Simulations of Adaptation-Oriented Strategy for Climate Variability

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A coupled atmosphere-ocean-land model MSSG has been developed in the Earth Simulator Center, which is designed to model multi-scale interactions among the atmosphere, the ocean and the coupled system. In this project of this fiscal year, we focused on introducing computational optimization architecture to the MSSG to be run with maximizing the computational power of the Earth Simulator 2. As the results, the computational performance of MSSG attained about 20% of the theoretical peak of ES2. Characteristics of cloud micro-physics with turbulence effects and heat transfer in urban area are presented and non-hydrostatic physical performance for the oceanic component of MSSG are validated in this report.

Keywords: Coupled atmosphere-ocean model, multi-scale, multi-physics, high performance computing, the Earth Simulator

1. Introduction

Multi-Scale Simulator for the Geoenvironment (MSSG), which is a coupled atmosphere-ocean-land global circulation model, has been developed for the purposed of promoting multi-scale multi-physics simulations for predicting weather or climate variabilities. Furthermore, MSSG is optimized to be run on the Earth Simulator with high computational performance and it is designed to be flexibility for different space and time scales. MSSG can simulate various scales phenomena with several different optional versions such as global/regional MSSG-A, global/regional MSSG-O, or global/regional MSSG, where MSSG-A and MSSG-O are atmospheric and oceanic components of MSSG, respectively.

In the development of MSSG of this fiscal year, we focus on the following issues,

- Improvement of MSSG computational performance on the Earth Simulator 2 (ES2) to be fit the discritization schemes for ultra high resolution simulation to the architecture of ES2,
- Improvement of physical performance of atmospheric boundary layer and cloud micro physics with turbulent scale effects,
  and
- Improvement of forecasting schemes and validate results of multi-scale simulations.

This report summarizes results of our project in FY2009.

2. MSSG model configuration

An atmospheric component of MSSG, which we call it MSSG-A, is a non-hydrostatic global/regional atmosphere circulation model. MSSG-A is compromised of fully compressive flux form of Satomura (2003)[1], Smagorinsky-Lilly type parameterizations by Lilly (1962)[2] and Smagorinsky (1965)[3] for sub-grid scale mixing, surface fluxes by Zhang

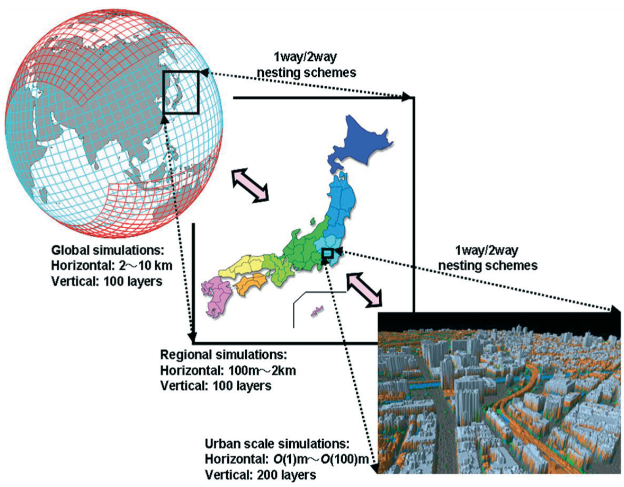

Fig. 1 Scales of MSSG for global/regional models with nesting schemes and resolution.

(1982)[4] and Blackadar (1979)[21], cloud microphysics with mixed phases by Reisner (1998)[5] and cumulus convective processes by Kain (1993)[6] and Fritsch (1980)[7]. Cloud-radiation scheme for long wave and shortwave interactions with both explicit cloud and clear-air are adopted which is based on the scheme in MM5. Over land, the ground temperature and ground moisture are computed by using a bucket model. As upper boundary condition, Rayleigh friction layer is set.

In the ocean component, which we call it MSSG-O, incompressive and hydrostatic /nonhydrostatic equations with the Boussinesq approximation are introduced based on describing in Marshall (1997a) and Marshall (1997b). Smagorinsky type scheme by Lilly (1962) and Smagorinsky (1965) is used for the sub-grid scale mixing. Algebraic Multi-Grid (AMG) method in Stuben (1999) is used in order to solve a Poisson equation in MSSG-O. In MSSG, we used the AMG library based on aggregation-type AMG in Davies (1976), which has been developed by Fuji Research Institute Corporation.

In both the atmospheric and ocean components, Yin-Yang grid system presented in Kageyama (2004) and Arakawa C grid is used. The atmospheric component utilizes the terrain following vertical coordinate with Lorenz type variables distribution in Gal-Chen (1975). The ocean component uses the z-coordinate system for the vertical direction. In discritization of time, the 2nd, 3rd and 4th Runge-Kutta schemes and leap-flog schemes with Robert-Asselin time filter are available. The 3rd Runge-Kutta scheme presented in Wicker (2002) is adopted for the atmosphere component. In the ocean component, leap-flog schemes with Robert-Asselin time filter is used for the ocean component. For momentum and tracer advection computations, several discritization schemes introduced in Peng (2004) are available. In this study, the 5th order upwind scheme is used for the atmosphere and central difference is utilized in the ocean component. The vertical speed of sound in the atmosphere is dominant comparing with horizontal speed, because vertical discritization is tend to be finer than horizontal discritization. From those reasons, horizontally explicit vertical implicit (HEVI) scheme in Durran (1991)[15] is adopted in MSSG-A.

Conservation scheme was discussed in Peng (2006)[16] and no side effects of over lapped grid system such as Yin-Yang grid were presented due to validations results of various benchmark experiments in Takahashi (2004a,b)[17] [18] and Takahashi (2005)[19].

3. High performance computing in MSSG

ES2 has different architecture with points of memory latency, memory band width and penalty of bank complicit. Considered those characteristics of the architecture of ES2, MSSG is required to be improved computational performance by optimizing on the ES2.

Table 1 shows computational performance statistics of main modules of MSSG on ES2. 18GFLOPS per one CPU of ES2 has attained and is estimated by about 20% of the theoretical peak of ES2. In near future, especially, we are planning to optimize the performance of cloud micro physics processes using Assignable Data Buffer (ADB) architecture of ES2.

4. Physical performance improvements in MSSG

In this report, present several topics results on key issues in order to execute weather/climate seamless simulations/forecasting with MSSG.

4.1 Impacts of turbulence in clouds and validation results of cloud micro-physics in MSSG

There is a growing consensus that the collision growth rate of cloud droplets can be increased by cloud turbulence. We have investigated the turbulence impacts in turbulent convective clouds using the hybrid-bin method with our turbulent collision model in MSSG (MSSG-Bin model). In MSSG-Bin model, two kinds of convective clouds have been simulated; free (heat) convective clouds and forced (orographic) convective clouds. Preliminary results show that the turbulent collisions cause

Table 1 MSSG current status of computational performance on ES2.

EXCLUSIVE TIME [sec]	%	MFLOPS	V.OP RATIO	AVER. V.LEN	I-CACHE MISS	O-CACHE MISS	BANK CONFLICT		PROC. NAME
							CPU PORT	NETWORK	
19777.543	99.7	18592.9	99.54	236.1	256.595	772.348	262.653	6554.572	(A1) main loop
4479.512	22.6	22277.2	99.51	239.2	90.681	198.871	74.955	1697.248	(A2) N-S HEVI
2632.633	13.3	24765.7	99.50	238.7	26.207	71.759	52.430	821.099	(A2) N-S eq.(large)
4649.974	23.4	34140.6	99.80	238.7	16.851	60.720	20.966	566.511	(A2) tracer eq.
3996.377	20.1	7798.0	99.20	213.7	87.334	272.048	57.238	1878.027	(A2) physics
285.278	1.4	1471.8	99.36	230.4	8.858	15.927	10.138	198.995	(A2) boundary
596.373	3.0	584.6	99.40	224.2	5.130	8.725	13.396	445.971	(A2) boundary (side)
235.785	1.2	6361.6	99.11	239.6	0.385	1.991	5.099	93.416	(A2) z2ps
1073.107	5.4	305.1	81.38	172.9	1.550	3.569	1.977	218.644	(A2) output
130.365	0.7	23363.6	99.42	238.4	0.399	1.103	22.172	65.026	(A2) RKG
504.566	2.5	646.3	98.62	239.8	0.295	0.326	0.012	352.960	(A2) diagno
448.958	2.3	13480.8	99.24	227.6	16.439	33.263	4.128	192.399	(A2) subfield
734.071	3.7	1083.8	79.70	236.7	0.406	99.532	0.134	23.240	(A2) recalc dt
0.317	0.0	2.1	90.13	236.1	0.037	0.091	0.001	0.013	(A2) restart

significant changes on the droplet size spectra.

Fig. 2 shows surface precipitation distribution in time with MSSG-Bin model. It shows the discrepancy of the distribution and turbulent collision model reveals the impact with increasing of the volume of precipitation by the effect of turbulent droplet collisions in cloud development.

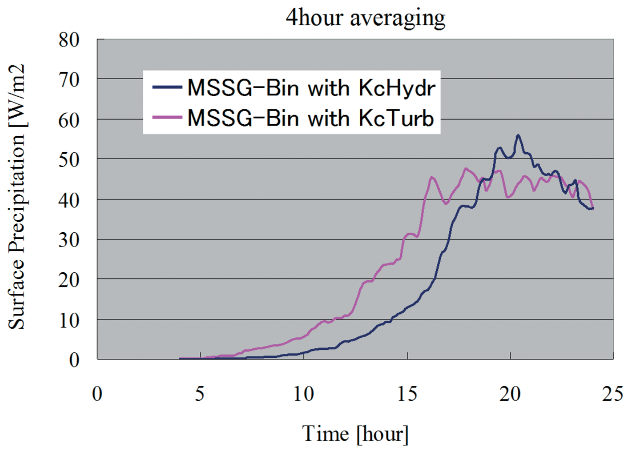

Fig. 2 Impacts of surface precipitation distribution during development of cloud.

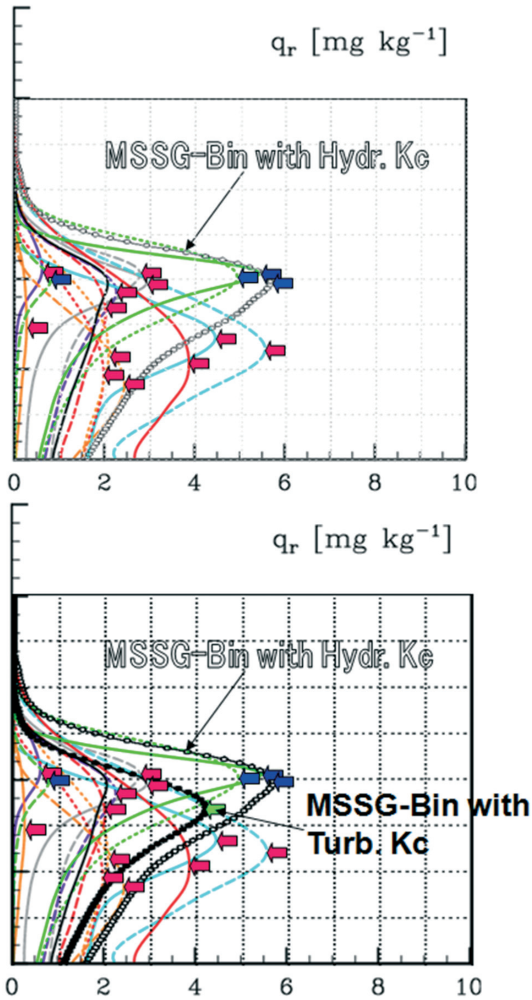

Fig. 3 Turbulent collisions impacts of precipitation throughout RICO mode comparison. Above: without the effects of turbulence. Below: with effects of turbulence collision.

As the results of experiments in RICO (shallow Cu) case, turbulent collisions significantly weaken the updraft, consequently decrease turbulence intensity due to quick removal of water, make be lower the cloud height and shorten the rain initiation time. Fig. 3 presents a part of the results of experiments.

4.2 Advanced scheme to simulate weather/climate in urban area

High performance solver for fully compressible fluid is applied to atmospheric flow field in MSSG to resolve and understand mechanism of heat transfer in urban canyon.

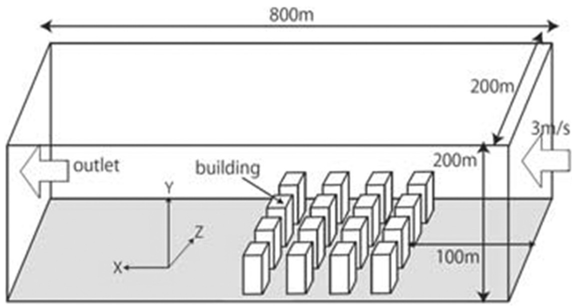

Fig. 4 Schematic view of canyon case.

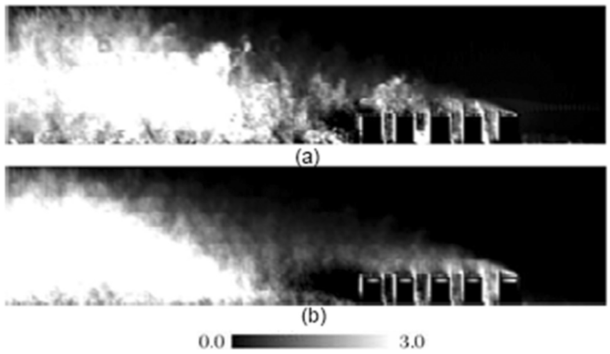

Fig. 5 Time averaged vertical heat flux distributions, (a) with Boussinesq approximation (BS), and (b)with fully compressive formulation (CP).

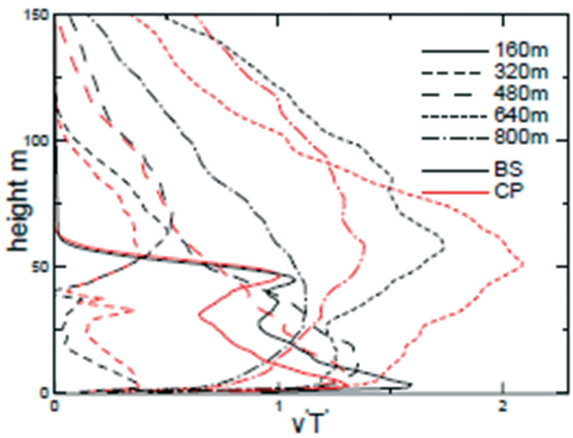

Fig. 6 Vertical heat flux profiles in four stream wise points.

Implementation of efficiency and applicability of the fully compressible formulation is investigated in the atmospheric boundary layer with simplified buildings (Fig. 4). Simulations with conventional scheme using Boussinesq approximation are also performed under the same condition to validate differences and shortcomings of the incompressible solver. As the results from the experiments, vertical heat flux is tend to increase at the vicinity of the ground, which is induced by fluid expansion. Incompressible solver overestimates turbulence intensity while fully compressible solver can capture the effect of turbulence suppression due to the increase of kinematic viscosity as caused from heat transfer as shown in Fig. 5 and Fig. 6. This suggests that fully compressible formulation is required to represent the mechanism of heat transfer in urban area.

4.3 Validation of physical performance of MSSG-O

MSSG-O model which is an oceanic component of MSSG is developed to simulate oceanic flows on various spacial and time scales with numerical stability and reasonable precision. For this fiscal year, various idealized model validation experiments were pursued to examine the capability of the model. One of validation plan was focusing on "Non-hydrostatic term" and the validation results are introduced in this report.

Non-hydrostatic capability of MSSG-O is tested by simulating dense overflows around Antarctic. To test the feature in presence of wind-driven circulation, we examined the interaction of overflow and the wind-driven coastal current. MSSG-O simulations results suggest that coastal currents can modify the pressure gradient of the overflow and change the strength of water mass exchange between the open ocean and the marginal sea. Past non-hydrostatic model studies have focused on simulating single oceanic process. Our model simulation is new that it now includes interaction of two processes (wind-driven circulation and overflow).

Figs. 7 and 8 are validation results of MSSG-O, which is set up with non-hydrostatic term. Fig. 6 shows development of disturbances in MSSG-O which are comparable to previous results[22]. Fig. 8 represents bottom gravity current and K-H instabilities[23][24] above the bottom in the ocean.

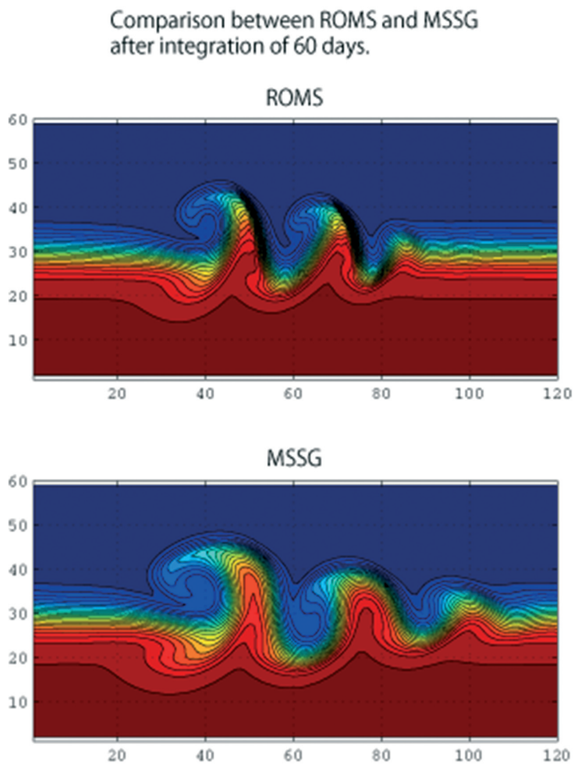

Fig. 7 Development of disturbance of sea surface temperature.

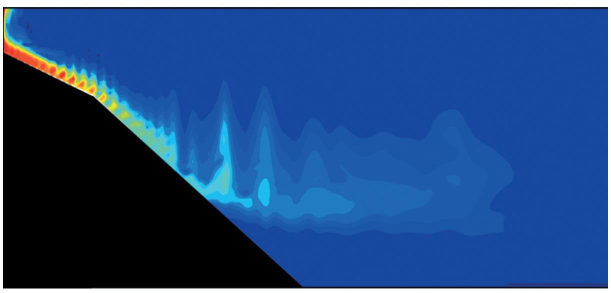

Fig. 8 Development of Dynamics of turbulent bottom gravity currents in MSSG-O.

5. Near future work

In this report, we showed computational performance of MSSG and advances of model development. At the same time, we now begin forecasting of weather/climate in urban area under the condition of climate variability. It will be further clear that interaction process between weather and climate as previous studies pointed out. Detail analysis is required for each scale phenomena in order to understand those mechanics. In addition, implementation of dynamic AMR (adaptive mesh refinement) schemes on MSSG has been almost completed. Multi-scale and multi-physics simulations with MSSG will be begun in order to predict climate variability in near future.

References

[1] Satomura, T. and Akiba, S., 2003: Development of high- precision nonhydrostatic atmospheric model (1): Governing equations, *Annuals of Disas. Prev. Res. Inst.*, Kyoto Univ., 46B, 331-336.

[2] Lilly, D. K., 1962: On the numerical simulation of buoyant convection, *Tellus, 14*, 148-172.

[3] Smagorinsky, J. , Manabe, S. and Holloway, J. L. Jr., 1965: Numerical results from a nine level general circulation model of the atmosphere, *Monthly Weather Review, 93*, 727-768.

[4] Zhang, D. and Anthes, R. A., 1982: A High-Resolution Model of the Planetary Boundary Layer - Sensitivity Tests and Comparisons with SESAME-79 Data, *Journal of Applied Meteorology, 21*, 1594-1609.

[5] Reisner, J., Ramussen R. J., and Bruintjes, R. T., 1998: Explicit forecasting of supercoolez liquid water in winter

storms using the MM5 mesoscale model, Quart. J. Roy. Meteor. Soc. 124, 1071-1107.

[6] Kain, J. S. and Fritsch, J. M., 1993: Convective parameterization for mesoscale models: The Kain-Fritsch Scheme, *The Representation of Cumulus Convection in Numerical Models of the Atmosphre, Meteor. Monogr., 46*, Amer. Meteor. Soc., 165-170.

[7] Fritsch, J. M., and Chappell, C. F., 1980: Numerical prediction of convectively driven mesoscale pressure systems, Part I: Convective parameterization, *J. Atmos. Sci., 37*, 1722-1733.

[8] Marshall, J., Hill, C., Perelman, L. and Adcroft, A., 1997a: Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling, *Journal of Geophysical Research, 102*, 5733-5752.

[9] Marshall, J., Adcroft, A., Hill, C., Perelman, L. and Heisey, C., 1997b: A finite-volume, incompressible Navier-Stokes model for studies of the ocean on parallel computers, *Journal of Geophysical Research, 102*, 5753-5766.

[10] Stuben, K., 1999: A Review of Algebraic Multigrid, *GMD Report 96*.

[11] Davies, H. C., 1976: A lateral boundary formulation for multi-level prediction models, *Quart. J. R. Met. Soc., 102*, 405-418.

[12] Gal-Chen, T. and Somerville, R. C. J., 1975: On the use of a coordinate transformation for the solution of the Navier-Stokes equations, *Journal of Computational Physics, 17*, 209-228.

[13] Wicker, L. J. and Skamarock, W. C., 2002: Time-splitting methods for elastic models using forward time schemes, *Monthly Weather Review, 130*, 2088-2097.

[14] Peng, X., Xiao, F., Takahashi, K. and Yabe T., 2004: CIP transport in meteorological models, *JSME international Journal (Series B), 47(4)*, 725-734.

[15] Durran, D., 1991: Numerical methods for wave equations in Geophysical Flud Dynamics, Springer.

[16] Peng, X., Feng Xiao, F. and Takahashi, K., Conservation constraint for quasi-uniform overset grid on sphere, *Quarterly Journal Royal Meteorology Society.* (2006), 132, pp. 979-996.

[17] Takahashi, K. et al., 2004a: Proc. 7th International Conference on High Performance Computing and Grid in Asia Pacific Region, 487-495.

[18] Takahashi, K., et al., 2004b. "Non-hydrostatic Atmospheric GCM Development and its computational performance", http://www.ecmwf.int/newsevents/meetings/workshops/2004/ high_performance_computing-11th /presentations.html

[19] Takahashi, K, et al. 2005: Non-hydrostatic atmospheric GCM development and its computational performance, *Use of High Performance computing in meteorology, Walter Zwieflhofer and George Mozdzynski Eds., World Scientific*, 50-62.

[20] Kageyama, A. and Sato, T., 2004: The Yin-Yang Grid: An Overset Grid in Spherical Geometry, *Geochem.Geophys. Geosyst., 5*, Q09005, doi:10.1029/2004GC000734.

[21] Blackadar, A. K., 1979: High resolution models of the planetary boundary layer, *Advances in Environmental Science and Engineering, 1*, Pfafflin and Ziegler, Eds., Gordon and Breach Publ. Group, Newark, 50-85.

[22] Kelmann and Kase (1987) "Numerical Modeling of Meander and Eddy Formation in the Azores Current Frontal Zone", *JPO*.

[23] Jones, H., and J. Marshall, 1993: Convection with Rotation in a Neutral Ocean: A Study of Open-Ocean Deep Convection. J. Phys. Oceanogr., 23, 1009-1039.

[24] Özgökmen, T.M., and E.P. Chassignet, 2002: Dynamics of two-dimensional turbulent bottom gravity currents. *J. Phys. Oceanogr.*, 32/5, 1460-1478.

気候変動に適応可能な環境探索のためのマルチスケールシミュレーション

プロジェクト責任者

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A coupled atmosphere-ocean-land model has been developed in the Earth Simulator Center, which is designed to model multi-scale interactions among the atmosphere, the ocean and the coupled system. In this project of this fiscal year, we focused on introducing computational optimization architecture to the MSSG to be run with maximizing the computational power of the Earth Simulator 2. At the results, the computational performance of MSSG attained about 30% of the theoretical peak of ES2. Cloud micro-physics with turbulence effects, characteristics of heat transfer in urban area and non-hydrostatic physical performance in the oceanic component of MSSG is validated and present those results in this report.

キーワード: Coupled atmosphere-ocean model, multi-scale, multi-physics, high performance computing, the Earth Simulator

本年度は、サブテーマ（1）～（4）は、ES2 上における計算性能最適化であり、ベクトル長、通信に関わる並列化性能の問題点をコンポーネントごとに詳細な計算性能解析を行い、MSSG の大気、海洋、および結合バージョンそれぞれについての計算性能最適化を行った。計算性能最適化は、理論ピーク性能値に対して約 20% の計算性能を達成し（平成 21 年 11 月現在）、MSSG の従来の物理的性能に影響を与えないことを確認した。

加えて、MSSG の物理的性能向上のためのモデル開発、および検証結果、研究成果の一部を紹介する。

- MSSG-A における雲物理計算手法の高度化

  都市エアロゾルが対流雲の発達への影響評価を行い、乱流衝突効果が GCCN もともに有意なインパクトを与えることを明らかにした。

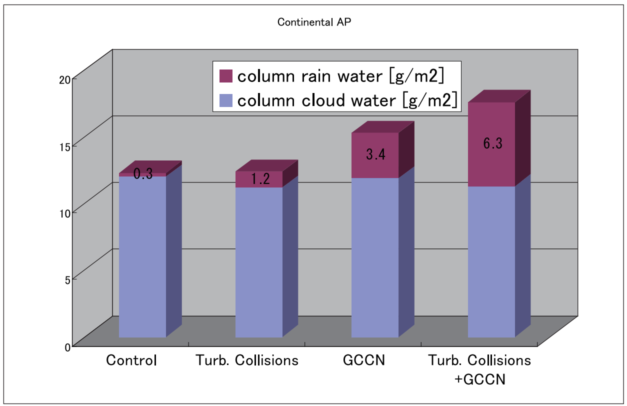

Fig. 1 都市エアロゾルが対流雲の発達への影響。

- 大気境界層内に密度成層が存在する場合の都市スケールの水平・鉛直混合過程の解明
  熱フラックスによりシアー支配から対流支配へと遷移する過程において特徴的渦構造があることを明らかにした。

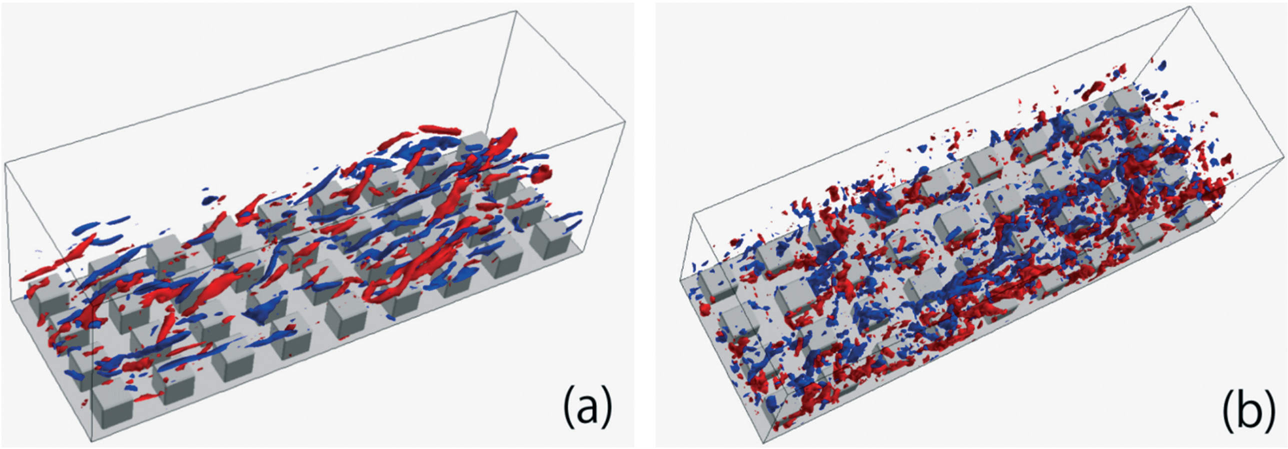

Fig. 2 遮蔽物の配置と渦構造の相違。(a) は中立条件から底面に境界条件として熱フラックスを与えない場合、(b) 底面に境界条件として熱フラックスを与えた場合。

- MSSG-O における非定常擾乱発達過程の検証
  60 日後の海面温度の変化の様子を示す。波の発達など擾乱の発達していく様子よく再現されており、他のモデルとの比較においても何ら遜色がないことを示した。

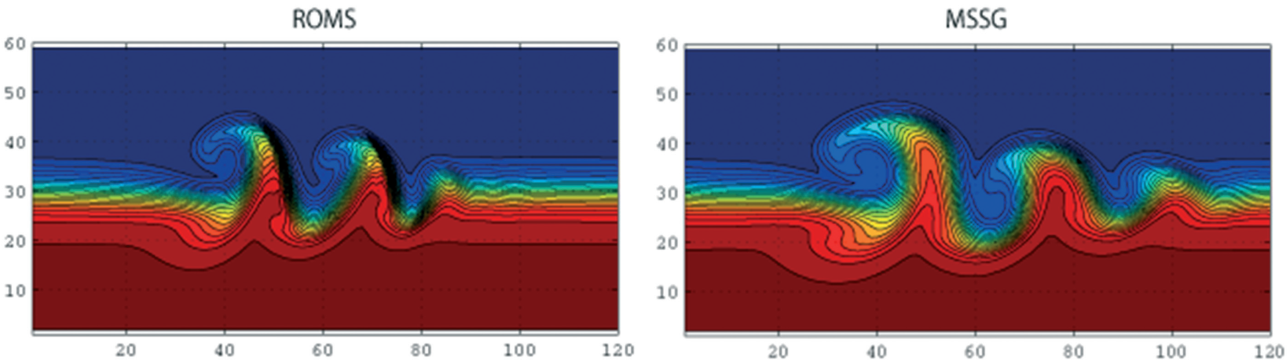

Fig. 3 ROMS と MSSG の 60 日後の海面温度分布。擾乱の発達過程がいずれにおいても再現されている。