Broadening of droplet spectra and stochastic activation in turbulent clouds

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Workshop on particle-based modeling of cloud microphysics 2018

November 19, 2018
LES of cloud-scale flow

cloud updraft and interfacial instabilities (entrainment)

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

Entrainment

CCN

Entrainment
Köhler potential

Growth equation:

\[ r \frac{dr}{dt} = D \left[ \langle S \rangle - \frac{A}{r} + \frac{B}{r^3} \right] \]

\[ x \equiv r^2 \]

\[ \frac{dx}{dt} = - \frac{\partial V}{\partial x} \]
Köhler potential

Deterministic activation

\[ r \frac{dr}{dt} = D \left[ \langle S \rangle - \frac{A}{r} + \frac{B}{r^3} \right] \]

\[ x \equiv r^2 \]

\[ \frac{dx}{dt} = -\frac{\partial V}{\partial x} \]
On the CCN (de)activation nonlinearities
Sylwester Arabas and Shin-ichiro Shima

Phase portraits

\[ \text{RH} = S + 1, \quad \xi = x \equiv r^2 \]
Stochastic activation

Köhler potential plus fluctuations

\[ r \frac{dr}{dt} = D \left[ \langle S \rangle + S' - \frac{A}{r} + \frac{B}{r^3} \right] \]

\[ x \equiv r^2 \]

\[ \frac{dx}{dt} = - \frac{\partial V}{\partial x} + 2DS' \]

Abade, Grabowski and Pawłowska, JAS, 75 (2018)
Stochastic activation
Köhler potential plus fluctuations

\[ r \frac{dr}{dt} = D \left[ \langle S \rangle + S' - \frac{A}{r} + \frac{B}{r^3} \right] \]

\[ x \equiv r^2 \]

\[ \frac{dx}{dt} = - \frac{\partial V}{\partial x} + 2DS' \]

Abade, Grabowski and Pawłowska, JAS, 75 (2018)
Stochastic activation

\[ S = \langle S' \rangle + S' \]

**Köhler potential**

![Diagram showing Köhler potential with relevant conditions and labels.]

**Feedback on \( \langle S' \rangle \)**

![Diagram illustrating feedback on the average of \( S' \) with specific conditions and labels.]

Abade, Grabowski and Pawłowska, JAS, 75 (2018)
Supersaturation and velocity fluctuations

\[ \frac{dS_i'}{dt} = -\frac{S_i'}{\tau_c} - \frac{S_i'}{\tau_m} + aW_i'(t) \]

\[ \tau_c \sim \frac{1}{DN\langle r \rangle} \quad \text{(condensation)} \]

\[ \tau_m \sim \text{eddy turnover time (mixing)} \]

- Statistical model for \( W'(t) \)

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

Stationary homogeneous isotropic turbulence

\[ \langle W'(t) \rangle = 0 \]

\[ \langle W'(0)W'(t) \rangle = \sigma^2_W, \exp(-|t|/\tau_m) \]

Kolmogorov scaling (inertial subrange)

\[ \sigma^2_W \sim (L\varepsilon)^{2/3} \quad \tau_m \sim \frac{L^{2/3}}{\varepsilon^{1/3}} \]
Super-droplets (SDs)

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

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

- Multiplicities:
  \[ \xi_1 = 6, \xi_2 = 10, \ldots \]

- SDs have the same attributes
  \[ (r, \ldots, S', W', \ldots) \]

- Well-mixed

10 – 100 meters
Frameworks

- Entraining cloud parcel
- Synthetic turbulent-like ABL flow
Entraining cloud parcel

stochastic entrainment events

$\lambda \sim 200 \text{ m}$

\[ \langle W \rangle \]

Decreasing pressure and temperature

LCL

Entrainment of unsaturated air + CCN

Cool

Entrainment rate

$\mu = \frac{1}{m} \frac{dm}{dt}$

Warm

Krueger et al., JAS, 54 (1997); Romps and Kuang, JAS, 67 (2010)
Droplet-size distribution
after a 1-km parcel rise

PDF($r > r_c$) [µm$^{-1}$] vs $r$ [µm]

adiabatic, non-turbulent
Droplet-size distribution
after a 1-km parcel rise
Droplet-size distribution

after a 1-km parcel rise
Droplet-size distribution

after a 1-km parcel rise
Droplet-size distribution

after a 1-km parcel rise

(a) adiabatic, non-turbulent
(b) adiabatic, turbulent

PDF\((r > r_c)\) (µm\(^{-1}\))

PDF\((r)\) (µm\(^{-1}\))

\(r\) (µm)
Stochastic activation and feedback on $\langle S \rangle$

Adiabatic parcel
Stochastic activation and feedback on $\langle S \rangle$
Aerosol indirect effect

induced by turbulence

\[ \tau_c \approx 1 \text{ s} \]

\[ \tau_c \approx 8 \text{ s} \]

\[ \tau_m \approx 45 \text{ s} \]

\[ N_{\text{CCN}} = 25 \text{ cm}^{-3} \]

- fast \times slow microphysics

\[
\frac{dS'}{dt} = - \frac{S'}{\tau_S} + aW'(t), \quad \tau_S \sim \min\{\tau_{\text{condens}}, \tau_{\text{mixing}}\}
\]

Chandrakar et al., PNAS, 113 (2016); Siebert and Shaw, JAS, 74 (2017)
Turbulent-like ABL flow

\[ u(r, t) = \sum_{|k_n| < K} \hat{u}(k_n, z, t) \exp(i k_n \cdot r) \]

turbulence resolution, \( \Delta = \frac{2\pi}{K} \)

Pinsky et al., JAS, 2008
Turbulent-like ABL flow

Statistical structure

\[ \langle w^2 \rangle = \sigma_w^2(z) \quad C_w(x, z) = \langle w(x', z) w(x' + x, z) \rangle \]
Turbulent-like ABL flow

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

- Balance equations for entropy and water vapor

- grid spacing $< \Delta$

- Super-droplets

- $\epsilon = 10^{-3} \text{ m}^2 \text{ s}^{-3}$ everywhere
Turbulent-like ABL flow

Droplet-size PDF
Turbulent-like ABL flow

Droplet-size PDF
Turbulent-like ABL flow

Droplet-size PDF

(a) $z = 845 \text{ m}$

no SGS model

$\varepsilon = 10^{-3} \text{ m}^2 \text{ s}^{-3}$

(b) $z = 725 \text{ m}$

(c) $z = 605 \text{ m}$
Turbulent-like ABL flow

Droplet-size PDF

PRISTINE conditions

POLLUTED conditions
Microphysical profiles

horizontally averaged
Microphysical profiles

horizontally averaged

(a)

(b)

(c)
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 structural SGS models
Acknowledgements

University of Hyogo and R-CCS

UNIwersytet Warszawski

National Science Centre
Poland