DNS study of the effect of turbulence on condensational and collisional growth of cloud droplets - Warm-Rain Initiation

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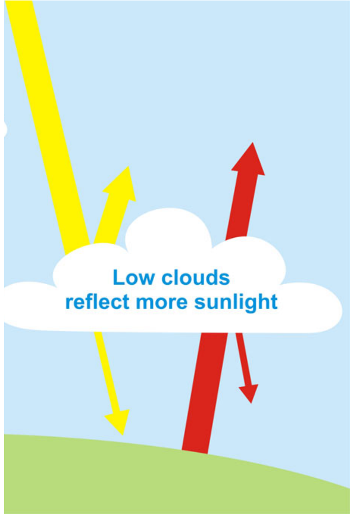
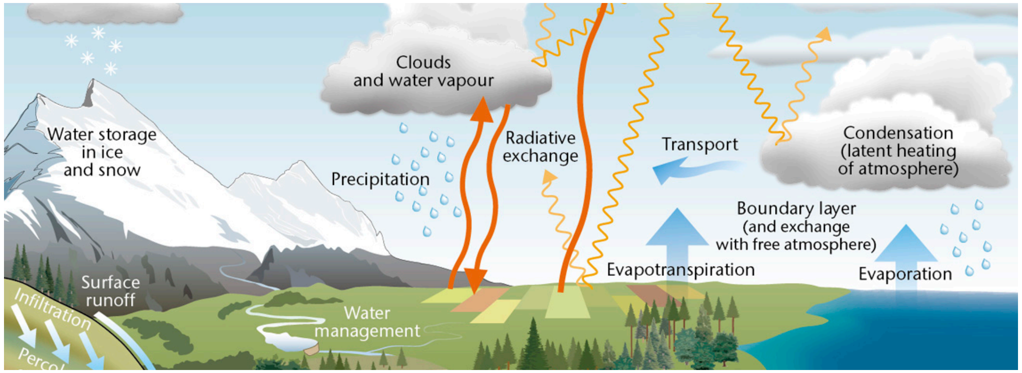
Radiation budget



Hydrological cycle



(Fig credit: Metoffice)

Redistribute water through condensation/precipitation

Reflect SW to cool atmosphere

Warm cloud system

Disasters and accidents

Contriibute 31% of total rainfall on the planet & 72% in tropical regions (Lau & Wu, 2003)

2013 Corolado flood

(Photo credit: Denver Post)

Aircraft carburetor icing

http://www.flightsafetyaustralia.com

2013 Colorado floods

- A warm-rain process (Friedrich et al., 2016)
- Caused $2 billion US dollars of damages.

Denver Post https://www.denverpost.com/2017/09/14/colorado-floods-2013-photos/

Shallow cloud system

Why research still needed?

- Representation of low clouds remains a dominant source of uncertainty in climate models (IPCC AR5)
- Poor understanding of cloud microphysics leads to poor simulation of cloud properties using LES and CRMs, and inaccurate forecast of precipitation in NWPs(Fan et al., 2016)
- No convergence of model results using different microphysics schemes (White et al. 2017; Xue et al., 2017)

Microphysical processes in warm clouds

Warm cloud system

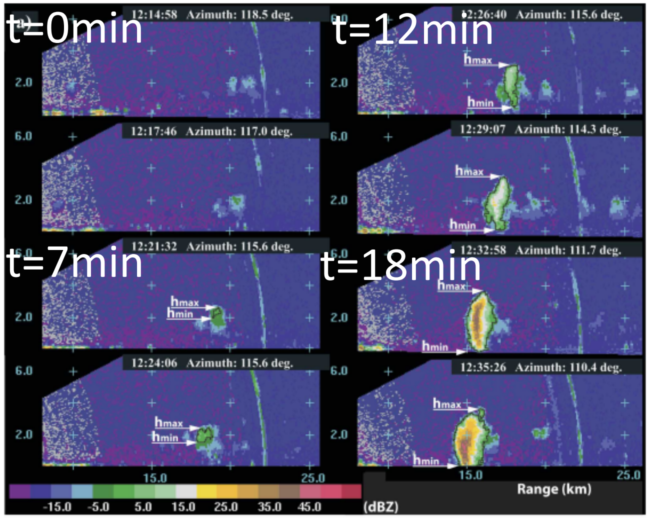
Processes involved in the formation and evolution of cloud droplets and raindrops, such as condensation, evaporation, collision~~, and breakup~~.

Warm rain initiation:
Discrepancy between observation and theory

Observations

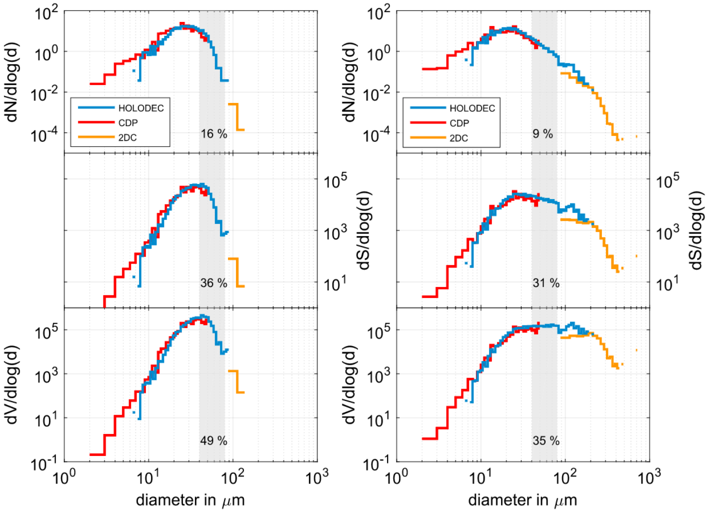
- Fast rain initiation (~15-20min)
- Heavy precipitation
- Broad droplet size distributions

Fast warm rain formation



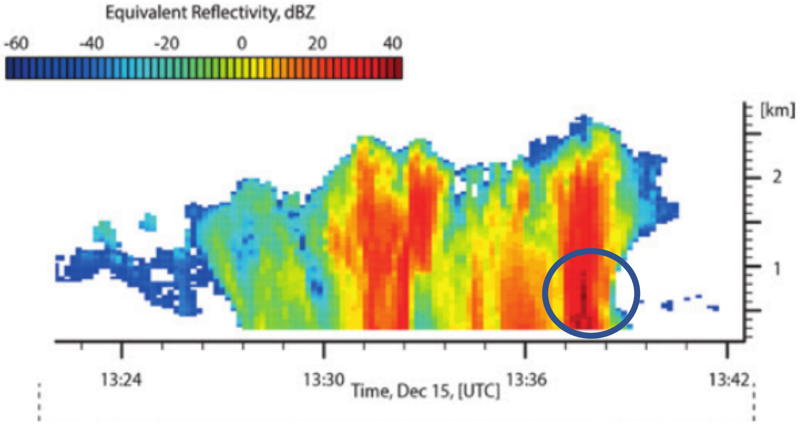
SABINE GÖKE (2007)

Broad DSDs in stratocumulus



(Glienke et al., 2017)

Strong echo in trade wind cumuli



(B. Stevens et al. 2016)

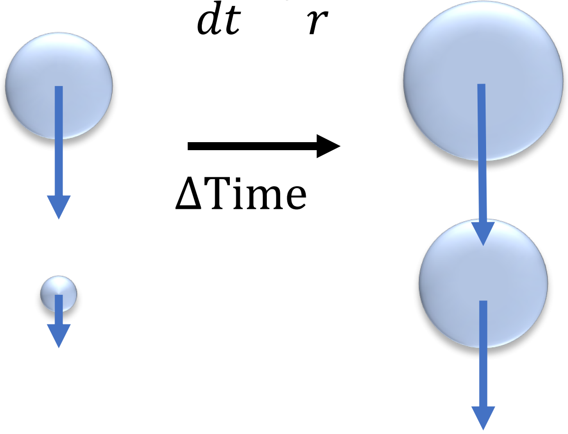
Warm rain initiation:
Discrepancy between observation and theory

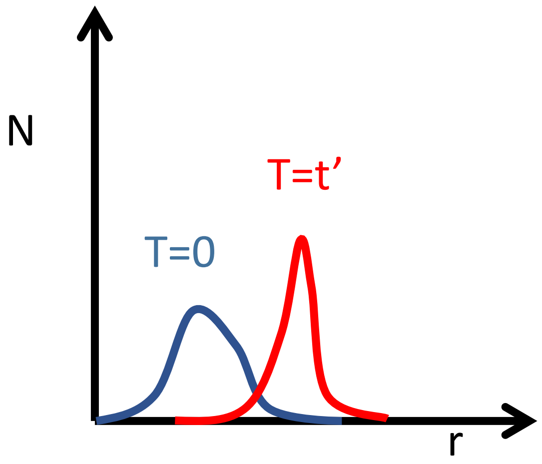
Theoretical Models

- Narrow droplet size distribution from condensational growth
- Effective to grow drops to about 15 microns

Condensational growth rate:

$$\frac{dr}{dt} \propto \frac{1}{r}$$

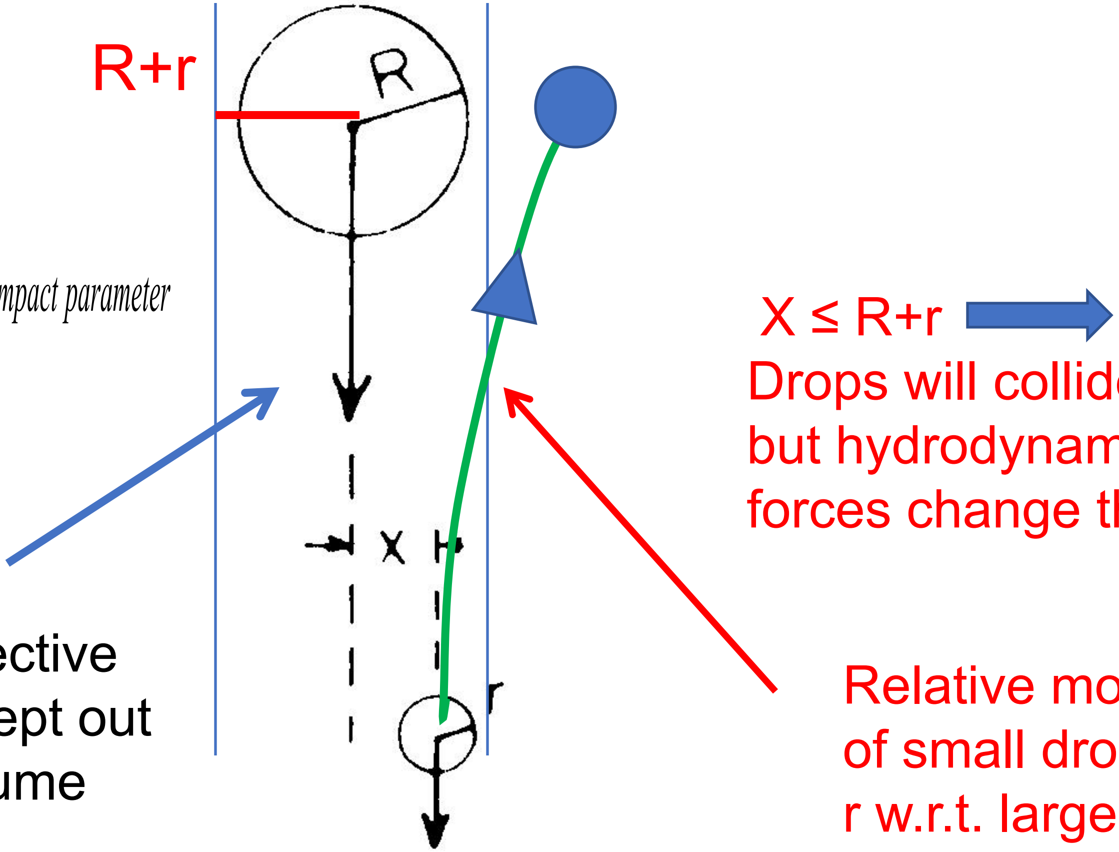




Next stage – collision growth

(R or r2 is collector drop radius)

$$\text{Collision efficiency } E(R,r)=\frac{X_0^2}{(R+r)^2},\quad X_0=\text{critical impact parameter}$$



R+r

X ≤ R+r

Drops will collide but hydrodynamic forces change this

Effective Swept out volume

Relative motion of small droplet r w.r.t. large drop R

FIG. 8.1. Collision geometry.

Non-turbulent Collision Efficiencies

R

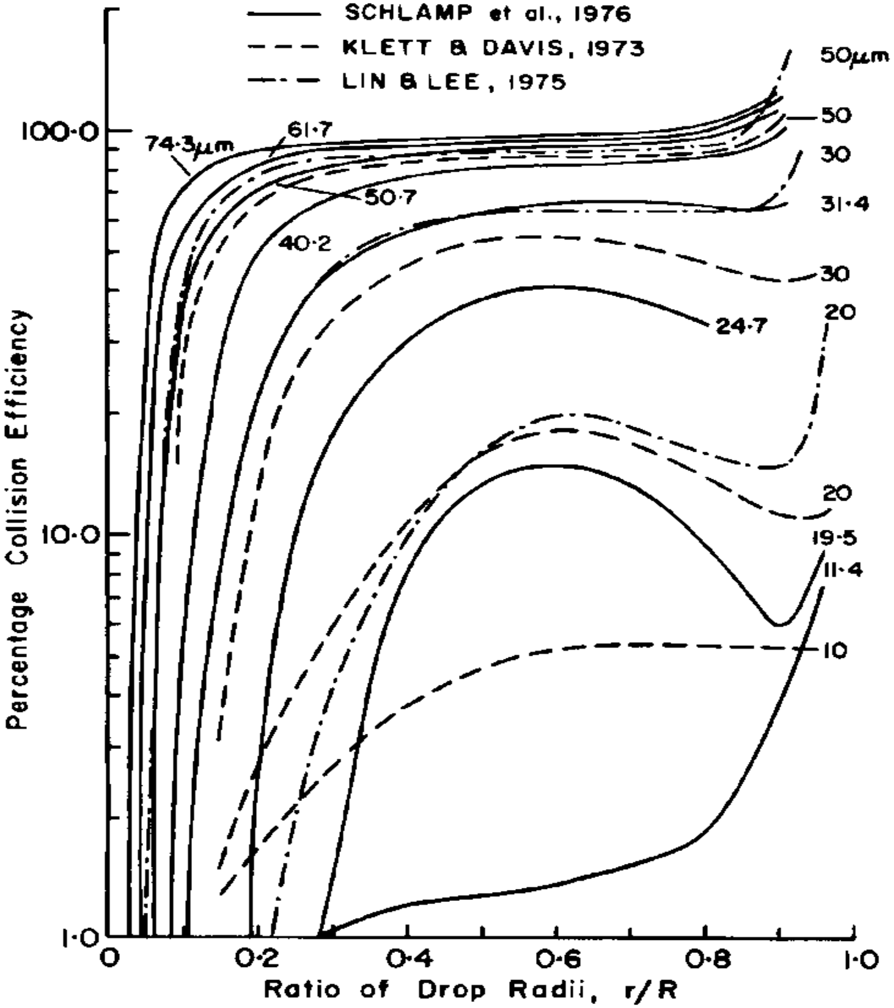
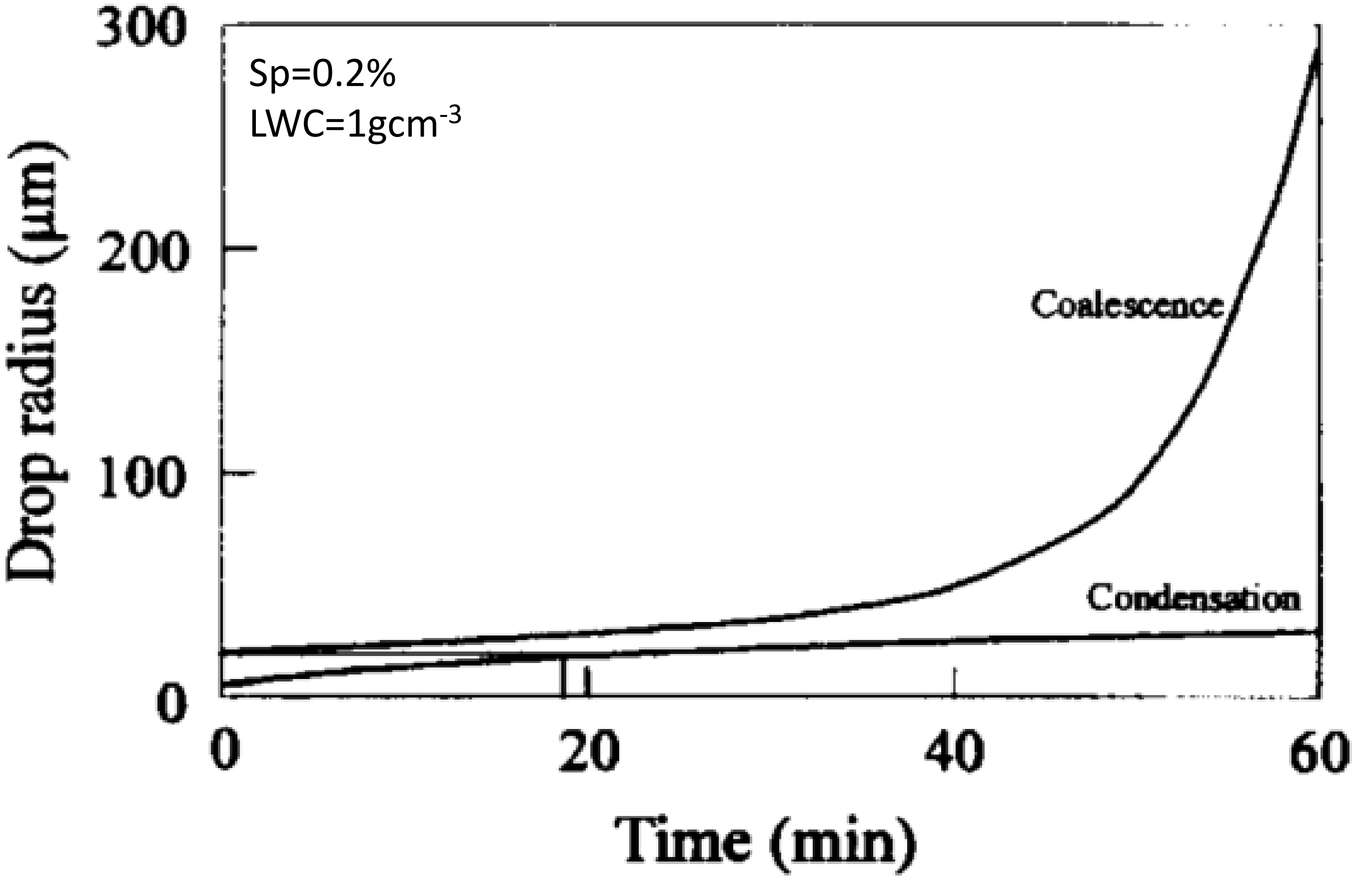


FIG. 8.2. Computed collision efficiencies for pairs of drops as a function of the ratio of their radii. Curves are labeled according to the radius *R* of the larger drop.

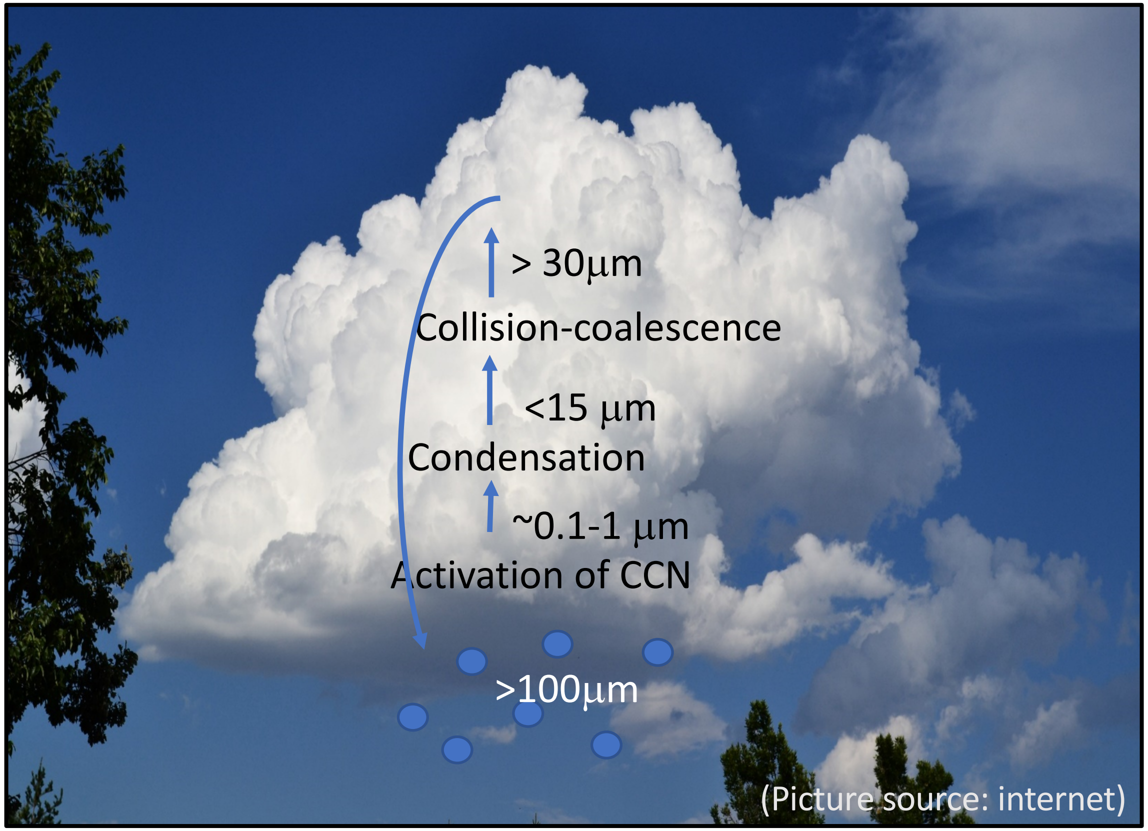
Note: E ~ 10% only when R<20 μm

>1hr to produce drizzle drops



(Jonas 1996)

Condensation-collision bottleneck



(Picture source: internet)

Condensational growth $\frac{dr}{dt} \propto \frac{1}{r}$

1) narrows the droplet size distribution (DSD)
2) is only effective for r<15μm

Condensation-collision bottleneck

Effective gravitational collisional growth requires:

1) broad droplet size distribution (DSD)
2) large droplets (r>30μm)

Possible mechanisms to broaden the droplet size spectrum

- Aerosol effect:
  - Giant aerosols (d>1μm) serve as raindrop embryos (Johnson, 1982, Blyth et al. 2003, Jensen and Nugent 2017, etc.)
  - Low aerosol number concentrations generate large variability of supersaturation (Chandrakar et al. 2016, etc.)
- Cloud-scale mixing
  - Various droplet growth histories through eddy hopping (Cooper 1989, Grabowski and Abade, 2017 etc.)
  - Entrainment of unsaturated air (additional activation of CCN, larger Sp. fluctuation) (Baker et al. 1980, Lasher-Trapp et al. 2005, Tolle and Krueger 2014, etc.)

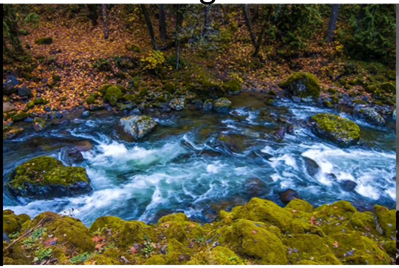
- **Small-scale turbulence**
    - **Induce supersaturation fluctuation** (Vaillancourt and Yau 2000; Vaillancourt, Yau, and Grabowski 2001; Vaillancourt, Yau, Bartello, and Grabowski 2002; Paoli and Shariff 2009, Sadina et al. 2015, etc.)
    - **Speed up in collision**
        - Enhanced geometric collision kernel (Franklin, Vaillancourt, Yau, and Bartello 2005; Franklin, Vaillancourt, and Yau 2007, Ayala et al. 2008 etc.)
        - Enhanced collision efficiency (Wang et al. 2008, Pinsky et al. 2008, etc.)

Turbulence

- Characteristics:
  - Irregularity: chaotic changes in flow velocity
  - Intermittency
  - Multi-scale interactions & energy cascade
  - Dissipation, diffusion, and mixing

Cigarette smoke

Running creak



Billowing clouds

Bumpiness in the air

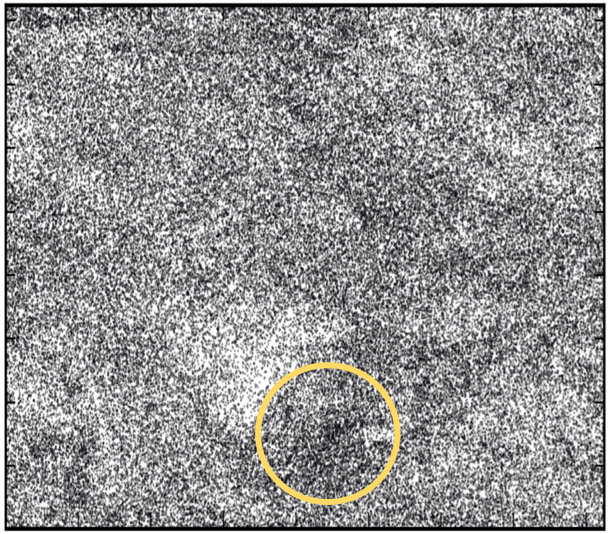
Stirring the coffee

Photos from internet

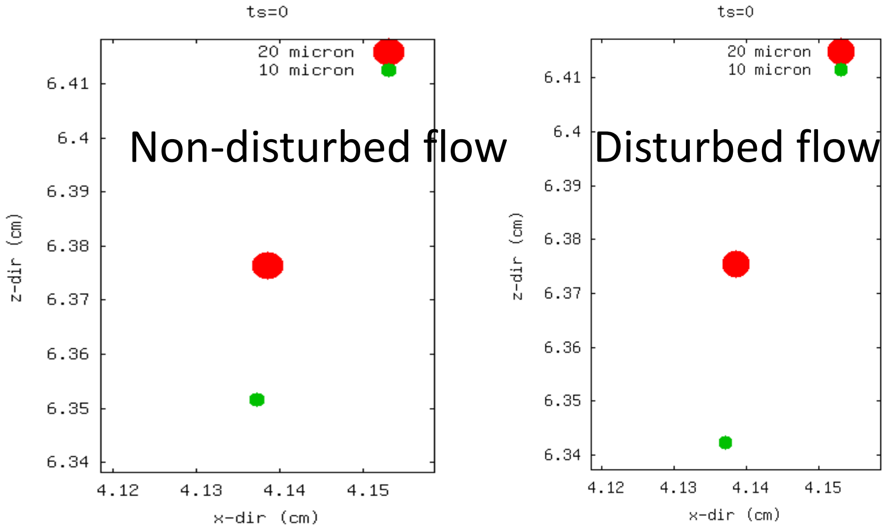
Turbulence mechanisms in speeding up collisions

- Increase clustering
- Increase relative motion
- Counteract droplet hydrodynamic interaction
- Modify the collision rates

Droplet clustering



Droplet hydrodynamic interaction



Non-disturbed flow

Disturbed flow

Research questions

Collision

1. What are the **crucial scales** of turbulent motions related to collisions?
2. How does turbulence affect droplet **geometric collision**?
3. What is the impact on the droplet **hydrodynamic interaction** and thus modify the **collision efficiency**?

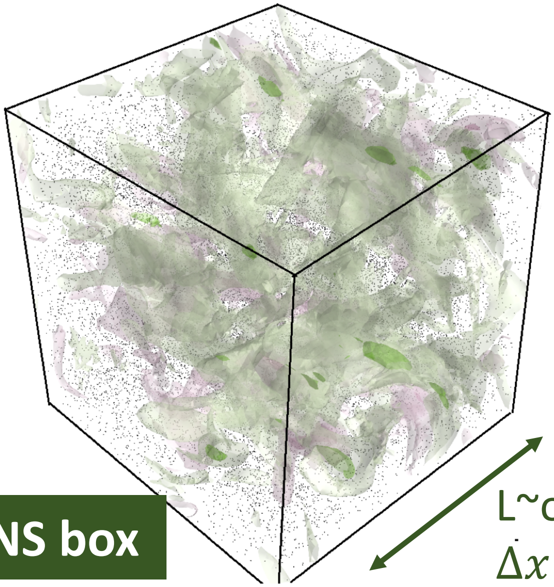
Collision and Condensation

4. How does **condensational** process interact with collisional process?
5. How does turbulence modulate such interaction?
6. What is the role of turbulence in accelerating **rain formation**?

Methodology

Direct Numerical Simulation (DNS)

- Dynamics: homogeneous and isotropic turbulence
- Cloud microphysics: droplet motion, collision, and growth



DNS box

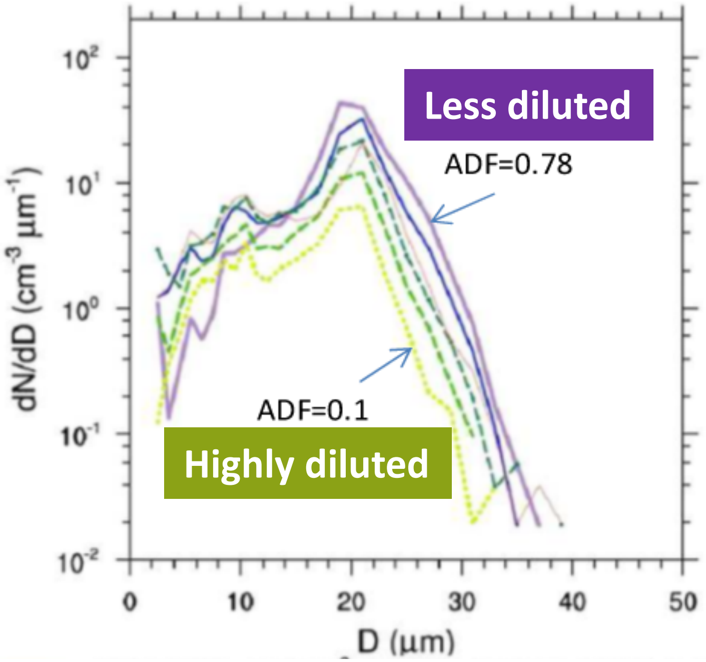
L~o(10cm)

$\Delta x \sim o(1mm)$

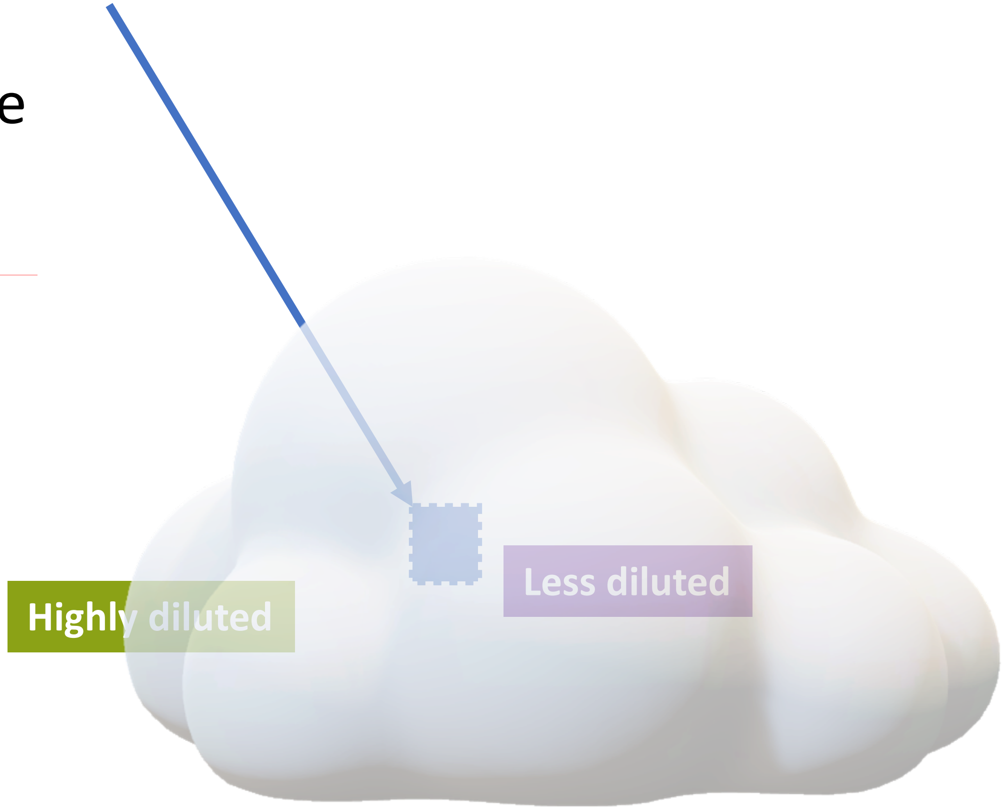
DNS explicitly resolves every scale of the turbulent flow without any parameterization

The adiabatic cloud core

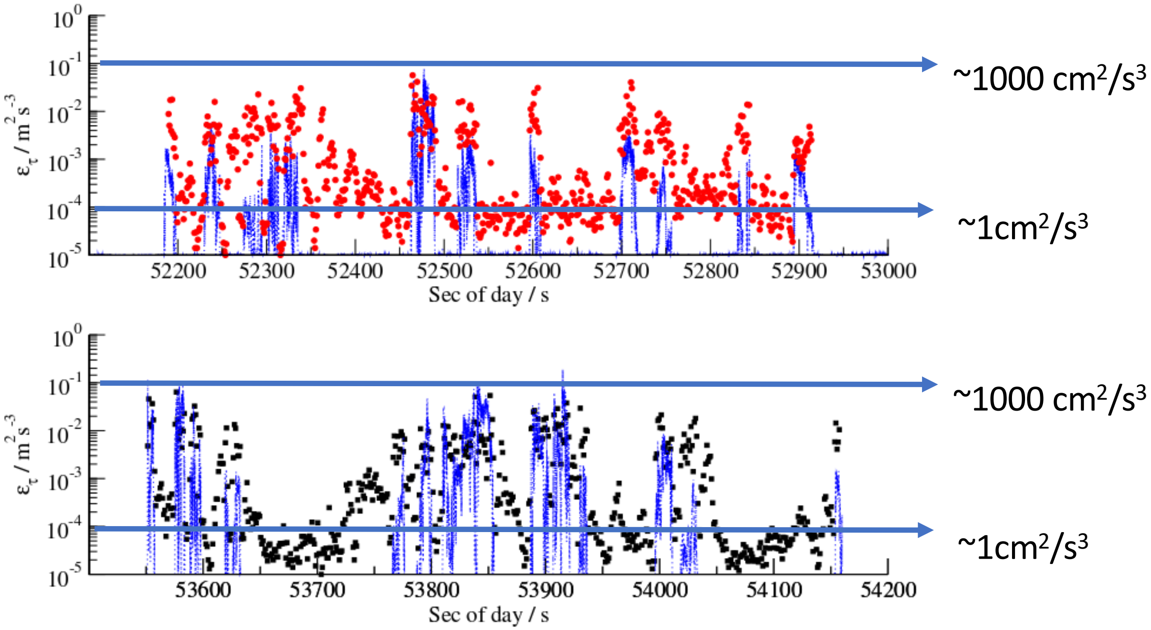
More large droplets than the diluted cloud body.



(Fig. 2 in Khain et al., 2013)



Local eddy dissipation rate in cloudy and cloud-free regions



~1000 cm^2/s^3

~1cm^2/s^3

~1000 cm^2/s^3

~1cm^2/s^3

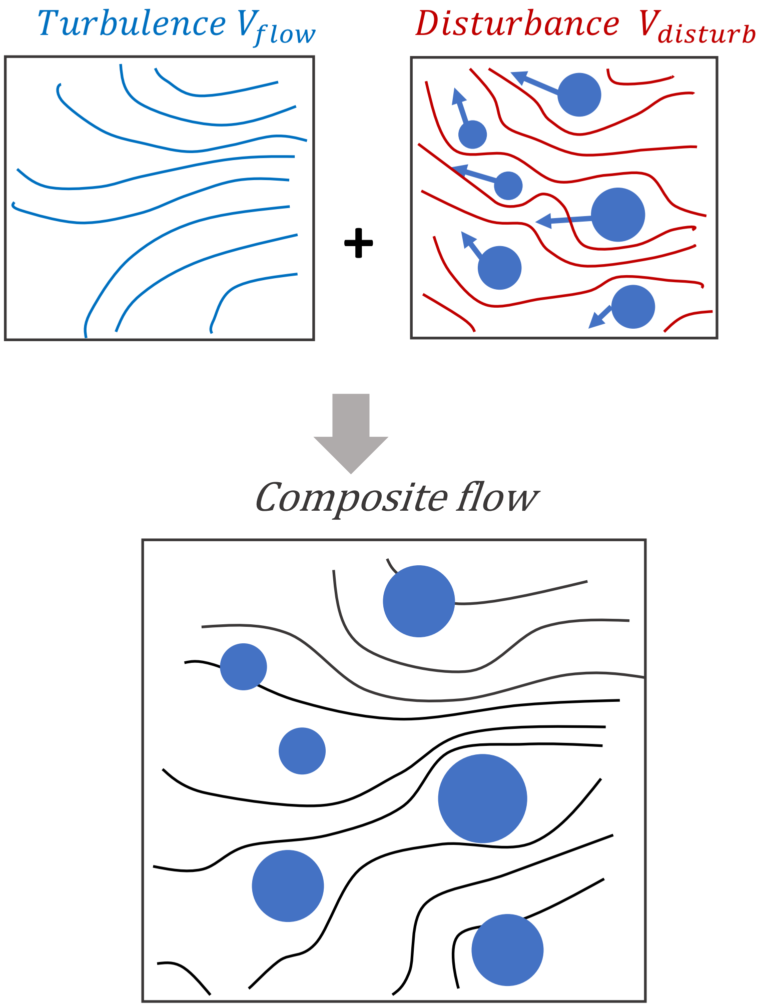
Fig. 12. Time series of local energy dissipation rates ε_τ (symbols) with each point representing a one-second average. The dotted blue lines indicate cloud events (unscaled LWC).

Helicopter-borne measurement by Siebert et al., (2013)

Model equations

- Turbulence flow: 3D homogeneous and isotropic turbulence

$$\begin{cases} \dfrac{\partial \boldsymbol{V}_{flow}}{\partial t} + (\boldsymbol{V}_{flow} \cdot \nabla)\boldsymbol{V}_{flow} = -\dfrac{1}{\rho_a}\nabla P + \nu\nabla^2\boldsymbol{V}_{flow} + \boldsymbol{F} \\ \nabla \cdot \boldsymbol{V}_{flow} = 0 \end{cases}$$



- Droplet disturbance flow:

$$\boldsymbol{V}_{disturb}(\boldsymbol{X}, t) = \sum_{k=1}^{N} \boldsymbol{V}_{disturb}^{(k)}(\boldsymbol{X}, t)$$

$k\ is\ droplet\ index\ number$

- Droplet motion:

$$\frac{d\boldsymbol{V}_{drop}}{dt} = \boldsymbol{F}_D + \boldsymbol{g}$$

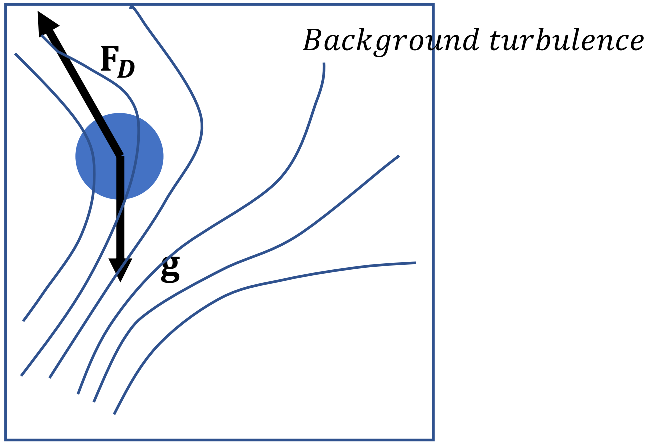
$$\boldsymbol{F}_D = \frac{1}{\tau_{drop}}\left(\boldsymbol{V}_{flow} + \boldsymbol{V}_{disturb} - \boldsymbol{V}_{drop}\right)$$

Resolving the droplet disturbance flow

- Without disturbance flow

$$\frac{dV_{drop}}{dt} = F_D + g$$

$$F_D = \frac{1}{\tau_{drop}}(V_{flow} - V_{drop})$$



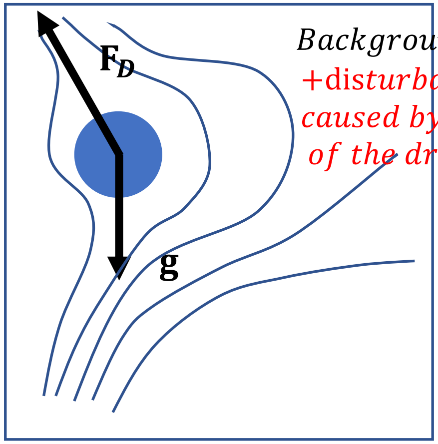
Resolving the droplet disturbance flow

- Droplet disturbance flow

$$V_{disturb} = \left[\frac{3}{4}\frac{r}{d} - \frac{3}{4}\left(\frac{r}{d}\right)^3\right]\frac{\vec{\boldsymbol{d}}}{d^2}\left(\vec{\boldsymbol{V}}_{\boldsymbol{drop}} \cdot \vec{\boldsymbol{d}}\right) + \left[\frac{3}{4}\frac{r}{d} + \frac{1}{4}\left(\frac{r}{d}\right)^3\right]\vec{\boldsymbol{V}}_{\boldsymbol{drop}}$$

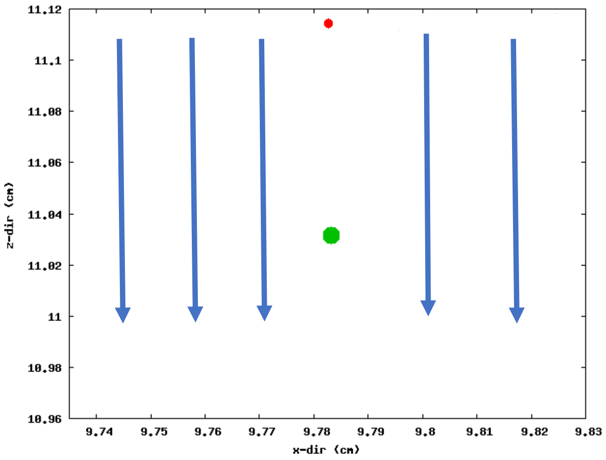
$$\frac{dV_{drop}}{dt} = F_D + g$$

$$F_D = \frac{1}{\tau_{drop}}\left(V_{flow} - V_{drop}\right)$$



Background turbulene
+disturbance flow caused by the present of the droplet

Stokes flow around a sphere



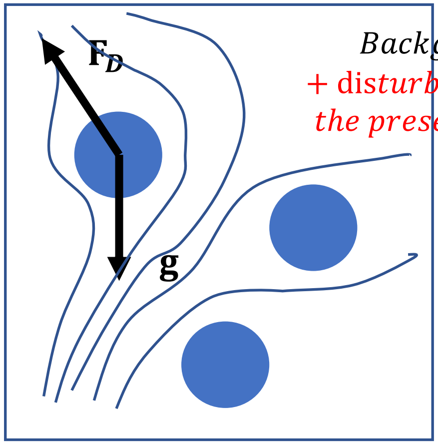
Resolving the droplet disturbance flow

- Droplet disturbance flow

$$V_{disturb}^{(i)} = \sum_{k=1,k\neq i}^{N} V_{disturb}^{(k)}$$

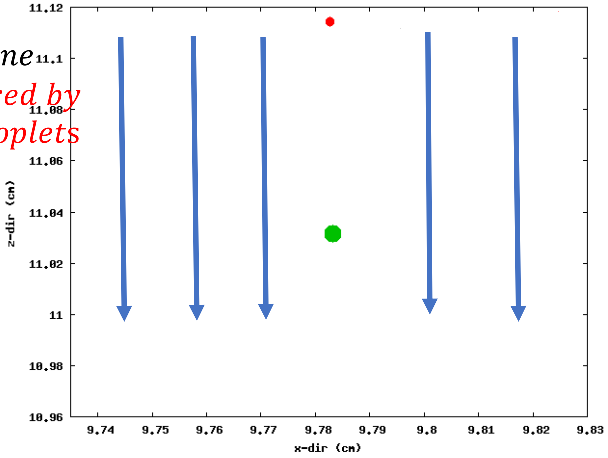
$$\frac{dV_{drop}}{dt} = F_D + g$$

$$F_D = \frac{1}{\tau_{drop}}(V_{flow} + V_{disturb} - V_{drop})$$

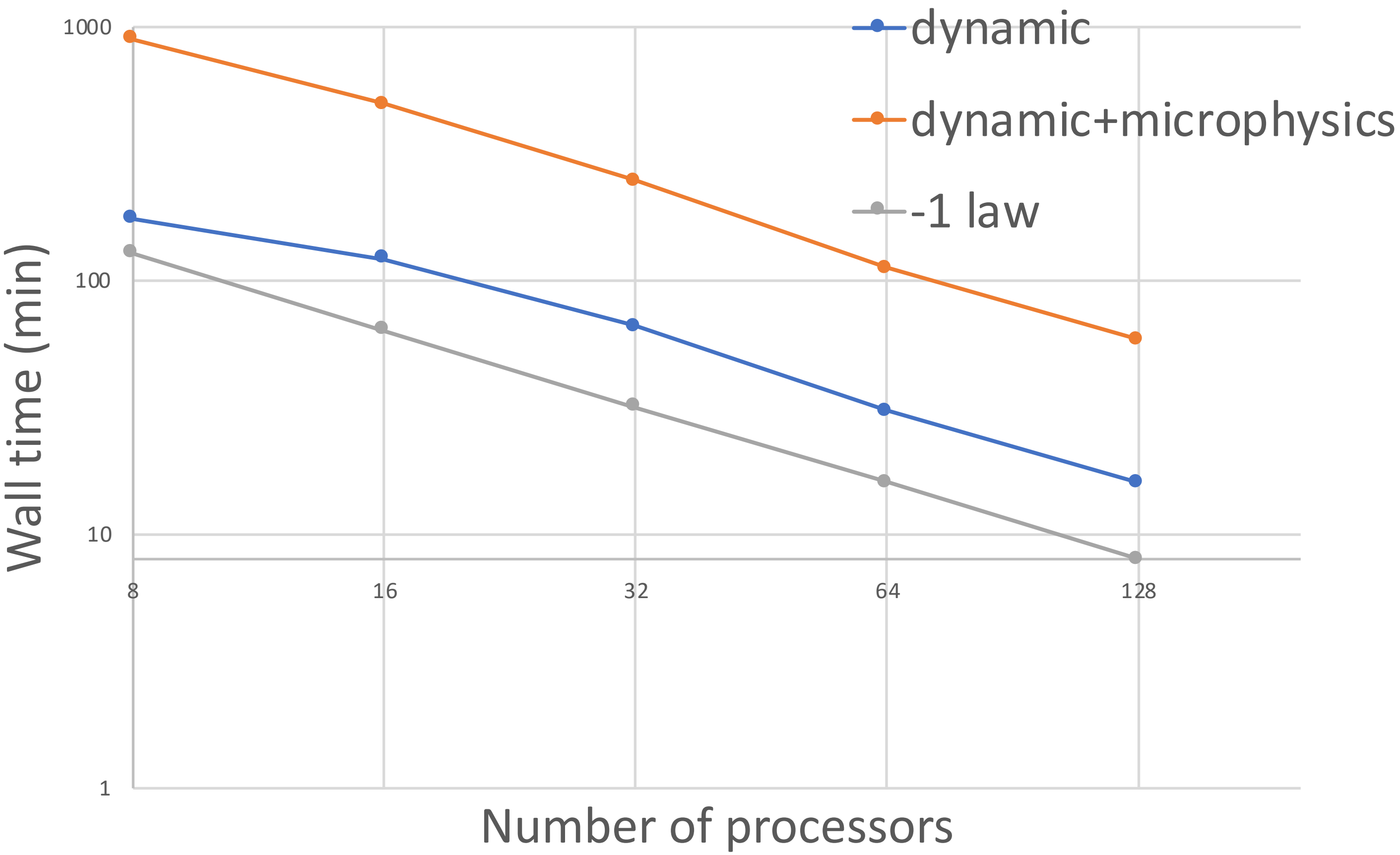


Background turbulene
+ disturbance flow caused by the present of more droplets

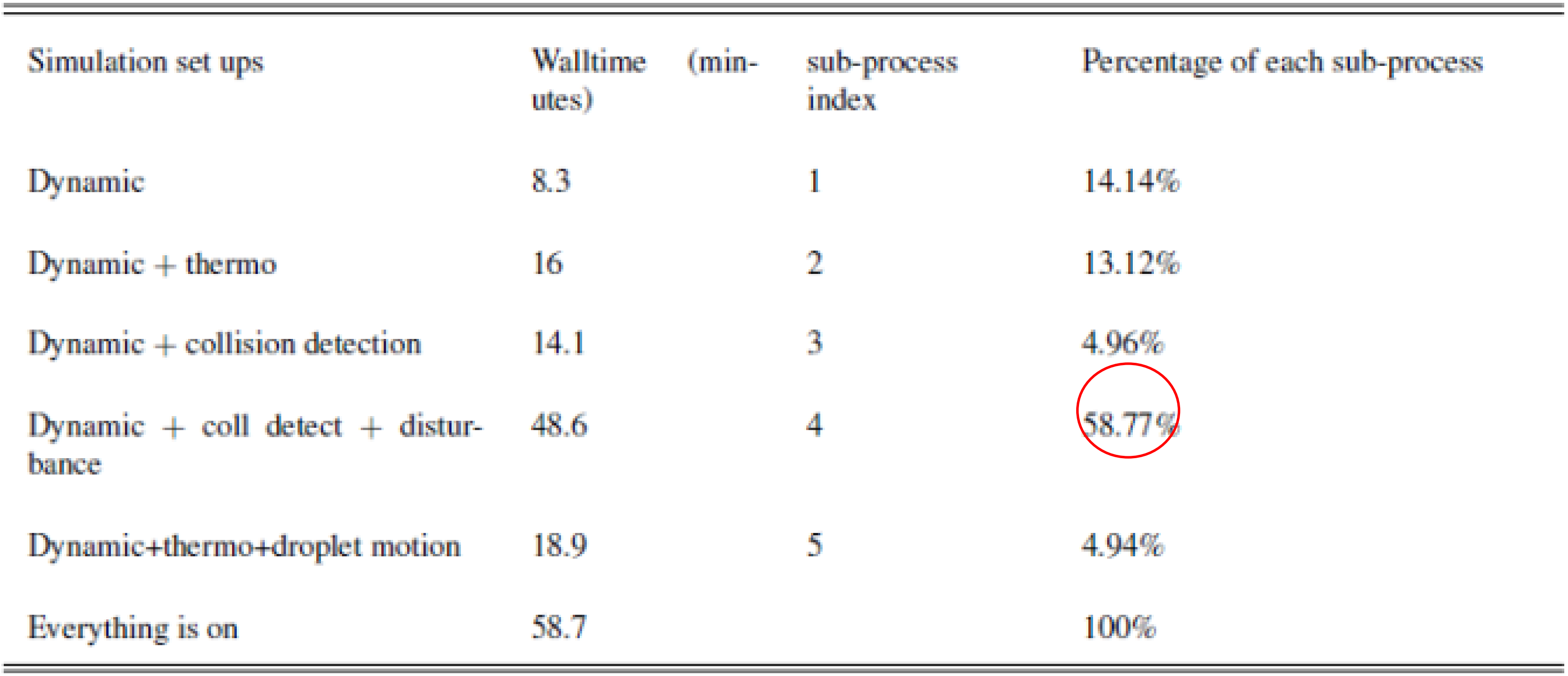
Stokes flow around a sphere



Model Scalability



Computational cost of each model component

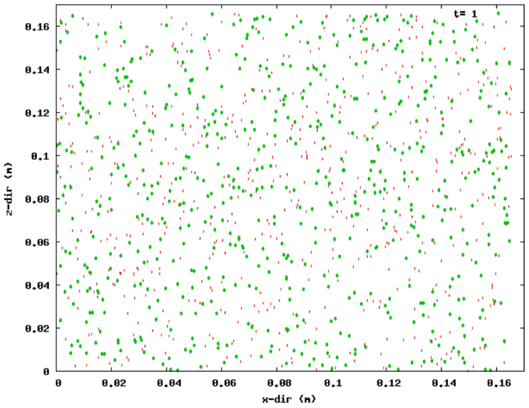


Simulation set ups	Walltime (minutes)	sub-process index	Percentage of each sub-process
Dynamic	8.3	1	14.14%
Dynamic + thermo	16	2	13.12%
Dynamic + collision detection	14.1	3	4.96%
Dynamic + coll detect + disturbance	48.6	4	58.77%
Dynamic+thermo+droplet motion	18.9	5	4.94%
Everything is on	58.7		100%

1. Dynamics (v)
2. Thermodynamics (T & qv)
3. Collision detection contains generating linked lists of droplets for collision and collision process
4. Disturbance refers to resolving the local disturbance flow of droplets (flow passing the droplet surface)
5. Droplet motion refers to only resolve droplet velocity and tracking their locations.

Two types of experiments

Droplets do not grow

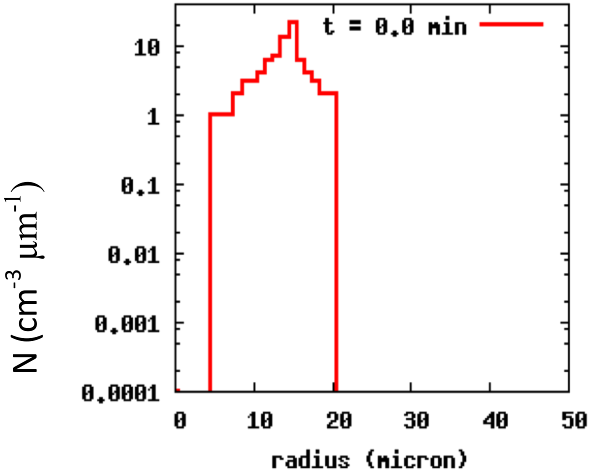


- Collect collision statistics
- Quantify turbulent effect

Two sets of simulations

1. Non-disturbed flow
2. Disturbed flow

Droplets grow with time



- DSD evolution in different turbulent environments
- Turbulence impact on collisions, condensation, and condensation-collision interaction

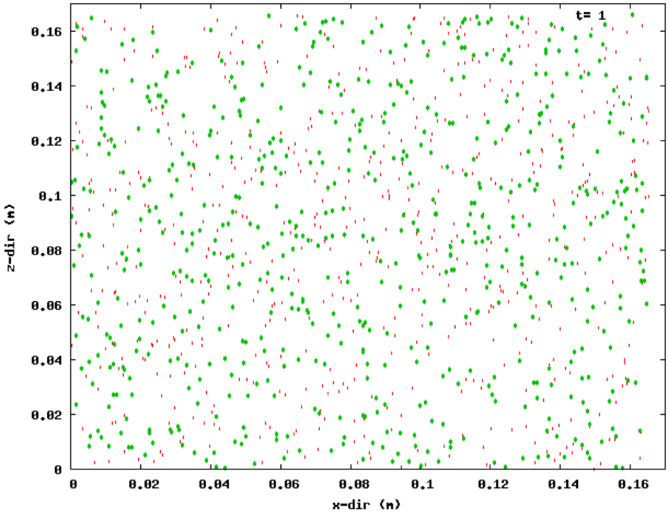
Three sets of simulations

1. Collision only
2. Condensation only
3. Condensation + Collision

Experiment 1
Turbulence effect on droplet collisions

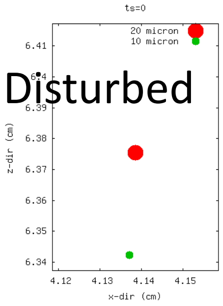
Research Questions (Collision)

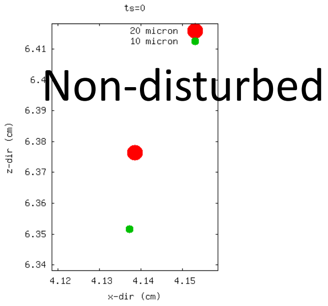
1. What are the **crucial scales** of turbulent motions related to collisions?
2. How does turbulence affect droplet **geometric collision**?
3. What is the impact on the droplet **hydrodynamic interaction** and thus modify the **collision efficiency**?



Model setup:

- Turbulence intensities: ε=0-1500cm^2/s^3
- r=5-25µm
- Turn off/on droplet disturbance flow:


Disturbed


Non-disturbed

Droplet statistics to be investigated

- Radial distribution function $g(r_1 + r_2)$

  (g>1 clustering)
- Radial relative velocity $\boldsymbol{W_r}$

  (diff. btw velocity of colliding particles)
- Geometric collision kernel Γ^{GEO}

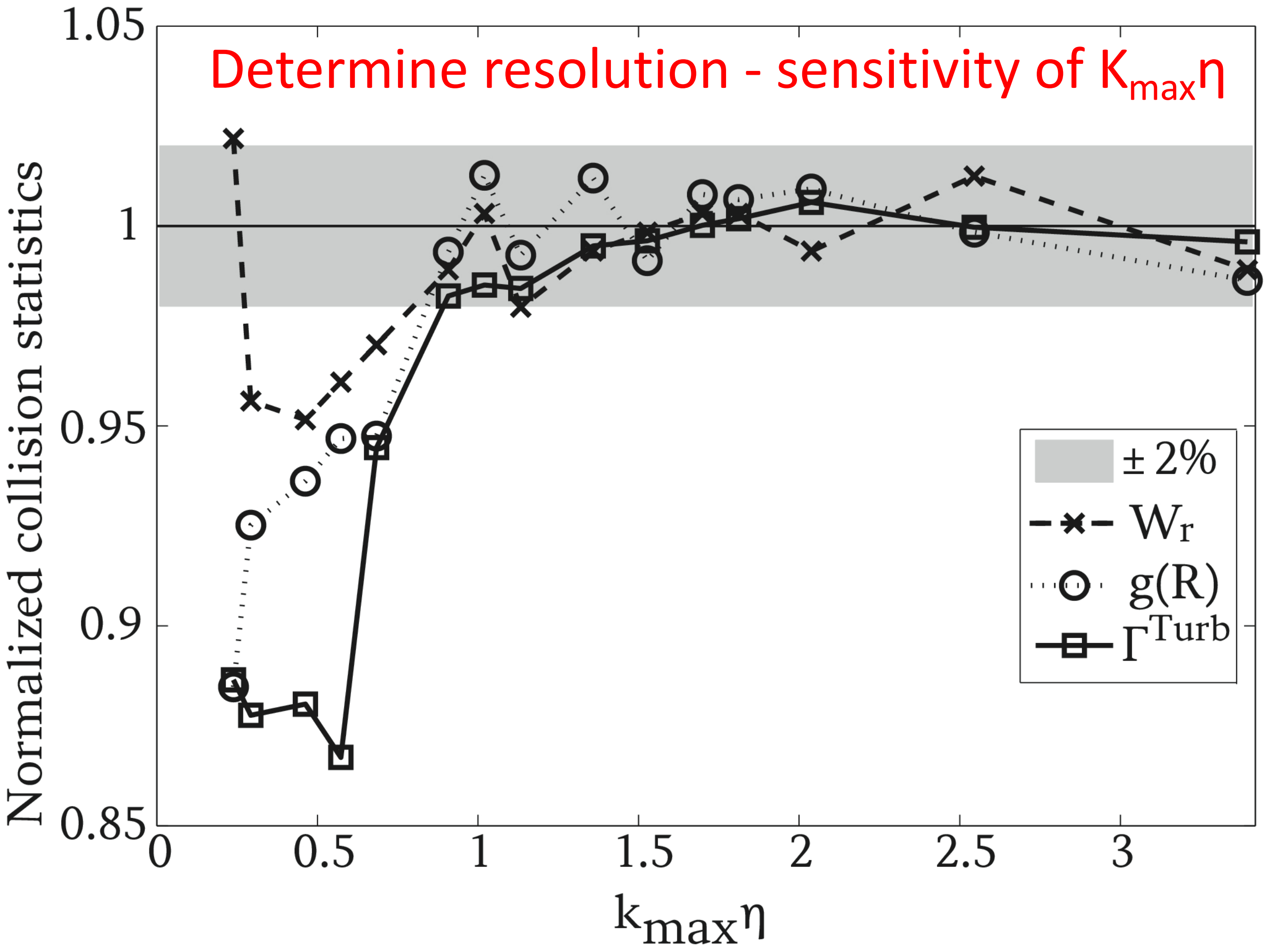
  (no disturbance flow)
- Collision efficiency $E(r_1, r_2)$

- (Effective) collision kernel $\Gamma^{EFF} = \Gamma^{GEO} E(r_1, r_2)$

  rate at which an R drop collides with an r droplet

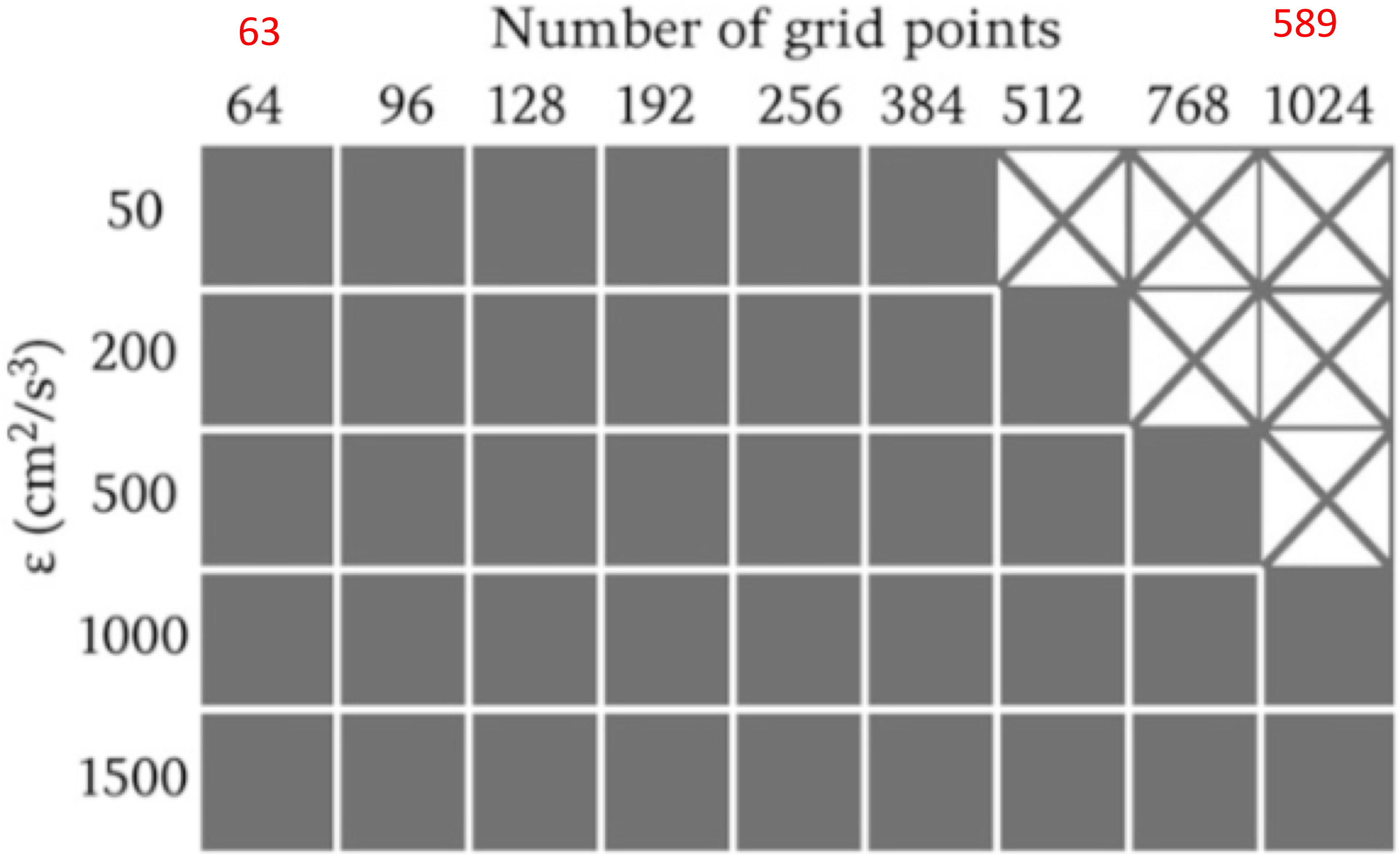
$$\Gamma^{GEO} = 2\pi(r_1 + r_2)^2 \langle|\boldsymbol{W_r}|\rangle g(r_1 + r_2)$$

Determine resolution - sensitivity of $K_{max}\eta$



$$\eta \propto \left(\frac{\nu^3}{\epsilon}\right)^{\frac{1}{4}} \quad R_\lambda \propto \left(\frac{L}{\eta}\right)^{\frac{2}{3}}$$

choose $K_{max}\ \eta = 1.3$

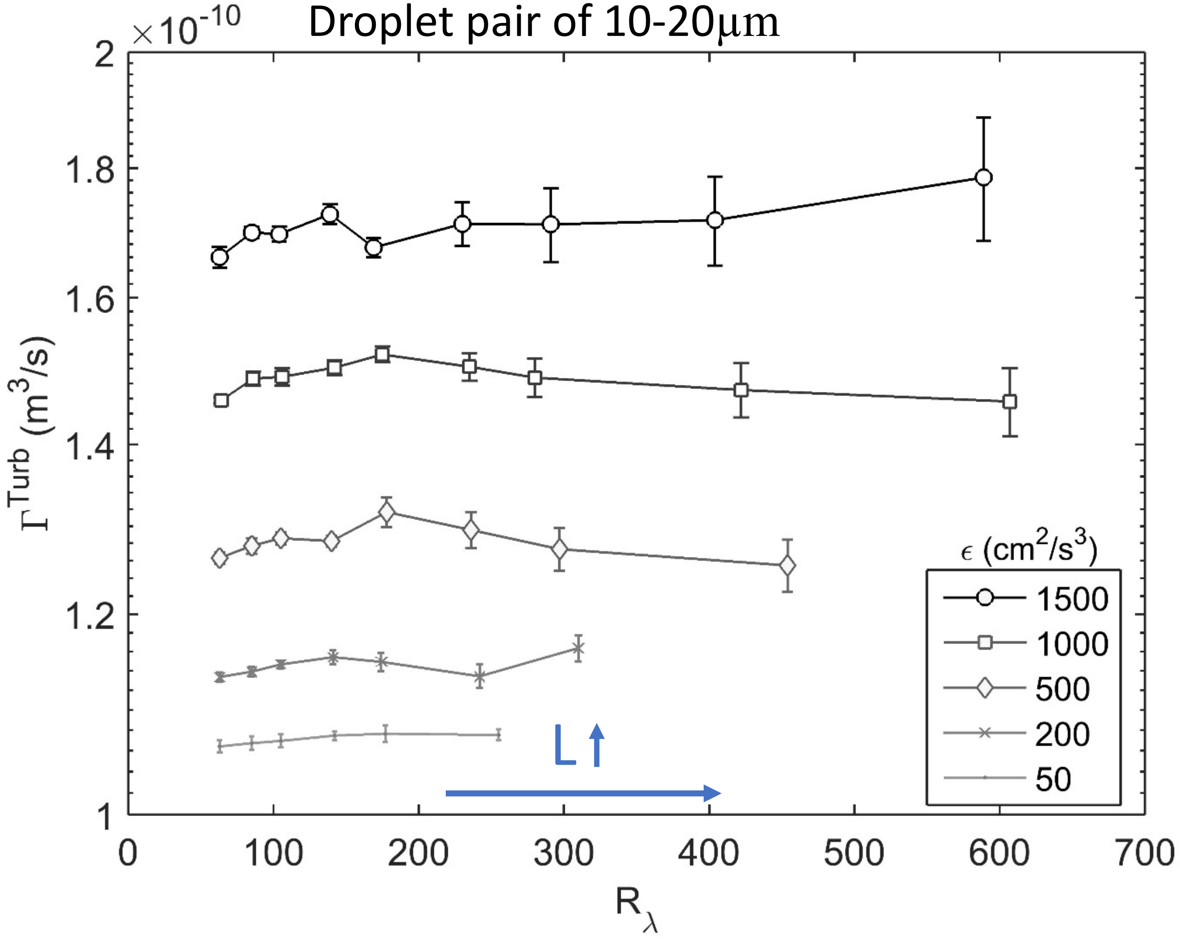


ε (cm²/s³)	64	96	128	192	256	384	512	768	1024
50	▨	▨	▨	▨	▨	▨	×	×	×
200	▨	▨	▨	▨	▨	▨	▨	×	×
500	▨	▨	▨	▨	▨	▨	▨	▨	×
1000	▨	▨	▨	▨	▨	▨	▨	▨	▨
1500	▨	▨	▨	▨	▨	▨	▨	▨	▨

FIG. 3. Overview of performed simulations over different R_λ values and EDRs. Successful runs are shaded with gray; failed runs are marked by ×.

Relative importance of different scales of turbulence

Droplet pair of 10-20μm



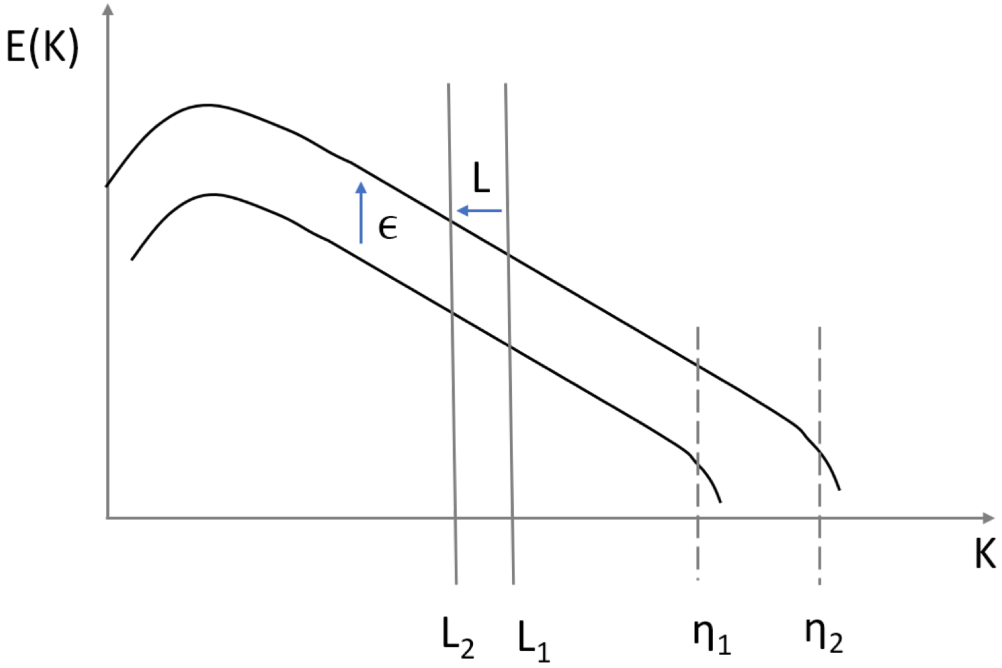
Insensitive to R_λ (i.e., large scale motions).

Collisions are mainly affected by small-scale turbulence.

We can perform DNS in small domain sizes!

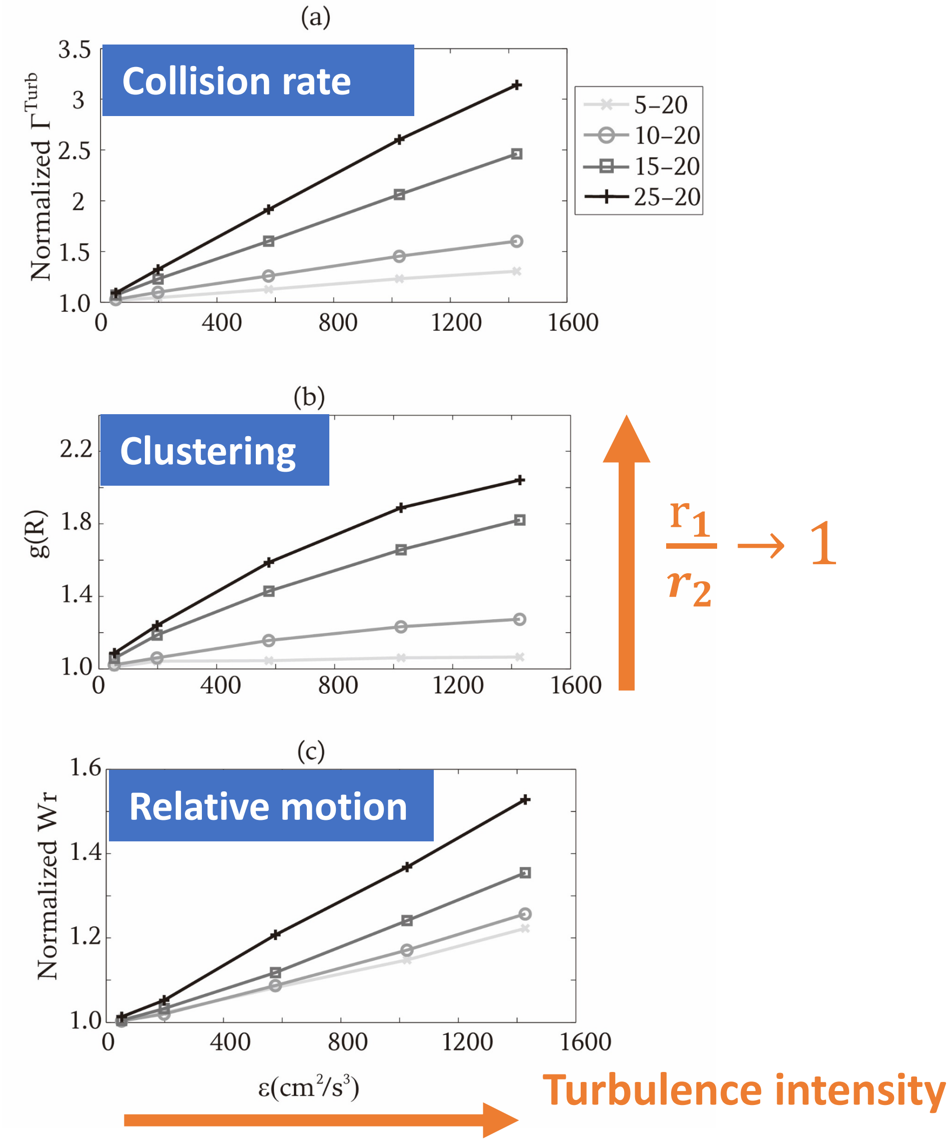
Microphysics Reynolds number $R_\lambda \propto (\frac{L}{\eta})^{\frac{2}{3}}$

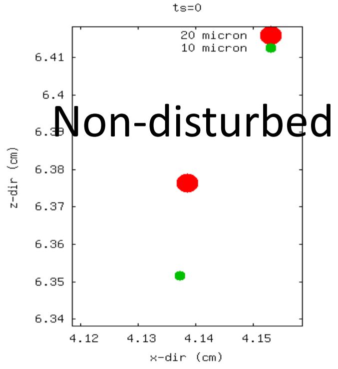
Energy spectra for two different flow conditions



$$E(k) \propto \epsilon^{\frac{2}{3}} k^{-\frac{5}{3}} \qquad R_\lambda \propto \left(\frac{L}{\eta}\right)^{\frac{2}{3}} \qquad \eta \propto \left(\frac{\nu^3}{\epsilon}\right)^{\frac{1}{4}}$$

Droplet geometric collisions





All statistics increase with turbulence intensity

Enhancement is stronger in similar-sized collision

Droplets of similar sizes cluster in same region of flow because of similar inertia and fallspeed to increase collision (Franklin et al. 2005; Ayala et al. 2008)

Parameterization of the turbulent geometric collision kernel

Excluding **Reynolds number term** and replacing it with **dissipation rate**, **ε**

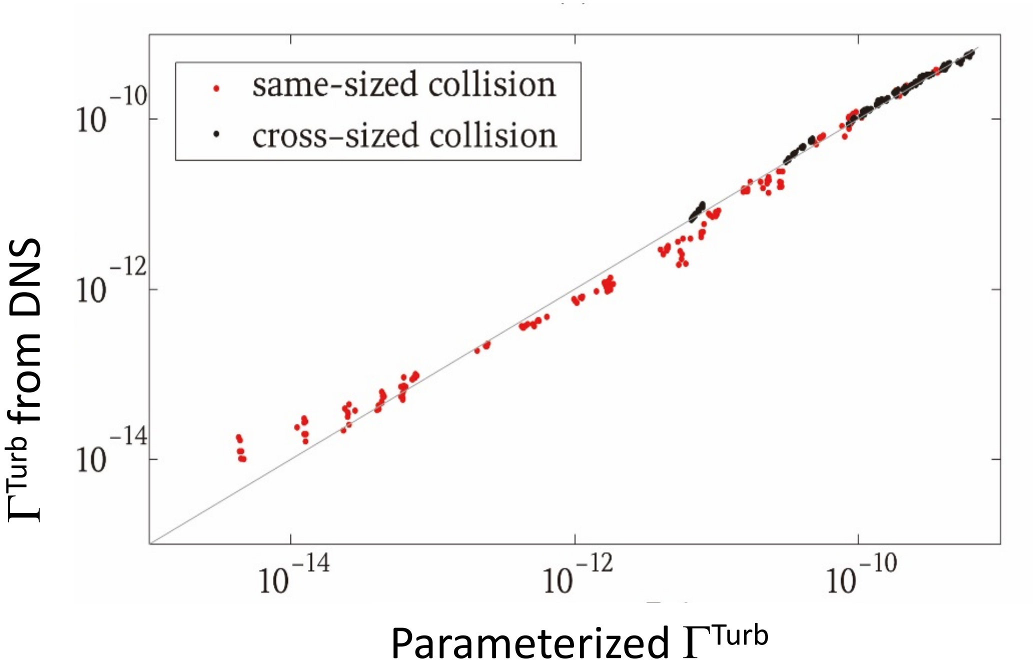
$$\Gamma^{\mathrm{Turb}} = \underline{\Gamma^{\mathrm{Grav}}} + 2\pi R^2 \underline{\left[\left(\frac{R}{\eta} \right)^{0.84} + (7\mathrm{St}_1 \mathrm{St}_2)^{0.85} \right]}$$

$$\times \underline{\sqrt{0.5\varepsilon(|\tau_{p1} - \tau_{p2}| + 0.3\sqrt{\tau_{p1}\tau_{p2}})}},$$

Gravitational collision kernel

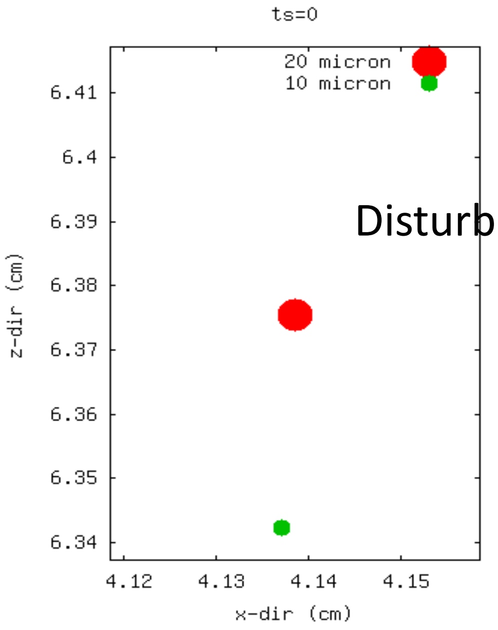
$$\Gamma^{grav} = \pi R^2 | V_{T1} - V_{T2} |$$

Turbulent enhancement



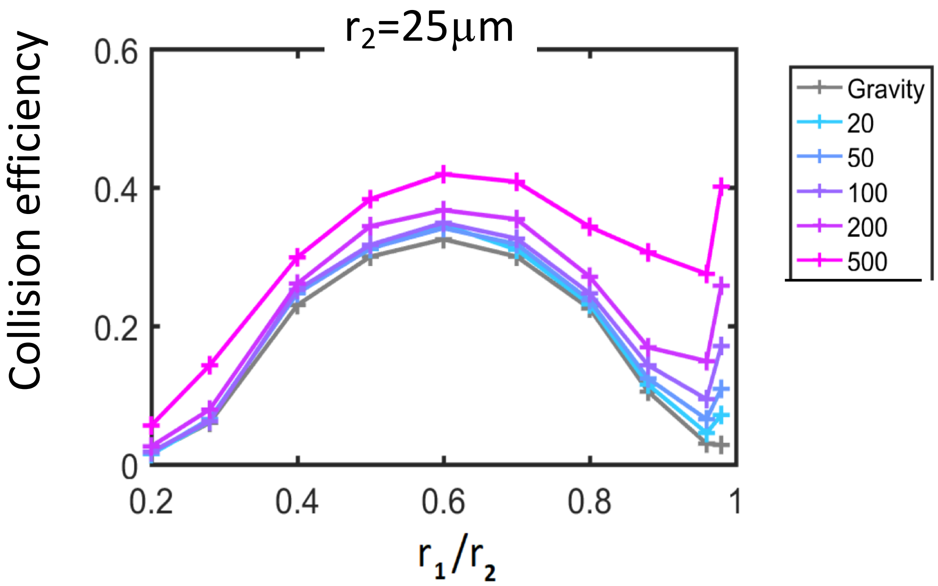
Next step: turn on droplet disturbance flow

Hydrodynamic interaction → collision efficiency



Disturbed flow ✓

Collision efficiencies: droplet hydrodynamic interaction

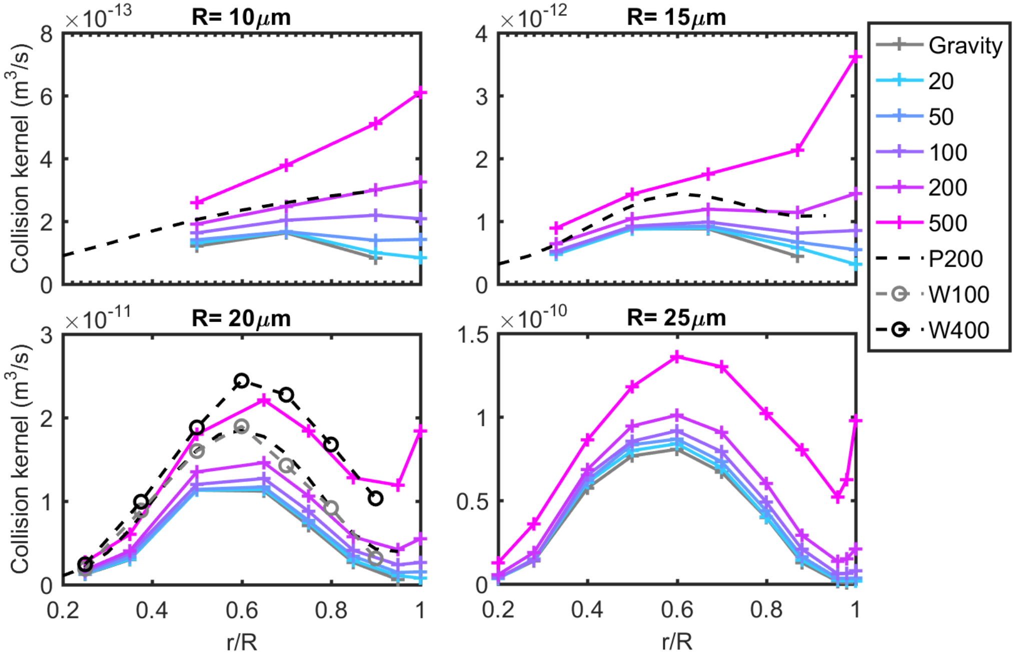


CE increases with turbulent intensity

Turbulence tends to counteract the disturbance field and increases the collision efficiency

Turbulent Collision kernel (R=r2, r=r1)

Collision Kernel at different turbulent intensities



A significant enhancement of collision kernel by turbulence.

Hydrodynamic interaction and its response to turbulence play critical role in determining its collision rate.

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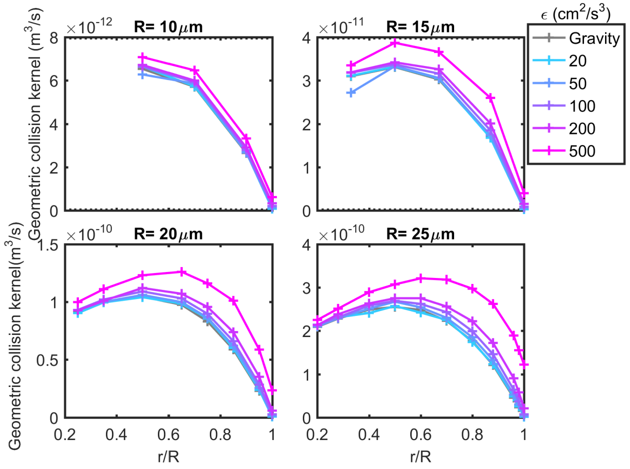
Geometric collision kernel



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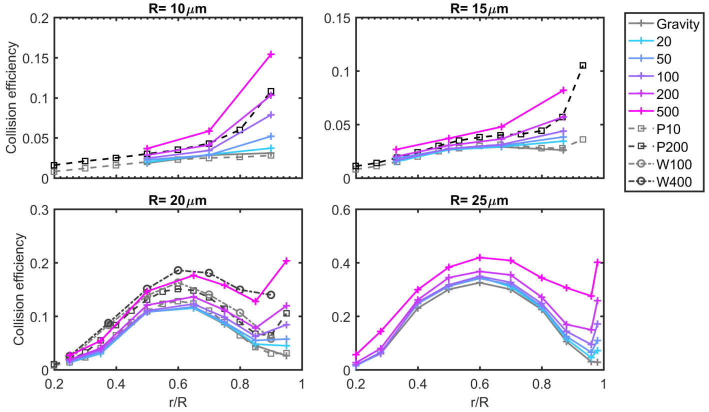
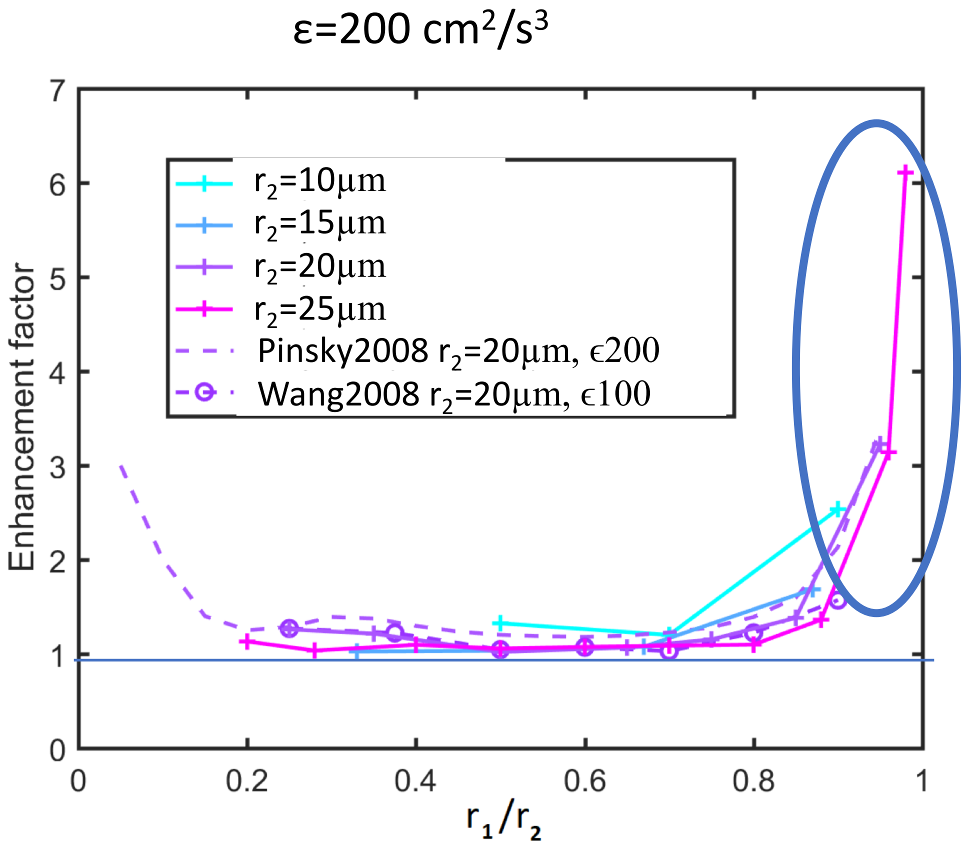
Collision efficiency



Turbulence enhancement factor at varying r_1/r_2



Turbulence enhancement factor on collision efficiency (CE) depends on **r_1/r_2**, but is insensitive to **r_2**

Strong effect on similar-sized collisions

$$\text{Enhancement factor}=\frac{CE(\varepsilon)}{CE(gravity)}$$

Summary and discussion

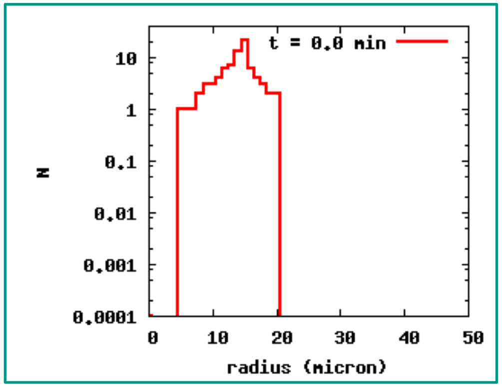
- Droplet motion are mainly affected by **small-scale turbulence** & insensitive to large-scale features.
- **Parameterizations** should get rid of R_λ-related terms (u', R_λ, …)
- Compared to **clustering** and **relative motion**, **hydrodynamic interaction** and its response to turbulence play critical role in determining its collision rate.
- Turbulence effect is strongest on **similar-sized collision**: can be effective in broadening the narrow size spectrum formed by **condensational growth**

Experiment 2
Complete the story: adding droplet condensational growth

Research Questions (Collision and Condensation)

4. How does **condensational** process interact with collisional process?
5. How does turbulence modulate such interaction?
6. What is the role of turbulence in accelerating **rain formation**?

Experiment 2
Complete the story: adding droplet condensational growth



Model setups:

Include thermodynamic fields (T & q_v) → Supersaturation

Droplets grow with time

Initial condition

DSD shape	Aircraft observations of marine cumulus clouds (Raga et al., 1990)
LWC	1 g/m^3
ε	0-500 cm^2/s^3
r	5-20 μm
CDNC	80 cm^{-3}
T	6.5 min

Thermodynamic equations

Macroscopic equations

$\bar{W}, P, \rho, C_{dM}, T_M, q_{vM}, S_{pM}$

$$\frac{dP}{dz} = -\rho g$$

$$\rho = \frac{P}{RT}$$

$$\frac{dT_M}{dt} = -W_M \Gamma_d + \frac{L}{c_p} C_{dM},$$

$$\frac{dq_{vM}}{dt} = -C_{dM},$$

Microscopic equations

$V', R_i, C_d, T', q'_v, S_p{}'$

$$R_i \frac{dR_i}{dt} = f_v K (S - \frac{a}{R_i})$$

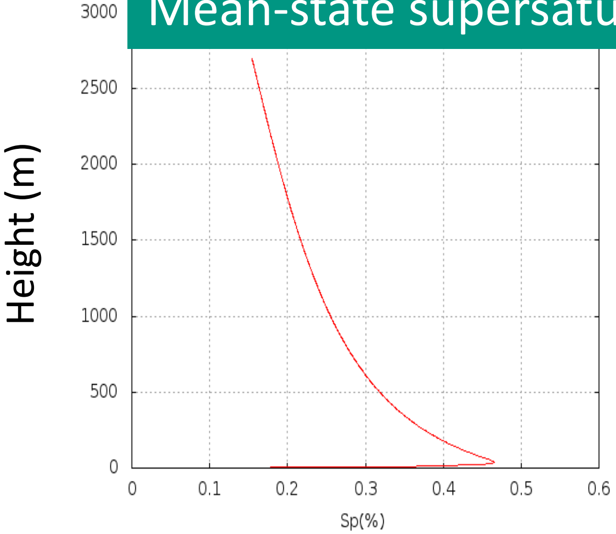
$$C_d = \frac{1}{M_a} \frac{dM_{Liq}}{dt} = \frac{1}{M_a} \frac{4}{3} \pi \rho_w \sum_{i=1}^{n} \frac{dR_i^3}{dt}$$

$$\frac{dT'}{dt} = -W' \Gamma_d + \frac{L}{c_p} (C_d - C_{dM}) + k_a \nabla^2 T'$$

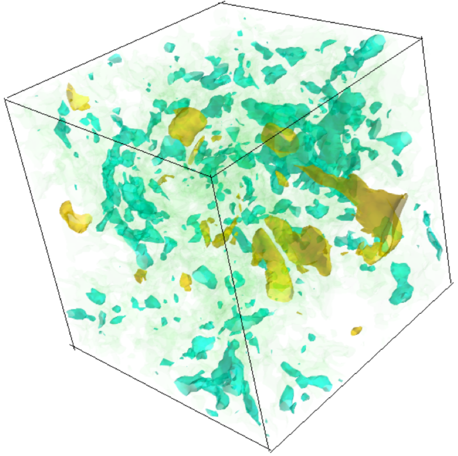
$$\frac{dq'_v}{dt} = -(C_d - C_{dM}) + D_v \nabla^2 q'_v,$$

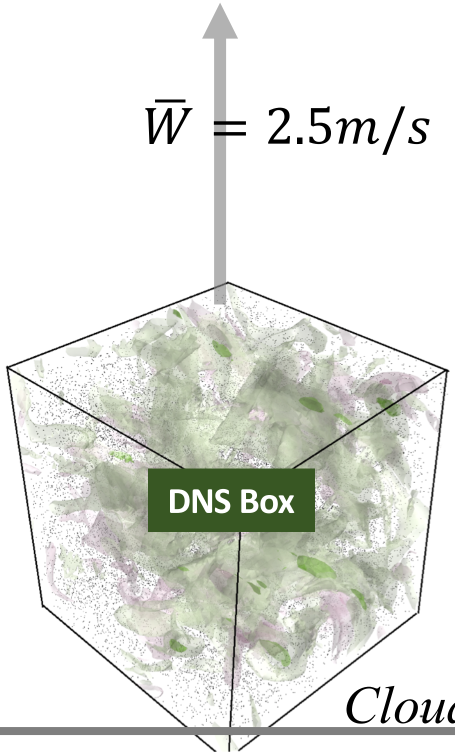
Droplet continuous growth in turbulent, supersaturated environment

Mean-state supersaturation



Supersaturation fluctuation





$\overline{W} = 2.5m/s$

Macroscopic variables

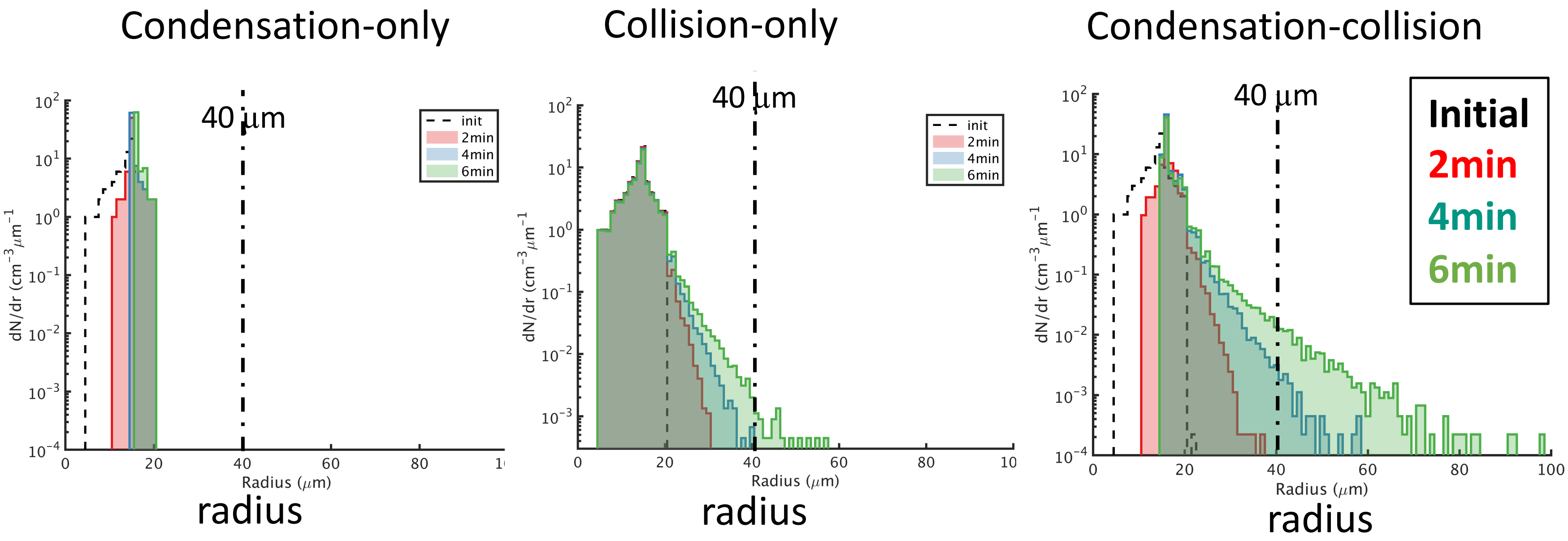
$\overline{W}, P, \rho, C_{dM}, T_M, q_{vM}, S_{pM}$

Microscopic variables

$V', R_i, C_d, T', q_v', S_p{}'$

Cloud Base

DSD in three simulations, $\varepsilon=500 cm^2/s^3$


Condensation-only

Collision-only

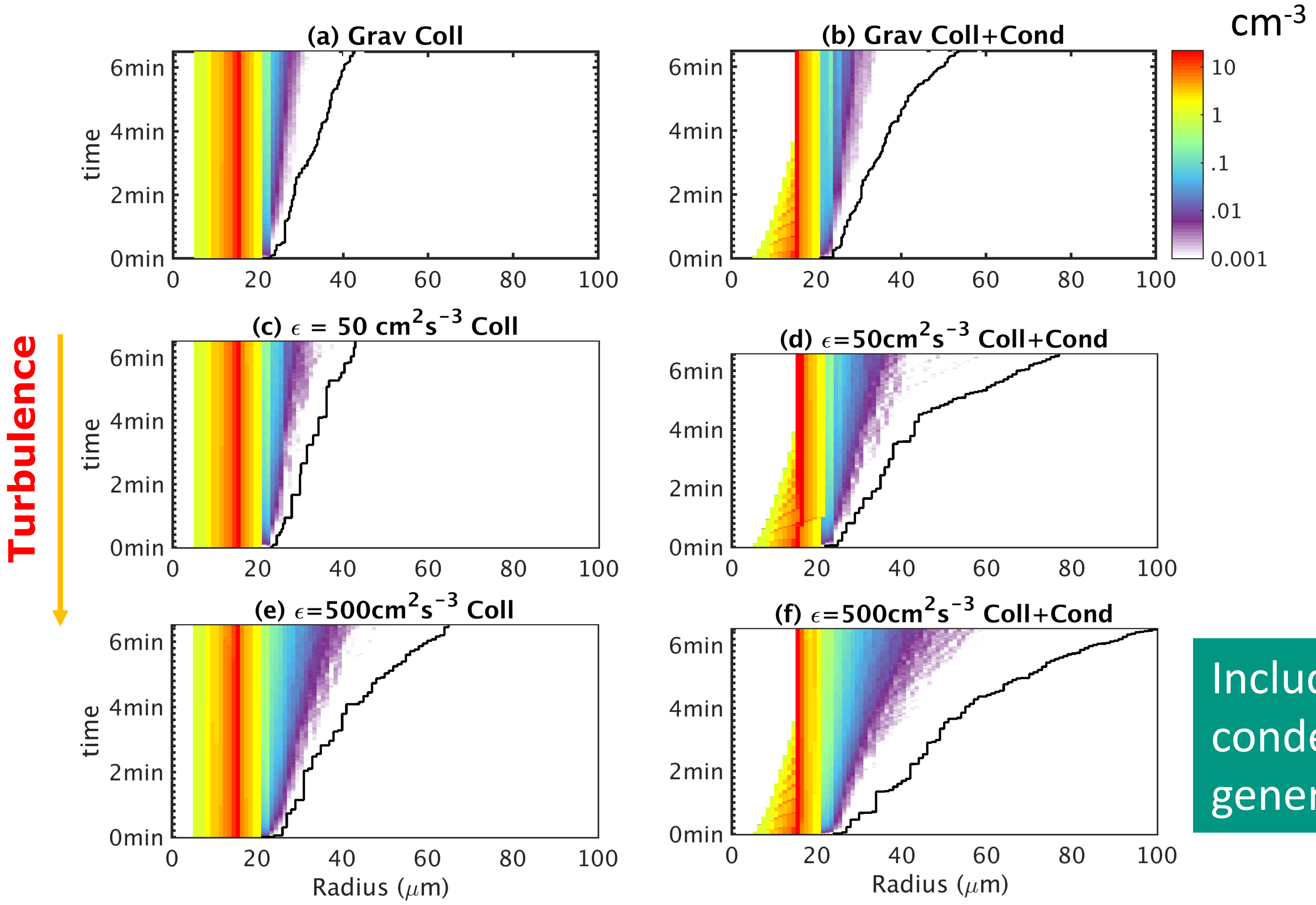
Condensation-collision

1. Condensation-only produces very narrow DSD.
2. Collision-only process can produce large droplets.
3. Inclusion of condensation helps further boost collisions: **condensation-mediated collision**.

DSD evolution in different turbulent flows

Collision-only

Condensation-collision



r>35 micron negligible

r>35 micron at 3.5 min

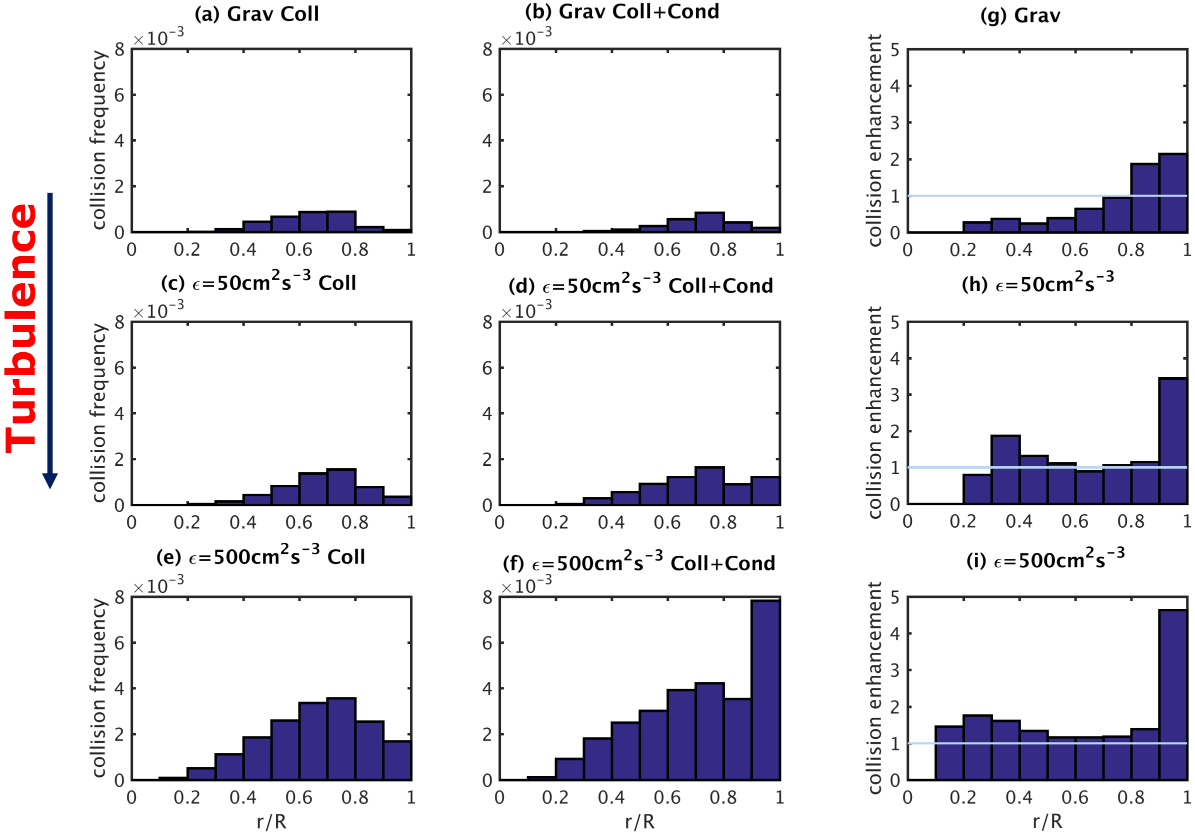
Including droplet condensation effectively generates large droplets

Black line largest droplet in domain

Collision frequency distribution -/+ condensation for different flows

Collision Frequency (cm^{-3}s^{-1}) Enhancement

Collision-only Collision-condensation Normalized



As turbulence intensifies…

- Collision frequency increases for all droplet pairs!
- Large contribution from similar-sized collisions

Includingcondensation

(r/R<0.7)

- Reduces collisions in still air
- Some enhancement in turb.

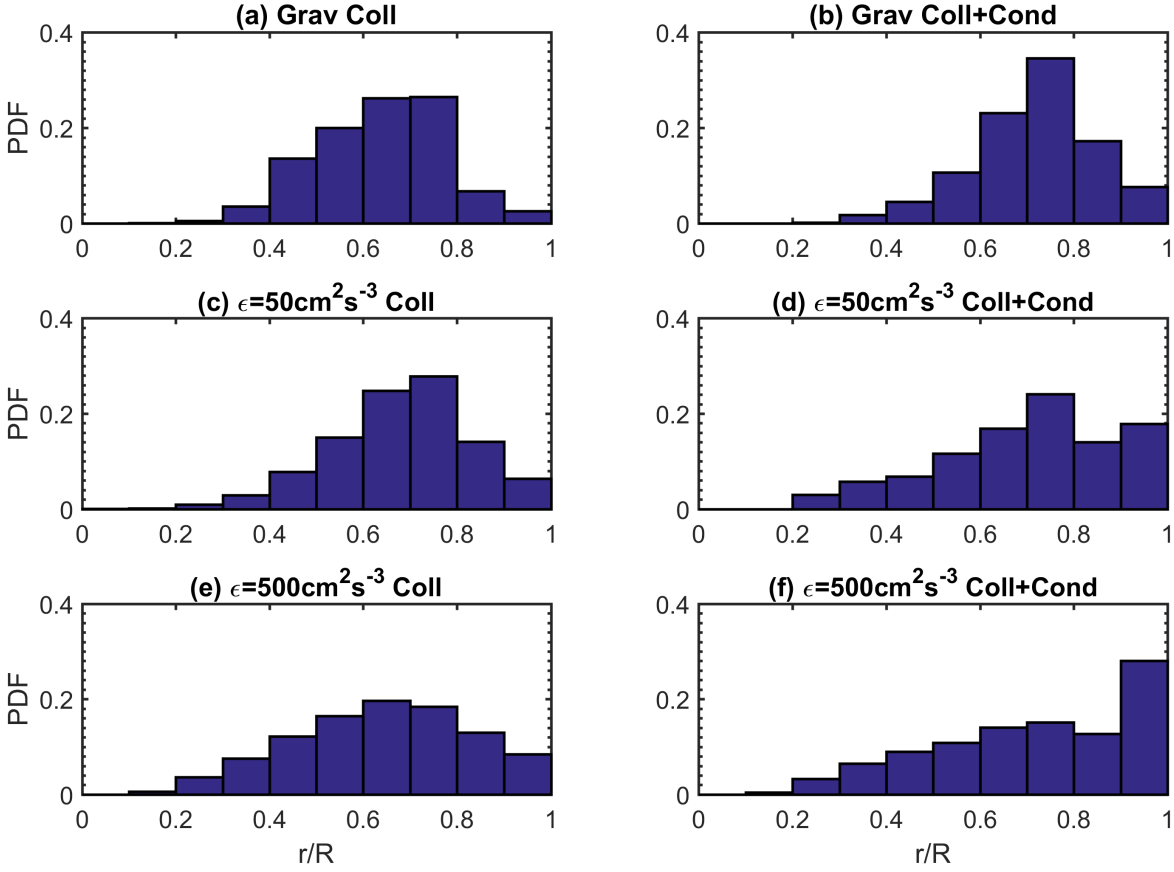
(r/R>0.8)

- Enhanced coll. freq. by 2, 3.5, 4.7 fold with inc. in turb.

PDF of collisions
Different flows

Collision-only

Condensation-collision



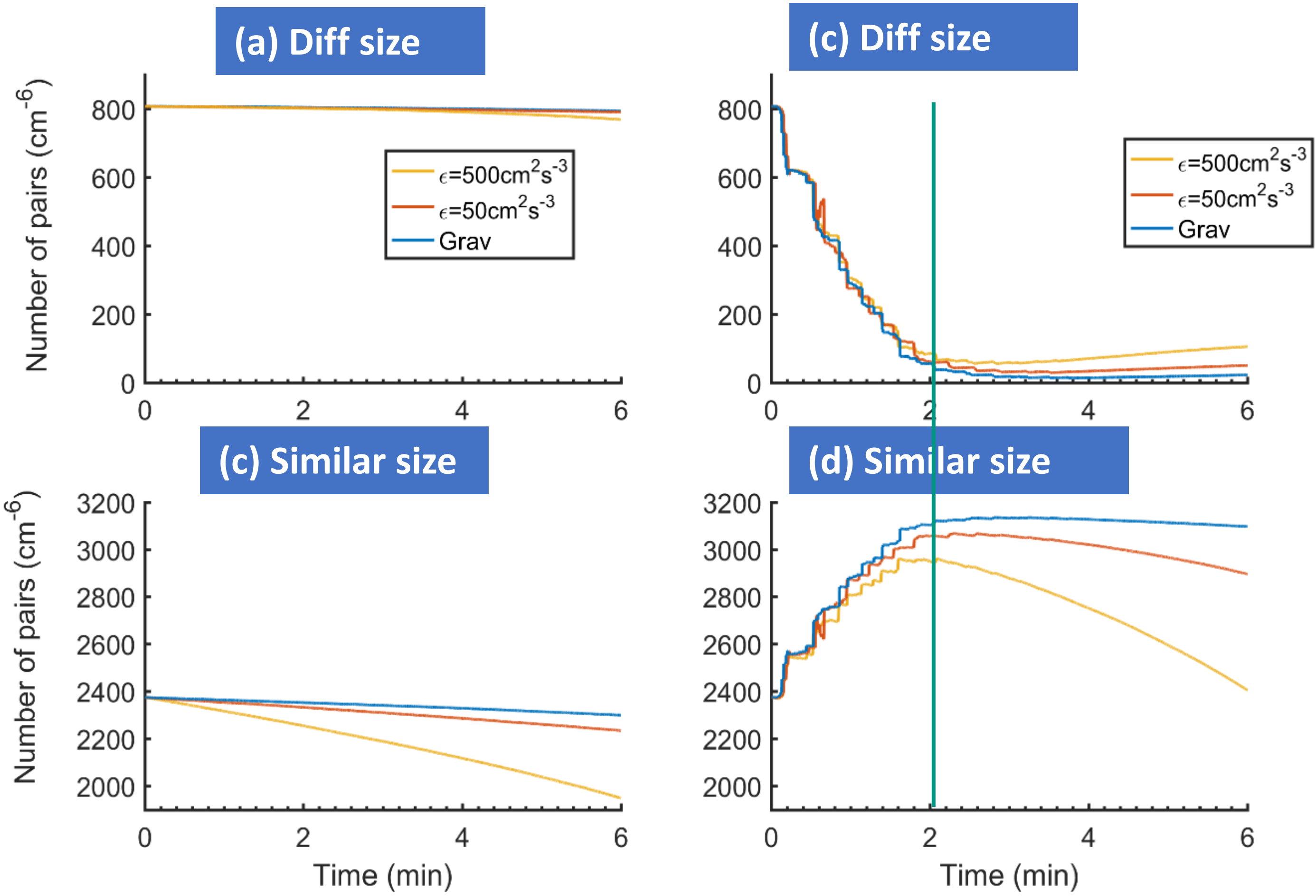
Flattened

Skewed towards similar-sized collisions

Evolution of number of droplet pairs

Diff size (r/R<=0.7)   Similar size (r/R>0.7)

Collision-only   Condensation-collision



Condensation dec. diff. size droplets, inc. similar size droplets

In turb., similar size droplets tend to cluster in same region of flow because of similar inertia and fallspeed

The inc. clustering and CE rapidly inc. collision of similar size droplets after 2 min in turb.

The physics learned so far:

- Collisions are mainly affected by small-scale turbulence.
- Turbulence has strong effects on accelerating droplet collisions and producing wide droplet size spectrum.
    - Strong on collision efficiency and milder on geometric collision
    - Strongest on similar-sizes collision
- Condensation alone does not produce large droplets. However, turbulence promotes the condensation-mediated collisions and thus boosts the formation of big droplets.

Condensation, Collisions, and Turbulence collaborate dynamically to accelerate the rain formation!

Future work

- The impact of different initial DSD on cloud development.
- Cloud-aerosol interaction (include aerosol activation)
  - e.g., effects of giant/ultra giant aerosols, aerosol loading, hygroscopic seeding, etc.
- Comparisons with in-situ measurement/ lab experiment
  - e.g., Cloud chamber, HOLODEC measurements, etc.
- Autoconversion parameterization
- Extension to include ice particles

- Publications

- Chen, Bartello, Yau, Vaillancourt, Zwijsen: 2016 JAS
- Chen, Yau, Bartello:2018 JAS
- Chen, Yau, Bartello, Xue: 2018 ACP

Thank you!

A warm rain process observed in Lishui, East China