Chapter 12

Computational Climate Science Research Team

12.1 Members

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12.2 Overview of Research Activities

The primary aim of Computational Climate Science Research Team is to indicate a direction of future climate modeling with a reliable suggestion for the age of high-performance computers. For this purpose, we intend to construct a basic library, in which model components and their numerical method are inter-exchangeable among multiple models. This work contributes directly to the climate modeling community for the enhancement of fast output/outcome creation. Using the library, we also develop a more advanced climate model with new techniques that is necessary for efficient climate simulation. We promote to develop them, considering the following issues; the readability of code, its convenience for users, and traceability of computational results. The second aim is to pursue the high efficiency of the climate model in massively parallel computers. Computational meteorology and climatology always require large-scale numerical experiments. However, it is recently pointed out that conventional computer architecture with the straightforward extension of existing simulation codes would be a limitation in getting a higher performance. From the viewpoint of hardware and climate modeling, we consider the numerical method, algorithm, and their implementation to large-scale computers, cooperating with research teams of computational and computer sciences in R-CCS. The third aim is to apply our model to address the meteorological/climatological problems, collaborating with outside research institutes. Climate studies are widely spread from the basic understanding of phenomena to assessment of the environment. The former is more scientific and the latter is more practical for the requirement of the society. Several issues we currently focus on are as follows; feedback mechanism between cloud, aerosol, and radiation, theory for the moist process linked to the turbulence process, comprehensive understanding of our earth's particularity by investigation other planets, and so on. The assessment of future environmental change for disaster prevention at the regional scale level is also one of our targets. In this fiscal year, we improved the basic library for more reliable simulation results. We also evaluated characteristics of moist convections in high-resolution simulations, especially their dependence on simulation resolution.

12.3 Research Results and Achievements

12.3.1 Research and development of SCALE

SCALE (Scalable Computing for Advanced Library and Environment) is a basic library for numerical atmospheric calculations. For the next generation atmospheric simulations, we have been evaluating existing schemes and developing new schemes for higher resolution simulation. In this year, we have improved several components to improve the reproducibility of simulations, including the planetary boundary layer turbulent model, cumulus parameterization, ocean model, and land model. Three target phenomena were selected: the total amount of precipitation in the 2018 heavy rainfall event around Hiroshima, the climatological distribution of precipitation in the summer Asian region, and extratropical cyclone in the 1966 heavy rainfall event around Kobe. Several sensitivity simulations of model components and simulation configurations were performed to optimize them.

12.3.2 The Hyogo-Kobe COE establishment project

We continued to drive the subject "Computational Research on Estimation to Complex Disaster Risk for Better Urban Planning" in Hyogo-Kobe COE establishment project started in FY2018. In this year, we conducted the study of the rainfall system during the recent catastrophic heavy rainfall event in western Japan in July 2018 and attempted to build the framework of the urban model in our SCALE library.

During the heavy rainfall event in July 2018, it is found that the number of sediment disasters in the Hiroshima area was larger than that in Keihanshin area including Hyogo-Kobe although the rainfall amount did not show a significant difference over these two areas. In order to figure out the possible reasons for the difference, we examined the characteristics of rainfall systems striking above two areas based on the radar observations with a special focus on the size of the rainfall system. We found that significantly large rainfall systems with areas equal to or larger than 104 km^2 were dominant in the Hiroshima area, inducing rapid accumulation of the rainfall amount. Eventually, it enhanced the risk of deadly sediment disasters. In contrast, the relatively small rainfall system with moderate intensity was found to be dominant in the Keihanshin area. We suggested that the difference in the damage between the two areas was anchored by the size difference of the rainfall system. A high vertical wind shear environment was also suggested to be a preferable condition for the large rainfall system formation (Sueki and Kajikawa, 2019).

We also built the framework of the urban model to advance our climate model (SCALE library) by reducing the model uncertainty. We improved the model to give the roughness lengths for momentum and heat and artificial heat in each grid point; the model can describe the inhomogeneous heating in the urban area. In the case we set the parameters based on the observation instead of the default value we have used in previous, wind speed and temperature in the urban area tend to be suppressed.

12.3.3 Numerical convergence for simulation of atmospheric deep moist convection

Deep convective clouds are responsible for thermal convection with moist processes in the atmosphere and impact the Earth's climate significantly. However, their representation in climate models is imperfect, causing great uncertainty in climate prediction. Convective clouds often form self-organized systems with spatially hierarchical structures, such as super cloud clusters associated with Madden–Julian oscillations. This self-organization of convective clouds makes it difficult to assess their impact on the climate. High-resolution simulations that correctly reproduce organized cloud systems are necessary to understand the role of deep moist convection in the Earth's climate system. However, the numerical convergence for simulation of organized cloud systems remains debatable. To investigate the model resolution necessary for a reasonable simulation of deep moist convection, we conducted grid-refinement experiments using the SCALE-RM on the K computer. Figure 12.1 shows horizontal grid-spacing dependence of the statistics of convective updrafts in an organized cloud system. We found that both the number of updrafts (Figure 12.1a) and the mean distance between two adjacent updrafts (Figure 12.1b) converge at progressively smaller scales as the grid spacing is reduced. The gap between two adjacent updrafts converges to a particular distance when the grid spacing becomes as small as 1/20–1/40 of the updraft effective radius. We also found that the converged inter-updraft distance value is not significantly different between Reynolds-averaged Navier–Stokes simulations (dashed line in Figure 12.1) and large eddy simulations (solid line in Figure 12.1) for grid spacings in the terra incognita range.

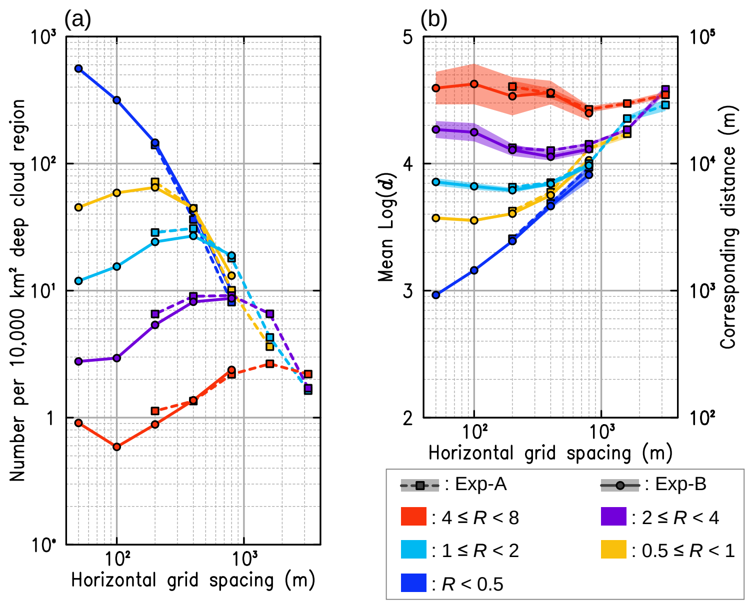

Figure 12.1: Horizontal grid-spacing dependence of the statistics of convective updrafts in an organized cloud system. (a) Number of updrafts per 10,000 km^2 deep cloud region. (b) Mean value of the logarithm of the distance, d, between two adjacent updrafts, denoted by mean Log(d). The dashed and solid lines indicate the results of Reynolds-averaged Navier–Stokes simulations (Exp-A) and large eddy simulation (Exp-B), respectively. Different colors indicate different size classifications: Each updraft is classified by its effective radius, R (unit: km), which is defined as the square root of area S divided by π: $R \equiv (S/\pi)^{1/2}$. In (b), a confidence interval of 99% for mean Log(d) is indicated by the translucent color. (Figure 4 in Sueki et al. 2019, *Geophysical Research Letters*)

12.3.4 Self-organization of moist convection in the idealized radiative-convective equilibrium simulation

Atmospheric moist convection plays significant roles in the earth's weather and climate system: it not only causes clouds and precipitation at a local scale but also organizes into a hierarchical structure extending to a global scale. Despite its importance being widely recognized, the representation of cloud-related processes is still insufficient and brings large uncertainties in climate model simulations. Recently, toward deepening basic understanding of the role of clouds, a numerical simulation framework of idealized climate, called radiative-convective equilibrium (RCE), is spotlighted in the climate modeling community. In the RCE simulation, it is known that moist convection can be organized into an aggregated cloud system even under a uniform boundary condition; that process is called convective self-aggregation (CSA) and is recognized as a key for the relationship of clouds and climate. Previous studies have shown that the CSA occurred if the simulation domain was larger than 200–300 km to a horizontal extent, which suggests the existence of critical length for the CSA onset. On the other hand, the CSA onset also depends on the simulation resolution; only in the low-resolution simulation CSA have been found to spontaneously occur.

In this fiscal year, to investigate the characteristic length of CSA onset, we conducted systematic cloud-resolving simulations, with a scope covering the horizontal domain size and resolution, by using SCALE on the supercomputers including the K-computer. As a result, we updated an RCE regime diagram compared to Muller and Held (2012, MH12), as shown in Fig. 12.2. The main conclusions are summarized as follows: (1) CSA is unlikely to occur with a high resolution or small domain (the lines II and III, and MH12 reference line). (2) CSA occurs in sub-kilometer high-resolution cloud-resolving simulations with domain sizes larger than 500 km (line I).

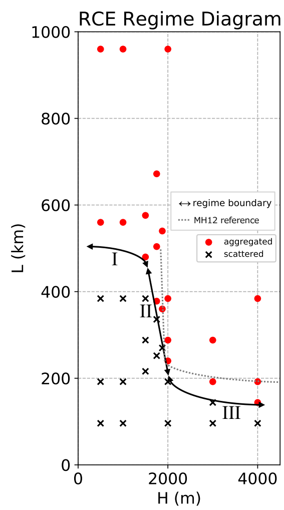

Figure 12.2: RCE regime diagram in a parameter space of horizontal domain size (L in kilometer) and grid spacing (H in meter). Red circles (black crosses) indicate aggregated (scattered) regime. (Figure 2b in Yanase et al. 2020 *Geophysical Research Letters*)

12.4 Schedule and Future Plan

The basic library SCALE is being advanced. At the moment, major processes such as dynamics and physics have already been comprehensively developed. In the future, we will pursue ease of use for external users. The advanced climate models based on the schemes continue to be improved in principle and provide a direction for future climate models. The key to advancement is the sub-grid scale models. A more accurate representation of cloud physics requires a turbulence model that takes into account moist processes. The combination of a turbulence-aware LES and Super Droplet Method (SDM) for cloud microphysics will be a useful tool for solving this issue. As well as developing accurate schemes for high-resolution simulations, there is also a need to improve parameterizations for coarser-resolution simulations. Data science techniques are useful for this purpose, including optimization of model parameters in the parameterizations and development of AI-based parameterization generated using a high-resolution simulation database.

One of our primary missions is to provide tools for the analysis of simulation results as well as improve the computational and physical performance of simulations. This is critical for accelerating scientific and social outcomes. Specifically, we will parallelize major analysis programs and make them suitable for massively parallel computer systems. In addition, we will continuously develop a short- and medium-range numerical weather forecasting system in collaboration with Data Assimilation Research Team. LETKF is an important application for data assimilation. Combining our models with LETKF, which combines high-resolution and large-scale ensemble simulations and observational big data, will enable us to take a new stage in numerical weather forecasting, especially for sudden and heavy rainfall. This has already begun as an applied research project under the AIP project and Program for Promoting Researches on the Supercomputer Fugaku (Issue 04).

12.5 Publications

12.5.1 Articles/Journal

[1] Sato, Y., Y. Miyamoto, and H. Tomita (2019): Large dependency of charge distribution in a tropical cyclone inner core upon aerosol number concentration, Prog Earth Planet Sci 6, 62.
[2] Sueki, K., and Y. Kajikawa (2019): Different precipitation Systems between Hiroshima and Keihanshin during extreme rainfall event in Western Japan in July 2018, Journal of the Meteorological Society of Japan, Volume 97 No.6.
[3] Grabowski, W. W, H. Morrison, S. Shima, G. C. Abade, P. Dziekan, and H. Pawlowska (2019): Modeling of cloud microphysics: Can we do better?, Bulletin of the American Meteorological Society, Volume 100 No. 4.
[4] Yamaura, T., S. Nishizawa, and H. Tomita (2019): Theoretical time evolution of numerical errors when using floating point numbers in shallow-water models, Journal of Advances in Modeling Earth System, Volume 11, Issue 10.
[5] Sueki, K., T. Yamaura, H. Yashiro, S. Nishizawa, R. Yoshida, Y. Kajikawa, and H. Tomita (2019): Convergence of convective updraft ensembles with respect to the grid spacing of atmospheric models, Geophysical Research Letters, Volume46, Issue24.
[6] Yoshida, R., and H. Fudeyasu (2020): How significant are low-level flow patterns in tropical cyclone genesis over the Western North Pacific?, Monthly Weather Review, Volume. 148 No.2.
[7] Bai, L., K. Sueki, G. Chen, and R. Zhou (2019): Climatology of tropical cyclone tornadoes in China from 2006 to 2018, Science China Earth Sciences, Volume 63.

12.5.2 Oral Talks

[8] 末木健太, 梶川義幸: 平成30年7月豪雨における広島と兵庫の降水特性の比較, 気象学会2019年度春季大会, Tokyo, Japan, May 15, 2019.
[9] 柳瀬友朗: 高解像度公領域放射対流平衡実験における湿潤対流の自己組織化, 第6回マッデン・ジュリアン振動研究会, Kami, Japan, Sep 12, 2019.
[10] 松嶋俊樹, 西澤誠也, 島伸一郎: 超水滴法を用いた雄大積雲のラージ・エディ・シュミレーション, 日本流体力学年会2019, Chofu, Japan, Sep 14, 2019.
[11] Adachi, S. A.: Characteristics of Nonlinearity Between Climatology and Perturbation Components, 15th International Conference on Atmospheric Sciences and Applications to Air Quality, Kuala Lumpur, Malaysia, Oct.30, 2019.
[12] 松嶋俊樹, 西澤誠也, 島伸一郎: 超水滴法を用いた雄大積雲のラージ・エディ・シミュレーション, 日本気象学会2019年度秋季大会, Fukuoka, Japan, Oct.31, 2019.
[13] 山浦剛, 西澤誠也, 富田浩文: 浮動小数点演算エラーの理論的時間発展, 第21回非静力学モデルに関するワークショップ, Tsu, Japan, Nov. 21, 2019.
[14] 山浦剛, 西澤誠也, 富田浩文: 浅水波モデルにおける浮動小数点演算誤差の理論的時間変化, 第33回数値流体力学シンポジウム, Sapporo, Japan, Nov.27, 2019.
[15] 末木健太, 山浦剛, 八代尚, 西澤誠也, 吉田龍二, 梶川義幸, 富田浩文: 大気モデルの格子間隔に対する深い湿潤対流の収束性, 第11回熱帯気象研究会, Toyama, Japan, Dec. 26, 2019.
[16] Yamaura, T.: The parameter estimation system in SCALE for reduced-precision floating-point numbers, The Second IMT-Atlantique & RIKEN Joint Workshop, Brest, France, Feb. 11, 2020.
[17] Sueki, K.: Estimation of key parameters in cloud microphysics using ensemble Kalman filter, The Second IMT-Atlantique & RIKEN Joint Workshop, Brest, France, Feb. 11, 2020.
[18] 松嶋俊樹: 超水滴法を用いた雄大積雲のラージ・エディ・シミュレーション, 2019年度 エアロゾル・雲・降水の相互作用に関する研究集会, Tachikawa, Japan, Feb. 19, 2020.

12.5.3 Posters

[19] 足立幸穂, 西澤誠也, 安藤和人, 山浦剛, 吉田龍二, 梶川義幸, 八代尚, 富田浩文: 将来領域気候予測における不確定性の要因評価手法の提案, 気象学会2019年度春季大会, Tokyo, Japan, May 15, 2019.
[20] 末木健太, 山浦剛, 八代尚, 西澤誠也, 吉田龍二, 梶川義幸, 富田浩文: 大気モデルにおける組織化した対流雲の数値的収束, 第6回メソ気象セミナー, Ise, Japan, Jul 14, 2019.
[21] Adachi, S. A., and Hirofumi Tomita.: Characteristics of nonlinearity between mean state change and per-

turbation change, Latsis Symposium 2019, Zurich, Switzerland, Aug 21, 2019.
[22] Sueki, K., and Yoshiyuki Kajikawa.: Different Precipitation Systems between Hiroshima and Hyogo during the Extreme Rainfall Event in July 2018 Revealed by the Radar Observation, 39th International Conference on Radar Meteorology, Nara, Japan, Sep 17, 2019.
[23] Matsushima, T., Seiya Nishizawa, and Shin-ichiro Shima.: Large-Eddy Simulations of Cumulus Congestus Cloud Using Super Droplet Method, 39th International Conference on Radar Meteorology, Nara, Japan, Sep 17, 2019.
[24] 末木健太: 対流雲の大規模パラメータスイープ実験, 日本気象学会2019年度秋季大会, Fukuoka, Japan, Oct.30, 2019.
[25] Sueki, K.: Massive parameter-sweep warm bubble experiment on convective cloud environment, 10th European Conferences on Severe Storms, Krakow, Poland, Nov.7, 2019.

12.5.4 Books

[26] 筆保弘徳, 山崎哲, 中村哲, 安成哲平, 吉田龍二, 釜江陽一, 下瀬健一, 大橋唯太, 堀田大介 (2019): ニュース・天気予報がよくわかる気象キーワード事典, ベレ出版, 276ページ, 2019/10/18出版.

12.5.5 Software

[27] SCALE, Library and environment for Meteorological and Climate calculations, urlhttps://scale.riken.jp/.