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Research Paper

Mapping the spatio-temporal distribution of solar radiation within street canyons of Boston using Google Street View panoramas and building height model

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ABSTRACT

Studying the solar radiation within street canyons would provide an important reference for increasing human thermal comfort and decreasing the potential health issues caused by too much exposure from sunlight. In this study, we used building height model and publicly accessible Google Street View panoramas to map the spatio-temporal distribution of solar radiation within street canyons of Boston, Massachusetts. Hemispherical images generated from Google Street View panoramas and building height model together with sun paths in summer and winter were used to estimate the spatio-temporal distribution of solar radiation within street canyons. Results show that street canyons in the downtown area have shorter sunshine duration and lower solar radiation to the ground compared with other regions of the study area in the whole year. The southwestern part of the study area with the abundance of vegetation canopies has relatively short direct sunshine duration and low solar radiation reaching the ground in summer, and relatively long direct sunshine duration and high solar radiation reaching the ground in winter. This study also shows that it is possible to estimate shading precisely within street canyons for a specific time and date at a specific location. Considering the public accessibility of Google Street View data in cities around the world, this study can be easily deployed in other cities. This study would give a great impetus to all studies relating the solar radiation at street level in future.

1. Introduction

The energy balance in street canyons would create a unique microclimate, which would further affect human thermal comfort and exposure to sunlight (Carrasco-Hernandez et al., 2015). As an important part of life quality, the thermal comfort in street canyons would influence personal outdoor activity levels and the utilization of urban space (Huang, Lin, & Lien, 2015; Hwang et al., 2011; Lin, Tsai, Liao, & Huang, 2013; Jin, Kang, Jin, & Zhao, 2017). The severe heat would have negative impacts on human well-being and efficiency (Lee, Holst, & Mayer, 2013; Jin et al., 2017). In the United States, extreme heat events are responsible for about one-fifth of natural hazard deaths (Borden & Cutter, 2008). As global warming, many cities are expected to experience more severe heat waves (IPCC 2007). Other than the severe heat, the cold outdoor environment would also bring thermal discomfort and cause inconveniences of the outdoor activities to urban residents (Jin et al., 2017; Kurazumi et al., 2013). This is especially important during winter for those cities located in temperate and cold climates.

Designing thermally comfortable streets is therefore becoming more and more important. The incoming solar radiation within street canyons is an important environmental parameter that affects human thermal comfort (Hodder & Parsons, 2007; Richards & Edwards, 2017). In hot summer, the solar radiation is considered as a thermal discomfort (Hwang et al., 2011; Lin, Matzarakis, & Hwang, 2010; Lin et al., 2013), however, in cold winter, the sunlight would be considered as a thermal comfort (Kurazumi et al., 2013; Hwang et al., 2011). In addition, the incoming solar radiation influences human exposure to the sunlight (Schmalwieser et al., 2010), which directly affects pedestrians’ experience on the ground. Therefore, estimating the spatio-temporal distribution of solar radiation within street canyons would provide an important reference for designing thermally comfortable environments.

The incoming solar radiation that reaches the ground within street canyons is influenced by street tree covers, geometrical characteristics of street canyons, and orientations of street networks (Carrasco-Hernandez et al., 2015; Johansson, 2006; Hwang, Lin, & Matzarakis,
The vegetation canopy cover can absorb solar radiation and use it for evaporation, which would moderate the microclimate (Chen, Zhao, Li, & Yin, 2006; Onishi, Cao, Ito, Shi, & Imura, 2010). The tree canopies also provide shade during sunny days and block solar radiation from reaching the ground (Arms, Rahman, & Ennos, 2013; Li, Ratti, & Seiferling, 2018). The geometrical characteristics of the street canyon, e.g. height/width (H/W) ratio, would influence the amount of solar radiation received on the ground (Ali-Toudert & Mayer, 2006; Algeciras, Consuegra, & Matzarakis, 2016; Johansson, 2006; Zhao, Liu, & Sun, 2008). Street canyons with larger H/W ratio usually have more shade and thermal comfort conditions in summer. In addition, the income solar radiation to the ground is also influenced by the spatial configuration of the building blocks and the orientation of the street canyons (Ali-Toudert & Mayer, 2007; Sanusi, Johnstone, May, & Livesley, 2016; Zhang, Du, & Shi, 2017). The east-west orientation streets tend to have more incoming solar radiation because the east-west streets are oriented in the same direction as the sun’s zenith (Zhang et al., 2017). The orientation of the streets would also influence the shading effectiveness of street trees. Sanusi et al. (2016) found that street trees along east-west orientation streets would provide a greater cooling effect for microclimate within street canyons.

Proliferating methods and tools have been proposed and developed to model the solar radiation within street canyons. Different metrics, e.g. canopy coverage, vegetation indices, were calculated based on remotely sensed imageries to indicate the microclimate moderation of urban vegetation (Chen et al., 2006; Kong, Yin, Wang, Cavan, & James, 2014a,b). However, it is difficult to simulate the solar radiation reaching the ground based on the overhead view remotely sensed data (Li et al., 2018). With the availability of high-resolution digital surface models, it would be possible to simulate the transmission of solar radiation within street canyons. However, most digital city models oversimplify the complex geometries of urban canyons (Carrasco-Hernandez et al., 2015). In addition, the street tree canopies are usually not included in those digital city models (Li et al., 2018).

Using ground-based hemispherical images would be a good supplemental data source for the simulation of the solar radiation within street canyons (Hwang et al., 2011; Matzarakis, Rutz, & Mayer, 2007; Matzarakis, Rutz, & Mayer, 2010). In situ measurements together with hemispherical images taken on the ground would provide precise measures of the solar radiation and the thermal environment within street canyons (Matzarakis et al., 2010). However, it is time and cost consuming to take measurements in a large area, both of which limit the in situ measurements into a small study area. In addition, it is difficult to upscale the site measures to an urban region (Richards & Edwards, 2017).

In this study, we used the publicly accessible Google Street View (GSV) panoramas and building height model to simulate the solar radiation within street canyons of Boston, Massachusetts in summer and winter, respectively. Hemispherical images generated from GSV panoramas by geometrical transform can represent the streetscape appearance in summer with considering the street tree canopies (Li et al., 2018). The building height model with no tree canopy information is suitable to simulate the solar radiation within street canyons in winter when deciduous trees are leafless. By estimating the sun positions at different moments and locations and overlaying the sun positions with corresponding hemispherical images, we simulated the solar radiation reaching the ground within street canyons of Boston. This study would provide a useful reference for the urban planning to increase the

Fig. 1. The location and maps of the study area, (a) the LiDAR data in Boston, (b) the street map of Boston, (c) the generated sample sites along streets, (d) the vegetation canopy map of Boston.
thermal comfort of the pedestrians. Considering the fact that street-level images are increasingly available in most countries around the world (Anguelov et al., 2010; Gebru et al., 2017; Li et al., 2015; Long & Liu, 2017), this study would provide a promising method to study the thermal environment within street canyons of cities around the world.

2. Study area and data

The city of Boston is one of the largest cities in both Massachusetts and New England (Fig. 1). According to the recent census data (American Census Survey 2009–2014 data), Boston has a total population of about 660,000. Boston is located in the northeast of the United States, with the land area of 125 km². Boston has spatially varied street canyon types ranging from skyscrapers in the downtown area and the low-lying residential area in the periphery areas (Fig. 1(a)). Boston has a humid subtropical climate with the annual temperature of 14.9 °C, and summers are typically warm to hot, while winters have cold temperatures. June, July, and August are the three hottest months, with a mean temperature of 26.1 °C. January and February are the coldest months, with the mean temperature around −1.0 °C. The spatial variations of street canyons types and dramatic temperature difference in winter and summer make Boston as a good case study area to check the spatio-temporal difference of solar radiation.

The datasets used in this study include street map, building footprint map, LiDAR data, and vegetation canopy map. The street map was collected from MassGIS data (MassGIS, 2005). Based on the street map (Fig. 1(b)), we generated 15,674 sample sites along the streets with the distance between two nearby points are 100 m (Fig. 1(c)). The coordinates of these sample sites were then used to download GSV panoramas through Google Street View application programming interfaces (APIs). More details about the GSV panorama collection are described in the following section.

In order to generate the building height model (Fig. 1(a)), we collected LiDAR data from NOAA Digital Coast (https://coast.noaa.gov/dataviewer/#/lidar/search/) and building footprint map from MassGIS (2005). The LiDAR data used in this study has a horizontal accuracy of 50 cm and vertical accuracy of 15 cm. The building footprint map and land use map in the study area were collected from MassGIS (2005). The LiDAR data was further overlaid on the building footprint map to generate the building height model.

The tree canopy data of Boston was delineated from remotely sensed data with a spatial resolution of 1 m (Fig. 1(d)). The multispectral satellite imagery and LiDAR were integrated for vegetation canopy classification with an overall accuracy of 95% (Raciti, Hutrya, & Newell, 2014).

3. Methodology

3.1. Google Street View (GSV) panorama collection

In this study, GSV panoramas were collected in two steps. The first step is to get the metadata of GSV panoramas using coordinates as inputs. The second step is to download GSV panorama tiles from Google servers and mosaic tiles to complete GSV panoramas. Based on the coordinates of those generated sample sites (Fig. 1(c)), we further collected the metadata of GSV panoramas in the study area. Here is an example of the metadata of a GSV panorama located at (42.345722, −71.085855),

```
metadata of a GSV panorama
{
    "copyright": "© 2017 Google",
    "date": "2014-6",
    "location": {
        "lat": 42.345722,
        "lng": -71.085855
    },
    "pano_id": "Y3yHsZunw28ywaSNsZn7JA",
    "pano_yaw_deg": "283.61"
}
```

The returned metadata includes the date information, the panorama ID, and the yaw angle degree. Based on the panorama ID in the metadata, GSV panoramas can also be downloaded from Google’s Server.
The geometrical transform of equidistant cylindrical projection (a) to equidistant azimuthal projection (hemispherical image) (b) (Li, Ratti, & Seiferling, 2017).

Fig. 2 shows the two tiles of a GSV panorama together with their corresponding uniform resource locators (URLs). In these URLs, the panoid represents the unique panorama ID, x and y represent the column and row number of the tile, respectively. A complete panorama includes 26 × 13 tiles. By setting the x and y from the ranges of 0 to 25 and 0 to 12 in the URLs, respectively, we can download all tiles of a GSV panorama, which can be further mosaicked to a complete GSV panorama for any input panorama ID. In this study, we developed a Python script to download those 26 × 13 tiles and mosaic them to a panorama for each site using the panorama ID as input.

### 3.2. Hemispherical images generation and classification

The downloaded GSV panoramas are in form of equidistant cylindrical panorama as shown in Fig. 2. In this study, we created hemispherical images by transforming those GSV panoramas from equidistant cylindrical projection to equidistant azimuthal projection. Fig. 3 shows the geometric model of transforming cylindrical projection to azimuthal projection. The $W_c$ and $H_c$ are the width and height of the cylindrical panorama, so, the radius of the hemispherical image should be, $r_0 = W_c/2\pi$, and the width and height of the hemispherical image are $W_c/\pi$. Therefore, the center of the result hemispherical image $(C_x, C_y)$ is,

$$C_x = C_y = \frac{W_c}{2\pi}$$

(1)

For pixel $(x, y)$ on the result hemispherical image, the corresponding pixel on the cylindrical panorama should be $(x_c, y_c)$,

$$x_c = \frac{x}{\theta} W_c$$

$$y_c = \frac{y}{\theta} H_c$$

(2)

where $\theta$ and $r$ are,

$$\theta = \begin{cases} \frac{\pi}{2} + \arctan\left(\frac{y - C_y}{\frac{W_c}{2} - C_x}\right), & x_f < C_x \\ \frac{3\pi}{2} + \arctan\left(\frac{y - C_y}{y - C_x}\right), & x_f > C_x \end{cases}$$

(3)

$$r = \sqrt{(x_f - C_x)^2 + (y_f - C_y)^2}$$

(4)

Based on the above geometrical model, we further applied the affine transform to generate synthetic hemispherical images based on the cylindrical GSV panoramas. Considering the fact that the central column in the cylindrical image represents the driving direction of the Google Street View car rather than the true north direction. Therefore, the generated hemispherical images need to be further rotated by the yaw angle to make sure that the generated hemispherical images represent the north, east, south, and the west direction (Fig. 4). The pixel $(x_f, y_f)$ on the synthetic hemispherical images should be further converted into $(x_f', y_f')$ on the rotated hemispherical images as,

$$x_f' = x_f \cos \phi - y_f \sin \phi$$

$$y_f' = x_f \sin \phi + y_f \cos \phi$$

$$\phi = 360 - \text{yaw}$$

(5)

where yaw is the yaw angle from the metadata of GSV panorama. Fig. 4 shows the generation of a rotated hemispherical image from a GSV panorama at one site of the study area. The rotated hemispherical images have the same coordinate system with the sun path diagram, which would make it possible to overlay the sun path with hemispherical images directly.

The sky extraction is a requisite step to model the solar radiation within street canyons using hemispherical images. In this study, we applied the object based image analysis to extract the sky pixels from the hemispherical images (Li et al., 2018). The meanshift algorithm was used to aggregate nearby pixels in the hemispherical images into physically meaningful objects (Comaniciu & Meer, 2002; Li et al., 2018). The sky pixels are usually brighter than non-sky pixels and have a higher reflectance in the blue channel. Therefore, we used a modified brightness, which gives more weight to the blue band and less weight to the red band, to extract the sky pixels from the segmented hemispherical images. The modified brightness is calculated as,

$$\text{Brightness} = \frac{(0.5 \times \text{red} + \text{green} + 1.5 \times \text{blue})}{3}$$

(6)

where red, green, and blue are the pixel values in red, green, and blue.
bands in the segmented hemispherical image, respectively. The Otsu’s method (Otsu, 1975) was then used to find the optimum threshold to separate sky pixels and non-sky pixels. Those pixels that have higher Brightness values than the threshold are sky pixels.

Different from the sky and building pixels, the tree canopy pixels show as green in the hemispherical images. Therefore, in this study, we calculated the ExG (2 × green – blue – red) from the segmented hemispherical images to enhance the difference between greenery pixels and non-greenery pixels (Ribeiro, Fernández-Quintanilla, Barroso, & García-Alegre, 2005; Woebbecke et al., 1995). The Otsu’s method (Otsu, 1975) was then used to find the optimum threshold to separate greenery pixels and non-greenery pixels. Those pixels other than greenery pixels and sky pixels were categorized as building pixels.

In order to refine the sky classification results, we further applied geometrical rules to the preliminary sky classification results, such as sky pixels should be above the building pixels, the center of the fisheye images should be sky pixels or tree canopy pixels. Fig. 5 shows the classification results of sky pixels on three generated hemispherical images based on the above spectral and geometrical rules.

3.3. Generation of hemispherical images based on building height model

In summer, buildings and the vegetation both are major obstructions of solar radiation in street canyons. In winter, deciduous trees in Boston become leafless and building blocks act as the major obstruction of solar radiation in street canyons. In order to estimate and map the solar radiation within street canyons in winter, we further used building height model to generate synthetic hemispherical images based on the standard ray-tracing algorithm (Rich, 1989; Rich, Dubayah, Hetrick, & Saving, 1994). Since street greenery is not considered in the building height model, therefore, the building height model based simulation method would be suitable to estimate the solar radiation within street canyons in winter. Fig. 6 shows the geometrical model that projects building height model to an equidistant hemispherical image at one site of the study area.

For each sample site, we searched for all buildings within a search radius of 500 m in all 360° horizontal directions with a step of 1° (Fig. 6(a)). The obstruction angle at each horizontal direction can be calculated as,  \[ \theta_{\alpha} = \max \left( \arctan \frac{H_{ia} - 2.5}{D_{ia}} \right) \] (7)
where \( H_{ia} \) is the height of building \( i \) at horizontal direction \( \alpha \) within the search radius, \( D_{ia} \) is the ground distance between the sample site and the building \( i \). Therefore, the distance of the skyline at horizontal direction \( \alpha \) to the center of the generated hemispherical images \( r_{\alpha} \) can be calculated as,  \[ r_{\alpha} = \frac{90 - \theta_{\alpha}}{90} \] (8)
where \( r_{0} \) is the radius of the hemispherical image; \( \theta_{\alpha} \) is the obstruction angle in degrees at horizontal direction \( \alpha \). The skyline at horizontal direction \( \alpha \) should be projected at pixel \((H_{x}, H_{y})\) in the hemispherical image,  \[ C_{x} + r_{\alpha} \cos(\alpha) \]
\[ C_{y} + r_{\alpha} \sin(\alpha) \] (9)
where \((C_{x}, C_{y})\) is the center of the generated hemispherical image; \( r_{\alpha} \) is the distance of skyline at horizontal direction \( \alpha \) to the center of the generated hemispherical image.

Fig. 7 shows the comparison of the hemispherical images generated based on GSV panoramas and the building height model. Generally, those hemispherical images generated from building height model (Fig. 7(c)) match very well with the hemispherical images generated from GSV panoramas (Fig. 7(b)). The matched results further proved the validity of the geometrical model that generates equidistant hemispherical images from GSV panoramas.

3.4. Simulation of solar radiation within street canyons

Street trees and building blocks are the two major obstructions of
solar radiation within street canyons. By overlaying the sun paths at different times for a given site with the corresponding hemispherical images, it would be possible to estimate the proportion of solar radiation reaching the ground precisely at site level.

3.4.1. The sunshine duration at the day level

The sunshine duration, which measures the duration of sunshine in a given period, is an important climatological indicator influencing the microclimate within street canyons. Because of different spatial configurations of street geometries, the sunshine duration is different at different sites within street canyons. This part shows how to estimate the expected duration of sunshine throughout a day for a given geometry of street canyons and canopy openings.

The sun positions can be calculated with a high accuracy, as it varies with the location of those sites and time. By overlaying the hemispherical image and sun path for a given day at one site, it is possible to measure the duration of sunshine throughout a day for the site. Fig. 8 shows the overlays of sun positions on hemispherical images from 5:00 am to 7:00 pm on June 1st, July 15th, August 15th, and September 1st, 2014 at different sites.

By assuming that the sunlight would be blocked if the sun were not located in the open sky areas on the hemispherical images, we calculated the sunshine duration for one site as the duration of sunlight not blocked by obstructions for this site within the street canyon. The calculation was based on the assumption that the weather is sunny and cloudless. Although the result may not represent the real sunshine duration in cloudy or raining days, this simulation would give an estimate of the potential sunshine duration theoretically, which would provide a reference for urban planning.

3.4.2. Estimation of solar radiation to the ground within street canyons in summer and winter

Generally, direct radiation and diffuse sunlight radiation are the two largest components of the total solar radiation to the ground (Anderson, 1964; Fu & Rich, 2002). Based on hemispherical images generated from GSV panoramas and building height model, it is possible to make reasonable estimates of solar radiation penetration to given positions within street canyons (Rich, 1989). In this study, we estimated the proportion of direct radiation and diffuse radiation reaching the ground within street canyons using the generated hemispherical images and sun path diagram of the study area.

The proportion of direct solar radiation to the ground can be estimated by determining the intersection of the sun paths with open sky pixels in the hemispherical images. Therefore, the proportion of direct solar radiation reaching the ground for one day can be calculated as:
where the $h_1$ is the sunrise time and the $h_2$ is the sunset time; $\theta_h$ is the sun zenith angle at time $h$ in one day; $B_h$ is the Boolean variable to indicate whether the sun is blocked or not at time $h$; if the sun is blocked at time $h$ the $B_h$ equals 0, or the $B_h$ is 1. In this study, we calculated the direct solar radiation at time interval of 0.1 h. Variations due to cloudiness and other site-specific atmospheric conditions are not easily predicted and are best measured empirically. Therefore, we only calculated the proportion of the direct solar radiation and estimated solar radiation by multiplying the proportion with the total direct solar radiation from the ground stations.

The diffuse radiation is a result of scattering by atmospheric components at all directions. The amount of diffuse radiation can be estimated by overlaying the obstruction images with a diagram of the expected distribution of diffuse skylight (Rich, 1989). Based on previous studies (Rich, 1989; Richards & Edwards, 2017), we assumed that the diffuse radiation is distributed evenly in 360° surround and the region directly above the camera has a higher proportion of diffuse radiation than the periphery parts (Rich, 1989). We created the sky map by dividing the whole sky into $8 \times 16$ sky sectors that are defined by 8 zenith and 16 azimuth divisions. The proportion of the diffuse radiation reaching the ground can be estimated as,

\[
PD = \frac{\sum_{h=h_1}^{h_2} B_h \cos \theta_h}{\sum_{h=h_1}^{h_2} \cos \theta_h}
\]

(10)

where $G_{a_z}$ is the proportion of visible sky for the sky sector; $\theta_{a,z,2}$ and $\theta_{a,z,1}$ are the bounding zenith angles of the sky sector; $\theta_a$ is the sun zenith angle at the centroid of the sky sector; $\text{Azimuth}_{av}$ is the number of azimuthal divisions in the sky map, which is 16 in this study.

The total radiation to the ground can be estimated as the sum of the direct radiation and diffuse radiation based on the previous proportion of direct solar radiation and the proportion of diffuse radiation together with the amount of total direct solar radiation and the total diffuse solar radiation collected from the ground station as (Richards & Edwards, 2017),

\[
R = PD \cdot \text{Rad}_{dir} + PF \cdot \text{Rad}_{dif}
\]

(12)

where $G_{a_z}$ is the proportion of visible sky for the sky sector; $\theta_{a,z,2}$ and $\theta_{a,z,1}$ are the bounding zenith angles of the sky sector; $\theta_a$ is the sun zenith angle at the centroid of the sky sector; $\text{Azimuth}_{av}$ is the number of azimuthal divisions in the sky map, which is 16 in this study.

The total direct solar radiation $\text{Rad}_{dir}$ and the total diffuse solar radiation $\text{Rad}_{dif}$ in the study area were collected from ground station data. Based the National Solar Radiation Database (http://www.nrel.gov/rredc/), the average daily direct solar radiation and diffuse radiation from June 1st to August 31st are 4632.0 Wh/m$^2$ and 2406.0 Wh/m$^2$, respectively. The average daily direct radiation and diffuse radiation from December 1st to February 28th are 3272.3 Wh/m$^2$ and 913.3 Wh/m$^2$, respectively.

4. Results

In the study area, among the generated 15,637 sample sites along
streets, there are 12,153 unique GSV panoramas available, considering the fact that some sites have no available GSV panoramas around. Those GSV panoramas that were captured in tunnels were removed from the further analysis. In addition, street trees change colors in different seasons, which would influence our analysis. By checking the visual appearances of street trees in different months, we removed those GSV panoramas taken in non-green seasons from further analysis. Finally, we used 11,451 GSV panoramas in the study area. Generally, those green GSV panorama sites are distributed evenly in the study area. Therefore, it is suitable to use those green GSV panorama sites to represent the whole study area, although there still have a small portion of the study area has no green GSV panorama sites available.

The proposed method makes it possible to map the spatio-temporal distribution of sunshine duration at the city scale. In this study, we only presented the spatial distributions of the sunshine duration in two days for illustration purpose. Fig. 9(a), (c) show the spatial distributions of sunshine duration on August 1st, 2014 and January 1st, 2014 in the study area at the site level, respectively. The average direct sunshine duration within street canyons of the study on August 1st is 7.6 h, and the average direct sunshine duration hour on January 1st is 5.2 h. In order to see the spatial patterns more clearly, we further aggregated these site-level sunshine duration maps to census tract level by mean values (Fig. 9(b, d)). In summer, the downtown area generally has shorter sunshine duration than the periphery parts of the study area (Fig. 9(a, b)). This is because high-rise buildings in the downtown area (Fig. 1(a)) would obstruct the sunlight, which would further shorten the direct sunshine duration there. The southwestern part of the study area also has much shorter sunshine duration compared with the eastern and northeastern parts. This is caused by the shading effect of the street tree canopies. This can be proved by the abundance of tree canopy cover in the southwestern part of the study area and little tree canopy cover in the eastern and northeastern regions (Fig. 1(d)). Similar with summer pattern, in winter the direct sunshine duration is much shorter in the downtown area than the rest areas in Boston (Fig. 9(c, d)). Different from the summer pattern, the southwestern area has a relatively long sunshine duration in winter. This is because in winter the leafless trees and low-rise buildings in the southwestern Boston would not block as much direct sunlight as it does in the downtown area.

Fig. 10 shows the spatial distributions of the amount of average daily solar radiation to the ground within street canyons at the site level and census tract level in summer and winter. On average, 4900.2 Wh/m² daily solar radiation reaching the ground within the street canyons of Boston from June 1st to August 31st, which is 69.6% of the total incoming solar radiation from the sky in this time period. The direct solar radiation reaching the ground is 3,184.0 Wh/m² (68.7% of incoming direct solar radiation), and the diffuse radiation in the street canyons is 1716.2 Wh/m² (71.3% of incoming diffuse solar radiation). The solar radiation reaching the ground distributes unevenly in the study area (Fig. 10(a, b)). The downtown area, southern and southwestern parts of the study area have much less solar radiation reaching
the ground compared with the northern and eastern parts. This is in accordance with the shorter sunshine duration in southern and southwestern parts (Fig. 9(a, b)). The high-rise buildings in the downtown area (Fig. 1(a)) and the abundant vegetation covers in the southern and southwestern (Fig. 1(d)) parts provide shade in street canyons, which further contribute to lower sunlight exposure and shorter sunshine duration there.

Fig. 10 (c), (d) show the spatial distributions of solar radiation at the site level and census tract level from December 1st to February 28th, respectively. The average daily solar radiation reaching the ground within street canyons is 3,296.1 Wh/m$^2$ in winter, which is 78.8% of total incoming solar radiation in this time period. The direct solar radiation reaching the ground is 2464.7 Wh/m$^2$ (75.3% of incoming direct solar radiation), and the diffuse solar radiation is 831.4 Wh/m$^2$ (91.0% of incoming diffuse solar radiation). In winter, the percentage of direct solar radiation reaching the ground is higher than summer when tree canopies would block the direct solar radiation. Without the obstruction of tree canopies, the percentage of diffuse solar radiation reaching the ground in winter is much higher than summer. Similar to the summer pattern, the downtown area still has lower solar radiation in winter compared with other regions in Boston. This is because of the obstruction effects of high-rise buildings in the downtown area. Different from the summer pattern, in winter, the southwestern and southern parts of the study area have relatively high-level solar radiation. This is because trees turn leafless in winter and not act as obstruction of solar radiation.

5. Discussion

The solar radiation within the street canyons is an important factor that influences human thermal comfort (Hodder & Parsons, 2007; Kurazumi et al., 2013). This study investigated the spatio-temporal distribution of the amount of solar radiation reaching the ground within street canyons of Boston in summer and winter. The sunshine duration and solar radiation were estimated by overlaying sun’s zeniths on hemispherical images generated from GSV panoramas and building height model. The GSV panorama generated hemispherical images can represent the physical environment of street canyons objectively with

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**Fig. 8.** The sun paths on hemispherical images, (a) the sun paths in three days (June 1st, 2014, July 15th, 2014, August 15th, 2014) at three different sites of Boston, (b) the overlay of the sun path of September 1st, 2014 on three hemispherical images taken in September 2014.
consideration of the obstructions of both building blocks and tree canopies (Li et al., 2018). Therefore, the GSV panorama generated hemispherical images were used to estimate and map the solar radiation in summer when tree canopies would shade sunlight. In winter, we used hemispherical images generated from building height model to estimate and map the sunlight duration and solar radiation within street canyons considering the fact that trees become leafless in winter and building height model considers the obstruction of building blocks only.

In Boston, the sunshine duration and solar radiation are distributed unevenly. Different regions have very different spatial distributions of sunshine duration and solar radiation within street canyons. Generally, the downtown areas have shorter sunshine duration and lower solar radiation reaching the ground than other regions of the study area. This is caused by the obstruction effect of the high-rise buildings on solar radiation in the downtown area. The sunshine duration and solar radiation have different spatial patterns in summer and winter. In summer, compared with street canyons in the eastern and northern parts, the southwestern part and the downtown area have shorter sunshine duration and lower solar radiation that reaches the ground. This is in accordance with the high-rise buildings in downtown (Fig. 1(a)) and the abundant vegetation cover in southwestern Boston (Fig. 1(d)). The high-rise buildings and tree canopies would block the incoming solar radiation from reaching the ground. Similar to the summer pattern, in winter, the downtown area still has shorter sunshine duration and lower solar radiation than the rest regions. However, the southwestern area has longer sunshine duration and more solar radiation reaching the ground than the downtown area because the leafless trees in southwestern would not block the solar radiation in winter. Considering the fact that sunlight would influence human thermal comfort negatively in hot summer and positively contribute to the thermal comfort in cold winter, the different performances of urban trees on solar radiation in winter and summer would provide maximum benefits to residents all the year.

The proposed study can estimate the solar radiation to the ground within street canyons at a fine temporal resolution. Fig. 8 shows the overlays of sun paths on hemispherical images generated from GSV panoramas on different days for different sites. It is possible to estimate shading precisely for a specific time at any specific location along streets, since the sun position can be calculated accurately at that moment based on the coordinate of the location. This would provide important information for human outdoor activities to maximize thermal comfort in summer and winter. In addition, the fine level solar radiation simulation within street canyons would also provide some references for designing more thermally comfortable streets in cities using street trees by considering the seasonal changes and the geometrical characteristic of street canyons. The proposed method can be applied to many more cities around the world to model the sunshine duration hourly considering the global availability and public accessibility of GSV images.

While this study investigated spatio-temporal distribution of the sunshine duration and solar radiation within street canyons, there are
still some limitations that need to be solved in the future studies. Firstly, the sunshine duration and solar radiation fluxes estimated in this study are not identical to the human thermal comfort. The human thermal comfort is also influenced by the wind speed, the humidity, weather conditions, etc. (Lin et al., 2013; Richards & Edwards, 2017). Future studies should also investigate the connection between the sunlight and the human thermal comfort within street canyons. More parameters and in situ measurements are in need to develop more objective measures of the human thermal comfort.

Secondly, the hemispherical images were generated based on GSV panoramas captured in summer in this study and the street tree canopies were assumed to be the same in different months of the green season. The estimated sunshine duration may not be suitable to represent those cloudy or raining days in summer in summer. The solar radiation simulation in winter is based on the assumption that all trees are leafless in winter. However, the evergreen trees and the branches of deciduous trees would also act as obstruction of solar radiation in winter.

In addition, since all GSV panoramas are taken along streets, therefore, the sunshine duration and solar radiation estimation method in summer is only applicable to estimate the solar radiation within street canyons.

6. Conclusions

This study estimated and mapped the spatial distributions and the seasonal changes of solar radiation within street canyons at city scale using GSV panoramas and building height model. Results show that street canyons in different parts of the study area have very different spatial distributions of sunshine duration and solar radiation reaching the ground. Generally, the downtown area has shorter sunshine duration and lower solar radiation within street canyons compared with other regions in the whole year. The southwestern part of the study area with the abundance of vegetation canopies has relatively short direct sunshine duration and low solar radiation reaching the ground in summer, but relatively long direct sunshine duration and high solar radiation reaching the ground in winter.

This study provides a method to estimate shading precisely within street canyons for a specific time and date at any specific location based on the estimation of the sun position and the image analyses on GSV panoramas. The proposed method would provide an important reference to maximize pedestrian’s thermal comfort within street canyons in summer and winter.

This study also shows that it is possible to estimate and map the spatio-temporal distributions of sunshine duration and solar radiation within street canyons on a large scale with a fine temporal resolution. Considering the abundance of GSV data in cities around the world, the proposed automatic method would provide a huge impetus to the all studies relating street canyons level solar radiation.

Fig. 10. The spatial distributions of the solar radiation in street canyons of Boston during summer and winter.
Reference


