

# Recent development of assessment tools for urban climate and heat-island investigation especially based on experiences in Japan

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## Abstract:

In recent years, problems concerning the urban climate—including the urban heat-island effect and urban air pollution – have attracted much attention in terms of the widespread urbanization in many parts of the world, including Japan. Assessment tools for urban climate are very important to understand effective countermeasures for heat-island mitigation. In this paper, various assessment tools are introduced and classified according to corresponding modelling scales. Special attention is given to the recent progress in Japan. It is shown that these assessment tools are very powerful at estimating the effectiveness of countermeasures. Furthermore, these assessment tools should become design tools for practical applications in the future. Copyright © 2007 Royal Meteorological Society

KEY WORDS assessment tool; heat island; urban climate; modelling scales

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## INTRODUCTION

In recent years, urbanization has been spreading all over the world, including Japan. These urban developments have caused regional climatic changes, i.e. urban climate – including urban heat-island effect and urban air pollution. Figure 1 illustrates the development of urbanization in Tokyo since the Meiji era (Ojima, 1991). The increase in air temperature measured during the period (1880–1980) is given in Figure 2, and is 2 °C at a height of about 1.5 m. The rise in air temperatures across Tokyo during the past 100 years is much more than that of global air temperatures. The existence of an urban heat island around Tokyo is both clear and remarkable from the above two figures. Numerous environmental problems have occurred in concert with this urban heat island; thermal discomfort, heat disorders, increased demand for electricity for cooling, ecological changes, etc. Various countermeasures to these problems have been proposed and implemented – such as, roof greening, use of high albedo (highly reflective) paints, water-permeable materials, and energy-saving initiatives, etc. However, the effects of such countermeasures have not been clearly confirmed. Accordingly, tools to assess urban climate are very important to estimate the effects of these measures, and various tools have already been proposed. The urban climate is composed of various spatial scale phenomena in and around the urban area as shown in Figure 3. Thus,

the various tools proposed correspond to various scales respectively.

In this paper, various assessment tools are introduced and classified according to the corresponding modelling scales. Special attention is given to recent progress in Japan. Finally, future subjects are discussed.

## CLASSIFICATION OF ASSESSMENT TOOLS

Urban climate assessment tools can be classified under four models, i.e. mesoscale meteorological, microclimate, building and human thermal models. These models correspond respectively to various scales; the meteorological model to an urban and city block scale, the microclimate model to a city block and building scale, the building model to a building and room scale, and the human thermal model to a human body scale.

The mesoscale meteorological model is also sub-classified as a mesoscale meteorological model in the narrow sense, and a one-dimensional urban canopy model. Originally, the one-dimensional urban canopy model was developed as a surface sublayer model for the mesoscale meteorological model. However, thanks to its ease of use, the one-dimensional urban canopy model is often used independently to estimate the effect of urban heat-island countermeasures. As the calculation load is very small, many case studies of various measures to mitigate the heat-island effect can be handled. With regard to the mesoscale meteorological model, it is well suited to predicting phenomena in the 100 km order (mesoscale),

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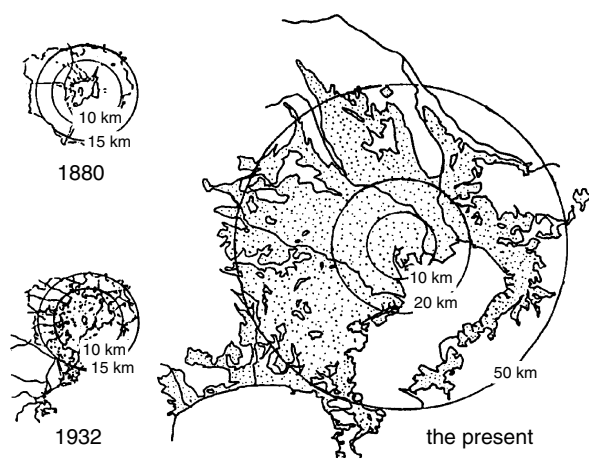


Figure 1. Development of urbanization in Tokyo (Ojima, 1991).

such as land and sea breeze. However, the smallest applicable mesh size for the mesoscale meteorological model is about 1 km, so it is unsuitable for evaluating pedestrian level outdoor thermal environments.

On the other hand, the microclimate model was developed in the engineering field as well as the meteorological field and is usually based on a three-dimensional computational fluid dynamics (CFD) model, often being coupled with radiation and conduction calculations. This model is useful for predicting detailed spatial distributions of flow, temperatures, and scalar fields inside complex urban areas.

These models are sometimes used separately, and sometimes simultaneously, depending on the targeted scale and resolution level required. The present situation and application of meteorological and microclimate models for urban heat-island analysis are described below.

## MESOSCALE METEOROLOGICAL MODEL

### *Mesoscale meteorological model and its application*

Bornstein (1972, 1975) and Lee and Olfe (1974) were possibly the first to simulate the heat-island

phenomena using a meteorological model. In Japan, Kikuchi *et al.* (1981) conducted a numerical simulation of the sea breeze over the Kanto plain. From that point, a number of organizations developed their own models. For example, the National Center for Atmospheric Research (NCAR) and Pennsylvania State University developed their fifth-generation Mesoscale Model (MM5), while Colorado State University developed the Colorado State University Mesoscale Model (CSUMM), and later, the Regional Atmospheric Modelling System (RAMS). Yamada and Bunker (1988) developed a Higher Order Turbulence Model for Atmospheric Circulation (HOTMAC). Recently, a Weather Research and Forecasting model (WRF) was developed by NCAR. Many urban climate researchers employ these models. Table I shows a comparison of the various mesoscale meteorological models that are used for urban climate and heat-island research.

Mochida *et al.* (1999) analysed the flow and temperature fields in summer in the greater Tokyo area using HOTMAC. Their results are shown in Figure 4 and compared with actual observations. The measurements and predictions demonstrate fairly good correspondence. Figure 5 compares the temperature distributions at ground level at 3:00 p.m. in early August under land use conditions from the present back to the Edo era (about 200 years ago). The current surface temperature in central Tokyo is about 4 °C higher than that of the Edo era. This indicates that urbanization, as evidenced by a decrease in greenery and an increase in anthropogenic heat, has advanced the progress of this urban heat island. Ichinose *et al.* (1999) evaluated the impact of anthropogenic heat and greenery coverage ratio on the urban climate across the Tokyo metropolitan area using CSUMM. The air temperature without anthropogenic heat would be about 1.5 °C lower at 22:00 h in Otemachi than it is at present. The air temperature in the case where the entire study area is assumed to be grassland would be about 2.5 °C lower at 21:00 h in Otemachi than at present. Fan and Christian (2005) also evaluated the impact of

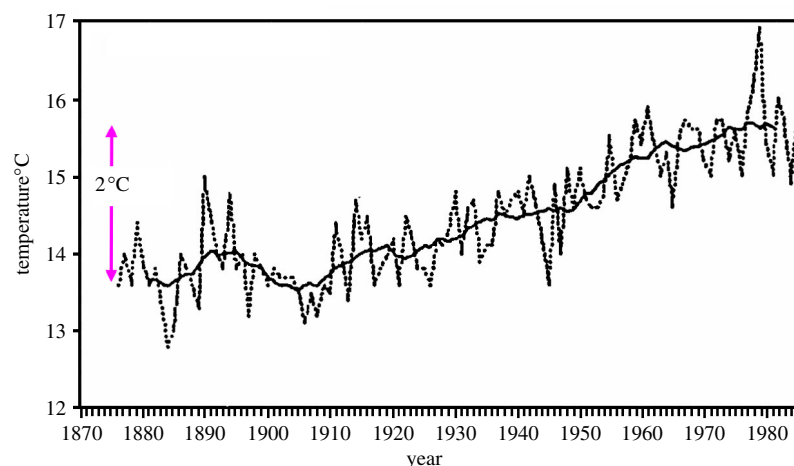


Figure 2. Increase of air temperature in Tokyo (height of about 1.5 m). This figure is based on the report of the Environmental Agency of Japan, 1990. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)

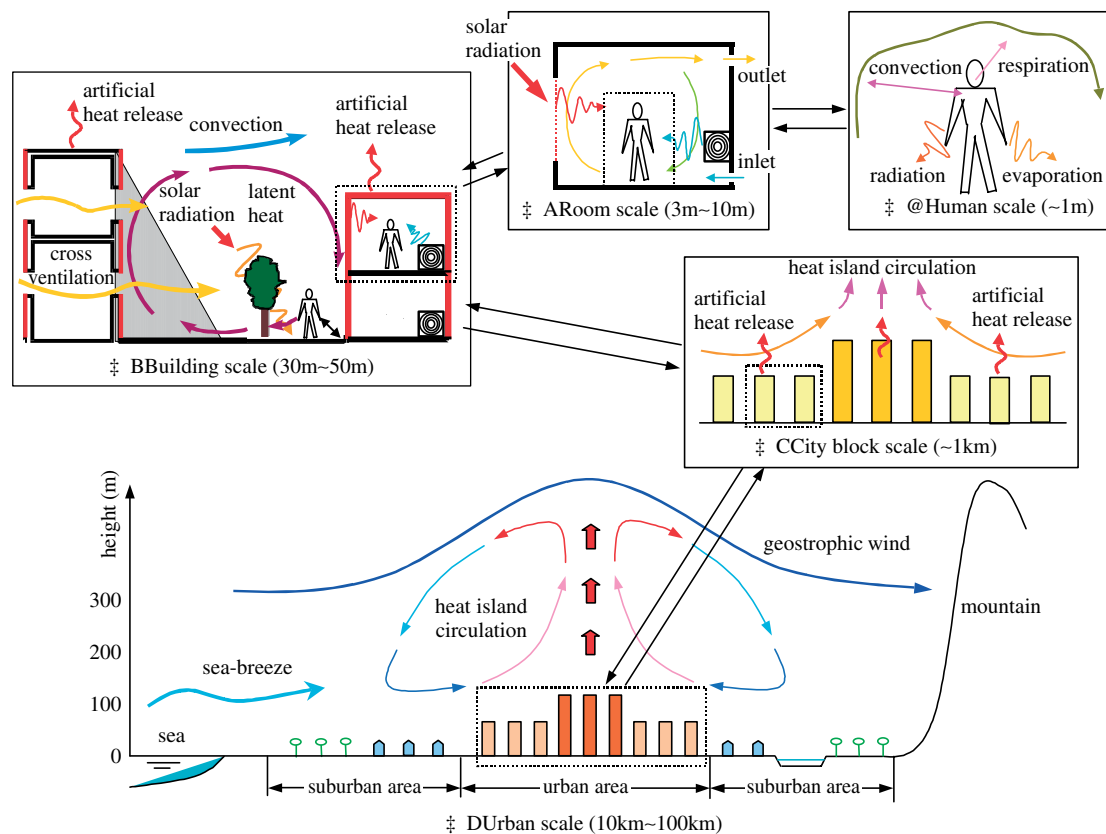


Figure 3. Various scales of phenomena concerned with Urban Climate. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)

anthropogenic heat on the urban climate of Philadelphia using MM5. Kondo *et al.* (2001) investigated the effects of high albedo paint on the road on the urban heat island in Osaka using OASIS. The air temperature at pedestrian level in the case where the albedo value of the road surface is 0.45 is about 0.15 °C lower at 12:00 h in the central part of Osaka than at present (albedo value = 0.15). Taha (1996, 1997) evaluated the impacts of increased urban vegetation and albedo change on the air quality in California's South Coast Air Basin. Although increased urban vegetation and increased albedo reduces the air temperature in the area, the increase in urban vegetation causes more biogenic hydrocarbon emissions and a higher ozone concentration through photochemical reactions. Kanda *et al.* (2001) simulated a small-scale cloud over a main street in the Tokyo metropolitan area using RAMS. Murakami *et al.* (2003) proposed the concept of a heat balance model in which heat balance within a virtual control volume in urban space is estimated from the calculation results of the mesoscale meteorological model. This model enables quantitative consideration of the various factors that form the urban thermal environment.

#### *One-dimensional urban canopy model and its application*

There are three kinds of surface sublayer models for surface boundary conditions in mesoscale meteorological models, i.e. a surface-layer scheme, a single-layer model

and a multi-layer model. Here, the single-layer and multi-layer models are called the canopy model. However, the urban canopy model is often used independently because of its ease of use as described above. Sometimes the urban canopy model is coupled with the building energy model in order to investigate the interaction between urban climate and building energy use. Table II shows various urban canopy models.

Kikegawa *et al.* (2001) and Genchi (2001) used the Advanced Industrial Science & Technology – Canopy Model (AIST-CM) to evaluate the effect of heat release from building air-conditioning units in Tokyo. Three scenarios were studied; an external air-conditioning unit is placed on the roof of a building (Case 1), at a height of 3 m above the ground (Case 2), and with heat from the air-conditioning system being injected into the ground (Case 3). The daily average temperatures at a height of 3 m for cases 1, 2 and 3 were 30.37, 30.99, and 29.09 °C, respectively. Thus, the inclusion of heat released from air-conditioning systems is very important. Hagishima *et al.* (2002) carried out sensitivity analyses on the various factors closely related to the urban heat-island effect, such as building density, ground coverage conditions, building roof and wall surface conditions, use and type of air-conditioning systems, and so on. They clarified that the highest temperature inside the urban canopy is most strongly affected by the air-conditioning systems, internal heat generation from buildings and the conditions of ground coverage. Recently, the urban canopy model has

Table I. Comparison of various mesoscale meteorological models for urban climate and heat-island study.

Name	Developer	Equation	Turbulence model	Surface sublayer	Main user for heat-island study
LSM	Kimura and Arakawa (1983)	Hydro	0 equation	Monin Obukhov	F. Kimura, H. Kusaka
FITNAH	Wippermann and Gross (1986)	Non-hydro +dynamic	1 equation	Non-slip for momentum and Heat Balance	G. Gross
AIST <sup>a</sup> -MM	Kondo (1995)	Hydro	0 equation Gambo (1978)	Monin Obukhov AIST-CM	H. Kondo, Y. Genchi, Kikigawa
NEDO <sup>b</sup> Software Platform	Murakami <i>et al.</i> (2000)	Hydro	k-l two equation Yamada and Bunker (1988)	Monin Obukhov urban canopy	S. Murakami, A. Mochida, R. Ooka
BRIC <sup>c</sup> UCSS	Ashie <i>et al.</i> (1999) Ashie and Vu Thanh (2004).	Non-hydro	k- $\epsilon$ two equation Vu Thanh <i>et al.</i> (2000, 2002)	urban canopy	Y. Ashie
Osaka-Univ. OASIS	Oh <i>et al.</i> (2000) Kondo <i>et al.</i> (2001).	Non-hydro optional	k-l two equation Yamada and Bunker (1988)	urban canopy	D. Narumi, A. Kondo
YSA <sup>d</sup> HOTMAC	Yamada and Bunker (1988)	Non-hydro optional	k-l two equation Yamada and Bunker (1988)	Monin Obukhov forest canopy	S. Murakami, A. Mochida
CSU <sup>e</sup> CSUMM	Pielke (1974)	Hydro	0 equation Pielke's model	Monin Obukhov	T. Ichinose, I. Uno
RAMS	Pielke <i>et al.</i> (1992)	Non-hydro optional	k-l two equation, LES optional	Monin Obukhov	M. Kanda, A. Velazques-Lozada C. Sarraf
NCAR <sup>f</sup> MM5	Grell <i>et al.</i> (1994)	Non-hydro	k-l two equation	Monin Obukhov	A. Kondo, H. Fan
MC2	Laprise (1995) Benoit <i>et al.</i> (1997)	Non-hydro	0 equation	Monin Obukhov	E. Kravynhoff
NCAR <sup>f</sup> WRF	Skamarock <i>et al.</i> (2005)	Non-hydro	k-l two equation	Monin Obukhov urban canopy	H. Kusaka

<sup>a</sup> Advanced Institute of Science and Technology.<sup>b</sup> New Energy Development Organization.<sup>c</sup> Building Research Institute, Japan.<sup>d</sup> Yamada Science and Art Co.<sup>e</sup> Colorado State University.<sup>f</sup> National Center for Atmospheric Research.

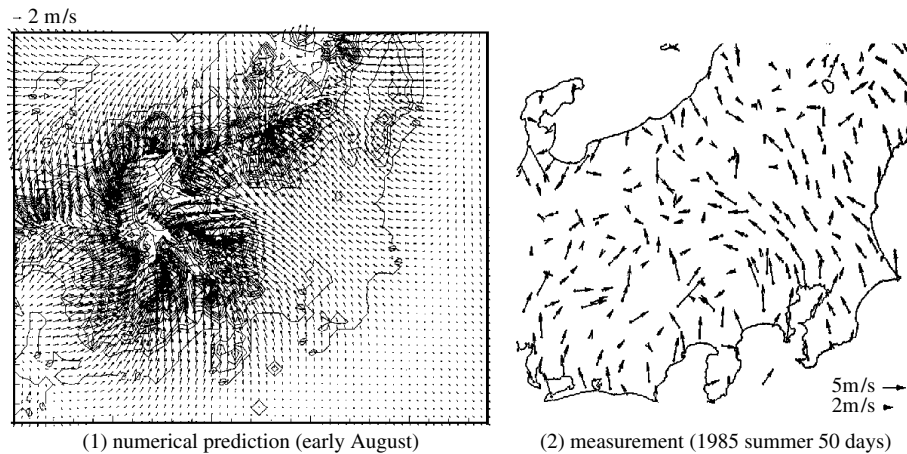


Figure 4. Comparison between numerical prediction and measurement (horizontal distribution of velocity vectors at the height of 100 m, at 3:00 p.m.). Left figure (Mochida *et al.* 1999): Right figure (Ku wagata and Kondo, 1990).

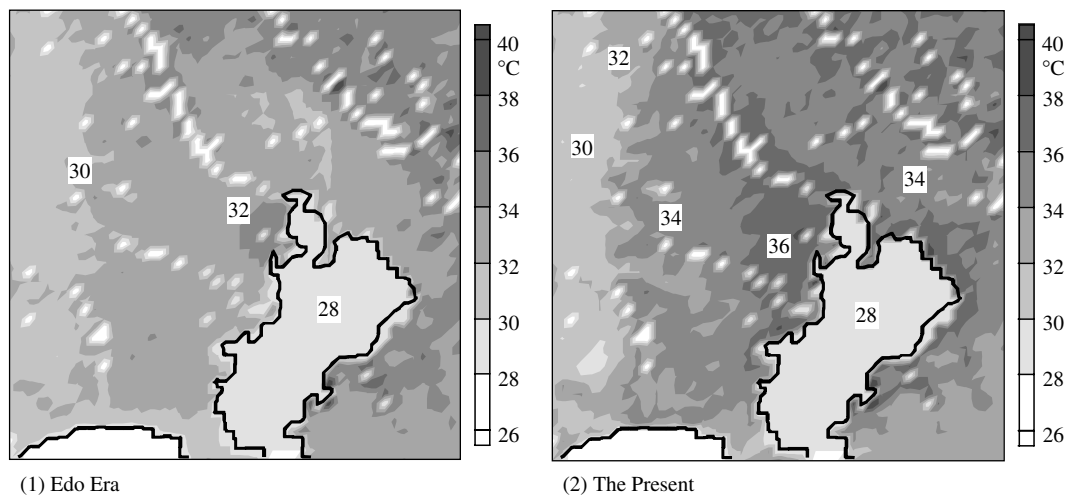


Figure 5. Prediction of climatic change in Tokyo from the Edo era up to the present (ground temperature at 3:00 p.m., early August) (Mochida *et al.*, 1999).

sometimes been coupled with mesoscale meteorological model interactively in order to estimate the relationship between human activity and mesoscale climate. By way of example, please note the references [Kondo *et al.* (2005), Ooka *et al.* (2004), Narumi *et al.* (2002), and Kusaka and Kimura (2004)]. Figure 6 shows a schematic view of incorporating the urban canopy model into the mesoscale meteorological model. Figure 7 presents a comparison of ground surface temperatures at 13:00 h in the Tokyo area between observations from a satellite and simulations both with and without the urban canopy model calculated by the author (Ooka *et al.* 2004). While the results of the conventional mesoscale meteorological model without the urban canopy model show poor agreement with the observations, those of the mesoscale model with the urban canopy model afford excellent agreement. This is because the urban canopy model defines the building and ground surfaces clearly, while the heat balance model used as the boundary condition in the conventional meteorological model does not define such surfaces clearly.

## MICRO CLIMATE MODEL

The Micro Climate Model is composed of CFD, radiation transfer and heat conduction models. CFD has been developed on the basis of recent developments in computational technology. Quantitative analyses of flow fields within building complexes have been conducted using wind engineering expertise (e.g. Murakami *et al.* (1990)). In these analyses, the prediction accuracies and performances of various turbulence models have been estimated. Table III shows a comparison of various turbulence models used for wind engineering. Although the prediction accuracy of large eddy simulations (LES) is better than that of the Reynolds-Averaged Navier-Stokes (RANS) models such as the  $k-\epsilon$  model, the RANS model is still generally used because of its ease of use and low computational load.

Sievers and Zdunkowski (1986) developed a micro-scale urban climate model – MUKLIMO. Bruse and Fler (1998) and Bruse (1999) also developed a micro-climate model – ENVIMET – in which the turbulence

Table II. Comparison of various urban canopy models for urban climate and heat-island study.

Name developer	Turbulence model	Building area density	Drag coefficient	Radiation calculation
AIST-CM Kondo and Liu (1998), Kondo <i>et al.</i> (2005)	0 equation Gambo (1978)	$a = BP_w(z)/((B+W)^2 - B^2P_w(z))$	Fixed value Cd <sub>rag</sub> = 0.4	Kondo and Liu (1998), Kondo <i>et al.</i> (2005)
RAUSSM Hagishima <i>et al.</i> (2001)	0 equation Gambo (1978)	$a = B/((B+W)^2 - B^2)$	Maruyama (1991)	Radio City
UCSS Ashie <i>et al.</i> (1999) Ashie and Vu Thanh (2004)	k-ε two equation Vu Thanh <i>et al.</i> (2000a, 2002)	$a = \sqrt{bldr}$	Fixed value	Ashie <i>et al.</i> (1999) Ashie and Vu Thanh (2004)
Kusaka <i>et al.</i> (2001)	Single Layer	Single Layer	Simple Layer	Sakakibara (1995)
SUMM Kanda <i>et al.</i> (2005a, 2005b)	Single Layer	Single Layer	Single Layer	Kanda <i>et al.</i> (2005a)
Martilli <i>et al.</i> (2002)	k-1 two equation Bougealt and Lacarrere (1989)	$a = 4\xi B/(B+W)^2$	Fixed Value Cd <sub>rag</sub> = 0.4	Martilli <i>et al.</i> (2002)
Hiraoka <i>et al.</i> (1989)	k-ε two equation	$a = 2B/((B+W)^2 - B^2)$	–	–
Ooka <i>et al.</i> (2004)	k-1 two equation Yamada and Bunker (1988)	$a = 4B/(B+W)^2$	Fixed Value Cd <sub>rag</sub> = 0.1	Kondo and Liu (1998)
TEB Masson (2000)	Single Layer	Single Layer	Single Layer	Masson (2000)
Arnfield (2000)	Single Layer	Single Layer	Single Layer	Arnfield (2000)
Best (2005)	Single Layer	Single Layer	Single Layer	Heat Balance in urban canopy

B, building width; w, building interval; bldr, building area ratio (gross).

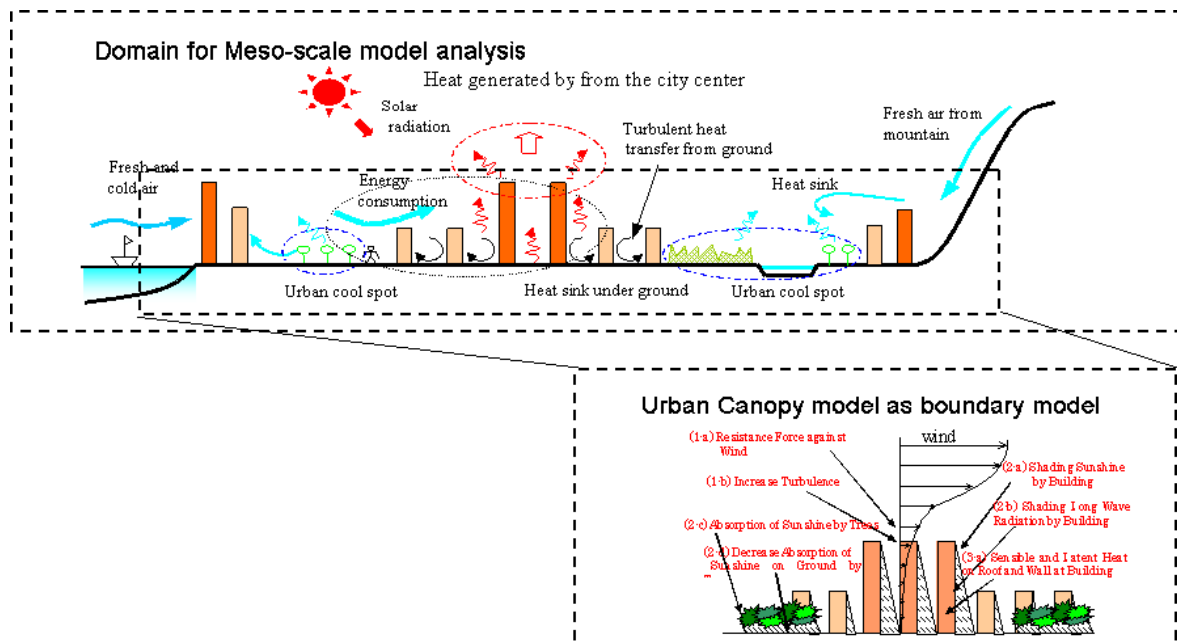


Figure 6. Schematic view of incorporating urban canopy model into mesoscale meteorological model. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)

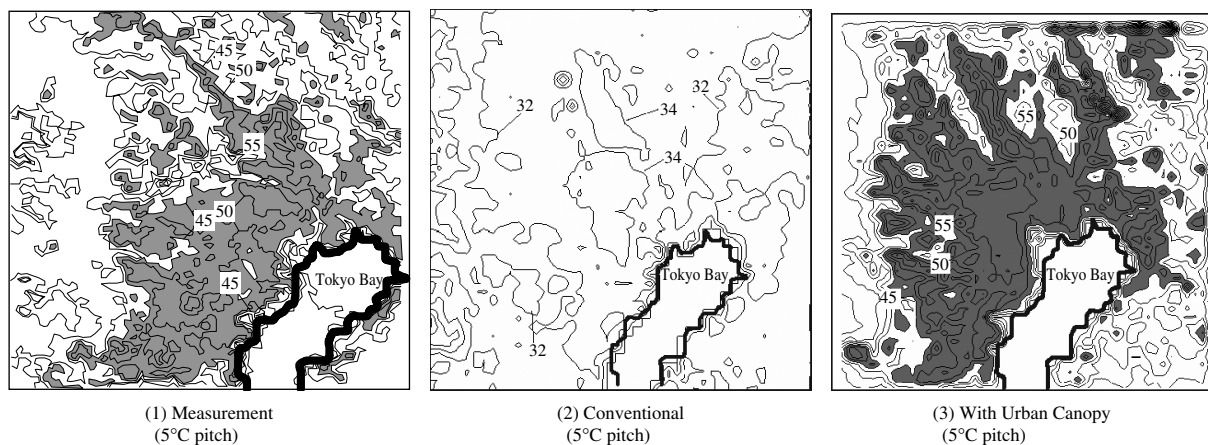


Figure 7. Comparison of ground surface temperature (24 July, 13:00 h) (Ooka *et al.*, 2004).

Table III. Relative performance of various turbulence models for practical applications.

Turbulence model		RANS			LES	
		Standard k- $\epsilon$	Nonlinear k- $\epsilon$	RSM	Conventional SGS	Dynamic SGS
1. Simple flows (channel flow, pipe flow, etc.)		O	O	O	O	O
2. Flow around bluff body (with turbulent approaching wind, local equilibrium is not valid)	1) Impinging area	×	$\Delta$ , O	×	O	O
	2) Separated area	×	$\Delta$ , O	$\Delta$	O**	O
	3) With oblique wind angle	×, □	$\Delta$ , O	$\Delta$	O**	O
3. Transitional flow (low Reynolds number effects)	1) Near wall	O*	O*	O*	O**	O
	2) Non near wall	×	×	×	×	O
4. Unsteady flow	1) Vortex shedding	×	$\Delta$	$\Delta$	O	O
	2) Fluctuation over wide-spectrum range	×	×	×	O	O
5. Stratified flow		×	×	$\Delta$	$\Delta$	O
6. CPU time required		O	O	$\Delta$	×	×

Note : O: functions well,  $\Delta$ : insufficiently functional, ×: functions poorly, O\*: functions well when low Reynolds number type model is employed, O\*\*: functions well with wall damping function.



model is the modified  $k-\varepsilon$  two-equation model including the effect of the plant canopy. Yoshida *et al.* (2000) and Chen *et al.* (2004) proposed a prediction method for microclimates within city blocks, which is a coupled simulation using CFD, radiation and conduction calculations including the effect of radiation heat transfer between buildings and ground surfaces within building blocks. Figure 8 presents the calculation flow for the microclimate model. The human thermal sensation index, a new standard effective temperature ( $SET^*$ ) proposed by Gagge *et al.* (1986) is also incorporated in this method. The prediction accuracy of this method was confirmed by Chen *et al.* (2004) through comparisons with field measurements. Mochida *et al.* (2001) estimated the effect of an increase in the albedo of building surfaces on the outdoor thermal environment. Although an increased albedo of the building walls decreases the air temperature at pedestrian level, the  $SET^*$  increases offset these changes because of the increase in reflected radiation from the wall onto pedestrians. Thus, one advantage on the microclimate model is its ability to estimate detailed spatial distribution of various quantities at the human level. Yoshida *et al.* (2006) developed a three-dimensional tree plant model for microclimate models. Oguro *et al.* (2002)

simulated the flow and temperature fields in a complex building block area using an unstructured mesh system. In this study, the cooling effect of wind from a river is estimated. Figure 9 shows an example of the analysis on a complex wind field using an unstructured mesh system. Recently, improved computer performance has enabled massive CFD calculations for urban climates over a scale of several kilometers with a relatively fine mesh resolution in the order of meters. [For examples, note the following references: Ashie *et al.* (2004), Coirier and Kim (2006), and Camelli *et al.* (2006)]. Some trials combining a meteorological model with a microclimate model have also been carried out [Murakami *et al.* (2000), and Yamada (2006)].

### HUMAN THERMAL MODELS

There are many indices which account for outdoor thermal environments other than air temperature. The Wet Bulb Globe Temperature (WBGT) is used for heat disorder prevention information in Japan. However, the human body heat balance and human thermal physiological response are not taken into account in this index. The

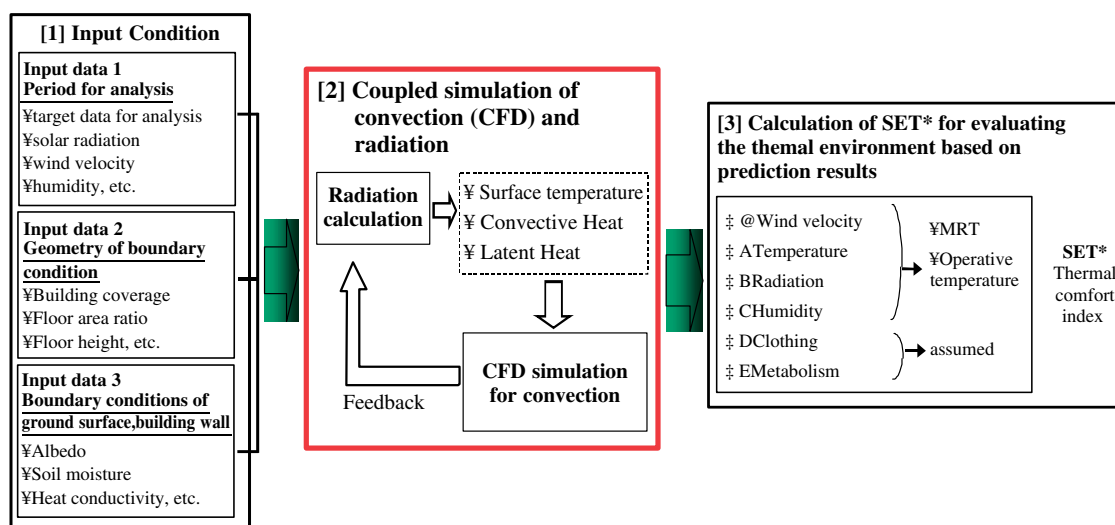


Figure 8. Flow of microclimate simulation. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)

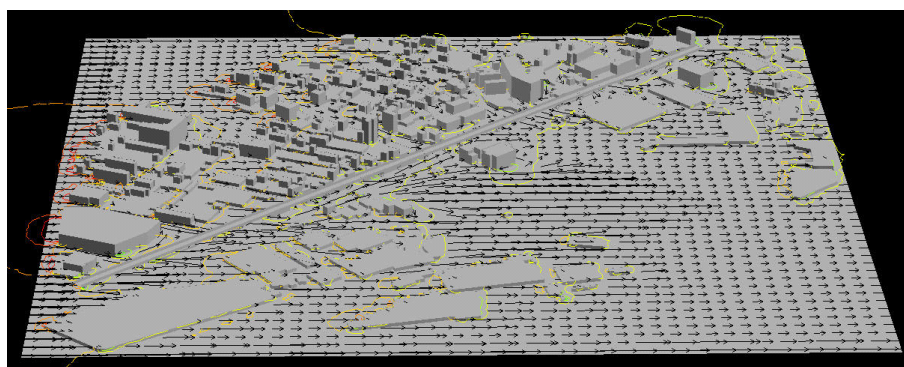


Figure 9. Velocity vectors within a complex flow field. This figure is made by the author. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)



human thermal model, which includes these processes, is very important for predicting human thermal sensations in the outdoor environment. Various other indices such as the Predicted Mean Vote (PMV) by Fanger (1970), a SET\* by Gagge *et al.* (1986), Predicted Heat Strain (PHS) model by Malchaire *et al.* (2001) include their own human thermal models respectively. However, it is not clear whether these models can be applied to outdoor environments or not, as these have been developed for indoor environments. For outdoor environments, the Steadman Apparent Temperature by Steadman (1979), physiological equivalent temperature (PET) by Hoeppe (1999) and Matzarakis *et al.* (1999) and Out-SET\* by Pickup and de Dear (1999), Expected Thermal Sensation by Kuwabara *et al.* (2005) have been proposed as new thermal indices. The accuracy of these models should be examined from the viewpoint of human thermal physiology for hot outdoor environments. For example, PET is almost completely insensitive to latent heat fluxes because the potential (= maximum) evaporation is employed as the measure for evaporation heat loss by sweating [Hoeppe (1999)]. Minami *et al.* (2006) compared the performance of SET\* and PHS models with the results of a subject experiment in a hot environment and developed a new sweating model for SET\* including the effect of the metabolic rate.

There are still many problems pertaining to human thermal models such as clothing, typical metabolic rate, etc. The accurate prediction of heat exchange between a human body and the outdoor environment is one such problem. Ono *et al.* (2006) estimated the convective heat transfer coefficient of the human body surface with the aid of wind tunnel experiments and CFD analysis. Figure 10 presents the distributions of the convective heat transfer coefficient on the surface of the human body under various wind velocity conditions. In this figure,  $\overline{\alpha_c}$  represents the average surface value of the convective heat transfer coefficient of a human body. In

the future, it is expected that a comprehensive human thermal model integrating various factors described above will be developed.

## DISCUSSION AND FUTURE SUBJECTS

As described above, various assessment tools have been proposed. These are very powerful tools to estimate the mechanism of the urban heat island and the potency of countermeasures. However, there are still some problems. Validations of the prediction accuracy of these methods are insufficient. Thus, the application limits have yet to be established. Old reference data [such as Clarke *et al.* (1971)] are still used to validate mesoscale meteorological models. In particular, a validation database for surface boundary layers is required. The results of the following references – Uehara *et al.* (2000), Christen *et al.* (2003), Moriwaki *et al.* (2003), Offerle *et al.* (2003), Rotach *et al.* (2003), and Mutoh and Narita (2005) – are expected to be very useful. The scaled model experiments are also important, such as Yee and Biltoft (2004), Pearlmutter *et al.* (2005), and Narita *et al.* (2006). The results of the detailed simulation in the urban canyon space such as Kanda *et al.* (2004) are useful to develop the urban canopy model. Benchmark tests are required in order to understand the properties of the various models developed. Surface data and GIS data for the boundary conditions of these models are also required. As described above, there are various spatial scale phenomena in urban climates and there are interactions between each scale. The entire structure of urban climates cannot be understood by partial analysis in each scale alone. Therefore, it is important to combine the assessment tools of each scale, from human scale to mesoscale, comprehensively.

Nevertheless, these tools have contributed to the development of urban climatology. A detailed structure of

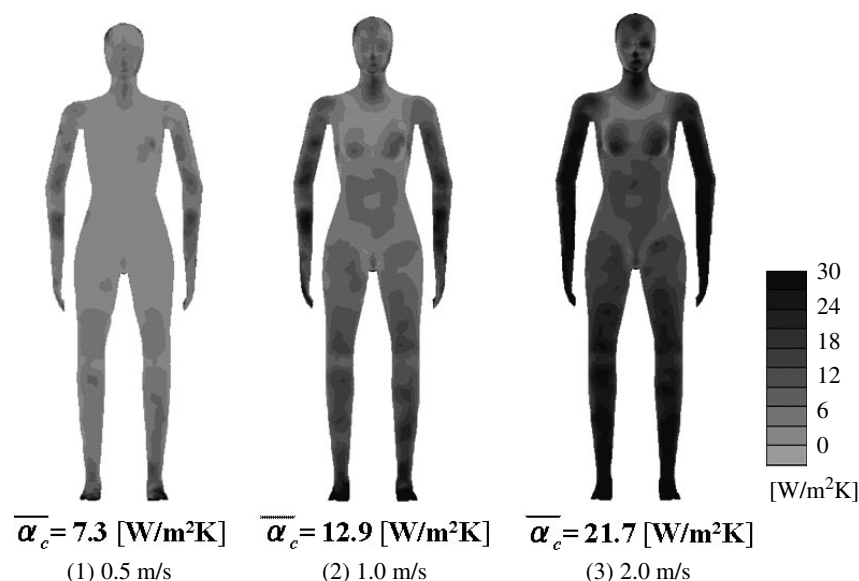


Figure 10. Distribution of convective heat transfer coefficients on human body surface under various wind velocity conditions (Ono *et al.*, 2006).

the urban climate, which cannot be observed experimentally, can be obtained using these tools. However, there is still a deep gap between researchers, or specialists, in urban climates and urban planners, or policy makers. This vast wealth of urban climate knowledge has not been sufficiently applied to urban design or planning. For the application of this knowledge to actual urban design, it is important to make it clearly understandable with some examples. Visualization techniques are one of the most powerful methods to express the influence of various urban heat-island mitigation strategies easily and concretely for non-specialists. Moreover, for urban heat-island mitigation strategies, the priorities for various countermeasures should be clearly shown. Thus, the effects of various measures should be compared with each other. It is also important to indicate the cost benefit of each countermeasure. Genchi *et al.* (2006) conducted a lifecycle assessment of various countermeasures for urban heat islands. In the next stage, these assessment tools should evolve into design tools which integrate all processes described above for practical applications.

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