Chapter 12

Computational Climate Research Team

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12.2 Research Activities

Our research team conducts the pioneering research work to lead the future climate simulation. In order to enhance the reliability of climate model, we have aimed to construct a new climate model based on the further theoretically physical principles. Conducting such a new model needs tremendously large computer resources. Therefore, it is necessary to design the model to pull out the capability of computers as much as possible. Recent development of supercomputers has a remarkable progress. Hence another numerical technique should be needed under the collaboration of hardware research and software engineering for the effective use on the future HPC, including the K computer and Post K computer.

For the above research purpose and background, our team is cooperating with the computational scientists in other fields and computer scientists. We enhance the research and development for the future climate simulations including effective techniques; we build a next-generation climate model. The establishment of the above basic and infrastructure research on the K Computer is strongly required, because this research leads to the post K computer or subsequent ones in the future.

We have proposed the subject Estimation of different results by many numerical techniques and their combination as a synergetic research to MEXT from 2011. We develop a new library for numerical simulation. In this fiscal year, we improved computational performance of SCALE library and validation of its physical performance, aiming at the reliability of SCALE. In addition, for the user expansion and promotion, we vigorously maintained the users manual and model document. New developments are highlighted as follows.

12.2.1 Redesign of Structure and API of SCALE

SCALE contains a library providing fundamental components (SCALE-lib) and an atmospheric regional model using the library (SCALE-RM). So far, SCALE-lib has been developed to be used by SCALE-RM. The design of SCALE is not suitable for use in programs for pre- and post-processes. We redesign the structure and application programming interfaces (APIs) of SCALE-lib for the general purposes. The followings are the key points of the redesigning.

- reduction of dependency between individual components
- minimization of initialization of the components for individual use of each component
- dynamical grid size handling for multiple problem sizes in a program
- trace information in the error messages for improving traceability
- standardization of name of files and modules for easier understanding of the structure

In this year, we redesigned the whole structure APIs and implemented the modules for the physical processes. We also prepared sample programs for analysis using a part of physical process calculations to provide use case and template for users.

12.3 Research Results and Achievements

12.3.1 Research for Estimating Complex Disaster Risk in Hyogo-Kobe COE Establishment Project

The Hyogo-Kobe COE establishment project newly accepted the six research subjects in this fiscal year. Our team participates one of six subjects "Computational Research on Estimation to Complex Disaster Risk for Better Urban Planning." In this project, our team is responsible for future regional climate projection by a model with high spatial resolution and sophistication of the model for it.

Recently, climate changes associated with global warming are observed in the world: increase of air temperature and changes in precipitation. Studies projecting future climate change by the numerical simulations have been actively carried out to provide information of the future climate. To consider adaptation plans to future climate change, it is important not only to estimate range of projections but also to understand mechanisms controlling regional climate. Previous studies often used a downscaling method (pseudo global warming (PGW) method) that considers only changes in "mean state" of large-scale climate as influential factor to regional climate. However, this method cannot precisely evaluate future regional climate change because the method does not consider changes in "perturbation" of large-scale climate, i.e., changes in weather disturbances such as typhoon and midlatitude cyclones.

We extended the PGW downscaling method considering only the changes in mean state and proposed a new downscaling method considering the changes in perturbation. The proposed method uses four downscaling experiments: two direct dynamical downscaling (DDS) experiments for the present and future climates and two experiments with boundary conditions exchanging either climatology or perturbation components between the two climates. The DDS experiments are conventional downscaling simulations, for which boundary conditions are given directly from global circulation model (GCM) outputs. From these four experiments, we can estimate both influences of changes in mean state and changes in perturbation of large-scale climate on regional climate change. In addition, the method allows the influence due to the nonlinear effect between the two components to be extracted. That is, from four experiment, we can separate the regional climate change Δ into contributions of three factors: (1) changes in mean state ΔC, (2) changes in perturbation ΔP, and (3) the nonlinear effect Δcp.

To demonstrate the usefulness of the method, we applied the method to the future precipitation change in western Japan. The results indicate that the changes in perturbation account for a large part of the decrease in mean precipitation (Fig. 12.1 a). It means that consideration of only the mean state change is insufficient for projection of the future precipitation change. The result of extreme precipitation shows little change between the present and future climates (Fig.12.1 b), The small change between the present and future climates is simply a consequence of cancelling the contributions from mean state and perturbation changes, i.e., ΔC and ΔP. On the perspective of an adaptation strategy, both the changes in the cumulative precipitation amount and those in the frequency and intensity of precipitation are important. The former information is related to securing water resources, while the latter information is helpful to reduce the risk of disaster. An analysis shows that the changes in mean state have a large impact on the intensity of precipitation. On the other hand, the changes in perturbation strongly affect on the cumulative precipitation amount. These results are published as Adachi et al. (2017).

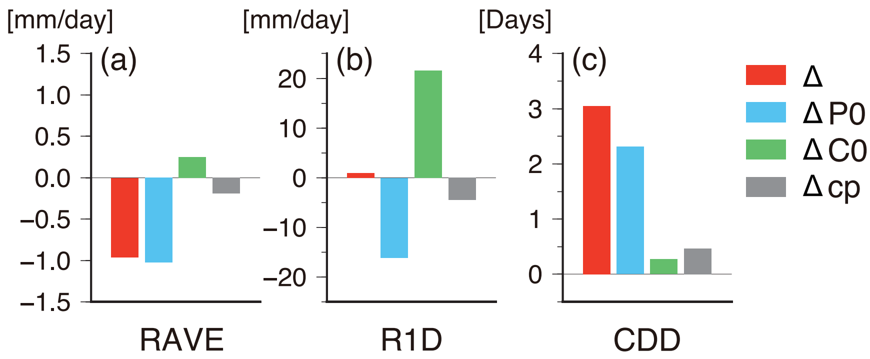

Figure 12.1: Differences from the present climate in 25-year means of the **a** daily mean precipitation (RAVE), **b** maximum one-day precipitation (R1D), and **c** maximum number of consecutive dry days (CDD), respectively. Δ is the total change estimated by the DDSs (Future-DDS−Present-DDS). ΔP_0 and ΔC_0 indicate the contributions of the perturbation and climatology, respectively. Δcp is the contribution of the nonlinear effect.

12.3.2 Development of Super Droplet Method (SDM)

In this year, we confirmed the validity of the SDM coupled with SCALE (SCALE-SDM) through the comparison between the results of SCALE-SDM and those of SCALE coupled with two-moment bulk microphysical scheme (Seiki and Nakajima 20014; SCALE-bulk). The validity of SCALE-bulk has been confirmed by previous studies (e.g., Sato et al. 2014, Sato et al. 2015, Adachi et al 2017), and the comparison between SCALE-SDM and SCLAE-bulk enables us to confirm the validity of SCALE-SDM.

For the comparison, we conducted the numerical simulations targeting on the shallow cumulus using the SCALE-SDM and SCALE-bulk. The experimental setup was based on one of the common experimental setups called the Barbados Oceanographic and Meteorological Experiment (BOMEX: Siebesma et al. 2003). In Siebesma et al. (2003), the horizontal (vertical) grid resolution of 100 (40) m was used, but we conducted

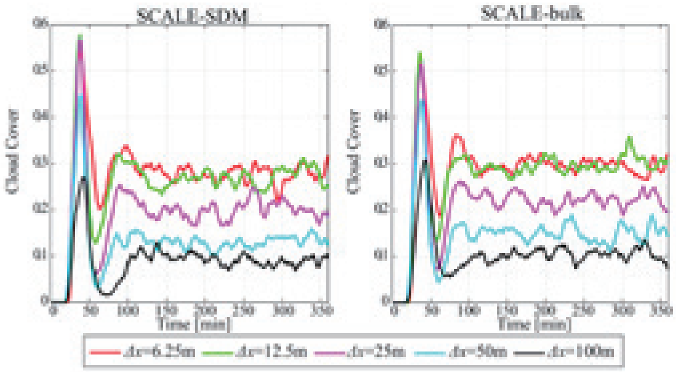

Figure 12.2: The temporal evolution of cloud cover simulated by (left) SCALE-SDM and (right) SCALE-bulk. Cited and from Sato et al. (2018).

the same simulation with changing the horizontal (vertical) grid resolution from 100 (80) m to 6.25 (5) m. We conducted the experiment using both SCALE-SDM and SCALE-bulk, and compared the results of SCALE-SDM and SCALE-bulk.

The results indicate that the cloud cover increased with higher the grid resolution, and the cloud cover with the grid resolution of 6.25 m and 12.5 m were similar. The numerical convergence was achieved with the horizontal (vertical) grid resolution of 12.5 (10) m. This indicates that the grid resolution used in Siebesma et al. (2003) was insufficient to accurately simulate the cloud cover, and the grid resolution of 12.5 m or finer is required. The resuls also indicate that the dependency of the cloud cover on the grid resolution was commonly seen in the results of SCALE-SDM and SCALE-bulk (Fig. 12.2). Since the validity of which has already confirmed through the several previous studies, the validity of the SCALE-SDM was confirmed.
We also investigated the reason of the numerical convergence of the cloud cover with the grid resolution of 12.5 m or finer. Our analyses elucidated that the numerical convergence of the cloud cover was originated from the numerical convergence of the turbulence structure below cloud (sub-cloud layer). The roll convection (LeMone 1973) was clearly seen in the sub-cloud layer simulated with the numerically converged grid resolution (dx = 12.5 m or finer). On the other hand, the roll convection was unclear with the coarse grid resolution.

We indicate that the number of layers near the surface was critical for the accurate simulation of the cloud cover. Based on the discussion in Skamarock (2004), numerical models can hardly simulate the phenomena whose spatial scale is smaller than six to seven times the grid length. With the coarse grid resolution, only a few layers existed near the surface, and the number of layers near the surface was insufficient to reproduce the turbulence structure in sub-cloud layer. In this case, the roll convection was unclear. With the fine grid resolution, in contrast, the number of layers near the surface was sufficient to accurately simulated the turbulence structure, and therefore, the roll convection and the cloud cover was accurately simulated.

These results were submitted as two papers, one was published as Sato et al. (2017), the other was accepted as Sato et al. (2018).

12.3.3 Understanding of Back Building Meso-scale Convective Systems

Quasi-stationary meso-scale convective systems (MCSs) cause heavy rainfall and lead to natural disasters such as floods and landslides. Back-Building MCSs (BBMs), in particular, cause heavy rains during the Baiu season in western Japan (Kato and Goda, 2001, Seko et al., 1999, Yoshizaki et al., 2000). It is essential to understand the maintenance process of BBMs for disaster prevention and mitigation. Moteki et al. (2004) proposed a conceptual environmental condition of the BBMs in the Baiu season. BBMs are observed around the confluence zone of a synoptic scale Baiu front and a water vapor front. However, this conceptual environmental condition

Table 12.1: Numerical simulation model settings

Items	Settings
Micro physics	Six-category one-moment bulk scheme (Tomita 2008)
Radiation	k-distribution scheme (Sekiguchi and Nakajima 2008)
Planetary boundary layer	MYNN level 2.5 scheme (Nakanishi and Niino 2009)
Time integration period	2010/07/10 09 JST ? 2010/07/12 09 JST
Initial and boundary condtions input data	GSM-GPV data (1 x 1 degree with 30 levels, 3 hourly)

is proposed on the ground of a case study. Therefore, confirmations are necessary to consolidate the conceptual environmental condition.

In this study, a heavy rainfall event during June 11?-12, 2010, in western Japan was numerically simulated using SCALE-RM (Nishizawa et al., 2015, Sato et al., 2015). Three computational domains are set by using 1-way online nesting system of CONeP (Yoshida et al. 2017). The outermost domain is 7.5 km grid spacing with 48 layers, the intermediate domain is 2.5 km grid spacing with 60 layers, and the innermost domain is 0.5 km grid spacing with 80 layers. Other model settings are shown in Tab. 12.1.

Fig. 12.3 shows simulated BBM in 2.5 km grid spacing. A linear precipitation area (rainband) is simulated. The rainband consists of multiple smaller precipitation area, and each area is simulated BBMs. These are simulated with a similar linear shape at similar location to these of the observed BBM. Vertical cross sections of a BBM which locates at the western edge of the rainband are shown in Fig. 12.4. Concentrated areas of hydrometeor correspond to convective cells, and the BBM consists of multiple convective cells. The new convective cells are formed at the western side of the BBM, and move eastward in the BBM. This is a typical back-building structure of MCSs.

Fig. 12.5 shows environmental conditions of specific humidity and temperature at 750 m height. The initiation point of the new convective cells in the BBM (indicated by yellow circle) is located over the meso-scale confluence zone of the synoptic-scale cold fronts and the meso-scale moist area at low-level. In the confluence zone, the synoptic-scale cold front can continuously trigger an updraft, and the meso-scale moist area supplies water vapor to the updraft. This suggests that new cells are continuously formed in the meso-scale confluence zone over the synoptic-scale cold front. This environmental condition is similar to the conceptual environmental conditions for BBMs proposed by Moteki et al. (2004). Therefore, this simulated BBM and its environmental condition support the conceptual environmental condition. On the other hand, the meso-scale moist area is a significant characteristic in this case, which is not reported in Moteki et al. (2004). Although Moteki et al. (2004) emphasized a local minimum of temperature in a cold front, such a characteristic is not observed in this case.

12.3.4 Improvement of Numerical Stability with Steep Mountains

In SCALE-RM, a terrain-following coordinate scheme is employed to introduce the effect of topography. So far, simulations in which maximum slope of the topography exceeds the grid aspect ratio of the bottom layer often result in an error due to a numerical instability. We improved numerical stability of the terrain-following coordinate scheme to enable simulations with more realistically steep mountains. The improvements contain the following three points:

- higher accuracy in calculation of the horizontal pressure gradient
- introducing a limiter to reduce numerical instability
- removing high-frequency components in the topography data

With these improvements, we can execute a simulation with 5 times steeper topography than before (Fig. 12.6. The details of the improvements follows. The horizontal pressure gradient is calculated from anomaly pressure from a reference. The reference was calculated with the linear interpolation. We change to use the spline interpolation to calculate the reference. This reduces error in the horizontal pressure gradient and consequent spurious acceleration of the horizontal wind (Fig. 12.7). In the terrain-following coordinate scheme, calculation of metrics due to coordinate transform. In SCALE, momentum is defined at staggered grid point depending on its direction. The metric terms in the momentum equation for each direction are calculated at the individual grid point. This may cause inconsistency between the different directions. We introduce a limiter to the calculation of the metric terms in the vertical momentum equation to reduce the inconsistency from those in

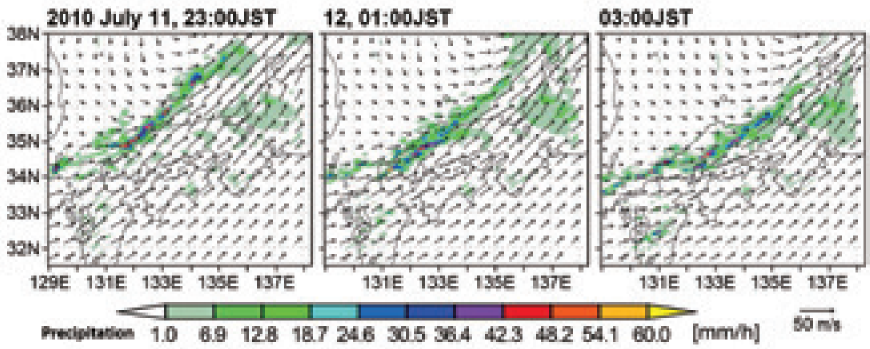

Figure 12.3: Horizontal distribution of the simulated precipitation in Domain 2 (2.5 km grid spacing). Vectors shows horizontal wind at 750 m height.

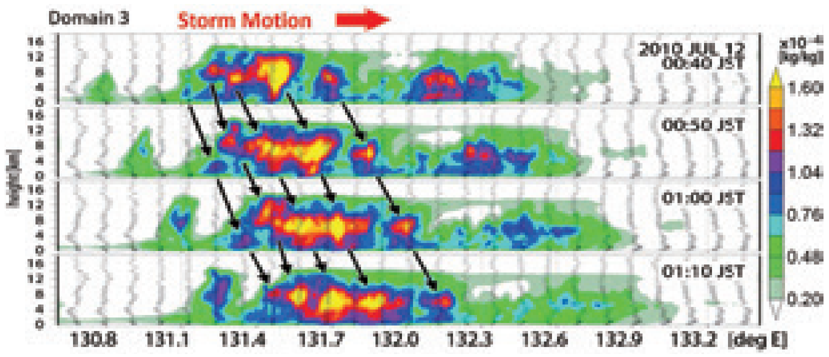

Figure 12.4: Vertical-longitudinal cross section for total mixing ratio of hydrometeors. Hydrometeors are defined as the sum of the mixing ratios of cloud water, rain droplets, cloud ice, snow, and graupel at each level. Each variable is averaged in the latitudinal direction from 33.8 ˚ N to 34.9 ˚ N, which is the rainband width. Black arrows trace the movement of each cell.

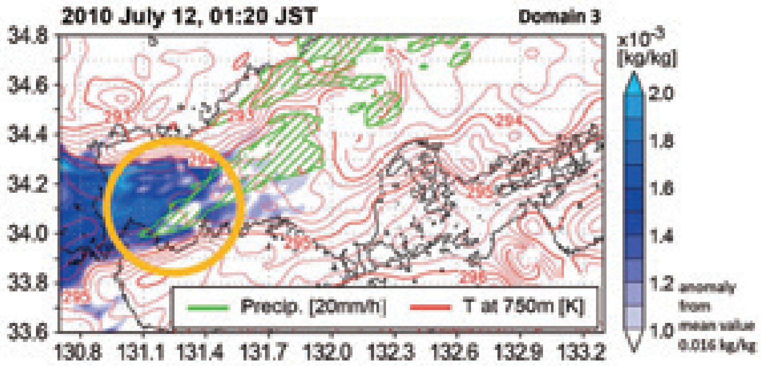

Figure 12.5: Positional relationship between cold fronts and moist air. Areas within green contours have a precipitation rate of 20 mm/h and the red contours represent the temperature at 750 m height. The color scale shows the residual specific humidity (Qv) relative to the average specific humidity of the area (0.016 kg/kg). Shaded areas have higher moisture content than the average specific humidity of the area.

the horizontal momentum equations. This enhances the numerical stability. The topography data is generated from a DEM dataset with the Laplacian filter not to exceed the given slope. Even if the maximum slop of obtained topography does not exceed the given slope, high-frequency components may still remain. The high-frequency components act as an external noise forcing and cause artificial atmospheric variability. Therefore, we use a high-order filter aiming removing high-frequency components together with the Laplacian filter. It results in reducing high-frequency noise in the atmospheric variability.

12.4 Schedule and Future Plan

We continue to sophisticate the basic library SCALE. At the present, the main processes, both of dynamics and physics, have already been developed comprehensively. We will pursue higher usability for the outside users. We keep elaborating the advanced climate model based on schemes in principle and indicate a direction to future climate model. At the same time, not only to make computational and physical performance of simulation code higher but also to provide useful analysis methods of simulation results is a main issue in the next phase. This is of great importance for acceleration of scientific output and social outcome.

The research for contribution of prevention from future heavy rainfall event and thermal environment in urban is also continuous in the second term COE project, which starts from the FY2017. There are still many uncertainties for the future prediction due to model bias. One of main causes is bias in regional model itself. Since SCALE has already implemented many components and schemes, construction of different models is easy. This advantage would be able to evaluate biases caused from regional models. This is done by the way of multi-model ensembles with data assimilation science.

12.5 Publications

12.5.1 Articles

[1] Sato, Y., D. Goto, T. Michibata, K. Suzuki, T. Takemura, H. Tomita, and T. Nakajima (2018): Aerosol effects on cloud water amounts were successfully simulated by a global cloud-system resolving model, *Nature Communications*, 9, 985, Doi: 10.1038/s41467-018-03379-6

[2] Nishizawa, S., S. A. Adachi, Y. Kajikawa, T. Yamaura, K. Ando, R. Yoshida, H. Yashiro, and H. Tomita (2018): Decomposition of the large-scale atmospheric state driving downscaling: a perspective on dynamical downscaling for regional climate study, *Progress in Earth and Planetary Science*, 5, 2, Doi: 10.1186/s40645-017-0159-0 [2017]

[3] Adachi, S. A., S. Nishizawa, R. Yoshida, T. Yamaura, K. Ando, H. Yashiro, Y. Kajikawa, and H. Tomita

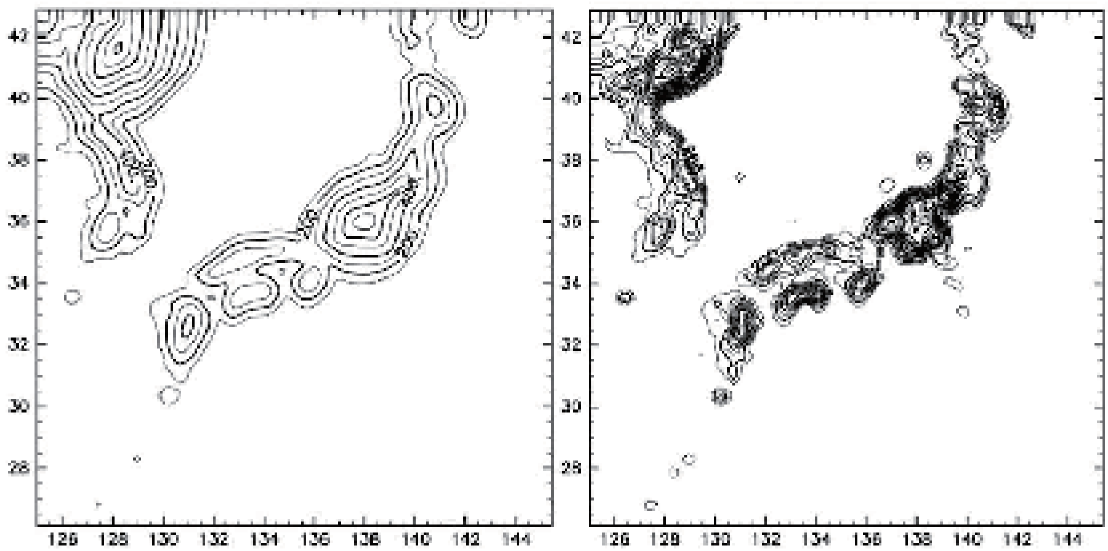

Figure 12.6: The topography in 20-km resolution simulation (left) before and (right) after the improvoment. The contour intervals are 100 m.

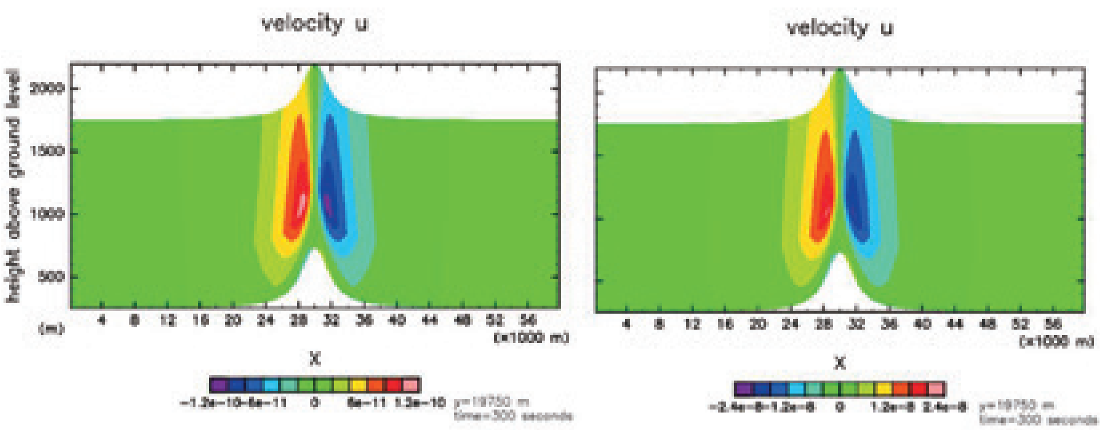

Figure 12.7: The horizontal and vertical corros section of thehorizontal wind field at t=300 s acceralated by the suprious horiaontal pressure gradient force from the steady state in the hydrostatic balance. The result of simulations with the reference generated using (left) the spline interpolation and (right) linera interpolation. Only a part of the calculation domain is drawn in vertically. The tone interval is (left) 2.0×1^{-11} and (right) 4.0×10^{-9} m/s.

(2017): Contributions of changes in climatology and perturbation and the resulting nonlinearity to regional climate change, *Nature Communications*, 8, 2224, Doi: 10.1038/s41467-017-02360-z

[4] Miyakawa, T., H. Yashiro, T. Suzuki, H. Tatebe, and M. Satoh (2017): A Madden-Julian Oscillation event remotely accelerates ocean upwelling to abruptly terminate the 1997/1998 super El Nio, *Geophysical Research Letters*, 44, 18, 94899495, Doi: 10.1002/2017GL074683

[5] Satoh, M., H. Tomita, H. Yashiro, Y. Kajikawa, Y. Miyamoto, T. Yamaura, T. Miyakawa, M. Nakano, C. Kodama, A. T. Noda, T. Nasuno, Y. Yamada, and Y. Fukutomi (2017): Outcomes and challenges of global high-resolution non-hydrostatic atmospheric simulations using the K computer, *Progress in Earth and Planetary Science*, 4, 13, Doi: 10.1186/s40645-017-0127-8

[6] Goto, D., Y. Sato, H. Yashiro, K. Suzuki, and T. Nakajima (2017): Validation of high-resolution aerosol optical thickness simulated by a global non-hydrostatic model against remote sensing measurements, *AIP Conference Proceedings*, 1810, 1, Doi: 10.1063/1.4975557

[7] Trieu, T. T. N., D. Goto, H. Yashiro, R. Murata, K. Sudo, H. Tomita, M. Satoh, and T. Nakajima (2017): Evaluation of summertime surface ozone in Kanto area of Japan using a semi-regional model and observation, *Atmospheric Environment*, 153, 163-181, Doi: 10.1016/j.atmosenv.2017.01.030

[8] Sato, Y., S. Shima, and H. Tomita (2017): A grid refinement study of trade wind cumuli simulated by a Lagrangian cloud microphysical model: the super-droplet method, *Atmospheric Science Letters*, 18, 9, 359-365, Doi: 10.1002/asl.764

[9] Tokutake, H., H. Hiraguri, and S. Nishizawa (2017): Exploration of Wind Structure on Mars using an Airplane and Flight Feasibility Study, *Transactions of the Japan socienty for aeronautical and space sciences*, 60, 4, 212-220, Doi: 10.2322/tjsass.60.212

[10] Yoshida, R., S. Nishizawa, H. Yashiro, S. A. Adachi, Y. Sato, T. Yamaura, and H. Tomita (2017): CONeP: A cost-effective online nesting procedure for regional atmospheric models, *Parallel Computing*, 65, 21-31, Doi: 10.1016/j.parco.2017.04.004

[11] Takane, Y., Y. Kikegawa, M. Hara, T. Ihara, Y. Ohashi, S. A. Adachi, H. Kondo, K. Yamaguchi, and N. Kaneyasu (2017): A climatological validation of urban air temperature and electricity demand simulated by a regional climate model coupled with an urban canopy model and a building energy model in an Asian megacity, *International Journal of Climatology*, 37, S1, 10351052, Doi: 10.1002/joc.5056

[12] Adachi, S. A. (2017): Sophisticated model infrastructure for urban climate study. *Annual issue of Heat island institute international*, 12, 23-27 (in Japanese).

12.5.2 Presentations and Posters

[13] Sato, Y., D. Goto, T. Michibata, K. Suzuki, T. Takemura, H. Tomita, and T. Nakajima: Estimation of the second indirect effect by using a " Global Cloud System Resolving Model, *Aerosols, Clouds, Precipitation and Climate(ACPC) 639. WE-Heraeus-Seminar*, Bad Honnef, Germany, Apr. 3-4, 2017. (Invited)

[14] Sato, Y., H. Miura, H. Yashiro, D. Goto, T. Takemura, T. Michibata, K. Suzuki, and T. Nakajima: Suggestions from a global cloud system resolving simulation to global climate model -Transportation of black carbon aerosol to the Arctic-, *JpGU-AGU Joint Meeting 2017*, Chiba, Japan, May 22, 2017. (Invited)

[15] Yamaura, T., and H. Tomita: Optimum numerical calculation with mixed precision floating point number for a regional shallow-water model, *JpGU-AGU Joint Meeting 2017*, Chiba, Japan, May 20, 2017.

[16] Yoshida, R.: CONeP: A Cost-Effective Online Nesting Procedure for Regional Climate Model, *7th JLESC Workshop*, Urbana, USA, Jul. 17, 2017.

[17] Yamaura, T., and H. Tomita: Optimum Numerical Calculation with Mixed Precision Floating Point Number for a Regional Shallow-Water Model, *7th JLESC Workshop*, Urbana, USA, Jul. 17, 2017.

[18] Sueki, K., and H. Niino: Entrainment rate of typhoon-associated supercells estimated by a large eddy simulation, *9th European Conference on Severe Storms*, Pula, Croatia, Sep. 19, 2017.

[19] Sueki, K., T. Yamaura, H. Yashiro, and H. Tomita: Numerical Convergence for Statistical Characteristics of Deep Moist Convection, *Comparison of tornadic supercells and their environmental condition in Japan and Italy*, Lecce, Italy, Sep. 27, 2017.

[20] Adachi, S. A., S. Nishizawa, R. Yoshida, T. Yamaura, K. Ando, H. Yashiro, Y. Kajikawa, and H. Tomita: Downscaling Procedure for Evaluating Future Regional Climate Change, *International Workshop on Climate Downscaling Studies*, Tsukuba, Japan, Oct. 2, 2017.

[21] Kajikawa, Y., and T. Yamaura: Decadal change in the boreal summer intraseasonal oscillation, *Sixth International Workshop on Monsoons*, Singapore, Nov. 14, 2017.

[22] Kajikawa, Y., T. Yamaura, H. Tomita, and M. Satoh: Impact of Tropical Disturbance on the Indian Summer Monsoon Onset simulated by a Global Cloud-System-Resolving Model., *Sixth International Workshop on Monsoons*, Singapore, Nov. 16, 2017.

[23] Kajikawa, Y., and T. Yamaura: Decadal change in the boreal summer intraseasonal oscillation, *2017 AGU Fall Meeting*, New Orleans, USA, Dec. 12, 2017.

[24] Tomita, H., S. A. Adachi, S. Nishizawa, R. Yoshida, T. Yamaura, K. Ando, H. Yashiro, and Y. Kajikawa: How does the regional climate assessment make more advance?, *The 8th AICS INTERNATIONAL SYMPOSIUM*, Kobe, Japan, Feb. 8, 2018.

12.5.3 Software

[28] SCALE version 5.1.0–5.2.5, URL:https://scale.aics.riken.jp/