SENSIBLE HEAT FLUXES MEASURED IN AND NEAR VANCOUVER, B.C.

by

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ABSTRACT

A yaw sphere-thermometer assembly (YST), to measure sensible heat flux density by the eddy correlation method, was built following the design of Tanner and Thurtell (1970). Wind tunnel experiments indicate that the sphere constant should be 1.57, which is significantly less than the previously used theoretical value of 2.25. The effects of tilt indicate that heat fluxes may be in error by 5 per cent per degree of tilt in unstable, and up to 11 per cent per degree in stable conditions. A modified thermometer assembly was found necessary to provide durability. Field comparisons of the heat fluxes measured by the yaw sphere-thermometer system and a Bowen ratio apparatus produced satisfactory agreement.

Direct measurements of sensible heat fluxes over a grass surface at Ladner, B.C. indicate a diurnal course very similar to that of the net radiation. In general, half-hour averaging periods showed no phase lag between sensible heat and net radiation. Field comparison of two YST systems gave good and consistent agreement. At a height of 2 m above ground and a horizontal crosswind separation
of 1.5 m, less than 5 per cent variability was noted in the heat flux measurements from the two systems. For a 19 m horizontal separation, the variability was found to be less than 20 per cent. It is shown that the parameter \( \alpha \), advanced by Priestley and Taylor (1972), can be a useful climatic indicator.

The applicability of the eddy correlation technique to the measurement of sensible heat transfer between the atmosphere and the urban interface is demonstrated for a limited area of the city of Vancouver, B.C. Despite the enormous complexities of the turbulent heat exchange processes, the urban sensible heat flux pattern, obtained directly at heights of 1.2, 2, 4 and 20 m above roof-top level, largely reflected time and magnitude changes in the net radiation field, during the daytime. Nocturnal urban sensible heat fluxes, near roof-top level, were found to be directed away from the active surface. This is the reverse of the normal rural case. Within the local roof-top boundary layer, the sensible heat flux was found to be approximately constant with height and space (20\% variation) during the daytime. At night, the existence of flux divergence and hence, non-constancy of the heat flux, is suggested.
Daytime roof-top energy balances indicate that a significant portion of the net radiation is utilized in sensible heat transfer and in heat storage in the roof. The greatest energy is used in sensible heat transfer, which is about three times the heat storage at noon. With typical values of net radiation of 60 mWcm\(^{-2}\), the sensible heat flux is about 30 mWcm\(^{-2}\) and the heat storage 10 mWcm\(^{-2}\). The residual term (equated to latent heat transfer) is quite appreciable. It is possible that the role of latent heat transfer is important for urban energy balance considerations. The nocturnal roof-top energy balance required a latent heat term of about 15 mWcm\(^{-2}\) directed towards the active surface.

The energy balance of the surrounding urban area was deduced from measurements of sensible heat flux and net radiation at heights above the roof-top boundary layer. On the assumption that these point measurements approximately reflect areally integrated averages, partitioning of the heat between sensible and latent heat yields a Bowen ratio of ~ 1 at midday.
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LIST OF SYMBOLS

\( \alpha \) angle between the wind vector and the bisector of the ports (Chapter 3)

\( \alpha \) Priestley and Taylor parameter (Chapter 4)

\( b \) sphere constant

\( B \) bridge constant

\( \beta \) Bowen ratio (H/LE)

\( C_p \) specific heat at constant pressure

\( C_{pb} \) thermal capacity of city structures

\( d \) diameter of the sphere

\( D \) divergence terms

\( \delta \) tilt error

\( e \) vapour pressure

\( E \) water vapour flux

\( \bar{E}_0 \) bridge output

\( \varepsilon \) ratio of the mole weight of water vapour to that of dry air (Chapter 1)

\( \varepsilon \) ratio of meter conductivity to medium conductivity (Chapter 6)
f ratio of mean flux density through the meter to the mean flux density through the medium

F artificial generation of heat and water vapour

$\Phi_{wT}$ cospectrum between the vertical velocity (w) and the air temperature (T)

G amplifier gain (Chapter 3)

G soil heat storage

H sensible heat flux

$I_s$ true effective outgoing radiation from the surface

L latent heat of vapourization

LE latent heat flux

M pressure transducer constant

v kinematic viscosity

n frequency

p pressure

$P_s$ static pressure

q specific humidity

R specific gas constant

Re Reynolds no.

Rn net radiation

$\rho$ air density
\( \sigma \) Stefan-Boltzmann constant

\( \psi \) slope of the saturation vapour curve at the appropriate temperature

\( T \) air temperature

\( T_b \) temperature of city structures

\( T_s \) surface temperature

\( \theta \) included angle between the ports

\( \tau \) negative momentum flux

\( u \) horizontal wind velocity component along direction of the wind

\( \bar{u} \) mean wind speed

\( V \) air speed (Chapter 3)

\( V \) storage terms in volume (Chapter 1)

\( \vec{W} \) velocity vector

\( v \) crosswind horizontal component of the wind velocity

\( w \) vertical velocity component

\( x_T, z_T \) tilt axis plane

\( (\overline{\cdot}) \) time average at a given point

\( (\cdot)' \) fluctuation about the mean

\( \nabla_H \) \( \partial/\partial x + \partial/\partial y \)
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Chapter 1

INTRODUCTION

General Background

The receipt, transformation and transfer of energy at the earth-atmosphere interface is basic to a rational understanding of climates. Estimation of the vertical eddy fluxes of physical entities, such as sensible heat, water vapour and momentum in the atmospheric boundary layer remains at the core of micrometeorological research. Knowledge of these fluxes is also important in the study of the general circulation of the atmosphere since they define the lower boundary conditions of the larger scale atmospheric dynamics.

Until very recently, the field of urban micro-meteorology was almost non-existent. Although a large body of urban climate literature exists (see the summaries given by Brooks (1952), Kratzer (1956), Landsberg (1961), Chandler (1968) and Peterson (1969)), attention has been primarily confined to the description of the basic nature of climatic effects produced by urban areas. The processes giving rise
to urban climates remained largely speculative. This lack of information concerning the underlying mechanisms governing urban climate has attracted many researchers, especially since the recent WMO Symposium on Urban Climates (WMO, 1970). Most of the work, however, seems to be centred on modelling the urban environment (see for example, the Conference on Urban Environment, 1972). Experimental research to probe the physical basis of urban climate is still largely deficient, due to the enormous complexity of the city/atmosphere interface and the need for sophisticated measurement techniques. This study seeks to achieve some insight into the manner in which heat is utilized in the urban atmosphere and into the energetics of urban micrometeorology through direct measurements.

For most natural surfaces, the nature of their energetic basis has been elucidated through heat budget studies. Similar studies for cities are fragmentary or absent. This dearth of knowledge concerning the energy fluxes in urban areas has been mentioned by many authors in recent years (e.g. Munn (1966), Miller (1968), Lowry (1969) and Oke (1969)). It is to be expected that urbanization will markedly modify the surface heat balance. Determination of this altered heat balance is one of the tasks of urban climatology (Landsberg, 1970). Throughout this study, the heat balance approach has been utilized, and therefore it is useful to review the framework here.
Review

The concept of heat balance is embodied in the principle of conservation of energy: the difference between heat inflow and outflow is the heat stored or used within the system of concern. The heat balance of a volume, one face of which is the Earth's surface, is schematically shown in Fig. 1. Using the conservation principle, it can be expressed as a general equation at any instant in time as follows:

\[ \pm R_n = \pm H \pm LE \pm G \pm V \pm D \]  \hspace{1cm} (1.1)

where \( R_n \), \( H \), \( LE \) and \( G \) represent the vertical fluxes of net radiation, sensible heat, latent heat and soil heat respectively. \( V \) is the storage of heat in the volume and \( D \) is the horizontal divergence of sensible and latent heat.

For a flat, solid surface or a homogeneous vegetated surface with adequate fetch, the divergence and volume storage terms are usually small compared with the vertical fluxes (e.g. Begg et al., 1964; Brown and Covey, 1967; Lemon, 1967), and accordingly, the heat balance expression reduces to:

\[ \pm R_n = \pm H \pm LE \pm G \]  \hspace{1cm} (1.2)
Fig. 1. Schematic heat balance of a volume, one face of which is the Earth's surface (after Suomi, 1957).
The neglect of other terms usually involves an error of less than 10 per cent of the net radiation (Davies et al., 1969). Numerous examples of heat balance studies of typical rural surfaces (grass, crops and forest) can be cited (for example: Lettau and Davidson, 1957; Wright and Lemon, 1962).

Through volume considerations, it is also possible to formulate the heat balance of an urban area. A schematic representation of the heat balance of an urban-building air volume is shown in Fig. 2. It may be represented by the following equation

\[ \pm Rn \pm F = \pm H \pm LE \pm G \pm \int_{0}^{Z} \frac{L e}{R T} \frac{\partial e}{\partial t} \delta z \pm \int_{0}^{Z} \rho C_p \frac{\partial T}{\partial t} \delta z \pm \int_{0}^{Z} \nabla_H \left( \rho u T \right) \delta z \pm \int_{0}^{Z} \frac{L e}{R} \nabla_H \left( \frac{u e}{T} \right) \delta z \]

(1.3)

where the meaning of the symbols is: \( C_p \), specific heat of air at constant pressure; \( \rho \), air density; \( u \), horizontal wind velocity; \( T \), air temperature; \( L \), latent heat of vaporization; \( E \), water vapour flux; \( e \), the ratio of the mole weight
Fig. 2. Schematic heat balance of urban building-air volume.
of water vapour to that of dry air; \( R \), the specific gas constant; \( e \), vapour pressure; \( C_p, T_b \) thermal capacity and temperature of city structures, respectively; \( F \), artificial generation of heat and water vapour and \( \nabla H, \partial \partial x + \partial \partial y \). Other symbols have their meaning as before.

Although the governing energy budget equations may be readily specified for the urban situation, the three-dimensional nature of the problem is most formidable. The complex city system raises serious difficulties. In particular, it becomes almost impossible to define such basic concepts as the location of the 'surface' itself. The many buildings and multiple-level surfaces present a complex geometry to the atmosphere. Further complications arise from man-made production of heat and water vapour in cities. Each element of the mosaic which forms a city (the home, building, pavement, road, garden, etc.) creates its own distinctive microclimatic envelope. One should therefore expect that the inhomogeneities (horizontally and vertically) produced by these elements would result in significant microclimatic variability. It may not however be unreasonable to suggest that a first order unity of building development should give a regional continuity to the basic urban climate (Chandler, 1965). Indeed, evidence from studies of the heat island (the characteristic warmth of the city) supports this view since the horizontal temperature pattern near street
level often closely parallels the urban morphology, e.g. Maxwell (1971). Hence, by confining our investigation in the complex city system to a limited urban-building-air volume where buildings are of uniform type, height, density and function, some degree of climatic continuity may be expected. In doing so, we necessarily restrict the scope of the research to a small portion of the diversified urban landscape. At the same time however, it offers a rational approach towards probing the urban atmosphere and should enable an elucidation of the energetic basis of city climate. The complexity of the three-dimensional nature of the problem is evident. It is not however proposed to evaluate all the energy terms indicated for such a volume, but rather to use this framework, and to focus attention primarily on the vertical energy exchanges.

In recent years, urban heat budget studies have attracted the attention of a number of researchers. Even so it is not surprising that we know so little about the components of the heat budget in urban areas in view of the complexities of the environment and out lack of appropriate measuring techniques to assess quantitatively these energetic exchanges. Experimental evidence of the urban energy components is still fragmentary. The radiational aspects have now been investigated to some extent (e.g. Tag, 1968; Hawkins, 1969; Terjung, 1970; Bach, 1970 and Oke and Fuggle,
The effect of radiative exchanges between building elements, and shadow areas remain outstanding problem areas for investigation. The few attempts made to measure the heat stored in the city building materials (e.g. Davis, 1968 and Terjung, 1970) only provide gross estimates of this energy balance component. A spatial averaging procedure that includes geometrical considerations might yield reasonable heat storage estimates, but has not yet been attempted. Estimation of the artificial heat produced in cities can be found in the literature (e.g. Oke, 1969; SMIC, 1971). The artificial energy flux density for various cities is given in Table 1.

Determination of the vertical fluxes of sensible and latent heat over urban areas remains an outstanding problem. Attempts have been made to assess these fluxes indirectly via the Bowen ratio/energy balance method with little success (e.g. Bach, 1970; Myrup and Morgan, 1972). Fuggle (1971) and Terjung (1971) have obtained stable measurements in this regard, but of a limited nature. There have been no attempts at direct measurements of these energy fluxes. It is thus obvious that much research is still needed in this area of urban heat balance climatology. Accordingly, the principal aim of this research will be directed towards direct assessment of the eddy fluxes in
### Table 1
Comparison of artificial energy flux density and average net radiation for selected urban areas
(c.f. (SMIC, 1971)) **

<table>
<thead>
<tr>
<th>City</th>
<th>Area (km²)</th>
<th>Population 10⁶</th>
<th>Artificial energy flux density (mWcm⁻²)</th>
<th>Average net radiation (mWcm⁻²)</th>
<th>Averaging Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Berlin</td>
<td>234 *</td>
<td>2.3</td>
<td>2.1</td>
<td>5.7</td>
<td>Year</td>
</tr>
<tr>
<td>Hamburg</td>
<td>747</td>
<td>1.8</td>
<td>1.3</td>
<td>5.5</td>
<td>Year</td>
</tr>
<tr>
<td>Moscow</td>
<td>878</td>
<td>6.4</td>
<td>12.7</td>
<td>4.2</td>
<td>Year</td>
</tr>
<tr>
<td>Cincinnati</td>
<td>200 *</td>
<td>0.54</td>
<td>2.6</td>
<td></td>
<td>Summer</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>3500 *</td>
<td>7.0</td>
<td>2.1</td>
<td>10.8</td>
<td>Year</td>
</tr>
<tr>
<td>Manhattan, New York</td>
<td>59</td>
<td>1.7</td>
<td>19.8</td>
<td></td>
<td>Summer Winter</td>
</tr>
<tr>
<td>Fairbanks, Alaska</td>
<td>37 *</td>
<td>0.03</td>
<td>1.9</td>
<td>1.8</td>
<td>Year</td>
</tr>
<tr>
<td>Montreal</td>
<td>78 *</td>
<td></td>
<td>9.8</td>
<td></td>
<td>Year</td>
</tr>
</tbody>
</table>

* Building area only.

** Based on modified SMIC (1971), Summers (1964) and Ōke (1969).
the urban context, and in particular, sensible heat. It is therefore useful to review the measuring technique.

Most of micrometeorological research has been centred on means of deriving the fluxes of heat, water vapour and momentum through indirect methods, based on temperature, water vapour and wind profiles, which necessarily involve assumptions about the character of the atmosphere. A considerable literature on profile formulas to accomplish this has been developed. Direct measurement of these fluxes has received much impetus in recent years, as suitable measuring techniques have been developed to utilize such an approach.

Except for the few millimeter of air above the ground (the laminar boundary layer), where entities are transferred by molecular processes, turbulence is the principal mechanism for atmospheric transport near the Earth's surface.

The direct measurement of eddy fluxes is based on fluctuation theory. By considering the vertical transport of a physical entity (s) across unit horizontal area, it can be shown (e.g. Swinbank, 1951, Priestley, 1959) that the vertical flux ($F_s$) under conditions of steady-state and horizontal uniformity is given by

$$ F_s = (\rho w)s $$ (1.4)
where \( \rho \) is the air density; \( w \) is the vertical wind component and the bar indicates a time average at a given point.

Thus, for example, the turbulent heat flux may be written

\[
H = C_p (\bar{\rho} \bar{w}) \bar{T} \tag{1.5}
\]

where \( T \) is the air temperature and \( C_p \) is the specific heat at constant pressure. The variables \( \rho \), \( w \) and \( T \) may furthermore be expressed in terms of a mean quantity plus a fluctuation about that mean so that

\[
H = C_p [\bar{\rho} (\bar{\rho} + \rho') (\bar{w} + w')(\bar{T} + T')] \tag{1.6}
\]

and if there is no significant convergence or divergence (i.e. \( \bar{\rho}w = 0 \)) the sensible heat flux expression can be expanded to give

\[
H = C_p [\bar{\rho} \bar{w}'\bar{T}' + \bar{w} \bar{\rho}'\bar{T}' + \bar{\rho}'\bar{w}'\bar{T}'] \tag{1.6}
\]
If the mean vertical wind is close to zero, the second term in the bracket can be neglected. The magnitude of the third term (the triple moment), compared to the first term in the bracket, has been shown by Businger and Miyake (1968) experimentally to be a ratio of about 0.0014 and therefore the sensible heat flux expression reduces to

$$H = C_p \, \overline{\rho \, w' \, T'}$$  \hspace{1cm} (1.7)

In a similar manner, the vertical fluxes of latent heat and momentum can be obtained directly from the covariances of $w$ and $q$ (specific humidity) fluctuations and $w$ and $u$ fluctuations, respectively. Hence

$$LE = \rho \, L \, \overline{w'q'}$$ \hspace{1cm} (1.8)

$$\tau = -\rho \, \overline{w'u'} \quad (\tau : \text{negative momentum flux})$$

This approach (the eddy correlation technique) is a fundamental method for measuring turbulent transfer, and it possesses the advantage of directly measuring eddy fluxes. The direct measuring techniques, however, are not easily accomplished since they require very fast-response sensors that must measure the pulsations of the wind and the
appropriate physical entity over the entire frequency range contributing to the flux. In this study, attention is limited to the use of this technique in the measurement of sensible heat.

For the measurement of $H$, the stringent requirements of the wind sensor are hardest to meet. Two of the most promising approaches are the sonic anemometer (Mitsuta, 1966, 1968; Kaimal et al., 1968) and the pressure-sphere anemometer (Thurtell et al., 1970; Wesely et al., 1972). Comparisons of $H$ determined by instruments incorporating these wind sensors have been most encouraging (e.g. Wesely et al., 1970).

Recently Tanner and Thurtell (1970) developed a relatively simple yaw sphere-thermometer (YST) system for the measurement of sensible heat flux incorporating the pressure-sphere principle. The yaw sphere when directed into the wind flow generates a pressure difference between two ports that is proportional to the product of the horizontal and vertical winds. The analog pressure signal is used to drive a resistance-thermometer bridge. The bridge output is then directly related to the sensible heat flux. This system was chosen for the purpose of our investigation. A significant aspect of this research includes instrumental development and improvement, and field comparison tests over a simple rural surface.
Objectives

In summary, the primary objectives of this thesis can be stated as follows:

1) to construct, calibrate and test a yaw-sphere-thermometer system for direct measurements of sensible heat flux density,

2) to examine the spatial variability of the eddy flux in the atmospheric boundary layer,

3) to determine the magnitude and sign of the sensible heat fluxes over an urban area,

4) to investigate the role of this parameter in the urban energy balance framework.

It should be emphasized that some of these objectives are very difficult to achieve, and coupled with limitations in observation must necessarily create shortcomings. This study is however expected to contribute to our knowledge of eddy flux measurement in the atmospheric boundary layer, and in particular, to heat exchange processes in the urban environment.
Chapter 2

SITE AND INSTRUMENTATION

Experimental Sites

General aspects.

For the purpose of this investigation, two experimental sites were chosen in and near Vancouver, B.C.

Greater Vancouver, with a population exceeding one million, covers the westernmost portion of the Lower Mainland area of British Columbia. A map of the region depicting geographical and political landmarks, land use and the location of the experimental sites is shown in Fig. 3. Dense, high-rise buildings are confined primarily to the Central Business District (CBD) on the Burrard Peninsula. The topography is varied. The land over the area slopes gradually from south to north, rising rapidly from Burrard Inlet to the mountain ridges along its north shore. These mountain peaks rise to heights in excess of 1000 m. In the southwestern areas of Richmond and Delta, the land is flat and is used primarily for agriculture,
Fig. 3. The Greater Vancouver area.
although rapid urbanization is becoming evident. The Surrey area is one of rolling farmlands with occasional hills reaching to elevations of 100 m. In the city proper, the ground slopes gradually from the Fraser upwards to form a slight ridge between this river and Burrard Inlet. Here land elevations reach 100-150 m and contain several crests. The varied topography, the close proximity of the land to water bodies, and the degree of urbanization exert marked influences on the local climate.

The climate of the region is best described as modified maritime, characterized by wet mild autumn and winter, and relatively dry cool summers.

**Temperature.**

Temperatures are modified by proximity to Georgia Strait. Mean daily temperatures range from about 2-5°C during the months of January and February to about 17-18°C during the months of July and August. The temperature pattern of the Greater Vancouver area has recently been reported by Emslie (1972). Large variations in the surface temperature field exist. The cause of these variations is attributed to the following factors:
a) The distance from the ocean and its modifying effect on air temperature,
b) sea breezes,
c) cold air drainage to low areas at night,
d) the normal decrease of temperature with height,
e) heat island effect,
f) southerly aspect,
g) systematic variations in cloudiness,
h) atmospheric pollution in the downtown area.

Precipitation.

Extremely varied precipitation patterns occur in the Greater Vancouver region as a result of westerly winds, coupled with the abrupt terrain level changes in the northern sections (Wright and Trenholm, 1969). Annual precipitation varies from < 100 cm in the Tsawassen area to > 250 cm in parts of North Vancouver. A similar trend in cloud cover may be inferred from the precipitation pattern. The seasonal variation of precipitation in Vancouver is shown in Fig. 4. The summer is generally dry with only a few days of rain, whereas the winter is characterized by many days of rain in each month.
Fig. 4. Percentage of days with measurable precipitation - Vancouver City (1906-1955) - 7 day running mean (c.f. Harry and Wright, 1967).
Winds.

The prevailing wind directions are easterly and westerly along the axis of the Fraser Valley. Easterly winds are associated with the development of nighttime land breezes and with the general flow ahead of any frontal system. Westerlies occur as afternoon sea breezes or following frontal passages and are generally much stronger than the easterly winds. Easterlies are predominant throughout the year, diminishing gradually from winter to summer. Westerlies show an increase in frequency of occurrence from winter to summer. Mean wind speeds do not show much variation from month to month. The presence of a local sea breeze-land breeze circulation and valley constriction often combine to inhibit the transport of atmospheric pollutants away from the area in prolonged period of anticyclonic weather conditions. Visual observations indicate that the pollutants in such situations are carried up the valley during the daytime with the onshore breeze, only to return to the city at night with the land breeze circulation.

Heating season.

Heating requirement to provide reasonable comfort throughout the year is generally expressed in terms of
"degree days" (the number of degrees F that the mean daily temperature is below 65°F). For Vancouver, on the average, 90 per cent of the heating season (heating degree-days) occurs between September and April, with January and February being the two greatest heating months. In contrast, July and August may be considered to be non-heating months (Harry and Wright, 1967).

This general picture provides the basic climate context within which the microclimatic investigations of this study took place. A more detailed description of the general climate of the Vancouver area is given by Harry and Wright (1967).

Site considerations.

Experimental studies in the atmospheric boundary layer are strongly influenced by the spatial variability of meteorological phenomena in both the horizontal and vertical directions. To some extent, observations in such an environment can only be conducted imperfectly. For while spatial sampling is highly desirable, especially over rugged terrain, this is often difficult to achieve because of practical limitations. One is then led to consider point measurements with their inherent limitations, and to
limit study of the processes to the time domain. Particular attention then must be given to the important and often difficult problem of site selection.

In choosing the site, objective criteria should be specified. Primary consideration should be given to:

a) the purpose of the investigation,
b) the nature of the underlying surface,
c) practical limitations.

In this study the following general site selection criteria were employed.

a) the site and its immediate environs should be as nearly as possible characteristic of the area, the climate of which is to be explored,
b) it should be within an area that is fairly uniform and extensive so as to minimize small scale-adveotive influences and to ensure adequate fetch,
c) proper allowance should be made with reference to the exposure of the site for the entities to be measured,
d) the site should be accessible, with adequate power and protection from vandalism.

Apart from practical limitations (see (d) above), an experimental site that satisfies these general criteria can usually be found in rural areas. Thus, an extensive, uniform flat area or a homogeneous vegetated surface with
adequate fetch would be appropriate for the rural experimental site. A fixed sampling point may then be considered sufficiently representative of the area.

Site selection in the urban environment, to meet the above criteria, is extremely difficult. Indeed, it is impossible to define a sampling site which could be considered 'representative' of the city as a whole, because the urban 'topography' and the source and sink distributions of heat, water vapour and momentum is highly irregular. By considering only a very small portion of the urban landscape (a limited urban-building-air volume), it may be possible to obtain a site and its immediate environs that is approximately characteristic of an urban area. If the area possesses a basic continuity of form, criterion (b) may be adequately satisfied. It should be pointed out, however, that where distinct changes in the properties of the underlying surface occur, internal boundary layers develop and deepen downwind. In urban areas, many changes occur due to the variety of surface types and the nature of the surface geometry. Surface discontinuities may also be created by temperature anomalies (for example, contrasting areas in shadow and direct sunlight). The problem of achieving suitable height/fetch ratio to ensure representativeness would become formidable if these changes resulted
in distinct localized boundary layers. Dyer (1963) indicates a height/fetch ratio 1:200-300 for 90 per cent adjustment to a new surface condition. Sufficient fetch would thus only be realized for conditions very close to the particular surface over which measurements were made. Such localized effects may not be very significant over a relatively dense uniform urban area since the internal boundaries are likely to become diffused through turbulent motion of the air as it traverses over the building elements. The choice of site may thus minimize this effect. To allow for proper exposure at the site and to ensure a relatively uniform meteorological field, measurements in the urban context should be conducted above roof level.

In choosing the urban experimental site, the following criteria were specified:

a) the site should be located in an area of building continuity (uniform type, height, density and function) and measurements should be made above roof-level, so as to ensure some uniformity in the meteorological fields,

b) the site should have suitable fetch from non-urban surfaces so as to avoid large scale advective influences,

c) the area of concern should be near the centre of the urban heat island, but horizontal temperature gradients should be relatively small,

d) there should be no major anomaly nearby that might sporadically affect results (ex. industrial plant with high waste heat and water vapour emissions).
The following two sections describe the sites chosen in light of these criteria.

The rural site.

The rural observational site was located on the flat delta region of the Fraser, about 28 km south of Vancouver (c.f. Fig. 3). The site chosen was an extensive, flat grassed surface on the abandoned airport at Canadian Forces Station, Ladner. The general location of the site is shown on Figs. 5 and 6.

Interruptions in the grass surface properties were created by the airport runways, Boundary Bay and by a step change in the grass height in the NNE-SSE sector during the field programme of 1971. The grass over the experimental site was ~ 90 cm tall, giving a roughness length of ~ 10 cm based on analysis of neutral wind profiles. Radiation measurements gave a short-wave albedo of 0.23 and a long-wave emissivity of 0.98 for the grass surface. Height/fetch ratios (1:165 to 1:200) were found to be sufficient to ensure representative observations in most instances. Minimum fetch distances, and the general location of the instruments are shown in Fig. 6. The site was considered satisfactory in respect of the general criteria previously stated (e.g. uniformity in terrain
Fig. 5. Map of Ladner experimental site.
Fig. 6. Sketch of Ladner site showing minimum fetch distances.
and vegetation cover, freedom from vertical obstructions, accessibility, available power and security). A positive feature of this site was the fact that it had been previously used for extensive studies of the turbulent transfer mechanisms in the atmospheric boundary layer (e.g. McBean and Miyake, 1972).

The urban site.

The urban experimental site, chosen for this study was located in a mixed commercial and medium-rise residential district. Observations were conducted over the flat-top roof of a four-storey building (the Vancouver School Board Building) in the midtown area (Fig. 3). The minimum fetch to non-urban surfaces was approximately 1.5 km (N. to False Creek, and NW to English Bay). Otherwise the buildings within a 2 km radius of the site were fairly uniform in height, density and function (except in the easterly sector, where irregularities in the surface due to the different shape and heights of buildings were noticeable). Average building heights were ~ 10-13 m. Within a 2 km radius of the experimental site, buildings occupied ~ 70-80 per cent of each block, except near the periphery in the northeast and southerly sectors. Approximately 70 per cent of these
buildings consisted of medium-rise residential dwellings, primarily of flat-top roofs covered with gravel and tar. A site plan showing the location of the Vancouver School Board Building (VSB) and its immediate environs is shown in Fig. 7. A survey based on land uses within the 2 km circle gave estimates of impervious horizontal surface area of approximately 70 per cent. Closer to the actual site, the impervious land area was about 80 per cent. The area slopes gradually downwards from south to north, dropping approximately 50 m over the 4 km distance (i.e. slope ~ 1 in 80).

The influence of water surfaces to the north (mainly English Bay), could not always be avoided at the VSB site. Air flow sometimes occurred from this direction. Measurements conducted close to the VSB roof-top surface would not be affected by this influence. At greater heights, however, it was recognized that measurements would probably be affected by the contrasts in water/land temperatures and humidities. This necessitated consideration of the prevailing wind direction during observation periods.

A plan view of the roof-top surface of the VSB building is shown in Fig. 8. The roof materials consisted of tar with a covering layer of fine gravel which had a short-wave albedo of 0.21 and a long-wave emissivity of 0.92. The rest of the building was constructed of red brick and concrete. There were no major ventilation outlets at roof
Fig. 7. Site plan of the urban area (Vancouver School Board Building and its immediate environs).
1. LOCATION OF Rn, YST (20m) ON MAST, 20m ABOVE POSITION 4
2. G. ROOF (ON SUPER STRUCTURE)
3. LOCATION OF TAR AND CONCRETE SLABS
4. YST LOCATION FOR MEASUREMENTS AT 1.2, 2.0 AND 4.0m

Fig. 8. The Vancouver School Board Building. (Plan view)
level except for the incineration chimney on the superstructure. In general, daytime wind directions were predominantly from the north, west and southerly sectors. At night, there was a tendency sometimes for the development of easterly winds. The exact locations of the instruments on the roof are shown in Fig. 8.

During the observation programme of 1972, a survey of Vancouver's heat island was undertaken. It was found that the area of the experimental site was close to one of the cores of the heat island at night (see Fig. 9). Relatively small temperature gradients occur within the area. A few daytime surveys indicated even smaller horizontal temperature gradients. It must however be noted that contrasting areas in shadow and sunlight would be likely to produce localized temperature gradients. In our area, these could hardly be avoided. It will be assumed that these effects are small, on the basis that turbulent mixing of the air tends to produce uniformity in the temperature field.

Although this site possesses obvious limitations, it was considered acceptable for the study, based on the criteria specified previously.
Fig. 9. An example of the location of the heat island cores in Vancouver, B.C.
General Instrumentation and Experimental Procedures

The single most important instrument for this study was the yaw sphere-thermometer eddy correlation system to measure sensible heat flux directly. Since the development, calibration and testing of this apparatus forms an integral part of the research, it will be presented separately in the next chapter. Here attention is limited to other relevant instrumentation used in the course of the investigation.

Radiation.

Net radiometers (Swissteco Pty. Ltd., Model S1) were used to measure the net surface all-wave radiation. The radiation sensor consists of a cross-shaped thermopile constructed of copper-plated constantan wire. The thermopile surfaces are enclosed within a pair of molded polyethylene domes, 0.5 mm in thickness, which are transparent to radiation in the wavelengths between 0.3 μ and 100 μ. The domes were kept rigid and free of interior condensation by a controlled flow of dry nitrogen. A more practical way to keep the domes purged by means of dry air (Davies et al., 1970) was adopted during the measuring programme in 1972. The radiometer time constant was 23 s, and the thermopile sensitivity was approximately 0.39 mv/mWcm⁻² (calibrations
supplied by National Radiation Laboratory, Canada AES). Except where noted in the text, the outputs of the radiometers were recorded continuously on volt-time integrators (Lintronic, Ltd.), using a 30 min integration period.

In all studies concerned with the measurement of surface radiation fluxes, it is important that the radiation received by the sensor is representative of the surface under study. At the rural site, this was not difficult to achieve since the surface was relatively homogeneous, and net radiation was monitored at a conventional height of 1 m. At the urban site, correct location of the sensor is important for view factor considerations. To ensure a good horizontal field of view, the radiometer was mounted approximately 20 m above the principal roof-top surface on a fixed telescoping mast at the position shown in Fig. 8. A test of the height variability in the net radiant flux over the height range 11 to 20 m showed less than 5 per cent variation during the daytime. Horizontal variability of the urban net radiation field was not examined. Some variations are to be expected in measurements over a roof as opposed to those over a canyon (between building elements), particularly when shadow areas are extensive (e.g. Craig and Lowry, 1972). View factor considerations and the effect of the intervening air layer between the radiation sensor and the roof-top surface will be examined in Chapter 6.
Soil heat storage

Soil heat storage was measured using heat flux plates (Middleton and Co.). The heat flux plate consists of two metallic surface plates separated by a substance of known conductivity. A thermopile with alternate junctions in good thermal contact with one of the surface plates measures the temperature differential between the surfaces, and hence can be calibrated to provide the heat flux density.

At the rural location, three such plates (of approximately equal calibration: 0.28 mv/mWcm\(^{-2}\)) were connected in series and placed about 2.5 cm below the soil surface. This arrangement provided a larger signal for measurements, and gave a better spatial sampling. Soil flux divergence between the 2.5 cm depth and the surface was computed via the calorimetric (temperature integral) method (Fuchs and Tanner, 1968). This was found to be very small in magnitude and was subsequently neglected in this study. At the urban site, a heat flux plate was embedded in the gravel and tar roof, care being taken to ensure no exposure to solar radiation. The plate was located about 0.5 cm below the surface. The measured heat flux provided an estimate of the amount of heat passing into or out of the roof. Heat flux plates were also embedded in slabs of tar and concrete and placed on the VSB roof in order to
provide some understanding of the way in which other urban materials may differ from the roof value. No attempt was made to estimate the storage by the vertical walls of the building. Errors associated with the use of the flux plate in the roof will be discussed in Chapter 6.

The roof flux plate output signal was also recorded on a volt-time integrator, using a 30 min integration period. The plates in the slabs of tar and concrete were continuously monitored on a potentiometric recorder (Honeywell, Electronik 194).

Other instruments.

The following additional equipment was used:

1. For the field tests of the yaw sphere-thermometer system, comparison was made against the Bowen ratio/energy balance method. The Bowen ratio apparatus used is described in detail in the paper by Black and McNaughton (1971). It is a psychrometric apparatus design for Bowen ratio determination that measures the wet- and dry-bulb differences over a vertical distance of 0.6 or 1 m with an error less than 0.01°C. The temperature sensors consist of two matched pairs of 1N2356 germanium diodes. The germanium diode has a linear voltage-temperature characteristic and
large sensitivity of about 2.3 mv°C⁻¹. The time constant of the sensing heads is approximately 1 min. Accordingly, only data recorded for the last 10 min of each 15-min period is used in the Bowen ratio calculations. Half-hourly Bowen ratios are computed from the differences between voltage averages from two consecutive 10-min periods. The output signals were continuously monitored on a potentiometric recorder (Honeywell, Electronik 194).

2. Surface roughness characteristics at the Ladner site were determined from profile measurements with a six-level sensitive wind profile system (C.W. Thornthwaite Associates). Wind speeds were measured at 1.13, 2.00, 1.43, 1.73, 2.33 and 2.93 m above ground level.

3. Short-wave albedo measurements were occasionally monitored with dome solarimeters (Lintronic, Ltd.) (Monteith, 1959). These instruments consist of an eighty-junction thermopile, enclosed by a thin-walled frosted glass dome (transparent to radiation in the wavelength range 0.3μ to 3.3μ.

**Measurement Programme**

The observation programme was initially started in the late summer of 1970 in Montreal as a preliminary research
project. Climatological approaches to the determination of the urban sensible heat fluxes were investigated (Oke et al., 1972). The eddy correlation method appeared most likely to achieve success in the context of the city and accordingly was adopted. Only subsequent work is reported in this thesis.

The yaw sphere-thermometer system was constructed and calibrated in 1971. Later that summer the field comparison tests were conducted at the rural site in Ladner, B.C. During the following winter, a second YST system was constructed. The main field programme was carried out at Ladner and in Vancouver during the summer of 1972.

Observations were conducted under various weather conditions throughout this period and were only omitted during spells of wet weather. In general, during an observational sequence, continuous measurements were made throughout the day and in the city often throughout the night as well. In this manner, it was possible to investigate the diurnal behaviour of the energy fluxes under most weather conditions that typically occur in Vancouver during the summer. The normal sampling interval was set at 30 min for each system in evaluating the heat fluxes.
Chapter 3

THE YAW SPHERE-THERMOMETER SYSTEM

Introduction

The principle of the yaw sphere-thermometer system for direct measurements of sensible heat flux density was briefly mentioned in the first chapter. The sphere, when directed into the flow, generates a pressure difference between two ports that is proportional to the product of the horizontal and vertical winds. This pressure difference, converted to an analog signal and electrically filtered, is then used to drive a resistance-thermometer bridge. Integration of the output, divided by the mean horizontal wind speed yields $H$. Full details of the construction and theory of operation of the system are given in Tanner and Thurtell (1970) and our system closely followed their original design. Here, we shall be primarily concerned with four important aspects. Firstly, certain aerodynamic characteristics on the basis of wind tunnel experiments are investigated. Secondly, the effects of tilting the
sphere are analysed. Thirdly, the temperature sensor performance is evaluated for different configurations. Finally, the results of a field comparison between the YST system and a Bowen ratio apparatus are presented. We shall proceed first with a brief description of the instrument and a review of the yaw sphere-thermometer theory.

**Equipment Description**

The yaw sphere consists of two 1.59 mm diameter holes, drilled off-centre, through a 5-cm plastic sphere so that the included angle between the port holes and the centre of the sphere is 45°. A Gill propeller vane (R.M. Young Co.) was modified so that the sphere could be mounted in the position where the propeller is normally situated. Two 1.59 mm O.D. polyethylene tubes were brought through the stem and base of the vane housing and attached to a capacitive pressure transducer (Datametrics Inc., Model 511-8 Barocel). The pressure transducer was located below the vane housing in a thermally regulated box.

A schematic diagram of the recording system is shown in Fig. 10. The electrical analog of the pressure generated between the yaw sphere ports (ΔP) is obtained from the Barocel and its signal conditioner. It is then passed through an active hi-pass filter (approximately
Fig. 10 Schematic diagram of the recording system.
unity gain, and a time constant of 8 min) to provide the signal of \((\Delta P - \bar{\Delta P})\). This signal is used to drive the resistance-thermometer bridge so that the output becomes proportional to \(\Delta T(\Delta P - \bar{\Delta P})\), where \(\Delta T\) is the bridge imbalance. By periodically balancing the bridge, it is possible to prevent undue saturation of the output fluctuations in the next stages of the circuit. A differential amplifier is used to increase the output signal from the bridge. This is followed by a 5 sec low-pass filter to decrease transient response and dynamic range requirements before integration on a recorder with a ball and disc integrator (Honeywell, Electronik 194 and Disc Integrator). A nearby sensitive anemometer (C.W. Thornthwaite Associates) wind system is used to obtain the mean horizontal wind speed at the height of the sphere. A photograph of the complete yaw sphere-thermometer assembly is shown in Fig. 11.

**Review of the Yaw Sphere-Thermometer Theory**

In real fluid flow, the pressure distribution at points on a sphere can be written (after Martinot-Lagarde *et al.*, 1952)
Fig. 11. The yaw sphere-thermometer assembly.
\[ P = P_s + \left( \frac{\rho}{2} \right) V^2 \left[ 1 - b \sin^2 \psi \right] ; \quad \psi < 60^\circ \] (3.1)

where \( P_s \) is the static pressure, \( \rho \) the air density, \( V \) the air speed and \( \psi \) is the angle between \( W \) and the radius vector of the point. The 'sphere constant' \( b \) is to be determined experimentally. It is a function of the Reynolds number \( Re = \frac{Vd}{\nu} \) (\( d \), the diameter of the sphere and \( \nu \), the kinematic viscosity of the fluid) but is relatively constant for \( 2000 < Re < 200,000 \). In ideal, irrotational fluid flow, the theoretical value of \( b \) is 2.25.

On directing the sphere azimuthly into the wind, the components of the wind vector with respect to the \( x, z \) plane (formed by the yaw sphere ports and its bisector) are

\[ u = |W| \cos \alpha , \quad v = 0 \quad \text{and} \quad w = |W| \sin \alpha \]

where \( \alpha \) is the angle between the wind vector and the bisector of the ports. The pressure difference between the ports of the yaw sphere is then given by

\[ \Delta P = \rho b(\sin \theta)uw \] (3.2)
where \( \theta \) is the included angle between the ports. A schematic diagram to illustrate the angles \( \psi, \alpha \) and \( \theta \), and the wind vector \( \mathbf{W} \), is given in Fig. 12.

The pressure difference (\( \Delta P \)) is converted to an analog signal and passed through a high-pass filter which is subsequently used to drive a resistance-thermometer bridge. Amplification and integration of this bridge output, expressed in Reynolds' notation, gives

\[
\bar{E}_0 = \rho b (\sin \theta) GBM (\bar{u} \bar{w}'T' + \bar{w} \bar{u}'T' + \bar{u}'\bar{w}'T') \quad (3.3)
\]

where, \( G \) is the amplifier gain, \( B \) is the bridge constant and \( M \), the pressure transducer constant.

The nature of this output signal needs careful consideration. In equation (3.1) the moment \( \bar{u}'T' \) characterizes the turbulent heat flow in the direction of the mean wind velocity. One would expect this quantity to be negative for unstable, and positive for stable stratification (Monin and Yaglom, 1971). Direct measurements show that on the average, the ratio \( \bar{u}'T' / \bar{w}'T' \) grows with increasing stability (e.g. Zubkovskii and Tsvang, 1966; Wesely et al., 1970; Sheppard, see Monin and Yaglom, 1971) and indicates that \( |\bar{u}'T'| \) is larger than \( \bar{w}'T' \) over a range
Fig. 12. Schematic representation of the angles $\psi$, $\alpha$, $\theta$ and the wind vector $W$ on the yaw sphere.
of stability. However, since $\bar{w}$ is typically very small compared to $\bar{u}$, the term $\bar{w} \bar{u}'T'$ will be small compared to $\bar{u} \bar{w}'T'$, and will be assumed negligible. If we can assume the triple moment $\bar{u}'w'T'$ to be small when compared to the term $\bar{u} \bar{w}'T'$, then, as shown by Tanner and Thurtell (1970), the expression for $\bar{E}_0$ reduces to

$$\bar{E}_0 \approx \rho b(\sin \theta) GBM \bar{u} \bar{w}'T'$$  \hspace{1cm} (3.4)$$

and since the sensible heat flux can be written as

$$H = \rho C_p \bar{w}'T'$$

then

$$H \approx C_p \left[ b(\sin \theta) GBM \right]^{-1} \bar{E}_0 / \bar{u}$$  \hspace{1cm} (3.5)$$

Thus the sensible heat flux can be determined from the yaw sphere-thermometer system output if $\bar{u}$ is measured nearby at the same height. Kondo et al. (1970) suggest that measurements with cup anemometers overestimate the mean wind speed by about 4-7 per cent for the wind over land by day, and by about 1-3 per cent at night, but more recent work by Hyson (1972) shows the overestimation to be of the order of 1 per cent. Slight underestimation of
H may therefore be expected if $\bar{u}$ is measured with a cup anemometer.

A sample calculation of the sensible heat flux, with the appropriate constants involved, is given in Appendix A.

**Determination of the Sphere Constant**

The sphere constant was derived from data collected in a series of wind tunnel experiments with the yaw sphere. The sphere ports were aligned azimuthly into the direction of the mean flow thus allowing $\alpha$ (the angle of attack of the flow to the yaw sphere axis), to be measured directly. Equation (3.2) can be rewritten

$$b = 2 \frac{\Delta P}{\rho |V|^2 \sin 2\alpha \sin \theta}$$

(3.6)

For our sphere $\theta$, the included angle between the ports, was 45°. An electrical analog of the pressure difference between the yaw sphere ports ($\Delta P$) was monitored on a chart recorder. The parameters $\rho$ and $W$ were known for each wind tunnel experiment. Thus, knowing all the terms on the right hand side of equation (3.6) the sphere constant could be evaluated. Firstly, for a constant angle of attack
of the flow ($\alpha$), a series of measurements were made at various wind speeds ($V$) with $6000 < Re < 20,000$. Then the axis of the yaw sphere probe was tilted through a series of angles, $|\alpha| < 10^\circ$. Inherent limitations of the wind tunnel did not allow larger angles of attack, nor to calibrate the sphere for $Re < 6000$. The sphere constant was obtained from measurements in both laminar flow and in grid turbulence (produced by introducing a grid into a uniform flow). This grid allowed generation of a $9$ per cent turbulence level at the yaw sphere ports.

In the wind tunnel, the angle of attack ($\alpha$) was measured as that between the horizontal and the apparent axis of the yaw sphere probe (i.e. the sphere and its supporting stem). Any inherent misalignment in the yaw sphere axis and supporting stem would manifest itself as a constant error in the measurement of $\alpha$ in the wind tunnel. Let this tilt error be $\delta$. With the assumption that $2\delta$ is small

$$\sin(2\alpha + 2\delta) = \sin 2\alpha + 2\delta \cos 2\alpha$$

and equation (3.6) becomes
\[ b = 2 \Delta P / \left\{ \rho |W|^2 (\sin 2\alpha + 2\delta \cos 2\alpha) \sin \theta \right\} \]  \hspace{1cm} (3.7)

The above expression will be written

\[ \tan 2\alpha + 2\delta = 1/b \left\{ 2 \Delta P / (\rho |W|^2 \cos 2\alpha \sin \theta) \right\} \]  \hspace{1cm} (3.8)

so that a plot of \( \tan 2\alpha \) versus \( 2\Delta P / \rho |W|^2 \cos \alpha \sin \theta \) yields a slope of \( 1/b \), intercept values of \(-2\delta\) on the abscissa and \( 2b\delta \) on the ordinate. Fig. 13 represents such a graph for \( V = 4 \text{ m s}^{-1} \) and \( 6 \text{ m s}^{-1} \) in laminar flow. The sphere constant obtained was 1.57 with a tilt error of \( \approx 1^\circ \). This value for \( b \) is significantly less than the theoretical value of 2.25. Data from the 9 per cent turbulence level experiments yielded a \( b \) estimate within 6 per cent of the 1.57 value. Little emphasis is placed on this variation since the \( \Delta P \) trace on the chart recorder could not be resolved to better than \( \pm 10 \) per cent for the grid turbulence experiment. Fig. 13 also reveals the constancy of the \( b \) value for varying Reynolds number. In another series of experiments in the wind tunnel, the fast-response resistance thermometer (used with the yaw sphere to measure the sensible heat flux) was mounted at the side of the sphere in its usual position for field
Fig. 13. Graphical determination of the sphere constant \( b \) and alignment error \( \delta \). The equation of the line is:

\[
\tan 2\alpha = -2\delta + \frac{1}{b} \left( 2\Delta P/\rho |W|^2 \cos 2\alpha \sin \theta \right)
\]

The slope \( = 1/b = 0.638 \), therefore \( b = 1.57 \); the intercept \( = -2\delta = -0.023 \), therefore \( \delta = 0.0175 \text{rad} \approx 1^\circ \). Also since \( 2b\delta = 0.055 \) again \( b = 1.57 \).
measurements. This configuration had no noticeable effect on the pressure generated at the ports, or on the sphere constant. Accordingly, a value of $b = 1.57$ was chosen.

It is interesting to note that a value of $b = 1.79$ has recently been established for the original yaw sphere used by Tanner and Thurtell (Tanner, 1971, private communication). Values of $b$ less than 2.25 have also been reported by Martinot-Lagarde et al. (1952) and Wesely et al. (1972) for other spheres with different port-hole configurations. The reason for these lower values may be due to slippage of the flow around the smooth surface of the sphere. Thurtell (private communication, 1972) indicates that roughening the sphere surface gives a $b$ value closer to that predicted by theory.

While it was not possible to investigate the nature of $b$ below $Re = 6000$, we shall assume (after Martinot-Lagarde et al., 1952) that it behaves approximately constant down to $Re = 2000$. For our 5-cm yaw sphere this implies that the experimentally determined sphere constant should be used only when the mean wind speed is $> 60$ cm s$^{-1}$. In view of this, great caution must be used in interpreting results from the yaw sphere under very light wind conditions, for instance at night.
Effect of Yaw Sphere Axis Tilt

In section "Determination of the Sphere Constant," it was shown that any inherent misalignment in the yaw sphere axis could be determined from general considerations of the angle of attack of the flow incident on the sphere in a wind tunnel. Knowledge of this could then be applied in accurately aligning the axis of the sphere horizontally in field measurements. In practice, horizontal levelling of the yaw sphere axis may not always be assured. Consequently some estimate of likely error in sensible heat flux measurements due to a tilt off-axis (due to construction misalignment or inaccurate levelling in the field) is given here.

Let us assume that the sphere is tilted off-axis so that the tilt angle (δ) is positive (i.e. upwards, see Fig. 14). The components of the wind vector with respect to the \( x_T, z_T \) plane (formed by the ports and the tilt-axis) are

\[
\begin{align*}
    u_T &= (u \cos \delta - w \sin \delta), \\
    v_T &= 0 \\
    w_T &= (u \sin \delta + w \cos \delta)
\end{align*}
\]
Fig. 14. The effect of tilt on the geometry of the sphere.
If we assume $\delta$ to be small, then $u_T = (u - \delta w)$ and $w_T = (u \delta + w)$. Substituting these approximations of $u_T$ and $w_T$ for the $u$ and $w$ components in equation (3.1) yields

$$E_0(TILT) \approx \rho b(\sin \theta)GBM \left\{ (\overline{u} \overline{w}^\top + \overline{w} \overline{u}^\top + \overline{u} \overline{w'}^\top) + \right.$$

$$\left. \delta(2\overline{u} \overline{u'}^\top - 2\overline{w} \overline{w'}^\top + \overline{u'}^2 \overline{T'} - \overline{w'}^2 \overline{T'}) \right\}$$

(3.9)

Since $\overline{w}$ is typically very small when compared to $\overline{u}$, the above expression reduces to

$$E_0(TILT) \approx \rho b(\sin \theta)GBM(\overline{u} \overline{w}^\top + 2\delta \overline{u} \overline{u'}^\top)$$

(3.10)

if we assume the triple moment terms to be negligible. Then

$$E_0(TILT) = E_0 + E_{\delta 0},$$

where

$$E_{\delta 0} = \rho b(\sin \theta)GBM 2\delta \overline{u} \overline{u'}^\top$$
is the error caused by the tilt. This effectively produces an error in the heat flux

$$\delta H = C_p \left[ b(\sin \theta) GBM \right]^{-1} \frac{E_{\delta \theta}}{u' u} = \rho C_p 2 \delta \frac{u'T'}{\overline{u'T'}}$$  \hspace{1cm} (3.11)$$

For a small positive tilt off-axis the YST system will therefore produce a heat flux measurement

$$H_{(\text{tilt})} = H + \delta H = \rho C_p \left[ \overline{w'T'} + 2 \delta \overline{u'T'} \right]$$  \hspace{1cm} (3.12)$$

Thus, for $\delta = 1^\circ$, $H_{1^\circ} = \delta C_p \left[ \overline{w'T'} + 0.035 \overline{u'T'} \right]$. From previous studies concerning the dependence of $\overline{u'T'}/\overline{w'T'}$ on Richardson number, we note that the ratio increases from -1.4 in unstable to -3.2 in slightly stable conditions. Using these results, we can make some estimate of the error $\delta H$ under different stability conditions. During the daytime with moderately negative $Ri$, $- \overline{u'T'} = 1.4 \overline{w'T'}$ so that $H_{1^\circ}$ would then effectively include an error of $\sim$ 5 per cent. On the other hand, under night-time conditions with weak stability,
\[ u'T' \approx -3.2 \ w'T' \] in the limit. In this case \( H_{10} \) would include an error of ~ 11 per cent.

It can thus be seen, as an approximation, that the error caused by a 1° tilt off-axis in the yaw sphere would result in an error of ~ 5 per cent in the daytime, and that the error would grow with increasing stability to approach a value of ~ 11 per cent at night. Although large tilt errors (of the order of 5°) should not occur in practice, we shall consider such an effect on our system to help delineate the error magnitude at small angles of tilt. For a 5° off-axis tilt of the sphere, the error in measuring the sensible heat flux would be ~ 25 per cent in moderately unstable stratification. The above analysis again suggests that the YST system needs careful consideration if used at night, when light winds and stable stratification generally prevail. Large tilts in the yaw sphere axis would lead to considerable errors in the measurements of the sensible heat flux. With conventional leveling devices, it should be possible to minimize this off-axis tilt so that this source of error in the sensible heat flux measurements is within the range of general heat flux spatial variability.

Field measurements of the tilt effect on heat flux measurements with the Fluxatron (an eddy correlation
instrument) are reported in the recent paper of Dyer and Hicks (1972). An error of approximately 4 per cent per degree was found. It would seem from our analysis that the YST system is slightly more sensitive to levelling errors than the Fluxatron.

Thermometer System and Frequency Response

The fast-response thermometer was initially built following the design of Wesely et al. (1970). The thermometer element consisted of about 65 cm of platinum-coated tungsten wire with a diameter of 5.6μ. This wire was welded to its stainless steel side support with the aid of a Disa hot-wire anemometer welding assembly. A photograph of the resistance thermometer is shown in Fig. 15. The temperature coefficient of resistance of the temperature element was obtained from measurements of the thermometer resistance in a temperature-controlled oil bath over the range 15°C to 30°C. It was found to be 0.0033 ± 0.00005°C⁻¹.

Calculations by Wesely et al. (1970) indicate that for the resistance wire used in the thermometer, the time constant is approximately 1.5 millisec in "still air" and about 0.6 millisec in 10 m s⁻¹ winds. Up to a
Fig. 15. The resistance thermometer.
frequency of 20 Hz, reduction in amplitude should be less than 2 per cent and phase shift about $10^\circ$. Solar heating of the fine resistance wire was shown to be negligible for eddy flux calculations.

Under field conditions our thermometer responded well, but its durability was not always satisfactory. As a result, a slightly modified design was developed. The thermometer element and support terminals remained the same. The triangular frame however was eliminated by winding the element directly around the side supports which were covered with an insulating layer of epoxy resin. The rigidity of the thermometer was maintained by inserting two thin ceramic spacers (Fig. 16). Field tests of the two thermometer designs in two YST systems placed 2 m apart produced almost identical results (see Fig. 17) under a variety of wind and cloud conditions. The new design has proved to be more durable.

Frequency response and phase shift of the yaw sphere tubing and Barocel closely followed that reported by Tanner and Thurtell (1970, Fig. 18). The increase in length of tubing in our system resulted in slightly more attenuation. In the frequency domain the turbulent heat flux could be measured to an upper frequency limit of $\sim 8$ Hz without significant attenuation.
Fig. 16. The modified resistance thermometer.
Fig. 17. Comparison of the two yaw sphere-thermometer systems for sensible heat flux measurements (a) with original resistance thermometers (b) with modified resistance thermometer design in YST1.
LEGEND

- x RELATIVE AMPLITUDE
- • PHASE SHIFT

Fig. 18. Frequency response of the yaw sphere tubing and Barocel. Data points from this study; lines from results of Tanner and Thurtell (1970).
Field Tests Results

There is no standard to calibrate an instrument which measures sensible heat flux density. To gain confidence in the YST system however, we compared the measurements against independent evaluations of $H$ from a Bowen ratio apparatus.

The site used was the extensive grass surface at Ladner, B.C. The grass was dry, and the ground surface consisted of a dense old-grass litter layer. The instrument heights and mast locations ensured adequate fetch/height ratios from all wind directions except from the NNE-SSE sector. Winds were predominantly SW-NW during the test runs. The complete YST system was mounted approximately 1.5 m above ground level with the Bowen ratio apparatus mounted at the same height, and 4 m from the YST system. Net radiation and soil heat flux density were also recorded continuously during daylight hours for a period of four days.

The results of the comparison experiments are presented in Figs. 19 (a-c) and 20. Clearly, with the possible exception of August 24, 1971 (Fig. 19(a)), the agreement between the independent sensible heat flux measurements ($H_{YST}$ and $H_B$) is very promising. There are two possible explanations for the poor agreement on August 24.
Fig. 19 (a-c). Comparison of sensible heat flux densities from the yaw sphere-thermometer system ($H_{YST}$) and the Bowen ratio system ($H_B$) over grass at Ladner, B.C. for (a) August 24, (b) August 25 and (c) August 26, 1971.
Fig. 20. Comparison of $H_{YST}$ and $H_{B}$ at Ladner, B.C. on August 27, 1971. Net radiation (Rn) and soil heat flux density (G) are included.
Firstly, wind direction was variable on this day, and in addition flow from the E sector was not uncommon. Secondly, net radiation was very variable in the afternoon contributing to a non-steady state atmosphere. This makes it difficult to integrate the recorder trace and could lead to errors in Bowen ratio computations. In general, the energy partitioning resulted in $H \approx 0.5 \ R_n$ at noon on most days. The soil heat flux density was small, probably as a result of the insulating effect of the grass canopy and litter layer.

Table 2 gives the cumulative sensible heat flux densities for each day for each method, expressed as a ratio. Sampling periods have been adjusted to conform to those of the YST system. Except for August 24 the difference between the two methods is less than 10 per cent.

We may conclude that, in general, there is good and consistent diurnal agreement between the YST and Bowen ratio approaches to evaluating H. Dyer and Hicks (1972) indicate that H may show a 10 per cent spatial variability over uniform terrain, and this may account for a part of the differences between the H traces in Figs. 19(a-c) and 20. Other possible errors in the YST system include tilt error, overestimates of $\bar{u}$ by the cup anemometer, frequency response limitation and small zero drifts in the electronics. Similarly, the Bowen ratio method relies
upon the assumption of equality between the transfer coefficients for heat and water vapour.
Table 2

Comparison of daytime cumulative sensible heat flux densities from the yaw sphere-thermometer ($H_{YST}$) and Bowen ratio ($H_\beta$) systems

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration (min)</th>
<th>$H_{YST}/H_\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 August 1971</td>
<td>476</td>
<td>1.23</td>
</tr>
<tr>
<td>25 August 1971</td>
<td>458</td>
<td>0.99</td>
</tr>
<tr>
<td>26 August 1971</td>
<td>549</td>
<td>0.92</td>
</tr>
<tr>
<td>27 August 1971</td>
<td>582</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Chapter 4

SENSIBLE HEAT FLUX MEASUREMENTS OVER A RURAL SURFACE

Introduction

It was shown in the previous chapter that the promise of the yaw sphere-thermometer system appears to have been substantiated. As no standard exists against which our instrument can be calibrated, it was necessary to make comparative but independent evaluation of H. Good agreement was obtained between the measurements of sensible heat flux by this direct technique and the Bowen ratio/energy balance method. This relatively simple eddy correlation device enabled measurement of sensible heat fluxes close to the surface, and at the same time, to make real time analysis almost immediately in the field. The latter advantage needs little emphasis for most other direct measuring techniques require an extensive labour of data processing and computation. This problem has tended to limit the body of direct heat flux measurements which cover substantial time periods. The YST system overcomes this problem and hence permits the acquisition of significant lengths of heat flux data.
This chapter deals mainly with measurements made at the Ladner site during the months of June and early July 1972, and is confined primarily to a consideration of the following three aspects. Firstly, the diurnal behaviour of the sensible heat flux and other energy budget parameters is discussed. Secondly, a limited investigation of the spatial variability of $H$ and the problems associated with sampling in the time domain is presented. The success achieved with the initial YST system led to the construction of a second system with identical design features. The availability of two such instruments allowed examination of the spatial variability of the sensible heat flux in the atmospheric boundary layer. The fundamental premise in much micrometeorological research, that the fluxes of heat, water vapour and momentum are relatively constant in the horizontal and vertical within the atmospheric boundary layer, requires further testing. A limited investigation of the validity of assuming a 'constant flux layer' near the surface is presented here. Thirdly, extensive measurements of $H$ and other energy balance components, provided the necessary data to attempt an assessment of the energy partitioning between the sensible and latent heat fluxes. The value of using large-scale parameterization of heat fluxes (as advanced by Priestley and Taylor, 1972) was investigated.
Experimental Site and Procedures

During this period of observation, the grass surface was approximately 90 cm tall, as in the previous summer, and had a roughness length of approximately 10 cm. No attempt was made to measure soil wetness. Extensive rain throughout the previous winter and spring and as well, between days on which our measurements were made, ensured that the surface had ample moisture supply. The water table was only about 30 cm below the surface of the site.

Two YST systems (designated YST₁ and YST₂) were mounted 2 m above ground level with their sensitive cup anemometers at the same height about 1 m away. Net radiation at 1 m and soil heat flux density at a depth of 2.5 cm were continuously monitored nearby.

The frequent spells of rain throughout this observation period resulted in a discontinuous set of data involving twelve days of record. Continuous record lengths varied from three hours to 14 hours on a given day. Experiments were terminated at the onset of rain or dewfall since the YST instruments are unable to operate under such conditions without risk of damage. The basic averaging period used was 30 min, based on consideration of steady-state conditions. Problems associated with this choice of sampling interval will be examined.
Diurnal Behaviour of the Sensible Heat Flux

Some example results of direct measurements of the sensible heat flux, along with other measured energy fluxes, for various weather conditions are shown in Figs. 21-25. Heat fluxes from both YST systems are shown (these will be discussed in the next section). The illustrated examples consist only of observation days on which fairly long records of continuous measurements were obtained.

The diurnal changes in $H$ are clearly evident. By day, the sensible heat flux is directed away from the active surface, whereas at night a reverse flow is generally indicated. It is particularly significant to note the close relationship in the diurnal course of the heat flux with that of the net radiation. This is well exemplified on days when there are fluctuations in the net radiation field (i.e. on days when variable cloudiness occurred). A similar phase agreement has been found by Hanafusa (1971). While no attempt was made to quantify the phase difference through harmonic analysis, it is apparent that there is virtually no lag between $R_n$ and $H$ when averages are taken for half-hour intervals. Maxima and minima in the diurnal course of $R_n$ generally resulted in a corresponding behaviour of $H$. Under clear skies, the peak sensible heat flux is attained around noon. Thus, the sensible heat flux in the
Fig. 21. Diurnal variation of $H$ and comparison of the two YST systems.
Fig. 22. Diurnal variation of $H$ and comparison of the two YST systems.
Fig. 23. Diurnal variation of H and comparison of the two YST systems.
Fig. 24. Diurnal energy balance and spatial variation of $H$. 
Fig. 25. Diurnal energy balance and spatial variation of $H$. 

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LADNER, B.C.  
JULY 2, 1972  

$H_{YST_1}$  
$H_{YST_2}$  

HEIGHT : 2m  
HOR. SEPARATION : 19m
planetary boundary layer shows an immediate response to the change of net radiant energy supply at the surface.

Exceptions to this distinct phase relationship were noted on two days, one of which is shown in Fig. 22. After 1300 PST on June 21, 1972, the net radiation progressively decreased while the sensible heat flux remained consistently high for several hours. The maximum value of $H$ occurred a few hours after the radiation maximum. In addition, the sensible heat fluxes do not appear to decline as rapidly with the approach of sunset and the anticipated 'turnover' to a downward flux is clearly delayed. A similar trend was observed on June 30 (see Fig. 26), a day on which sunny skies prevailed. This observed feature was not evident in the measurements taken on the day preceding or following June 30 when similar weather conditions prevailed. The reason for these two exceptions is not clear. It is suggested that this behaviour was caused by advective influences from the runway as westerly winds prevailed on both occasions (Figs. 22 & 26). While much care was taken in our choice of measuring height for the YST systems to ensure suitable fetch from all wind directions, it may have been possible that the measurements at the 2 m height on these particular afternoons did not reflect the processes of the underlying surface.
Fig. 26. An example of large fluctuations in $H$ with 30 min averaging periods.
During a succession of days (July 1-5), clear skies persisted. The heat utilized to warm the air via sensible heat flux showed a progressive decrease from July 1 to July 5. One would have expected the opposite trend if drying out of the soil was occurring, but on the contrary, the surface seemed to have had ample supply of water. An examination of this behaviour will be discussed in the section "Parameterization of the Sensible Heat Flux and Evaporation."

It should be noted that the heat storage in the ground is unusually low during all these measurements. This was probably created by the tall grass cover and its insulating effect. In general, there existed a diurnal course of G. It did not however show close similarity to the Rn pattern on days with variable net radiant energy input. Under clear skies at noon, maximum values of G were only about 5 per cent of Rn.

Measurements of Spatial Variation of the Sensible Heat Flux

General aspects.

The basic assumption of much micrometeorological research is that H is relatively constant in the surface boundary layer over a homogeneous surface. The justification of this assumption can be seen from an analysis of the Reynolds equation for temperature. The development is given
in Mordukhovich and Tsvang (1966) and is briefly summarized below. The Reynolds equation for temperature may be written

\[
\frac{\partial \bar{\theta}}{\partial t} + \bar{u} \frac{\partial \bar{\theta}}{\partial x} + \bar{v} \frac{\partial \bar{\theta}}{\partial y} + \bar{w} \frac{\partial \bar{\theta}}{\partial z} = \frac{\partial \bar{R_n}}{\partial z} \frac{1}{\rho C_p}
\]  

(4.1)

where the notations are similar to those previously defined. On application of the equation of continuity and the assumption that \( \bar{v} = \bar{w} = 0 \), equation (4.1) can be expressed as follows

\[
\frac{\partial \bar{\theta}}{\partial t} + \bar{u} \frac{\partial \bar{\theta}}{\partial x} + \frac{\partial \bar{u'\theta'}}{\partial x} + \frac{\partial \bar{v'\theta'}}{\partial y} + \frac{\partial \bar{w'\theta'}}{\partial z} = \frac{\partial \bar{R_n}}{\partial z} \frac{1}{\rho C_p}
\]  

(4.2)

For steady-state conditions and in the absence of radiative flux divergence, the terms \( \frac{\partial \bar{\theta}}{\partial t} \), \( \frac{\partial \bar{R_n}}{\partial z} \) equal zero. Symmetry with respect to the average transport suggests that \( \frac{\partial \bar{v'\theta'}}{\partial y} \) should also be zero. A comparison of the remaining terms indicate that the primary cause of a change in \( H \) with height would be due to the advection term since \( \frac{\partial \bar{u'\theta'}}{\partial x} \ll \bar{u} \frac{\partial \bar{\theta}}{\partial x} \). Thus, in the absence of advection,
one would expect \( H \) to be relatively constant with height in the atmospheric boundary layer. In a similar way, only slight variation in \( H \) should be expected in the horizontal over an extensive homogeneous surface.

Experimental evidence to test this assumption has been gathered in recent years through direct measurements of \( H \) via the eddy correlation technique. The recent work of Dyer and Hicks (1972) indicates a variation in \( H \) of less than 10 per cent for vertical heights of 4-14 m, and horizontal separation of 1-150 m, over an extensive uniform plant surface. Their results are given in Table 3. This provides some validity for the traditional assumption of the constant flux layer. On the other hand, the earlier works of Mordukhovich and Tsvang (1966) and Businger et al. (1967) indicate large spatial variability in the heat fluxes of the order of a factor of 2. Measurements were made between the 1 and 4 m height by Mordukhovich and Tsvang while the results of Businger et al. were for a horizontal separation of 5 m. These results are most disturbing for they suggest that Eulerian point observations may yield questionable samples even over a uniform surface with adequate fetch. To explain their discrepancy, Businger et al. advanced the following postulation. The convective elements contributing to the heat flux may consist of horizontal
Table 3

Comparison of average fluxes

a. Comparison of average fluxes (H_{14}) at 14 m height with average fluxes (H_4) at 4 m height at Tsimlyansk, U.S.S.R. (c.f. Dyer and Hicks, 1972)

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration (min)</th>
<th>H_4/H_{14}</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 July 1970</td>
<td>300</td>
<td>0.92</td>
</tr>
<tr>
<td>17 July 1970</td>
<td>390</td>
<td>1.00</td>
</tr>
</tbody>
</table>

b. Comparison of average fluxes (H_1 and H_2) taken at a nominal height of 4 m at various cross-wind separations at Tsimlyansk, U.S.S.R. (c.f. Dyer and Hicks, 1972)

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration (min)</th>
<th>Separation (m)</th>
<th>H_2/H_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 June 1970</td>
<td>570</td>
<td>1</td>
<td>1.05</td>
</tr>
<tr>
<td>25 June 1970</td>
<td>313</td>
<td>1</td>
<td>0.98</td>
</tr>
<tr>
<td>12 July 1970</td>
<td>420</td>
<td>10</td>
<td>1.13</td>
</tr>
<tr>
<td>14 July 1970</td>
<td>360</td>
<td>10</td>
<td>0.94</td>
</tr>
<tr>
<td>3 July 1970</td>
<td>622</td>
<td>30</td>
<td>1.03</td>
</tr>
<tr>
<td>5 July 1970</td>
<td>513</td>
<td>30</td>
<td>1.12</td>
</tr>
<tr>
<td>29 June 1970</td>
<td>207</td>
<td>60</td>
<td>1.08</td>
</tr>
<tr>
<td>9 July 1970</td>
<td>268</td>
<td>60</td>
<td>1.14</td>
</tr>
<tr>
<td>18 July 1970</td>
<td>470</td>
<td>150</td>
<td>1.07</td>
</tr>
</tbody>
</table>
rolls with their length axis in the direction of the mean wind. These rolls rotate slowly in opposite direction, thereby creating zones of convergence and divergence. Measurements in two contrasting zones, even over considerable time periods, would thus yield the noted variation in H. Evidence of the organized behaviour of these convective elements has recently been reported by Davison and Miyake (1972) for heights greater than 50 m.

It is apparent that much research remains around this fundamental hypothesis. The measurements reported here, though limited in scope, should contribute to the small body of pertinent data that presently exists.

**Spatial variability experiments.**

In order to preserve an adequate height/fetch ratio at the Ladner site, no attempt was made to examine the vertical variation of heat flux. Only measurements above the ground, at heights of 2 m or less could ensure suitable fetch from all wind directions. While it might have been possible to investigate variation of H between the 1 and 2 m heights, the frequency response of the YST system did not favour such measurements. Accordingly, only the horizontal variation of the sensible heat flux at a fixed height of
2 m above the ground was investigated. Comparison of the two YST systems were first made for a horizontal crosswind separation of 1.5 m. The two instruments were then placed 19 m apart to investigate the spatial variation.

The 1.5 m separation provided a basic comparison between the two instruments. The small separation between instruments was to ensure that sampling occurred in the same air stream. The close agreement between heat fluxes obtained from the two instruments can be seen in Figs. 21-23. Only a few per cent variation can be noted. In general, slightly higher values were obtained with the YST₂ instrument. This difference appears to be systematic and may have been caused by slight differences in calibration constants which were not taken into account. The difference is however small enough to be considered insignificant.

Cumulative sensible heat fluxes for each instrument, expressed as a ratio, for the 1.5 m horizontal crosswind separation are given in Table 4. Sampling periods have been adjusted to only those for which comparison is possible. The difference is generally less than 5 per cent in the heat flux measurements for the two instruments. Indirectly, this result also suggests small spatial variability.

For the 19 m crosswind separation, relatively good agreement was found in the H measurements (Figs. 24-26).
Table 4

Comparison of cumulative sensible heat flux densities from the yaw sphere-thermometer systems ($H_{YST_1}$ and $H_{YST_2}$) at 2 m above ground for an horizontal crosswind separation of 1.5 m

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration (min)</th>
<th>$H_{YST_1}/H_{YST_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 June 1972</td>
<td>593</td>
<td>0.97</td>
</tr>
<tr>
<td>16 June 1972</td>
<td>170</td>
<td>1.09</td>
</tr>
<tr>
<td>21 June 1972</td>
<td>712</td>
<td>1.01</td>
</tr>
<tr>
<td>22 June 1972</td>
<td>274</td>
<td>0.99</td>
</tr>
<tr>
<td>24 June 1972</td>
<td>704</td>
<td>0.96</td>
</tr>
<tr>
<td>29 June 1972</td>
<td>114</td>
<td>0.99</td>
</tr>
</tbody>
</table>
At this large separation distance, the two YST systems could be possibly sampling in different airstreams. The degree of flux variation is more pronounced than at the 1.5 m separation. This is also evident from the cumulative sensible heat fluxes, expressed as a ratio, given in Table 5. The horizontal variability is less than 20 per cent and is consistent with the hypothesis of the relative constancy of the heat fluxes in the surface boundary layer. These results tend to suggest that representative heat fluxes may be achieved by Eulerian point sampling to within twenty per cent.

On a few occasions, short-term time variation (less than 30 min) in the heat flux measurements was noted. This was particularly evident on June 30 (Fig. 26). The cause of these large fluctuations in H are clearly not related to the changes in the net radiation field. Rather, it may be associated with the choice of an adequate sampling interval. The use of one-hour sampling intervals would have eliminated these short term fluctuations. Smoothing of the data cannot however be easily justified since these fluctuations may contain physical significance. On this particular day, the measured H fluctuations occurred at the two sites 19 m apart. Afternoon, the course of H at the two sites is out of phase, although the cumulative heat fluxes for that period remain approximately equal at the two locations.
Table 5

Comparison of cumulative sensible heat flux densities from the yaw sphere-thermometer systems (H\textsubscript{YST\textsubscript{1}} and H\textsubscript{YST\textsubscript{2}}) at 2 m above ground for an horizontal crosswind separation of 19 m

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration (min)</th>
<th>H\textsubscript{YST\textsubscript{1}}/H\textsubscript{YST\textsubscript{2}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 June 1972</td>
<td>60</td>
<td>0.98</td>
</tr>
<tr>
<td>30 June 1972</td>
<td>450</td>
<td>0.94</td>
</tr>
<tr>
<td>1 July 1972</td>
<td>728</td>
<td>0.94</td>
</tr>
<tr>
<td>2 July 1972</td>
<td>728</td>
<td>0.85</td>
</tr>
<tr>
<td>3 July 1972</td>
<td>331</td>
<td>0.83</td>
</tr>
</tbody>
</table>
Thus, in a statistical sense, there is little spatial variability for a long-term average. The existence of convective rolls could also explain these short-term fluctuations.

Parameterization of the Sensible Heat Flux and Evaporation

In investigating the partitioning of energy between the sensible heat flux and evaporation, the general framework suggested by Priestley and Taylor (1972) has been employed. The data is analyzed in terms of the quantity $\alpha$, defined by

$$\alpha = \frac{LE}{\frac{S}{S+\gamma} (H+LE)} = \frac{LE}{\frac{S}{S+\gamma} (Rn-G)}$$

(4.3)

where $\gamma$ the psychrometric constant

$s$ defined as $\partial q_s/\partial T$ at the appropriate temperature.

The parameter $\alpha$ provides some measure of the aridity of the surface. A priori, one would expect it to be smaller for unsaturated surfaces than for saturated surfaces.

The diurnal behaviour of $\alpha$ at the Ladner site was examined using data for late August 1971 and June 1972. The period in August was preceded by two months of fairly dry weather, whilst in June the area had been under the
influence of wet weather conditions for some time. Examples for August 26, 1971 and June 24, 1972 are shown in Fig. 27. The values of LE in equation 4.3 were obtained as residuals from the energy balance equation since the fluxes Rn, H and G were known. It can be seen from the graph that \( \alpha \) was lower in the late summer of 1971 than at the start of the summer of 1972. Estimates of \( \alpha \) for the days shown gave a mean value of 0.73 on August 26, 1971 and 1.09 on June 24, 1972 for the period 1000-1600 PST. The spread of these values may be expected to reflect the nature of the soil-plant system water availability. Data from a number of saturated land and open water sites were examined by Priestley and Taylor (1972). From these data, the best estimate of \( \alpha \) was found to be 1.26. If we may use \( \alpha = 1.26 \) for saturated surfaces (as obtained by Priestley and Taylor from mean daily quantities), aridity indexes may be computed for these two days. The aridity index (the ratio of the alpha for non-saturated to that for a saturated surface) would be 0.58 for August 26, 1971 and 0.87 for June 24, 1972.

The usefulness of the parameter \( \alpha \) in a climatological sense appears most encouraging. It may prove appropriate in a classification scheme for various climates when determined on a monthly basis.
\[ \alpha = \frac{LE}{(S/S + \gamma)(Rn - G)} \]

Fig. 27. Diurnal variation of \( \alpha \) (examples of early and late summer observations).
It can be seen from equation 4.3 that $\alpha$ is related to the Bowen ratio through the following equation

\[ \beta + 1 = \frac{1}{\alpha} \left( 1 + \frac{\gamma}{s} \right) ; \quad \beta = \frac{H}{LE} \]  

(4.4)

It is thus possible to examine the partitioning of the sensible and latent heat fluxes through the above expression. For a saturated surface, $\alpha$ being approximately constant, one would expect $\beta$ to show a dependence on surface temperature. The predicted partitioning of energy between $H$ and $LE$ as a function of temperature is shown in Fig. 28 (using $\alpha = 1.26$ in equation 4.4). Curves for a constant $\alpha$ of 1.10 and 1.00 are also shown. Using the energy balance measurements for Ladner, approximate Bowen ratios were computed for all observation days during June and early July 1972. These data are plotted against mean daily screen-level air temperature for the corresponding days in Fig. 28. (It should be noted that our values are only approximate since the length of the heat flux records do not provide 24 hour totals. Accordingly the temperature record has been adjusted to consider only the periods of flux measurements.)

With the exception of two points, the $\beta$ data clearly show a temperature dependence similar to that of a
Fig. 28. Ratio of H/LE vs. temperature.
saturated surface with an alpha value between approximately 1.00 and 1.10. The two anomalous data points are for the days discussed in the section on "Diurnal Behaviour of the Sensible Heat Flux," when the diurnal behaviour of H did not reflect the net radiation pattern. The exceptions on Fig. 28 are therefore possibly also due to advective influences. These results indicate that the partitioning of H and LE during the observation period at the Ladner site was strongly related to temperature. It is to be expected that this relationship would not continue through the summer when moisture is not as freely available for evapotranspiration.
Chapter 5

SENSIBLE HEAT FLUXES OVER AN URBAN AREA

Introduction

The results of direct measurements of urban sensible heat fluxes have not been previously reported. This has largely been due to the need for complex instrumentation to determine this eddy flux and, in addition, the highly irregular urban surface imposes severe limitation on any instrumental technique. As a result, there is very little experimental evidence to verify or refute the commonly held assumptions on the nature of the sensible heat flux in an urban area. The magnitude and behaviour of this energy component has remained largely speculative.

The success and confidence derived from the YST eddy correlation system over the relatively simple grass surface, suggested its use over the city surface to investigate the behaviour of the sensible heat flux. Therefore, such measurements were conducted over a limited portion of the urban area in Vancouver, B.C. It must be emphasized that the scope of this study is very limited. Spatial
sampling, both horizontally and vertically, is confined to a limited urban building-air volume.

Due to practical limitations, measurements were only attempted above an individual building roof. The choice of measuring at roof-top level and above, rather than between the building elements, was governed primarily by instrumental considerations. The successful implementation of the eddy correlation technique, employing Eulerian point measurements of heat fluxes, requires sufficient spatial homogeneity in the meteorological fields to ensure negligibly small mean vertical air movement. Within the canyon (between building elements) this requirement would be unlikely to be satisfied. Hence it would be necessary to devise a means of spatially integrating the fluxes in the horizontal to achieve truly meaningful results. Above the building elements, however, the possibility of success with this technique is enhanced, particularly if the urban area under study possesses a degree of building continuity (uniformity of type, height, density and function). Convergence or divergence in the mean air motion would then tend to be minimized above roof-top level. It may then be possible to make reasonable estimates of the sensible heat flux from point measurements that are of more general applicability for the study area. A description of our urban experimental site was given in Chapter 2. The extent to which the surrounding area possesses
the desired building continuity will undoubtedly affect the
degree of generalization that is possible from our measure-
ments.

**Boundary Layer Considerations**

In the presence of an abrupt change in surface
roughness, the development of a boundary layer can be antici-
pated. As the air flows downstream from this change, three
regions in the boundary layer flow can be envisaged (Fig.
29(a)). Region I consists of the upstream flow, and also
forms the downstream flow above the boundary layer of the
new surface condition. Region II is the internal layer
where the flow has responded and is adjusting to the new
surface. This merges further downstream into Region III,
the asymptotic self-preserving state of the new surface.
Experimental evidence based on wind tunnel work by Luxton
(1970) suggests that the growth of the internal boundary
layer following an abrupt change in roughness, where the
new surface consists of elements that stand proud from the
surface, c.f. Fig. 29(b), may be dominated by the wake from
the leading roughness element. It may be useful to use this
case as an analogy when considering the air flow from the
country to the city and the subsequent development of an
Fig. 29. (a) Boundary layer development over an abrupt change in surface roughness.

(b) Boundary layer development following a change from smooth to a rough surface where the roughness elements are above the surface.
internal urban boundary layer. Furthermore, we shall make
the common assumption that any boundary layer growth
associated with the individual building elements in the
urban area will be strictly localized.

Since the investigation of the urban sensible
heat fluxes was confined to measurements above the roof of
an individual building in the city, careful consideration
to the type of flow pattern around the building is necessary.
A schematic representation of the typical wind flow pattern
around a building is shown in Fig. 30 (c.f. Halitsky, 1962).
While the situation in the atmosphere is more complex, and
particularly so in the urban context, this flow visualiza­
tion around a building in an ideal fluid situation does
provide some insight into the nature of the problem that is
likely to occur in the case of measurements made above
the roof of a building. For example, we might expect dis­
similarities in the measurements close to the roof surface
(within the turbulent zone) as compared with those made
above the surface of separation. For this study, it will
be assumed that measurements of sensible heat fluxes above
the local boundary of the roof are representative of areal
urban heat fluxes, while those conducted in the turbulent
zone reflect to a large extent values associated with the
roof-top itself. Thus, at heights above the surface of
separation, the assumption is made that local inhomogeneities
Fig. 30. Schematic of the local boundary above a building for a constant angle of attack of the wind flow.
in the sensible heat fluxes become insignificant in comparison with the meso-scale urban fluxes. The existence of a return flow (as shown in Fig. 30) might be expected to complicate the measurements near the surface. Munn (1966) indicated that the fluxes of heat, momentum and water vapour in this turbulent zone of the roof had not been studied in detail. The present work should therefore help elucidate the behaviour of $H$ in this zone.

The principal levels, at which heat flux measurements were conducted, were 1.2, 4.0 and 20 m above the roof-top surface. Measurements at the 1.2 m level were probably within the local boundary layer of the roof, while those at 4.0 m appeared to be above the surface of separation. This classification is based on the fact that the wind direction at the 1.2 m level was quite variable, whereas those at 4.0 m appeared generally more constant, and consistent with the wind direction recorded at 20 m above the roof surface. Variations in the height of the boundary layer above the roof seem to have affected the 4.0 m level measurements occasionally and were probably caused by the change in angle of attack of the wind flow to the building. In general, however, the sensible heat flux measurements at 4.0 m and above, may be considered a reflection of values above the roof-top turbulent zone.
In presenting these results, we shall limit our attention in this chapter primarily to aspects of sampling considerations, the diurnal behaviour and the spatial variability of $H$ at this urban site. Discussions in terms of the energy balance framework will be limited since it will be treated more extensively in the following chapter.

Mean Vertical Velocity Considerations

The complex nature of the atmosphere-urban interface presents a serious difficulty in obtaining an experimental site above which the vertical convergence or divergence in the mean air motion is very small. It may be possible, however, through careful site selection, to minimize this effect appreciably so that sensible heat flux measurements by the eddy correlation technique can be employed successfully. For our urban site, investigation of the $\bar{w}$ field was only of an exploratory nature. No suitable means of accurately measuring the mean vertical air movement was available. Some attempts, however, were made to determine $\bar{w}$ with a vertical Gill anemometer at various positions and heights above the roof-surface. Near the surface, typical values of $\bar{w}$ (30 min averages) were within $\pm 10 \text{ cm s}^{-1}$. Little confidence could be placed
on these magnitudes as they were within the resolution capability of the instrument and the precision to which \( \bar{w} \) could be measured. In general, small negative values of \( \bar{w} \) (downdraft situation) were found near the surface, whereas at 20 m, a tendency for positive values (updraft situation) seemed to prevail. While uncertainties in the measurements preclude any definitive statement on the nature of the \( \bar{w} \) field above the roof surface, the relatively small values measured may permit us to assume that \( \bar{w} \) (averaged over a sufficient time period) is generally insignificant.

**Sampling Considerations**

The optimum averaging period for sensible heat flux measurements was investigated by Chou (1966). For sampling intervals greater than 20 min, he found stable average values of \( H \) were achieved in the lowest 10 m of the atmosphere. This was based on extensive measurements conducted over a uniform rural surface under different stability conditions. Based on these results, 30 min sampling interval was adopted for heat flux measurements at the rural experimental site. In general, this choice appears to have been adequate. A few exceptions were noted where a longer averaging period might have been more appropriate, as discussed in Chapter 4. The suitability of applying the
same sampling interval to the $H$ measurements over the urban surface requires careful consideration.

Short period oscillations in the heat flux field are directly related to the scales of turbulence over the spatial domain. To avoid these statistical fluctuations, it is necessary to use a suitable sampling interval. This is governed by the cospectrum of $H$ over the frequency domain.

\[ H = \rho C_p \int_{n_L}^{n_H} \phi_{wT}(n) \, dn \]  \hspace{1cm} (5.1)

where

- $\rho$ air density
- $C_p$ specific heat of air at constant pressure
- $\phi_{wT}$ cospectrum between the vertical velocity ($w$) and the air temperature ($T$)
- $n$ frequency (subscripts $L$ and $H$ refer to the lower and upper limits of $n$, respectively)

The limits of the integral should contain all frequencies that contribute to the heat flux. In practice the lower limit of the integral is determined by a sampling period sufficiently long to contain the important low frequency contributions to the flux. The work of Businger et al. (1967) over grass shows significant contributions to the
flux in the cospectrum of \( w \) and \( T \) \( (\Phi_{wT}) \) down to 0.003 Hz. Accordingly, the choice of a 30 min sampling period for our rural heat flux measurements is further supported. In contrast, there is no experimental evidence available to suggest the significant frequency domain for urban sensible heat fluxes. However, the recent work of Steenbergen (1971) suggests a shift of energy in the vertical velocity spectrum towards longer wavelengths (i.e. lower frequencies) close to the surface in the city, as compared to the country. This shift may be ascribed to mechanical turbulence. The temperature spectrum over the city is not known, but it would seem reasonable to expect a shift in the heat flux cospectrum toward lower frequencies in the city. Consequently, the need for longer sampling intervals to achieve stable urban sensible heat flux values may be anticipated (i.e. longer than 30 min).

As sensible heat flux measurements were monitored continuously (except for periodic interruptions for instrumentation checks), heat flux values for various averaging periods could be obtained by subdividing the record appropriately. Two examples of urban heat flux variations, 4.0 m above the roof, using both half-hour and one hour averaging periods, are shown in Figs. 31 and 32. (The corresponding net radiation field at 20 m above the roof is also indicated on these graphs (n.b. all net radiation measurements in the
Fig. 31. Urban sensible heat fluxes for half-hour and one hour averaging periods.
Fig. 32. Urban sensible heat fluxes for half-hour and one hour averaging periods.
city will refer to this level). The use of half-hour averages shows considerable fluctuations in the diurnal course of H that are clearly not related to time changes in the net radiation field. It may therefore not be unreasonable to suggest that they are primarily a manifestation of the scales of turbulence over the spatial domain that are generated by the urban surfaces. These oscillations can be avoided by the use of a longer averaging interval. By the use of one hour heat flux averages, the fluctuations are smoothed out and the resultant heat flux field can then be seen to be a more direct response to the time changes in the net radiation pattern. Thus, if we can assume that the low frequency contributions to the heat flux in the city are appreciable, the oscillations may simply arise from the choice of sampling interval. Furthermore, in order to achieve stable H values and to contain all frequencies that contribute to the heat flux, an averaging period longer than half-hour should be adopted.

Closer to the roof-top surface, within the turbulent zone, the application of a one hour sampling interval was not always satisfactory. Large oscillations seem to occur, especially around mid-day, that were not associated with changes in the net radiation field and that could not be eliminated by one hour averages. These could have been the result of inhomogeneities in the meteorological field,
created partly by return flow unto the roof from neighbouring street canyons, that affect the Eulerian point measurements. Fig. 33 illustrates this feature using heat flux variations at the 1.2 m level. Between 1000 and 1400 PST, we note that two hour averaging intervals would smooth the fluctuations and produce a diurnal behaviour in $H$ that is more consistent with the net radiation changes. There is, however, some danger in using such long sampling intervals as non-steady state conditions are like to occur.

While the above examples seem to suggest the need for sampling intervals beyond 30 min, there were occasions when the use of 30 min averages appeared to be adequate. This occurred consistently under conditions of low net radiation input. The heat flux values were stable and corresponded to changes in the radiation pattern. An example is shown in Fig. 34. Thus, with a reduction in thermal convection, the apparent low frequency contribution to the city becomes less important.

The results presented above indicate the difficulties encountered in determining suitable averaging periods for urban heat flux measurements. The important scales of turbulence over the spatial domain for city surfaces are probably quite variable and are undoubtedly controlled by the complex nature of the roughness and thermal properties of the underlying surface. As a result, the use of a fixed
Fig. 33. Urban sensible heat fluxes for half hour, one hour and two hour averaging periods.
Fig. 34. Urban sensible heat fluxes for half-hour averaging periods.
averaging period is often unsatisfactory. For the purposes of this study, a sampling period between one-half hour and one hour is adopted for all subsequent discussions of the urban heat flux, unless otherwise noted.

**Diurnal Urban Sensible Heat Flux Pattern**

From the continuous series of urban H measurements, an assessment of the diurnal pattern can be made. Some of the characteristic features are indicated in Figs. 31-34. During the daytime, the fluxes are directed away from the urban surface. Peak values of H are attained around noon under clear skies when net radiation values reach a maximum. In addition, these examples exhibit a diurnal course that closely parallels the time changes in the net radiation field. In general, these features were consistent on all observation days and for the measurements at 1.2, 4.0 and 20 m above the roof. The actual magnitude of the sensible heat fluxes show a decrease with height (from 1.2 to 4.0 m). This is not surprising since we might anticipate that measurements conducted within the turbulent zone of the roof primarily reflect the roof-top surface conditions whereas those at 4.0 m are a manifestation of a spatially averaged heat flux of the roof and surrounding areas which should include a larger proportion of evaporating surfaces.
On many afternoons and evenings, the urban sensible heat values remained consistently high for several hours. This was found in the measurements at all observation heights. A few examples are given in Figs. 35-37. The cause of this behaviour is not known, but the following explanation is postulated. During a great portion of the daytime, appreciable amounts of heat are stored within the city's fabric. This source of energy is then expected to become available for release to the air at night. Heat releases from the urban structures, however, are likely to occur somewhat earlier than sunset since the geometrical configuration of building arrays is conducive to the generation of extensive shadow areas when the sun is at low zenith angles (extensive shadow areas in the early morning would presumably cause a retardation in the sensible heat flow to warm the urban air). An example of this behaviour can be seen in Fig. 38, for a tar slab on the urban roof. Around 1600 PST, the slab was influenced by the shadow cast by the superstructure on the roof. Shortly thereafter, the heat flux \((G)\) in the slab reversed its direction of flow. There occurred a large flow of heat out of the tar slab into the air. In contrast, the point measurements of \(G\) in the unshaded roof-top itself showed a flow inwards throughout this period. This type of behaviour (created by shadow areas) can be expected to enhance the urban sensible heat
Fig. 35. Diurnal variation of the urban sensible heat flux at 1.2 m above roof.
Fig. 36. Diurnal variation of the urban sensible heat flux at 1.2 m above roof.
Fig. 37. Diurnal variation of the urban sensible heat flux at 20 m above roof.
Fig. 38. Effect of shadow on the diurnal behaviour of urban roof heat storage.
fluxes by drawing upon storage. Thus, while the gain of net radiation progressively decreases with the approach of sunset, a relative enhancement of sensible heat flow may develop. This would favour the slow decline in $H$ towards sunset as has been noted on many occasions. While this explanation may be applicable to conditions above the boundary layer of the roof, it would seem less satisfying for conditions within the turbulent zone. Perhaps heat releases from urban structures towards sunset into the neighbouring street canyons are coupled with the return flow onto the roof to provide the necessary enhancement of $H$ as we have observed in the measurements at the 1.2 m level. It is interesting to note that the start of rapid growth of the urban heat island, $\Delta T$ (urban-rural) is observed to occur during the period near sunset (Oke and East, 1971; Hage, 1971; and Oke et al., 1972).

Night-time values of $H$ are also shown in Figs. 35-37. While there is less confidence in the absolute magnitudes of the nocturnal values, the observed pattern appears consistent and is most interesting. Near the roof surface (1.2 m), there is consistently a flow of heat away from the surface at night. At 4.0 m, the nocturnal values are more variable giving flows towards, and away from the surface during the same night. The few nocturnal measurements at 20 m show a similar pattern to that observed at
the 4 m level (Fig. 37). The apparent lack of reversal of sensible heat flow near the surface in the city at night (as compared to a rural site) must therefore be considered as one of the source terms for the observed heat island.

The few sensible heat flux measurements at 20 m above the roof were generally smaller in magnitude than those found at the 4 m level, both by day and by night. This apparent divergence in the heat flux above the boundary layer of the roof seems to suggest that either advective influences are important or else convergence will have warmed the air layer. This however does not preclude the existence of a constant flux layer above the roof-top boundary layer since inadequate fetch/height ratio may have affected the measurements at 20 m, particularly during the daytime with the prevailing wind from the northwest. It was mentioned earlier that the minimum fetch is approximately 1.5 km from non-urban surfaces (water bodies) for this experimental site. This occurs for winds from the northwest. As a result, the principal boundary layer development over the area studied during the daytime may be relatively shallow. The measurements at 20 m may thus be only partially representative of the underlying conditions. Unfortunately, we do not have any H data for intermediate levels between 4 and 20 m to confirm or refute the constancy of flux in the internal boundary layer of the city.
Another interesting example of the behaviour of urban sensible heat fluxes is shown in Fig. 39. Fig. 39(a) shows the diurnal course of $H$ on July 7, 1972 for dry conditions. The values of $G$ shown are those obtained for the roof-top surface. For the discussion to follow, we shall assume that the residual (obtained as the residual of the vertical heat balance expression, equation 1.2) may be approximately equated to the latent heat flux. Following this observation day, there was a period of heavy rain which ceased on July 12. The results for July 13 (Fig. 39(b)), when roof-top areas were saturated show a remarkable drop in the sensible heat flux, which suggests that most of the available energy was utilized for evaporation. In the days following, there was a period of dry weather conditions. The sensible heat flux showed a progressive increase so that by July 17 (Fig. 39(c)), it had regained values similar to those observed prior to the rainfall. The residual term, however, was still appreciable, the implications of which will be discussed in the next chapter in the context of urban energy balance. It is interesting, however, to note that significant amounts of rainfall are intercepted by flat-top roof surfaces during wet spells. An appreciable quantity does not run off but remains as puddles on the surface, or is absorbed in the uppermost layer of the roof. This water then becomes available for
Fig. 39. Urban energy balances (a) July 7, 1972 with dry conditions; (b) July 13, 1972 following wet period.
Fig. 39. Urban energy balance (c) July 17, 1972, 5 days after wet period.
evaporation into the urban atmosphere. Under such conditions, energy utilization to warm the urban air via sensible heat transfer is clearly retarded at the expense of latent heat transfer.

This brief study of the diurnal pattern of urban H values indicates that the eddy correlation technique can be used with relative success in the urban context, and that a number of uniquely urban features are evident.

**Spatial Sampling**

A limited study of the spatial variability of the sensible heat fluxes over a uniform grass surface was presented in Chapter 4. The results supported the basic assumption of a constant flux layer, assuming less than 20 per cent variability to be acceptable. The applicability of this premise in the context of the city is very questionable since the mosaic of urban structures may induce advective influences that result in the formation of a non-constant flux layer. Where there exists a measure of building continuity, some uniformity in the meteorological fields can be anticipated. Accordingly, small spatial variability in the H measurements above local roof-top boundary layers may be taken to reflect the extent to which the urban area studied possesses building continuity.
(outlined in the first section). Here, we assume that the measurements are made within a larger scale urban boundary layer (i.e. free of non-urban influences).

Although it was not possible to study large scale areal variations, a limited study of the spatial variability of H in the immediate vicinity of the roof-top surface was conducted. As a parallel, we might expect that spatial measurements conducted simultaneously within the turbulent zone of the roof should yield consistency if the flow is primarily responding to the underlying surface. Measurements beneath and above the surface of separation over the roof would not be expected to show this consistency.

Simultaneous measurements during the daytime with two YST systems were made for vertical separations of 0.8 m (between 1.2 and 2.0 m), of 2.8 m (between 1.2 and 4.0 m) and for horizontal separations of 2.5 and 7.0 m, at a vertical height of ~1.5 m. Only measurements at the 4.0 m level can be expected to be above the local roof-top boundary layer. Examples of H measurements ~1.5 m above the roof for a horizontal separation between the two YST systems of 2.5 m are shown in Fig. 40(a). The diurnal behaviour of the two H values exhibits close similarity with this small separation distance. There is, however, some variability in the individual one hour averages of H from the two instruments. Cumulative totals of the heat
Fig. 40. Horizontal spatial variation of the urban sensible heat fluxes.
fluxes from both instruments, expressed as a ratio \( \frac{H_{YST_1}}{H_{YST_2}} \) indicate ~ 20 per cent variation. Similar results were obtained in the \( H \) comparison for a horizontal separation of 7.0 m (Fig. 40(b)). These results are consistent for other observation days on which horizontal comparisons were made (see Table 6). While they indicate relatively large horizontal variation when compared to that for the rural grass surface, they do support the premise of approximate horizontal flux constancy in the turbulent zone of the roof. Similarly, the height variation within the boundary layer of the roof (observed from the 1.2 and 2.0 m levels) appeared consistent (Fig. 41(a)). Less than 20 per cent variation was noted.

The two observation days on which \( H \) comparisons between the 1.2 and 4.0 m levels were made, showed more variability. Good agreement was found on August 30, 1972 (Fig. 41(b)), whereas on September 1, 1972, a 50 per cent reduction was noted in the 4.0 m values. Table 6 gives a summary of the spatial experimental days and the cumulative totals from the two YST instruments, expressed as a ratio. They support the premise of constancy within the boundary layer of the roof, if we consider 20 per cent variation to be acceptable.

While no measurements of the spatial variability of the nocturnal fluxes were attempted, it may be possible
Fig. 41. Vertical spatial variation of the urban sensible heat fluxes.
Table 6
Comparison of daytime cumulative sensible heat flux densities from the yaw sphere-thermometer systems ($H_{YST1}$ and $H_{YST2}$) above the urban roof

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration (min)</th>
<th>$H_{YST1}/H_{YST2}$</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 August 1972</td>
<td>584</td>
<td>0.79</td>
<td>Horizontal separation 2.5 m at 1.5 m level above roof-top</td>
</tr>
<tr>
<td>28 August 1972</td>
<td>420</td>
<td>1.09</td>
<td>Horizontal separation 7.0 m at 1.5 m level above roof-top</td>
</tr>
<tr>
<td>29 August 1972</td>
<td>332</td>
<td>0.98</td>
<td>*Vertical separation 0.8 m, at 1.2 m and 2.0 m levels above roof-top</td>
</tr>
<tr>
<td>25 August 1972</td>
<td>682</td>
<td>0.88</td>
<td>*Vertical separation 2.8 m, at 1.2 m and 4.0 m levels above roof-top</td>
</tr>
<tr>
<td>30 August 1972</td>
<td>525</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>1 September 1972</td>
<td>426</td>
<td>1.48</td>
<td></td>
</tr>
</tbody>
</table>

$H_{YST1}$ at the 1.2 m level and $H_{YST2}$ at the 2.0 and 4.0 m levels.
to make some inferences from the diurnal behaviour of H previously discussed. Consistently, it was found that the H values at the 1.2 m level were directed away from the surface at night (see Figs. 35 and 36). At the 4 and 20 m levels, nocturnal fluxes were more variable but smaller than those at the 1.2 m level. With the persistence of light winds at night, the boundary layer development over the roof-top surface would not be expected to be as marked. As a result, non-constancy in the urban sensible heat flux may be inferred from our night-time observations. Fuggle (1971) arrived at a similar conclusion from studies of radiative flux divergence in the air layer immediately above city structures at night. An increase in radiative divergence (cooling) appeared to be partially offset by a corresponding increase in sensible heat convergence (warming). The results from this study also indicate sensible heat flux convergence in the lower atmosphere. Thus, the interaction of flux divergence in the net radiation field, with that of the vertical temperature structure could have produced the sensible heat convergence. In the absence of advective influences, this is offered as a possible explanation for the night-time behaviour of urban H values close to the roof surface.
Chapter 6

URBAN ENERGY BALANCE

Introduction

The applicability of the eddy correlation technique to the measurement of sensible heat transfer between the atmosphere and the urban interface was demonstrated in the previous chapter. Despite the enormous complexities of the turbulent heat exchange processes in the city, it was shown that the urban sensible heat flux pattern, obtained directly from Eulerian point measurements, largely reflects time changes in the net radiation field. Even the magnitudes of the heat fluxes do not appear inconsistent with those of the net radiation during the daytime. In the absence of artificially generated heat at the surface and advection effects, it should be expected that the amount of heat used to warm the air via sensible heat transfer will not exceed the net radiant heat gained at the surface. The independent measurements of urban $H$ support this. It should be emphasized that this result has been derived from completely independent measurements of net radiation.
and sensible heat flux. In addition, it was possible to make a limited assessment of the diurnal behaviour, and spatial variability of $H$ over a restricted urban area. These results are now considered in the context of the energy balance framework.

Measurements of $H$ concurrently with other energy components (net radiation and soil heat storage) provide the basis for a discussion of the urban heat balance. Since both $R_n$ and $G$ are obtained from point measurements, doubts as to their usefulness and validity must arise when they are used to characterize an urban area. Furthermore, it is necessary to make assumptions in order to simplify the three-dimensional nature of the problem and the existence of anthropogenic sources of heat and moisture. Recognizing these shortcomings, it is still possible to gain some general insights into the energetic exchanges in the urban environment via the energy balance framework.

**Artificial Heat and Moisture Production**

In cities, artificial heat and moisture are released into the atmosphere primarily from industrial, transportation and domestic sources. These sources generate heat by combustion processes, which then enters the atmosphere either directly or indirectly in the form of sensible heat. A
relatively small fraction of this artificial heat generated will be utilized in the evaporation of liquid water and therefore enters the atmosphere in the form of latent heat. The artificial heat generation can thus be expected to produce primarily a modification of the natural sensible heat exchange. For many metropolitan areas, the magnitude of this artificial energy flux density has been estimated (see for example, Oke (1969), SMIC (1971)). They indicate that man-made heat production has attained values which are a significant fraction of the natural net radiation for many mid-latitude cities. In some instances (e.g. cities with a cold winter climate), this term may even be larger than Rn. This energy, emitted directly or indirectly into the urban atmosphere in the form of sensible heat, is generally accepted as the prime cause for the three-dimensional urban heat islands observed during the winter in mid-latitudes. Artificial heat generation is directly related to energy consumption and therefore shows a strong seasonal pattern with summer values considerably lower than those for the winter heating season. Bornstein (1968) has reported summer values of artificial energy flux density for Manhattan, New York, that are about 1/6 of the winter values. Similarly, Oke (1969) showed the summer artificial heat production to be about 1/3 of winter values in Montreal. This point is emphasized since the study period here refers
to a summer-time situation in Vancouver. We thus anticipate that the effect of this term will diminish from winter to summer in our energy balance considerations.

Using the procedure outlined by Bach (1970) the average annual artificial heat production for Vancouver in 1970 was calculated. The estimate was based on unpublished data of electricity, gas, fuel oil, gasoline and coal consumption and metabolic heat generation for the Vancouver area in 1970. The primary sources of artificial heat, in descending order of importance, were fuel oil, gas, gasoline and electricity. The estimate was found to be approximately 1.9 mWcm$^{-2}$ and is somewhat smaller than those of other mid-latitude North American cities. For example, Bach (1970) reported an average summer value of 2.6 mWcm$^{-2}$ for Cincinnati, while Summers (1964) estimated an average annual value of 9.8 mWcm$^{-2}$ for Montreal (see Table 1). The value for Vancouver, however, does not appear unreasonable since heating degree days here are lower than those of continental mid-latitude cities, and consequently may be expected to produce lower energy consumption demand. The seasonal variation of the artificial heat flux density for Vancouver showed that 60 per cent of the artificial heat was produced in the winter months (October-March). For 1970, the winter and summer values were found to be 2.3 and 1.5 mWcm$^{-2}$ respectively.
While the exact partitioning of this available energy into sensible and latent heat is not known, it is not unreasonable to suggest that less than 10 per cent enters the urban atmosphere as latent heat. It is noted, for example, that Oke and Hannell (1970) estimated that less than 10 per cent of the energy output of a steel mill at Hamilton, Ontario, entered the atmosphere as latent heat. Consequently, we shall ignore the artificial heat contribution to latent heat processes for the Vancouver summertime situation.

Although the overall artificial heat generation for summer in Vancouver is relatively small, it should be pointed out that all estimates of man-made heat production (including our estimate) represent an average value over the horizontal areal dimensions of the city. We thus expect higher values in the more densely urbanized area of the city. Furthermore, the three-dimensional aspect of the surface and the nature of building heat exchange may cause localization of this heat as it enters the urban atmosphere. For a limited urban building-air volume in the absence of industrial sources, the primary artificial heat is generated by transportation and domestic sources. Heat generated by transportation enters the air volume at street level, within the canyon between building elements, whereas domestically generated heat may partly enter the
atmosphere directly at roof-level or through vents on the
sides of a building. Some of the heat will also pass
indirectly to the atmosphere through the walls and windows
of the imperfectly insulated building. The net effect
could accentuate the warming between dense building elements,
particularly at night, when the natural energy components
are small.

As an approximation, we shall assume that the value
of 1.5 mWcm\(^{-2}\) can be applied to the study area. Consequently,
the error created by neglecting this energy source term
should be insignificant during the daytime since the value
is at least an order of magnitude smaller than the natural
energy components. Omission of this heat term at night,
however, may be unreasonable as the artificial energy flux
density is then likely to be an appreciable fraction of
the natural energy components.

**Roof-Top Energy Balance**

To begin discussion of the urban heat balance, we
first consider the situation close to the surface, within
the local roof-top boundary layer (see Fig. 30). In doing
so, we avoid most of the three-dimensional aspects and
attempt to view the heat balance as basically a one-dimen-
sional problem. For the roof-top surface itself, we can
use the following simple heat balance expression
\[ Rn = H + LE + G \]  

(6.1)

Since the net radiation (\(Rn\)), the roof heat flux (\(G\)) and the sensible heat flux (\(H\)) were known via direct measurements, the latent heat flux (\(LE\)) in the above expression remained as the residual. (We should note that this procedure enables us to use the energy balance framework but does not provide a budgetary check on the independently measured energy parameters. A heat balance check is only possible if we assume the roof-top surface to be completely dry (i.e. \(LE\) is zero).)

Let us now examine the applicability of the energy flux measurements for the roof surface. As net radiation was only monitored continuously at 20 m above the main roof surface, the measurements obtained at this level will be used in the roof-top energy balance consideration. This should not be unreasonable during the daytime since it was previously noted that the height-variation in \(Rn\) between 11 and 20 m above the roof was less than 5 percent. The measurement of \(G\) was made in the uppermost gravel and tar layer of the roof. This provided a measure of the heat flowing into or out of the roof surface. If we assume that some artificial heat passes indirectly to the atmosphere through the imperfectly insulated roof, then the roof-top \(G\) measurements also contain a measure of this
term. During the daytime, this artificial heat will reduce the natural G of the roof and by night, will augment the natural G. Direct H measurements at the 1.2 m level above the roof only will be used for the roof-top energy balance considerations. They represent values within the local turbulence zone of the roof and should largely reflect the underlying surface conditions.

Daytime balance.

Two examples of typical daytime variation of the measured energy balance components near roof-level are given in Figs. 42 and 43. These results indicate that a significant portion of the net radiant energy gained at the roof surface is utilized in sensible heat transfer and in heat storage in the roof. Of these two transfer processes, the greatest amount of energy is used in sensible heat to warm the air (for example, at midday H is typically ~ 3 G). Even so, the residual term (equated to LE) is quite appreciable. It should be noted that the diurnal cycle of the residual term shows a morning peak on July 27 (Fig. 42) whereas on the following day (Fig. 43), the peak occurs in the late evening. The cause of this behaviour is not known but it may be related to the presence of advection even at the 1.2 m level above the roof. If the residual
Fig. 42. Daytime roof-top energy balance.
Fig. 43. Daytime roof-top energy balance.
term, equated to LE, is real, we must conclude that the roof-top surface is not thoroughly dry but that it contains available water which is subsequently released as moisture to the urban atmosphere and consumes latent heat of vaporization. On the other hand, the relatively large residual term may arise from consistent underestimation of the surface sensible heat flux by the eddy correlation instrument, as well as from underestimation of the surface net radiation and soil heat storage terms. These possibilities are examined further below.

Theoretical considerations indicate that net radiation measurements become increasingly less representative of surface conditions with increasing height above the surface when surface temperatures are significantly different from that of the ambient air. Experimentally, this effect was found to create a 7 per cent discrepancy between net radiation measured at 50 cm above a dry, bare soil and that measured at 215 cm for daylight hours (Idso and Cooley, 1971). A similar effect can be anticipated in the net radiation measurements above the urban roof surface, when surface temperatures are significantly warmer than the ambient air temperatures. Measurements of true roof-top surface temperature were made with a Barnes sensor during the daytime by isolating the surface from sky radiation and allowing it to radiate as an apparent blackbody. The
method used is described by Fuchs and Tanner (1966). The roof-surface temperatures thus obtained were found to be larger than 40°C, while screen height air temperatures were ~ 20°C. The maximum effect of air-roof surface temperature differences on the effective outgoing radiation could then be determined approximately from the empirical relationship (based on the data of Rider and Robinson (1951)) when screen height is 1 m and the surface emissivity is assumed equal to one.

\[
\frac{I_s - I}{\sigma (T_s^n - T^n)} = 0.205 \quad \text{(upper limit)} \quad (6.2)
\]

where
- \(\sigma\)  Stefan-Boltzmann constant
- \(I_s\)  is the true effective outgoing radiation from the surface
- \(I\)  is the true effective outgoing radiation at screen height
- \(T_s\)  temperature of the surface
- \(T\)  ambient temperature at screen height

If we assume a maximum air-roof surface temperature difference of 30°C and an ambient temperature of 20°C, it can be seen that \(I_s\) is approximately 4 mWcm\(^{-2}\) greater than \(I\). The effect of such large air-roof surface temperature differences can then be expected to produce an overestimation of the
surface net radiation of 4 mWcm$^{-2}$ when net radiation measurements at the 1 m level are extrapolated to the roof surface. Furthermore, if we assume that Rn measurements at the 20 m level are greater than those at 1 m by 5 per cent, the net effect would yield a maximum overestimation of roof-surface Rn of ~ 7 mWcm$^{-2}$ when Rn measurements at 20 m are used to represent surface conditions. Thus, the relatively large residual term, derived from the heat balance expression, can be partly attributed to the extrapolation of Rn at 20 m to the roof surface.

In the roof-top surface energy balance, G values were obtained from a flux plate embedded in the uppermost gravel and tar layer of the roof, approximately 0.5 cm below the surface. Accordingly, an underestimation of surface G will arise from divergence effects in the 0.5 cm layer between the plate and the surface, during the daytime. The roof surface G can be expressed in the following manner

$$G_{\text{roof surface}} = \Delta G_{0-0.5 \, \text{cm}}$$

$$+ G_{\text{heat flux plate at 0.5 cm}}$$

(6.3)

where $\Delta G$ is the change in heat storage in the top 0.5 cm. No attempt was made to measure $\Delta G$. Its contribution to the
roof-surface value, however, is unlikely to be significant. It is noted, for instance, that Turner (1969) obtained AG values for the top 0.5 cm in a concrete slab that were \(~10\) per cent of the flux plate G values at the 0.5 cm depth, during the daytime. Thus, if we assume a similar order of magnitude effect for the top 0.5 cm of the roof, the use of G measurements at the 0.5 cm depth to represent surface values would produce a maximum underestimation of \(~1\) mWcm\(^{-2}\) during the daytime.

In addition to divergence effects, errors of G may arise from differences in thermal conductivities of the flux plate and the gravel and tar roof medium. The magnitude of this effect can be determined approximately from the formula given by Phillip (1961)

\[
f = \frac{1}{{1 - \alpha r(1 - \varepsilon^{-1})}}
\]  

(6.4)

where

- \(f\) ratio of mean flux density through the meter to the flux density through the medium
- \(\varepsilon\) ratio of meter conductivity to medium conductivity
- \(r\) ratio of the mean meter thickness in the general direction of the heat flow to the square root of the mean cross-section the meter presents normal to the direction
- \(\alpha\) a constant, equal to 1.70
For the heat flux plate, the thermal conductivity is \(~ 84.0 \text{ mWcm}^{-1}\text{K}^{-1}\) and the value of \(r\) is 0.13. If we assume a thermal conductivity of the gravel and tar medium of \(~ 25.2 \text{ mWcm}^{-1}\text{K}^{-1}\), the above equation yields a value of \(f = 1.18\). Thus, the heat flux measured by the meter is 18 per cent larger than that through the gravel and tar medium. Since peak flux plate \(G\) values measured during the daytime were \(~ 10 \text{ mWcm}^{-2}\), maximum overestimation of \(G\) for the roof-tar and gravel medium would be \(~ 2 \text{ mWcm}^{-2}\). It can thus be seen that errors of the roof-surface \(G\) from the use of the heat flux plate embedded at 0.5 cm in the gravel and tar medium are likely to be negligible.

The possibility of consistent underestimation of surface sensible heat fluxes by the eddy correlation instrument at 1.2 m above the roof surface during the daytime could not be readily assessed. Some uncertainties must exist in the use of \(H\) values at the 1.2 m level to represent surface conditions. The complex nature of the flow in the turbulent zone of the roof, including a return flow onto the roof from neighbouring street canyons may create difficulties in the actual measurement of the sensible heat flow off the roof. It is not known, however, if this effect would produce a systematic underestimation of \(H\) during the daytime. In using the eddy correlation technique, it is necessary to assume that the vertical velocity,
averaged for a sufficient time period, is close to zero over the roof surface. Although some attempts were made to determine $\bar{w}$ with a vertical anemometer, little confidence can be placed on the actual magnitudes as these values ($\pm 10 \text{ cm s}^{-1}$) were within the resolution capability of the instrument. It appeared, however, that there was a tendency towards slight downdraft conditions during the daytime near the roof surface. Accordingly, eddy flux measurements of sensible heat would be underestimating the sensible heat transport from the roof. On the other hand, the nature of the output from the yaw sphere-thermometer assembly suggests a slight overestimation of the eddy flux of sensible heat during the daytime with small negative mean vertical velocities. Thus, the existence of small negative $\bar{w}$ may not have affected the sensible heat flux measurements to any appreciable extent. As an approximation, it may thus not be unreasonable to assume no systematic underestimation of $H$ for the roof surface during the daytime.

The preceding analysis of errors associated with the use of $R_n$, $G$ and $H$ measurements to represent roof surface conditions during the daytime can thus explain only part of the large residual term noted from the heat balance considerations. A maximum possible contribution to the residual term from these errors is likely to be $\sim 7 \text{ mW cm}^{-2}$. The remaining portion of the residual term (equation to LE)
would still be appreciable. Accordingly, the possibility of latent heat transfer from the roof-top surface is examined further below.

It is often stated in the literature that the city has little available water for evaporation (for example, Chandler, (1965), Peterson (1969)). This assessment is offered on the basis that the replacement of natural spongy rural surface by urban materials renders the surface more impervious to water. It is suggested that precipitation then leads primarily to more rapid run-off. Lacy (1972, private communication), however, indicates that quantitative measurements do not support this. He cites examples from the results of measurements in a number of English towns which show that, on the average, run-off is only 40 per cent of the total rainfall. Over a test district, 95 per cent paved, the run-off was about 50 per cent of the rainfall. These results suggest that a large fraction of the rainfall is absorbed by unpaved grounds, by porous materials or remains as puddles. This water would subsequently be available as a source for evaporation. It would thus seem that the widely held assumption that LE << H over an urban area is unfounded.

The recent work of Oke et al. (1972) in Montreal should also be noted in this regard. The partitioning of energy between H and LE over a roof-top surface was derived
from the Bowen ratio method, using temperature and wet-bulb gradients between 2, 4 and 6 m above the roof surface, and assuming similarity in the transfer coefficients for heat and water vapour. Their results indicate that a greater portion of energy is used for latent heat transfer than for sensible heat (i.e. $\beta < 1$) during most of the daytime, and hence LE was found to be an important term in the urban energy balance.

In view of these experimental findings, it is apparent that one may not be justified in assuming that the role of latent heat transfer in the city is insignificant. The extent to which one can generalize urban area latent heat transfer to individual roof-top surfaces must remain somewhat speculative. Although there were no quantitative measurements of the moisture state of the roof surface, it seems dubious if not unreasonable to expect such large latent heat flows during the daytime as shown in Figs. 42 and 43. At the same time, we must expect some latent heat transfer from the roof if it is not thoroughly dry.

The large residual term obtained from our roof-top energy balance considerations may therefore partly arise from the presence of latent heat transfer and partly from errors associated with the use of $R_n$, $G$ and $H$ measurements at a finite distance from the actual roof surface.
In general, the roof-top energy balance showed that the major partitioning of the available net radiation at midday was into sensible heat transfer. For a net radiant input of 60 mWcm$^{-2}$, $G$ was typically 10 mWcm$^{-2}$ and $H$ about 30 mWcm$^{-2}$. If the residual energy was converted to latent heat, we obtain a Bowen ratio of 1.5. This value is approximately twice that of the maximum value obtained for the Ladner grass surface, at midday. On the other hand, overestimation of surface $R_n$ by 7 mWcm$^{-2}$ would yield midday value for the residual term of 13 mWcm$^{-2}$. Typical Bowen ratios for the roof surface would then be 2.3, if this residual energy was converted to latent heat.

Nocturnal balance.

The applicability of the nocturnal energy flux measurements for the roof surface needs careful considerations. The existence of radiative flux divergence at night (e.g. Fuggle, 1971) presents a difficulty in extrapolating $R_n$ measurements at 20 m above the roof to that of the roof-surface. Similarly, sensible heat flux divergence would invalidate attempts to use the $H$ measurements at the 1.2 m level as representative of the underlying surface. It should be noted that the YST instrument is less reliable at
night if light winds prevail. With these limitations in mind, a brief assessment of the nocturnal situation is presented below.

Two examples of typical nocturnal variation of the measured heat balance components are shown in Figs. 44 and 45. As previously noted in Chapter 5, the nocturnal sensible heat fluxes remain directed away from the active roof surface throughout the course of the night. The magnitudes were typically 5 to 10 mWcm$^{-2}$. If we assume that all the measured energy components are applicable to the roof surface, it is necessary to suggest a large flow of latent heat to the active surface at night (~ 10 to 15 mWcm$^{-2}$). This would presumably result in significant dew formation on the roof surface. While the occurrence of extensive dew formation on the roof surface was observed during the latter part of August 1972, there was no visible evidence during the observation program in July. The apparently large latent heat transfer to the surface at night may have arisen from the inapplicability of our measurements of Rn and H for surface conditions. However based on the results of Fuggle (1971) the Rn divergence and H convergence would tend to be complimentary. It is interesting to note that the heat flow towards the roof surface (G) was never greater than 3 mWcm$^{-2}$. This value includes a measure of the artificial heat flow towards
Fig. 44. Nocturnal roof-top energy balance.

Fig. 45. Nocturnal roof-top energy balance.
the roof surface, and hence it can be concluded that artificial heat through the roof does not significantly contribute to the roof-top energy balance at night.

Energy Balance of an Urban Area

Although we may readily specify the governing energy balance expression for a limited urban-building air volume, the three-dimensional nature of the problem remains most formidable (see Fig. 2). Some of these complexities may be avoided if we can assume that horizontal advection and artificial heat generation are small within the area of concern. As an approximation, these assumptions do not appear unreasonable based on the site characteristics and artificial heat computations. Experimental measurements of the energy balance components over a limited urban area then become basically a spatial problem and all terms in the heat balance expression must refer to spatially integrated averages. This, however, is still extremely difficult to achieve, particularly in the measurement of Rn and G. Meaningful estimates of Rn should include measurements above the street canyons and roof surfaces. Similarly, the measurement of G must represent an integrated value for the various city fabrics over the three-dimensional solid surface area. On the other hand, measurement of LE
or H over the limited urban area may be achieved from point measurements, provided that these are made at a height above the local roof-top boundary layer. At this height, we assume that local inhomogeneities in the sensible and latent heat fluxes become insignificant in comparison to the meso-scale urban boundary layer fluxes. The turbulent eddy fluxes should then be representative of spatially integrated values. We shall now examine our measurements in this context.

In this study, both Rn and G were derived from point measurements. Accordingly, their usefulness in the energy balance expression for an urban area appears somewhat doubtful. The measurement of Rn at 20 m above the urban roof surface does provide a good horizontal field-of-view that includes the urban roof surface, as well as street canyons, but the radiant energy received by the sensor from below reflects primarily that fraction emitted by the immediate underlying surface, namely, the roof-top. The horizontal area contributing to 90 per cent of the flux measured by the net radiometer at 20 m above the roof encompasses a circle of radius equal to 60 m. Generalization of these Rn results to that over the street canyons may not be justified, especially in situations where large shadow areas occur at street level.
As the net radiation field above street canyons has not been previously investigated in any depth, its contribution to the spatially integrated Rn value over an urban area can only be treated qualitatively. The recent model of the effect of the trapping of solar radiation by the canyon, advanced by Craig and Lowry (1972), suggests that the canyon lowers the urban albedo. Hence, we might expect an increase in the effective net solar radiation above the street canyon compared with that over an open horizontal roof surface. Similarly, the effective outgoing long-wave radiation from the canyon can be expected to be somewhat reduced in comparison with that of an open horizontal surface because of the vertical walls (Munn, 1966). These two processes are likely to enhance the net radiation above the street canyon. In the absence of quantifiable estimates of these effects, we can only suggest that our point-measurement of Rn above the roof surface is likely to be somewhat lower than that of a spatially integrated average Rn for the surrounding urban area.

The roof-top G measurements are only indicative of one urban fabric in a horizontal position, and cannot be used solely to arrive at an estimate of spatially integrated values of G for the three-dimensional system. A spatially integrated average of G is therefore very difficult to achieve, but since we do have simultaneous measurements
of G in tar and concrete slabs, placed horizontally on the urban roof surface, we may be able to indicate upper limits to an average G value for the urban area.

An example of the diurnal behaviour of G in various urban fabrics is shown in Fig. 46. The values for concrete and tar were obtained from soil heat flux plates embedded in slabs of the respective materials placed on the urban roof surface. It can be seen that the heat stored in the tar block is quite appreciable (approximately 70 per cent higher than that of the urban roof surface). On this particular day, G in the tar block was about 25 per cent of the net radiation at midday. It is not unreasonable to suggest that the G value for the tar block provides an upper limit to the amount of energy that can be stored over the three-dimensional solid surface during the daytime. The actual spatially averaged G will be significantly lower than this upper limit when the urban fabrics of varying thermal capacities are all taken into account.

The sensible heat flux variation at heights of 4 and 20 m above the urban roof surface was presented in the previous chapter. As these measurements were conducted above the local roof-top boundary layer, they may be assumed indicative of spatially integrated averages. Another example of the H measurements for the 4 m level above the roof is given in Fig. 47, along with the point measurements
Fig. 46. Diurnal behaviour of G in various urban fabrics.
Fig. 47. Urban sensible heat fluxes and point measurements of Rn and G.
of Rn and of the roof-top G. In general, midday values of urban H were ~ 20 to 25 mWcm$^{-2}$, when Rn was 60 mWcm$^{-2}$. If we consider this point measurement of Rn to be the lower limit of an areally integrated average, we can perform the following analysis for the energy balance of the urban area.

As an extreme case, let us assume the upper limit of an average G identical to that typically in the tar block at midday (i.e. ~ 15 mWcm$^{-2}$). The urban energy balance then yields a residual term (taken to be LE) of ~ 20 to 25 mWcm$^{-2}$. Thus, the result would indicate approximately equal partitioning of the heat utilization between sensible and latent heat transfer (i.e. $\beta \sim 1$) around noon. These values of Rn and G are considered extreme limits. Accordingly, if we assume H to be correct, we can anticipate LE to be slightly larger than H in the real situation for the urban area at midday. This brief analysis provides some insight into the energy partitioning over an urban area. The results are consistent with similar findings from the energy balance estimations over Montreal (Oke et al., 1972).
Chapter 7

SUMMARY OF CONCLUSIONS

A yaw sphere-thermometer assembly (YST), to measure sensible heat flux density by the eddy correlation method, was built following the design of Tanner and Thurtell (1970). From wind tunnel experiments the 'sphere constant' was determined to be 1.57. This value is significantly less than that predicted theoretically, namely, 2.25. It is important that the yaw sphere approach be modified to include an experimentally determined 'sphere constant.' Analysis of the effects of tilting the yaw sphere axis indicates that an error of approximately 5 per cent per degree of tilt is likely with moderately unstable conditions. This error may attain 11 per cent per degree in very stable conditions. A modified thermometer assembly was found necessary to provide durability in the field. In the frequency domain the turbulent heat flux could be measured to an upper frequency limit of 8 Hz without significant attenuation. Field comparisons of the heat fluxes measured by the yaw sphere-thermometer system and a Bowen ratio apparatus
produced satisfactory agreement. Daytime cumulative sensible heat flux densities indicate that the difference between the two methods is generally less than 10 per cent.

Direct measurements of sensible heat fluxes over a grass surface at Ladner, B.C. indicate a diurnal course very similar to that of the net radiation. In general, half-hour averaging periods showed no phase lag between sensible heat and net radiation. Field comparison of two YST systems gave good and consistent agreement. At a height of 2 m above ground and a horizontal crosswind separation of 1.5 m, less than 5 per cent variability was noted in the heat flux measurements from the two systems. For a 19 m horizontal separation, the variability was found to be less than 20 per cent. These results give support to the basic assumption that the sensible heat flux is relatively constant in the atmospheric boundary layer. It is shown that the parameter (α), advanced by Priestley and Taylor (1972), can be a useful climatic indicator, and hence large scale parameterization of surface heat fluxes appears encouraging. The partitioning of energy between sensible and latent heat (i.e. the Bowen ratio) during June and early July 1972 shows a temperature dependence similar to that of a saturated surface with an alpha value between approximately 1.00 and 1.10.
The applicability of the eddy correlation technique to the measurement of sensible heat transfer between the atmosphere and the urban interface is demonstrated for a limited area of the city of Vancouver, B.C. Despite the enormous complexities of the turbulent heat exchange processes, the urban sensible heat flux pattern, obtained directly at heights of 1.2, 2, 4 and 20 m above roof-top level, largely reflected time and magnitude changes in the net radiation field during the daytime. Nocturnal urban sensible heat fluxes, near roof-top level, were found to be directed away from the active surface. This is reverse of the normal rural case. Within the local roof-top boundary layer, the sensible heat flux was found to be approximately constant with height and space (20 per cent variation) during the daytime. At night, the existence of flux divergence and hence, non-constancy of the heat flux, is suggested.

Daytime roof-top energy balance indicates that a significant portion of the net radiation is utilized in sensible heat transfer and in heat storage in the roof. The greatest energy is used in sensible heat transfer, which is about three times the heat storage at noon. Artificial energy flux density appears to be insignificant. With typical values of net radiation of 60 mWcm$^{-2}$, the sensible heat flux is about 30 mWcm$^{-2}$ and the heat storage
10 mWcm$^{-2}$. The residual term (equated to latent heat) is appreciable. On the other hand, the errors associated with the use of net radiation measurements to represent actual surface conditions could have resulted in an overestimation of the residual term up to 7 mWcm$^{-2}$. Accordingly, if the sensible heat flux measurements are not systematically biased and the storage term errors are small, the residual energy, converted to latent heat, would be 13 mWcm$^{-2}$ at midday. This would then yield a Bowen ratio for the rooftop surface of 2.3. It would seem that the role of latent heat transfer for the roof-surface needs further investigation. The nocturnal roof-top energy balance required a latent heat term of about 15 mWcm$^{-2}$ directed towards the active surface.

The energy balance of the surrounding area was deduced from measurements of sensible heat flux and net radiation at heights above the roof-top boundary layer. On the assumption that these point measurements approximately reflect areally integrated averages, partitioning of the heat between sensible and latent heat yields a Bowen ratio of ~1 at midday. The city does not appear to act as a "desert" as has sometimes been suggested. It would seem that the role of latent heat transfer is important for urban energy balance considerations. The accurate determination of the energy balance for an urban area
remains outstanding. This task can only be accomplished by some means of obtaining spatially integrated averages of all the energy balance components. Such a formidable and essential task was beyond the scope of this research undertaking.

Suggestions for Future Work

From this research, many questions have been raised which warrant more attention. Some of these are offered here as suggestions for future work.

1. The spatial variability of sensible heat fluxes in the atmospheric boundary layer over a flat uniform surface should be fully examined. Extensive and reliable data are required to test the fundamental hypothesis of the constant flux layer.

2. The parameter ($\alpha$), advanced by Priestley and Taylor (1972) should be investigated further, to determine its usefulness as a climatic indicator and in large scale parameterization of surface heat fluxes over various surfaces. This could prove most useful in numerical modeling of the larger scale atmospheric dynamics.
3. The significant frequency domain for urban sensible heat fluxes remains outstanding. A detailed study of the urban sensible heat flux cospectrum via other eddy correlation instruments (e.g. acoustic anemometer-thermometer) is suggested. Furthermore, the integrated urban cospectrum could then be compared with simultaneous measurements from the yaw sphere-thermometer system.

4. The effect of radiative exchanges between building elements, and shadow areas remain areas for investigation. Extensive radiation measurements, within an urban canyon, may provide insight into this formidable problem.

5. Heat storage or release in the various city building materials (including shadow areas) deserves much attention. A spatial averaging procedure, over the three-dimensional surface of an urban canyon, is suggested as an initial approach to this task.

6. Studies of the coupling between the energetic processes at street level and those at roof-level and above, are required.
7. In this study, the magnitudes of divergence terms, heat storage in the air and latent heat storage for the limited urban building-air volume were considered negligible. The validity of these assumptions needs to be explored.

8. The role of latent heat transfer in urban energy balance studies warrants more attention. It should be possible to use the eddy correlation technique with appropriate sensors to measure this energy component directly.

9. For an areal urban energy balance, extensive spatial sampling is required of all the energy components. This presently remains a formidable task.

10. Finally, it is suggested that attempts should be directed towards a budgetary check of the urban heat balance through independent evaluation of all the energy components.
REFERENCES


---, 1968. Application of sonic anemometer-thermometer to the studies of vertical eddy transport processes in the atmospheric boundary layer. Contributions, Geophysical Institute, Kyoto Univ., 8, 45-60.


APPENDIX A

SAMPLE CALCULATION OF THE SENSIBLE HEAT FLUX

The sensible heat flux expression for the yaw sphere-thermometer system is given by equation 3.5.

\[ H = C_p [b(\sin \theta)GBM]^{-1} \bar{E}_0/\bar{u} \]

where

- \( C_p \): the specific heat at constant pressure (1.01 Jg\(^{-1}\)K\(^{-1}\))
- \( b \): sphere constant (1.57)
- \( \theta \): the included angle between the ports (45°)
- \( G \): amplifier gain
- \( B \): bridge constant
- \( M \): transducer constant
- \( \bar{E}_0 \): integrated output voltage from the bridge
- \( \bar{u} \): mean horizontal wind speed

Transducer Constant (M)

This constant is obtained from the specifications of the Barocel and its electronics. It is given by the following expression
full scale
M = ---
(range switch position)(pressure range)

where   full scale = 10 volts
pressure range = 10 mb = $10^4$ dyne cm$^{-2}$ange switch position (e.g. 0.03, 0.01, 0.003, 0.001)

Thus, for a range switch position of 0.003

\[ M = \frac{1}{3} \text{ volts cm}^2\text{dyne}^{-1} \]

**Bridge Constant (B)**

The bridge circuit is shown in Fig. 48. $E_i$ is the voltage applied to the bridge (i.e. the hi-pass filtered analog pressure signal) and $E_0$ is the bridge output (the imbalance). Accordingly,

\[ E_0 = \left[ \frac{R_4 + R_3}{R_1 + R_4 + R_3} \left( \alpha_{T_0} \right) \right] \Delta T \ E_i \]

where   $\alpha_{T_0}$ = coefficient of resistance of the thermometer at $T_0$ (0.0033 °K$^{-1}$)
Fig. 48. The bridge circuit.
\[
B = \frac{R_4 + R_3}{R_1 + R_4 + R_3} \quad \text{(where } R \text{ refers to the appropriate resistances shown in Fig. 48)}
\]

Thus, for a bridge balance of \( R_4 = 650 \Omega \) (i.e. the thermometer resistance of 1950\( \Omega \))

\[
B = 1.53 \times 10^{-4} \, ^\circ \text{K}^{-1}
\]

**Example**

Using the values of \( M \) and \( B \) above and an amplification gain (\( G \)) of 290

\[
H = 614 \times 10^2 \frac{E_0}{\bar{u}} \quad \begin{cases} 
E_0 \text{ in volts} \\
\bar{u} \text{ in cm} \text{s}^{-1} \\
H \text{ in mWcm}^{-2}
\end{cases}
\]

Thus, with a 30 min average \( E_0 \) value of 0.0901 volts and a mean wind speed (\( \bar{u} \)) of 296 cm\( \text{s}^{-1} \) at noon

\[
H = 18.6 \, \text{mWcm}^{-2}
\]