Effect of Turbulent Enhancement of Collision-coalescence on Warm Rain Formation in Maritime Shallow Convection

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Cloud-turbulence problem spans a wide range of scales

from few hundred of meters (small cumulus) down to
1 mm (a typical mean distance between cloud droplets) –
the typical Kolmogorov microscale for cloud turbulence

Such a range cannot be resolved by single model - multiscale
approaches and theory help us to understand the interactions
between turbulence and cloud particles
Multiscale interactions in atmospheric clouds

The turbulent kinetic energy flows from cloud-scale motion to dissipative eddies.

Turbulent kinetic energy

cloud-scale flow

~ 1 km

Entraining eddies (energy-containing)

~ 100 m

Inertial -range eddies

10 cm ~ 10 m

Dissipative eddies

1 mm ~ 1 cm

Latent heat energy

Latent heat energy flows from individual droplets to cloud-scale motion.

typical cloud of dimension 1 km could consist of \( O(10^{17}) \) droplets
Multiscale interactions in atmospheric clouds

Full spectrum of scales divided into two ranges: LES and DNS

- Cloud-scale flow
- Entraining eddies (energy-containing)
- Inertial-range eddies
- Dissipative eddies

LES

DNS

Cloud-resolving LES
- L \approx 1 \text{ km}
- dx \approx 1 \text{ m}

Hybrid DNS
- L \approx 1 \text{ m}
- dx \approx 1 \text{ mm}

GAP
The hybrid DNS approach: including disturbance flows due to droplets

\[ \vec{U}(\vec{x}, t) + \sum_{k=1}^{N_p} \vec{u}_s(\vec{r}_k; a_k, \vec{V}_k - \vec{U}(\vec{Y}_k, t) - \vec{u}_k) \]

Features: Background turbulent flow can affect the disturbance flows; No-slip condition on the surface of each droplet is satisfied on average; Both near-field and far-field interactions are considered.

Large Eddy Simulations vs HDNS

- Only the large eddies need to be resolved
- Important small-scale processes can be parameterized
- Problem of intermittency

♦ Multi-phase DNS approach: following individual droplets; impractical for LES and larger-scales.

♦ Continuous-medium approach: condensed water as mixing ratios (total mass of particles per unit of mass of air)
Nonhydrostatic, anelastic, Navier-Stokes

\[
\frac{dv}{dt} = \nabla \pi' - g \frac{\theta'}{\bar{\theta}} + D_m(\kappa_m, e, v)
\]

\[
\frac{d\theta'}{dt} = -v \cdot \nabla \theta_e + \frac{L_v}{\Pi c_p} C + D_\theta(\kappa_h, e, \theta)
\]

\[
\frac{dq_v}{dt} = -C + D_{q_v}(\kappa_h, e, q_v)
\]

\[
\frac{de}{dt} = S(e)
\]

\[
\nabla \cdot (\bar{\rho} v) = 0
\]

\[
\frac{\partial f}{\partial t} + \frac{1}{\bar{\rho}} \nabla \cdot (\bar{\rho} [v - k v_t(r)] f) + \frac{\partial}{\partial r} \left( \frac{dr}{dt} f \right) = \left( \frac{\partial f}{\partial t} \right)_{ACT} + \left( \frac{\partial f}{\partial t} \right)_{COAL} + D_f(\kappa_h, e, f)
\]

\(f\) – spectral density of cloud drops   \(f(r) = dn(r) / dr\)  \(dn(r)\)  Droplet concentration between \((r, r + dr)\)

\(\theta_d = \theta + \bar{\theta} (\varepsilon q_v - q_c)\)

Density potential temperature

\(\pi' = p' / \bar{\rho}\)

Normalized pressure perturbation

\(C = -\frac{4}{3} \pi \rho_w \int r^3 \frac{\partial}{\partial r} \left( \frac{dr}{dt} f \right) dr\)  Condensation rate

\(q_c = \frac{4}{3} \pi \rho_w \int r^3 f dr\)  Condensed water vapor
Nonhydrostatic, anelastic, Navier-Stokes

\[ \frac{\partial f}{\partial t} + \frac{1}{\rho} \nabla \cdot \left( \overline{\rho} [\mathbf{v} - k \mathbf{v}_t(r)] f \right) + \frac{\partial}{\partial t} \left( \frac{dr}{dt} f \right) = \left( \frac{\partial f}{\partial t} \right)_{ACT} + \left( \frac{\partial f}{\partial t} \right)_{COAL} + D_f \]

\[ \frac{d \delta}{dt} = Bw - \frac{\delta}{\tau} \]
\[ \delta \text{ - absolute supersaturation} \]

\[ \frac{dN_{ACT}}{dt} = DN_{ACT} \]
\[ N_{ACT} \text{ - concentration of activated droplets} \]
\[ (\text{if no collision/coalescence } N_{ACT} = N) \]

\[ DN_{ACT} \text{ - tendency due to cloud droplet activation and deactivation} \]

\[ \tau \sim \int rfdr \]
\[ \tau \text{ - phase relaxation time scale} \]

\[ N = \int fdr \]
\[ N \text{ - total concentration of cloud droplets} \]

\[ r(i) = 0.25(i - 1) + 10^{0.055(i-1)} \]
\[ r \text{ - mean radius [μm]} \]
WARM RAIN PROCESS

Time scale of raindrop development:

In real clouds: 15 min

Condensation only: 120 min.
WARM RAIN PROCESS

- Larger drops are created by coagulation, i.e. by mutual collision of droplets

- quasi-stochastic collection equation (SCE) + collection kernel usually dominated by the gravitational sedimentation of the droplets, i.e. bigger droplets fall faster than smaller ones -> larger drops collect smaller and slower droplets located in the swept volume

- collision efficiency: not all droplets in the geometrical swept volume are collected (Hall1980 - drops move in air at rest, with gravity being the only external force.)

- purely gravitational coagulation becomes effective only for cloud droplets with radii larger than about 20μm (Beard and Ochs, 1993; Pruppacher and Klett, 1997).

- collision–coalescence process effective for mid size droplets (Wang and Grabowski, 2009).

- kinematic collection kernel (Saffman and Turner 1956)
TURBULENCE AFFECTS GROWTH OF DROPLETS

Growth by collision/coalescence: nonuniform distribution of droplets in space affects droplet collisions…

Turbulence effects on the collision-coalescence process
1. turbulent transport - turbulence modifies the relative velocity between colliding droplets
2. preferential concentration - formation of spatial inhomogeneities in droplet concentration
3. hydrodynamic interaction – influences flow around droplets, modifying collision efficiency
TURBULENCE AFFECTS GROWTH OF DROPLETS

- broadening of cloud droplet spectra which cannot result from pure condensational growth of droplets: increase in collision/coagulation frequency for droplets with radii roughly between 10 and 50\(\mu\)m (e.g. Brenguier and Chaumat, 2001):

- increase the collision kernel (in a certain size range of droplets) for turbulence accelerations characteristic of clouds (cf. Pinsky, et al., 2006, 2008; Franklin, et al., 2007; Ayala, et al., 2008b; Wang, et al., 2008)

- assumed homogeneous isotropic turbulence with dissipation rates that are smaller measured in clouds -> relatively low Taylor-microscale Reynolds numbers (\(Re_\lambda \leq 500\)), compared with the much larger values (\(Re_\lambda \sim 104\)) observed in real clouds (Vaillancourt and Yau, 2000; Wang, et al., 2005; Siebert, et al., 2006a,b).
Growth of water droplets by gravitational collision-coalescence:

mechanisms of turbulent enhancement of gravitational collision/coalescence:

- Turbulence modifies local droplet concentration (preferential concentration effect)

- Turbulence modifies relative velocity between colliding droplets (e.g., small-scale shears, fluid accelerations)

- Turbulence modifies hydrodynamic interactions when two droplets approach each other

Collision efficiency:

\[ E_c = \frac{y_c^2}{(a_1 + a_2)^2} \]
Collisions between drops

Stochastic equation for collisions:

\[
\frac{\partial f(m,t)}{\partial t} = \int_0^{m/2} f(m',t)K(m',m-m')f(m-m',t)dm' - \int_0^\infty f(m,t)K(m,m')f(m',t)dm',
\]

\(f(m,t)\) – The mass distribution function for drops (of mass \(m\) at time \(t\))

Probability of collision of droplets \(m_1\) and \(m_2\) in unit of time

\[K(m_1, m_2) = \pi(r_1 + r_2)^2 \left| V_1 - V_2 \right| E^g(r_1, r_2)\]

Collision kernel Geometrical cross section Relative drop velocity Collision efficiency

\[K(m_1, m_2) = E^o(r_1, r_2)E^g(r_1, r_2)\eta_E\]

collision-efficiency enhancement factor \(\eta_E\) obtained from HDNS; Wang et al. 2005, Ayala et al. 2007, Wang et al. 2008)
Enhancement factor for the collision kernel (the ratio between turbulent and gravitation collision kernel in still air) including turbulent collision efficiency; \( \varepsilon = 100 \) and 400 cm\(^2\) s\(^{-3}\).

The ratio on the 45° degree line is undefined due to the zero value of the Hall kernel. The ratio is essentially one when droplets are above 100 μm. The flow dissipation rate is 400 cm\(^2\)/s\(^3\) and rms velocity is 202 cm/s.
The rate of change ($\frac{\partial g}{\partial t}$, g m$^{-3}$ s$^{-1}$) of droplet mass density in each numerical bin as a function of droplet radius:

- Autoconversion
- Accretion
- Hydrometeor self-collection (Berry and Reinhardt, 1974)

Flow dissipation rate of 400 cm$^2$/s$^3$ and root mean square (rms) fluctuation velocity of 2.0 m/s.
Idealized baby-EULAG 2D simulations with bin microphysics:

Setup as in Grabowski et al (JAS 2009): 2D domain, 50 m
gridlength, 72 bins, maritime aerosol.

Initial moisture perturbation
(temperature perturbation as well)
2D simulation of a small precipitating cloud: $t=16$ min

*no turbulence*

*with turbulence - Ayala kernel with 100 cm$^2$s$^{-3}$*
2D simulation of a small precipitating cloud: \( t=20 \ \text{min} \)

**no turbulence**

**with turbulence**

with turbulence - Ayala kernel with 100 cm\(^2\)s\(^{-3}\)
2D simulation of a small precipitating cloud: $t=26$ min

**no turbulence**

**with turbulence**

**with turbulence - Ayala kernel with 100 cm$^2$s$^{-3}$**
Time evolution of the surface precipitation intensity in an idealized simulation of a small precipitating cloud:

Turbulent collisions lead to earlier rain at the ground and higher peak intensity…
Time evolution of the surface rain accumulation

...but also to more rain at the surface. This implies higher precipitation efficiency!
MICROPHYSICS OF SHALLOW CONVECTIVE CLOUDS

- Why and how clouds form?
- How cloud droplets grow into raindrops?
- Growth of cloud droplets in adiabatic cores.
- Entrainment

Factors affecting cloud droplet sizes and concentrations
- in-cloud activation,
- homogeneity of parameterized subgrid-scale mixing
- effect of aerosol (cloud condensation nuclei CCN)
Entrainment leads to fresh activation of cloud droplets and results in multimodal spectra

Brenguier and Grabowski (JAS 1993)
The Barbados Oceanographic and Meteorological Experiment (BOMEX) case (Holland and Rasmusson 1973)

**Fig. 1.** Initial profiles of the total water specific humidity $q_t$, the liquid water potential temperature $\theta_t$, and the horizontal wind components $u$ and $v$. The shaded area denotes the conditionally unstable cloud layer.

**Siebesma et al. JAS 2003**
LES bin-microphysics simulation of shallow convection
Wyszogrodzki et al. (*Acta Geophysica* 2012)

Cloud condensation nuclei (CCN)

\[
N_{CCN} = \begin{cases} 
3.16 \times 10^6 S^4 & \text{if } S < 0.1 \\
1000 S^{0.5} & \text{if } 0.1 < S < 1.0 \\
1000 & \text{if } S > 1.0 
\end{cases}
\]

\[
N_{CCN} = \begin{cases} 
4.78 \times 10^5 S^4 & \text{if } S < 0.1 \\
120 S^{0.4} & \text{if } 0.1 < S < 1.0 \\
120 & \text{if } S > 1.0 
\end{cases}
\]

 activations

\[N_{CCN} = \begin{cases} 
3.16 \times 10^6 S^4 & \text{if } S < 0.1 \\
1000 S^{0.5} & \text{if } 0.1 < S < 1.0 \\
1000 & \text{if } S > 1.0 
\end{cases}
\]

A Supressed activation above 700m

B

Cloud water mixing ratio

---

activation tendency
Effective radius (ratio between the third and the second moment of the cloud droplets size distribution)

Droplet concentrations

Activation not allowed above 700m

Activation always on
Cloud droplets size distribution

Spectra at height 740

Spectra at height 1040

Spectra at height 680

Spectra at height 1040
EFFECT OF AEROSOL

Large CCN are nucleated first, activation of smaller ones follow as the supersaturation builds up.

In general, concentration of activated droplets depends on the updraft speed at the activation region and characteristics of CCN (e.g., clean maritime versus polluted continental).

\[ N = a S^b \]

\( N \) - total concentration of activated droplets

\( S \) – supersaturation (in %)

\( a, b \) – parameters characterizing CCN:

- \( a \sim 100 \text{ cm}^{-3} \) – pristine (e.g., maritime) air
- \( a \sim 1,000 \text{ cm}^{-3} \) – polluted (e.g. continental) air

\( 0 < b < 1 \) (typically, \( b=0.5 \))
Indirect aerosol effects (warm rain) - impact on cloud processes, radiation and hydrological cycle

1\textsuperscript{st} Indirect effect

2\textsuperscript{nd} Indirect Effect

cloud base

cloud updraft

maritime ("clean")    continental ("polluted")
correlation versus causality:

If clouds correlate with aerosol, this does not imply that aerosols are solely responsible for changing clouds…

Clouds and aerosol can simply vary together (for instance, because of the large-scale advection patterns…).

cloud-ensemble /system-dynamics includes all the feedbacks and forcings in the system

Rosenfeld et al. Science, 2008
The Barbados Oceanographic and Meteorological Experiment (BOMEX) case (Holland and Rasmusson 1973)

**Fig. 1.** Initial profiles of the total water specific humidity $q_t$, the liquid water potential temperature $\Theta_t$, and the horizontal wind components $u$ and $v$. The shaded area denotes the conditionally unstable cloud layer.

*Siebesma et al. JAS 2003*
collision-efficiency enhancement factor $\eta_E$ depends on the flow energy dissipation rate
R<25 microns (cloud droplets)

- Gravity only
- Gravity + turbulence

25<R<40 microns (mist)

- Gravity only
- Gravity + turbulence

- $N_0=30$
- $N_0=60$
- $N_0=120$
- $N_0=240$
40<R<100 microns (drizzle)

100<R microns (rain)

\( N_0 = 30 \)
\( N_0 = 60 \)
\( N_0 = 120 \)
\( N_0 = 240 \)

gravity only     gravity + turbulence
Precipitation flux droplets 40<R microns
Simulations of a shallow cumulus field – the BOMEX case

**N₀ = 30**

**N₀ = 60**

**N₀ = 120**

Qᵣ – cloud water mixing ratio
Conclusions:

• Activation of cloud droplets above the cloud base is essential for realistic simulation of cloud microphysics.

• Activation mimic entrainment-related activation observed in higher-resolution cloud simulation, and is the key to understand droplet spectral evolution in clouds.

• Guided by DNS, turbulent enhancement of the gravitational collision kernel has been developed (Ayala et al. papers).

• Simple tests show that turbulence can significantly enhance growth of cloud droplets by collision/coalescence, resulting in earlier rain formation, but also in more rain falling from a given cloud.

• More realistic large-eddy simulations based on BOMEX with local enhancement of the kernel assess the impact of turbulence on rain development.