18th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
9-12 October 2017, Bologna, Italy

EFFECTS OF ANTHROPOGENIC HEAT FLUX USING DIFFERENT AIR CONDITIONING SYSTEMS ON THE HEAT WAVE EVENTS IN THE CITY OF HONG KONG

Yi Wang[1], Silvana Di Sabatino[2], Alberto Martilli[3], Yuguo Li[1]and Pak Wai Chan[4]

[1]Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong SAR, China
[2] Department of Physics and Astronomy Alma Mater Studiorum, University of Bologna, Italy
[3] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain
[4]Hong Kong Observatory, Hong Kong SAR, China

Abstract: Anthropogenic heat flux is the heat generated by human activities in the urban canopy layer, which is considered the main contributor to the urban heat island (UHI). The UHI can in turn increase the use and energy consumption of air-conditioning systems. In this study, two effective methods for water-cooling air-conditioning systems in non-domestic areas, including direct cooling system (DCS) and central piped cooling towers (CPCT) are physically based, parameterized, and implemented in a weather research and forecasting (WRF) model at the city scale of Hong Kong. A period of extremely high temperature (June 23–28, 2016) in the urban areas was examined, and we assessed the effects on the surface thermal environment, the interaction of sea–land breeze circulation (SLBC) and urban heat island circulation (UHIC), boundary layer dynamics, and a possible reduction of energy consumption. The results showed that both water-cooled air-conditioning systems could reduce the 2-m air temperature by around 0.5–0.8 °C during the daytime, and around 1.5 °C around 7:00–8:00 pm when the planetary boundary layer (PBL) height was confined to a few hundred meters. The cooling tower (CPCT_AC) contributed around 80%–90% latent heat flux and significantly increased the water vapor mixing ratio in the atmosphere by around 0.29 g/kg on average. The implementation of the two alternative air-conditioning systems could modify the heat and momentum of turbulence, which inhibited the evolution of the PBL height (a reduction of 100–150 m), reduced the vertical mixing, presented lower horizontal wind speed and buoyant production of turbulent kinetic energy (TKE), and reduced the strength of sea breeze and UHI circulation, which in turn affected the removal of air pollutants. Moreover, the two alternative air-conditioning systems could significantly reduce the energy consumption by around 30% during extremely high-temperature events. The results of this study suggest potential UHI mitigation strategies and can be extended to other megacities to enable them to be more resilient to UHI effects.
Key words: *anthropogenic heat, air-conditioning systems, urban heat island circulation, extreme high temperature events, boundary layer dynamic, energy consumption*

INTRODUCTION

The substitution of natural surfaces with impervious urban structures because of the rapid ongoing urbanization and human activities has resulted in changes in the urban surface energy and water balance and has influenced the local atmospheric boundary layer structure and urban climate (Oke, 1976; Bonacquisti et al., 2006). Almost all the energy consumption for human activities can eventually transform into anthropogenic heat and be released into the atmosphere within the Earth's land–atmosphere system (Xie et al., 2016). Anthropogenic heat fluxes can increase turbulence fluxes, including both the sensible and the latent heat fluxes (Oke, 1976). Moreover, anthropogenic heat fluxes influence the surface meteorological conditions, particularly the air temperature and water vapor pressure; the vertical motion of the urban air flow, which in turn affects the urban heat island circulation (UHIC) and dynamics and thermal dynamics of the boundary layer; and the air pollutants within the urban canopy layer (Oke 1976; Xie et al., 2016).Buildings are found to be the major source of anthropogenic heat fluxes; residential and commercial buildings account for 40% of the total energy consumption (Quah and Roth, 2012). Studies on the effects of air-conditioning systems on the urban climate were only found for a few cities. These studies focused mainly on the effect of air-conditioning systems on the outdoor air temperature by using models with different levels of sophistication, and did not directly parameterize air-conditioning systems into urban canopy models and neglected the effects of the main physically based processes on the atmosphere. In Hong Kong, electricity consumption in non-domestic buildings accounted for 61.8% of the total consumption in June 2016 (www.censtatd.gov.hk). Statistical analysis shows that air-conditioning accounts for around 30% of the total electricity consumption, of which 68% is in non-domestic premises (Ho et al., 2007). The Hong Kong government encourages the adoption of water-cooled air-conditioning systems, including direct cooling systems (DCS) and central piped cooling towers (CPCT), which seems to be an effective method of territory-wide energy improvement and reduction of electricity consumption and greenhouse gas emissions from 2020 onward (Ho et al., 2007). The effects of the altered air-conditioning systems on the urban thermal and dynamic environment at the city scale are rarely studied but essential. A central component of our study is whether the implementation of two alternative air-conditioning systems can result in an improvement of urban resilience to UHI effects.

METHODOLOGY

The advanced research WRF model (ARW version 3.6.1) is a non-hydrostatic, compressible model with a mass coordinate system (Skamarock et al., 2008). The model was set up with four nested domains with 79 × 79, 79 × 79, 118 × 118, and 142 × 136 grid points with spatial resolutions of 13.5, 4.5, 1.5, and 0.5 km, respectively. The innermost domain covered entire Hong Kong and provided sufficient information on UHI effects and sea–land breeze circulation (SLBC). The vertical grid contains 51 terrains following full sigma levels from the ground up to 50 hPa. The planetary boundary layer (PBL) scheme of Bougeault and Lacarrere (1989) was used. The other physical schemes used in this study please refer to Wang et al. (2017). A 120-h simulation (from 0000 UTC June 23 to 0000 UTC June 28, 2016) is conducted with the initial and boundary conditions from the National Centers for Environmental Prediction (NCEP) Global Forecast System Final Analyses data (FNL) at 1° at 6-h intervals and daily updated sea surface temperatures from NCEP Marine Modeling and Analysis Branch data at 0.5°.To study the effect of air-conditioning systems in non-domestic areas on the urban climate in the city of Hong Kong, several configurations or scenarios of air-conditioning systems in non-domestic areas were simulated, as summarized in Table 1.

Table 1. Configurations and scenarios of air-conditioning systems in non-domestic areas

Numerical simulations	**Urban scheme**	**Anthropogenic heat release description**
Baseline case	BEP/BEM	Based on the real situation, central air-cooled air systems on the rooftop are used to replace the Wall_AC scenario
DCS_AC case	BEP/BEM	DCS with the use of sea water to cool the condenser is assumed
CPCT_AC case	BEP/BEM	CPCT systems are used and assumed to be settled on the rooftop level
No-heat case	BEP/BEM	A scenario without air-conditioning anthropogenic heat releases.

Because of the unrealistic assumption of wall-type air-conditioning systems in the commercial buildings, the baseline case is studied. The baseline case could reasonably reproduce the physical characteristics of the surface air temperature, while the original wall type air-conditioning systems significantly overestimates the air temperature. For the wind fields, the baseline case can well capture the wind rotation, particularly when the wind direction changed from southwestern to southeastern at the HKO station on June 24, 2016. The agreement between the baseline model and observations for the urban areas is set in accordance with the criteria value of the mean bias error (MBE) for 2-m air temperature, which is −0.09 °C. The MBE between the Wall_AC case and the observations is 0.65 °C for the urban areas. In general, the baseline case could well capture the temperature distribution of the urban areas, particularly the commercial areas, which can fulfill the goal of this study.

RESULTS AND DISCUSSIONS

Effects of air-conditioning systems on air temperature, humidity and vertical structures

The averaged 2-m air temperature, water vapor mixing ratio, sensible heat fluxes, and latent heat fluxes are compared among the different scenarios (Figure 1). The use of water-cooled air systems can reduce the 2-m air temperature by around 0.5–0.8 °C during the daytime, and the DCS_AC case presents around 0.1–0.15 °C lower air temperature as compared to the CPCT_ AC case. The temperature differences between the baseline and the alternative systems reach 1.5 °C at 7:00–8:00 pm, as the impact of air-conditioning systems are more significant during the night-time (Fan and Sailor, 2005). The use of cooling tower systems in commercial areas can significantly increase the water vapor mixing ratio in the atmosphere by around 0.29 g/kg on average. However, an increase in the water mixing ratio in the air will result in an increase in the apparent temperature and the heat index level, which will in turn increase the energy consumption to remove the humidity in the supply air (Gutiérrez et al., 2015).

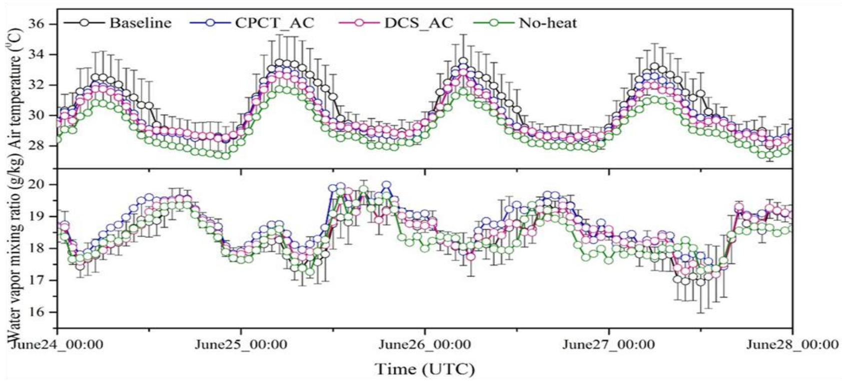

Figure 1. Comparison of mean 2-m air temperature and water vapor mixing ratio in non-domestic areas in the commercial areas for the baseline case, CPCT_AC case, DCS_AC case, and no-heat case

The effects of city-scale air-conditioning systems on vertical structures were investigated. The PBL height presents The implementation of the two alternative air-conditioning systems modifies the heat emitted and generation of turbulence, which induces a 100–150m reduction in the PBL height. The baseline case has a relatively high urban canopy temperature, as shown in Figures 2 a1–a4 on the vertical potential temperature, which leads to thermal discomfort for pedestrians and high building energy consumption. The vertical profile of the potential temperature (Figure 2) shows higher value below 300m in the baseline case than in the other cases at the same height, which illustrates that the anthropogenic heat from the air-conditioning systems enhance the vertical mixing (Salamanca et al., 2014). Differences in the potential temperature between the different cases are reduced with an increase in height (Figures 2a1–a4), which shows the effect of anthropogenic heat fluxes on the potential temperature distribution at the lower level. The momentum fluxes for the horizontal surfaces are determined by the bulk Richardson number based on Louis formulation, which is a function of roof roughness length, wind speed and the air temperature (Martilli et al., 2002). The differences in the potential temperature affect the wind speed, and the baseline case has the largest horizontal wind velocity (Figures 2b1–b4). The buoyant production of TKE has the largest magnitude for the baseline case and the smallest for the no-heat case (Figures 2c1–c2).

Influences on the air quality

The baseline case has a higher air temperature within the urban canopy layer than the CPCT_AC and DCS_AC cases, which implies that the alternative systems can enhance the pedestrian thermal comfort from this aspect. However, the CPCT_AC and DCS_AC cases show a decrease in the sensible heat fluxes, horizontal and vertical wind speed, buoyant production of TKE) and PBL height. The air-conditioning systems also affect the secondary circulation, SLBC, and UHIC. The changes may cause air stagnation and air pollution issues near the ground level, particularly in the convergence areas in Kowloon Peninsula (Xie et al., 2016). Xie et al. (2016) clearly showed that the changes in the meteorological conditions due to the anthropogenic heat fluxes can significantly affect the spatial and vertical distributions of air pollutants, particularly in the big cities in China. Therefore, the hypothesis for air quality issues needs to be confirmed in the future.

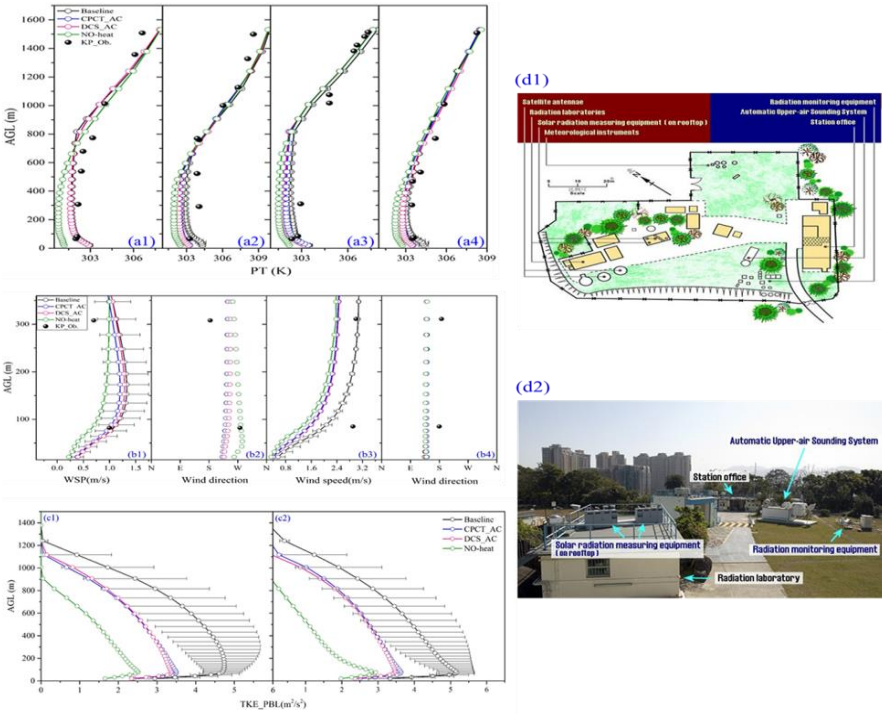

Figure 2. Comparison of mean potential temperature (K), mean wind speed and wind direction, and mean TKE_PBL in the nine grid points near King's Park station for different cases and measurement.

Analysis of urban air-conditioning electricity consumption

The energy consumption using different air-conditioning systems is investigated, and in this study, the COP for the baseline, CPCT_AC, and DCS_AC cases are set as 2.5, 3.5, and 3.5, respectively, on the basis of the findings of other studies (Salamanca et al., 2010). Figure 3 shows the averaged air-conditioning fluxes in the commercial areas and the energy saving with the alternative air-conditioning systems referring to the baseline case. The results clearly show that in the CPCT_AC and DCS_AC cases, the energy consumption by the air-conditioning systems was effectively reduced, with 30% energy savings in comparison to that in the baseline case. Note that here, the cost of changing the systems and maintenance is not considered. In making the decision to choose alternative systems, one must consider the competing benefits and disadvantages.

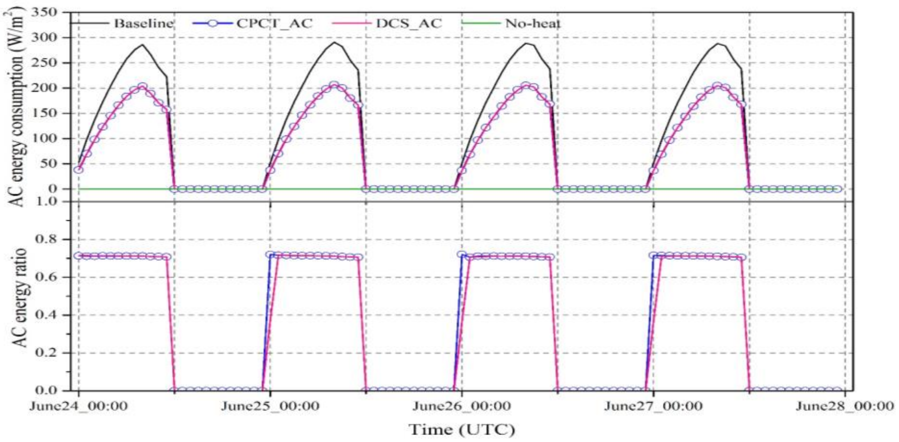

Figure 3. Comparison of air-conditioning energy consumption in the non-domestic areas for different cases.

CONCLUSION

This study is a step forward in investigating the effects of two alternative air-conditioning systems (DCS_AC and CPCT_AC) on urban climate according to the real-life conditions of Hong Kong. The two air-conditioning systems are physically based, parameterized, implemented in the weather research and forecasting (WRF) model coupled with the BEP-BEM urban canopy model, and assessed during an extremely high-temperature period at the city scale of Hong Kong. The results show that both the water-cooled air systems could reduce the 2-m air temperature by around 0.5–0.8 °C during the daytime, and the temperature differences between the baseline and the two alternative systems could reach 1.5 °C at 7:00–8:00 pm when the PBL height was confined to 100 m. Environmental and meteorological effects are not confined at the rooftop where the air-conditioning systems are located, but can extend to the surface and alter the vertical distribution of various parameters within the urban boundary layer. Moreover, the CPCT_AC and DCS_AC cases exhibited lower horizontal wind speed and buoyant production of TKE, which might cause air pollution issues, particularly near the ground level. The CPCT_AC and DCS_AC cases could effectively reduce the air-conditioning energy consumption by 30% as compared to the baseline case. In making the decision to choose alternative systems, one must consider the competing benefits and disadvantages.

REFERENCES

Bonacquisti, V., G. R. Casale, S. Palmieri and A. M. Siani, 2006: A canopy layer model and its application to Rome. *Sci. Total Environ.*, 364(1), 1–13.

Bougeault, P. And P. Lacarrere, 1989: Parameterization of orography-induced turbulence in a mesobeta-scale model. *Mon. Weather Rev.*, 117(8,) 1872–1890.

Fan, H. and D. J. Sailor, 2005: Modeling the impacts of anthropogenic heating on the urban climate of Philadelphia: a comparison of implementations in two PBL schemes. *Atmos. Environ.*, 39(1), 73–84.

Gutiérrez, E., J. E. González, A. Martilli and R. Bornstein, 2015: On the anthropogenic heat fluxes using an air conditioning evaporative cooling parameterization for mesoscale urban canopy models. *J. Sol. Energy Eng.*, 137(5), 051005.

Ho, S. K., L. S. Tam and S. K. Lo, 2007: Proc. Int. Conf. on Climate Change (Hong Kong), vol 1.

Martilli, A., A. Clappier and M. W. Rotach, 2002: An urban surface exchange parameterisation for mesoscale models. *Boundary-Layer Meteorol.*, 104(2), 261–304.

Oke, T. R., 1976: The distinction between canopy and boundary-layer urban heat islands. *Atmosphere*, 14(4), 268–277.

Quah, A. K. and M. Roth, 2012: Diurnal and weekly variation of anthropogenic heat emissions in a tropical city, Singapore. *Atmos. Environ.*, 46, 92–103.

Salamanca, F., A. Krpo, A. Martilli and A. Clappier, 2010: A new building energy model coupled with an urban canopy parameterization for urban climate simulations-part I. formulation, verification, and sensitivity analysis of the model. *Theor. Appl. Climatol.*, 99(3-4), 331.

Salamanca, F., M.Georgescu, A. Mahalov, M. Moustaoui and M. Wang, 2014: Anthropogenic heating of the urban environment due to air conditioning. *J. Geophys. Res. Atmos.*, 119(10), 5949–5965.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. Barke, M. G. Duda, X. Y. Huang and W. Wang, 2008: A Description of the Advanced Research WRF Version 3. NCAR Technical Note NCAR/TN-475+STR, 113 pp.

Wang, Y., S. Di Sabatino, A. Martilli, Y. Li, M. S. Wong, E. Gutiérrez and P. W. Chan, 2017: Impact of land surface heterogeneity on urban heat island circulation and sea-land breeze circulation in Hong Kong. *J. Geophys. Res. Atmos.*, 122(8), 4332–4352.

Xie, M., J. Liao, T. Wang, K. Zhu, B. Zhuang, Y. Han, M. Li and S. Li, 2016: Modeling of the anthropogenic heat flux and its effect on regional meteorology and air quality over the Yangtze River Delta region, China. *Atmos. Chem. Phys.*, 16(10), 6071–6089.