Towards Multiscale Simulations of Cloud Turbulence

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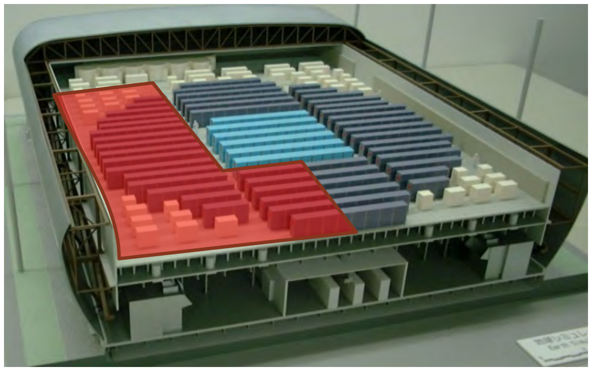
Some figures and slides are removed from original talk

Contents of my talk

- MSSG (Multi-Scale Simulator for the Geoenvironment)
- High-resolution cloud simulations (LES) with MSSG-Bin microphysical scheme
  - Turbulent collisions of droplets
  - RICO
- DNS for colliding droplets in high-Re flows
  - Our numerical schemes
  - validation of turbulent collision models

EARTH SIMULATOR

Earth Simulator 2



Earth Simulator

Mar. 2002 – Sept. 2008

Processors : 5,120 (640 nodes)

Peak performance : 40 TFLOPS

Main memory : 10 TB

Earth Simulator 2

Mar. 2009 -

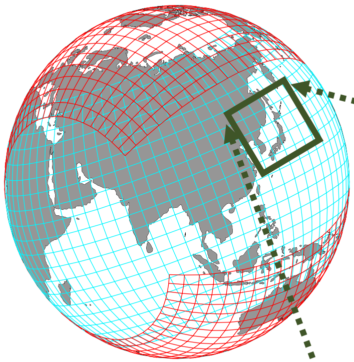
Processors : 1,280 (160 nodes)

Peak performance : 131 TFLOPS

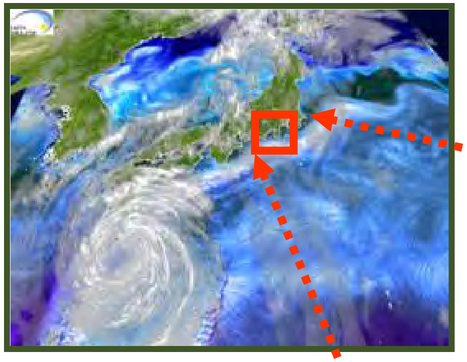
Main memory : 20 TB

Multi-Scale Simulator for the Geoenvironment (MSSG)

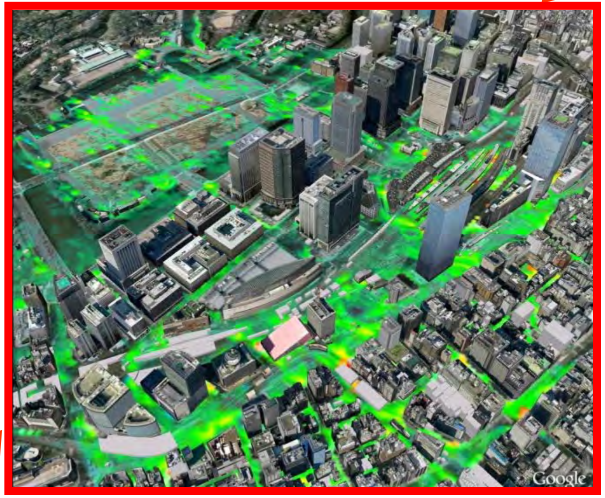
- **Applicable to global, regional and local scales seamlessly**
- **Ying-Yang grid for globe**
- **Consists of 3 modes; atmos. / ocean / coupled**
- **Highly optimized for the Earth Simulator (ES)**



global scale



mesoscale

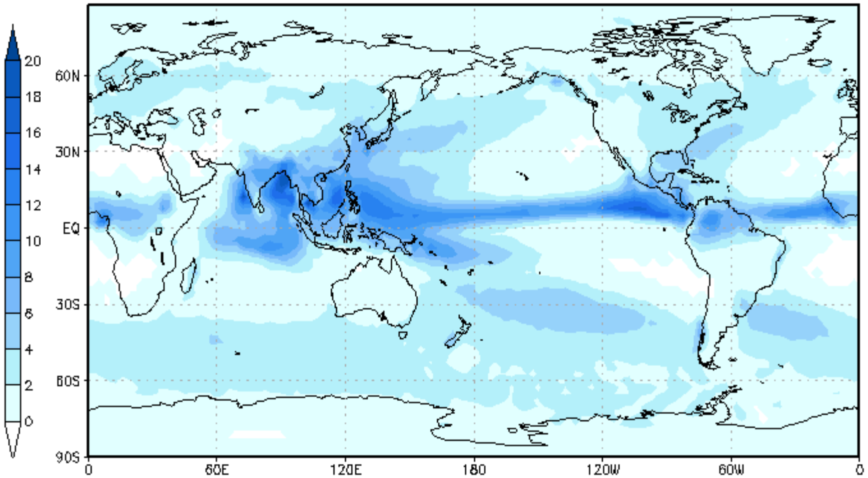


urban scale


Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Data © 2009 MIRC/JHA
Google

Seasonal simulation

Observation
(CMAP, 1979-2001JJA)



MSSG-A
(Δ_H=40 km, 32 levels, 5yrs ave-JJA)

skip

precipitation at JJA

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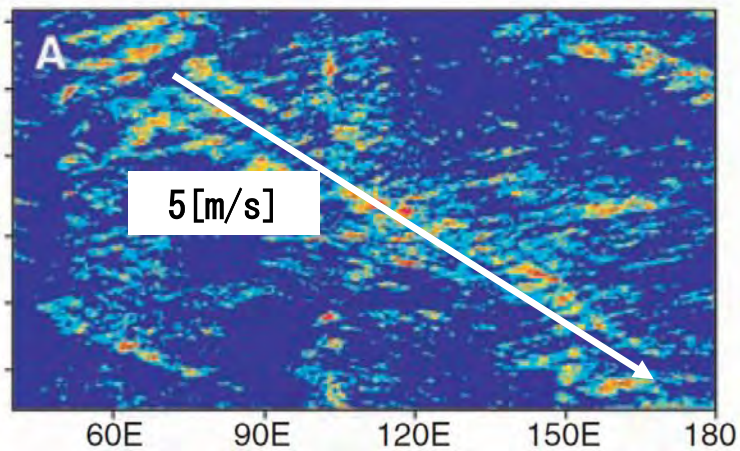
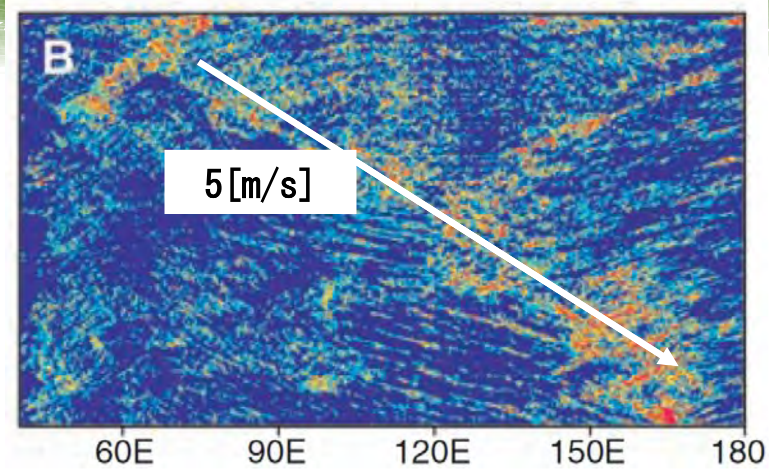
MJO experiment

observation (TRMM 3B42)

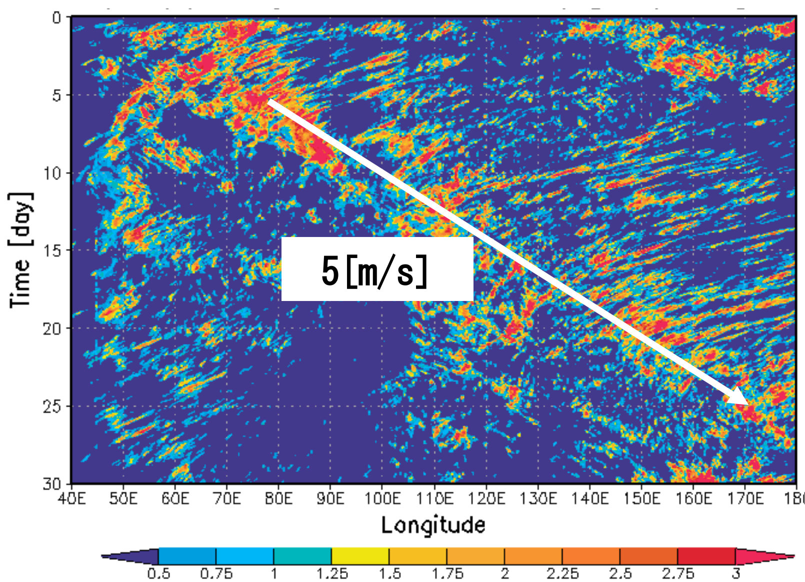


30 days from Dec 15, 2006

NICAM-7km (Miura et al., 2008)

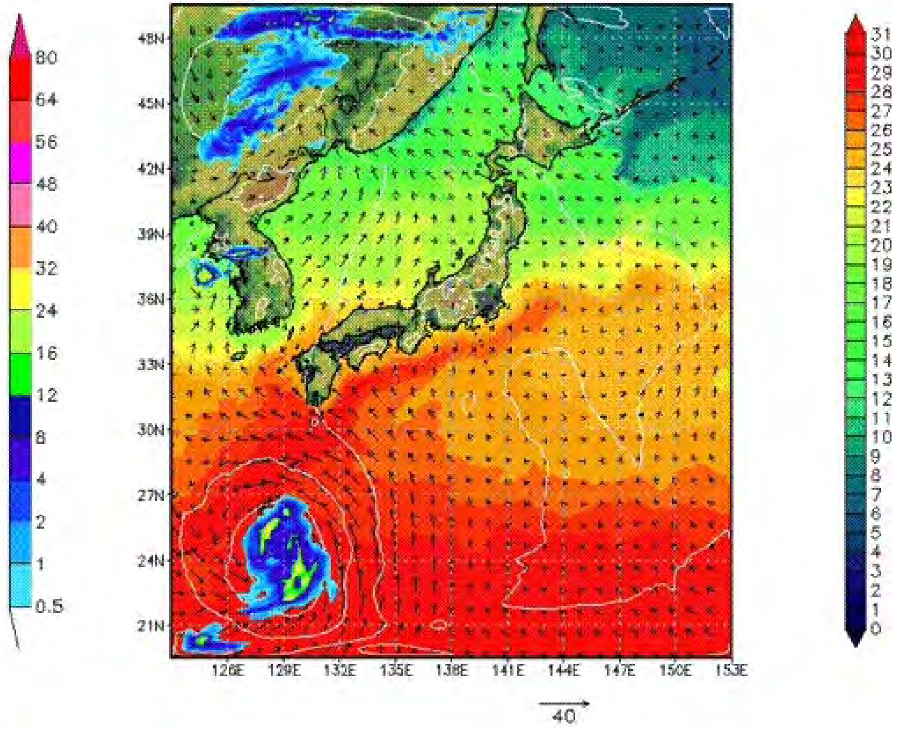


MSSG-10km

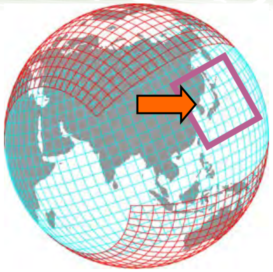


SIMULATOR

Coupled simulation for a Typhoon



Δ_H=2.7 km, 72 layers



MSSG result is operationally provided to

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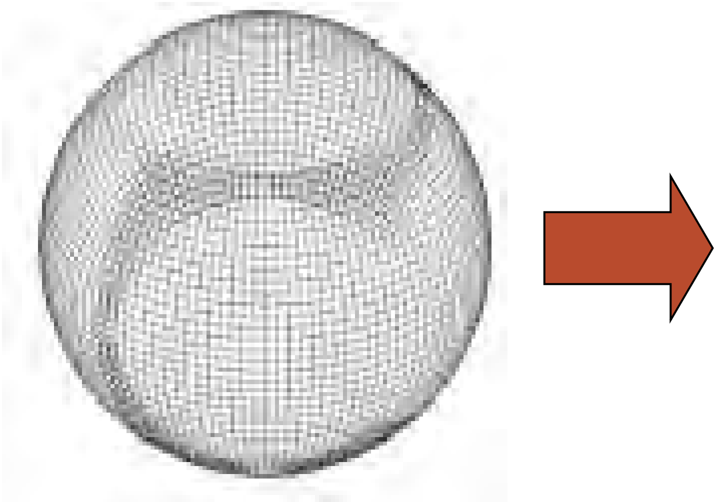
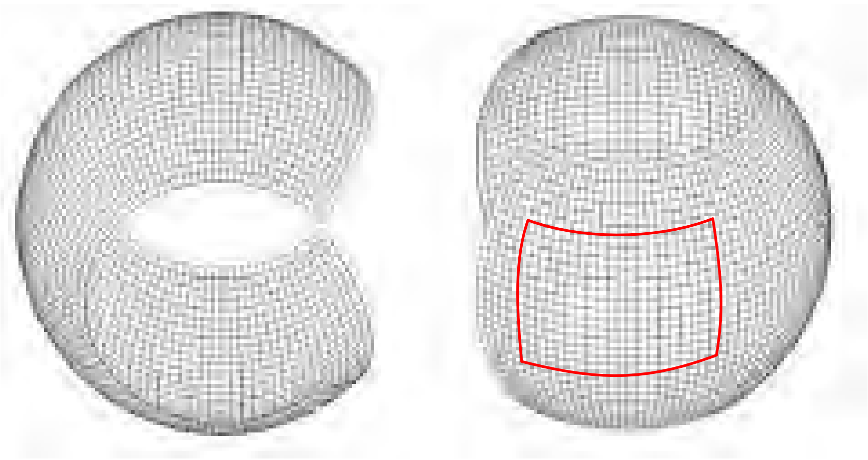
High-resolution cloud simulations with Bin scheme

turbulence (large-eddy)
resolving mesoscale simulation

Use of MSSG as a mesoscale model



Yin-Yang system
for global simulations



lat-long system
for regional simulations

Ref.
Kageyama & Sato (2004)*GGG*
Baba et al. (2010)*MWR*

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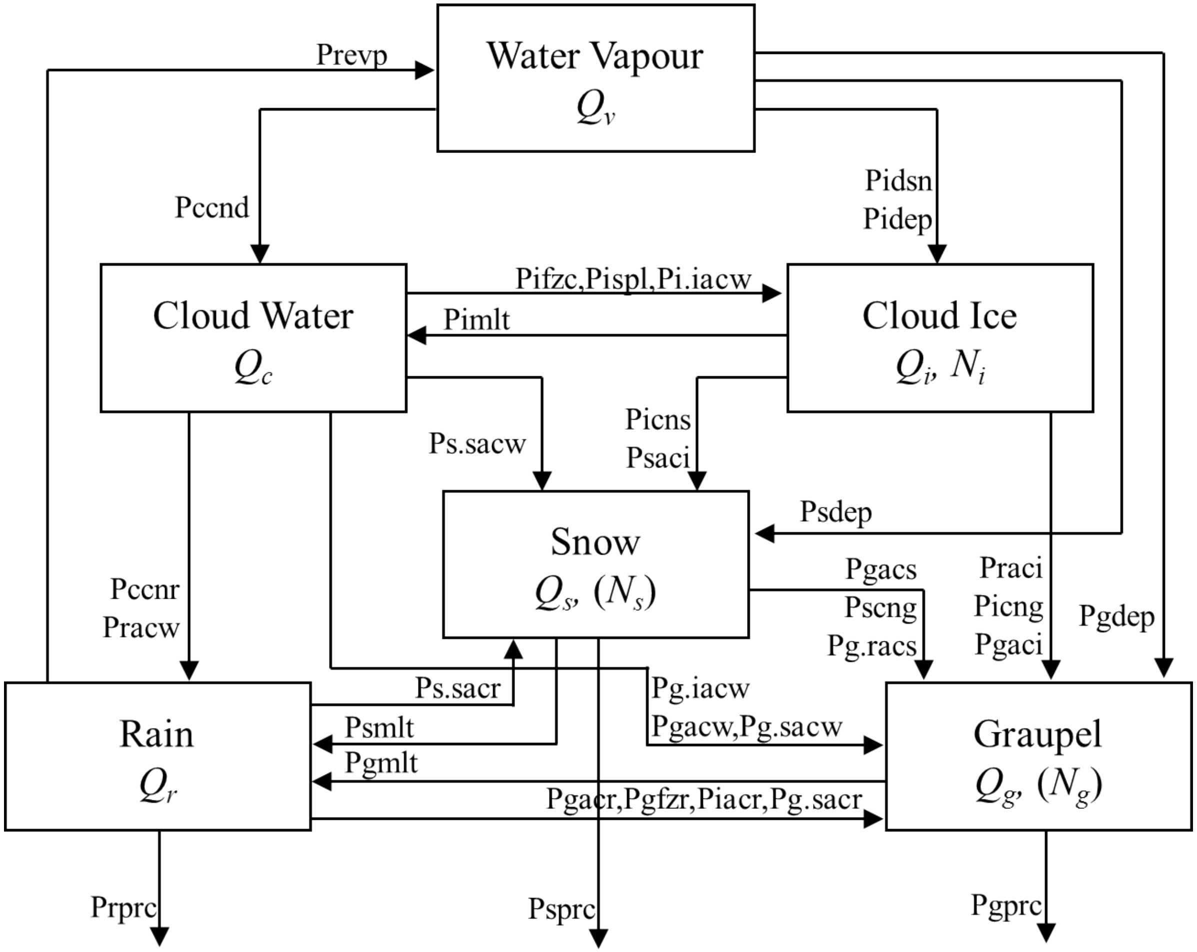
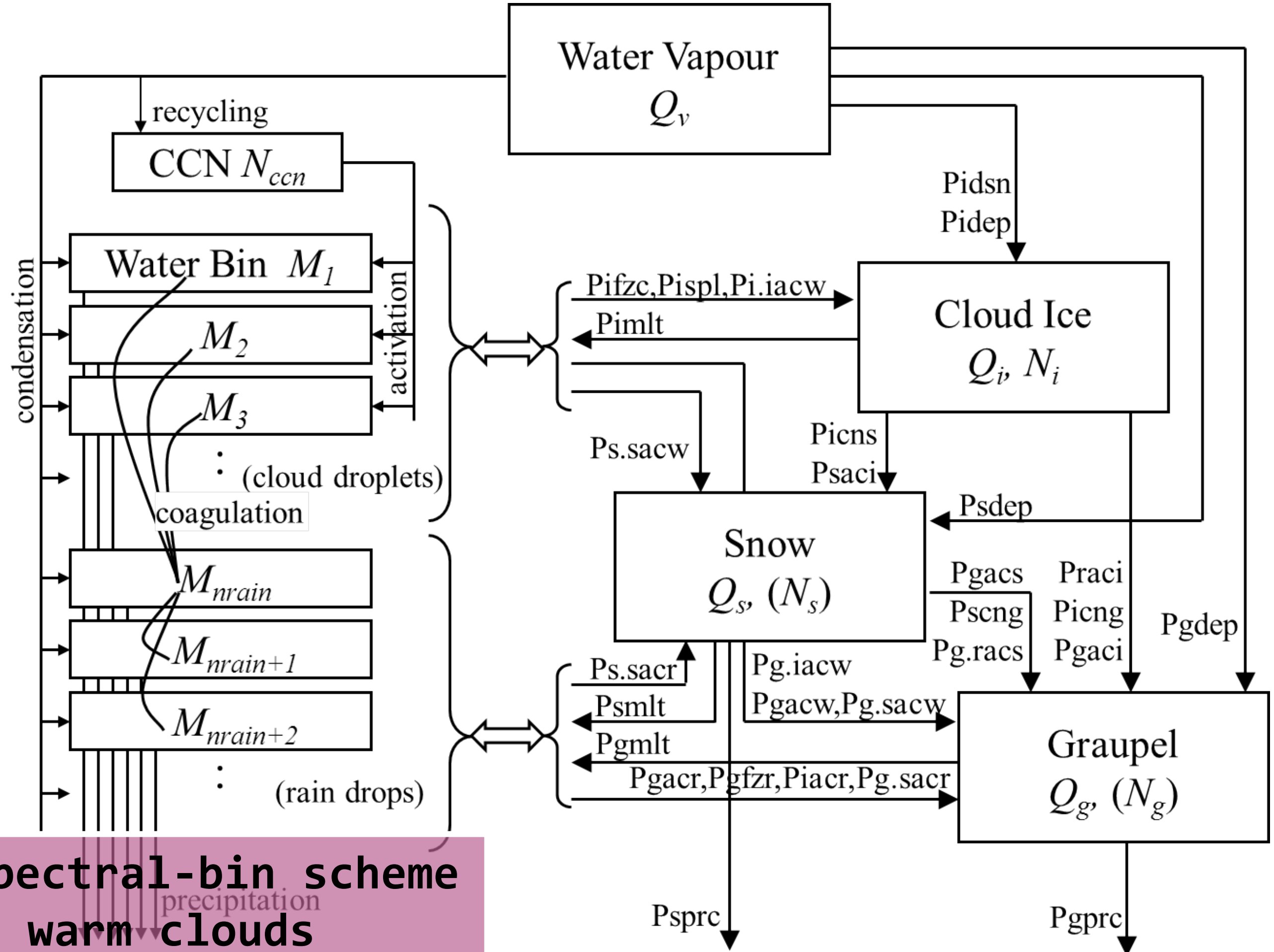
Bulk microphysical scheme



MSSG-Bulk model

(Reisner et al. (1998) with modification by Thompson (2004))

Bulk-Bin hybrid microphysical scheme



purely spectral-bin scheme for warm clouds

MSSG-Bin model
(Onishi & Takahashi, submitted)

Collision growth calculation in Bin scheme

Stochastic Collision Equation (SCE)

$$\left(\frac{\partial n_p(r)}{\partial t}\right)_{col} = \frac{1}{2}\int_0^r K_c(r'',r')\,n_p(r'')\,n_p(r')\,dr' - \int_0^\infty K_c(r,r')\,n_p(r)\,n_p(r')\,dr'$$

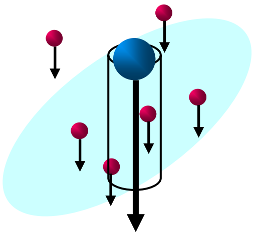
Collision kernel

Gravitational (Hydrodynamic) Collision Kernel

(No turbulent collisions)

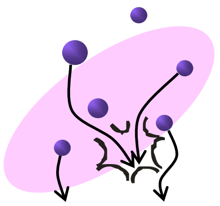
$$K_c(r_1,r_2) = \pi R^2 \left|V_\infty(r_1) - V_\infty(r_1)\right|$$

(R : collision radius (=r_1+r_2), V_∞:settling velocity)



Turbulent Collision Kernel

$$\left\langle K_c(r_1,r_2,l_\eta,\mathrm{Re}_\lambda)\right\rangle = 2\pi R^2 \left\langle |w_r| \right\rangle g(R)$$



$|w_r|$: radial relative velocity at contact (Wang et al. 2000)

$g(R)$: radial distribution function at contact (Onishi 2005, Onishi et al. 2007 etc…)

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Algorithm for explicit turbulent collision calculation

MSSG

Dynamics

- compressive N-S eq. (static Smagorinsky model)
- etc…

Flow turbulent statistics

$$\varepsilon \approx \varepsilon_{SGS} = \left(C_s \overline{\Delta}\right)^2 \left|\overline{S}\right|^3$$

$$u' \approx \overline{\Delta} \left|S\right| / 2$$

local isotropy

$$l_\eta = \left(\nu^3 / \varepsilon\right)^{1/4}$$

$$l_\lambda = \sqrt{\frac{15\nu}{\varepsilon}} u'$$

$$\mathrm{Re}_\lambda = \frac{u' l_\lambda}{\nu}$$

$$\left\langle K_c\left(r_1, r_2, l_\eta, \mathrm{Re}_\lambda\right)\right\rangle$$

Microphysics（Bin method）

- collision growth
- condensation growth
- etc…

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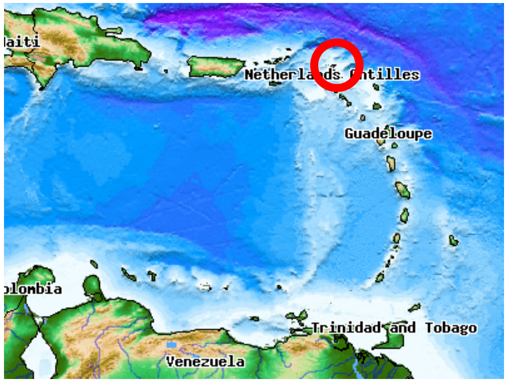
RICO (Rain In Cumulus over the Ocean)

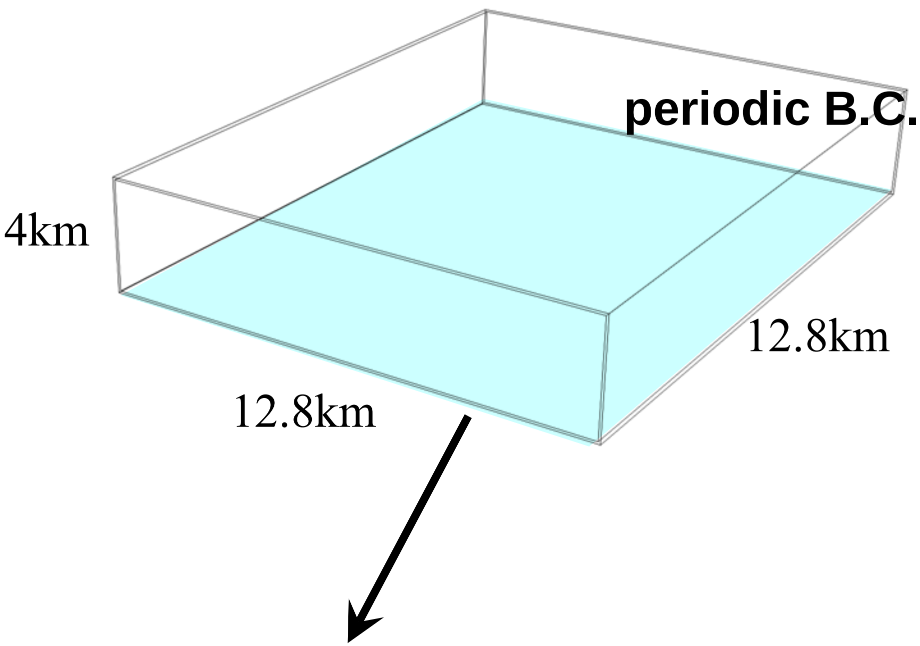
Field campaign for shallow cumulus developing over the ocean near the Barbuda islands (18.0N;61.5W).

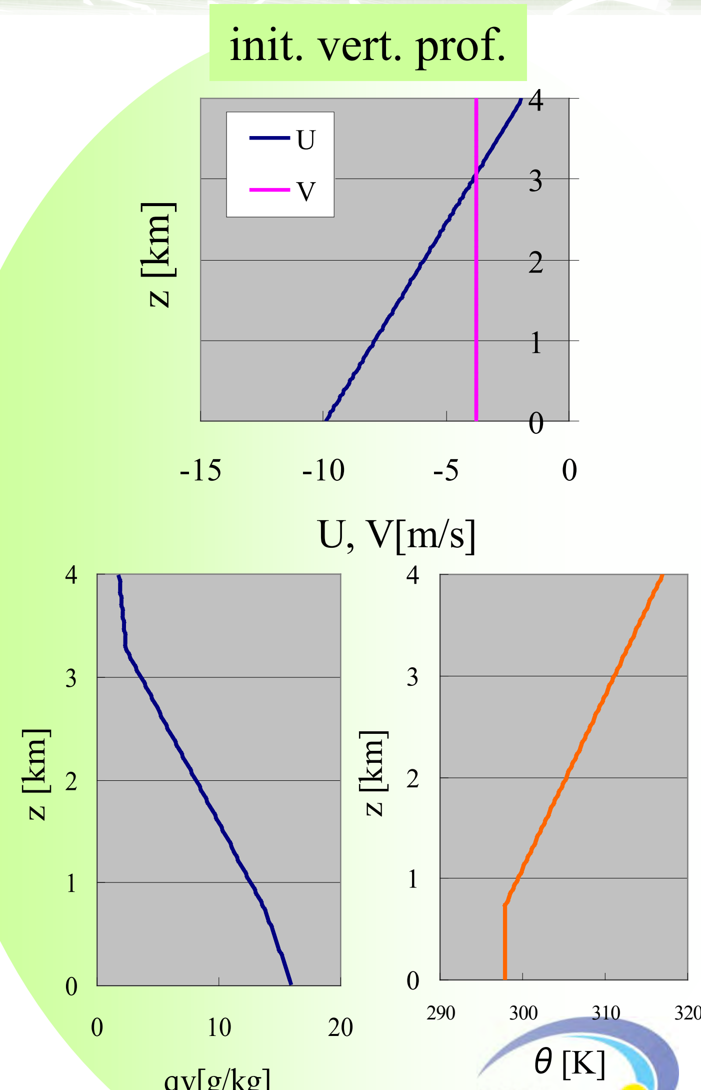


www.eol.ucar.edu/ projects/rico/

RICO model intercomparison

24h simulation with$\Delta x=\Delta y=100$m, $\Delta z=40$m





surface fluxes

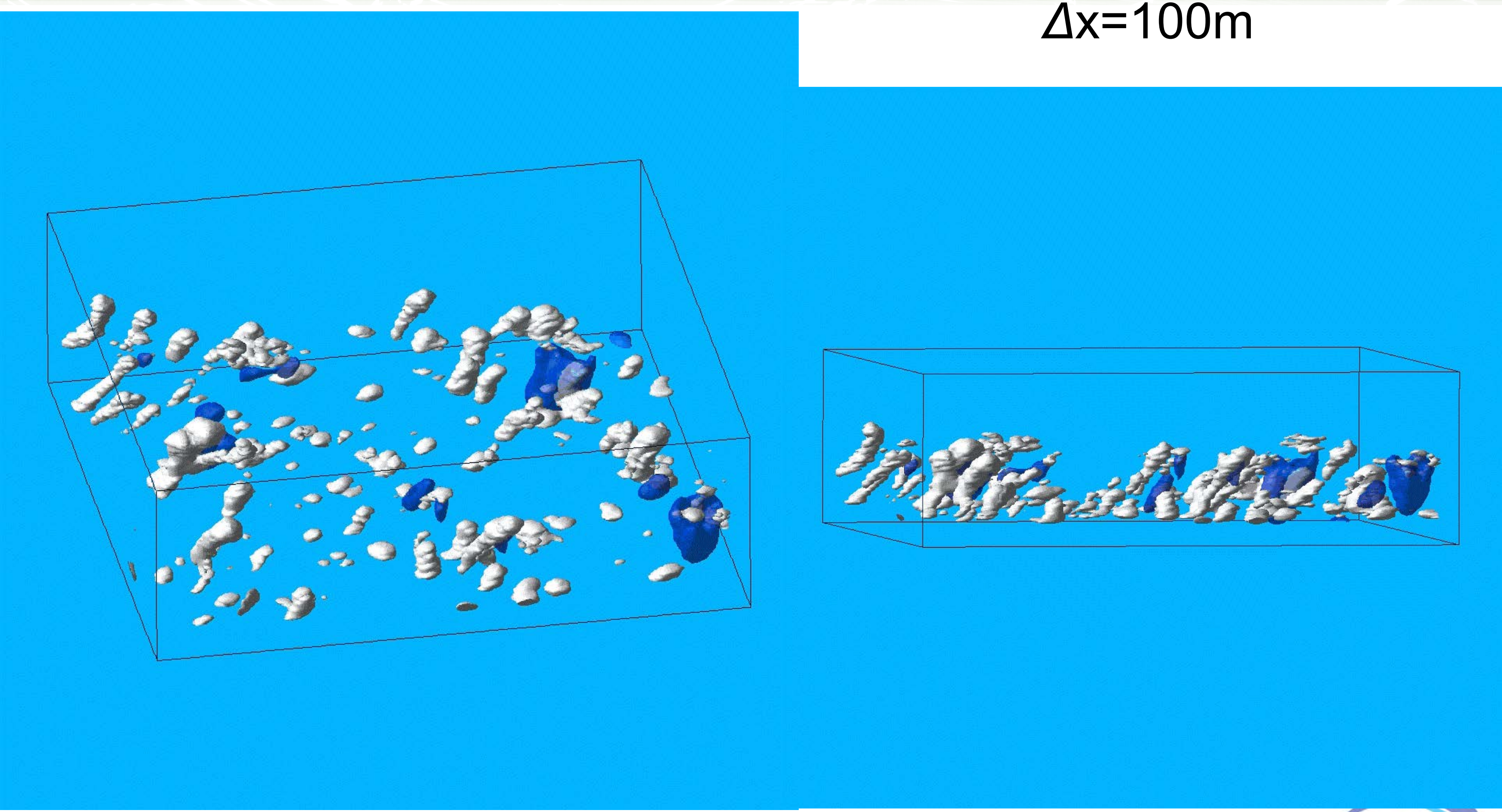
- Heat flux: $w\theta_1 = -C_h*|U|*(\theta_1 - SST*(p_0/p)(R_d/c_p))$
- Water vapor flux: $wq_t = -C_q*|U|*(q_t - q_{sat}(T_{sfc}))$
- Momentum flux:

$$uw = -u*C_m*|U|$$
$$vw = -v*C_m*|U|$$

where, C_m=0.001229, C_h=0.001094, C_q=0.001133

extra 1-hour simulation for visualization (MSSG-Bulk)

Δx=100m

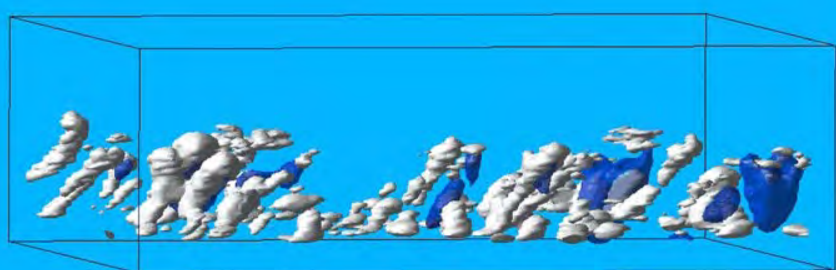


1-hour-simulation with MSSG-Bulk method (for visualization)

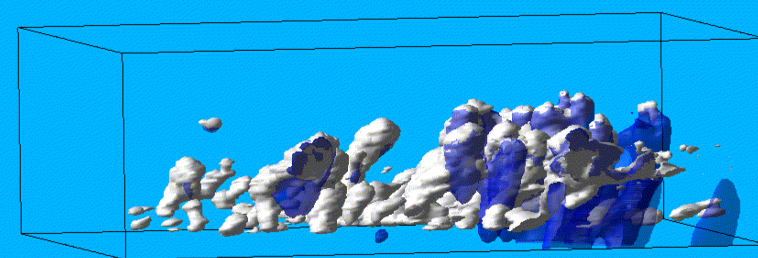
Visualization – Bulk v.s. Bin scheme

*Δ*x=100m

Bulk scheme



Bin scheme



(r>40μm droplets are recognized as rain drops)

Clouds distribute uniformly in Bulk simulation (w/o CCN), while rather patchily in Bin simulation (with CCN).

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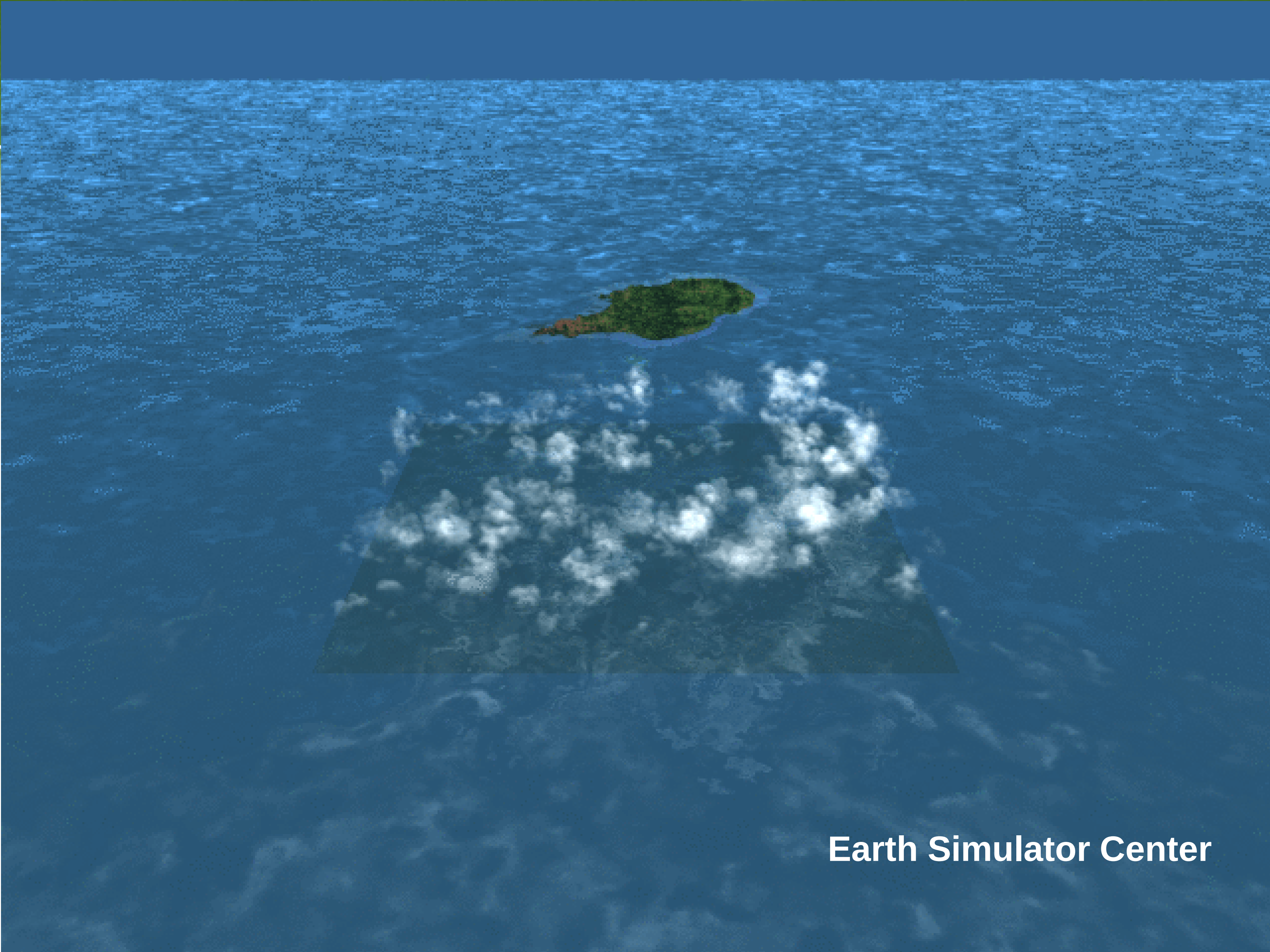
www.eol.ucar.edu/ projects/rico/

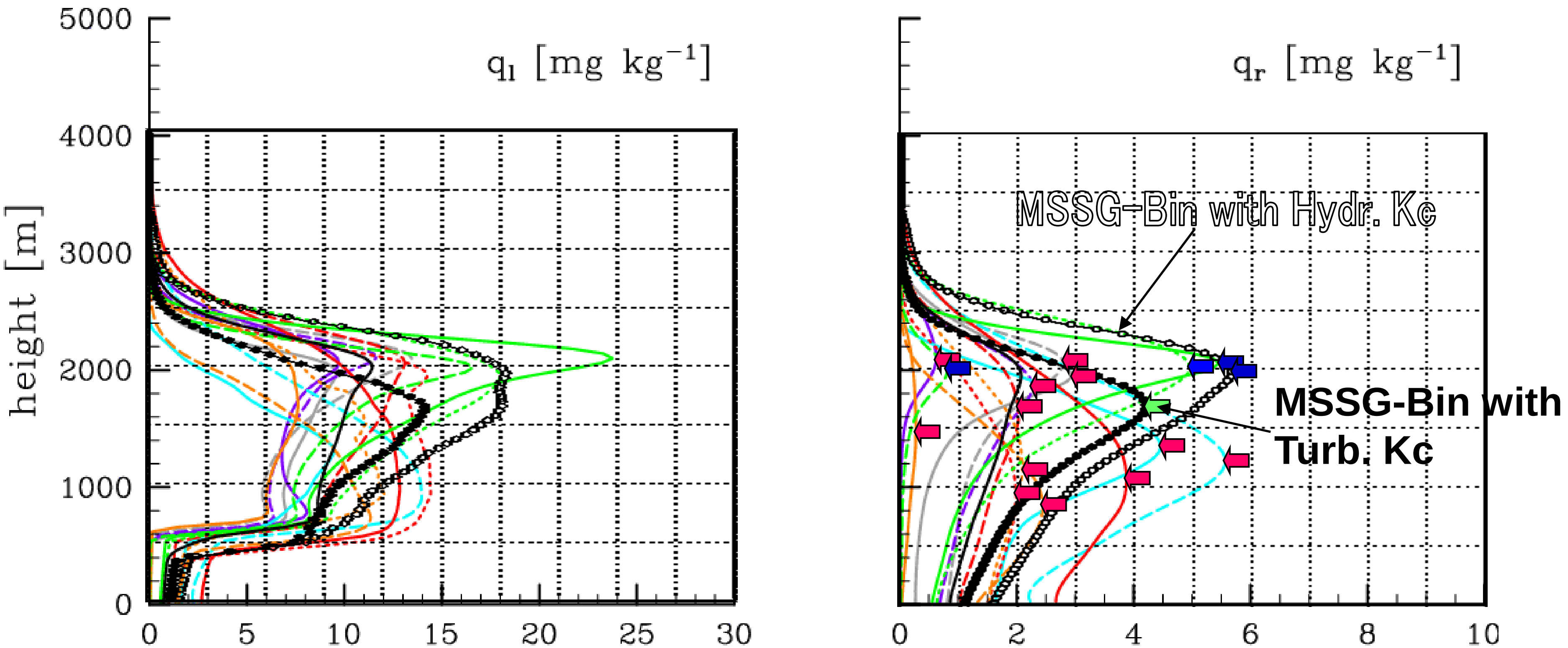

Earth Simulator Center

Cloud simulation using MSSG-Bin scheme

- Δ_H=25m, Δ_V=20m
- 512x512x200 grids
- 33 bins
- 3D Mie scattering

with Kaiser-Wilhelm Memorial Church

Mixing ratios of liquid water (q_l) and rain water (q_r)



Significant impact of turbulent collisions

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Can we really trust this result?

- Applicability of the turbulent collision model has not been confirmed.
  - $Re_\lambda=10^{3\sim4}$ in cumulus clouds,
  - while available DNS data is for $Re_\lambda<10^2$.

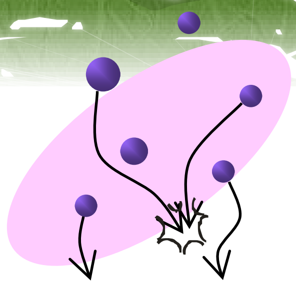
- We need DNS data for high Re_λ.

DNS for colliding droplets in high-Re flows

>Our numerical schemes

>Validation of turbulent collision models

Turbulent collision kernel model in isotropic turbulence

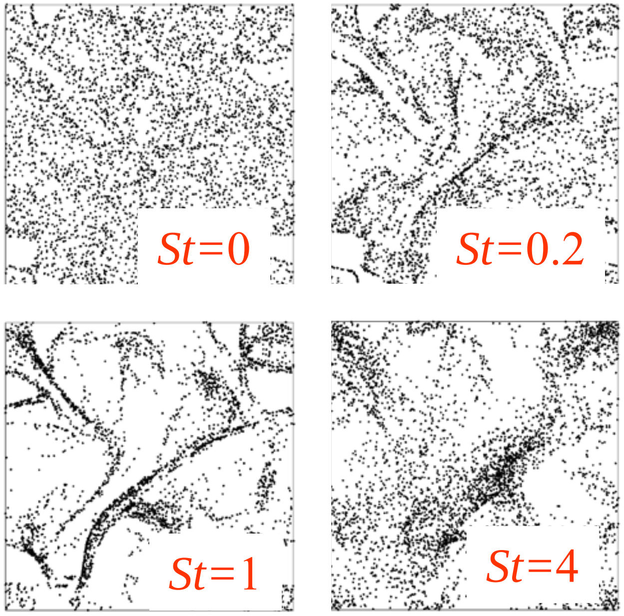


$$\left\langle K_c\left(\underbrace{\frac{r_1}{l_\eta},\frac{r_2}{l_\eta}}_{\text{St}},\mathrm{Re}_\lambda,\left(\frac{\rho_p}{\rho_f}\right)\right)\right\rangle = 2\,\pi\,R^2\langle|w_r|\rangle g(R)$$

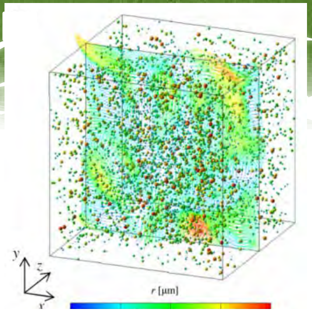
- R : collision radius (=r_1+r_2)
- $|w_r|$: radial relative velocity at contact
- $g(R)$: radial distribution function at contact

↑ **preferential distribution**

$$St = \tau_p \big/ \tau_\eta = \frac{2}{9}\frac{\rho_p}{\rho_f}\left(\frac{r}{l_\eta}\right)^2$$



Recent DNS data on colliding inertial-particles in air turbulence



Flow: Euler
Particle: Lagrange

Paper name	fluid calculation	cell-index method	parallelization	$Re_{\lambda,max}$
Wang et al.(2000)*JFM*	PSM	w	-	75.4
Reade&Collins(2000)*PF*	PSM	-	-	82.5
Zhou et al.(2001)*JFM*	PSM	w	-	58
Ayala et al.(2007)*JCP*	PSM	w	shared	72.4
Ayala et al.(2008)*NJP*	PSM	w	shared	72.4
Wang et al.(2008)*NJP*	PSM	w	shared	72.4
Woittiez et al.(2009)*JAS*	FDM	-	-	**84.9**
Onishi et al.(2009)*PF*	PSM	w/o	shared	68.4

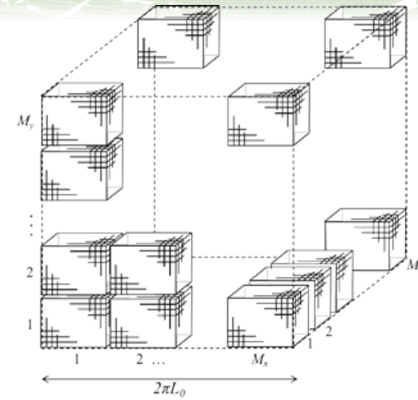
Table 1 Review of recent studies on collision frequencies of inertia particles in stationary isotropic turbulence.

Pseudo-Spectral Model (PSM) has been used for flow!

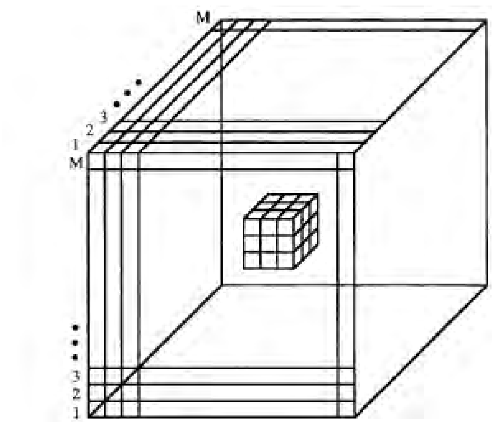
Our numerical schemes for high-Re DNS

- Steady isotropic air turbulence:
  - **Finite-Difference Model (FDM)**
    - 4^{th}-order conservative scheme (Morinishi et al. (1998)*JCP*)
  - MPI, i.e., distributed-memory parallelization, for 3D domain decomposition
  - **RCF**(Reduced-Communication Forcing) to attain a stationary state (Onishi et al. (2011)*JCP*)

- Particle motion:
  - Lagrangian tracking method
  - Cell-index method for efficient collision detection
  - MPI for 3D domain decomposition



3D domain decomposition



Cell-index method

(Allen & Tildesley (1987))

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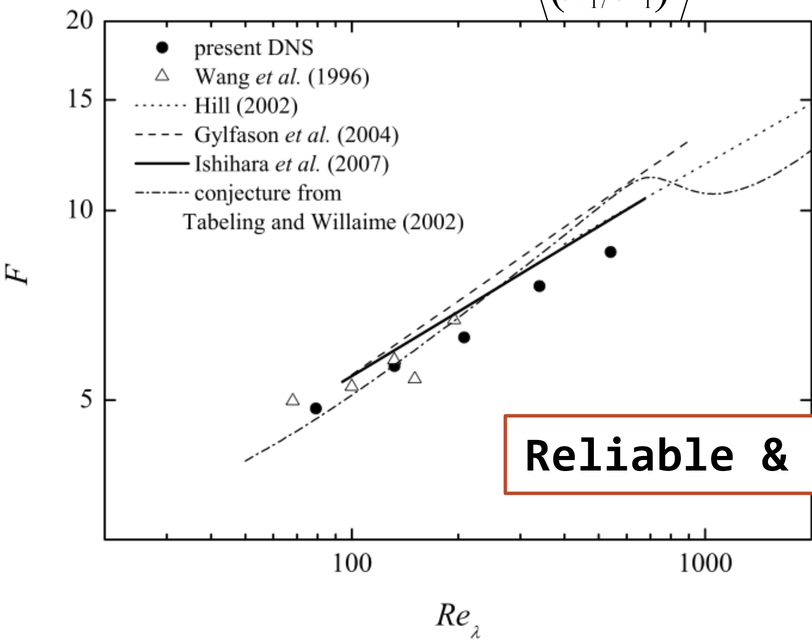
Checks of our code

Flow simulation

Flatness factor: $F = \dfrac{\left\langle (\partial u_1 / \partial x_1)^4 \right\rangle}{\left\langle (\partial u_1 / \partial x_1)^2 \right\rangle^2}$

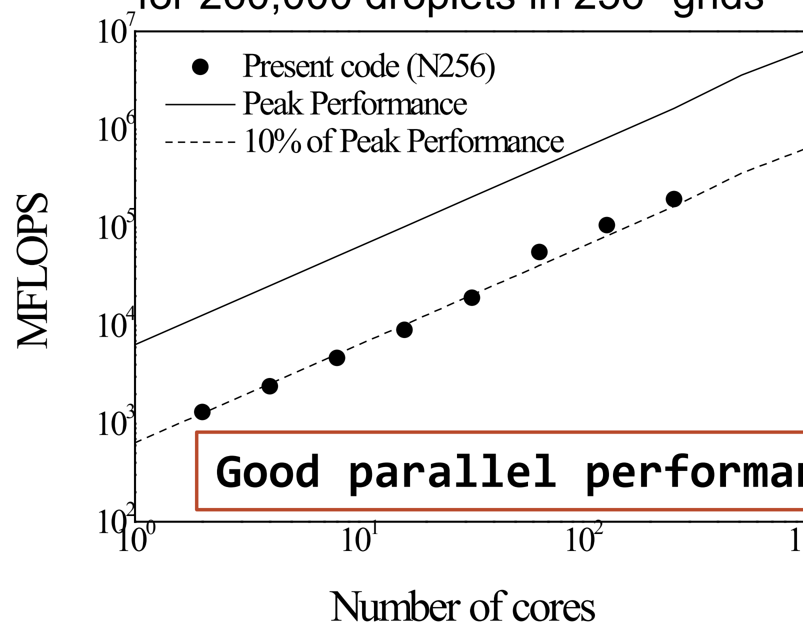


Reliable & Fast

Present FDM is estimated to be **x3.8 faster** than conventional PSM (not shown here).

Flow & Particle simulation

Performance on ALTIX
for 260,000 droplets in 256^3 grids



Good parallel performance

REF:Onishi et al. (2011)*JCP*

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Collision kernels of St=1 droplets

$Re_\lambda=340$
1000^3 grids,
50million particles

?

Collision data for Re_λ~540 (2000^3 grids, billion particles) is obtainable on ES2

newly obtained data appears in the contribution paper

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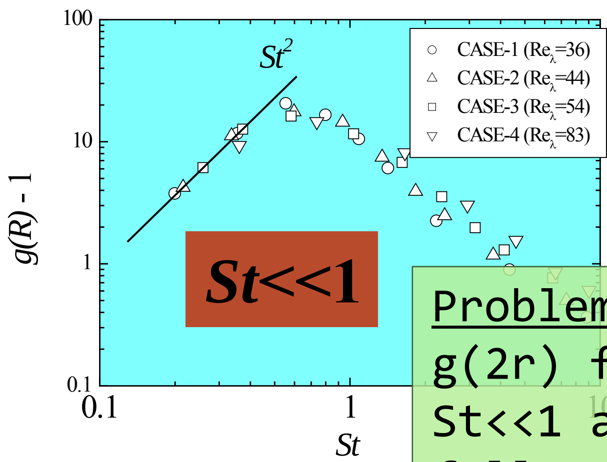
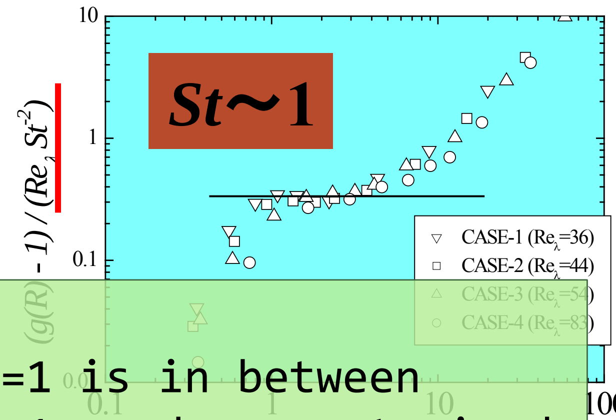
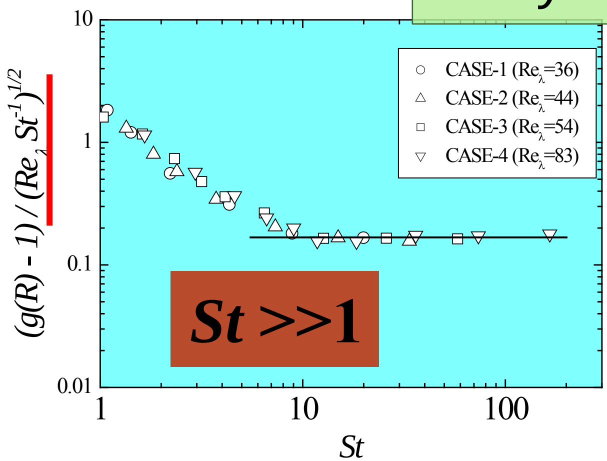
Radial distribution function -g(R=2r)- model

$$\langle K_c(r,r)\rangle = 2\pi R^2 \langle |w_r| \rangle \underline{g(2r)}$$





Problem:
g(2r) for St=1 is in between St<<1 and St~1, and parameterized fully-empirically.



$$g(R) - 1 \propto \begin{cases} St^2 & (St \ll 1) \\ Re_\lambda St^{-2} & (St \sim 1) \\ Re_\lambda^{1/2} St^{-1/2} & (St \gg 1) \end{cases}$$

$$Re_\lambda \propto (l_\lambda / l_\eta)^2$$
$$St \propto (r/l_\eta)^2$$

$$g(R) - 1 \propto \begin{cases} (r/l_\eta)^4 & (St \ll 1) \\ (l_\lambda/r)^2 \; (l_\eta/r)^2 & (St \sim 1) \\ l_\lambda/r & (St \gg 1) \end{cases}$$

Empirical, but with some physical support

Concluding Remarks

- ***MSSG*** (Multi-Scale Simulator for the Geoenvironment)
  - Non-hydrostatic atmos-ocean coupled model
  - Yin-Yang grid

- High-resolution cloud simulations (LES) with MSSG-Bin scheme
  - useful to see the turbulence role in clouds
  - Δ=25m simulations are feasible on the ES2

- DNS for colliding droplets in high-Re flows
  - useful to check the applicability of turbulent collision models to cloud turbulence with $Re_\lambda=10^{3\sim4}$
  - Data for up to $Re_\lambda=340$ has been obtained, and one for $Re_\lambda=540$ is coming.
    -These atmos. flows have energy scales *L* of *O*(1m).

Turbulence models validated by the DNS for *L*=*O*(10m) will strengthen the Δ=*O*(10m) cloud simulations, on *O*(10 PFLOPS) supercomputers!