Multi-Scale Simulations for Adaptation to Global Warming and Mitigation of Urban Heat Islands

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We have investigated the role of atmosphere-ocean coupled process by using the MSSG in the coupled mode. The coupled simulation has shown that a strong convection was initiated soon after the simulation start and propagated eastward at the similar speed with observed. We have also conducted downscaling simulations using the pseudo-global warming technology to provide high-resolution data under the warmed condition. It has been confirmed that the degree of temperature increase is very much different for different places, which cannot be resolved by O(10 km-100 km) simulations. We have also worked for coupling the MSSG and GETFLOWS to construct an integrated simulation for the general water cycle in atmosphere, ocean and land (under ground). Preliminary results have confirmed that the coupling has a significant impact on the surface latent heat flux. MSSG ocean simulations have clarified the mechanism of the long-term descending trend of water temperature observed in the Tokyo Bay. We have performed a high-resolution simulation with 1m mesh for the Marunouchi area, near the Tokyo station, and clarified the role of the courtyard trees on urban heat environment. In order to investigate the role of microscale turbulence on cloud development, we have developed the Lagrangian cloud simulator, which adopts the Euler-Lagrangian framework and can provide reference data for cloud microphysical models by tracking the growth of particles individually. Comparisons between the results for stagnant and turbulent flows confirm that in-cloud turbulence enhances collisional growth. In conclusion, we have performed large-size simulations on a wide range of phenomena in ocean and atmospheric sciences in order to clarify their mechanism for reliable predictions.

Keywords: atmosphere-ocean coupled model, MSSG, multi-scale, global warming, urban heat island

1. Atmosphere-ocean coupled simulation of an MJO event

Current prediction skill for the Madden-Julian Oscillation (MJO; Madden and Julian, 1972 [1]) is still limited even though the supercomputer system has been advanced and the model resolution has been improved. The inability of global models to reproduce the MJO degrades their seasonal to interannual prediction and lessens our confidence in their ability to project future climate. This study investigates the role of atmosphere-ocean coupled process by using the MSSG in the coupled mode (Sasaki et al., 2015 [2]). The horizontal resolution was set to 20 km. The NCEP_fnl data was used for the initial atmosphere condition and the data from the four-dimensional variational (4D-VAR) coupled data assimilation (CDA; Toyoda et al., 2009 [3]) system for the ocean. The simulation targeted the time period starting from 15 December 2006 and ending at 10 January 2007.

Figure 1 shows the outward long-wave radiation. A strong convection was initiated soon after the simulation start and propagated eastward at the similar speed with observed. Fig. 2 shows the time evolutions of statistics near the atmosphere-ocean interface. Fig. 2(a) and (b) clearly shows that the inward short-wave radiation and its variability were weakened by the cloud system, which brought the surface precipitation on 20–22 December (Fig. 2(c)) associated with the MJO. The cloud system also weakened the diurnal variability of the water temperature in the ocean upper layer (Fig. 2(f)). The westerly wind burst, after the system passed, lead to a large latent heat flux (Fig. 2(d), resulting in a weak diurnal variability of water temperature in the ocean upper layer (Fig. 2(e)). Then the enhanced mixing in the ocean upper layer caused a drop in the water temperature, which seemed to trigger the destruction of salinity stable layer (Fig. 2(f)). These results have shown that the atmosphere-ocean coupled MSSG simulation successfully reproduced the couple processes.

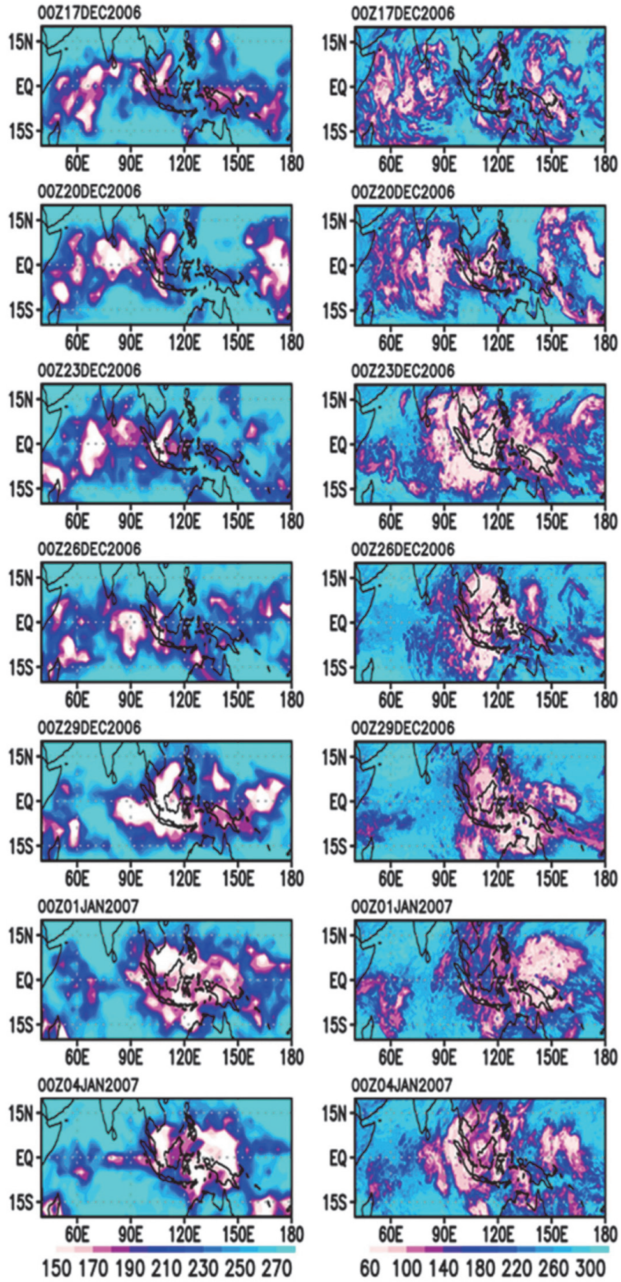

Fig. 1 Observed outward long-wave radiation (left column) and simulated one (right column) in (W/m^2) from 17 December 2006 at every 3 days.

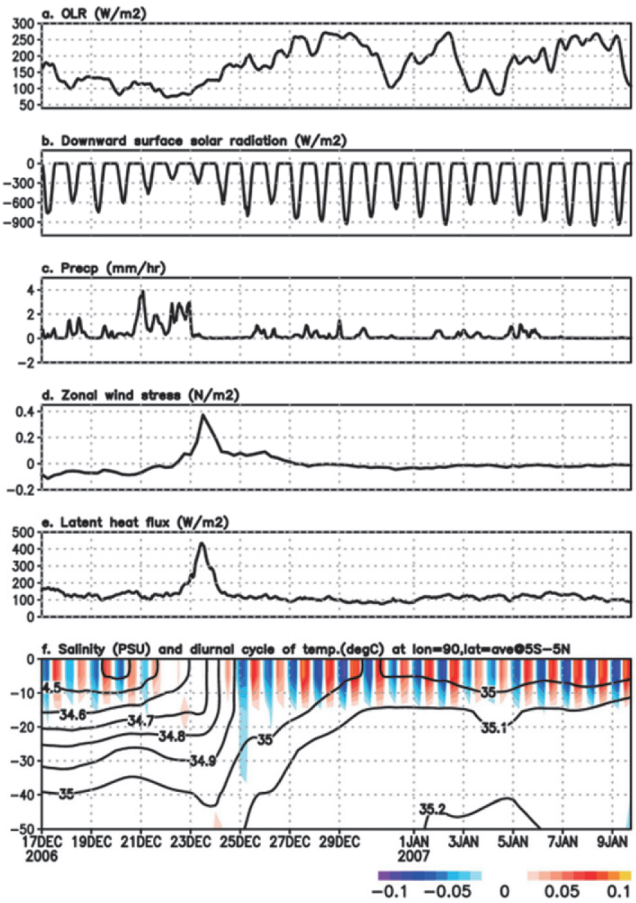

Fig. 2 Time evolutions of (a) outward long-wave radiation, (b) inward short-wave radiation, (c) surface precipitation, (d) longitudinal surface stress, (e) latent heat surface flux and (f) salinity (contour) and diurnal variability of water temperature (shade) averaged over 5°S-5°N at 90°E in the Indian ocean.

2. Pseudo-global warming simulation for Kanagawa prefecture

The IPCC report provides useful data regarding the impact of the global warming. The provided data with resolution of O(10 km-100 km) can contribute to the national-level policy making for adaptation, but cannot really to the city-level one, for which much higher resolution data is needed. This study, therefore, has conducted downscaling simulations using the pseudo-global warming technology to provide high-resolution data under the warmed condition. Figure 3 shows the computational domain for the downscale simulation and the difference in 2 m temperatures between the future and current climate in Kanagawa prefecture. The horizontal resolution was 1 km in the downscale simulation and the future climate corresponded to the warmed climate in 30 years later. The figure shows that the degree of temperature increase is very much different for different places, which cannot be resolved by O(10 km-100 km) simulations ([4]).

3. An integrated simulation for investigations of general water cycle in atmosphere, ocean and land

Water management is a key to construct a sustainable society. An integrated numerical simulation for investigations of general water cycle (Fig. 4) will become a promising tool for assessing the impact of human activities on the cycle and for suggesting solutions for sustainable water management.

MSSG (Multi-Scale Simulator for the Geoenvironment) can simulate water transport in both atmosphere and ocean and can consider the water exchange between the two, but cannot consider the water flow (transport) under ground. GETFLOWS (GEneral purpose Terrestrial fluid-FLOW Simulator), on the other hand, is a three-dimensional finite difference and multi-phase fluid-flow simulator with a fully-coupled surface and subsurface fluid-flow (Tosaka et al. 2000 [5], 2010 [6]; Mori et al. 2011 [7]). GETFLOWS can perform simulations of terrestrial

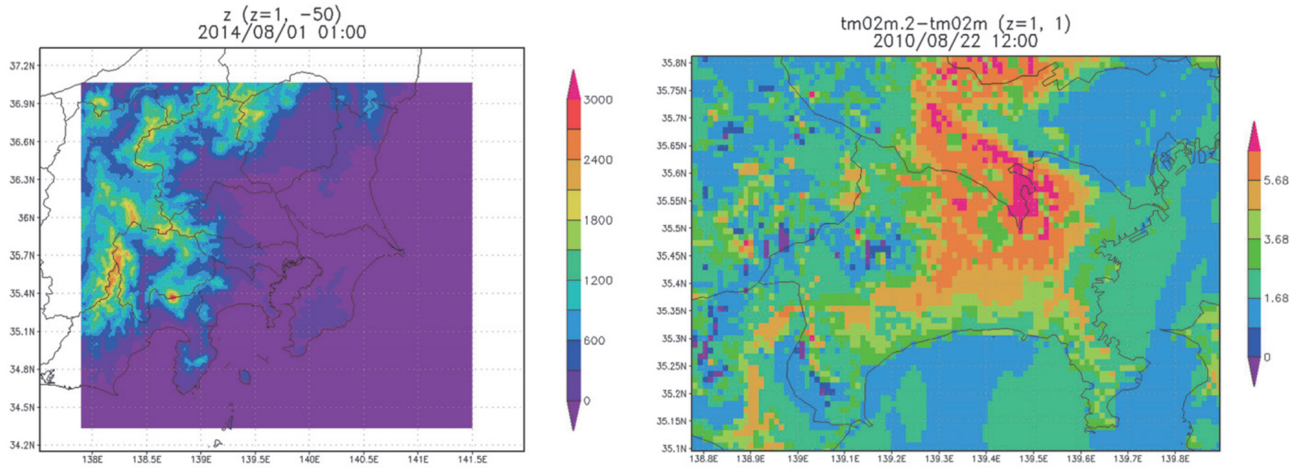

Fig. 3 The computational domain for the downscale simulation, with the elevation drawn in shade (left). The difference in 2 m temperature between the future and current climate in Kanagawa prefecture (right).

underground fluid-flow system if surface fluxes of water substances -such as surface precipitation, evapotranspiration, land use and water use- are provided.

We have coupled the MSSG and GETFLOWS to construct an integrated simulation for the general water cycle in atmosphere, ocean and land (under ground). For the coupling, we have used the OASIS3-MCT coupler (Valcke 2013 [8]).

Figure 5 shows the test domain that covers 260 km x 360 km area in Kanto province, which includes the Tonegawa, Arakawa and Tanigawa river basins. The test simulation was performed for the 12 hours starting at 15:00 on 4 September 2005. The interface data between MSSG and GETFLOWS was exchanged every 10 minutes. Figure 6 shows the impact of the coupling on the latent heat flux on the ground. The flux obtained by the coupled simulation was suppressed compared with the result by the isolated MSSG due to the improvement of the land surface model.

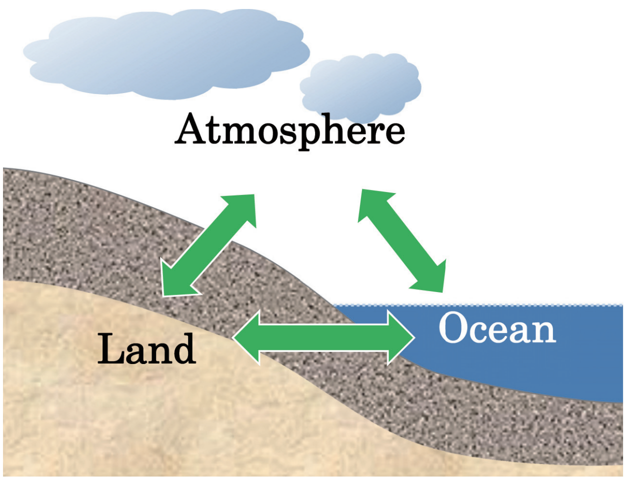

Fig. 4 Schematic illustration of atmosphere-ocean-land coupled system.

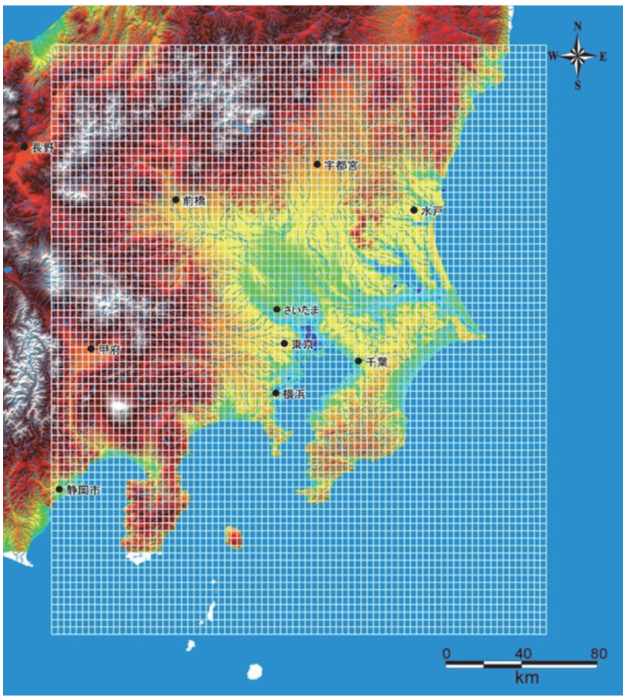

Fig. 5 The computational domain and horizontal mesh for the test simulation.

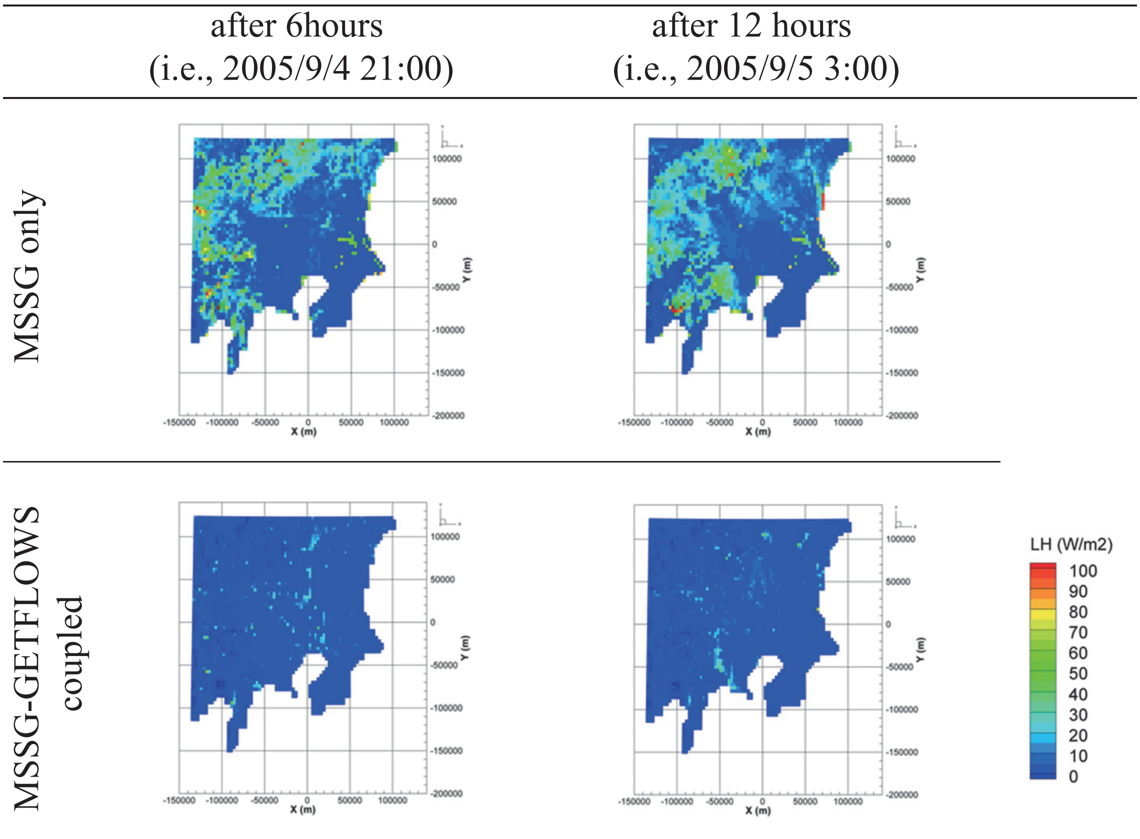

Fig. 6 Surface latent heat flux (W/m^2).

4. Long-term summer SST trend in Tokyo Bay

Trends of increasing coastal water-temperature with significant impacts on local ecosystems have been recently reported (e.g., Nixon, et al, 2004 [9]). However, in Tokyo Bay, a semi-closed bay located along the east coast of Japan, water temperature exhibited a descending trend in the surface and bottom layers in July from 1976 to 1997 (Figures 3 and 4 in Ando et al. 2003 [10]). Previous studies have shown that descending water temperature trends in Tokyo Bay are associated with strengthened cool-water intrusion from the open ocean due to increased river discharge and decreased tidal amplitude (Yanagi, 2008 [11]). However, the mechanisms behind some processes remain unclear. To further elucidate the mechanisms that control water temperature trends in Tokyo Bay during strong summer stratification periods, the detailed heat transport pathways in the bay and their dominant processes must be identified.

The Multi-Scale Simulators for the Geoenvironment (MSSG) model is employed to simulate the currents and temperature distributions in the Tokyo Bay. Wind observations at Honmoku station, which is located at west coast of central bay, shows that the wind field over Tokyo Bay was mainly dominated by southerly wind from year 1979 to 1997 except for the years of 1988, and 1993 when the summer was abnormally cool. Linear regression analysis shows that the southerly wind amplitudes have a trend of roughly 0.08 m/s yr^{-1}, suggesting that southerly winds increased by more than 1 m/s from 1979 to 1997. To investigate heat transport and water temperature distribution responses to this intensified southerly wind, we conducted another experiment under the 4 m/s southerly wind condition.

Figure 7 shows the differences between 3 m/s and 4 m/s southerly wind experimental results. The results suggest that the intensified southerly wind lowers water temperatures in most

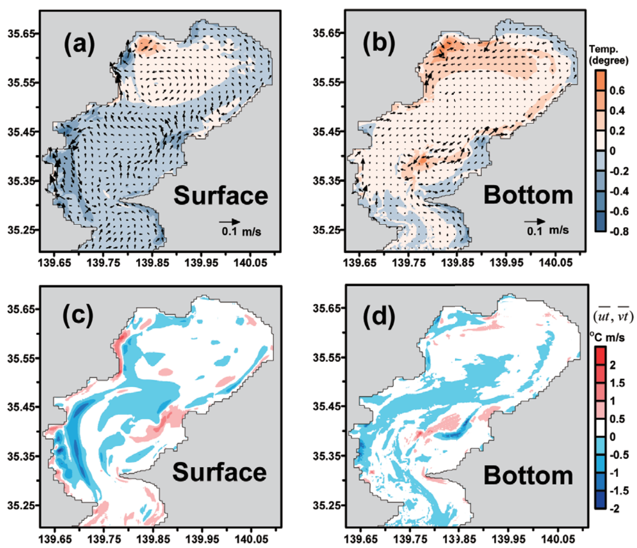

Fig. 7 Differences in monthly mean currents and temperatures (upper) and heat-transport strengths (lower) between 3 m/s and 4 m/s southerly wind experimental results in surface (left) and bottom (right) layers. Note that different reference vectors are used for the bottom layer.

areas of the bay through enhancing upwelling and open ocean-water intrusion near the bay mouth while increases temperatures in bottom layer of the bay head by suppressing southward warm-water transport.

5. Ultra-high resolution multiscale simulations of heat and flow in urban streets with tree canopy influence considered by 1 m resolution

Planting trees in cities is a popular way of mitigation of the urban heat island (Hiruta and Ishikawa, 2012 [12]). It has been, however, difficult to evaluate its effect qualitatively. Recently, we developed the tree model that can consider the influence of trees on thermal radiation as well as on flow and implemented it in MSSG (Matsuda and Takahashi 2014 [13]; Matsuda et al. 2014 [14]). This study has investigated the influence of the trees in a courtyard in the Tokyo metropolitan area. A high resolution simulation with 1 m mesh has been performed for the Marunouchi area near the Tokyo station.

Figure 8 shows the temporal evolutions of the wind speed and direction in the courtyard of the Marunouti Park Builing from 21:00 on 7 August to 3:00 on 8 August. The simulation results show consistent trends with those observed, which confirm the reliability of the high-resolution numerical simulation. In order to investigate the impact of the courtyard trees on the heat environment, we have performed the simulation with removing the trees inside the courtyard for comparison. Figure 9 shows the ten-minutes averaged temperature distribution for the realistic case, with trees in the courtyard, and that for the sensitivity test case, where the trees in the courtyard are removed. The warmer the color is, the higher the temperature is. The simulation result shows that the temperature inside the courtyard is cooler by 1 K than outside in the realistic case. This agrees with

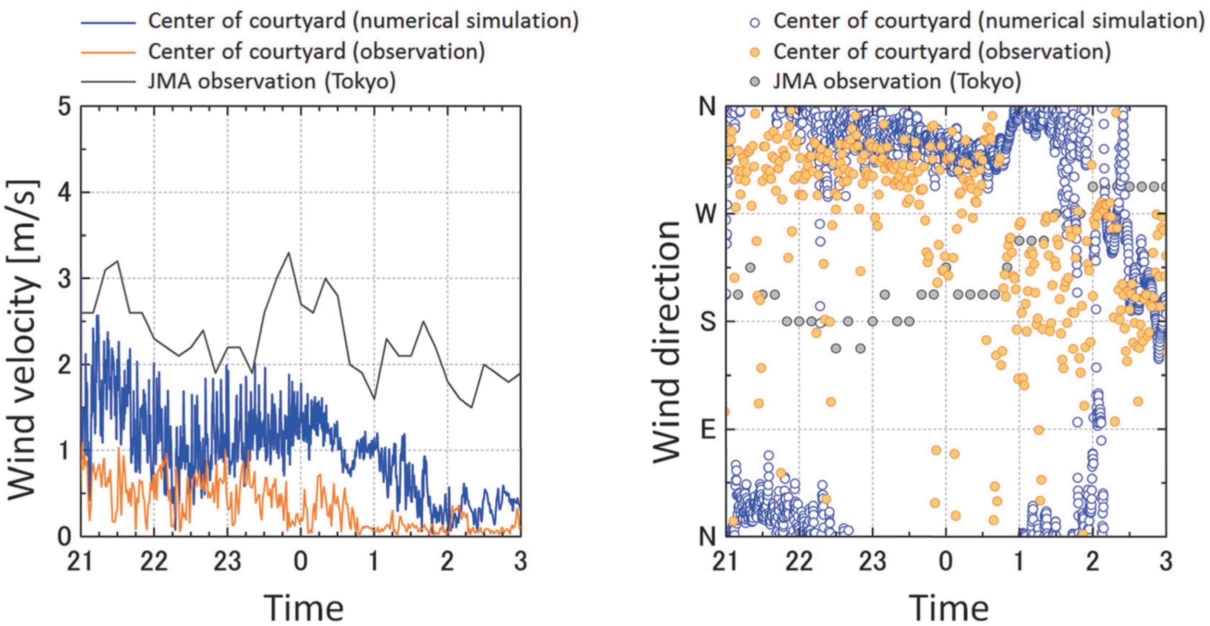

Fig. 8 Temporal evolutions of the wind speed (left) and wind direction (right) in the courtyard of the Marunouti Park Builing. The observation data was provided by Tsubota et al. (2014 [15]), and Andou et al. (2014 [16]).

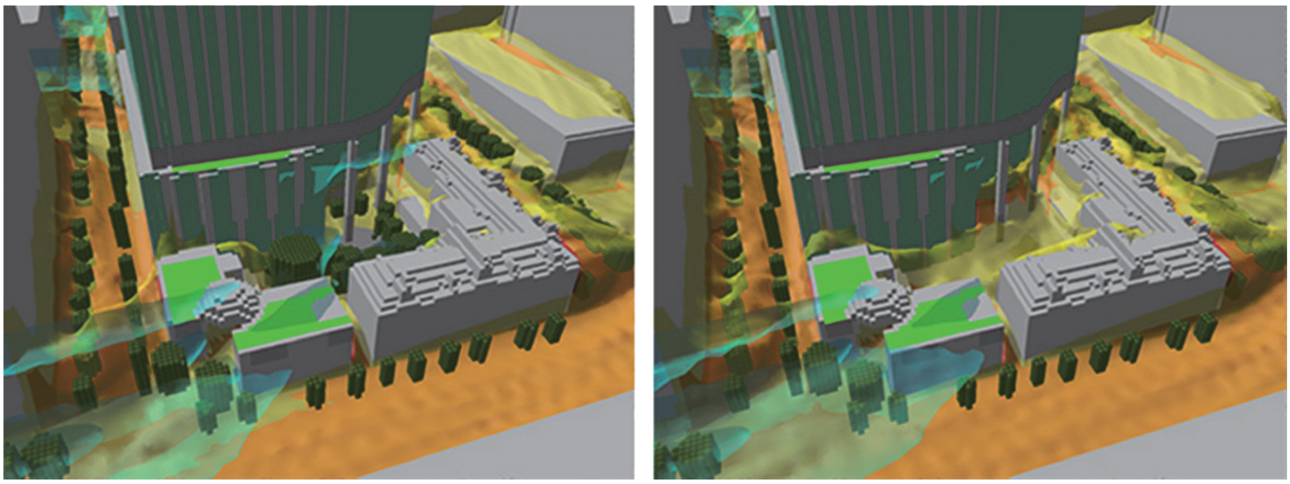

Fig. 9 Ten-minute averaged temperature distribution for the realistic case with trees in the courtyard (left) and that for the sensitivity test case with removing the trees (right). Warmer color shows higher temperature.

the observation quantitatively as well as qualitatively. The comparison between the realistic and test cases shows that the courtyard trees contribute to the 1 K cooling.

This study has been conducted under the collaboration with the Mitsubishi Jisho Sekkei Inc. and the Takenaka Corporation.

6. Multiscale simulation of droplet collision growth in cloud turbulence

We have developed the Lagrangian cloud simulator (LCS), which simulates droplet growth in air turbulence (Onishi et al. 2011 [17]; 2013 [18]). The LCS adopts the Euler-Lagrangian framework and can provide reference data for cloud microphysical models by tracking the growth of particles individually. The collisional growth in a stagnant flow is calculated by the LCS and also by solving the stochastic collision-coalescence equation (SCE). Good agreement is obtained between the LCS and SCE simulations if proper collision model is used. Comparisons between the results for stagnant and turbulent flows confirm that in-cloud turbulence enhances collisional growth. Figure 10 shows the autoconversion rates in turbulent flows for different energy dissipation rates. The autoconversion rate is larger for larger energy dissipation rate ε, which clearly shows that the autoconversion is enhanced by turbulence. The maximum values in the figure clearly show that the autoconversion rate increases and reaches its highest value earlier for larger energy dissipation rates. It is also shown that the SCE simulation can predict the ε-dependence. The shift in time of the peak autoconversion rate is caused by the decay of the autoconversion rate occurring earlier, which is due to the quicker consumption of cloud droplets for larger ε.

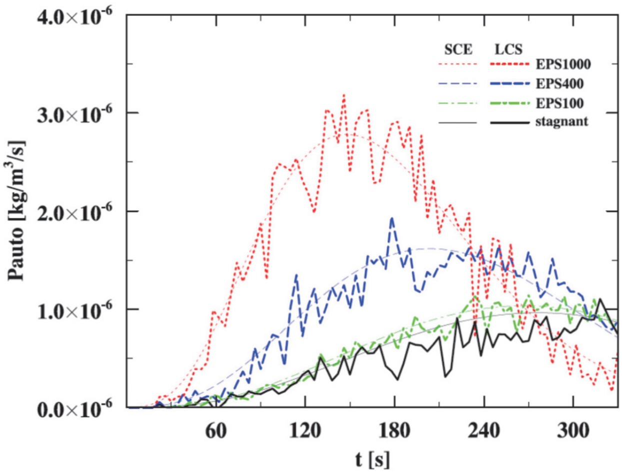

Fig. 10 Autoconversion rates for different energy dissipation rates. The Onishi collision kernel with the product of the Pinsky et al. (2001) [19] collision efficiency and η_E of Wang et al. (2008) [20] was used for the SCE simulations.

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気候変動や都市ヒートアイランドに強い社会づくりのための環境予測マルチスケールシミュレーション

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地球温暖化に伴って気候変動現象が変化し、さらにそれらに影響を受けて、台風や豪雨、都市環境などのメソスケールあるいは局所的な気象や気候変動がどのような影響を受けるのかについての予測は、社会的な関心が非常に高い。加えて、これらの気候変動に対する適応策の検討には、近い将来の身近な環境変化についての定量的な予測が必要不可欠である。このための予測シミュレーションは、気候変動現象から都市スケールの環境変化までの複数の異なる時空間スケール間を対象とするシミュレーションが必要であり、学術的にも意義が大きく、また、積極的な研究開発が世界的に展開されようとしている。本年度は、MJO 現象における、海洋と大気の結合過程を明らかにするために、MSSG モデルを用いた大気海洋結合全球高解像度を行った。また、数十年スケールの東京湾 SST の変化の物理メカニズムを明らかにするために、MSSG モデルを用いた高解像度海洋シミュレーションを行った。さらに、温暖化した際の都市部の降雨変化を明らかにするために、MSSG を用いた擬似温暖化ダウンスケールシミュレーションを行った。一方、大気・海洋・地下水系の統合水大循環システムを明らかにするために、MSSG と地表水・地下水系モデル GETFLOWS を OASIS3-MCT カプラーを用いて結合し、その動作を確認するとともに検証シミュレーションを実行した。さらに、微小雲粒子の成長に及ぼす雲乱流の影響を明らかにするために、乱流を直接計算し、微小水滴の運動と成長をラグラジアン法によって追跡する計算法を開発し、その大規模計算を行った。また、樹木が都市街区の暑熱環境に与える影響を明らかにするめに、MSSG を用いた都市街区の熱・風シミュレーションにおいて、樹木が風況でなく熱放射場に及ぼす影響までを考慮できる計算手法を開発し、実際の都市街区に適応した。以上のように、全球スケールから領域、都市スケール、さらには雲マイクロスケールと、多岐にわたるスケールの現象に対して、大規模計算を行うことによって、その解明と予測に関する研究を行った。

キーワード : atmosphere-ocean coupled model, MSSG, multi-scale, global warming, urban heat island