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The influence of tree crowns on urban thermal effective anisotropy

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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 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 ($\sim\lambda_P > 0.25$), anisotropy tends to decrease with λ_V, whereas in open geometries the relation is reversed. 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.

Symbols

BH/BL	Building height to width ratio
BH/SW	Canyon aspect ratio
f_b	Fraction of direct solar radiation
f_d	Fraction of diffuse solar radiation
f_{width}	Foliage element width, m
g_{vs}	Stomatal conductance of water vapour, mol m^{-2} s^{-1}
H_T/BH	Tree height to building height ratio
i, j	Patch index/number

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K_e	Elliptical extinction coefficient
LAD	Leaf angle distribution
L_j	Radiance for patch j, W sr^{-1} m^{-2}
L_{MAX_j}	Maximum radiance for patch j (sunlit), W sr^{-1} m^{-2}
L_{MIN_j}	Minimum radiance for patch j (shaded), W sr^{-1} m^{-2}
L_{S_j}	Sensor-detected radiance for patch j, W sr^{-1} m^{-2}
n	Total number of patches
P	Gap probability (solar direction)
P_b	Gap probability for direct solar radiation
P_d	Gap probability for diffuse solar radiation
P_T	Proportion of sunlit leaf elements
P_V	Gap probability (sensor direction)
S	Path length through tree crown (solar direction), m
S_V	Path length through tree crown (sensor direction), m
T_a	Air temperature, °C
$T_{B(\theta,\varphi)}$	Directional brightness temperature, °C
$T_{B_{MAX}}$	Maximum directional brightness temperature, °C
$T_{B_{MIN}}$	Minimum directional brightness temperature, °C
T_{lh}	Shaded leaf surface temperature, °C
T_{lS}	Sunlit leaf surface temperature, °C
YD	Day of year
z_S	Sensor height above the surface, m
Z_T	Proportion of shaded leaf elements
α_L	Leaf albedo
ε_L	Leaf emissivity
η	Street orientation, °
θ_S	Solar zenith angle, °
θ_V	Sensor off-nadir angle, °
λ_P	Building plan fraction
λ_V	Tree crown plan fraction
$\lambda_{V_{Crit}}$	Critical threshold tree crown plan fraction
Λ	Maximum effective anisotropy, °C
μ_L	Foliage area density, m^{-1}
φ_S	Solar azimuth angle, °
φ_V	Sensor azimuth angle, °
$\Psi_{di,j}$	View factor from patch j to sensor di
$\Psi_{di,jV}$	View factor for tree crown foliage
$\Psi_{di,jS}$	View factor for surface between foliage
$\Psi_{di,jVs}$	View factor for sunlit foliage
$\Psi_{di,jVh}$	View factor for shaded foliage
ϕ	Latitude, °
Ω_C	Clumping index

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 (Voogt and Oke, 2003). 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 a variation in remotely-detected directional brightness temperature with viewing angles ($T_{B(\theta,\varphi)}$). This directional dependence has been termed *effective thermal anisotropy* to distinguish it from the potential non-lambertian radiant emission from individual component surfaces (Voogt and Oke, 1998).

Effective thermal anisotropy presents a significant bias—on par with atmospheric influences—and potential source of error in urban surface temperatures obtained using passive thermal infrared (TIR) remote sensors. Roth et al. (1989) were the first to recognize the potential for directional variation in remotely-detected urban surface temperatures. They noted the potential for a disproportionate contribution of horizontal surfaces, and corresponding neglect of vertical surfaces, to remotely-detected radiance measurements obtained using a sensor at nadir.

The magnitude of effective thermal anisotropy over cities is large by day, with observed differences in directional brightness temperature in excess of 9 °C over downtown areas in Vancouver (Voogt and Oke,

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