Direct Numerical Simulation of Inertial Particles/Droplets in Turbulent Flows

湍流中惯性粒子/液滴的直接数值模拟*

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大阪大学 Osaka University
日本 Japan

*英文翻译成中文 by 'google translate'

Research group and topic contents　研究组和主题内容

- **Osaka University**

  梶島 岳夫・竹内 伸太郎（大阪大学 工学研究科 機械工学専攻）

  IBM/ISM (Immersed boundary/solid method)

  ➔ Particle-laden flow, Flow in complex geometry, Fluid-structure interaction

  含颗粒流动，复杂流场，流固相互作用

- **JAMSTEC** (Japan Agency for Marine-Earth Science and Technology)

  大西 領* ・松田 景吾（海洋研究開発機構 地球情報基盤中心）

  MSSG (Multi-Scale Simulator for the Geo-environment)

  ➔ Atmosphere-ocean coupled simulation, Prediction of typhoons, Urban heat environment

  大气 - 海洋耦合模拟，台风预测，城市热环境

- Joint research by Grant-in-Aid from MEXT, Japan

  ISM-LCS (Immersed Solid Method into the Lagrangian Cloud Simulator)

  沉浸式实体法在拉格朗日云模拟器中的应用

* Leader of Grant-in-Aid Project (2016-2019)

Inertial Particles/Droplets in Turbulent Flows 湍流中的颗粒和水滴

- CFD of single phase flows (gas or liquid of single component) has been matured
  单相流（单组分气体或液体）的数值模拟已经成熟
- On the other hand, a little have been established for CFD of multiphase flows*
  已经建立了一些用于多相流的数值模拟

  Particle/droplet-laden flows are typical examples
  含有粒子/液滴的流动是典型的例子

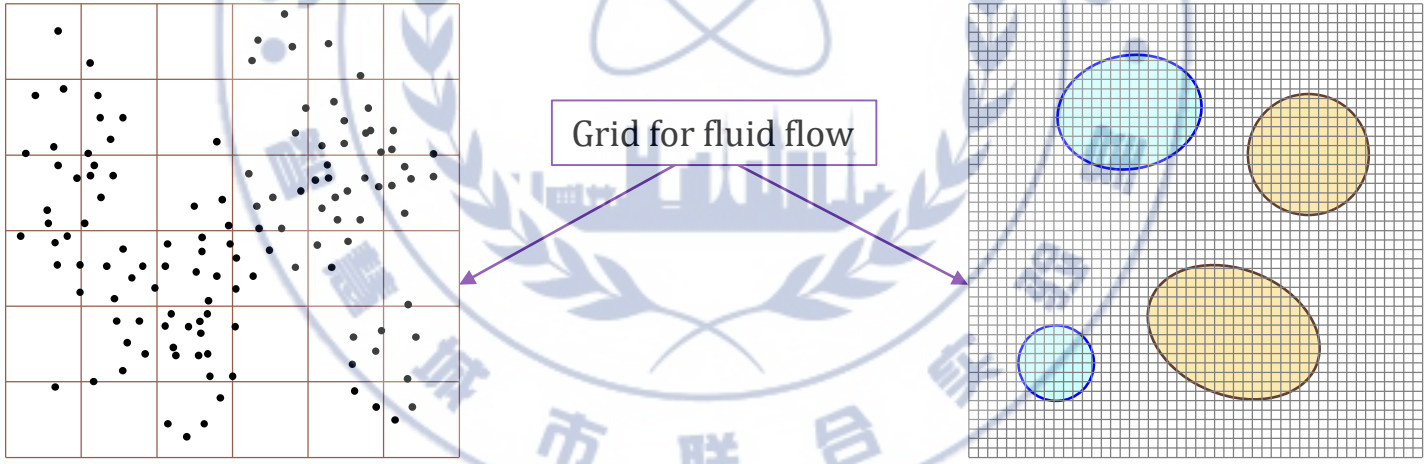
* Simultaneous flow of materials with different states or phases (i.e. gas, liquid or solid)
具有不同物态或阶段的材料的同时流动

Sandstorm and Downburst 沙尘暴和暴流 near Phoenix, Arizona, USA (2016)

https://www.washingtonpost.com/news/capital-weather-gang/

How to deal with particles/droplets in CFD 如何处理颗粒/液滴

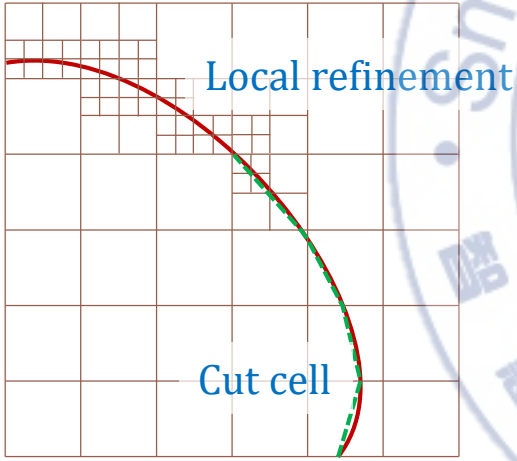
- Point particle model 点粒子模型
  - Practical 实际的
  - Depend on empirical models 取决于经验模型
    (drag, lift and so on for each particle)
- Finite-sized particle 有限尺寸颗粒
  - Expensive 昂贵
  - Free from empirical assumptions 没有经验假设
    ➔ suitable for basic research

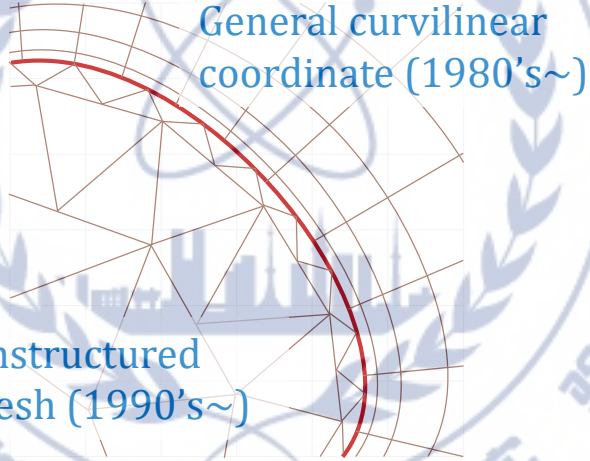


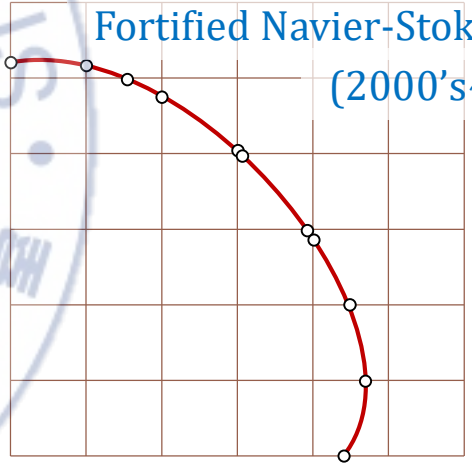
Trend of the computational grid 计算网格的趋势

固定直交网格 Fixed Cartesian → 曲线坐标 Curvilinear → 非结构化网格 Unstructured → 固定直交网格 Fixed Cartesian (revival)

Bitmap	Boundary fitted 边界拟合	Immersed boundary
(in pioneer days before 1970's)	(for industrial application)	(for more complex fields)





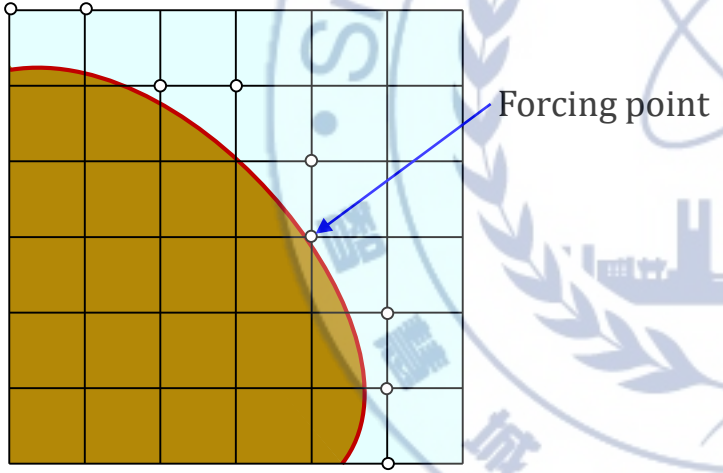


For moving boundaries, 're-mesh' is necessary and it requires high cost.
对于移动边界，"网格再生成"是必要的，并且需要高成本

'Fixed grid' is suitable for moving boundary.
'固定网格'适合移动边界

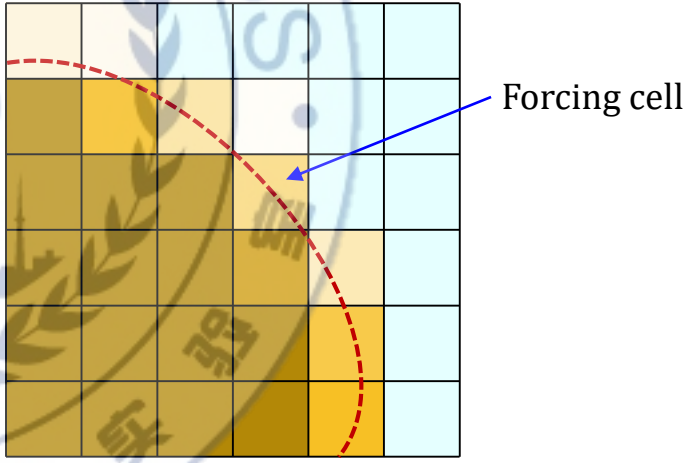
Our immersed boundary/solid method since 2000 我们的方法自2000年以来在大阪大学开发

- **IBM** (Immersed boundary method)
  浸入边界法
  - Fortified NS approach
    ➔ Complex geometry
    适用于复杂几何体



  - Ikeno et al. (2007)
  - Sato et al. (2013)

- **ISM** (Immersed solid method)
  沉浸式固体法
  - Body force approach
    ➔ Solid-fluid two-phase flows
    适用于固液两相流

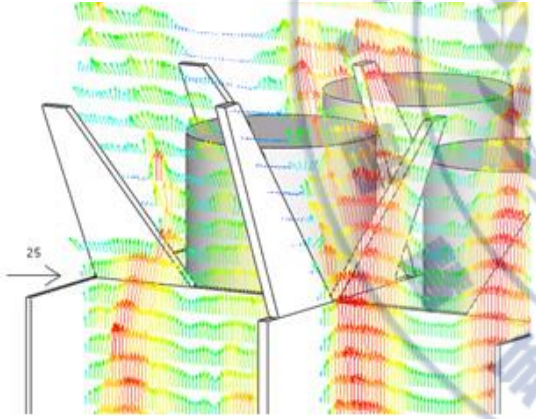


  - Kajishima et al. (2001, 2002)
  - Takeuchi et al. (2010)

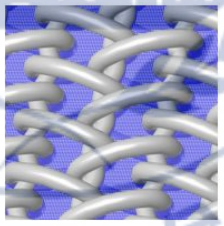
Applications of IBM (immersed boundary method) to complex flow fields

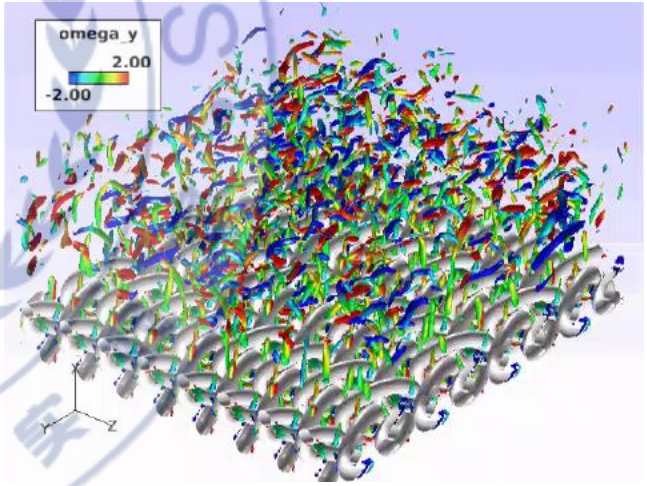
浸入边界法在复杂流场中的应用・・・产学合作研究

- LES (Large-Eddy Simulation) of turbulent flows 湍流的大涡模拟
  - in rod-bundle 核反应堆燃料棒束
  - Nuclear Fuel Industry (Ikeno, 2006)



- Flow with heat transfer 流动传热
  - through wire mesh 金属丝网通过
  - Toyota Central R&D Labs., Inc. (Sato, 2015)



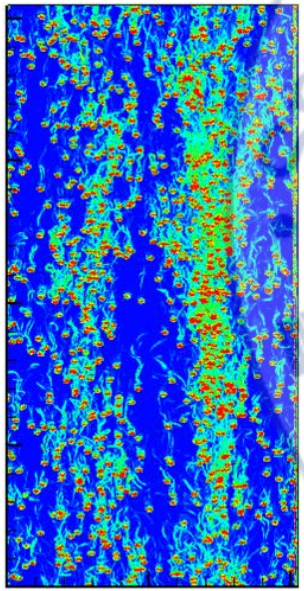


JSME Fluids Engineering Division Homepage, 2016.1

Applications of ISM (immersed solid method) to particle-laden flows

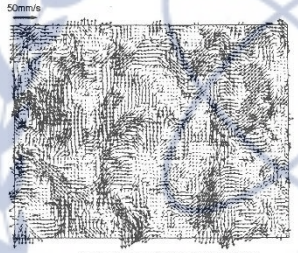
浸入式固体法在带粒流动中的应用

- Clustering in 1000-particles system (Kajishima et al., 2001) $d_p/\Delta = 10$
- Sedimentation of 10^5-particles system (Hidaka et al., 2006) $d_p/\Delta = 5$



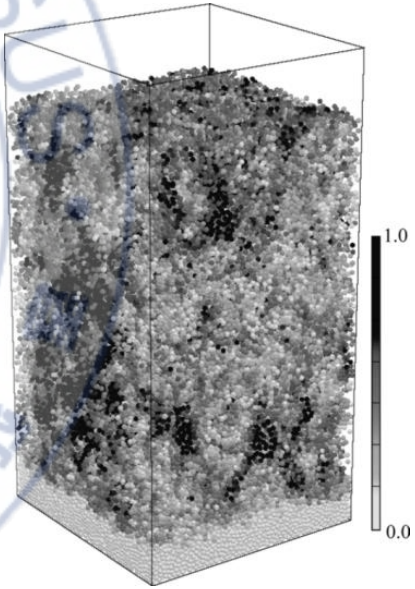
1024 Particles of Re_{ps}=300
by Kajishima & Takiguchi

颗粒团聚



Exp.
Nishino et al. (2003)

流化床

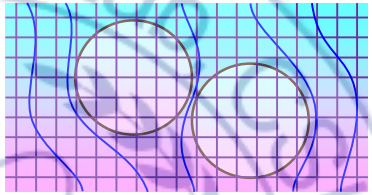


10^5 Particles of Re_{ps}<50
by Hidaka, et al.

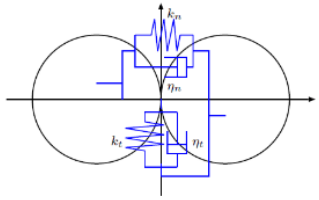
Direct numerical simulation of solid-liquid two-phase heat transfer

固液两相流动传热的直接数值模拟

- Computational method (2013)
  S.Takeuchi, T.Tsutsumi & T.Kajishima,
- Full 3D simulation (2018)
  J.C.Gu, S.Takeuchi, T.Kajishima



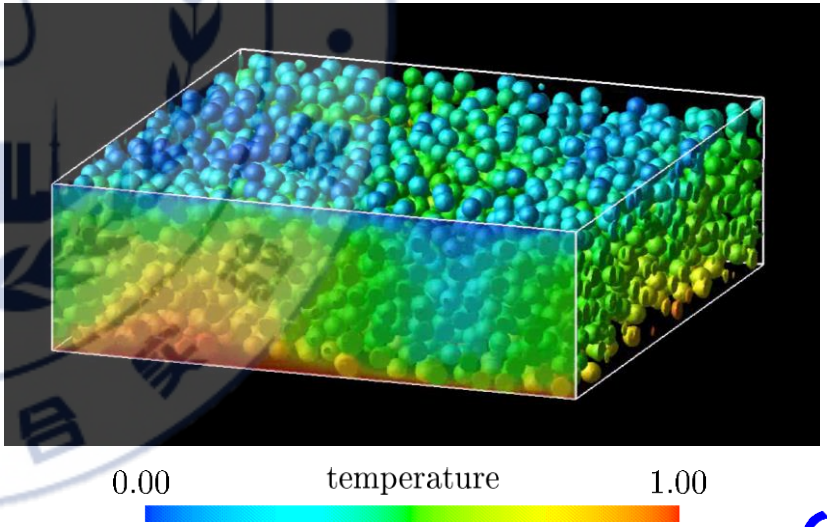
Immersed boundary method
for fluid-solid interaction
用于流固相互作用的浸入边界法



Discrete element method
for solid-solid interaction
弹簧和阻尼碰撞模型

- Major findings 主要发现
  - Oscillatory mode (2015) 振荡模式
  - Convection inverse (2017) 对流逆转

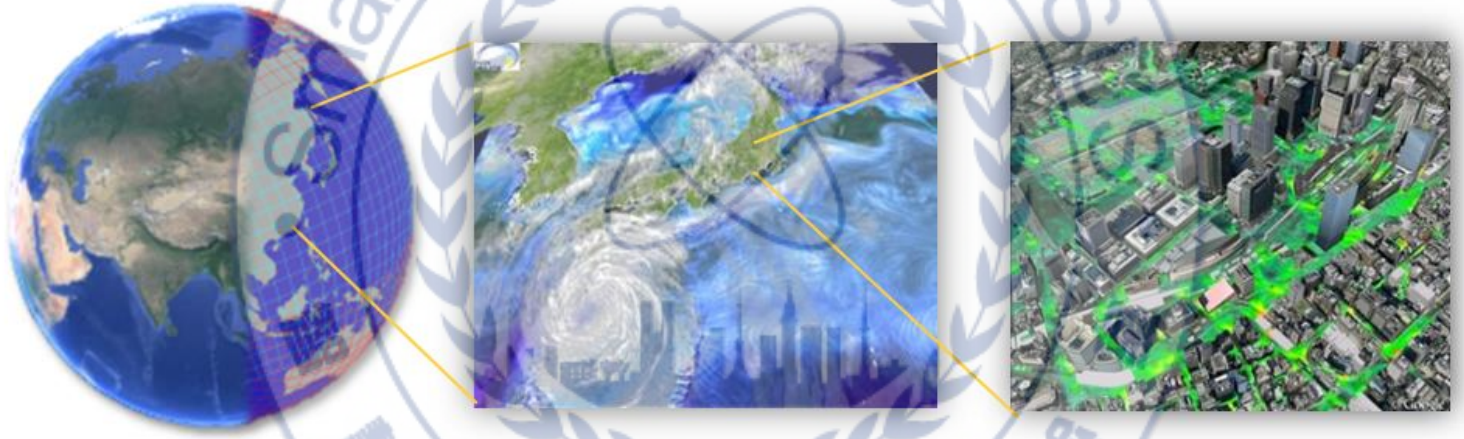
$$\mathrm{Ra} = 10^5,\ E_p = 10^7,$$
$$\mathrm{N_p} = 3087,\ d_p/\Delta = 10$$
$$\phi = 30.8\%,\ \lambda_s/\lambda_f = 10^2$$



Multi-Scale Simulator for the Geo-environment (MSSG)

用于地理环境的多尺度模拟器
由日本海洋地球科学和技术研究中心（JAMSTEC）开发

http://www.jamstec.go.jp/ceist/e/activity/aeird/esrg/



global scale	regional sale	street scale
O(1~10 km) reso.	O(100 m~1km) reso.	O(1~10 m) reso.

Multi-Scale Simulator for the Geo-environment (MSSG)

http://www.jamstec.go.jp/ceist/e/activity/aeird/esrg/

收集物联网传感器数据．预测信息按需分发给各种设备

IoT sensor data are collected. Prediction information is distributed to various IoT devices on demand

边缘计算机（本地模拟）

Edge servers (local simulations for end users)

Super computers

(Long-term wide-area simulations with, e.g., the Earth Simulator)

超级计算机（使用Earth Simulator进行长期广域模拟）

Multi-Scale Simulator for the Geo-environment (MSSG)

东京热岛现象 --- 城市热环境模拟

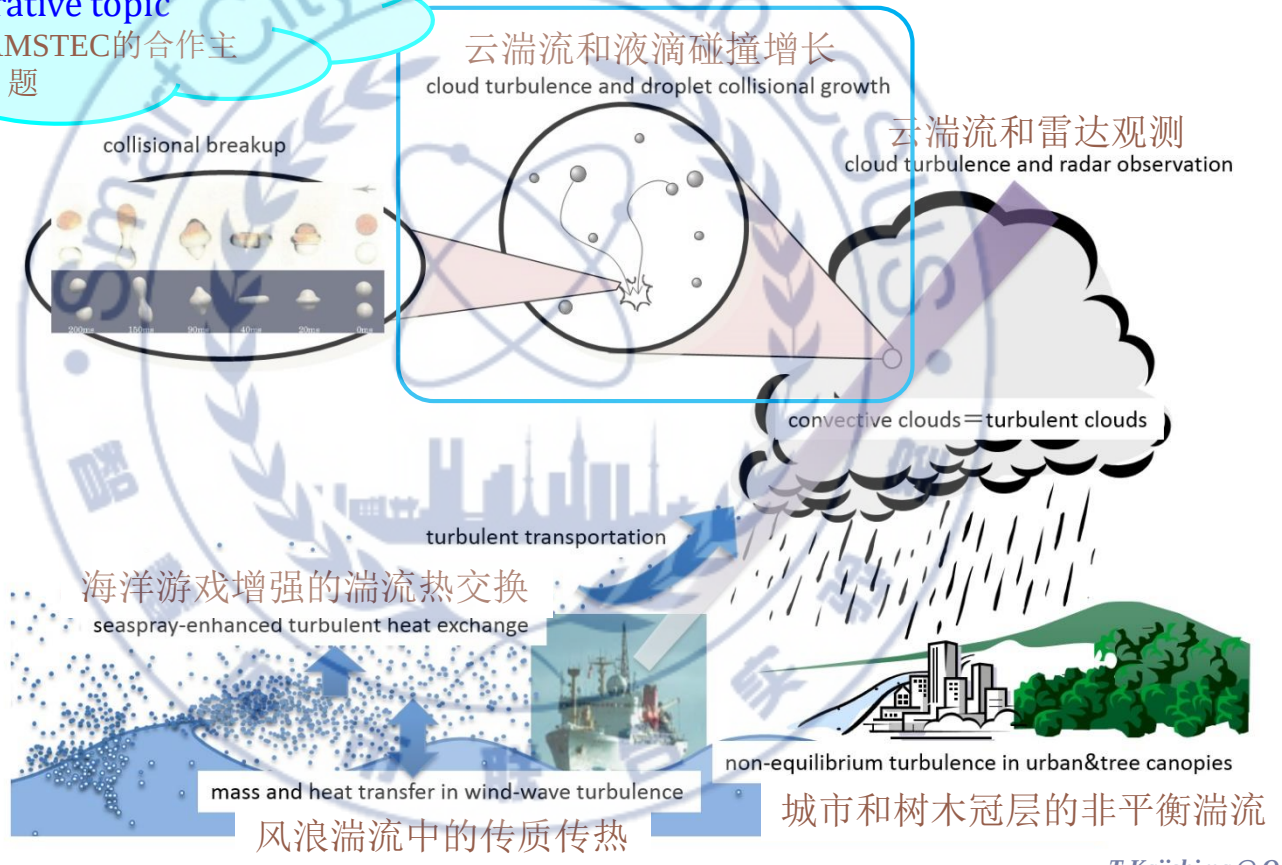
由日本海洋地球科学和技术研究中心（JAMSTEC）进行

http://www.jamstec.go.jp/ceist/e/activity/aeird/esrg/

Multi-Scale Simulator for the Geo-environment (MSSG)

Osaka Univ.-JAMSTEC collaborative topic
大阪大学和JAMSTEC的合作主题

http://www.jamstec.go.jp/ceist/e/activity/aeird/esrg/



Particle collision as a cloud microphysics

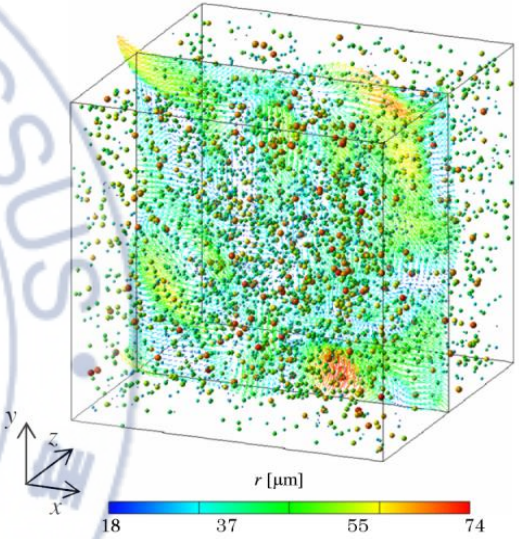
云微物理学中的颗粒（水滴）碰撞

Size-Resolving Simulation for Colliding Inertial Particles in Homogeneous Isotropic Turbulence

均匀各向同性湍流中碰撞惯性粒子的尺寸分辨模拟

12 July, 2018
THMT2018, Rio de Janeiro, Brazil
(Turbulence, Heat and Mass Transfer 9, Begell House, Inc., 2018)

R. Onishi (Japan Agency for Marine-Earth Science and Technology)
S. Takeuchi (Osaka University)
T. Fukada (Central Research Institute of Electric Power Industry)
K. Matsuda (Japan Agency for Marine-Earth Science and Technology)
T. Kajishima (Osaka University)

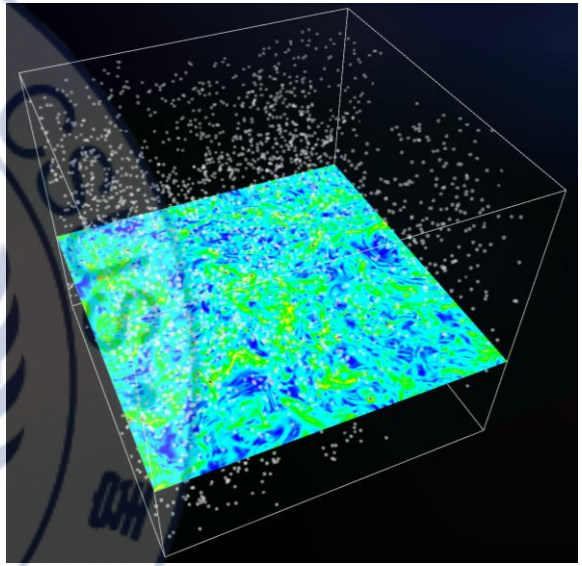


Lagrangian Cloud Simulator (LCS)
拉格朗日云模拟器
Onishi et al, J. Atomos. Sci. (2015)

Particle collision as a cloud microphysics

- Immersed Solid Method (ISM) was implemented into the Lagrangian Cloud Simulator (LCS)
  在拉格朗日型云模拟器中实现了浸入式固体方法
  - Drag coefficient and collision efficiency were validated
    验证了阻力系数和碰撞係数
  - Massively parallel simulations was performed
    进行了大规模并行模拟
  - Turbulent collision statistics was obtained
    获得了湍流碰撞统计数据
  - Errors induced by traditional model (i.e., point-particle assumption) was quantified
    传统模型引起的误差被量化

Onishi et al., THMT2018, Rio de Janeiro, Brazil



Remarks of current status 当前状态的评论

- Immersed boundary/solid strategy developed in Osaka University is useful for simulating multiscale-multiphase phenomena
  在大阪大学开发的浸入式边界/固体策略可用于模拟多尺度 - 多相现象
  e.g.,
  - heat and fluid flows in complex geometries like urban canopies
    城市檐篷等复杂几何形状的热量和流体流动
  - basic study of the mechanism of cloud development and local heavy rain
    降雨云形成与局地暴雨机制的基础研究
- Implementation of the immersed methods into Multi-Scale Simulator for the Geo-environment (MSSG by JAMSTEC) is now going on by the collaboration between JAMSTEC and Osaka University
  JAMSTEC与大阪大学合作将沉浸式方法应用到地理环境的多尺度模拟器当中（MSSG）

Temperature distribution around Tokyo Station on a midsummer day (by JAMSTEC)