

A dissertation submitted in partial fulfilment of the requirement for the degree of MSc Applied Meteorology

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Abstract

Although surface sensible heat flux of an urbanised area is known to differ from a rural location (under the same synoptic conditions) assessments of how the buildings and streets of an urban area modify the transport of heat is a recent area of research in comparison to most aspects of meteorology. This investigation aims to assess the magnitude and characteristics of these microscale variations in urban sensible heat flux. Surface radiative temperature measured at twelve nearby sites in an urban area is combined with air temperature and wind data to produce three different models of surface sensible heat flux. The models are compared to heat flux derived from a sonic anemometer located on a rooftop in the study area and show good agreement with the site-averaged model heat flux. The inclusion of an excess resistance to heat flux term in addition to aerodynamic resistance is found to be important for the urban site. Urban and solar geometry are considered the main factors in microscale variations of surface radiative temperature and therefore sensible heat flux during fair weather conditions. During overcast days it is suggested that anthropogenic heat sources such as traffic contribute most to these microscale variations (although with a smaller magnitude) since the effects of shadowing are not present. In addition to heat flux model output, a value of kB^{-1} (a representation of the excess resistance to sensible heat transfer) was calculated for the study area and ranged between 26 and 29. This range is in accordance with values determined during pervious urban campaigns using a similar heat flux model.

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List of Symbols

- B^{-1} Dimensionless parameter
- c_p Specific heat capacity (for air)
- *k* Von Karman constant
- kB^{-1} Parameter related to resistance to heat transfer, calculated using Brutsaert (1982)
- *P* Atmospheric MSL Pressure
- Q_H Sensible heat flux
- ρ Density (of air)
- *R* Gas constant for dry air
- R_{am} Aerodynamic resistance for momentum
- *Re*^{*} Roughness Reynolds number
- r_h Aerodynamic resistance to heat
- r_T Excess resistance between Z_{0m} and the surface T_r
- T_a Air temperature
- T_s , Perturbation of sonic temperature from the mean
- u(z) Mean horizontal windspeed at specific height
- *u*^{*} Friction velocity
- *u'* Perturbation of horizontal eastward component of windspeed from the mean
- *U*_{can} Mean horizontal windspeed in street canyon
- *v* Kinematic molecular viscosity of air
- v' Perturbation of horizontal northward component of windspeed from the mean
- *w*' Perturbation of vertical windspeed from the mean
- W_{can} Mean vertical windspeed in street canyon
- Z_{0h} Roughness length for heat
- *Z*_{0m} Roughness length for momentum

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1 Introduction

Air near the ground is warmed by sensible heat flux from the surface. Therefore knowledge of the size and variation of heat flux will be crucial for estimation of urban ground level environmental conditions, especially as the often dry, impermeable surface means that sensible heat flux is often dominant over latent heat flux as a means by which energy from incoming solar radiation is lost from the surface. Since urban meteorology is a relatively recent area of research, factors influencing the small-scale variation of heat flux, or indeed the strength of this variation, are still not well understood.

Sensible heat fluxes from an urban area are known to differ from that of rural, more vegetated surfaces assumed in more traditional accounts of the surface energy balance (Voogt and Grimmond 2000). However, with an increasingly large proportion of the global population now living in urban areas, the study of environmental conditions such as the exchange of heat between the urban surface and the atmosphere is obviously important for town planning, energy efficiency and human comfort (Oke 1988).

Although mesoscale observations of sensible heat flux modification by urban areas such as the urban "heat island" effect are widely documented (for example Oke 1982), the microscale variation of heat flux such as that observed between adjacent roads or even between pavement and road surface, was still relatively unexplored until recently (Voogt and Grimmond 2000), although it is at this scale that the individual at street-level will directly experience the urban environment.

This investigation aims to assess the magnitude and characteristics of these microscale variations in sensible heat flux. Since the source of sensible heat is considered to be the surface (such as heat generated via conversion of incoming short wave solar radiation into thermal energy) it is the heat exchange between the urban surface and adjacent air that is to be considered. A heat flux will develop wherever there is a gradient of thermal energy (i.e. temperature) and a mechanism for its transfer. The majority of heat transfer at this scale in the atmosphere is by turbulent mixing and it is the efficiency of this transfer (or resistance to it) and the temperature gradient between the surface and adjacent air that will be measured in the urban field site. This method of sensible heat flux estimation therefore requires spatial and

temporal measurement of surface (radiative) temperature, air temperature and wind flow to determine the characteristics of sensible heat flux in the selected urban area.

Once the heat fluxes are calculated a comparison will be made between the measured heat flux (using a sonic anemometer) and the modelled heat flux using the temperature and wind data to assess the accuracy of the model. Additionally, results of this investigation will be compared to that of similar fieldwork. This will suggest if the findings are applicable to other urban areas as well as providing an order of magnitude for the calculations to make sure the results (both measured and modelled) are realistic.

Once a literature review is presented at the start of this dissertation, the experimental methodology will be described. The fieldwork results will then be displayed, analysed and used to produce heat flux models using three different methods. The models will be compared to measured values and the models sensitivity and absolute error will be estimated, with final conclusions of the dissertation and suggestions for further research given at the end.

2 Literature Review

2.1 Overview of recent research

The motivation for research into urban meteorology is in part due to the needs of the urban population itself, with improvements in town planning coming from a realisation of the effects of urban geometry and physical characteristics on the street level environment (Oke 1988) and also the need to incorporate the effects of urban areas into the increasingly higher resolution mesoscale meteorological and climatological forecast models (e.g. Mascart et al. 1995, Masson 1999 and Grimmond and Oke 2002).

The main difference between urban and rural areas is the surface physical characteristics and geometry. As a result, the majority of research has been focused on parameterisation of these differences and the effects on the surface energy balance. The aspect of particular interest and importance to urban meteorology is the temperature of the urban surface since this variable determines the outgoing long wave radiation and temperature gradient resulting in the transfer of heat between the urban surface and adjacent atmosphere.

The importance of sensible heat flux estimation over urbanised areas was recognised early in the development of urban meteorology as a major factor in air pollution transport and mixed layer dynamics in addition to the significant forcing that urban surface heating has on mesoscale circulation patterns (Carlson and Boland 1978).

A useful quantifier of the excess resistance (i.e. resistance other than that of aerodynamic resistances) to heat transfer between the surface and adjacent air is the quantity B^{-1} given as equation 1 (see chapter 5 of this dissertation for a more detailed account):

$$B^{-1} = \frac{1}{k} \ln \left(\frac{Z_{0m}}{Z_{0h}} \right)$$
(1)

With *k* being the Von Karman constant, Z_{0h} and Z_{0m} as the roughness lengths for heat and momentum respectively. This quantifier was originally proposed by Owen and Thompson (1963) and Chamberlain (1966) and is a value (or its proportional value kB^{-1}) widely adopted in the literature as a representation of the excess resistance to sensible heat transfer.

The ambition of most research into sensible heat flux in urbanised areas is to develop a way of using measurable characteristics of the urban terrain and atmospheric observations to produce a realistic model of the corresponding heat flux. Additionally, the spatial variation is expected to be considerable in urban areas due to the complex geometry not usually associated with rural locations, providing an additional aspect to urban heat flux research. Early attempts to model this flux were made by Carlson and Boland (1978) who constructed a simple one-dimensional model based on K-theory (eddy diffusivity) for surface fluxes. Although the precise influence of wind speed on the resistance of vertical heat transport was not considered, a constant of proportionality was used and assumed to be related to wind speed and increased with height in order to produce the large temperature differences that were known to exist immediately above the surface.

Carlson and Boland (1978) concluded that thermal inertia and moisture availability were the major influences on the diurnal surface temperature (and therefore heat flux) in an urban environment, with atmospheric turbidity, wind speed, ground albedo and surface roughness identified as important secondary factors. Since the model required knowledge of moisture content and conductivity of the surface medium, a numerical/graphical inversion method using measured temperature and heat flux to back-calculate the moisture content and conductivity, which can then be used to calculate successive heat flux assuming slow (if any) change in conductivity and moisture content. This inversion method by Carlson and Boland (1978) appeared to be successful, with model outputs agreeing closely with observed data, with model errors equivalent to a difference between surface temperature calculation and observation of 1°C to 2°C.

Attempts to measure surface temperatures and associated sensible heat flux were made by Stewart et al. (1994) with the use of radiometric surface temperatures measured by infrared radiometers mounted on ground, airborne and satellite platforms. The range of scales associated with these different observational platforms allowed evaluation of the surface energy balance from microscale to regional scales. Although this study was for semiarid areas and not urban locations, this paper demonstrates the concepts behind the use of radiometric surface temperatures and aerodynamic resistance measurements to estimate sensible heat flux in areas where latent heat flux is comparatively low (therefore applying to sparsely-vegetated areas of largely dry, impermeable surface such as cities).

Stewart et al. (1994) finds considerable scatter in plotted values of kB^{-1} and roughness Reynolds number (a value proportional to the friction velocity and roughness length for momentum, see chapter 5 for definition) implying that the theoretical estimation of excess resistance for bluff rough and permeable rough surfaces is not necessarily valid for this surface. In contrast, Voogt and Grimmond (2000) found a general agreement between their observed and calculated values of kB^{-1} using the bluff rough calculation for urban areas, perhaps implying that the difference in surface geometry between the semiarid areas and by extension the bare soil approximation of urban areas in earlier mesoscale models (Louis 1979) and urban canyons is important in the valid use of the bluff rough resistance calculation method.

Findings from research into urban meteorology were used to modify existing operational mesoscale models to challenge assumptions such as equal roughness lengths for heat and momentum, an assumption used by the widely adopted Louis (1979) model. Mascart et al. (1995) found that the roughness length for momentum may be an order of magnitude larger than the roughness length for heat in urban areas, although a difference was suggested by earlier observations such as those of Garratt and Hicks (1973), with the difference being attributed to the roughness Reynolds number by Brutsaert (1975,1982).

Mascart et al. (1995) proposed minor changes to the Louis (1979) model that still assumed equal roughness lengths in its surface-layer parameterisation, with particular inaccuracies expected over urban terrain (as the research by Mascart et al. (1995) suggested that the urban geometry greatly reduced the roughness length for heat in relation to that of momentum) resulting in significant overestimation of sensible heat flux, as seen in studies over similar dry, heated terrain (Braud et al. 1993).

Sun and Mahrt (1995a) used surface radiative temperature and a resistance formulation to estimate surface heat flux in an urban area. Again, the difference in roughness lengths of momentum and heat was apparent with the introduction of a "radiometric exchange coefficient" to increase the resistance for heat transfer and thus reduce the overestimation caused by assuming no difference in momentum and heat roughness lengths. Differences in radiometric and actual temperature were kept to a minimum by using appropriate emissivity values for the surfaces considered.

The radiometric exchange coefficient was found to be closely related to $\theta^*/\Delta\theta$ (temperature fluctuation divided by the difference between surface radiative temperature and air temperature). θ^* can also be defined as:

$$\theta^* = \frac{w'\theta'}{u_*} \tag{2}$$

Where w' and θ ' are deviations of vertical windspeed and temperature respectively, and u_{*} is friction velocity. Additionally, this correlation was believed to be independent of the static stability since the Monin-Obukhov similarity theory does not apply when the surface radiative temperature is used instead of aerodynamic temperature at roughness height (Sun and Mahrt 1995a). Also, there is no evidence of a systematic relationship between radiometric roughness length and roughness length for momentum due to the assumed flow dependency of the former making the relationship a function of an independent variable (wind velocity).

There does however appear to be a dependence on the microscale distribution of surface radiative temperature in the footprint of the heat flux measurement since the radiometer essentially records the average temperature within the footprint, which may not be spatially representative if the differences within the footprint are large. This may imply that the radiometric exchange coefficient is sensitive to the highly variable surface temperature of an urban area and therefore may be difficult to generalise.

This microscale variability of the surface radiation temperature was explored again by Sun and Mahrt (1995b) using aircraft data collected over a black spruce site in the boreal forest during the Boreal Ecosystem-Atmosphere Study (BOREAS). The sensible heat flux was estimated from this data using the assumption that thermal roughness length is flow dependent as found in their last study (Sun and Mahrt 1995a) and earlier campaigns (Kustas et al. 1989 for instance). Relatively large differences in surface radiative temperature were observed between sides of the tree canopy exposed to direct incoming solar radiation and those that were shaded – an observation of significant relevance to urban areas.

2.1.1 Representation of surface temperature

The importance of accurate observation of the "complete" urban surface temperature was discussed in Voogt and Oke (1997) defined as the combination of observations obtained from



Figure 1: Schematic illustration of different definitions of the urban surface (from Voogt and Oke 1997).

all viewing angles to take into account the temperatures of all the surfaces present (figure 1). The study attempts to account for the surface (radiative) temperatures of all facets, not just those seen from one perspective such as airborne nadir surveys by combining nadir and off-nadir observations of surface temperature from aerial surveys and ground-based vehicle traverses measuring wall temperature. A wide range of surface temperatures due to shading effects within the urban canyons was observed. There was also a significant difference between nadir/off-nadir remotely sensed

data and the combined data used to estimate the "complete urban surface temperature" with consequent implications for urban sensible heat flux calculations using remotely sensed data.

Voogt and Oke (1998) continued their research into observation of the surface radiative temperature with a paper detailing the methodology and difficulties of using side-looking infrared radiometers mounted on the back of a truck to sample the temperature of urban canyon walls that was considered necessary to represent the complete urban surface temperature from their earlier work (Voogt and Oke 1997). The vehicle traversed the field site and logged the radiative temperature at regular intervals (generally 4.76m if travelling at 34kmh⁻¹). One of the main practical difficulties encountered was that a portion of the radiometers field of view (FOV) was sky if the FOV included a wall edge, which would cause an anomalously low recording, although this artefact was removed during data analysis. However, the lack of knowledge of the exact materials present in the FOV (i.e. not

instantaneous FOV since the instrument was recording for 0.5s whilst in motion) at the time of observation remained a source of uncertainty.

As found in similar studies (e.g. Sun and Mahrt 1995b) significant spatial variations in surface temperature were found due to shading from direct solar radiation as well as strong temporal variations in wall temperatures due to solar loading, leading to the recommendation of caution to be taken in the extrapolation of data from single canyon studies to larger scales. The effect of view angle on estimating surface radiative temperature was highlighted, with different angles having a different pattern of temperature throughout the day due to the effects of canyon and solar geometry. This difference was noted for its implication on biases in remotely sensed surface temperature when a complete urban surface temperature is desired for realistic sensible heat flux estimates (Voogt and Oke 1997).

2.1.2 Incorporation of street canyon geometry into heat flux modelling

In general form, a flux can be calculated by equation 3:

$$Flux = \frac{k(gradient)}{R}$$
(3)

Where k is a constant and R is the resistance to transfer along the gradient, hence this equation is the basis for flux calculation using "resistance notation" and is widely used in the literature involving heat flux.

The importance of street canyon geometry in mesoscale modelling was recognised by Masson (1999) who presents a surface scheme (the Town Energy Balance or TEB) for mesoscale modelling designed to be suitably general to be used with any city in the world, irrespective of latitude. Consequently, the scheme includes the effect of snow cover, standing water and anthropogenic heat and water sources as well as solar input.

The scheme uses the resistance method for sensible heat flux estimation, with the magnitude of the resistance to heat exchange between the canyon surface and air derived from Rowley et al. (1930) and Rowley and Eckley (1932). Only the horizontal and vertical canyon wind speed is necessary to calculate the resistance. For simplicity, the resistance is assumed to be the same for both road and walls. The resistances are illustrated in figure 2. One omission of this

generalised scheme is the difference in wall temperature due to solar loading, so inaccuracies are expected when using this model in the microscale environment with asymmetric solar forcing as wall and road temperatures are only given one value, although this microscale asymmetry will become unimportant at the larger (city) scale assuming a near-even range of street canyon directions causing this microscale asymmetry to be averaged out.

The TEB scheme derived by Masson (1999) was tested by Masson et al. (2002) using a dry



Figure 2: Resistances used in Masson's TEB scheme. w, r and "can" denote wall, road and canyon respectively. (After Masson 1999).

urban area with "simple" canyon geometry. The aerodynamic resistance formulation was modified for improved accuracy, with the formulation derived by Rowley et al. (1930) and Rowley and Eckley (1932) being replaced by a roughness length formulation for the road surface-air heat flux, but the former was still used for the wall surface-air calculation. This modification was shown to produce realistic values of heat flux in accordance with observations despite the unconventional choice of 50mm as the road roughness length for momentum that is usually considered to be much smaller (Masson et al. 2002). This value was chosen to incorporate the approximately 1m high

obstacles (cars etc) in the road and therefore assumes a consistently busy road. In addition, no direct anthropogenic heat flux was prescribed as the instruments used to measure the net, sensible heat and latent heat measurements included any effect of anthropogenic sources. The TEB scheme was generally found to be robust and reliable, with the model being most sensitive to changes in roof characteristics and incoming solar radiation.

Sensible heat flux was calculated using a radiometer (for radiative surface temperature) and eddy correlation by Grimmond and Oke (1999) in their investigation of heat storage in urban canyons. The storage heat flux component of the surface energy budget was found to be significant in urban areas, affecting the diurnal pattern of sensible heat flux as a result of the

release of stored heat from the urban materials. This result is in agreement with earlier studies on urban surface energy budget such as Carlson and Boland (1978) who concluded that thermal inertia (with associated storage heat flux) and moisture availability were the two dominant influences on the urban diurnal temperature pattern. Storage heat flux contributes to the urban heat island effect, with sensible heat flux continuing to be positive (i.e. outgoing) for most of the night, or even throughout the night and into the following morning (Grimmond and Oke 1999).

2.1.3 Use of resistance divisions in the urban surface layer

The bulk heat transfer approach to calculating sensible heat flux was used by Voogt and Grimmond (2000) aiming to model surface sensible heat flux using surface radiative



Figure 3: Resistances used in modelling urban sensible heat flux using surface radiative temperature and the bulk heat transfer approach from Voogt and Grimmond (2000). See text for notation used.

The field site was located in a light industrial area of Vancouver, Canada and the geometry of this urban area was considered suitable for initial model formulation due to its comparative simplicity. As with earlier campaigns (Voogt and Oke 1997, 1998) surface radiative temperature observed by aerial and ground-based vehicle traverses was combined to estimate the complete surface radiative temperature (i.e. combination of horizontal and vertical facets). Values of kB^{-1} were obtained using three methods for an independent assessment, firstly by the excess

temperature and derived resistances (figure 3).

resistance compared to aerodynamic resistance for momentum (therefore requiring the knowledge of sensible heat flux to generate back-calculated resistance values), secondly by using theoretical values for bluff-rough surfaces (ground including obstructions to wind flow which have bold, regular geometry with a rough surface such as buildings) (Brutsaert 1982) and thirdly by determining the roughness length for heat for isothermal and anisothermal cases. The results were shown to generally agree with the bluff-rough theory although they accounted for the high end of the range.

Values of kB^{-1} were in the range of 13-27, which is considerably higher than those estimated by Stewart et al. (1994) over semiarid areas, implying that the urban geometry and materials significantly decrease the sensible heat flux compared to more vegetated, smooth surfaces. The affect of using "complete" surface radiative temperatures over more traditional aerial nadir temperatures was to reduce kB^{-1} by 3-6, which was a significant fraction of the absolute value.

A conclusion of Voogt and Grimmond (2000) is that the methods of kB^{-1} estimation can be used to produce first-order estimates of sensible heat flux but the definition of "surface temperature" (i.e. complete or simply nadir-surveyed temperature) must be considered, as should be diurnal variability of the model parameters, particularly kB^{-1} itself.

2.1.4 Urban parameterisation using standard meteorological observations

Observations of turbulent heat fluxes in urban areas were used by Grimmond and Oke (2002) to create a scheme that may be used by operational mesoscale models to account for urban terrain and associated structure of the boundary layer (figure 4). The scheme called Local-Scale Urban Meteorological Parameterisation Scheme (LUMPS) uses simple equations and standard observations made by meteorological stations along with a basic knowledge of surface cover to produce realistic outputs of urban sensible heat flux. A further model, as used in the LUMPS scheme to account for storage heat flux, is the OHM (objective hysteresis model) of Grimmond et al. (1991). The OHM requires additional measurements of the local-scale net all-wave radiation. Sensible heat flux is found to represent 40%-60% of daytime net all-wave radiation in residential sites, with storage heat flux being more dominant in the downtown and light-industrial areas of the city (at least 50% of daytime net all-wave radiation) with much more of the net radiation used to heat the urban materials in the morning after the nocturnal emission of stored thermal energy that sustained the outgoing sensible heat flux after sunset.



Figure 4: Layers used in the LUMPS parameterisation scheme (from Grimmond and Oke 2002)

The dependence on knowledge of net all-wave radiation as an input to schemes such as LUMPS is addressed by Offerle, Grimmond and Oke (2003) with their research into parameterisation of net all-wave radiation for urban areas. The method, of using a regression model and an urban canopy-layer model that accounts for urban canyon geometry, was compared to the proposed net-all wave radiation parameterisation (NARP) scheme. The regression model showed significant scatter compared to NARP and the more complex canopy model, even when the effects of clouds were omitted. However NARP and the more complex canopy model produced similar estimates of net all-wave radiation for the urban area if observations of downwelling radiation were also used as an input.

2.2 Critical analysis of discussed literature

It would appear that there is sufficient evidence (e.g. Mascart et al. 1995, Sun and Mahrt 1995a, Voogt and Grimmond 2000) that the earlier assumptions made by Carlson and Boland (1978) and Louis (1979) of equal roughness lengths for heat and momentum is not acceptable for urban heat flux modelling, due to the different (bluff-rough) characteristics of urban surface and geometry compared to that of more rural locations (Brutsaert 1982). Indeed, the difficulty in estimating the roughness length for heat, as required when using surface radiative temperature, has lead some researchers to the conclusion that surface radiative temperature is not very useful for calculating sensible heat flux (Stewart et al. 1994) although this opinion appears to be in the minority for modern research. There is also evidence that the assumption used by the majority of urban flux models that the roughness length is independent of the flow

may also be incorrect (i.e. the roughness length for momentum in an urban environment is a function of wind velocity over obstacles and not just their average heights (Sun and Mahrt 1995a)) although this omission is unlikely to be a major source of error.

Spatial averaging will omit the microscale variations apparent in urban areas and therefore the heat flux from individual street canyons may not be accurately represented. This problem is identified in many urban campaigns (e.g. Grimmond and Oke 2002, Carlson and Boland 1978) with the heterogeneity of urban terrain being spatially averaged to model a more local-scale diurnal response at the expense of the often highly variable microscale detail observed in individual street canyons. Although this problem is recognised by research such as Grimmond and Oke (2002) as necessary to prevent model over complexity and input data amount, the models would tend to average out microscale extremes and it is these extremes that may have the greatest impact on urban planning and human comfort.

Since many near-instantaneous observations of surface temperature over a large area of urban terrain are required for local-scale models such as the LUMPS scheme (Grimmond and Oke 2002) the surface characteristics within the field of view comprising an individual data point are generally not known since careful inspection of the surface in the individual footprints would be too time consuming. Therefore a quick, generalised method of distinguishing between different surface components in the instruments FOV must be used. The method chosen by Voogt and Grimmond (2000) used a limiting temperature to distinguish between shaded and sunlit walls. However, this method was subject to misclassification such as if walls were initially heated by direct sunlight in the morning but shaded in the afternoon, they may still have had a sufficiently warm surface temperature when shaded to be classified as in direct sunlight, introducing errors in the microscale variability classification scheme. Although the authors were aware of this problem, it identifies the difficulties caused when compromising between resolution and speed of data acquisition when the requirement is to identify microscale features from large instantaneous fields of view (such as aerial surveys).

A similar problem occurred with vehicle traverses measuring wall radiative temperature (Voogt and Oke 1998) where sky in the instrument's FOV caused anomalously low temperature recordings. This was another example of the problems caused by not knowing the radiometer's FOV for individual recordings, adding to the lack of reliable microscale detail and consequent need to generalise.

The effective anisotropy of surface radiative temperature observations is an important feature in urban meteorology (Voogt and Oke 1997) due in part to the bold geometry of surface features such as buildings. Therefore the view angle of remotely sensed data must be taken into consideration when observing an urban environment, although this consideration was not accounted for in more rural studies such as Sun and Mahrt (1995b) even though trees may be similar to buildings in their range of surface orientations. However, the temperature difference between sunlit and shaded tree sides was less than that observed for urban walls (Voogt and Oke 1997) producing a less marked effective anisotropy of surface radiative temperature.

This meant that the advantage using a microscale variability approach as suggested by Voogt and Oke (1997) is less important for rural studies as the increased complexity of observations required to produce a "complete" surface temperature may not be worthwhile as a simple nadir-view may be sufficiently representative.

Although the presence of anthropogenic heat flux is recognised, it appears to be neglected in the formulation or set to zero in many urban models (Carlson and Boland 1978, Grimmond and Oke 2002, Masson et al. 2002). The reason for this exclusion may be due to its expected relatively unpredictable nature but may also be neglected as a value in its own right as it is already accounted for by instruments of latent and sensible heat flux (Masson et al. 2002).

However, the omission of anthropogenic heat flux during the morning commuter activity was suggested as a reason for TEB model inaccuracy in Masson et al. (2002) despite the model having the ability to account for anthropogenic heat flux (Masson 1999) therefore implying the assumption that instruments measuring latent and sensible heat flux alone was insufficient to account for all of the anthropogenic heat input. Furthermore, the paper gives an example of the findings of Ichinose et al. (1999) that traffic-induced heat flux in downtown Tokyo reached 60Wm⁻², which would represent a significant fraction of the total observed heat flux if the urban area to be modelled had an anthropogenic heat flux of this magnitude, especially at night or on days with low solar input.

Grimmond and Oke (2002) considered inclusion of an anthropogenic heat flux to be unnecessary in their LUMPS model due to its expected minor contribution to the heat flux in the study area as well as their assumption that the instruments used to measure the fluxes were likely to sense the anthropogenic contribution in the flux measurements, which would therefore be inferred in the parameterised terms that use the results. However, the authors do note that this assumption may not be valid for urban areas expected to have high anthropogenic heat fluxes, although no model appears to account for the expected diurnal (or otherwise) variation of anthropogenic heat flux.

Advection is also often neglected in the discussed models although many are derived with the ability to incorporate an advective term if necessary (Masson et al. 2002), primarily as it would greatly increase the complexity (Carlson and Boland 1978) and the net advective flux may be neglected for a homogeneous flux source area (Masson et al. 2002).

The simple model described by Carlson and Boland (1978) appears to be the only model encountered with a daytime mixed layer included above the surface layer that is modified at night to allow downward heat transfer through the stable nocturnal surface layer to improve radiative balance. However, Grimmond and Oke (1999) find that sensible heat flux can remain positive throughout the night implying that a stable surface layer often seen in cloudless rural locations may not be representative of urbanised areas with high storage heat flux, thereby making the mixed layer inclusion of Carlson and Boland (1978) redundant for situations where a stable nocturnal surface layer does not occur.

Using the microscale variability method to calculate the "complete" urban surface temperature, some models calculate the complete surface radiative temperature by weighting the temperature of the component types by their area-fraction within the study area (e.g. Voogt and Grimmond 2000). Although this would be the logical method of assessing the average surface radiative temperature, it is unclear as to whether this linear proportionality is valid for the resultant heat flux, as no account would be taken for dynamical effects such as increased efficiency of turbulent heat flux by organisation of convective cells, including plume combination (Stull 1988), although the existence of long-lasting turbulent structures in an otherwise more sporadic turbulent urban surface layer, as well as the coupling of this surface layer to the overlying boundary layer where the convective plumes exist is subject to ongoing research.

2.3 Suggested future work in the field of urban heat flux modelling

Ground (storage) heat flux is a component of the surface energy balance that is directly linked to surface sensible heat flux with the atmosphere as one may increase at the expense of the other (Carlson and Boland 1978). The significance of the large heat storage by large stone buildings in Mexico City was found in heat flux research by Oke et al. (1999). However, the influence of long-term changes in the ground heat flux (with consequences for the sensible heat flux) due to changing urbanised terrain does not appear to be addressed in the literature. For instance, the effect of the construction of underground railways and subways on the microscale (or perhaps even local scale) distribution of surface heat flux may be of interest to town planners. The large-scale extraction of ground water beneath large urban areas such as London will alter the heat capacity and conduction of the ground and may therefore have larger-scale consequences on the surface heat flux component.

The influence of attenuation of short and long wave radiation by airborne particles frequently found in urban areas has been investigated and included in heat flux models (e.g. Carlson and Boland 1978) however, modern models such as LUMPS (Grimmond and Oke 2002) do not have a separate input for such particles since net all-wave radiation is measured directly or parameterised using measured or modelled solar radiation (e.g. Grimmond and Oke 2003). However, a thick (and spatially variable) concentration of pollutant close (1-10m) to the ground may have a considerable influence on the surface radiation balance that may not be accounted for if the measurements are taken above this layer.

For instance, at the study site the author observed that the intensity of thermal infrared radiation ("sky temperature") measured by an upward pointing handheld infrared radiometer at ground level on a relatively highly polluted London road appeared to be considerably more variable on scales of less than one minute than if the measurements were taken on a rooftop 14m above the surface, where a more consistent value was observed.

This may imply that the knowledge of incoming short wave solar radiation and surface radiative properties required for the urban models may neglect the influence (or even existence) of a near-surface distribution of particles (pollution) that influence long wave radiation at vertical scales too small to be resolved by the local-scale models. This effect of near-surface modification of the long wave radiation surface energy component may be likened to the more widely considered influence of short wave radiation attenuation by clouds. However, it is unclear as to how well represented this mechanism is by changes in air temperature, which is already an input variable to the models under investigation. This

suggests a possible topic of future investigation, especially if the effect of pollution on microscale heat fluxes is to be considered.

Heat flux during unsettled weather is an observation rarely found in the literature, with Masson (2000) commenting that there had been no recording of heat fluxes during precipitation other than a brief rain shower, with cloud not considered in most model sensitivity tests such as Carlson and Boland (1978). Therefore, future work may be directed towards these observations, especially considering the frequent occurrence of precipitation (both rain and snow) over urbanised areas in high and mid-latitudes and the regular heavy showers affecting low-latitude cities. Other meteorological conditions such as dew/frost and fog may produce interesting results as well as considering thermal absorption by water vapour as well as latent heat effects.

An objective of urban heat flux research is to implement a suitable scheme to allow more accurate representation of urban areas in operational mesoscale forecast models (Mascart et al. 1995, Masson 1999 and Grimmond and Oke 2002). Obviously it is not feasible to include the entire range of urban area sizes in such models (i.e. the inclusion of every small town and village). However, the required size of an urban area before its influence should be included is not defined in the literature. This threshold of minimum influence is likely to depend on the contrast of factors such as heat storage, roughness length and moisture availability (Carlson and Boland 1978) between the urban site and adjacent rural terrain. However, this contrast is likely to have a seasonal variation (at least in mid to high-latitudes) as well as diurnal changes, so this threshold may have to vary likewise.

Although urban heat flux models do not generally consider advection as a significant factor (as mentioned in the previous section) no discussion has been found in the literature of the effect (if any) a turbulent wake produced by an urban area (Oke 1987) has on the heat flux of downwind (rural) terrain. Although this urban wake will be elevated and diluted with increased fetch over the downwind terrain (Stull 1988) this advected turbulence would still influence sensible heat flux as the layer would inevitably be coupled to the surface layer for a certain downwind distance. Presumably the size of an urban wake (not just the city) may also be a factor that will influence which urbanised areas are above a minimum threshold of significance to be included in a mesoscale model.

3 Experimental Methodology

3.1 Site Location

The aim of the fieldwork was to measure air and surface radiative temperature at sample positions within a selected field site. These temperature measurements were combined with wind velocity data to produce estimates of surface sensible heat flux.

The site that will be used for this investigation was located in central London, UK containing two major road junctions of Marylebone Road with Gloucester Place and Baker Street (figures 5 and 6). The site was chosen principally as it was already under investigation by researchers into air pollution as part of the DAPPLE (Dispersion of Air and Pollution and their Penetration into the Local Environment) project so consequently had equipment useful to the study of heat flux (such as temperature loggers and sonic anemometers) already positioned at the field site. Furthermore, the site is a good example of an urban environment easily accessible from the author's location and includes an "urban canyon" (Oke 1987) of regular geometry (Bickenhall Street) convenient for primary data collection and subsequent modelling.

Once the field site was identified, the individual sampling sites were chosen. These were the points at which the main air and surface radiative temperatures were to be recorded and therefore should be placed with roughly equal separation to be spatially representative of the whole field site area. Twelve regularly spaced sites were chosen in total, covering the two main road junctions and the Bickenhall Street canyon (figure 6). Although more sites would have been preferable, the amount and spacing of the chosen sites was limited due to the time needed to individually survey the site in the hourly frequency interval required. Thus the emphasis was based on sampling the characteristic areas of the site such as sheltered canyons, open junction, quiet and busy roads etc. whilst maintaining an adequate resolution considering the time and data available.

The sonic anemometer used for the wind velocity sampling of the field site was located on the rooftop of a building within the field site.



Figure 5: Field site location in central London



Figure 6: Detailed plan of the field site and location of the twelve sampling sites (road width increased for display purposes).

3.2 Site physical characteristics

Throughout the field site the pavements are constructed of concrete and the roads of asphalt. The field site can be separated into four roads, each containing at least three sampling sites. The characteristics of these four adjoining roads will now be briefly described (see figure 6 for reference).

3.2.1 Marylebone Road (Sites 1, 10,11 and junction Sites 9 and 12)

Marylebone Road is a busy, wide road consisting of three lanes of traffic on each side. Due to its almost east-west orientation, the pavement along the southern side of the road (where the sampling sites are located) is shaded by buildings and trees for most of the day, except at the junctions (sites 2,12 and 9). A brief description of the six individual sites located along this road follows:



Figure 7: Site 1

Site 1: This site is located outside the council building on Marylebone Road. The pavement is adjacent to large stone steps leading up to the building's entrance. Beyond the pavement is a parking bay and bus lane before the main road. The council building is approximately 16m tall and consequently shades the pavement until 1430 UT. (Picture taken at 1130 UT).



Figure 8: Sites 10 and 11 (looking west)

Sites 10 and 11: These sites experience shading from a row of trees between the wide pavement and building (Bickenhall Mansions) as well as shade from the building itself in the morning (picture taken at 1430UT). There is a bus lane between the pavement and the main road.



Figure 9: Site 9

Site 9: Located at the junction of Marylebone Road and Baker Street, with sampling taken in the Marylebone Road portion of the junction. This site is approximately five metres from any building and therefore has good exposure. The junction experiences heavy traffic on both sides. (Picture taken at 1130 UT).



Figure 10: Site 12 looking from Site 2

Site 12: Although at an open junction similar to that of site 9, the pavement of this site was shaded until early afternoon by a large tree, although the road was mostly exposed to direct solar radiation ("SITE 12" in figure 10 identifies the point where the road temperature was measured). Picture taken at 1130 UT.

3.2.2 Gloucester Place (Sites 3,4 and junction Site 2)

Although not as busy as Marylebone Road, this wide three lane one-way road was in almost constant use (the majority being buses and taxis), although the traffic was stationary about half of the time due to a pedestrian crossing before the Marylebone Road junction (as seen in figure 11). A brief description of the three individual sites located along this road follows:



Figure 11: Site 2

Site 2: The site at the junction between Marylebone Road and Gloucester Place, with sampling taken on the Gloucester Road portion of the junction. A busy junction with an active pedestrian crossing and therefore often experiences stationary traffic. Partially shaded by a tree and the edge of the council building.



Figure 12: Sites 3 and 4

Sites 3 and 4: These sites are exposed to direct solar radiation in the morning but are shaded by the council building in the afternoon. The small road joining Gloucester Place at site 4 was rarely used compared to the main road. Red "SITE" positions on figure 12 are where pavement temperatures were measured. Picture taken at 1130 UT.

3.2.3 Bickenhall Street (Site 6 and junction site 5)

This street is enclosed by identical tall buildings (Bickenhall Mansions) forming a regularly shaped urban canyon. The road is rarely used compared to adjoining roads but has parked cars on both sides. Due to the east-west orientation and the relatively narrow (two-lane) road, the northern side of the road is kept shaded until about 1430UT (with the northern pavement experiencing direct solar radiation before this and the northern wall being exposed to direct solar radiation until the evening). However, the narrowness of the road and height of the surrounding buildings means that the southern half of the road, pavement and southern wall are kept in shade throughout the day, so the canyon is never totally exposed to direct solar radiation. The ends of the canyon are exposed to direct solar radiation due to the increased

exposure, especially site 7 (Baker Street junction). This is called the "sky view factor" in most literature.



Figure 13: Site 5

Site 5: Located at the junction of Bickenhall Street and Gloucester Place, this site has relatively good exposure away from the direct of influence the tall walls surrounding Bickenhall Street canyon. Subject to direct solar radiation after mid morning (pavement exposed before road). Picture taken at 1130 UT.



Figure 14: Site 6

Site 6: The site representative of the middle of the Bickenhall Street canyon. Experiences direct solar radiation after mid morning as located on the northern (south facing) side. It is at this site that the northern and southern wall radiative temperatures are measured. Generally calmer winds as less exposure and traffic than the other sites. Picture taken 1130 UT.

3.2.4 Baker Street (Sites 7 and 8)

This one-way (eastward only) road is similar in size and traffic intensity to Gloucester Place, although the majority of traffic was cars, not buses. The road has generally good exposure due to its width and relatively short surrounding buildings. The pavement is busy (in contrast to Gloucester Place) due to the street's roadside shops, stalls and open-air cafés.



Sites 7 and 8: The junction of Baker Street with Bickenhall Street (site 7) is exposed to direct solar radiation throughout the day, although the nearby buildings shade site 8 during the afternoon. Small trees line the road but do not directly shade the two sites. Picture taken at 1130 UT.

Figure 15: Sites 7 and 8 (looking south)

3.3 Equipment Used

The primary data was collected using two instruments - a handheld infrared radiometer (Raytek ST 20 Pro) for radiative surface temperature measurement and a handheld multisensor data logger (Kestrel 4000) including a thermistor thermometer and impeller anemometer for measurement of air temperature and wind speed. In addition, data from a sonic anemometer installed for the DAPPLE project was available (illustrated in figure 16).

The accuracy of the infrared radiometer is given as $\pm 1^{\circ}$ C for the range of temperatures experienced on the site (with a 0.2°C display resolution). Emissivity is pre-set at 0.95 (reasonable for this study as 0.95 was also used for road emissivity by Masson et al. (2002)). The instrument has 12:1 optics, implying that 90% of the energy received at a distance of 12 metres would be from a circular field of view (FOV) of 1m diameter about the focal point. Response time is quoted as 500msec for 95% of the reading.

Recent field campaigns to study the surface temperature of an urban area have successfully used handheld infrared radiometers to provide some guidance as to the thermal conditions of the site (e.g. Masson et al. 2002), although the point measurements do not necessarily provide a representative sample of all facets found within the local-scale turbulent source area

(Masson et al. 2002) due to the widely varying geometry and surface materials found in street canyons.



Figure 16: Equipment used on the field site (left to right: Raytek ST 20 infrared radiometer, Kestrel 4000 (actual size 126mm by 45mm), data logger and sonic anemometer (approximately 60cm from top to base). The sonic anemometer pictured was not the instrument used on the rooftop but is of identical design).

Infrared radiometers mounted on a vehicle that traverses the road network have been also been used to successfully measure adjacent building wall temperatures (Voogt and Oke 1997 and Voogt and Grimmond 2000) although the lack of knowledge of the instantaneous field of view from the moving instruments makes interpretation of results difficult and requires extra data assimilation (Voogt and Oke 1998).

The thermistor thermometer on the Kestrel 4000 has an accuracy of $\pm 1^{\circ}$ C (with a display resolution of 0.1°C) and an on axis (wind direction parallel to axis of rotation) accuracy of 0.1ms⁻¹ for the impeller anemometer, which can operate at speeds upward of 0.3ms⁻¹. The typical response times for the thermistor and impeller are 1 minute and 2 seconds respectively.

Sonic anemometers are considered to be one of the most accurate ways of determining accurate, reliable measurements of high frequency changes in the three-dimensional wind field required for turbulence research. The sonic anemometer used at the field site was a Research R3 manufactured by Gill Instrument Ltd. The reported accuracy is less than $\pm 1\%$ RMS (root mean squared) of the windspeed (up to 32ms^{-1}) equating to a maximum error of $\pm 0.05 \text{ms}^{-1}$ at 5ms^{-1} , which is expected to be suitable for this investigation.

3.4 Observational Procedure

Measurements of pavement and adjacent road (i.e. between the pavement and mid-road marking) radiative temperatures and air temperature (measured 1m above the pavement) were recorded at each sampling site. Radiative temperatures were observed for approximately ten seconds (well in excess of the instrument's response time) to make sure the values were stable and representative of the site. If the road was experiencing heavy traffic then it was found that each passing vehicle caused a temporary (less than three second) increase in road temperature (believed to be due to the frictional effect of the vehicles hot tyres) then the measurements were taken in gaps in traffic when the values were more stable. It was also noted that vehicle exhaust produced a temporary increase in observed surface temperature since the hot gasses come between the surface and the radiometer (causing values in excess of 100°C) so this was also avoided.

The air temperature was recorded over one minute upon arriving at the site, making sure that the instrument had adequate response time and to ignore any temporary anomalies. Care was taken to avoid the instrument experiencing direct solar radiation on the thermistor or casing as this may have produced an overestimate of the site's air temperature, as did blasts of hot exhaust gasses from large vehicles such as busses. The instrument was held at arm's length with hands as far from the thermistor as possible (usually by a short lanyard to avoid body heat contamination), at approximately one metre above the surface.

Radiative surface temperature of the north and south facing walls of the Bickenhall Street urban canyon (site 6) were recorded in addition to the standard observations at site 6 by pointing the radiometer at a section of the wall approximately half way up the building. Unlike the more spatially uniform response from the pavement and road, the range of different angles and building materials on the sunlit wall caused difficulty in obtaining a constant measurement, especially as the field of view was approximately 36 times larger due to the increased distance, at approximately 6m from radiometer to middle of the wall but only 1m between the radiometer and ground. Choosing a specific site on the walls to measure on
all occasions was expected to reduce the potential inconsistency. This problem was also recognised by Voogt and Oke (1997).

The fieldwork was conducted on the 30 April and 18-19 May 2004, with the majority of data collected in the latter two days. The meteorological conditions experienced on the 18 and 19 May were similar (due to the presence of an anticyclone), being generally clear with scattered cumulus appearing at 1100 UT on 18 May but not until 1500 UT on the 19 May. In contrast the conditions on the 30 April were overcast with intermittent rain. However, only one survey of the field site was conducted on this date.

Since at least one minute was spent at each sampling site, the author took approximately 15-20 minutes to complete one survey of the complete field site. Consequently the field site was sampled every hour between 0800 UT and 1700 UT (Sunrise at London on 18 May was 0406 UT and sunset at 1954 UT) to obtain a time series of daytime temperature variation. A complete 24 hour survey was considered impractical considering the objectives and time allocated for the completion of the investigation as well as the practical difficulties associated with conducting a regular night time survey. Although other field campaigns measuring urban surface temperature used a sampling interval of 15 minutes (such as Grimmond and Oke 2003) the hourly interval was expected to allow the general daytime trends to be observed.

Measurements were manually logged on a data sheet along with any significant observations (such as cloud cover and occurrence of direct sunshine) before being inputted into *Microsoft Excel* for analysis.

4 Results of Fieldwork

The observations of road and pavement radiative surface temperature and one metre air temperature for the two main fieldwork days (18 and 19 May 2004) are shown graphically in this chapter. The graphs show hourly temperature variations of the two days. Lines corresponding to the twelve individual sampling sites have not been distinguished as they are used to indicate the degree of spread throughout the field site in order to give the reader an overview of the across-site trends, with the red line indicating the average. Characteristics of individual sampling site graphs will be discussed later.

In general, the results obtained on the two days are in good agreement due to the similar prevailing meteorological conditions (a quantitative account of the differences between the two days is given later in this chapter).

4.1 One Metre Air Temperature

The hourly trend of air temperature is somewhat different to that expected for a rural location with a noticeable decline in afternoon temperature, with the field site experiencing little change in (site-averaged) afternoon temperatures between 1300 UT and 1700 UT after a more rapid increase throughout the morning (figures 17 and 18). Air temperatures seem to follow the same general trend across all the sampling sites with small differences in observed temperature compared to the road and pavement observations. There is a broader spread from the 0800 UT measurements, reaching a peak in sampling site temperature spread around 1200 UT before the spread becomes more confined after 1400 UT. This can be seen in the standard deviations of tables 3 and 4 and will be discussed in more detail further in this chapter.

Since the air is heated by the surface, it is not surprising that the broad maximum occurs around the time of peak solar heating, especially as the windspeed was generally calm allowing significant heating from the surface directly below the measurements. Continued heating of the air from radiation of stored heat in the urban materials during the afternoon could explain why there is only a gentle decline of air temperature after the maximum value.

Although the source of heating is the surface, the difference between surface temperature and air temperature is believed to be a result of horizontal advection of heat, therefore reducing microscale anomalies and creating a more evenly distributed air temperature field, although the effects of shade and/or canyon geometry are believed to have an effect on the specific sample site air temperature, causing deviations from the field site mean.



Figure 17: Sample site air temperature (grey) with time and site-average (red) for 18 May 2004.



Figure 18: Sample site air temperature (grey) with time and site-average (red) for 19 May 2004.

4.2 Pavement Temperature

The most noticeable feature of pavement surface temperature is the broad range of values at the twelve sampling sites, especially during 19 May (figure 20). Although there is variation in the shapes of the individual sampling site graphs, the average indicates a general peak in temperature around 11-1200 UT on both days, although a secondary peak is apparent at 14-1500 UT on the 19 May, with a narrowing of the spread occurring afterwards. An increasingly narrow spread of values was also apparent on 18 May (figure 19) beginning earlier in the day, from around 1300 UT.



Figure 19: Sample site pavement temperature (grey) with time and site-average (red) for 18 May 2004.

The reason for this broad range of pavement temperature is likely to be due to shading effects, since the thermal energy gained by the surface can not be freely advected like that stored in the air to create a more even distribution such as in figure 17. Also, since the surface is a much more effective absorber and converter of incoming solar radiation into outgoing thermal radiation than the air which is near-transparent to visible wavelengths, the maximum temperature of the surface exposed to direct solar radiation greatly exceeds that of the adjacent 1m air temperature (causing the large temperature gradient and consequent heat flux between the surface and atmosphere).

The narrowing of sample site pavement temperature distribution towards the evening is expected to be a result of reduced differential heating across the field site with the decrease in solar radiation. The excess heat gained by the warmest pavements during the day produces a larger heat flux than the cooler ones, causing the more rapid cooling rate seen on both days, with the coolest pavements actually increasing in temperature towards the evening due to conduction (expected to occur on timescales of a few hours due to the thickness and relatively low conductivity of concrete) of heat stored in adjacent warmer surfaces (such as the road). This late afternoon reduction of spatial surface temperature difference is also seen in the 1m air temperature due to the mixing of thermal energy as previously discussed.



Figure 20: Sample site pavement temperature (grey) with time and site-average (red) for 19 May 2004.

4.2.1 Time Difference of Pavement Maximum Temperature

Different times for sample site pavement temperature maxima are illustrated using figure 21 for the mainly clear day of 19 May 2004. The large council building shades the pavement at site 1 until 1400 UT, when forcing by direct solar radiation produces a maximum surface temperature an hour later. However, this maximum value is small compared to other sample sites as although the rate of heating is comparable to other sites exposed to direct sunshine, the solar radiation weakens before sufficient thermal storage can be gained. The outward heat flux exceeds the dwindling incoming radiative energy and the temperature drops in accordance with the rest of the site. Afternoon shading occurs at site 8 and therefore the pavement temperature reaches a maximum value in the morning, before decreasing in the

shade, rapidly at first, then more gradually as the surface temperature approaches the area average in the afternoon (by radiative loss and conduction from adjacent warmer areas). However, the pavement at site 7 is exposed to direct sunshine throughout the day and therefore has a more symmetric, sinusoidal temperature pattern, reaching the highest temperature at peak solar input (1200 UT). The lack of an observed lag between peak solar input and pavement temperature suggests that the thermal inertia of the pavement must be less than the sampling frequency (one hour) and further suggests that any extended temperature lags due to the release of stored heat must have originated from sources deeper than the pavement unit itself. Similar reasoning may be applied to the road surfaces.



Figure 21: Times of different surface temperature maxima across the field site due to solar and urban geometry

4.3 Road Temperature

Road temperature displays less variation between sampling sites than the adjacent pavement on both days (figures 22 and 23). This is due largely to the fact that the majority of roads remained sunlit, where as shading by nearby buildings tended to affect the pavement instead (except in the Bickenhall Street canyon), hence the larger temperature range of the pavement. A rapid increase of site-averaged road temperature was experienced in the morning, reaching a broad maximum around 1200 UT and gentle decline during the afternoon. This trend is followed by most (but not all) of the sampling sites. As with air and pavement temperature (and for the same expected reasons), a broader spread of sampling site temperatures was experienced during the morning and narrowing of the spread in the afternoon, with a smaller range of sampling site temperature at the end of the survey (1700 UT) than the beginning (0800 UT). However, this broadening of the spread is less marked due to the majority of roads being subjected to a similar amount of solar forcing thus causing less spatial temperature variation, especially on the 18 May (where afternoon cloud cover would have meant a more even distribution of solar radiation across the field site).



Figure 22: Sample site road temperature (grey) with time and site-average (red) for 18 May 2004.



Figure 23: Sample site road temperature (grey) with time and site-average (red) for 19 May 2004.

4.4 Bickenhall Street Canyon (Site 6) Wall Temperature

In addition to the standard air, pavement and road temperatures recorded at sampling site 6, the temperature of the north and south walls of the Bickenhall Street Canyon were recorded on the 18 and 19 May survey days (see figure 24 for an illustration of the canyon).

Unsurprisingly, the northern (south facing) wall measured consistently higher radiative temperatures than the shaded southern wall, with the greatest temperature difference coinciding with the peak solar intensity around 1200 UT (figures 25 and 26). The shaded wall had a relatively consistent temperature throughout the day, with the largest change occurring in the morning (a trend characteristic of all observed temperatures). However, both walls have a similar temperature at the end of the survey (1700 UT) when the difference in solar intensity (and therefore energy input) was less.

The overall warmer air and surface radiative temperatures experienced on the 19th were also observed in wall temperature (figure 26), with the 19th being warmer than the 18th on average and larger temperature difference between the two walls. The lack of midday cloud on 19 May also caused a smoother curve of northern wall temperature and a peak at 1200 UT believed to be due to less interruption of direct solar radiation by cloud cover. The warmer than expected 0800 UT measurement on the 19 May is suggested to be due to inconsistency

of radiometer field of view thereby incorporating a warmer surface, as spatial variation of northern (sunlit) radiative temperature was large and consequently sensitive to small changes in radiometer field of view.



Figure 24: The Bickenhall Street Canyon with cross section imposed at the position of site 6. Picture taken looking east from site 4, identifying the sunlit northern and shaded southern walls.



Figure 25: Bickenhall Street Canyon wall temperature with time. Red line indicates north wall (south facing) temperature and south wall (north facing) temperature as blue, for 18 May 2004.



Figure 26: Bickenhall Street Canyon wall temperature with time. Red line indicates north wall (south facing) temperature and south wall (north facing) temperature as blue, for 19 May 2004.

In addition to the data obtained on the 18 and 19 May, the spatial distribution of radiative temperature in the Bickenhall Street Canyon (site 6) was investigated on 30 April 2004. This data is useful as it was measured during overcast conditions therefore omitting the strong thermal bias induced by direct solar radiation. These results can be seen in figure 27.



Figure 27: Cross section of the Bickenhall Street Canyon at 1335 UT on 30 April 2004 during overcast conditions. The red values are radiative temperature in degrees Celsius at the approximate position of radiometer FOV focus. The blue value indicates 1m air temperature. Note that even without direct solar radiation the canyon walls and floor are warmer than the air temperature, assuming radiative temperature is equal to the actual surface temperature. A difference would occur if wall emissivity was not 0.95 (the fixed emissivity of the radiometer) which may be the case as Masson et al. (2002) used values of wall emissivity between 0.85 and 0.90 corresponding to a difference of 8K with a 300K actual temperature if emissivity was actually 0.85, not 0.95. However, this should not affect the general shape of the time series and absolute values were not required in either of the heat flux models considered in later chapters.

Both canyon walls are of near-uniform temperature (which may be considered uniform if the accuracy of the radiometer is taken into account) with the road and pavement (canyon floor) being consistently 0.4-0.8°C cooler. It is unclear whether the 0.4°C difference between the northern and southern pavements represents a physical difference or instrumental error but all measurements were tested on site for stability and general spatial conformity so it is suggested that despite the diffuse solar radiation there may still be a small difference between northern and southern (shaded) canyon areas.

The higher temperature of the canyon walls may be due at least in part to anthropogenic heating as the building is occupied. This anthropogenic heating may also mask any temperature differences due to wall orientation such as those inferred on the canyon floor.

4.5 Effect of traffic on road temperature in overcast conditions

The variation of surface temperature across both lanes of Marylebone road was observed 30 minutes after the survey of the Bickenhall Street canyon in figure 27. Two transits were completed using the pedestrian crossings (the eastern crossing being completed a few minutes before the west), with recordings made of pavement and road radiative temperature for both sides of the road, as well as the surface temperature of the island between the lanes. 1m air temperature was also recorded on the islands.



Figure 28: Recorded surface radiative and air temperatures from two crossings of Marylebone Road at 1415 UT 30 April 2004.

From the results displayed in figure 28 it can be seen that the pavement has a temperature similar to the air but there is a significant difference in surface radiative temperature between the air and road. Since the recordings were not instantaneous, the difference in air temperature between the two islands may be due to temporal (not spatial) fluctuation. The more consistent surface temperatures between the same sections of the two crossings are expected to be due to the longer response time (thermal inertia) of the surface than the adjacent air.

The reason for this difference in air/pavement and road temperature can not be attributed to shading effects since the measurements were taken during persistently overcast conditions. Rather, the higher road temperature is expected to be an example of anthropogenic heat transfer as a result of frictional heating by vehicle tyres and direct heating from vehicle exhaust gasses and engine radiation (it was noted that vehicle wheels had a radiative temperature between 18-25°C at this time and location, with exhaust gasses (inferred by exhaust pipe temperature) exceeding 100°C on occasions).

The island in the middle of the road between the two traffic routes was also a degree warmer than the pavement despite being similarly out of direct contact with the traffic. It is suggested that this difference may be due to the island having heat sources on both sides maintaining its temperature above that of the air, whereas the pavement has the heat source on one side only, which may be insufficient to maintain a positive temperature difference with the air before the heat is lost to the air and adjacent cooler surface.

Although the differences in radiative temperature are within the maximum error of the radiometer, the consistency of the results from the two crossings suggests the findings to be

significant. There is also a small increase of radiative temperature on the northern half of the road for both crossings (therefore suggesting that there may be a physical cause and not simply instrument error unless coincidental). The reason for this slight difference may be due to an increased flow of traffic on the northern (towards the east) lanes, with associated increase in vehicle generated heat. Unfortunately, no data supporting this suggestion is available for the crossing times.

4.6 Wind-induced short period air temperature changes

Since the air temperature measurements were recorded only one metre above the ground, the response time of the air to surface heat flux was found to be rapid, especially at times of high surface temperature during prolonged exposure to direct sunshine. Figure 29a shows a three minute log of air temperature and windspeed, recorded every two seconds (although this was less than the response time, the exposed thermistor seemed to be able record a change of temperature within this time, even if the true value may not have been reached. Therefore the measurements should be taken as an indication of air temperature trends rather than absolute values). The results illustrate the dependence on mixing as a regulator of the 1m air temperature, with rapid warming during periods of calm wind when the air is directly heated by the warm surface followed by cooling during breezes as the near-surface air is mixed with cooler air aloft or by horizontal advection from a cooler (shaded) place in the field site (negative correlation seen in figure 29b).

The magnitude of these wind-induced air temperature fluctuations is significant (up to two degrees Celsius between calm and breeze conditions, with the true difference expected to be more since response time was not reached) and confirms the need to measure the average air temperature at each site, especially during times of calm, sporadic windspeed and high surface temperature. It is noted that although the surface was exposed to direct solar radiation this was not the case for the recording instrument (Kestrel 4000), which was kept shaded to reduce radiation errors. Due to the short lag observed in figure 29b between the onset of a breeze and subsequent drop in air temperature, the time taken for the thermistor (which was small and fully exposed to the air) to detect a change in temperature (but not necessarily its absolute value) is considered short but can only be estimated from figure 29b as approximately 6 seconds (in the absence of a controlled laboratory test) as it is with this lag that the section on the graph of minimum correlation begins. This does of course assume that the change in windspeed and temperature actually occur simultaneously in reality.



Figure 29a: Effect of horizontal windspeed (mixing) on 1m air temperature above a pavement exposed to direct sunshine. Recordings were taken every two seconds at site 6 (Bickenhall Street canyon) on 19 May 2004.



Figure 29b: Correlation of lagged 1m air temperature with windspeed at site 6 (Bickenhall Street canyon) on 19 May 2004.

4.7 Quantitative analysis of temperature recordings

The daily averages and standard deviations of air, pavement and road temperatures for each site are given in Table 1 for both of the main survey days. It can be seen that site 7 (junction of Bickenhall Street and Baker Street) has the warmest surface temperatures on both days due to its near-unobstructed exposure to direct sunshine. Since the wind was generally calm during both the survey days, the overlying air that was heated by the high surface temperatures remained near the source, so the warmest air temperatures occurred at or near the warmest surface temperatures.

An interesting result was found in the Bickenhall Street canyon, with site 6 (mid-canyon) having one of the warmest average air temperatures in the field site despite having the coldest average road temperature. An explanation of this is that although the road remained cool relative to the surrounding surfaces, the northern pavement at site 6 was exposed to direct sunshine for most of the day, allowing its temperature to be one of the warmest of the field site. Since the majority of turbulent heat flux would be directed upwards by the action of buoyant uplift, the relatively cooler road apparently caused little effect in air temperature despite its close proximity. However, advection of cooler air collecting over the road by turbulent airflow may have contributed to the relatively large short period air temperature fluctuations seen in figure 29a, with the large standard deviation of hourly air temperature recorded at this site during 19 May being attributed to the correspondingly high variability of surface (pavement) temperature as a result of morning shading followed by afternoon direct solar radiation. Additionally, the close proximity of the warm south-facing wall (figures 25 and 26) at site 6 may have also contributed to the warm air temperature of the canyon.

18-May	Average Temperature (°C)									ALL SITE			
Site No.	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Air	22.0	22.4	22.3	22.4	22.6	22.5	23.2	23.3	23.2	22.4	21.9	21.8	22.5
Pavement	21.2	28.2	28.9	33.0	34.5	33.3	36.3	31.1	33.4	22.9	21.8	25.7	29.2
Road	31.2	30.0	30.7	33.1	28.2	25.6	35.2	30.9	34.2	30.6	30.8	30.9	30.9
			Standa	ard Dev	viation	(°C) o	f temp	eratur	e at ea	ch site	;		ALL SITE
Site No.	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Air	2.2	2.3	2.2	2.2	2.2	2.1	2.0	2.1	2.2	2.3	2.4	2.1	2.2
Pavement	3.9	6.0	6.0	4.4	7.1	6.4	6.2	6.0	6.2	2.6	2.2	4.6	5.1
Road	4.8	5.8	5.6	4.8	6.1	2.6	6.5	6.3	5.8	4.4	4.5	6.8	5.3
19-May					Averag	je Tem	peratu	ire (°C)				ALL SITE
Site No.	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Air	22.1	22.6	23.3	23.4	23.7	24.5	24.9	24.7	24.4	23.3	22.8	22.7	23.5
Pavement	20.2	28.0	29.6	35.4	38.4	39.1	42.8	32.9	37.2	22.4	21.7	27.6	31.3
Road	34.0	31.7	32.8	36.4	30.4	28.5	41.6	33.0	39.0	34.1	34.5	33.3	34.1
	Standard Deviation (°C) of temperature at each site ALL SITE												
Site No.	1	2	3	4	5	6	7	8	9	10	11	12	AVERAGE
Air	2.1	2.2	2.0	2.1	2.5	2.9	2.4	2.1	2.0	2.1	2.0	2.2	2.2
Pavement	6.0	7.4	7.4	6.2	8.9	9.9	6.8	8.0	8.4	2.6	2.1	7.4	6.8
Road	5.3	7.3	8.0	5.5	9.0	6.3	7.2	7.4	6.4	5.6	5.8	9.8	7.0

Table 1: Daily average and standard deviation temperatures at the sample sites and the all

site daily average for the 18 and 19 May 2004. Orange and blue cells represent all site maxima and minima respectively.

30-April	Temperature (°C) on 30 April 2004 at 1300 UT													
Site No.	1	2	3	4	5	6	7	8	9	10	11	12	Site Av	Site SD
Air	12.5	13.4	13.0	13.0	13.0	12.6	12.6	12.4	12.4	13.2	12.8	12.3	12.8	0.35
Pavement	12.4	13.0	13.4	13.8	13.6	13.2	13.6	13.6	13.8	13.4	13.2	13.2	13.4	0.39
Road	12.8	14.4	14.8	14.8	14.2	13.4	13.6	14.4	14.8	14.8	14.8	14.4	14.3	0.66

Table 2: Results of a single complete field site survey in overcast conditions

18-May	Standard deviation (°C) of hourly temperature across all sites							DAILY			
TIME (UT)	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	AVERAGE
Air	0.5	1.1	0.8	1.1	0.9	1.0	0.9	0.7	0.7	0.5	0.8
Pavement	3.0	5.0	7.4	9.2	8.2	7.4	5.8	4.7	3.8	2.8	5.7
Road	2.0	3.2	4.7	5.9	3.9	4.5	3.1	1.8	1.9	1.6	3.3

Table 3: Hourly standard deviation of temperature recorded at the sample sites and the daily

19-May	Standard deviation (°C) of hourly temperature across all sites							DAILY			
TIME (UT)	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	AVERAGE
Air	0.8	1.0	1.0	1.8	1.1	1.3	1.4	1.1	0.7	0.4	1.1
Pavement	5.1	7.7	9.2	10.6	12.2	10.7	11.3	9.0	6.6	4.4	8.7
Road	4.0	5.6	6.7	6.0	5.8	5.3	5.0	5.2	3.4	1.9	4.9

Table 4: Hourly standard deviation of temperature recorded at the sample sites and the dailyaverage for 19 May 2004.

The greater correlation of pavement temperature (over which the 1m air temperature was recorded) than road temperature is also seen at site 1 (Marylebone Road, outside the council building). This site has the coldest average pavement temperature, and one of the coldest air temperature in the survey area, due mostly to its shaded location.

The difference in standard deviation of sample site road and pavement temperature (table 1) is small, implying that these two surfaces generally had a similar (and large) diurnal variation at each sample site. Exceptions to this include site 11, with a low standard deviation due to its lack of exposure to direct solar radiation throughout the day (i.e. less pronounced variation in solar forcing relative to surfaces fully exposed to the larger diurnal variation of direct solar radiation). However, the effect of microscale advection is seen here as well, with the site experiencing the greatest variation of air temperature despite having the smallest variation of pavement temperature, although the difference between sampling sites 1m air temperature standard deviation is small.

It is also noted that air temperature often followed a gradient along the shaded side of Marylebone road that corresponded to the wind direction. The airflow had an easterly component down Marylebone road on both days so air warmed by the hot surfaces upwind around site 9 (exposed junction) were progressively cooled during the flow along the shaded pavement sites on Marylebone road (10,11 and 12), with site 12 experiencing the coolest air temperature corresponding to the longest "fetch" of cool pavement.

Although the individual sample site standard deviation shows little difference between road and pavement temperature patterns, care must be taken with interpretation since observation of figures 20 and 23 clearly indicates significant difference between the time series for each site. This hourly standard deviation of temperature across the complete field site is shown in tables 3 and 4 with the difference in appearance of graphs in figures 20 and 23 quantified by the significantly large difference in the standard deviation of the hourly data, especially around 1200 UT when the difference between sites exposed to direct sunshine and shade is most pronounced.

The reason for the large standard deviation of hourly pavement temperatures has been attributed to shading effects at some sites which keep the surface temperature well below that of pavements fully exposed to direct solar radiation. Since most roads were only partially shaded throughout the day due to their greater exposure, the road standard deviation follows a similar pattern as the pavement, but with a smaller magnitude. However, the hourly standard deviation of air temperature is considerably lower than the two surfaces, with little temporal variation. This observation is explained by mixing and advection allowing a more evenly distributed temperature field despite being only one metre above the more variable surface temperature distribution.

So far only the temperature range for the two fair weather days has been considered. Table 2 shows the observations, field site average and standard deviation taken at 1300 UT on the 30 April 2004. The meteorological conditions were overcast, with intermittent light rain. Since all sample sites experienced only indirect (and relatively weak) solar radiation, the standard deviation for surface and air was low, with average pavement and road temperatures only 0.6°C and 1.5°C warmer than air, respectively. This contrasts to the statistics derived for the two fair weather days, with the overcast conditions producing considerably lower means and standard deviations, as the effect of selective shading is not present.

As suggested by figure 28, anthropogenic (specifically traffic) heat sources appear to provide a significant contribution to the surface heat flux during overcast conditions, relative to solar forcing. For example, road temperature had almost twice the standard deviation of pavement and air temperatures as well as being the warmest of the three variables (table 2). This is expected to be due to differences in traffic flow along the roads in the field site, with the warmest roads found in areas of greatest traffic flow such as Marylebone Road and the busdominated Gloucester Place. However, roads with little or no traffic such as Bickenhall Street had cool road temperatures, although both surfaces at site 1 were the coolest in the field site. The reason for this is unclear since the road was well used, but the bus lane and the large, solid council building (believed to act as a heat sink) may have been a factor, although it must be remembered that all the differences between sample site surface and air temperatures are close to or within the limit of instrumental error on this overcast day.

5 Heat Flux Modelling

Three methods of calculating the surface sensible heat flux (Q_H) using surface radiative temperatures will be discussed in this section. All methods are based on the general formula for flow across a gradient at a rate determined by a resistance:

$$Q_{H} = \frac{\rho C_{p} (T_{R} - T_{a})}{r}$$
(4)

where ρ is air density, C_p is the specific heat capacity for dry air, T_R and T_a denote radiometric surface temperature and air temperature respectively and r is a form of resistance to heat transfer (units of sm⁻¹). It is the difference in calculating the resistance to heat transfer (r) that differs between the three methods.

The combination of turbulent fluxes for an area can be represented as a constant mechanism for heat transfer along a temperature gradient, despite the inherent randomness and spread of magnitude of the individual turbulent units that contribute to the single resistance term. This is the analogy used for the bulk aerodynamic formulation, which is a component of all the methods investigated.

The three methods to be assessed are:

- Method 1: The bulk surface response as described by Voogt and Grimmond (2000) using the idea of an excess resistance (i.e. in addition to aerodynamic resistance for momentum) between the surface radiative temperature and the roughness length for momentum (Stewart et al. 1994). This excess resistance term is calculated using the equation of Brutsaert (1982) for bluff-rough situations (i.e. ground including obstructions to wind flow which have bold, regular geometry with a rough surface such as buildings).
- Method 2: The semi-empirical resistance formulation of Rowley and Eckley (1932) adopted by Masson (1999).

• Method 3: Resistance calculated simply by assuming aerodynamic resistance for momentum is equal to that of heat.

The results are compared with measurements of heat flux calculated from observations of wind velocity and temperature fluctuations using a sonic anemometer.

5.1 Method 1

This method requires the calculation of B^{-1} (originally proposed by Owen and Thompson (1963) and Chamberlain (1966)) that in turn needs an estimate of the roughness length for heat (Z_{0h}). Brutsaert (1982) derived a formula to calculate this roughness length using the roughness Reynolds number (Re*), a value that requires only the friction velocity (u_*), kinematic molecular viscosity of air (v) and the more easily estimated roughness length for momentum (Z_{0m}).

The resistance term used in method 1 is r_h which is the sum of the aerodynamic resistance for momentum, r_{am} , and the excess resistance r_T to heat transfer between the surface radiative temperature level and the roughness length for momentum (Stewart et al. 1994). Excess resistance (r_T) is defined by Voogt and Grimmond (2000) as the product of bulk aerodynamic excess resistance and the excess resistance from different heat source and momentum sink locations, as represented in figure 3. Quantitatively:

$$r_T = \frac{B^{-1}}{u_*} \tag{5}$$

The value of B^{-1} is found using the formula:

$$B^{-1} = \frac{1}{k} \ln \left(\frac{Z_{0m}}{Z_{0h}} \right)$$
(6)

where k is the Von Karman constant. The roughness length for heat (Z_{0h}) is estimated using the equation for bluff-rough field sites derived by Brutsaert (1982):

$$Z_{0h} = Z_{0m} \left[7.4 \exp\left(-2.46 \operatorname{Re}_{*}^{0.25}\right) \right]$$
(7)

With Z_{0m} assigned as 1m (a value in general accordance with similar urban meteorology studies) for this investigation in the absence of a suitable vertical profile of horizontal windspeed. The roughness Reynolds number (Re*) is calculated from:

$$\operatorname{Re}_{*} = \frac{Z_{0m}u_{*}}{v} \tag{8}$$

The kinematic molecular viscosity of air (v) was assumed constant at $1.461 \times 10^{-5} \text{m}^2 \text{s}^{-1}$.

The aerodynamic resistance for momentum (r_{am}) is found using the equation:

$$r_{am} = \frac{u(z)}{u_*^2} \tag{9}$$

Finally, the heat flux is calculated using equation (4) with r_h (the sum of r_{am} and r_T) as the resistance term.

5.2 Method 2

The resistance formulation of Rowley and Eckley (1932) adopted by the Town Energy Budget (TEB) scheme of Masson (1999) is as follows:

$$RES_{r} = \left(11.8 + 4.2\sqrt{U_{can}^{2} + W_{can}^{2}}\right)^{-1}$$
(10)

Where U_{can} and W_{can} are the average horizontal and vertical wind speeds of the street canyon respectively (obtained from the sonic anemometer data). This resistance is used in the generic heat flux equation (4) according to the paper by Masson (1999) although initial results suggest that the density and specific heat capacity of air terms have been included in error, with the actual heat flux between the surface and canyon air calculated simply by the temperature difference divided by this resistance term (*RES_r*). Notice that this method is semi empirical and does not require an estimation of the roughness length for momentum.

5.3 Method 3

This method simply uses equation (9) for the resistance term combined with (4) and therefore ignores the excess resistance term that was accounted for in method 1, meaning that heat and momentum are assumed to be transported in the same way.

Since air density is temperature dependent, it was calculated using the ideal gas equation:

$$\rho = \frac{P}{RT_a} \tag{11}$$

Where ρ is air density, *P* is atmospheric pressure (taken as 1020hPa, which was the surface pressure during the two fieldwork days), *R* is the gas constant for dry air (287 JKg⁻¹K⁻¹) and T_a is air temperature. This equation was used whenever air density was required.

5.4 Sonic anemometer measurements

The sonic anemometer was positioned on a rooftop next to the council building (see figure 6) and the high frequency wind and virtual temperature data was used to calculate friction velocity, mean horizontal and vertical wind speed as well as turbulent heat flux.

Friction velocity was calculated using the formula:

$$u_* = \left[\overline{u'w'}^2 + \overline{v'w'}^2 \right]^{0.25}$$
(12)

with u' and v' representing horizontal (northward and eastward respectively) wind perturbations from the mean flow, with w' representing the vertical perturbation. These perturbations were averaged over 30 minutes taken from fifteen minutes before the sampling hour (e.g. 10:45-11:15) to account for the time taken to record temperature at all the sampling sites.

The sonic anemometer measures virtual (sonic) temperature, not absolute air temperature, the difference between the two is dependent on humidity. The difference is expected to be small since the relative humidity was quite low (in accordance with the expected urban environment

during fair weather). The effect of humidity is expected to be small since it is the rapid perturbations about the mean temperature (that would be near-linear to absolute temperature perturbations for small values) that are required. Therefore turbulent heat flux has been calculated from the sonic data with these assumptions using the equation:

$$Q_{H} = \rho c_{p} \overline{w' T_{s}'}$$
(13)

where T_s ' is the perturbation of sonic temperature from the half hour mean (note that this is assumed to be the same as the perturbation of absolute temperature as previously described). Like the friction velocity calculation, the covariance was averaged between fifteen minutes before and after the sampling hour.

Since the sonic anemometer is located on a rooftop and not near the street canyon floor (where the temperature measurements were obtained) a possible error of representativity must be considered since observations of friction velocity are actually rooftop values, therefore not necessarily the same as expected approximately 1m above the street canyon floor. However, since no observations of friction velocity were taken at this height the rooftop values were assumed to be representative of the street canyons below.

5.5 Model Results



Figure 30: Results of the three sensible heat flux calculation methods and the sonic-derived values for 18 May 2004.

The average road surface heat flux for the field site was calculated using the three methods described using the hourly road surface – air temperature difference averaged across all sampling sites for the 18 and 19 May 2004. The sonic-derived heat flux was used as an approximation to the "actual" heat flux expected for the area. The model results for 18 May 2004 are shown in figure 30. It is clear that the heat flux calculated using method 3 is a considerable overestimate (the values predicted are in excess of the direct solar radiation itself!) so only the heat flux modelled using methods 1 and 2 will be studied further as a consequence.

From this finding it can be deduced that it is important to acknowledge the difference between heat and momentum transport. This difference is quantified using the concept of excess resistance (r_T) required when radiative surface temperature is used (see appendix for tables showing this result). Graphs omitting method 3 are shown in figures 31 and 32.



Figure 31: Site-average hourly sensible heat flux for 18 May 2004 calculated using methods one and two compared with heat flux calculated directly using the sonic data.



Figure 32: Site-average hourly sensible heat flux for 19 May 2004 calculated using methods one and two compared with heat flux calculated directly using the sonic data.

From figures 31 and 32 it can be observed that the modelled road heat flux using methods one and two correspond well to the heat flux calculated from the rooftop sonic data, particularly after 1500 UT on both days.



Figure 33: Difference between modelled and sonic sensible heat flux for 18 May 2004

The difference between the modelled and sonic-derived heat flux is quantified by figures 33 and 34 for the two main survey days. Heat flux was underestimated by both models in the early morning but overestimated (by up to 100 Wm⁻² on 19 May using method two) between 1000 UT and 1300 UT on both days. Both methods performed equally

well on 18 May (although method two had a smaller difference during the 1400 UT peak in sonic heat flux), with method one being generally closer to the sonic values on 19 May.

However, consideration must be taken for the difference in position between where the temperatures used by both models were measured and the sonic heat flux site located on a rooftop on the western edge of the sampling site. Analysis of the time series of sonic temperature with site averaged air temperature would show if the two temperatures agreed



Figure 34: Difference between modelled and sonic sensible heat flux for 19 May 2004

reasonably, although a quantitative assessment was not considered necessary for this investigation.

This difference in height above the ground as well as the different properties of the rooftop and road surfaces are extra variables that are likely to cause a difference in surface

heat flux, although the magnitude of this difference can not be easily quantified using the available data. However, the sonic-derived heat flux is assumed to represent the "actual" heat flux of the field site (from which the accuracy of the models are assessed), although a

variation is expected. This variation makes a precise account of the model accuracy unfeasible due to the close association of heat flux with specific properties of the nearby surface materials and geometry, including the effects of shading (which is not known for the rooftop site).

Additionally, the model input is the site-averaged road temperature, not data measured at one point only like the sonic heat flux site, although the mean windspeed and friction velocity used by all the models do come only from the sonic site, therefore any spatial variation of these parameters is ignored. This is unavoidable as only one (fixed) sonic anemometer was available. However, the average friction velocity and windspeed are not expected to have varied greatly in the small field site used in this investigation due to the relative spatial similarity of street geometry, calm wind conditions and close proximity of sampling sites.

The reason for caution to be taken when using the difference between modelled and sonicderived heat flux for assessing the accuracy of the former is illustrated by figure 35.



Figure 35: Modelled road sensible heat flux for each sampling site (grey lines), with the site averaged flux (red) and sonic-derived rooftop heat flux (black).

From figure 35 it is clear that the heat flux varies greatly (by up to 350Wm⁻²) between individual sampling sites despite their close proximity (with the Bickenhall Street canyon road (sites 5 and 6) actually being a heat sink in the morning. The reason for this microscale variation is the large differences in surface-air temperature gradient, which was attributed to differences in shading during fair weather conditions as previously described. Indeed, perhaps it is more interesting that the difference between the site-averaged model road heat flux and sonic-derived rooftop heat flux is generally so small.

A reason for this close agreement may be due to mixing of the air by turbulence near the ground so that the large spatial variation of heat flux is rapidly averaged-out away from the surface heat source, with the rooftop sonic site being high enough to measure this mean surface heat flux and therefore produce values close to the spatial mean. However, the rooftop surface itself would be expected to contribute to this measured heat flux as well and it is this contribution that may have caused the more significant deviation of sonic and modelled average heat flux due to effects of rooftop shading. Additionally, it must be remembered that it is the rooftop friction velocity that was used in the models since this is where the sonic anemometer was located, which may have been a factor in the close agreement between models and observation.

5.6 Model Sensitivity Assessment

It is important to assess how changes in inputs will alter the model output, as this is a method of estimating likely error in calculated heat flux. The sensitivity of the two models considered (methods one and two) will be assessed by altering an input variable (keeping the others constant) and observing the deviation of the resultant heat flux estimation. The non-perturbed ("standard") input variables have values consistent with those found on the main survey days of 18 and 19 May 2004.

The chosen variable was perturbed about its standard value (usually including an order of magnitude more and less) and the heat flux calculated, with the results displayed graphically. All other input variables were given their standard values as described in table 5. Although the model response to changes in the variables are plotted, it is the gradient of these graphs that indicate the model sensitivity.

5.6.1 Sensitivity of Model Method 1

The input variables of this model are as follows:

Symbol	Variable	Standard Value
Z_{0m}	Roughness length for momentum	1m
U_*	Friction velocity	0.3ms ⁻¹
U(z)	Mean horizontal windspeed	1ms^{-1}
T_r - T_a	Surface-air temperature gradient	20K
T_a	1m Air temperature	293K

Table 5: Method 1 model input variables and standard values for sensitivity tests



Figure 36: Method 1 model sensitivity to roughness length for momentum



Figure 37: Method 1 model sensitivity to friction velocity

Figure 36 shows the sensitivity of the model to roughness length for momentum. It can be seen that the model is highly sensitive to changes for small (<1m) values of roughness length, indicated by the steeper gradient, with less sensitivity to changes in This larger values. high sensitivity is due to the linear proportionality between roughness length and roughness Reynolds number (equation 8) and in turn, the logarithm of the inverse exponential relationship between the roughness Reynolds number and the B^{-1}

transfer resistance term

value which determines the

(equation 5) – as previously seen to be the dominant component of the resistance to heat transfer by the failure of model 3. The large heat flux values for small Z_{0m} are also party due to the dependence of this variable with friction velocity, i.e. U_* decreases as Z_{0m} decreases, causing an increase in calculated heat flux by lowering the resistance.

The model is also highly sensitive to changes in small values of the friction velocity, as demonstrated by figure 37. Maximum model sensitivity occurs at 0.08ms⁻¹ with a sensitivity of 2198Wm⁻² per 1ms⁻¹, with a sharp reduction either side of this value. The calculated heat flux reaches a maximum (and therefore lowest sensitivity) with a friction velocity of 0.33ms⁻¹, beyond which the model is less sensitive to change (and has negative sensitivity).

The reason for this large sensitivity to changes in friction velocity below 0.33ms^{-1} is due to the inverse square dependency of the aerodynamic component of the resistance to heat flux (equation 9). For values greater than 0.33ms^{-1} the same inverse square relationship means that the excess resistance component r_T dominates over the aerodynamic component r_{am} . The dominance is also due to the first order inverse proportionality of friction velocity (equation 5) reducing the resistance at a lesser rate than the increase imposed by the B^{-1} value due to the influence of the roughness Reynolds number (equation 8).



Figure 38: Method 1 model sensitivity to surface-air temperature gradient

The linear proportionality to surface-air temperature gradient is seen in figure 38 and is a result of this variable being numerator of the heat flux equation 4. Therefore the model has

uniform sensitivity that is independent of this gradient, being about 15Wm⁻² per degree temperature difference.



Figure 39: Method 1 model sensitivity to 1m air temperature

Since it is the gradient and not absolute temperature that is the important factor in heat flux calculation, the sensitivity of the model to 1m air temperature is expectedly low. The reason for the slight sensitivity (about $1Wm^{-2}$ per degree) is due to the inverse relationship between air temperature and density as seen in equation 11. However, as the change is small relative to the other factors, the change in sensitivity may be neglected for the temperature range considered in this investigation.

5.6.2 Sensitivity of Model Method 2

A sensitivity assessment of the model using method 2 will be undertaken with the same method used in the assessment of the method one model.

Symbol	Variable	Standard Value
U(z)	Mean horizontal windspeed	1ms ⁻¹
W(z)	Mean vertical windspeed	0.02ms^{-1}
$T_r - T_a$	Surface-air temperature gradient	20K

Table 6: Method 2 model input variables and standard values for sensitivity tests



Figure 40: Method 2 model sensitivity to average horizontal windspeed

From the resistance equation 10 used in method 2 it is apparent that since the magnitude of windspeed is inversely related to resistance that is in turn inversely related to heat flux, the heat flux is linearly proportional to windspeed, specifically $\sqrt{U_{can}^2 + W_{can}^2}$. However, when the two vector components of windspeed are considered individually, the relationship is not quite as straightforward. Figure 40 shows apparently linear relationship between Q_H and U(z).

If horizontal windspeed U(z) is considered much greater than the vertical component W(z) then this near-linear proportionality shown in figure 40 is explained as the $\sqrt{U_{can}^2 + W_{can}^2}$ component of equation 10 tends to just $\sqrt{U_{can}^2}$, hence the linearity. Therefore the sensitivity to horizontal windspeed is uniformly high, at approximately 84Wm⁻² per 1ms⁻¹ change.



Figure 41: Method 2 model sensitivity to average vertical windspeed

The change in calculated heat flux with variation of the vertical component of windspeed is non-linear as seen in figure 41. It can be seen that even for order of magnitude changes in vertical windspeed, the calculated heat flux for this model only varies by less than 2 Wm^{-2} . This implies that sensitivity to changes in W(z) is negligible when the horizontal windspeed is much larger than the vertical component (i.e. horizontal windspeed may be considered as absolute windspeed).

Physically, this assumption relates to the idea that shear in the horizontal wind component is the dominant process in creating turbulence rather than the vertical component of turbulence itself, under the atmospheric conditions of the survey days. However, this assumption may not be valid during times of convection, where the vertical component of windspeed may approach the magnitude of the horizontal component as well as any locations where there is enhancement of the vertical component induced by airflow around the urban geometry.



Figure 42: Method 2 model sensitivity to surface-air temperature gradient

Like the previous model, this model is linearly related to the surface-air temperature gradient (equation 4) as demonstrated by figure 42, with a uniform model sensitivity of $16Wm^{-2}$ per degree difference.

5.6.3 Comparison of model sensitivity using Methods 1 and 2

Both models share mean horizontal windspeed and surface-air temperature gradient as common input variables. The sensitivity of the two models to these variables are compared using figures 43 and 45. From figure 43 it is apparent that the model using method 1 is less

sensitive to the temperature gradient than using method 2 (with a uniform sensitivity difference of 1Wm^{-2} per degree between the models).

However, the difference in model sensitivity with mean horizontal windspeed is pronounced in magnitude and response (figures 44 and 45) with method one producing a model less sensitive to changes in mean horizontal windspeed, especially at high values where the sensitivity of the model based on method 1 is less than 20% of that using method 2. However, even at low windspeed the model using method 1 is still more robust, meaning it is less sensitive to changes in input values. It is interesting to note that both models predict the same heat flux using a mean horizontal velocity of 1ms^{-1} (the standard value) which indicates their similarity despite the two very different approaches to resistance calculation.



Figure 43: Sensitivity of the two models to the surface-air temperature gradient







Figure 45: Sensitivity of the two models to mean horizontal windspeed

5.7 Estimation of model absolute error

The absolute error of the model as a result of expected input inaccuracies can be estimated using the sensitivity analysis. The sensitivity was measured for the standard value of the variable and multiplied by the expected absolute error in measurement of that variable (acknowledging the accuracy of the instrumentation) to obtain an estimation of the variable's contribution to model absolute error. Results are presented in tables 7 and 8 for models based on methods 1 and 2 respectively.

Estimation of Method One Model Absolute Error						
Input variable	Measuremental error	Model abs error (Wm ⁻²)				
Z_{0m}	0.5m	35				
U*	0.05ms ⁻¹	3				
U(z)	0.05ms ⁻¹	2				
T _r -T _a	2K	30				
Ta	1K	1				

Table 7: Results of method 1 model error estimation per variable

Estimation of Method Two Model Absolute Error							
Input variable	Measuremental error	Model abs error (Wm ⁻²)					
U(z)	0.05ms^{-1}	4					
W(z)	$0.05 { m ms}^{-1}$	0.1					
T _r -T _a	2K	32					

Table 8: Results of method 2 model error estimation per variable

From the two tables it appears that the model calculated using method 1 is most sensitive to the expected error in estimation of roughness length for momentum and measurement of the surface-air temperature gradient. However, despite the relatively large estimation of measuremental error for the sonic derived windspeed values (the instrumental error was given at only <1% but has been increased to include non-instrumental sources of error such as sonic platform misalignment, rounding errors and differences in observation times between the windspeed data and temperature recordings), the effect on the models is considerably less than the error induced by inaccurate input of roughness length or temperature gradient.

5.8 Comparison of model output with literature

The model using method 1 produces a value of kB^{-1} , which is a common parameter used in the literature as an indicator of the properties of the site with respect to the efficiency of heat transport (see equation 6). The average kB^{-1} calculated for the field site using method 1 was 28 for both survey days. Although evidence of a diurnal variation has been reported (Voogt and Grimmond 2000), the range of calculated hourly kB^{-1} varied only between 26 and 29 for both days.

Stewart (1994) determined kB^{-1} for eight semiarid areas and obtained values between 3.5 and 12.5. However, kB^{-1} calculated by Voogt and Grimmond (2000) for an urban site using three methods ranged between 13 and 27. Using the bluff-rough curve of Brutsaert (1982) which was the equation used for method 1, the values were more confined to the upper portion of the range, at 25-27. Therefore the kB^{-1} values calculated for the London field site are within the values calculated using a similar method by Voogt and Grimmond (2000) for an urban site, although the London site values tend to the upper end of this range.

The mean difference between modelled and observed sensible heat flux using method 1 was 30Wm⁻² on 18 May and 23Wm⁻² on 19 May, with 22Wm⁻² and 31Wm⁻² being the mean difference using method 2 for the respective survey days. Although this is only an indication of the absolute model accuracy (due to previously discussed reasons), the values are comparable to stated accuracy of models found in the literature, with the models used by Voogt and Grimmond (2000) being generally within 15Wm⁻² of the observed heat flux, and up to 200Wm⁻² difference discovered in Vancouver (with approximately 40Wm⁻² for Mexico City) during the evaluation of the Town Energy Balance scheme undertaken by Masson et al (2002).
Unsurprisingly, the sensible heat flux was the poorest modelled component of the TEB's urban surface energy budget. The TEB model tended to overestimate heat flux around the time of maximum insolation (local noon). This characteristic is also evident in the two methods used for this investigation, suggesting a common problem in the models. A reason for this overestimation may be due to errors in measuring the "complete" urban surface temperature (Voogt and Oke 1997), since measurements taken from remotely sensed surface temperature are often biased to nadir-viewing of the near-horizontal facets, without adequate consideration of the vertical walls. Voogt and Grimmond (2000) reported a decrease in the kB^{-1} values (and therefore heat flux) of 3-6 when wall temperatures were not included to produce a complete surface radiative temperature. Neglect of the wall/shaded component of the complete urban surface temperature may be most apparent during maximum insolation, hence the overestimation during these times. Although wall temperature was recorded at one location (site 6) in the sampling site, the lack of temperature and geometrical data for the rest of the field site made its inclusion into the two models inappropriate.

6 Conclusions

An account of the conclusions based on the discussion of results and model output is presented in this section.

- Shading is the most significant contributor to microscale variations of surface temperature and hence heat flux by causing a variation of the surface-air temperature gradient during fair weather, especially for surfaces adjacent to urban structures such as the pavement, which will have a greater range of shading throughout the day. Street canyons with high aspect ratios (such as the Bickenhall Street canyon) are subject to greater periods of shade and therefore lower heat flux, with some areas even acting as heat sinks if air warmed over nearby sunlit areas is advected over the shaded surface. Sites with greatest exposure (and therefore direct solar radiation) such as road junctions have the greatest heat flux.
- Anthropogenic heat sources (such as traffic-induced surface heating by tyre friction and emission of hot exhaust gasses) appear to contribute most to microscale surface temperature variations during overcast conditions, although the magnitude of this effect on the surface-air temperature gradient is generally less than 10% of that caused by solar generated surface heating during fair weather conditions.
- The importance of the excess resistance term when considering resistance to heat flux using the surface radiative temperature is shown by the failure to produce a reasonable heat flux estimation using only the aerodynamic component i.e. method 3. Therefore the resistance to heat and momentum fluxes can not be assumed equal for the atmospheric conditions and urban environment considered.
- Values of kB⁻¹ obtained on both days at the field site ranged from 26 to 29 with an average of 28. This is within the observed values calculated by Voogt and Grimmond (2000) for an urban site using the same bluff-rough equation of Brutsaert (1982).
- The two methods used in the production of a heat flux model produced site-averaged values similar to the heat flux calculated using a sonic anemometer located on a nearby rooftop. The close agreement of the site-averaged model heat flux and rooftop

heat flux is suggested to be a result of turbulent mixing; causing the measured flux at rooftop level to be similar to the horizontally averaged surface flux in the canyon.

- Although the two methods produced similar results, method 1 has the advantage of an input of the roughness length for momentum, allowing greater refinement of the model to suit different site geometries. However, method 2 requires only mean horizontal and vertical windspeed (as well as surface-air temperature gradient) which needs less sophisticated equipment and computer analysis than the calculation of friction velocity using a rapid response sonic anemometer. Indeed, the model output using method 2 is not significantly affected by the complete omission of mean vertical windspeed if this value is much smaller than the mean horizontal windspeed (i.e. 0.02ms⁻¹ recorded on the two survey days).
- The model error using method 1 is mostly attributed to errors in roughness length estimation (accounting for approximately 35Wm⁻²) and surface-air temperature gradient (30Wm⁻²), with the latter being the only major contributor to model error using method two (32Wm⁻²) when measurement error is considered. The magnitude of suspected error is similar to models used in other field campaigns, although the models appear more sensitive than the more sophisticated models used in recent literature.

6.1 Suggestions for further research

The investigation has concentrated on the use of microscale variations in air and surface radiative temperature to model surface sensible heat flux. Although heat flux is a dominant component of the surface energy budget in urban areas (i.e. Oke et al. 1999) the latent heat component should not be neglected, especially for urban areas with vegetation such as the trees along Marylebone Road at the London study site. It would be interesting to compare the latent heat component with the sensible heat flux for such an area, especially during precipitation and surface storage of water.

Although the anthropogenic component of the sensible heat flux was recognised in this investigation during overcast conditions, the extension of this component would be beneficial for a more complete understanding of the surface energy budget, especially during overcast conditions and night time when direct solar forcing is not present, since it was suggested from

the results that this (along with the large storage component of urban sites) may be a significant forcing in the microscale distribution of surface heat flux.

The rapid fluctuations in intensity of thermal infrared radiation ("sky temperature") measured by an upward pointing handheld infrared radiometer at ground level on a relatively highly polluted London road compared to measurements taken on a rooftop 14m above the surface may have indicated a thin surface layer of pollutant affecting the surface energy balance. This thin (under 14m deep) layer may not be adequately resolved in mesoscale model or field campaigns so should be subject to further investigation to assess its significance.

Further study could be undertaken regarding the unexpectedly close relationship between spatially averaged 1m and sonic-derived rooftop heat fluxes, including validation of the suggestion that the relationship is due to rapid horizontal mixing regulating the rooftop heat flux towards the spatially averaged mean flux 1m above the surface. The appropriateness of using rooftop wind velocities to represent mixing in the street canyon should also be investigated further. Additionally, the use of the "complete" surface radiative temperature (incorporating the wall radiative temperatures) could be compared to simply using the road temperature to calculate surface heat flux of the study site.

Although the two models perform well in the study area under fair weather conditions, it would be beneficial to see how they perform at other urban sites and under different atmospheric conditions. Any significant discrepancies between modelled and observed heat flux could be further investigated to refine the model methodologies so they may be applied to more general situations, with associated benefits to microscale modelling of the urban environment.

Model Resistances and Output

	esistances fo	Site averaged model heat flux (Wm ⁻²)							
TIME (UT)	R _{am}	Re∗	kB ⁻¹	R _T	R _h	RESr ⁻¹	Method 1	Method 2	Method 3
8:00	10.8	22541.7	28.1	70.4	81.2	0.060	52.2	57.8	418.3
9:00	8.0	20554.7	27.5	68.6	76.6	0.067	62.9	58.7	648.6
10:00	12.5	18094.9	26.5	66.3	78.8	0.065	151.4	152.3	1027.4
11:00	10.0	20755.3	27.5	68.8	78.8	0.064	193.7	198.6	1656.4
12:00	11.5	17814.9	26.4	66.0	77.6	0.066	181.1	176.0	1325.5
13:00	10.5	19305.3	27.0	67.5	78.0	0.065	179.4	178.3	1455.4
14:00	9.8	26822.0	29.5	73.7	83.5	0.055	136.0	171.0	1260.6
15:00	8.9	22868.3	28.2	70.6	79.6	0.063	129.3	136.9	1249.5
16:00	12.3	18880.4	26.8	67.1	79.4	0.064	109.3	113.8	764.7
17:00	9.9	21766.0	27.9	69.7	79.6	0.062	91.4	97.0	797.6

Resistances for 19 May 2004							Site averaged model heat flux (Wm ⁻²)		
TIME (UT)	R _{am}	Re∗	kB ⁻¹	Rτ	R _h	RESr ⁻¹	Method 1	Method 2	Method 3
8:00	8.1	22649.3	28.2	70.4	78.5	0.064	51.5	51.5	535.8
9:00	9.4	23043.6	28.3	70.8	80.1	0.061	90.1	96.7	827.7
10:00	10.4	21196.1	27.7	69.2	79.6	0.063	135.6	142.8	1123.2
11:00	13.2	19999.2	27.3	68.1	81.3	0.061	222.5	248.2	1491.3
12:00	18.2	17773.1	26.4	66.0	84.2	0.059	221.9	264.5	1118.0
13:00	10.8	18847.9	26.8	67.1	77.8	0.066	234.2	231.9	1844.9
14:00	11.0	23724.7	28.5	71.3	82.3	0.058	205.7	245.3	1685.5
15:00	8.8	23497.4	28.5	71.1	79.9	0.062	181.2	195.7	1801.5
16:00	13.2	20568.1	27.5	68.6	81.8	0.060	128.4	147.6	871.0
17:00	11.9	19041.3	26.9	67.2	79.2	0.064	99.4	102.8	718.8

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