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Improvement of the Outdoor Thermal Comfort by Water Spraying in a High-Density Urban Environment under the Influence of a Future (2050) Climate

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Abstract: Adaptation to prepare for adverse climate change impacts in the context of urban heat islands and outdoor thermal comfort (OTC) is receiving growing concern. However, knowledge of quantitative microclimatic conditions within the urban boundary layer in the future is still lacking, such that the introduction of adequate adaptation measures to increase OTC is challenging. To investigate the cooling performance of a water spraying system in a sub-tropical compact and high-rise built environment in summer under the influence of future (2050) climatic conditions, results from two validated models (Weather Research and Forecast (WRF) and ENVI-met models) have been used and analyzed. Our results indicate that the spraying system provides cooling of 2–3 °C for ambient air temperature at the pedestrian-level of the urban canyons considered here, which benefits pedestrians. However, improvement of the OTC in terms of the physiological equivalent temperature (PET—a better indicator of human thermal sensation) was noticeable (e.g., <42 °C or from very hot to hot) when the urban canyon was orientated parallel to the prevailing wind direction only. This implies that in order to improve city resilience in terms of heat stress, more holistic adaptation measures in urban planning are needed. This includes the introduction of more breezeways and building disposition to facilitate the urban ventilation, as well as urban tree arrangement and sunshades to reduce direct solar radiation to plan for the impact of future climate change.

Keywords: urban climate; adaptation measures; outdoor thermal comfort; city resilience; sustainable cities

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1. Introduction

The urban heat island (UHI), which features higher air and surface temperatures in urban areas relative to rural areas, affects the human health [1] and deteriorates the quality of urban living in sub-tropical and tropical regions. The short-wave insolation and long-wave radiation emitted from various ground-level surfaces, as well as moisture, are the major factors to control the outdoor thermal comfort (OTC) (Figure 1). Multiple reflections of solar radiation within the urban street canyons increase the heat stored in the built environment.

Meanwhile, climate change presents negative effects (e.g., via increasing ambient air temperature) to the built environment and OTC [2,3], and, thus, receives growing concern [4–6]. The maximum increases in global average surface air temperature of 2 °C and 4 °C in 2050 and 2010, respectively, have projected by the Intergovernmental Panel on Climate Change (IPCC; [7]). However, quantification of the climate change impact on the urban built environment remains challenging. Nevertheless, knowledge of future climatic conditions at an urban scale is necessary to adequately propose climate change adaptation measures in urban built environments.

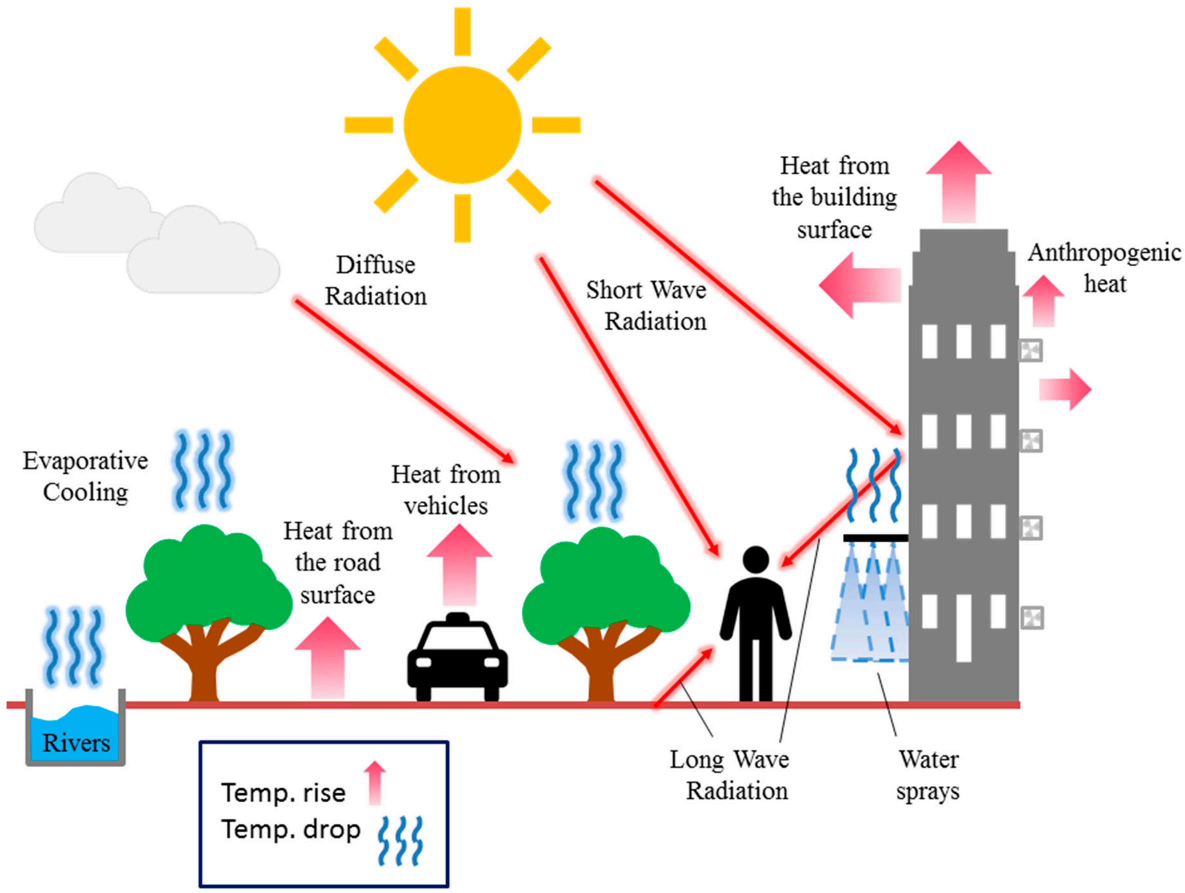

Figure 1. Relationship between the OTC and surrounding environmental settings.

To help reduce the adverse effects of UHI and climate change on the urban thermal environment, such as heat-related mortality [8], the most common adaptation measures are to provide different types of shade, including trees [9–11] and building structures (e.g., [12–14]) to reduce the absorption of direct solar radiation. Apart from these, spray cooling by water evaporation to reduce the air temperature could be another efficient way of improving the OTC (Figure 1).

Small-scale in-situ and numerical cooling experiments for water spraying systems have been conducted in the past. For instance, the performance of solar energy powered aerial misting systems that could be deployed at the roadside was examined in Saudi Arabia [15]. The performance of a water spraying system within a courtyard in the Netherlands was examined via a computational fluid dynamics (CFD) model [16]. The authors concluded that the system is an effective measure for improving the OTC. For urban-scale studies, improvement of OTC with a physiological equivalent temperature (PET) reduction of 15% through introducing fountains and sprinklers in the ENVI-met model was reported for an urban redevelopment design project (covering 11 ha) in Greece [17]. By adopting the same model in an urban heat island adaptation measures study covering a development area of 35.5 ha in France, a water spray facility (blue technology) was adopted as one of the major adaptation measures [18]. Recently, an observations-based study on evaporative misters has highlighted the efficiency of this strategy in an urban setting [19]. Despite the above studies, it is unclear whether the water spraying system is an effective measure to provide thermally comfortable urban built environments under the influence of a future climate.

To fill the mentioned knowledge gaps, our study aims to investigate the impact of complicated interactions between microclimate, urban built environment, blue technology and climate change on the OTC. With the future condition obtained from a Weather Research and Forecast (WRF) model, the ENVI-met model version 3.1 has been first used to simulate the microclimate in urban built environments in 2050. Then, the ENVI-met model version 4.4.4 has been used to quantify the cooling performance in terms of air temperature and PET as a result of water spraying system applied to the urban street canyons. The results were analyzed and compared with those reported in the literature. Finally, implications on UHI mitigated measures were discussed, including different blue and green technologies.

2. Materials and Methods

The study adopted two models, namely, WRF and ENVI-met models. The urban-scale daytime ambient air temperature in 2050 was provided by the WRF model for initialization of ENVI-met model version 3.1, which, after validation, provided daytime hourly predicted air temperatures as the boundary conditions for ENVI-met model version 4.4.4. We used such a model to evaluate the cooling performance of the water spraying system in urban built environments. Details of settings for each model were discussed as follows.

2.1. Model Setting for the WRF Model

The WRF model (version 3.8) was used in the study. The model settings were similar to those described in Situ et al. [20]. Briefly, the simulations were made over 3-nesting domains with grid spacing of 27, 9, and 3 km and 145 × 145, 244 × 244 and 184 × 184 grid points, respectively. Vertical sigma levels were up to 100 hPa and 13 levels were below 1 km to better resolve the processes in the planetary boundary layer. For present meteorology, the National Center for Environmental Prediction (NCEP) 1° × 1° final analysis data were used as initial and boundary conditions. The physical schemes utilized in this study were the Lin et al. [21] microphysics scheme, the Goddard shortwave radiation scheme [22], the RRTM longwave radiation scheme [23], the Mellor–Yamada–Janjic TKE Boundary layer scheme [24], the Kain–Fritsch cumulus parameterization scheme [25], the Noah land surface model [26], and the multi-layer urban canopy model [27]. The Kain–Fritsch cumulus parameterization scheme was used in the two outer domains and no cumulus parameterization scheme was used for the finest-grid domain because the convection is assumed to be reasonably well characterized by the explicit microphysics [28]. The model was evaluated against meteorological observations before applying it for future climate projections. The modelled meteorology in 2010 was evaluated by comparing observed meteorological variables (including wind velocity and air temperature) in nine meteorological stations within the Pearl River Delta, China. The model performance statistics for air temperature (at 2 m AGL were briefed here, namely the bias (1.2), mean absolute errors (MAE; 1.4), and root mean square errors (RMSE; 1.6). The details were reported in [20]. Furthermore, we evaluated the modelled near-ground air temperature in summer 2005 with the hourly observed one in an urban area of Hong Kong (22.30° N, 114.17° E) and found high accuracy of the modelling results. Model performance statistics for mean bias, RMSE, and normalized mean error were −0.26 °C, 1.06 °C, and 0.26%, respectively.

For the simulations of future (2050) meteorology, all model settings were similar to those mentioned above except the followings. The WRF model was used to dynamically downscale the version 1 of NCAR's Community Earth System Model (CESM) future projections. The global six-hourly, bias-corrected CESM dataset [29] was used as the initial and boundary conditions for the WRF model. The CESM model participated in Phase 5 of the Coupled Model Intercomparison Experiment (CMIP5). The dataset were of 26 vertical pressure levels and at approximately one-degree grid spacing [30]. A Representative Concentration Pathway (RCP) future forcing scenario 8.5 was adopted here to study the impacts of intensive fossil fuel consumption with high greenhouse gases emissions and considering the limited computational resources for this study. The WRF model was run for three summer months, from June to August 2050. The model results were chosen from the urban environment of Hong Kong (i.e., Sham Shui Po). The predicted air temperature at 2 m above ground was defined as the ambient temperature. The maximum daytime increase in air temperature was 4.5 °C in 2050 relative to the prevalent condition (2004–2006). The increase is comparable to that reported in other relevant studies e.g., [7,31,32]. The increase was adopted in the future scenarios to drive the ENVI-met model (Table 1). Details of the ENVI-met model settings were discussed subsequently.

Table 1. Meteorological inputs for different versions of the ENVI-met models. AGL: Above ground level.

ENVI-Met (Version 4.4.4)	
Hourly air temperature	Based on ENVI-met model version 3.1 outputs
Prevailing wind speed (at 10 m AGL)	2.0 ms^{-1}
Prevailing wind direction	225°
Relative humidity (at 2 m AGL)	84.3%
Roughness length	0.1 m
ENVI-Met (Version 3.1)	
Initial air temperature at the present-time	26.4 °C
Initial air temperature in 2050	30.9 °C, see text

2.2. Model Setting for the ENVI-Met Models

A three-dimensional computational fluid dynamics (CFD) model (ENVI-met) was used to simulate interactions between atmosphere, surface, vegetation, and buildings within the urban canopy and boundary layer [33]. The model has been successfully applied to simulate the micrometeorological and thermal comfort within an urban environment e.g., [10–12,34]. The effect of the local reduction of air temperature due to water droplet evaporation via latent heat transfer [17,35] has been included in the up-to-date model version. Relevant studies using such version for water spray cooling effect are available in the literature [17,18,35]. Model version 4.4.4 was adopted for our numerical simulations here. The model inputs, such as the hourly water spray emission rate and location/height of spray, were required for water cooling simulation.

The urban morphology of the study site was set to be similar to our previous study [10] in Sham Shui Po (SSP, covering 130 ha), Hong Kong. The site is a traditional residential district with a regular block array geometry. The average building height is 32 m with a standard deviation of 15 m. The urban canyons in the site are oriented to be parallel, perpendicular, or 45° to the prevailing summer wind from the sea. A more detailed description can be referred to in our previous study. A model domain with a 250 × 250 × 30 grid version was applied in the simulations. The grid sizes for the site were set to be 6 m. As the thermal environment at pedestrian level was the focus of this study, three layers of vertical grids were set in the first 2 m height level. Above 2 m, a telescoping factor was adopted for vertical grid generation. The building façade albedo was set to 0.2 [36]. Numerical simulations were performed for the summer solstice of 2050 at clear sky and started at 6:00 a.m. (local time) and ran for a continuous period of 10 h.

The meteorological inputs for the model are detailed in Table 1. To represent the present-time meteorology, the prevailing wind speed and direction, relative humidity, and initial air temperature were adopted from the corresponding three-year (2004–2006) averages measured at a meteorological station near the study site. The inter-annual variation of air temperature was very small (≤0.2 °C). For future simulations, all meteorological inputs were kept identical to the mentioned prevailing situation, apart from air temperatures. The predicted daytime hourly air temperature in 2050 by ENVI-met model version 3.1 was selected as the model input of model version 4.4.4 after considering its better performance on the diurnal variation of air temperature in an urban environment, especially during the afternoon. The model setup (e.g., building layout) was kept identical as much as possible for the two model versions.

To quantify the cooling effect of the water spray, a base scenario (S0, Table 2) to represent the future thermal environment and two spraying scenarios (S1 and S2, Table 2) were considered in order to investigate the cooling effect due to different operation durations.

ENVI-met model version 4.4.4 was used to perform all the spraying simulations. Figure 2 shows the spraying system deployment at the urban canyons. The urban canyon in region 1 (2) is parallel (perpendicular) to the prevalent wind direction, while the canyon in region 3 is oriented 45° to the prevalent wind.

Table 2. Summary of the scenarios used to investigate the water spray cooling effect in the urban environment.

Scenarios	Remarks
S0, no spray	No spraying applied to the urban thermal environment, representing the future base scenario
S1, early operation of the spray system	The spray system operating at an injected water flow rate of 4.5 L min^{-1}, from 10:00 to 16:00 at urban canyons
S2, late operation of the spray system	Same as scenario S1, but operating from 12:00 to 16:00

Figure 2. Deployment of the spraying system at the urban canyons in regions 1 (white lines), 2 (orange line), and 3 (black line). Buildings are in pink.

2.3. Adopted Thermal Sensation Category

The human thermal sensation category reported for the study in Taiwan-Sun Moon Lake (23.8° N, 120.9° E; [37]) were employed (Table 3) because of the similar latitude as Hong Kong. This represented the best information on PET categories available in the literature for the study. Details of the survey (or questionnaires) and the methodology to obtain relevant micrometeorological parameters are to be referred to Lin and Matzarakis [37] and not repeated here.

Table 3. Human thermal sensation category for the study.

Thermal Sensation	*PET* (°C)
Very cold	<14
Cold	14 to 18
Cool	18 to 22
Slightly cool	22 to 26
Neutral	26 to 30
Slightly warm	30 to 34
Warm	34 to 38
Hot	38 to 42
Very hot	>42

3. Results and Discussion

3.1. Evaluation of the ENVI-Met Model Version 3.1 Regarding Air Temperature

To evaluate the model performance to simulate the air temperature, measurements and simulation results on 22 June 2004, were compared (Figure 3). The measurement data were derived from the mentioned meteorological station. The hourly variation of air temperature shown in Figure 3 indicates good agreement between the predicted results and the measurements, especially in the morning and early afternoon. The differences between the measured and predicted air temperatures were less than 1 °C, which is comparable to the differences from 1.0–2.0 °C from other studies [38,39]. Berardi [40] indicated that the discrepancy could be explained by the inaccuracies in the input parameters for the simulation, such as the surface material or vegetation. A high correlation ($r^2 = 0.90$) between the simulated and measured air temperatures was similar to that found from the above studies. These factors demonstrate that the model is a reliable tool to simulate the urban thermal environment. It is noted that various methods to evaluate the performance of the urban-scale model are available including the adoption of satellite observations for model evaluation [41,42].

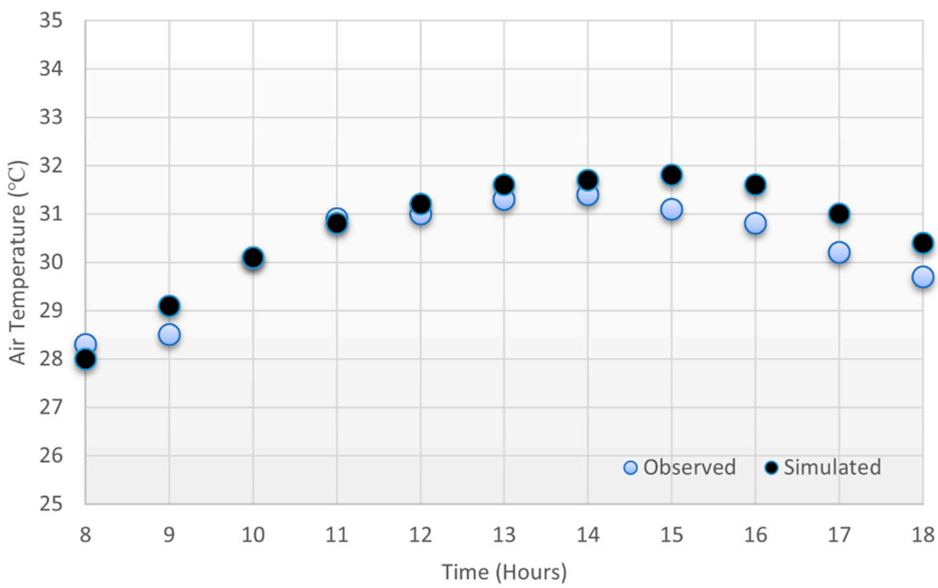

Figure 3. Comparison between measured and calculated daytime air temperature.

3.2. Evaluation of the ENVI-Met Model Version 4.4.4 Regarding Water Spray Model Performance

To evaluate the model performance of the cooling effect of water in our study, a spraying simulation was performed on 17 July 2006. The air temperature distribution calculated by the model near a spraying system was compared with that calculated by a well-validated CFD model (ANSYS/Fluent 12.1) [16]. The environmental setting was detailed in the mentioned work. Briefly, it included a courtyard surrounded by low-rise buildings (~10 m high) with the spraying system located near the courtyard center. The spraying system consisted of 15 nozzles on a spray line at a height 3.0 m above ground level (AGL) with an injected water flow rate of 9.0 L min^{-1}. An ANSYS/Fluent simulation was performed on the mentioned date at noon. Figure 4 shows a comparison of the calculated air temperature by the ENVI-met and ANSYS/Fluent models around the spraying system. It shows good agreement between their results with a coefficient of determination (r^2) of 0.97 and demonstrates the good performance of the ENVI-met model in the water cooling simulations.

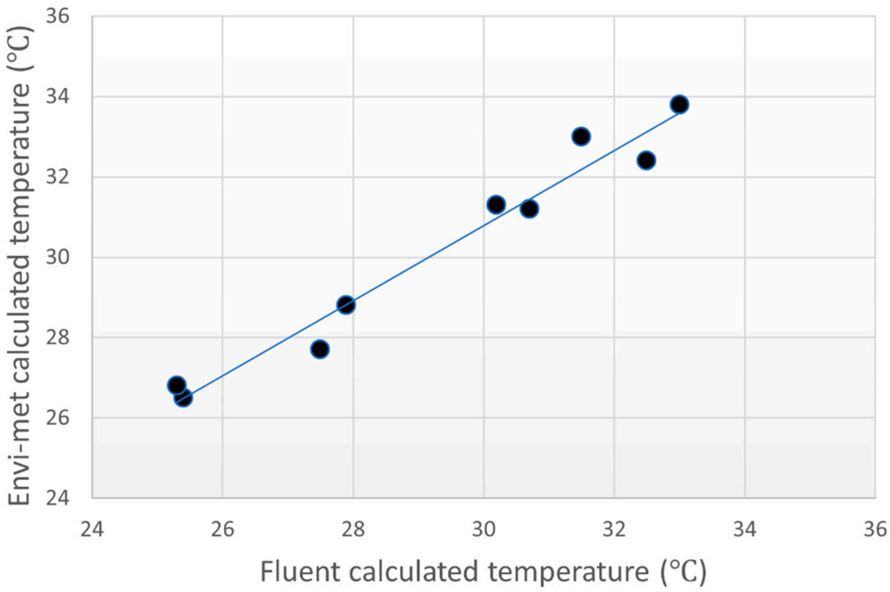

Figure 4. Comparison of calculated air temperature distribution by the Envi-met and ANSYS Fluent models around the spraying system.

3.3. Reduction in Ambient Air Temperature by Water Spraying

With respect to scenario S0, air temperature reduction for scenario S1 ranged from 2.0–5.5 °C at the pedestrian level and was achieved at 11:00 in region 1. With continuous cooling by the spraying system, the relative reduction in temperature became larger in the afternoon. For instance, cooling of more than 7.5 °C was achieved at 15:00 in region 1 (Figure 5). Atieh and Shariff [15] reported that the maximum cooling temperature achieved in roadside experiments with a small-scale water spraying system was 10 °C. Narita et al. [43] conducted an outdoor experiment using their water misting system to obtain a maximum air temperature drop of 6 °C in Japan. Our model predictions are comparable with the measurements. A noticeable cooling effect of 2 °C was still found at some areas 50 m away from the spraying source in region 1 due to water vapor dispersion. This is consistent with a study in Japan, which reported that the cooling effect of the water system could be felt up to a 35 m distance leeward from the source [44]. Vertically, a noticeable air temperature drop of more than 2 °C was found up to 17 m AGL (i.e., the fifth story of nearby residential buildings) for the whole of region 1. Such temperature drops could extend vertically to 36 m above ground (or at the 11th story) for some areas of region 1. Since the outdoor air temperature plays an essential role to indoor thermal comfort and in turn the cooling loads in buildings [45,46], ambient air cooling by the spraying system in the residential areas in summer months has a positive effect on energy conservation, especially in sub-tropical areas such as Hong Kong. For instance, Fung et al. [46] reported that for a 1 °C ambient temperature rise, the electricity consumption would increase by 9.2% in a domestic section of Hong Kong. While the relationship between outdoor spraying cooling and indoor thermal comfort/energy conservation is not the focus here, further relevant investigations under the influence of climate change are encouraged.

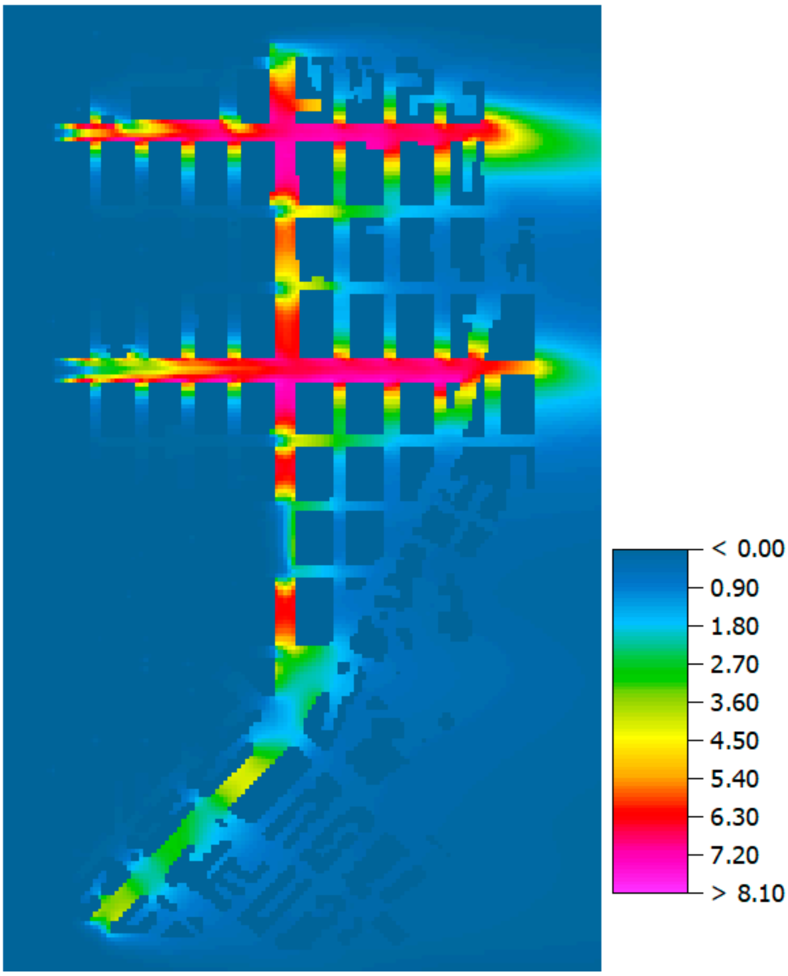

Figure 5. Reduction of air temperatures (°C) in different regions due to the cooling of spraying system.

While the cooling effect at the pedestrian level in region 2 could be achieved as more or less similar to region 1, a small portion of region 2 experimented with the spraying system deployed only at one side of the canyon, creating an area of less cooling (temperature drop <2.5 °C) at 15:00. Similarly, the cooling effect in region 3 was less than region 1, since parallel installation of the system along both sides of the street in region 3 was not possible in some areas (Figure 5).

3.4. Reduction in PET by Water Spraying

Without applying the spraying system, daytime street-level PETs within the site varied from 32.5 °C in the early morning to >60.0 °C in the late afternoon. The high-end and low-end values were found in the sunlit and shaded areas, respectively. The high-end values were also found within the urban canyons where low wind speeds were located. Higher PETs (>45 °C and up to 58.0 °C) were reported during heat wave events [47,48]. When comparing our results with those in a European city during a heat-wave study [47], our PET was 54.5 °C with an air temperature of 35.4 °C at 15:00 and their PET was 58.0 °C with an air temperature of 38.0 °C at 15:00, indicating consistence between the results of the two studies.

Under the influence of the predicted 2050 climate at 11:00 for scenario S0, street-level PETs were found to exceed 42 °C (i.e., in the very hot category) near the model domain boundaries (figure not shown). In region 1, 30 percent of the area was shaded by high-rise buildings with PETs lower than 36.0 °C (i.e., in the warm category). PETs for the rest of the sunlit areas (70% of the area) marginally exceeded 42 °C. However, PETs reached >50.0 °C in region 2, mainly due to the weak wind situation there. A weak wind situation is one of the major reasons to increase PETs [14,49,50]. Spraying scenario S1 indicated a significant cooling effect (up to 5 °C) in region 1. It led to a one-class improvement (from very hot to hot) in thermal sensation in most of the areas and even further improvement (i.e., warm category) for the rest of the areas. A higher reduction in PETs (4.0–7.5 °C) in region 1 was attributed to the high wind speeds and relatively low air temperatures there. Although equipped with the spraying system, the maximum cooling effect was less (<3.5 °C) in regions 2 and 3 due to the weak wind situation there. The occurrence of the weak wind situation is because the studied streets are not parallel to the prevailing wind direction.

At 13:00, when the building shading effect became small, PETs in region 1 marginally exceeded 42 °C for scenario S0 (Figure 6). The spraying could provide improvement of thermal comfort from very hot to hot in the area. Again, the cooling effect at other urban canyons with the spraying system was less than desirable (<3.0 °C) for most of the areas, resulting in PETs >42 °C. Although there was a small increase in PET for the whole study domain at 15:00 with respected to 13:00, PETs of more than 65% of region 1 marginally exceeded of 42 °C (similar to the situation at 13:00) because of the building shading effect. Water spraying provided better improvement of thermal comfort from very hot to hot. For some areas, thermal comfort could reach the warm class (i.e., PET reduction of >7.0 °C at maximum). Far fewer cooling effects were found elsewhere, similar to those discussed above. The PET drops reported here are comparable to the results found elsewhere. Chatzidimitriou et al. [17] revealed a PET reduction of 7.7 °C when applying sprinklers and fountains at noon in the hottest summer day in Greece. In France, a maximum PET reduction of 5 °C was predicted by an ENVI-met model using a water spray facility as the cooling measure [18]. Gómez et al. [51] obtained a PET reduction of 6.5 °C near a spray fountain via measurement at noon in a typical summer day in Spain.

3.5. Implications on Climate Change and UHI Adaptation Measures

Since the ambient air temperature in the future (2050) could be increased by more than 4 °C relative to the current situation, climate change adaptation measures to reduce heat stress in urban areas are urgently needed. This is especially true as PETs (as a better indicator of human thermal sensation) were calculated to be 5 °C higher in the urban street canyons than those in the ambient open areas in our study due to the low wind speeds in the urban canyons. This finding is consistent to other studies elsewhere [49,50]. The proposed water spraying system in the urban canyons performed well here in terms of PET reduction; however, only when the canyons were oriented parallel to the prevailing wind direction. This implies that the availability of breezeway/wind paths in the built environments is essential to facilitate the penetration of the prevailing wind (i.e., sea breeze in our case) into inland areas, and also to facilitate the performance of the spraying system. A similar synergistic effect of combining a mitigation strategy with the local wind path was reported in our previous study [10]. It is a crucial point for urban design planning and emphasizes the importance of climatic design in both new development and urban renewal projects. For instance, orientating urban canyons in parallel to the prevailing wind, connecting open spaces, maximizing the penetration of sea breezes, and optimizing urban geometry, including building heights, scale, and building disposition are effective measures to form wind corridors in urban areas e.g., [52,53] and references therein). Further, more frequent and intense heat waves associated with climate change are predicted in the future. Various mitigation interventions such as greenery, water bodies, and cool materials should be considered and adopted in urban built environments.

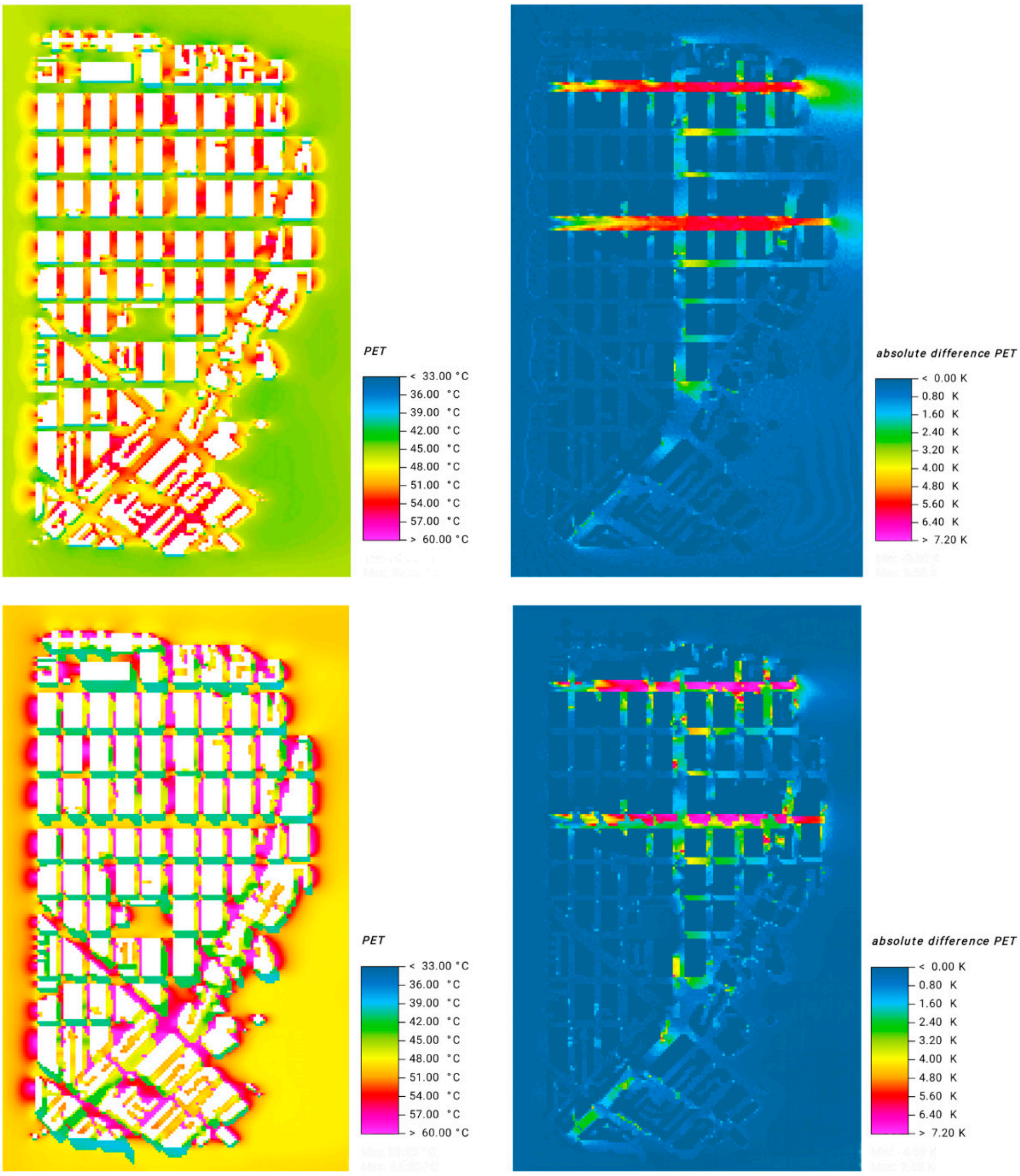

Figure 6. (Upper left) PETs for the scenario S0 at 13:00; (Lower left) PETs for the scenario S0 at 15:00; (Upper right) PETs reduction at 13:00; (Lower right) PETs reduction at 15:00.

4. Conclusions

While the application of green technology as a climate change adaptation measure has been documented, studies of blue technology (e.g., water spraying) at an urban scale for the same purpose are rarely available in the literature. Therefore, in the current study, the cooling performance of a water spraying system deployed in a high-rise-built environment in a sub-tropical city in summer has been investigated under the influence of the predicted future (2050) climatic conditions through the usage a regional model—the WRF model, and a microclimate model—the ENVI-met model. Based on our well-validated model predictions, the water spraying system provides an air temperature decrease of more than 5 °C at the pedestrian level (1.2 m AGL), agreeing with the results reported elsewhere. However, weak winds (<0.5 ms^{-1}) featured within the urban canyons not oriented parallel to the prevailing wind direction reduce the cooling performance of the spraying system in terms of PET reduction. Therefore, measures to increase urban ventilation and reduce direct solar radiation are recommended for new urban development and urban renewal projects to improve the OTC. For the purpose of energy and water conservation, a scenario of late operation was considered here. The result concluded that such operation could achieve a similar OTC level in the urban canyons in the afternoon relative to the early operation scenario. Our study has demonstrated that water spraying could be an additional option as an efficient adaptation measure for combating heat stress under the influence of a future climate, also considering other adaptation measures such as urban ventilation, sunshades, and tree cooling of course. The water spraying could be applied to other hot sub-tropical and tropical areas within different kind of built environments. More studies for this, as well as the observations-based efforts, are recommended. Furthermore, ambient air temperature decreases of more than 2 °C via the spraying system at heights up to the 11th story of residential buildings present a positive implication for energy conservation and indoor thermal comfort, especially in sub-tropical areas such as Hong Kong. Further relevant investigations in this area are encouraged.

Author Contributions: K.-M.W. designed the study; K.-M.W. and L.X. collected the data; K.-M.W., L.X. and T.Z.T. analyzed the data; K.-M.W. and T.Z.T. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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