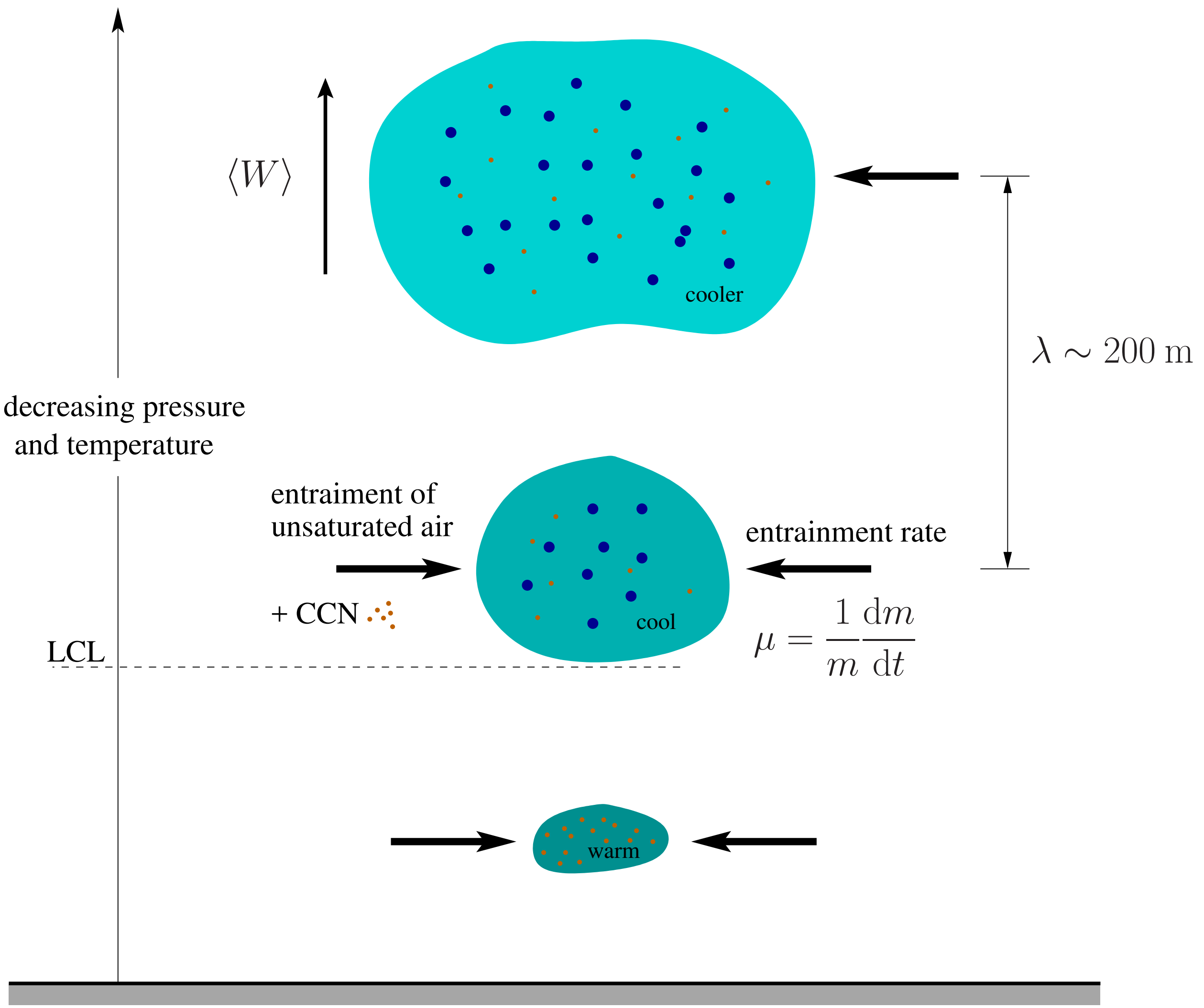
- Well-mixed

Frameworks

- Entraining cloud parcel
- Synthetic turbulent-like ABL flow

Entraining cloud parcel

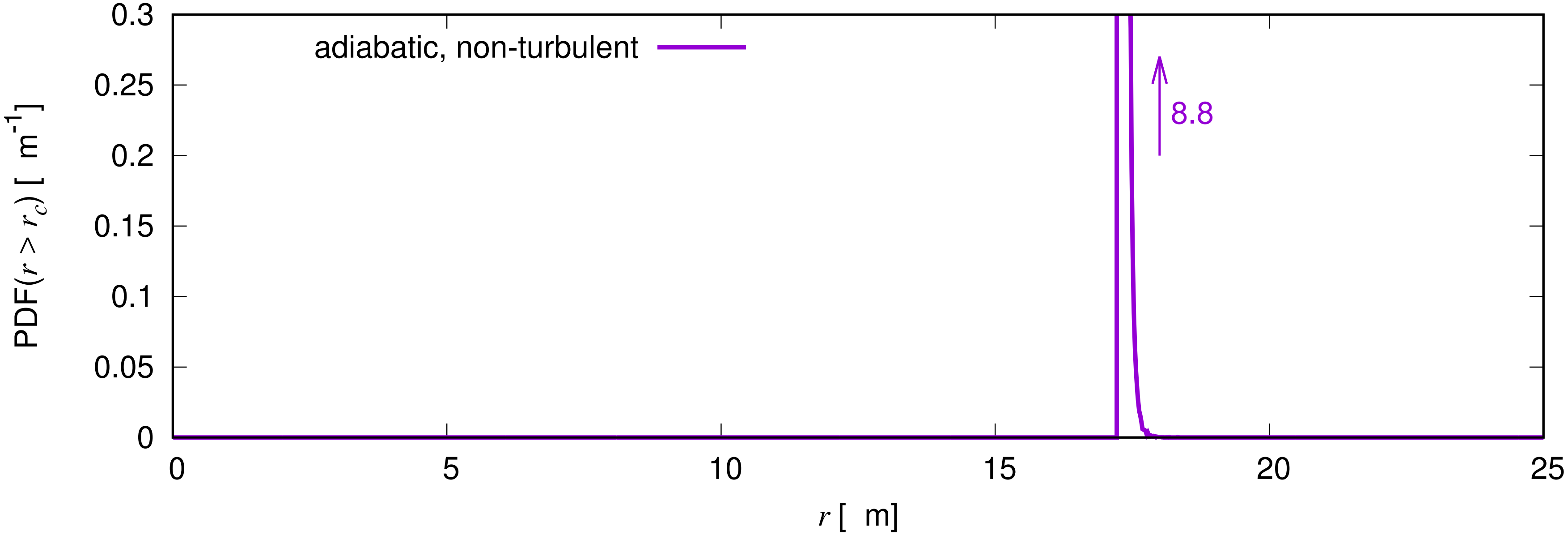
stochastic entrainment events



Krueger *et al.*, JAS, **54** (1997); Romps and Kuang, JAS, **67** (2010)

Droplet-size distribution

after a 1-km parcel rise



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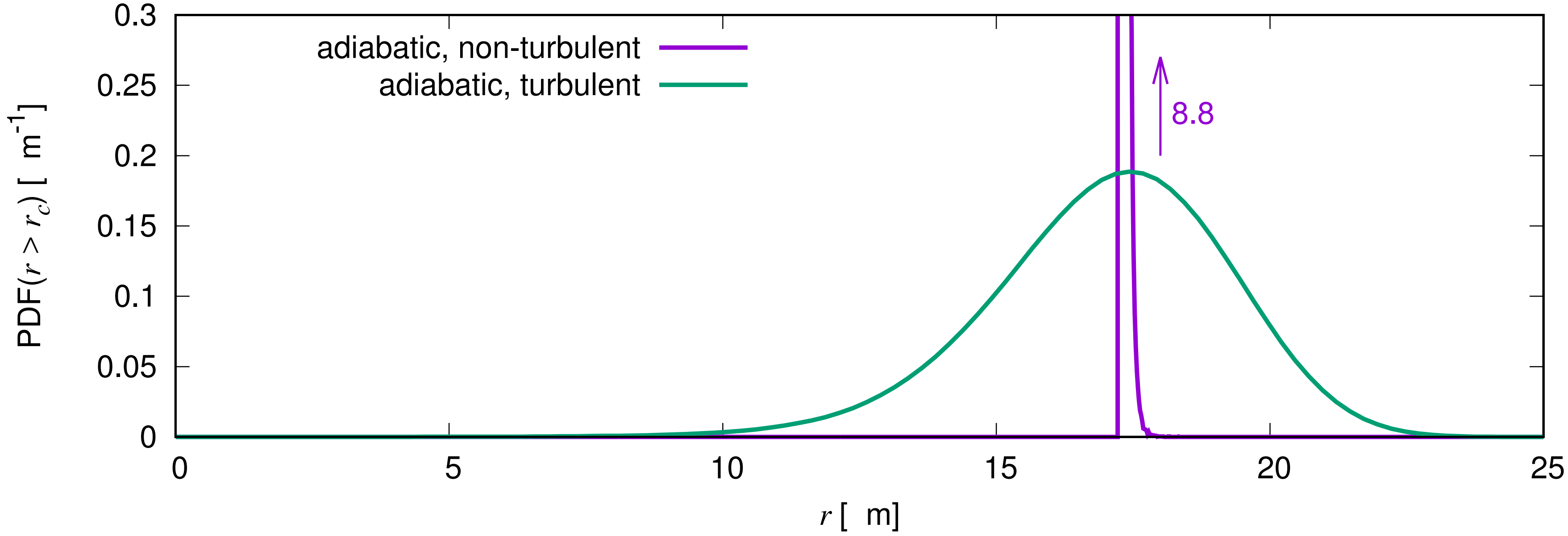

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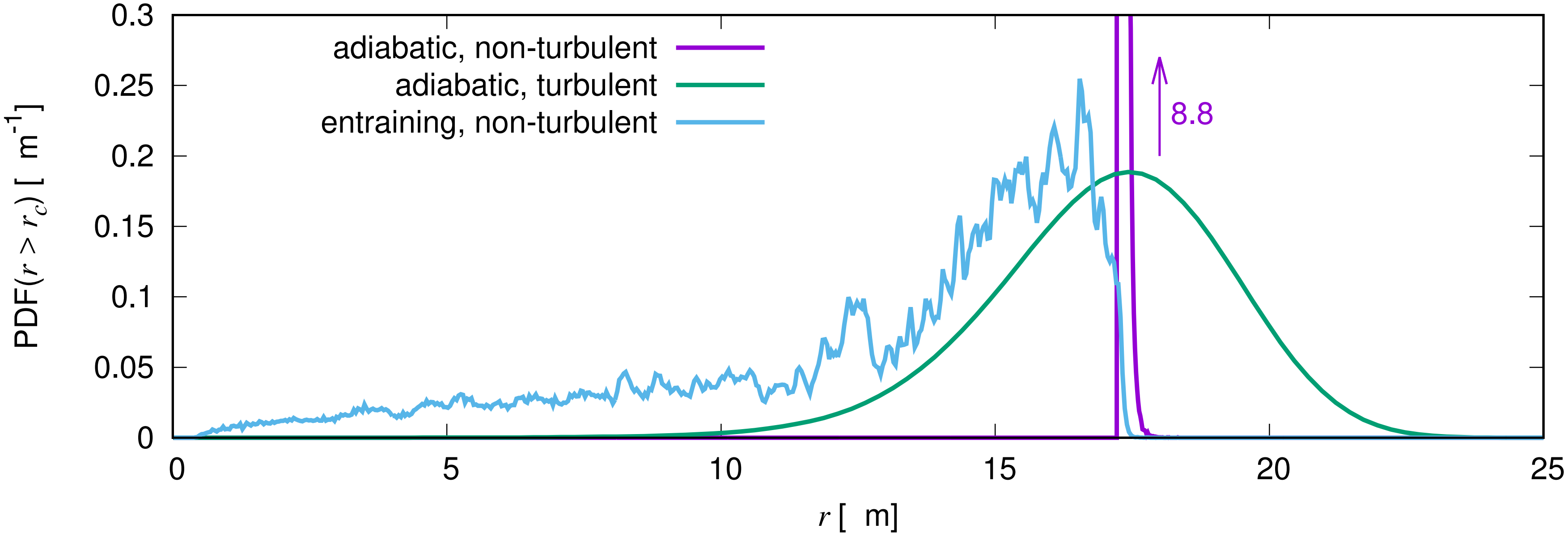

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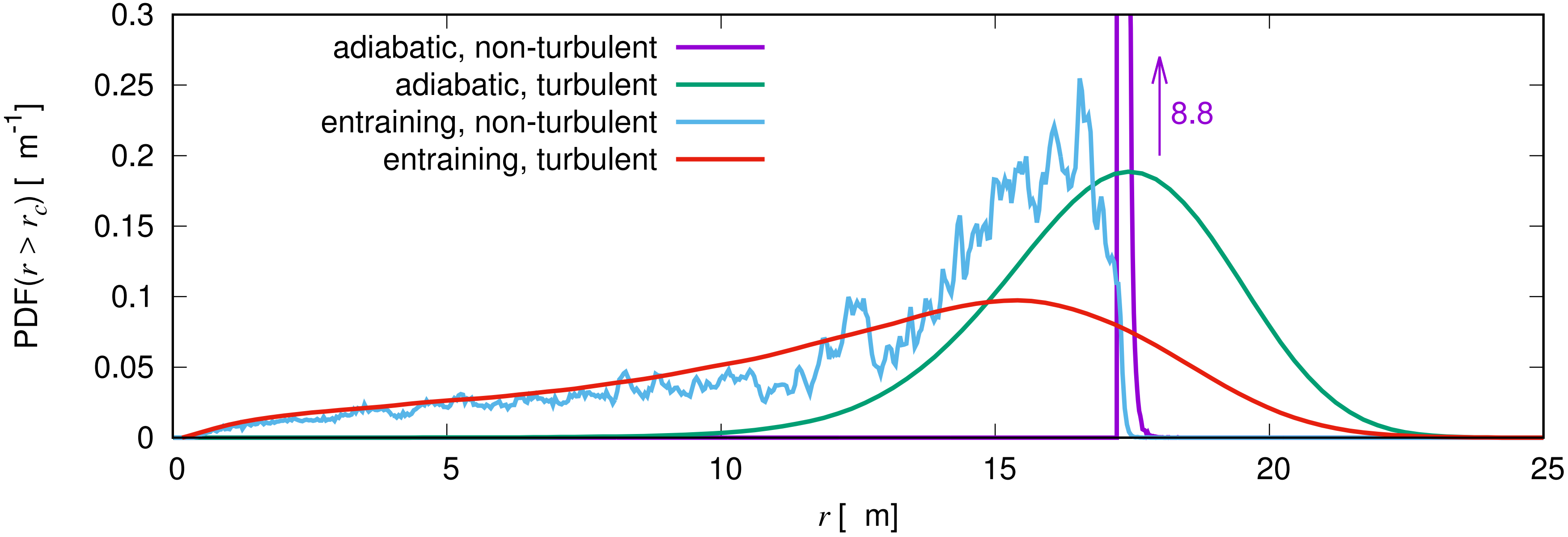

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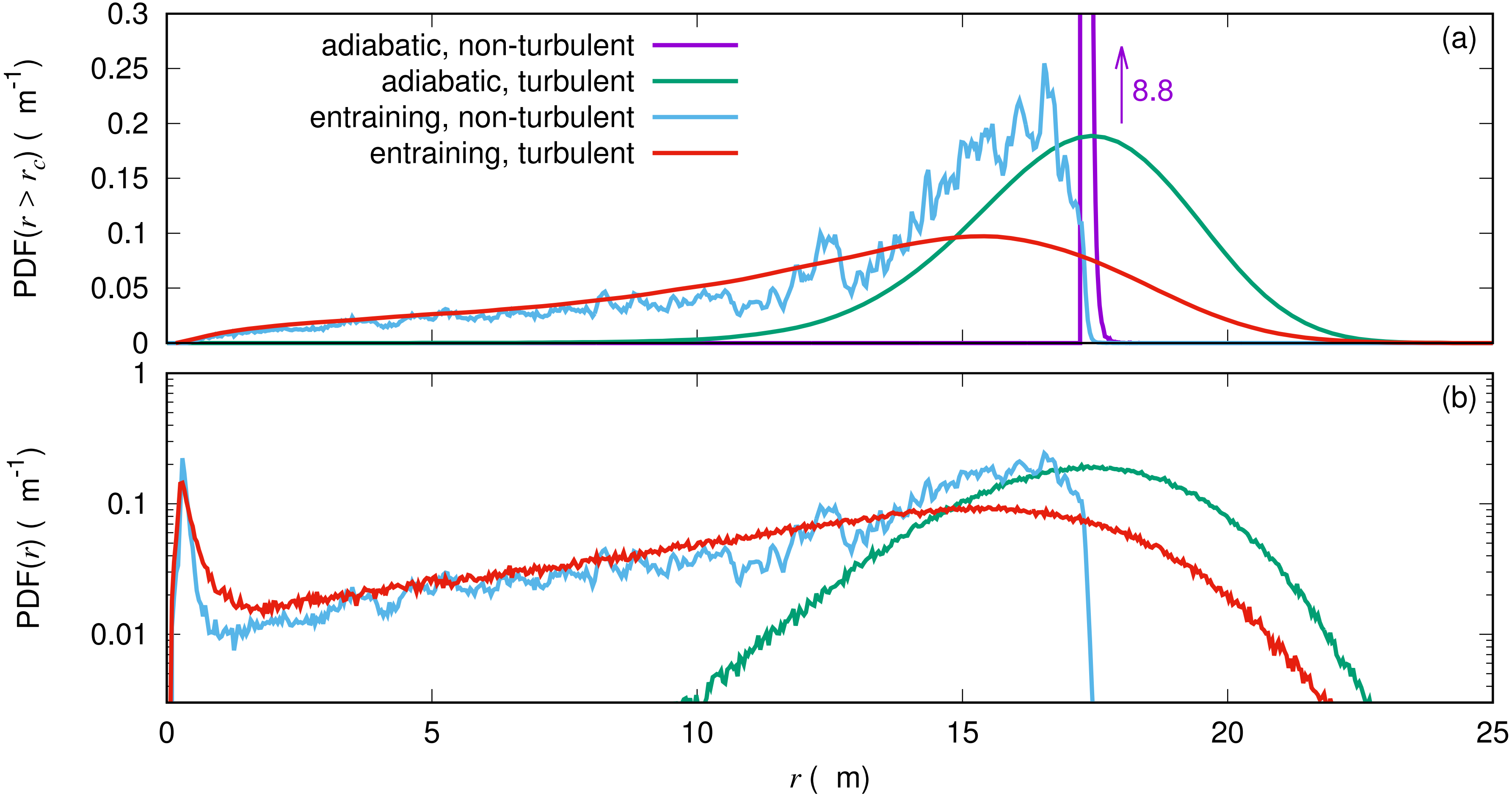
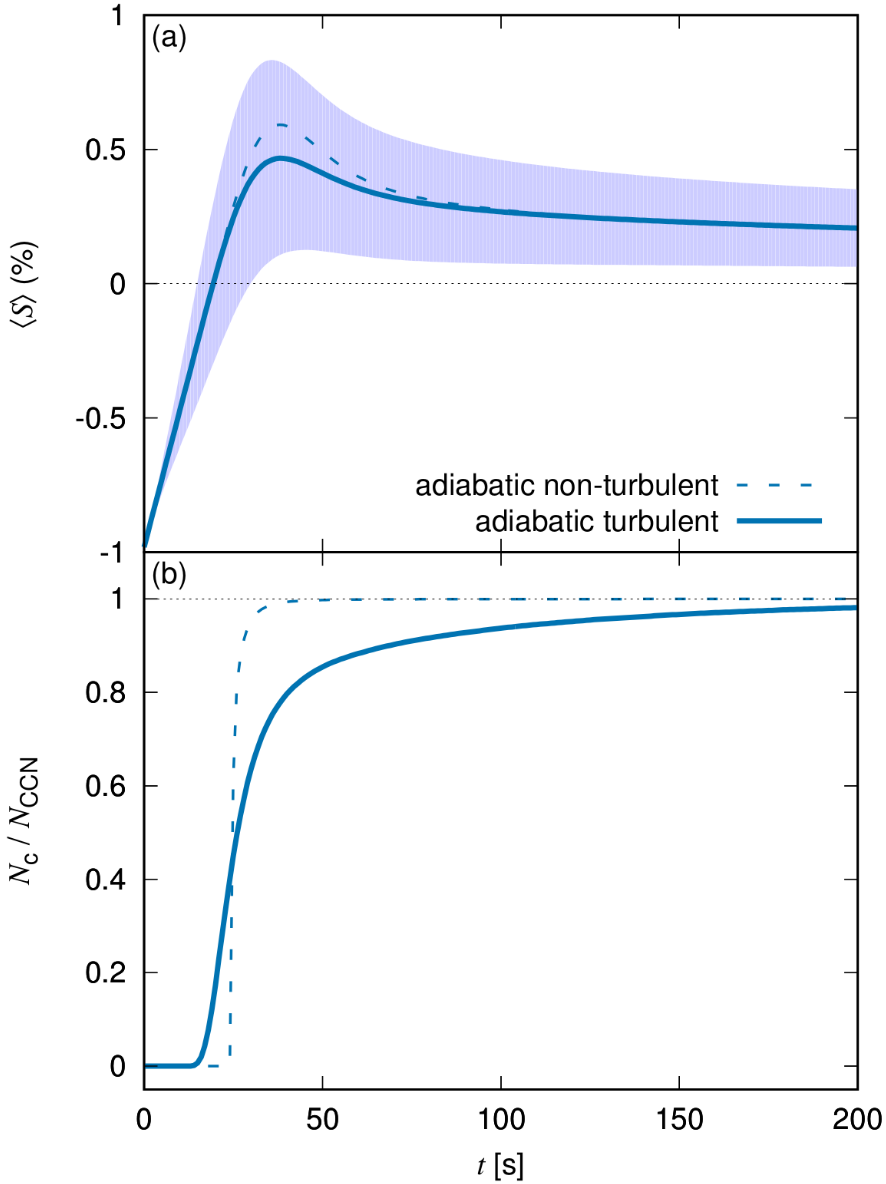
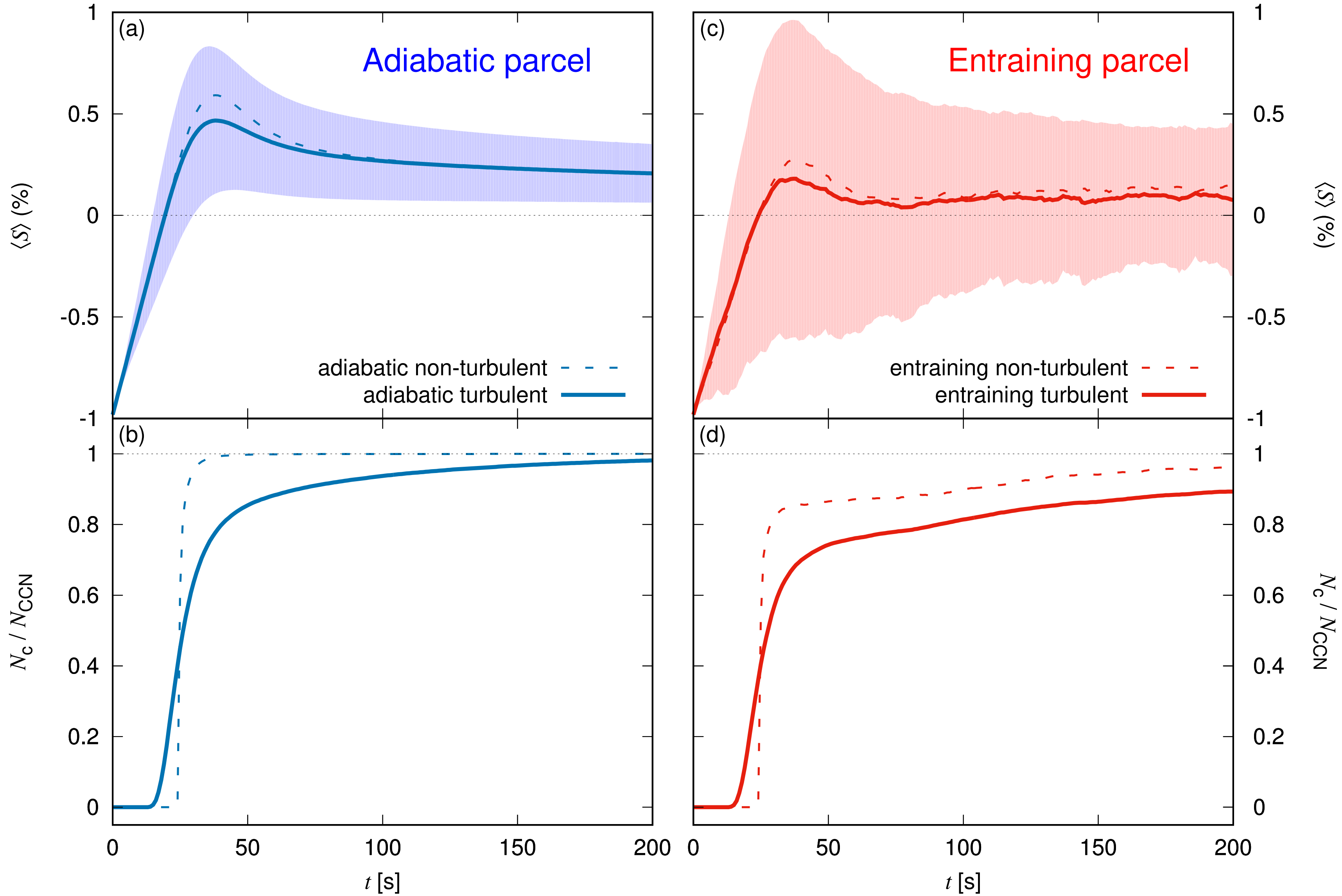


Stochastic activation and feedback on $\langle S \rangle$

Adiabatic parcel

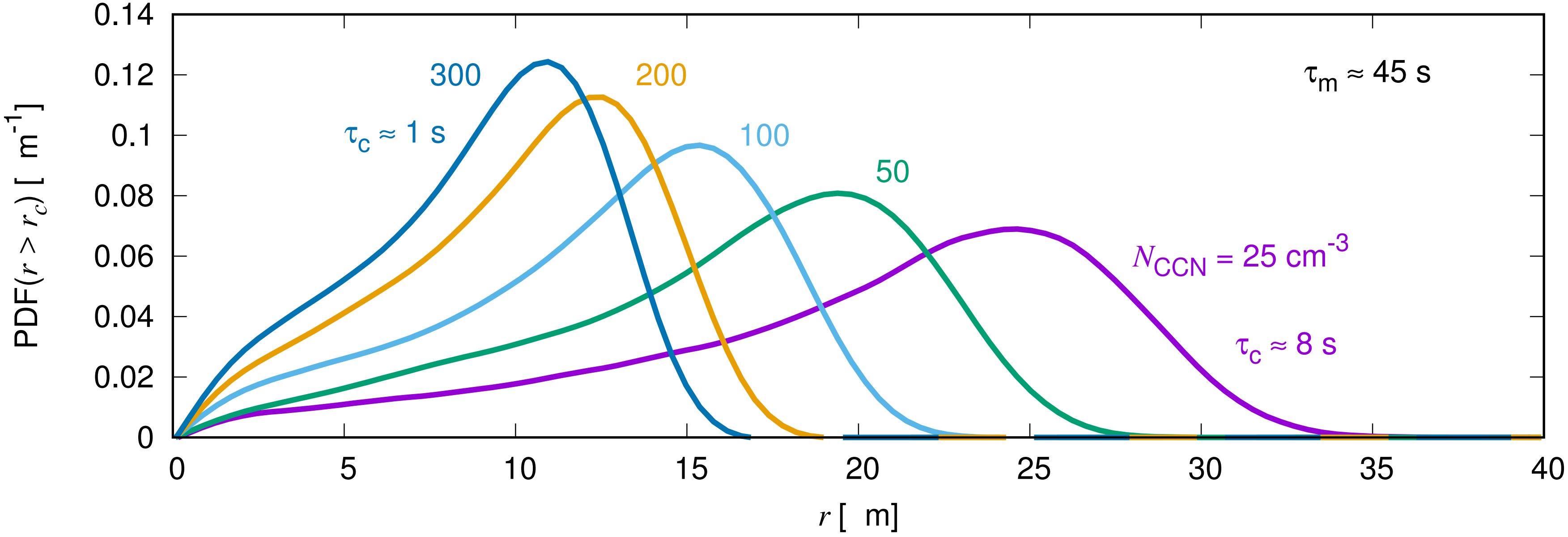


Stochastic activation and feedback on $\langle S \rangle$



Aerosol indirect effect

induced by turbulence



- fast × slow microphysics

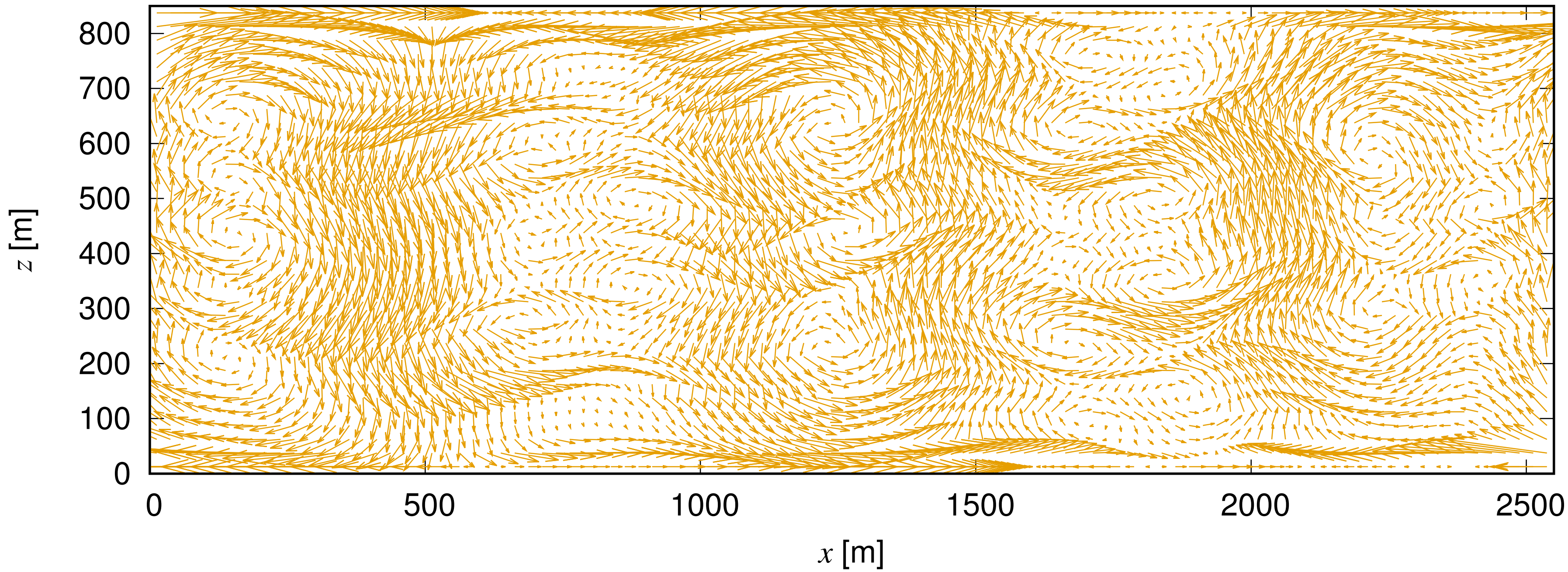
$$\frac{\mathrm{d}S'}{\mathrm{d}t} = -\frac{S'}{\tau_S} + aW'(t), \qquad \tau_S \sim \min\{\tau_{\text{condens}}, \tau_{\text{mixing}}\}$$

Chandrakar *et al.*, PNAS, **113** (2016); Siebert and Shaw, JAS, **74** (2017)

Turbulent-like ABL flow

$$\mathbf{u}(\mathbf{r}, t) = \sum_{|\mathbf{k}_n| < K} \hat{\mathbf{u}}(\mathbf{k}_n, z, t) \exp(i \mathbf{k}_n \cdot \mathbf{r})$$

$$\text{turbulence resolution,} \quad \Delta = \frac{2\pi}{K}$$

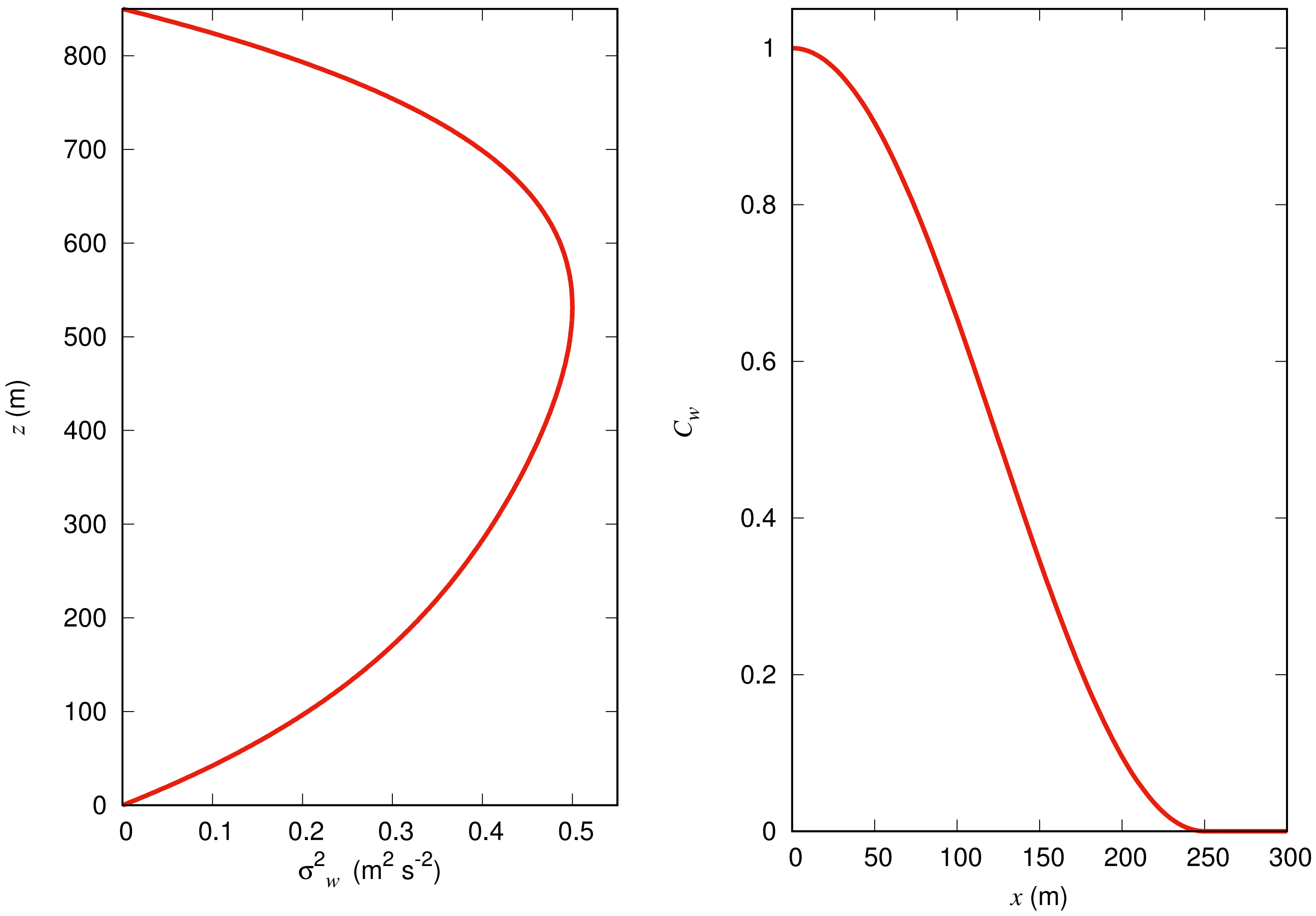


Pinsky *et al.*, JAS, 2008

Turbulent-like ABL flow

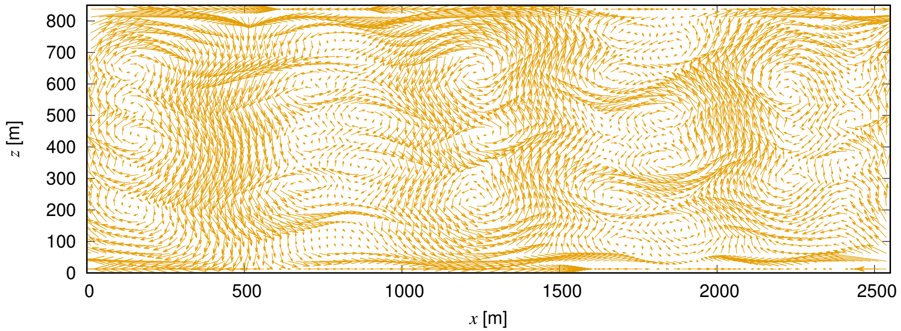
Statistical structure

$$\langle w^2 \rangle = \sigma_w^2(z) \qquad C_w(x,z) = \langle w(x',z)w(x'+x,z)\rangle$$



Turbulent-like ABL flow

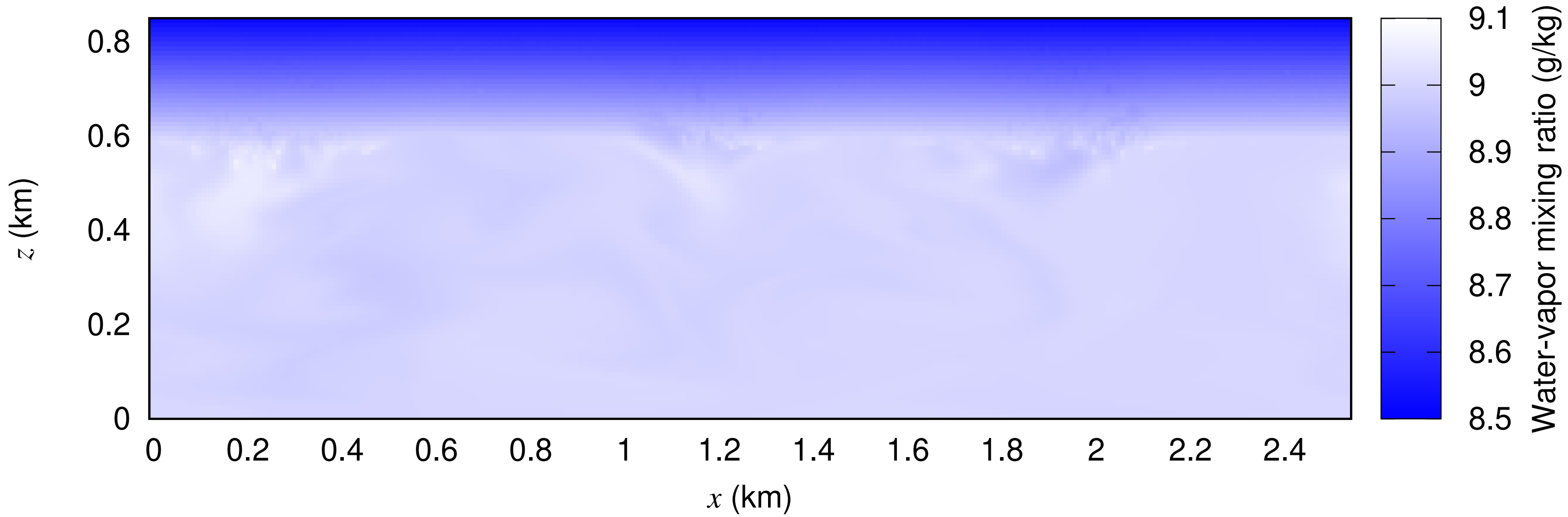
- Prescribed flow $\mathbf{u}(\mathbf{r}, t)$



- Balance equations for entropy and water vapor
- grid spacing $< \Delta$
- Super-droplets
- $\epsilon = 10^{-3}$ m^2 s^{-3} everywhere

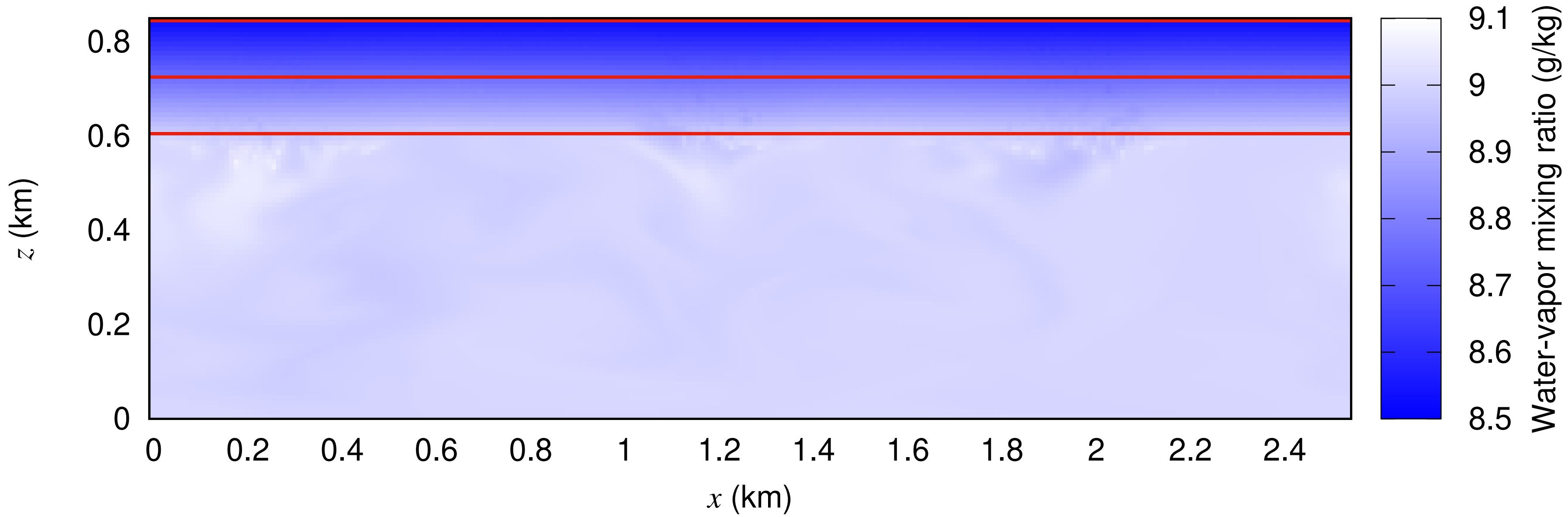
Turbulent-like ABL flow

Droplet-size PDF



Turbulent-like ABL flow

Droplet-size PDF



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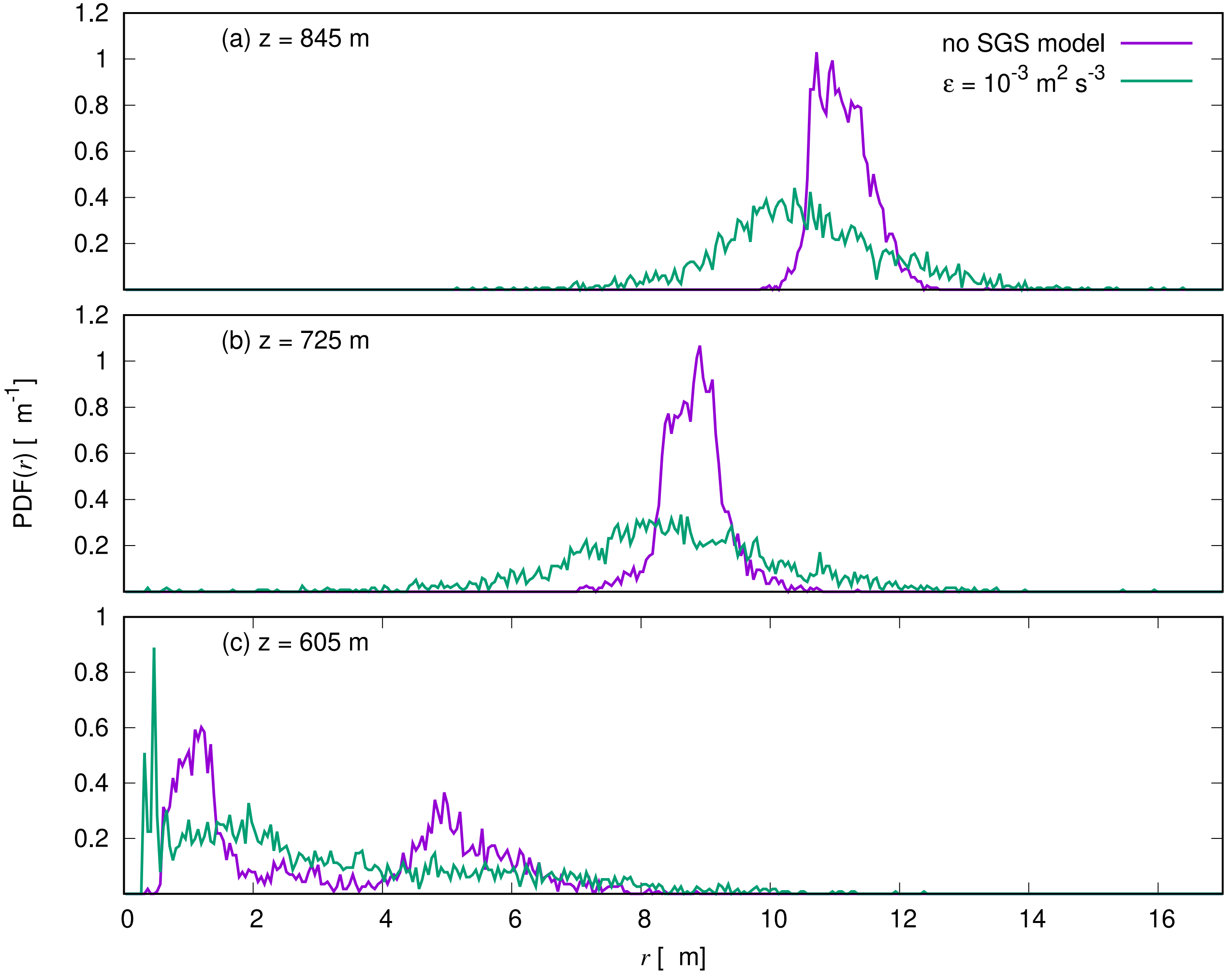
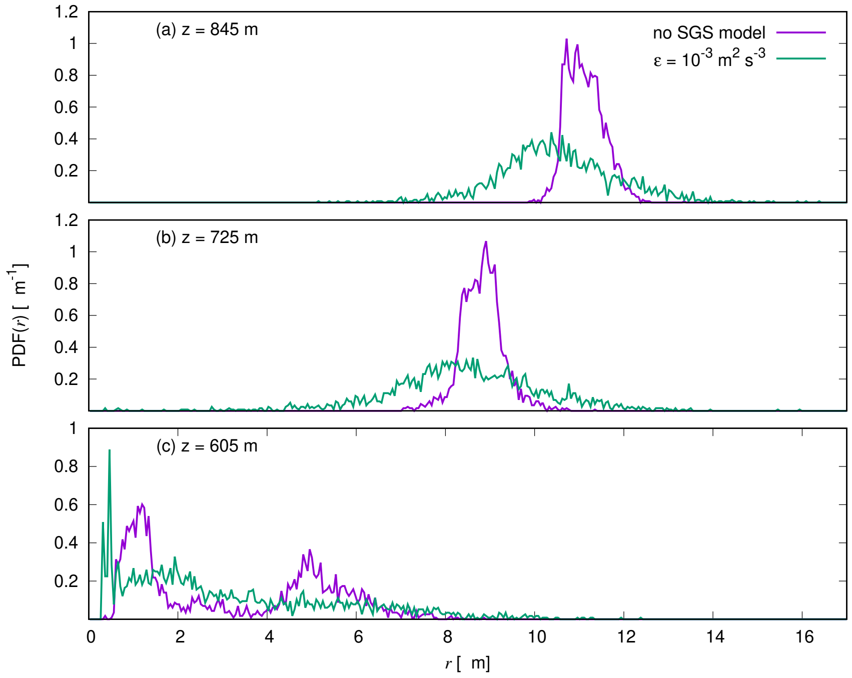


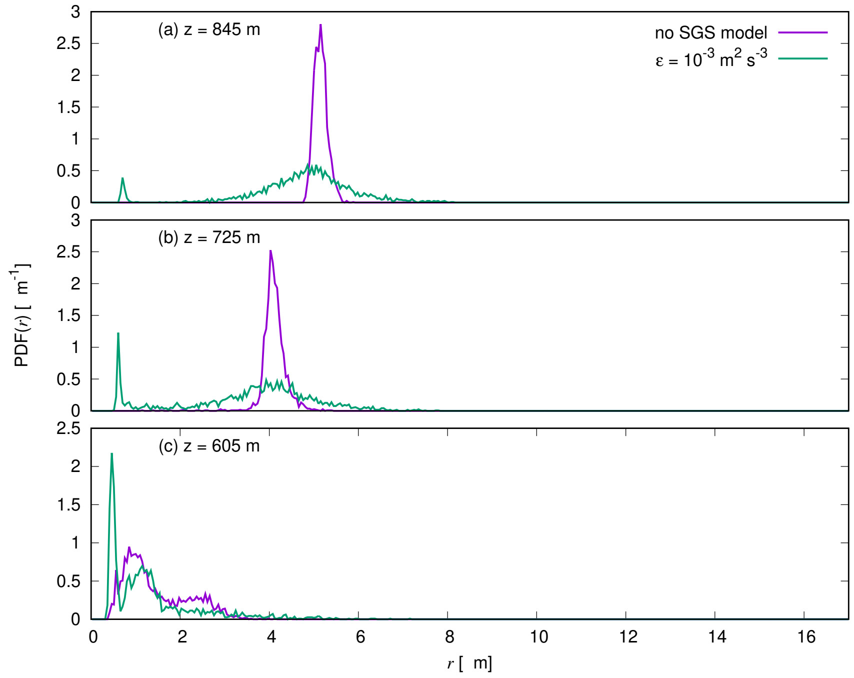
Turbulent-like ABL flow

Droplet-size PDF

PRISTINE conditions

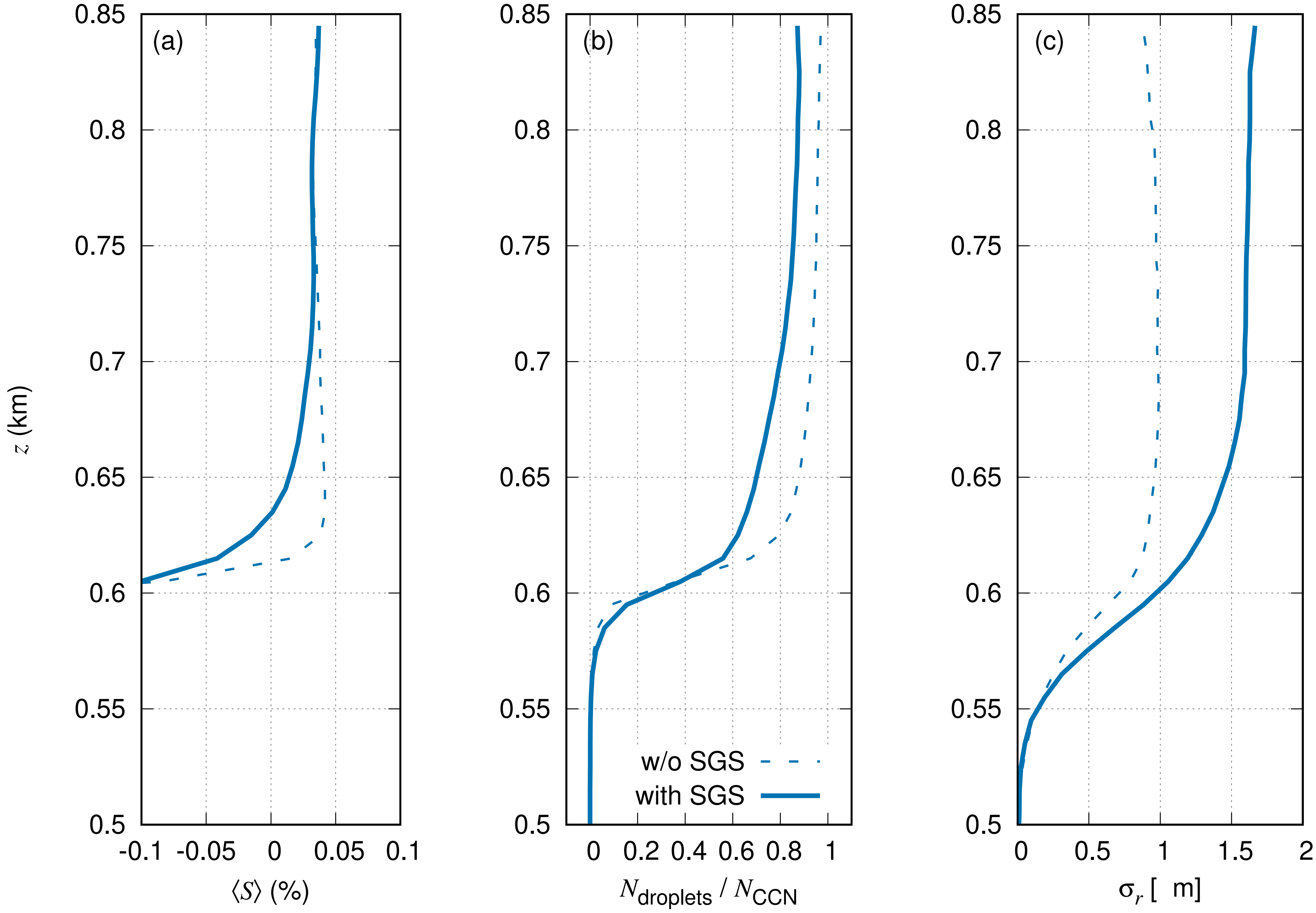


POLLUTED conditions



Microphysical profiles

horizontally averaged



Microphysical profiles

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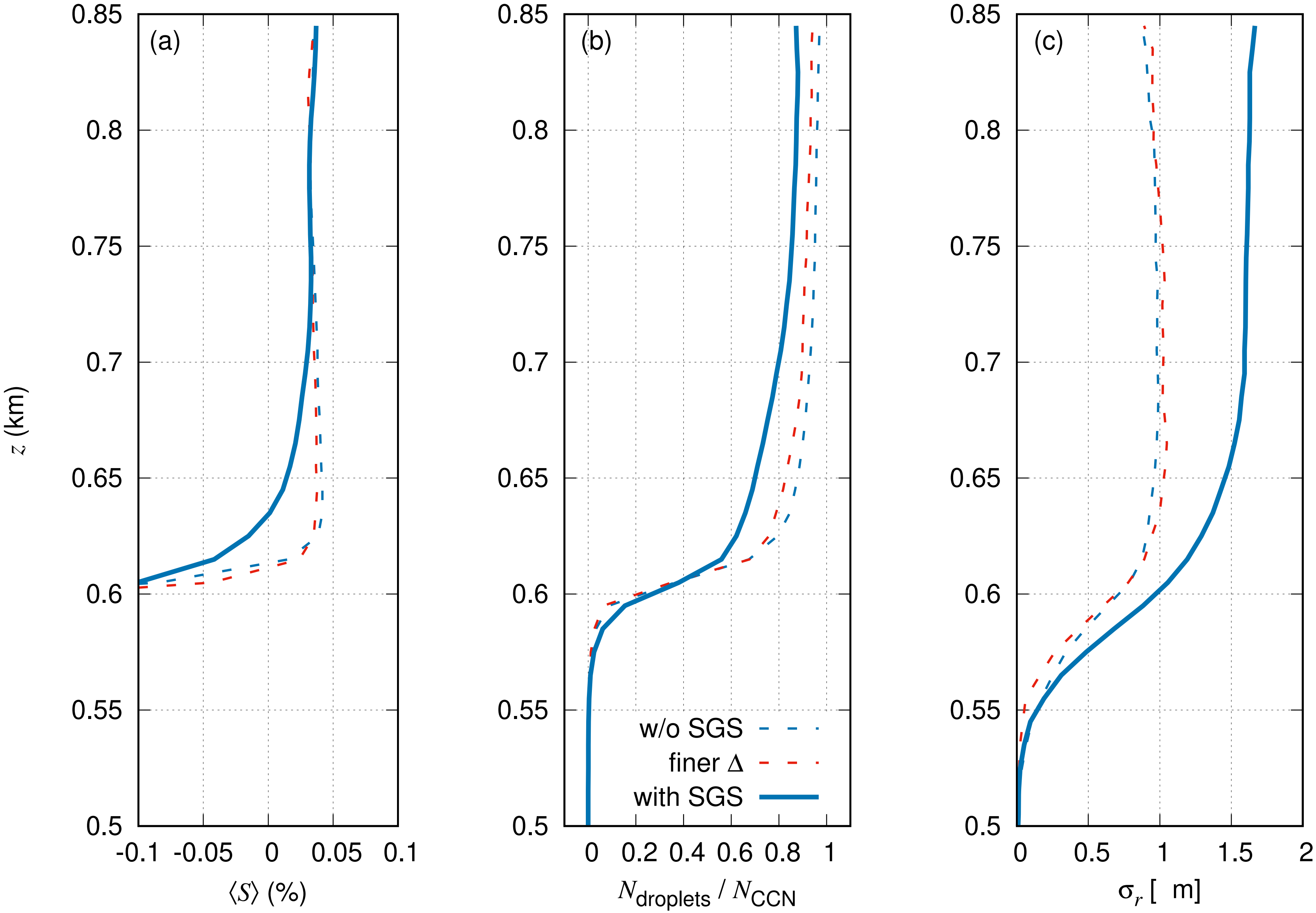

Summary and outlook

- Simple model to mimic SGS variability
- Straightforward for super-droplets, difficult for bin microphysics
- Important for rain development through collision/coalescence
- Thermodynamic feedback: extends the distance of activation
- Future: use <u>structural</u> SGS models

Acknowledgements

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