Mathematical Climatology Laboratory
Chief Scientist: Hirofumi Tomita (D.Eng.)

(0) Research field

CPR Subcommittee**:** Physics and Engineering

Keywords:
Self-organization and hierarchical structure of cloud / Multi-Equilibrium Solution of climate / Development of regional climate assessment method

(1) Long-term goal of laboratory and research background

From the mathematical viewpoint, we clarify the essential mechanism, such as the self-organization of clouds and their hierarchical structure, based on the understanding of the processes of clouds, turbulence, and radiation that are important for climate change. Based on these understandings, we will develop mathematical methods for climate assessment while interpreting the uncertainty of future climate projection. Through this, we aim to make a direct contribution to society. In the former essential subject, we evaluate the convergence of the solution of the cloud and turbulence schemes and aim to construct the theory of Large Eddy Simulation (LES), including the phase change of water. In addition, our aim includes the improvement of the physical processes and the development of high-speed algorithms for those schemes. Finally, it leads to the proposal of appropriate parameterization for low-resolution models. We will apply the new climate assessment methods we have developed to various problems in the latter subject. As one concrete theme, we will downscale the forecast results of the global climate projected by each model. Thus, it will allow us to understand the uncertainty and evaluate the future climate in each region with more objectivity.

(2) Current research activities (FY2020) and plan (until Mar. 2025)

1. Rearrangement of the dynamical downscaling method by a new perspective

Dynamic downscaling (DDS) is one of the numerical experimental methods for predicting regional-scale climate and understanding the mechanism of climate change. In a general DDS method, climate data calculated by a parent model (often a global climate model: GCM) is given as a boundary condition of a child model (regional climate model: RCM) to estimate a regional climate. Limiting the calculation area makes it possible to use high-resolution calculations with the same calculation resources and schemes that more accurately simulate complex actual phenomena.

On the other hand, the atmospheric conditions calculated by the DDS method include model bias because neither GCM nor RCM can completely reproduce the actual atmospheric conditions. In targeting the past climate, the observed value is available, so it is possible to reduce the model bias by assimilating it into the calculation. However, when predicting future climate, model bias is inevitable because the actual atmospheric conditions are not known. In particular, since the RCM is calculated within the GCM climate constraint given as a boundary condition, the GCM-derived model bias has been a significant issue in future climate projection. With the above background as motivation, many modified DDS methods have been proposed to reduce model bias in future climate projection and understand the factors of future climate change.

In FY2020, we published a comprehensive review paper on these improved DDS methods, called the modified boundary dynamical downscaling (MBDDS) methods. This year, we analyzed the characteristics of nonlinear effects in the FSCC method, one of the MBDDS methods proposed by Adachi et al. (2017).

When estimating the impact of multiple climate change factors with the MBDDS methods, there are nonlinear effects between the multiple factors in addition to the direct impact of each factor (Stein and Alpert, 1993). Adachi et al. (2017) used the FSCC method to analyze future precipitation changes in western Japan and showed the example that nonlinear effects could not be negligible compared with the increased frequency of intense precipitation due to changes in the mean state of climate associated with global warming. The importance of the nonlinear effect on the estimated sensitivity is still not fully understood. Therefore, this year, we analyzed the characteristics of nonlinear effects for the same case of Adachi et al. (2017).

First, a ΔC-ΔP-Δcp scatters diagram was proposed to analyze the characteristics of the nonlinear effect (Fig. 1). In this diagram, the horizontal axis represents the changes in the mean state of a large-scale atmospheric condition (ΔC), and the vertical axis represents the changes in the perturbation component of a large-scale atmospheric condition (ΔP); the nonlinear effects (Δcp) are indicated by colors on the phase space with these axes. The nonlinear effect is obtained by $\Delta cp=\Delta-\Delta C-\Delta P$, where Δ is the regional climate response to the changes in a large-scale atmospheric condition.

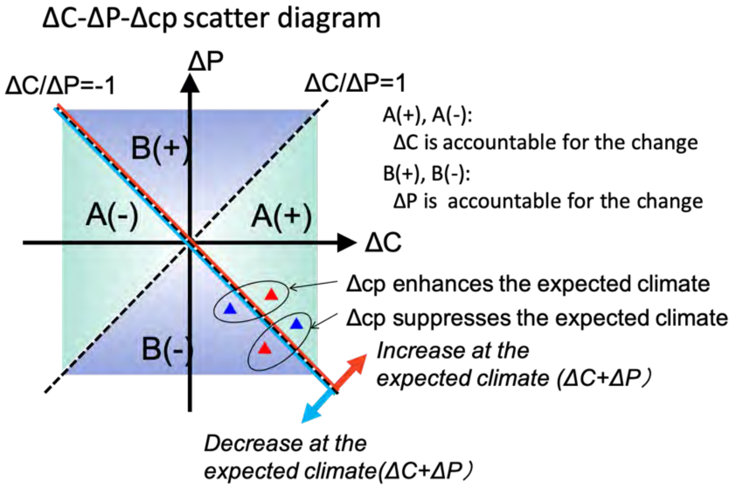

Figure 1 : ΔC-ΔP-Δcp scatters diagram.

Next, Fig. 2 shows the results of the ΔC-ΔP-Δcp scatters diagram for the maximum daily precipitation (R1D) and mean precipitation (Rave). In the case of R1D, when the expected climate change ($\Delta C+\Delta P$), estimated by the linear response only, is positive, the nonlinear effect (Δcp) is negative, and vise versa (Fig. 3a-d). In other words, the nonlinear effect acts to suppress the linear response of the regional climate to large-scale climate change. This characteristic was common to the results of four future climate experiments using different large-scale climate change. On the other hand, for mean precipitation (Rave), the contribution of nonlinear effects to the expected climate change is not clear (Fig. 2e-h). The suppressing and enhancing effects of Δcp are distributed in a mixed manner, and an absolute value of Δcp is small at many points.

The reason for the different results between R1D and Rave is explained by the different magnitudes of nonlinear effects between precipitation with different intensities. Adachi et al. (2017) showed that suppression by nonlinear effects is more dominant for intense precipitation above 300 mm/day. Since the mean precipitation includes various types of precipitation events, the characteristics of nonlinear effects are considered to have averaged out when viewed in terms of mean precipitation. The results of this analysis are currently under preparation for submission.

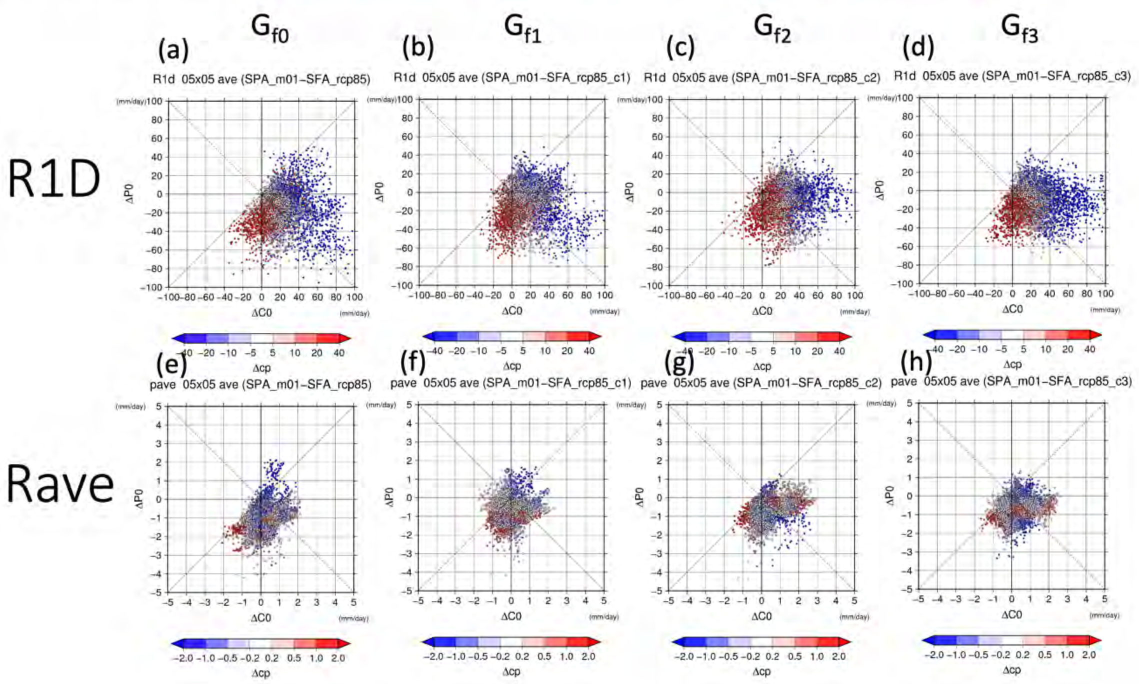

Figure 2: ΔC-ΔP-Δcp scatter diagrams of (a) daily maximum precipitation (R1D) and (b) mean precipitation (Rave). The color indicates the sign of the nonlinear effect (Δcp).

2. Derivation of required numerical precision of turbulence scheme LES

In recent years, large eddy simulation (LES) has begun to be adopted in meteorological and climate simulations as a promising method for parameterizing subgrid-scale turbulence. However, the numerical precision required for the dynamic core is not yet fully understood. In this year, we derived two theoretical criteria for the required accuracy of advection terms. Their validity was verified by numerical experiments that set the typical conditions of the atmospheric boundary layer. The results for the grid-scale is O (10 m) are shown below.

Based on the theoretical criteria for numerical diffusion error, the upwind scheme must have an accuracy of at least 7th order. Also, the 4th-order central scheme usually is used with the 4th-order explicit diffusion, but its coefficient must be one or two orders of magnitude smaller than the implicit diffusion coefficient of the third-order upwind scheme to meet the theoretical criteria. Based on the theoretical criteria for numerical dispersion error, at least 7th or 8th order is required. Actually, the dispersion error has only an indirect effect on the energy spectrum, but it is necessary to consider that it may affect the local turbulence mechanism. We also investigated the effect of time discretization of the compressible model. If the time step is small enough from acoustic wave limitation, a relatively low-order time scheme up to a grid-scale of O (10 m) is available. The derived theoretical criteria mean that as the grid spacing decreases, the order of accuracy required increases. This suggests that considerable attention should be paid to future high-resolution LES numerical error problems (Kawai & Tomita, 2021). In the future, while considering the above, we will aim for a highly efficient and highly accurate dynamical core. Currently, we have considered that the Discontinuous Galerkin method is superior in terms of accuracy and computational performance. The development has just started.

3. Model parameter estimation using data assimilation

Physical process components in climate models contain various parameters. These parameters have their own uncertainties that contribute to the uncertainty of climate projection. To improve the reliability of climate projection, we are trying to establish a method to estimate the optimal parameter values by assimilating observation into model simulations. In this fiscal year, we performed an idealized experiment. In the experiment, we considered the output of moist convective system simulation (nature run) as observation and estimated the true parameter value used in the nature run by using the ensemble Kalman filter (EnKF). In EnKF-based parameter estimation, different parameter values are given to each member in the ensemble. Then, the results of the ensemble forecast are compared with observation, and the parameter values are updated to approach the value that provides a closer forecast to the observation. Here, the parameter's standard deviation (σ) in the ensemble is a key value. As the σ increases, while the convergence time to the true value is shortened, the estimation precision gets worse. In this study, we conducted a sensitivity experiment about σ and found that the optimal σ providing the best precision exists. Furthermore, we approximated the estimation time series with the first-order autoregressive model and quantified the dependency of estimation precision and convergence time on σ. Based on this, we proposed guidelines for determining the optimal σ. Now we are preparing to submit our results to a journal published by the American Meteorological Society.

(3) Members

as of March, 2021

Hirofumi Tomita Chief scientist
Sachiho A. Adachi Researcher
Kenta Sueki Post-doctoral researcher
Keiko Muraki Assistant

(4) Representative research achievements

1. "Numerical Accuracy of Advection Scheme Necessary for Large-Eddy Simulation of Planetary Boundary Layer Turbulence", Kawai, Y. and H. Tomita, *Monthly Weather Review*, accepted (2021).
2. "Methodology of the constraint condition in dynamical downscaling for regional climate evaluation:A review", Adach, S.A., and H.Tomita, *J. Geophys.Res-Atmos*, 125,e2019JD032166 (2020).
3. "Impacts of Number of Cloud Condensation Nuclei on Two-Dimensional Moist Rayleigh Convection", Miyamoto, Y., S. Nishizawa, and H. Tomita, *J. Meteorol. Soc. Japan*, 98(2), 437−453, (2020).
4. "Environment of tornado occurrences. Understanding Tornadoes", Sueki, K., and E. Tochimoto, *Meteorological Research Note*, No. 243, the Meteorological Society of Japan, 47–70. (2020) (Japanese)
5. "Structure and environment of tornado-spawning typhoons", Sueki, K., Tornado Symposium－Commemorating the 100th Anniversary of the Birth of Dr. Tetsuya Fujita－, Mar. 11-12, 2021. (Oral)
6. "The Essence of Dynamical Downscaling Method for the Assessment of Regional Climate Change", Adachi, S. A. and H. Tomita, 61st Annual Meeting of Japan Society for Atmospheric Environment, Sep. 14 - Oct. 4, 2020. (Oral)
7. "Parameter estimation for cloud microphysics scheme using an ensemble Kalman filter", Sueki, K., T. Yamaura, S. Nishizawa, and H. Tomita, The Meteorological Society of Japan Spring Meeting 2020, May 19-22, 2020. (Oral)

Laboratory Homepage
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