The influence of tree crowns on effective urban thermal anisotropy

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Abstract

A sensor view model is modified to include trees using a gap probability approach to estimate foliage view factors and an energy budget model for leaf surface temperatures (SUM_{VEG}). The model is found to compare well with airborne thermal infrared (TIR) surface temperature measurements. SUM_{VEG} is used to investigate the influence of trees on thermal anisotropy for narrow field-of-view TIR remote sensors over treed residential urban surfaces. Tests on regularly-spaced arrays of cubes on March 28 and June 21 at latitudes of 47.6°N and 25.8°N show that trees both decrease and increase anisotropy as a function of tree crown plan fraction (λ_V) and building plan fraction (λ_P). In compact geometries (~λ_P>0.25), anisotropy tends to decrease with λ_V, with the opposite in open geometries, though trees taller than building height cause anisotropy to increase with λ_V at all λ_P. These results help better understand and potentially correct urban thermal anisotropy.

Keywords: Urban climate, Urban surface temperature, Thermal anisotropy, Urban vegetation, Thermal remote sensing, Sensor view model

1. Introduction

Accurate surface temperatures are important for applications such as modelling the urban energy balance, determining the internal climates of buildings, and studying urban dweller thermal comfort [8]. However, at the land-use scale, urban and many natural surfaces consist of a three-dimensional (3D) assemblage of surface elements. This 3D surface geometry, combined with differential patterns of solar insolation which generate micro-scale variations in surface temperature, create an angular variation in remotely-detected temperature. Angular dependence of brightness temperature above composite urban surfaces has been termed *effective thermal anisotropy* to distinguish it from the potential non-lambertian radiant emission from individual component surfaces [6].

Thermal anisotropy has been both directly observed (e.g. [6]; [7]; [2]) and modelled (e.g. [3]; [9]) for a range of urban geometries and meteorological conditions. However, there has been no attempt to quantify the influence of urban tree vegetation despite their influence on micro-scale shading patterns and expected influence on thermal anisotropy magnitude. The objectives of this research were to (1) incorporate trees into the surface-sensor-sun urban model (SUM; [5]) and (2) use the model to investigate the influence of trees on thermal anisotropy over vegetated urban domains.

2. Model Theory and Evaluation

2.1 Model Theory

In SUM the surface configuration is described with a four-dimensional array containing three spatial co-ordinates (x, y, z) and a fourth dimension that contains surface property descriptors for each spatial co-ordinate [5]. These arrays describe a surface consisting of equal sized patches that can replicate the three-dimensional geometry of urban surface structures.

Based on solar geometry, SUM uses ray tracing techniques to determine the shading patterns within the modelled domain. Using solid angle geometry, SUM calculates the view factor occupied by each surface patch within a sensor IFOV, projected onto the surface.

Trees are represented in SUM_{VEG} as rectangular block structures comprised of patches containing a turbid media. In its current configuration, all trees have identical geometrical and biophysical dimensions and no branch architecture in order to minimize computational requirements and model run-time. Similar to buildings, trees consist of patches described using four dimensions where the non-spatial dimension holds tree and leaf biophysical descriptors. For the simplified nature of trees in SUM_{VEG}, four primary biophysical descriptors are used to calculate a statistical density for the turbid media: foliage area density (μ_L), leaf angle distribution, clumping index (Ω_C), and foliage element width (f_w).

In SUM_{VEG}, the simplifying assumption is made that the portion of view factor occupied by tree crown patch *j* to sensor position *di* is equal to the projection of tree crown foliage upon the underlying surface. SUM_{VEG} does not explicitly calculate the view factor occupied by tree crown foliage within the sensor IFOV. Instead, SUM_{VEG} first computes the view factors for the urban surface devoid of tree crowns elements. Following this, tree crown structures are added to the model domain and ray-tracing is used to isolate surface patches within the array that are partially obscured from sensor view by tree crown foliage. Tree crown patch biophysical parameters are used to calculate the probability of gap along lines through tree crown envelopes based on a modified Beer-Lambert-Bouguer Law approach. SUM_{VEG} uses the probability of gap within tree crowns to weight view factors and determine the relative contribution of tree crowns and surfaces partially obscured by tree crowns to the remotely-detected surface temperature (T_S).

2.2 Model Evaluation

SUM_{VEG} is evaluated using remotely-detected surface brightness temperatures measured using an airborne thermal remote sensor over the Sunset residential neighbourhood of Vancouver, B.C. Several airborne TIR frames obtained on August 17, 1992 during the observational campaign of [6] were chosen such that four frames from nadir and two from each cardinal viewing direction (N-S-W-E) at 45° off-nadir are included in the evaluation (3 flights x 12 frames/flight = 36 frames in total).

The Sunset neighbourhood surface was digitized from VanMap orthophoto imagery and used to create GIS layers of building footprints and heights, as well as street and alley surfaces. Following digitization of all building footprint, street, and alley surfaces, the residual ground level surface is categorized as grass vegetation. Building heights are determined using Google Street View© to estimate the height in number of stories (to the nearest 0.25 stories) for all houses within the study domain, with 1 story = 3.05 m. VanMap orthophotos are also used to generate a GIS layer of points to indicate the location of tree crowns within the Sunset domain, taking care to avoid low level shrub vegetation.

Temperatures for horizontal facets are extracted from TIR images acquired via helicopter-mounted TIR cameras. Temperatures for vertical surface components are extracted from remotely-detected temperatures obtained via truck-mounted infrared thermometers (IRT) during traverses through the residential streets performed concurrently with the airborne flights. Sunlit and shaded foliage kinetic surface temperatures are calculated using the SUM_{VEG} leaf temperature model based on the humid operative temperature [1] and using hourly forcing data provided by the Sunset Urban Climate Research Tower (49.23°N, 123.08°W).

Table [1] presents the results of a number of statistical tests, recommended by [10], examining the ability of SUM_{VEG} to replicate remotely-detected directional brightness temperatures, and directional differences, of the Sunset residential surface. SUM_{VEG} estimates generally correspond well with measurements and present significant reduction of error over the SUM model when estimating remotely-detected directional brightness temperatures over the Sunset residential neighbourhood. The reduction in correlation coefficient and slight increase in unsystematic root mean square error is probably due to the additional complexity resulting from the inclusion of tree crowns. For all frames used in the SUM_{VEG} evaluation, the inclusion of tree crowns, on average, decreases T_S by 3.23°C. With a *MAE* (overestimation) of 3.56°C in the absence of tree crowns, the inclusion of trees into SUM_{VEG} substantially increases the accuracy of modelled T_S estimates.

Table 1: Validation statistics for the SUM_{VEG} evaluation with Sunset airborne T_S and ΔT_S.

Statistic	T_S		ΔT_S
	SUM_{VEG}	SUM	SUM_{VEG}
RMSE	1.06	3.65	1.06
# **$RMSE_S$**	0.41	3.57	0.49
$RMSE_U$	0.98	0.77	0.83
MAE	0.87	3.56	0.88
b (*slope*)	0.95	1.05	1.00
a (*intercept*)	1.93	1.92	0.54
d (*index of agreement*)	0.99	0.88	0.97
r^2	0.96	0.98	0.92
n (*# of images*)		36	

$RMSE_S$ and $RMSE_U$ represent the systematic and unsystematic RMSE, respectively

3 Model Simulations

3.1 Sunset Case Study

The same domain used to evaluate SUM_{VEG} was used as a case study to investigate the influence of trees on thermal anisotropy for the Sunset Residential Neighbourhood at 0900 and 1200LMST on August 17, 1992. Tree height, trunk height, and crown radius values of 8m, 3m, and 3m are used based on observations reported for the Sunset neighbourhood by [6]. It is also assumed, in absence of detailed measurements of leaf angular distributions, that the tree crowns within this domain exhibit a spherical distribution of leaf angles as this offers a close fit to many actual tree crown species [1]. Visual approximations of μ_L for tree crowns within the Sunset northwest sub-domain made by [6] are used to estimate a representative μ_L of 2.4m^{-1}, assumed to be randomly distributed within the crown envelopes.

3.2 Anisotropy and Vegetated Urban Domains

SUM_{VEG} is used to investigate the sensitivity of maximum daytime thermal anisotropy (Λ) to a range of treed residential urban geometries and tree crown biophysical parameters. These tests use a regular urban geometry characterized by a repeating array of square footprint, block structure buildings separated by equal width streets. Tree crowns line the edge of streets along the building length in order to represent a treed urban surface common to many North American cities. Simulations are performed using forcing conditions and solar geometry for the Basel-Sperrstrasse canyon site in Switzerland (47.57°N, 7.58°E) on March 28th and June 21st and the Miami International Airport, Florida (25.79°N, 80.29°W) on June 21st for a number of treed urban geometries. Hourly forcing data are available for both areas and indicate that both dates are characterized by relatively minimal cloud cover. These locations are chosen in order to cover a range of latitudes–and solar zenith angles–upon which the influence of trees on thermal anisotropy is examined.

The current investigation uses three λ_P that are chosen to broadly represent the range used by [9] which corresponds to typical values for real cities: 0.14, 0.28, and 0.41 with corresponding canyon aspect ratios of 0.53, 1.00, and 1.67, respectively. Mean sunlit and shaded facet temperatures for built components are calculated using TUF-3D while leaf temperatures are estimated using the SUM_{VEG} internal leaf temperature model. Since vegetation is not embedded in TUF-3D, built facet temperatures do not account for the interaction with tree canopies. Research is currently underway on a vegetated TUF-3D that could allow for a direct coupling with SUM_{VEG} [4]. Given the paucity of vegetated micro-scale energy budget models, SUM_{VEG} includes a simple routine to parameterize temperatures for surface patches shaded from the sun by vegetation based on the probability of gap of light radiation through the canopy.

For simplicity, buildings are rectangular to maintain a building height to building length ratio (*BH/BL*) and building length to building width ratio equal to unity. Since the *BH/BL* ratio is held constant for all λ_P values, this can be thought of as a single urban land use (residential) where increasing λ_P indicates increasingly dense urban geometries. These scenarios are chosen, rather than a more diverse range of urban forms for two reasons: 1) the coupled SUM + TUF-3D has already been used to extensively investigate the influence of urban form on effective thermal anisotropy (e.g. [9]), and 2) the current geometrical configurations, which can be envisioned as a residential surface with a range of building densities, are expected to present the most obvious influence of tree crown vegetation on thermal anisotropy magnitude.

The influence of tree crowns is investigated based on the total cover of tree crowns (λ_V) rather than on some other tree crown metric since λ_V, as opposed to a single structural dimension, is expected to have a stronger correlation with the magnitude of Λ. For the current investigation five discrete λ_V are simulated, corresponding approximately to 0.0, 0.06, 0.13, 0.25, and 0.32.

When testing the influence of tree crowns on Λ magnitude in a range of treed urban forms, all biophysical parameters are held constant. Foliage elements are assumed to be randomly distributed in crown volumes with a spherical distribution of leaf inclination angles. The influence of clumping, leaf width, and foliage density on sensitivity of SUM_{VEG} modelled Λ is investigated for a number of the treed urban geometries (not shown).

4 Simulation Results

4.1 Sunset Case Study

The Sunset residential neighbourhood is a relatively open geometry ($\lambda_P = 0.10$) with extensive ground level vegetation mostly in the form of grassed lawns. The addition of trees to the Sunset surface reduces the remotely-detected brightness temperature, relative to the treeless surface, at every sensor view angle (Figure [1]). This is due to the fact that modelled sunlit and shaded foliage temperatures are lower than built facet temperatures except for shaded street surfaces, which are slightly lower in temperature than shaded foliage.

The inclusion of a hot spot model to estimate sunlit and shaded foliage proportions as a function of solar and sensor position results in an unequal distribution of sunlit and shaded foliage proportions; this causes a dependence of the view factor occupied by sunlit and shaded foliage on sensor view angle. At the hot spot, the view factor occupied by foliage is predominantly sunlit foliage. The view factor occupied by foliage is predominantly shaded at sensor view angles sufficiently far from the hot spot. As a result of this unequal view factor occupied by sunlit and shaded foliage across a distribution of sensor view angles, the 'cooling' influence of trees on T_S varies as a function of sensor view angle. At the hot spot, with the IFOV dominated by sunlit foliage, directional brightness temperatures experience the lowest reduction with the addition of trees. Brightness temperatures exhibit the largest reduction at sensor view angles far from the hot spot where cooler shaded foliage dominates the sensor IFOV.

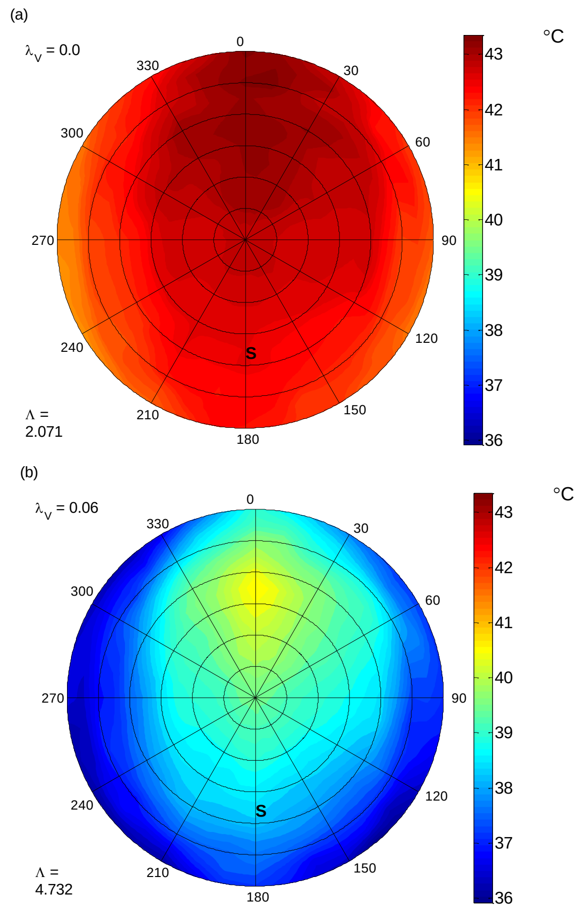

Figure 1: Polar co-ordinate plots of T_S at 1200 LMST for the Sunset surface (b) with and (a) without tree crowns.'S' indicates solar coordinate.

Several pertinent findings arise from the Sunset case study results:

a) Tree crowns, by presenting a surface cooler than the built components and by shading of sunlit surfaces, decrease T_S at every sensor view angle. However, due to the hot spot effect generating differences in the view factor occupied by sunlit and shaded foliage with a remote sensor IFOV, the influence of tree crowns varies as a function of sensor view position.

b) For the relatively open Sunset urban geometry, even a relatively low cover of tree crowns ($\lambda_V \approx 0.06$) increases Λ by generating contrasts in surface temperature between opposing sensor view angles. In particular the relative dominance of view factor occupied by shaded foliage at oblique θ_V results in an enhanced 'cooling' influence of tree crowns on the minimum T_S, relative to the sunlit foliage dominated IFOV for the sensor view angle corresponding to the maximum T_S (i.e. at the hot spot).

c) The difference in Λ resulting from the use of the treed and treeless SUMVEG model is large with respect to the actual magnitude of thermal anisotropy. For example, the addition of trees in the northwest sub-domain at 1200LMST on August 17 increases Λ by approximately 2.7°C, which constitutes approximately 58% of the total Λ magnitude (4.7°C). This indicates the important influence of tree crown vegetation on thermal anisotropy and supports the use of SUMVEG, as opposed to SUM, for treed urban surfaces.

4.2 Anisotropy and Vegetated Urban Domains

Figure [2] presents a surface plot of thermal anisotropy magnitude as a function of λ_P and λ_V for latitude 47.6°N on June 21. Each surface plot is interpolated based on 3 λ_P x 5 λ_V = 15 street orientation averaged simulations and each (λ_P,λ_V) co-ordinate corresponds to a narrow IFOV (12°) remote sensor viewing a treed urban surface over a range of sensor view angles: off-nadir (θ_V) of 0° to 60° in 5° increments and azimuth (φ_V) (relative to North = 0°) of 0° to 360° in 10° increments (481 sensor view angles).

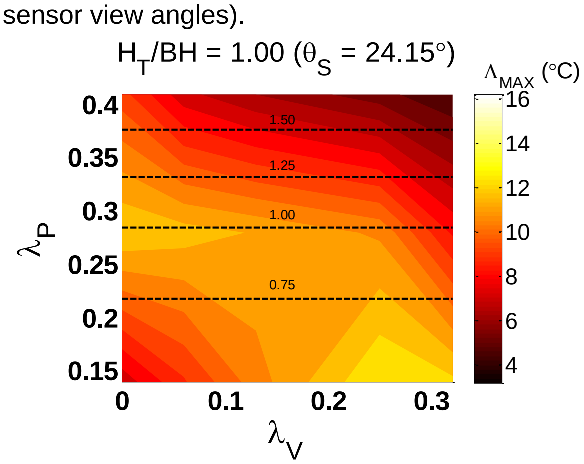

Figure 2: Surface plot of Λ for June 21 at 1200 LMST using forcing conditions and solar geometry from Basel-Sperrstrasse. Dashed lines indicate lines of equal BH/SW.

For simulations on June 21 and March 28 at latitude 47.6°N, the inclusion of tree crowns tends to shift the maximum Λ to lower λ_P as a function of λ_V. For example, in the surface plot in Figure [2], at λ_V = 0, Λ is approximately 11.6°C for a surface with λ_P = 0.28. Increasing the cover of tree crowns while maintaining λ_P = 0.28 has two repercussions: 1) the magnitude of Λ decreases with increasing λ_V, and 2) the λ_P corresponding to the maximum Λ decreases with increasing λ_V. The latter is found in all surface plots for June 21 and March 28 at all simulation times (0800, 1000, and 1200LMST) and tree height to building height (H_T/BH) ratios for both latitudes investigated (25.8°N and 47.6°N).

The influence of λ_V depends on λ_P, H_T/BH ratio, and solar angle. There tends to be an inflection point (range) corresponding to moderate building plan fractions (λ_P≈0.25−0.30) and *BH/SW* = 1.0. For λ_P values above this range, Λ tends to decrease with increasing λ_V while, for surfaces with λ_P fractions below this range, Λ tends to increase with increasing λ_V. This relationship is most evident with high solar elevation angles and does not hold for simulations with H_T/BH>1.0.

This λ_P inflection range tends to shift to lower λ_P with increasing λ_V and with increasing solar zenith angle (θ_S). There is also generally a broad range of λ_P and λ_V with relatively minimal change in Λ (Figure [2]). This region is usually located at low to moderate λ_P (~0.0–0.25) while the λ_V range shifts to higher λ_V with decreasing θ_S. The Sunset case study showed that, in relatively open geometries, Λ increases with the inclusion of tree crowns due mainly to the 'cooling' influence of shaded foliage at oblique θ_V. This broad area of relatively minimal change in Λ probably corresponds to an optimal balance between the 'cooling' influence of the tree canopy at oblique θ_V and at the hot spot. For λ_P below this range, the relatively open canyon results in a substantial view factor occupied by shaded foliage at oblique θ_V which enhances the 'cooling' effect at these θ_V. Conversely, in compact geometries, the narrow canyon limits the view factor occupied by shaded foliage at oblique θ_V.

For simulations with λ_P below the inflection range there is a maximum value effect evident whereby initial increases in λ_V result in an increase in Λ until a critical value of λ_V is reached after which subsequent increases cause a reduction in modelled Λ. This critical value results from the 'saturation' of the sensor IFOV with tree crown foliage which reduces the contrast between opposing sensor view angles. This value is dependent upon urban form; the λ_V critical value decreases with increasing λ_P. For open geometries, this generally corresponds to moderate λ_V ratios of 0.15–0.25. For compact geometries, this critical value is found at λ_V=0.0. In other words, maximum Λ occurs in the absence of tree crowns.

In compact geometries, as a result of the relatively narrow street canyons, the inclusion of tree crowns essentially 'fills' the urban canyon with tree crown foliage. This reduces the substantial contrast in T_S between opposing sensor view angles, such as those between normally sunlit south-facing walls and shaded north-facing walls (in the northern hemisphere). The λ_V 'critical value' varies with λ_P since λ_P controls the relative canyon size and subsequently the amount of canopy cover needed to 'fill' the canyon.

5 Conclusions

These results indicate the importance of accounting for vegetation when modelling thermal anisotropy over urban domains with significant vegetated cover. Inclusion of tree crowns into SUM_{VEG} substantially improves its accuracy when estimating remotely-detected brightness surface temperatures, and hence thermal anisotropy magnitude, acquired from TIR images of a treed residential surface, relative to the non-vegetated SUM.

Tree crowns have the ability to both increase and decrease the magnitude of effective thermal anisotropy as a function of tree crown plan fraction, building plan fraction, and, to a lesser extent, solar path (i.e. date, time, and location). Tree crown foliage, with surface temperatures generally lower than built facets, reduce remotely-detected brightness surface temperatures at every sensor view angle. It is the unequal reduction of T_S across the range of sensor view angles that results in changes to the magnitude of Λ.

Given the relatively high fraction of tree canopy cover present in many urban centres, the inability of SUM to represent tree crown vegetation represents a significant model limitation. SUM_{VEG} extends the applicability of SUM to a more diverse range of urban geometries including often heavily vegetated residential neighbourhoods.

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