Mathematical climate studies from K to Fugaku

Computational Climate Study Research Team
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Introduction of our Team

Two activities

1. **Model library development:**
   construction the basic library for meteorology and climate simulation as a research infrastructure

   Using the library, we can ...
   - Compare the simulated results by different models, inter-exchanging “model components” and “numerical method”
   - Construct a more advanced climate model with highly efficiency in massive parallel computers

2. **Climate science research:**

   Using our model based on the library, we want ...
   - To understand the feedback mechanism between cloud, aerosol and radiation
   - To understand the role of cloud and their organization
   - To develop the assessment method of future climate
   - To construct the theory for the moist process with the turbulence process
**SCALE**: a highly sophisticated **common library** for meteorological/climatic simulations

**Scalable Computing for Advanced Library and Environment.**

Many components and, including CFD & computer science techniques

**Free software! : under BSD2-license**

https://www.r-ccs.riken.jp/software_center/software/scale/overview/

- **SCALE is a library, but it has also models**
  - SCALE-RM : regional model:
  - SCALE-GM: global model(NICAM-DC clone)

- **Data assimilation has been already equipped in cooperation with Data Assimilation Research Team**
  - SCALE-LETKF
Highlights of our scientific achievement on K computer
~selected two topics~

1. Cloud convection convergency in high resolution simulation
2. Regional climate assessment method
Sub km global atmospheric model simulation

Background & Motivation:
15 years ago, Global Cloud Resolving Simulation started!(NICAM: the first GCRM in the world)

Debatable issue: Cloud permitting? or resolving?

Simulation with much higher resolution on K Computer
By using grid refinement approach
Q. How the convection aspects change?

NICAM  870 m - 96 levels
Real Case Simulation: 25 - 26, Aug., 2012

SPIRE field-3: Study of extended-range predictability using GCSRAM
RIKEN / AICS: Computational Climate Science Research Team

--- Research highlight
--- Eos research spotlight
--- Press release from RIKEN

Conclusion
1. Convection aspects (# of density, convection distance) change around Δx=2km drastically.
2. The core of deep convections becomes resolved from this resolution.
Much higher resolution in cloud cluster!
The convection aspects in the sub-km GCM was still perfectly converged.

Q. If the resolution becomes much higher,

1. How is statistics of deep convection converged by grid refinement?
2. Which is the convergence point?

Sueki et al. (2019, Geophys. Res. Lett.)

- Downscaling the cloud organized system!
  from: Global model result (NICAM/3.5km)
  to: Regional model (SCALE-RM).
  - High resolution run: LES (promising for high resolution)
  - Medium resolution run: RANS (conventional method)

- Simulation Target: a well organized cloud system, Madden Julian Oscillation.

- Evaluation Metrics:
  distance of “scale-categorized” convection cluster.

Schematic illustration of the experiments. (A)
Outline of the experiments. Timeseries is expressed in universal time coordinated (UTC). (B) Snapshots of total column condensate for each simulation at 18:00 UTC on 24 November 2011.
Convergence result by downscaling

Dash-line : RANS  
Solid-line : LES

- In less than 200m resolution, the convection system with horizontal scale greater than 500m-1km radius is almost converged.

- Surprisingly, convergence of RANS is quite similar to that of LES.

※ Still debatable point : RANS is available even in high resolution, or not?

Future analysis:
Comparison of turbulence structure in the PBL btw LES & RANS.
also, an important point is convergence of moisture mass flux
Basic idea: dividing GCM results into components,

- Climatology (Mean state): e.g. monthly mean atmospheric state
- Perturbation (Fluctuation): e.g. synoptic low pressure system/tropical cyclone

Main result: we can extract the contribution of climatology change and perturbation change and its interaction.

Schematic figure for evaluation of each effect:

Detection of contributions from \( \langle A \rangle \) and \( A' \)

Severe rainfall cannot be assessed by conventional only-climatology-change downscaling because of large contribution of perturbation change and its interaction with climatology change.

Nishizawa et al. (2018, PEPS)
Adachi et al. (2017, Nat. Commun.)

--- Press release

Main result: we can extract the contribution of climatology change and perturbation change and its interaction.
We Apply the A2017 method for uncertainty evaluation of regional climate, using multi GCM results

- Focus point: which of change in climatology or change in perturbation is dominant for uncertainty.
- Almost same contribution for precipitation

A2017, A2018 are proof-of-concept papers for methodology

- We will assess the regional climate, fully using this method
Other epoch making results on K Computer (with Press release)

- High prediction skill of Madden Julian Oscillation by GCRM: (Miyakawa et al. 2015, *Nat. Commun.)*

- Possibility of underestimation of ice-albedo feedback due to black carbon transport (Sato et al. 2016, *Sci. Rep.)*

- Precise sensitivity of cloud lifecycle by interacting with aerosol (Sato et al. 2018, *Nat. commun.)*

Future plan of our team on Fugaku supercomputer
Future plan toward Fugaku(1)

1. Extension and sophistication of basic library SCALE
   - Pursue higher usability for the outside users.
   - Provide useful analysis methods of simulation results for enhancement of scientific output and social outcome.

2. Improvement of simulation code for big data assimilation system toward the future weather prediction system
   Coupling our models with data assimilation for high resolution, large ensembles, and observational big data with Data Assimilation Research Team.

We have already prepared
   - NICAM-LETKF: global mid-range prediction (large scale disturbance)
   - SCALE (RM)-LETKF: regional short-range prediction (each of deep convections)

NICAM-LETKF is one of main models in the FUGAKU prior subject 4
Future plan toward Fugaku(2)

3. Enhancement of model parameter estimation by data science

- Already, we have started the basic study.
- A parameter for rainfall (Cr: one of the most important parameters in the Numerical Weather prediction) is tuned by Ensemble Kalman Filter

We want to establish this technique in Fugaku era, and install it to SCALE as the model estimation tool.

- At the larger variance among the members, Cr values converge quickly around the true value
- At the smaller variance among the members, uncertainty of Cr is smaller
4. Investigation of uncertainties in environment assessment by regional climate model

Current issues:
- To clarify the cause of uncertainties for the future prediction both in RCM itself and GCM boundary conditions
- To establish a new perspective for use of regional climate model

From the viewpoint of N2018 & A2017, we reorganize all of the past downscaling methods

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**Methodology review paper**
5. Establishment of moist LES (theory and validation)

- Conventional LES: Lack of water condensation/evaporation: violation of dry theory
- Direct Numerical Simulation with particle-level microphysics is useful:
  - The data science approach using big simulation data would help us for construction of moist LES theory (e.g. equation discovery field)

Toward the Global Large Eddy Simulation!!

6. Scientific subject in Fugaku era: based on the modeling subjects, Mechanism of Self-organization and hierarchical structure in the atmosphere. i.e., Go back again to idealized simulations Radiation-convection equilibrium exp / Aqua planet exp.