Sky View Factor Analysis of Street Canyons And Its Implication For Urban Heat Island Intensity

A GIS-based methodology applied in Hong Kong

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ABSTRACT: The sky view factor (SVF) has been shown to be an important factor in determining the micro climate in urban canyons. However the results analyzing the relationships between urban heat island intensity (UHI) and SVF found in the literature are empirical and location dependent, and sometimes, contradictory, while the studies are mostly based on individual field measurement (e.g. fisheye photo). Continuous SVF values for a whole terrain are important to derive the thermal pattern of that area. However, a rapid method for calculating continuous SVF values with enough accuracy for large areas (1000 km2 scale, e.g.), is yet to be developed. This paper presents a GIS-based approach where a computer program is developed for calculating continuous SVF values in an entire urban environment. A map of SVF values is generated. The result is evaluated against data obtained in field measurements from seaside to downtown area. Various parameters such as areal mean are studied. The study aims to investigate the relationship between SVF and UHI in Hong Kong and to derive an overall pattern of how Hong Kong's unique building bulk characteristics and UHI are related. The expected significance of this research work is that the relationship derived can be used as a prognostic approach for categorizing Hong Kong's urban area for planning concerns for high dense sub-tropical cities.

Keywords: Sky View Factor (SVF), Urban Heat Island (UHI), Geographic Information System (GIS)

INTRODUCTION

Urban geometry has a complex influence on the micro climate of the urban environment, e.g. difference in urban geometry and building density may result in intra-urban air temperature differences (Chandler, 1965). The most important effect is that built-up areas obstruct open sky and delays the cooling of the surface during clear, calm nights (Oke, 1981). In radiation budget models, this aspect is often described by the sky view factor (SVF). As the name implies, the sky view factor, often denoted by ψ_{sky}, indicates the ratio of the radiation received (or emitted) by a planar surface to the radiation emitted (or received) by the entire hemispheric environment (Johnson and Watson, 1984). It measures the percentage of radiation penetrated into the urban canopy layer (UCL) (Oke, 1978). SVF is a dimensionless value ranging from 0 to 1: $\psi_{sky} = 0$ indicates that the sky is completely obstructed and the outgoing long-wave radiation is trapped within the urban canyons, while $\psi_{sky} = 1$ means the sky is completely open and the radiation emits freely outside the UCL.

The difference in cooling rates between urban built-up areas and rural surroundings results in nocturnal temperature difference between urban and rural areas, which is often referred to as Urban Heat Island (UHI). Likewise within an urban area, different building densities also cause intra-urban temperature difference. Due to its role in radiation balance schemes, the sky view factor is commonly used by climatologists to develop relations with urban heat exchange. This can be traced back to the 1970's when Lindqvist (1970) first showed the differences of intra-urban surface air temperatures was strongly dependent on the sky view factor. Oke (1981) developed a hardware simulation model showing that the sky view factor can produce a nocturnal urban heat island intensity up to 7 ˚C and a function can be derived between the sky view factor and the urban heat island intensity. Oke's pioneer work led two decades of research work aiming at identifying the role of the sky view factor in determining the urban heat island intensity. Different approaches are taken and notable studies include Eliasson (1990-1991), Upmanis and Chen (1999), Brown et al. (2001), Svensson (2004), Voogt (2007), etc. Unger (2004) has provided a thorough review of research work in this domain.

In contrast with the broad literature analyzing the relationships between urban heat island intensity and sky view factor, discussions are still sparse for high rise and compact city structures such as Hong Kong. There lacks a comprehensive climatic analysis regarding Hong

Kong's unique urban characteristics. Two problems need to be solved before this goal is achieved:

1. Continuous SVF values for a whole terrain are important to derive the thermal pattern of that area. However, a rapid method for calculating continuous SVF values with enough accuracy for large areas (1000 km2 scale), is yet to be developed.

2. The relation between SVF and UHI found in the literature are empirical and location dependent, and sometimes the results are contradictory. Due to Hong Kong's unique high density characteristics (with SVF values mostly smaller than 0.5), these models are not suitable. A comprehensive analysis of use of SVF needs to be conducted.

It is with no doubt that other factors also contribute to the development of the UHI. As Johnson and Watson very nicely stated in their paper: "Urban heat islands are no longer thought to be the outcome of an all-inclusive set of parameters peculiar to a city environment. Rather, their existence is regarded as the product of a more subtle interplay of factors subject of spatial and temporal variation." (Johnson and Watson, 1984) However the focus of this work is to investigate the SVF – UHI relationship for real case of Hong Kong.

BACKGROUND

Determination of the sky view factor "SVF is commonly determined using either analytical (geometrical), photographic or software methods," (Unger, 2004)

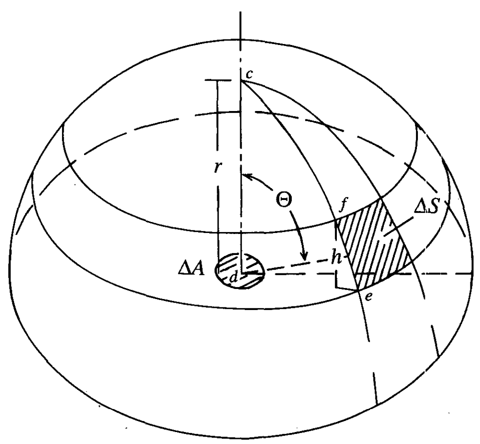

Figure 1. Model of radiation exchange between the sky and a surface element. After (Johnson and Watson, 1984).

Analytical methods (geometrical methods) Analytical methods are based on the geometrical characteristics of the urban canyons to calculate ψ_{sky}. Geometrical features are illustrated above in Figure 1. For the most general case:

$$\psi_{sky} = \frac{1}{\pi R^2}\int_{S_v} \cos\phi dS$$

Where S_v is the section of the hemisphere representing the visible sky (Johnson and Watson, 1984).

Oke (1981) simplified the model by defining an urban canyon of infinite length with height (H) and width ($W = 2D$). Under this simplified model, SVF is defined as:

$$\psi_{sky} = \cos[\tan^{-1}(H/D)]$$

In reality, buildings within urban canyons are always asymmetric and of finite length, which requires refinement of the equation. (Johnson and Watson, 1984) uses azimuths (α) and elevation angles (β) of surrounding buildings and calculate wall view factor ψ_w as:

$$\psi_w = \frac{1}{2\pi}\{(\gamma_1 - \gamma_2) + \cos\beta[\tan^{-1}(\cos\beta\tan\gamma_1) - \tan^{-1}(\cos\beta\tan\gamma_2)]\}$$

$\psi_{sky} = 1 - \sum_{i=1}^{n}\psi_w(i)$,where n is the number of buildings surrounding this surface element.

Photographic methods The photographic technique uses fish-eye photos taken at site with hemispheric lens. The photos are then processed (converting color to grey image, altering brightness and contrast, etc.). The equation provided by Johnson and Watson (1984) is always used to determine ψ_{sky}:

$\psi_{sky} = \frac{1}{2\pi}\sin\frac{\pi}{2n}\sum_{i=1}^{n}\sin\left[\frac{\pi(2i-1)}{2n}\right]\alpha_i$, where n is the number of annuli, i is the annulus index and α_i is the width of each annulus.

The photographic technique is particularly suitable for real cases in that it can deal with buildings of variable size and irregular shape. Further more vegetation information is also present so that precise SVF values can be calculated while the analytical technique may result in errors under this situation (GRIMMOND et al., 2001).

Software methods using building Datasets With the rapid development of GIS systems and wide application of GIS techniques, software methods have been increasingly used for computing sky view factors and computer programs and algorithms have been developed (GAL et al., 2007, Ratti and Richens, 1999, Gal et al., 2008). 3-D GIS building datasets are always used, and depending on the types of database used, the two main approaches are: vector method and high resolution raster method.

Vector database of 3-D buildings is just a simplified reconstruction of the real urban geometry: buildings are all flat-roofed and represented by polygons. After dividing the hemisphere equally into slices by rotation angle, the visibility of a slice is tested by Oke (1978). For a slice, a line is drawn to sweep the top of the buildings to search a single building which obstructs the largest part from the sky at that direction. SVF calculation for urban basin is illustrated in Figure 2. The accuracy of the calculation depends on the rotation angle and smaller rotation angle result in more accurate SVF values.

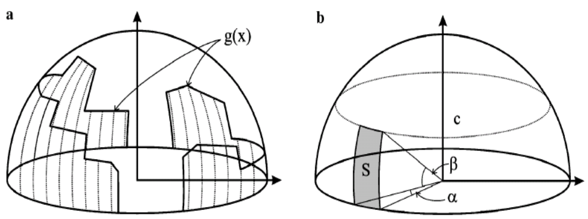

Figure 2. a) Polygon g(x) as the border of the visible sky and division of the overlying hemisphere under g(x) into equal slices. (b) a slice of a basin with an elevation angle. After (Gal et al., 2008).

Compared with vector method, calculating SVF values based on high resolution raster data is more commonly used. It shares the same geometrical arrangement with the vector model. The main difference is that a DEM (digital elevation model) database is often employed where surface topography and terrain information are stored in raster format. Shadow casting algorithm is developed (Ratti and Richens, 1999) for calculating SVF values through image processing techniques. Direct calculation based on geometric characteristics is another approach. The accuracy of the calculation depends on the resolution of the raster database and high resolution results in more accurate values.

Analysis Unger (2004) has made a comprehensive literature review of intra-urban relationship between surface geometry and urban heat island. Some issues deserve a careful look in the review.

a. Analysis results from previous studies can be rather contradictory, “especially if comparisons are based on a few element pairs measured at selected sites within the city” (Gal et al., 2008). While most of the studies have developed reasonable agreement between SVF value and temperature variation (Oke, 1981, Eliasson, 1990-1991), other results reveal different conclusion, “Among the geographical factors, the SVF could not be shown to have any influence on the air temperature… but it seems that the SVF has very little influence on the air temperature in an urban environment...A question about the suitability of the SVF is raised.” (Upmanis and Chen, 1999)

b. Correlations of element pairs (SVF, ΔT) are rather location-dependent. Other ways to calculate the influence of SVF may be required. A noticeable example is the approach proposed by (Unger, 2004) where comparison between areal means of both geometry and temperature variations are constituted.

c. Despite the broad literature, discussions based on continuous SVF values are rather sparse, especially for high density cities (SVF < 0.5). Most of the studies employ photographic methods to measure SVF values for selected sites. It is not exaggerating to say that an exemplar routine for analyzing relationship between surface geometry and urban temperature variation for compact cities such as Hong Kong is yet to be developed.

DEVELOPMENT OF A RAPID METHOD TO CALCULATE CONTINUOUS SVF VALUES

In this study, we develop a rapid method to calculate continuous SVF values for an entire urban environment using GIS database. A computer program is developed and embedded as VBA script in ArcGIS system. A SVF map for an entire chosen area is generated. The accuracy of the map can be verified by comparing the result with fish-eye photo method for selected sites.

GIS-based SVF calculation *Algorithm and methodology* We employ geometric methods introduced in the previous section as the theoretical basis for our SVF calculation. Optimizations are made to accelerate the algorithm. The algorithm is explained by the figure and the box below.

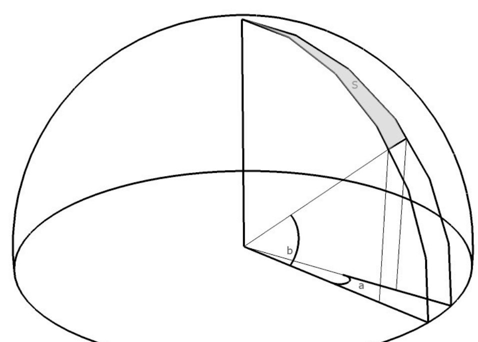

Figure 3.Geometric characteristics of the SVF calculation.

Table 1: Algorithm for SVFcalculation

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For an imaginary dome with radius R
For a: 0 ~ 360 degree
  For r: 0 ~ R
      h = building height at point P
      i = sin (-1) h/R
      b = Max (i)
  surface S is visible
```

3-D building database (with building height information) and DEM data are used for the calculation. The result is stored in a raster format file with geographic information preserved. To manage the raster files and manipulate the geographic information, the algorithm is implemented as an ArcGIS macro written in VBA.

Performance In implementation, the imaginary doom's radius is 100m, and the interval angle a is set as 3 degree. The result SVF map is 2m resolution. With this precision, a basin test is carried out in which the calculated SVF value is within 5% error of the theoretical value. On a daily used PC with CPU of 3 GHz and 4G RAM, this macro calculated continuous SVF for an entire terrain of 4km by 2km in two hours, which is a huge progress compared with traditional photographic method.

Continuous SVF Map *Study area* The study is carried out in Tsim Sha Tsui of Hong Kong (22 15 N, 114 10 E), a flat terrain with similar land use along the seaside of the Victoria Bay. Differences in building densities can be found in this area.

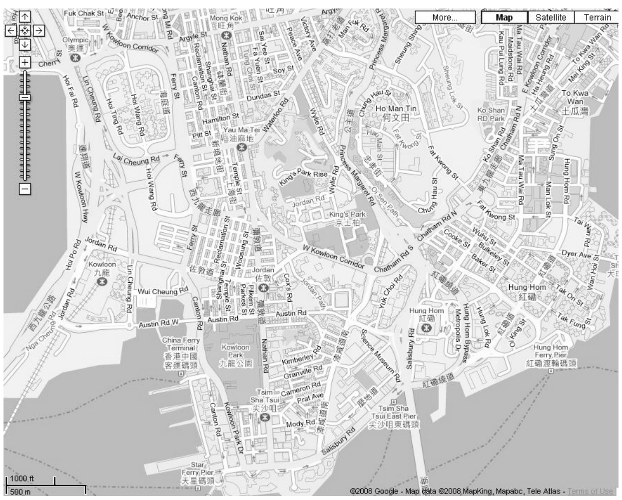

Figure 4: Google Map for study are: Tsim Sha Tsiu.

SVF Map A map of the continuous SVF value at the ground level for the entire terrain is generated using the ArcGIS macro developed.

Figure 5: SVF map for the study area.

TEMPERATURE MEASUREMENT

Temperature differences can be observed from the seaside to inner built-up area. On a calm summer afternoon, ground-level measurements are carried using handheld equipments along pre-selected measuring paths at this area. The equipments used in the measurement included a 3-function sensor probe from TESTO for the measurement of air temperature and wind speed, and TESTO 400 data logger for instant processing of the measured data. The data logger was set to have a sampling time of 10 seconds and an averaging time of 3 minutes. All the equipments were ISO certified. The measured result is synchronized with the Hong Kong Observatory's data assuming that temperature changes at the same pace at different sites.

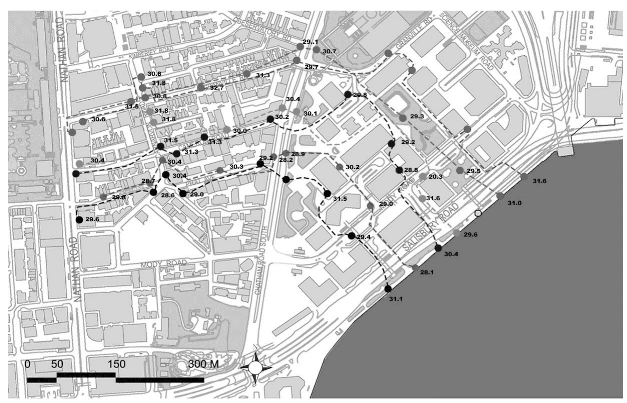

Figure 6: Temperature measurement map for the study area.

SPATIAL ANALYSIS AND CORRELATION

Literature has shown that areal average of SVF value has a closer correlation with temperature differences (Unger, 2004) than point value. Our continuous SVF map makes it possible and easy for calculating the areal average for the studied area. The following figure shows average SVF value with radius R = 100m.

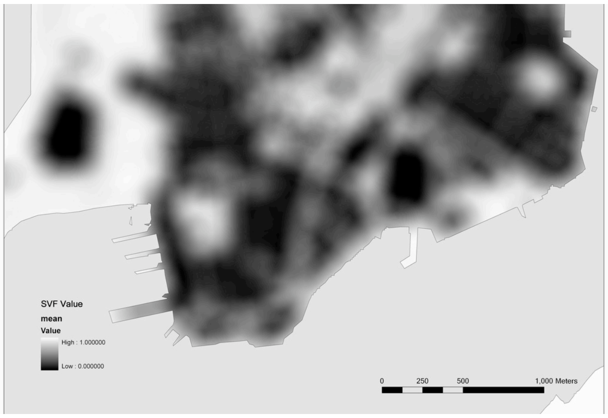

Figure 7: Areal average SVF map for the study area.

Then with the help of the GIS system, we coded the measurement result into the continuous SVF map, and correlate it with the SVF value.

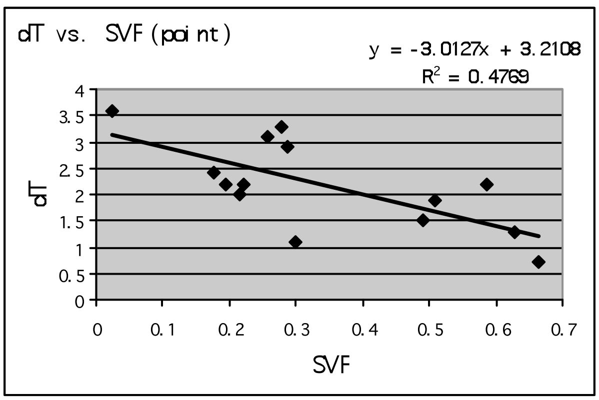

Figure 8: Correlation of dT and point SVF value.

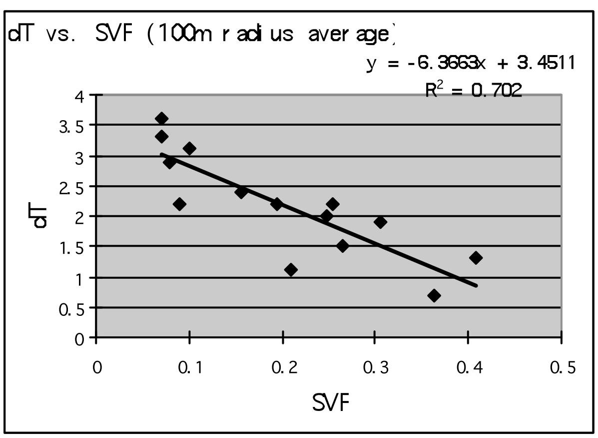

Figure 9: Correlation of dT and areal average SVF value.

FINDINGS AND DISCUSSION

1) The software methods are particularly suitable for calculating SVF values for large areas. They have two advantages over other methods: first, they can calculate continuous SVF values instead of SVF values for individual spot, second, the speed is fast, which makes it possible for calculating SVF values for large areas. In this sense, the software methods open new possibilities to generate SVF maps to analyze thermal patterns for an entire urban environment. The key issue is the availability of dataset. Often the building model can be constructed from government database (Lindberg, 2007).

2) SVF values of smaller than 0.5 are commonly observed in urban areas of Hong Kong. In the case of the study area (similar land use, difference in building height, with highway and heavy traffic absent), they show reasonable agreement with temperature variations along the urban canyon. One thing to be noted is that SVF here refers to the areal average of SVF value over an entire terrain. It does show a great extend of increase in correlating with temperature difference, proving that areal SVF can be used as a factor that reflects unban density more comprehensively.

3) There are also noises in the correlation, vegetation database can also be included to decrease error caused by software method.

4) With planning concern, accurate correlation such as Tdiff = a*SVF +b may not be that necessary. Our understanding is that classification and zoning of SVF values as an implication for temperature differences may be a more comprehensive support tool for planners. This idea is also welcomed by the planners we work with.

5) The GIS approach opens up new horizon for large scale urban geometry simulation. Integration with other whole building simulation methods such as CFD (computational fluid dynamics) is expected to provide more comprehensive understanding of the relation between climatic data and building form.

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