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Multiscaled analysis of hydrothermal dynamics in Japanese megalopolis by using integrated approach

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Abstract:

We coupled the process-based National Integrated Catchment-based Eco-hydrology (NICE) model to an urban canopy model and the Regional Atmospheric Modeling System to simulate the effect of urban geometry and anthropogenic exhaustion on the hydrothermal changes in the atmosphere/land and the interfacial areas of the Japanese megalopolis. The simulation was conducted with multiscale in horizontally regional-urban-point levels and in vertically atmosphere–surface–unsaturated–saturated layers. The model reasonably reproduced the observed hydrothermal values by using ground-truth data in various types of natural/artificial land covers. The simulated results also suggested that the latent heat flux in the new water-holding pavement (consisting of porous asphalt and water-holding filler made of steel by-products based on silica compound) has a strong effect on hydrologic cycle and cooling temperature in comparison with the observed heat budget by newly incorporating the effect of water amount on the heat conductivity in the pavement. Furthermore, the model predicted the hydrothermal changes under two types of land cover scenarios to promote evaporation and to reduce air temperature against heat island phenomenon. Finally, we evaluated the relationship between the effect of groundwater use to ameliorate the heat island and the effect of infiltration on the water cycle in the catchment. These procedures to integrate the multiscaled model simulation with political scenario based on the effective management of water resources as heat sink/source would be very powerful approaches for recovering a sound hydrologic cycle and for creating thermally pleasing environments in the megalopolis.

KEY WORDS multiscaled model; hydrothermal characteristics; urban geometry; anthropogenic exhaustion; symbiotic urban scenario

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INTRODUCTION

The urban heat island effect (Oke, 1987; Golden, 2003), where the urban temperature is higher than its rural surroundings, has become a serious environmental problem with the expansion of cities and industrial areas. Surfaces covered by concrete or asphalt can absorb a large amount of heat during the day and release it to the atmosphere at night. Many researchers have attempted to reproduce the heat island by using some regional weather forecast models (Pielke *et al*., 1992; Dudhia, 1993; Skamarock *et al*., 2005). Zhang *et al*. (2008) coupled Regional Atmospheric Modeling System (RAMS) with a single-layer Urban Canopy Model (UCM) (Kusaka *et al*., 2001; Kusaka and Kimura, 2004a,b) to improve a reproducibility of the urban heat island, in particular, nocturnal temperature, which the original RAMS could not reproduce accurately. Ichinose *et al*. (1999) investigated the influence of anthropogenic heat on the urban heat island in comparison with the short wave radiation in summer and winter. Ohashi *et al*. (2007) integrated building energy analysis model into the UCM and showed an importance of anthropogenic heating with indoor worker to reproduce diurnal temperature variation on the weekday in the Tokyo office areas.

Previous researchers pointed out that open parks and water surfaces are vital in urban areas for creating urban cool island because the evaporation of water provides an important counter to this effect (Spronken-Smith and Oke, 1999; Chang *et al*., 2007). The convective heat transfer, the so-called sum of advective and diffusive transfer, of urban surfaces is a crucial parameter for estimating the turbulent heat flux in urban areas and should be estimated quantitatively (Hagishima *et al*., 2005). Some researchers have used process-based models to estimate the transport of water vapour under a paved surface, which can regulate the temperature distribution (Grimmond and Oke, 1991; Asaeda and Ca, 1993; Dupont *et al*., 2006). Numerical model showed that road hydrological behaviour influences thermal exchange and that evaporation makes the temperature of bare soil much lower than that of covered surfaces (Asaeda and Ca, 1993). Using a submesoscale urban scheme, Objective Hysteresis Model (OHM) (Grimmond and Oke, 1991) and Sub-mesoscale Soil Model, urbanized version (SM2-U) (Dupont *et al*., 2006) showed that urban hydrological parameters determine how much water is available for evaporation from artificial surfaces (engineered pavements) and reduce the evapotranspiration from natural surfaces. However, in these models, the

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lack of accurate measured data on infiltration of water into largely impermeable urban surfaces has led some urban hydrologists to assume that infiltration is almost zero and runoff is 100% of rainfall, which could lead to overestimation of runoff and underestimation of recharge to groundwater. Hollis and Ovenden (1988a,b) and Ragab *et al*. (2003) showed that streets cannot be considered fully impermeable and that the runoff also represents a significant source of pollution. It is also important to assess the effects of land use change scenarios on hydrology based on observations, which are closely related not only to water resources management but also to mitigation of heat island (Alberti *et al*., 2007).

Permeable pavements and other stormwater control devices are increasingly being used to store stormwater to lose it by evaporation in fine weather and thus to reduce runoff from the urban environment (Andersen *et al*., 1999; Sansalone and Teng, 2005). Ramier *et al*. (2004) assessed losses due to infiltration, evaporation and runoff on asphalt, concrete and porous plates in a lysimeter. The promotion of vaporization by using water-holding pavement would be effective as strategies to mitigate the urban heat island phenomenon in combination with use of light-coloured surfaces and vegetated surfaces (Saaroni *et al*., 2000; Chang *et al*., 2007; Nakayama and Fujita, 2010). Because this heat relaxation in newly symbiotic pavement is closely related to the heat capacity of water and the conductivity of the pavement, it is estimated that groundwater use in almost constant temperature as a heat sink would be very effective for tackling the heat island (Ministry of Environment, 2003). A policy to promote infiltration into the aquifer is important to prevent ground degradation as has occurred in the past (Endo, 1992), in addition to holding some water in the unsaturated layer. The heat island related to hydrologic cycle also differs between surface level and street level (Saaroni *et al*., 2000) and between local scale and regional scale (Nichol and Wong, 2005), which makes it difficult to evaluate in actual urban regions. Therefore, it is very important to develop the process-based model and to evaluate the relationship between the effect of groundwater use to ameliorate the heat island and the effect of infiltration on the hydrologic cycle in the catchment. The model simulation in a political scenario for the effective selection and use of ecosystem service sites (Millennium Ecosystem Assessment, 2005) would be also a powerful approach to create thermally pleasing environments and to achieve sustainable development in megacities.

The objective of this study is to construct a simulation system with multiscale levels in horizontal regional to urban area and in vertical atmosphere–surface–unsaturated–saturated layers. Previously, we have developed the National Integrated Catchment-based Eco-hydrology (NICE) model (Nakayama, 2008a,b, 2010, 2011a,b, 2012a,b; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Watanabe, 2004, 2006, 2008a,b; Nakayama *et al*., 2006, 2007, 2010), which includes surface–unsaturated–saturated water processes and assimilates land–surface processes describing the variation in phenology with Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data. This model was newly coupled with UCM (Nakayama and Fujita, 2010) and RAMS (Pielke *et al*., 1992) to simulate the effect of urban geometry and anthropogenic exhaustion on the change of water and heat cycles in the atmosphere/land and the interfacial areas of the Japanese megalopolis (NICE-Urban). Furthermore, we predict the hydrothermal changes with some political scenario to promote evaporation and to reduce air temperature against heat island phenomenon and to create thermally pleasing environments in the megalopolis.

STUDY AREA

The study area, Kawasaki City, is in approximately 1.3 million inhabitants, located on the western shore of the Tokyo Bay, and lies halfway between Tokyo metropolitan area and Yokohama City, the largest and second largest cities in Japan (Figure 1). This area is in the Keihin industrial zone, the largest industrial area in Japan, and has seen widespread and rapid development as the industrial and urbanized area. After the severe environmental deterioration mainly caused by heavy and chemical industries in the 1970s, the pollution situation has improved gradually through stricter standards (Kawasaki City Government, 2004). On the other hand, this area suffers from serious problem in the 'floating' of subways, stations and buildings in the urban area (Ministry of Environment, 2004a) after the prohibition of groundwater use against overexploitation during the rapid development from the 1970s to the 1980s (Endo, 1992; Nakayama *et al*., 2007). Nowadays, this area is one of the most severe heat island regions that have caused a serious environmental problem. The central and local governments have taken various measures to mitigate this effect by changing and rearranging surface layer via albedo, emissivity, sky view and ventilation path (wind path), rooftop garden (green roof), use of light-coloured surfaces and highly infrared reflective coating (using special coating material), reconstruction of elderly buildings and urban geometry by spatially adequate arrangement, green infrastructure system in parks and flood plains, and so on, in addition to by increasing energy efficiency and managing traffic/transportation system (Ministry of Environment, 2003; Kawasaki City Government, 2008). The Tama River flows through the northern boundary of Kawasaki City and the west suburban Tokyo into the Tokyo Bay (Figure 1). Kawasaki City is located at an alluvial plain in the downstream of this river and at the Shimosueyoshi upland in the middle of the river, and most of the area consists of residential (40%), commercial/industrial (28%) and other areas (32%). Recently, this river has been considered important not only as flood control, drinking water and irrigation but also as environmental amenity in the Japanese megalopolis. In particular, the roles of water resources such as river, lake, sea and groundwater are recognized as important for the mitigation of the urban heat island. Watersides of river and sea in the urban are now thought better of as an urban

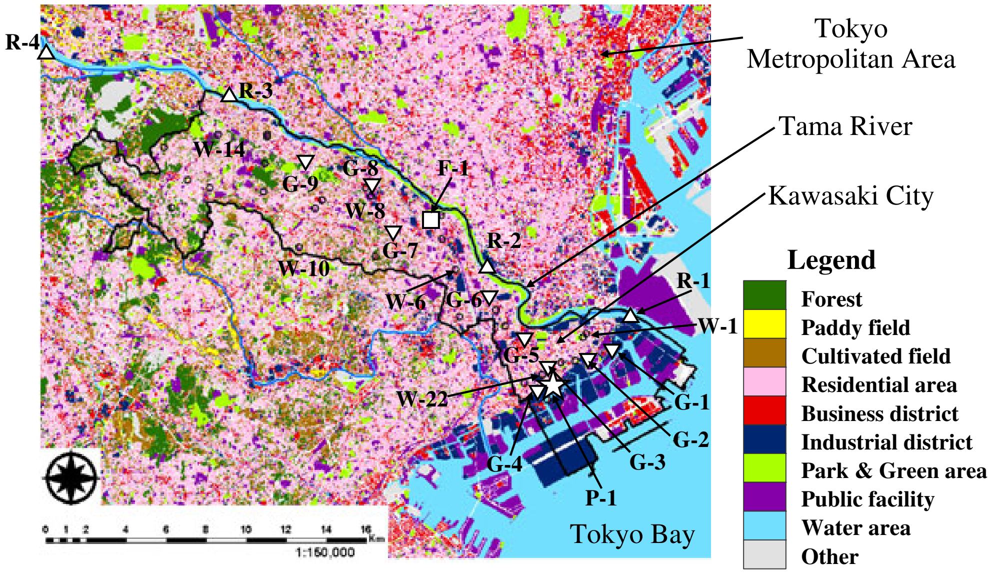

Figure 1. Study area in the Kawasaki City and the Kanto Plain including the Tokyo Bay and the Tama River catchment (area: 1240 km^2) about land cover including the Tokyo metropolitan area (Geographical Survey Institute of Japan, 2000, 2002). The sampled data of 206 points of geological structure by (Digital National Land Information GIS Data of Japan, 2002) was used to input to the NICE-Urban model (Nakayama *et al.*, 2007). The observed data of 29 points of weather data (W; ○), 6 points of river discharge (R; △), 9 points of groundwater level (G; ▽) (Kawasaki City Government, 2004a,b; Kanto Regional Development Bureau, 2005–2006) during 2004–2006, 1 point of flux tower data at the Todoroki car parking (F; □) and 1 point of various pavement blocks at the rooftop of the Keihin building (P; ☆) (Nakayama and Fujita, 2010) were used for the validation of the model

cool island in addition to open parks and green areas (Ministry of Environment, 2003).

EXPANSION OF NICE MODEL FOR LAND–ATMOSPHERE INTERACTIONS IN URBAN AREAS (NICE-URBAN)

NICE model series

Previously, we developed the NICE model, which includes surface–unsaturated–saturated water processes and assimilates land–surface processes describing the variations of *LAI* (leaf area index) and *FPAR* (fraction of photosynthetically active radiation) from satellite data (Nakayama, 2008a,b, 2010, 2011a,b, 2012a,b; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Watanabe, 2004, 2006, 2008a,b; Nakayama *et al.*, 2006, 2007, 2010) (Figure 2). The seepage between river and groundwater was also calculated at each time step from the head gradient between the flow depths at river and groundwater level. Details are available in (Nakayama and Watanabe, 2004). In this study, the NICE was expanded to couple with the UCM (Nakayama and Fujita, 2010) to include the effect of water and heat budgets at various engineered pavements in the urban areas and with the RAMS (Pielke *et al.*, 1992) to include the water/heat interaction between land and atmosphere regions (NICE-Urban), as described in the following sections (Figure 3).

Coupling with UCM in urban areas

Land–surface processes were firstly coupled with UCM in NICE-Urban. On the basis of the specific heat conductivity c_s and heat conductivity k_s for natural soil (Sellers *et al.*, 1996), we expanded these values for engineered pavement in the following equations by

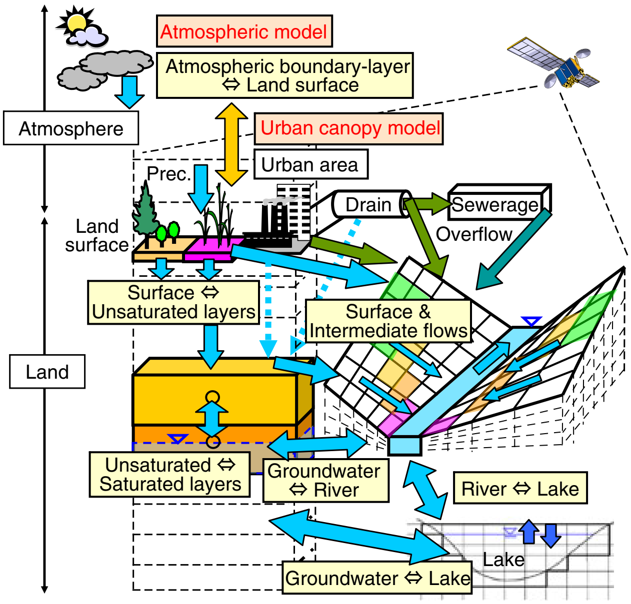

Figure 2. NICE model (Nakayama, 2008a,b, 2010, 2011a,b, 2012a,b; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2011; Nakayama and Watanabe, 2004, 2006, 2008a,b; Nakayama *et al.*, 2006, 2007, 2010)

including the effect of water amount on the heat characteristics in the material:

$$\begin{aligned} c_s &= [0.5(1-\theta_s)+\theta_s W_1]C_w\rho_w \quad \text{for soil} \\ &= C_p\rho_p(1-\theta_s)+C_w\rho_w\theta_s W_1 \quad \text{for engineered pavement} \end{aligned} \tag{1}$$

$$\begin{aligned} k_s &= 0.4186\frac{1.5(1-\theta_s)+1.3\theta_s W_1}{0.75+0.65\theta_s-0.4\theta_s W_1} \quad \text{for soil} \\ &= k_p(1-\theta_s)+k_w\cdot\theta_s\cdot W_1 \quad \text{for engineered pavement} \end{aligned} \tag{2}$$

C_p (J/kg/K) is the specific heat of pavement material, C_w (J/kg/K) is the specific heat of water (4.18×10^6), c_s

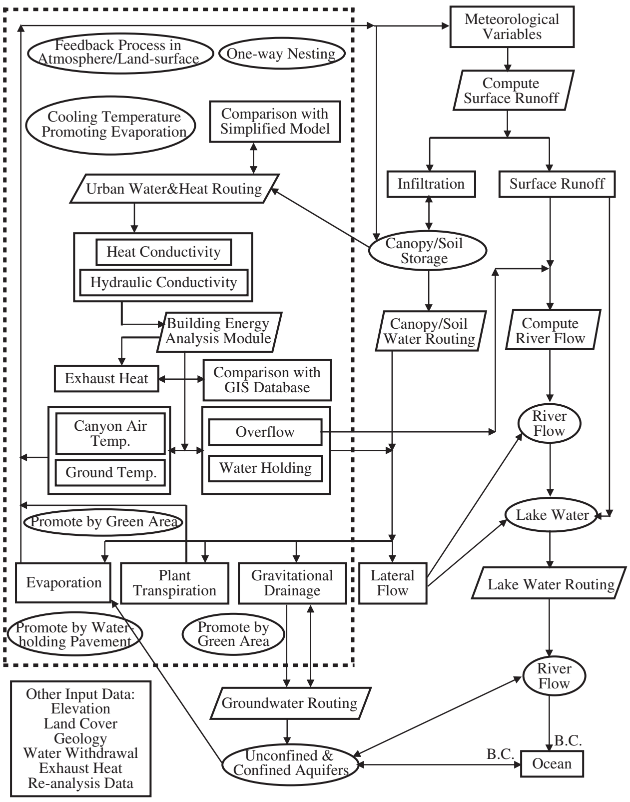

Figure 3. Flow diagram of NICE-Urban model. Dotted frames indicate the newly developed processes in this study. About the detailed process of original NICE, please see the related papers (Nakayama *et al.*, 2007; Nakayama, 2008a,b; Nakayama and Watanabe, 2008a,b)

(J/m^3/K) is the specific heat conductivity including the effect of water, k_s (W/m/K) is the heat conductivity including the effect of water, k_p (W/m/K) is the heat conductivity of pavement material, k_w (W/m/K) is the heat conductivity of water (0.59), ρ_p (kg/m^3) is the specific gravity of pavement material, ρ_w (kg/m^3) is the density of water (1000), W_i is the soil moisture fraction of the ith layer (θ_i/θ_s), θ_i (m^3/m^3) is the volumetric soil moisture in the ith layer and θ_s (m^3/m^3) is the value of θ at saturation.

The area-averaged sensible and latent heat fluxes from the urban surfaces are also defined in the extension of Deardorff's (1978) concept of vegetation fraction covered by intercepted water, as follows:

$$H_g = \frac{\rho_a C_a}{r_g}\left(T_g - T_a\right) \tag{3}$$

$$\lambda E_g = \frac{\rho_a C_a}{\gamma}\frac{W_g}{r_g}\left(e_*\left(T_g\right) - e_a\right) \tag{4}$$

$$\begin{aligned} W_g &= M_g/S_g \quad \text{when } e_*\left(T_g\right) > e_a \\ &= 1 \quad \text{when } e_*\left(T_g\right) \le e_a \end{aligned} \tag{5}$$

where H_g (W/m^2) is the sensible heat flux from the ground, ρ_a (kg/m^3) is the density of water (1.2), C_a (J/kg/K) is the specific heat of air (1010), r_g (m/s) is the aerodynamic resistance of the ground, T_a (K) is the canyon air space temperature, λE_g (W/m^2) is the latent heat flux from the ground, γ (mb/K) is the psychrometric constant (0.662), $e(T_g)$ (hPa) is the saturation vapour pressure at T_g, e_a (hPa) is the vapour pressure at canyon air space, W_g (−) is the fractional wetted area of ground, M_g (m) is the water on the canopy and on the ground and S_g (m) is the maximum value of water store at the ground. For bare soils, Equation 4 is altered when the soil is undersaturated with relative humidity. For vegetation covers, the transpiration flux adds to the evaporation to form the evapotranspiration flux.

Land–atmosphere interactions in urban areas

The general equations for the atmospheric model (RAMS) are standard hydrostatic Reynolds-averaged primitive equations (Pielke *et al.*, 1992). The equations are consisted of motion, thermodynamic, water species mixing ratio continuity, mass continuity and hydrostatic equations. All variables, unless otherwise denoted, are grid-volume-averaged equations where the overbar has been omitted. Downward short- and long-wave radiation, precipitation, atmospheric pressure, air temperature, air humidity and wind speed simulated by the atmospheric model are input into UCM, whereas momentum, sensibility, latency and long-wave flux simulated by the UCM are input into the atmospheric model at each time step. This procedure means that the feedback process about the interaction of water and heat transfers between atmospheric region and land surface are implicitly included in the simulation process (Figures 2 and 3).

Hydrothermal cycles between buildings

One-dimensional equations for momentum, heat and vapour (wind velocity, air temperature and specific humidity) inside the boundary layer between buildings are described by considering the influence of building existence on diffusing potentials in the following equations:

$$m\frac{\partial U_a}{\partial t} = \frac{\partial\left(K_m m \frac{\partial U_a}{\partial z}\right)}{\partial z} - F_{ex} \tag{6}$$

$$m\frac{\partial T_a}{\partial t} = \frac{\partial\left(K_h m \frac{\partial T_a}{\partial z}\right)}{\partial z} + H_{ex} \tag{7}$$

$$m\frac{\partial q_a}{\partial t} = \frac{\partial\left(K_v m \frac{\partial q_a}{\partial z}\right)}{\partial z} + \lambda E_{ex} \tag{8}$$

where z (m) is the vertical direction from the ground surface, U_a (m/s) is the wind velocity, T_a (K) is the canyon air space (outdoor) temperature, q_a (kg/kg) is the specific humidity, m is the ratio of volume density of air, F_{ex} (m/s^2) is the friction coefficient, K_h and K_v (m^2/s) are the eddy coefficients of heat and vapour, respectively, and H_{ex} and λE_{ex} (W/m^2) are the sensible heat and latent heat flux exhausted from the buildings, respectively. The sensible heat and latent heat flux exhausted from buildings are described in the following equations:

$$H_{\mathrm{ex}} = \left(1 + \frac{1}{\mathrm{COP}(T_{\mathrm{a}})}\right)\alpha_{\mathrm{s}}(T_{\mathrm{a}} - T_{\mathrm{set}}) \tag{9}$$

$$\lambda E_{\mathrm{ex}} = \left(1 + \frac{1}{\mathrm{COP}(T_{\mathrm{a}})}\right)\alpha_{\mathrm{l}}(q_{\mathrm{a}} - q_{\mathrm{set}}) \tag{10}$$

where T_{set} (K) is the target air temperature set by air-conditioning system inside the buildings, COP is the coefficient of performance, the so-called total mechanical performance of heating ventilating and air-conditioning systems depending on the outside air temperature T_a (K) in the same way as (Hagishima *et al*., 2001); and α_s and α_l are coefficients, respectively. After simulating the previously mentioned one-dimensional equations for momentum, heat and vapour, the horizontal momentum equation was solved for preserving the continuity equation at each time step. Although this scheme simplifies the anthropogenic heat calculation on the assumption that all of the anthropogenic heat is emitted from the buildings depending on the difference between the outside air temperature and the temperature inside the buildings, this was coupled to the urban canopy and the atmospheric models to automatically simulate the feedback processes of hydrothermal cycles between the outdoor and each urban building (Figure 3).

INPUT DATA AND BOUNDARY CONDITIONS FOR SIMULATION

Input data and boundary condition

Hourly observation data from Automated Meteorological Data Acquisition System (AMeDAS) data (Japan Meteorological Agency, 2005a) at 126 points were assimilated with NICE-Urban. The artificial augmentation of waterworks and sewerage systems discharging into the sea was input to the model using statistical data for domestic and industrial water use (Digital National Land Information GIS Data of Japan, 2002). Annual data on groundwater use covering the Kanto Plain (Digital National Land Information GIS Data of Japan, 2002) were digitized and input to the model. The rate of water withdrawal at the surrounding (western) area of Kawasaki district was approximately 149 000 m^3/day in 2004 (Kawasaki City Government, 2004a,b). Because there were no annual time series data for agricultural groundwater use, we assumed that the time series of water withdrawal would be similar for the entire study area and used the data that had been reported inside the study area, in the same way as for the Lake Kasumigaura catchment (Nakayama and Watanabe, 2008a).

Vertical geological structures were divided into 10 layers with a weighting factor of 1.1 by using a 206-sample database and a digital elevation model (Geographical Survey Institute of Japan, 1999), where the upper layer was set at a 2-m depth and the 10th layer was defined as an elevation of −500 m. The geological structure was divided into four types on the basis of hydraulic conductivity (K_h and K_v), specific storage (S_s) and specific yield (S_y) (Nakayama *et al*., 2007). Approximately 50 vegetation and soil parameters were calculated on the basis of vegetation class and soil texture obtained from the Digital National Land Information GIS data of Japan (2002).

At the upstream boundaries, conditions affecting the hydraulic head were used for the model on the supposition that there is no inflow from the opposite direction of mountains. The time series of tidal level was input as a constant head at the sea boundary (Nakayama *et al*., 2007). The hydraulic head values parallel to the ground level were input as the initial conditions for the groundwater flow submodel. At the lateral boundaries of regional area, some meteorological data such as temperature, humidity, wind speed, altitude and sea surface temperature are input to the model from the European Centre for Medium-Range Weather Forecasts (ECMWF) with a resolution of 1° × 1° and from the Meso Scale Model (MSM) with a resolution of 10 km x 10 km (Japan Meteorological Agency, 2005b).

Building structure and anthropogenic heat source in urban areas

The anthropogenic exhaustion heat generated by consuming energy considering the difference of sensible and latent heat was analysed by using the GIS database about fundamental investigation for urban planning in the study area (Kawasaki City Government, 1994; Tokyo Metropolitan Government, 2001; Yokohama City Government, 2003) (Figure 4). Because some studies discuss that the main sources of anthropogenic heat emission are from buildings and from factories in Kawasaki City, which is located in the centre of Keihin Industrial Area, were analysed the anthropogenic sensible and latent heats generated by buildings (office, household, etc.) and factories (including chimney) on the basis of unit anthropogenic heat. The anthropogenic sensible, latent and sewage heats at each mesh (200-m resolution) every hour were calculated by multiplying an area of each building use and land use with a unit energy consumption in eight types of land use (detached house, apartment house, office, business, hotel, school, factory and other) in the previous report (Ministry of Environment, 2004b). The calculated heats were input into each layer of the model, including the vertical direction of a vent and an exhaust fan within averaged building height as much as possible, because this location is very different from building and factory. These calculated heats were also used to calibrate and validate the anthropogenic heat emissions simulated automatically by the feedback process of NICE-Urban in Equations 9 and 10 (Figure 3).

Running the simulation and validation

The simulation was conducted with multiscale levels in horizontal regional area (260 km wide × 260 km long with a grid spacing of 2 km, covering almost all of the Tone River catchment and Tokyo Bay) nesting with one way to urban area (36 km wide × 26 km long with a grid

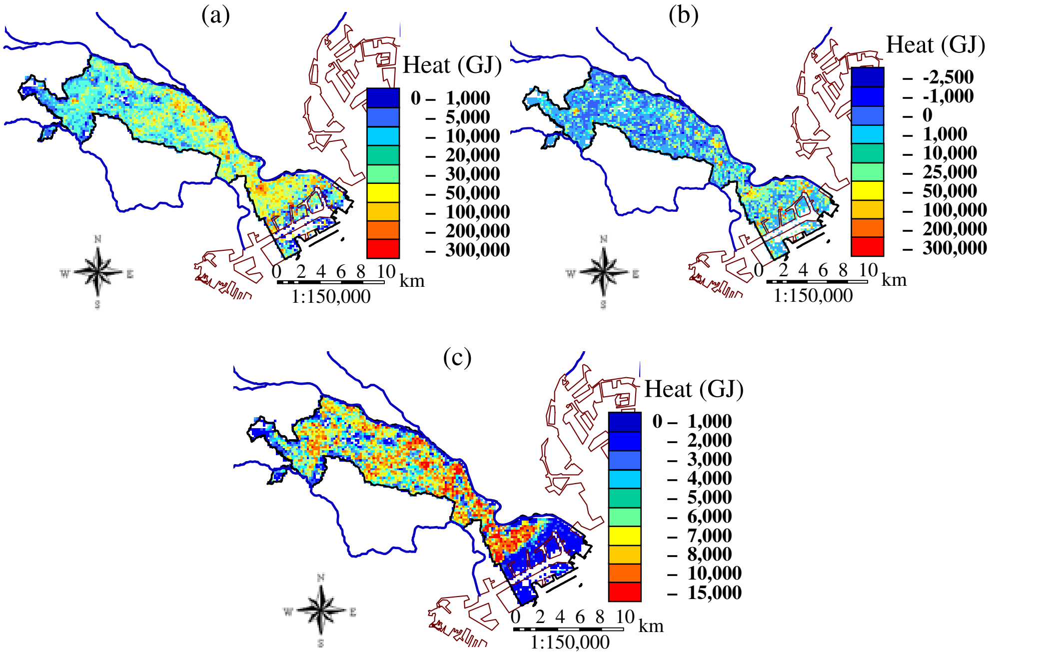

Figure 4. Distribution of anthropogenic heat sources about (a) sensitive heat flux, (b) latent heat flux and (c) sewage heat flux

spacing of 200 m, covering the entire Kawasaki City) not only for atmospheric models but also for groundwater models (Nakayama *et al.*, 2007), and in vertical atmosphere–surface–unsaturated–saturated layers (Figure 1). The NICE-Urban simulation was conducted on an NEC SX-8 supercomputer. Simulations were performed for 3 years from 1 January 2004 to 31 December 2006. The first 6 months were used as a warm-up period until equilibrium water levels were reached, and parameters were estimated by the comparison of simulated steady-state values under steady-state conditions with observed values published in the literature (Clapp and Hornberger, 1978; Rawls *et al.*, 1982). A time step of the simulation was changed from $\Delta t = 1.5$ s to 1 h, depending on the spatial scale and the submodels. Observed data (9 points for groundwater level, 6 points for river discharge and 29 points for air temperature and humidity) (Kawasaki City Government, 2004a,b; Kanto Regional Development Bureau, 2005–2006) were used to validate the simulations (Figure 1).

ALTERNATIVE LAND COVER SCENARIOS TO IMPROVE HYDROTHERMAL CHARACTERISTICS BY ADOPTING POLICIES AND TECHNOLOGY

Various urban structures interrupt the infiltration of groundwater, and the return period of the water cycle becomes shorter because of increased surface flow. Because industrial, agricultural and domestic water demand has been increasing year by year in urban areas, the use of groundwater for human activity, in addition to river flow, is very important because of its constancy and magnitude. Because groundwater is constantly cool, it has recently received attention as a possible means of controlling the urban heat island phenomenon (Ministry of Environment, 2003) in addition to its effect on global warming. Therefore, it is urgently necessary to prevent the overpumping of groundwater and to promote its infiltration into aquifers to avoid groundwater degradation, land subsidence and saltwater intrusion around urban areas.

In the field of land use planning, scenario-based analyses have long been used since the 1940s to obtain better understanding about the effectiveness of alterative policy and technology options under uncertain situation (Shearer *et al.*, 2004; Kahyaogˇlu-Koracˇin *et al.*, 2008). In this study, in addition to a reference scenario that represents present land cover, we have prepared two types of land cover scenarios to promote evaporation and to reduce air temperature against heat island phenomenon in the urban areas (Figure 5) because the promotion of infiltration or natural restoration has recently been considered as one of the proven measures against the urban heat island phenomenon (Ministry of Environment, 2004c; Ministry of Environment, 2006). The first scenario is a technology-oriented approach that introduces water-holding pavement to promote the positive cooling through evaporative latent heat effects (Nakayama and Fujita, 2010). In contrast, the second scenario is a natural restoration–oriented approach that introduces new or expands existing green areas to promote the passive cooling effect from plant evapotranspiration (Nakayama *et al.*, 2007). These scenarios are designed in line with Techno-Garden scenario and Adapting-Mosaic scenario, both of which were developed for the Millennium Ecosystem Assessment (2005). The former scenario expects technological enhancement of ecosystem services, whereas the latter integrates ecological processes with management institutions. In this study, to evaluate the maximum cooling effect, the two scenarios were applied to all the vacant spaces of building sites and open spaces such as parks available in Kawasaki (Table I). The

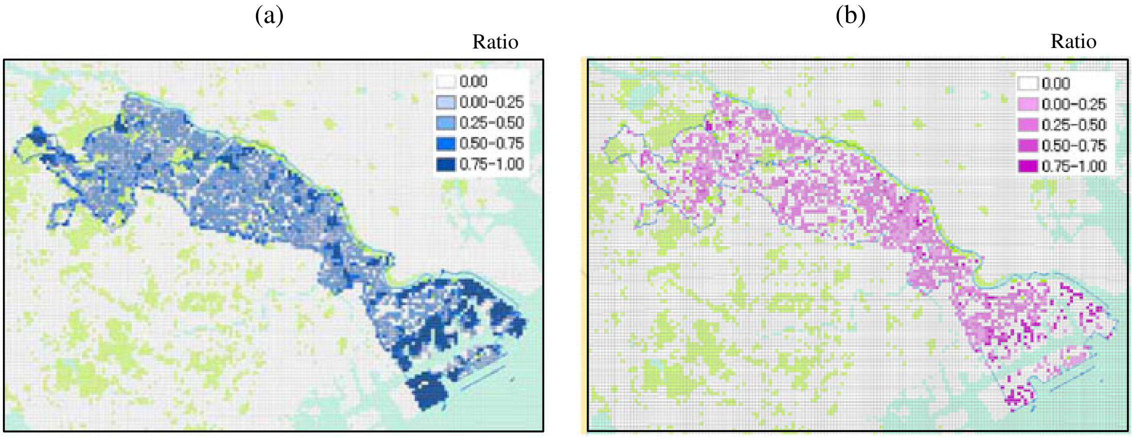

Figure 5. Ratio to apply political scenario for promoting evaporation and reducing air temperature against heat island phenomenon in the urban areas; (a) water-holding pavement as the positive cooling effect and (b) green area as the passive cooling effect

Table I. Present land use and available vacant space considered in the scenario simulation

Land use	Area (km^2)	Available vacant space (km^2)
Industrial site	18.4	13.5
Low-rise residential area (general)	40.0	12.8
Low-rise residential area (high density)	0.5	0.1
Medium-to-high-rise residential area	17.0	5.6
Commercial and business area	4.8	3.0
Parks and green area	2.2	1.9
Public institution area	16.6	5.3
Road	10.8	N/a
Forest	9.9	N/a
Rice paddy	0.1	N/a
Cultivated land	2.2	N/a
River and lake	6.3	N/a
Sea	8.8	N/a
Other	6.7	N/a
Total	144.4	42.1

vacant spaces taken into account here were identical to the target areas of existing land use legislation put in place aiming at nature restoration and amenity creation (Kawasaki City Government, 2008). Thus, the difference of cooling effects to be clarified by comparing the three scenarios would help policy makers prioritize alternatives or decide which approach to promote as a countermeasure against the urban heat island phenomena. Building and land use GIS database originally developed for city planning of Kawasaki were used in this study to identify the vacant spaces and open spaces, which provide realistic conditionings for numerical simulation.

RESULTS

Effect of urban structures on land–atmosphere interactions

The simulated air temperature was compared with the observed value in the entire Kawasaki area from 1 August to 31 August 2006 (Kawasaki City Government, 2004a,b) (Figure 6). The previous research at the rooftop of the

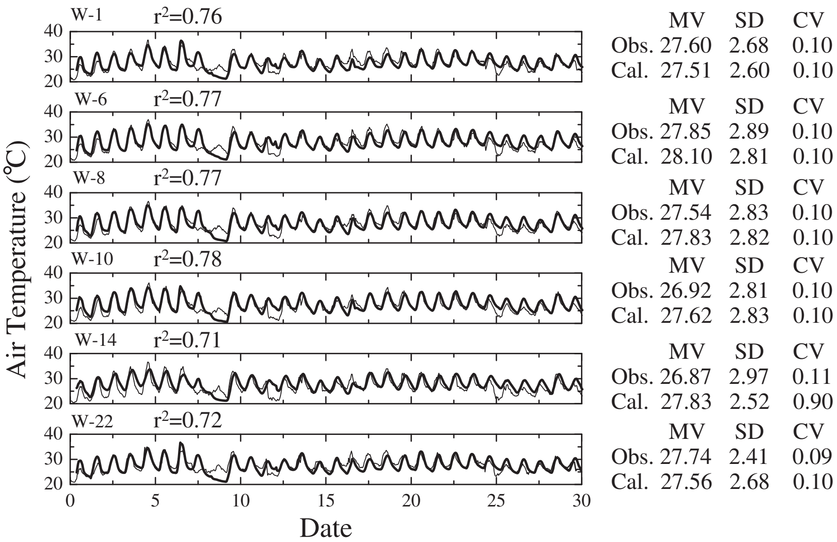

Figure 6. Comparison of simulated air temperature with observed value (Kawasaki City Government, 2006) at 2.0 m above the ground surface in the points in Figure 1 (○; W-1 to W-29). Solid line, observation data; bold line, simulated results by NICE-Urban. Date = 0 in the horizontal axis corresponds to 1 August 2006. r^2, MV, SD and CV are correlations between observed value and simulated value, mean value, standard deviation and coefficient of variation (SD/MV), respectively

Keihin building (P-1 in Figure 1) (Nakayama and Fujita, 2010) showed that NICE could reproduce excellently the observed air temperature at various surface pavements related to the water cycles and that the air temperature was less sensitive to the forcing data than the surface temperature in the same way as Asaeda and Ca (1993). The simulated air temperature does not agree with the observed value after 9 August mainly because of the inaccuracy of simulated precipitation. Generally, the simulated air temperature in NICE-Urban agrees well with the observed value at various land covers such as cultivated field, residential area, business district and industrial area, which can be seen at the high correlation (r^2 = 0.70–0.80) and the similar statistical value (MV, SD and CV).

Figure 7 compares the simulated groundwater level in the Kawasaki area from 1 January to 31 December 2004 with the observed value (Kawasaki City Government, 2004a,b). The simulated river discharge and groundwater level for the riverbed transmissivity: $k_r = 300\,m^2/h$ agrees closely with the measured value (Nakayama and Watanabe, 2004), and therefore this k_r value was used in the following simulations. In the mountainous areas (G-7 to G-9 in Figure 1), the observed groundwater level generally corresponded with the precipitation distribution and increased suddenly at the fall typhoon season, which could be well reproduced by the model, and the correlation is high. In the highly urbanized areas (G-1 to G-5 in Figure 1), the level was almost constant and sometimes showed a tendency unrelated to a precipitation pattern. This tendency is remarkable in the highly industrialized areas besides the seas (G-1 to G-2 in Figure 1), where the level gradually decreased mainly because of the ocean tide, almost impervious surface (road, embankment, dike, etc.) covered by asphalt and concrete, and the water withdrawal in the urban area (Nakayama *et al*., 2007). The simulated groundwater level reproduces the observed values very accurately, both in the mountainous area, plain area and near the sea, owing to the recharge rates simulated by the NICE-Urban between the lowest unsaturated layer and the highest saturated layer (Nakayama and Watanabe, 2004, 2006).

Validation of heat-flux budget in the symbiotic urban pavements

The simulated heat-flux budget was compared with the analysed value at the infiltration and water-holding pavements in the Todoroki car parking area (F-1 in Figure 1) from 3 August to 8 August 2007 (Figure 8). The water-holding pavement takes approximately 10.0 °C lower of the surface temperature than the infiltration pavement. The observed daily cycles of the road surface and air temperature at 1.5 m height were compared with those simulated by the NICE-Urban after water irrigation in the same way as the previous research (Nakayama and Fujita, 2010) (data not shown). The model generally captured the observed water amount and the associated diurnal cycle of the road surface and air temperature and could estimate the temperature decrease trend with high accuracy. This cooling temperature is closely related to the promotion of vaporization by using the water-holding pavement, and this trend continues during 5 days after the completion of the water-holding pavement. In this field experiment, these heat fluxes were estimated by using bulk method, and the errors in the cumulative heat flux had the range from −0.2% to 1.2% in the day following irrigation water of approximately 5.4 l per 1 m^2 at 3 August. The rapid increase of latent heat (438 W/m^2) relative to sensible heat (127 W/m^2) was reported in the field observation at sprinkling roads (Yamagata *et al*., 2008). The simulated maximum sensible and latent heat fluxes in the water-holding pavement just after water irrigation were 130 and 345 W/m^2, which had relatively good approximations of 161 and 337 W/m^2 in the observed values and the previous research. Although the simulated heat-flux budget in the infiltration pavement did not agree well with the estimated value, the model could simulate reasonably the general trend that the latent heat in this pavement was smaller than that in the water-holding pavement because the infiltration was more predominant than the evaporation, as described by the previous research (Nakayama and Fujita, 2010). The

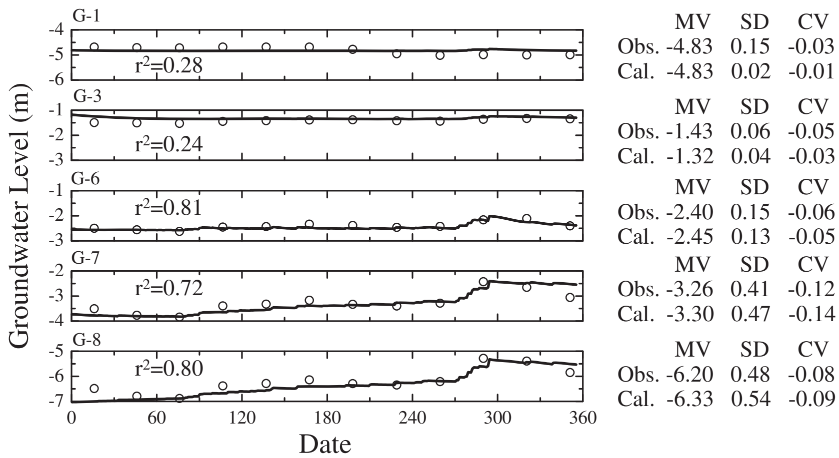

Figure 7. Comparison of simulated groundwater level with observed value (Kawasaki City Government, 2004) at the points in Figure 1 (△; G-1 to G-9). Circle, observation data; line, simulated results by NICE-Urban. Date = 0 in the horizontal axis corresponds to 1 January 2004. r^2, MV, SD and CV are correlations between observed value and simulated value, mean value, standard deviation and coefficient of variation (SD/MV), respectively

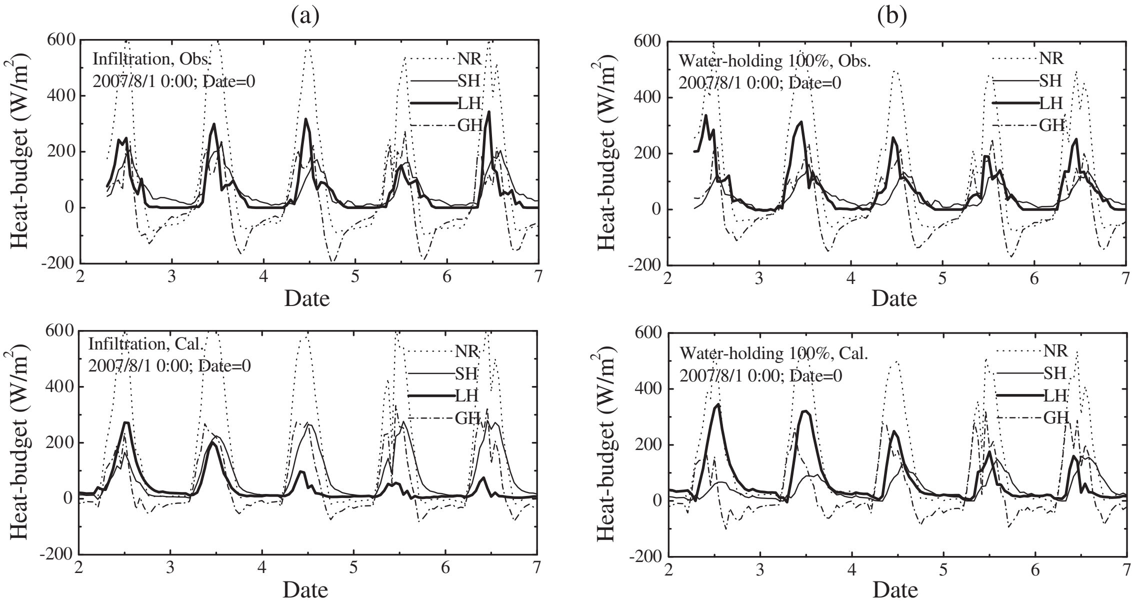

Figure 8. Validation of heat-flux budget in the symbiotic urban pavements after water irrigation (3 August 2007) at the points in Figure 1 (□; F-1); (a) infiltration pavement and (b) water-holding pavement. Dotted line, net radiation (NR); solid line, sensible heat flux (SH); bold line, latent heat flux (LH); and dash-dotted line, ground transfer heat flux (GH). Date = 0 in the horizontal axis corresponds to 1 August 2007

simulated result shows that the newly symbiotic urban pavement is very effective to promote the cooling temperature, which was expanded in the study area in the following sections.

Effect of anthropogenic heat on hydrothermal changes in urban area

We evaluated the effect of exhaust heat on the hydrothermal changes in the urban area (Figure 9). The simulated result indicates that the effect of exhaust heat (Figure 4) on the change of air temperature is important in the urban area, in particular, in the business and industrial districts beside the sea area (Figures 9a and 9b), which is similar to the previous research that the waste heat from the air conditioners has caused a temperature rise of 1–2 °C or more on weekdays in the Tokyo office areas (Ohashi *et al*., 2007). In the business and residential areas, the exhaust heat is predominant about the surface and the height of 10 m, which correspond to low-rise building/ house and high-rise building, and the corresponding

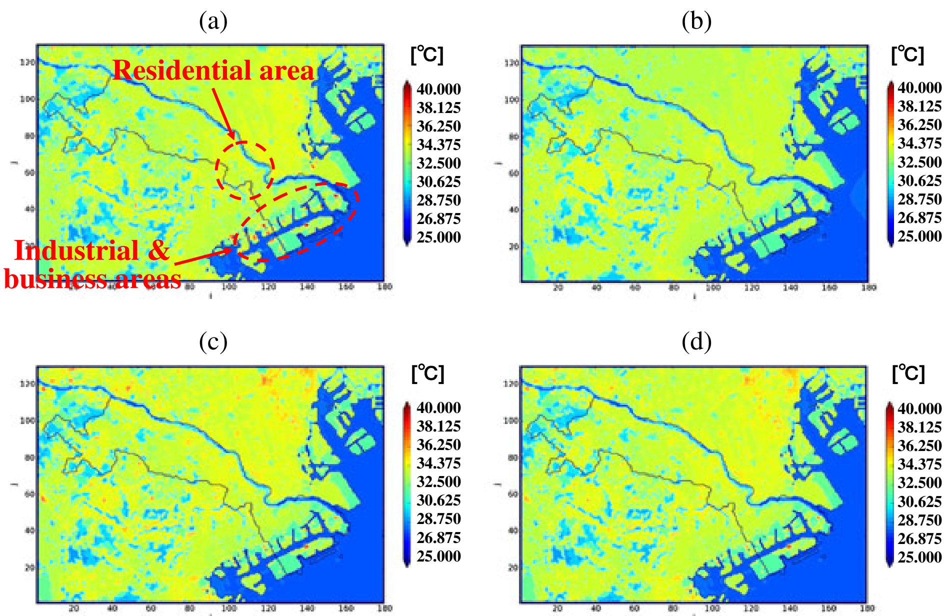

Figure 9. Effect of exhaust heat on the change of air temperature in the urban area at 15:00 h JST on 19 August 2006. Simulated values (a) by inputting anthropogenic heat source data in Figure 4, (b) without anthropogenic heat source and by coupling with the building energy analysis model at the target air temperature of (c) 26.0 °C and (d) 28.0 °C

temperature rise occurs up to the top of the buildings (data not shown). The simulated air temperature by coupling with the building energy analysis model (Figures 9c and 9d) agrees well with the temperature distribution by inputting anthropogenic exhaustion heat evaluated by the GIS database (Figures 9a), in particular, the higher temperature in the industrial and business districts around coastal landfills, which implies that the exhaust heat simulated by the building energy analysis model can reproduce generally the spatial distribution of real emission despite the simplified scheme. This result also indicates that the target air temperature set by air-conditioning system greatly affects the exhaust heat and the outside air temperature and that the energy consumption process in each building should be incorporated in the modelling of hydrothermal changes in the urban area (Ichinose *et al.*, 1999; Kusaka and Kimura, 2004b).

Prediction of hydrothermal changes in the symbiotic urban scenario

We forecasted the hydrothermal changes in the symbiotic urban scenario in Figure 5 (Figures 10 and 11). The previous research showed that the water content of the block affects not only the surface temperature but also the air temperature above the surface (Nakayama and Fujita, 2010). Because the model estimates that the air temperature at the water-holding pavement is 1–2 °C lower than that at the lawn and 3–5 °C lower than that at the building rooftop as the surface level (Saaroni *et al.*, 2000), it is very powerful to use this material for positive cooling effect in combination with the lawn for passive cooling effect not only at the surface level but also at the street level and regional scale (Nichol and Wong, 2005), as described in the previous section.

Because the air temperature was relatively high with no rainfall and the heat island was severe at 15:00 h JST on 5 August 2006 (Figure 6), it is better and effective to deal with such a time to evaluate and show clearly the cooling effect of water-holding pavement in addition to green area. The simulated surface temperature on the scenario of water-holding pavement shows the drastic decrease in the entire Kawasaki City (Figure 10b). In particular, the business district area beside the sea (Figure 10a), where the urban heat island is predominant mainly due to the paved surface (Figure 1) and the greater anthropogenic heat sources (Figure 4), has an effective cooling on this scenario. The simulation shows that the scenario of a natural zone and green area is also effective for cooling temperature in the study area (Figure 10c). The simulated air temperature in both cases decreased not only at the business district in the Kawasaki area but also at the Tokyo metropolitan area in the northern side of this study area (data not shown). This is very important from the political point of view, which indicates that we have to estimate more precisely the arrangement of symbiotic urban scenario in the study area together with the neighbouring administrations.

The predicted groundwater level change in August is interesting in contrast to the above-simulated air temperature (Figure 11). In the simulation on the scenario of water-holding pavement, all the necessary water to fill the water-holding pavement was automatically simulated by considering the difference between precipitation and

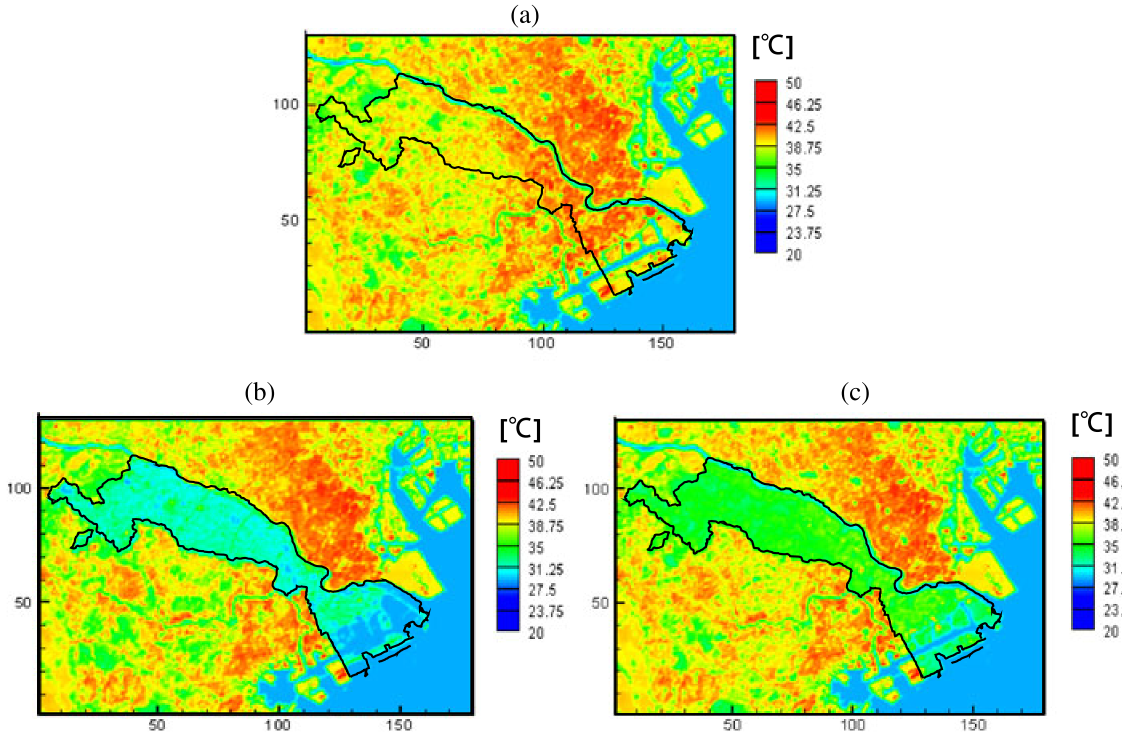

Figure 10. Simulation of thermal changes at 15:00 h JST on 5 August 2006 in the symbiotic urban scenario in Figure 5; (a) present surface temperature, (b) prediction after water-holding pavement and (c) after green area

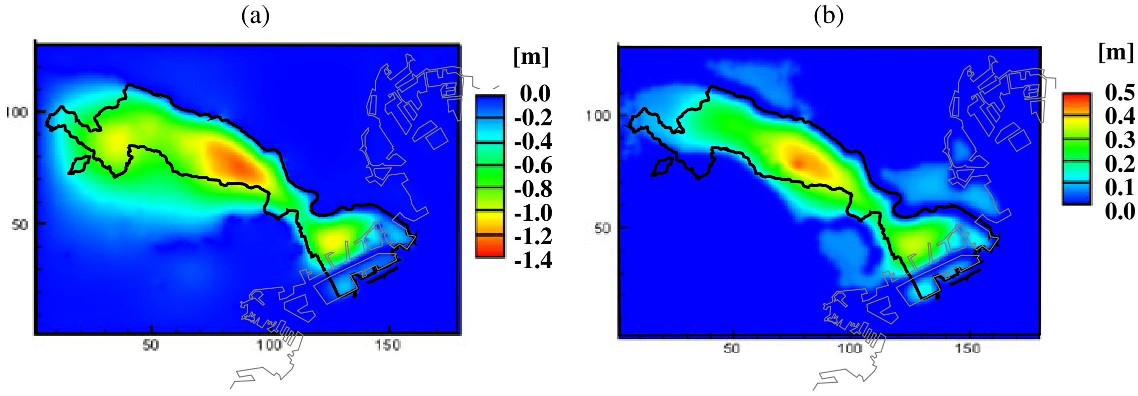

Figure 11. Prediction of monthly averaged groundwater level change in August after the symbiotic urban scenario in Figure 5; (a) after water-holding pavement and (b) after green area

evaporation and withdrawn from the underneath groundwater in the NICE-Urban, which means that the pavement was always saturated. The increase of recharge rate and the consequent groundwater level increase on the scenario of a natural zone and green area are also very effective to promote the groundwater resources in the urban area covered by impermeable pavement (Figure 11b) (Nakayama *et al.*, 2007). As for the scenario of water-holding pavement, the groundwater level would decrease drastically, in particular, at the commercial and industrial areas beside the sea and at the inland residential area (Figure 11a), in exchange for a drastic cooling in the corresponding and the surrounding areas (Figure 10b). Because this phenomenon is closely related to the heat capacity of water and the conductivity of the pavement, the water temperature under the ground is also an important factor. Because the water temperature in an aquifer is almost constant throughout the year, we are convinced that the use of groundwater as a heat sink would be very effective for tackling the urban heat island phenomenon, particularly during the summer (Ministry of Environment, 2003; Nakayama and Fujita, 2010).

DISCUSSION

Although NICE-Urban generally reproduced reasonably hydrothermal characteristics such as air temperature (Figure 6), groundwater level (Figure 7) and heat-flux budget (Figure 8) at the observation stations in urban area where most of the urban area is covered by engineered pavements (Figure 1) by including the exhaust heat generated by buildings and factories (Figure 4), there are some disagreement between the simulated and the observed values. The simulated air temperature could not agree with the observed value after rainfall mainly because of the inaccuracy of simulated rainfall in NICE-Urban (Figure 6). Because the original atmospheric model (RAMS) cannot reproduce a rainfall correctly when nesting with one way to local scale (Pielke *et al.*, 1992) despite better reproduction of cloud cover (data not shown), it is necessary to improve the submodel of RAMS or to use another atmospheric model such as Weather Research and Forecasting (WRF) (Skamarock *et al.*, 2005) in the future. Because the weather observation data may have some inaccuracy due to some different methods to observe data between ambient air monitoring station at the top of buildings (W-21 to W-29 in Figure 1) and screen higher than 1 m from the ground (W-1 to W-20 in Figure 1) (Kawasaki City Government, 2004a,b), it is important to normalize somehow these data in the same standard, including the effect of heterogeneity in the urban area. The comparison of heat flux budget in engineered pavements is important in addition to the evaluation of water conservative mass in pavements (Andersen *et al.*, 1999; Ramier *et al.*, 2004; Nakayama and Fujita, 2010), including the overflowing water, surface storage, drainage and evaporation (Figure 8). Discrepancies between analysed and simulated values are more predominant in the latent heat flux than in the other fluxes. This is mainly because experiments on water content are very sensitive to internal factors such as surface tension and soil moisture and external factors such as wind velocity, sway of building and heterogeneity of materials, in addition to the sensitivity of saturated hydraulic conductivity and surface storage capacity of the pavements (Dupont *et al.*, 2006; Ramier *et al.*, 2006). Although the simulation could reproduce well the observed groundwater level both in the mountainous and in the urbanized areas (Figure 7), it underestimated the decreasing trend in the urbanized areas near the Tokyo metropolitan area (G-1 and G-2 in Figure 1). We have to obtain more data about underground urban structures and water withdrawal in the urban area to reproduce better the observed value (Nakayama *et al.*, 2007). Anyway, this validation (Figure 7) and the prediction in the symbiotic urban scenario (Figure 11) indicate that the heterogeneity of geological materials, in particular, impermeable layer and engineered pavements, affects greatly the groundwater flow and that the effect of the promotion of withdrawal and infiltration in the urban area (Figure 5) on the groundwater distribution spreads over the surrounding coastal and mountainous areas. Improvement in field experiments and further collecting data on various physical characteristics, human activities and artificial structure is important if we are to reproduce actual phenomena more accurately.

Actual heterogeneity in various buildings, roadways and parking composed of vertical multiple layers with different density should be further included in the model to estimate and improve the hydrothermal cycles of semi-infinite conditions more in detailed (Nakayama *et al*., 2007; Nakayama and Fujita, 2010). This complexity plays an important role not only in the vertical water exchange between pavement and unbound granular materials (Ragab *et al*., 2003; Ramier *et al*., 2006) but also in the horizontal water transport above ground and under subsurface. Because it is really difficult to get all the parameter values in experiments to consider this actual heterogeneity, we should simplify the mechanism as logically as possible in the model. It is also effective to apply a physically based 'mosaic' or 'tile' approaches (Ament and Simmer, 2006) by coupling ground-truth experiments with spatial analyses like using satellite data. Although NICE-Urban implied that the effect of main sources of anthropogenic heat emission generated by buildings and factories (Figure 4) on the change of air temperature is important, particularly in the business and industrial districts beside the sea area (Figures 9a and 9b), it is further necessary to include other exhaust heat such as the transportation in the model for the more detailed evaluation despite the difficulty of estimating the spatial/temporal traffic distribution and density (Ichinose *et al*., 1999). This is also related to the fact that the target air temperature set by air-conditioning system greatly affects the exhaust heat and the outside air temperature by incorporating with a simple building energy analysis model (Figures 9c and 9d). The hydrothermal prediction on the symbiotic urban scenarios like water-holding pavement and green area would be more attractive if the more detailed energy consumption process is further developed not only at the surface level but also at the street level and regional scale (Figure 11) (Nichol and Wong, 2005; Yamagata *et al*., 2008).

There are various measures to mitigate urban heat island in the world. The study area is one of the most severe heat island regions. The central and local governments have taken various measures to mitigate this effect by changing and rearranging surface layer, reconstructing elderly buildings and urban geometry and applying green-infrastructure system in parks and flood plains, in addition to increasing energy efficiency and managing traffic/transportation system. On the other hand, we are troubled with serious damage by flooding and buoyant forces to underground infrastructures after the regulation of groundwater use (Endo, 1992; Nakayama *et al*., 2007). Nowadays, the roles of water resources such as river, lake, sea and groundwater are thought important for the mitigation of the urban heat island. Watersides are becoming precious as an urban cool island in addition to open parks and green areas (Ministry of Environment, 2003; Kawasaki City Government, 2008). A policy to promote infiltration into the aquifer is nevertheless important to prevent ground degradation as has occurred in the past, in addition to holding some water in the unsaturated layer. Pavements and buildings made of materials such as concrete and asphalt cover most of the urban area, and here many of the rivers are covered on three sides, which resulting in a decrease of infiltration. This study showed that the groundwater level increases predominantly at a maximum value exceeding 40 cm in the scenario of green areas and that the level recovers in some parts of the urban area beside the Tokyo bay including Kawasaki City (Figure 11b), which are plausible by considering the detailed evaluation of hydrologic budget in our previous research (Nakayama *et al*., 2007). Although the predicted groundwater level might fluctuate to some degree on the assumption that all the necessary water to fill the water-holding pavement is automatically supplied from the underneath groundwater by considering the difference between precipitation and evaporation in the model (Figure 11a), the result would be relatively reasonable from the view point of hydrologic budget. Recently, Okada *et al*. (2007) have developed lotus-type porous ceramics with high water pump-up ability and confirmed that the possible pump-up height is as high as 80 cm by cylindrical capillary, which implies that this type of new technology and material would be practically effective as countermeasure against the urban heat island.

It is further necessary to evaluate the relationship between the effect of water resource's use to ameliorate the urban heat island phenomenon and its effect on the hydrologic cycle at regional scale (Nichol and Wong, 2005; Yamagata *et al*., 2008) in view of both surrounding administrations and catchments. In particular, the water temperature in an aquifer is almost constant throughout the year. The alternative land cover scenario of green area (Figure 5b) is effective for the urban area of groundwater depression and seawater intrusion to promote the infiltration and to cool temperature, whereas another scenario of water-holding pavement (Figure 5a) is effective for the urban area of floating subways, stations and buildings to use moderately groundwater and to ameliorate the severe heat island. Therefore, the effective management of water resources including groundwater as a heat sink, particularly during the summer, would be attractive for both recovering a sound hydrologic cycle and tackling the urban heat island phenomenon (Ministry of Environment, 2003; Nakayama *et al*., 2007), the so-called win–win approach. We are convinced that the integrated management of both surface water and groundwater by using NICE-Urban in a political scenario for the effective selection and use of ecosystem service sites (Millennium Ecosystem Assessment, 2005) would play an important role in the creation of thermally pleasing environments and in the achievement in sustainable development in urban regions.

CONCLUSION

The process-based NICE model was coupled with UCM and the RAMS, with horizontal and vertical multiscales, to simulate the effect of urban geometry and anthropogenic exhaustion on the hydrothermal changes in the

Japanese megalopolis (NICE-Urban). NICE-Urban reproduced reasonably the observed hydrothermal characteristics including the water and heat budgets in various types of natural and engineered pavements, evaluated the role of a new surface material (water-holding pavement) in promoting evaporation and cooling temperature to counter the urban heat island phenomenon and predicted the hydrothermal changes under alternative land cover scenarios. These procedures to integrate the multiscaled model simulation with political scenario on the basis of the effective management of water resources as heat sink/source would be very powerful approaches to recovering a sound hydrologic cycle and create thermally pleasing environments in the megalopolis.

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