**HEAT FLUXES THROUGH ROOFS AND THEIR RELEVANCE TO
ESTIMATES OF URBAN HEAT STORAGE**

by

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ABSTRACT

The storage heat flux (ΔQ_S) constitutes a large term in the heat balance of cities. This flux is difficult to measure but can be parameterized using relations between the net radiation (Q^*) and the heat flux conducted into and out of the typical materials that form the surface of cities (Q_G). The urban heat storage parameterization could be improved if there were more and better estimates of the net radiation vs. storage relation for typical urban and suburban roofs. This thesis presents the results of a study of the heat storage characteristics of 5 different roof assemblies (typical of many North American commercial/industrial and residential buildings) in Vancouver, B.C. These observations are used to verify the Simplified Transient Analysis of Roofs (*STAR*) model, which is then used to estimate the heat storage parameterization for other roof types, thereby extending the usefulness of the scheme to a wider range of cities.

Distinct differences in heat storage characteristics are observed between roofs with gravel surfaces and those with modified bitumen or asphalt shingles. The surface conductive heat flux (Q_G) ranges from 22% to 30% of the net radiation (Q^*) for gravel roofs under high wind (between 1.5 and 4 m s⁻¹) and low wind (less than 1 m s⁻¹) conditions respectively. For wet roof conditions, Q_G is approximately 25% of Q^* irrespective of wind speed. For modified bitumen surfaces and asphalt shingles, it is considerably less (~ 10%), indicating that these roof surface types are more energy efficient. It is concluded that the *STAR* model gives good agreement between measured and modelled surface heat fluxes, and is a useful tool for modelling a wide range of roof types. The model works very well for the case of dry roof conditions, but is less accurate under wet or mixed conditions because latent heat (Q_E) is not taken into account.

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Chapter 1

INTRODUCTION

The storage heat flux (ΔQ_S) constitutes a large term in the heat balance of cities. This flux is difficult to measure but can be parameterized using relations between the net radiation (Q^*) and the heat flux conducted into and out of the typical materials that form the surface of cities (Q_G). The parameterization of urban heat storage could be improved if there were more and better estimates of the net radiation vs. storage relation for typical urban and suburban roofs. This thesis presents the results of a study of the heat storage characteristics of five different roof assemblies (typical of many North American commercial/industrial and residential buildings) in Vancouver, B.C. These observations are used to verify the Simplified Transient Analysis of Roofs (*STAR*) model, which is then used to estimate the heat storage parameterization for other roof types, thereby extending the usefulness of the scheme to a wider range of cities.

This first chapter defines the nature of heat conduction in both simple and multi-layered systems (such as roofs), and links the conductive heat flux to storage change in roofs and urban environments. It then considers measurement and parameterization schemes for the urban heat storage (ΔQ_S) vs. net radiation (Q^*) relationship, and the importance of assessing the contribution of roof heat storage to this parameterization. Finally, an overview of the purpose and limitations of this research study are presented.

1.1 Heat Conduction in Simple and Complex Systems

1.1.1 One-dimensional single-layer system; dry and calm conditions.

First, take the simplest steady-state case: heat conducted through a continuous medium with a known thermal conductivity, k . The thickness of this medium (dz) is known, and the temperature difference (dT) between the upper face and lower face of this layer is known. According to Fourier's Law, the thermal conductivity of a homogeneous material and the temperature gradient across it (in the vertical direction in this case) determines the conductive heat flux (Q_G) through a plane:

$$Q_G = k \frac{dT}{dz} \quad (1.1)$$

In a single layer system such as a slab of concrete, the thickness of the layer is easily measured, and using a finite difference approximation to the gradient, the temperature difference (ΔT) can be obtained using a minimum of one thermocouple on the upper face, and one on the lower. The conductivity will depend on the type of concrete, but this can easily be obtained from references in the building materials literature. If this one-dimensional system is placed in a location away from direct solar radiation, moisture, or wind, the calculated heat flux density could be evaluated with high confidence. However, when these conditions vary, or when the conduction through several layers of material are considered, the level of confidence in the result of the calculation of Q_G is considerably diminished.

1.1.2 One-dimensional multi-layer system; varied weather conditions.

In a multi-layer system, the equation for the conductive heat flux density remains the same for each of the individual layers, but its solution is complicated by the thermal conductivities of different media (which may also vary with depth in one particular medium, e.g. insulation), and the need to measure the temperature differences at each of the layer interfaces. For a multi-layer system such as a roof assembly consisting of an outer layer or membrane, insulation, air spaces, and a concrete, steel, or wood deck, an exact analytical solution to the conductive heat flux density equation is difficult to obtain through experimental means, but perhaps less difficult through theoretical means. Both methods will be explored in this section.

To measure the conductive heat flux at an interface or directly in a medium, the most common method is to use heat flux plates (rather than thermocouple arrays). The typical heat flux sensor is designed using Fourier's Law (equation 1.1), and consists of a thermopile made up of many thermocouple pairs wound around glass or plastic resins and sealed in a cover. The thermopile measures the temperature gradient, and the conductivity of the material is known (a property of the resin) (van Loon *et al.*, 1998). However, two common measurement errors are caused as a result of this design: 1) the heat flux conduction is disturbed because the thermal conductivity of the sensor is different from that of the material being measured (Philip, 1961); 2) the plate impedes liquid and vapour water flow, including the coupled heat transport (van Loon *et al.*, 1998). Therefore, it is best to choose a thin sensor that is made of material of similar thermal conductivity to that of the

medium in which it is immersed, and similarly is calibrated in a medium similar to that of the material (although the sensor still impedes the movement of water). For measurement of fluxes through layered roofing materials, there are additional challenges to accurate measurement. Unless the building materials are specifically assembled for the project at hand, invasive measurements are usually unacceptable. Therefore, sensors must either be surface-mounted or placed between roofing assembly layers (e.g. between insulation and membrane) where there is access. Previous experiments have shown that surface-mounted sensors are prone to error because of wind and radiative effects (Hedlin, 1985). Thus, for this study, it is necessary to evaluate different methods of measuring the heat flux that are not invasive or expose the sensor to direct radiation. Traditional soil heat flux sensors (e.g. Middleton CN3) are ~ 4 mm thick and are too large to place between the roof insulation and membrane layer. A thin sensor such as the Hukseflux UTO3 ultrathin heat flux plate (see Chapter 2 for details) is likely to be a better choice because it is less than 1 mm thick and can easily slide under membranes or asphalt roofing shingles.

Air spaces, either in between roof layers or as intentional attic spaces, provide another problem for accurate measurement. If the air is completely still and the temperature is known, the conductivity can be easily assumed. However, in most cases this is unlikely to hold, access to these air spaces may be limited, or their locations may be unknown. In most cases, the simplest approach to solving the heat flux through the air layer may be through theoretical means, rather than through direct measurement.

Additional challenges to measuring the conductive heat flux through a roof assembly relate to the external boundary weather conditions affecting the outermost layer, and even some of the deeper (lower) layers. For example, moisture and wind not

only affect the external layer, but may also affect conditions in porous gravel layers or other layers above the waterproof membrane. Wind and moisture affect the heat sharing between the conductive heat flux into the roof, and the convective sensible or latent heat fluxes into the air above the roof. In most cases, one expects the conductive heat flux (Q_G) to be diminished under windy conditions (increased sensible heat flux) and diminished to a lesser degree under moist conditions (increased latent heat flux) (Oke, 1987). Therefore it is important to recognize the weather conditions under which measurements are taken, and understand that one can only speculate at the changes in the heat sharing or energy balance components over the roof surface unless all components are measured concurrently.

While the heat flow from layer to layer in a medium is calculated using Fourier's Law, the continuity equation is used to calculate the temperature variation with depth and time within one layer (Campbell and Norman, 1998) for non-steady state conditions. This equation is a useful means to evaluate how much heat is stored *within* the layer, rather than what flows through the interfaces *between* layers. This continuity equation is:

$$C \frac{\partial T}{\partial t} = - \frac{\partial Q_G}{\partial z} \quad (1.2)$$

where C is the heat capacity of the medium (which is equal to the density, ρ , multiplied by the specific heat, c), $\partial T/\partial t$ is the rate of temperature change, and $\partial Q_G/\partial z$ is the rate of change of heat flux density with depth through the medium, i.e. convergence. In soil heat storage measurement, usually an array of thermocouples through the soil layer is used to calculate the warming/cooling rate, $\partial T/\partial t$. While this would be ideal in a roof layer,

invasive placement of thermocouples is not practical. For a gravel layer on a roof, an array could be placed diagonally through the layer, or a “slab” approach could be used to measure only the surface and gravel/membrane interface temperature. The latter of these two methods may be the most appropriate for this study because of the complicated geometry of gravel layers (air spaces and different gravel sizes), and is presented in further detail in the Methods chapter (Chapter 2).

Using a theoretical or modelling approach to solve the problems associated with a multi-layer system proves to have its limitations as well. Without the ability to measure the temperature at each of the interfaces between the multiple layers, theoretical approaches to solving the heat flux through a multi-layered assembly often utilize only the outermost and innermost temperatures and boundary conditions (i.e. surface roof temperature and indoor ceiling temperature), and some knowledge of the characteristics and thicknesses of the layers in between.

In his model for roof thermal performance *STAR* (Simplified Transient Analysis of Roofs), Wilkes (1989) describes a finite difference solution method which divides the multi-layered assembly into a series or grid of nodes at which the temperature is calculated (as outlined in section 2.4). This method can be integrated over small increments of space and time by transforming a partial differential equation into a set of algebraic equations calculated at each node in the grid. This method requires full coupling to both external and internal boundary conditions, as well as knowledge of the thickness, and thermal and radiative characteristics of the individual layers. Obtaining the necessary information to utilize this theoretical/modelling approach to solving the conductive heat flux through a roof assembly requires access to information which is

often only available through building design and construction organizations. In addition, weather data is needed, which may or may not accurately reflect nearby conditions unless measured on-site. Therefore, to compare measurement and modelling approaches to obtain the conductive heat flux through a multi-layered system, measurements of the fluxes as well as the roof weather boundary conditions are needed.

One benefit to the theoretical approach is having the ability to see how a certain variable influences the magnitude of the conductive heat flux. For example, changing roof variables such as insulation thickness or the surface albedo may show how a roof's ability to store less heat energy could be improved. Changing weather variables such as wind speed or solar radiation could show how a roof assembly type could perform in different seasons or different climates.

A key reason for studying the conductive heat flux into and out of multi-layered systems such as roofs or buildings is to understand how this flux varies over the course of a day (its diurnal cycle). The diurnal cycle of the conductive heat flux influences the energy balance of the environment both outside and inside the building. Thus knowing the magnitude and direction of the heat flux moving through the roofing materials can help in studies of urban energy or heat islands, as well as in making decisions about the energy use and demand inside a building. The relationship between the conduction, heat storage change, and the net radiation of the surrounding environment is discussed in section 1.2.

1.2 Heat Fluxes in Roofs and in Complex Urban Areas

1.2.1 The Conductive Heat Flux in Roofs (Q_G)

The energy balance of a plane surface (such as a roof) is given by the equation:

$$Q^* = Q_H + Q_E + Q_G \quad (\text{W m}^{-2}) \quad (1.3)$$

where Q^* is the net radiation, Q_H is the sensible heat flux into the air, Q_E is the latent heat flux into the air, and Q_G is the conductive heat flux into the roof. This theoretical formulation neglects advected or anthropogenic sources of heat, although they would be present in the “measured” energy balance. In general, on a clear, summer day with little or no surface moisture, the diurnal cycle of the conductive heat flux (Q_G) in relation to the net radiation, would follow a pattern similar to that shown in Figure 1.1.

Figure 1.1 Generalized diurnal cycle of the conductive heat flux (Q_G) and net radiation (Q^*) components of the energy balance for a summer day over a dry building surface. Adapted from Oke (1987).

The generalized diurnal cycle shown in Figure 1.1 depicts a conductive heat flux which is greater than the net radiation during the night (i.e. releasing heat from the surface into the air), and upon heating after sunrise (8 h), begins to rise at a similar energy flux density as the net radiation. A few hours after sunrise (11h), Q_G reaches its peak. This peak is several hours before the peak in Q^* (14h). By the late afternoon (16-17h), the heat energy stored in the surface during the daytime begins to be released to the surface, which continues throughout the night.

The partitioning of energy between the Q_H , Q_E and Q_G fluxes largely depends on the moisture available for evaporation, with sharing occurring mostly between Q_H and Q_E . In studies over soil surfaces, Q_G does not vary greatly (Novak and Black, 1983). Typically, Q_G ranges from 5% of Q^* in wet conditions, to 15% under dry conditions (Oke, 1987) over natural surfaces such as soil. The fraction of the net radiation which is partitioned into Q_G is higher for urban materials, as discussed in section 1.2.2. While the range of Q_G values under varying wind conditions is not widely known, one would expect the magnitude of Q_G to diminish under high wind conditions (more convection, higher convective losses).

The relationship between the conductive heat flux and the net radiation has been extensively studied in the agricultural meteorology literature. Camuffo and Bernardi (1982) found that this relationship was best described by the following equation for a diurnal cycle:

$$Q_G = a_1 Q^* + a_2 \frac{\partial Q^*}{\partial t} + a_3 \quad (1.4)$$

The coefficients a_1 and a_2 are related to the magnitude of Q^* and its derivative respectively, and a_3 is an intercept term, independent of Q^* . Redrawing the diurnal cycles of Q_G and Q^* vs. time (Figure 1.1) to one of Q_G vs. Q^* at different times (Figure 1.2), gives a curve described by equation 1.4. This time-dependent lag between Q^* and Q_G is known as hysteresis-type behaviour.

Figure 1.2. Hysteresis loop of Q_G vs. Q^* (drawn from data in Figure 1.1).

1.2.2 The Storage Heat Flux in an Urban Volume (ΔQ_S)

Adapting the concept of the conductive heat flux to an urban area involves shifting our model from a simple plane (rooftop) to an urban volume (including many surfaces, whole buildings, soil and air layer). This urban building-air volume is depicted in Figure 1.3. As indicated by the labelling of the fluxes, this also suggests that an appropriate energy balance equation is required to accompany this shift.

Figure 1.3 Schematic depiction of the fluxes involved in the energy balance of an urban building-air volume.
Source: (Oke, 1987, p. 275)

The fluxes involved in the energy balance of an urban building-air volume are given in the equation from Oke and Cleugh (1987):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (1.5)$$

This theoretical equation uses the Q^* , Q_H , and Q_E terms used in the planar energy balance equation (1.3), except that they now refer to the top of the volume (box). This volume extends down to the depth of the zero net vertical flux over the period of interest. The equation also introduces the anthropogenic heat flux (Q_F), the net horizontal heat advection (ΔQ_A), and the net heat storage change in the volume per unit horizontal area (ΔQ_S). This term, ΔQ_S , is also known as the storage heat flux, and is the volumetric equivalent of the planar energy balance term, Q_G .

The “measured” energy balance equation (i.e. the equation which presents only those terms which can be measured individually), as opposed to the theoretical one

presented in equation 1.5, does not need to include Q_F because it is included as part of the other measured terms, and its inclusion would be “double-counting”. If an extensive and reasonably homogeneous site is used, it is also permissible to neglect the advective term, so the measured balance is:

$$Q^* = Q_H + Q_E + \Delta Q_S \quad (1.6)$$

The diurnal cycle of the storage heat flux (ΔQ_S) has a pattern similar to that shown in Figure 1.1. The magnitude of the heat storage term in the overall energy balance of an urban volume is thought to depend largely on its thermal inertia. Thus, for an urban area consisting mostly of dry asphalt parking lots, the heat storage term would be relatively large compared to an area with urban parks, lawns, and a few suburban houses. On average, measurements suggest that the ΔQ_S term at the top of an urban canyon ranges from 17 to 31% of the net radiation at suburban sites, and ~ 50 to 60% at industrial sites in North America (Grimmond and Oke, 1999).

1.2.3 *Measuring and Parameterizing the Storage Heat Flux (ΔQ_S)*

Of the main components of the urban energy balance, the storage heat flux is clearly the most difficult to measure because of the wide variety of different surface materials, and the complex geometry of canyons, inclined roofs, roads, and patchwork greenspace (Oke *et al.*, 1981). In an urban environment, the only workable means of obtaining ΔQ_S from measurements is to solve for it as the residual in equation (1.6), i.e.

by measuring spatial averages of Q^* , Q_H , and Q_E at the top of the volume (box). The drawback to this approach is the fact that this means all errors in assessing the other fluxes accumulates in ΔQ_s . Nevertheless, reasonable values have been obtained in this manner (e.g. (Grimmond and Oke, 1999; Roth and Oke, 1994))

An alternative method to measuring the storage heat flux is to develop a parameterization method. Following the energy balance work in soil science, the diurnal pattern of the storage heat flux for urban areas was parameterized using linear models (Oke *et al.*, 1981) and hyperbolic functions (Doll *et al.*, 1985). Linear functions were found to be inappropriate to describe the now recognized hysteresis behaviour described by Camuffo and Bernardi (1982).

The Objective Hysteresis Model (*OHM*) developed by Grimmond *et al.* (1991) incorporates this type of hysteresis parameterization. It requires only the net radiation, (Q^*), and the fraction of the urban surface covered by buildings, vegetation, canyon surfaces, etc. as input. It uses a form of the Camuffo and Bernardi (1982) equation which is summed over each component urban surface type:

$$\Delta Q_s = \sum_{i=1}^n \left[a_{1i} Q^* + a_{2i} \left(\frac{\partial Q^*}{\partial t} \right) + a_{3i} \right] \quad (1.7)$$

The regression coefficient a_1 indicates the strength of the mean dependence of the storage heat flux on the net radiation. The a_2 coefficient indicates the degree and direction of the phase relations between ΔQ_s and Q^* , and the a_3 coefficient is the intercept term. These three regression coefficients are illustrated in Figure 1.4.

Figure 1.4 Camuffo-Bernardi regression coefficients as descriptors of the ΔQ_S vs. Q^* relationship.

The net radiation term in equation 1.7 is considered to be the net radiation measured over the general area, and not a different one for each specific surface type (Q_i^*). In most cases, the empirically-derived coefficients are derived via the Q_G vs. Q^* relationship for that surface type. This raises the issue of whether the final summation over many surface types (i) for an urban area is representative of the ΔQ_S vs. Q^* relationship for the entire area. A study by Schmid *et al.* (1991) showed that differences between synchronous net radiation measurements at point sites in the city of Vancouver and at a fixed point site (at 25-30 m above the surface) were very small (<5%). This may be due to an albedo – surface temperature feedback effect which is balanced in the net radiation measurement.

OHM was evaluated in seven North American cities, and was considered to perform remarkably well in both urban (downtown) areas and more variable suburban areas. For a light industrial site in Vancouver, the measured vs. modelled relationship between ΔQ_S and Q^* is shown in Figure 1.5.

Figure 1.5 Measured vs. *OHM*-modelled relationship between the storage heat flux (ΔQ_S) and the net radiation (Q^*) over a light industrial site in Vancouver, B.C.

— (measured); - + - (Fitted); - x - (*OHM*)

Source: Grimmond and Oke (1999)

Notable problems in *OHM*'s performance arose because of variability in the convective fluxes, which could be attributed in part to surface moisture, wind speed, and synoptic conditions at each of the sites. The authors also conceded that one of the major limitations to the application of *OHM* was the sparse availability of data (i.e. coefficients) representing the ΔQ_S vs. Q^* relationship for individual surface types. In particular, Grimmond and Oke (1999) noted that only three sets of coefficients are available for rooftops, and that there is a disturbingly large difference between them. A summary of available measured coefficients for different urban surfaces is presented in Table 1.1.

Table 1.1 Summary of available Camuffo and Bernardi-type coefficients for urban surface types.

Surface type	City	Material	Source	a_1	a_2	a_3
Roof	Vancouver	tar and gravel	Yap (1973)	0.17	0.10	-17.0
	Uppsala	not specified	Taesler (1980)	0.44	0.57	-28.9
	Kyoto	membrane and concrete	Yoshida et al. (1991)	0.82	0.34	-55.7
Paved/Impervious		concrete	Doll et al. (1985)	0.81	0.48	-79.9
		concrete	Asaeda and Ca (1993)	0.85	0.32	-28.5
		asphalt	Narita et al. (1984)	0.36	0.23	-19.3
		asphalt	Asaeda and Ca (1993)	0.64	0.32	-43.6
	Vienna	asphalt – summer	Anandakumar (1999)*	0.72	0.54	-40.2
		asphalt – winter	Anandakumar (1999)*	0.83	-0.83	24.6

*Indicates averaged values for June-August (summer) and November-February (winter).

Some of the variability in the roof surface coefficients can be attributed to the experimental methodologies in the different studies. The heat flux plate was placed directly on the surface of the roof membrane in the Yoshida et al (1991) study, while in the Yap (1973) study, it was placed just underneath the surface of the gravel (on top of the tar layer). Taesler (1980) states that his roof-top experiment may have been influenced by a “kitchen effect”, i.e. additional anthropogenic heat from a hotel kitchen ventilation outlet on the roof! In all cases, descriptors of wind conditions are lacking.

The limited number and quality of these roof surface coefficients outlined here formed the basis for the present thesis research project. The objectives of the study are presented in the following section.

1.3 Research Objectives

The aim of this thesis is to extend the number and quality of available roof surface coefficients available for *OHM*-type parameterizations, and to enhance understanding of the energy efficiency and heat storage characteristics of industrial/commercial and residential roof types. In addition to providing information about Q_G vs. Q^* relationships under dry/fair conditions, this study aims to include both moisture and variable wind conditions and evaluate their effect on the coefficients.

The availability and accessibility of a variety of different roof types is an important factor in the development of the experimental methodology. The University of British Columbia campus in Vancouver, B.C. is an ideal location for study because it has several industrial/commercial roof types, and a support of professional roofers and engineers with access to detailed information regarding the individual roof layers. Residential roof types are equally accessible, but do not have such detailed roofing layer information available. Details of the research methodology are outlined in Chapter 2.

Chapter 2

METHODS

2.1 Objectives

The aim of this study is to measure the heat fluxes and weather conditions of five different roof assembly types, and to parameterize the relationship of net radiation (Q^*) and the conductive heat flux into and out of the roof (Q_G) for each roof type. The data collected at each site, combined with information gathered about the weather and the roof assembly structure and its associated properties, are then used to verify the Simplified Transient Analysis of Roofs (*STAR*) model. The successful verification of the model will allow its use to determine hysteresis coefficients used in the Camuffo and Bernardi (1982) equation (1.4) for roof assembly types not measured, and thereby extend the usefulness of the parameterization to a wide range of cities. These objectives are met through comprehensive measurement of roof surface heat flux characteristics, weather variables, and interior building temperature. A survey of typical roof assembly types and their radiative and thermal properties complement the measured data for use in the *STAR* model.

2.2 Rooftop Measurement

The heat storage characteristics of 1 residential, and 4 different industrial/commercial roof assembly types were determined in Vancouver, B.C., on buildings in and around the University of British Columbia (U.B.C.) campus (Figure 2.1). The data sets provide continuous records ranging from 1 week to 1.5 months for each site during the period June 1999 to September 1999.

Figure 2.1 Location of measured building sites in Vancouver, B.C.
 [Note: U.B.C. campus on left side. YVR = Vancouver International Airport]

The five rooftop sites and the periods of observation are:

- 1) Bookstore/N.C.E. building, U.B.C.(July 20 – July 27, 1999)
- 2) Buchanan C building, U.B.C.(July 27 – August 10, 1999)
- 3) Music building, U.B.C.(August 17 – modified August 24 – September 8, 1999)
- 4) University Services Building – Plant Operations, U.B.C.(August 10 – Sept. 27, 1999)
- 5) Residential home, Dunbar area (September 2 – September 22, 1999).

The specific building dimensions, roof assembly structures, and characteristics of each of the six sites are given in Appendix A. A typical industrial/commercial roof assembly type consists of a deck (concrete, steel, or wood), insulation, a membrane, and often a gravel layer, or several plies of membrane at the surface (Figure 2.2).

Figure 2.2 Commercial/Industrial roof assembly layers.
 Diagram not to scale.

2.3 Instrumentation

Each site was equipped with a standard array of instruments to measure heat fluxes, temperature and moisture at or below the roof surface; a tripod tower to measure radiation, air temperature, humidity, and wind; as well as a small tripod to measure the indoor building temperature. These instruments and the variables they measured are summarized in Table 2.1. All measurements were logged at a 5 second execution interval and averaged over a 15-minute period. Factory calibration of instruments used in this study occurred prior to, or just after, the measurement period. The Everest Interscience infrared temperature sensors were calibrated in the UBC Soil Science laboratory, generating the equations presented in Appendix B. Modifications to instrument placement were made depending on site characteristics.

2.3.1 Below-roof Surface Instrumentation

The standard instrument array below or within the roof surface consisted of 2 Middleton CN3 heat flux plates, 2 Hukseflux UTO3 Ultrathin (~0.6 mm thickness) heat flux plates, 2 surface moisture sensors, and 4 type T (copper-constantan) thermocouples wired in parallel and arranged in a 'handprint' pattern. These instruments were placed at the bottom of the layer of gravel (above the membrane or insulation), attached with minimal amounts of silicon gel around the edges at Sites # 1, 2, and 4, away from shadows.

In order to determine the heat flux at the surface of the gravel or membrane layer, a 'slab' approach was used. That is, the surface layer was treated as a single, homogeneous object, and only the temperatures and fluxes on either surface/interface need be measured. The equation used to calculate the surface conductive heat flux (Q_{Go}) is:

Table 2.1 Summary of standard instrument array used at each site.

Location	Measured Variable	Instrument, model
Roof surface	Surface temperature	2 Everest Interscience, Inc. 4000-A infrared temperature sensors
	Net all-wave radiation	1 Swissteco net radiometer S-1
	Incoming solar radiation	1 Kipp and Zonen pyranometer CM-5
	Outgoing longwave radiation	1 Eppley PIR pyrgeometer
Below 1 st roof layer	Sub-surface temperature	4 type-T thermocouples, 2 Hukseflux UTO3 internal thermocouples
	Conduction heat flux	2 Middleton CN3 heat flux plates, 2 Hukseflux UTO3 heat flux plates
	Surface moisture	2 Wetness sensors
3.5 m above roof surface	Air temperature and humidity	1 Campbell Scientific HMP35C temperature and humidity probe in a radiation shield
	Wind speed and direction	RM Young Wind Sentry set 03002
Inside building	Air temperature	Campbell Scientific ASP-TC aspirated type E thermocouple
All locations	Data retrieval and storage	2 Campbell Scientific 21X dataloggers

$$Q_{Go} = Q_{Gz} + C_r \left(\frac{\Delta T_s}{\Delta t} \right) \Delta z \quad (2.1)$$

where Q_{Gz} is the heat flux at the base of the surface layer. The second term on the right-hand-side of the equation represents the heat storage in the gravel layer, where the heat capacity ($C_r = \rho_r c_r$, where ρ_r is the density and c_r the specific heat of the surface roof material) is a characteristic of the surface layer (i.e. gravel or membrane), and ΔT_s is the average of the temperatures measured at the surface (using an I.R. thermometer) and at the base of the surface layer (using thermocouples and heat flux plate internal thermocouples). The experimental set-up and the fluxes presented in equation 2.1 are depicted in Figure 2.3.

Figure 2.3. Depiction of surface and below roof-surface fluxes determined using “slab” approach. Note below roof-surface placement of heat flux plate.

At Site 3, no Middleton sensors were used. Instead, 4 Hukseflux UTO3 sensors were inserted as far as possible (~ 20 cm) under the bitumen membrane, one each facing north, south, east and west. To prevent moisture entering beneath the membrane, the UTO3 wires were fed through a lead pipe that was torch-applied to the membrane, as shown in Figure 2.4. The four thermocouples wired in parallel were not used at this site, leaving only the UTO3 plate thermocouples to measure the below-roof surface temperature. Moisture sensors were affixed to the surface of the membrane.

Figure 2.4. Site 3 (Music Building) UTO3 wires leading from a pipe. Surface is 2-ply modified SBS bitumen. Image facing south.

At Site 5 (Figure 2.5), only the UTO3 sensors were used because of the narrow space between residential asphalt roofing shingles. As at Site 3, the parallel-wired thermocouples were not used. The moisture sensors were affixed with silicon gel to the shingle surface. Because the roof was inclined (2 slopes), a separate set of instruments was placed on each side of the roof.

2.3.2 *Roof Surface and Lower-tripod Tower Instrumentation*

On each rooftop, solar radiation input was measured with a Kipp and Zonen pyranometer mounted away from the tripod tower and other obstructions. At each site, an aluminum tripod tower was placed on the roof surface, with instruments extending out from it to measure both near-surface (~ 0.5 m) and above surface (~ 3.5 m) variables. A Swissteco net pyrradiometer was mounted 1 m above the surface to measure net all-wave radiation. Two Everest Interscience infrared temperature sensors (15° field-of-view) were mounted at a height of 0.5m (from nadir) and directed at the surface to measure the surface temperature of the gravel, membrane or shingle.

Hemispheric-view (fish-eye) photos were taken at each site to quantify sky obstructions to the net pyrradiometer's skyward field-of-view, and to verify how much of the roof surface was captured in the downward field-of-view.

Due to the dual-sloped nature of the residential roof at Site 5, the exposure of the instruments on the tower was adjusted to accommodate the slope of the two roof facets. The lower instruments were mounted on an aluminum pipe extending from the chimney and supported by a smaller aluminum pipe positioned on a wooden brace (Figure 2.5). Net radiometers were mounted on either side of the roof, oriented parallel to the sloped surface.

Figure 2.5. Site 5 instrumentation showing net pyr-radiometers on either side of roof slope, an infrared temperature sensor and pyrgeometer on the center post, and a pyranometer on top of the chimney. (Yellow cord was not present during sampling).

2.3.3 Upper-tripod Tower Instrumentation

The upper tripod tower was placed on the roof top of all of the sites, with the exception of Site 5 where the tower was placed on a nearby flat deck (~ 0.5 m above ground). At the top of the tower (3.5 m), wind speed and direction was monitored with a wind sentry and air temperature and humidity via a probe in a radiation shield. A schematic drawing and photograph of the tripod tower and instrument array are shown in Figure 2.6.

Figure 2.6. [a] Schematic drawing and [b] northward facing photograph (at Site 3) of tripod tower instrument array for Sites 1-4.

2.3.4 Building Interior Instrumentation

A small tripod with a Campbell Scientific aspirated type E thermocouple was placed in a room of the building directly beneath the experimental area, or in an adjacent room. At Site 5, no interior measurements were taken, while at Sites 1, 2, and 3 the interior temperatures were taken in adjacent rooms, and at Site 4, the temperature in the corridor directly beneath the rooftop site was measured.

2.4 *STAR* Model

A numerical model, *STAR* (Simplified Transient Analysis of Roofs) was developed at the Roof Research Center at Oak Ridge National Laboratory by K.E. Wilkes (1989). It was designed to guide thermal/energy efficiency experiments, and to extrapolate the results of experiments to other sites and conditions. The model was tested against field observations and found to work effectively by capturing the effects of diurnal cycles of radiation forcing and weather conditions, although further refinements were deemed necessary to better represent incident radiation and convective heat transfer (Wilkes, 1989). The model applies to transient one-dimensional conduction in multilayer roof systems, and is fully coupled to weather conditions. As discussed in Chapter 1, the heat flow equation for a roof system (by substituting Fourier's Law into the continuity equation) would be:

$$C_r \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_r \frac{\partial T}{\partial x} \right) \quad (2.2)$$

where T is temperature, t is time, x is the depth or thickness of the roof, k_r is its thermal conductivity, C_r is its heat capacity. Exact analytical solutions of equation 2.2 are difficult to obtain because of the multi-layered nature of a roof system containing different thermal properties, as well as problems of coupling the external weather to the roof boundary conditions. Therefore, a finite difference solution method is used in *STAR*, which breaks down the layers into a grid of "nodes" at which the temperatures are

calculated. Thus equation 2.2 is integrated over small increments of distance (x) and time (t) for each node.

Assuming node P is at the centre of a volume with width Δx , and neighbouring nodes to the east and west are denoted by E and W , the heat balance equation for node P becomes:

$$C_r \frac{\Delta x}{\Delta t} (T_P^1 - T_P^0) = f \left[\frac{k_e (T_E^1 - T_P^1)}{(\delta x)_e} - \frac{k_w (T_P^1 - T_W^1)}{(\delta x)_w} \right] + (1-f) \left[\frac{k_e (T_E^0 - T_P^0)}{(\delta x)_e} - \frac{k_w (T_P^0 - T_W^0)}{(\delta x)_w} \right] \quad (2.3)$$

where the superscripts 0 and 1 represent the beginning and end of the time step, and subscripts for the thermal conductivity (k) indicate the effective conductivity between that node and P , and subscripts for thickness (δx) represent the distance between that node and P (see Figure 2.7). There are three solutions to this equation: classical explicit ($f=0$), fully implicit ($f=1$), and the Crank-Nicolson method ($f=0.5$). Of these three methods, the fully implicit method is the most numerically stable, but a time-step must be chosen which is small enough to capture the temperature and heat flow changes (Wilkes, 1989). The model then calculates the hourly values of temperature and heat flux at each interface between the roof materials.

The inputs to this model include specific geometric, radiative and thermal roof layer properties for each roof type, along with an hourly weather data file for the site. These inputs are outlined in Table 2.2.

Figure 2.7. Finite difference grid used in *STAR*. Adapted from Wilkes (1989).

Table 2.2. Inputs to *STAR* Model.

Input data type	Variable	Unit
Weather	Outdoor temperature	°C
	Relative humidity	%
	Incident solar radiation	W m ⁻²
	Wind speed	m s ⁻¹
	Cloud amount (to parameterize incident infrared radiation)	in eighths
Roof assembly	Slope	cm m ⁻¹
	Length and width	m
	Number of layers	integer
	Size of time step	integer
	Choice of transient solution method	$f = 0, 0.5, \text{ or } 1$
	Absorptivity (1- α) and emissivity of surface layer	Unitless
	Outside convection coefficient	Btu (hr ft ² °F) ⁻¹ or calculated
	Indoor temperature	°C
	Inside convection coefficient	Btu (hr ft ² °F) ⁻¹ or calculated
Individual roof layers	Name	characters
	Thickness	cm
	Number of nodes	integer
	Thermal conductivity	W m ⁻¹ K ⁻¹
	Specific heat	J kg ⁻¹ K ⁻¹
	Density	kg m ⁻³

The effective conductivity, k_e , given in equation 2.3 is evaluated at the interface between nodes P and E (or P and W). By assigning a value of thermal conductivity to

each node in the model, this allows each node to represent a different material type, or to allow thermal conductivity to vary with temperature within the roof material layer. A series arrangement of the thermal resistances between two nodes is used to determine the effective thermal conductivities at the interfaces, as shown in Figure 2.7. With reference to this figure, the effective thermal conductivity, k_e , is given by:

$$k_e = \left[\frac{1-f_e}{k_p} + \frac{f_e}{k_E} \right]^{-1} \quad \text{where} \quad f_e = \frac{(\delta x)_{e+}}{(\delta x)_e} \quad (2.4)$$

Figure 2.8. Node spacings for effective thermal conductivity in *STAR*. Adapted from Wilkes (1989).

The exterior boundary (weather) conditions drive the thermal model in *STAR* according to the following heat balance equation:

$$K \downarrow (1 - \alpha) + \varepsilon L \downarrow - \varepsilon \sigma T_s^4 + h_r (T_a - T_s) + Q_E + Q_{\tilde{G}} = 0 \quad (2.5)$$

where the terms of the equation represent absorbed solar radiation, absorbed incident longwave radiation, radiation emitted by the surface, sensible heat convection between

the air and the surface, heat delivered to the surface by condensation (or removed by evaporation) of moisture, and heat conducted into or out of the roof surface, respectively.

The terms α and ϵ represent the albedo and the longwave emissivity of the surface, respectively. The surface layer is assumed to be grey in the infrared, thereby equalizing the infrared absorptance and emittance.

The convection coefficients for heat transfer (h) from the interior and exterior surfaces are based on correlations that have been developed for isolated isothermal flat plates (Wilkes, 1989). The correlations are in the form of a Nusselt number (Nu) as a function of a Rayleigh number (Ra), a Reynolds number (Re), or a Grashof number (Gr) as given by the following equations:

$$Nu = \frac{hL}{k_a} ; Ra = g\beta\rho_a c_p \Delta T \frac{L^3}{\nu k_a} ; Re = V \frac{L}{\nu} ; Gr = \frac{Ra}{Pr} ; Pr = \frac{\nu}{K_a} \quad (2.6)$$

where

h = convective heat transfer coefficient

ρ_a = density of air

L = characteristic length of plate

ν = kinematic viscosity of air

k_a = thermal conductivity of air

K_a = thermal diffusivity of air

g = acceleration of gravity

V = velocity of air stream

Pr = Prandtl number for air

c_p = specific heat of air at constant pressure

ΔT = temperature difference between surface and air

β = volume coefficient of expansion of air

The model uses correlations for both laminar and turbulent flow, depending on the Raleigh number (natural convection) and the Reynolds number (forced convection)(Table 2.3). Separate coefficients are calculated for natural and forced flow, and a mixed flow coefficient is calculated by taking the third root of the sum of the cubes of the two separate coefficients. The model also uses correlations which have been developed for various orientations of the plate with respect to gravity, as well as for the direction of heat flow (Wilkes, 1989).

Table 2.3. Correlations for convection coefficients in *STAR*. Source: Wilkes (1989)

Natural convection	Horizontal surface, heat flow up	$Nu = 0.54 Ra^{1/4}$ $Nu = 0.15 Ra^{1/3}$	For $Ra < 8 \times 10^6$ For $Ra > 8 \times 10^6$
	Horizontal surface, Heat flow down	$Nu = 0.58 Ra^{0.2}$	
	Vertical surface	$Nu = 0.59 Ra^{1/4}$ $Nu = 0.10 Ra^{1/3}$	For $Ra < 1 \times 10^9$ For $Ra > 1 \times 10^9$
	Nearly horizontal surface (tilt angle $< 2^\circ$), heat flow down	$Nu = 0.58 Ra^{0.2}$	
	Tilted surfaces (tilt angle, $\phi > 2^\circ$), heat flow down	$Nu = 0.56 [Ra \cos(\phi)]^{1/4}$	
	Tilted surface, heat flow up	$Nu = 0.56 [Ra \cos(\phi)]^{1/4}$ $Nu = 0.14 [Ra^{1/3} - (Gr_c Pr)^{1/3}] + 0.56 [Ra \cos(\phi)]^{1/4}$ $Gr_c = 1 \times 10^6$ $Gr_c = 10^{[\phi/(1.1870 + 0.0870 \phi)]}$ $Gr_c = 5 \times 10^9$	For $Ra/Pr < Gr_c$ For $Ra/Pr > Gr_c$ For $\phi < 15^\circ$ For $15^\circ < \phi < 75^\circ$ For $\phi > 75^\circ$
Forced convection		$Nu = 0.664 Pr^{1/3} Re^{1/2}$ $Nu = Pr^{1/3} (0.037 Re^{0.8} - 850)$	For $Re < 5 \times 10^5$ For $Re > 5 \times 10^5$

The correlations account for the effects of: surface-to-air temperature difference, heat flow direction, film (surface) temperature, surface roof area, surface orientation and velocity of air flow past the plate. Exterior air speed is assumed to be the measured wind speed taken from meteorological data (measured on-site; measurements by Wilkes taken at a height of 0.30 m)(Wilkes, 2000), while interior air speed is assumed to be zero. This

estimate for interior air speed is deemed sufficient because natural convection should dominate over forced convection inside.

The latent heat term, Q_E , only accounts for condensation/evaporation at the roof surface, and not moisture migration through the roof. Q_E is the product of the rate of mass transfer at the surface $\dot{m}_v$, and the latent heat of vaporization of water, h_v :

$$Q_E = \dot{m}_v h_v \quad (2.7)$$

where the mass transfer rate per unit of roof area is:

$$\dot{m}_v = h_m (W_a - W_s) \quad (2.8)$$

where W is the humidity mixing ratio of the air or surface, and h_m is the mass transfer coefficient. In this model, h_v is taken to have a constant value of 1060 Btu lb⁻¹ (2464 kJ kg⁻¹). The humidity mixing ratios, W_a and W_s , are obtained from the known values of relative humidity and temperature of the air and surface using psychrometric relations. When condensed moisture is present on the surface, it is assumed that the moisture in the air near the surface is in equilibrium with the surface moisture, allowing the humidity ratio at the surface to correspond to saturation conditions at the temperature of the surface (Wilkes, 1989). The mass transfer coefficient, h_m , is found from the analogy between heat and mass transfer as presented in equation 2.9:

$$\frac{h_c}{h_m c_p} = \left(\frac{K_a}{K_v} \right)^{2/3} \cong 1 \quad (2.9)$$

where h_c is the convection heat transfer coefficient, c_p is the specific heat of air, K_a is the turbulent thermal diffusivity of air, and K_v is the coefficient for diffusivity of water vapour through air.

Infrared radiation in the *STAR* model is linearized by defining the temperature for the surrounding air (T_a) using the Stefan-Boltzmann equation:

$$T_a = \left(\frac{L \downarrow}{\sigma} \right)^{1/4} \quad (2.10)$$

where $L \downarrow$ is the downward infrared (longwave) radiation, and σ is the Stefan-Boltzmann constant. If $L \downarrow$ values are not available, the model uses an effective sky temperature algorithm to calculate T_a as a function of relative humidity, time of day and cloud cover based on the equation given by Martin and Berdahl (Wilkes, 1989).

The value of T_a and the given surface temperature, T_s , are then used to calculate the net longwave radiation at the surface (L^*):

$$\begin{aligned} L^* &= \varepsilon \sigma (T_a^4 - T_s^4) \\ &= \varepsilon \sigma (T_a^2 + T_s^2) (T_a + T_s) (T_a - T_s) \\ &= h_L (T_a - T_s) \end{aligned} \quad (2.11)$$

The radiation coefficient, h_L , is estimated from previous estimates of the surface temperature. When a new surface temperature is calculated, a new h_L is estimated until convergence is obtained. This is done similarly with the convective coefficients, which

depend upon the surface temperature through the temperature difference between T_s and T_a (Wilkes, 1989).

When the weather boundary conditions are used, the model performs the calculations iteratively until it achieves a self-consistent set of nodal temperatures. Once these nodal temperatures are known, the heat flux between the nodes can be calculated (Wilkes, 1989).

2.4.1 Validation and Application of the STAR model

The measured interior and exterior weather data, combined with the thermal and radiative properties of the roof layers, were used as input to the *STAR* model for each of the six sites (for inputs, see Appendix A). For Sites 1 through 5, those periods where no moisture was measured were modelled using *STAR* for comparison with measured roof surface and roof layer-interface fluxes. The weather data input are hourly values of time, outdoor temperature, relative humidity, solar radiation, wind speed, and cloud amount (to parameterize downward infrared radiation). These variables were measured following the methods outlined in section 2.3, and averaged over 1 hour. The cloud amount data was obtained from the Vancouver International Airport (YVR) weather files (airport location relative to measurement sites is shown in Figure 2.1). Indoor temperatures were averaged over the measurement period and input as a constant temperature for the model.

The *STAR* model was run using the fully implicit method ($f=1$) to avoid numerical instability problems, and thus the possibility of physically unrealistic solutions. There were 10 time-steps per hour of simulated time, and inside and outside convective coefficients were obtained from model correlations.

Results of the model simulations were compared with measured fluxes, and statistically analyzed for error and agreement. The error index used is the root mean squared error (RMSE), calculated as:

$$RMSE = \left[n^{-1} \sum_{i=1}^n (P_i - O_i)^2 \right]^{0.5} \quad (2.12)$$

where n is the number of values, P is the predicted (modelled) flux value, and O is the observed (measured) flux value (Willmott, 1981). This RMSE is reported in the same units as O and P (W m^{-2}), and therefore gives a good indication of the actual size of the error produced by the model.

Common indices of agreement used to evaluate measured and modelled data are r and r^2 . The coefficient of multiple determination, r^2 is calculated by dividing the sum of squares due to regression by the total sum of squares. The equation for r^2 is given in von Storch and Zwiers, 1999, p. 151. The indices r^2 and r describe proportional increases or decreases about the respective means of the two variates, but they do not differentiate between the type or magnitude of possible covariations. To avoid these problems associated with r and r^2 , an index of agreement, D , was presented by Willmott (1981):

$$D = 1 - \frac{n(RMSE)^2}{\sum_{i=1}^n [(P_i - \bar{O}) + (O_i - \bar{O})]^2} \quad (2.14)$$

where $\bar{O}$ represents the mean of the observed values. This index of agreement reflects the degree to which the measured variables are accurately estimated by the modelled variables. It is not a measure of correlation, but a measure of the degree to which the model's predictions are error free. It varies between 0.0 and 1.0, where 1.0 indicates perfect agreement between observed and predicted values. For the purpose of comparison, the $RMSE$, r^2 , r and D index statistics are presented for the modelled and measured data at each site (results are given in Chapter 4).

Chapter 3

RESULTS OF ROOF HEAT FLUX MEASUREMENTS

This chapter describes the results of the roof heat flux measurements carried out on both industrial/commercial and residential roof types in Vancouver, B.C. The aim of this chapter is to present an overview of the relationship between the measured surface conductive heat flux and the net radiation for each of the five sites. This chapter is structured according to individual measurement sites. For each site, details about the roof assembly structure and site characteristics are given. This is followed by an overview of the range of temperatures, heat fluxes, and wind conditions observed. The diurnal cycles of the surface conductive heat flux (Q_{Go}) and the net radiation (Q^*) are then presented, along with the corresponding hysteresis loops and Camuffo and Bernardi –type coefficients. For those sites where the measurement period was extensive, analysis of the Q_{Go} and Q^* relationship is separated into wind and moisture categories.

3.1 Industrial/Commercial Roof Assembly Types

3.1.1 Commercial/Industrial Site 1– U.B.C. Bookstore (BKS) /N.C.E. building

The measurements at the Bookstore (BKS) site were conducted on a roof with the approximate dimensions of 25 x 50 m. Working from the bottom to the top, the roof assembly consists of a concrete deck, vapour retarder (plastic film), 2 layers of rigid insulation, a modified bitumen membrane, another layer of rigid insulation, and a gravel ballast approximately 4.5 cm thick. The site was unobstructed in all directions with the

exception of the north, where a taller building (3 storeys higher) was located approximately 25 m away.

The standard instrument array described in Chapter 2 was placed at the site. All instruments were operable with the exception of the 2 Hukseflux Ultrathin heat flux plates (UTHFP), which appeared to react erratically in gravel layers, giving negative fluxes (out of the roof) at mid-day. Possible reasons for this erratic behaviour could be due to the heterogeneous nature of the gravel layer, with gravel touching some parts of the plate, and air spaces over other parts. Convection through the gravel layer or reflected solar radiation onto the plate surface may also have caused this behaviour. Results from both UTHFPs had standard deviations greater than 10 times those of the Middleton heat flux plates. The UTHFP data was therefore eliminated from the analysis. During periods when the moisture sensors indicated periods of prolonged moisture (24 h), the in-parallel thermocouples gave faulty readings. This left only three 24-hour moisture-free days for analysis at the BKS site (July 21-23, 1999). The range of daily maximum and minimum temperatures and fluxes at the surface and at the gravel/insulation interface, as well as the 3.5 m tower wind speed observed over this period are given in Table 3.1.

Table 3.1. Range of daily temperatures and fluxes for July 21-23, 1999 at Site 1 (BKS).

Fluxes (W m^{-2})	Q^*	Range of daily max	Range of daily min
		498 to 595	-68 to -89
	Q_{Gz}	19 to 25	-8 to -10
Temperatures ($^{\circ}\text{C}$)	T_s	49 to 57	10 to 11
	T_z	49 to 56	12 to 13
	$T_s - T_z$	2.0 to 3.6	-3.2 to -3.6
Wind speed (m s^{-1})	u	2.15 to 2.50	0.51 to 0.79

The heat flux at the surface of the gravel layer, Q_{Go} , was calculated according to equation 2.1 using a density of 1121 kg m^{-3} and a specific heat of $1.67 \text{ kJ kg}^{-1} \text{ K}^{-1}$ for the gravel/air layer. The calculated surface conductive flux, along with the measured Q^* , were averaged on an hourly basis, and are presented for the three days (Figure 3.1). The surface fluxes show considerable fluctuation on July 21 and 22. The “spikes” can be attributed to fluctuations in the solar radiation reaching the surface (due to cloud cover or building shadows). Figure 3.1(b) gives the hysteresis relationship between the net radiation and the surface conductive heat flux. While the hysteresis loops are relatively smooth for July 21 and 23, the sharp spike on the 22nd relates to that shown in Figure 3.1(a) at 1200h. The severity of the spike can be attributed to a large shift in temperature at the surface (a 6°C drop at 1200h followed by an 11°C rise at 1400h) as well as relatively large shifts in the interface flux (Q_{Gz}). The coefficients which correspond to the regression of Q_{Go} vs. Q^* are given in Table 3.2 for each of the 3 days.

Table 3.2. Coefficients for Site 1 (BKS)

Date	a_1	a_2 (h)	a_3 (W m^{-2})	r^2
July 21	0.26	1.27	-33	0.77
July 22	0.34	1.21	-36	0.78
July 23	0.24	1.43	-32	0.95
<i>Average</i>	<i>0.28</i>	<i>1.30</i>	<i>-34</i>	

The a_1 coefficients at this site are considerably lower than those presented by Taesler (1980) and Yoshida et al. (1991), but are similar to that measured by Yap (1973) (Table 1.1). The a_2 coefficient is larger than has been found for any urban surface material (Table 1.1). This implies that this industrial/commercial roof type hysteresis is large, i.e. the phase of the conductive flux leads the radiation forcing by more than in the case of surfaces such as concrete or asphalt. The a_3 coefficients are within the range

Figure 3.1: Bookstore (BKS) Building/Industrial-Commercial Site 1, dry measurement days – (a) diurnal cycle of the roof surface heat flux (Q_{Go}); (b) hysteresis loop of the net radiation vs. the roof surface heat flux; and (c) diurnal variation of the surface conductive heat flux normalized by the net radiation (Q_{Go}/Q^*).

found for most urban materials. These remarks should be tempered by the fact that the statistics are based on only 3 days of observations.

Figure 3.1(c) shows the diurnal cycle of the roof surface conductive heat flux normalized by the net radiation. In many urban areas, the integrated local scale ratio is ~ 1 between about 2100h and 600h (Grimmond and Oke, 1999), but for this roof, the ratio is only ~ 0.5 . This means that for most of the night, the roof does not release a large amount of heat from storage to offset the radiation drain. This implies that one or both of the turbulent fluxes (Q_H , Q_E) from the air supplies the remainder.

If these results are representative, roof heat fluxes may not account for a significant portion of the storage heat flux in an urban area. That would mean that the observed large ratio depends on several other materials found in the urban area.

3.1.2 *Commercial/Industrial Site 2- Buchanan B building, (BUC) U.B.C.*

The measurements at the Buchanan B (BUC) site were conducted on a roof which is approximately 75 x 50 m. From bottom to top, the roof assembly consists of a concrete deck, a vapour retarder, polyisocyanurate insulation, covered by a tar and pea gravel layer (gravel depth ~ 2 cm). The site was in disrepair and subject to poor drainage and flooding. The layers above the concrete deck were replaced the following year. The site was unobstructed in all directions with the exception of a concrete high-rise building approximately 150 m to the northeast and a few trees at the line of the horizon to the east.

The standard instrument array was placed at the site. All instruments functioned well with the exception of one of the Hukseflux Ultrathin heat flux plates (UTHFP #1).

It gave results with standard deviations greater than 5 times those of the Middleton and other Hukseflux heat flux plates. The UTHFP #1 data was therefore eliminated from the analysis. Further, during the final two days of the measurement period, one of the Middleton sensors was completely submerged in water and produced erratic values. For this period, only the remaining two flux plates were considered in the analysis of Q_{Gz} .

A total of 14 wet days (there were none with 24h-rain-free period) were observed at this site from July 27 to August 10, 1999. The range of daily maximum and minimum temperatures and fluxes observed over this period are presented in Table 3.3.

Table 3.3. Range of daily temperatures and fluxes for July 2-Aug. 2, 1999 at Site 2 (BUC).

Fluxes (W m^{-2})	Q^*	Range of daily max	Range of daily min
		400 to 476	-46 to -96
	Q_{Gz}	45 to 56	-16 to -31
Temperatures ($^{\circ}\text{C}$)	T_s	54 to 63	13 to 17
	T_z	54 to 60	14 to 18
	$T_s - T_z$	2.1 to 3.0	-1.6 to -5.1
Wind speed (m s^{-1})	u	1.44 to 2.37	0.20 to 0.49

The heat flux at the surface, Q_{Go} , was calculated using a density of 1100 kg m^{-3} and a specific heat of $1.47 \text{ kJ kg}^{-1} \text{ K}^{-1}$ for the gravel layer. The calculated surface flux, and the measured Q^* , were averaged on an hourly basis. Due to complete flooding of the instruments at the site and the lack of a discernable hysteresis loop at these times, the measurements taken from July 29-30, and Aug. 3 and 5-10 were not considered, leaving only those for five days in the period July 28 – Aug 4, 1999 (Figure 3.2).

The surface fluxes at Buchanan B are lower than those at the BKS site (compare Figures 3.1(a) and 3.2(a)). This can probably be attributed largely to the wet roof surface during the entire measurement period. The curves are relatively smooth, with a few

Figure 3.2: Buchanan B (BUC) Building/Industrial-Commercial Site 2, for five wet measurement days - (a) diurnal cycle of the roof surface heat flux (Q_{Go}) ; (b) hysteresis loop of the net radiation vs. the roof surface heat flux ; and (c) diurnal variation of the surface conductive heat flux normalized by the net radiation (Q_{Go}/Q^*).

“spikes” due to passing clouds. No shadow effects are visible. The hysteresis loop in Figure 3.2(b), which is on the same scale as that in Figure 3.1(b), is quite smooth, with some irregularity at the time of peak net radiation.

Table 3.4. Coefficients for Site 2 (BUC)

Date	a_1	a_2 (h)	a_3 (W m ⁻²)	R^2
July 28	0.21	0.85	-22	0.93
July 31	0.22	0.65	-15	0.93
August 1	0.18	0.81	-18	0.87
August 2	0.19	0.92	-18	0.82
August 4	0.21	0.91	-20	0.94
<i>Average</i>	<i>0.20</i>	<i>0.83</i>	<i>-19</i>	

The BUC coefficients for this period (Table 3.4) are lower than those of the gravel roof under dry conditions (BKS), but the a_1 coefficient, which indicates the mean heat sharing, is only approximately 0.03 less. The smaller a_2 and a_3 coefficients reflect the general “dampening” of the roof’s response to the net radiation. Again the nocturnal Q_{Go}/Q^* fraction is relatively small (c. 0.1 – 0.5) (Figure 3.2c). Thus the roof does not appear to sustain large heat release after about 2100 h.

3.1.3 Commercial/Industrial Site 3 – Music Building (MUS), U.B.C.

The measurements at the Music Building (MUS) site were conducted on a ~ 25 x 25 m roof. From bottom to top, the roof assembly consists of a concrete deck, a vapour retarder, phenolic insulation, surmounted by a 2-ply modified SBS (styrene butadiene styrene) bitumen membrane. The site was in good condition, although prone to flooding in some areas. The site was unobstructed in all directions with the exception of a one

storey penthouse 20 m to the southeast and two multistorey buildings >200 m to the north.

A total of 8 wet days (no 24h-rain-free period) in the period August 17 – 24, 1999 under variable (sun and rain conditions) were observed at this site, but again, due to flooding, only 4 days were considered for analysis. The range of daily maximum and minimum temperatures and fluxes observed over this period are presented in Table 3.5. The range of daily maximum and minimum fluxes for both Q^* and Q_{Gz} are considerably smaller in magnitude than those at the gravel roof sites (BKS and BUC).

Table 3.5. Range of daily temperatures and fluxes for Aug. 19-Aug. 23, 1999 at Site 3 (MUS).

Fluxes (W m^{-2})	Q^* Q_{Gz}	Range of daily max	Range of daily min
		302 to 408 9 to 10	-55 to -67 -2 to -5
Temperatures ($^{\circ}\text{C}$)	T_s	56 to 61	7 to 11
	T_z	51 to 55	9 to 13
	$T_s - T_z$	5.6 to 13.0	-3.6 to -6.1
Wind speed (m s^{-1})	u	2.62 to 3.77	0.20

The heat flux at the surface, Q_{Go} , was calculated using a density of 1081 kg m^{-3} and a specific heat of $1.466 \text{ kJ kg}^{-1} \text{ K}^{-1}$ for the 2-ply modified SBS bitumen layer. The calculated surface flux, along with the measured Q^* , were averaged on an hourly basis, and are presented for Aug 19– Aug 23, 1999. Figure 3.3(a) shows that the MUS roof had the smallest of the roof surface conductive heat fluxes measured, reaching a peak of only $\sim 38 \text{ W m}^{-2}$ on most days with a small hysteresis loop (Figure 3.3b). It should also be noted that net radiation was somewhat smaller at this site. The coefficients corresponding to the hysteresis loop are presented in Table 3.6.

Figure 3.3: Music Building (MUS) /Industrial-Commercial Site 3, for 4 wet measurement days - (a) diurnal cycle of the roof surface heat flux (Q_{Go}) ; (b) hysteresis loop of the net radiation vs. the roof surface heat flux ; and (c) diurnal variation of the surface conductive heat flux normalized by the net radiation (Q_{Go}/Q^*).

Table 3.6. Coefficients for Site 3 (MUS)

Date	a_1	a_2 (h)	a_3 (W m ⁻²)	r^2
August 19	0.06	0.30	-3	0.86
August 21	0.06	0.25	-4	0.73
August 22	0.06	0.29	-3	0.78
August 23	0.06	0.27	-3	0.76
<i>Average</i>	<i>0.06</i>	<i>0.28</i>	<i>-3</i>	

After normalization of Q_{Go} by Q^* (Figure 3.3c) there is a near-zero amount of heat release from storage between the hours of 2200h and 600h. Hence it is much lower than the standard ratio of about unity for a whole urban area, but also much below that measured at the gravel building sites. This indicates the bitumen roof surface is more energy conservative than those previously measured, i.e. it takes in relatively little heat by day and therefore has little to release at night. This implies significantly enhanced convective fluxes compared to other roofs.

3.1.4 Commercial/Industrial Site 4 – University Services Building (USB) /Plant Operations, U.B.C.

The measurements at the University Services Building (USB) were conducted on a ~ 10 x 40 m roof. From bottom to top, the roof assembly consists of a steel deck with a gyproc overlay, a membrane, extruded EPS insulation, a 2-ply SBS modified bitumen membrane, topped by approximately 4.5 cm of river gravel. The roof was in good condition. The site was partially obstructed by a glass dome running the length of the building toward the south (~ 10 m away from measurement tower), but there were no other sources of interference.

A total of 27 rain-free (dry) days and 6 wet days during the period August 10 – Sept. 27, 1999, under a wide range of sun, wind, and moisture conditions were observed at this site. As was observed at the other gravel sites, one of the Hukseflux ultrathin heat flux plates gave readings that were greater than 2 standard deviations from the other heat flux plates, and was therefore eliminated from the analysis. As well, one of the infrared thermometers was eliminated from the analysis because of erratic readings and possible moisture leakage inside the instrument. Due to the considerable size of the data set, the results are divided into those during dry and wet conditions.

DRY CONDITIONS

The range of daily maximum and minimum temperatures and fluxes observed over the dry period (Table 3.7) reflect the wide range of cloud conditions observed during the measurement period.

Table 3.7. Range of daily temperatures and fluxes for dry days at Site 4 (USB).

Fluxes (W m^{-2})	Q^* Q_{Gz}	Range of daily max	Range of daily min
		292 to 560	-66 to -110
		11 to 16	-4 to -8
Temperatures ($^{\circ}\text{C}$)	T_s	29 to 49	1 to 12
	T_z	27 to 44	3 to 16
	$T_s - T_z$	2.5 to 7.2	-2.8 to -5.7
Wind speed (m s^{-1})	u	1.63 to 3.76	0.20 to 1.20

The heat flux at the surface, Q_{Go} , was calculated according to equation 2.1 using a density of 1100 kg m^{-3} and a specific heat of $1.47 \text{ kJ kg}^{-1} \text{ K}^{-1}$ for the gravel and air layer. There are sufficient results of these daily measurements and calculations to categorize them into 3 classes according to the average daily wind speed ($\bar{u}$) (24 hour average) :

$\bar{u} \leq 1 \text{ m s}^{-1}$; $1 < \bar{u} < 1.5 \text{ m s}^{-1}$; and $\bar{u} \geq 1.5 \text{ m s}^{-1}$ at the 3.5 m above-roof measurement height.

CASE A: Average Daily Wind Speed $\leq 1 \text{ m s}^{-1}$

The calculated surface flux Q_{Go} , together with the measured Q^* , were averaged on an hourly basis, and are presented for the $\bar{u} \leq 1 \text{ m s}^{-1}$ cases in Figure 3.4. The fluxes are relatively high, and are similar to those observed at the BKS site. The corresponding hysteresis loop is shown in Figure 3.4b, and the derived coefficients of this relationship are given in Table 3.8.

Table 3.8. Coefficients and average daily wind speed for dry, Case A wind speeds at Site 4 (USB)

Date	a_1	a_2 (h)	a_3 (W m^{-2})	r^2	$\bar{u}$ (m s^{-1})
August 23	0.24	0.94	-23	0.82	0.92
September 3	0.29	1.05	-25	0.92	0.89
September 13	0.38	1.10	-29	0.90	0.69
September 14	0.35	1.06	-27	0.92	0.68
September 17	0.24	0.77	-20	0.87	1.00
September 19	0.31	0.99	-21	0.89	0.86
September 21	0.30	0.80	-23	0.86	0.84
<i>Average</i>	<i>0.30</i>	<i>0.96</i>	<i>-24</i>		

The a_1 coefficients in Table 3.8 are highest for those days where the average daily wind speed is very low (i.e. September 13 and 14). Only for those days where the average daily wind speed is $> 0.90 \text{ m s}^{-1}$ do we find a_1 coefficients < 0.25 . This suggests that the sharing between the sensible convective and conductive heat fluxes is the likely cause for this trend. Figure 3.4(c) again shows a nocturnal ratio of Q_{Go}/Q^* that is numerically similar to, but more variable than, the results seen at the BKS site. The slope

Figure 3.4: University Services Building (USB)/Industrial-Commercial Site 4, for 7 dry measurement days, with Class A wind speeds ($\leq 1 \text{ m s}^{-1}$) - (a) diurnal cycle of the roof surface heat flux (Q_{Go}) ; (b) hysteresis loop of the net radiation vs. the roof surface heat flux ; and (c) diurnal variation of the surface conductive heat flux normalized by the net radiation (Q_{Go}/Q^*).

of the Q_{Go}/Q^* between 800 h and 1500 h is relatively steep compared to previous sites, indicating a strong hysteresis relationship.

CASE B: Average Daily Wind Speed between 1 to 1.5 m s⁻¹

The diurnal cycles of the calculated roof surface conductive heat flux, Q_{Go} , for 17 days with CASE B wind speeds ($1 < \bar{u} < 1.5 \text{ ms}^{-1}$) (Figure 3.5) show daily maxima of Q_{Go} to be slightly lower than those for the low wind speed days. The relationship between the conductive heat flux and the net radiation (Figure 3.5b) is again similar in shape and magnitude to that of the hysteresis loop at the BKS gravel roof site. The corresponding derived coefficients are presented in Table 3.9.

Table 3.9. Coefficients and average daily wind speed for dry, Case B wind speeds at Site 4 (USB)

Date	a_1	a_2 (h)	a_3 (W m ⁻²)	r^2	$\bar{u}$ (m s ⁻¹)
August 18	0.27	1.07	-29	0.88	1.24
August 22	0.23	1.04	-27	0.90	1.04
August 26	0.26	0.72	-22	0.71	1.44
September 1	0.25	1.00	-25	0.94	1.37
September 2	0.25	0.92	-22	0.86	1.16
September 4	0.34	0.77	-16	0.82	1.13
September 7	0.23	0.95	-21	0.89	1.15
September 8	0.28	0.86	-22	0.84	1.22
September 9	0.23	0.84	-17	0.87	1.33
September 11	0.22	0.79	-19	0.80	1.37
September 12	0.25	0.96	-18	0.91	1.18
September 15	0.25	0.96	-23	0.91	1.13
September 16	0.30	0.81	-14	0.83	1.04
September 18	0.24	0.90	-21	0.85	1.24
September 20	0.28	0.75	-22	0.83	1.11
September 22	0.33	0.97	-15	0.92	1.03
September 26	0.26	0.80	-18	0.85	1.38
<i>Average</i>	<i>0.26</i>	<i>0.89</i>	<i>-21</i>		

The variability in the range of coefficients is considerably greater than for the Case A days, although in general, the coefficients are lower with an a_1 average of 0.26.

Figure 3.5: University Services Building (USB)/Industrial-Commercial Site 4, on 17 dry measurement days with Class B wind speeds ($1 \text{ m s}^{-1} < u < 1.5 \text{ m s}^{-1}$) - (a) diurnal cycle of the roof surface heat flux (Q_{Go}) ; (b) hysteresis loop of the net radiation vs. the roof surface heat flux ; and (c) diurnal variation of the surface conductive heat flux normalized by the net radiation (Q_{Go}/Q^*).

The nocturnal ratio Q_{Go}/Q^* appears to be slightly lower and shows even more variability than for the low wind conditions (Figure 3.5c).

CASE C: Average Daily Wind Speed $\geq 1.5 \text{ m s}^{-1}$

The calculated roof Q_{Go} for the 3 days with Case C average daily wind speeds ($\bar{u} \geq 1.5 \text{ m s}^{-1}$) is given in Figure 3.6. The daily maximum Q_{Go} is considerably lower in Figure 3.6(a) than those for Case A conditions in Fig 3.4(a). The relationship between Q_{Go} and Q^* (Figure 3.6b) reflects this diminished Q_{Go} influence; lesser slope and “thinner” hysteresis loop than for lower average daily wind speeds. The corresponding coefficients (Table 3.10) show the a_1 values are consistently less than those for moderate wind conditions (compare with Table 3.8).

Table 3.10. Coefficients and average daily wind speed for dry, Case C wind speeds at Site 4 (USB)

Date	a_1	a_2 (h)	a_3 (W m^{-2})	r^2	$\bar{u}$ (m s^{-1})
August 19	0.23	0.93	-28	0.90	1.76
August 27	0.22	0.96	-21	0.91	1.67
September 10	0.22	0.87	-23	0.89	1.82
Average	0.22	0.92	-24		

These results are consistent with a trend of decreasing nocturnal ratios of Q_{Go}/Q^* with increasing average wind speeds (Figure 3.6c). These results, however, are based on only 3 days.

The influence of wind speed on the magnitude of the a_1 coefficient (i.e. mean heat sharing going into the roof) is clearly portrayed in the summary plot of the a_1 coefficients for all measurement days at the USB site under dry conditions vs. the average daily wind speed ($\bar{u}$) (Figure 3.7). It suggests that the conductive : convective sensible heat sharing

Figure 3.6: University Services Building (USB)/Industrial-Commercial Site 4, for 3 dry measurement days with Class C wind speeds ($> 1.5 \text{ m s}^{-1}$) - (a) diurnal cycle of the roof surface heat flux (Q_{Go}); (b) hysteresis loop of the net radiation vs. the roof surface heat flux; and (c) diurnal variation of the surface conductive heat flux normalized by the net radiation (Q_{Go}/Q^*).

increasingly favours convection (Q_H) as wind speed, and therefore forced convection, increases.

Figure 3.7. Average daily wind speed vs. a_1 coefficient for all measurement days at Site 4 (USB).

While the relationship between increasing wind speed and decreasing coefficients is clear in Figure 3.7, it is difficult to determine an exact mathematical relationship without the benefit of a larger data set and a wider range of wind conditions.

WET CONDITIONS

The range of daily maximum and minimum temperatures and fluxes observed over the wet period at the USB site are presented in Table 3.11.

Table 3.11. Range of daily temperatures and fluxes for wet cases at Site 4 (USB).

Fluxes (W m ⁻²)	Q^*	Range of daily max	Range of daily min
		174 to 572	-35 to -81
	Q_{Gz}	6 to 20	-4 to -7
Temperatures (°C)	T_s	18 to 43	6 to 14
	T_z	18 to 36	9 to 13
	$T_s - T_z$	1.4 to 10.7	-1.6 to -3.6
Wind speed (m s ⁻¹)	u	2.11 to 4.04	0.20 to 0.82

Note the large range in Q^* that is possible with weather conditions that conform to the definition “no 24-hour rain-free” period. A total of 6 days were included in the analysis. The diurnal cycle of the conductive heat flux for those days is shown in Figure 3.8(a). The variability seen in this figure can be attributed to the timing and duration of “wet” events over the course of the diurnal cycle on any given day. The hysteresis loops of Q_{Go} vs. Q^* (Figure 3.8b) also reflect this variability, where some days (August 29 and September 23) indicate more cloud cover and rain (both fluxes are small). The regression coefficients for these hysteresis loops are presented in Table 3.12. The average a_1 coefficient is similar in magnitude to that of the dry, moderate wind cases. However, the average daily wind speed in the wet roof case does not seem to affect the magnitude of the a_1 coefficient as significantly as for the dry set (e.g. high wind case on August 25 has a higher coefficient than a low wind case on August 13). On days when it is raining and the roof surface is wet, all fluxes are diminished, but Q_H is considerably less than would be for a dry roof case. While an increase in wind speed may enhance the forced convection, the effect on Q_H under wet conditions is so small that it is not discernable in the resultant coefficients for the Q_{Go} vs. Q^* relationship.

Table 3.12. Coefficients and average daily wind speed for wet cases at Site 4 (USB)

Date	a_1	A_2 (h)	A_3 (W m ⁻²)	r^2	$\bar{u}$ (m s ⁻¹)
August 13	0.22	0.61	-27	0.85	0.93
August 21	0.24	0.58	-32	0.87	1.31
August 25	0.25	0.66	-28	0.80	1.95
August 29	0.30	0.52	-18	0.77	1.66
September 5	0.22	0.36	-18	0.78	1.88
September 23	0.25	0.69	-14	0.76	1.59
Average	0.25	0.57	-23		

Figure 3.8: University Services Building (USB)/Industrial-Commercial Site 4, for 5 wet measurement days - (a) diurnal cycle of the roof surface heat flux (Q_{Go}) ; (b) hysteresis loop of the net radiation vs. the roof surface heat flux ; and (c) diurnal variation of the surface conductive heat flux normalized by the net radiation (Q_{Go}/Q^*).

The normalized surface conductive heat flux is the most variable of all of the sites and cases presented thus far (Figure 3.8c). This is particularly true in the early morning (midnight to 800 h) where the surface conductive heat flux is often positive. The likely cause of this is the layer of water over the roof surface may act as an insulator, preventing the heat from being released. This implies that one or both of the turbulent fluxes are exclusively offsetting the radiation drain (negative Q^*).

3.2 Residential Roof Assembly Type

3.2.1 Residential Site 5 – Single family detached home in Dunbar (RES).

The residential (RES) roof measurement site consists of both east and west-facing slopes, as described in Chapter 2 and shown in Figure 2.4. The analysis therefore consists of separate east and west slope cases, followed by a general summary for the entire roof.

The RES site was measured for a period of 9 continuous days from September 4 – 12, 1999. The weather conditions were variable, but rain was not problematic because the slope eased drainage. At this site, most moisture recorded by the moisture sensors was in the early morning hours (2300 – 800 h), indicating that the source may have been dewfall. Records from the same period do not indicate any moisture at the USB site, which further supports the likelihood of dewfall rather than rainfall at RES.

The individual roof layers at this site are not fully known. The roof attic is insulated, and from bottom to top consists of an air layer (ranging from near 0 at the roof edges to ~ 1.5 m in the middle), a plywood deck, a vapour retarder, and overlapping light

grey asphalt shingles. The site was unobstructed by trees, but shading from the chimney onto the roof surface occurred in the late afternoon (1700 – 1800 h). All instrumentation was fully functioning, although the pump supplying air to the net radiometer dome was accidentally disconnected on occasion. This did not have discernable effect on the net radiation data.

EAST

The range of hourly-averaged measured fluxes, temperatures and wind conditions of the east-facing slope of the residential site are presented in Table 3.13. Most notable are the small values of the surface conductive heat flux, Q_{Go} . These are similar in magnitude to the MUS site, which had a 2-ply modified SBS bitumen surface, with similar thermal and radiative properties as the asphalt.

Table 3.13. Range of daily temperatures and fluxes for wet days on the east-facing roof slope at Site 5 (RES).

Fluxes (W m^{-2})	Q^*	Range of daily max	Range of daily min
		363 to 474	-40 to -164
	Q_{Go}	34 to 49	-11 to -20
Temperatures ($^{\circ}\text{C}$)	T_s	36 to 53	3 to 12
	T_z	37 to 56	3 to 13
	$T_s - T_z$	6.5 to 13.3	-1.9 to -11.3
Wind speed (m s^{-1})	u	1.08 to 3.35	0.20

The diurnal cycle of the surface conductive heat flux (Figure 3.9a) gives an indication of when the sun passes to the west-facing slope. After 1000h, the surface flux diminishes, but remains positive until approximately 1500h. This indicates that although incident radiation is diminished, there is still sufficient diffuse radiation to continue

Figure 3.9: Residential Building (RES) Site 5 for 9 wet measurement days, east-facing slope - (a) diurnal cycle of the roof surface heat flux (Q_{Go}) ; (b) hysteresis loop of the net radiation vs. the roof surface heat flux ; and (c) diurnal variation of the surface conductive heat flux normalized by the net radiation (Q_{Go}/Q^*).

heating the east-facing slope throughout the day. The Q_{Go} vs. Q^* plots for the east-facing slope show very little hysteresis (i.e. the conductive heat flux Q_{Go} and the net radiation Q^* are almost in phase) (Figure 3.9b), i.e. small a_2 coefficients (Table 3.14). The reason for this behaviour is related to the “cut-off” of incident-beam radiation to the eastern surface (where BOTH Q_{Go} and Q^* are being measured). This halted what would have been a continual diurnal pattern in Q^* , thereby giving the appearance that both Q_{Go} and Q^* behave similarly. The radiation normalized Q_{Go} (Figure 3.9c), is predictably small (< 0.1) from 2100 h to 1600 h (from early morning until late afternoon), based on its similarity with the MUS site. It then becomes erratically large or small between 1600 h and 2000 h, as Q^* drops suddenly (in most cases it is still a positive value at 1700 h) while Q_{Go} becomes negative.

Table 3.14. Coefficients and average daily wind speed for all days on the east-facing roof slope at Site 5 (RES)

Date	a_1	a_2 (h)	a_3 (W m ⁻²)	r^2	$\bar{u}$ (m s ⁻¹)
September 4	0.13	0.24	-3	0.89	0.43
September 5	0.12	0.20	-4	0.65	1.01
September 6	0.10	0.17	-7	0.79	2.01
September 7	0.14	0.19	-8	0.85	0.50
September 8	0.16	0.19	-7	0.89	0.33
September 9	0.11	0.21	-4	0.91	1.28
September 10	0.12	0.18	-6	0.85	1.07
September 11	0.14	0.18	-6	0.84	0.74
September 12	0.15	0.27	-7	0.86	0.48
Average	0.13	0.20	-6		

Thus, this surface type takes in relatively little heat during the day, and therefore has little to release at night, indicating that it is more energy conservative than the gravel surfaces, and similar to the modified bitumen surface.

WEST

The range of hourly-averaged fluxes, temperatures and wind speeds measured on the west-facing slope for September 4 –12 are presented in Table 3.15. The range of daily maximum and minimum net radiation is not greatly different from that measured on the east-facing slope, indicating that the “cut-off” of the east-facing Q^* probably occurred after its peak.

Table 3.15. Range of daily temperatures and fluxes for all days on the west-facing roof slope at Site 5 (RES).

Fluxes (W m^{-2})	Q^*	Range of daily max	Range of daily min
		280 to 463	-43 to -170
	Q_{Gz}	50 to 77	-17 to -46
Temperatures ($^{\circ}\text{C}$)	T_s	36 to 53	3 to 12
	T_z	37 to 56	3 to 13
	$T_s - T_z$	1.1 to 12.3	-2.5 to -12.5
Wind speed (m s^{-1})	u	1.08 to 3.35	0.20

The diurnal cycle of the surface conductive heat flux (Figure 3.10a) is more fully developed on the west-facing slope, and closely resembles the cycles seen at other sites, with the exception of a gentle slope to the relation in the morning hours (800 to 1000h). This gentle slope is caused by the lack of direct-beam radiation on the west-facing slope. The hysteresis loops of Q_{Go} vs. Q^* are wider (have a larger a_2 coefficient) than those on the east-facing slope because Q^* had time to become fully developed (Figure 3.10b). The bend in the hysteresis loop in the lower right-hand side (at 1800 h) is a purely local artifact due to a shadow-effect of the chimney onto the source area of the net radiometer. The coefficients from the regression of the hysteresis loops in Figure 3.10b (Table 3.16) show that average a_1 and a_3 coefficients are similar for both roof slopes, but the average a_2 coefficient is 0.30, versus 0.20 for the east-facing slope.

Figure 3.10: Residential Building (RES) Site 5 for 9 wet measurement days, west-facing slope - (a) diurnal cycle of the roof surface heat flux (Q_{Go}) ; (b) hysteresis loop of the net radiation vs. the roof surface heat flux ; and (c) diurnal variation of the surface conductive heat flux normalized by the net radiation (Q_{Go}/Q^*).

The diurnal cycle of Q_{Go}/Q^* (Figure 3.10c) more closely resembles the pattern seen at other sites than the east-facing facet, with more variation at the time of initial heating of the surface (700 to 900 h) and a gently decreasing slope from 0.5 to 0 in the afternoon (1100 to 1600 h). The magnitude of the nocturnal Q_{Go}/Q^* ratio is similar to that of the east-facing slope and the MUS site.

Table 3.16. Coefficients and average daily wind speed for all days on the west-facing roof slope at Site 5 (RES)

Date	a_1	a_2 (h)	a_3 (W m ⁻²)	r^2	$\bar{u}$ (m s ⁻¹)
September 4	0.15	0.29	-5	0.91	0.43
September 5	0.15	0.23	-6	0.78	1.01
September 6	0.09	0.28	-4	0.77	2.01
September 7	0.15	0.36	-7	0.84	0.50
September 8	0.19	0.38	-8	0.90	0.33
September 9	0.12	0.33	-5	0.87	1.28
September 10	0.12	0.32	-5	0.89	1.07
September 11	0.13	0.35	-6	0.89	0.74
September 12	0.16	0.39	-5	0.91	0.48
Average	0.14	0.33	-6		

Based on the radiation “cut-off” effect described for the east-facing slope, it is reasonable to speculate that the a_2 coefficient for this roof (particularly when considered as a flat roof) is closer to the west-facing value of 0.33. The impact of wind speed on the a_1 coefficients at this site can be seen on September 6 for both the east- and west-facing slopes. As there are no other days with high measured wind speeds, it is not possible to establish wind categories and a wind relation as was done at the USB site.

3.3 Discussion of Roof Measurement Results

It is reasonable to speculate that based on the findings in this chapter, the range of α_i coefficients for a particular site can vary by $\sim 10\%$ depending on wind conditions, and perhaps by about 5% depending on moisture conditions. A summary table of the measured coefficients for each roof surface type is given in Chapter 5.

If the results from these measurements are typical for the roof types of most North American cities, then the overall contribution of the roof heat fluxes to the urban storage heat flux may not be as significant as has been estimated previously from the coefficients presented in Table 1.1. Indeed, for suburban areas, where roof surfaces are almost exclusively asphalt shingles, the contribution of roof heat fluxes may be relatively minor in comparison to paved roads and other surface materials. An example of an *OHM* calculation using previous (Table 1.1) coefficients versus those measured in this study is presented in Chapter 4.

Ideally, verification and extension of these measured values would be done through repeated measurements on similar roof assembly and surface types over a wider range of weather and surface moisture conditions and roof angles. But, based on the coefficients of the conductive surface heat flux versus net radiation relationship, it appears that for industrial/commercial roof assembly types with insulation, a membrane, and gravel surface, the findings are very similar, whereas the shingle case is distinctly different. Further verification of these results will be examined in Chapter 4, where the surface conductive heat flux Q_{Go} is modelled using the Simplified Transient Analysis of Roofs (*STAR*) model.

Chapter 4

VALIDATION OF *STAR* AND ITS APPLICATION TO OTHER URBAN ROOF TYPES

4.1 Objectives

The primary reason for using the *STAR* model is to decrease or completely eliminate the need for relatively laborious and expensive measurements of heat fluxes and temperatures of many different roof assembly types. The use of *STAR* to calculate the surface conductive heat flux requires only the radiative and thermal properties of the roofing materials and weather data. In order to see if this approach is feasible, it is first necessary to validate *STAR*. Therefore the output from *STAR* was compared against the measured roof flux data described in Chapter 3. The input to *STAR* consisted of the weather data collected at each site, and the roofing material properties derived from sources such as building contracts, warranty evaluations, and estimation using ASHRAE tables. Validation of *STAR* could enable an assessment as to its usefulness as a tool to estimate the surface heat flux and its ability to generate Camuffo-Bernardi coefficients using measured Q^* and estimates of thermal properties from standard tables. An evaluation of *STAR*'s ability to simulate temperatures and heat fluxes at each roof layer interface has been carried out previously by the designers of *STAR*. It was shown to give very good approximations of the temperatures and fluxes (Wilkes, 1989).

4.2 Evaluation of Modelled Surface Heat Fluxes (Q_{Go}) and Derived Coefficients (a_1, a_2, a_3).

At each of the sites of the present study, input weather data for the *STAR* model was measured on location. These data were augmented with cloud cover data from Vancouver International Airport, the location of which is shown in Figure 2.1. In each case, the model was run using the fully implicit transient solution method, using a nodal spacing of approximately 4 per centimetre thickness of roofing material.

4.2.1 Bookstore building (BKS), Site 1

The surface heat flux at the Bookstore site was modelled using measured downward solar radiation, wind speed, air temperature and humidity (at 3.5 m above roof level), and cloud cover. The roof layer material types were described in U.B.C Plant Operations files, and the corresponding radiative and thermal properties were taken from ASHRAE tables of roof and building properties (ASHRAE and American Society of Heating, 1993). The nature of the layers and of the *STAR* input data for the BKS site are given in Appendix A.

The model was run for July 20-27, 1999. These conditions included both wet and dry conditions, but only the dry conditions were compared with measured results because of instrument error when the site was inundated by water. The modelled surface heat flux (Q_{Go}) is compared against that measured in Figure 4.1. The statistical evaluation of these fluxes is given in Table 4.1. For an explanation of these statistics, refer to section 2.4.1.

Table 4.1. Statistics of modelled vs. measured surface heat flux (Q_{Go}) at Site 1 – Bookstore (BKS).

Site	n	D	r^2	r	RMSE
1 - BKS	114	0.95	0.82	0.90	47.8 W m ⁻²

Figure 4.1: Modelled and measured surface conductive heat flux (Q_{Go}) at Site 1(BKS) from July 21 to July 27, 1999.

The statistics indicate that the model's agreement with measured data is quite good, and it appears from Figure 4.1 that the modelled surface heat flux approximates the daily and most short-term changes well. Most of the discrepancies between the measured and modelled fluxes are seen at the time of the peak daytime flux. This may be due to errors in estimation of the radiative properties of the roof gravel surface, but it may also be caused by model errors in estimating the amount of radiative and convective heat transfer to and from the surface. Although there is a possibility that the measured surface heat flux is erroneously low, results from previous tests of *STAR* are consistent with the pattern shown here (i.e. modelled values higher at the time of the peak daytime flux)(Wilkes, 1989).

The Camuffo-Bernardi coefficients derived from the modelled surface heat flux against the measured net radiation during dry conditions (Table 4.2) show reasonable agreement. There is a tendency, however, for the modelled values to be slightly larger

than the measured coefficients. Again, this overestimation may in part be due to the overestimation of the peak daytime conductive surface flux.

Table 4.2. Modelled and measured coefficients for Site 1 – BKS.

Date	MODELLED			MEASURED		
	a_1	a_2 (h)	a_3 (W m ⁻²)	a_1	a_2 (h)	a_3 (W m ⁻²)
July 21	0.30	1.41	-40	0.26	1.27	-33
July 22	0.33	1.26	-35	0.34	1.21	-36
July 23	0.30	1.65	-46	0.24	1.43	-32
Average	0.31	1.44	-40	0.28	1.30	-34

4.2.2 Buchanan B building (BUC), Site 2

The surface heat flux at the Buchanan B site was modelled using measured downward solar radiation, wind speed, air temperature and humidity (at 3.5 m above roof level), and cloud cover. The description of roof layer material types were taken from U.B.C Plant Operations files, and the corresponding radiative and thermal properties were taken from ASHRAE tables of roof and building properties (ASHRAE and American Society of Heating, 1993). The nature of the layers and STAR input data for the BUC site are given in Appendix A.

The model was run for July 27-Aug 10, 1999. The original measurements were taken under wet conditions. Thus it is expected that the modelled surface flux (Q_{Go}) and coefficients will be higher than those measured, because latent heat exchange is not incorporated into *STAR*. The modelled surface heat flux (Q_{Go}) is compared against the measured (Figure 4.2) and the statistics describing the relationship between the two are given in Table 4.3. The agreement, despite the wet measurement conditions, is remarkably good, and even exceeds the agreement at the BKS site (index of agreement, $D = 0.97$). This may be because the radiative and thermal property data is more accurate for

the BUC site, but could also be credited to other sources such as differences in precision of measurement, weather conditions, or other characteristics at the two sites.

Figure 4.2 Measured and modelled surface conductive heat flux (Q_{Go}) at Site 2 (BUC) from July 27 – Aug. 10, 1999.

Table 4.3. Statistics of modelled vs. measured surface heat flux (Q_{Go}) at site 2 – Buchanan B (BUC).

Site	n	D	r^2	r	RMSE
2 - BUC	330	0.97	0.89	0.94	21.1 W m ⁻²

The coefficients derived from the modelled surface heat flux vs. the measured Q^* for this site are presented in Table 4.4. These coefficients reflect the higher Q_{Go} flux modelled at this site (difference of 0.06 for average a_1 coefficient between modelled and measured).

Table 4.4. Modelled and measured coefficients for Site 2 - BUC

Date	MODELLED			MEASURED		
	a_1	a_2 (h)	a_3 (W m ⁻²)	a_1	a_2 (h)	a_3 (W m ⁻²)
July 28	0.27	0.88	-30	0.21	0.85	-22
July 31	0.24	0.77	-30	0.22	0.65	-15
August 1	0.24	0.81	-26	0.18	0.81	-18
August 2	0.26	0.90	-28	0.19	0.92	-18
August 4	0.27	0.88	-28	0.21	0.91	-20
Average	0.26	0.85	-28	0.20	0.83	-19

While an increase in the magnitude of the coefficients due to the absence of latent heating in the *STAR* model is expected, the increase could also be due to the same effects seen at the BKS site. That is, the largest differences in the modelled and measured surface fluxes are again seen at the peak of the radiation curve, and may be due to incorrectly modelled convection coefficients.

4.2.3 *Music Building (MUS), Site 3*

The surface heat flux at the Music building site was modelled using measured downward solar radiation, wind speed, air temperature and humidity (at 3.5 m above roof level), and cloud cover. The description of roof layer material types were taken from U.B.C Plant Operations files, and the corresponding radiative and thermal properties were taken from ASHRAE tables of roof and building properties (ASHRAE and American Society of Heating, 1993). The nature of the layers and *STAR* input data for the MUS site are given in Appendix A.

The model was run for Aug. 18-Aug 24, 1999. The original measurements were taken under relatively wet (no 24-hr dry period) conditions. Again, it is expected that the modelled surface flux (Q_{Go}) and coefficients will be higher because latent heat exchange is not incorporated into *STAR*. The modelled surface heat flux (Q_{Go}) is compared against the measured (Figure 4.3), and the statistics describing the relationship between the two are given in Table 4.5. The statistics for this site are the lowest of the three reviewed thus far, but are still reasonably good (index of agreement, $D = 0.93$)

Table 4.5. Statistics of modelled vs. measured surface heat flux (Q_{Go}) at Site 3 – Music Building (MUS).

Site	n	D	r^2	r	RMSE
3 - MUS	137	0.93	0.87	0.93	10.4 (W m^{-2})

Remarkably, although it is slightly higher, the modelled surface flux is within the same magnitude (between -30 and 50 W m^{-2}) as the measured data, indicating that the radiative and thermal properties of the surface material have been modelled accurately. This also reinforces the hypothesis that the principle cause for the smaller (relative to gravel roof surfaces) heat flux is due to the surface material property,

Figure 4.3 Modelled and measured surface conductive heat flux (Q_{Go}) for Site 3 (MUS), August 18 – 24, 1999.

and not the roof structure or conditions not represented in the model. The coefficients derived from the modelled Q_{Go} and measured Q^* are again higher than the measured a_1 , a_2 , and a_3 coefficients (Table 4.6). The wet conditions during the measurement period could be suspect, and the noticeable difference in the fluxes at the daytime peak (1100 to 1200h) indicate that the model is consistently overestimating the amount of heat conduction into the roof.

Table 4.6 Modelled and measured coefficients for Site 3 - MUS

Date	MODELLED			MEASURED		
	a_1	A_2 (h)	a_3 (W m ⁻²)	a_1	a_2 (h)	a_3 (W m ⁻²)
August 19	0.11	0.46	-8	0.06	0.30	-3
August 21	0.11	0.40	-9	0.06	0.25	-4
August 22	0.10	0.43	-7	0.06	0.29	-3
August 23	0.11	0.39	-7	0.06	0.27	-3
Average	0.11	0.42	-8	0.06	0.28	-3

4.2.4 University Services Building (USB), Site 4

The surface heat flux at the University Services Building site was modelled using measured downward solar radiation, wind speed, air temperature and humidity (at 3.5 m above roof level), and cloud cover. The description of roof layer material types were taken from U.B.C Plant Operations files, and the corresponding radiative and thermal properties were taken from ASHRAE tables of roof and building properties (ASHRAE and American Society of Heating, 1993). The nature of the layers and STAR input data for the USB site are given in Appendix A. The surface conductive heat flux was modelled from August 10 to September 27, 1999. These conditions included the range of wind and moisture conditions described in Chapter 3. Therefore the model results are also divided into dry and wet days, and the effect of wind conditions analysed.

DRY CONDITIONS

A total of 30 days with dry conditions were modelled and compared with the measured surface conductive heat flux at the USB site. These fluxes would be too numerous to plot in a figure, and are presented only in table form. Considering the wide range of wind conditions, the statistical indexes shown in Table 4.7 indicate that the model has handled these conditions within the same range of accuracy as the previous sites.

Table 4.7 Statistics of modelled vs. measured surface conductive heat flux (Q_{Go}) at Site 4 – USB, dry measurement days.

Site	N	D	r^2	r	RMSE
4 – USB (dry)	877	0.94	0.86	0.93	38.8 (W m ⁻²)

The modelled and measured Camuffo-Bernardi coefficients for all 30 of the dry days (Table 4.8) show a general trend toward over-prediction by *STAR* of the surface conductive heat flux, and the resulting coefficients. While these coefficients are not divided into wind categories, there is some evidence to suggest that the a_1 coefficient -

Table 4.8 Modelled and measured coefficients for Site 4 – USB dry measurement days

Date	MODELLED			MEASURED		
	a_1	a_2 (h)	a_3 (W m ⁻²)	a_1	a_2 (h)	a_3 (W m ⁻²)
August 18	0.31	1.49	-36	0.27	1.07	-29
August 19	0.32	1.41	-35	0.23	0.93	-28
August 22	0.31	1.60	-36	0.23	1.04	-27
August 23	0.31	1.42	-30	0.24	0.94	-23
August 26	0.30	1.23	-28	0.26	0.72	-22
August 27	0.36	0.99	-27	0.22	0.96	-21
September 1	0.31	1.42	-29	0.25	1.00	-25
September 2	0.31	1.40	-27	0.25	0.92	-22
September 3	0.31	1.39	-29	0.29	1.05	-25
September 4	0.38	1.24	-23	0.34	0.77	-16
September 7	0.29	1.40	-27	0.23	0.95	-21
September 8	0.32	1.33	-24	0.28	0.86	-22
September 9	0.33	1.26	-27	0.23	0.84	-17
September 10	0.29	1.41	-26	0.22	0.87	-23
September 11	0.29	1.35	-23	0.22	0.79	-19
September 12	0.30	1.38	-22	0.25	0.96	-18
September 13	0.36	1.44	-26	0.38	1.10	-29
September 14	0.34	1.40	-27	0.35	1.06	-27
September 15	0.32	1.43	-31	0.25	0.96	-23
September 16	0.42	0.99	-20	0.30	0.81	-14
September 17	0.34	1.30	-22	0.24	0.77	-20
September 18	0.32	1.41	-27	0.24	0.90	-21
September 19	0.34	1.39	-23	0.31	0.99	-21
September 20	0.32	1.31	-23	0.28	0.75	-22
September 21	0.35	1.38	-27	0.30	0.80	-23
September 22	0.35	1.36	-17	0.33	0.97	-15
September 26	0.32	1.29	-20	0.26	0.80	-18
Average	0.33	1.35	-26	0.27	0.91	-22

Figure 4.4 Modelled vs. measured a_1 coefficients stratified by wind speed classes for 30 dry days at Site 4 – USB.

wind speed relationship (seen in Figure 3.7) is captured by the model (e.g. September 4), but this is not always consistent (e.g. September 16 – reverse situation). A plot of the measured vs. modelled a_1 coefficients stratified by wind speed classes (Figure 4.4) shows that the model does not capture the full range of coefficient variation seen in the measured cases under different wind speeds. The likely cause for this problem is the *STAR* model's wind speed dependent convection coefficient calculation. It appears from Figure 4.4 that under conditions of forced convection (higher wind speeds), the heat conducted into the surface by the model is more than that measured. If the convection coefficient problem is indeed the primary source of the error, its correction in the model would allow the extrapolation of the coefficient-wind speed relationship, and present the

modeller with more finely-tuned coefficients for hourly shifts in wind speed to model in *OHM*, if desired.

WET CONDITIONS

As demonstrated by the results from previous sites, the anticipated ability for *STAR* to accurately predict the surface conductive heat flux is diminished in those cases where measurements were taken under wet roof conditions. The modelled fluxes at the USB site under wet conditions were, in fact, the least accurate of all of the measured sites (Table 4.9). The days with the largest model error are August 29 and September 23,

Table 4.9 Statistics of the modelled vs. measured surface conductive heat flux at Site 4 – USB wet measurement days.

Site	N	D	r^2	R	RMSE
4 –USB (wet)	150	0.87	0.73	0.86	49.5 W m ⁻²

as seen in the differences between the measured and modelled Camuffo-Bernardi coefficients (Table 4.10). It appears that on these two days, responses to solar changes such as passing clouds were slower in the measured Q_{Go} and Q^* data than in the modelled Q_{Go} case. This could be due to a small layer of water on the roof surface that affects response times or heat sharing at the surface. In general, the modelled Q_{Go} magnitude is not significantly larger than on those days when this phenomenon did not occur (e.g. August 21), and thus the a_1 coefficient error is affected by both the exclusion of the latent heat flux in the model, and the faster response time of the modelled Q_{Go} to solar changes.

Table 4.10. Modelled and measured coefficients for Site 4 – USB (wet)

Date	MODELLED			MEASURED		
	a_1	a_2 (h)	a_3 (W m ⁻²)	a_1	a_2 (h)	a_3 (W m ⁻²)
August 13	0.27	1.46	-26	0.22	0.61	-27
August 21	0.30	1.29	-36	0.24	0.58	-32
August 25	0.29	1.34	-27	0.25	0.66	-28
August 29	0.45	0.97	-24	0.30	0.52	-18
September 5	0.26	1.02	-16	0.22	0.36	-18
September 23	0.39	1.04	-20	0.25	0.69	-14
Average	0.33	1.19	-25	0.25	0.57	-23

4.2.5 Residential Building (RES), Site 5

The sloping roof at the residential site makes it inherently difficult to model using *STAR* because the model only takes slope into account for wind, not solar radiation conditions. Thus roof slope and its relation to sun angle is neglected by the model, because it is treated as a flat plane. For this reason, the RES site was modelled as a plane. The site having the most similar radiative characteristics to the RES site ($\alpha = 0.30$, $\varepsilon = 0.87$) is the MUS site ($\alpha = 0.40$, $\varepsilon = 0.84$). Because of the difference in the albedo, it is expected that the Q_{Go} modelled at the MUS site will be smaller than if it were modelled at the RES site.

The RES site was modelled for the days August 19 – August 23, 1999 using the weather data and measured Q^* from Site 3 (MUS). As there was no documentation available regarding the roof layers at the RES site, the model was run using a 2-layer (the asphalt shingles and a plywood deck) and 3-layer (shingles, deck, and insulation) approximation. Details of the roof layers are given in Appendix A.

The 2-layer model of RES yielded coefficients similar in magnitude to that modelled for the MUS site (although the a_2 coefficients were larger), and similar to those measured on the east-facing slope of the RES site ($a_1 = 0.13$, $a_2 = 0.20$ h, $a_3 = -6$ W

m^{-2})(Table 4.11). While it may seem illogical to model a roof without a layer of insulation, the *STAR* model allows the interior temperature to be held constant, thereby masking any heat loss that would occur under real, uninsulated conditions. Thus, this approximation may be sufficient when knowledge about the insulating layer of a home is not known, and the interior temperature is held constant.

Table 4.11. Modelled coefficients for Site 5 (RES) using weather data and net radiation from Site 3 (MUS). 2-layer roof.

Date	a_1	a_2 (h)	a_3 (W m^{-2})	r^2
August 19	0.11	0.27	-2	0.97
August 20	0.11	0.25	-1	0.90
August 21	0.11	0.23	-3	0.93
August 22	0.10	0.25	-1	0.97
August 23	0.11	0.22	0	0.94
Average	0.11	0.24	-1	

For comparison, the 3-layer model of the RES site was run using the same weather and net radiation conditions as the 2-layer model. The resulting coefficients were lower, as would be expected given the extra layer of low thermal conductivity (Table 4.12). In this case, the a_2 and a_3 coefficients look similar to those measured on the west-facing RES roof slope, but the a_1 coefficient is even lower than that modelled for the MUS site.

Table 4.12. Modelled coefficients for Site 5 (RES) using weather data and net radiation from Site 3 (MUS). 3-layer roof.

Date	a_1	a_2 (h)	a_3 (W m^{-2})	r^2
August 19	0.09	0.41	-7	0.94
August 20	0.09	0.37	-6	0.82
August 21	0.10	0.36	-7	0.89
August 22	0.09	0.38	-6	0.93
August 23	0.09	0.36	-5	0.90
Average	0.09	0.38	-6	

Therefore, considering the low albedo at the RES site, and the difference between the 2- and 3-layer models, it appears that the *STAR* model underestimates the conductive heat flux when using the MUS data. It is also probable that an insulating layer directly next to the plywood deck is not the most effective way of modelling a residential roof with attic space. Further, the properties assumed for this insulating layer may not accurately reflect the properties of the insulation at Site 5. Thus, while direct comparison can not be made between the measured and modelled fluxes at Site 5 (RES), the coefficients derived from a modelled horizontal roof using weather data from another site with similar radiative properties gives a reasonable approximation to a sloped roof, probably within ~ 0.05 (or 5% of the net radiation) for the α_1 coefficient.

An alternative method to the horizontal plane approach to modelling Site 5 is to use the relationship between Q^* and $K\downarrow$ at Site 3 (MUS), and apply it to the net radiation measured over each slope to determine an approximation to the $K\downarrow$ for that slope. The relationship between Q^* and $K\downarrow$ at Site 3 was calculated via linear regression to be:

$$K\downarrow = 2.27615Q^* + 93.50473 \quad (4.1)$$

This equation was used on both the east- and west-facing slopes of the RES site to calculate the $K\downarrow$ for the weather input files for each slope. The coefficients derived from the modelled surface conductive heat flux (Q_{Go}) using a 2-layer approach and measured net radiation (Q^*) for the east-facing slope are compared against the measured values in Table 4.13. The modelled α_1 and α_3 coefficients are very similar to the measured coefficients, although slightly overestimated. The α_2 coefficient, however, is largely underestimated. The cause of this underestimation is likely due to the equation used to

model the solar radiation (4.1) rather than a fault of the *STAR* model itself. As mentioned previously, the net radiation is abruptly “cut-off” on the east-facing slope when the sun moves to the west. The solar radiation used as the input in the model reflects this “cut-off” and effectively removes the hysteresis relationship between Q_{Go} and Q^* (both are cut-off at the same time).

Table 4.13 Modelled and measured coefficients for east-facing slope of Site 5- RES

Date	MODELLED			MEASURED		
	a_1	a_2 (h)	a_3 (W m ⁻²)	a_1	a_2 (h)	a_3 (W m ⁻²)
September 4	0.16	0.03	-3	0.13	0.24	-3
September 5	0.17	0.00	-4	0.12	0.20	-4
September 6	0.12	0.02	-4	0.10	0.17	-7
September 7	0.13	0.06	-5	0.14	0.19	-8
September 8	0.14	0.05	-4	0.16	0.19	-7
September 9	0.13	0.08	-3	0.11	0.21	-4
September 10	0.12	0.08	-4	0.12	0.18	-6
September 11	0.13	0.07	-4	0.14	0.18	-6
September 12	0.14	0.05	-3	0.15	0.27	-7
Average	0.14	0.05	-4	0.13	0.20	-6

A statistical evaluation of the modelled vs. measured surface conductive heat flux (Table 4.14) reveals that the model gives reasonably good agreement, particularly considering that the model’s solar radiation ($K_{\downarrow}$) was modelled from the net radiation-solar radiation relationship from Site 3 (MUS).

Table 4.14 Statistics of the modelled vs. measured surface conductive heat flux at Site 5 – RES, east-facing slope.

Site	n	D	r ²	r	RMSE
5 –RES east	231	0.92	0.75	0.86	12.9 W m ⁻²

For the west-facing slope, the same procedure was used to model the surface conductive heat flux, which proved to give slightly better agreement for all three coefficients (Table 4.15) than for the east-facing slope. Oddly, the typical trend of

overestimation by the model is not seen for this slope, and may indicate that equation 4.1 underestimates the amount of solar radiation received by the west-facing slope.

Table 4.15 Modelled and measured coefficients for west-facing slope of Site 5- RES

Date	MODELLED			MEASURED		
	a_1	a_2 (h)	a_3 (W m ⁻²)	a_1	a_2 (h)	a_3 (W m ⁻²)
September 4	0.14	0.26	-3	0.15	0.29	-5
September 5	0.16	0.23	-4	0.15	0.23	-6
September 6	0.11	0.24	-3	0.09	0.28	-4
September 7	0.12	0.25	-5	0.15	0.36	-7
September 8	0.13	0.24	-4	0.19	0.38	-8
September 9	0.11	0.24	-2	0.12	0.33	-5
September 10	0.11	0.24	-4	0.12	0.32	-5
September 11	0.12	0.25	-3	0.13	0.35	-6
September 12	0.12	0.26	-2	0.16	0.39	-5
Average	0.12	0.25	-3	0.14	0.33	-6

The statistical evaluation of the modelled vs. measured results show that the agreement is slightly better than that of the east-facing slope, but not as good as the agreement for horizontal roof surfaces under dry conditions (Table 4.16). It would appear that for roofs

Table 4.16 Statistics of the modelled vs. measured surface conductive heat flux at Site 5 – RES, west-facing slope.

Site	n	D	r ²	r	RMSE
5 – RES west	231	0.93	0.79	0.89	14.3 W m ⁻²

with sloping surfaces, the coefficients are most accurately modelled using a $K_{\downarrow}$ for the individual slope (whether calculated or measured). If the site is modelled as a horizontal surface, the a_2 coefficient will likely reflect a hysteresis value mid-way between the east and west values, and the a_1 and a_3 coefficients may be slightly underestimated.

4.3 Modelling Coefficients for Other Roof Surface Types

Based on the successful validation of the *STAR* model in the previous section, a similar method was used to model Camuffo-Bernardi coefficients for other roof surfaces. Since no measured net radiation data exists for these hypothetical roof surfaces, the net radiation and weather data used for these surfaces were taken from the site in the present study where the radiative surface properties most closely resemble those to be modelled (i.e. the albedo and emissivity are the same or similar). The resulting coefficients for these hypothetical roof surfaces are therefore derived from the Q^* at a measured site and the Q_{Go} modelled for a hypothetical roof using known roof properties, and weather data from the measured site. The 2-layer modelling approach described in section 4.2.5 was used for each of the modelled roof types. The modelled roof surfaces include a Japanese ceramic tile, a slate tile (common in Asia and Europe), and a high-albedo asphalt roof shingle.

4.3.1 Japanese Ceramic Tile

A type of ceramic roof tile constructed from industrial wastes has been developed in Japan. The tile has a high (~ 70%) porosity, and the ability to retain water for long periods of time (Fujino *et al.*, 2000). In tests on the saturated tile, it was found to reduce the sensible heat flux into the surrounding atmosphere by as much as 100 W m^{-2} . This tile, when dry (i.e. 70% air), was modelled using 2-layers (tile and plywood) and the September 7 – 14 weather data from the USB site. The original surface had an assumed emissivity of 0.92 and albedo of 0.16. The emissivity of the ceramic tile is assumed to be

0.90, and the albedo is 0.10 according to Asaeda (2000). Details about the layers and thermal properties are given in Appendix A.

The coefficients derived from the modelled surface heat flux vs. the measured Q^* over the USB site are given in Table 4.17.

Table 4.17 Modelled coefficients for a 2-layer Japanese ceramic tile roof using weather data and net radiation from Site 4 (USB).

Date	A_1	a_2 (h)	A_3 (W m ⁻²)	r^2
September 7	0.07	0.26	-6	0.97
September 8	0.07	0.25	-5	0.96
September 9	0.07	0.24	-6	0.98
September 10	0.07	0.26	-6	0.97
September 11	0.07	0.25	-5	0.97
September 12	0.07	0.26	-5	0.97
September 13	0.08	0.27	-5	0.97
September 14	0.08	0.26	-6	0.97
<i>Average</i>	<i>0.07</i>	<i>0.26</i>	<i>-6</i>	

The coefficients for the Japanese ceramic tile show that even without saturation, the roof takes in and releases very little heat (i.e. is energy efficient, due in part to its high air content). It is difficult to interpret the accuracy of the model results, but it seems reasonable to conclude that the dry Japanese ceramic tile coefficients are in the same range ($a_1 \sim 0.10$, $a_2 \sim 0.25$ h, $a_3 \sim -5$ W m⁻²) as the asphalt roofing shingle.

Although it would be very interesting to see the effect that saturation of the ceramic tile has on the coefficients for this roof type, the *STAR* model is not capable of modelling a tile which utilizes changes in sensible vs. latent heat sharing as the primary “cooling” method (as opposed to changes to surface radiative properties). This is because the *STAR* model does not use an energy balance approach, and the increased latent heat flux that would occur if the tile were saturated is not modelled. In fact, if only the changes in the thermal properties are modelled (i.e. thermal properties when the tile is

saturated), the modelled surface conductive heat flux is slightly greater! Therefore, this type of tile can only be modelled once an energy balance model is incorporated into *STAR*.

4.3.2 Slate tile

A slate-tiled roof (slate is more common in Europe and Asia) was modelled using the same conditions as the ceramic roof tiles (i.e. 2-layers, weather conditions, Q^*). In this case, the modelled coefficients (Table 4.18) were similar but slightly lower than those calculated at the RES site. Interestingly, the a_2 coefficient is larger than that for the asphalt shingle and ceramic tile. A large a_2 coefficient indicates that this slate tile roof requires a long time to release the heat it has accumulated during the day, which in turn leads to a higher than usual a_3 coefficient (Q_{Go} is still relatively high when Q^* becomes negative).

Table 4.18 Modelled coefficients for a 2-layer slate tile roof using weather data and net radiation from Site 4 (USB).

Date	a_1	a_2 (h)	a_3 (W m ⁻²)	r^2
September 7	0.07	0.33	-1	0.96
September 8	0.08	0.31	0	0.95
September 9	0.07	0.31	-1	0.97
September 10	0.07	0.33	-1	0.97
September 11	0.07	0.32	0	0.97
September 12	0.07	0.32	1	0.97
September 13	0.09	0.34	1	0.97
September 14	0.08	0.33	-1	0.96
Average	0.08	0.32	0	

Whether the a_2 and a_3 coefficients are artefacts of the modelling method (i.e. using 2-layers and keeping the indoor air temperature constant) is difficult to determine without modelling a range of scenarios with different layers and interior conditions.

Even after such an investigation, knowing which set of coefficients is *correct* would still be impossible to determine. Therefore, given the sites analyzed thus far, it is reasonable to conclude that the coefficients for the slate roof are within the same range as that for the asphalt shingle and ceramic tile.

4.3.3 High-albedo asphalt shingle

A high-albedo asphalt shingle is one that has the same thermal properties as a typical asphalt shingle, but has a higher albedo, usually due to modification of the surface colour. Prototypes of these “cool-roof” shingles have albedos of about 0.50, a considerable improvement upon the shingles currently used (albedos from 0.10 to 0.30) (Berdahl and Bretz, 1997). Although no surface measured in this study had such a high albedo, the closest surface was that of Site 3 (MUS) ($\alpha = 0.40$). The weather and net radiation data from this site, and the modelled Q_{Go} for a high-albedo roof (the radiative and thermal properties are given in Appendix A) were used to determine the Camuffo-Bernardi coefficients for a high-albedo shingled, 2-layer roof (Table 4.19).

The coefficients in Table 4.19 can not be directly compared with the results for the lower albedo roof (Site 5 – RES) because the net radiation used for this site was

Table 4.19 Modelled coefficients for a 2-layer, high-albedo asphalt shingled roof using weather and Q^* data from Site 3 (MUS).

Date	a_1	a_2 (h)	a_3 (W m ⁻²)	r^2
August 19	0.09	0.21	-2	0.96
August 20	0.09	0.19	-1	0.90
August 21	0.09	0.17	-3	0.93
August 22	0.08	0.18	-1	0.96
August 23	0.08	0.16	0	0.94
<i>Average</i>	<i>0.09</i>	<i>0.18</i>	<i>-1</i>	

measured over a surface with a higher albedo and slightly lower emissivity (a difference of 0.10 for the albedo and a difference of 0.03 for the emissivity). Thus the Q^* measured over the MUS site is greater than would be measured over the hypothetical high-albedo site. For example, with a surface temperature difference between the MUS and high-albedo site of 10°C, the Q^* near the daytime peak at the MUS site would be 39 W m⁻² higher (assuming $K_{\downarrow} = 800 \text{ W m}^{-2}$ and $L_{\downarrow} = 325 \text{ W m}^{-2}$). For a surface temperature difference of 5°C, the net radiation at the MUS site would be 67 W m⁻² higher. The effect of the overestimation of the Q^* would result in a slight underestimation of the a_l coefficient. The degree of underestimation would be impossible to determine without specific knowledge of the radiation components over the MUS surface, but it would be reasonable to speculate that the average a_l coefficient for high-albedo shingles is somewhere between the modelled values of 0.09 and 0.11, based on the results in Table 4.11.

4.4 OHM Calculation Using New Coefficients

The Camuffo-Bernardi coefficients presented in this thesis contrast considerably with those from previous roof studies (Table 1.1). They also present information about the role of moisture and wind conditions which were previously unavailable. The impact these differences may have on storage estimated using *OHM* remains to be studied. However, sample calculations based on previous *OHM* calculations give a brief insight.

In a previous study conducted by Grimmond *et al.* (1991) at a suburban site in Vancouver, the weighting factors for the land cover types were as follows:

greenspace/open 43%; rooftop 13%; paved 11%; canyon 33%. The coefficients used for rooftops in that study were $a_1 = 0.30$, $a_2 = 0.34$ h, $a_3 = -22.9$ W m⁻². The resultant model coefficients calculated from equation 1.7 for that suburban area were $a_1 = 0.35$, $a_2 = 0.25$ h, $a_3 = -29.4$ W m⁻².

Assuming that most of the roof surfaces in the same urban area are asphalt shingle, the new rooftop coefficients become $a_1 = 0.14$, $a_2 = 0.33$ h, $a_3 = -6$ W m⁻², and using the same weighting factors in equation 1.7, gives new suburban area coefficients of $a_1 = 0.33$, $a_2 = 0.25$, $a_3 = -27.2$. Thus for such a suburban region where rooftops only represent a small fraction of the urban surface area, the a_1 coefficient is only 0.02 (or 2% of the net radiation) less than previously predicted. Thus, for areas such as this with small areal rooftop percentages, errors in the coefficients of other surface types may play a more important role in the overall error. In previous tests of *OHM*, the model slightly under-predicted the hourly storage heat flux averaged over two hours at most suburban sites where wind speeds were low or moderate.

On the other hand, for a light industrial site in Vancouver, such as the one measured and modelled in *OHM* by Grimmond and Oke (1999) (Figure 1.5), the roof fraction is significantly larger (37%). For this site, the urban area coefficients originally calculated were $a_1 = 0.57$, $a_2 = 0.22$ h, $a_3 = -29.2$ W m⁻², and the rooftop coefficients were an average of Yap (1973) and Yoshida *et al.*'s (Yoshida *et al.*, 1991) values ($a_1 = 0.50$, $a_2 = 0.22$ h, $a_3 = -28$ W m⁻²). Using new roof coefficients for this area (where the site is mostly bitumen (assume 70%)) with some gravel of $a_1 = 0.12$, $a_2 = 0.47$ h, $a_3 = -9$ W m⁻², the resultant urban light industrial area coefficients become $a_1 = 0.43$, $a_2 = 0.27$,

$\alpha_3 = -23$. In this case, the difference in the urban area α_l coefficient is 0.14 (or 14% of the net radiation), which is significantly large.

Incorporation of wind and moisture descriptors for the coefficients for all land surface types would probably greatly improve *OHM* predictions. Most of the over-prediction in *OHM* occurs during times of peak solar heating (Grimmond and Oke, 1999), rather than throughout the day. This suggests that not only new coefficients are necessary, but that they should vary with wind speed or stability. This may lead to better agreement between *OHM*-modelled and measured urban storage heat fluxes. With improvements in the convective portions of *STAR*, it may be possible to derive a set of Camuffo-Bernardi coefficients for roofs that incorporate the varying heat sharing between convection and conduction due to wind effects and stability.

Chapter 5

CONCLUSIONS

This thesis presents the results of observations and analysis of the heat storage characteristics of industrial/commercial and residential roof types. In particular it focuses on the fraction of the net radiation flux that is conducted into or out of roofs, including the value of the coefficients emerging from the Camuffo-Bernardi statistical parameterization scheme. The use of the Simplified Transient Analysis of Roofs (*STAR*) model realizes the potential to model Camuffo-Bernardi coefficients, that relate the roof surface conductive heat flux to the net radiation. The role of wind and moisture as controls on the fraction of Q^* conducted into or out of the roof (the α_i coefficient) are also examined.

5.1 Summary of Conclusions

- The method of calculating the roof surface heat flux (Q_{Go}) via measurement of the flux at the nearest below-surface interface (Q_{Gz}), and adding the measured heat storage in the surface layer, proved to be effective. For gravel surfaces, heat flux plates of the type commonly used to measure soil heat fluxes were adequate (i.e. Middleton CN3), but ultrathin plates (i.e. Hukseflux UTO3) were required for all other measurements. The UTO3s were very sensitive to 'seeing' any direct or diffuse solar radiation, as well as the heterogeneity of the gravel/air pocket layer.

- The value of the a_I coefficient (the overall strength of the dependence of Q_G on Q^*) for the common industrial/commercial and residential roof types measured is much lower than those measured in previous studies, with the exception of the tar and gravel roof measured by Yap (1973).
- For roofs with gravel surfaces, the a_I coefficient is ~ 0.26 under dry, moderate wind conditions (daily average of 1 to 1.5 m s⁻¹ measured at 3.5 m above the roof surface). Under high wind conditions (daily average ≥ 1.5 m s⁻¹), the a_I coefficient is ~ 0.22 , and under conditions of negligible winds (daily average ≤ 1 m s⁻¹), it may be as high ~ 0.35 . Moisture lowers the average roof a_I coefficient for gravel roofs to between ~ 0.20 and 0.25. Wind does not have a significant effect on the a_I coefficient of wet roofs.
- For roofs with modified SBS (styrene butadiene styrene) bitumen, measurements were conducted only under wet (no 24-hour rain free period) conditions, which resulted in an a_I coefficient of 0.06. This is considerably lower than for roofs with gravel layers, due to the radiative and thermal properties of the material.
- For residential roofs with asphalt shingle surfaces, the a_I coefficients for the east and west slopes ranged from 0.11 to 0.19 under slightly wet (predominantly dewfall) conditions. This indicates that the a_I coefficient of an asphalt shingle is somewhere between that of bitumen and gravel roof surfaces.

- The Simplified Transient Analysis of Roofs (*STAR*) model gives good agreement between measured and modelled surface heat fluxes. The model works very well for the case of dry roof conditions, but is less accurate under wet or mixed conditions because latent heat is not taken into account.
- The *STAR* model consistently slightly overestimates the surface heat flux, resulting in slightly higher α_l coefficients than those measured. For dry roofs, the α_l coefficient is overestimated by 0.03 on average under conditions of $\bar{u} \leq 1 \text{ m s}^{-1}$, and by 0.07 under $\bar{u} \geq 1.5 \text{ m s}^{-1}$ conditions.
- The *STAR* model does not fully capture the relationship between wind speed and α_l coefficients. The most likely cause for this discrepancy, as well as the consistent overestimation of the α_l coefficient, is the insensitivity of the outside convection coefficient used in the model. In a sensitivity analysis performed on the *STAR* model by its developers, they found that the best fit to measured data was obtained by using a coefficient that is $\sim 20\%$ lower than found in the literature (Wilkes, 1989). This error was based on wind speeds measured at 0.30 m above the roof level.
- The surface layer is the most important layer for determining the surface conductive heat flux. That is, the effect of sub-surface layers of insulation, deck material type, etc., do not play as significant a role in determining the range of coefficients.

A summary of the measured and modelled coefficients for 6 different roof types under a range of wind and moisture conditions is presented in Table 5.1. These values would be suitable for use in *OHM* calculations.

Table 5.1. Summary of measured and modelled Camuffo-Bernardi coefficients for commercial/industrial and residential roof types.

Roof Type	Roof Surface	Moisture Conditions	Wind Speed $\bar{u}$ (m s ⁻¹)	a_1	a_2 (h)	a_3 (W m ⁻²)
Commercial or Industrial	Gravel	Dry	≤ 1	0.30	0.96	-24
		Dry	1 to 1.5	0.26	0.89	-21
		Dry	≥ 1.5	0.22	0.92	-24
		Wet*	N/A	0.23	0.70	-21
	Bitumen	Mixed	N/A	0.06	0.28	-3
Residential	Asphalt shingle	Mixed**	N/A	0.14	0.33	-6
	Low-albedo asphalt shingle	Dry	1 to 1.5	0.09	0.18	-1
	Japanese ceramic tile	Dry	1 to 1.5	0.07	0.26	-6
	Slate	Dry	1 to 1.5	0.08	0.32	0

*Coefficients based on average of coefficients at Sites 2 and 4 (BUC and USB).

**Coefficients based on average of east- and west-facing roof slopes.

5.2 Recommendations for Further Research

While one of the main objectives of this study was to produce a more complete set of coefficients for common roof types, further modelling remains to be done for other roof types, including clay tile, adobe, sod, wood, corrugated iron, and many more. Ideally, the model would be run using actual measurements of the net radiation over these sites, although Q^* measured over sites with similar radiative properties may suffice. Data from a nearby meteorological station would give reasonable inputs to the weather-coupling portion of the model.

Both the measured and modelled coefficients have not yet been used extensively in the Objective Hysteresis Model (*OHM*) to evaluate their effects. A first step in applying

the new coefficients to *OHM* involves using GIS databases or other sources of information to determine the surface roof type in an urban area previously evaluated by *OHM*. The next step is to determine the percent coverage by each roof type in the urban area, and to evaluate the urban heat storage using *OHM*. The comparison of these values of urban heat storage vs. previous estimates is likely to show that the contribution of urban heat from rooftops was overestimated. This may be less significant in areas where vegetation, urban canyons, or paved surfaces dominate the urban volume.

Other projects that could be tested in *OHM* include creating hypothetical urban areas using “cool roof” technology. For example, how dramatically is the urban heat storage reduced when all of the roof shingles in a suburb are replaced with high-albedo shingles? The data provided in this study would make this a relatively simple question to answer.

Improvements in the *STAR* model would also benefit the accuracy of the coefficients derived from the surface heat fluxes. At present, the original model developers suggest that the outside convection coefficient requires a reduction of 20% at times of peak heating of the roof surface. Further sensitivity analyses of the model and the resulting changes would further enhance the ability of the model to predict more precise coefficients. In particular, an investigation into the wind speed height for which the correlations were derived, and the effects that using winds measured at 0.30 m and 3.5 m above roof level have on these convection coefficients may help to solve this aspect of the model error. Other points of investigation that were not included in the original *STAR* model validation include the height of boundary temperature and relative humidity measurement, as well as the effectiveness of the longwave radiation parameterization.

As there are many multi-layered materials in the urban environment, the applicability of the *STAR* model could be extended to a variety of other urban surface types. For example, the model could be run using typical thermal and radiative properties of materials such as pavement or concrete walls, and compared with those previously measured by Anandakumar (1999) and Asaeda and Ca (1993).

The annual variation in the Camuffo-Bernardi coefficients for a particular surface was not investigated in this thesis. In his measurement over a dry asphalt surface in Austria, Anandakumar (1999) found that the hysteresis loop behaviour of the Q_G vs. Q^* relationship was anti-clockwise during the cooler periods, and clockwise during warmer periods. Modelling the surface conductive heat fluxes of roofs under a variety of seasonal external boundary weather conditions may be an alternative method by which this phenomenon can be investigated. However, it should be noted that the fluxes are so small in winter that this anti-clockwise hysteresis behaviour may not play a significant role in the overall storage budget of an urban area.

Lastly, in order to test roofing materials that utilize energy balance / heat sharing methods of reducing the surface conductive heat flux (e.g. the saturated Japanese ceramic tile), the *STAR* model should be modified to accommodate latent as well as sensible heat fluxes. At present, only those roofing materials which utilize modified radiative and thermal properties can be adequately modelled (e.g. high-albedo asphalt shingles).

This research has shown that there are significant differences in the heat conduction characteristics of different industrial/commercial and residential roof assembly types. The results from the *STAR* model validation indicate that it is a useful and reasonably accurate tool for assessing the heat storage characteristics and Camuffo-

Bernardi coefficients for roofs and potentially other multi-layer urban structures. The impact of these new coefficients on the effectiveness of the *Objective Hysteresis Model* remains to be thoroughly tested, although results from sample calculations indicate that the storage heat flux in urban areas with a large roof surface area may be over-predicted by as much as 10-15%. Results from urban areas with high wind speed conditions suggest that the use of wind descriptors for the coefficients will greatly improve *OHM's* accuracy.

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Appendix A

ROOF LAYER INFORMATION AND INPUT DATA TO *STAR*

A.1 Introduction

The following pages contain the roof layer information and input data for each site modelled in *STAR*. Unless stated otherwise, the source for the roof layer types and thicknesses are U.B.C. Plant Operations files, contained at the University Services Building under the direction of Jim Leggott. The indoor temperatures at Sites 1 through 4 were measured (averaged over the entire measurement period), and all other sites used assumed indoor temperatures. The thickness of the deck for sites 1 through 4 was assumed. At the bottom of each input table are additional notes regarding the information sources for the layers, radiative properties, and thermal properties.

VARIABLE	UNIT	VALUE
Slope of roof	cm/m	0
Length and width of roof	m	100, 23
Layers of roof (max 20)	integer	4

LAYER DATA				
VARIABLE	UNIT	pea gravel Layer 1:	tar & grav. BUR Layer 2:	polyisoc. insulation Layer 3:
Name of material	3 char	GRV	MEM	IN1
Thickness	cm	2	1	2.54
Number of nodes (max 100)	integer	8	4	10
Thermal conductivity	W m ⁻¹ K ⁻¹	1.47	0.19	0.02
Slope of Thermal Cond. with T	unitless	0	0	0
Specific heat	J kg ⁻¹ K ⁻¹	1670	1460	920
Slope of Specific Heat with T	unitless	0	0	0
Density	kg m ⁻³	1100	1100	32

VARIABLE	UNIT	VALUE
Time steps per hour of sim time	integer	10
Transient solution technique	(0, 5, or 1)	1
Boundary conditions OUTSIDE	(0 or 1)	1
Solar absorptance, IR emittance		0.84, 0.92
Outside convection coefficient	(0 or 1)	1
Condensation/evaporation	(0 or 1)	0
Boundary conditions INSIDE	(0 or 1)	1
Indoor temperature	deg C	22
Inside convection coefficient	(0 or 1)	1

Note:

Solar absorptance and IR emittance from Oke (1997)

VARIABLE	UNIT	VALUE			
Slope of roof	cm/m	0			
Length and width of roof	m	25,25			
Layers of roof (max 20)	integer	4			
LAYER DATA					
VARIABLE	UNIT	2ply SBS membrane Layer 1:	polystyr. insulation Layer 2:	phenolic insulation Layer 3:	concrete deck Layer 4:
Name of material	3 char	MEM	IN1	IN2	CON
Thickness	cm	1.12	7.62	2.54	5
Number of nodes (max 100)	integer	5	30	10	20
Thermal conductivity	W m ⁻¹ K ⁻¹	0.19	0.029	0.02	0.138
Slope of Thermal Cond. with T	unitless	0	0	0	0
Specific heat	J kg ⁻¹ K ⁻¹	1670	1210	920	840
Slope of Specific Heat with T	unitless	0	0	0	0
Density	kg m ⁻³	1121	30	32	288
VARIABLE	UNIT	VALUE			
Time steps per hour of sim time	integer	10			
Transient solution technique	(0,5,or 1)	1			
Boundary conditions OUTSIDE	(0 or 1)	1			
Solar absorptance, IR emittance		0.60,0.84			
Outside convection coefficient	(0 or 1)	1			
Condensation/evaporation	(0 or 1)	0			
Boundary conditions INSIDE	(0 or 1)	1			
Indoor temperature	deg C	22			
Inside convection coefficient	(0 or 1)	1			

Note:

Solar absorptance and IR emittance from Petrie (2000)

VARIABLE	UNIT	VALUE					
Slope of roof	cm/m	2					
Length and width of roof	m	40,10					
Layers of roof (max 20)	integer	6					
LAYER DATA							
VARIABLE	UNIT	river gravel Layer 1:	2-ply SBS membrane Layer 2:	insulation ext. EPS Layer 3:	type 4 membrane Layer 4:	gyproc layer Layer 5:	steel deck Layer 6:
Name of material	3 char	GRV	MEM	IN1	MEM	GYP	STL
Thickness	cm	4.5	0.6	7.62	0.2	1.25	0.5
Number of nodes (max 100)	integer	18	2	30	1	5	2
Thermal conductivity	W m ⁻¹ K ⁻¹	1.436	0.19	0.029	0.19	0.3	45
Slope of Thermal Cond. with T	unitless	0	0	0	0	0	0
Specific heat	J kg ⁻¹ K ⁻¹	1670	1670	1220	1670	1050	500
Slope of Specific Heat with T	unitless	0	0	0	0	0	0
Density	kg m ⁻³	1121	1121	40	1120	1420	7850
VARIABLE	UNIT	VALUE					
Time steps per hour of sim time	integer	10					
Transient solution technique	(0,5,or 1)	1					
Boundary conditions OUTSIDE	(0 or 1)	1					
Solar absorptance, IR emittance		0.84,0.92					
Outside convection coefficient	(0 or 1)	1					
Condensation/evaporation	(0 or 1)	0					
Boundary conditions INSIDE	(0 or 1)	1					
Indoor temperature	deg C						
Inside convection coefficient	(0 or 1)	1					

Note:

Solar absorptance and IR emittance from Oke (1997)

VARIABLE	UNIT	VALUE		
Slope of roof	cm/m	0		
Length and width of roof	m	20.5		
Layers of roof (max 20)	integer	4		
LAYER DATA				
VARIABLE	UNIT	asphalt shingle Layer 1:	plywood deck Layer 2:	insulation Layer 3:
Name of material	3 char	SHN	PLY	INS
Thickness	cm	0.66	1.2	14
Number of nodes (max 100)	integer	2	5	56
Thermal conductivity	W m ⁻¹ K ⁻¹	0.1	0.12	0.04
Slope of Thermal Cond. with T	unitless	0	0	0
Specific heat	J kg ⁻¹ K ⁻¹	1260	1210	840
Slope of Specific Heat with T	unitless	0	0	0
Density	kg m ⁻³	1122	540	90
VARIABLE	UNIT	VALUE		
Time steps per hour of sim time	integer	10		
Transient solution technique	(0,5,or 1)	1		
Boundary conditions OUTSIDE	(0 or 1)	1		
Solar absorptance, IR emittance		0.70, 0.87		
Outside convection coefficient	(0 or 1)	1		
Condensation/evaporation	(0 or 1)	0		
Boundary conditions INSIDE	(0 or 1)	1		
Indoor temperature	deg C	22		
Inside convection coefficient	(0 or 1)	1		

Note:

First two layers used in 2-layer model. All three layers used in 3-layer model.

Solar absorptance and IR emittance from Petrie (2000).

Shingle thickness measured. Plywood thickness estimated.

Input for STAR Japanese Ceramic Tile

VARIABLE	UNIT	VALUE	
Slope of roof	cm/m	0	
Length and width of roof	m	20,5	
Layers of roof (max 20)	integer	2	
LAYER DATA			
VARIABLE	UNIT	ceramic tile Layer 1:	plywood deck Layer 2:
Name of material	3 char	CER	PLY
Thickness	cm	4.5	1.2
Number of nodes (max 100)	integer	18	5
Thermal conductivity	W m ⁻¹ K ⁻¹	0.3	0.12
Slope of Thermal Cond. with T	unitless	0	0
Specific heat	J kg ⁻¹ K ⁻¹	630	1210
Slope of Specific Heat with T	unitless	0	0
Density	kg m ³	730	540
VARIABLE	UNIT	VALUE	
Time steps per hour of sim time	integer	10	
Transient solution technique	(0,5,or 1)	1	
Boundary conditions OUTSIDE	(0 or 1)	1	
Solar absorptance, IR emittance		0.90, 0.92	
Outside convection coefficient	(0 or 1)	1	
Condensation/evaporation	(0 or 1)	0	
Boundary conditions INSIDE	(0 or 1)	1	
Indoor temperature	deg C	22	
Inside convection coefficient	(0 or 1)	1	

Note:

Solar absorptance and IR emittance from Asaeda (2000)
 Thickness of ceramic tile from measurements.
 Thickness of plywood deck estimated (same as Site 5).
 Length and width of roof same as Site 5.
 Interior temperature same as Site 5.

Input for STAR Slate tile

VARIABLE	UNIT	VALUE
Slope of roof	cm/m	0
Length and width of roof	m	20,5
Layers of roof (max 20)	integer	2
LAYER DATA		
VARIABLE	UNIT	slate tile Layer 1: plywood deck Layer 2:
Name of material	3 char	SLT
Thickness	cm	0.7
Number of nodes (max 100)	integer	2
Thermal conductivity	W m ⁻¹ K ⁻¹	0.25
Slope of Thermal Cond. with T	unitless	0
Specific heat	J kg ⁻¹ K ⁻¹	1060
Slope of Specific Heat with T	unitless	0
Density	kg m ⁻³	1510
VARIABLE	UNIT	VALUE
Time steps per hour of sim time	integer	10
Transient solution technique	(0,5, or 1)	1
Boundary conditions OUTSIDE	(0 or 1)	1
Solar absorptance, IR emittance		0.90, 0.92
Outside convection coefficient	(0 or 1)	1
Condensation/evaporation	(0 or 1)	0
Boundary conditions INSIDE	(0 or 1)	1
Indoor temperature	deg C	22
Inside convection coefficient	(0 or 1)	1

Note:

Solar absorptance and IR emittance from Asaeda (2000)
 Thickness of slate tile from ASHRAE (1993).
 Thickness of plywood deck estimated (same as Site 5).
 Length and width of roof same as Site 5.
 Interior temperature same as Site 5.

Input for STAR High-Albedo Asphalt Shingle

VARIABLE	UNIT	VALUE	
Slope of roof	cm/m	0	
Length and width of roof	m	20.5	
Layers of roof (max 20)	integer	4	
LAYER DATA			
VARIABLE	UNIT	asphalt shingle Layer 1:	plywood deck Layer 2:
Name of material	3 char	SHN	PLY
Thickness	cm	0.66	1.2
Number of nodes (max 100)	integer	2	5
Thermal conductivity	W m ⁻¹ K ⁻¹	0.1	0.12
Slope of Thermal Cond. with T	unitless	0	0
Specific heat	J kg ⁻¹ K ⁻¹	1260	1210
Slope of Specific Heat with T	unitless	0	0
Density	kg m ³	1122	540
VARIABLE	UNIT	VALUE	
Time steps per hour of sim time	integer	10	
Transient solution technique	(0,5,or 1)	1	
Boundary conditions OUTSIDE	(0 or 1)	1	
Solar absorptance, IR emittance		0.50, 0.87	
Outside convection coefficient	(0 or 1)	1	
Condensation/evaporation	(0 or 1)	0	
Boundary conditions INSIDE	(0 or 1)	1	
Indoor temperature	deg C	22	
Inside convection coefficient	(0 or 1)	1	

Note:

Solar absorptance and IR emittance from Berdahl (2000).
All other conditions same as Site 5.

Appendix B

EVEREST INTERSCIENCE 4000A IRT CALIBRATION

The Everest Interscience infrared thermometer (EIRT) is a small, self-contained, micro-computer based infrared temperature transducer. The original factory calibration checks at two different surface temperatures (25 and 76 °C) at an air temperature of approximately 25°C were done in 1991. Further calibrations were conducted in 1992 and 1993 (Voogt, 1995), showing that all six of the EIRTs showed some difference between the EIRT temperature (T_{ev}) and the temperature of a black body cavity (T_{cav}). The calibrations in 1992 utilized a long-term exposure to a slowly changing blackbody cavity temperature. These calibrations revealed that the error was greater at low cavity temperatures, possibly due to thermal coupling between the cavity and EIRT creating temperature gradients within the EIRT (Voogt, 1995).

The application of the EIRTs to this thesis project required measurement of a much larger range of temperatures (particularly high roof temperatures) than those measured by Voogt (1995). Therefore, the EIRTs were recalibrated using the same techniques used in 1992, for a larger range of temperatures. The regression relations between T_{cav} ($\epsilon = 1.0$) and T_{ev} ($\epsilon = 0.98$) are presented in Table A.1, using the equation:

$$T_{ev} = a + bT_{cav} \quad (A.1)$$

Table A.1 EIRT Calibration results, 1999.

Instrument Serial Number	a	b	Temp. range (°C)
2094-1	0.256	0.994	23 to 81
2094-2	3.050	0.922	24 to 82
2094-3	1.138	0.985	21 to 78
2094-6	2.487	0.914	-16 to 78

The results of this most recent calibration (Table A.1) indicate that all of the EIRTs show some difference from a perfect fit, and that the regression relations are slightly different for the higher temperatures than those found by Voogt (1995) in 1992. In this study, the instruments were corrected using these most recent calibration results to obtain the equivalent blackbody temperature.