Impact of urban morphology on microclimate and thermal comfort in northern China

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ABSTRACT

This work is an experimental study focusing on the impact of urban morphology on the urban heat island (UHI) intensity, microclimate conditions and thermal comfort in a newly-developed urban area in Tianjin city, China. According to the Köppen–Geiger climate classification system, the studied area is classified as hot summer continental climate, characterized by hot and humid summers as well as cold and dry winters. Air temperature, relative humidity (RH) and wind speed at 46 points within an 8-km² area are measured during both winter and summer seasons. Based on measured results and climatic mapping, the impacts of urban constituents such as building, pavement, greenery and water area on UHI intensity and microclimate conditions are analyzed. Results show that UHI intensity reaches up to 4.5 °C during daytime and 5.3 °C at night in summer, and 2.6 °C during daytime and 5.0 °C at night in winter. The presence of both greenery and water body result in an increase in RH in air. Trees tend to reduce wind speed and improve thermal comfort in winter. Radiant heat dissipated from buildings and roads is the main contributor to nighttime UHI in both summer and winter seasons. Based on research results, urban design recommendations are proposed so as to improve outdoor thermal comfort in urban areas located in temperate climate zone during summer and winter.

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1. Introduction

More than half of the world’s population became urban residents in 2009 and this number is projected to reach 66% by 2050 (Valladares-Rendón and Lo, 2014). Although the urbanization process brings along rapid economic growth and industrial development, it also causes a general deterioration of urban environment. Urban Heat Island (UHI) effect is one of the environmental problems caused by human modification of land surfaces. UHI refers to a city or metropolitan area which is significantly warmer than its surrounding rural areas (Oke, 1982). This problem is commonly present in cities of all climate regions. In the context of global warming, the UHI effect has garnered the attention of city planners, building engineers and government policy makers, especially in the tropical or subtropical areas such as Singapore (Wong and Yu, 2009), Hong Kong (Siu and Hart, 2013) and Malaysia (Rajagopalan et al., 2014).

Heat islands can be categorized into three types: canopy layer heat island, boundary layer heat island and surface heat island. The first two heat islands refer to the warming of urban atmosphere at different vertical scales and can be directly measured using thermometers. The surface heat island refers to the warming of urban surfaces and is often measured by remote sensors mounted on satellites or aircraft (Voogt, 2004). Air temperature in urban canopy layer plays an important role in determining outdoor thermal comfort as well as space heating and cooling loads in buildings. Extensive usage of air-conditioning to achieve thermal comfort in summer can intensify the UHI effect due to emission of waste heat (Santamouris and Asimakopoulos, 2001). The increased air temperature could further exacerbates peak electricity demand for air-conditioning by 5–10% (Akbari et al., 2001). The UHI effect has a profoundly negative effect on outdoor thermal comfort and could increase health risks of urban residents in summer (Santamouris et al., 2011).

Urban air temperature is affected by climatic and urban factors such as solar radiation, wind, precipitation, Sky View Factor (SVF), building density, greenery, albedo and water area (Jusuf and Wong, 2014).
Generally, the UHI effect is more prominent at night than during daytime and is larger in winter than in summer. Daytime UHI intensity is stronger on sunny days with clear sky and low wind speeds. Various strategies have been developed and implemented to mitigate the UHI effect, such as using cool roof and pavement (Taha et al., 1988), greennery (Zoulia et al., 2009), green roof or façade (Susca et al., 2011), phase change materials (Karlessi et al., 2011) and anthropogenic heat reduction (Taha, 1997). However, the effectiveness of these strategies relies heavily on local climate and urban morphology. Currently, few studies have been reported on the UHI intensities in cities located in northern China.

Outdoor thermal comfort is becoming an increasing concern for residents as well. Rupp et al. (2015) summarized that several indices have been developed to predict the outdoor thermal comfort based on human being’s energy balance, such as universal effective temperature (UET) Nagano and Horikoshi, 2011, index of thermal stress (ITS) Givoni, 1963, MENEX model (Blazejczyk, 2005), predicted mean vote (PMV) Fanger, 1972, perceived temperature (PT) Jendritzky et al., 2000, outdoor standard effective temperature (OUT_SET) Spagnolo and de Dear, 2003, physiologically equivalent temperature (PET) Spagnolo and de Dear, 2003 and universal thermal climate index (UTCI) Bröde et al., 2012. Although these indices were widely applied to predict the outdoor thermal comfort, they are based on the energy balance approach without considering the differences in thermal adaptation and preference of occupants living in different climatic regions. Outdoor thermal comfort studies revealed that a purely physiological approach is inadequate to characterize the outdoor thermal comfort conditions. Thermal adaptation, which involves behavior adjustment, physiological factor and psychological factor, also plays an important role in the assessment of thermal environments (Yang et al., 2013). Occupants in different climatic regions may have different thermal adaption capabilities. Therefore, it is preferred to employ an empirical index to evaluate the occupants’ thermal comfort level by considering both local climate and human thermal adaptation factors. Thermal Sensation Vote (TSV) is one such index to evaluate thermal sensation (Government of Singapore, 2016). In order to propose a local TSV model, questionnaire surveys are often conducted to record the respondents’ demographic information, duration of their activities and overall thermal comfort level. At the same time, microclimatic parameters are measured during each questionnaire survey. An empirical TSV model is therefore proposed to define the outdoor thermal sensation in terms of meteorological parameters, such as air temperature, global radiation, wind speed and relative humidity (RH).

This study focuses on the impacts of urban morphology on microclimate conditions and thermal comfort in a newly developed urban area in northern China, Tianjin. The studied urban area of 8-km² is part of the Sino-Singapore Tianjin Eco-city (SSTEC), which has been a cooperative project between the governments of Singapore and China since 2007, aiming to develop a socially harmonious, environmentally friendly and resource-conserving city (Government of Singapore, 2016). The total land area of SSTEC will reach 30 km² after an urban development period of 10–15 years. Results from this study will be used to examine the effectiveness of various urban environmental solutions in SSTEC, as well as to improve environmental conditions and human comfort in other urban areas in northern China.

In this study, field measurements are conducted over the studied urban area covering different urban morphology settings from Jan of 2015 to Jul of 2016. Based on measured results, air temperature, RH, wind speed and thermal comfort at different locations are analyzed and mapped. Based on the obtained results, urban design recommendations are proposed to improve the microclimate conditions and thermal comfort during both summer and winter.

2. Field measurement

The studied urban area is located in the southern part of SSTEC and 40-km away from the city center of Tianjin. As a major port city, Tianjin is located along the north coastal region of China, surrounded by Hebei Province, Beijing City and the Bohai Sea. According to Köppen–Geiger climate classification system, Tianjin is classified as hot summer continental climate (Climate: China, 2016). According to meteorological data collected during 1970–2000 (China Today, 2016), January is the coldest month with an average air temperature of −4 °C, and July is the hottest of 26.8 °C. It is more humid in summer than in winter and RH varies from 51% to 77% throughout the year. The recorded average annual precipitation is 559.1 mm, with the rain occurring mostly in summer.

In Jan 2015, a total number of 46 weather stations were installed over the 8-km² studied area, to measure the outdoor weather conditions at 2.5 m height. As shown in Fig. 1(a) and (b), two types of weather stations were installed. One type is complete with sensors measuring air temperature, RH, wind speed and wind direction, another measures air temperature and RH only. Data was logged continuously at 5-min intervals from Jan 28 in 2015 to Jul 30 in 2016. The specifications of temperature, RH, wind speed and wind direction sensors are given in Table 1.

The 46 measurement points were deployed within the urban area to represent various urban morphology contexts, as shown in Fig. 2. Moreover, fish-eye lens photos were taken on Jun 29 in 2015 and Mar 15 in 2016, so as to calculate the SVFs (S-SVF) and winter (W-SVF) at each measurement point respectively. In addition, meteorological data was collected at a nearby meteorological station as reference during the same period, including the hourly solar radiation, RH, precipitation, wind speed and wind direction.

3. Research methodology

3.1. Selection of weather data for typical summer and winter days

The UHI effect and impact of urban morphology on microclimate are most evident on days with fairly clear and calm days in both summer and winter. It is thus reasonable to select such days for analysis. In this study, the typical summer and typical winter days are selected by examining the hourly weather data collected at a nearby meteorological station based on specified criteria, which are proposed based on long-term weather observation.

The following criteria are proposed to select the typical summer days.

- Daily maximum solar radiation of higher than 800 W/m²;
- Daily average temperature of higher than 22 °C;
- No rain and daily average wind speed of lower than 3 m/s;
- Both the hourly temperature and hourly solar radiation showing a bell-shape profile.

Meanwhile, the selected typical winter days should satisfy the following criteria.

- Daily maximum solar radiation of lower than 900 W/m²;
- Daily average temperature of lower than 10 °C;
- No rain;
- Both the hourly temperature and hourly solar radiation showing a bell-shape profile.

The monthly averaged air temperature and solar radiation data collected at the meteorological station in Jan and Jul of 2015 are
illustrated in Fig. 3(a). Moreover, an example of the hourly air temperature and solar radiation variations on the selected typical summer day (Jan 28, 2015) and typical winter day (Jul 8, 2015) are shown in Fig. 3(b). The daily air temperature on the typical summer day is 28 °C higher than that on typical winter day. The peak hourly solar radiation is 982 W/m² on Jul 8, which is much higher than that of 544 W/m² on Jan 28.

According to the criteria above, a total number of 50 summer days and 25 winter days are selected, as shown in Table 2. The number of selected typical winter days is fewer than that of the typical summer days. This is due to the fact that during the period from Nov 2015 to Apr 2016, some weather stations did not record any readings or recorded extremely unstable readings. Therefore, data collected during this period is not included in the analysis. All the sensors were recalibrated and put into use again at the end of Apr in 2016.

### 3.2. Thermal comfort model

Thermal comfort, as defined by American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), is the condition of mind that expresses satisfaction with the thermal environment and assessed by subjective evaluation (ASHRAE, 2010). A thermal sensation vote (TSV) model was developed in a previous study to predict the outdoor thermal comfort in Tianjin (Dayi, 2012). The study involved both microclimatic monitoring and questionnaire thermal comfort surveys during both winter and summer seasons at parks in Tianjin, China. The ranges of weather parameters during the survey period are given in Table 3. Although outdoor thermal environment varied greatly with air temperature from 4.4 °C to 34.5 °C, 83.3% of respondents consider the outdoor thermal comfort as “acceptable”. The respondents’ preferences in solar radiation, wind speed and RH were related to air temperature. It is concluded that the higher the air temperature was, the higher the wind speed and the lower the solar radiation and RH desired by the occupants, and vice versa.

A total of 1385 questionnaire surveys were conducted. The scale of respondents’ thermal sensation was −1, −0.5, 0, 0.5 and 1, representing the thermal stress of cold, cool, neutral, warm and hot respectively. The assumed ranges of TSV and corresponding thermal stress categories are given in Table 4.
Using correlation analysis, a TSV model with a correlation coefficient of 0.63 is proposed as below (Dayi, 2012),

\[
TSV = 0.0418 T_{air} + 0.0021 \text{SOLAR} + 0.28 WIND + 0.007 RH - 1.186
\]

where TSV is thermal sensation vote, \(T_{air}\) is air temperature in \(^\circ\mathrm{C}\), SOLAR is solar radiation intensity in W/m\(^2\), RH is relative humidity (%) and WIND is wind speed in m/s. From the TSV prediction model, it is derived that increasing TSV by 0.1 requires increasing either \(T_{air}\) by 2.39 \(^\circ\mathrm{C}\), SOLAR by 47.6 W/m\(^2\), WIND by 0.35 m/s or RH by 14.3%.

It was observed that most occupants preferred lower air temperature and less solar radiation in hot season, and the reversal in cold season.

4. Results and analysis

4.1. UHI intensity

The UHI intensity of the studied area is analyzed by comparing the air temperatures measured at 46 points with those at the meteorological station. Daily maximum and minimum temperatures (\(T_{max}\) and \(T_{min}\)) collected at each measurement point are firstly extracted. Subsequently, the highest and lowest \(T_{max}\) measured among the 46 measurement points on each selected day are extracted. Similar approach is applied to extract the highest and lowest \(T_{min}\) among the 46 measurement points.

In summer, air temperature usually peaks from 12:00 to 14:00 in the afternoon. The highest and lowest \(T_{max}\) as well as the daily \(T_{max}\) at meteorological station (MET \(T_{max}\)) on the selected 50 summer days are shown in Fig. 4. It is observed that the temperature difference between the highest and lowest \(T_{max}\) in the studied area is up to 4.5 \(^\circ\mathrm{C}\) during daytime, and the average difference is around 2.8 \(^\circ\mathrm{C}\). The daily maximum temperature at meteorological station (MET \(T_{max}\)) is quite close to the lowest \(T_{max}\), with the average temperature difference between MET \(T_{max}\) and lowest \(T_{max}\) being 0.7 \(^\circ\mathrm{C}\).

In summer, the daily \(T_{min}\) usually occurs in early morning from 03:00 to 06:00. The highest and lowest \(T_{min}\) as well as the daily minimum temperature at meteorological station (MET \(T_{min}\)) on selected summer days are shown in Fig. 5. The difference between the highest and lowest \(T_{min}\) in the studied area is 5.3 \(^\circ\mathrm{C}\) at most, and the average difference is around 2.5 \(^\circ\mathrm{C}\). The MET \(T_{min}\) is slightly higher than the lowest \(T_{min}\) with an average difference of 0.7 \(^\circ\mathrm{C}\).

In winter, air temperature usually peaks from 12:00 to 15:00. As shown in Fig. 6, the temperature difference between the highest

<table>
<thead>
<tr>
<th>Season</th>
<th>Temperature (°C)</th>
<th>RH (%)</th>
<th>Wind speed (m/s)</th>
<th>Solar radiation (W/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>Avg 10.0</td>
<td>40.62</td>
<td>1.06</td>
<td>347.15</td>
</tr>
<tr>
<td></td>
<td>Max 15.1</td>
<td>71.00</td>
<td>1.50</td>
<td>570.60</td>
</tr>
<tr>
<td></td>
<td>Min 4.4</td>
<td>13.00</td>
<td>0.60</td>
<td>98.90</td>
</tr>
<tr>
<td>Summer</td>
<td>Avg 30.7</td>
<td>56.60</td>
<td>0.27</td>
<td>323.23</td>
</tr>
<tr>
<td></td>
<td>Max 34.5</td>
<td>70.70</td>
<td>0.70</td>
<td>755.60</td>
</tr>
<tr>
<td></td>
<td>Min 25.6</td>
<td>42.80</td>
<td>0.00</td>
<td>144.60</td>
</tr>
</tbody>
</table>
and lowest $T_{\text{max}}$ is approximately 2.6 °C, and the average difference is around 1.7 °C. The average difference between the highest $T_{\text{max}}$ measured at weather station and MET $T_{\text{max}}$ is around 1.6 °C. The MET $T_{\text{max}}$ is very close to the lowest $T_{\text{max}}$ measured at weather station in winter.

In winter, the daily $T_{\text{min}}$ usually occurs in early morning from 05:00 to 06:00. As shown in Fig. 7, the difference between the highest and lowest $T_{\text{min}}$ is 5.0 °C at most, and the average difference is around 2.2 °C. The average difference between the highest $T_{\text{min}}$ and MET $T_{\text{min}}$ is 1.6 °C.

### Table 4

<table>
<thead>
<tr>
<th>TSV</th>
<th>Thermal stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; -0.6</td>
<td>Cold</td>
</tr>
<tr>
<td>-0.6 to -0.2</td>
<td>Cool</td>
</tr>
<tr>
<td>-0.2 to 0.2</td>
<td>Neutral</td>
</tr>
<tr>
<td>0.2-0.6</td>
<td>Warm</td>
</tr>
<tr>
<td>&gt;0.6</td>
<td>Hot</td>
</tr>
</tbody>
</table>

![Fig. 4. Daily maximum temperature on selected days in summer.](image1)

![Fig. 5. Daily minimum temperature on selected days in summer.](image2)

![Fig. 6. Daily maximum temperature on selected days in winter.](image3)
4.2. Microclimate conditions in summer and winter

4.2.1. Air temperature

The distribution of daily maximum temperature ($T_{\text{max}}$) in the studied area on a typical summer day of Jul 8, 2015 is shown in Fig. 8(a). The temperature difference between the hottest and coolest point is 2.5 °C. As shown in Fig. 8(b) and (c), the hot locations (measurement points 9, 12, 11) during daytime are mostly located in areas without shading, or with shading but are close to construction sites (possible anthropogenic heat source). The cool points, measurement points 22, 26, 30, are located within the shaded area of trees, buildings and device respectively.

The distribution of daily minimum temperature ($T_{\text{min}}$) on a typical summer day of Jul 8, 2015 is shown in Fig. 9 (a). The temperature differences between the hottest and coolest points reach up to 2.7 °C. As shown in Fig. 9(b), the hot locations, measurement points 13, 16, 30, are located near tall buildings in the commercial areas with restaurants, inside a residential estate and in a technology park respectively. The extensive building surfaces near these locations absorb a large amount of solar heat during daytime and this heat is subsequently released to the outdoor environment at night. Anthropogenic heat released from cooking or air-conditioners may have also contributed to the temperature rise at locations near restaurants or residential estates. As shown in Fig. 9(c), cool points 18, 22 and 27 at night are mostly located in open parks, due to the evaporative cooling effect of greenery.

On a typical winter day of Jan 28, 2015, the distribution of daily maximum temperature ($T_{\text{max}}$) is shown in Fig. 10(a). The temperature difference between the hottest and coolest points is not significant of 1.9 °C. The slightly warmer points are mostly located near the trees, such as points 11, 23 and 43 in Fig. 10(b). These points are more exposed to solar radiation in winter than the time when the pictures are taken in summer, due to the falling of leaves in winter. As shown in Fig. 10(c), cold points 14, 29 and 33 are mostly located in open areas with fewer trees, where it might be windy or under the shaded area near buildings.

At night, the temperature difference between the hottest and coolest point in winter reaches up to 2.9 °C as observed from the

![Fig. 7. Daily minimum temperature on selected days in winter.](image)

![Fig. 8. (a) Measured $T_{\text{max}}$ in summer, (b) hot points and (c) cool points during daytime.](image)
map in Fig. 11(a). As shown in Fig. 11(b), warm points 13, 14 and 11 are located in commercial areas with restaurants, inside residential areas and near the road respectively, which is very similar to the nighttime situation in summer. The surfaces of buildings and pavements absorb a large amount of solar heat during the daytime, and they release the radiant heat to ambient environment at night. At night, cold points shown in Fig. 11(c) are mostly located in open parks. Radiant heat is dissipated at these locations easily due to large SVFs.

4.2.2. Relative humidity

The distribution map for daily average RH in summer (Jul 8, 2015) and winter (Jan 28, 2015) are shown in Fig. 12(a) and (b) respectively. It can be observed that the RH in summer is 10–15% higher than that in winter. In summer, the southwest area near parks are most humid, followed by northeast area near river and central areas with most buildings. The maximum difference in RH reach up to 7.5%, between the locations in parks and in built areas. In winter, the northeast area near river become more humid.
than the southwest area near parks, due to the falling of tree leaves. The largest RH difference of 10.4% is observed between the locations near river and those near buildings. It is thus concluded that trees and water areas are quite effective in increasing the RH in the studied area, although the effect of trees is reduced in winter due to falling of leaves.

4.3. Wind speed distribution

The impact of urban morphology on wind speed at locations installed with wind sensors is also investigated. The distribution of daily average wind speed in the studied area during summer is shown in Fig. 13(a). The windy points are mostly located in open
areas with less obstruction from buildings, as shown in Fig. 13(b), while the calm points with lower wind speed are mostly located near trees, such as measurement points 6, 8 and 46 in Fig. 13(c). The SVFs at the windy measurement points are generally larger than those at calm points in summer.

The distribution of daily average wind speed in winter is shown in Fig. 14(a). Similar to the pattern in summer, windy points 21, 34 and 41 in winter are located in open areas with less obstruction from trees and buildings as shown in Fig. 14(b), while the calm points 8, 11 and 12 are located near buildings or trees as shown in Fig. 14(c). It is noticed that the measured daily wind speed is quite low of 0.2–0.7 m/s, which is much lower than the measured wind speed at nearby meteorological station. This may be explained by the fact that buildings and trees impede the wind flow and reduce the wind speed significantly at the measurement points, while the meteorological station is located in open areas without wind blockage.

4.4. Thermal comfort

Thermal comfort levels in the studied area during summer and winter are also evaluated by means of calculating the TSV values...
using Eq. (1) for those measurement points with complete air temperature, RH and wind speed data.

The distribution of TSV in the studied area on Jul 28, 2015 is shown in Fig. 15(a), for the scenario when air temperature reaches its maximum in summer afternoon. The calculated TSVs are found within the range of 0.63–0.96 and the thermal stress falls into the category of “hot”, according to Table 4. As shown in Fig. 15(b), the hot points 7, 20 and 23 are mainly located in open areas with solar exposure, where both air temperature and wind speed tend to be higher. Whereas, the slightly cooler points 6, 8 and 46 are all located in shaded area near trees, as shown in Fig. 15(c). It is thus noticed that the shading of trees is very effective in improving the outdoor thermal comfort in summer.

In winter, when air temperature reaches its maximum on Jan 28, 2015, the calculated TSVs are found within the range of 0.33–0.57 and the thermal stress falls into the category of “cool”. As shown in Fig. 16(b), the slightly warmer points 1, 20 and 45 are located in open areas with greenery. As deciduous trees may drop leaves in winter, these points become partly or fully exposed to solar radiation, where air temperature rises during daytime and human sensation becomes slightly warmer. As shown in Fig. 16(c), cold points 13, 17 and 28 are located near buildings, where wind flow might be blocked and the shading from buildings lower the air temperature, so that the thermal sensation at these locations becomes colder. It is concluded that greenery and buildings play an important role in determining the outdoor thermal comfort in winter.

5. Discussion and urban design recommendations

This section presents the discussion on measured results presented in Section 4, as well as proposes some urban design recommendations for outdoor thermal comfort in the studied area during both summer and winter.

Firstly, the UHI intensities on the selected days in both summer and winter are summarized in Table 5. In general, the UHI effect is slightly more evident in summer than in winter. The maximum UHI intensity reaches up to 4.5 °C during daytime and 5.0 °C at night in summer, and 2.6 °C during daytime and 5.0 °C at night in winter. The average temperature differences measured between the hottest and coolest locations in the studied area reach 2.8 °C during daytime and 2.5 °C at night in summer, which are 1.7 °C and 2.2 °C respectively in winter. In winter, the UHI effect becomes more evident at night than that during the daytime.

Although many studies have examined the temporal variation of UHI effect in cities in China, most of them were conducted at regional scale by comparing air temperatures measured at urban and rural weather stations (Hua et al., 2008). However, the representativeness of such weather stations are often criticized due to the ambiguous definitions of “urban” and “rural” in UHI studies. This work investigates the microclimate UHI intensity in an urban area in temperate climate, while most microclimate UHI studies were conducted in tropical or subtropical regions previously (Roth, 2007). The UHI intensity in the studied area is found comparable to those tropical or subtropical urban areas, such as Taipei with a maximum UHI intensity of 4.9 °C in summer (Chang et al., 2007), Hong Kong with an annual UHI intensity of 2–4 °C (Siu and Hart, 2013) and Singapore with a maximum UHI intensity of 4 °C (Wong and Yu, 2005).

Secondly, based on climatic maps, the impact of urban morphology on air temperature, RH, wind speed and thermal comfort are summarized in Table 6. It is concluded that greenery (trees and turfing) and SVF are important factors to microclimate conditions and thermal comfort in temperate climate. Planting trees is an effective solution to improve outdoor thermal comfort in both summer and winter. In summer, trees and turfing help cool down the ambient environment due to shading and evaporative cooling. In winter, locations with trees become exposed to solar radiation and less cold as the trees lose their leaves. Moreover, trees and water areas help to increase RH in both summer and winter, although the impact of trees on RH becomes less significant in winter. The SVF, mainly affected by building and pavement, is important to air temperature during both daytime and nighttime as well. In summer, locations near tall buildings usually have lower SVF and are more likely to be shaded, which help to cool down the environment during daytime. In winter, buildings tend to reduce...
the wind speed. However, at night, air temperature tends to build up in the narrow street canyons with tall buildings and low SVF, which contributes to nighttime UHI and additional cooling load in summer.

Thirdly, some general recommendations are provided on how to design urban environment to achieve more comfortable conditions in northern China, as below.

- Add roadside trees to provide shading and lower air temperature in summer, as well as to provide a warmer and less windy environment in winter.
- Increase park space and plant trees in commercial and residential areas to provide evaporative cooling on summer nights, as well as to increase the relative humidity during both summer and winter.
- Add shading device in public activity areas or along the sidewalk to lower air temperature and improve pedestrians’ thermal comfort in summer.
- Avoid narrow street canyons with low SVFs to facilitate heat dissipation at night in summer.
- Increase water areas (lakes, ponds or river) to enhance the RH in winter.

![Image](image.png)

**Table 5**
UHI intensities in summer and winter.

<table>
<thead>
<tr>
<th>UHI</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max (°C)</td>
<td>Avg (°C)</td>
</tr>
<tr>
<td>Daytime (Tmax)</td>
<td>Highest - MET</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Highest - Lowest</td>
<td>4.5</td>
</tr>
<tr>
<td>Nighttime (Tmin)</td>
<td>Highest - MET</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>Highest - Lowest</td>
<td>5.3</td>
</tr>
</tbody>
</table>

![Image](image.png)

**Table 6**
Summary of weather parameters and thermal comfort distribution.

<table>
<thead>
<tr>
<th>Air temperature</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH Wind speed</td>
<td>Daytime, Hot spots have less/no shading</td>
<td>Daytime, Warm spots are near trees</td>
</tr>
<tr>
<td>Thermal comfort-Hot/warm spots</td>
<td>Nighttime, Hot spots are near tall buildings</td>
<td>Warm spots are near trees with less obstruction from trees</td>
</tr>
<tr>
<td>Thermal comfort-Cool/cold spots</td>
<td>Open areas without shading, where air temperature and wind speed are higher</td>
<td>Spots shaded by trees, where air temperature is higher and wind speed is lower</td>
</tr>
<tr>
<td></td>
<td>Areas with trees and greenery, which are partly or fully shaded with lower air temperature</td>
<td>Near buildings with shading, where air temperature and wind speed are lower</td>
</tr>
</tbody>
</table>
6. Conclusions

In this study, microclimate conditions and thermal comfort in a newly developed urban area in northern China are analyzed. It is found that the UHI effect is more evident in summer than in winter. UHI intensity reaches up to 4.5 °C during daytime and 5.3 °C at night in summer, and 2.6 °C during daytime and 5.0 °C at night in winter.

The impact of urban morphology on air temperature, RH, wind speed and thermal comfort is analyzed through climatic mapping. It is concluded that shading from buildings contributes to lowering the ambient temperature during daytime in both summer and winter. The evaporative cooling effect of trees is evident during both daytime and nighttime in summer, but it becomes less evident in winter due to reduction of leaf area. Moreover, trees tend to reduce outdoor wind speed in winter. Radiant heat dissipated by buildings and roads is the main contributor to nighttime UHI in both summer and winter. In addition, planting trees and increasing water areas are found effective to increase the RH during summer and winter respectively. Based on climatic maps, it is highly recommended to increase the greenery and plant trees in the urban area to improve the outdoor thermal comfort, as well as to avoid narrow street canyons to mitigate the nighttime UHI effect.

There are some limitations in this work as well. The impact of wind speed on outdoor thermal comfort could be further studied. The adopted TSV prediction model was proposed based on previous studies on thermal comfort in Tianjin under conditions of wind speed lower than 1.5 m/s. Therefore, the TSV model might not be applicable under weather conditions with wind speed larger than 1.5 m/s, which might be common in open areas during winter.

Some future works include regression analysis to investigate the correlation between daily air temperature and urban morphology parameters, such as SVF, green plot ratio, pavement percentage and building height. Utilizing Geographical Information System (GIS) analysis, empirical models will be developed to predict the daily air temperatures in urban areas under similar climatic conditions. Therefore, the impacts of urban modifications on ambient temperature will be predicted by the empirical models and thus evaluated through parametric study.

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