Analysis of Urbanization Effects on the Local Climate in Kanto During the Warmest Period of August, 2006

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Abstract
The effects of urbanization on the local climate in Kanto in August 2006 were analyzed, focusing on the statistical analysis of the warmest days of this period in Tokyo. By utilizing the Weather Research and Forecasting mesoscale model (WRF), there were 8 events of sultry nights found in the simulation, when the temperature did not decrease below 25°C from late afternoon to the next morning in the WRF default; however, the number of events increased to 11 with the incorporation of anthropogenic energy (AE) and to 14 using the urban canopy model (UCM). The incorporation of AE and UCM augmented the ensemble air temperature by 0.5°C and 0.9°C, respectively, during the analysis period. Simultaneously, AE and UCM improved the accuracy of nighttime predictions, although these parameterizations tended to overestimate the real temperatures in the afternoon by up to 0.9°C. Moreover, urban parameterizations may greatly divert the wind direction, which may subsequently diminish the mixing ratio and enhance the air temperature.

Keywords: urban meteorology; mesoscale numerical simulation; Kanto region; urban planning

1. Introduction
Global urban population reached a milestone of 3.5 billion people, which corresponds to 50.5% of mankind\textsuperscript{1}. Concomitant to this achievement, this growth poses a great challenge in securing healthy urban environments. Urbanization profoundly alters the surface and atmospheric processes\textsuperscript{2,3}, thereby giving rise to urban climatology.

The development of urban climatology was accompanied by the rapid progress of computers, enabling researchers to devise numerical models. In order to improve the bottom layer parameterization, there are two pivotal factors: urban morphology represented by using the urban canopy model (UCM) and anthropogenic energy (AE), which is compounded by anthropogenic heat and anthropogenic moisture. These anthropogenic sources have been extensively documented and when incorporated in WRF simulation, they increase air temperature, mixing layer height and hamper sea breeze inland flow\textsuperscript{4}.

However, the effects of AE and urban morphology in real cities can become more acute according to seasonality and peculiarities such as building materials and morphology. Ohashi \textit{et al.}\textsuperscript{5} estimated air conditioning use increases air temperature by between 1°C to 2°C in Tokyo on summer weekdays, and that this discharge is considerable in Asian cities. Urbanization has a significant effect on temperature in Japanese cities in summer; the Japanese Meteorological Agency (JMA) observed the occurrence of nights when the temperature did not fall below 25°C from late afternoon to the next morning, the "sultry nights"\textsuperscript{6}.

Therefore, the scope of this research is to analyze the impacts of AE and UCM and the synergic relation with sea breeze in Kanto. It is divided into two parts: the statistical analysis focuses on days characterized by sultry nights of August 2006 in Tokyo, whilst the second part focuses on the relationship between urbanization and sea breeze on a mesoscale context and the output of different runs on August 5, 2006, in Tokyo by utilizing the numerical mesoscale model Weather Research and Forecasting modeling system, hereafter referred to as WRF\textsuperscript{7}.

2. Simulation Settings
The effects of UCM and AE on urban climate are examined by conducting 3 runs in the scrutiny: Run 1 incorporates UCM and AE, Run 2 considers only AE, and Run 3 is the WRF default. AE is obtained by combining statistical data of building floor area provided by the Geographical Information System released by the Tokyo Metropolitan Government, whilst energy consumption is provided by the Japanese District of Heating and Cooling Association (See Moriwaki \textit{et al.}\textsuperscript{8}) and is released into the lowest pressure level. The UCM utilized here consists of a single-layer model, capable of providing momentum...
exchange between the urban surface and the atmosphere; it recognizes the influence of street-canyons, shadowing and radiation reflection as well as estimating surface temperatures of roofs, walls, and roads available in WRF\textsuperscript{9,10}.

This two nesting simulation comprises a greater domain (parent), which has an extension of 400 km in both the north-south and east-west axes, whilst the smaller domain (child) is defined by axes in the same directions measuring 100 km. Both domains were divided into 80 cells in each direction, with the unit cell size of the greater domain measuring 5 km and that of the smaller domain 1.25 km (Fig.1.). Further details can be found at Suga et al. (2009)\textsuperscript{9}.

Regarding the time span, initially WRF simulations encompassed the entire month of August 2006, however, rainfall events were discarded according to the following criteria: daily rainfall higher than 5 mm and a rainfall period longer than 4 hours in a row. Later, a further mining was done in order to obtain the hottest days of August, or the sultry night events. There were 8 sultry night events in Run 3; 11 events in Run 2, and 14 events in Run 1 in Tokyo. These 8 sultry night events were established as a benchmark for all the runs in order to set a comparison amongst them.

3. Statistical Results

The statistical analysis comprises of 192 hours for each run, with an hourly time step, considering the WRF predictions of air temperature and mixing ratio were obtained at 2 m height, and the wind velocity at 10 m height.

These results are compared to the station data point (SDP) results provided by the Japanese Meteorological Agency, which are obtained at 1.5 m height. Since these results did not differ significantly, a conversion equation was not used.

By using the box plot method, the range of data can be split into first, second, third, and fourth quartiles ($Q_1$, $Q_2$, $Q_3$, and $Q_4$, respectively), which corresponds to 25%, 50%, 75%, and 100% within which the data values fall\textsuperscript{11}. The lower fences, higher fences and outliers were also determined in this investigation by adopting the following equations:

\begin{align}
F_l &= Q_1 - k (Q_3 - Q_1) \\
F_u &= Q_3 + k (Q_3 - Q_1)
\end{align}

where, $F_l$ is the lower fence, $F_u$ is the higher fence and $k$ is a constant whose value is 1.5\textsuperscript{12}. Values below or above the lower fence and higher fence are outliers, which \textit{a priori} suggests blunders, but may mean a subtle mechanism remaining to be considered.

3.1 Air temperature in Tokyo

All three runs provide reliable predictions; the ensemble average of the SDP records is 29.0°C whilst Run 1 averages 29.2°C, Run 2 averages 28.9°C, and Run 3 records 28.4°C. The inclusion of AE in Run 2 provides betterments, whilst UCM in Run 1 overestimates the WRF predictions from 13:00 to 17:00 by up to 0.9°C; however, Run 1 performs better from 05:00 to 12:00 and from 20:00 to 0:00 (Fig.2.). UCM is more sensitive to temperature changes. At 20:00, the difference between Run 2 and Run 3 peaks at 0.7°C and between Run 1 and Run 1 and Run 3 reaches 0.9°C. However, the difference between Run 1 and Run 3 at 13:00 peaks at 1.2°C. This difference can be justified by the combination of the higher solar height and UCM, which traps the heat more efficiently.

Overall, Run 2 has the best performance, although in certain periods Run 1 performs better. Computing the anthropogenic energy values for weekdays and weekends, where the difference can reach 0.3°C according to Fujibe (1987, \textit{apud} Fujibe\textsuperscript{13}) and a suitable value of albedo for UCM could result in incremental improvements. Although the predictions are robust, a further glance shows outliers, especially in Run 1, which occurred on August 5\textsuperscript{th}. This will be analyzed later in the mesoscale analysis.

3.2 Mixing ratio in Tokyo

The ensemble average of the WRF predictions agrees well with the SDP data. The ensemble average of SDP for this period is 17.0 g/kg, whilst for Run 1, Run 2, and Run 3 it is 16.6 g/kg, 17.1 g/kg and 17.2 g/kg, respectively (Fig.2.).

The population distribution of WRF predictions narrows from 15:00 to 20:00, especially for Run 1, where the difference of quartiles reaches a low of 0.5 g/kg at 16:00. However, it widens throughout the day and peaks mainly in the morning. Generally, outliers are underestimated values, especially in Run 1. From these, 14 out of 17 events in Run 1 suggested dependence on wind direction, which prevailed from the north, occurring on August 5\textsuperscript{th} and 24\textsuperscript{th}.

3.3 Wind field in Tokyo

The wind velocity predictions reproduced the daily trends of SDP fairly well. The ensemble average of SDP for this period is 2.7 m/s; Run 1 averages 2.4 m/s, Run 2 records 3.1 m/s and Run 3 averages 2.7 m/s. Run 1 performs well from 14:00 to 0:00, however, it underestimates the real velocity in the morning (Fig.2.). The inclusion of AE boosts the wind velocity, whilst UCM slows it down by means of drag. The wind
AE production enhances penetration is complete in all the runs in the eastern side of the domain (Fig.4.). AE production enhances the air temperature difference between Run 2 and Run 3, whilst the presence of UCM increases the temperature difference between Run 1 and Run 3. The UCM presence ensues in a surface enlargement, and throughout the day, it traps the incoming solar radiation, which is stored and peaks 1-2 h after sunset [14]. The obtained results ratify the relevance of the storage heat of UCM.

At 01:00, the air temperature in Tokyo is 26.8°C in Run 3, 28.2°C in Run 2, and peaks at 30.0°C in Run 1. In addition to that, the combined effects of AE and UCM, especially in western Kanto, enhances the nocturnal heat island development in Run 1, which subsequently diminishes the air pressure and coupled with the drag generated by UCMs, drives a front formation, hindering the flow of the sea breeze and causing it to divert to the east of Kanto. Conversely, there is no sharp veering of the wind produced by AE per se, and the absence of UCM in Run 2 and Run 3 eases the inland sea breeze flow. Therefore, the storage

direction may also be important to predictions, and summer winds are mainly southerly winds.

Moreover, the obtained results suggest that the presence of AE and UCM also augments the occurrence of southerly winds (Fig.3.). Plausibly, the air temperature difference between the ground and ocean is enlarged, therefore inducing the occurrence of southerly winds. However, the SDP wind rose shows that Runs 1 and 2 were successful in reproducing the wind predictions in SW, SSW and S although they could not properly predict easterly events. Arguably, the land surface definition may not be able to reproduce local peculiarities or a higher definition on the smaller domain might be necessary to improve these predictions.

4. Mesoscale Analysis

On August 5, 2006, at 01:00, the sea breeze penetration is complete in all the runs in the eastern side of the domain (Fig.4.). AE production enhances...
heat effects at night modifies the wind direction patterns, inducing and boosting the northerly winds in Run 1, and by means of the UCM drag effects, hobbles the sea breeze penetration and drives it to the northeast (Fig.5.). Also at 01:00, the wind velocity registers 1.6 m/s in Run 1, 1.4 m/s in Run 2 and 1.4 m/s in Run 3. Some investigations report that the veering of the wind direction is favored at low speeds. However, the change of wind direction ensues in further consequences. The mixing ratio of Run 2 and Run 3 registered in Tokyo are 17.0 g/kg and 17.1 g/kg, whilst Run 1 is lower with 12.3 g/kg (Fig.4.). Therefore, by altering the prevailing southerly wind to a northerly wind in Run 1, the mass of water vapor greatly decreases due to the advection of drier air from the continent, whilst the sea breeze in the other runs augments the mixing ratio. Furthermore, the shifting of wind direction in Run 1 in the first hours of the day greatly shortens the mixing ratio values, which bottoms at 06:00 in Run 1 with 10.4 g/kg (Fig.5.). Concomitant to the curtailing of the mixing ratio in Run 1, the air temperature increases between 01:00 and 05:00 being 2°C–3°C warmer than the average sultry events but August $5^{th}$, whilst this bias is smaller in other runs. The air temperature in all the runs is 1.6°C to 3.3°C warmer than the average of the sultry events except for August $5^{th}$ during 11:00 to 15:00, which can be attributed to the higher solar height at the beginning of the month.

A further issue lies in the accuracy in comparison to SDP in August $5^{th}$. Run 2 and Run 3 predicted prevailing southerly winds from 01:00 to 05:00, agreeing with SDP, whilst Run 1 predicted northerly winds (Fig.5.). Run 2 and Run 3 did not present a sharp difference compared to SDP from 01:00 to 05:00. On the other hand, after this period, Run 1 drastically improves its accuracy throughout the day and the deviation is smaller than 0.6°C, except from 15:00 to 17:00 when there is an overestimation above 1.2°C. Run 2 and Run 3 present a reasonable performance throughout the day, but underestimate the real values in the early night time. At 23:00, Run 2 and Run 3 underestimate the SDP values by 1.3°C and 2.1°C, respectively, whilst Run 1 closes the gap to 0.7°C, thus ratifying the relevance of UCM and AE to provide incremental betterments to local predictions.

5. Conclusions

Urbanization reinforces the occurrence of sultry night events. A comparison of Run 2 and Run 3 shows that AE enhanced the air temperature in this period by 0.5°C whilst Run 1, by means of incorporating UCM, was 0.9°C higher than Run 3.

Regarding the accuracy in comparison to SDP, AE betters the predictions of air temperature, whilst UCM provides incremental improvements in the early morning and early night, although it overestimates the afternoon predictions. Overall, Run 2 presented a better accuracy, although during certain periods Run 1 performed better; however, the incorporation of urban parameters is beneficial for improving nighttime

![Fig.4. Air Temperature (upper row), Mixing Ratio (lower row) and Wind Field in Kanto Region, Aug. 5, 2006, 01:00](image-url)
Fig. 5. Comparison of Air Temperature (°C), Mixing Ratio (g/kg), Wind Velocity (m/s) Results Obtained on August 5, 2006, Tokyo; and Average of Sultry Events Excluding August 5th, and SDP Wind Direction and Wind Velocity

predictions. However, both runs tend to overestimate the real temperature in the afternoon, especially Run 1 with predicted temperatures higher by roughly 0.8°C–0.9°C. AE and UCM can also influence the wind direction; in Run 1, the storage heat effects can enhance the vertical heat island circulation. This localized system hinders the sea breeze flow and may simultaneously induce northerly winds, due to temperature differences; these winds might ensue in a lower mixing ratio and higher air temperature. Therefore, the urbanization process affects the bottom surface creating an extended heat island throughout Kanto, which in a feedback process greatly enhances the air temperature and affects the local climate.

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References

1) UN. (2009) Revision of World Urbanization Prospects. Available on http://esa.un.org/unpd/wup/Documents/WUP2009 Press Release Final Rev1.pdf.
2) Grimmond, C.S.B., Salmond, J. A., Oke, T. R., Offerle, B. and Lemonsu, A. (2004) Flux and turbulence measurements at a densely built-up site in Marseille: Heat, mass (water and carbon dioxide), and momentum. Journal of Geophysical Research, 109, doi: 10.1029/2004JD004936.
3) Kusaka, H. (2008) Recent Progress on Urban Climate Study in Japan. Geographical Review of Japan, 81 (5), pp.361-374.
4) Suga, M., Almkvist, E., Oda, R., Kusaka, H. and Kanda, M. (2009) The impacts of anthropogenic energy and urban canopy model on urban atmosphere. Annual Journal of Hydraulic Engineering, JSCE, 55, pp.283-288.
5) Ohashi, Y., Genchi, Y., Kondo, Y., Kikegawa, Y., Yoshikado, H. and Hirano, Y. (2007) Influence of Air-Conditioning Waste Heat on Air Temperature in Tokyo during Summer: Numerical Experiments Using an Urban Canopy Model Coupled with a Building Energy Model. Journal of Applied Meteorology and Climatology, 46, pp.66-81.
6) Masuda, Y., Miyazaki, K., Takaguchi, H. and Kagiya, K. (2009) Cooling Effect of Tokyo Bay on “Sultry Nights” with Calm Wind Conditions. JAABE, 8 (2), pp.555-562.
7) Skamarock, W. C. (2004) Evaluating Mesoscale WNP Models Using Kinetic Energy Spectra. Mon. Wea. Rev., 132, pp.3019-3032.
8) Moriwaki, R., Kanda, M., Senoo, H., Hagiwara, H. and Kinouchi, T. (2008) Anthropogenic Water Vapor Emissions in Tokyo. Water Resources Research, 44, doi.10,1029/2007WR006624, in press, 2008.
9) Kusaka, H., Kondo, H., Kikegawa, Y. and Kimura, F. (2001) A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. Boundary-Layer Meteorology, 101, pp.329-358.
10) Kusaka, H. and Kimura, F. (2004) Thermal effects of urban canyon structure on the nocturnal heat island: Numerical experiment using a mesoscale model coupled with an urban canopy model. Journal of Applied Meteorology, 43, pp.1899-1910.
11) Freund, J. E. and B. M. Perles (1987) A new look at quartiles of ungrouped data. American Statistical Association, 41 (3), pp.200-203.
12) Tukey, J. W. (1977) Exploratory Data Analysis. Addison-Wesley.
13) Fujibe, F. (2010) Day-of-the-week variations of urban temperature and their long-term trends in Japan. Theoretical and Applied Climatology. DOI:10,1007/s00704-010-0266-y (in press).
14) Christen, A. and Vogt, R. (2004) Energy and Radiation Balance of a Central European City. International Journal of Climatology, 24, pp.1395-1421.
15) Klais, Z. B., Nitis, T., Kos, L. and Moussiopoulos, N. (2002) Modification of the local winds to the hypothetical urbanization of the Zagreb surroundings. Meteorology and Atmospheric Physics, 79, pp.1-12.
16) Grimmond, S. (2007) Urbanization and global environmental change: local effect on global warning. The Geographical Journal, 173 (1), pp.83-88.