Development of a High-resolution Meteorological Model for Urban Heat Island Effect Assessment

Steve Yim, PhD  
[Dept. of GRM, CUHK]  
Email address of corresponding author: steveyim@cuhk.edu.hk

Alan Lai, BSc  
[School of Archi., CUHK]

Chao Ren, PhD  
[School of Archi., CUHK]

ABSTRACT

Facing rapid urbanization, sustainable urban developments become important in urban planning. To tackle urban climate issues in a planning context, a meteorological model with high resolution is useful for evaluating different planning scenarios. This study used the Weather Research and Forecast (WRF) with a single-layer urban canopy model to simulate summer meteorological conditions in Hong Kong, downscaling the spatial resolutions from 4.5 km to 500 m. Hong Kong (HK) was taken as an example due to its high building density in a sub-tropical climate region. The model results were compared against measurements at 25 weather stations. We quantified the urban heat island effect (UHI) in the summer in 2009, and estimated the resultant health impacts based on a temperature-response function. The model results and measurements show a good agreement with an index of agreement of 0.71 and a percentage difference of mean temperature of 1.33%. Our analysis estimated that the hourly temperature in urban areas (29.6°C) is higher comparing to that in rural areas (28.1°C). The Urban Heat Island Intensity (UHII) was estimated to be 1.6°C on average. The UHI results in different Primary Planning Units show a north-south gradient pattern over Hong Kong: the highest UHII (1.7°C) in northern part of HK, whereas the lowest UHII (0.8°C) in southern part of HK. We found UHII correlates well with urban area size instead of population, highlighting that policy makers of high-density cities should pay attention to urban area size when tackling UHI. In addition, UHI was estimated to cause 75 [95% C.I. 22-158] mortalities in summer. Of which, ~55% of the UHI-related health impact occurs in New Territories, while 39% and 6% of the impact happen in Kowloon and Hong Kong Island, respectively. The results provide critical implications for urban planners to mitigate UHI in cities, especially in less developed countries.

NOMENCLATURE

PPU Primary Planning Units  
TPU Tertiary Planning Units  
UHI Urban heat island effect  
UHII Urban Heat Island Intensity

Author A is an assistant professor in the Department of Geography and Resource Management, The Chinese University of Hong Kong, Hong Kong, China. Author B is a research assistant in the School of Architecture, The Chinese University of Hong Kong, Hong Kong, China. Author C an assistant professor in the School of Architecture, The Chinese University of Hong Kong, Hong Kong, China.
INTRODUCTION

Urban heat island effect (UHI) is one of the major environmental problems in urban areas. Increases in temperature were found to have impacts on energy consumptions, public health and even air quality (Sarrat et al., 2006). According to the United Nations (2012), total urban population is projected to increase to ~67%. Thus, it is of importance to understand the urban heat island effect and the resultant impacts, especially in high-density cities such as Hong Kong (HK) given that the urban infrastructure and building morphology play an important role in the UHI (Rizwan et al., 2008).

Previous studies have shown that UHI was observed in Hong Kong. Memon et al. (2009) examined the reliability of urban heat island intensity (UHII), which was defined as the temperature difference between urban and rural areas. Based on the measurements collected at six weather stations, the study estimated that the mean hourly UHII ranged between 0.8°C and 2.0°C. Giridharan et al. (2004 and 2005) investigated the UHI in urban high-density residential developments in both daytime and nighttime. Based on the measurements on several selected days in the summer in 2002, Giridharan et al. estimated that the magnitudes of UHI within an estate were 1.5°C and 1.3°C in daytime and nighttime, respectively. Although the UHI was estimated in the previous studies, the majority of the studies were based on measurements at sparsely-distributed locations. Thus, the spatial distribution of UHI and the resultant impacts have not yet been fully understood.

Changes in ambient temperature due to UHI may cause heat-related mortality, especially in summer. The health impacts of extreme hot weather events such as heat wave were previously studied (Bai et al., 2014; Zeng et al., 2014; Amengual et al., 2014). For Hong Kong, Chan et al. (2010) employed a statistical approach to investigate the relationship between the heat-related mortality due to changes in ambient temperature. However, the mortality due to UHI was not calculated in the study.

Therefore, this study is aimed at estimating the magnitude of summer UHI in Hong Kong and the resultant heat-related mortality. The results are anticipated to provide critical implications for urban planners and authorities to mitigate UHI in cities, especially for the ones which are being developed in less developed countries such as mainland China.

METHODS

Meteorological Model

In this study, two months (Jul and Aug, 2009) were selected to investigate the summer UHI in HK. The Weather Research and Forecast model (WRF) (Skamarock et al., 2008) was used to reproduce the spatial...
distribution of temperature over Hong Kong in the study period. The WRF model has been widely used in urban heat island studies (Chen et al., 2014; Giannaros et al., 2013; Salamanca et al., 2012; Yang et al., 2012). The WRF model was configured to have three one-way domains, using which the meteorology was downscaled from a regional scale to a local scale. Figure 1(a) depicts the WRF domains. The outermost domain (D1) covers most of Guangdong province. D1 has 264x240 grid points with a spatial resolution of 4.5 km. The results of the D1 were then downscaled to the second domain (D2), which encompasses the Pearl River Delta. D2 has 136x124 grid points with a spatial resolution of 1.5 km. The innermost domain (D3) covers Hong Kong. D3 has 130x112 grid points with a spatial resolution of 500 m. A single-layer urban canopy model was adapted to improve the lower boundary conditions and the WRF performance within the urban regions (Masson, 2000). The WRF was configured to have 34 vertical sigma levels from the ground to the model top (50 hPa), with the first 11 layers being concentrated in the first 1 km above the ground level to resolve the structure of meteorology in the planetary boundary layer.

<table>
<thead>
<tr>
<th>Station name</th>
<th>Label</th>
<th>Station name</th>
<th>Label</th>
<th>Station name</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheung Chau</td>
<td>CCH</td>
<td>Tai Mei Tuk</td>
<td>PLC</td>
<td>Tuen Mun</td>
<td>TUN</td>
</tr>
<tr>
<td>Ching Pak House</td>
<td>CPH</td>
<td>Shek Kong</td>
<td>SEK</td>
<td>Tsak Yue Wu</td>
<td>YW</td>
</tr>
<tr>
<td>Ping Chau</td>
<td>EPC</td>
<td>Sha Tin</td>
<td>SHA</td>
<td>The Peak</td>
<td>VPI</td>
</tr>
<tr>
<td>Wong Chuk Hang</td>
<td>HKS</td>
<td>Sai Kung</td>
<td>SKG</td>
<td>Waglan Island</td>
<td>GL</td>
</tr>
<tr>
<td>Tseung Kwan O</td>
<td>JKB</td>
<td>Sha Lo Wan</td>
<td>SLW</td>
<td>HKO</td>
<td>HKO</td>
</tr>
<tr>
<td>Kat O</td>
<td>KAT</td>
<td>Tap Mun</td>
<td>TAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>King's Park</td>
<td>KP</td>
<td>Tate's Cairn</td>
<td>TC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lau Fau Shan</td>
<td>LFS</td>
<td>Ta Kwu Ling</td>
<td>TKL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ngong Ping</td>
<td>NGP</td>
<td>Tai Mo Shan</td>
<td>TMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nei Lak Shan</td>
<td>NLS</td>
<td>Tai Po</td>
<td>TP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple WRF simulations were conducted with a length of each simulation not exceeding a seven-day period. The results of first 24 hours were discarded as a spin-up period. The land use data was provided by the Lands Department of Hong Kong. The initial and boundary conditions were provided by the 1°x1° NCEP FNL (Final) Operational Global Analysis data (NCEP, 2000) at six-hour intervals.

Measurement data to evaluate the WRF model were provided by the Hong Kong Observatory (HKO). The HKO stations are listed in Table 1 and plotted in Figure 1(b). To quantify the model performance, a set of statistical measures was computed similar to Yim et al. (2007; 2012; 2013).

The UHI was quantified by the Urban Heat Island Intensity (UHII), which represents the temperature difference between urban and rural areas. In this study, non-urban areas (except water bodies) were defined as rural areas. Both hourly and two-monthly mean UHII were estimated based on the WRF outputs. Figure 2 depicts urban areas (brown), non-urban areas (green) and water bodies (blue) in Hong Kong.
Figure 2  A land use map for urban areas (brown), non-urban areas (green) and water bodies (blue) in Hong Kong.

Health Impact

Figure 3  The nine Primary Planning Units (PPU) in Hong Kong. The PPU numbers are marked in the figure. New Territories includes PPUs 3, 4, 5, 6, 7, 8 and 9. Kowloon includes PPU 2, while Hong Kong Island includes PPU 1. The urban heat island intensity (UHII) (°C) values are provided in the brackets.

The health impact due to UHI was estimated based on the Chan et al. (2010). Their study estimated that 1.83% (95% C.I.: 0.73%-3.00%) increase in mortality in Hong Kong is associated with an average of 1°C temperature increase in daily mean temperature above 28.2°C. In their study, the increase of relative risks of heat-related mortality in different areas of residence including Hong Kong Island, Kowloon, New Territories and others were estimated to be 1.43% (95% C.I.: -1.20%-4.30%), 1.36% (95% C.I.: -0.63%-3.47%), 1.40% (95% C.I.: -0.53%-3.43%) and 9.27% (95% C.I.: 1.93%-18.17%), respectively. The areas of residence are depicted in Figure 3.

To estimate the population-exposure to UHI, the daily mean temperature of each day in the study period was overlaid onto the population data in a Tertiary Planning Units (TPU) level provided by the Hong Kong Planning Department. The average daily mortality per 1,000 persons was derived by
dividing the annual mortality rate (6.1 deaths per 1,000 persons) provided by the Centre for Health Protection (2012) by 365 days. Thereafter, based on the aforementioned temperature-response function (Chan et al. 2010), the resultant mortality was estimated. We note that the temperature in indoor environments and the influence of population daily mobility were not taken into account in this study due to lack of data that may result in a higher bias in our results.

Uncertainty

For all the input data in the heat-related mortality calculation, an uncertainty distribution was estimated based on a Monte Carlo simulation, in which a triangular distribution of estimates was constructed on the basis of 10,000 samples. Uncertainty bounds were for a 95% confidence interval.

RESULTS

Model Evaluation

Figure 4 depicts time series plots of temperature at 2 m above ground at two HKO stations: HKO (urban) and TKL (rural). The results show that the modelled temperature agrees well with the measurements. As shown in Table 2, the index of agreement of temperature is 0.71 on average. The percentage difference of mean temperature is 1.33%, indicating that the simulation results are promising for our analyses in this study.

![Time series plots of model evaluation of hourly temperature at 2 m above ground at Ta Kwu Ling – TKL (rural) and Hong Kong Observatory – HKO (urban). Blue lines represent observation data, whereas red lines represent model results. The two small figures are zoomed for a randomly-selected day (26/07) for clarity. The locations of the two stations are shown in Figure 1(b).](image)

Table 2. The Statistical Measures of Model Evaluation. Obs: Observation; IOA: Index of Agreement; Corr: Correlation coefficient; RMSE: Root Mean Square Bias; MB: Mean Bias; MNB: Mean Normalized Bias; NMB: Normalized Mean Bias; MFB: Mean Fractional Bias; ME: Mean Error; MNE: Mean Normalized Error; MFE: Mean Fractional Error; MPD: Mean Percentage Difference; DA: Data Availability.
Temperature Differences between Urban and Rural Areas

Figure 5 depicts the hourly temperature distributions in urban (red) and rural (blue) areas. The results show that the hourly temperature in urban areas (29.6°C) is higher comparing to that in rural areas (28.1°C).

Chan et al. (2010) has found that a unit change in temperature in daily temperature above 28.2°C is associated with an increase in relative risk of heat-related mortality. Thus, 28.2°C was defined as a critical temperature. As shown in Figure 6(a), the daily temperature in rural areas exceeds the critical temperature. However, only ~35% of the time daily temperature in rural areas exceeds the critical temperature. The mean daily temperature in rural areas was found to be 28.1°C, which is slightly lower than the critical temperature. As shown in Figure 6(b), the mean UHII was estimated to be 1.6°C on average.

Figure 3 depicts the UHII in different Primary Planning Units (PPU). In the figure, a north-south UHI gradient pattern is shown. We estimated that the magnitude of UHI (1.7°C) in northern part (PPU 5 and PPU 6) of HK is the highest among the PPs. The urban population of the both PPs, when combined, accounts for 12.6% of the total urban population in HK. The lowest UHI (0.8°C) was estimated to occur in PPU 1, which is located at the southern part of HK. The PPU 2, where its population accounts for 29.6% of total urban population in HK, was estimated to have 1.4°C UHI.

Our estimate shows that the intensity of UHI correlates well with the size of urban areas instead of population. Hong Kong is a high building-density and high-population density city (Ng et al., 2012) due to limited lands for development, and thus its population is not proportional to the size of urban areas. Despite a lower population such as PPU 5 which accounts for only 8.2% of the total HK population, a larger urban area receives more solar radiation and may therefore result in a higher UHII. On the other hand, it should be highlighted that the urban area size pattern is consistent with the UHII pattern as observed in Figure 3. Figure 7 depicts that PPU 5 and 6 have a larger urban area, while PPU 1, 8 and 9 have a smaller urban area. This result indicates that the north-south UHI gradient pattern is associated with the urban area size pattern.
with the pattern of urban area size.

**Figure 5** The frequency distribution of hourly temperature in rural (blue) and urban (red) areas in the study period. The x-axis represents temperature (°C), while y-axis represents normalized frequency.

**Figure 6** (a) The time series of daily mean temperature (°C) at 2 m above ground in urban (+ in red) and rural (○ in blue) areas. (b) The time series of daily urban heat island intensity (UHII) in the study period.
Figure 7: the relationship between area of urban areas (km$^2$) and urban heat island intensity (UHII) ($^\circ$C). The numbers near the data points represent the corresponding Primary Planning Unit number.

Health Impacts

We estimated that UHI causes 75 [95%C.I.: 22-158] mortalities in HK in summer, indicating that ~38 [95%C.I.: 11-79] mortalities are more likely associated with UHI each month in summer. The results show that ~55% of the UHI-related health impact occurs in New Territories, while 39% and 6% of the impact happen in Kowloon and Hong Kong Island, respectively.

DISCUSSIONS

Our results show that HK is affected by UHI in summer, where the mean hourly UHII is 1.6°C. This estimate is consistent with Memon et al. (2009), in which mean hourly UHII was estimated to range between 0.8°C and 2.0°C. According to Leung et al. (2004), the temperature increase rates at an urban station (HKO) and a rural station (TKL) from 1989 to 2002 were estimated to be 0.61°C and 0.15°C per decade. The different increase rate between urban and rural areas indicates that the magnitude of UHI and the resultant health impact may increase in the next decade. Thus, mitigation measures should be implemented to address the UHI. Previous research has studied different mitigation measures such as green roof (Coutts et al., 2013; Zhao et al., 2014), vertical greening (Perini et al., 2011; Tan et al., 2014), and root coating (Bretz et al., 1997). On the other hand, Cheung et al. (2012) showed the importance of air ventilation for enhancing thermal comfort in a city.

Chen et al. (2010) reported that some sensitive groups such as the elderly may be more vulnerable to heat-related mortality. However, age distributions were not taken into account in our estimation due to lack of data. Therefore, more investigations should be done to further estimate the UHI-related mortality among different groups within urban community. In addition, we note that anthropogenic heat emissions, which could play an important role in the formation of UHI, were not taken into account in this study due to lack of the corresponding data. The lack of anthropogenic emissions may cause a lower bias of our results. Nevertheless, this work identified the UHI and its health impacts due to land use variations (urban vs rural).

Another important impact of UHI is additional energy consumption. Fung et al. (2005) studied the energy consumption due to increase in urban temperature of Hong Kong. Based on the data from 1990 to 2004, the study estimated that the energy cost in summer due to an increase in 1°C ambient temperature would increase by HK$1.6 billion per year. The study showed an important relationship between the
additional energy consumption due to change in ambient temperature. However, the change in energy consumption due to UHI has not been studied in the literature, and thus needs to be quantified in a global change adaption context in the future work.

CONCLUSION

In this study, we quantified the urban heat island effect (UHI) in the summer in 2009 and estimated the resultant health impacts based on a temperature-response function reported in the literature. Our analysis estimated that the hourly temperature in urban areas (29.6°C) is higher comparing to that in rural areas (28.1°C). The Urban Heat Island Intensity (UHII) on average. The UHI results in different Primary Planning Units show a north-south gradient pattern over Hong Kong: the highest UHI (1.7°C) in northern part of HK, whereas the lowest UHI (0.8°C) in southern part of HK. We found that UHII correlates well with urban area size instead of population, indicating that policy makers of high-density cities should pay attention to urban area size when tackling UHI. In addition, UHI was estimated to cause 75 [95% C.I. 22-158] mortalities in summer. Of which, ~55% of the UHI-related health impact occurs in New Territories, while 39% and 6% of the impact happen in Kowloon and Hong Kong Island, respectively. The results provide critical implications for urban planners to mitigate UHI in cities, especially for the ones which are being developed in less developed countries such as mainland China.

ACKNOWLEDGEMENT

The study was supported by the Direct Grant of the Social Science Panel of the Chinese University of Hong Kong [Project ID 4052014]. The authors would like to thank the following government departments for the provided data: the Hong Kong Observatory, the Lands Department of Hong Kong and the Planning Department of Hong Kong.

REFERENCES


Leung, Y.K., Yeung, K.H., Ginn, E.W.L., Leung, W.M. 2004. Climate Change in Hong Kong, Technical Note No. 107, the HONG KONG OBSERVATORY, the Hong Kong Special


