Mathematical climate studies from K to Fugaku

Computational Climate Study Research Team
TL: Hirofumi Tomita

Feb 2020 The 2nd R-CCS international Symposium

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 <u>common library</u> for meteorological/climatic simulations

Scalable **C**omputing for **A**dvanced **L**ibrary and **E**nvironment.

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 <u>it has also models</u>**
  - SCALE-RM : regional model:
    Nishizawa et al.(2015, *Geophys. Model Dev.*)
    Satoh et al.(2015, *Progress in Earth and Planetary Scicence*)
  - SCALE-GM: global model(NICAM-DC clone)
    - Porting from NICAM(Tomita & Satoh(2004,*Fluid Dyn.Res.*)

NICAM Dynamical Core Package

- **<u>Data assimilation has been already equipped</u> in cooperation with Data Assimilation Research Team**
  - SCALE-LETKF

SCALE version 4.1 ESCALATE!

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:

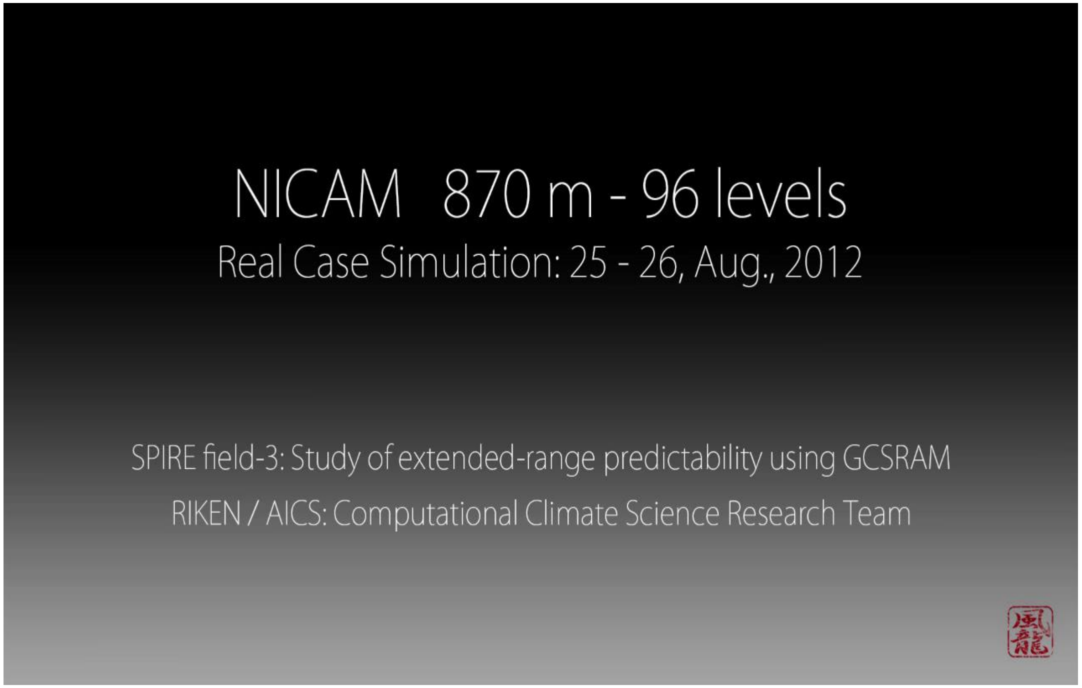
15 years ago, Global Cloud Resolving Simulation started!(NICAM: the first GCRM in the world)

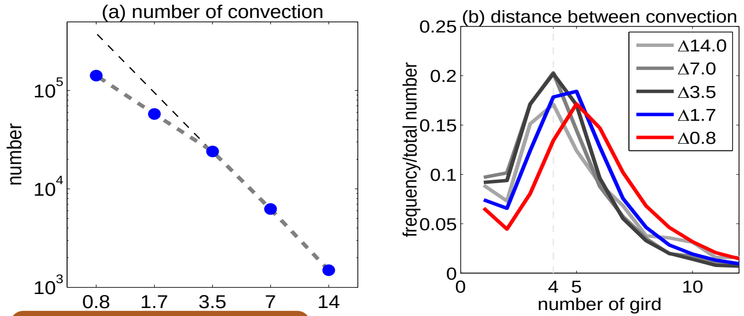
--- Tomita et al.(2005, *GRL) / Miura et al.(2007,Science)*

Debatable issue : Cloud permitting? or resolving?

Miyamoto et al.(2015, *Geophys.Res.Lett.*)
--- Research highlight
--- Eos research spotlight
--- Press release from RIKEN

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





Conclusion

1. Convection aspects (# of density, convection distance) change <u>around Δx=2km drastically.</u>
2. The core of deep convections becomes resolved from this resolution

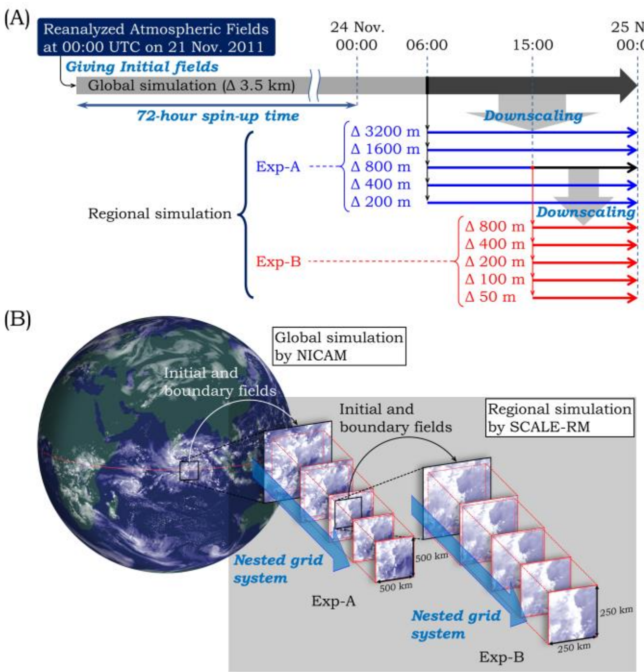
Much higher resolution in cloud cluster!

The convection aspects in the sub-km GCM was still perfectly converged.

Q. If the resolution becomes much higher,

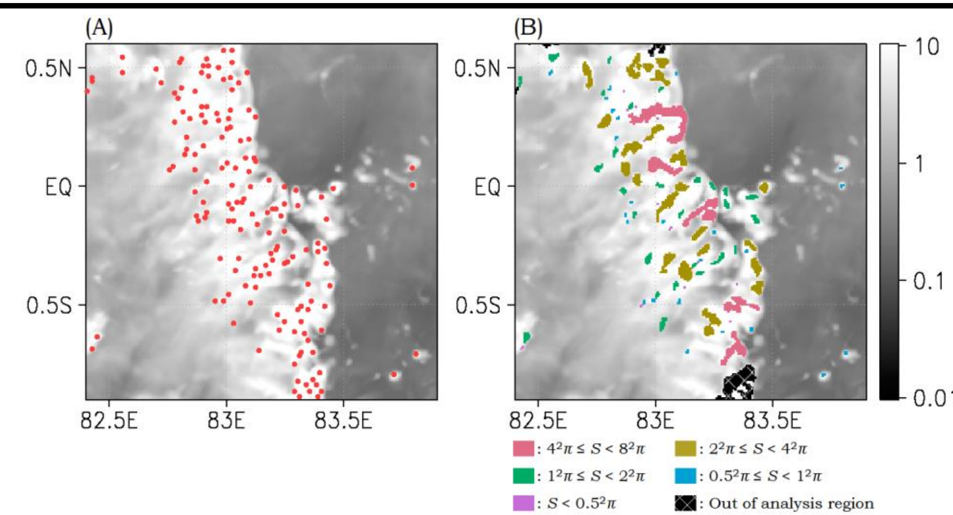
1. How is statistics of deep convection converged by grid refinement?
2. Which is the convergence point?

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

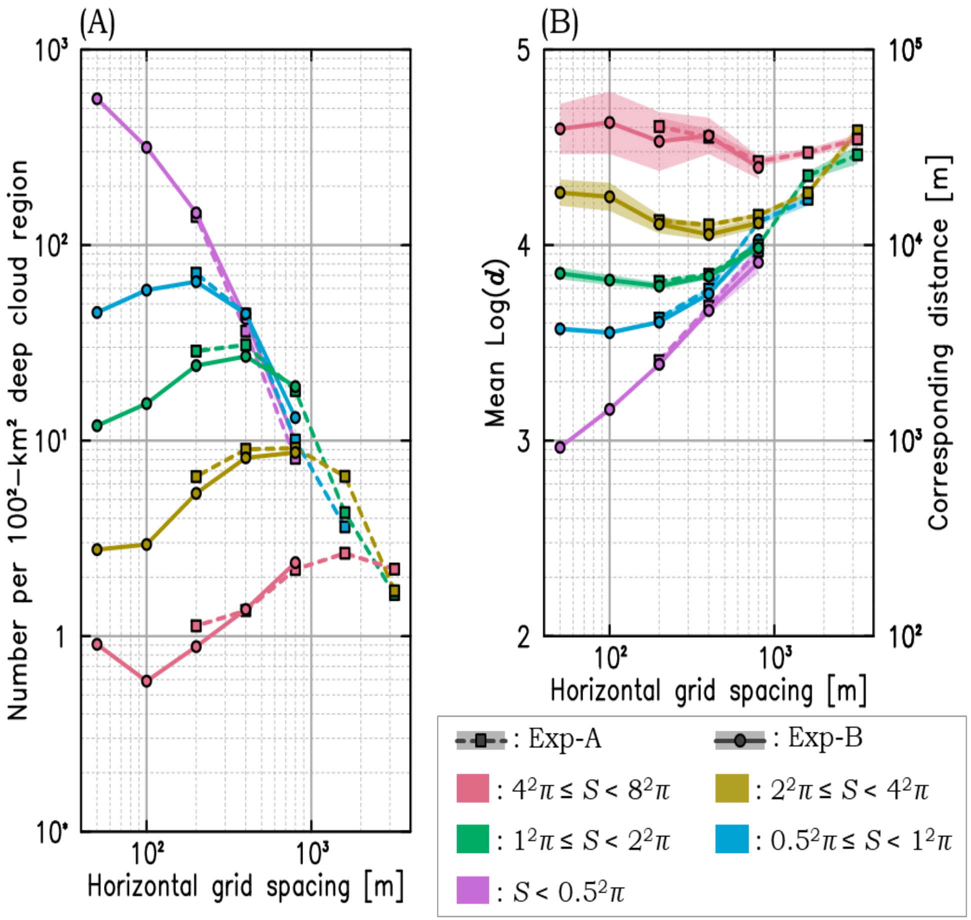


Schematic illustration of the experiments. (**A**) Outline of the experiments. Timeseries is expressed in universal time coordinated (UTC). (**B**) Snapshots of total column condensate for each simulation at 18:00 UTC on 24 November 2011.

- **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.



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

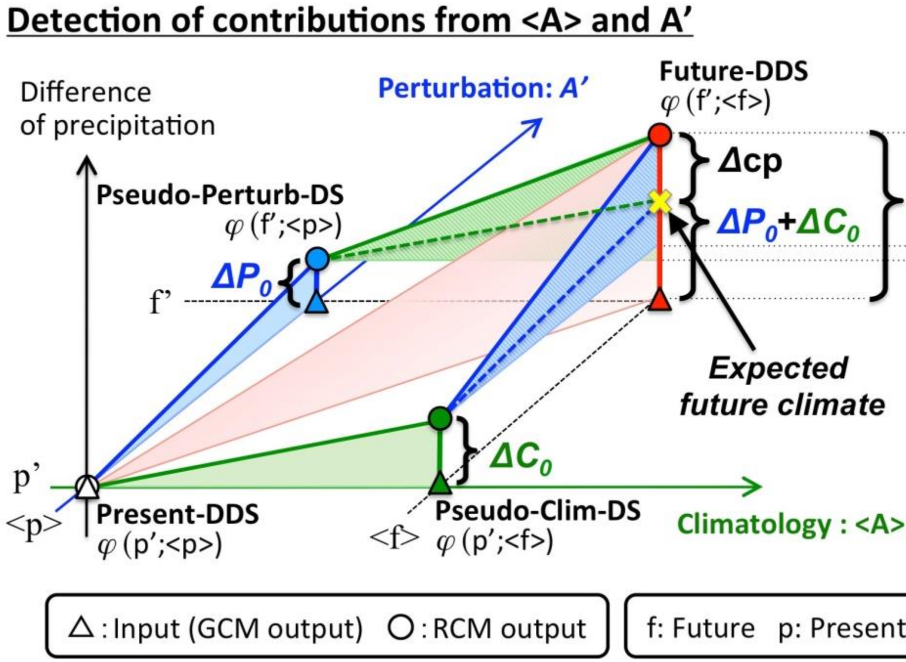
Development of New downscaling procedure for regional climate

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

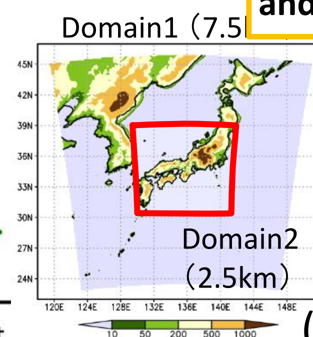
Nishizawa et al.(2018,PEPS)
Adachi et al.(2017, *Nat. Commun.*)
--- Press release

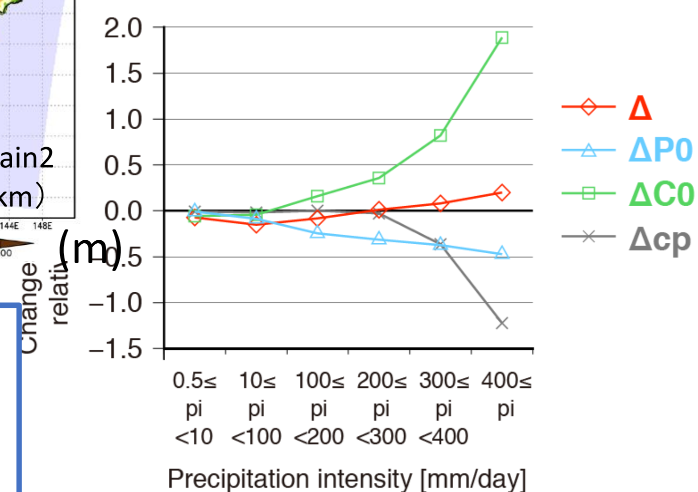
Schematic figure for evaluation of each effect



Appling this downscaling method to western japan climate,

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

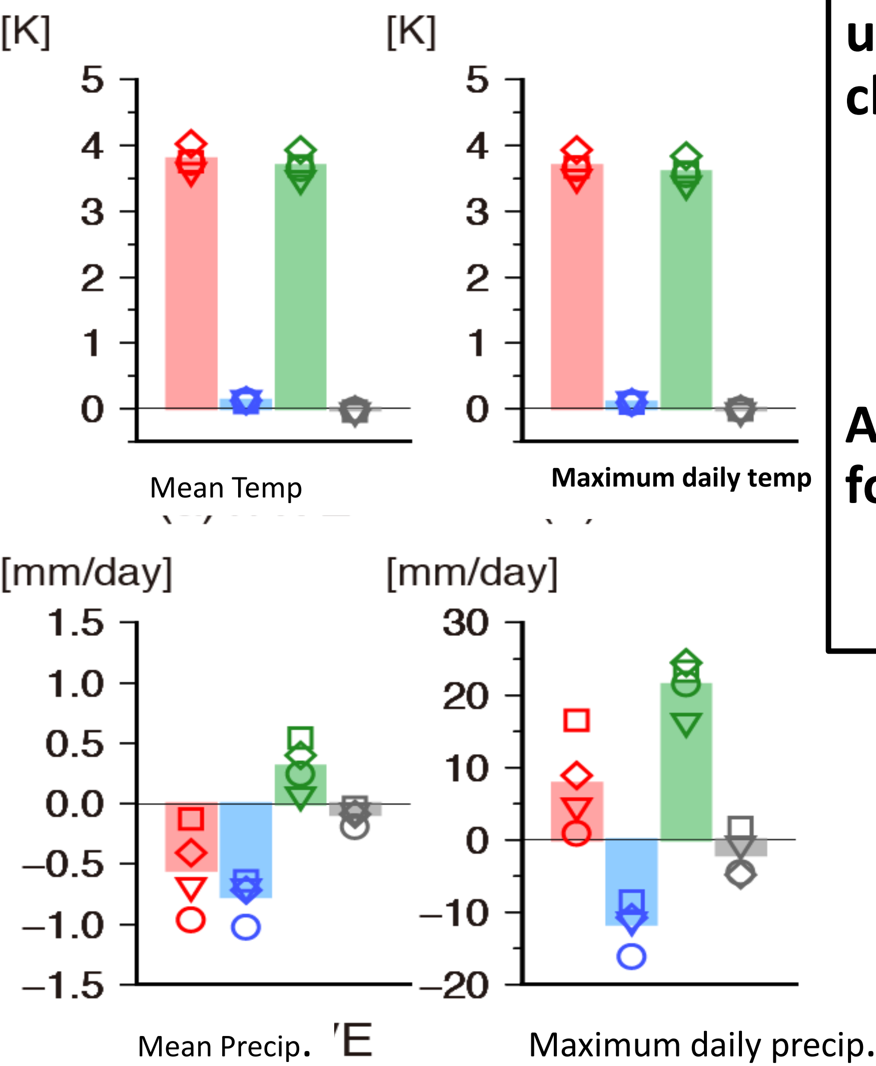




Main result: we can extract the contribution of climatology change and perturbation change and **its interaction**.

Development of New downscaling procedure for regional climate(2)

Adachi et al.(2018,*Atmos.Sci.Lett.)*



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

Δ Future change

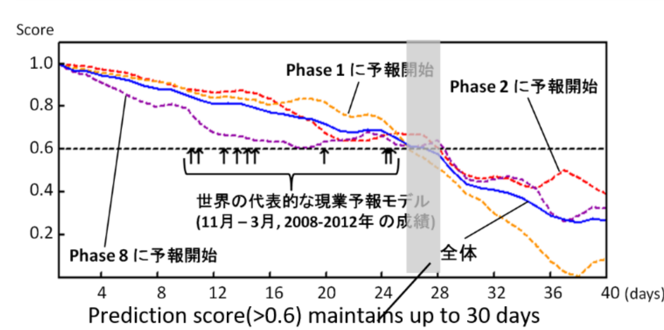
ΔP_0 Contrib. of Perturbation

ΔC_0 Contrib. of Climatology

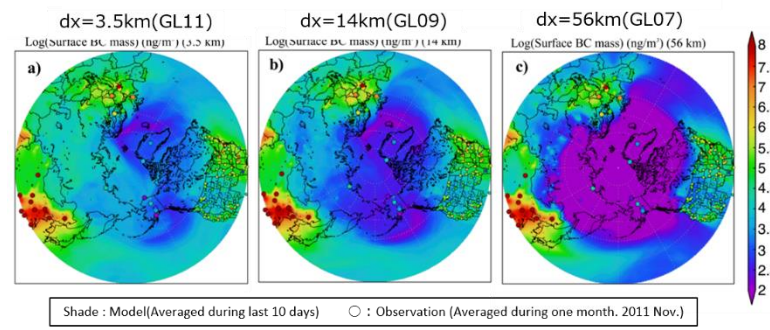
Δcp Contrib. of Nonlinearity

Other epoch making results on K Computer (with Press release)

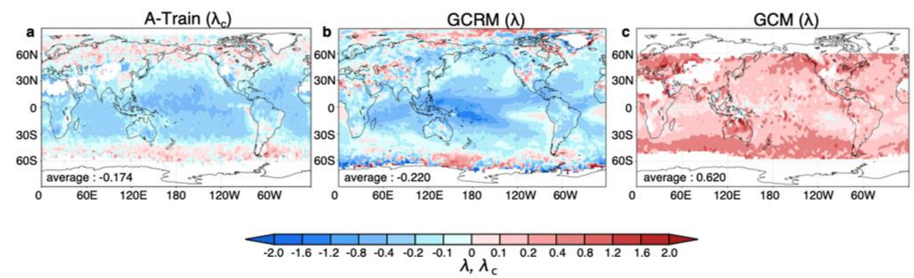
- **<u>High prediction skill of Madden Jullian Oscillation by GCRM</u>:**
  (Miyakawa et al. 2015, *Nat. Commun*.)



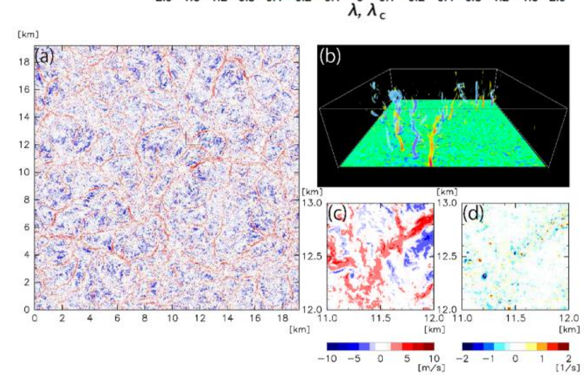
- **<u>Possibility of underestimation of ice-albedo feedback due to black carbon transport</u>**
  (Sato et al. 2016, *Sci. Rep.)*



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



- **<u>Investigation of dust devil statistics in the Martial PBL</u>**
  (Nishizawa et al.2015, *Geophys.Res.Lett.*)



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

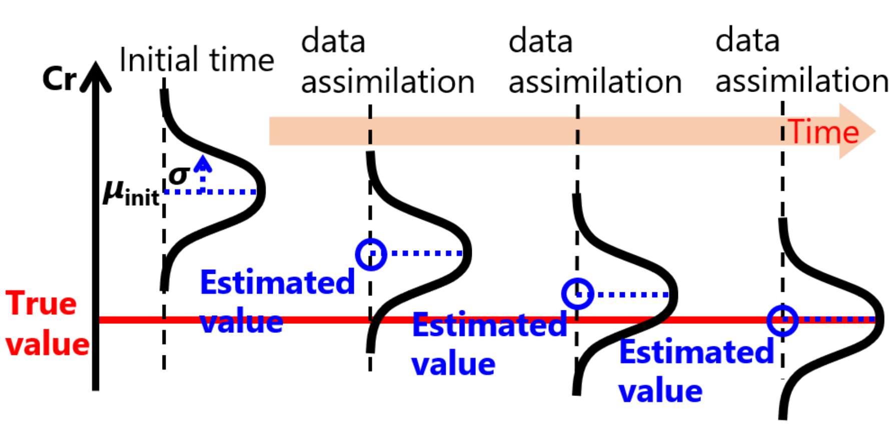
- **NICAM-LETKF** : global mid-range prediction (large scale disturbance)
- **SCALE (RM)-LETKF :** regional short-range prediction (each of deep convections)

NICAM-LETKF is one of main models in the FUGAKU prior subject 4

Future plan toward Fugaku(2)

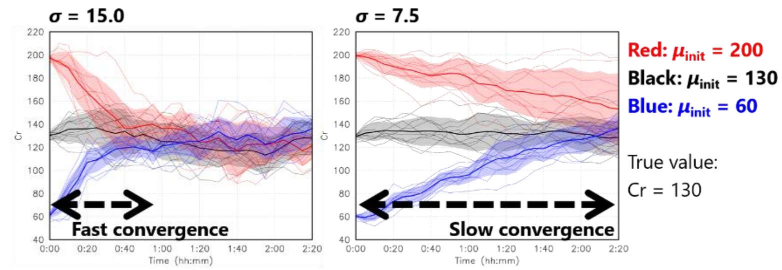
3. Enhancement of model parameter estimation by data science

- 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.

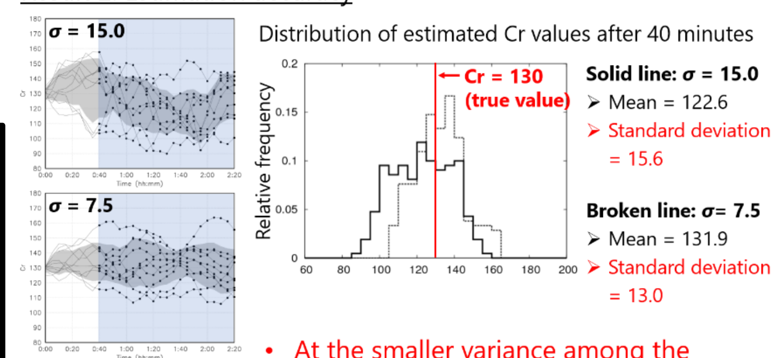
Result 1: Estimation speed



* 10 trials with slightly different initial Cr values for each experiment

- At the larger variance among the members, Cr values converge quickly around the true value

Result 2: Estimation accuracy



- At the smaller variance among the members, uncertainty of Cr is smaller.

Future plan toward Fugaku(3)

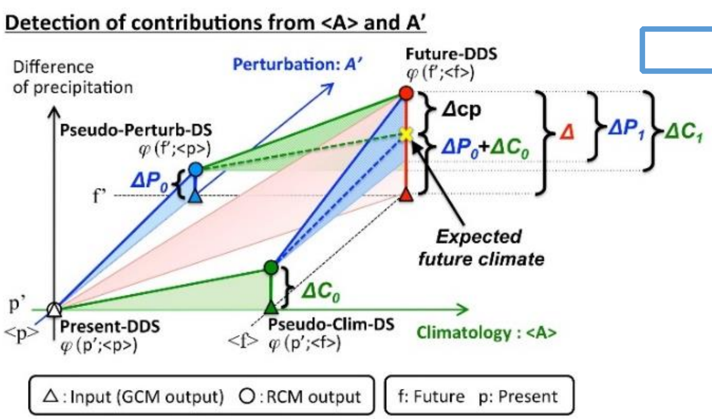
4. Investigation of uncertainties in environment assessment by regional climate model

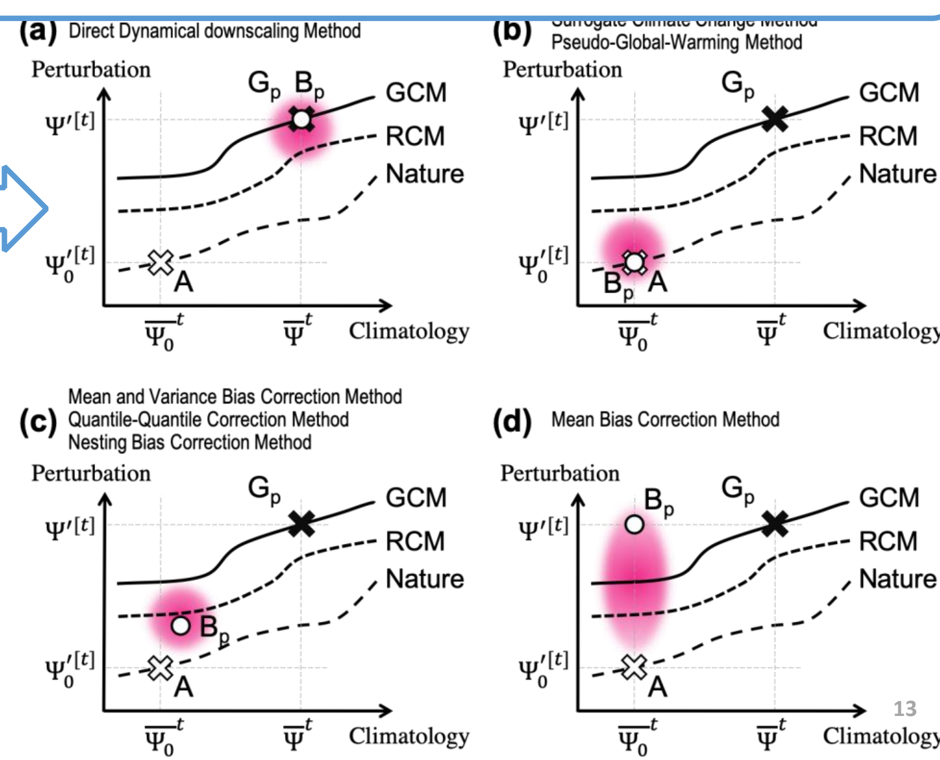
Current issues:

- **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

Adachi and Tomita(2020, *J.Geophys.Res.*) in revision
--- Methodology review paper



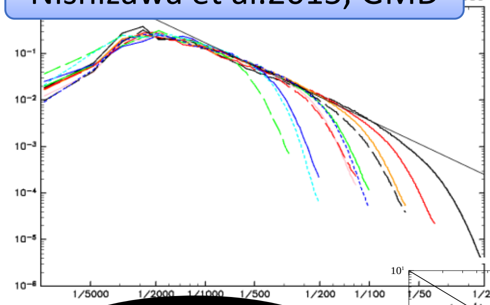


Future plan toward Fugaku(4)

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)

Nishizawa et al.2015, GMD



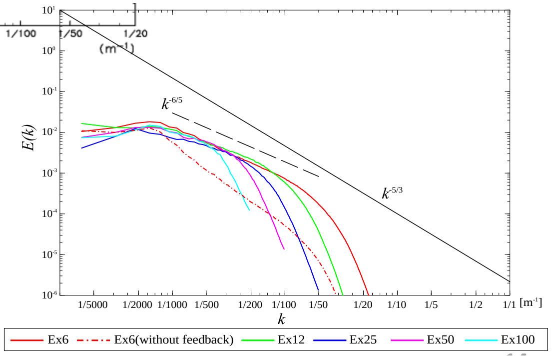
Dry case

-5/3 power

Sato et al.2018（ASL）

Moist case

Not -5/3 power but -6/5? in cloud area



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.