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A Review of Mitigating Strategies to Improve the Thermal Environment and Thermal Comfort in Urban Outdoor Spaces

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Abstract:
Urban open space provides various benefits to citizens, but the thermal environment of this space is impacted by global warming and urban heat islands. A growing number of studies have been conducted on strategies for improving the urban thermal environment and attracting more people to outdoor spaces. This paper reviews the mechanisms and cooling effects of four major mitigation strategies, namely, changing the urban geometry, planting vegetation, using cool surface, and incorporating bodies of water. Our review found that on summer days these four strategies yielded a median reduction in air temperature of 2.1 K, 2.0 K, 1.9 K, and 1.8 K, respectively. In terms of integrated effect on thermal comfort, changing the urban geometry provided the greatest improvement, with the largest reduction in physiologically equivalent temperature (PET) in summer (median ΔPET = 18.0 K). The use of vegetation and water bodies reduced the median PET by 13.0 K and 4.6 K, respectively. However, some simulation studies found that reflective surface led to higher PET in summer because of the increased amount of reflected solar radiation. The mitigation strategies improved the urban thermal environment to a greater extent in hotter and drier climates. Vegetation, cool surface, and water bodies provided less cooling in compact urban spaces than in open areas. The results that we reviewed can be used by designers and planners seeking to create thermally comfortable urban open spaces.

Keywords: Urban heat island; Outdoor thermal comfort; Urban geometry; Vegetation; Cool surface, Water body;

1. Introduction

As a result of rapid urbanization in the past half century, over fifty percent of the world's population lives in cities (Population Reference Bureau, 2016). Urban outdoor spaces contribute to the livability and vitality of cities by providing citizens with various benefits, including physical, environmental, economic, and social benefits (Woolley, 2003). For example, a study in Japan (Takano et al., 2002) analyzed the five-year survival rate of 3,144 elderly people and concluded that walkable urban green spaces positively influenced the longevity of urban senior citizens. In addition to health benefits, urban open spaces offer a feeling of social support. By measuring the social contacts and health of 10,089 residents in the Netherlands, Maas et al. (2009) found that a larger number of outdoor green spaces coincided with fewer feelings of loneliness. Since urban open spaces provide these benefits, one of the goals in urban space design and planning is to make urban open spaces attractive. This goal could be realized in part by improving the thermal environment of outdoor spaces. As found by many researchers (Lin et al., 2012; Zacharias et al., 2001; Thorsson et al., 2004; Eliasson et al., 2007; Nikolopoulou and Lykoudis, 2007), the outdoor thermal environment or the concomitant outdoor thermal comfort is directly related to usage of outdoor spaces. In addition, improving the outdoor thermal environment could create energy-saving opportunities in two ways. First, the cooling load in buildings could be reduced because of the cooler urban temperature (Hassid et al., 2000; Santamouris et al., 2001; Hirano and Fujita, 2012; Fung et al., 2006; Davies et al., 2008). Second, as people spend more time in the outdoor spaces, their usage of air conditioners and other electronic equipment would decrease (Lai et al., 2014a).

However, the urban outdoor thermal environment faces two major challenges: global warming and urban heat islands. From a time perspective, a large body of scientific evidence shows that the world's climate system is becoming warmer (Meinshausen et al., 2009). The Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC), 2013) has projected that the global mean surface air temperature will increase by 0.3 to 4.8 ^{o}C by the year 2100, depending on the specific emissions scenario and climate model. From a space perspective, the air and surface temperatures in urban centers are higher than in rural areas. This phenomenon is known as the "urban heat island" (UHI) effect (Santamouris, 2013a). A UHI worsens a city's thermal environment, increases building cooling loads, and reduces the thermal comfort of open spaces. In addition, during the summer, the combination of global warming and UHIs is likely to result in increased heat-related mortality. For example, in January 2009, a four-day heat wave in Melbourne resulted in 374 excess heat-related deaths (Jamei et al., 2016). During the summer of 2003, a European heat wave resulted in 25,000 to 70,000 deaths throughout Europe (Zuo et al., 2015).

To help city dwellers better adapt to the possible effects of global warming and urban heat islands on the urban thermal environment, and to improve thermal comfort in urban open spaces, numerous design strategies have been proposed and assessed. Some researchers suggest changing the urban geometry (Charalampopoulos et al., 2013; Chatzidimitriou and Yannas, 2017; Ali-Toudert and Mayer, 2006), while others recommend the use of vegetation (Lee et al., 2016; Klemm et al., 2015a), reflective surfaces (Fintikakis et al., 2011; Gaitani et al., 2011; Santamouris et al., 2012), or water bodies (Nishimura et al., 2003; Saaroni and Ziv, 2003; Xu et al., 2010). Different levels of improvement have been demonstrated in different urban spaces in cities located in a wide range of climate regions. An up-to-date review of studies of the urban thermal environment and thermal comfort is necessary to provide further understanding of the current research status and to quantify the cooling effects of these strategies. This study conducted a comprehensive and systematic review of the effectiveness of various strategies in improving the urban thermal environment and thermal comfort. Our literature search identified a number of related review articles that may be useful to readers: summaries of urban heat island research approaches by Mirzaei and Haghighat (2010) and Mirzaei (2015); a review of computational fluid dynamics (CFD) studies by Toparlar et al. (2017); reviews of the effects of urban greening by Bowler et al. (2010), Raji et al. (2015), and Koc et al. (2018); reviews of uses of cool pavement by Santamouris (2013b), Yang (2015), Qin (2015b), and Taleghani (2018); a review of reflective and green roofs by Santamouris (2014); a review of green roof by Berardi et al. (2014); a review of the influences of urban geometry and greening by Jamei et al. (2016); and reviews of the effects of various strategies by Gago et al. (2013), Santamouris et al. (2017) and Nouri et al. (2018a). Two books, Boundary Layer Climates (Oke, 2012) and Urban Climates (Oke et al., 2017), are also helpful in studying and understanding the urban thermal environment. However, these reviews primarily focused on the urban heat island mitigation potentials, for example, the mitigations in air and surface temperatures. Other important parameters related to urban thermal environment and thermal comfort, such as thermal radiation, wind speed, and humidity were neglected. This review comprehensively summarizes the impact of different strategies on all important parameters of outdoor thermal environment and presents the integrated effect on outdoor thermal comfort.

The structure of this review is shown in Figure 1. First, the parameters that define the urban thermal environment are introduced. We then address different methods of obtaining these parameters. Next, various mitigation strategies for improving the urban thermal environment, including changing the urban geometry, planting vegetation, using cool surface, and incorporating water bodies, are summarized, and the effectiveness of these strategies in improving the thermal environment is reported. Finally, we compare the mitigation effects of the reviewed strategies, discuss interactions between strategies, and discuss the influences of climate on the cooling effects of these strategies.

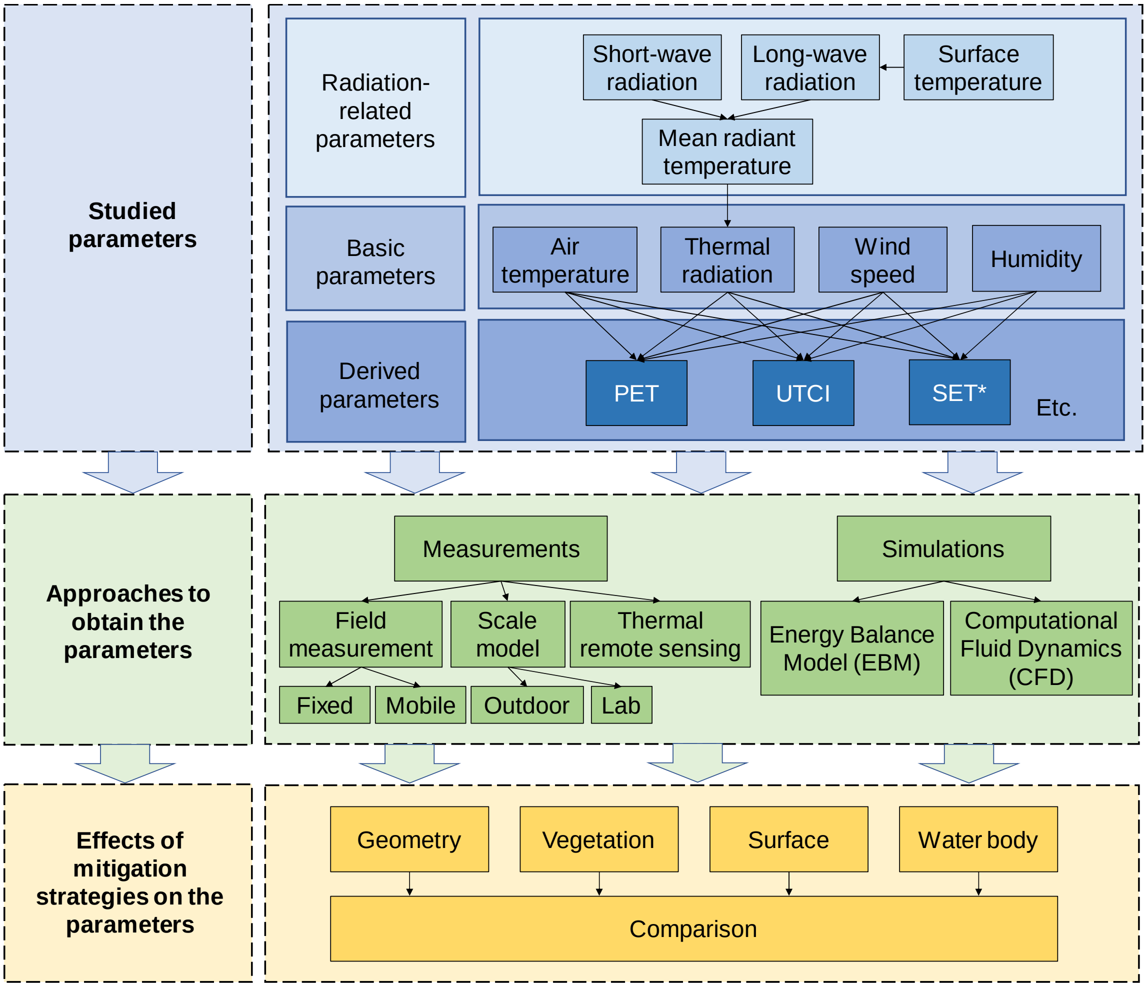

Figure 1. Structure of this review.

2. Urban thermal environment

This section first discusses the parameters that constitute the urban thermal environment. The methods for obtaining these parameters are then summarized.

2.1 Parameters constituting the urban thermal environment

The human body exchanges heat with the urban surroundings by means of convection, radiation, evaporation, and conduction (Fanger, 1970). The determination of heat transfer between a human body and its surroundings requires not only human parameters such as clothing insulation and activity level, but also physical parameters describing the thermal environment. The first part of Figure 1 shows the physical parameters that are most commonly used to describe the urban thermal environment. Four basic parameters, air temperature, thermal radiation, wind speed and humidity, are required to fully describe the human thermal environment in urban open spaces. Each of the basic parameters characterizes the thermal environment independently of the others. Connections among these parameters in the calculation of various gains and losses of heat in relation to the human body can be found in Lai and Chen (2016) and Lai et al. (2017b).

The most complicated parameter among the four basic parameters is thermal radiation. The thermal radiation within an urban open space is usually described by mean radiant temperature T_{mrt}, which is defined as the uniform surface temperature of an imaginary space where the net radiant heat transfer between a human body and the space is equal to the heat transfer in an actual enclosure with non-uniform temperatures (ASHRAE, 2009). In urban open spaces, T_{mrt} sums the long-wave and short-wave radiation to which a human body is exposed. Short-wave radiation includes direct, diffuse, and reflected solar radiation from the sun (ASHRAE, 2009), while long-wave radiation is from the sky and from solid surfaces such as building facades and the ground. According to the Stefan-Boltzmann law, the amount of long-wave radiation is proportional to the fourth power of the surface temperature of the emitting material. As a result, the surface temperature of the surroundings, such as pavement and building walls, can be used as an indication of the level of long-wave radiation.

The four basic parameters can be integrated into "equivalent temperatures" to evaluate the thermal stress of the urban thermal environment on a human body. These "equivalent temperature" parameters enable a layperson to compare the integrated effects of complex outdoor thermal environments with his or her own experience indoors. The equivalent temperature is defined as the ambient temperature of a reference environment that will cause the same physiological response for a standard person as the actual environment would. Examples of these parameters are the physiologically equivalent temperature (PET) (Höppe, 1999), the universal thermal climate index (UTCI) (Bröde et al., 2012), and the standard effective temperature (SET*) (Gagge et al., 1986). Since PET is the most widely used integrated parameter (Potchter et al., 2018), this review uses PET to assess the integrated effects of different strategies in improving the urban thermal environment.

In order to analyze the urban thermal environment, the above parameters are obtained through measurements or simulations, which are discussed in the next section.

2.2 Methods for obtaining urban thermal environmental parameters

2.2.1 Measurements

In the studies we reviewed, measurements were usually conducted in the field, which offered "real-world" records of the urban thermal environment. To study the effect of a certain feature, places with different metrics of that feature were selected, and their thermal environmental parameters were monitored. For example, to investigate the influence of urban geometry on thermal environment, Johansson (2006) conducted measurements at sites with various geometric characteristics in old and new cities of Fez, Morocco. A fixed meteorological station was used to conduct long-term monitoring at two sites in the old city and the new city. Since two meteorological stations can record parameters of the thermal environment in only a limited number of spaces, and using more stations would have been costly, Johansson (2006) conducted short-term measurements at another ten locations to capture the spatial characteristics of the urban climate. Another way to acquire spatial distributions in urban climates is to conduct mobile measurements. For example, Qaid et al. (2016) mounted sensors on top of a vehicle and surveyed the urban thermal environment of the city of Putrajaya, Malaysia, along a 4 km route and an 8 km route. Bicycles can also be transformed into mobile measurement platforms. With the use of a mobile station mounted on a bicycle, Klemm et al. (2015a) cycled along nine streets in Utrecht, the Netherlands, continuously from 9:00 a.m. to 16:00 p.m. to collect data for evaluating the physical and psychological impact of street greenery on pedestrians' outdoor thermal comfort. In addition to fixed and mobile meteorological stations, a thermal remote sensing technique can be used to study the urban thermal environment. With the help of a satellite and aircraft, thermal remote sensing can provide the surface temperature over a large area (Voogt and Oke, 2003). Sun and Chen (2012) extracted the surface temperature from a remote thermal sensing image of Beijing, China, and analyzed the mitigating effect of 197 water bodies on an urban heat island. Drawbacks of the remote thermal sensing technique are that it is very expensive and cannot provide direct information about air temperature and other parameters. In addition, a significant portion of the urban surface is vertical and thus cannot be viewed in remote thermal sensing images (Mirzaei, and Haghighat, 2010).

Conducting research in real urban settings can be challenging because it is hard to study the effect of one variable while holding other variables constant. As a result, some researchers have built scaled models, both outdoors and in laboratories. The Comprehensive Outdoor Scale Model (COSMO) on the campus of Nippon Institute of Technology, Japan, is a one-fifth-scale outdoor physical model that represents a low-rise urban setting with the same building geometry and surface materials. In addition to evaluating momentum, heat, and mass transfer in urban spaces (Kanda and Moriizumi, 2009), the model can be used to study the effect of different mitigation strategies, such as adding vegetation (Park et al., 2012) and water bodies (Syafii et al., 2017). The outdoor use of scaled model relies on the outdoor climate for the input "boundary conditions." To enable changing the climate environment at will, some researchers have built scaled models in laboratories (Oke et al., 2017). For example, Spronken-Smith (Spronken-Smith, 1994) built a scaled model and used a cold chamber to simulate nighttime urban conditions in order to study the radiative, conductive, and evaporative nocturnal cooling of urban parks. Scaled models can also be built in wind tunnels for the study of urban ventilation. For example, Meng and Hibi (Meng and Hibi, 1998) built a scaled model in a wind tunnel and evaluated the flow field around an isolated high-rise building.

2.2.2 Simulations

Measurements in the field lack experimental control, while tests using scaled models require careful design for similitude and are expensive. With advances in computational resources, numerical modeling approaches have become increasingly popular (Toparlar et al., 2017). Numerical models simulate real-world phenomena by solving sets of equations that link urban climate properties (Oke et al., 2017). Among these models, energy balance models (EBM) and computational fluid dynamics (CFD) have displayed the most reliable and satisfactory outcomes (Mirzaei, and Haghighat, 2010). By using the law of conservation of energy on limited nodes, energy balance models can provide acceptable accuracy at a reasonable calculation speed on a large scale.

However, a significant drawback of EBMs is the absence of a velocity field. Without the coupling of velocity and temperature fields, the EBM cannot be used to explicitly study the effect of flow pattern, the formation of atmospheric phenomena, or the sensible and latent heat flux. According to Toparlar et al. (2017), computational fluid dynamics offers two advantages over EBMs: (1) CFD is capable of performing simulations with the explicit coupling of velocity and temperature fields and, if necessary, with the addition of humidity and pollution fields; and (2) with CFD, it is possible to resolve the urban climate on a small scale, such as the building scale or the human scale. However, CFD simulations require a high-resolution representation of the urban geometry, knowledge of the boundary conditions, and adequate computational resources. It is worth noting that ENVI-met (Huttner and Bruse, 2009) is a very popular CFD microclimate simulation software program. One weakness of ENVI-met is that it offers only the Yamada and Mellor E-ε (Yamada and Mellor, 1975) model as the turbulence model (Toparlar et al., 2017).

Simulations of urban outdoor thermal environment can be conducted on various scales from a city, a district, a neighborhood block, to one or several buildings. Since specific models are usually suitable for one scale and not for the others, multi-scale modeling system were developed and implemented according to the research objective (Fang et al., 2004). For example, Yang et al. (2016b) combined the advantages of high computational efficiency of a neighborhood scale Urban Canopy Model (UCM) and the land-atmosphere computation capability of a Weather Research and Forecasting (WRF) model to study the urban thermal environment at multi-scales.

Although the simulation provides complete experimental control and can account for climates of all scales, it is recommended that the simulation be validated against field measurements in order to establish confidence and gain useful insights (Oke et al., 2017). As summarized by Toparlar et al. (2017), only 57 out of the 122 (46.7%) simulation studies for real urban areas compared at least one of the simulated parameters with those measured from the field or in the wind tunnel. Because air temperature is relatively easy to obtain, many studies used air temperature as a validation criterion. Rosso et al. (2018) found from 15 ENVI-met studies that the root mean square error (RMSE) between the predicted and measured air temperature to be from 0.66 K to 4.83 K. The notable contrast between the simulated and observed values indicate that care should be taken when interpreting simulation results.

2.2.3 Measurements and simulations in combination

Simulations can supplement measurements on occasions when instrumentation is lacking. For example, because they did not have an instrument to measure mean radiant temperature and wind speed, Morakinyo et al. (2016) used ENVI-met to generate data for the analysis of the outdoor thermal environment of a Nigerian university. Liu et al. (2016) combined a wind speed distribution simulated by CFD and the air temperature, radiant temperature, and humidity acquired from onsite measurements to study the thermal comfort under an elevated building.

2.2.4 Screening measurement and simulation studies

Since the studies of urban thermal environment were conducted by a relatively small and diverse group of scientists (Stewart, 2011), it is important to use a critical review process to screen the studies to ensure the quality of the selected studies. For the field measurement, this review defines four screening rules by referring to the scientific evaluation criteria set by Stewart (2011): (a) Measurement of thermal environment variable(s) below roof level at contrasting sites; (b) Clear documentation of the number, location, and the measured variables; (c) Sufficient description of the site by site map, sketch, or photographs; (d) Demonstration of effort to control confounding effects such as weather, local settings, or time. Generally, only field studies satisfying the above four rules will be used in this review. However, exception applies when the study can provide useful insight. Scaled model studies are all included in the review because they offer a higher level of control over field studies.

For simulations, three screening rules are employed: (a) Clear indication of the numerical models, tools, and turbulence models (if any); (b) Sufficient documentation of the computational domain by site maps or parameterization of the studied scenarios; (c) Demonstration of effort to validate the simulation by comparing with measurement result. However, because some unvalidated generic numerical studies (Ali-Toudert and Mayer, 2006; Andreou, 2013) can offer insightful results, they are still used in this review.

3. Mitigation strategies to improve the urban thermal environment

This section assesses various strategies for improving the urban thermal environment for human beings. These strategies include changing the urban geometry, planting vegetation, using cool surface, and incorporating bodies of water. First, the effects of these strategies on thermal radiation, air temperature, wind speed, humidity, and thermal comfort, if any, are reviewed. Next, the effectiveness of different strategies is compared.

3.1 Urban geometry

Urban open spaces are characterized by various geometries. The primary effect of urban geometry on the urban thermal environment is to modify the radiative and convective heat exchange within urban open spaces. High and dense urban morphology often blocks solar radiation and reduces wind speed. In studies of the thermal environment, the urban geometry is usually quantified by the following parameters: the sky-view factor (SVF) for irregular and complex spaces, such as spaces in squares, parks, and housing communities; or the height-to-width ratio (H/W) and orientation for street canyons (Lai et al., 2017a). The height-to-width ratio, defined as the ratio between the height of buildings and the width of the street, is an important factor indicating the openness of an urban canyon. A higher H/W value implies less openness, and vice versa. The sky-view factor is a dimensionless number ranging from zero to unity, representing the amount of unobstructed sky seen from a given point (Oke, 1988). A lower SVF indicates greater obstruction by urban elements such as buildings and trees, resulting in less radiation from the sun and the sky, and more long-wave radiation from urban surfaces.

3.1.1 Effect of urban geometry on radiation

Compact urban spaces with low SVF or high H/W are characterized by reduced exposure to solar radiation, thus creating greater thermal comfort in hot climates. Charalampopoulos et al.

(2013) carried out field measurements at six sites within a university in Athens, Greece, in the month of July, and found that where SVF was lower, heat stress was less frequent. In an elementary school in Tainan, Taiwan, Shih et al. (2017) investigated the thermal environment in seven spaces with different SVF and found that the time-averaged PET decreased with a reduction in SVF. Similar results were observed in Putrajaya, Malaysia (Qaid et al., 2016), Dhaka, Bangladesh (Kakon et al., 2009), and Huwei, Taiwan (Lin et al., 2010).

In addition to the reduction in solar exposure, the level of radiation in compact areas is also lower than in open spaces. Many studies have confirmed the positive relationship between SVF and mean radiant temperature (T_{mrt}). Measurements by Tan et al. (2013) in Singapore and Krüger et al. (2011) in Brazil, and a simulation by Wang et al. (2016) in Canada all found that the value of T_{mrt} increased with SVF. Although T_{mrt} values are greater in places that are more open, the amount of long-wave radiation in such spaces is lower, as the spaces are surrounded by fewer solid surfaces, which are major contributors to long-wave radiation. Such a result was demonstrated by Lai et al. (2017a) in Hong Kong, where the authors found an inverse correlation between SVF and the amount of long-wave radiation.

At night, when short-wave radiation is absent, T_{mrt} is affected only by long-wave radiation. As a result, T_{mrt} decreases with an increase in openness. Measurements conducted by Andrade and Alcoforado (2008) in Lisbon, Portugal, and a simulation conducted by Wang and Akbari (2014) in Montreal found strong negative associations between SVF and T_{mrt} at night. However, a contrasting result was presented by Wang et al. (2016), who demonstrated in a simulation study in Toronto, Canada, that T_{mrt} increased with SVF at night. The authors attributed this finding to greater solar energy storage during the day for those places with higher SVF.

The orientation of a street canyon also greatly affects the amount of radiation it receives. Ali-Toudert and Mayer (2006) showed that streets with E-W orientation experienced more prolonged exposure to direct solar radiation than streets with other orientations. Taleghani et al. (2015) determined the solar exposure durations of E-W and N-S streets (H/W = 0.9) to be 12.5 and 4.5 hours, respectively, on June 19 in the Netherlands. Andreou (2013) found that an increase in H/W ratio to 3.0 did not improve the thermal environment of E-W oriented streets. On the contrary, N-S oriented streets with H/W higher than 0.8 can provide thermally comfortable conditions for most of the day. Johansson (2006) found that in a traditional neighborhood in Fez, Morocco, where the H/W ratio was higher than 6, the effect of street orientation was negligible because it was difficult for solar radiation to penetrate. Although some researchers have found the thermal environment of E-W oriented streets to be less favorable than that of N-S oriented streets in summer, Chatzidimitriou and Yannas (2017) found that the south side of an E-W oriented street (H/W=3.2) provided the most comfortable conditions among 18 investigated sites because that street was permanently shaded. A similar result was obtained in a simulation study in Hong Kong by Lau et al. (2016), as the authors found that T_{mrt} was about 1.5 ^{o}C lower on the southern side of E-W canyons than in other places, but the area of the "cool spot" was limited. Lau et al. (2016) also found that N-S oriented streets generally did not produce "hot spots" because they were shaded by buildings.

In comparison with E-W and N-S orientations, intermediate orientations such as NE-SW and NW-SE have been studied less frequently. Ali-Toudert and Mayer (2006) found that although the discomfort duration of intermediate orientations was greater than that for a N-S street with the same H/W ratio, the intermediately oriented streets were always partially shaded, thus offering an alternative to pedestrians. If a winter scenario were considered, NE-SW and NW-SE orientations might provide a good compromise because they offer a greater degree of sun exposure than the N-S orientation.

3.1.2 Effect of urban geometry on wind speed

The wind decelerates when it encounters buildings. The more open the urban form, the more exposed it is to wind (Taleghani et al., 2015). Wang and Akbari (2014) found by simulation in Montreal, Canada, that in an open area (SVF = 0.85), the wind speed was around 2.5 m/s, while in a compact place (SVF = 0.3), the wind speed was approximately 0.5 m/s. According to extensive field measurements by Yang et al. (2013) in Shanghai, a 10% increase in SVF resulted in an 8% increase in wind speed at the pedestrian level. The average wind speed in a deep canyon in Fez, Morocco, measured by Johansson (2006) was 0.4 m/s, while the speed in a shallow canyon was 0.7 to 0.8 m/s. A parametric study using CFD by Yuan and Ng (2012) indicates that on the whole, a decrease in site coverage ratio helps promote ventilation, but the ventilation effect depends mostly on pedestrian-level building porosity. However, on the building scale, Berardi and Wang (2016) showed that with the construction of new buildings, wind speed accelerated around the building corners.

The direction at which the wind enters a street greatly affects wind speed in an urban canyon. Previous literature has usually characterized the flow direction with respect to streets as parallel, normal, or oblique (Ahmad et al., 2005). Georgakis and Santamouris (2008) and Santamouris et al. (2008) proposed a framework to estimate wind speed inside street canyons for different flow directions. On the street level, the flow is channeled into the canyon if the street is oriented in a parallel direction to that of the wind. In coastal cities, an effective ventilation strategy is to make the street orientation parallel to the sea breeze (thus normal to the coast). In a study in Colombo, a coastal city in Sri Lanka, Johansson and Emmanuel (2006) recommend widening roads that are perpendicular to the coast to allow the penetration of sea breeze into the city. In Thessaloniki, Greece, in summer, Chatzidimitriou and Yannas (2017) found that the wind speed in streets normal to the coast reached 2.5 m/s, while in canyons parallel to the coast, the maximum wind speed was only 1.0 m/s. When the wind direction is normal to the streets, according to Oke et al. (2017), one or more vortices develop, thus limiting the wind speed within the canyon. Oblique flow combines the features of normal and parallel flow (Oke et al., 2017). A helical vortex circulates the air in the cross-canyon direction, and at the same time it channels the flow along the street. Ng (2009) suggested limiting the angle between the street and the flow orientation to less than 30^{o} to achieve good ventilation in high-density cities.

3.1.3 Effect of urban geometry on air temperature

Blocking direct solar radiation in a compact area makes it cooler than an open area. In an extreme case in Fez, Morocco (Johansson, 2006), the summer daytime air temperature in a very deep canyon (H/W = 9.7) was 6 K lower than that in a shallow canyon (H/W = 0.6). Similarly, in a measurement in Dhaka, Bangladesh (Kakon et al., 2009), the maximum difference in air temperature between shallow and deep canyons (SVF = 0.51 and 0.13, respectively) was found to be 6.6 K. Berardi and Wang (2016) found that the addition of new constructions reduced the ambient air temperature by up to 1 K during the day. Usually, during the day, a positive relationship exists between SVF and air temperature. For example, in simulation studies in Montreal, Canada (Wang and Akbari, 2014), and Toronto, Canada (Wang et al., 2016), variation in SVF from 0.30 to 0.85 would lead to an air temperature difference of up to 1.5 K. Chen et al. (2012) confirmed this phenomenon in Hong Kong through field measurement, but with a higher impact of SVF on air temperature than in Montreal and Toronto, Canada. They demonstrated that 0.15 decrease of a 100 m radius neighborhood average of SVF resulted in a 1 K air temperature elevation. At night, when direct solar radiation is absent, open places were found to lose more heat to the sky through long-wave radiation that did compact places, the result being lower air temperature. Measurements by Yan and colleagues in Beijing (Yan et al., 2014) and a simulation by Wang and Akbari (2014) in Montreal all showed that increases in SVF resulted in lower air temperature at night.

In practice, the thermal environment in urban open spaces is influenced by a combination of factors. The general results summarized in this review may not always apply. For example, since the intensity of anthropogenic heat is often higher in cities centers than in rural areas, the actual relationship between SVF and air temperature can be negative. Horrison and Amirtham (2016) investigated the thermal environment in T. Nagar, Chennai, India, and found the highest air temperature in a space with the lowest SVF, because of the anthropogenic heat from a nearby bus terminal.

3.1.4 Effect of urban geometry on thermal comfort

As demonstrated in the preceding analysis, the levels of radiation, wind speed, and air temperature in compact urban spaces are generally lower than those in open spaces. In hot climates, reducing radiation and air temperature is helpful for achieving thermally comfortable conditions. However, a decrease in wind speed worsens the urban thermal environment in summer. These integrated effects can be evaluated by thermal indices such as PET. According to several studies, PET values in compact spaces were lower than in open spaces (Cheung and Jim, 2018a; Kántor et al., 2018; Shashua-Bar et al., 2012), indicating that the influence of shade outweighs the effect of reduced wind. This conclusion was supported by Andreou’s (2013) parametric analysis. He found that the PET difference between shaded and exposed areas was 10 K, while the PET difference between wind speeds of 3.5 m/s and 1.0 m/s was only 6.5 K. From the above analysis, it is reasonable to conclude that compact spaces provide a better urban thermal environment than open spaces in the hot season.

Winter scenarios have received much less research attention than summer ones. Compact urban forms exhibit better thermal conditions during summer but are disadvantageous during winter (Jamei et al., 2016). Johansson (2006) showed that although a shallow canyon was extremely uncomfortable in summer, the solar access in winter made it more comfortable than a deep canyon. A trade-off between the hot and cold seasons should be considered when designing urban morphology for outdoor thermal comfort, especially in temperate regions. For example, while many studies have demonstrated the advantages of parallel flow in summer (Johansson, 2006; Ng, 2009), a winter measurement campaign in Thessaloniki, Greece (Chatzidimitriou and Yannas, 2017), observed the most comfortable conditions in a street canyon perpendicular to the prevailing wind.

3.2 Vegetation

Vegetation in urban open spaces can make various contributions to high-quality urban living. The primary effects of vegetation on the urban thermal environment are to block radiation, decelerate wind, and reduce air temperature.

3.2.1 Effect of vegetation on radiation

Trees effectively reduce thermal radiation in urban open spaces. By reflection and absorption, trees can remove a great amount of incoming short-wave solar radiation. According to Brown and Gillespie (1995), generally, only 10% of visible and 30% of infrared radiation is transmitted through trees. Like urban buildings, trees contribute to the lowering of the sky view factor (SVF) in urban spaces. Many studies have quantified the reduction in mean radiant temperature (T_{mrt}) under trees. Onsite measurements in the Netherlands by Wang et al. (2015b) demonstrated that on average, the T_{mrt} in a grove of trees was 7.4 K lower than in an open space. In Athens, Greece, Charalampopoulos et al. (2013) found that the T_{mrt} of a "green atrium" with tall trees and irrigated grass was about 8 K lower than that of an ordinary building atrium. Increasing the urban tree coverage can protect pedestrians from direct sunlight. Wang et al. (2016) found by simulation that a 10% increase in urban vegetation coverage could reduce T_{mrt} by up to 8.3 K. As with compact urban areas, when solar radiation is low or absent, trees can increase T_{mrt} by trapping long-wave radiation. Morakinyo et al. (2016) showed that before 7:00 a.m., the T_{mrt} was 2.5 K higher at a tree-shaded site, but the opposite was true after sunrise.

A number of researchers have studied the optimum vegetation arrangement for sheltering an area from radiation. By rearranging tree locations in a street parking lot, Milosevic et al. (2017) achieved an improvement in outdoor thermal comfort at 77% of the locations. Radiation can be further reduced by planting trees with larger crowns. By increasing the tree coverage and using trees with larger crown, Wang and Akbari (2016) achieved the highest T_{mrt} reduction, 40 K. Different shapes of tree crowns have also been studied. Milosevic et al. (2017) showed by simulation that cylinder-shaped tree crowns reduced heat stress more effectively than sphere-shaped and cone-shaped crowns of the same height and diameter. The leaf area index (LAI), which is the ratio of leaf area to ground cover (Kong et al., 2017), quantifies the effect of trees in intercepting radiation. Higher LAI indicates denser leaves and greater ability to block radiation. For example, Shahidan et al. (2010) demonstrated by field measurements that LAI was a significant parameter in radiation filtration. The authors found that the Mesua ferrea L. species, which has a mean LAI of 6.1, was able to reduce radiation by 92.55%, while Hura crepitans L., with a mean LAI of 1.5, provided only 79% radiation filtration.

In addition to blocking short-wave radiation, vegetation reduces long-wave radiation because of the decrease in surface temperature due to transpiration. Chatzidimitriou and Yannas (2015) found that the mean surface temperature of a grass field (34.4 ^{o}C) was considerably lower than that of concrete (45.5 ^{o}C). In a simulation study, Zheng et al. (2016) compared the surface temperatures of a lawn, shrubs, ground under trees, and exposed ground. They demonstrated that the lawn had the lowest surface temperature, followed by the shrubs and the ground under the trees. The difference between the surface temperature of the lawn and the bare ground exceeded 20 K. Because of the ability of vegetation to reduce surface temperature, some researchers have proposed the use of vertical greenery to improve the outdoor thermal environment. Through measurements, Bianco et al. (2017) found that the maximum surface temperature of vertical greenery was 24 K lower than that of a reference wall. In a vertical greenery experiment, Tan et al. (2014) found that the T_{mrt} increased by up to 12.8 K after the removal of a green wall. A green roof can also reduce surface temperature. According to Ouldboukhitine et al., (2014), the installation of a green roof on a building in the campus of University of La Rochelle, France yielded a maximum reduction of 20 K in roof surface temperature in summer. However, because of its location, the reduced roof surface temperature of a green roof may have a negligible effect on radiation environment at pedestrian level.

3.2.2 Effect of vegetation on wind speed

Trees increase the roughness of the urban surface and impose a drag on airflow. The effect of porous trees in reducing urban airflow is different from that of solid buildings. While buildings create high pressure difference between the windward and leeward directions, the pressure difference created by trees is much smaller because of their porous nature. As a result, the wind is significantly accelerated around the edges and roofs of buildings, whereas trees cause smooth changes in wind speed (Oke et al., 2017).

After conducting measurements at a scale model site, Park et al. (2012) concluded that the presence of four sidewalk trees reduced the wind speed by up to 51%. Heisler et al. (1990) measured the wind speed in neighborhoods with and without trees. The buildings in the neighborhood reduced the wind speed by 22%, and the addition of 77% coverage by trees further increased the wind-speed reduction, to 70%. In the three-year Chicago Urban Forest Climate Project, Heisler (1994) extensively measured the wind speed in various locations in Chicago and concluded that trees can decrease wind speed by up to 90%. Simulation by Morakinyo et al. (2016) showed a decrease in wind speed by up to 50% in an area with trees compared to an open area. However, in a CFD study by Zheng et al. (2016), although the wind speed in the region downstream of a planted area was reduced by 40.5% to 61.6%, the wind in the region downstream of an open area was accelerated by 12.8% to 15.4%.

3.2.3 Effect of vegetation on air temperature

When vegetation converts liquid water to water vapor through transpiration, the temperature of the leaves and the surrounding air decreases (Oke, 2002). In addition to direct cooling by transpiration, trees reduce the air temperature indirectly by means of shading. The reduction of air temperature by trees has been studied by numerous researchers. Abreu-Harbich et al. (2015) reported that individual trees reduced the air temperature by 0.9 to 2.8 K between 10:00 a.m. and 2:00 p.m. in summer. A five-month measurement in Assen, Netherlands, by Wang et al. (2015b) demonstrated an average reduction in air temperature of 0.6 to 0.9 K under tree shading compared to an unshaded area. On hot and dry days, the difference in air temperature between a tree-shaded area and a location near a building façade could reach 3.3 K. Increasing the tree coverage can provide a greater reduction in air temperature. By conducting simulations, Ng et al. (Ng et al., 2012) concluded that in Hong Kong, 33% of the urban area needed to be covered by trees to lower the pedestrian level air temperature by 1 K.

Planting vegetation on the roofs (green roof) may also lead to reduction in air temperature. When used on a city scale, green roofs were found to reduce the average ambient air temperature by 0.3 to 3 K, according to a review summarized by Santamouris (2014). But the cooling effect on pedestrian level depends on the height of building. The measurement conducted in Singapore (Wong et al., 2003) indicated that when implemented on buildings with height under 10m, green roof may have cooling effect on pedestrian level. Similarly, a model test in France (Berardi, 2006) and a simulation study in Toronto, Canada (Ouldboukhitine et al., 2014) found a maximum air temperature reduction of 0.8 and 0.4 K at pedestrian level, respectively, when green roofs were employed on buildings with height of around 10m. However, when used on medium and high rise buildings, the cooling effect of green roof on the height of pedestrian became negligible. For example, Chen et al., (2009) carried out simulations for two districts in Tokyo, Japan with average building height of 29 and 68 m, and found almost no cooling effect of green roofs at street level. Ng et al. (2012) came to the same conclusion after conducting simulation for 60 m buildings in Hong Kong.

Along with the air-temperature reduction achieved by the transpiration and radiation interception of trees, irrigation can provide additional cooling. Broadbent et al. (2018) investigated the cooling potential of purposefully managed irrigation and found that the diurnal average air temperature was reduced by up to 2.3 K. However, the authors demonstrated that additional cooling was negligible when the irrigation rate exceeded 20 $L/m^2/day$.

3.2.4 Effect of vegetation on humidity

While the transpiration process of vegetation decreases the air temperature, it increases the humidity. Morakinyo et al. (2016) demonstrated by measurement and simulation that the presence of trees increased the relative humidity by 4.6% to 7.5% in September and October in Nigeria. Irrigation also increases humidity. Broadbent et al. (2018) found that although irrigation increased humidity in Adelaide, Australia, it still improved outdoor human thermal comfort during heatwave conditions.

3.2.5 Effect of vegetation on thermal comfort

Although vegetation decreases wind speed, it still significantly improves the urban thermal environment by reducing radiation and cooling the air. Because trees can provide shading, whereas grass cannot, trees are usually more effective than grass in improving the thermal environment. For example, Lee et al. (2016) demonstrated that the average reduction in PET by trees was 3.0 K, while the average reduction by grasslands was only 1.0 K. In addition to observing the decrease in thermal indices, researchers have provided subjective evidence from occupants by means of subject tests and questionnaire surveys. Yoshida et al. (2015) measured physiological responses in a human subject test and found that the human thermal load under a tree canopy was closer to neutral than in sunlit spaces. Klemm et al. (2015b) found that momentary perceived thermal comfort tended to be related to the amount of street greenery, but the relationship was not statistically significant. Nevertheless, people greatly appreciate the aesthetic value of street greenery. People's subjective responses were also studied by Qin et al. (2013) in Shanghai. After analyzing questionnaires collected in Shanghai Botanical Garden, China, Qin et al. (2013) concluded that color is one of the most important factors in people's overall satisfaction with the surrounding vegetation.

3.3 Reflective surface

The excess absorption of solar heat by urban structures contributes greatly to the development of urban heat islands (Santamouris, 2013b). To counterbalance the effects of an urban heat island, natural or artificial materials with high solar radiation reflectivity are applied to the facades and roofs of buildings, and to the pavements of urban spaces. Reflective surface modifies the environment in terms of radiation and air temperature.

3.3.1 The effect of reflective surface on radiation

By reflecting a large amount of solar radiation, reflective surface absorbs less solar radiation and thus has a lower surface temperature than traditional pavement. The temperature decrease of high albedo surfaces was documented in many studies (Doulos et al., 2004; Synnefa et al., 2011; Niachou et al., 2008; Georgakis and Santamouris, 2006; Yang et al., 2016b). For example, Chatzidimitriou and Yannas (2015) measured the surface temperature of three pavement areas with albedo ranging from 0.21 to 0.38 on a summer day and found the maximum difference in surface temperature among the pavements areas was 9 K. The difference in surface temperature increased with the increase in albedo. Taha et al. (1992) demonstrated by measurement that the temperature difference between surface with white coating (albedo=0.72) and black coating (albedo=0.08) can be as high as 45 K on clear and warm days. With the lowering of surface temperature, the long-wave radiation in the space can be reduced.

Although a reduction in surface temperature decreases the long-wave radiation in a space, a number of researchers have demonstrated by simulation that the total radiation will increase due to the increase in reflected short-wave radiation. In numerical studies by Kazuaki and Hoyano (2008), after raising the solar reflectance from 0.1 to 0.6, the increase in reflected short-wave radiation was almost twice the reduction long-wave radiation. In addition, a simulation by Taleghani and Berardi (2018) demonstrated that the mean radiant temperature (T_{mrt}) increased by 10.3 K when the albedo of pavement changed from 0.1 to 0.5. Similarly, simulations by Yang et al. (2011) in summer in Shanghai, China, showed an increase of 8 to 14 K in T_{mrt} when the ground albedo was increased by 0.4. Besides simulations, the measurement conducted by Chatzidimitriou and Yannas (2015) found that although high albedo surfaces were cooler than low albedo surfaces, the obtained mean radiant temperatures above them were higher. The reflective roof shares the same effect on radiation with reflective pavement. As measured by Taleghani et al., (2014) in summer at the campus of Portland State University, the T_{mrt} of a white roof (albedo = 0.91) was 2.9 K higher than that of a black roof (albedo = 0.37).

3.3.2 The effect of reflective surface on air temperature

Cool materials reduce the temperature of surface, decrease convective heat transfer from the surface to the air, thus producing cooler air temperatures than traditional surface. By summarizing data from a number of city-scale simulations, Santamouris (2014) estimated the average air temperature reduction to be 0.3 K per 0.1 rise in albedo, when a global increase in the city's albedo was considered. When the reflective surface was applied only at roofs, the cooling effect on air temperature at 2 m height was close to 0.2 K per 0.1 increase in roof albedo, as summarized by Santamouris (2014) from two city-scale simulation studies at New York, US (Savio et al., 2006) and Athens, Greece (Synnefa et al., 2008). The cooling effect of reflective roof at pedestrian level may diminish as the building height increase, since the convective cooling of air happens at the roof surface. Through coupled simulation of convection, radiation and conduction, Chen et al., (2009) found a reduction of street level air temperature of less than 0.12 K, when the albedo of roofs increased from 0.2 to 0.5 for buildings with average height of 29 m and 68m. However, when reflective roof was applied on low rise buildings, higher cooling effect can be expected. For the same reason that the convective cooling occurs at the surface, it is not surprising that the cooling effect decreased with increased height above the reflective surface, as demonstrated by Taleghani and Berardi (2018) and Li (2013).

3.3.3 The effect of reflective surface on thermal comfort

Although reflective surface cools a city, many simulation studies claim that pedestrian discomfort often increases because of the increased reflected solar radiation on the human body. Yang et al., (2016b) calculated an increase of thermal stress of up to 100 W/m^2 on pedestrians around noontime under high albedo scenario. The same conclusion can be reached by looking at the PET values. In a simulation by Taleghani and Berardi (2018), the PET increased by 6 K at midday when albedo was raised by 0.4. A similar value was obtained by Yang et al. (2011), who found that the PET was increased by 5 to 7 K when ground albedo was raised by 0.4. While the previous study only investigated the effect of changing ground albedo, Rosso et al. (2018) tested the effect of combinations of façade and paving albedos in historical urban canyon with an aspect ratio of 3.5. Their simulation showed that the scenario with lowest thermal stress used high albedo pavement and low albedo walls. But the reason for such result is not clearly identified. In addition to the simulation studies, a perception test conducted in the field by Rosso et al. (2016) demonstrated that the asphalt was less favored than the gravels with higher albedo in terms of thermal comfort. The authors also observed a negligible difference in thermal perception among types of gravel with differing albedo. Besides thermal preference, it is interesting to note that in terms of visual perception, people's perception deteriorated with increasing albedo as a result of glare.

It should be pointed out that the existing investigations concerning the thermal comfort effect of reflective surfaces were almost simulations studies. Although Rosso et al. (2016) conducted subjective test, the test was conducted under mild conditions with air temperatures ranging from 23.3 to 29.6 ºC. The conflicting results found by this review indicates that the influence of reflective materials on occupant thermal comfort should be further tested by carefully designed measurements and subject tests.

3.4 Water bodies

The primary influence of water bodies on the urban thermal environment rests in their ability to cool the air through evaporation (Oke, 2002). Furthermore, the high thermal capacity of water bodies leads to a lower temperature than that of the surrounding buildings and grounds. The lower temperature of water body provides higher temperature gradient between the air and water surface for convective heat transfer. In addition, water surface with lower temperature emits less radiation.

3.4.1 The effect of water bodies on radiation

The thermal capacity of water is 4200 J/kg/K, which is about four times the thermal capacity of common building and pavement materials, such as concrete, asphalt, granite, gravel, and marble (Chatzidimitriou and Yannas, 2015). As a result, when absorbing the same amount of solar radiation, water exhibits a much smaller temperature increase than regular building and pavement materials. Therefore, water bodies can be considered as heat sinks in urban spaces. On-site measurements by Chatzidimitrioua and Yannas (2015) in summer showed that the surface temperature of water (T_s = 26.2ºC) was much lower than that of asphalt (T_s = 46.2ºC) and grey marble (T_s = 42.8ºC) pavement. Similarly, Robitu et al. (2006) demonstrated by simulation that the water surface temperature was 25 K lower than the asphalt surface temperature in the early afternoon in summer. Lower surface temperature leads to reduced long wave radiation, shown by the lower mean radiant temperature. For example, the mean radiant temperature in the measurement by Chatzidimitrioua and Yannas (2015) above a water fountain was 4K lower than that above asphalt pavement. Furthermore, a simulation study by Taleghani and Berardi (2018) showed that adding a large pond could reduce T_{mrt} by up to 6.2 K.

3.4.2 The effect of water bodies on air temperature

The evaporation of water removes ambient heat. Besides, the surrounding air is cooled due to convective heat transfer between the ambient air and the water surface. It is evident that natural water bodies contribute to the decrease of air temperature in urban spaces. From existing experimental data, Manteghi et al. (2015) identified a reduction of 1-2 K in ambient temperature with the presence of nearby water bodies. The cooling effect of water body depends on many parameters. For example, by analyzing the urban cool island (UCI) intensity of 197 water bodies in Beijing from a remote sensing image, Sun and Chen (2012) determined that a water body's area, geometry, and location, and the proportion of the surroundings that were built up, significantly influenced the microclimate around the water body. Wind direction also has an impact on the cooling effect of a water body. By conducting measurements at an outdoor scaled model, Syafii et al. (2017) demonstrated a greater cooling effect when ponds were oriented in a parallel direction to prevailing winds. Saaroni and Ziv (2003) found that the air temperature on the leeward side of a water body was 1.5 K lower than that on the windward side.

3.4.3 The effect of water bodies on humidity

The evaporation of water increases humidity in the air. Syafii et al. (2017) found that the absolute humidity near ponds was increased by 1-2 g/kg. Xu et al. (2010) detected an increase in relative humidity of 10% on hot summer days at the edge of a water body, and the increase gradually became smaller as the measurement point moved away from the water. Very few studies have documented the effects of vegetation and water bodies on humidity. High humidity under hot conditions may inhibit the evaporative heat loss by sweat on the human body. Thus, it is necessary to quantify the trade-off, in terms of human comfort, between the reduced air temperature and increased humidity that arise from vegetation and water bodies.

3.4.4 The effect of water bodies on thermal comfort

Because water bodies cannot block direct solar radiation, the improvement in thermal comfort by a water body is usually much less than that provided by adding vegetation and changing the urban geometry. The reduction in PET due to the presence of a water fountain was only 1.4 K, as found by Chatzidimitrioua and Yannas (2015). Besides, the cooling effect of water bodies depends on wind condition and distance. Measurements by Gomez et al. (2013) on a summer afternoon showed that the PET on the leeward side of a spray fountain was 1.6 K lower than on the windward side. Xu et al. (2010) proposed a method for evaluating thermal comfort near water bodies. Through a calculation process, the authors demonstrated that thermal comfort improvement was the greatest in areas that were 10 to 20 m from the water's edge. Regarding subjective thermal comfort evaluation of space with water body, the field survey conducted by Mahmoud (2011) in different spaces in an urban park in Egypt demonstrated that in hot months, occupants were less dissatisfied in the lake zone and cascade zone compared with the other zones without water body.

3.5 Comparison of mitigation effect among different strategies

Sections 3.1 to 3.4 show the mechanisms and mitigation effects of changing geometry, adding vegetation, using reflective surface, and incorporating water bodies. To further compare the cooling benefits among strategies, this section summarizes the maximum reductions in air temperature and PET for each strategy in the reviewed studies. To ensure the reliability of the summarized result, the values used in this section all come from studies that conform to the screening rules defined in Section 2.2.4. Because the cooling did not happen on pedestrian level for green roof and reflective roof, the results from these two strategies were not included in the comparison. The results are presented in Figure 2. In each of these cases, a comparison was made between a place that employed a specific strategy and a reference place. The reference places were often open ground without dense vegetation, reflective surface, or ponds. The reductions were either from values reported by the authors or from our estimations from the figures and tables in the papers. It should be pointed out that a direct comparison is hardly possible because the values were obtained via different methods, and under different climates. Besides, even the same strategy has various configurations in different studies. To reduce comparison uncertainty, the results used here were all recorded in summer at noon or in the afternoon, when the cooling effects were the highest for the day. Tables 1 and 2 provide the details of each comparison case, including city, climate, research method, time, and a brief description of the case configuration.

An analysis of the data source in Table 1 and 2 shows that a reasonable portion (41% to 67%) of data was from measurements for the studies of geometry, vegetation, and water body. However, for the evaluation of reflective surface, the data was mainly from simulation. This is probably because many studies were aimed at comparing the effect of high albedo materials and traditional surface applied to the same outdoor space (Taleghani et al., 2016; Salata et al., 2017). Conducting measurements for this purpose is impossible. Even for real retrofit projects (Fintikakis et al., 2011; Gaitani et al., 2011; Santamouris et al., 2012), it is a common practice to use validated simulation to quantify the mitigating effect, because the climatic conditions before and after the retrofit were different. It is also worthy to note that the number of studies concerning the influence of water bodies is less than the studies on the other three strategies.

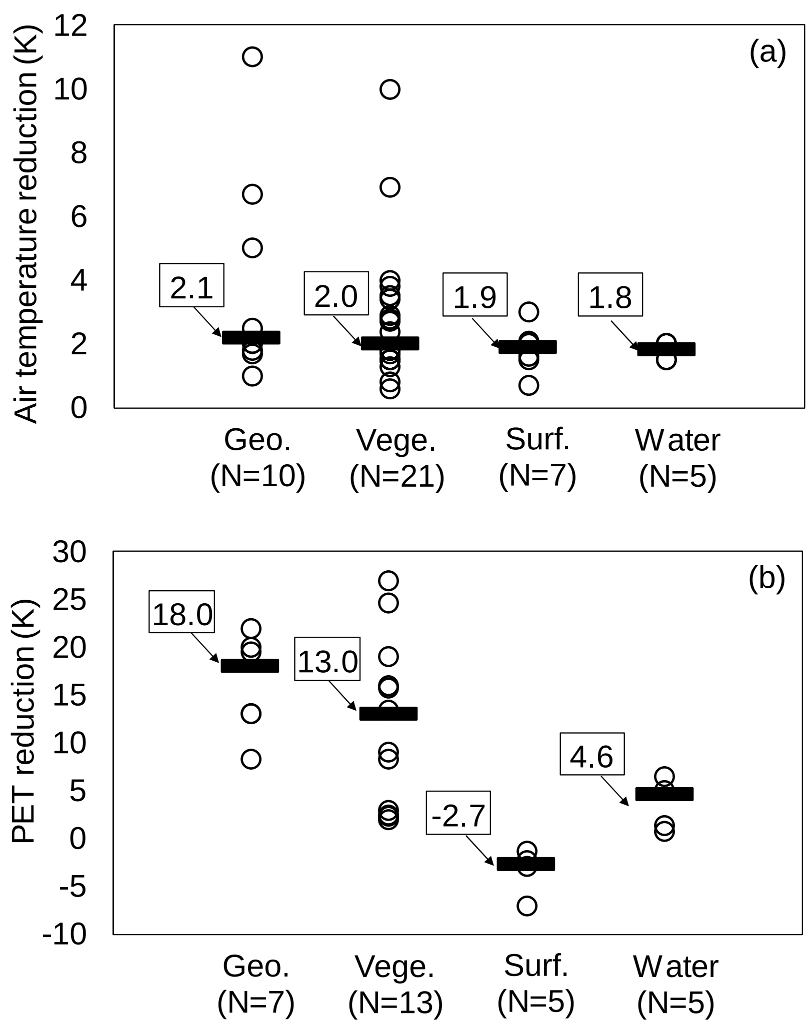

Figure 2. Summary of maximum reductions in (a) air temperature and (b) PET for different strategies. The solid black bars represent the median values.

As summarized in Figure 2(a), the median reductions in air temperature for different strategies were similar, reaching 2.1 K, 2.0 K, 1.9 K, and 1.8 K for changing geometry, adding vegetation, using reflective surface, and incorporating a water body, respectively. Although the reductions in air temperature were similar, variations among strategies were obvious for PET reduction. Changing geometry had the greatest cooling effect (median reduction = 18.0 K), followed by adding vegetation (median reduction = 13.0 K). Because ponds cannot shield an area from solar radiation, PET reductions of using water bodies were much lower than those of changing geometry and adding vegetation. In addition, a number of studies has shown that reflective surface worsens outdoor thermal comfort in summer, with a median increase in PET of 2.7 K. However, the majority of PET data for reflective surfaces were from similar simulation studies. As discussed in Section 3.3.3, measurements and subject tests should be performed to further evaluate the influence of reflective materials on occupant thermal comfort.

Table 1. Summary of air temperature reduction by various mitigation strategies in summer at noon or in the afternoon, from the reviewed literature.

Strategy	Author, date	City	Climate[1]	Method	Time	Description	ΔT_a (K)
Geometry	Johansson, 2006	Fez, Morocco	BWh	Measurement	Jul. 19, 15:00 p.m.	H/W = 11 vs. H/W = 1.3	11.0
	Kakon et al., 2009	Dhaka, Bangladesh	Aw	Measurement	Apr. 18, 14:00 p.m.	SVF = 0.126 vs. SVF = 0.51	6.7
	Johansson and Emmanuel, 2006	Colombo, Sri Lanka	Af	Measurement	May 3, 14:00 p.m.	SVF = 0.49 vs SVF = 0.75	5.0
	Chatzidimitriou and Yannas, 2017	Thessaloniki, Greece	Bsk	Simulation, ENVI-met	Jul. 29, 16:30 p.m.	NE-SW street vs. NW-SE street	2.5
	Shashua-Bar et al.,2012	Athens, Greece	Csa	Simulation, CTTC	Jun. 19, 15:00 p.m.	H/W = 0.42 vs. H/W=0.66	2.2
	Yang et al., 2016a	Singapore	Af	Measurement	Mar. 14:00 p.m.	Shaded street vs. relatively open spaces	2.0
	Cheung and Jim, 2018a	Hong Kong, China	Cwa	Measurement	Aug. 6, 14:00 p.m.	SVF = 0.004 vs. SVF = 0.452	2.0
	Ali-Toudert et al., 2005	Beni-Isguen, Algeria	Csa	Measurement	Jun. 23, 14:00 p.m.	SVF = 0.09 vs. SVF = 0.67	1.8
	Lee et al., 2013	Freiburg, Germany	Cfb	Measurement	Jul. 15, 13:00 p.m.	SVF = 0.2 vs. SVF = 0.65	1.7
	Yang et al., 2011	Shanghai, China	Cfa	Measurement	Aug. 5, 13:00 p.m.	SVF = 0.11 vs. SVF = 0.6	1.0
Vegetation	Oliveira et al., 2011	Lisbon, Portugal	Csa	Measurement	Aug. 9, early afternoon	Shaded site in the garden vs. sunny site in the surrounding street	6.9
	Song and Wang, 2015	Phoenix, U.S.	BWh	Simulation, UCM	Jul. 13-19, 10:30 a.m.	Under a tree with crown diameter = 1 m vs. no tree	6.0
	Shashua-Bar and Hoffman, 2000	Tel-Aviv, Israel	Csa	Measurement	Aug. 26-27, 15:00 p.m.	Vegetation cover = 61%, crown spread = 6-12 m, height = 5-8 m vs. no tree	4.0
	Skoulika et al., 2014	Athens, Greece	Csa	Measurement	Sep. 2, afternoon	Within urban park vs. 220 m from urban park	3.8
	Potchter et al., 2006	Tel-Aviv, Israel	Csa	Measurement	Jun. 6, 16:00 p.m.	An urban park vs. surrounding areas	3.5
	Shashua-Bar et al., 2010	Tel-Aviv, Israel	Csa	Simulation, CTTC	Jul. 15:00 p.m.	Street (H/W = 0.6) with 90% trees vs. street without trees	3.4
	Skelhorn et al., 2014	Manchester, U.K.	Cfb	Simulation, ENVI-met	Jul. 19, 15:00 p.m.	Addition of 5% mature trees vs. current scenario	2.9

	Wang and Akbari, 2014	Montreal, Canada	Dfb	Simulation, ENVI-met	Jul. 23, 12:00 p.m.	Vegetation cover = 44.3% vs. vegetation cover = 3.4%	2.8
	Cheung and Jim, 2018a	Hong Kong, China	Cwa	Measurement	Aug. 6, 14:00 p.m.	Under a tall tree (H = 9.7 m, crown diameter = 14.0 m) vs. exposed lawn	2.4
	Abreu-Harbich, 2015	Campinas, Brazil	Cfa	Measurement	A typical summer day, 11:00 a.m.	Under a cluster of trees vs. under the sun	2.0
	Wong and Jusuf, 2010	Singapore	Af	Measurement	Aug. 6, 16:00 p.m.	Canyon (H/W = 1.3) covered with mature trees vs. reference rooftop	1.8
	Ng, 2012	Hong Kong, China	Cwa	Simulation, ENVI-met	A typical summer day, 11:00 a.m.	Vegetation coverage = 56% vs. no coverage	1.8
	Shashua-Bar et al., 2012	Athens, Greece	Csa	Simulation, CTTC	Jun. 19, 15:00 p.m.	Vegetation coverage = 50% vs. vegetation coverage = 7.8%	1.8
	Lee et al., 2013	Freiburg, Germany	Cfb	Measurement	Jul. 24, 14:00 p.m.	SVF = 0.06 (tree shade) vs. SVF = 0.70	1.7
	Spangenberg et al., 2008	São Paulo, Brazil	Cfb	Simulation, ENVI-met	Dec. 19, 15:00 p.m.	Under tree canopy vs. no vegetation	1.5
	Wang et al., 2015b	Assen, the Netherlands	Cfb	Measurement	May 28th	Grove vs. open space	1.5
	Tan et al., 2016	Hong Kong, China	Cfa	Simulation, ENVI-met	Jul. 13:00 p.m.	SVF = 0.8, tree crown spread = 10-12m, height = 18m vs. without greenery	1.5
	Salata et al., 2017	Rome, Italy	Csa	Simulation, ENVI-met	Jul. 18, 13:00 p.m.	Vegetation coverage = 14.23% vs. vegetation coverage = 5.35%	1.3
	Wang et al., 2016	Toronto, Canada	Dfb	Simulation, ENVI-met	Jul. 15, 16:00 p.m.	Base design vs. addition of 10% of vegetation	0.8
	Salata et al., 2015	Rome, Italy	Csa	Simulation, ENVI-met	Aug. 7, 14:00 p.m.	Under a tree vs. bare ground	0.7
	Duarte et al., 2015	Sao Paulo, Brazil	Cfb	Simulation,	Feb. 6, 15:00 p.m.	Under street trees vs. open area	0.6

				ENVI-met			
Surface	Fintikakis et al., 2011	Tirana, Albania	Csa	Simulation, PHOENICS, Standard k-e	A September afternoon	Concrete pavement with reflective paint, albedo = 0.65 vs. black asphalt, albedo = 0.4	3.0
	Tan and Fwa, 1992	Singapore	Af	Measurement	Oct. 18, 15:00 p.m.	Concrete, albedo = 0.22 vs. asphalt, albedo = 0.13	2.1
	Gaitani et al., 2011	Athens, Greece	Csa	Simulation, PHOENICS, Standard k-e	A typical summer day, 14:00 p.m.	Black asphalt, albedo = 0.3 vs. asphalt with photocatalytic compound road	2.0
	Santamouris et al., 2012	Athens, Greece	Csa	Simulation, PHOENICS, Standard k-e	A typical summer day, 14:00 p.m.	Reflective paint, albedo = 0.6 vs. dark paving	1.9
	Salata et al.,2015	Rome, Italy	Csa	Simulation, ENVI-met	Aug. 7, 14:00 p.m.	High albedo vs. base case	1.6
	Salata et al., 2017	Rome, Italy	Csa	Simulation, ENVI-met	Jul. 18, 13:00 p.m.	Concrete pavement with higher albedo vs. asphalt pavement	1.5
	Yang et al., 2011	Shanghai, China	Cfa	Measurement	Aug. 5, 13:00 p.m.	Albedo = 0.21 vs. albedo = 0.14	0.7
Water	Xi et al., 2012	Guangzhou, China	Cfa	Measurement	July 4, 14:30 p.m.	Lakeside vs. concrete surrounding	2.0
	Nishimura et al., 1998	Osaka city, Japan	Cfa	Measurement	Jul, 12:00-15:00	Near a pond vs. in a park	2.0
	Xu et al., 2010	Shanghai, China	Cfa	Measurement	Jul. and Aug. afternoons	Near waterbody vs. 20 m away from water body	1.8
	Zhao and Fong, 2017	Hong Kong, China	Cwa	Simulation, ENVI-met	A typical summer day, 15:00 p.m.	Water body coverage ratio = 56% vs. concrete pavement landscape	1.5
	Saaroni and Ziv, 2003	Tel Aviv, Israel	Csa	Measurement	May 17,12:10 p.m.	Leeward of a pond vs. windward of the pond	1.5

[1]The categorization of climate is based on the Koppen climate classification system (Kottek et al., 2006) retrieved from en.climate-data.org.

Table 2. Summary of PET reduction by various mitigation strategies in summer at noon or in the afternoon, from the reviewed literature.

Strategy	Author, Date	City	Climate	Method	Time	Description	ΔPET (K)
Geometry	Chatzidimitriou and Yannas, 2017	Thessaloniki, Greece	Bsk	Simulation, ENVI-met	A typical summer day, 12:30-15:30 p.m.	H/W = 1.7 vs. H/W = 1.0	22.0
	Cheung and Jim, 2018a	Hong Kong, China	Cwa	Measurement	Aug. 6, 11:00 a.m.	SVF = 0.004 vs. SVF = 0.45	19.5
	Ali-Toudert et al., 2005	Beni-Isguen, Algeria	Csa	Measurement	Jun. 24, 15:00 p.m.	SVF = 0.11 vs. SVF = 0.45	18.0
	Lee et al., 2013	Freiburg, Germany	Cfb	Measurement	Jul. 15, 14:00 p.m.	SVF = 0.2 vs. SVF = 0.65	13.1
	Kántor et al., 2018	Pécs, Hungary	Cfb	Measurement	Aug. 14, 14:00 p.m.	H/W = 1.66 with artificial shading vs. open square	13.0
	Johansson and Emmanuel, 2006	Colombo, Sri Lanka	Af	Measurement	May 3, 14:00 p.m.	SVF = 0.49 vs SVF = 0.75	10.0
	Shashua-Bar et al., 2012	Athens, Greece	Csa	Simulation, CTTC	Jun. 19, 15:00 p.m.	H/W = 0.66 vs. H/W = 0.42	8.3
Vegetation	Tan et al., 2016	Hong Kong, China	Cfa	Simulation, ENVI-met	Jul. 13:00 p.m.	SVF = 0.8, tree crown spread = 10-12 m, height = 18 m vs. without greenery	27.0
	Oliveira et al., 2011	Lisbon, Portugal	Csa	Measurement	Aug. 9th, early afternoon	Shaded site in the garden vs. sunny site	24.6
	Cheung and Jim, 2018a	Hong Kong, China	Cwa	Measurement	Aug. 6, 11:00 a.m.	Under a tall tree (height = 9.7 m, crown diameter = 14.0 m) vs. exposed lawn	19.0
	de Abreu-Harbich et al., 2015	Campinas, Brazil	Cfa	Measurement	A typical summer day, 11:00 a.m.	Under individual tree shade vs. under the sun	16.0
	Lee et al., 2013	Freiburg, Germany	Cfb	Measurement	Jul. 24, 14:00 p.m.	SVF = 0.06 (tree shade) vs. SVF = 0.70	15.7
	Duarte et al., 2015	Sao Paulo, Brazil	Cfb	Simulation, ENVI-met	Feb. 6, 13:00 p.m.	Street trees vs. without street trees	13.4
	Wong and Jusuf, 2010	Singapore	Af	Measurement	A clear hot day, 15:00 p.m.	Canyon (H/W = 1.3) covered with mature trees vs. reference rooftop	13.0

	Chatzidimitriou and Yannas, 2017	Thessaloniki, Greece	Bsk	Measurement	Jul. 26, 11:30 p.m.	Street canyon (H/W = 0.6) with trees vs. street canyon (H/W = 0.7) without trees	9.0
	Shashua-Bar et al., 2012	Athens, Greece	Csa	Simulation, CTTC	Jun. 19, 15:00 p.m.	Vegetation coverage = 50% vs. vegetation coverage = 7.8%	8.3
	Lee et al., 2016	Freiburg, Germany	Cfb	Simulation, ENVI-met	Aug. 4, 16:00 p.m.	Tree crown coverage = 17% vs. tree crown coverage = 0%	3.0
	Chatzidimitriou and Yannas, 2015	Thessaloniki, Greece	Bsk	Measurement	Jul. 27, 16:00 p.m.	Concrete tiles under tree shade vs. concrete tiles without tree shade	2.4
	Wang and Akbari, 2014	Montreal, Canada	Dfb	Simulation, ENVI-met	Jul. 23, 12:00 p.m.	Vegetation coverage = 44.3% vs. vegetation coverage = 3.4%	2.3
	Jamei and Rajagopalan, 2017	Melbourne, Australia	Cfb	Simulation, ENVI-met	Jan. 6, 15:00 p.m.	Tree coverage = 40% vs. tree coverage = 14%	2.0
	Chatzidimitriou and Yannas, 2015	Thessaloniki, Greece	Csa	Measurement	Aug. 1, 16:00 p.m.	Albedo = 0.38 vs. albedo = 0.21	-1.3
	Li et al., 2016a	Phoenix, USA	BWh	Simulation, pavement thermal model	A day in July, 15:00 p.m.	Albedo = 0.5 vs. albedo = 0.1	-2.3
	Li et al., 2016a	Los Angeles, USA	Csa	Simulation, pavement thermal model	A day in July, 15:00 p.m.	Albedo = 0.5 vs. albedo = 0.1	-2.7
	Li et al., 2016a	Sacramento, USA	Csa	Simulation, pavement thermal model	A day in July, 15:00 p.m.	Albedo = 0.5 vs. albedo = 0.1	-2.9
	Yang et al., 2011	Shanghai, China	Cfa	Simulation, ENVI-met	A typical summer day, 13:00 p.m.	Albedo = 0.6 vs. albedo = 0.2	-7.0
Surface	Chatzidimitriou and Yannas, 2015	Thessaloniki, Greece	Csa	Measurement	Aug. 1, 16:00 p.m.	Albedo = 0.38 vs. albedo = 0.21	-1.3

	Li et al., 2016a	Phoenix, USA	BWh	Simulation, pavement thermal model	A day in July, 15:00 p.m.	Albedo = 0.5 vs. albedo = 0.1	-2.3
	Li et al., 2016a	Los Angeles, USA	Csa	Simulation, pavement thermal model	A day in July, 15:00 p.m.	Albedo = 0.5 vs. albedo = 0.1	-2.7
	Li et al., 2016a	Sacramento, USA	Csa	Simulation, pavement thermal model	A day in July, 15:00 p.m.	Albedo = 0.5 vs. albedo = 0.1	-2.9
	Yang et al., 2011	Shanghai, China	Cfa	Simulation, ENVI-met	A typical summer day, 13:00 p.m.	Albedo = 0.6 vs. albedo = 0.2	-7.0
Water	Gomez et al., 2013	Valencia, Spain	Csa	Measurement	A typical summer day, 13:00 p.m.	Leeward of a spray fountain vs. paved ground	6.5
	Gomez et al., 2013	Valencia, Spain	Csa	Measurement	A typical summer day, 12:00 p.m.	Leeward of a spray fountain vs. windward of a spray fountain	5.0
	Gomez et al., 2013	Valencia, Spain	Csa	Measurement	A typical summer day, 15:00 p.m.	Leeward of a spray fountain vs. windward of a spray fountain	4.6
	Chatzidimitriou and Yannas, 2015	Thessaloniki, Greece	Bsk	Measurement	Aug. 1, 16:00 p.m.	Water fountain vs. asphalt pavement	1.4
	Zhao and Fong, 2017	Hong Kong, China	Cwa	Simulation, ENVI-met	A typical summer day, 15:00 p.m.	Water body vs. conventional concrete pavement	0.8

4. Discussion

4.1 Influence of climate on cooling effect

Large variations were observed in the air temperature and PET reductions for the same strategy, as summarized in Figure 2. While one reason is the different configurations of the compared cases in various studies, climate is also an important factor in difference in the cooling effect. It can be seen that a larger cooling effect was achieved when mitigation strategies were applied in hotter climates, since these climates provided greater potential for heat reduction. For example, a large cooling effect can be achieved with the use of compact urban geometry in a hot climate. In the hot summer afternoons of Fez, Morocco (Johansson, 2006), the air temperature in a very deep canyon (H/W = 11, T_a = 31°C) was 11 K lower than in a shallow canyon (H/W = 1.3, T_a = 42°C). Similarly, in hot Dhaka, Bangladesh (Kakon et al., 2009), and Colombo, Sri Lanka (Johansson and Emmanuel, 2006), the maximum air temperature reductions achieved in deep canyons were 6.7 K and 7.0 K, respectively. Figure 3 demonstrated clear positive relationships between background air temperature and the cooling of ambient air temperature for the geometry and vegetation strategies. The cases were from Table 1, and the local maximum monthly air temperature data were obtained from http: // en.climate-data.org for the month when the measurement took place.

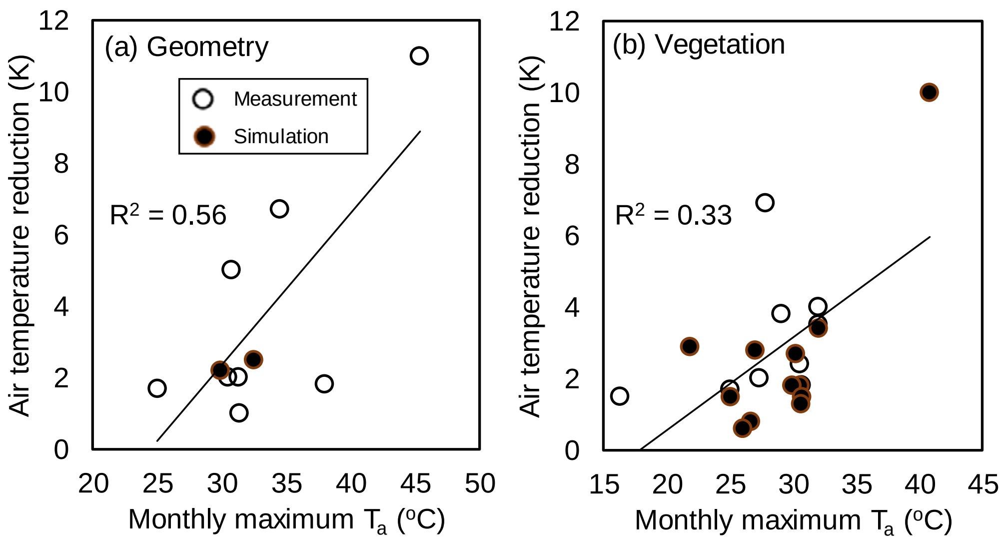

Figure 3. Increase in the air temperature reduction as functions of local maximum monthly air temperature for: (a) geometry strategy and (b) vegetation strategy. Local maximum monthly air temperature data from: en.climate-data.org.

A comprehensive simulation study by Alexandri and Jones (2008) demonstrated that the use of a green wall and green roof could achieve a greater reduction in urban air temperature in a hotter and drier climate. For example, for the same configuration of green wall and green roof, the calculated air temperature reduction in Riyadh, Saudi Arabia, was over 11 K, while the value for Moscow, Russia, was below 4 K. To further demonstrate the impact of dry and humid climates on cooling potentials, this study separated the vegetation cases from Table 1 into arid and humid climates according to the monthly precipitation from http://en.climate-data.org. If the precipitation for the studied month were less than 80 mm, the case was regarded as from arid climate (Kottek et al., 2006). Otherwise, the case was considered as from humid climate. The boxplots in Figure 4 clearly show that vegetation strategy had a higher cooling magnitude in arid climate than in humid climate.

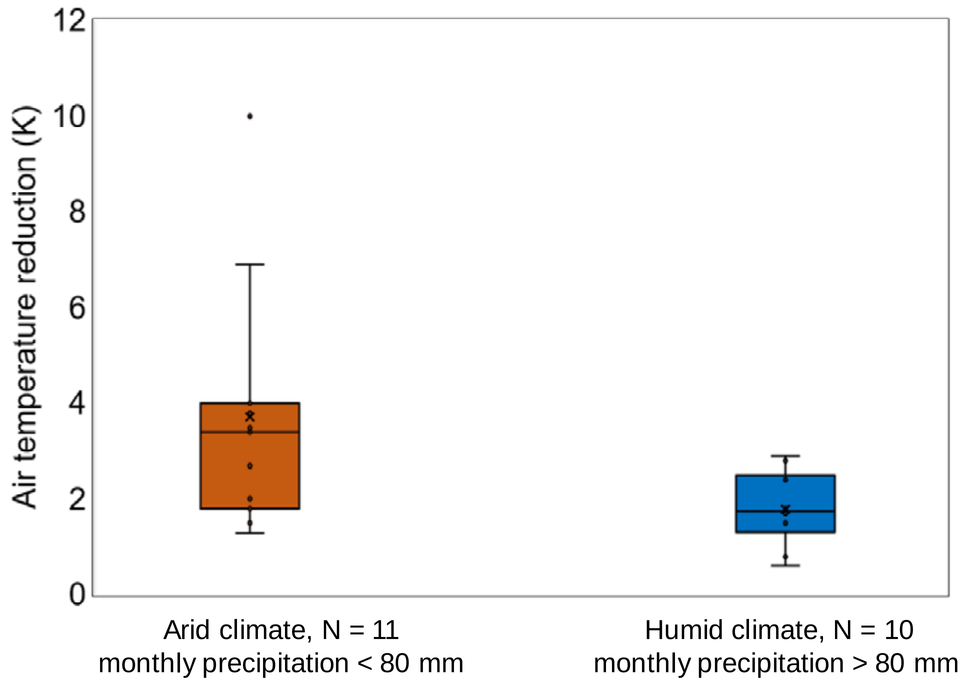

Figure 4. Box plots of air temperature reduction for vegetation strategies for arid (monthly precipitation < 80 mm) and humid (monthly precipitation > 80 mm) climate data. Monthly precipitation data from: en.climate-data.org.

Shashua-Bar and Hoffman (2000) demonstrated by extensive measurement that a stronger cooling effect was achieved with higher background air temperature. Statistical analysis of their data showed that when the background air temperature increased by 10 K, the cooling effect of vegetation was enhanced by 3.15 K. Wang et al. (2015a) showed that the cooling effect of trees on hot, clear days was two times higher than on cold, cloudy days. Similarly, the effect of high albedo in reducing the surface temperature was greater on sunny days than on cloudy days, as demonstrated by experimental measurements by Rosso et al. (2016). Meanwhile, the cooling effect of water on sunny days is stronger than on cloudy days because the higher solar radiation on sunny days provides extra energy for water evaporation and air temperature reduction.

Apart from background air temperature and solar radiation, wind condition can impose influence on the cooling effect by changing advective heat transfer. For example, in windy sea front areas with an average wind speed of 4 m/s in Athens, the effect of reflective pavement was almost negligible (Santamouris et al., 2012). In contrast, in a nearby urban park having an average wind speed of 1.5 m/s, the decrease of surface temperature of reflective pavement can be as high as 7.6 K.

4.2 Interactions among the mitigation strategies

Studies have indicated that vegetation, reflective pavement, and water bodies do not alleviate the hot thermal environment in compact urban spaces to the same extent that they do in open urban spaces. The reason for this difference is that compact spaces have a long shading duration, which decreases the effective cooling period of the vegetation, reflective pavement and water bodies.

For example, Johansson et al. (2013) showed that the addition of trees achieved a greater T_{mrt} reduction in a low-rise area (13 K) than in a high-rise area (6 K). Furthermore, Ng et al. (2012) demonstrated that the cooling benefits of trees were greater in spaces around lower buildings (height = 20 m) than spaces around taller buildings (height = 40-60 m). Meanwhile, trees planted along E-W oriented streets were more effective in regulating the environment than trees planted along N-S oriented streets because the thermal comfort on N-S streets was already satisfactory (Andreou, 2013). Lin et al. (2008) even argued that when planted in heavily shaded spaces, trees may worsen thermal comfort in summer, because the addition of trees decreases the wind speed.

In compact spaces, the effective period of reflective pavement is short. Yang et al. (2016b) found that the daily peak surface temperature reduction by reflective pavement decreased from 27 K to 14 K when the canyon H/W ratio increased from 0.5 to 4.0. Wang et al. (2016) demonstrated that reflective pavement provided a larger cooling effect in the areas around a medium-rise building than in the areas around a high-rise building. In addition to shorter effective cooling time for reflective surfaces, the radiation exchange in compact spaces is more complex than open spaces. In compact urban canyon, a large part of the reflected radiation will be absorbed by the building walls. Thus, Qin (2015a) suggested reflective pavements can be used only if an urban canyon has an aspect ratio less than 1.0 based on model calculation.

Since solar radiation and airflow provide extra energy for water evaporation, it is expected that a change in radiation and wind speed by urban geometry would alter the cooling effect of a water body. For example, Syafii et al. (2017) found that a larger pond produced a greater decrease in air temperature (ΔT_a = 1.25 K) than did a smaller pond (ΔT_a = 0.7 K) when solar radiation was able to reach these water bodies. However, when the ponds were shaded and the primary source of energy for evaporation was absent, the cooling benefits of large and small ponds were similar.

5. Future studies

This review has demonstrated the effectiveness of various design strategies in improving the thermal environment and increasing human thermal comfort in outdoor spaces. However, more effort is required to develop a comprehensive framework to guide the design of thermally comfortable urban open spaces. Future studies should consider the following perspectives:

1) Climate: The climate differs from city to city, and it changes throughout the year. Most of

the existing studies focused on only a few typical summer days in one city. Results obtained in one city cannot be directly applied to other cities with different climates. Similarly, a design that improves thermal comfort in summer may cause discomfort in winter. In addition, the current strategies may not be suitable for the future climate under global warming. Thus, it is necessary to comprehensively consider the influence of climate in different climate zones, at different times of the year, and in the future.

2) Context: In reality, the use of different strategies is highly related to context. For example, in some places where the climate is hot and arid, it is costly to use vegetation or water bodies on a large scale. In addition, although changing the geometry of outdoor space has been found to be the most effective passive cooling strategy, in actual projects, the extent to which the geometry of an outdoor space can be changed is often limited. The type of outdoor space, and whether it is a new or retrofit project, affect the available options. Further studies of the constraints of actual projects would yield suggestions for choosing feasible strategies that produce good results.

3) Occupants: Occupants are the center of any design. This article reviewed studies of various strategies for improving the outdoor thermal environment, but the effect on occupant thermal comfort is almost from objective indices, such as PET. It is hard to accurately infer occupants' subjective thermal comfort levels from the results. Outdoor thermal comfort itself is a complex issue. For psychological, physiological, social, and cultural reasons, residents in various regions have different thermal sensations under similar thermal environments (Lai et al., 2014a; Lin and Matzarakis, 2008; Huang et al., 2017; Nikolopoulou and Lykoudis, 2006; Krüger et al., 2017; Cheung and Jim, 2018b; Golasi et al., 2018; Liu et al., 2016; Lam and Lau, 2018; Shooshtarian and Ridley, 2017; Xie et al., 2018). Some studies used thermal comfort models to estimate the subjective perception of occupants. However, because of the complex nature of outdoor thermal comfort, an accurate and universally applicable model for the outdoors is still lacking (Potchter et al., 2018; Cheung and Jim, 2017; Fang et al., 2018). In addition to thermal comfort, occupant behavior is a critical factor to be considered. The usage of outdoor spaces is influenced by occupants' daily life pattern. Zacharias et al. (2001) found that outdoor spaces near downtown plazas were used mainly at noon because the users were mostly employees of nearby companies who had free time only during the noon break. In contrast, open spaces near residential communities were not used by residents at noon because they were in the habit of going home for lunch and taking a nap afterward (Lai et al., 2014b; Li et al., 2016b). Further studies of occupants' comfort and behavior in outdoor spaces are required to bridge the gap between design and occupants' perception and satisfaction.

6. Conclusions

Urban open spaces with a suitable thermal environment attract citizens and boost the vitality of cities. The thermal environment in outdoor spaces can be decomposed into air temperature, thermal radiation, wind speed, and humidity. This paper reviewed various measurement and simulation techniques for obtaining these parameters, and the effectiveness of different mitigation strategies in modifying the urban thermal environment. The following conclusions can be drawn from the literature review:

1) Urban geometry changes the radiative and convective heat transfer in outdoor spaces. Generally speaking, compact space provides a better urban thermal environment than open space in hot climates. Although the wind is weaker in compact outdoor space than in open outdoor space, the influence of blocked solar radiation on the thermal environment exceeds the impact of reduced wind. North-south oriented streets offer a longer shading period than east-west oriented streets. Streets with orientation parallel to the wind direction are beneficial in increasing wind speed and promoting urban ventilation.

2) Like buildings, vegetation blocks short-wave radiation and decelerates the wind. In addition, vegetation can reduce air temperature by transpiration. Long-wave radiation in outdoor spaces can also be reduced when a lawn or green wall is used to decrease the surface temperature.

3) Reflective surface absorbs less solar radiation, and thus has a lower surface temperature than traditional surface. Hence, in comparison with traditional materials, cool surface emits less long-wave radiation, and the surrounding air temperature is lower. However, some simulation studies demonstrated that the increase in reflected solar radiation by reflective surface outweighs the reduction in long-wave radiation, and the thermal comfort of pedestrians worsens.

4) Water bodies reduce the air temperature of outdoor spaces by means of evaporation. In addition, the high heat capacity of water makes it an ideal heat sink in cities. The cooling effect of a water body depends on many factors, such as the size, geometry, and location of the water body, the wind direction, and the proportion of the surroundings that is built up.

5) A comparison of the cooling effects of various strategies revealed that urban geometry has the greatest effect on the thermal environment in summer, followed by vegetation and water bodies. Cool surface may actually worsen the thermal comfort of pedestrians because of the increase in reflected solar radiation. The review demonstrated that these strategies had a greater cooling effect in hotter climates. It was also found the use of vegetation, cool surface, and water bodies in already highly shaded areas was less effective than in open areas.

The review summarized the available evidence of the effectiveness of mitigation strategies in improving the thermal environment in urban outdoor spaces. When choosing a strategy, one should consider the local climate, the feasibility of different strategies, and occupants' behavior and perception.

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