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Investigation of the Effects of Urban Heating on the Heavy Rainfall Event by a Cloud Resolving Model CReSiBUC

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Synopsis

In this study, effects of urban heating on the development of the heavy rainfall on 21 July 1999 in Tokyo (the Nerima heavy rainfall) were investigated by a coupled model of a cloud resolving model CReSS and a precise land surface model SiBUC (CReSiBUC). Four numerical simulations were carried out for this rainfall event. The first simulation had realistic land cover, second one had imaginary land cover (urban area was changed into paddy field), the third one had imaginary land cover (urban area was enlarged) and forth one had realistic land cover and imaginary anthropogenic heat. From those simulations, it was found that changes of distribution of urban and anthropogenic heat amount greatly affected on the positions and amounts of rainfall.

Keywords: urban heat island, heavy rainfall, cloud resolving model, CReSiBUC

1. Introduction

In late years, localized heavy rainfall over urbanized area with a short time duration has become problem. Frequent occurrence of localized heavy rainfall over urbanized area and its connection with heat island phenomena have been pointed out, but a clear answer is not obtained. As for the connection of heat island and rainfall, Shepherd (2003) pointed out that heat island associated with artificial influence causes rainfall and increases the frequency of a thunderbolt in a big city along the seashore such as Houston in Texas. Kobayashi (2003) investigated the generation and the development processes of cumulonimbus clouds in an urban area using weather radar data. They pointed out that the processes of the cumulonimbus clouds in the urban area were different from those in mountainous regions. Fujibe (2003) suggested that the “heat island” affected the frequency of strong rainfall events in the Tokyo metropolitan area. These suggestions with observational studies were encouraged by some numerical studies (e.g. Gero and Pitman, 2006). However, the urban effects on rainfall events have never been discussed very well in Japan.

In this study, the effects of urban heating on the development of the strong cumulonimbus clouds were investigated by a coupled model of a non-hydrostatic meteorological model CReSS (Cloud Resolving Storm Simulator) developed at Nagoya Univ., Japan and a precise land surface model SiBUC (Simple Biosphere model including Urban Canopy) developed at Kyoto Univ., Japan. This model (CReSiBUC) is able to include the existence of urban area and anthropogenic heat release as a part of land surface processes. To study the effects of urban heating on rainfall, sensitivity tests for distribution of existence of urban area and anthropogenic heat in urban are conducted by the CReSiBUC. A case of the heavy rainfall on 21 July 1999 in Tokyo (the Nerima heavy rainfall) is selected for the sensitivity tests. This rainfall event was a localized one occurred in a highly

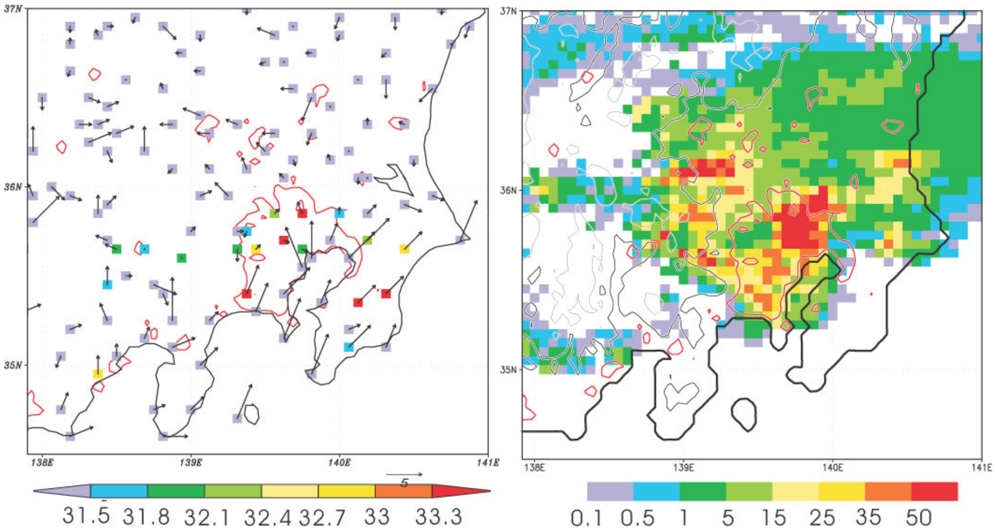


Fig.1 (a) Averaged surface temperature for 12-14 JST with the AMeDAS, and (b) accumulated rainfall for 15-18 JST with the Rader-AMeDAS on 21 July 1999. TMA is surrounded by the red line.

urbanized area (Nerima-ward, Tokyo, Japan), and the rainfall amount was 130 mm within 3 hours (15-18 JST). This is a typical and suitable case for studying the urban effects on rainfall.

2. Observational Characteristics of the Nerima Heavy Rainfall

Averaged surface temperature and wind by the AMeDAS (Automated Meteorological Data Acquisition System) for 12-14 JST (the times to consider the atmosphere ground before several hours of rainfall outbreak) and accumulated rainfall by the Radar-AMeDAS for 15-18 JST are shown in Fig.1. In this study, a domain where the ratio of urban area per 5 km square unit is more than 30% is defined as "Tokyo Metropolitan Area (TMA)" in real land use distribution for convenience. Before the generation of the Nerima heavy rainfall, the weather was sunny around Tokyo district, and the feature of the “heat island” was clearly shown in the distribution of the surface temperature. The temperature above 33 degree C was observed in TMA and the temperature outside of TMA was below 31 degree C (Fig. 1(a)). The surface winds in and around TMA tended to converge into the center of TMA

The strong rainfall exceeding 50 mm associated with the Nerima heavy rainfall was locally induced in the area of about 50 km square (Fig. 1(b)). The position of the strong rainfall corresponded to that of the area of high temperature and convergence zone. From these observational evidences, it is suggested that the Nerima heavy rainfall was strongly affected by the existence of urban area.

3. Model Description of CReSiBUC

The CReSiBUC is a coupled model of the CReSS and the SiBUC. The CReSS is a non-hydrostatic meteorological model developed in Hydrospheric Atmospheric Research Center, Nagoya University (Tsuboki and Sakakibara, 2001). The CReSS has two significant advantages. One is a high readability of the source code so that the CReSS is easy to couple with models for other processes. The other is a high calculation efficiency that satisfies a condition to use the “Earth Simulator,” which is one of the fastest super computers in the world. Using the CReSS, atmospheric simulations for the broader domain with the higher resolution are possible.

The SiBUC is a land surface processes model developed in Water Resources Research Center, Disaster Prevention Research Institute, Kyoto University (Tanaka, 2004). The SiBUC calculates surface fluxes and related hydrological quantities considering detailed processes. In the normal CReSS, the land surface processes are calculated with empirical constant values of albedo, evaporation efficiency, and roughness for simplifying calculations. To the contrary, the SiBUC calculates budgets of radiation, heat, water, and momentum while changing parameters for the surface condition. For example, for an urban area in the SiBUC, uneven distribution of roof height is considered on the basis of the urban canyon concept. Additionally, the SiBUC adopts a "mosaic" approach. In case that a horizontal grid of the CReSS is including a number of various land use categories, values on each category are calculated and a grid averaged surface fluxes are returned to the CReSS. This mosaic scheme is an effective facility especially for the domain where multiple artificial landuse categories of urban, paddy, etc. are mixed as like Japan.

4. Simulation Design

In the simulations with the CReSiBUC, precipitation physics of mixed-phase processes are used. The horizontal grid size is 5 km, and the vertical grid contains 45 levels with variable grid intervals (⊿z=100 m near the surface and ⊿z=500 m at the top level). The horizontal domain has 100×100 grid points, and big and small time steps of ⊿t=10 seconds and ⊿t=5 seconds are used.

The initial and lateral boundary data were provided from output produced by the Regional Spectral Model (RSM: a hydrostatic model used operationally in Japan Meteorological Agency, referred in Segami et al., 1987). The CReSiBUC simulation was one-way nested within the RSM started at 0900 JST on 21 July 1999. The integration time of the CReSiBUC simulation was 12 hours from 0900 JST on 21 July 1999, and lateral boundary data were given every hour. The simulation domains for the RSM and the CReSiBUC are shown in Fig.2.

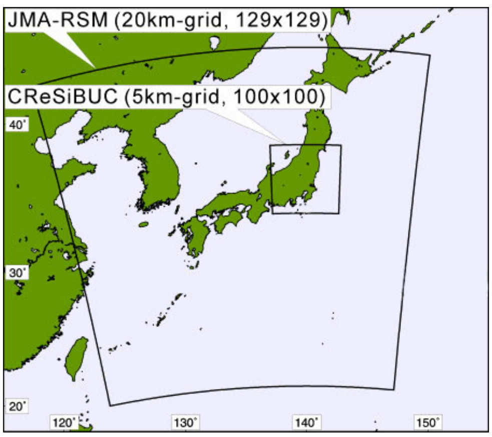
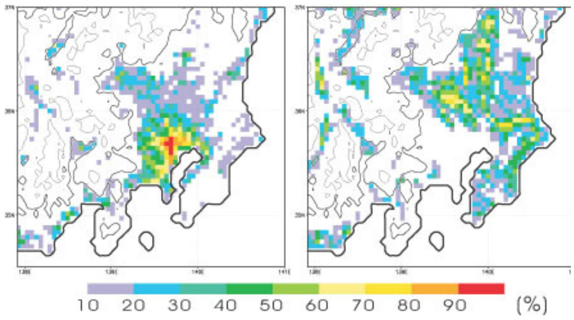
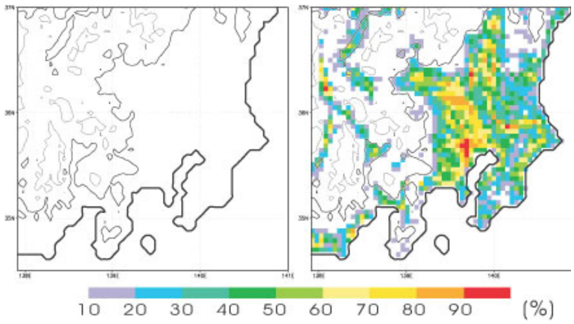


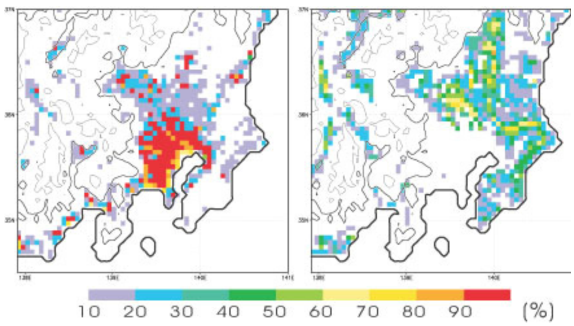
Fig.2 Model domains of JMA-RSM, and CReSiBUC.



(CTL)



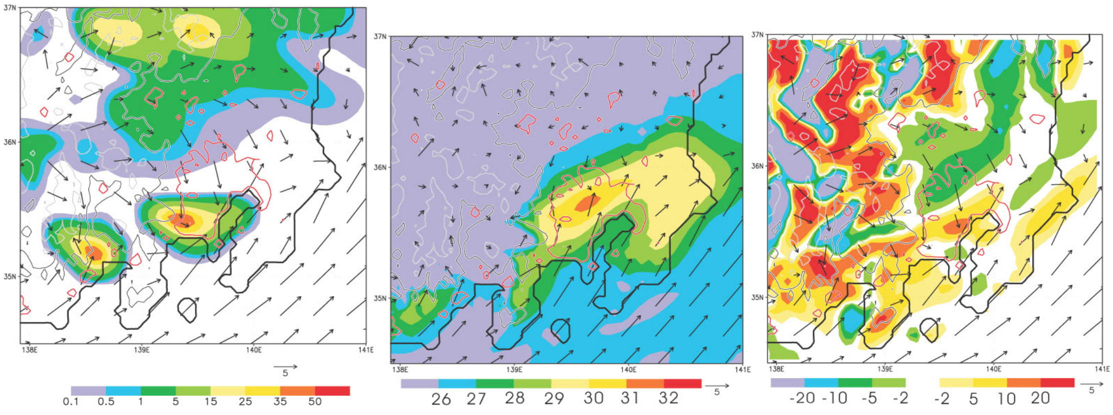
(PDY)



(UBN)

Fig.3 Land-use distribution given to the CTL, PDY, and UBN simulation. Fraction of urban area and paddy field are shown in the left and right side, respectively.

To study the effects of the existence of urban heating on the generation of the Nerima heavy rainfall, simulations called CTL, PDY, and UBN (abbreviations of control, paddy, and urban, respectively) are conducted using the following three patterns of the land-use distributions. Fig.3 shows that the first one (CTL) is the actual distribution, the second one (PDY) is the distribution in which urban area is replaced with paddy field, the third one (UBN) is the distribution in which fraction of urban in TMA is enhanced. In the UBN simulation, all land area (except water body) in TMA is treated as urban. In addition, to consider the effects of



(a) Rainfall (b) Temperature (c) Convergence

Fig.4 Simulated results with the CTL of (a) accumulated rainfall for 1500-1800 JST, (b) averaged temperature at 100 m for 1200-1400 JST, (c) averaged convergence accumulated in the 100-2000 m-layer for 1600-1800 JST. TMA where the fraction of urban area is over 30 % is surrounded by red line.

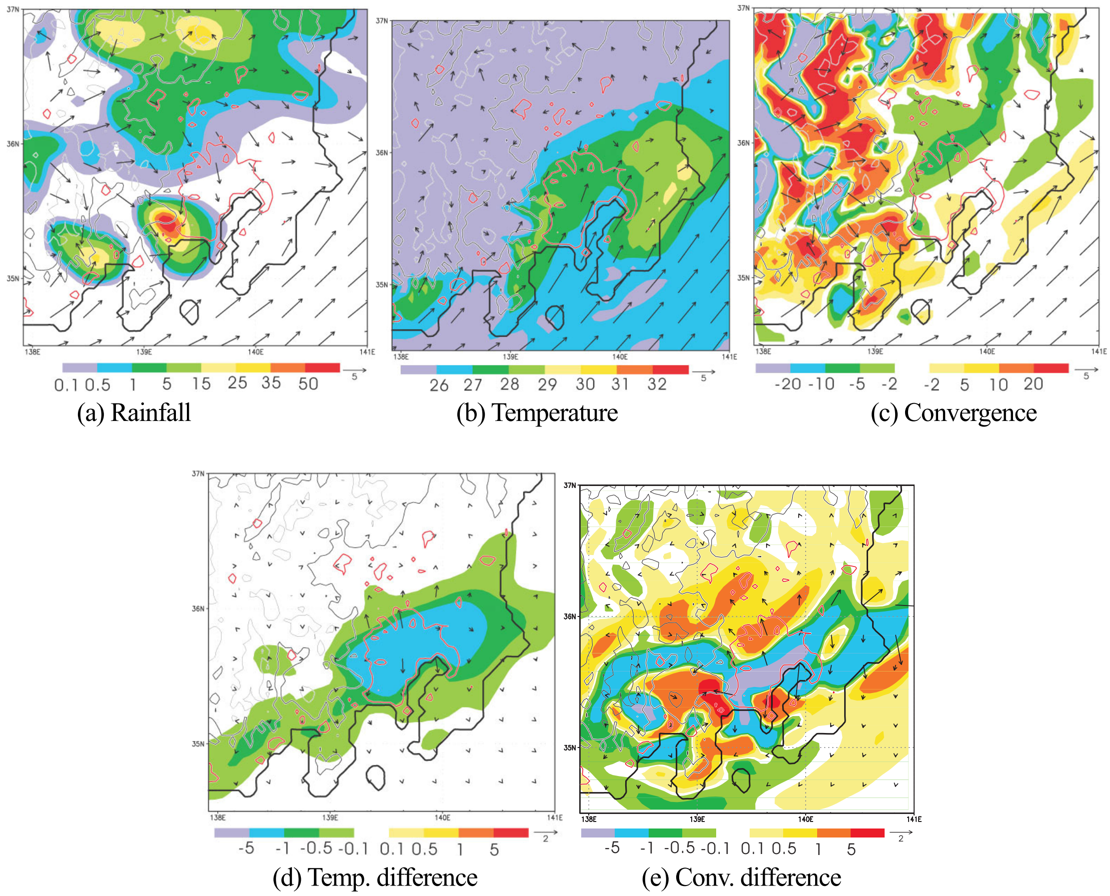


Fig.5 Simulated results with the PDY of (a) accumulated rainfall for 15-18 JST, (b) averaged temperature at 0.1 km for 12-14 JST, (c) averaged convergence accumulated in the 0.1-2.0 km-layer for 16-18 JST, (d) averaged temperature difference between the PDY and the CTL, and (e) averaged convergence between the PDY and the CTL.

anthropogenic heat in urban, a simulation that the anthropogenic heat of 400 Wm^{-2} is given (hereafter called AHD) is conducted. The anthropogenic heat is an artificial source due to cooling equipments, cars, etc. According to the distribution data of urban anthropogenic heat in Tokyo (Ichinose et al., 1994), a heat amount of about 300-400 Wm^{-2} is discharged in Tokyo during a summer season. Although the realistic anthropogenic heat amount is changed in time, the constant amount of 400 Wm^{-2} is assumed in the AHD simulation.

5. Results and Discussions

Comparing to the observation results in Fig.1, the main features of the Nerima Heavy Rainfall was well produced by the CTL simulation as shown in Fig.4. A local strong rainfall over 35 mm is located in TMA, although its position is slightly shifted in the southwest from that of the actual the Nerima Heavy Rainfall. This shift could result from accuracy of the initial and lateral boundary data from the RSM. A high temperature area (above 30 degree C) is seen in the distribution of lowest level (100 m) temperature as shown in the actual observation. The position of convergence in the lower level atmosphere (100-2000 m) exceeding 10×10^{-4} s^{-1} is well corresponded to the high temperature area.

The results of the PDY simulation and their difference from the CTL simulation are shown in Fig.5. Comparing to the CTL, a strong rainfall area is shifted further west. In the PDY, a high temperature area in TMA is not seen (Fig.5 (b)), that is, the "heat island" phenomenon is not occurred. Around the area where the temperature decrease is exceeding 2 degree C, winds are changed to the direction to the outside of TMA (Fig.5 (d)). No remarkable convergence zone is seen in TMA (Fig.5 (c)). Comparing to the CTL, the convergence in TMA is decreased by 5×10^{-4} s^{-1}, meanwhile the convergence in a mountainous region in the west is found to be increased (Fig.5 (e)).

The results of the UBN simulation and their difference from the CTL simulation are shown in Fig.6.

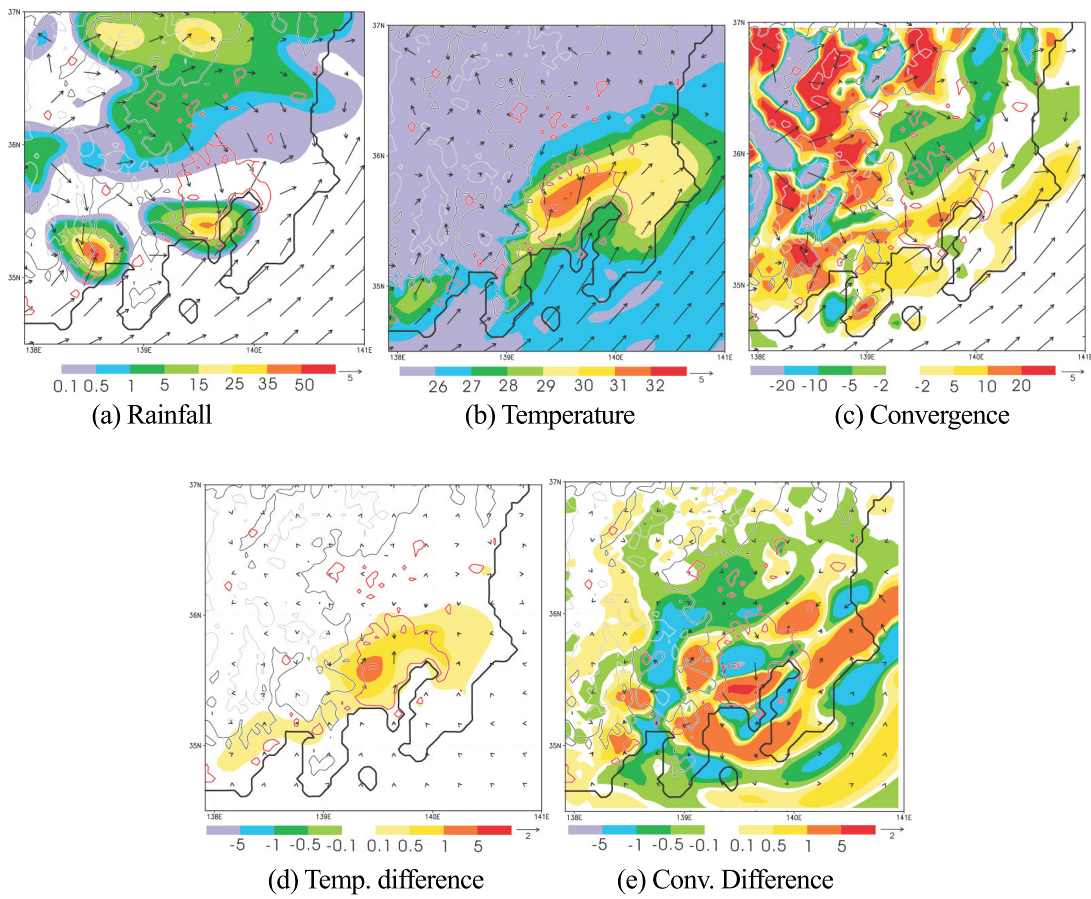


Fig.6 The same as Fig.5, but given to the UBN simulation.

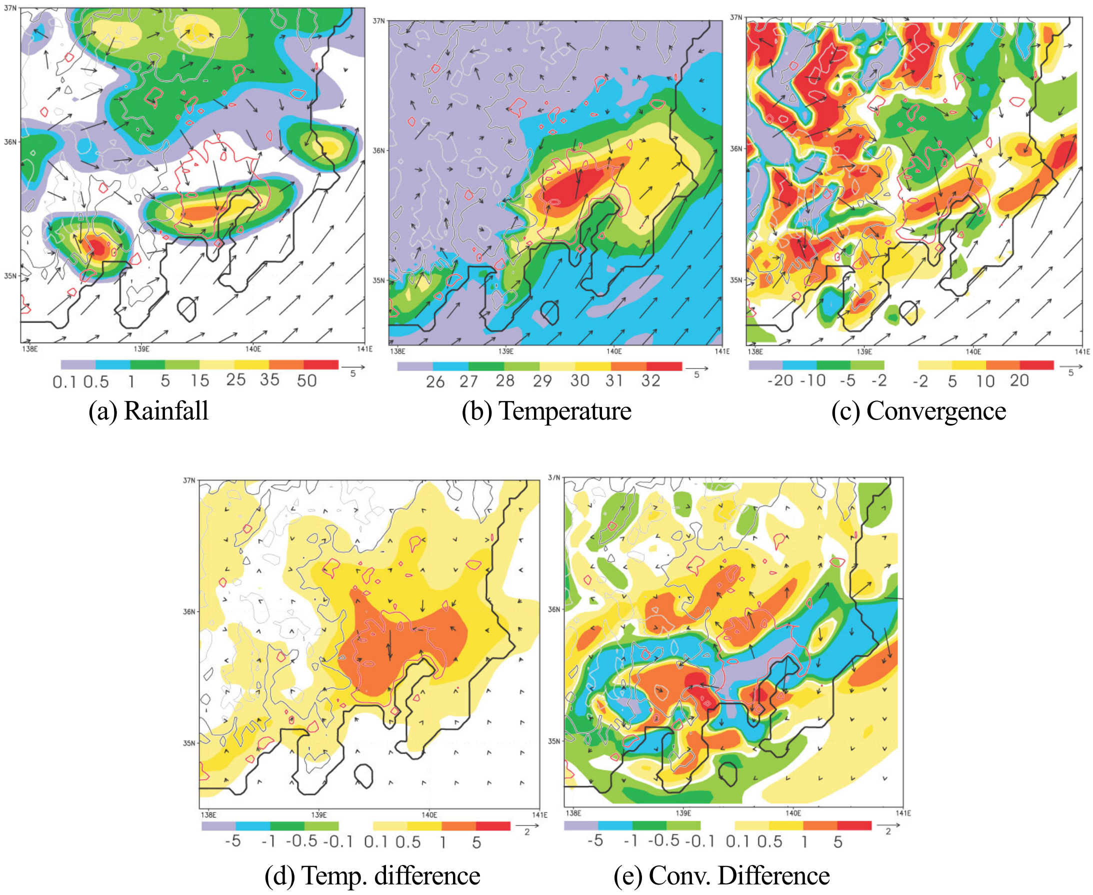


Fig.7 The same as Fig.5, but given to the AHD simulation.

Comparing to the CTL, a strong rainfall area is shifted further east. In the UBN, a high temperature area (above 30 degree C) in TMA is extended, that is, the feature of the "heat island" in the UBN is more significant than that in the CTL (Fig.6 (b)). Around the area where the temperature increase is exceeding 1 degree C, the winds are changed to the direction toward TMA (Fig.6 (d)). A remarkable convergence zone is seen in TMA as in the CTL (Fig.6 (c)). Comparing to the CTL, the convergence in TMA is increased by over $5\times10^{-4}\,s^{-1}$.

It can be explained that the position of the precipitation clouds formation is shifted due to the fact that the surface heating is changed resulting from the existence and concentration of urban area. From these results of the PDY and the UBN, it is considered that the existence of urban changes the low-level convergence through the effects of the "heat island," and significantly affects the position of the formation of cumulonimbus clouds to cause a heavy rainfall.

The results of the ADH simulation and their difference from the CTL simulation are shown in Fig.7. Comparing to the CTL, a strong rainfall area is extended in the west-east direction. An increase of rainfall amount of 10 mm in the maximum was seen in TMA In the AHD, a high temperature area (above 32 degree C) in TMA is seen, and the feature of the "heat island" in the AHD is more significant than that in the UBN (Fig.7 (b)). Around the area where the temperature increase is exceeding 2 degree C, winds are changed to the direction toward TMA (Fig.7 (d)). A remarkable convergence zone is seen in TMA as in the CTL (Fig.7 (c)). Comparing to the UBN, the area of the increase of 10×10-4 s-1 from the CTL is extended (Fig.7 (e)).

This result cautions about the following scenario. Buildings will become higher and higher, and anthropogenic heat per unit area associated with cooling equipments will increase more and more. It is suggested that growing of such kind of human-induced heating affects the intensity and frequency of heavy rainfall disasters in urban area.

6. Conclusions

In this study, effects of urban heating on the development of the heavy rainfall on 21 July 1999 in Tokyo (the Nerima heavy rainfall) were investigated by a coupled model of a cloud resolving model CReSS and a precise land surface model SiBUC (CReSiBUC). Changing the land cover condition, four numerical simulations were carried out for this rainfall event. From those simulations, it was found that changes of distribution of urban area and anthropogenic heat amount greatly affected on the positions and amounts of rainfall.

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雲解像モデルCReSiBUCによる都市の加熱が豪雨に及ぼす影響の検討

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要　旨

本研究では、1999年7月21日に発生した練馬豪雨を事例として取り上げ、都市の加熱が降水に及ぼす影響を、詳細な陸面過程を組み込んだ雲解像モデルCReSiBUCを用いて検討する。土地利用分布や人工排熱量を変化させた4種類の感度実験の結果から、都市の加熱に伴う強い収束が、水蒸気のより大きな集中化を招き、短時間・局所的な強雨現象の形成位置や水平規模に影響を与えていることが示唆された。

キーワード:ヒートアイランド，豪雨，雲解像モデル，CReSiBUC