Droplet dynamics in cloud turbulence: A numerical investigation

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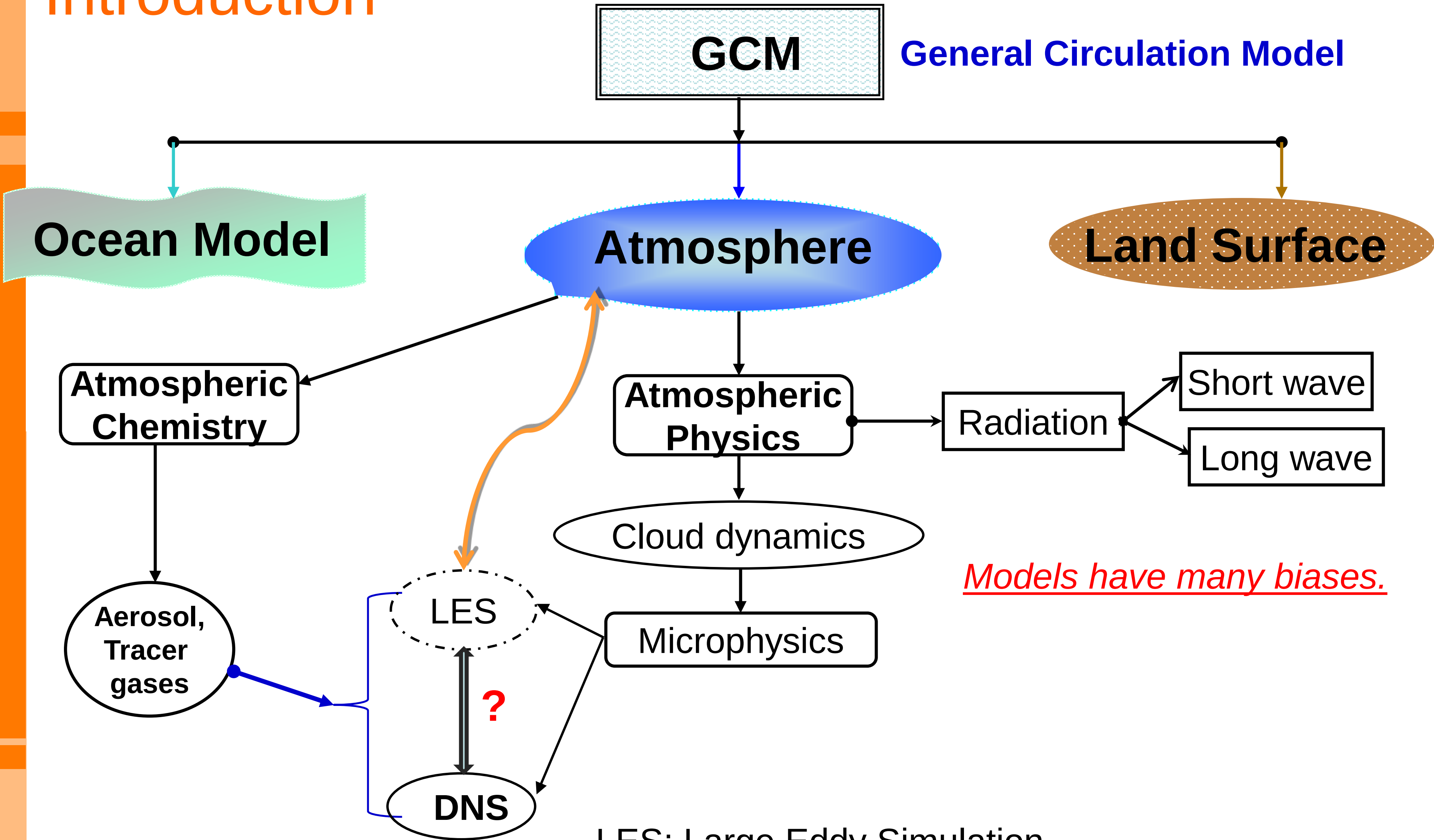
Outline

- Introduction
- Numerical model
- Results
  - Comparison with observation
  - Computational details
- Future direction

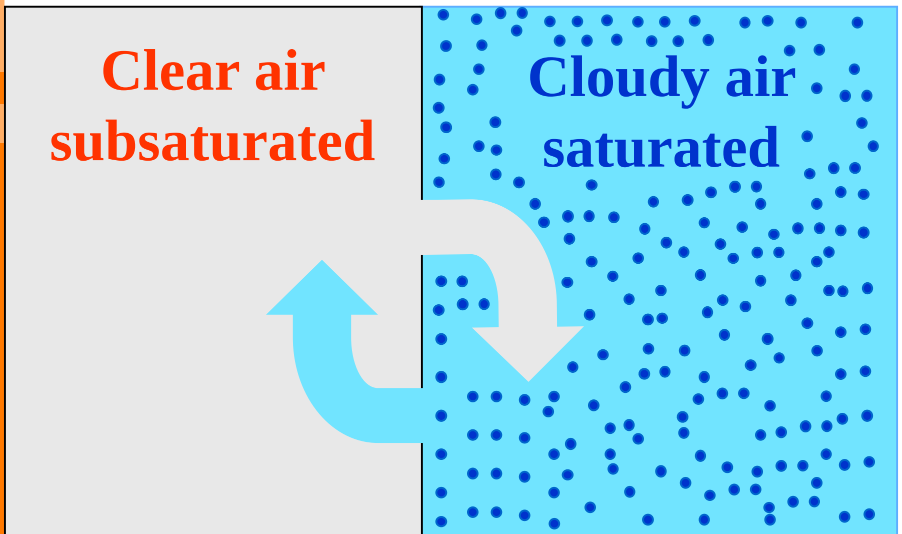
Introduction



Models have many biases.

LES: Large Eddy Simulation
DNS: Direct Numerical Simulation

Mixing process at cloud edge

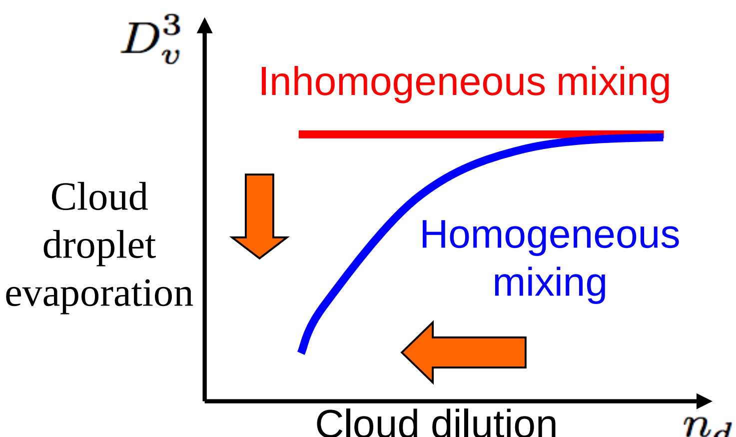


How does the intermittent turbulence microstructure at the clear air-cloud interface couple to the droplet dynamics at Kolmogorov scale?

Damköhler number

$$\mathbf{D}a = \frac{\tau_{fluid}}{\tau_{phase}}$$

- $\mathbf{D}a \ll 1$ → **Homogeneous mixing**
- $\mathbf{D}a \gg 1$ → **Inhomogeneous mixing**



Model

Eulerian

$$\nabla \cdot \mathbf{u} = 0$$

$$\partial_t \mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\frac{1}{\rho_0}\nabla p + \nu\nabla^2\mathbf{u} + g\left[\frac{T-T_0}{T_0} + \epsilon(q_v - q_{v0}) - q_l\right]\vec{e}_z + f_{LS}$$

$$\partial_t q_v + (\mathbf{u}\cdot\nabla)q_v = D\nabla^2 q_v - C_d$$

$$\epsilon = \frac{R_v}{R_d} - 1$$

$$\partial_t T + (\vec{u}.\nabla)T = \kappa\nabla^2\vec{u} + \frac{L}{c_p}C_d$$

κ : thermal conductivity

R_v : vapor gas constant

R_d : dry air gas constant

q_v : vapor mixing ratio

q_l : liquid water content

f_{LS}: turbulent forcing (form large scale)

Periodic BC

Lagrangian

$$\frac{d\mathbf{V}}{dt} = \frac{1}{\tau_p}[\mathbf{u}(\mathbf{X},t) - \mathbf{V}(\mathbf{X},t)] + \mathbf{g}$$

$$r(\mathbf{X},t)\frac{dr(\mathbf{X},t)}{dt} = KS(\mathbf{X},t)$$

$$\frac{d\mathbf{X}}{dt} = \mathbf{V}(\mathbf{X},t)$$

$$S(\mathbf{X},t) = \frac{q_v(\mathbf{x},t)}{q_{v,s}} - 1$$

$$\tau_p = \frac{2\rho_l r^2}{9\rho_0\nu}$$ Finite particle response time

ρ_l : water density

ρ_0 : air density

ν : kinematic viscosity

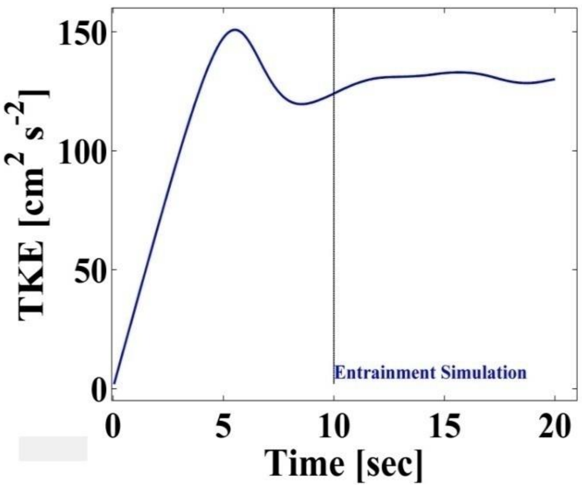
Kumar et al., *JAS, 2014* | *JAMES, 2017* |
Götzfried et al., JFM 2017

Simulation set up

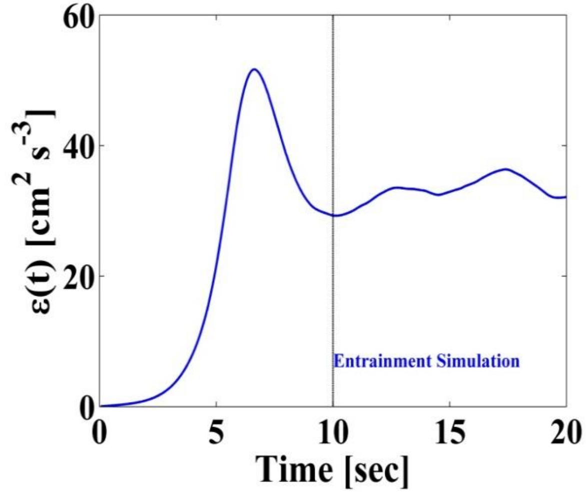
Initial condition

A relaxed statistically stationary turbulent is provided.

Turbulent K.E.

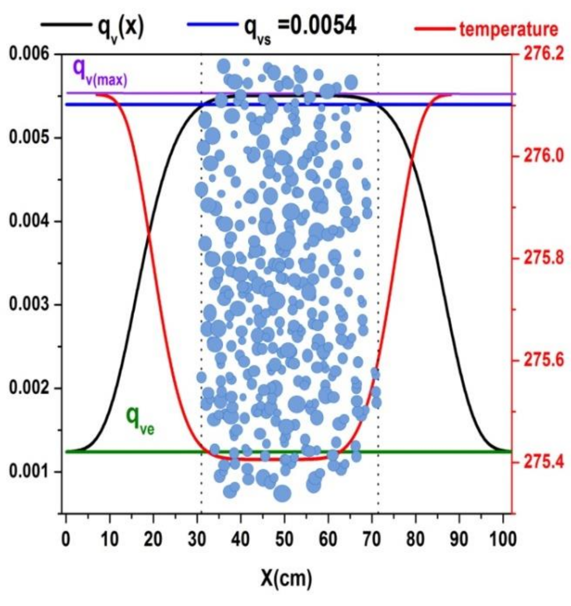


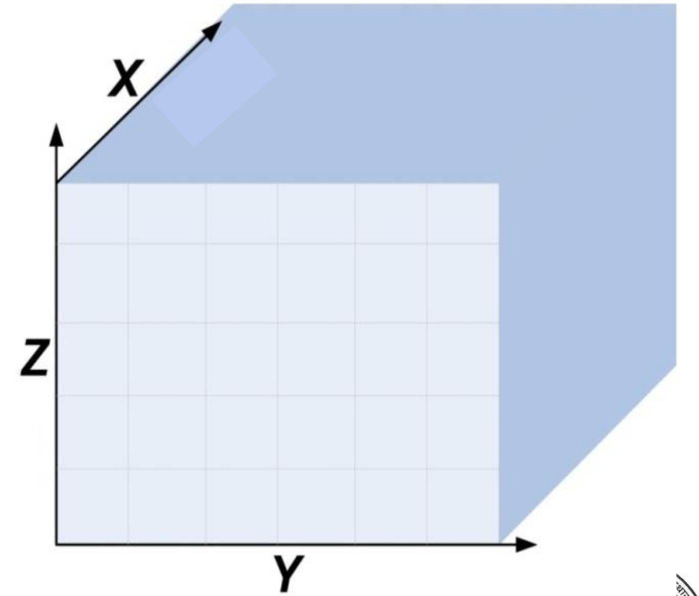
K.E. dissipation rate



$$\mathbf{q}_v(x,y,z,t=0) = (q_v^{max} - q_v^e)\exp\left[-A(x-x_0)^6\right] + q_v^e$$

$\mathbf{q}_v^{max}$: Max. amplitude = $\mathbf{q}_{vs}(t_0)$ + 2%

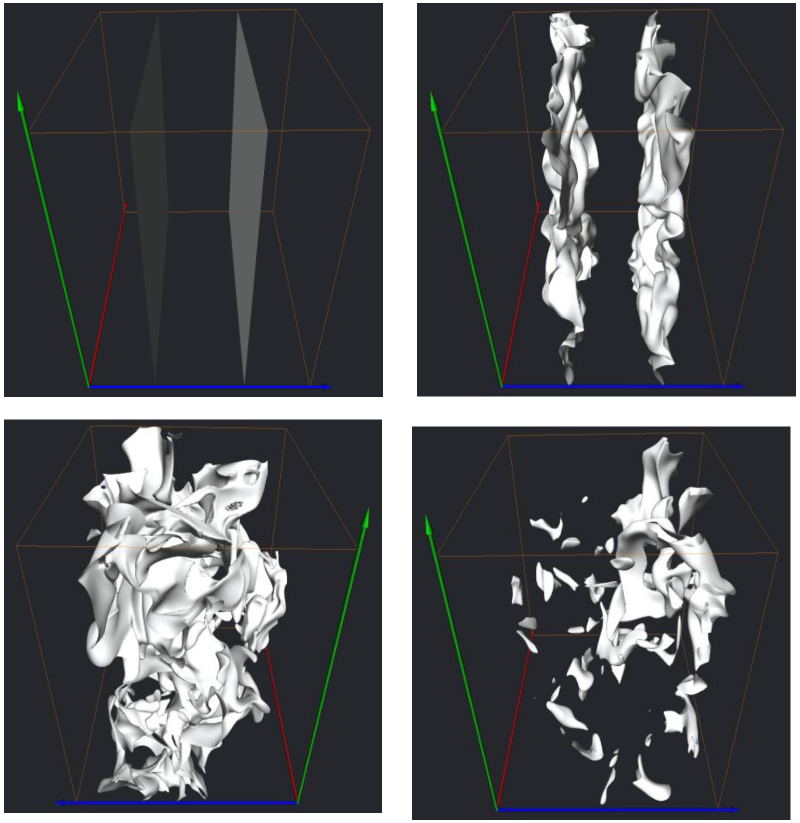




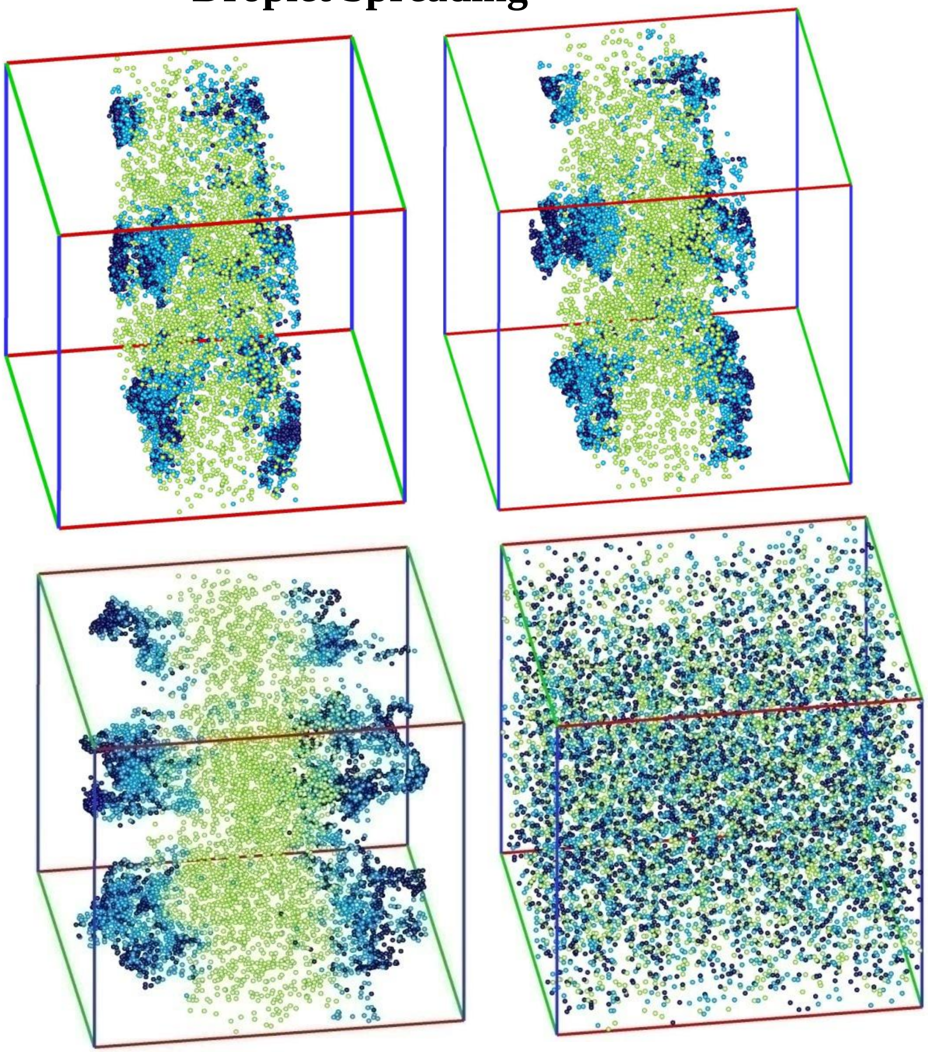
Kumar et al. , *JAMES, 2017*

Evolution stages

Isosurface of saturation mixing ratio



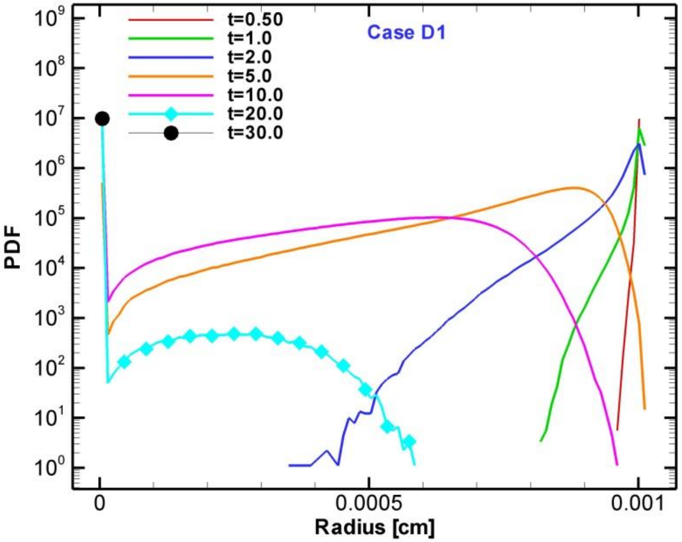
Droplet Spreading

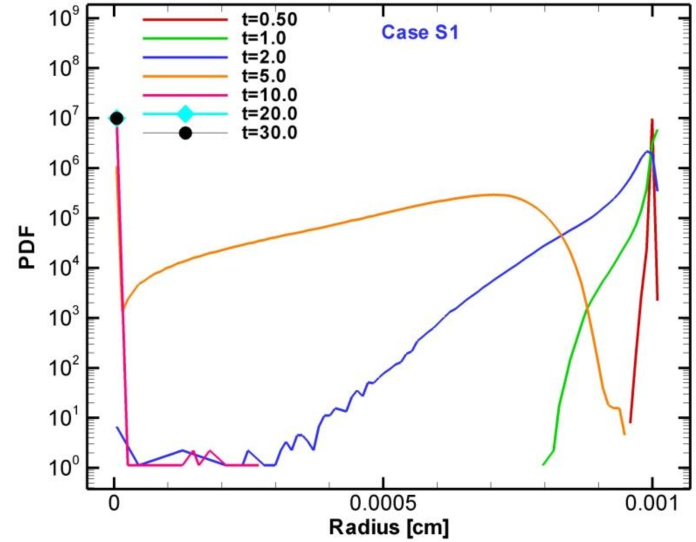


Kumar et al. ***TCFD 2013, NJP 2012***

Size distribution (data analysis)

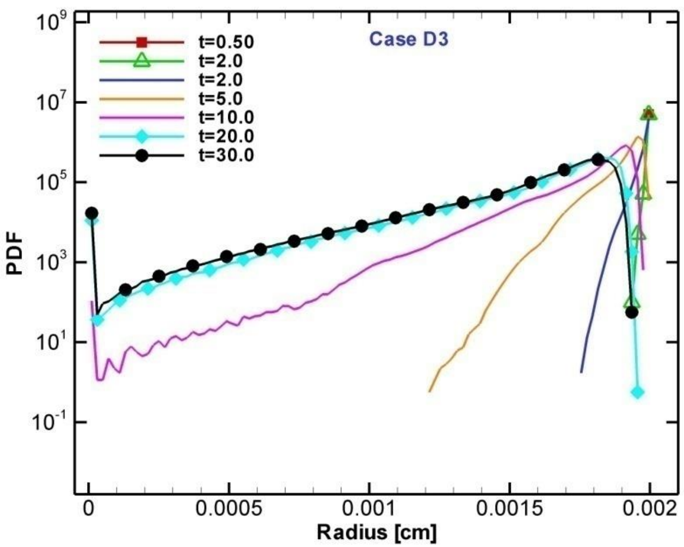
PDF: Probability Distribution Function

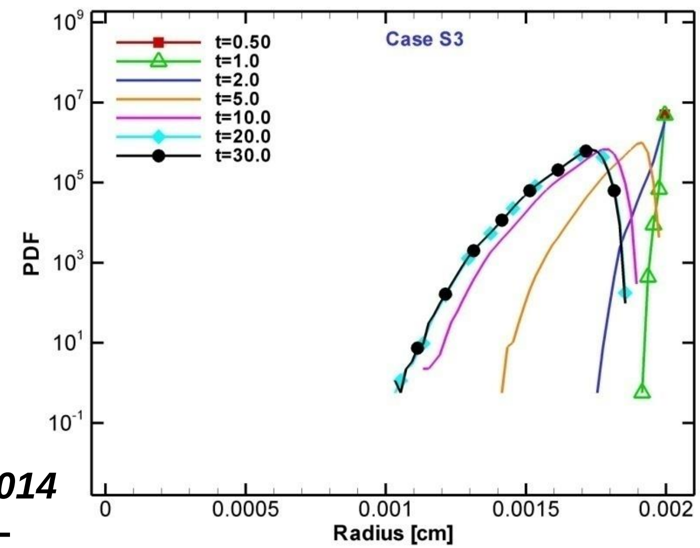




R0=10µm

nd =164



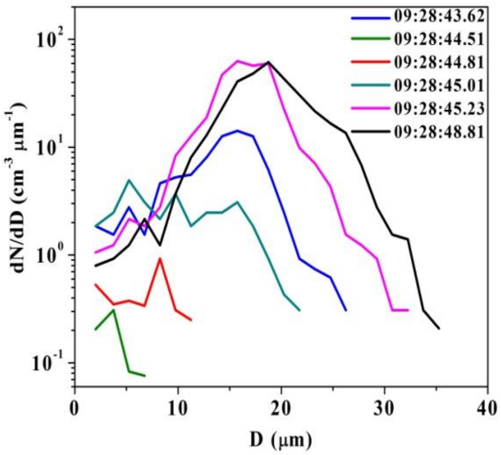


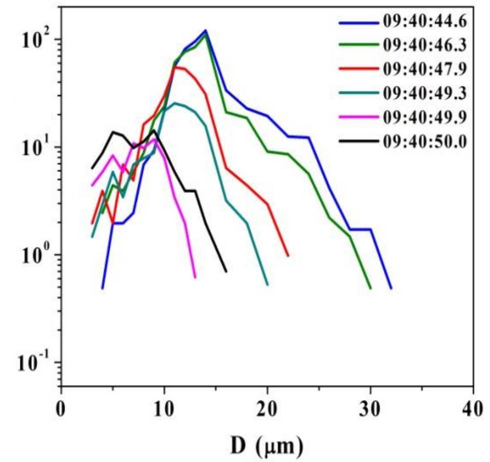
R_0=20µm

nd =164

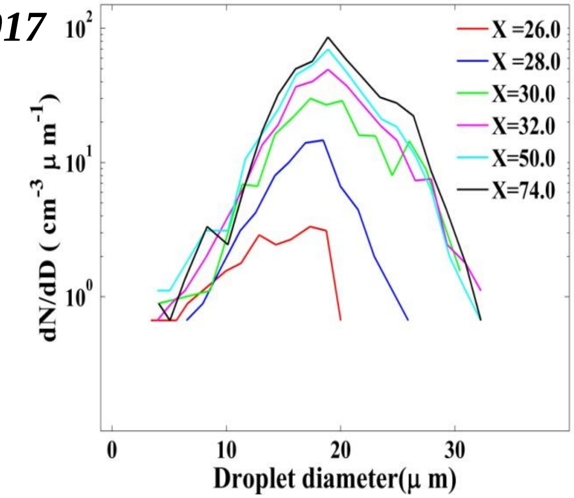
Kumar et. al., *JAS, 2014*

Comparison from observation





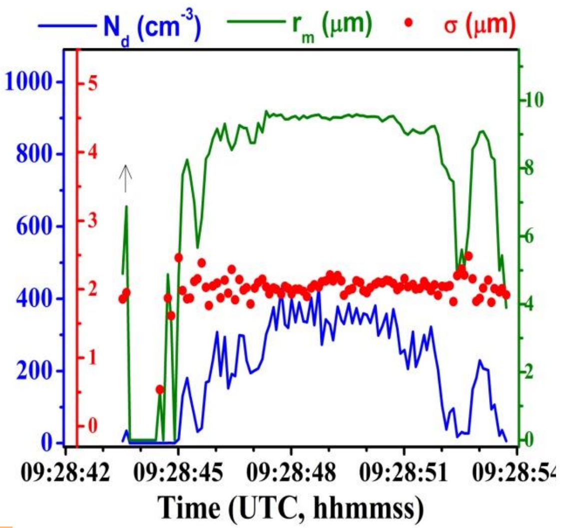
JAMES, 2017

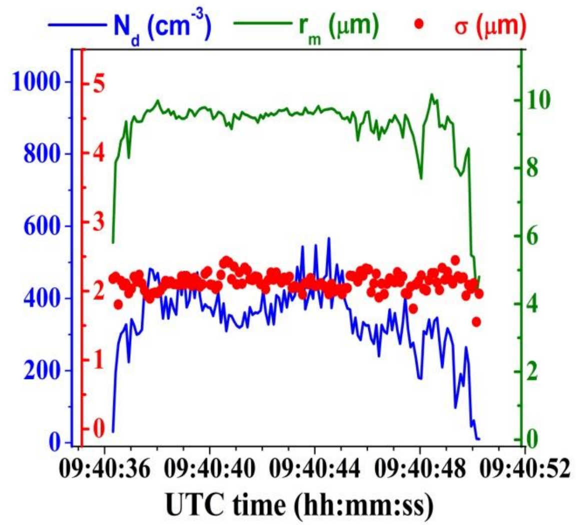


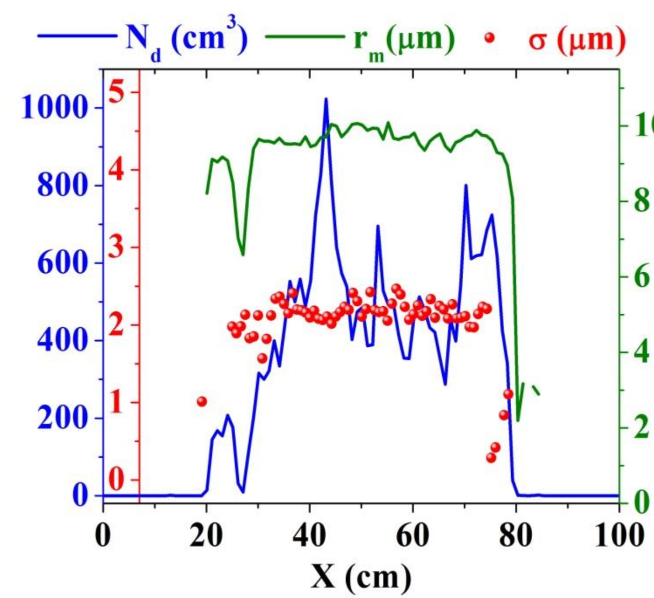
CAIPEEX RF45

Resolution : 10 m
Altitude : 5 Km

DNS

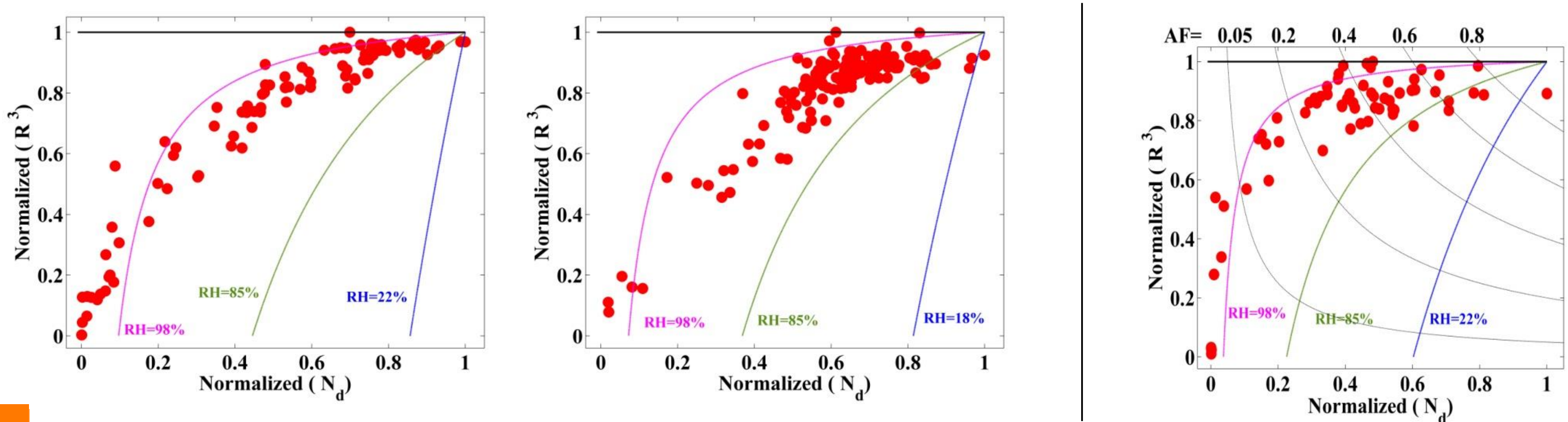






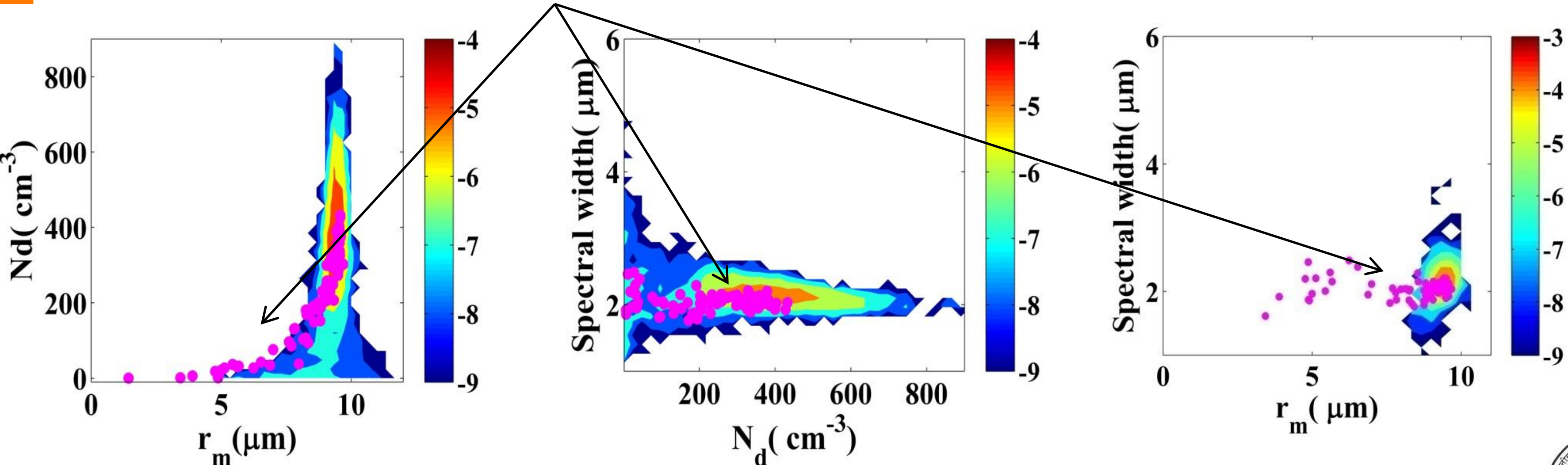
Comparison from observation

CAIPEEX RF45 **DNS**

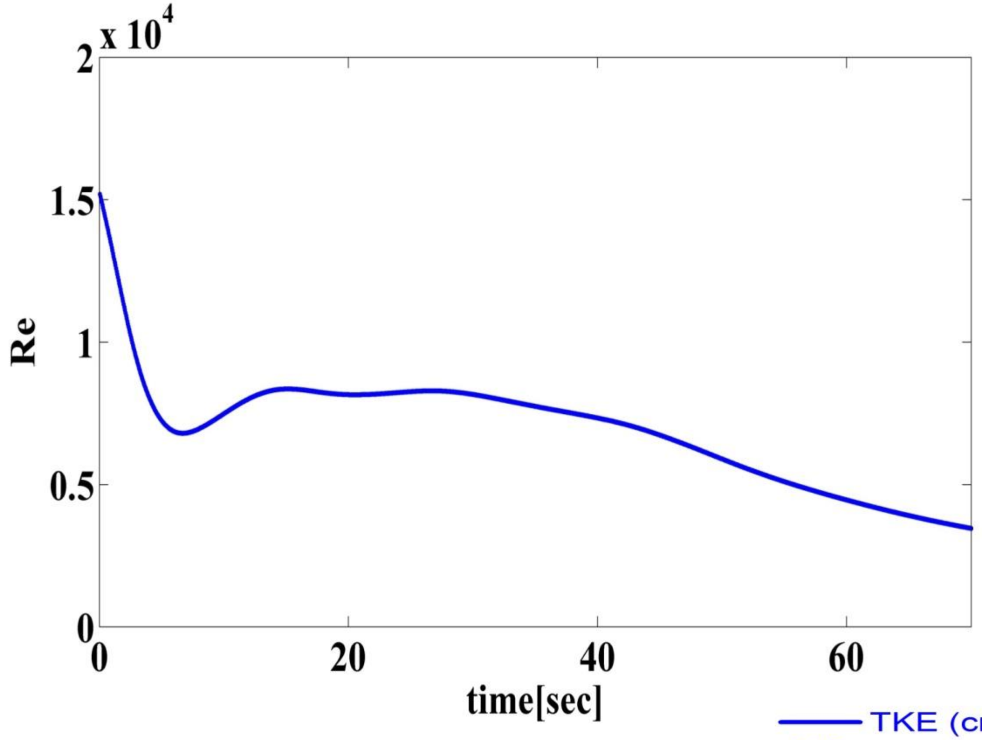


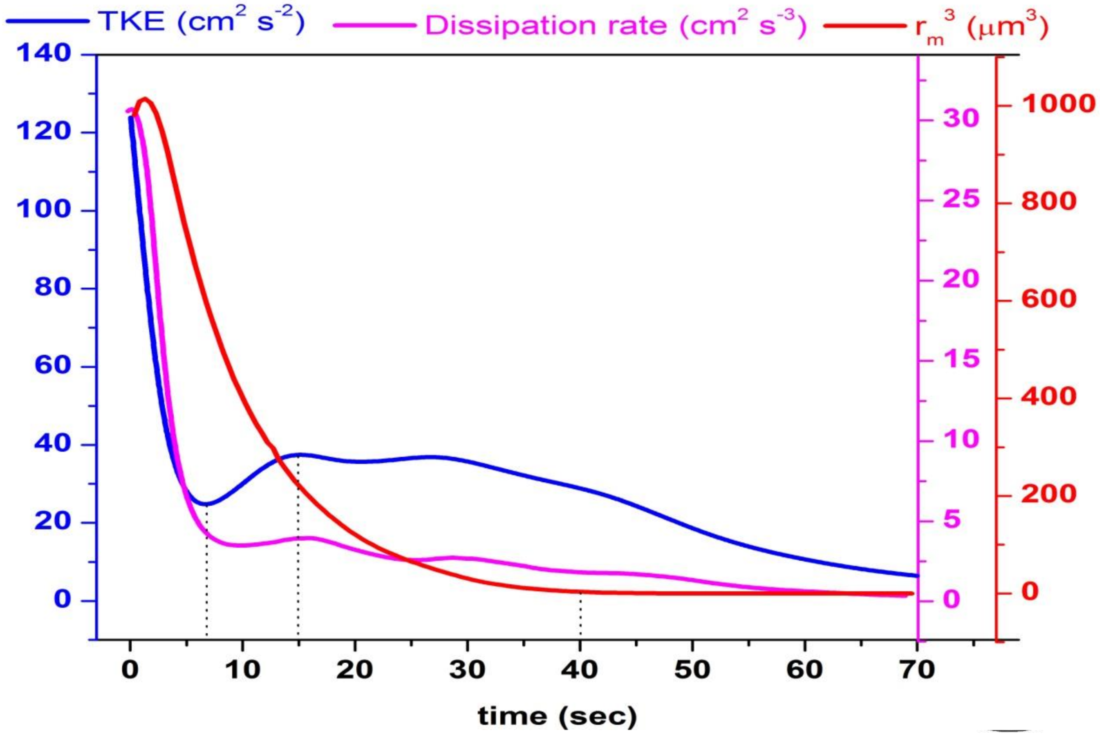
Pass 1 Pass 2

CAIPEEX RF45



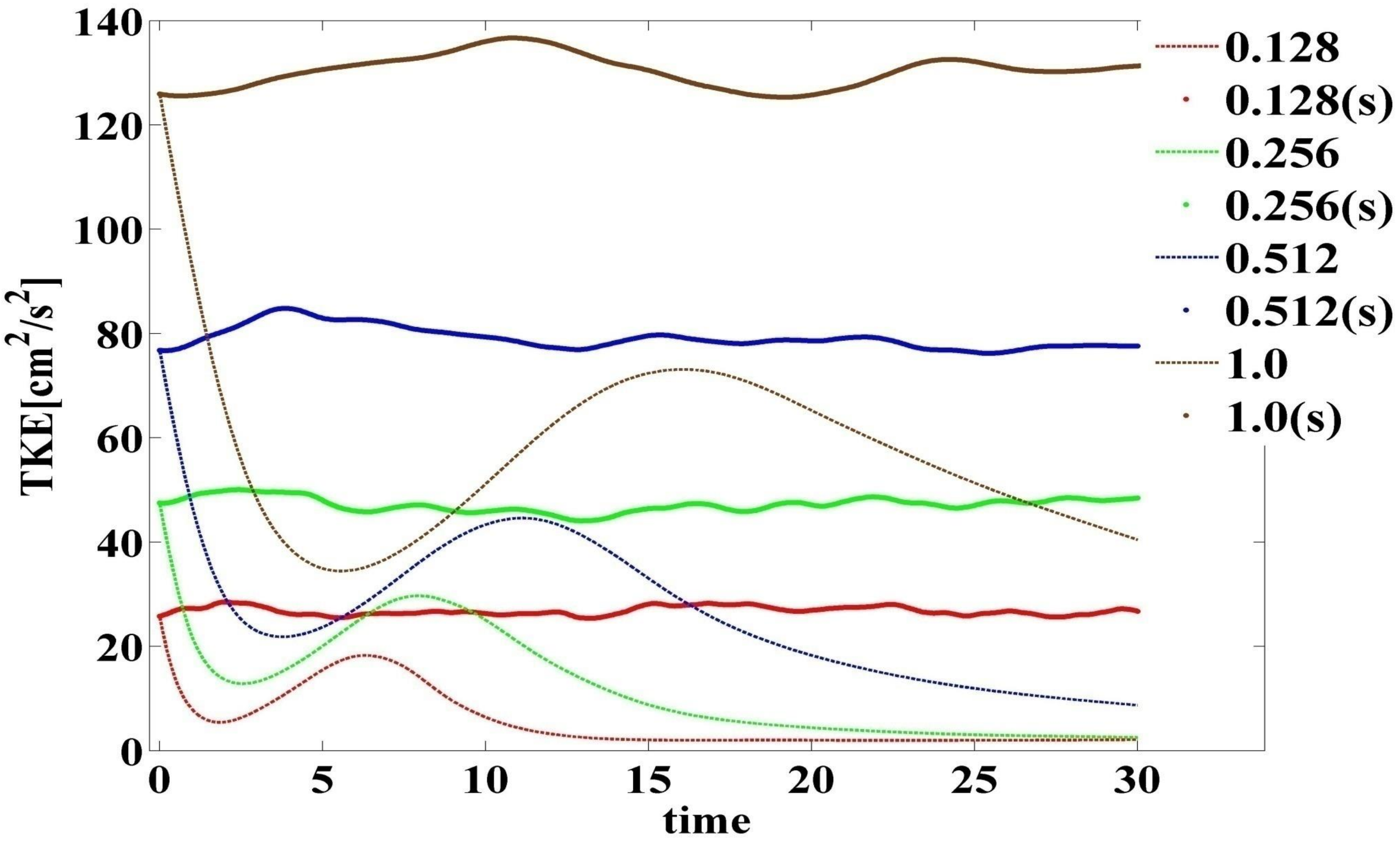
More properties





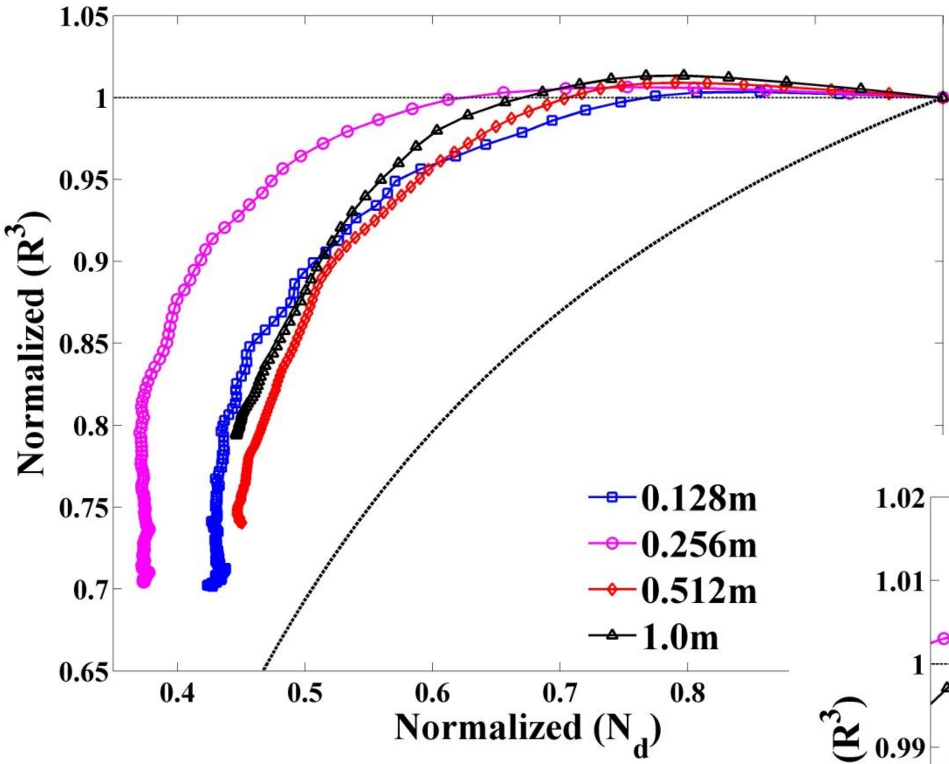
Varying domain size

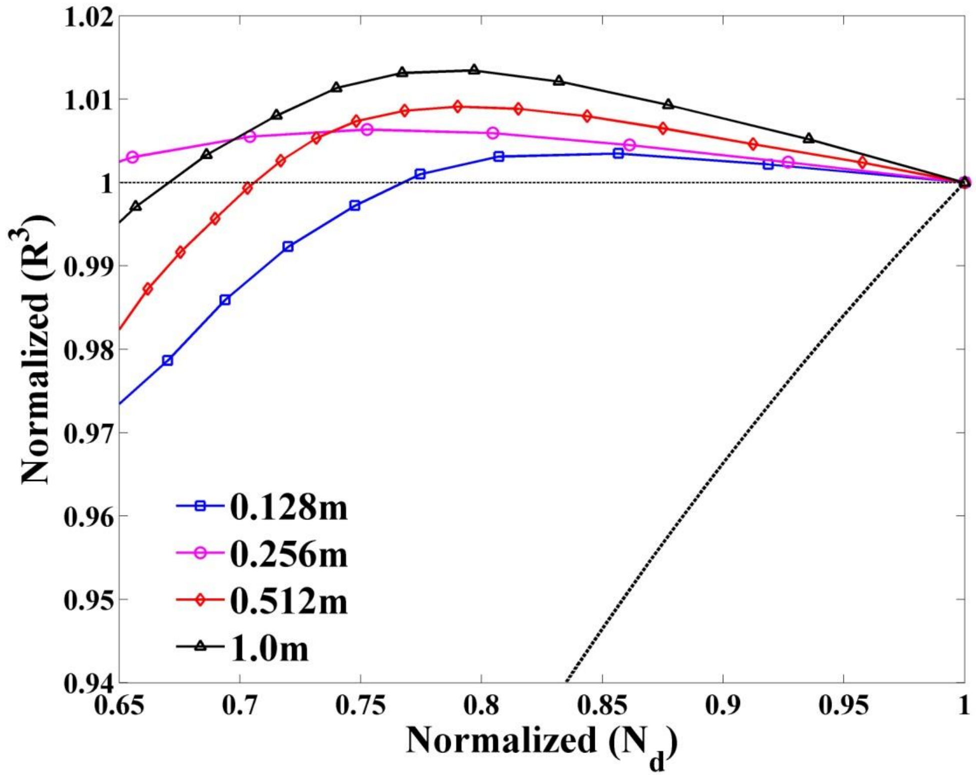
On going work



Varying domain size

On going work





Computational details

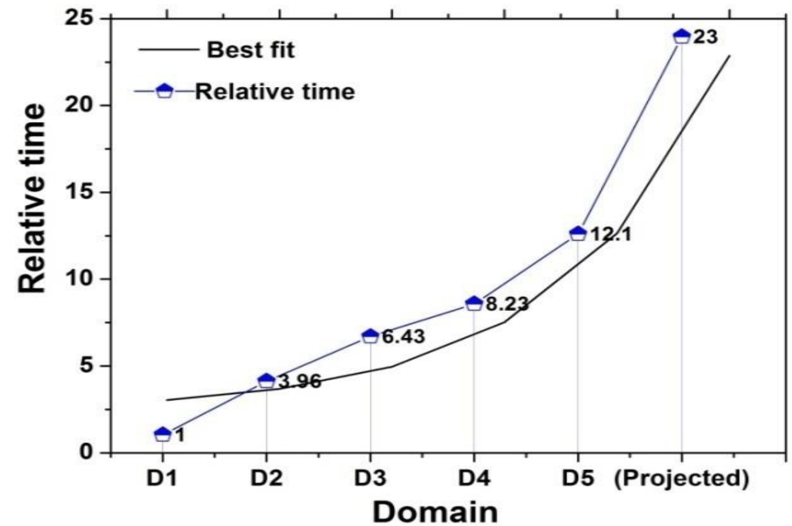
Five different domains

D1 : 12.8 cm^3, D2: 25.6 cm^3,
D3: 51.2 cm^3 , D4: 102.4 cm^3,
D5: 204.8 cm^3

Total times for 60000 iteration using 1024 cores with 2 OpenMP threads.

Domain (cm^3)	Time (sec)	Diff	N_t
D1	2759	1	108134
D2	10947	4	865075
D3	70394	6.43	6920601
D4	579642	8.23	57378078
D5	6989561 (Estimated) 80 days	12.1	433166745

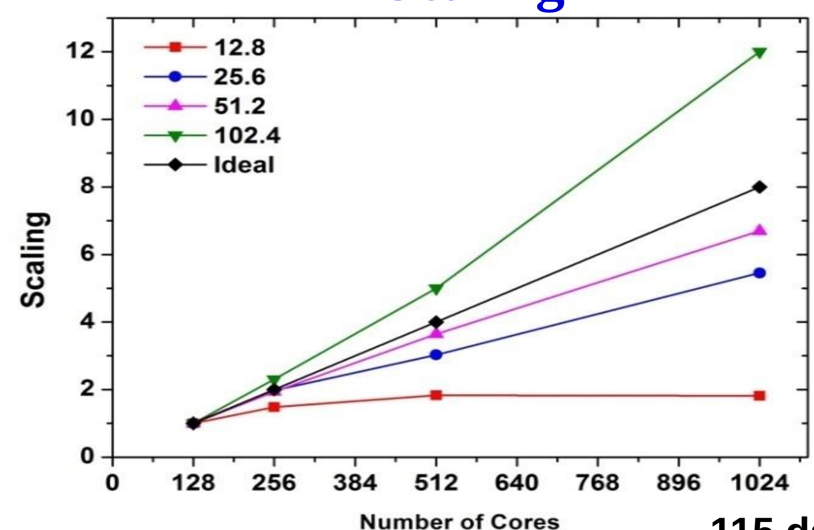
`Diff1 is the difference in times with respect t previous small domain.



Projected time for a domain of size 409.6 cm^3

23* 80 = 1840 days on 1024 cores

Scaling



115 days

Conclusions

DNS carried out in Eulerian-Lagrangian framework.

Evaluation stage were analysed.

Turbulace affect droplet dynamics

Results were compared with field observation.

Computational details provide projected time for bigger simulation.

Further directions

Model extension

Lagrangian

$$\frac{\mathrm{d}\mathbf{V}}{\mathrm{d}t} = \frac{1}{\tau_p}[\mathbf{u}(\mathbf{X},t) - \mathbf{V}(\mathbf{X},t)] + \mathbf{g}$$

$$\frac{\mathrm{d}\mathbf{X}}{\mathrm{d}t} = \mathbf{V}(\mathbf{X},t) \qquad S(\mathbf{X},t) = \frac{q_v(\mathbf{x},t)}{q_{v,s}} - 1$$

$$r(\mathbf{X},t)\frac{\mathrm{d}r(\mathbf{X},t)}{\mathrm{d}t} = KS(\mathbf{X},t)$$

$$\tau_p = \frac{2\rho_l r^2}{9\rho_0 \nu}$$ Finite particle response time

ρ_l : water density

ρ_0 : air density

ν : kinematic viscosity

Collision- coalescence physics.

For Aerosols

$$r_a(\mathbf{X},t)\frac{dr_a(\mathbf{X},t)}{dt} = K\left(S(\mathbf{X},t) - \frac{c}{r_a} + \frac{h}{r_a^3}\right)$$

c: curvature coefficient.
h: hygroscopic coefficient.

$$\left[r_a(\mathbf{X},t)\frac{dr_a(\mathbf{X},t)}{dt} = K\left(S(\mathbf{X},t) - \frac{c}{r_a} + \frac{h}{r_a^3}\right)\right]_i \qquad i = 1,2,3....$$

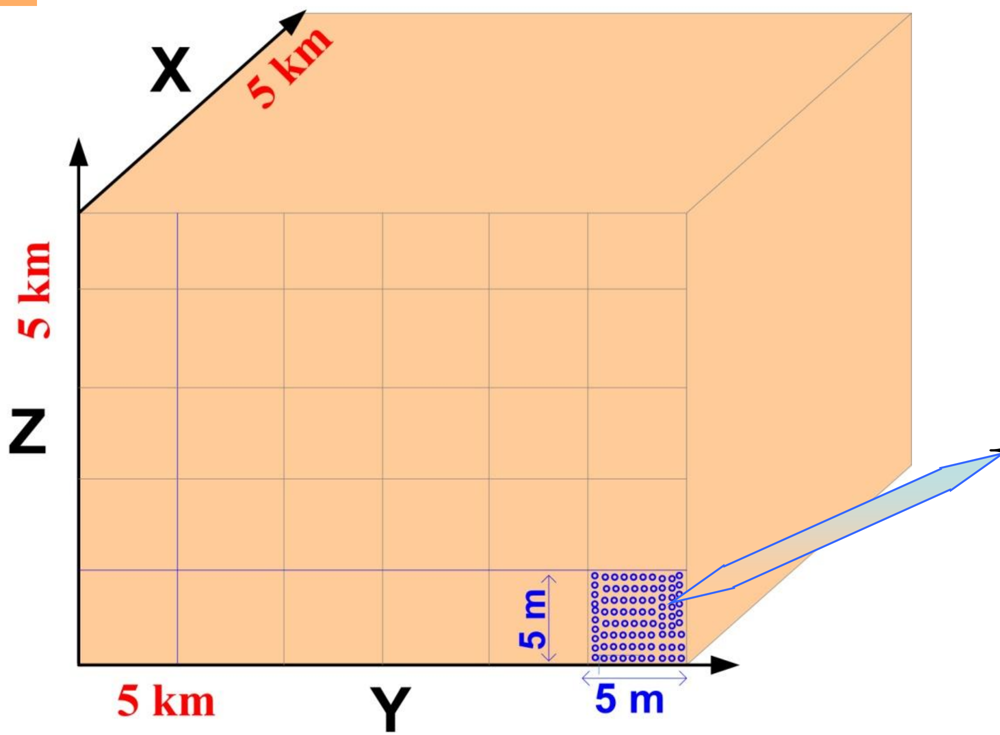
Total number of particles will increase.

Future directions

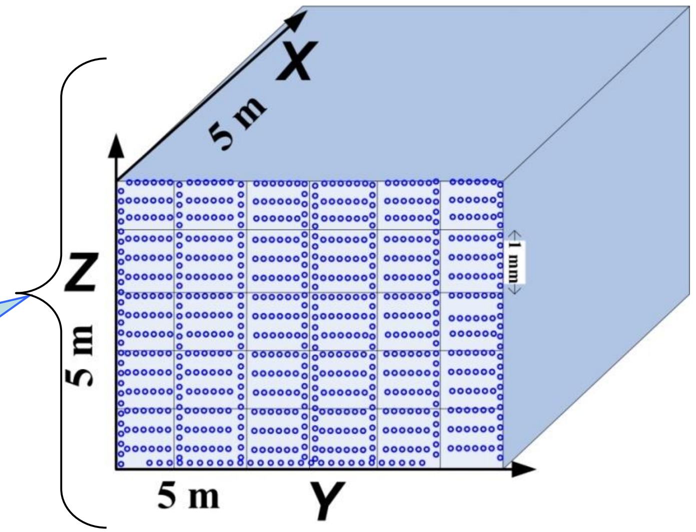
LES ←→ DNS

Domain : (5m ^{3})
Resolution : $(5120)^3$ grid cells
droplets : 31.25 billions
Time step : $1.0e^{-4}$

- ➢ Simulation in larger domain.



- ➢ Computationally more complex



Requirement (for one experiment)

- ❖ Core: min (16384)
- ❖ More memory per core/node
- ❖ Very fast inter-processor connections

Contributions:

- ✓Better understanding of micro-physics
- ✓Can provide seamless information to LES.
- ✓Improvement of LES will be helpful for parameterization of large models.

Future directions

- ✓ TKE (Turbulent kinetic energy)
- ✓ K.E. Dissipation rate
- ✓ Vertical velocity PDF
- ✓ Condensation rate
- ✓ Evaporation rate
- ✓ Entrainment rate

⇓

LES

⇓

Bigger scale models

Thank you for your attention

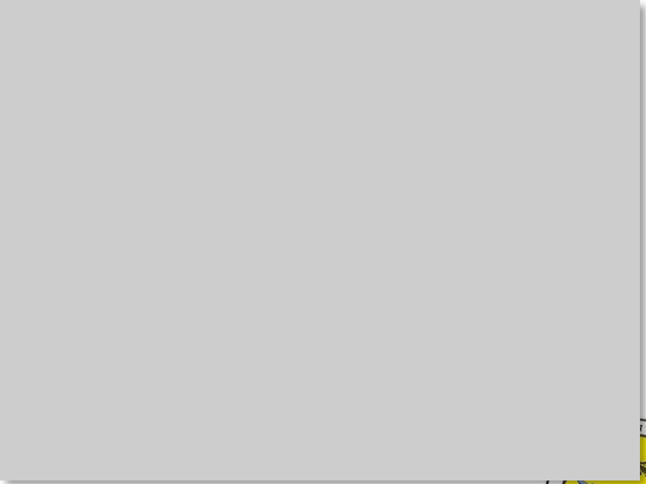
12.8

25.6

Vapor mixing ratio

51.2

102.4



Thank you for your attention

12.8

25.6

Temperature

51.2

102.4

Inhomogeneous mixing