Assessment of landscape design to fight against Urban Heat Island effects through various combinations of heat mitigation strategies

Tengfei Zhao

T.F. Zhao[1], K.F. Fong[2]

Division of Building Science and Technology, College of Science and Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China, tfzhao3-c@my.cityu.edu.hk

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1. Introduction

As cities around the world continue to urbanize, there is an increasing body of evidence suggesting that urbanization has led to the urban heat island (UHI) phenomenon, whereby cities become warmer than the surrounding suburbs (United Nations, 2014). Daily mean UHI typically ranges between 2 and 5 °C (Santamouris, M., 2007; Landsberg, H.E., 1981; Montávez, J. P., et al., 2000). Hong Kong has a high-rise, high-density morphology with tall buildings, which largely aggravate the UHI effects. Some urban areas are already experiencing an UHI of 4 to 5 °C (Ng, E., 2009), whist high heat stress creates an unbearable urban thermal environment. Above all, there is a pressing need to cushion the adverse impacts of UHI-induced microclimates by using appropriate mitigation measures.

Mitigation strategies of UHI through proper landscape design with natural elements have received growing interest, since they are able to remedy thermal environment in reasonable cost. The proposed techniques are those targeting (a) to increase the albedo of the urban environment, i.e. high albedo paving material (Yang, et.al., 2011; Taleghani et.al., 2014); (b) to expand the green spaces (Ng, E., 2012); (c) to use the natural heat sinks to dissipate the excess heat, like water bodies (Robitu et.al., 2006). Here, the outdoor environmental cooling achieved through combination of different heat mitigation strategies will be investigated for subtropical Hong Kong. In this study, Instead of evaluating those strategies qualitatively and separately, quantitatively parametric study will be conducted to widely investigate, compare and analyze their cooling effects. This research predicts the cooling potential of both single and various combinations, and provides a theoretical understanding of the relative effectiveness.

2. Methodology

The microclimate simulation tool ENVI-met will be utilized, which is developed according to the fundamentals of thermodynamics and fluid dynamics. It is a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in urban environment with a typical resolution of 0.5 to 10 m in space and 10 sec in time. In addition, this model states the effects of solar irradiance, humidity and heat storage in soil, the reflection/absorbance from buildings and the interactions of plants with the environment. This tool is therefore widely validated and usually used to improve our understanding of the urban environment in recent literature [Bruse, M., Fleer, H., 1998].

2.1 Climatic conditions and study area

Hong Kong locates in the southeast coast of China, with latitude of 22°15' N, longitude of 114°10' E and has been categorized as a monsoon-influenced humid-subtropical climate. The summer lasts from April to September, tending towards hot and humid, with common sunny conditions as well as brief showers and thunderstorms. June to September are the hottest months of the year, with daily average temperatures varying between 27.6 °C (September) to 28.7 °C (July), daily maximum temperatures ranging from 30.2°C (September) to 31.3 °C (July), and a relative humidity of around 80%. Long and sever hot summer period indicates the local climatic conditions are extremely uncomfortable for people in outdoor spaces.

The environmental benefits caused by aforesaid 3 heat mitigation strategies with different area proportions will be evaluated in a typical urban open space design, which includes the establishment of (a) high albedo pavements; (b) vegetation; and (c) water ponds. The typical urban open space mainly refers to the neighboring space among buildings, characterized with a central open space enclosed by four building blocks located at the corners of the site. This kind of communal open spaces baring frequent human outdoor activities in hyper-dense, land-hungry city of Hong Kong, therefore the comfort conditions should be highlighted. Each building block measures 30 m (L) x 30 m (W) x 60 m (H), and rises for 20 stories in the study site. Area of the site is 93 m x 93 m (8,649 m^2), with a building coverage ratio of 41.6%. The coverage ratios of different heat mitigation strategies are based on the whole site, not the open spaces.

2.2 Development of modification cases with various combinations of heat mitigation strategies

The whole site can be equally divided into 9 plots, four building blocks abut on four corners, and the remaining five plots will be filled up by other natural elements of the heat mitigation strategies. As shown in Fig. 1, totally 10 scenarios are proposed for comparison. For scenarios 1, 2, 3, and 4, the central open space totally consists of 58.4% conventional hard surfaces, 58.4% high albedo pavements, 58.4% green areas (trees), and 58.4% water ponds. Scenarios 5 and 6 are centered with high albedo pavements (covering 12.6%), whist the other 4 plots are filled by water and trees respectively (accounting for 45.8%). Similarly, scenarios 7 and 8 are centered by trees (12.6%), while the remaining open spaces are taken up by high albedo pavements and water ponds respectively (45.8%). Scenarios 9 and 10 have water ponds at the central open plot (12.6%) and the remaining plots (45.8%) are filled by trees and high albedo pavements respectively.

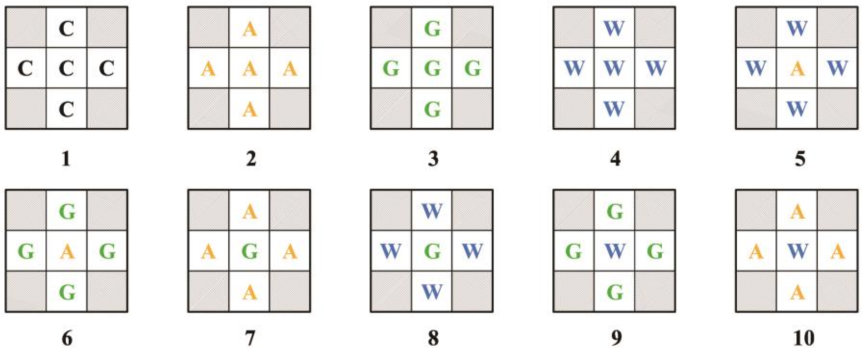


Fig. 1 Summary of the study cases

2.3 Envi-met model establishment

To ensure the reliability of the Envi-met models, the typical urban open spaces were modeled in a domain size of 51 x51 x30 grids, greater than the studied open space to ensure reliable boundary conditions. The horizontal grid dimension were dx, dy=3m. In the vertical direction, there are totally 30 grids, extended with a telescoping factor of 12%. 5 nesting grids were set around the main model area for numerical stability with used concrete pavement by considering real urban environment. 45 receptors were evenly distributed in each direction to extract local air temperature. The simulation ran for 24 hours, starting from 6:00 am to 6:00 am the day after.

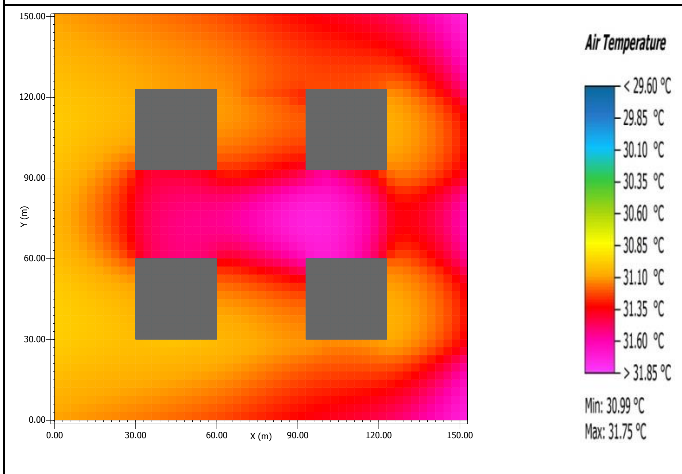
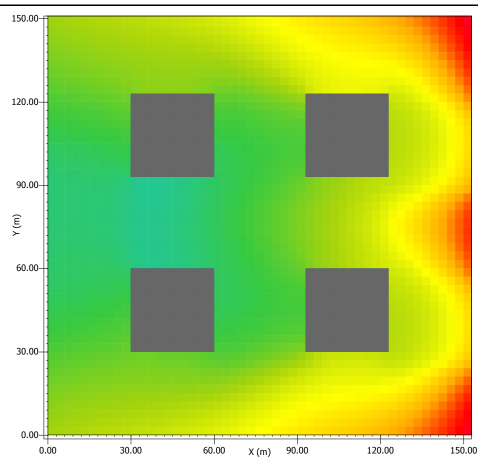
The possible cooling benefits of different mitigation schemes will be compared by using the ambient temperature at 1.5 m high. The surface type used as conventional hard surfaces in case 1 is asphalt concrete, whilst the light color basalt brick road with albedo of 0.8 was used as high albedo materials. The thermo-physical properties of the materials used in simulation were mainly referring to the default values in Envi-met. Trees rather than grass were selected as greening elements. Walls and roofs were constructed by lightweight concrete. The input meteorological inputs are summarized in Table 1.

Table 1 Summary of the main meteorological data input

Sunny day for simulation	Initial temp	Start time	Relative humidity at 2m	Wind direction	Wind speed at 10m
23rd June	28.15 °C	6:00 am	70 %	East	1 m/s

3. Results and discussions

3.1 Pedestrian level air temperature distribution in different cases

2-1 Max: 31.75 °C Min: 30.99 °C	2-2 Max: 31.40 °C Min: 30.24 °C
	

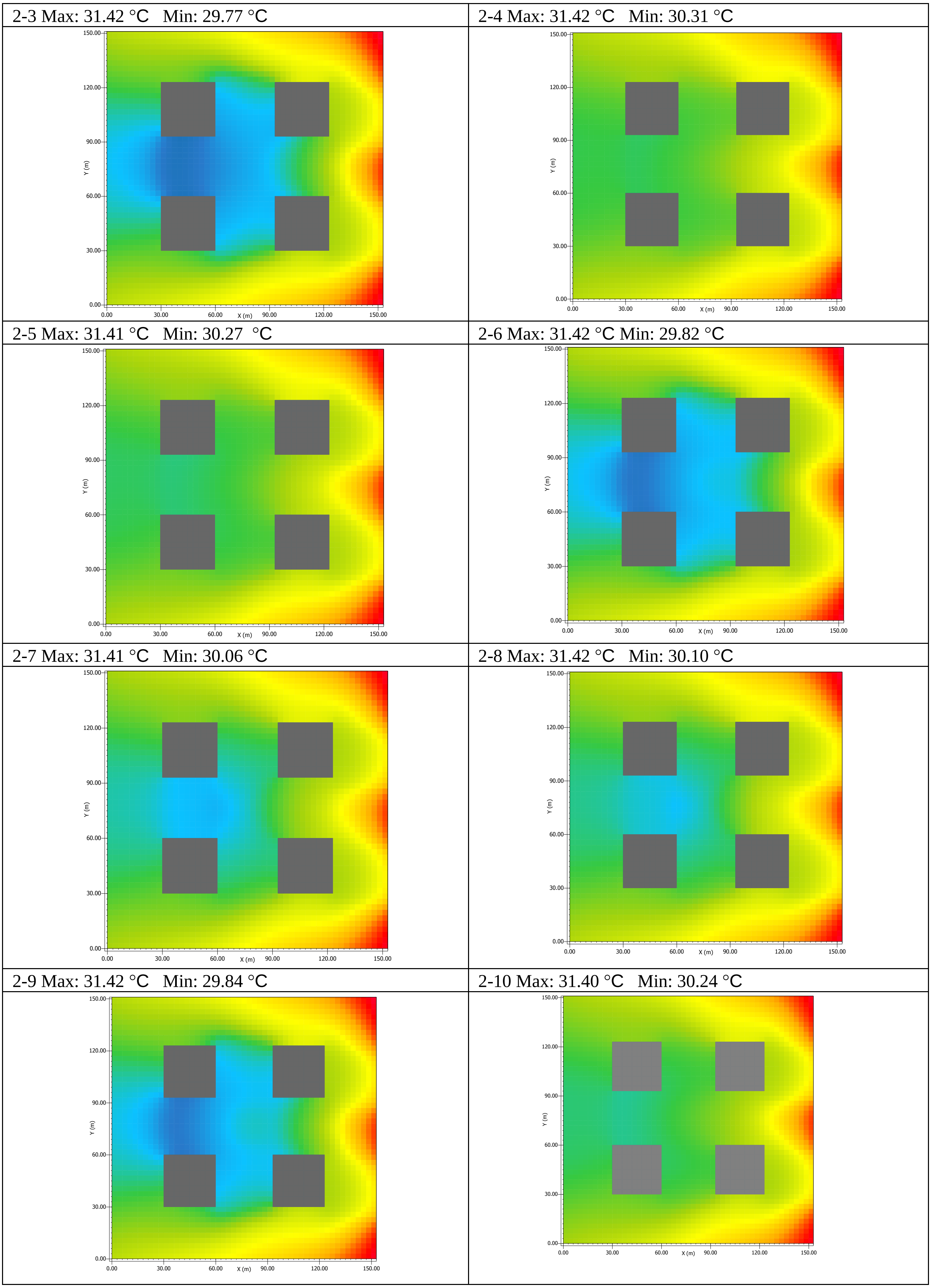


Fig. 2 Air temperature under 10 different conditions at 15:00 at the pedestrian level (1.5m height)

The pedestrian level (1.5m) air temperature distributions at 15:00 in different cases are illustrated in Fig. 2. For comparison convenience, all above figures are plotted using the same color range. The air temperature range is specified by a color gradient, and the low to high temperatures are represented by dark blue to magenta colors. Generally, the air temperatures in case 1 with conventional surface materials are obviously higher than the remaining cases with various combinations of mitigation strategies. The maximum and minimum air temperatures in the whole site domain are 31.75 °C and 30.99 °C, respectively. For cases 2, 3, 4, the open spaces are replaced totally by high albedo materials, trees and water, the corresponding maximum and minimum air temperatures are 31.40 °C and 30.24 °C, 31.42 °C and 29.77 °C, 31.42 °C and 30.31 °C, separately. It seems that greening elements show largest cooling potential, which is followed by high albedo materials and water surfaces. Case 3 demonstrated the lowest air temperature, followed by case 2 and 4.

Moreover, for case 7 and 10, with high albedo materials of 45.8% coverage ratio, centered by 12.6% green spaces and water surfaces, the recorded maximum and minimum air temperatures are 31.41 °C and 30.06 °C, 31.40 °C and 30.24 °C, respectively. This phenomenon further enhances that the greening elements utilization has greater cooling potential than water surfaces. Moving onto case 6 and 9, trees are the dominating elements (with coverage ratio of 45.8%), high albedo materials and water surface locates in the core spaces (with 12.6% coverage ratio). The demonstrated highest and lowest air temperatures are 31.42 °C and 29.82 °C, 31.42 °C and 29.84 °C, separately. On one hand, the two cases presents lower air temperatures in the spaces between buildings compared to case 7, 10, which proves that vegetation could bring more cooling possibilities than albedo. On the other hand, the cooling benefits brought by high albedo materials are slightly higher than water surfaces adoption, but no significant difference. In addition, for cases 5 and 8, 12.6% high albedo materials and vegetation are separately surrounded by water surfaces, which occupy 45.8% of the whole site. The highest and lowest air temperatures in case 5 are 31.41 °C and 30.27 °C, whist the same values for case 8 are 31.42 °C and 30.10 °C, respectively. High albedo materials adoption is more effective than water ponds in microclimate modification.

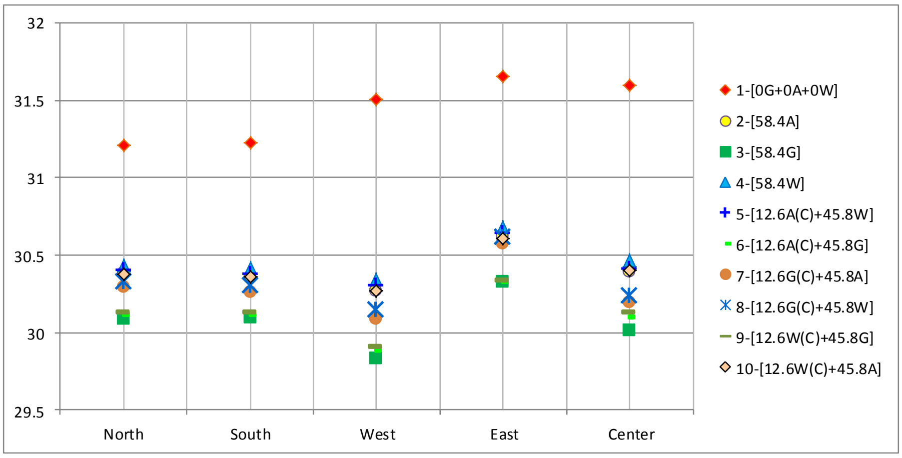


Fig. 3 The average pedestrian level air temperatures of 9 evenly distributed points in each direction extracted at 15:00

Fig. 3 illustrates the average pedestrian level air temperature of 45 evenly distributed receptors and plotted in 5 orientations. The dominating heat mitigation strategies are represented by distinct colors. Combinations of heat mitigation strategies all create cooler microclimates compared to case 1 with traditional surface materials. It can also be found the cases with large vegetation coverage areas all demonstrates lowest air temperature (cases 3, 6, 9), followed by cases dominated by high albedo materials (cases 2, 7, 10) and water surfaces (cases 4, 5, 8). Those finding are in accordance with previous. Thus, it can be concluded that vegetation could provide greatest cooling potential, followed by high albedo surfaces and water ponds. In addition, the local air temperatures in West are lowest among five directions, and in East are highest. While the air temperature distribution in North and South are similar, slightly higher than Central areas. In this study, wind blow from East, and gradually passing through the open spaces. The nesting grids surrounding main model areas were paved by used concrete materials. Therefore, the air temperature there may be higher than the open spaces, and then the hot wind increased the local air temperature in East. As wind passing by, the temperatures were gradually lowered down in the air path way, because relative cooler environment created by heat mitigation strategies. Then the cool currents were blow to West, so the temperature there were lower than East. Simultaneously, similar thermal environments in the leeward side (North and South) were built. No matter which measure has the highest coverage ratio or the relative locations of different heat mitigation strategies, the local air temperature in all cases demonstrates similar variation trends with orientation. From another perspective, it reflects that in a small regional domain, the cooling benefits brought out by various combinations of heat mitigation strategies are not so orientation sensitive.

The average pedestrian level air temperatures at 1.5m obtained from evenly distributed receptors in 10 cases are shown in Fig. 4. Similarly, the cases can be easily distinguished by colors, which were given according to the heat mitigation strategies with largest occupation. Generally, the average air temperatures in all cases are obviously lower than the base case, which proves the cooling benefits from heat mitigation strategies. The cases with large proportions of vegetation (case 3, 6, and 9) present lowest average air temperature. Besides, the open spaces mostly taken up by high albedo materials (case 2, 7, and 10) are slightly cooler than those with large areas of water surfaces (case 4, 5, and 8). It provides another evidence to support previous judgement about cooling potentials of different heat mitigation strategies.

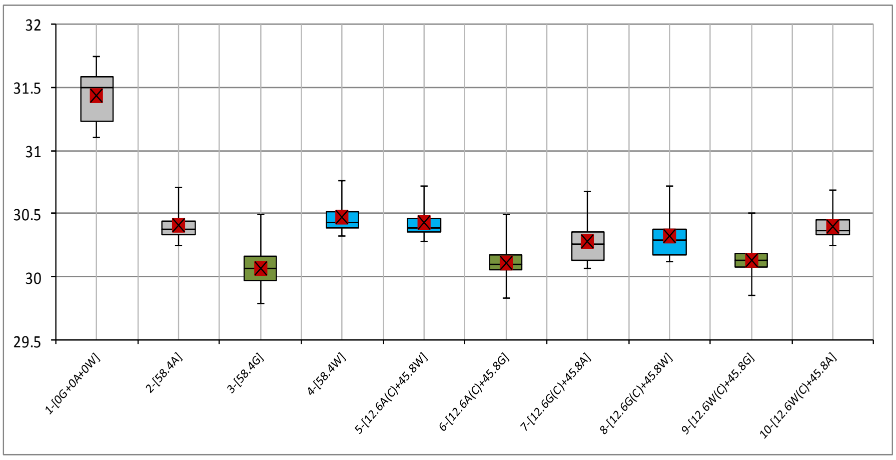


Fig. 4 The pedestrian level air temperatures extracted from 45 evenly distributed points at 15:00 for 10 different cases

3.2 The cooling potential comparison of various combinations of heat mitigation strategies

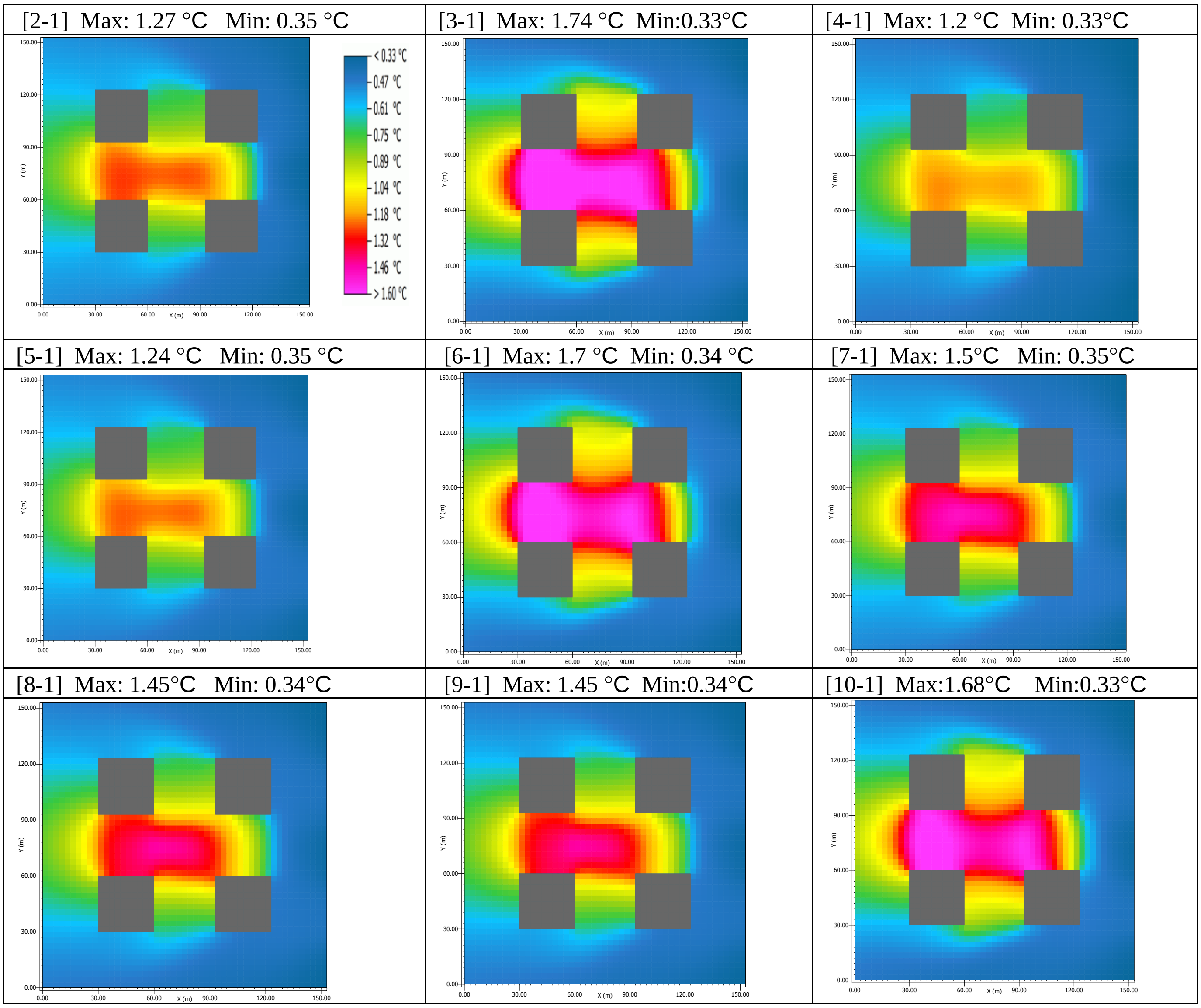


Fig. 5 Pedestrian level temperature reduction comparison from various combinations of heat mitigation strategies at 15:00

In this part, the comparisons were made between conventional conditions and 9 modification cases regarding air temperature variations. The peak temperatures at 15:00 of 45 different conditions were compared at the pedestrian level (1.5m) to understand the impact of these modifications on reducing air temperature at the study site, as shown in Fig. 5. To obtain a fair comparison and to identify the hot and cool spots on the study site, these temperatures were processed with the same color range. In general, the addition of heat mitigation strategies improves the thermal environment on the open spaces. Fig. 6 [2-1] illustrates the temperature variation between case 2 and 1. The associated air temperature reduction can reach up to 1.27 °C, and also bring in at least 0.35 °C temperature decreases. In these 9 comparison scenarios, the minimum cooling benefits are similar, ranges from 0.33 to 0.35 °C. The largest air temperature reduction occurred among these scenarios is with a maximum of around 1.74 °C. The air temperature decreases show a gradient associated with dominating heat mitigation strategies changes in the study site. More specifically, cases 3, 6, 9 demonstrate 1.74 °C, 1.7 °C, and 1.45 °C maximum temperature reduction with vegetation as the main feature. Along with the changes (large areas of high albedo materials) in cases 2, 7, 10, the thermal environment can be cooled by up to 1.27 °C, 1.5 °C, and 1.68 °C, respectively. Besides, the thermal environment of open spaces covered with large areas of water surfaces (case 4, 5, 8) shows relative small variation, with greatest temperature reduction of around 1.2 °C, 1.24 °C, and 1.45°C, separately. These air temperature reduction gradients rely on the cooling potentials of distinct heat mitigation strategies and also the area coverage ratio. Furthermore, areas locates at the main breeze way are more red, which indicates significant modification in thermal environment. In comparison, the spaces locates in leeward side are more yellow, like southern and northern areas, imply smaller temperature reductions.

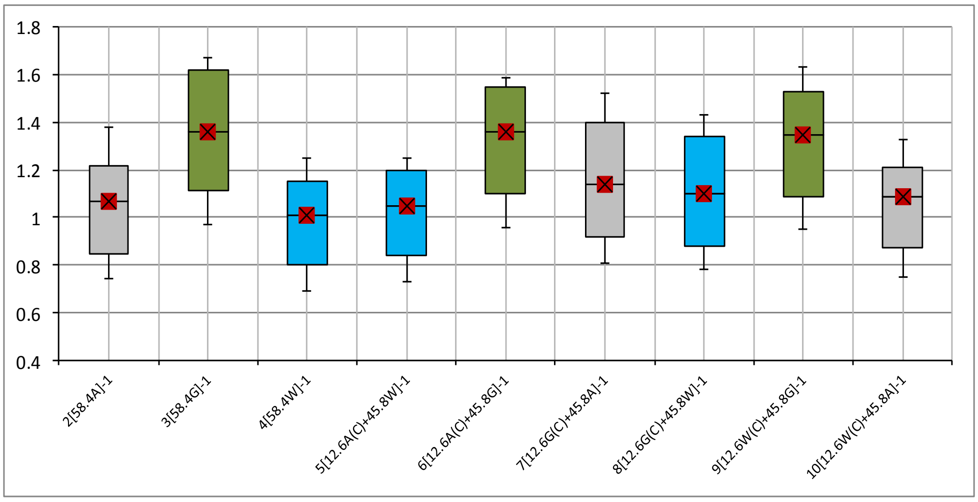


Fig. 6 The pedestrian level air temperature reduction extracted from 45 evenly distributed points at 15:00 for 10 different cases

The pedestrian level air temperature reductions at peak hour of 15:00 caused by various heat mitigation strategies combination are shown in Fig. 6. Therefore, the maximum and minimum average difference can be obtained. Specifically, the modification cases with large areas of greening features could effectively reduce air temperature by 1.37 °C, 1.33 °C and 1.32 °C for case 3, 6, and 9, separately. For case 3, 58.4% vegetation coverage can contribute an air temperature reduction as high as 1.72 °C. Besides, the average cooling benefits derived from introducing high albedo materials are 1.03 °C, 1.16 °C and 1.04 °C, for case 2, 7 and 10, respectively. The recorded maximum air temperature reduction is at around 1.49 °C, for case 7 with areas of 45.8% covered by high albedo materials and 12.6% vegetation. In addition, the thermal environments can be cooled down by 0.97 °C, 1.01 °C and 1.11 °C when conventional surfaces are replaced by water surfaces for case 4, 5 and 8, respectively. And the greatest cooling beneficial of 1.44 °C temperature decrease is brought in by case 8, where 45.8% areas are taken up by water surfaces whist 12.6% by vegetation. Finally, the cooling benefits are obtained in a sequence as: case 3[58.4G]> case 6[12.6A(C) +45.8G]> case 9[12.6W(C) +45.8G]> case 7 [12.6G(C)+45.8A]> case 8[12.6G(C)+45.8W]> case 10[12.6W(C)+45.8A]> case 2[58.4A]> case5 [12.6A(C)+45.8W]> case 4 [58.4W]. This ranking is in accordance with the cooling potential of heat mitigation strategies. To be specifically, vegetation shows greatest cooling potential in modifying microclimate, and high albedo materials could create slightly cooler environment than water ponds. In typical open spaces, the ground surfaces covered by more greening features demonstrate more cooling benefits. Hence case 3 with 58.4% vegetation coverage ratio could bring larger air temperature reduction than case 6. The air temperature reduction of case 9 is smaller than case 6 also resulted from that high albedo materials could reduce air temperature more significant than water surfaces. And so on, for the other cases.

4. Conclusions

In conclusion, knowledge regarding the landscape designs to fight against Urban Heat Island effects through various combinations of heat mitigation strategies was derived from these comparative results. In this study, nearly all combinations could decrease outdoor air temperatures at pedestrian level by around 1 °C in average during peak hour, and as high as 1.72 °C compared to conventional materials. Therefore, the above mentioned 3 heat mitigation strategies are suggested to be applied in outdoor open spaces to benefit people and fight against UHI.

Moreover, vegetation could provide greatest cooling potential, followed by high albedo surfaces and water ponds. The cooling potential highly relies on the area coverage ratio of the study site. Despite the air temperature reductions between various combinations are not so obvious, typically less than 0.5 °C, the cumulative effects caused by minor changes in outdoor spaces may produce significant thermal comfort improvement. Therefore, planting more trees is recommended first in landscape design. And it is better to replace more hard surfaces like pavements with high albedo materials and adding water ponds as heat sinks. In addition, the air temperature reduction ranking between different cases also indicates that in landscape design, the priority should be given to the utilization of heat mitigation strategies with greater cooling potentials and enlarge corresponding coverage ratio. Same principles also applied to the combinations of heat mitigation strategies.

At last, the cooling benefits brought out by various combinations of heat mitigation strategies are not so orientation sensitive, and this may be attributed to the small regional domain. Instead, replacing more surfaces locates in the main air breeze way with heat mitigation strategies helps to bring in cooling benefits in a larger area.

Through this study, an effective landscape design through different combination of heat mitigation strategies is established for fighting against UHI. In the proposed scenarios, the coverage ratios for different strategies are used to understand the extent of cooling benefit, and these ratios not fully practical or site-dependent. In future study, since many heat mitigation strategies are likely with free layout, more comprehensive parametric study will be conducted. In-depth investigation regarding thermal comfort should also be carried out. And in real urban open space design, one must consider various natural elements instead of one, while attempt to synergize and optimize the effect of heat mitigation measures.

References

Bruse, M., Fleer, H., 1998: Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software,* **13**, 373–384.

Landsberg, H.E., 1981: The Urban Climate. *International Geographic Series*, **28**, Academic Press, New York,

Montávez, J. P., Rodríguez, A. and Jiménez, J. I., 2000: A study of the Urban Heat Island of Granada. *International Journal of Climatology*, **20**, 899–911.

Ng, E., 2009: Wind and Heat Environment in Densely Built Urban Areas in Hong Kong (invited paper). *Global Environmental Research*, a Special Issue on Wind Disaster Risk and Global Environment Change. **13**, 169-178.

Ng, E., Chen, L., Wang, Y. N. & Yuan, C. 2012: A study on the cooling effects of greening in a high-density city: An experience from Hong Kong. *Building and Environment,* **47,** 256-271.

Santamouris, M., 2007: Heat Island Research in Europe: The State of the Art. *Advances in Building Energy Research,* **1(1)**, 123-150.

Taleghani, M., Sailor, D.J., Tenpierik, M., van den Dobbelsteen, A., 2014: Thermal assessment of heat mitigation strategies: the case of Portland State University, Oregon, USA. *Building and Environment*, **73**, 138–150.

United Nations, 2014: *World urbanization prospects: the 2014 revision, highlights*. http://esa.un.org/unpd/wup/index.htm. Accessed 1 November, 2014

Yang, F., Lau, S.S.Y., Qian, F., 2011: Thermal comfort effects of urban design strategies in high-rise urban environments in a sub-tropical climate. *Architectural Science Review,* **54**, 285–304.

Robitu, M., Musy, M., Inard, C., Groleau, D., 2006: Modeling the influence of vegetation and water pond on urban microclimate. *Solar Energy*, **80**, 435–447.