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Thermal remote sensing of urban climates

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Abstract

Thermal remote sensing has been used over urban areas to assess the urban heat island, to perform land cover classifications and as input for models of urban surface atmosphere exchange. Here, we review the use of thermal remote sensing in the study of urban climates, focusing primarily on the urban heat island effect and progress made towards answering the methodological questions posed by Roth et al. [International Journal of Remote Sensing 10 (1989) 1699]. The review demonstrates that while some progress has been made, the thermal remote sensing of urban areas has been slow to advance beyond qualitative description of thermal patterns and simple correlations. Part of the difficulty lies in the tendency to use qualitatively based land use data to describe the urban surface rather than the use of more fundamental surface descriptors. Advances in the application of thermal remote sensing to natural and agricultural surfaces suggest insight into possible methods to advance techniques and capabilities over urban areas. Improvements in the spatial and spectral resolution of current and next-generation satellite-based sensors, in more detailed surface representations of urban surfaces and in the availability of low cost, high resolution portable thermal scanners are expected to allow progress in the application of urban thermal remote sensing to the study of the climate of urban areas.

Keywords: Remote sensing; Urban climates; Rural

1. Introduction

The surface temperature is of prime importance to the study of urban climatology. It modulates the air temperature of the lowest layers of the urban atmosphere, is central to the energy balance of the surface, helps to determine the internal climates of buildings and affects the energy exchanges that affect the comfort of city dwellers. Surface and atmospheric modifications due to urbanization generally lead to a modified thermal climate that is warmer than the surrounding non-urbanized areas, particularly at night. This phenomenon is the urban heat island (UHI). UHIs have long been studied by ground-based observations taken from fixed thermometer networks or by traverses with thermometers mounted on vehicles. With the advent of thermal remote sensing technology, remote observation of UHIs became possible using satellite and aircraft platforms and has provided new avenues for the observation of UHIs and the study of their causation through the combination of thermal remote sensing and urban micrometeorology. In some ways, it has also complicated definitions of urban heat islands and interpretations of the resulting observations. The present review is prompted, in part, by the appearance of new satellite-based sensors and the increasingly wide-spread use of infrared sensors in the study of surface climates in general. This has also increased opportunities for studying the UHI and urban-modified climates more generally.

We begin by emphasizing the importance of using proper definitions in the application of thermal remote sensing to the study of urban climates. This is followed by a brief survey of literature appearing since Roth, Oke, and Emery (1989) that highlights several recurrent themes. It then re-examines the methodological questions raised by Roth et al. (1989) concerning problems involved in the application of remotely sensed thermal imagery to the study of urban climates. It makes comment on the progress made on these points by research conducted over urban and other surfaces. The review concludes by commenting on future prospects for progress in answering these questions.

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1.1. Thermal remote sensing of urban surfaces: definitions

Proper definition of remotely sensed variables is important in order to understand precisely the information content of remotely sensed quantities and how they relate to actual surface properties. Thermal remote sensing of urban surface temperatures is a special case of observing land surface temperature which varies in response to the surface energy balance. The resultant surface temperature incorporates the effects of surface radiative and thermodynamic properties, including surface moisture, thermal admittance and surface emissivity, the radiative input at the surface from the sun and atmosphere, and the effects of the near-surface atmosphere and its relation to turbulent transfer from the surface.

Becker and Li (1995), Norman and Becker (1995), Norman, Divakarla, and Goel (1995) and Prata, Caselles, Coll, and Sobrino (1995) have carefully examined the definitions associated with thermal remote sensing of land surfaces, and the reader is referred to them for details. Here, we use the term *directional brightness temperature* to describe the temperature derived from the inversion of Planck's law for a thermal sensor operating in a given waveband. Directional brightness temperatures relate the detector-received radiance to a temperature, without consideration of any processes influencing the received radiation along the path from the

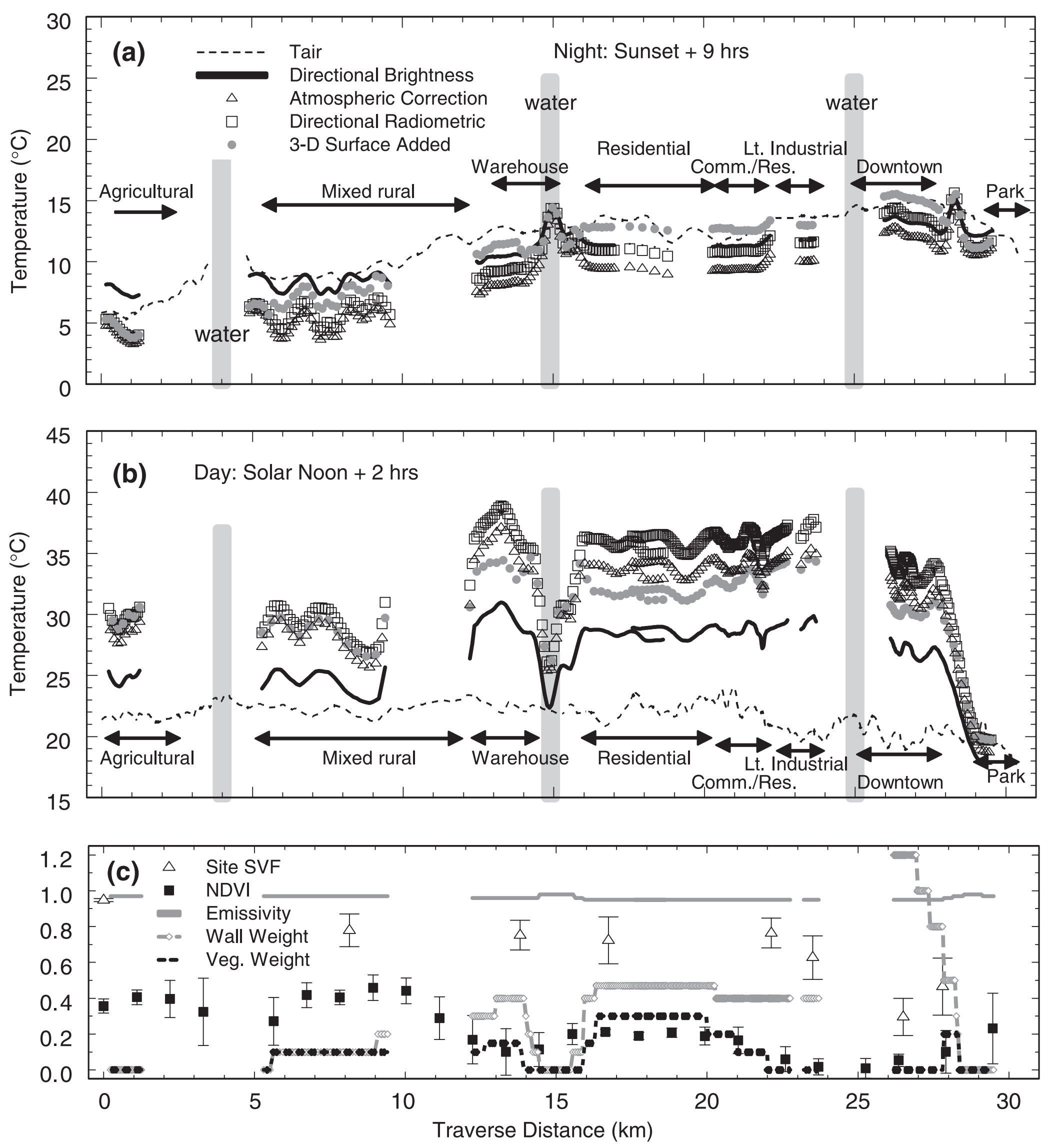

Fig. 1. Heat island transect across Vancouver BC for (a) nighttime (YD 238 1992; 9 h after sunset) and (b) daytime (YD 237 1992; 2 h following solar noon) showing canopy level air temperature and remotely sensed surface temperature with various levels of correction applied. The plotted results represent values normalized to a single time. Symbols are reduced to every third point to improve readability. The automobile traverse passed through a tunnel (~ 4 km) and over bridges (~ 15 and 25 km) along the route. Panel (c) is the sky view factor for sites along the traverse route as determined from digital fish-eye lens photographs, NDVI derived from AVHRR imagery during the traverse, emissivities applied during the conversion to obtain directional radiometric temperatures, and wall and vegetation area weightings applied to take into account "unseen" surfaces from the nadir viewing position.

surface through the atmosphere to the sensor (with appropriate sensor offsets and gains applied). *Directional radiometric temperatures* are those that have been corrected for atmospheric transmission and surface emissivity effects for a particular sensor-viewing angle. These definitions apply most strictly to a homogeneous surface, but techniques are available to extend their use to heterogeneous surfaces (Becker & Li, 1995; Norman & Becker, 1995).

Heat islands can be defined for different layers of the urban atmosphere, and for various surfaces and even the subsurface (Oke, 1995; Voogt & Oke, 1997). It is important to distinguish between these different heat islands as their underlying mechanisms are different (Oke, 1982; Roth et al., 1989). Unless otherwise indicated, an urban heat island refers to the excess warmth of the urban atmosphere compared to the non-urbanized surroundings. Atmospheric heat islands are best expressed under calm and clear conditions at night when radiative cooling differences are maximized between urban and surrounding rural locations (e.g. Fig. 1a).

Atmospheric heat islands may be defined for the urban canopy layer (UCL), that layer of the urban atmosphere extending upwards from the surface to approximately mean building height, and the urban boundary layer (UBL), that layer above the UCL that is influenced by the underlying urban surface. Canopy layer UHI are typically detected by in situ sensors at standard (screen-level) meteorological height or from traverses of vehicle-mounted sensors, such as that shown in Fig. 2. UBL heat island observations are made from more specialized sensor platforms such as tall towers, radiosonde or tethered balloon flights, or from aircraft-mounted instruments. These direct, in situ measurements require radiation shielding and aspiration to give representative measurements and their setting relative to surrounding features is important.

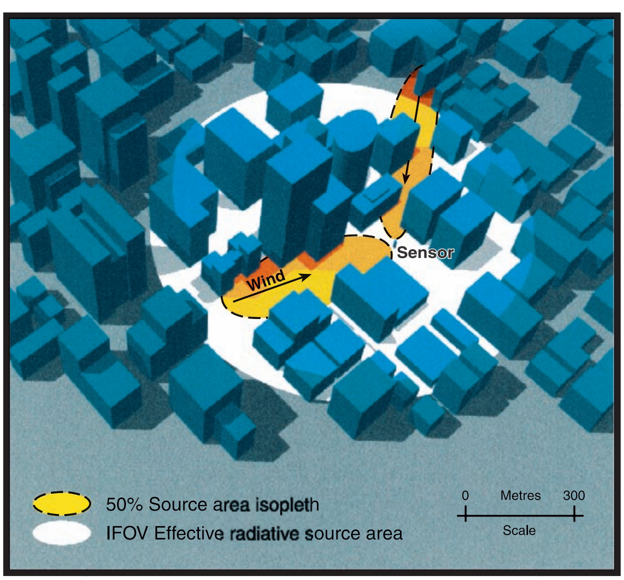

Fig. 2. Conceptual source areas. The Instantaneous Field Of View (IFOV, geometrically derived) defines the radiative source area for an aircraft or satellite-based thermal remote sensor viewing an urban surface. Source areas of a scalar, such as air temperature, for a sensor S located within the urban canopy layer are indicated by the hatched areas. Two different approximate scalar source areas are shown to illustrate that their location and size changes with wind direction and atmospheric stability; the precise shape of these source areas is approximate due to the complexities of flow within the UCL.

Measurements of atmospheric fluxes and scalar quantities such as air temperature are influenced by *turbulent* or *scalar source areas* that lie on the surface upwind of the measurement site. The shapes of these areas are determined by the sensor height and characteristics of atmospheric turbulence and stability (Fig. 2). They may be defined in a probabilistic sense using models (e.g. Schmid, 1997). Most current source area models apply to sensors positioned well above the surface roughness elements; the source areas of sensors located within the UCL are less well known due to the complexities of within canopy flows and are the subject of current research.

On the other hand, thermal remote sensors observe the *surface urban heat island* (SUHI), or, more specifically they 'see' the spatial patterns of upwelling thermal radiance received by the remote sensor (most often directional radiometric temperatures or directional brightness temperatures corrected only for atmospheric transmission). The *effective radiometric source area* for a remote thermal measurement is the instantaneous field of view (IFOV) of the sensor projected onto the surface. This geometrically defined source area is significantly different than the source areas of turbulent atmospheric fluxes and scalars (Fig. 2). The actual combination of surfaces viewed within the effective radiometric source area depends on the sensor viewing geometry and surface structure; a significant portion of the complete urban surface may not be viewed due to the three-dimensional structure of the surface.

In contrast to the direct in situ measurements made of atmospheric heat islands, the remotely sensed SUHI is an indirect measurement requiring consideration of the intervening atmosphere and the surface radiative properties that influence the emission and reflection of radiation within the spectral wavelengths detected by the sensor. Fig. 1 shows the surface temperatures along a cross-section of Vancouver, BC at each stage of the correction process. Observations were made from an airborne thermal scanner (8–14 μm) with a 12° FOV, at an altitude of approximately 2100 m (day) and 1500 m (night), yielding imaged areas on the ground of 450×450 m–320×320 m for which the mean temperatures are displayed. The original measured signal, converted to a temperature is the directional brightness temperature. The second stage is to apply correction for atmospheric effects. This is accomplished in the case study using locally launched balloon soundings of pressure, temperature and humidity as input to the LOWTRAN 7 atmospheric radiative transfer model (Kneizys et al., 1988) to estimate the atmospheric transmission and emission in the path between the sensor and the surface. Thirdly, the directional radiometric temperature series is calculated using estimates of the down-welling radiance derived from LOWTRAN and an estimate of the emissivity of the surface materials; varying from 0.97 (0.98 when dew was noted) for the vegetated agricultural surfaces to 0.95 for more highly urbanized surfaces (Fig. 1c). Finally, a crude correction is added to account for surfaces *not* viewed by the remote sensor, thereby incorporating the three-dimensional roughness of the surface (Fig. 1c; wall and vegetation weightings). Further details are provided in the section How do sensor detected radiant temperatures relate to the actual urban surface temperature? This illustration shows how significant such corrections can be. Indeed, if they are not applied, or are incorrectly estimated, it is possible to alter interpretations (e.g. the magnitude of the SUHI) or miscalculate derived quantities (e.g. the surface–air turbulent fluxes; note the change in the strength of the surface–air temperature differences in Fig. 1). It is sobering to realize that these corrections are relatively crude and can be expected to change as our knowledge of urban radiation properties and exchanges improves.

2. Literature review

The first SUHI observations (from satellite-based sensors) were reported by Rao (1972). Since then, a variety of sensor-platform combinations (satellite, aircraft, ground-based) have been used to make remote observations of the SUHI, or of urban surface temperatures that contribute to SUHI over a range of scales. Table 1 lists studies, since the review of Roth et al. (1989), that have used remote sensing to examine urban thermal climates. Gallo, Tarpley, McNab, and Karl (1995) also review procedures and prospects for satellite identification of urban heat islands.

The research in Table 1 has addressed several main themes. First, many studies have used thermal remote sensing to examine the spatial structure of urban thermal patterns and their relation to urban surface characteristics. This type of research dates back to the time of Rao's (1972) study. Satellite-based studies have continued to use AVHRR or Landsat thermal imagery combined with independent land use (description of urban activities occurring on the land surface), or sometimes land cover maps (with more specific description of the types of materials or structure present) to assess the spatial patterns of directional brightness or radiometric surface temperature (Balling & Brazel, 1988; Carnahan & Larson, 1990; Lougeay, Brazel, & Hubble, 1996). Multispectral techniques are now more frequently used to perform land use or land cover assessments at the same time as the thermal imagery is obtained (Aniello, Morgan, Busbey, & Newland, 1995; Dousset, 1991; Gallo & Owen, 1998; Lougeay et al., 1996; Nichol, 1996). High spatial resolution imagery obtained primarily from airborne remote sensing has been used to assess the thermal behaviour of urban surfaces in relation to surface characteristics such as sky view factors (Eliasson, 1992), surface materials (Ben-Dor & Saaroni, 1997; Quattrochi & Ridd, 1994) or NDVI (Lo, Quattrochi, & Luvall, 1997). With increasing sensor resolution and low-altitude flights, it is possible to extract temperatures from specific urban surfaces for analysis (Quattrochi & Ridd, 1994; Shoshany, Aminov, & Goldreich, 1994) or use in models (Iino & Hoyano, 1996; Voogt & Grimmond, 2000). A modelling study relevant to the study of remotely sensed urban surface temperatures and the SUHI is the surface heat island model (SHIM) presented by Johnson et al. (1991) that was used by Oke, Johnson, Steyn and Watson (1991) to evaluate proposed mechanisms for the genesis of the heat island. The SHIM model results underscore the importance of surface geometry and surface thermal properties (especially thermal admittance) in the creation of the SUHI and the importance of assessing these parameters in both the urban *and* rural environments. Some recent work has begun to address issues related to the three-dimensional roughness of cities through combination of ground-based and remotely sensed directional radiometric temperatures to generate more areally representative urban radiometric temperature estimates (Iino & Hoyano, 1996; Nichol, 1998; Voogt, 2000; Voogt & Oke, 1997). These combine thermal remote sensing with detailed urban surface morphology databases to assess the directional effects inherent in directional radiometric temperature observations made over urban areas (Voogt & Oke, 1998; Voogt & Soux, 2000).

The second theme found in the studies of Table 1 is the application of thermal remote sensing to the study of urban surface energy balances. This is accomplished by coupling urban climate models of the urban atmosphere with remotely sensed observations. The most frequently applied approach has been that of Carlson, Dodd, Benjamin, and Cooper (1981). This approach couples remotely sensed measurements of temperature with a 1-D atmospheric model to estimate surface energy balance fluxes and estimates of surface properties such as thermal admittance and surface moisture availability based on regression equations relating atmospheric model output versus remotely observed surface brightness temperature (corrected for atmospheric influences). The most recent application of this approach was to the city of Atlanta by Hafner and Kidder (1999) wherein a more detailed 3-D numerical model of the atmosphere was used. Thermal data, as well as information from other spectral bands, notably short-wave reflectance, to model surface absorption of short-wave radiation and NDVI to help parameterize the ground heat flux, have also been used (Kim, 1992; Parlow, 1999). Another method relating NDVI and directional brightness temperature has been used to study urban climate modifications, and to monitor changes in climate resulting from expansion of urban areas (Carlson & Sanchez-Azofeifa, 1999; Owen, Carlson, & Gillies, 1998). Bulk heat transfer approaches based on the use of remotely sensed directional radiometric temperatures, used extensively over agricultural and vegetated surfaces, have also been applied to urban areas (Voogt & Grimmond, 2000)

Table 1
Studies that have applied thermal remote sensing to the study of urban climates

Study	Platform: sensor	Application
Balling and Brazel (1988)	Sat: AVHRR	Relation between surface temperature patterns and land use and day-to-day variability of spatial patterns.
Dousset (1989)	Sat: AVHRR	Surface and air temperature relationships over an urban area.
Henry et al. (1989)	Sat: HCMM	Urban heat island analysis using remote sensing, ground observations and modelling.
Carnahan and Larson (1990)	Sat: Landsat TM	Urban–rural heating and cooling differences.
Caselles et al. (1991)	Sat: AVHRR	Satellite and ground-based heat island analysis.
Dousset (1991)	Sat: AVHRR, SPOT	Multispectral classification of urban land use areas and their relation to surface temperature.
Johnson et al. (1991)	Ground-based IRT	Surface urban heat island model.
Eliasson (1992)	Ac: AGEMA	Correlation between ground surface temperature and sky view factor.
Kim (1992)	Sat: Landsat TM	Energy balance modelling of an urban area.
Stoll and Brazel (1992)	Aircraft, Ground-based/IRT	Detailed assessment of surface and air temperature relations for different urban surface types.
Gallo et al. (1993a, 1993b)	Sat: AVHRR	Use of NDVI to assess the urban heat island.
Lee (1993)	Sat: AVHRR	Air and surface heat island assessment of Korean cities in relation to urban development.
Johnson et al. (1994)	Sat: TOVS	Estimation of rural air temperatures from satellite sounding data for deriving urban air temperature bias.
Quattrochi and Ridd (1994)	Ac: TIMS	Day and nighttime thermal response of individual urban surface types.
Shoshany et al. (1994)	Ac: Thermal Scanner	Extraction of roof top temperatures for heat island analysis.
Aniello et al. (1995)	Sat: Landsat TM, MSS	Spatial distribution of urban surface temperatures and tree cover.
Epperson et al. (1995)	Sat: AVHRR, DMSP	Estimating urban air temperature bias using NDVI and nighttime light data.
Gallo et al. (1995)	Sat: AVHRR	Review of procedures and future prospects for satellite assessment of urban heat island effects.
Gallo and Tarpley (1996)	Sat: AVHRR	Effect of compositing on the use of NDVI for assessing heat island effect.
Iino and Hoyano (1996)	Ac: MSS	Urban energy balance modelling using remote sensing and GIS databases.
Lougeay et al. (1996)	Sat: Landsat TM	Temperature patterns associated with land use and land use change.
Nichol (1996)	Sat: Landsat TM	Spatial patterns of surface temperature in relation to urban morphology.
Ben-Dor and Saaroni (1997)	Ac: TIrS	Simultaneous surface and air temperature heat island analysis.
Lo et al. (1997)	Ac: ATLAS	Relation of thermal data to land cover and NDVI.
Voogt and Oke (1997)	Ac: AGEMA	Creation of areally representative urban surface temperatures.
Gallo and Owen (1998)	Sat: AVHRR, DSMP/ Landsat MSS	Multispectral identification of urban areas for estimating heat island bias in large scale temperature records.
Nichol (1998)	Sat: Landsat TM	Incorporation of wall surface temperatures with remote sensing to create three-dimensional representation of urban temperatures.
Owen et al. (1998)	Sat: AVHRR	Use of thermal and NDVI data coupled with SVAT models for investigating climate change associated with urbanization.
Voogt and Oke (1998)	Ac: AGEMA	Thermal anisotropy of urban surfaces.
Carlson & Sanchez-Azofeifa (1999)	Sat: AVHRR	Urban microclimate change associated with urbanization.
Hafner and Kidder (1999)	Sat: AVHRR	SUHI and UHI patterns associated with thermal inertia and moisture availability.
Hoyano et al. (1999)	Ground-based thermal scanner	Calculation of sensible heat flux from individual buildings.
Parlow (1999)	Sat: Landsat TM	Energy balance modelling of an urban area using multispectral methods.
Wald and Baleynaud (1999)	Sat: Landsat TM	Air quality assessment using thermal remote sensing.
Quattrochi et al. (2000)	Ac: ATLAS	Use of thermal remote sensing in a GIS framework to assess urban heat islands.
Soux et al., 2000	Tower/IRT	Three-dimensional sensor view model of urban surfaces.
Voogt (2000)	Ac: AGEMA	Areally representative urban surface temperatures at different scales.
Voogt and Grimmond (2000)	Ac: AGEMA	Sensible heat flux modelling and estimation of surface thermal roughness lengths of an urban area using thermal remote sensing and ground observations.
Voogt and Soux (2000)	Tower/Thermal Scanner, IRT	Local scale urban thermal anisotropy.

and at the scale of individual buildings (Hoyano, Asano, & Kanamaru, 1999).

The third major theme in Table 1 is the application of thermal remote sensing to study the relation between atmospheric heat islands and SUHIs. Several studies combine coincident remote and ground-based observations (Ben-Dor & Saaroni, 1997; Caselles, Lopez Garcia, Melia, & Perez Cueva, 1991; Dousset, 1989, 1991; Lee, 1993; Stoll & Brazel, 1992) and some also with urban atmosphere models (Hafner and Kidder, 1999; Henry, Dicks, Wetterqvist, & Roguski, 1989) to study surface–air temperature relations, although this is more generally addressed through empirical models. Other studies have been motivated by the idea that satellite observations may be able to detect and correct for

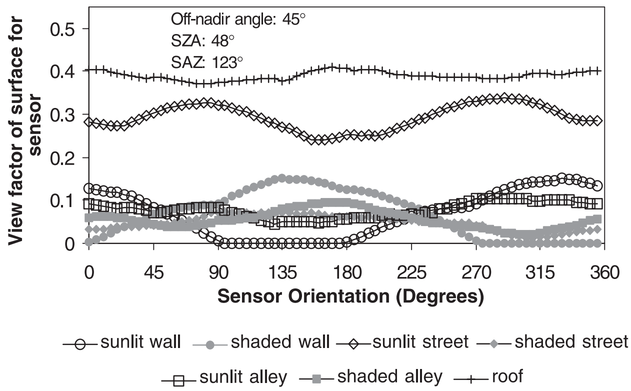

Fig. 3. View factors of urban surface components for an airborne thermal scanner sensor calculated using the S3mod model (Soux et al., 2000) for the light industrial area of Vancouver BC (Table 2). YD 228 1992, 1030 LDT.

any urban influence that may 'contaminate' screen-level air temperature records (Epperson et al., 1995; Gallo et al., 1993a, 1993b; Gallo & Owen, 1999; Gallo & Tarpley, 1996; Johnson, 1994). Gallo et al. (1995) review procedures for satellite assessment of the UHI effect and consider prospects for future use of satellite remote sensing in the evaluation and monitoring of UHI. Much emphasis has been placed on the use of urban–rural differences in the vegetation index (NDVI) as a measure of the difference in surface properties such as heat storage capacity and evaporation, to estimate urban and rural minimum air temperatures (e.g. Gallo & Tarpley, 1996). More recently, satellite observed nighttime light data have been found to help discriminate between urban and rural areas (Gallo & Owen, 1998). NDVI-based measures are found to be consistently slightly better than measures based on satellite-derived surface temperature differences, and to perform similarly to those based on population (Gallo & Owen, 1998). However, measures based on population are known to be less successful than those that incorporate site specific measures of surface properties known to be important to the establishment of differential cooling rates (e.g. Oke, 1982).

2.1. Progress on questions raised by Roth et al. (1989)

In a paper now commonly used to frame research proposals, Roth et al. (1989) raised four questions regarding the limitations of applying satellite-derived thermal imagery in urban climate studies. These were as follows.

(1) What are the characteristics of the urban surface as viewed by thermal remote sensors?
(2) What is the relation between remotely observed radiometric surface temperature and the actual temperature of the urban-atmosphere interface?
(3) How can surface urban heat islands be related to atmospheric urban heat islands?
(4) How can thermal remote sensing of urban surfaces provide input into models of urban climate?

In the following, any progress made toward answering each of these questions is reviewed in relation to the urban studies in Table 1, as well as to related developments over other rough, inhomogeneous surfaces such as agricultural and natural vegetated areas.

2.1.1. What is the nature of the urban surface as seen by a remote sensor?

Some progress has been made on the assessment of urban surfaces, as viewed by a remote sensor through the use of sensor view models (e.g. Soux, Voogt, & Oke, 2003) that advance our understanding beyond the basic conceptual description given by Roth et al. (1989) and illustrated in Voogt and Oke (1997). Sample results are shown in Fig. 3 for a modelled urban surface described in Table 2, where dimensions have been chosen to replicate the complete-to-plan area ratio of the study area as determined from GIS analysis (Voogt & Oke, 1997). Such models typically represent the buildings as block-like elements on a plane surface and therefore constitute only a crude approximation to the actual complexity of urban surfaces. These models have their basis in simple two-dimensional models of agricultural surfaces (e.g. Caselles, Sobrino, & Coll, 1992). Development and application of sensor view models are more advanced for agricultural and forested than for urban surfaces (Otterman, Brakke, Fuchs, Lakshmi, & Cadeddu, 1999; Otterman et al., 1995; Smith & Goltz, 1994) where better information on the structural attributes of vegetation canopies is available. Highly detailed canopy radiative transfer models are available for these surfaces to couple with sensor-viewing models (e.g. Myneni et al., 1995) including examples that use ray-tracing (Govaerts and Verstraete, 1998) and radiosity methods (Qin and Gerstl, 2000).

The canopy architecture of vegetated surfaces has received detailed attention (e.g. Fournier, Rich, & Landry, 1997) and techniques have been developed to extract surface structural parameters using remote sensing (e.g. Jasinski & Crago, 1999). The parameters are applied across a range of models of processes over these surfaces including models of thermal anisotropy (Otterman et al., 1995). In

Table 2
Surface dimensions for the light industrial region of Vancouver, BC (see Voogt and Grimmond 2000; Voogt, 2000) used for the model simulations shown in Figs. 3, 5, and 6

Surface dimension	Value (m)
Building height	7
Building width	30
Building length	23
Street width	22
Alley width	12
Building spacing	9
Number of buildings per street block	3
Roof-to-plan area ratio	0.4
Complete-to-plan area ratio	1.43

contrast, urban surface morphology, while subject to detailed inventories of land cover (e.g. Quattrochi & Ridd, 1994), has only recently been assessed quantitatively (Bottema, 1997; Grimmond & Oke, 1999) in relation to questions of urban climate. This has largely been through morphometric analysis intended to characterize the aerodynamic roughness of urban surfaces for use in air pollution dispersion (Brown, 2000; Cionco & Ellefsen 1998) and turbulent transfer. Even then, our ability to describe the combination of built and vegetative elements of the urban surface is lacking. Urban areas are typically represented at small scales as regular combinations of rectangular bluff-body elements, but this ignores significant small scale complexity such as pitched roofs, variable building height and it often completely ignores urban vegetation. Plane-parallel vegetation canopies and regular geometric urban surfaces form the end-members of a spectrum of surface types; more realistic urban surface representations need to include elements of both.

At small scales, more advanced depiction of urban areas in GIS models is becoming possible (Gruen & Wang, 1998; Kim & Muller, 1998). Haala and Brenner (1999) combine multispectral imagery and laser altimeter data to extract buildings, trees and grassy areas that can be used to generate 3-D visualizations of urban landscapes that combine buildings and trees. Other methods that combine laser altimeter data with building footprint maps can be used to reconstruct 3-D building geometry. Object extraction of buildings, and 3-D city and building models are listed among the major thematic topics published in the journal ISPRS (Baltsavias, 2000) and a future special issue on urban areas is planned to include detection and 3-D object reconstruction (including buildings and vegetation), generation of 3-D city models, and the application of multisensor data techniques to urban areas http://www.photogrammetry.ethz.ch/journal). In a modelling context, application of computer graphics techniques such as radiosity and ray tracing in complex structural environments may provide avenues for advancement.

At larger scales, databases with detailed land cover derived from field observation (Grimmond & Souch, 1994), or multispectral remote sensing, have contributed to a better understanding of the urban surface in relation to surface energy balances, but they have not been related specifically to structural parameters that could be used to better define the urban surface for use in sensor view models. The "triangle" method of Gillies and Carlson (1995) provides one approach to derive more physically relevant surface characteristics to urban climate (Owen et al., 1998).

Advances in our knowledge of urban surface structure and other properties may come from increases in capability afforded by digital hemispherical photography in the assessment of view factors of urban surfaces (Grimmond, Potter, Zutter & Souch, 2001) and the combined use of remote sensing and GIS to better characterize the structure of the urban surface. As noted, urban surface representation needs to be improved to include the impacts of small-scale structural features such as: roof geometry, variable building height and vegetation geometry (including stand parameters such as LAI, leaf angle distributions) as they contribute to the overall urban surface structure. Here, the use of remotely sensed parameters such as NDVI and other high-resolution multispectral remote sensing information (e.g. IKONOS imagery), or perhaps radar imagery, may contribute to better characterization of the urban surface as it relates to understanding remotely observed thermal imagery. Details of the small-scale structure of the urban surface also need to be parameterized, so it can be applied to remotely sensed variables observed at coarser resolution, such as the widely used AVHRR or Landsat TM instruments.

2.1.2. How do sensor detected radiant temperatures relate to the true temperature of the urban-air interface?

Research on the use of thermal remote sensing to determine land surface temperatures has been the subject of several reviews, e.g. Carlson et al. (1995), Norman et al. (1995), Prata et al. (1995), Qin and Karnieli (1999). Thermal remote sensors estimate surface temperature from the radiance received by a detector that has a narrow solid angle of view. Measurements are subject to the effects of: (a) atmospheric absorption and emission between the sensor and the surface, and (b) the characteristics of the surface, especially its emissivity and geometric form. Corrections for atmospheric effects are relatively well established in remote sensing practice, although there is little information on the role played by the known spatial variations of atmospheric transmissivity over urban areas that may influence accurate retrieval of surface temperatures. These variations may be particularly important to the determination of urban–rural temperature differences when effects of the polluted 'urban plume' are taken into account (e.g. Wald & Baleynaud, 1999).

The application of satellite sensors to the determination of land surface temperature is complicated by any heterogeneity or roughness of the land, therefore, this becomes a significant issue when dealing with urban surfaces. The three-dimensional nature of the urban surface, combined with solar and sensor geometric considerations, implies that:

(a) urban surfaces contain strong microscale temperature patterns that are influenced by the relative orientation of urban surface facets to the sun (or to the sky at night), as well as by the thermal properties of surfaces that usually also vary with their location and orientation, e.g. roof properties vs. wall properties;
(b) a biased view of the urban surface is ensured when narrow IFOV sensors are used to view a three-dimensionally rough surface. Together, these properties lead to an *effective anisotropy* of the upwelling long-wave radiation from the urban surface; i.e. directional variations in the sensor-detected upwelling long-wave radiance. The term "effective" anisotropy is used to

indicate that it is a function of the surface structure as distinct from the (assumed) near-Lambertian properties of individual surface components. In some presentations, anisotropic effects due to temperature differences are not distinguished from emissivity effects due to rough surfaces. An important discussion of the terminology related to thermal remote sensing of surfaces that underscores the difficulty in applying thermal remote sensing to rough surfaces is given by Norman and Becker (1995) and Norman et al. (1995).

Anisotropy is not unique to the study of urban surfaces. Treatment of anisotropic effects was identified as a priority item arising from the FIFE field campaign by Sellers and Hall (1992) who recommended that surface anisotropic effects be identified over a range of surface types. Here, observations of effective thermal anisotropy and modelling it for urban surfaces are considered separately.

2.1.2.1. Observations of effective thermal anisotropy. Thermal anisotropy of rough Earth surfaces has been studied at scales ranging from soil surface micro relief (Verbrugghe & Cierniewski, 1998) upwards through plant canopies (Chehbouni et al., 2001; Lagouarde, Kerr, & Brunet, 1995) and forests (e.g. Lagouarde, Ballans, Moreau, Guyon, & Coraboeuf, 2000; McGuire, Balick, Smith, & Hutchison, 1989) to mountainous terrain Lipton and Ward (1997) and the assessment of large scale satellite studies (Minnis & Khaiyer, 2000). Agricultural and natural vegetated surfaces have been studied most extensively (Paw U, 1992) including observations (Lagouarde et al., 1995) intended to validate models as well as to better represent heat fluxes over rough surfaces (e.g. Brutsaert & Sugita, 1996).

Effective thermal anisotropy from selected urban land use areas has been directly observed using both airborne (Iino & Hoyano, 1996; Voogt & Oke, 1998) and tower-mounted measurements (Voogt & Soux, 2000), as well as through combinations of ground-level and remote observations (Nichol, 1998). Asano and Hoyano (1996) tested a specialized spherical thermography technique to better sample the 3-D temperature structure of urban areas. To date, satellite assessment of urban thermal anisotropy has not been reported although satellite thermal anisotropy has been used in larger scale studies (Lipton & Ward, 1997; Minnis & Khaiyer, 2000).

The available observations indicate that urban areas show significant effective thermal anisotropy that ranks them high relative to other surfaces. Nadir remote views of the urban surface may yield temperatures that are warmer or cooler than off-nadir views, depending on the view direction relative to solar position. The observations also indicate that anisotropy remains surprisingly strong in residential areas with only relatively low building heights and large amounts of vegetation. In these areas, the microscale structure of some urban surfaces, especially peaked roofs and the anisotropy created due to shading patterns by a fairly sparse canopy of trees may be influencing factors. Confirmation awaits examination of a greater range of urban surfaces incorporating a range of vegetative canopy structures and/or modelling studies.

The daytime airborne traverse data displayed in Fig. 1b includes anisotropic effects as evident from the duplicated portion of the traverse over the residential area (~ 18 km). This arises due to a slight off-nadir viewing angle of the scanner and alternating directions of the airborne traverse so that the scanner azimuth was reversed between the two portions of the traverse (the temperature data has been normalized to account for surface cooling during the time of the traverse).

Thermal anisotropy is not limited to the daytime case. The effects of the thermal and structural properties of cities, as described by Roth et al. (1989), particularly the low thermal admittance and large sky view factor of roofs compared to building walls or other surfaces deeper within urban canyons, generates nocturnal effective anisotropy, such that near-nadir views generate lower directional radiometric temperatures than do off-nadir views (Fig. 4).

As yet, no long-term observational studies of urban areas have been conducted to assess the temporal nature of the effective anisotropy as related to varying solar zenith angle; however, the ongoing development of models is likely to allow progress in this area. Ground-based observations of hemispherical long-wave radiation that may be used to develop relations between hemispheric and directional temperature (e.g. Otterman et al., 1995) have not often been made as part of urban climate studies, but more recent urban field studies should correct this; ESCOMPTE, (Mestayer & Durand, 2002), BUBBLE (Rotach, 2002). In these studies, it will be necessary to assess the representativeness of the ground-based measurements, but here again, models may be useful.

Direct and indirect observations of urban thermal anisotropy have been used to devise methods to estimate more

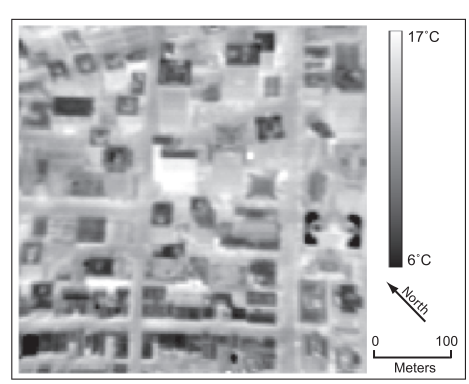

Fig. 4. Thermal image of downtown Vancouver, obtained from an airborne thermal scanner illustrating nighttime temperature variations from a small off-nadir viewing angle. Rooftops are cool relative to building walls and streets. The image is corrected for atmospheric effects.

representative temperatures of the urban surface (Nichol, 1998; Voogt, 2000; Voogt & Oke, 1997). These methods attempt to combine the temperatures of various component surface types (e.g. vertical as well as horizontal surfaces) to yield areally weighted temperatures that take into account all urban surfaces. Such results represent a step towards developing tools to correct or normalize for urban thermal anisotropy. The results themselves need to be considered in the context of the application intended; e.g. a fully areally weighted urban temperature may not be representative of surfaces that contribute to the urban sensible heat flux. Other weighting schemes may be considered, for example, based on the use of surface view factors. The application of GIS techniques to detailed urban surface representations also provides the ability to extract select surface components for combination with temperature data to allow various other surface combinations. Such techniques have already been applied to the study of urban aerodynamic roughness lengths (Bottema, 1997; Grimmond & Oke, 1999). The surface heat island traverses shown in Fig. 1 incorporate a crude correction for the wall and vegetated surfaces that cannot be seen by a nadir-pointing remote sensor. In this case, weighting for the wall and obscured vegetated surfaces is derived for the downtown, residential and light industrial areas studied by Voogt and Oke (1997) and is then extrapolated to other portions of the traverse. Average wall temperatures are derived from observations made during the study period (Voogt, 2000) and non-viewed vegetated surfaces are assumed to be at air temperature. The application of these corrections can be seen to have a substantial impact on the derived magnitude of the SUHI and of the difference between canopy level air temperatures and surface temperatures. It is also interesting to note that within the urbanized portion of the transect, the area weighting for unseen vegetation, calculated from analysis of field observed vegetation structural parameters, has a relatively good correspondence with the NDVI values calculated from the AVHRR sensor. However, the generality of this relationship is unknown due to the relative importance of tree canopies to the contribution of unseen vegetation area, and trees make up a large fraction of the vegetated area in the residential areas of the city relative to the agricultural area.

Extraction or inversion of component temperatures has been accomplished over vegetated areas where the surface can be generalized into two components, vegetation and soil, by coupling multi-directional thermal remote observations with either model results or ground observations (e.g. Chehbouni et al., 2001; François, 2002; François, Ottle, & Prevot, 1997). These results demonstrate that multi-directional measurements hold promise for better detection of soil moisture status using thermal remote sensing. It is not clear whether this can be accomplished over the more complex surfaces of urban areas, although there is some evidence that some urban surface components can be detected in the distribution of directional radiometric temperatures (Voogt & Oke, 1998) and the day and nighttime thermal response of individual urban surfaces has been documented (Quattrochi & Ridd, 1994).

Directional effects of effective thermal anisotropy are complicated by uncertainty in urban surface emissivities. Emissivities applied to urban surfaces have ranged from 0.87 (Balling & Brazel, 1988) up to 0.97 (Dousset, 1989; Henry et al., 1989), with most values in the range 0.92–0.95. A few studies incorporate variable emissivity corrections based on land use characteristics (Balling & Brazel, 1988; Caselles et al., 1991; Lougeay et al., 1996) with emissivity values derived from tabled properties. Very few direct observations of urban surface emissivity are available. Notable exceptions are the roof emissivity study of Artis and Carnahan (1982), and some field-based observations of the emissivity of component urban surfaces (Verseghy & Munro, 1989). Some newer compilations of spectral emissivities for common urban materials have become available (MODIS UCSB emissivity library: http://www.icess.ucsb.edu/modis/EMIS/html/em.html ASTER spectral library: http://speclib.jpl.nasa.gov/) based on laboratory measurements of sample materials. Current estimates of "bulk" urban emissivity (i.e. an estimate that would apply to scales larger than an individual component surface, and which takes into account the trapping effect of rough surface geometry, e.g. Sutherland & Bartholic, 1977) are limited to model results (Arnfield, 1982). Advances in the separation of land surface temperature and emissivity effects using satellites (Gillespie et al., 1998; Schmugge, French, Ritchie, Rango & Pelgrum, 2002; Sobrino, Raissouni, & Li, 2001) may offer some ability to generate urban surface emissivities, although the assumptions inherent in the methods may be restrictive over cities where strong small-scale heterogeneity is present. For example, Sobrino et al. (2001) note that algorithms are available to retrieve surface emissivity but under the restriction that the angular dependence of the bidirectional reflectivity of the surface is known and atmospheric corrections are applied. No studies have examined the former issue over urban areas, and the effect of spatially varying atmospheric transmission across urban areas has not been well studied in relation to thermal remote sensing. Newer generation satellites, such as ASTER, include multiple thermal wavelength channels and have significantly improved spatial resolution. This makes them ideal candidates to assess the surface variability of urban surface temperature and to extract surface emissivity estimates using multispectral methods. Gillespie et al. (1998) suggest that the emissivity algorithm developed for the new ASTER sensor should work well with mixed pixels although there is some dependence on the radiative trapping by rough surfaces such as urban canyons and some assumptions regarding the behaviour of individual surface component emissivities with relation to the methodology employed that have not been explicitly tested over urban areas. Work on the application of ASTER over urban surfaces is underway (Dousset, 2002).

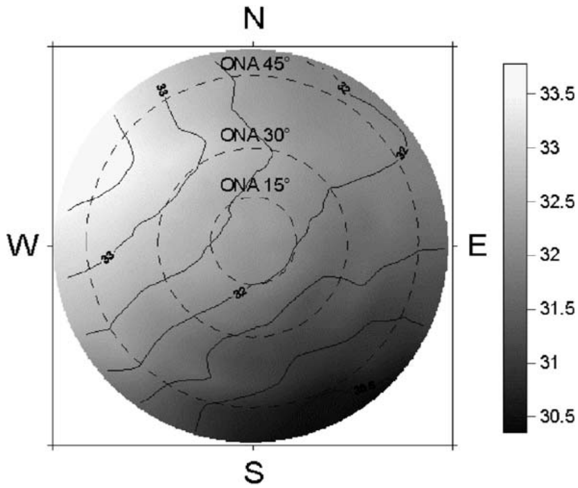

Fig. 5. Modelled directional brightness temperatures for an airborne thermal scanner (12° FOV) viewing a simple urban surface (Table 2) from an elevation of 650 m for a mid-morning simulation (YD 228, 1992) using S3mod (Soux et al., 2000). The image plots sensor-detected brightness temperature interpolated from modelled values at 5° azimuthal and off-nadir steps.

2.1.2.2. Modelling thermal anisotropy. Many models are available to correct anisotropic short-wave radiation distributions (e.g. Cabot & Dedieu, 1997; Privette, Eck, & Deering, 1997). These models provide the ability to normalize directional reflectance, predict directional behaviour and calculate integrated hemispherical values for a surface thereby supplementing the limited angular sampling of remote sensors (Cabot & Dedieu, 1997). However, only a few models are available for the thermal wavelengths and none are used operationally due to the relative complexity of the input data required (Minnis & Khaiyer, 2000).

Thermal models have been used over agricultural and forested surfaces (Paw U, 1992) to estimate the magnitude and timing of anisotropy. Some models allow inversion to recover a limited number of component temperatures from simple combinations of surface types (soil and vegetation) but they require extension to include more surface components (Smith, Ballard & Pedelty, 1997) that are characteristic of both vegetated and urbanized surfaces. A few models incorporate the canopy energy balance (e.g. Smith & Goltz, 1994); most others use prescribed temperatures. This limits their applicability to situations where observed temperature distributions are available, or an assumption of an isothermal or simple statistical temperature distribution for the canopy can be made (Otterman et al., 1999).

Typically, models developed for vegetated surfaces portray plane-parallel surfaces and require detailed canopy structural parameters (LAI, leaf angle distribution and directional gap fraction) to accurately model the anisotropy and/or to recover the component leaf and soil temperatures (François et al., 1997). This will be difficult for cities until characterization of urban surface morphology has received more attention.

Simple urban surfaces have now been modelled (Soux et al., 2000) by extending a 2-D orchard model (Caselles et al., 1992) to three dimensions and using prescribed surface temperatures (Figs. 3, 5 and 6). The model allows estimates of the directional brightness temperature to be estimated for any given view direction over a modelled urban surface. Fig. 5 illustrates results for a range of sensor off-nadir and azimuth view directions at mid-morning for the urban surface modelled using the parameters given in Table 2 and using observed component temperatures for sunlit and shaded components of building roofs, walls and streets from the study of Voogt and Oke (1997). Fig. 6 summarizes the model-derived anisotropy for a 45° off-nadir view angle, represented as the temperature range over all sensor azimuth directions, and compares these to observations from a helicopter mounted sensor. Observations are the average difference between sensor view directions using sequences of airborne thermal images along flight lines (Voogt & Oke, 1998). Modelled values use observed mean temperatures from building walls, streets and roofs (see Voogt & Oke, 1997) coupled with a 3-D sensor view model (Soux et al., 2003). The modelled sensor average is created by running multiple model simulations for different sensor positions (x and y location) over the modelled urban surface. The model requires further validation and continued development by coupling it to urban energy balance models and by incorporating better representation of urban canopy structure. Simple empirical models of thermal anisotropy are lacking, but recent work over other surfaces (Minnis & Khaiyer, 2000; Suleiman & Crago, 2002) suggests that the development of such models is feasible.

2.1.3. What is the relation between satellite-derived surface urban heat islands and those measured in the air?

The brief review presented with Table 1 indicates that a substantial body of work has been amassed on the subject of relating SUHI to atmospheric heat islands. To date relations remain empirical and no simple general relation has been found. Direct comparison of radiometric surface temperature with air temperature should consider the differing source areas for the two measurements (Fig. 2). In addition,

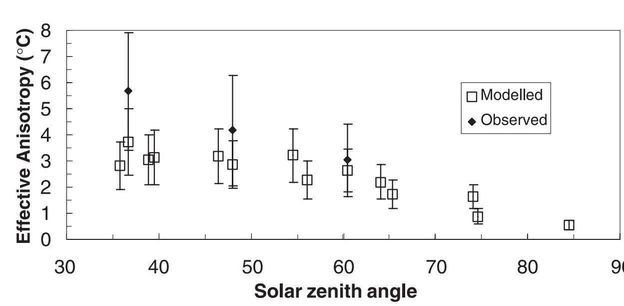

Fig. 6. Observed and modelled thermal anisotropy for a 45° off-nadir sensor (12° FOV) at 650 m during one summer day (YD 228 1992) over a simple urban surface (Table 2). Error bars represent ± 1 standard deviation.

urban air temperatures are also influenced by several other processes in the UCL. Air temperatures are partly determined by radiative divergence in the UCL air volume. This topic has been little studied in the UCL since the work of Nunez and Oke (1976). Advection (horizontal transport of heat by wind) that arises due to the spatial configuration of various components of the urban surface that have varying properties of surface moisture, thermal admittance, and aerodynamic roughness resulting in different energy balances and surface temperatures is also important. In urban areas, small-scale shading patterns can also be an important influence on the UCL air temperature structure leading to potential air quality problems due to altered atmospheric mixing (Reisner, Smith, Bossert, & Winterkamp, 1998; Ruffieux, Wolfe, & Russel, 1990).

The impact of microadvection was explored by Stoll and Brazel (1992) who found that correlations between surface and air temperatures measured from ground stations could be explained largely through the atmospheric mixing, mean wind velocity and thermal properties of surface materials. When extending the analysis to larger scales by using airborne observations of directional brightness temperature, the correlations were poorer because of the mixture of surfaces present within the sensor IFOV. At scales typical of most satellite sensors, the IFOV of the thermal remote sensor will view a substantial mix of surfaces incorporating significant subgrid scale advection, so that correlations may be expected to include substantial noise. To fully understand relations, detailed, fully coupled models of surface and atmospheric processes are required.

Correlations of surface temperature with air temperature are improved at night, (Fig. 1a; see also Dousset, 1989) when microscale advection is reduced. Predictive power at satellite resolutions remains limited (Gallo & Owen, 1998) although some improvements can be made through the use of NDVI. This is largely due to the relatively close coupling between surface and air temperatures that occur at night over vegetated surfaces.

The addition of weightings to incorporate "unseen" surfaces from nadir-viewing positions does reduce the difference between surface and air temperatures by overcoming the anomolously cold (night) and warm (day) surfaces viewed by near-nadir sensors (Fig. 1). These corrections have applied detailed knowledge of surface characteristics that are not routinely available for large-scale satellite observations. Operational use requires further research to determine their more general applicability and methods by which the surface structure and characteristics may be inferred from more routinely observed variables. However, even then, we expect that simple surface and air temperature correlations are likely to work well only in certain limited situations constrained by atmospheric conditions and surface properties. For the nighttime case of the UHI, surface–air temperature differences are expected to be minimized as winds increase, due to mixing and disruption of any surface-based inversion layer. Under calm winds and clear skies, when the UHI has its best expression, microscale processes dependent on surface thermal properties, sky view factor and microscale advection will be most apparent thereby increasing differences between the UHI and SUHI. We conclude that explanation of the air and surface temperature differences remains rooted in detailed study of the surface micrometeorology and geography and are only likely to be predicted by the application of detailed, fully coupled surface-atmosphere models.

2.1.4. How appropriate is thermal remote sensing data as input to models of urban climate?

Roth et al. (1989) note the difficulties inherent in defining the surface of observation and matching observations made over rough, incompletely viewed surfaces with the conceptual surfaces represented in models, and that this presents a significant problem for urban climatology. For progress in this area, we again refer to remote-sensing studies over rough vegetated surfaces. A topic much studied over the past decade is the ability to model sensible heat fluxes from such surfaces utilizing thermal remote sensing (ground, aircraft- or satellite-mounted sensors). For a recent review of the approaches to thermal remote sensing of the surface energy balance, see Friedl (2002).

A key difficulty in the estimation of turbulent sensible heat flux using thermal remote sensing is the relation (or difference) between the remotely observed surface temperature and the required *aerodynamic temperature* ($T_{0\ \mathrm{aero}}$) that yields the correct surface sensible heat flux (Mahrt, Sun, MacPherson, Jensen, & Desjardins, 1997). Over rough surfaces, there are real differences in the effective levels that act as momentum and heat sources, $z_{0\mathrm{m}}$ and $z_{0\mathrm{h}}$ respectively, and kB^{-1}=(ln $z_{0\mathrm{m}}/z_{0\mathrm{h}}$). While numerous studies on the nature of kB^{-1} and $z_{0\mathrm{h}}$ are available for vegetated surfaces, only one study has reported values for an urban surface (Voogt & Grimmond, 2000). The results suggest significant differences between urban and vegetated results due to the increased importance of bluff elements and the significant anisotropy of urban surfaces. Newer work over vegetated surfaces has begun to examine the diurnal and seasonal variations of kB^{-1} and $z_{0\mathrm{h}}$ that exist due to vertical temperature distributions (also yielding anisotropy) in plant canopies (Brutsaert & Sugita, 1996; Matsushima & Kondo, 1997; Crago, 1998; Qualls & Hopson, 1998). Relatively, little is known about the diurnal variation of $z_{0\mathrm{h}}$, but it has been suggested (Qualls & Hopson, 1998) that relations may be developed between the surface temperature patterns and solar elevation angle (the forcing for anisotropy) to correct for these effects. Coupling radiative transfer schemes to models of surface sensible heat flux (e.g. Smith & Goltz, 1994; Smith, Ballard et al., 1997; Smith, Chauhan et al., 1997) to handle vertical canopy temperature variations is also a possible solution (Qualls & Yates, 2001). Over urban surfaces, canopy radiative transfer schemes have been used extensively for assessing urban canopy layer climate (e.g. Arnfield, 1982) but they have not been coupled to remote sensing applications. One approach to avoiding inconsistencies arising from the use of dual- or single source heat flux models is to model the aerodynamic temperature (Mahrt et al., 1997; Sun, 1999). Another option is to use other remotely sensed parameters (Mahrt et al., 1997) to help determine the aerodynamic temperature, or the relation between the radiatively determined surface temperature ($T_{0\ rad}$) and $T_{0\ aero}$.

A promising approach termed the "triangular" method that couples a soil–vegetation–atmosphere transfer (SVAT) model to remotely sensed surface temperature and NDVI is given by Gillies and Carlson (1995) and validated over natural vegetated surfaces by Gillies, Carlson, Cui, Kustas and Humes (1997). This approach utilizes relations between temperature and NDVI to derive surface fractional vegetative cover and surface soil water content, and also instantaneous fluxes of sensible and latent heat. The approach can be used over a range of spatial scales. The method has also been applied to detect land cover alterations due to urbanization and to provide estimates of local scale climate change associated with those disturbances (Owen et al., 1998). This method gets around the weakness of classifications that provide land use descriptions rather than parameters known to be physically linked to surface–atmosphere exchange processes (Carlson & Sanchez-Azofeifa, 1999). The surface moisture parameter derived in his way is an important input to surface atmosphere models and has been observed to be important in the ratio of sensible and latent heat fluxes within urban areas (e.g. Grimmond & Oke, 1995, 2002).

3. Summary

This review suggests that progress on the questions raised by Roth et al. (1989) has been slow to emerge in studies of thermal remote sensing from urban areas, but that some first steps have been made. By way of comparison, the surface structure and anisotropic thermal behaviour of vegetated surfaces is much better documented and modelled, although in that field too, progress is noted to have lagged that in handling canopy—radiation processes in the short-wave region. Part of the lack of progress over urban surfaces can be attributed to the greater difficulties in making observations over the relatively tall urban surface, compared to shorter vegetated surfaces, and the more complicated surface structure that combines vegetation and buildings that has been less well observed or modelled.

To enhance progress, research should examine the ability to apply advances made in the study of thermal remote sensing over vegetated surfaces to urban areas, and particularly to provide progress in three key areas: (1) determine appropriate surface radiative (e.g. emissivity) and structural parameters from remote sensing to better describe the urban surface, and to ensure they are appropriate for use in urban atmospheric models; (2) couple canopy radiative transfer models with both sensor view models and surface energy balance models to better simulate and understand urban thermal anisotropy and the link between surface temperatures, the surface energy balance and air temperature in and above the urban canopy layer; and (3) perform observational studies with the goal of obtaining better independent validations of the surface effective parameters derived from remote thermal sensors.

Glossary

Ac	Aircraft
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
DMSP	Defence Meteorological Satellite Program
IRT	Infared Thermometer
IFOV	Instantaneous Field of View
MSS	Multispectral Scanner
NDVI	Normalized Difference Vegetation Index
SUHI	Surface Urban Heat Island.
TIMS	Thermal Infrared Multispectral Scanner.
TIrS	Thermal Infrared Scanner.
UHI	Urban Heat Island
UCL	Urban Canopy Layer
UBL	Urban Boundary Layer

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