Numerical Simulation of Turbulence-microphysics Interactions

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Outline

- Background
- Mathematics model
- Direct numerical simulation(DNS)
- Preliminary results
- Future work

Background

- **What**

  Water (vapor and liquid)

  Turbulence

  Interactions

- **How**

  Direct Numerical Simulation

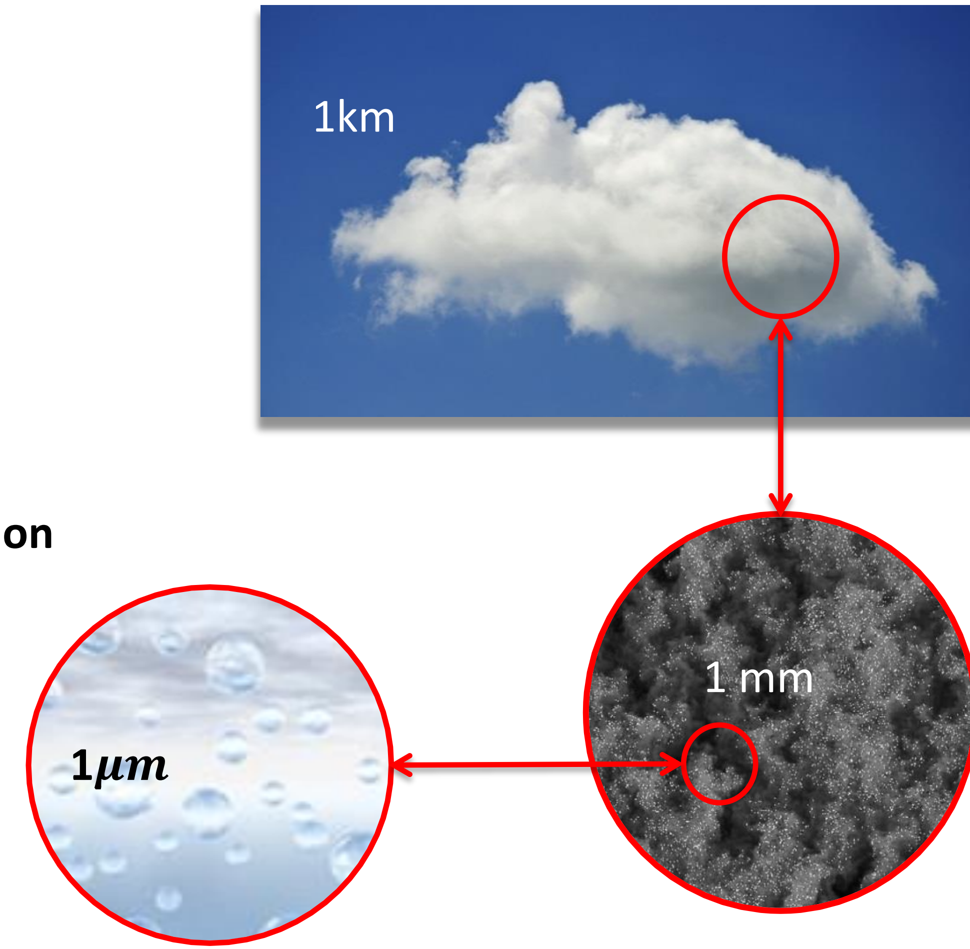
  Particle model

- **Why**

  Multi-scale

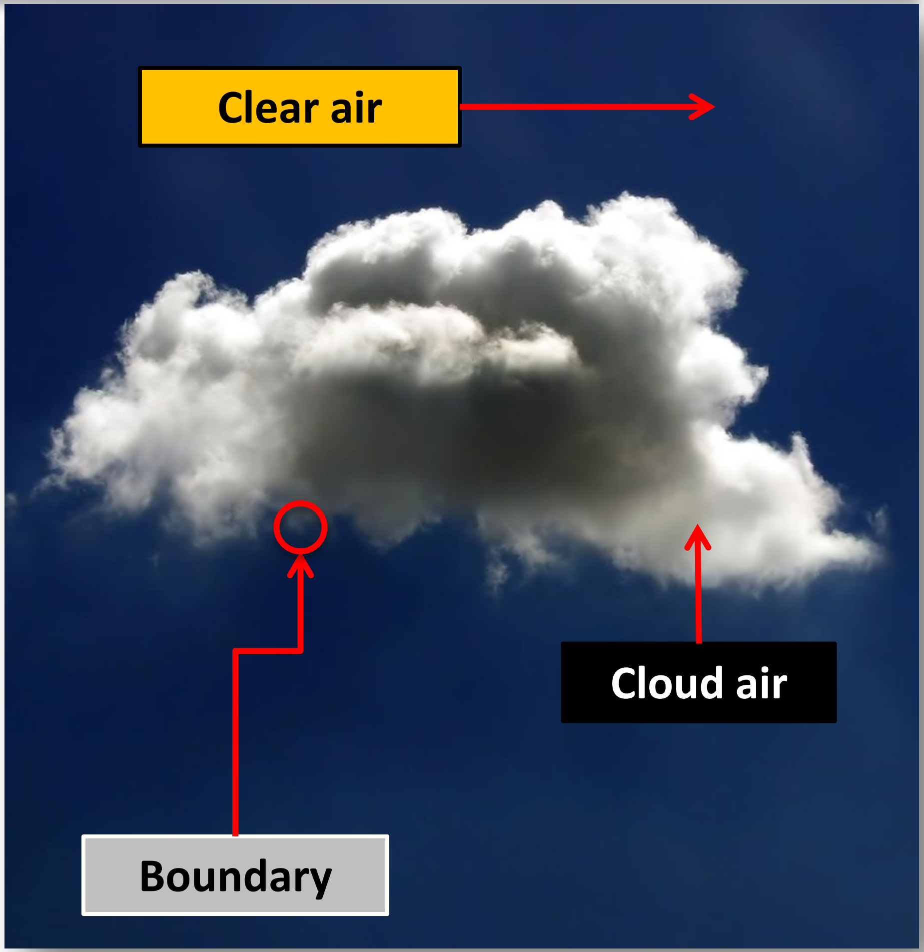
  Turbulence

  Particle tracking



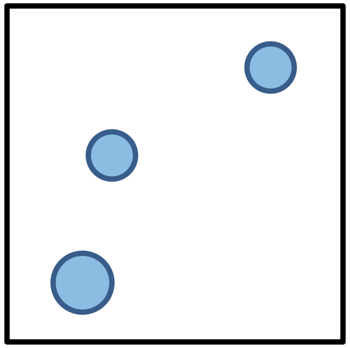
Background

- **Clear air:**
  - Less droplets
  - Low humidity
- **Cloud air:**
  - More droplets
  - High humidity
  - Collision
- **Boundary:**
  - Entrainment
  - Mixing
  - Measurement



Particle Model

Particles length scale:

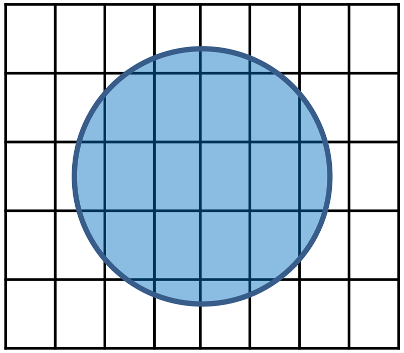


Cloud Droplets

Turbulence:

Dissipation scale > 1mm (10^3um)

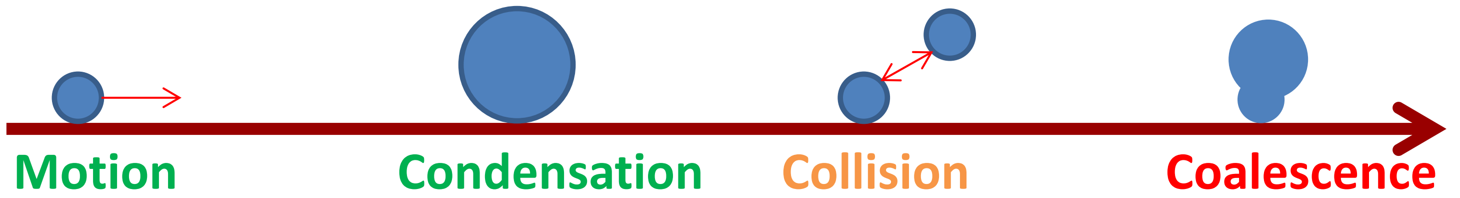
Much larger than droplets and comparable to raindrops



Raindrops

Particle Model

Simulation difficulty



Motion: inertial and sedimentation

Condensation: condensate or evaporate

Collision: detection and handling

Coalescence: merge or break up

Mathematics Model

1. Important variables

- Velocity field $\vec{u}(X, t)$: velocity of air (m/s)
- Vapor mixing ratio $q(X, t)$: ratio of vapor in dry air (g/kg)
- Temperature field $T(X, t)$: temperature of air (K)
- Saturated vapor mixing ratio $q_s(X, t)$: equilibrium state

Mathematics Model

2.1 Vector field

$$\frac{\partial u}{\partial t} + (u \cdot \nabla u) = -\frac{1}{\rho_0}\nabla p + \mu \Delta u + f$$ **Navier stokes equation**

$$\nabla \cdot u = 0$$

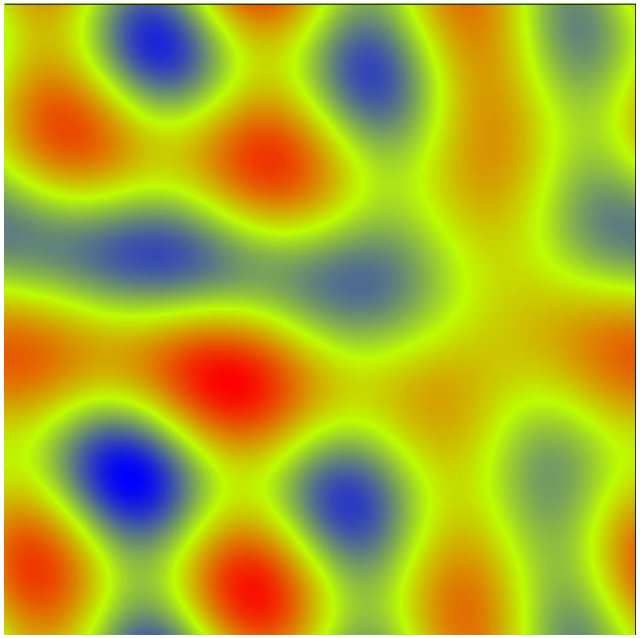
2.2 Scalar field

$$\frac{\partial q}{\partial t} + u \cdot \nabla q = -C_d + \kappa \Delta q$$ **Vapor mixing ratio**

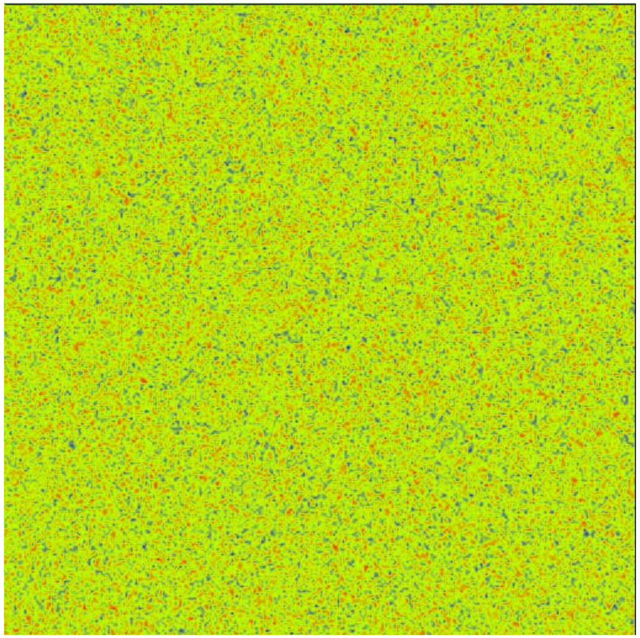
$$\frac{\partial T}{\partial t} + u \cdot \nabla T = \frac{L}{c_p} C_d + \mu_T \Delta T$$ **Temperature**

Mathematics Model

Magnitude of vorticity field



Vapor field



Mathematics Model

3. Droplets model

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

$$\frac{dR_i(t)}{dt} = A_3 \frac{S(x,t)}{R_i(t)}$$

Condensation and evaporation

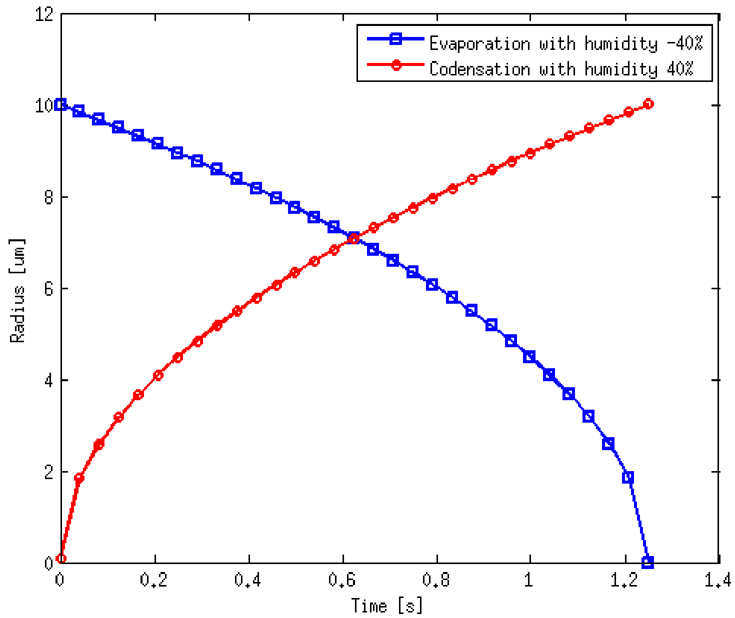
$$\frac{dX(t)}{dt} = V(t)$$

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

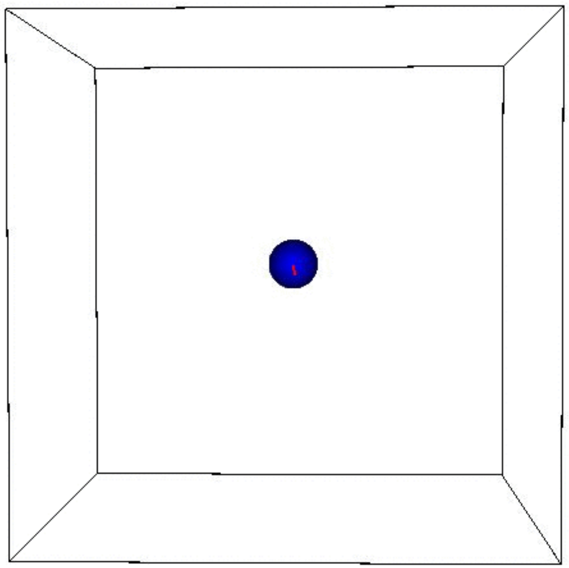
Droplets motion

Mathematics Model

Radius in condensation and evaporation process



Motion of droplets



Numerical Simulation

- **Domain:**

  $\mathbf{1}\boldsymbol{m} \times \mathbf{1}\boldsymbol{m} \times \mathbf{1}\boldsymbol{m}$

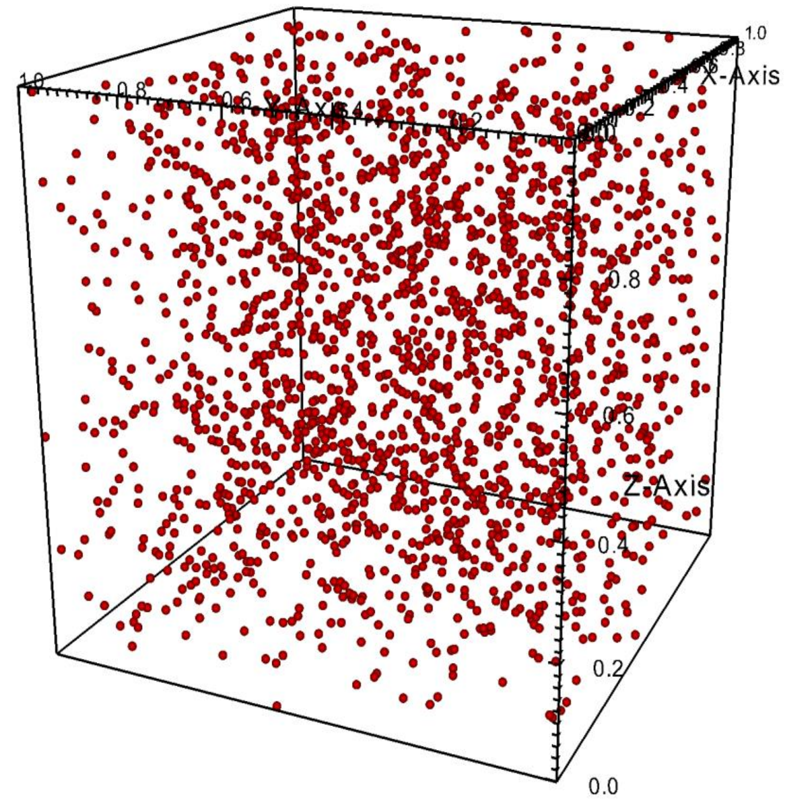
  Periodic boundary box

- **Droplets:**

  Radius $\mathbf{10}\boldsymbol{\mu m}$

  Density $\mathbf{10}/\boldsymbol{cc}$

  Number 10^7



Numerical Simulation

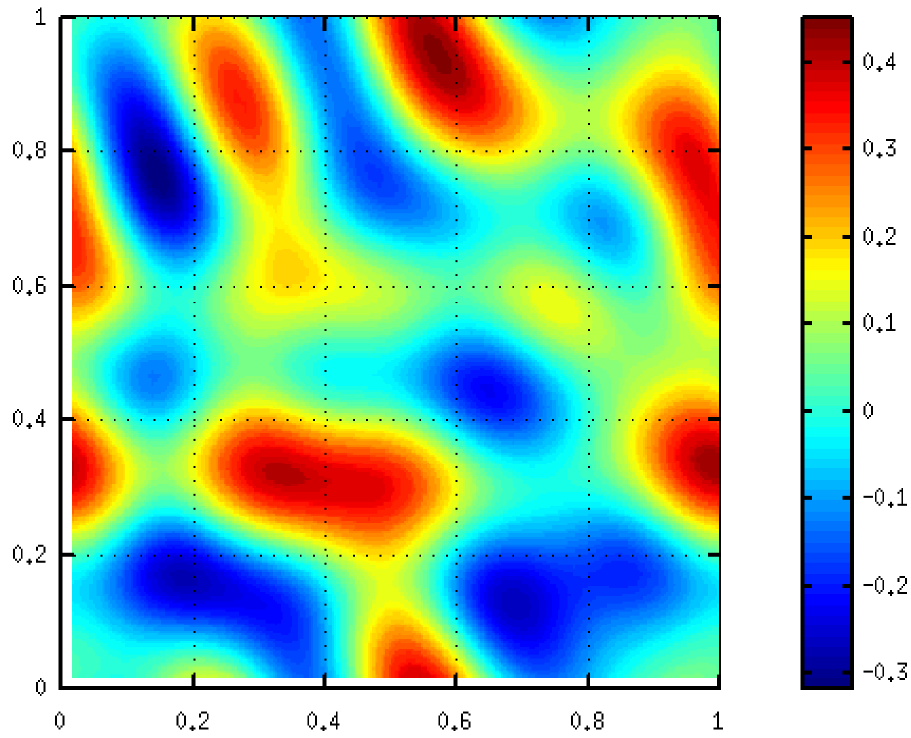
- Isotropic initialization with filter in Fourier space

$$\hat{u}(k) = k^2 \exp\{-\frac{k^2}{{k_0}^2}[\cos(2\pi\varphi) + isin(2\pi\varphi)]\}$$

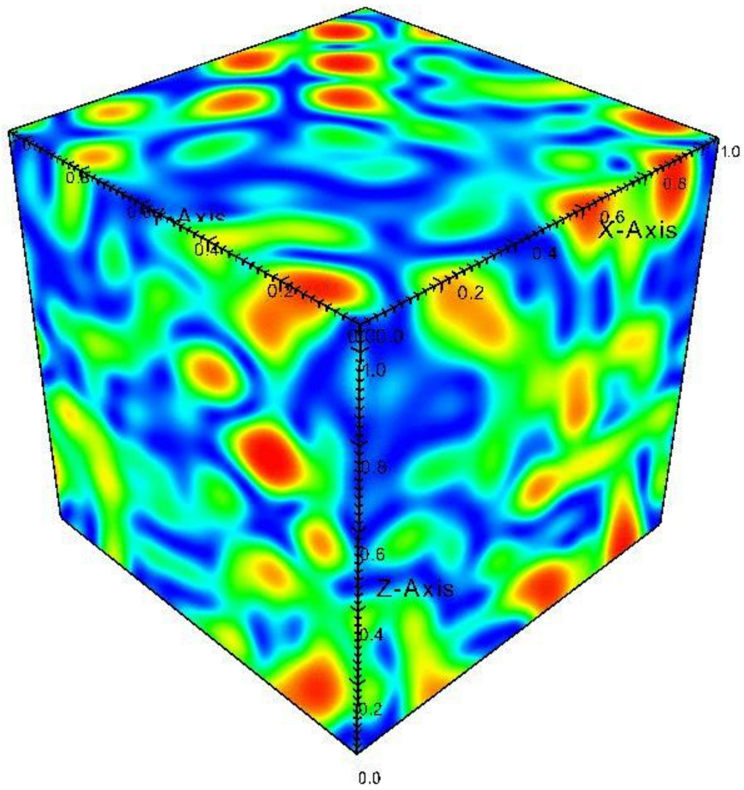
- Scale the velocity to control the intensity

- Use Taylor microscale Reynolds number

$$\boldsymbol{Re_\lambda = U_{rms}\lambda/\nu}$$



Numerical Simulation



- Energy input only in large wave length

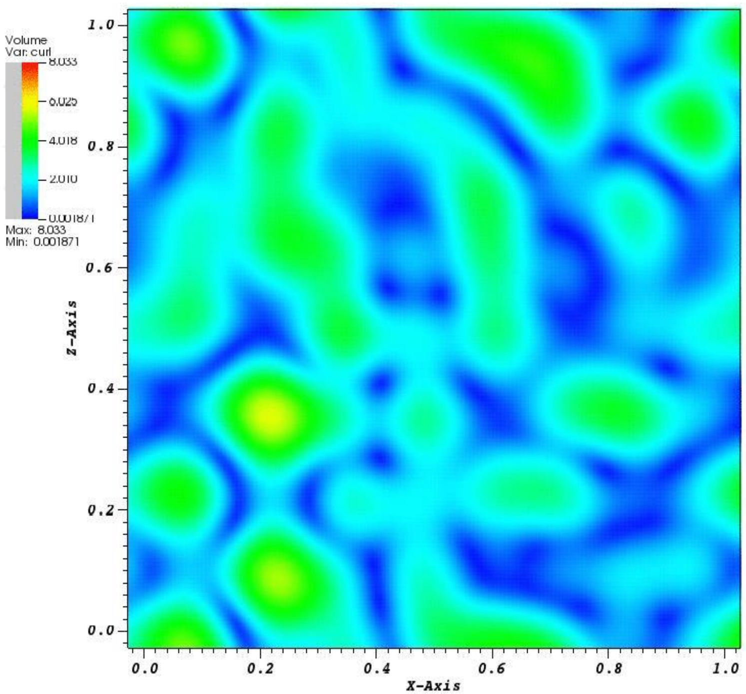
- Energy cascades to small length automatically

- Energy dissipated in Kolmogorov length scale

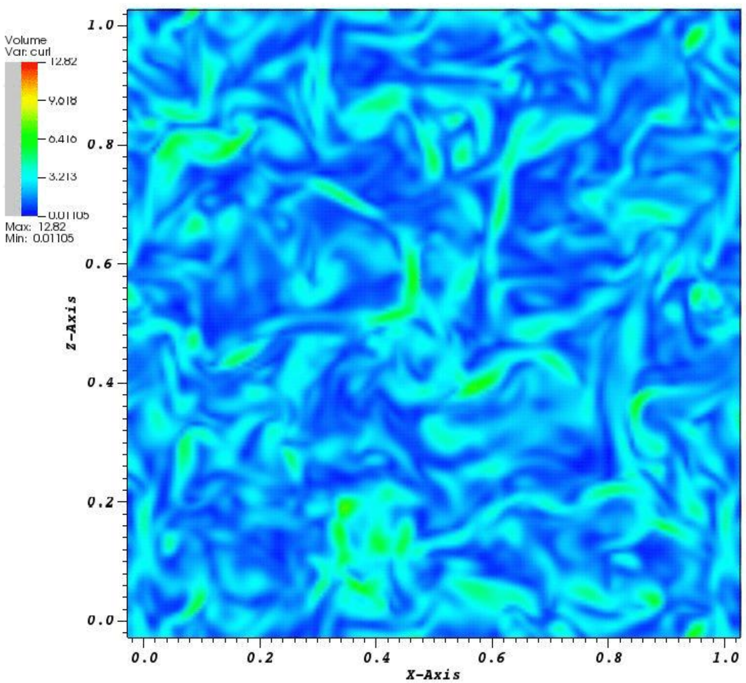
Numerical Simulation

Enstrophy ($|\nabla \times \mathrm{U}|^2$) in x-z cross sectional plane

Enstrophy at 0s



Enstrophy at 80s



Numerical Simulation

- **Turbulence properties**

Group	$\mathbf{u_{rms}(m/s)}$	$\boldsymbol{\varepsilon}(\mathbf{m^2 s^{-3}})$	$\boldsymbol{\eta}(\mathbf{m})$	$\mathbf{Re_\lambda}$
Flow A	0.01074	3.1e-5	0.003	20
Flow B	0.02109	1.7e-4	0.002	34
Flow C	0.03422	4.0e-4	0.001	58

- $\varepsilon = 2\upsilon \sum_{i=1}^{3} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$ $\quad \lambda = \sqrt{15\upsilon {u_{rms}}^2 / \varepsilon}$ $\quad Re_\lambda = U_{rms}\lambda/\nu$

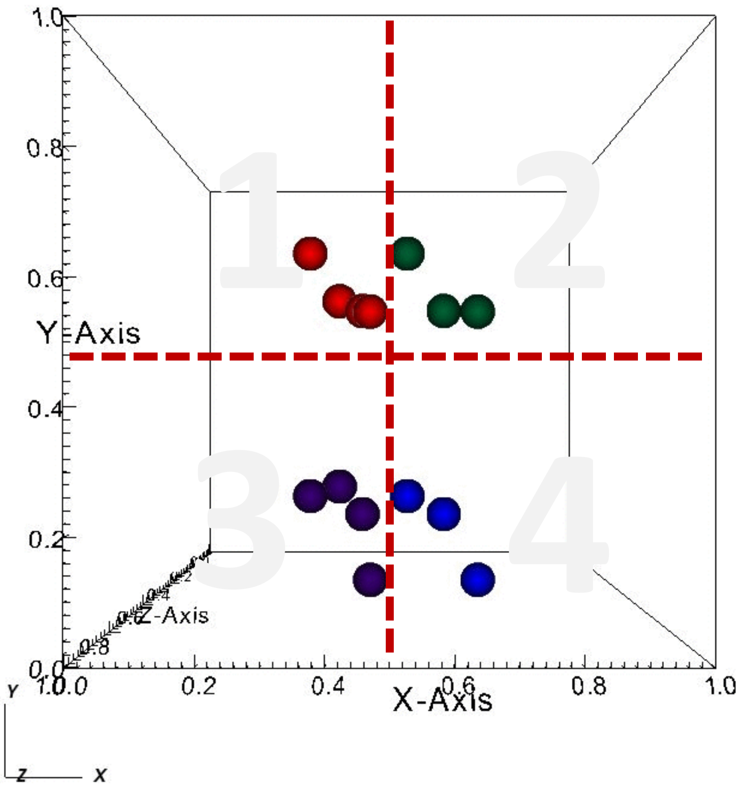
Parallel computing

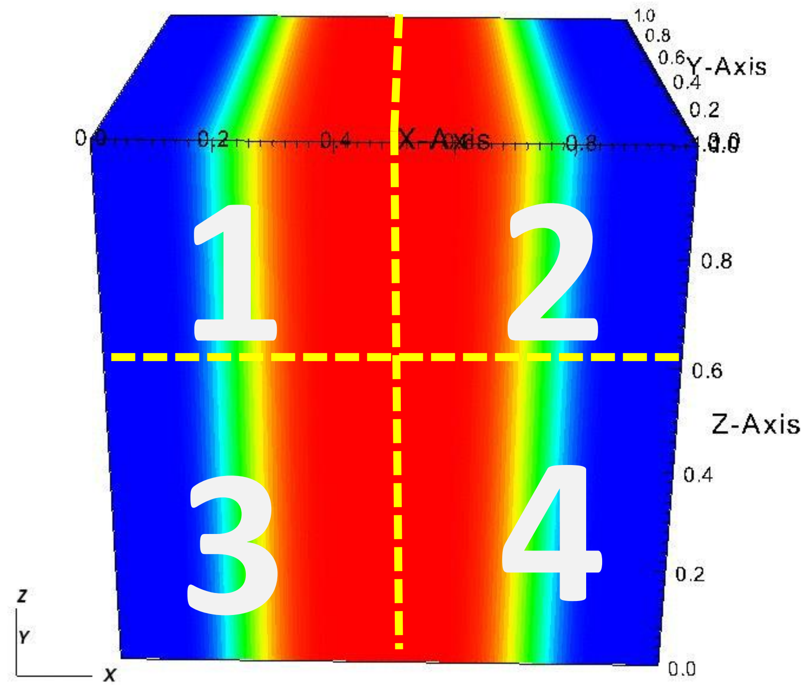
- **MPI**
- **Parallel communication of field (FronTier)**
- **Parallel communication of particles (New)**
- **Parallel statistics: deviation, PDF (New)**
- **Basic idea:**

  Add buffers at boundary

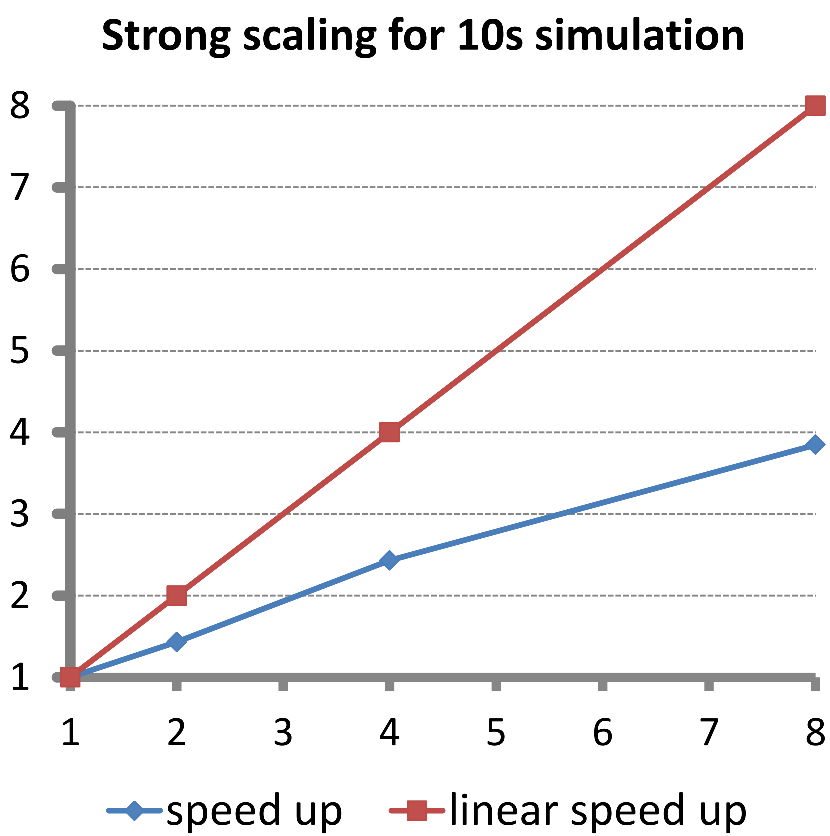
  Exchange buffers direction by direction (x, y, z)

Parallel computing





Parallel computing

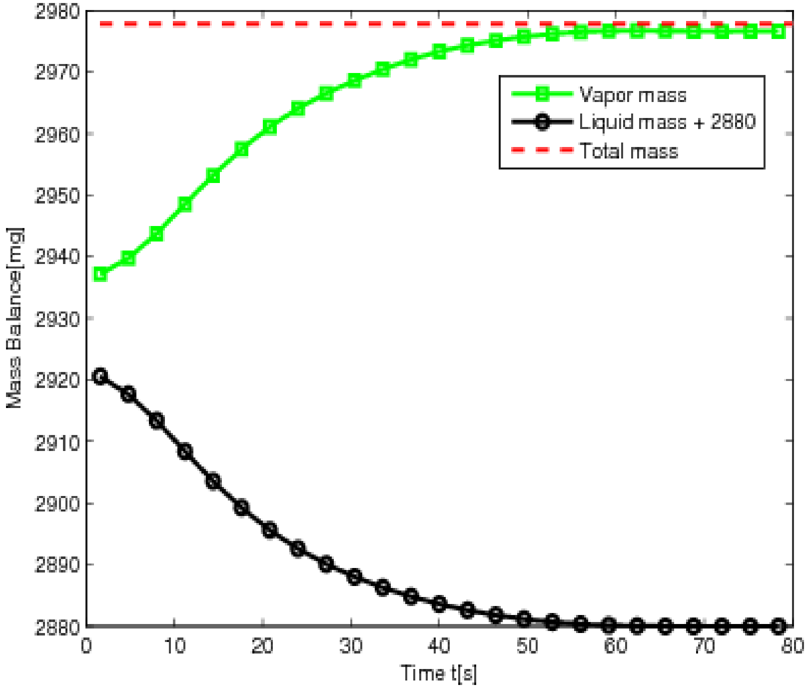


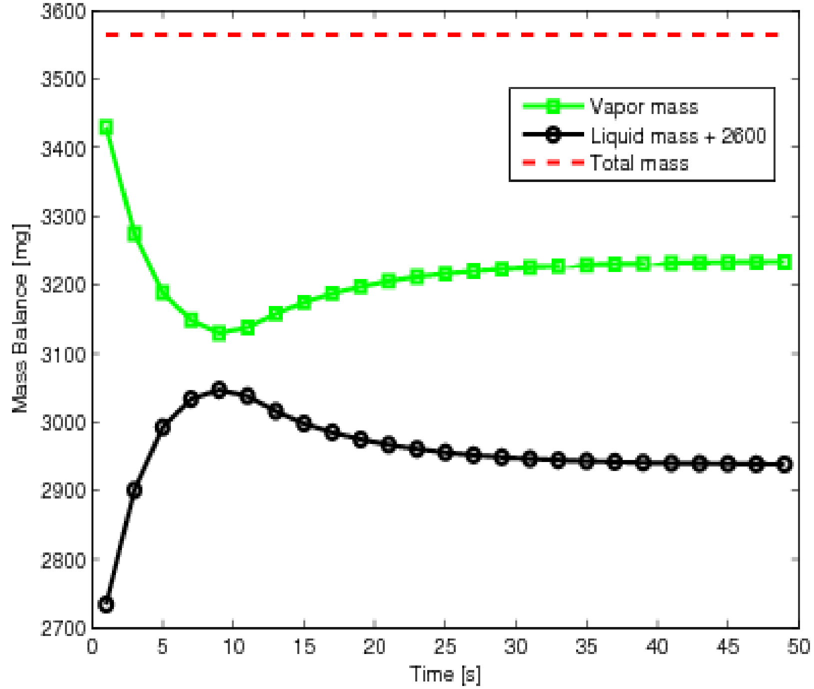
No.	Time	Speed up
1	1h 22m 19s	1
2	57m 33s	1.4
4	33m 52s	2.4
8	21m 24s	3.8

Speed up: t_1/t_N

Verification and Validation

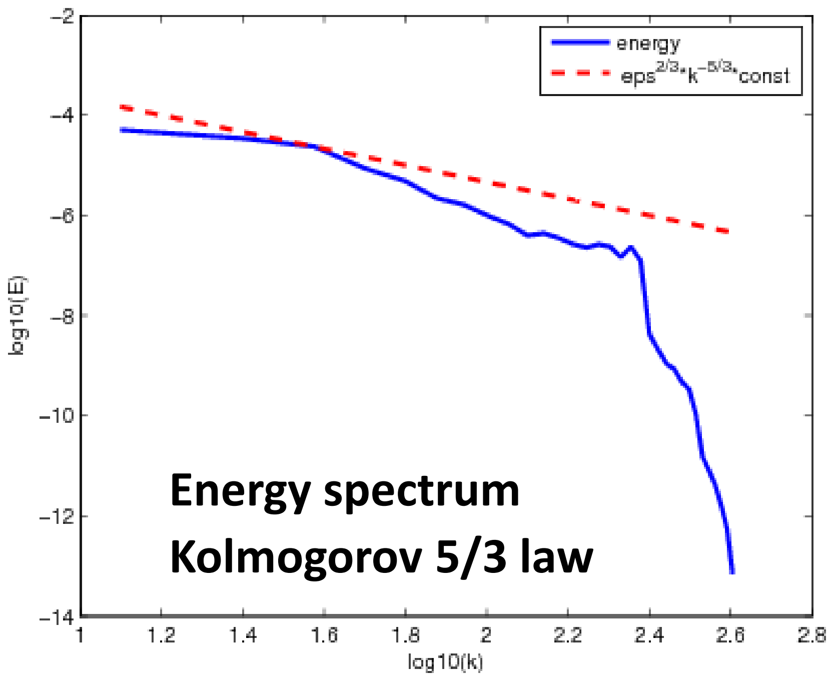
Mass conservation

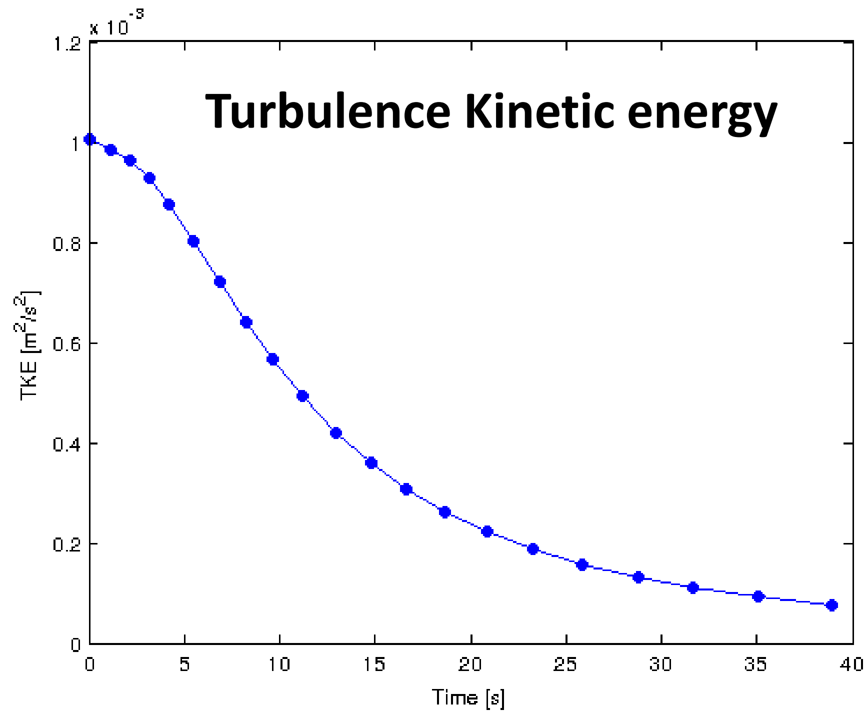




Verification and Validation

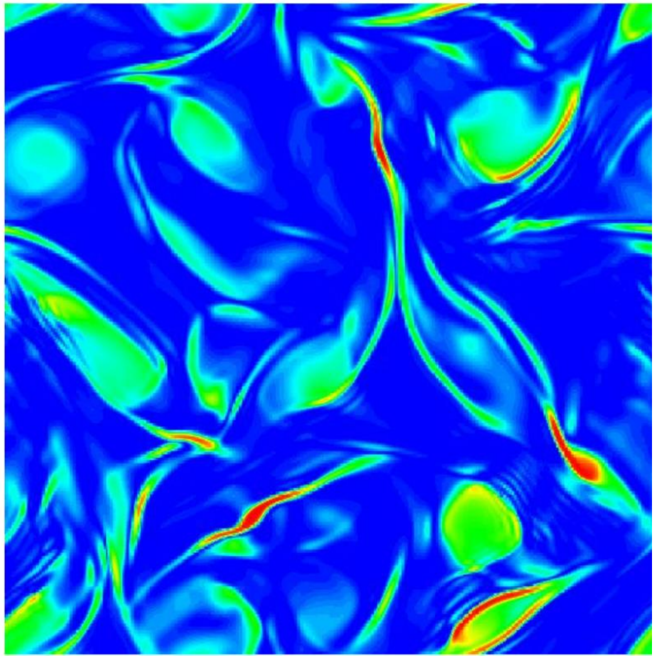
Turbulence properties



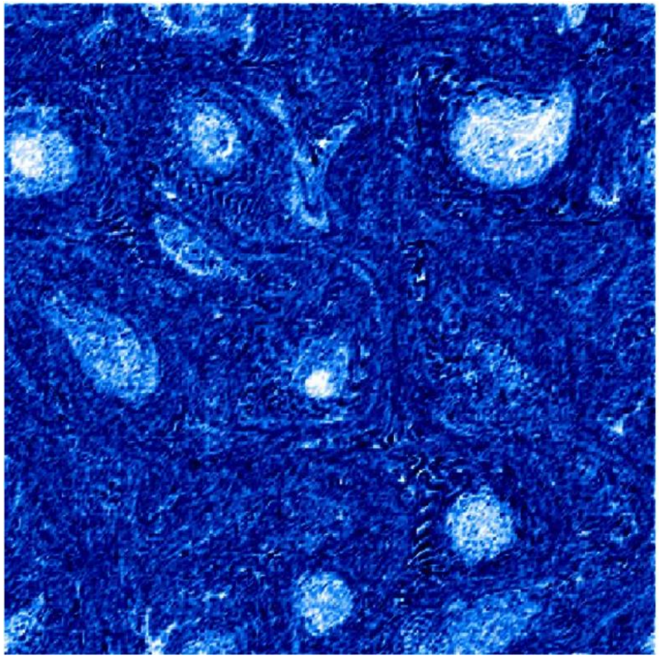


Cloud Microphysics

Preferential concentration



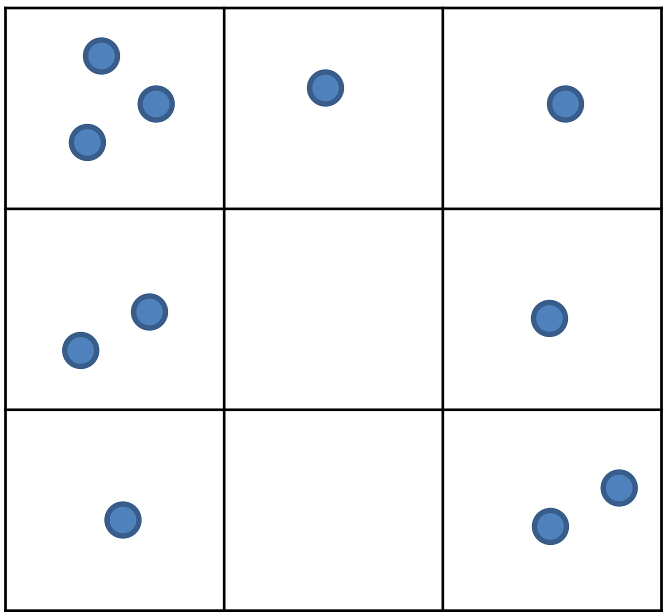
Magnitude of vortices



Number density of particles

Cloud Microphysics

Number density



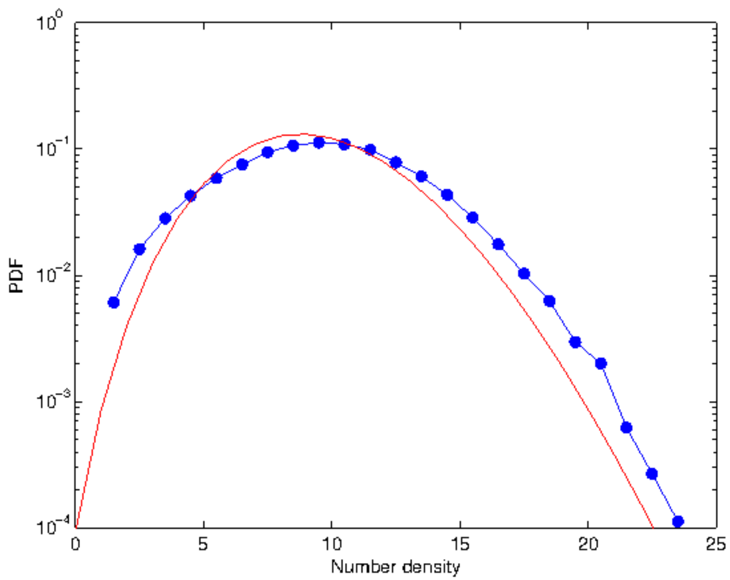
Particles in grid cell

3	1	1
2	0	1
1	0	2

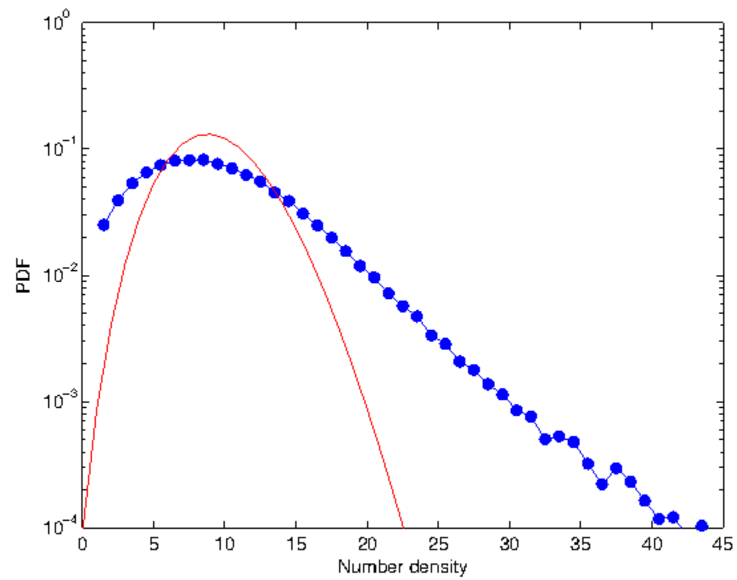
Number density of particles

Cloud Microphysics

Preferential concentration



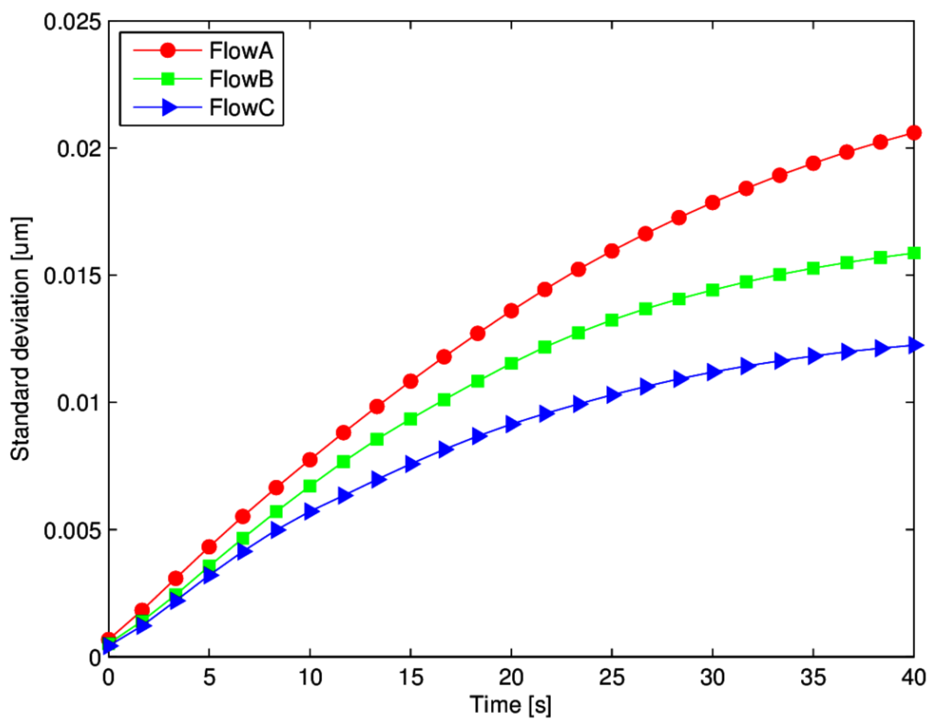
PDF of number density
at t = 0s



PDF of number density
at t = 40s

Cloud Microphysics

Condensational growth



Standard deviation of radius distribution with three different turbulence configuration.

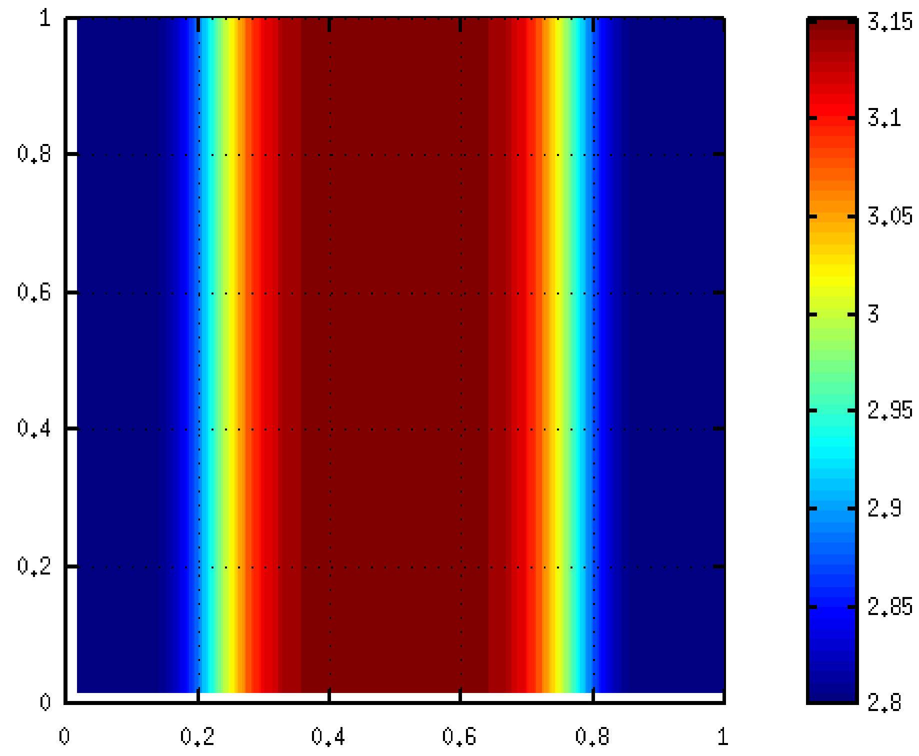
Intensity:

Flow A < Flow B< Flow C

Entrainment and Mixing

- **Vapor mixing ratio is set continuously from dry to moist**

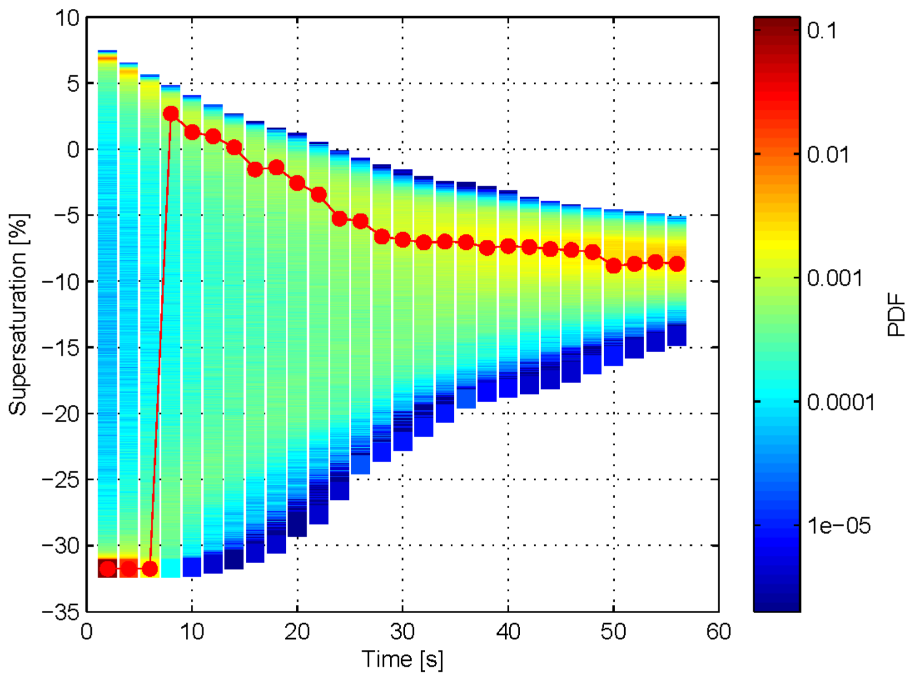
- **Define some variables for measurement**



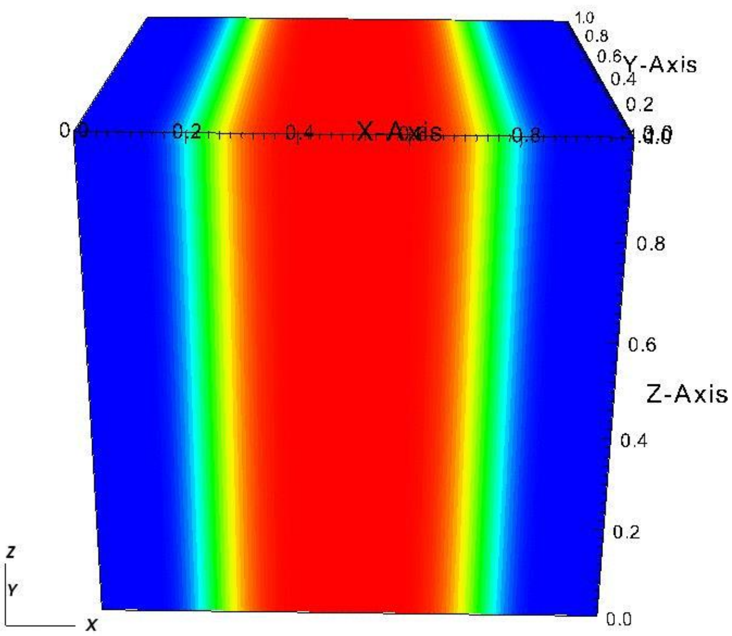
Vapor mixing ratio in x-z plane

Entrainment and Mixing

- Distribution of the humidity

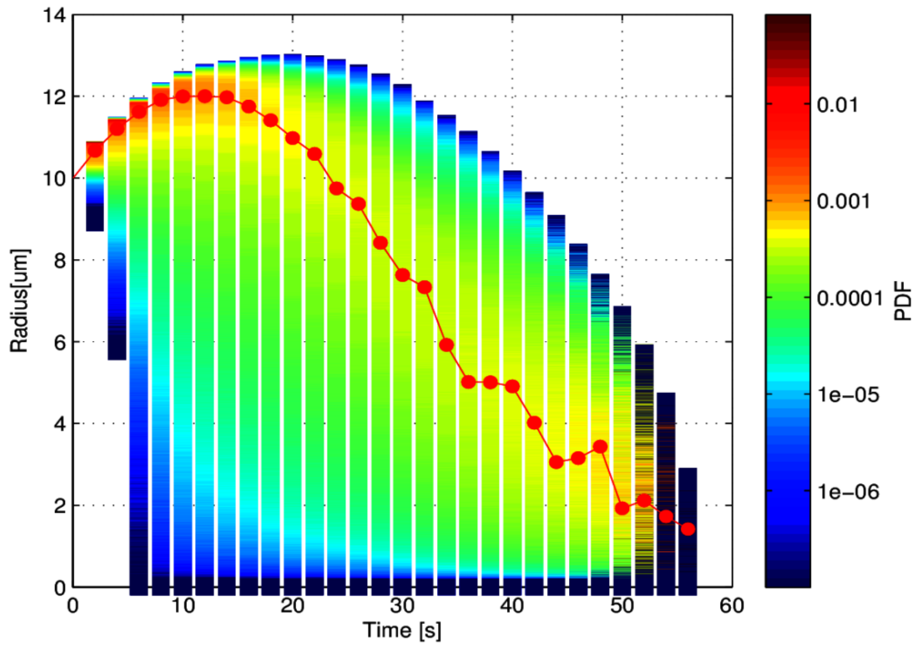


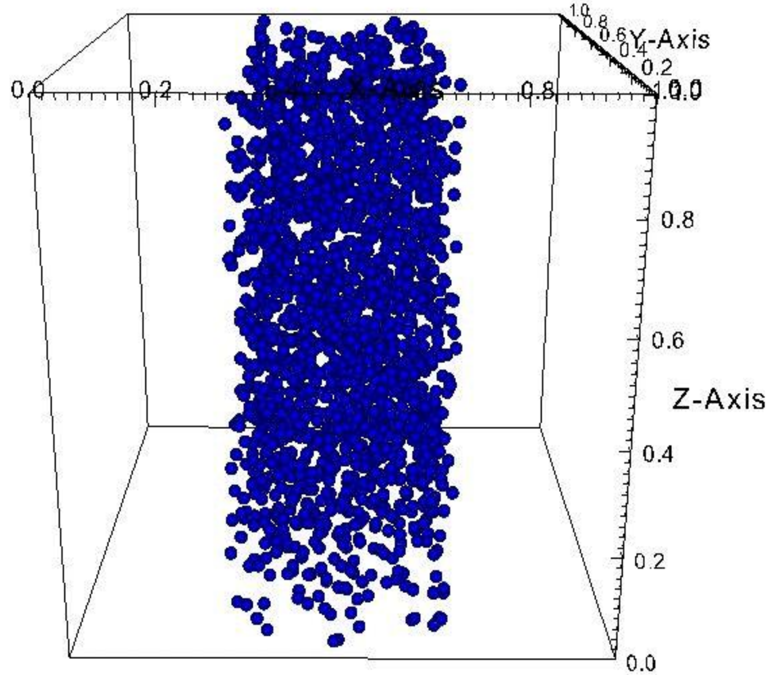
- The vapor mixing ratio field



Entrainment and Mixing

Radius distribution





Future Work

- Current resolution is 128^3, improve resolution
- CUDA-Aware MPI to accelerate particles
- Entrainment from the top and bottom
- Collision and coalescence
- Thank you for coming