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ScienceDirect
Remote Sensing of Environment 104 (2006) 226–237
Remote Sensing of Environment
www.elsevier.com/locate/rse

Longwave radiation flux from an urban canopy: Evaluation via measurements of directional radiometric temperature

Hirofumi Sugawara [a,*], Tamio Takamura [b]

[a] National Defense Academy of Japan, Japan
[b] Chiba University, Japan

Received 16 February 2005; received in revised form 21 January 2006; accepted 26 January 2006

Abstract

Longwave radiation flux, an important part of the surface heat budget, is generally represented by $\varepsilon\sigma T_r^4$, where ε is the surface emissivity, σ is the Stefan–Boltzmann constant, and T_r is the measured radiometric temperature. $\varepsilon\sigma T_r^4$ differs from hemispheric emission because the measured radiometric temperature is anisotropic for an uneven surface. This paper analyzes the anisotropy-related error in measurements of longwave radiation flux from a building canopy. The flux difference between $\varepsilon\sigma T_r^4$ and directly measured flux was up to 8% of the directly measured flux, which could be greater than the typical error in measurement of turbulent heat flux over a building canopy. The flux difference increased as the temperature variation within the urban street canyon increased, and also with increasing difference between the incident solar radiation of the building walls and street canyon floors (pavement, roads, ground surface). Theoretical calculations indicate that the flux difference is due to the structure of the building canopy and the temperature difference between the walls and canopy floors. A numerical model of a building canopy heat budget shows that the flux difference increases as the street canyon aspect ratio increases.

Keywords: Thermal hemispheric emission; Anisotropy; Urban canopy; Street canyon

1. Introduction

Remote sensing measurements are sensitive to the viewing geometry of the sensor. Upward surface radiation from an urban canopy is directionally variable due to local variations in areas of sunshine and shade. This directional variation can have a significant influence on estimates of sensible heat flux determined from radiometric temperature (e.g., Mahrt et al., 1997; Matsushima & Kondo, 1997; Suleiman & Crago, 2002; Troufleau et al., 1997). Estimation of longwave hemispherical emission, which is generally approximated as $\varepsilon\sigma T^4$, where ε is the surface emissivity and σ is the Stefan–Boltzmann constant, is also influenced by anisotropy in measured radiometric temperature. Otterman et al. (1995) described the errors involved in using directional radiometric temperature measurement to estimate longwave hemispheric emission from a vegetation canopy. The authors found that the viewing angle of the sensor can result in up to 10% error in hemispheric emission estimates. Many recent studies have reported a lack of energy balance closure, in which the sum of observed turbulent heat flux and subsurface conduction heat is less than the net radiation flux (e.g. Lee, 1998; Moore et al., 1996; Panin et al., 1998); the imbalance is as much as 20% of net radiation. Although spatial variation of net radiation is smaller than that of the other heat flux (Schmid et al., 1991), it is possible that the error related to the anisotropy of longwave emission is a key component of the imbalance problem.

The problem of emission anisotropy occurs for urban canopies as well as vegetation. Roth et al. (1989) described for urban areas how surface temperature estimated by remote sensing varies with sensor viewing geometry. Voogt and Oke (1998) measured the radiometric temperature in an urban canopy using a helicopter-mounted sensor. They showed that the surface temperature measured within an urban canopy varies by more than 9 °C with different sensor viewing geometries. Such large variations in estimated temperature produce

* Corresponding author. Department Earth and Ocean Sciences, National Defense Academy of Japan, 1-10-20 Hashirimizu Yokosuka, Kanagawa, Japan.
E-mail address: hiros@nda.ac.jp (H. Sugawara).

0034-4257/$ - see front matter
doi:10.1016/j.rse.2006.01.024

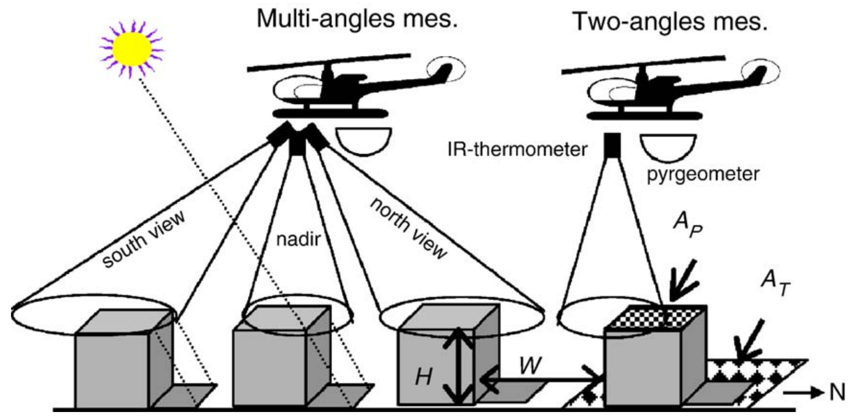

Fig. 1. Airborne sensor arrangements and the urban canopy structure. The roof area ratio λ_P is A_P/A_T, where A_P is the roof top area, and A_T is the total lot area. W is the average distance between buildings and H is the average building height. Two types of measurement were done, multi-angle measurements (left) and two-angles measurements (right).

correspondingly large variations in estimates of radiation flux. Kobayashi and Takamura (1994) demonstrated theoretically that the nadir-view sensor with a narrow field of view (FOV) produces errors of 0.5–1.5 K in estimated effective blackbody temperature when measuring longwave radiation flux, as the nadir sensor does not "see" walls. Soux et al. (2004) provided a summary of radiometric anisotropy in urban areas. Despite the concerns raised by the above studies, the radiometric anisotropy-related errors involved in evaluating longwave radiation flux over an urban canopy have not previously been discussed in terms of observational data as such measurements are difficult to obtain over an urban area. In addition, the basic characteristics of the flux error, including dependence on canopy structure and diurnal and seasonal variations, are still largely unknown. The current study addresses these problems using remote sensing data from an urban canopy, and discusses the process of estimating urban longwave radiation flux from radiometric temperature measurement.

Section 2 considers the theoretical difference between directly measured flux and calculated σT^4, in which T is radiometric temperature in a narrow FOV. Section 3 describes airborne observation methods, while Section 4 examines the ratio of directly measured flux to σT^4 for various times of day and different canopy structures. Section 5 presents a numerical model of the canopy heat budget that describes the influence of canopy structure on the evaluated flux σT^4. Finally, Section 6 contains a discussion of the methods for evaluating longwave hemispheric emission over an urban area.

2. Theoretical discussion

In this study, the canopy structure is parameterized by the roof area ratio λ_P and the aspect ratio of street canyon H/W (Fig. 1). The roof area ratio λ_P is taken to be the building base area A_P divided by the total lot area A_T, which includes the building base area. H is the average building height and W is the average distance between adjacent buildings. The parameters H, W, and A_p were calculated from an urban-planning database, and averaged over the sensor FOV.

Assuming isotropic emission and reflection of longwave radiation from roofs, walls and street canyon floors (ground surfaces, pavement, roads), the upward longwave radiation flux F_{global} from an urban canopy can be written as

$$F_{\mathrm{global}} = \lambda_p F_{\mathrm{roof}} + (1-\lambda_p)\{\psi_{\mathrm{FLR-SKY}} F_{\mathrm{floor}} + (1-\psi_{\mathrm{FLR-SKY}}) F_{\mathrm{wall}}\} \quad (1)$$

where F_{floor}, F_{roof}, and F_{wall} are the longwave radiation fluxes from floors, roofs, and walls respectively. F_{wall} is an average for walls of various orientations. F_{floor}, F_{roof}, and F_{wall} include both emission and reflection. Here, $\psi_{\text{FLR-SKY}}$ is the sky view factor from the center of the canyon floor, as described by (Johnson & Watson, 1984):

$$\psi_{\mathrm{FLR-SKY}} = \cos\left\{\tan^{-1}\left(\frac{H}{0.5W}\right)\right\} \quad (2)$$

Thus, $\psi_{\text{FLR-SKY}}$ is inversely proportional to H/W in an infinitely long urban street canyon. The nadir-view infrared thermometer housed on an aero- or space-platform cannot "see"

Table 1
Specifications of the onboard sensors

Type	Sensor	Wavelength [μm]	Total FOV (instantaneous FOV)	Response time	Accuracy
Nadir	Thermal imager, NEC-Sanei	8–13	25°×30° (0.1°×0.1°)*	0.05 s	0.5 °C
Off-nadir	Thermometer, MINOLTA	8–13	1°	0.5 s	0.5 °C
Flux	Pyrgeometer, Eppley	4–50	2π	2 s	**

*Pixel size.
**Temperature dependency is 2% and the linearity is 1%.