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Department of Geography

The University of British Columbia
Vancouver, Canada

Date 19 August 1994
Abstract

While there has been a long tradition for the integration of architecture and landscape to improve the urban environment, little is known about the effect of urban parks on local climate. In this study the park effect is determined through an integrated research approach incorporating field measurements of the thermal regime and energetics of urban parks, together with scale modelling of nocturnal cooling in urban parks.

The research is limited to consideration of the park effect in two cities with different summer climates: Sacramento, California (hot summer Mediterranean) and Vancouver, British Columbia (cool summer Mediterranean). In both these cities, surveys of summertime air temperature patterns associated with urban parks confirm and extend previous findings. In temperate Vancouver, the park effect is typically 1–2°C, rarely more than 3°C, although it can be higher under ideal conditions. However, in a hot, dry city, the effect is considerably enhanced with parks as much as 5–7°C cooler than their urban surrounds.

A comparison of the surface energy balance of small open, grassed parks in these two cities demonstrates the importance of evapotranspiration in park energetics. In hot, dry Sacramento, evaporation in the park was advectively-assisted and exceeded that at an irrigated rural site. Strong advective edge effects on evaporation were observed in this wet park. These decayed approximately exponentially with distance into the park. The urban park in Vancouver was moist, but unirrigated. While evaporation dominated the surface energy balance, the sensible heat flux was positive through most of the day, and evaporation was not strongly influenced by advection. The evaporation trend in the park probably reflected the turbulence and soil moisture regimes. However, an irrigated lawn
in Vancouver did exhibit edge-type advection. This suggests the soil moisture regime may be critical in determining whether evaporation exceeds the potential rate.

The contribution of processes to nocturnal cooling in urban parks was determined through scale modelling. It showed that surface geometry and the urban-park difference in thermal admittance may be of equal importance in nocturnal cooling. Parks with high sky view factors have increased radiative cooling and if the park is very dry (and therefore has a low thermal admittance), the cooling is further enhanced. Evaporative cooling is critical in establishing the park as a “cool island” at sunset, but the presence of moisture slows cooling through the night.

Integration of the field and model data leads to the development of guidelines for planners regarding the design of parks for maximum climatic benefit. The optimum size of the park depends to a large extent, on the geometry of the urban surrounds. To maximize radiative cooling, the width of open park areas should be at least 7.5 times the height of the trees or buildings around the park border. Large parks increase the size of the volume of air cooled and this increases the potential for advection of cool air into the neighbourhood. It is suggested that if cooling is the objective, the optimum design is a savannah-type park with loose clusters of trees interspersed by wide open, irrigated grass. The arrangement of trees must be chosen with great care to allow the advection of air both into, and out of, the park.
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Chapter 1

Introduction

There is a long tradition in human history involving the integration of architecture and landscape to improve the urban environment. It is not clear whether the early use of vegetation in urban areas represented a conscious attempt to enhance the environment or whether the improvements realized were merely accidental consequences of landscape manipulations performed for other reasons (Hutchinson et al., 1983). Urban vegetation improves the urban environment in a variety of ways through both social (e.g. aesthetic, psychologic, economic) and physical (e.g. climatic, air quality, hydrologic, biogeographic, acoustic) means. This thesis concentrates on the climatic benefits of urban vegetation but in so doing, the intention is not to downplay these other benefits. Indeed the attainment of maximum climatic benefit may be at the expense of other benefits and in the final analysis, the full costs and benefits of greenspace must be weighed.

The climatic benefits of urban greenspace (which includes private gardens, street trees, parks and undeveloped or derelict vegetated land) have long since been realized at least in a qualitative sense. Despite this recognition there has been little research effort as urban greenspace has not been a target for basic research. Consequently there has been little coordinated understanding based on field observations of meteorological processes or effects (Oke, 1989).
1.1 Definitions and scale considerations

It is important to maintain a sense of scale and an appropriate definition of the surface when studying atmospheric interaction between greenspace and the urban surrounds. In a sense, greenspace may be thought of as a rural surface in urban surrounds. In a rural setting the meteorological definition of a surface is generally straightforward, provided it is homogeneous and extensive. If there is a substantial plant canopy, energy exchanges involve a soil–plant–air volume (Fig. 1.1). Thus the near-surface energy balance (hereafter referred to as SEB) may be written:

\[ Q^* = Q_H + Q_E + \Delta Q_S + \Delta Q_P + \Delta Q_A \]  

(1.1)

where the terms are the flux densities and \( \Delta \) is a finite difference approximation (i.e. the difference or net change in a quantity): \( Q^* \) net all-wave radiation; \( Q_H \) the turbulent sensible heat flux; \( Q_E \) the turbulent latent heat flux; \( \Delta Q_S \) the net sensible heat storage by components in the system; \( \Delta Q_P \) the net biochemical heat storage due to plant photosynthesis; \( \Delta Q_A \) is an advection term for net energy gain or loss due to sensible heat and latent heat transport. The net biochemical heat storage is usually negligible for crops and grass surfaces and for such canopies the ground heat flux, \( Q_G \) is used to approximate \( \Delta Q_S \), assuming the canopy does not have a high storage capacity.

The SEB of greenspace, by virtue of being located in an urban environment, will interact with the SEB of the urban surface. Defining the urban surface is a more complex problem given the level of heterogeneity. Oke (1988) suggests the use of a near-surface active layer or volume, analagous to the soil–plant–air volume above (Fig. 1.2). The urban volume extends from below the ground surface to roof-top level. Anthropogenic heat input \( (Q_F) \) is added to the energy balance so that the SEB is given:

\[ Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \]  

(1.2)
Figure 1.1: The energy balance of a soil–plant–air volume (from Oke, 1987).

Figure 1.2: The energy balance of the urban "surface" (from Oke, 1984).
The energy release due to human activities depends on the city size and on the per capita energy use which is influenced by climate, the degree and type of industrial activity, the site of electricity generation, the urban transportation system, etc. (Oke, 1984). In densely populated cities in cold climates $Q_F$ can be substantial and even surpass the radiative energy input in winter. In summertime studies this flux is sufficiently small to be regarded as negligible.

This definition of the urban surface conveniently coincides with an urban classification developed by Oke (1976, 1984) (Fig. 1.3). The layer below roof-level is called the urban canopy layer (UCL) and is dominated by the microscale effects of the site characteristics. Above roof-level is the urban boundary layer (UBL) which includes the roughness layer immediately affected by roughness elements, the turbulent surface layer and the mixed layer.

A framework for studying climatic impacts of greenspace is developed from Oke (1984, 1989) (Table 1.1). At the microscale, greenspace can impact the climate of buildings and canyons; at the local–scale it impacts the climate of city blocks, while at the mesoscale the urban forest (which includes all woody vegetation) influences the climate of the land–use zone or the city.

In assessing the climatic impact of greenspace, careful consideration must be given to macroscale climate, as well as the scale of influence within the urban canopy. The macroscale climate is the climate background within which the city is located. Depending on the macroscale climate, greenspace can be manipulated in various ways to improve urban climate.
Figure 1.3: The classification of urban "surface" boundary layers (Oke, 1984).

Table 1.1: Scale classification of the urban canopy layer as a framework for studying the climatic impacts of greenspace.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Built feature</th>
<th>Greenspace features</th>
<th>Climate phenomena</th>
<th>Dimensions</th>
<th>Scale</th>
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<td>building street</td>
<td>tree, garden</td>
<td>wake, plume</td>
<td>10 10 10 m</td>
<td>micro</td>
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<td>boulevard</td>
<td>thermal climate shade</td>
<td>10 30 300 m</td>
<td>micro</td>
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<td>local breezes, park cooling</td>
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<td>— 25 25 km</td>
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</tr>
</tbody>
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1.2 Climatic amelioration by greenspace

Urban greenspace can have a marked effect on urban climate. Early attention focused on the role of vegetation in removing pollutants from city streets. Parks were "the lungs" of cities (Brezina and Schmidt, 1937). In recent years, research has started to assess the role of greenspace in modifying climate parameters such as air and surface temperatures, humidity and wind. Studies typically focus on the microclimatic effects of greenspace with little consideration to its effects at the mesoscale. Comprehensive reviews of progress in the field are given by Hutchinson et al., (1983) and Oke, (1989).

1.2.1 Impact of greenspace at the microscale

The major influence of vegetation on microclimates occurs through the interception of radiation (i.e. shading) and the deflection of winds by plant canopies (Hutchinson et al. 1983). The daytime energy balance of a tree (Figure 1.4) is discussed by Oke (1989). Tree leaves intercept, reflect, absorb and transmit solar radiation. Their effectiveness depends on the density of foliage, leaf shape and branching patterns. The largest effect can be gained from trees with tall, dense and wide canopies. Trees surrounded by built environments receive large amounts of reflected short-wave radiation. The long-wave radiative energy input is also greatly enhanced because of adjacent warm surfaces. It is also possible for the air temperature in a street canyon to exceed the leaf temperature, subjecting it to a sensible heat load by advection. Heat is dissipated primarily through evapotranspiration. Oke (1989) points out that this process is fundamentally dependent on the water balance and wind climate of the tree. The water supply may be restricted and/or contaminated. The stomata may be physically blocked by particulates or the excessive heat load may lead to stomatal closure. Furthermore, wind may be sheltered

Figure 1.4: Scheme of daytime energy exchanges between an isolated tree and its street canyon environment (from Oke, 1989). $T_l$ and $T_a$ are leaf and air temperatures.

in street canyons which reduces ventilation.

Vegetation reduces air temperature by day mainly through the provision of shade and evaporative cooling. Deciduous trees are instrumental in heat control in temperate regions. During summer they intercept solar radiation and lower ground temperatures, while in winter, when they are leafless, they provide pleasant warming effects by enabling more insolation to reach the ground. This effect though, has often been overestimated. Heisler (1982, 1986) found insolation reduced by as much as 80% by medium-sized deciduous trees in leaf, while in winter, insolation was reduced by 40–50%. Deciduous trees in leaf usually have a higher albedo (about 20%) compared to coniferous trees (5–15%) (Oke, 1987). Therefore deciduous trees are more effective in reflecting incoming radiation. However this effect decreases in winter.

Vegetation can also reduce temperatures by evapotranspirational cooling. Perhaps "cooling" is the incorrect term; rather it is a "prevention of heating" as available energy
is channelled into the evaporation of water (latent heat) rather than sensible heat. Lowry (1988) estimated evapotranspiration cooling rates from six trees along 10 m of a street canyon with a 10×10 m cross section. He assumed an average leaf transpiration rate of 70 W m⁻² at midday and a canyon ventilation rate of 100 volumes per hour. This resulted in a cooling rate of 0.3°C h⁻¹. However, Oke (1989) comments that even this "passive cooling" of isolated trees may not be significant in reducing air temperatures at ground level because most of the transpiration occurs at the top of the trees and may not be mixed throughout the volume.

The combined effects of shade and passive cooling can significantly reduce surface and air temperatures. In a descriptive survey of summertime urban surface temperatures, Kondo and Suzuki (1983) found that the presence of roof-gardens reduced surface temperatures of houses by up to 40°C. Measurements from Sacramento, California, suburbs with mature canopies found daytime air temperatures 1.7–3.3°C lower than in open areas (Taha et al., 1988). In Miami, Florida, average summer daytime air temperatures were reduced by 3.6°C under a large tree (Parker, 1989). In higher latitudes the effect of trees on lowering air temperatures is less. Souch and Souch (1993) report decreases of 0.7–1.3°C under a variety of trees in Bloomington, Illinois.

Given the potential of greenspace to decrease surface and air temperatures, several studies have tried to assess the energy savings of different landscape designs. McPherson (1989) used scale model houses to assess cooling and water impacts of different landscapes. He found that the high costs of maintaining a lawn outweighed the benefits from lower temperatures due to evapotranspirational cooling. However, the provision of shade and passive cooling by shrubs reduced energy used in air-conditioning by 30%. Similarly Parker (1981, 1983, 1987) used vegetative landscaping to reduce energy use in mobile homes. Substantial air-conditioning savings were made – up to 76%.

Such research has spawned efforts to model the effects of landscaping on residential
energy use. Thus microclimate models are linked with building energy simulations to quantify the effects of vegetation on energy savings. In simulations for Sacramento, California and Phoenix, Arizona, Huang et al. (1987) estimate that a 25% increase in urban tree cover can save 40% of annual cooling energy use in residences. Comparable savings in residential energy consumption were found for summertime simulations in large Canadian cities (Akbari and Taha, 1992).

The microscale shelter provided by vegetation affects pedestrian comfort and safety, air pollution dispersion and energy conservation (Oke, 1989). Trees and shrubs control the wind by obstruction, deflection and filtration. The effect and degree of control depends on species size and shape, foliage density and retention and the actual placement of plants (Grey and Deneke, 1978). Dense plantings can provide relief from cold winter winds, but in warm climates they can impede air flow and decrease human comfort by reducing both convective and evaporative heat loss (Heisler, 1977). In summary, therefore, each application requires careful consideration.

1.2.2 Impact of greenspace at the local–scale

There is a paucity of research on the local–scale effects of greenspace beyond descriptive surveys. It is well documented that urban parks can be cooler than their surrounding environment. Often the influence of parks on air temperatures is noted during urban heat island surveys. Few surveys assess the park effect itself. This effect can vary depending on the park type, the nature of the urban surrounds and the macroscale climate. Most surveys are in mid–latitude cities. Few studies are reported from low–latitude cities with either hot, dry or hot, humid, climates.

Parks can be classified by considering the arrangement of vegetation:

- Grass – open grass surface;
• Grass with tree border – open grass surface with a tree border;

• Savannah – grass surface with trees interspersed throughout;

• Garden – cultivated park with a mixture of grass, trees, shrubs and flowerbeds;

• Forest – park that has a continuous tree canopy coverage;

• Multi-use – park that has many different components e.g. grass playing fields, treed areas, swimming pools etc.

• Golf course

In addition to this simple classification the soil moisture regime of the park should be noted. Surveys of the thermal effect of parks should also comment on the nature of the urban surrounds. If the park is surrounded by a commercial area that is densely built with few pervious surfaces, its effect is likely to be enhanced. However, if it is surrounded by a well-treed residential area, the influence of the park on local temperatures will be reduced.

Only a few air temperature surveys are reported from hot, dry cities. This is surprising given the potential of parks to cool neighbourhoods. Kirby and Sellers (1987) studied air temperatures in Tucson, Arizona, during the period from late fall to early spring. They found that cold air drainage plays a dominant role in determining the fall and winter thermal climate of the city region, but they also note low temperatures centred on the largest park in the city.

Jauregui (1973, 1991) presents results from one of the few studies of thermal patterns associated with urban parks in a low latitude city with a tropical highland climate. In a study of a large park (525 ha) in Mexico City, he found maximum cooling during the dry season at which time minimum temperatures were 3–4°C cooler, and the extent of cooling reached about one park width into the urban neighbourhood (Fig. 1.5).
Figure 1.5: Isotherms (°C) in Chapultepec Park, Mexico City, on December 3, 1970 (about 600 h), in clear and calm conditions. The park area is shaded. (After Jauregui, 1991).
Studies of thermal regimes in hot, humid cities have indicated the park effect may be substantial. In Kuala Lumpur parks may be 4–5°C cooler than nearby commercial areas in the afternoon (Sham, 1986, 1987, 1991). Sham suggests that relatively small clumps of shady trees in the commercial area of a city can be far more effective than large grass-covered fields with isolated trees in moderating afternoon temperatures. However in the evening the well-treed parks are only slightly cooler (about 1°C) than their urban surrounds. In tropical Madras, India, Sundersingh (1991) reports parks may have a nocturnal cooling influence of up to 4°C.

In these hot, humid cities well-treed parks have an important role in lowering daytime air temperatures probably mainly through the provision of shade. In this humid environment the evaporative cooling of greenspace may be of reduced importance to that of a dry city. There is also a detrimental impact of transpiring vegetation on human comfort through increased humidification. In a moist environment, there will be several sources of moisture for evaporation other than urban parks (e.g. undeveloped lots, interception of precipitation by buildings, pervious surfaces etc.). Thus it is probable that sensible heat is less in hot, wet cities, with a higher latent heat flux than is observed in dry cities where moisture sources are much more limited. Therefore it is the macroscale climate, rather than any differences in greenspace characteristics, that determine the potential park effect. However, the park type, within the macroscale climate is of importance in realizing this potential.

Several park surveys have been conducted in mid-latitude cities: New York and Syracuse, N.Y. (Herrington et al., 1972; Herrington, 1977); London (Chandler, 1965); Montréal, P.Q. and Vancouver, B.C. (Oke, 1989). The thermal contrast between the park and urban surrounding is best developed on calm and cloudless nights (as for the urban heat island). The nocturnal coolness of the park is established soon after sunset following which the park and urban area cool at similar rates (Oke, 1989). For parks
ranging in size from 29 to 500 ha, results show that nocturnal temperatures inside the park are rarely more than 3°C, and typically 1–2°C, lower than the surrounding urban area. Larger thermal influences (up to 6°C) are reported from parks in Göteborg, Sweden (Eliasson, 1993; Lindqvist, 1992). The park cooling establishes a zone of larger influence beyond its borders. This zone of lower temperatures associated with the park is hereafter referred to as a “park cool island”.

In warm, dry summer climates it is likely that the park effect will be greater than in a warm, moist climate. The influence of parks is probably similar (but reduced in magnitude) to that in hot dry cities. This is due to the relative warmth of the city rather than any inherent difference in the greenspace. In warmer, dry cities, any moisture sources such as irrigated greenspace are likely to have a greater effect on the thermal regime of the urban environment.

As well as producing “cool islands”, urban parks are characteristically “moisture islands”. The humidity difference between urban and natural surfaces tends to be small and the spatial pattern is often complex. Given the similarity between park and rural surfaces it is useful to consider urban–rural humidity differences as an indicator of likely effects in a park. The consensus of mid–latitude studies is that urban canopy air is usually drier by day than rural air but slightly moister at night. This pattern is most pronounced during fine summer weather (Oke, 1987). Higher humidities by day over natural areas can be attributed to transpiring vegetation. Over open grassed areas this effect is small, but under a forest canopy, humidity is usually higher. While several researchers have noted the increased humidity in parks compared to urban surrounds, few studies give quantitative estimates. In the early evening parks cool more rapidly than

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2 This term is not strictly correct in Oke's framework of heat island terminology. He likens the typical temperature trace from the rural surrounds to the city centre to a warm (urban) island set amongst a cold (rural) sea. Parks thus form depressions (or cool pools) in the warm urban landscape. However, the term “cool island” is in widespread use and is appropriate for parks given the biogeographical analogy where “islands” are remnants of vegetation.
their urban surrounds. This may lead to convergence of moisture in the lower layers of the atmosphere as the evapotranspiration from the surface exceeds the loss to higher layers due to dampened turbulence. Thereafter, humidity decreases through the night and a vapour inversion may form and dewfall occurs. On the other hand, over built surfaces, the lack of evaporation, reduced dewfall, anthropogenic vapour and the stagnation of airflow all combine to maintain a less humid atmosphere.

Vegetation in parks through its effect on the wind regime, can lead to either a decrease or an increase in local air temperatures. Wind can increase evaporative cooling and the process of advection can carry cool air beyond the park boundaries. However, vegetative windbreaks can lead to a decrease of velocity and the creation of a sheltered zone within which air temperatures are increased. Therefore it is important to plan the configuration of the vegetation to achieve the desired effect.

There have been several cursory observations and suggestions of local park breezes (eg. Whiten, 1956; Gold, 1956; Bernatzky, 1982). In clear, calm conditions Oke (1989) suggests that parks develop their own climate in situ. A cool park may thermally induce a pressure gradient leading to a divergent outflow of cool air at low levels (park breezes) and subsidence over the park. This flow may explain the outward diffusion of cool air from its source that has been observed in park surveys (e.g Jauregui, 1991; Oke, 1989). In light winds, advection of cool park air can similarly result in the lowering of air temperatures in neighbourhoods downwind.

There have been a few attempts to numerically model the influence of greenspace at the local-scale. O’Rourke and Terjung (1981) combined a multi-layered canopy leaf energy budget model and a complex street canyon energy budget model. They simulated energy balances for four urban designs that incorporated parks and roof gardens in different building morphologies. The addition of greenspace increased net short-wave radiation and net radiation and decreased system re-radiation and sensible heat flux. A
numerical turbulence model used by Honjo and Takakura (1991) estimated the cooling effects of greenspace on urban surroundings. In the simulation, the scale and location of the park was changed. Advection of cool air from a park 100 m across resulted in lower air temperatures up to 300 m downwind. As the park size increased to 400 m the influence only increased to 400 m downwind. Their results suggest that smaller green areas (100 m across) with sufficient intervals (about 400 m) are preferable for effective cooling of surrounding areas.

1.2.3 Impact of greenspace at the mesoscale

The effects of greenspace on the urban meso-climate are little understood (Herrington, 1976). Givoni (1991) suggests that there are limited effects of greenspace beyond the microscale. Nevertheless much research is directed at assessing the use of the urban forest to mitigate urban heat islands (e.g. Akbari et al., 1988; Dwyer et al., 1992). Little attention has been given to other climatic impacts of the urban forest except in Oke's review (1989).

The urban landscape has aerodynamic roughness similar to forests (0.5–5 m) (Oke, 1987). There may be a seasonal variation in roughness; with greater values when deciduous trees are in leaf. This seasonal leaf change can also alter the roughness environment by removing some existing scales of regularity (streets are lined by trees with heights similar to houses), establishing new regularities (tree lines taller than the houses) or creating irregularities (scattered tall trees and clumps in an otherwise uniform array of buildings) (Oke, 1989).

There is remarkably little variation in radiation exchange across urban areas despite the wide range of surfaces found at the microscale (Oke, 1989). Greenspace that contains open grassland generally has higher albedos than either suburban or urban surfaces.
Brest (1987) estimated albedos for different land-uses in Hartford, CT. Downtown areas had albedos from 8–12%; suburban – 11–17%; treed greenspace – 7–19%; non-treed greenspace – 17–23%. He noted that vegetated surfaces have a higher albedo than most urban surfaces and exhibit seasonal patterns in reflectance associated with their phenology. However Vukovich (1983) found no difference in reflectivity between Forest Park (a savannah park) and adjacent neighbourhoods in St. Louis.

While greenspace may have a higher albedo, the emission of long-wave radiation is reduced due to passive cooling. Therefore, although net short-wave radiation may be reduced, net long-wave radiation is increased thus offsetting changes in net radiation. Hence there is little variation in net radiation across land-uses with varying amounts of greenspace. The conservative nature of net radiation has been noted by Schmid et al. (1991) who found less than 5% difference over suburban surfaces whose greenspace coverage varied substantially (35%–85%). At the mesoscale, White et al. (1978) found less than 10% difference in net radiation from different land-uses in St. Louis.

Oke (1989) suggests that it is the “hydrometeorological role of the urban forest that commands most attention”. A major problem of urbanization is the waterproofing of surfaces which results in rapid runoff. Urban greenspace plays an important role in intercepting and storing precipitation, thus slowing runoff. The other major hydrometeorological role of urban vegetation is transpiration which has important impacts on the moisture and thermal regimes of urban areas.

Recent measurements of the latent heat flux in suburban areas has shown that evapotranspiration can be substantial (30–50% of net radiation) (eg. Roth, 1991; Grimmond and Oke, 1994). This considerable water vapour flux is probably derived from irrigated gardens and parks, and trees tapping deeper soil water. Micro-advection of sensible heat from impervious surfaces may enhance the water loss by providing an additional energy source to net radiation. Advectively-enhanced evaporation was reported by Oke (1979)
in surface energy balance measurements over a suburban lawn in Vancouver, B.C.

While a single transpiring tree may not affect a significant reduction in air temperature at ground level, the collective effect of transpiring trees can affect air temperature at the mesoscale. Oke (1989) suggests the rate of heating declines with greenspace and that evaporative suppression (i.e. the thermal equivalent of energy used in evaporation which would otherwise contribute to turbulent warming) is of the same order of magnitude as the heating. Thus greenspace can generate significant intra land-use thermal differences.

Many numerical models have been used to assess the impact of greenspace on urban climates. Both Myrup (1969) and Rauner and Cernavskaja (1972) developed energy balance models to assess the influence of greenspace on the thermal regime of the city. They related temperature reductions to the amount of greenspace and both found a critical amount (20–30% cover) below which there was no amelioration of mesoclimate by vegetation. McElroy (1970\(^3\)), used a numerical model to simulate the nocturnal thermal structure over a city and good agreement was found with observations in Columbus, Ohio. The introduction of greenbelts resulted in marked cooling but it was localized both horizontally and vertically.

The model of Huang et al. (1987) (see section 1.2.1) has been used to project savings in energy use from greenspace at the mesoscale. Indeed Akbari et al. (1988) use projections from this model to indicate potential savings at the national level. They suggest that if every other single-family dwelling has three trees, annual energy use for the United States could be reduced by 30 billion kWh – an annual saving of about 2 billion dollars!

Predictions from these models should be used with caution as their treatment of evapotranspiration is very crude (Oke, 1989). Ross and Oke (1988) tested three models and found that none of them could simulate evapotranspiration satisfactorily.

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\(^3\)Cited in Oke, (1989).
Greenspace alters the climate of the urban environment. The microscale effects of greenspace have been well studied and careful landscape design can achieve significant reduction of temperatures and alter the wind regime. The local-scale effects of greenspace are only known in a qualitative sense, with few process-based studies. This highlights a need for basic research on the surface energy balance and climate of urban parks. There is also a lack of research on the influence of greenspace at the mesoscale. There have been many attempts to model the effect of greenspace but they fail to simulate evapotranspiration realistically.

1.3 Rationale and research approach

At the local-scale, effects of greenspace are poorly understood. Oke (1989) notes that considering the potential importance of parks in modifying urban climate, it is surprising how little research has been done beyond descriptive surveys of effects. The cooling potential of parks warrants further research. For cities with hot or warm summers, urban parks can be used to cool neighbourhoods, particularly at night when temperature reductions of only a few degrees can be critically important to high-risk groups such as the elderly (Clarke and Bach, 1971; Höppe 1991). The effect of parks on the urban temperature field has not been well described. Most studies are in temperate mid-latitude cities; few are reported for cities in hot-dry or hot-humid climates. Little is known about the diurnal influence of parks on the thermal regime. Further documentation of park effects on urban thermal climates is necessary, particularly for cities in hot climates.

These issues raised by Oke (1989) and others (e.g. Herrington, 1976; Hutchinson et al. 1983) highlight the need for process studies of urban parks. It is not known how urban parks modify the surface mass and energy balances or how they impact their urban surroundings. Yet an understanding of the SEB of urban parks is fundamental to
an understanding of park climate. This calls for field research with energy balance and climate measurements in urban parks. To assess the park influence fully, park climate and energetics should be compared to that of the surrounding land–use. To determine the degree to which parks behave as natural or rural surfaces, rather than urban (built) surfaces, comparisons should be made between the energetics and climate, of park, urban and rural environs.

Although the cooling effects of parks are well known, the primary processes for park cooling have not been elucidated. Oke (1989) raised the questions: Why is the within-park cooling not greater and why is it not similar to the rural case? Noting the nocturnal timing of the maximum temperature differential between the park and city, Oke suggested that the relative failure of the urban system to cool may be just as important as any special park cooling mechanism. However he felt it wise to await process studies before assigning energetic causes.

Scale modelling is an attractive tool to determine the relative contribution of cooling processes. It can overcome the inevitable complications and limitations of field studies and provides a valuable means to obtain experimental control. In addition, it is possible to manipulate park characteristics such as size and vegetation type and assess their impact on the magnitude and extent of cooling.

Scale modelling has been used successfully on a few occasions to simulate heating and cooling of urban surfaces. Oke (1981) used a simple hardware scale model to simulate nocturnal cooling rates for rural and urban surfaces. Surface cooling was simulated for calm and cloudless nights as the urban heat island is best developed in such conditions. Surface geometry was altered to simulate radiative cooling of a rural surface (flat) and several different urban surface (canyon) geometries. The influence of thermal admittance on cooling rates was also investigated by comparing cooling for a flat concrete “city” versus a wooden “countryside”. The model reproduced many features of the temporal
development of the urban heat island and compared favourably to field observations.

Johnson and Watson (1987) used a simple scale model to simulate nocturnal cooling in urban canyons in order to validate a numerical model. They created a simple (upside down) urban canyon by placing a plywood sheet, representing the floor of a canyon, on the open top of a freezer chest, whose walls act as canyon walls and whose floor is the cold, night sky. The modelled temperatures were in good agreement with the observed temperatures.

To study the park influence on local climate, the research strategy must consider both daytime and nighttime conditions. By day, radiant and turbulent processes are important in controlling park climate. This requires measurements of surface energy balance and climate parameters in parks, with comparisons to surrounding (urban), and rural sites. By night, turbulence is suppressed and radiative and conductive processes are probably the important controls on climate. While these processes could be studied in the field, scale modelling can overcome many limitations of field studies and provide much greater control.

The central objective of this thesis is to increase understanding of the energetics and cooling in urban parks. Research on the park influence is conducted in two cities with different summer climates: Sacramento, California (hot summer Mediterranean4) and Vancouver, British Columbia (cool summer Mediterranean5). While this represents only a subset of the macroscale climates where parks are important in cooling, the choice of these two cities will increase understanding of the range of influence of parks in different climates. The research adopts an integrated approach incorporating field studies that measure the park effect on the surface and air thermal regimes; direct measurement of park SEB; and scale modelling to determine the contribution of different processes to

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4 Köppen climate classification Csa.
5 Köppen climate classification Csb.
nocturnal cooling in parks. This results in practical guidelines for urban parks designed to gain the maximum climatic benefit.

1.4 Objectives

The specific objectives of this thesis are to:

1. increase our knowledge of the park effect on urban thermal regimes by
   
   • assessing the thermal effect of parks in two cities with different summer climates;
   
   • determining the diurnal pattern of the park effect on both air and surface temperatures.

2. measure the surface energy balance of urban parks in two cities with different summer climates;

3. determine the relative contribution of meteorological processes to nocturnal cooling in urban parks;

4. provide practical guidelines for planners regarding the manipulation of urban parks to attain maximum climate benefit.

This research incorporates three distinct parts. Chapter 2 realizes the first objective by providing results from summertime park surveys in hot Sacramento and cooler Vancouver. Chapters 3, 4 and 5 present the methodology and results from park surface energy balance studies in these cities. The final part involves scale modelling of nocturnal cooling in urban parks (Chapter 6 and Chapter 7). The results from each part are combined in Chapter 8. These are discussed and practical guidelines for planners regarding park design are developed.
Chapter 2

Survey of the Park Effect in Two Cities with Different Summer Climates

The objective of this part of the research is to provide a descriptive survey of the summertime thermal regime associated with urban parks in two cities from different climates: hot and dry Sacramento, California, and temperate Vancouver, British Columbia.

2.1 Method and Instrumentation

2.1.1 Survey areas

Sacramento

Sacramento (38°39'N, 121°30'W) is located in the extensive Sacramento Valley at the confluence of the American and Sacramento Rivers. The metropolitan area has a population of 1.48 million. Land-use surrounding the city is mainly intensive agriculture which requires heavy irrigation. The region has a Mediterranean-type climate with a hot dry summer. Typically the synoptic setting involves an anticyclone located west of the coast of California and predominantly westerly winds.

Air temperature surveys were conducted for ten parks in the Mission Oaks and Carmichael suburbs of Sacramento (Fig. 2.1). Their size ranges from 2 to 15 ha. Four are multi-use savannah-type parks with some playing fields, treed grassland, swimming pools and childrens’ playgrounds. Two are open grassed parks with heavy irrigation; one is a forested Botanical Garden; one is a golf course and the remaining two are undeveloped, dry, savannah parks.
Figure 2.1: Location of the fixed sites in Sacramento, California, and the traverse route for the park survey. The urban heat island traverse was from the dry rural site to downtown Sacramento.
Vancouver

Vancouver (49°15'N, 123°18'W) is located in the lower Fraser Valley on the west coast of British Columbia. The city lies north of the Fraser River and its Delta, and is bounded to the north by Coastal Mountains reaching 1500 m.

The general climatology for the Vancouver region is presented in Oke and Hay, (1994). The region has a Mediterranean-type climate with a cool summer. The large scale flow is predominantly from the west. In summer there are persistent high pressure systems with occasional weak frontal disturbances arriving from the north. Local climate variations are produced by the orography, and the proximity to water which generates land/sea breezes giving westerly winds by day and weaker easterly flow at night.

Air temperature surveys were conducted for ten parks on Vancouver's west side (Fig. 2.2). These include grassed parks (both irrigated and non-irrigated), grassed parks with substantial shade tree borders, savannah, garden, and multi-use parks. Park sizes range from 3 to 53 ha.

2.1.2 Data collection

Mobile surveys were used to collect air temperature data in the vicinity of parks. Most surveys were restricted to roads around the perimeter of parks (Howe and Carmichael Parks in Sacramento and Queen Elizabeth Park in Vancouver are the exceptions with road access.) Air temperatures were measured using an automobile equipped with a continuously-aspirated dry-bulb thermistor probe mounted in a radiation shield. Samples were taken at 0.2 to 0.5 Hz and the data continuously recorded either by a Campbell Scientific (CSI) 21X data logger, or a Fluke recorder which produces a temperature trace.
Figure 2.2: Location of the fixed sites in Vancouver, British Columbia and the traverse route for the park survey. The urban heat island traverse was from the rural site to downtown Vancouver.
In each city the traverses consist of two main routes. One concentrated solely on the parks, while the other was a more general traverse to measure the urban heat island (UHI) (see Figures 2.1 and 2.2). The UHI traverses were included to compare the park cooling with that at rural locations. Traverses usually began an hour after sunset because the time of the maximum urban heat island in mid-latitude temperate cities is often between sunset and midnight (Oke, 1982). Traverses were conducted mainly on calm and clear nights because these conditions permit the maximum microclimate temperature differences to develop. Wind speed and direction, and cloud conditions were obtained from climate observations and/or the local weather service. Cloud is classified according to height (high, mid or low) and cover: clear (< 0.1 sky cover); scattered (0.1–0.5 sky cover); broken (0.6–0.9 sky cover); or overcast (> 0.9 sky cover).

Continuous measurements from fixed stations were also used to compare air temperatures between parks, the city and the surrounding rural area. These measurements formed part of surface energy balance studies in different land–uses (Chapters 4 and 5).

The Vancouver study was more detailed, and included additional surveys using bicycles, because they are not restricted to the road network. These traverses were made at 4–5 hour intervals around Trafalgar Park and nearby Prince of Wales Park (see Fig. 2.2), for the period July 24–31 and August 24–25, 1992. Measurements of air and surface temperatures were gathered from a network of pre-assigned sites. Air temperature was measured with a thermistor probe mounted in a basket on the front of the bike and surface temperatures with a hand-held Minolta infra-red Compac 3 radiation thermometer. Data were recorded manually.

In addition to the ground surveys in Vancouver, surface temperatures of five parks were remotely sensed by an AGEMA Thermovision 880 system mounted in a helicopter. This system comprises an infra-red scanner (sensitive to radiation in the 8 to 14 micrometre waveband) with a 12° field of view and a computer with software for thermal image
analysis. The thermal range of the scanner is −30°C to +1300°C and the sensitivity of temperature is ± 0.05°C at +30°C. Flights were conducted at a height of 1–2 km, which gave a pixel resolution of 1.5–3×1.5–3 m on the ground.

2.1.3 Data analysis

Air temperatures were initially corrected to compensate for any warming or cooling during the time of the traverse. This method assumes that the warming or cooling rate is both linear and the same at all points on the traverse, regardless of land–use (ie. commercial, residential rural). Oke and East (1971) show that this is not strictly valid, therefore the corrections are only approximate. Temperature spikes at intersections and other anomalies were removed. All times given are in local apparent solar time (LAT) (Oke, 1987, p.340).

The maximum “park cool island” (PCI) is calculated for each traverse by subtracting the minimum park temperature (\(T_p\)) from the maximum neighbourhood temperature (\(T_n\)):

\[
PCI = T_n - T_p. \tag{2.1}
\]

In all the traverses the maximum neighbourhood temperature occurs in commercial land–use zones. This elevates estimates of the PCI which would be lower if a residential maximum is used. For traverses running into the surrounding rural region the maximum urban heat island (UHI) is also calculated:

\[
UHI = T_u - T_r, \tag{2.2}
\]

where \(T_u\) is the maximum urban temperature and \(T_r\) is the minimum rural temperature.

Temperature cross–sections were plotted to assist interpretaton of spatial patterns. Isotherm maps were drawn for selected traverses to show detailed spatial patterns of
temperature. In the more intensive Vancouver studies, the diurnal variation of the PCI for each park was also analysed.

Atmospheric corrections were made to the AGEMA surface temperatures, following the method of Voogt (pers. comm.). This uses an atmospheric radiation transfer model to estimate atmospheric emission and transmission using a description of the atmosphere and a model of the sensor–detected radiance which combines the atmospheric, surface, and reflected sky radiance components. Characteristics of the atmosphere were determined from vertical remote soundings, radiosonde ascents and climatological data (Voogt, pers. comm.). Once corrected, the images were processed by a GIS package (Idrisi) to obtain visual output.

2.2 Survey results

2.2.1 Spatial and temporal patterns of park influence on air temperatures in Sacramento

Mobile surveys

The thermal climate of several Sacramento parks was surveyed on 6 occasions over a three–day period with variable weather in August 1993. The PCIs were better developed on August 16 and 17 which were less cloudy and less windy (Table 2.1). In this warm climate, parks can have a substantial cooling influence (5–6°C). A pilot survey of the park effect in hot, dry Tucson, Arizona, measured a maximum PCI of 6.8°C (Appendix A).

The air temperature trace for the traverse at 2100 LAT on August 16 clearly shows the coolest parks are not only well–irrigated multi–use parks and a golf course, but also dry savannah parks (Fig. 2.3). Sutter Park in particular, which is set in a semi–rural neighbourhood, develops a large PCI which continues throughout the night until sunrise. This whole neighbourhood, due to its low density and semi–rural character, is
considerably cooler than surrounding suburban areas.

Although the small number of traverses does not constitute a full diurnal cycle, it appears that PCI may be largest soon after sunset. At this time several park types (dry savannah, forest and golf course) exhibit cool islands greater then 5°C. In the afternoon all park types have a small to moderate PCI (1.3–2.7°C). The larger PCIs are in multi-use parks where trees lower air temperatures (through shade and possibly evaporative cooling). Soon after sunset, cooling is well established in all the parks. The maximum cooling is in the dry savannah-type where a PCI of 6.5°C was observed. Although these parks are classified as “savannah” the trees are more dispersed than in the well-irrigated savannah areas of multi-use parks. The PCI in these open, dry parks is still large near sunrise. The other open parks (grass, golf course) also have high PCI near sunrise. The average PCI may be underestimated for the grass parks because one of the parks surveyed is located about 150 m away from the traverse road.

Table 2.1: The average PCIs for different park types in Sacramento in August, 1993. Four multi-use types, two irrigated grass, two dry savannah, one forest park and one golf course were surveyed. All PCIs and UHI are in Celsius. Sunrise was about 520 LAT and sunset about 1835 LAT.

<table>
<thead>
<tr>
<th>Date</th>
<th>LAT (h)</th>
<th>Grass (irrig.)</th>
<th>Savannah (dry)</th>
<th>Multi-use</th>
<th>Forest</th>
<th>Golf Course</th>
<th>UHI</th>
<th>Wind Spd. (m s⁻¹)</th>
<th>Cloud cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 14</td>
<td>1400</td>
<td>1.9</td>
<td>1.3</td>
<td>1.8</td>
<td>1.0</td>
<td>2.4</td>
<td>-3.5</td>
<td>6.2</td>
<td>high sct</td>
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<tr>
<td></td>
<td>2100</td>
<td>1.1</td>
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<td>7.2</td>
<td>high brkn</td>
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</tr>
<tr>
<td>Aug 16</td>
<td>400</td>
<td>3.0</td>
<td>3.8</td>
<td>2.9</td>
<td>3.8</td>
<td>3.0</td>
<td>2.1</td>
<td>clear</td>
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</tr>
<tr>
<td></td>
<td>1500</td>
<td>2.4</td>
<td>1.5</td>
<td>2.7</td>
<td>1.3</td>
<td>2.3</td>
<td>3.6</td>
<td>high sct</td>
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<tr>
<td></td>
<td>2100</td>
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<td>5.4</td>
<td>3.8</td>
<td>5.3</td>
<td>5.1</td>
<td>7.0</td>
<td>clear</td>
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<tr>
<td>Aug 17</td>
<td>400</td>
<td>2.2</td>
<td>3.1</td>
<td>1.7</td>
<td>3.0</td>
<td>2.3</td>
<td>3.1</td>
<td>high sct</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.3: Air temperature traverse including several parks and open spaces in Sacramento at 2100 LAT on August 16, 1993. Sunset was at 1835 LAT.

Legend:
1. Howe Pk. (multi-use)
2. Cottage Pk. (multi-use)
3. Orville Wright Pk. (grass)
4. Carmichael Pk. (multi-use)
5. Sutter Pk. (dry savannah)
6. Botanical Garden (forest)
7. Jan Pk. (dry savannah)
8. Mission Pk. (multi-use)
9. Eastern Pk. (grass)
10. Del Paso Country Club (golf course)
PCI and UHI at fixed sites

The two–day average PCI and UHI for fixed Sacramento sites is shown in Figure 2.4a (for locations of sites see Fig. 2.1). These air temperature differentials should be interpreted with caution since the measurements are at different heights (1.3 m park and wet rural (WR); 1.8 m dry rural (DR) and 9 m suburban (SU)). Over these two days there was some high cloud, therefore these results do not show a maximum effect.

In the early morning Orville Wright Park is only slightly cooler than the suburban site. Soon after midday the park is actually warmer than the suburban site and remains so until midnight. The Sacramento UHI may be negative by day. Comparison of the different UHI depending on the rural reference (SU–WR, SU–DR) serve to illustrate the importance of the character of the rural site for UHI measurements. These temperature differentials depend on more than the “urban” or “park” environment of interest – the nature of the base environment must be known and stable.

The cooling after sunset (Fig. 2.4b) shows the park rate is similar to that at the dry rural site. The dry rural site initially cools more quickly but for the latter half of the night these two sites have a similar rate. The wet rural site cools more slowly, at a rate similar to suburban site. Despite the rapid cooling of the park, the nocturnal PCI is small. This is because the park is about 2°C warmer than the suburban site in the late afternoon and park cooling must first erode this deficit before a PCI develops.

Summary of the park effect in Sacramento

In Sacramento, a dry savannah park in a semi–rural setting had the largest observed PCI. Irrigated parks can also create substantial cool islands, similar in magnitude to those observed in a pilot survey in Tucson. The irrigated and well–treed forest park and golf course induce the greatest effect (about 5°C). The UHI observed by mobile traverses
Figure 2.4: The PCI and UHI from fixed sites in Sacramento. The two–day average PCI, and UHI based on suburban–dry rural difference (SU–DR) and suburban–wet rural difference (SU–WR) are shown in (a) while the nocturnal cooling after sunset is shown in (b).
show the city to be a cool island in the afternoon, compared to dry rural areas, but after sunset it can be as large as 7°C. However, as windy conditions prevail at Sacramento, the creation of large PCIs and UHIs is relatively rare.

2.2.2 Spatial and temporal patterns of park influences on surface and air temperature in Vancouver

Overview

Nineteen automobile traverses were conducted in the vicinity of parks in Vancouver in the summer of 1992. There were three distinct study periods – June 22/23, July 28/29 and the most intensive – August 24/25. The weather for most traverses was mainly clear and calm; high scattered cloud occurred on a few occasions.

There is considerable temporal and spatial variability in the mean PCI (Fig. 2.5). It has a peak soon after sunset (about 3°C) which corresponds with a decrease in wind speed. The mean PCI then declines through the night but then increases again before sunrise. In the late afternoon when wind speed is at a maximum, the mean PCI is only 1.4°C. The extreme high PCI (about 5°C) occurs in garden parks soon after sunset. Shortly before sunrise open, grassed parks have a high PCI near 4°C. Another extreme PCI occurs in the afternoon in grass parks with large tree borders (about 4.5°C).

Traverse analysis for intensive period – August 24/25, 1992

This discussion reports observations from three surveys: park surface temperatures measured by the AGEMA system mounted in a helicopter; and air temperatures measured from automobile traverses and bicycle traverses.
Figure 2.5: PCI range and mean for parks surveyed in Vancouver in summer, 1992. The data are averages from 3 survey periods with comparable weather. The average wind speed is also shown as a dashed line.

Surface temperature

To assist interpretation of surface temperature patterns, aerial photographs of these parks are given in Figure 2.6. Four of the parks are grassed, but have very different soil moisture regimes. Tisdall and Prince of Wales Parks both have sand–based playing fields which are normally irrigated, maintaining a soil moisture of about 30%. Trafalgar Park was irrigated until a sprinkling ban in June, and by late August the soil moisture had dropped to about 13%. Montgomery Park and the field adjacent to Prince of Wales Park, are very dry (soil moisture 9%) because neither was irrigated.

Surface temperature images for the four flights (early afternoon, shortly after sunset, midnight and around sunrise) are given in Figures 2.7 to 2.10. In the early afternoon the surface temperature range is the greatest; tree canopies have temperatures of about 18°C whereas hot roofs approach 50°C. The dry grass parks have surface temperatures
comparable to built surfaces (35–37°C), while the irrigated grass parks are cooler (24–29°C). This is clearly seen in Figure 2.7c where irrigated and dry fields are side by side. In contrast, in the well–treed Shaughnessy area, surface temperatures are cooler throughout, and it is harder to locate Devonshire Park in the thermal image.

Shortly after sunset the parks establish cool islands. The drier open grass parks have the coolest surface temperatures (<8°C) while the irrigated fields are slightly warmer (9–12°C). The well–treed suburb is much warmer (12–14°C) with only the clearings in Devonshire Park showing substantial cooling.

By midnight the very dry Montgomery Park has the lowest temperatures (3.5–6°C). The other dry parks such as the field near Prince of Wales, and Trafalgar parks, have temperatures less than 8°C. Irrigated playing fields are much warmer, particularly at Prince of Wales Park where irrigation was occurring. At Shaughnessy the temperatures are uniformly warm with small patches (gardens and clearings) slightly cooler.

Near sunrise the patterns are the same as observed through the night, however the temperature contrast between the dry and moist parks has further increased.

**Automobile traverse air temperature**

August 24 and 25 were good days for thermal differences to develop. In mid afternoon of the 24th the UHI was about 4°C, increasing to 5.9°C near sunset with a peak near midnight at 9.8°C, and remaining around this value until sunrise. This is within 0.4°C of the maximum ever observed in Vancouver (Oke, 1981). Throughout the day, thermal effects of parks are clearly identifiable. Parks are represented by marked dips in the temperature trace, a “cool island”, relative to their neighbourhood (Fig. 2.11). The intensity of the PCI appears to depend upon the time of day and type of park (Fig. 2.12).

Whilst the diurnal patterns are not markedly different, certain consistent features relate to park type. Open grass parks have a relatively uniform mean PCI of about 2°C
Figure 2.6: Aerial photographs of Vancouver parks used in helicopter survey of surface temperatures.
Figure 2.7: Surface temperatures of Vancouver parks and neighbourhoods at 1400 LAT on August 24, 1992.
Figure 2.8: Surface temperatures of Vancouver parks and neighbourhoods at 1930 LAT on August 24, 1992. Sunset was at 1919 LAT.
Figure 2.9: Surface temperatures of Vancouver parks and neighbourhoods at 2300 LAT on August 24, 1992.
Figure 2.10: Surface temperatures of Vancouver parks and neighbourhoods at 500 LAT on August 25, 1992. Sunrise was at 518 LAT.
Figure 2.11: Trace of air temperature from a traverse in Vancouver at 1900 LAT on August 24, 1992. Sunset was at 1919 LAT.
Figure 2.12: Average PCIs for different park types in Vancouver on August 24/25, 1992. The survey comprised five grass parks (with varying soil moisture), two grass parks with large tree borders, a garden and a multi-use park and one savannah park.
through the day (Fig. 2.12a). The mean PCI increases soon after sunset and reaches a maximum close to 3.5°C shortly before sunrise. Grass parks with tree borders have a maximum effect in the afternoon, with a secondary peak near sunrise (Fig. 2.12b). The garden, multi-use and savannah parks show a distinct and large (4°C) mean PCI soon after sunset (Fig. 2.12c and d). They have a similar pattern of a decrease in the PCI beyond this maximum, and then a gradual increase towards sunrise.

Bicycle traverse air temperature

Figure 2.13 demonstrates the microscale variability of air temperatures around Trafalgar Park and Prince of Wales Park. The traverse at 1400 LAT shows little difference in air temperature between the parks and the neighbourhood. However, after sunset the cooling effect of the park quickly becomes established. The air in the vicinity of both parks is 1–2°C cooler than their surrounding environment. By 2300 LAT these temperature differences are accentuated, and Trafalgar Park has a PCI of approximately 2.5°C. Comparison of air temperatures with surface temperatures for Trafalgar Park at this time (see Fig. 2.9b) shows that cooler air has been advected beyond park boundaries, with the park’s influence felt up to about the park’s width away. The coolness of the surrounding neighbourhood may be due in part to cold air ponding due to drainage from higher land, but Trafalgar Park is clearly evident as a “cold island”. Prince of Wales Park is warmer than Trafalgar, probably due to the fact it is at a higher elevation. Shortly before sunrise the park is only about 0.5°C cooler than the urban surrounds.

This more detailed survey confirms that the cooling effect for open parks is most pronounced after sunset, and that it extends beyond the boundaries of the park. Bicycle traverses have the advantage of measuring air temperatures within parks to get a

1This neighbourhood is mainly residential. This explains the lower estimates for park cooling compared to Figure 2.12 which uses the maximum suburban temperature to derive the PCI.
Figure 2.13: Isotherms (°C) for air temperature around Trafalgar and Prince of Wales Parks and neighbourhoods, August 24 and 25, 1992. The data were gathered by bicycle surveys within and around the parks.
more accurate measure of the PCI. A comparison between air temperatures measured by bicycle and those measured from the mobile automobile traverses, which only measure air temperatures around the perimeter of the park, suggests that the latter may underestimate the nocturnal PCI in these parks by up to 1.5°C. On the other hand, by day automobile traverses may overestimate the PCI, particularly for drier parks where the surface can be warmer than near the bordering tree canopy where the automobile samples.

PCI and UHI from fixed sites.

Continuous measurements of air temperatures at fixed sites in an open grass park (Trafalgar), suburban (Sunset), downtown and rural (Delta) areas (see Fig. 2.2), allows comparison of PCI and UHI development together with their nocturnal cooling characteristics (Fig. 2.14a and b). As measurements were taken at different heights: 1–1.5 m at the park and rural sites; 11 m at the suburban site; and 3 m at the downtown site, the trends should be interpreted with caution.

Trafalgar Park is slightly warmer than the suburban site by day but is about 2–2.5°C cooler at night (Fig. 2.14a). The UHI (suburban–rural difference here) is larger at night; close to 5°C. Throughout the night, the park and the rural site have very similar cooling rates (Fig. 2.14b) which are considerably greater than for the city sites, especially in the first two hours after sunset. This divergence is probably due to differences in view factors (greater sky view factors at open sites enhance radiative cooling) and possibly in thermal admittance. Natural surfaces often have lower thermal admittance which means they have little heat to release and this heat is released more readily. This establishes the maximum difference in temperature between the land–uses, within three hours after sunset. The cooling rate in the suburban area remains almost constant throughout the night. At the downtown site the rate is more variable.
The park cooling is comparable to the rural case but the nocturnal PCI is less than
the UHI. This phenomenon was also observed in Sacramento. It occurs because the park
is warmer than the suburban site in the late afternoon. Thus park cooling must first
erode this deficit allowing only a small PCI to develop.

Summary of the park effect in Vancouver

The surveys in Vancouver were all conducted under “ideal” conditions (calm and clear
skies). Several researchers have observed maximum surface temperature contrasts by day
in urban areas with a reduced range at night (the opposite to air temperature patterns).
The Vancouver survey confirms this: surface temperature contrasts between greenspace
and the built environment peak in the early afternoon. However, open dry grass parks
are not necessarily cooler than urban areas. Nocturnal cooling is most pronounced in
parks with high sky view factors and dry soils. A savannah park is much warmer by
night probably because the canopy reduces radiative loss.

The ensemble average PCIs for all parks surveyed show considerable temporal and
spatial variability. However, there are consistent patterns relating to park type. Parks
with substantial tree canopies have maximum PCI in the afternoon. Garden, multi-use
and savannah parks peak soon after sunset, while open grass parks have a maximum PCI
near sunrise.

2.3 Comparison of PCIs in cities from hot and cool summer Mediterranean
climates

The air temperature surveys in the two cities confirm and extend earlier findings of the
thermal effects of parks. Observations in Vancouver are fairly consistent with Oke’s
(1989) discussion that the park effect in mid-latitude cities is typically 1–2°C and rarely
Figure 2.14: PCI and UHI, and nocturnal cooling for fixed sites in Vancouver. The data are four-day averages (July 25–28, 1992). The PCI is a suburban–park air temperature difference and the UHI is a suburban–rural air temperature difference (a). Nocturnal cooling for different land–use types is shown in (b).
more than 3°C. The park effect in Vancouver is slightly greater than previous estimates. Under ideal conditions PCIs approach 5°C.

The PCI and UHI in Sacramento and Tucson show many similarities. In both cities the PCI for irrigated parks can be substantial (5–7°C). Several of the observations were not conducted under ideal conditions. This suggests a larger effect may be possible. While the PCI is typically larger than in mid-latitude temperate cities, the UHI is somewhat smaller (2.5–7°C). By day, the city may be a cool island. Within this cool island are even cooler parks.

In each city the largest PCI are generally found in larger multi-use and garden parks, and golf courses. These parks have a PCI that is well established in the afternoon. Soon after sunset there is a marked increase in the urban-park temperature differential. Well-treed parks often have their maximum PCI at this time. Irrigated open grass parks usually have higher PCIs near sunrise, while unirrigated ones cool rapidly after sunset and continue to cool at a greater rate than other park types, establishing their highest PCIs in the hours prior to sunrise. Despite the large PCIs observed in all cities, the park effect remains fairly localized: up to about the park’s width away.

These observations suggest that during the day trees may play an important role in establishing a cool park effect, perhaps through a combination of shade and evaporative cooling. At night it appears that the surface geometry and moisture status of the park are important controls on surface cooling. Open parks (with higher sky view factors) that have dry soils (and hence lower thermal admittance) cool the most. The contribution of these processes to nocturnal cooling is investigated through scale modelling, in Chapters 6 and 7.

The potential park effect is largely determined through macroscale climate and the character of the urban surface. For a given park type, in a given urban setting (e.g. suburban) the potential for it to be cooler than its urban surrounds depends on the
macroscale climate. For example if the Van Dusen Gardens in Vancouver were transplanted to Sacramento, the effect of this park would be increased. The warmer the climate, and the drier the climate, the greater the effect.
Chapter 3

Conceptual Framework for Field Measurement

This chapter discusses the framework for surface energy balance (SEB) measurements in urban parks. First there is a discussion on the influence of the advective regime on the spatial variability of the SEB. This considers spatial variability in response to fetch (the distance of airflow in the upwind direction) and the turbulent regime in a park. The second part of the chapter discusses the basis for the selection of site locations. The chapter concludes with an overview of techniques used to measure the SEB fluxes.

3.1 Spatial variability of SEB across a park

The SEB framework for an open grassed park is more similar to the rural case of a pasture or low crop, than the urban case. With a low grass canopy, the storage term is replaced by the gound heat flux, \( Q_G \), and the net biochemical heat storage, \( \Delta Q_P \), is sufficiently small to be neglected. However, when placed in an urban setting a park is likely to experience advective effects so the advection term must be included. Thus the energy balance for a park is given by:

\[
Q^* = Q_H + Q_E + Q_G + \Delta Q_A. \tag{3.1}
\]

3.1.1 Influence of fetch on the SEB in a park

Rather than taking measurements at a central point in the park, several sites are chosen to provide an indication of the spatial variability of the surface energy balance. Net
radiation and soil heat flux are likely to be spatially relatively conservative in an open park (providing there are no trees and the soil is homogeneous), but the turbulent fluxes are likely to vary. For example, the latent heat flux varies in response to fetch (distance from the boundary between the park and the comparatively warm and dry suburban area). This is the "leading edge" or "fetch" effect (Oke, 1987) whereby $Q_E$ is greatest at the leading edge (i.e. the park boundary) because of microscale advection of dry air, and decreases rapidly with distance into the park. If the park is moist compared to the surrounding neighbourhood, and large enough, it may also act as an "oasis" (Tanner, 1957). In this case the advection is accompanied by subsidence of warm air from the upwind neighbourhood, over the cool park which supplements the radiative energy supply and thereby makes it possible to sustain abnormally high rates of evapotranspiration.

In the absence of advection, evapotranspiration from a well-watered, extensive surface, has a lower limit termed "equilibrium evaporation", $Q_{Eq}$, by Slatyer and Mcllroy, (1961):

$$Q_{Eq} = \frac{s}{s + \gamma}(Q^* - Q_G)$$  \hspace{1cm} (3.2)

where $s$ is the slope of the saturation vapour pressure–temperature curve (0.145 k Pa°C$^{-1}$ at 20°C) and $\gamma$ is the psychrometric constant ($\gamma = c_p \rho / (L_v \epsilon)$ where $c_p$ is the specific heat of air at constant pressure (1.01 J g$^{-1}$°C$^{-1}$), $L_v$ is the latent heat of vaporization (2440 J g$^{-1}$ at 20°C), $\rho$ is the density of air (1.20 kg m$^{-3}$ at 20°C) and $\epsilon$ is the ratio of the molecular weight of water to that of dry air (0.622)). The value of $s/(s + \gamma)$ at 20°C is 0.69.

Priestley and Taylor (1972) used equilibrium evaporation as the basis for estimating "potential evapotranspiration", $Q_{Ep}$. They defined this as the evaporation that would occur from a large-scale, well-watered region in the absence of advection. It is estimated
by:

\[ Q_{Ep} = \alpha Q_{Eq} \]  \hspace{1cm} (3.3)

where \( \alpha \) is an empirical constant. They showed that for oceans or extensive wet vegetated surfaces, evaporation was about 26\% greater than \( Q_{Eq} \) (i.e. \( \alpha = 1.26 \)). Equation 3.3 with \( \alpha = 1.26 \) has had widespread application and gives good estimates of evaporation even for areas much smaller than "regions"\(^1\).

Brutsaert (1982) suggests that over wet surfaces, equilibrium conditions are encountered only rarely, if ever. This is because the atmospheric boundary layer is never a truly homogeneous boundary layer, but is continually responding to large scale weather patterns. This contention was supported by \( \alpha = 1.26 \) to 1.28 observed over oceans or large wet surfaces. Hence he suggests that evaporation from these surfaces is assisted by large-scale advection. Similarly, McNaughton and Spriggs (1989) suggest that while Priestley and Taylor's potential evaporation is valid for estimates of evaporation in the absence of local advection, \( Q_{Ep} \) may include some large-scale advection. This is because Priestley and Taylor did not consider energy exchanges between the planetary boundary layer and the atmosphere at large. The additional evaporation comes from the entrainment of warm, dry air from the inversion above the growing daytime planetary boundary layer.

Lang et al. (1974) suggest that the advective component of evaporation, \( Q_{Eadv} \) can be determined from:

\[ Q_{Eadv} = ax^{-p} = Q_E - Q_{Ep} \]  \hspace{1cm} (3.4)

where \( a \) and \( p \) are empirical constants and \( x \) is the distance downwind from the leading edge. Parameter \( a \) is the amplitude of the advective evapotranspiration and \( p \) describes its rate of decay downwind. Exponent \( p \) is obtained from the profile law for windspeed.

\(^1\)The relation was developed for regions measuring tens of thousands of square kilometres.
and Lang et al. (1974) estimate it to be 1/6 for crops. This relation implies rapid decay in evaporation immediately downwind of the leading edge, and a gradual decrease towards potential evaporation with increasing distance. Equation 3.4 may underestimate the advective component by using $Q_{Ep}$ as a base reference to determine advective effects.

Few researchers distinguish between edge- and oasis-effects i.e. microscale and mesoscale advection. Often the confounding effects of proximity to a leading edge are avoided by siting instrumentation within an extensive homogeneous area. However, in the context of an urban park it is useful to make the distinction between edge and oasis effects. A conceptual framework for distinguishing these effects is developed after the method of Brakke et al. (1978).

Brakke et al. (1978) inferred advective effects by comparing evaporation with the term $Q^* - Q_G$. At a considerable distance downwind from the leading edge $Q_E$ does not change with distance. They suggested that the elevation of $Q_E$ over $Q^* - Q_G$ was due to regional sensible heat advection. Near the leading edge $Q_E$ surpasses this value and they suggested this was due to local advection.

It appears that Brakke et al.'s (1978) use of $Q^* - Q_G$ as a base reference for potential evaporation in the absence of advection, is too high. This framework is revised using equilibrium evaporation which is a more accepted definition for evaporation in the absence of advection. The advective scales are also revised on the basis of the scale classification of the urban canopy layer (Table 1.1).

It is suggested that due to the edge effect, evaporation in a wet park will show an approximately exponential decay immediately downwind of park boundary (Fig. 3.1a). The edge-effect results from microscale advection from surfaces immediately upwind from the park boundary. With distance into the park, evaporation will decrease until, if the park is large enough, it becomes steady (i.e. unchanging with distance). At this distance, the elevation of evaporation above the equilibrium rate indicates the degree
of mesoscale advection. It is foreseeable that in urban areas, oasis-type advection may further enhance evaporation. This is an extreme case of mesoscale advection and is said to occur if $Q_E > Q_{Ep}$.

Several studies of evapotranspiration from irrigated fields surrounded by semi-arid areas report both edge and oasis effects (see Rosenberg et al., 1983 for a review). For example, a number of observational studies at Davis, California (near Sacramento) (eg. Dyer and Crawford, 1965; Goltz and Pruitt, 1970) used a series of air temperature profiles across irrigated grass fields set in the midst of dry fields to infer $Q_H$. The latent heat flux was estimated from both closure of the energy balance ($Q^*$ and $Q_G$ were measured) and lysimetry. Lang et al. (1974) used lysimetry to study the influence of local advection on evaporation from an irrigated rice field and Rider et al. (1963) measured evaporation from
irrigated grass downwind from a paved surface. These studies all show local advection consistent with Fig. 3.1a. With increasing fetch the edge effect decays until, finally, it adjusts fully to the new surface and remains approximately constant with distance. Estimates of the extent of the edge effect vary widely from less than 20 m (Rider et al., 1963) up to 200 m (Rijks, 1971). Local advection contributes to increased evaporation in urban areas. Oke (1979) found advectively-assisted evapotranspiration over an irrigated suburban lawn in Vancouver, B.C.

The oasis effect has been reported from observations over crops at many locations (e.g., Fritschen and van Bavel, 1962; Rosenberg, 1969 and 1972; Wright and Jensen, 1972; Blad and Rosenberg, 1974; Rosenberg and Verma, 1978). Even at considerable fetch these studies show evaporation is significantly higher than the potential rate. For example, Rijks (1971), in a study of water use by irrigated cotton in the Sudan, found evaporation rates 1.8 times greater than the supply of net radiation when both edge and oasis-type advection were important. The oasis effect alone elevated $Q_E/Q^*$ to 1.5.

In an unirrigated park, the spatial pattern of $Q_E$ may be very different (Fig. 3.1b). It is suggested that if irrigation is not applied, soil moisture content near the upwind edge is likely to become depleted in comparison with the rest of the park, due to the cumulative loss of soil water associated with microscale advection. Eventually such enhanced $Q_E$ at the upwind edge of the park can no longer be sustained. Further away from the edge, $Q_E$ is greater than that of the background suburban value. Even if the surface is not saturated, mesoscale advection will probably elevate evaporation above the equilibrium rate. The size of this suburban–park difference in $Q_E$ probably depends upon many factors including the regional climate, and soil moisture content, suburban density and gardening practice.
3.1.2 Influence of the turbulence regime on the SEB in a park

The turbulence regime in a park

Since a park may be surrounded by buildings and/or trees, air-flow distortion can occur, especially near the upwind boundary. In the absence of work directly on flow in parks, there are three main sources of evidence that can assist understanding: studies of airflow around buildings, windbreaks and forest clearings. Research on airflow around buildings has concentrated on the turbulence field upwind and downwind of the building in order to model pollutant dispersion. Less consideration has been given to the spatial variability of turbulent fluxes downwind of a building, however, this work can yield important clues. Windbreak research is the most useful in providing data on the variation of turbulent fluxes behind a barrier. It often focuses on the variation of evaporation with distance from the barrier, so this literature is of direct interest. Finally, work on turbulence in forest clearcuts, can be of assistance. To date there has not been much quantitative research but some wind–tunnel studies can assist in interpretation of patterns of turbulent fluxes within a park.

The flow field immediately downwind of an isolated building is characterized by the wake cavity, which is a zone of low pressure and reduced mean windspeed, in which flow recirculates. Beyond the cavity is the turbulent wake zone in which a large velocity gradient interacts with a large downward momentum flux to produce considerable turbulence (Fig. 3.2). The length of the cavity ($x_r$) depends on the building dimensions (height, $H$, length in the along–wind direction, $L$, and width of the building in the cross–wind direction, $W$), the speed and vertical variation of the incident wind, the intensity and scale of the incident turbulence, the stability of the approach flow, the aerodynamics of the upwind surface, and the fluid viscosity (Hosker, 1984). There are several studies (mostly wind–tunnel) that give quantitative data on the dimensions of the wake cavity.
Figure 3.2: Flow distortion over a building – the cavity and turbulent wake zones. (From Hosker, 1984 based on Woo et al. 1977 and Hunt et al. 1978.)

Hosker (1986) in a review of the literature, reports a study by Fackrell and Pearce that estimates the along-wind extent of the cavity of an isolated building to be:

$$\frac{x_r}{H} = \frac{1.8\frac{W}{H}}{\left(\frac{L}{H}^{0.3}(1 + 0.24\frac{W}{H})\right)^{0.5}}.$$  \hspace{1cm} (3.5)

Typically, for approach flow perpendicular to a building with a $W/H$ of 1, the quiet zone extends to about 5 $H$ and increases to about 12 $H$ as $W/H$ increases to 40 (Hosker, 1984). If the building is oriented at an angle to the approach flow, the cavity is considerably broadened and lengthened (Robins and Castro, 1977; Ruck, 1993). The horizontal extent of the turbulent wake zone depends on the dimensions and orientation of the building, but Hosker (1984) suggests that the wake typically extends at least 10 to 20 $H$ downwind. The turbulent wake zone increases if the wind blows at an angle to the building and in stable conditions.

Windbreak studies typically assess impacts on the microclimate in the lee of the obstacle. The characteristic flow around a windbreak is similar to that around a building.
with both a cavity and a turbulent wake zone. Raine and Stevenson (1977) termed this cavity the "quiet zone", reflecting the reduced wind speed and turbulence dominated by small eddies. However, unlike buildings, windbreaks may be porous allowing some flow to "bleed" through the shelter (Fig. 3.3) so the nature of the quiet zone depends on the nature of the barrier (solid or porous) and the turbulent characteristics of the approach flow. McNaughton (1988) reports that denser barriers produce the largest reductions in velocity close in their lee and that the quiet zone is longer behind such barriers. One must also consider the height of the obstacle (H) in relation to the surface roughness, (z0). At higher values of H/z0 greater reductions in mean wind speed occur in the lee and a larger quiet zone is observed (van Eimern et al., 1964). Windbreak studies suggest that the quiet zone extends to about 8 H behind a long windbreak in near-neutral conditions with the approach flow perpendicular to the windbreak and H/z0 ≈ 100 (McNaughton, 1988). As for buildings, increasing stability greatly increases the extent of the quiet zone, and instability decreases it. Little research has been done on the turbulent wake zone.

The final source of data that is useful in determining the likely turbulence regime of a park is that of turbulence research at forest edges and clearcuts. The analogy between a forest clearcut and a park may be a useful one. Oke (1989) explored the similarities between the urban canopy layer and a forest canopy. With regards to aerodynamic properties, he noted that buildings are true bluff bodies because of their impermeability, inflexibility and sharp edges. Although trees are good generators of mechanical turbulence, buildings are far more effective roughness elements. Despite these differences it may be of some merit to consider studies of turbulence in forest clearcuts. The concept of canopy--airstream coupling may be similar in both cities and forests and in turn in urban parks and forest clearcuts.

As McNaughton (1989) noted, this field has received little attention. While some research has focused on wind regimes associated with forest edges (e.g. Raynor 1971,
Bergen 1975, Gash 1986) few studies have concentrated on turbulence. Chen et al., (1994) simulated a forest clearcut in a wind-tunnel and made intensive turbulence measurements. They observed a quiet zone that extended to about 3 H, a turbulent wake zone from 3 to 18 H, followed by a readjustment zone.

A significant difference between a park in an urban canopy and a windbreak in a forest is the geometry imposed in the urban case by streets. It is possible that street geometry could channel air-flow into and out of, parks. These jets could significantly alter the turbulence regime in the park.

In conclusion, despite the absence of turbulence measurements, it may be possible to infer the turbulent regime within a park, based on the foregoing discussion. The extent of the quiet and turbulent wake zones will depend greatly on the nature of the park boundary – whether buildings, vegetation or both, the angle of the prevailing wind to this boundary and on turbulent characteristics of the approach flow.
Impacts of the turbulent regime on the SEB in a park

From the foregoing, if the suburban–park boundary is abrupt, we may expect three distinct turbulent regimes to exist in the park (quiet zone, turbulent wake zone and readjustment zone). This will bring implications for climate variables such as humidity and temperature as well as the SEB fluxes. McNaughton (1988) discussed the likely patterns of these in both the quiet and turbulent wake zones.

In the quiet zone, eddy diffusivity is decreased due to the reduction in turbulent kinetic energy and eddy size, so the turbulent transport of scalars is suppressed. Hence it is expected that both surface temperatures and humidity will be higher during the day. The wake zone is characterized by considerable turbulence, consequently it is dominated by larger eddies giving enhanced eddy diffusivity and turbulent transport of scalars. This results in lower surface temperatures and humidity. The study by Chen et al. (1994) found a pattern of increasing eddy diffusivity with distance from the forest edge, reaching a maximum at 6 H in the turbulent wake zone (Fig. 3.4).

Effects on the SEB are more complex. As discussed earlier, net radiation and the ground heat flux are not likely to vary greatly across an open grass park with homogeneous soil, except at the park edges if there are any shadows cast by a vegetated or built border. However, since both $Q^*$ and $Q_G$ depend on surface temperature there is likely to be some variability of these fluxes between the quiet zone and the turbulent wake zone. With higher surface temperatures in the quiet zone $Q^*$ may be reduced due to the increase in out-going long-wave radiation, while $Q_G$ will increase. Conversely in the turbulent wake zone, where mixing tends to smooth out the diurnal temperature wave, $Q^*$ will be higher and $Q_G$ will be reduced (McNaughton, 1988).

Due to suppressed turbulent transport in the quiet zone, it is expected that the turbulent fluxes $Q_E$ and $Q_H$ will be reduced. However, the situation is more complex,
Figure 3.4: Eddy diffusivity patterns in a forest clearcut (from Chen et al., 1994).
due to the dependence of the evaporation rate on the saturation deficit. Evaporation, $E$, from a plant canopy can be described

$$E = \frac{pD_o}{r_c}$$

(3.6)

where $r_c$ is the canopy resistance and $D_o$ is the surface value of the saturation deficit (Monteith, 1963). If the canopy resistance is uniform across a field then changes in evaporation reflect changes in $D_o$. The surface saturation deficit will vary depending on the degree of “coupling” between the surface and the conditions overhead. If the surface is well coupled, such as in the turbulent wake zone, $D_o$ will approach the saturation deficit overhead, $D_z$, at a level uninfluenced by the windbreak. However in the quiet zone with reduced wind speed and turbulence the surface is effectively decoupled from the flow overhead so $D_o$ will increase or decrease depending on the relative amounts of heat and vapour added (McNaughton, 1988).

McNaughton and Jarvis (1983) introduced a decoupling factor $(\Omega)$ that varies from 0 when the surface is completely coupled to conditions overhead, to 1 when the surface is completely decoupled. In an open field $\Omega$ is given by:

$$\Omega = \left[1 + \frac{r_c}{r_a(1 + \varepsilon)}\right]^{-1}$$

(3.7)

where $r_c$ is the canopy resistance, $r_a$ is the aerodynamic resistance and $\varepsilon = sL_v/c_p$.

In the quiet zone it is expected that $\Omega$ will be larger than upwind as the sheltered surface is more decoupled from conditions above. When the surface is completely decoupled equilibrium evaporation prevails given by equation 3.2. This is equivalent to viewing $D_o$ in equation 3.6 as having an “equilibrium saturation deficit” (McNaughton, 1983):

$$D_{eq} = \frac{s(Q^* - Q_G)r_c}{\rho L_v(s + \gamma)}.$$

(3.8)
Given the concept of coupling, McNaughton (1988) then suggests that a change in coupling ($\Delta \Omega$) produces a change in $D_o$:

$$\Delta D_o = \Delta \Omega (D_{eq} - D_z) \quad (3.9)$$

and a change in evaporation rate

$$\Delta E = \frac{\Delta \Omega \rho (D_{eq} - D_z)}{r_c} \quad (3.10)$$

from the canopy-model equation 3.6. Thus evaporation in a sheltered area can be increased or decreased depending whether the air overhead is drier or wetter than $D_{eq}$, and also on the sign of $\Delta \Omega$. Under conditions of dry air advection the latent heat flux will be reduced in the quiet zone and enhanced in the turbulent wake zone.

The sensible heat flux can be considered as the residual after $Q_E$ is taken from the available energy, so as $Q_H$ increases, $Q_E$ decreases. Hence under conditions of dry air advection $Q_H$ will be increased in the quiet zone and decreased in the turbulent wake zone (McNaughton, 1988).

In summary, understanding the spatial variability of the SEB components in a park requires consideration both of the fetch and turbulent regimes of the park. Microscale advection is likely to occur at the upwind edge of parks if a moist park is surrounded by a warm, dry suburban neighbourhood. Thus one expects an exponential decay in evaporation with distance from the upwind park edge. However, urban air flowing from roof-level down into the park creates a turbulence regime that has a quiet zone at the upwind edge, and a turbulent wake zone further into the park. The dimensions of the zones will vary depending on characteristics of the approach flow and on the nature of the park boundary. In the quiet zone $Q^*$ may be slightly reduced while $Q_G$ may be slightly increased due to higher surface temperatures. Evaporation is substantially reduced due to decoupling of the surface from conditions overhead, which results in an increase in
Figure 3.5: Scenario for likely impacts of both fetch and the turbulence regime on the spatial variability of the daytime SEB in a suburban park. The length of the arrows indicates the approximate proportions.

$Q_H$. Conversely, in the turbulent wake zone increased turbulent transport reduces the decoupling, and $Q_E$ is enhanced, while $Q_H$ is reduced. These concepts are illustrated in Figure 3.5.

3.2 Site locations

The observation programme is designed to measure the surface energy balance of two suburban parks with similar characteristics (size, water status and vegetative cover) in different summer climates, viz:

- Sacramento, California – hot summer Mediterranean;

- Vancouver, British Columbia – cool summer Mediterranean.
The choice of two background climates is to assess any differences in the influence of parks in different climatic regimes. The traverse data indicate that the park cool island is greater in a hot dry climate. Energy balance measurements in both climatic regimes are designed to understand the driving forces of park climate. To achieve this, it is necessary to place the park in context with respect to its surroundings. Hence, in each study, observations are simultaneously taken at suburban and rural sites. A comparison of energy balance fluxes and climatic parameters at each site helps elucidate controls on park climate.

To facilitate study and interpretation, the research is conducted in a simple park system. In this reductionist approach, the park should be an open, well-irrigated, grassed park, in a flat area away from local topographic influences. This is to simplify measurements and reduce any confounding effects of different or layered vegetation or local drainage flows. In addition the park should be located in a residential area. This is to enable comparison with flux measurements available concurrently from a tower in a residential suburb. Research into the park system in its simplest form provides a tractable problem but does limit the generality of results. Finally, from a practical standpoint, the park must be accessible and secure, because equipment is installed for up to two weeks with continuous monitoring.

A compromise had to be reached regarding these criteria. In Sacramento, Orville Wright Park was selected, but a tree border at the upwind edge subjected measurements to greater edge effects than desired. In Vancouver, an unforeseen summer ban on irrigation of any grassed areas meant that most city parks were not irrigated unless they were grassed, sand-based playing fields. Also, access to parks was a problem, and severely limited the choice of park. Trafalgar Park was chosen, however it is located in a slight topographic depression and at the upwind boundary there is a school and a small step (0.8 m) in elevation to a gravel playing field which might cause flow distortion near the
leading edge. Due to the irrigation ban the water status of the Vancouver park was less comparable to that of the Sacramento park than wished for.

Given the expectations of spatial variability in the turbulent fluxes outlined in section 3.1, the measurement programme in each park is designed to include several sites along a transect aligned with the prevailing wind. Sites are spaced exponentially from the upwind edge to the centre of the park.

3.3 An overview of techniques used to measure the SEB fluxes

In this research several techniques are employed to measure the SEB of park, suburban and rural surfaces. These techniques are outlined below; details of sampling and instrumentation are given in Chapters 4 and 5.

Eddy correlation

Most micrometeorological methods to measure the turbulent fluxes require certain atmospheric conditions to be met and extensive surface homogeneity. Of the techniques to measure both sensible and latent heat, eddy correlation is theoretically the best and has few limiting assumptions. It provides a direct estimate of the sensible heat flux by simultaneously measuring turbulent velocity and temperature fluctuations and determining their covariance over the desired averaging time. Similarly the latent heat flux is estimated by simultaneous measurement of turbulent velocity and humidity fluctuations. However, as Schmid et al. (1991) caution, the position of the instruments, both in the horizontal and vertical, can significantly affect the meaning of flux measurements. The source area for the measured flux depends on the instrument height as well as on the turbulent characteristics of the flow.

While the eddy correlation technique has been successfully used to measure the SEB
of rural and urban areas, its application is restricted in a park setting. To implement this technique the sensors must be positioned such that the source areas for the turbulent fluxes originate within the park. Therefore, depending on the size of the park, this may restrict the use of eddy correlation instrumentation to the centre of the park, if at all. In addition, again to meet source area requirements, the sensors have to be mounted close to the surface. This may introduce under-sampling of the flux because the spectra and cospectra are truncated.

Bowen ratio energy balance

This method simplifies the evaluation of turbulent heat fluxes by taking the ratio of the sensible and latent heat fluxes and apportioning the available energy \((Q^* - Q_G)\) according to this non-dimensional ratio. The method relies on assumptions of constancy of fluxes with height; a homogeneous surface and similarity of the transfer coefficients for heat and water vapour. The Bowen ratio \((\beta)\) is calculated from a profile of temperature and humidity measurements:

\[
\beta = \frac{Q_H}{Q_E} = \frac{c_p \overline{\Delta T}}{L_v \Delta q},
\]

where \(c_p\) is the specific heat of air at constant pressure; \(\overline{\Delta T}\) is the difference in mean temperature between measurement levels; and \(\Delta q\) is the difference in average specific humidity. From the energy balance, \(Q_H\) and \(Q_E\) are individually estimated:

\[
Q_E = \frac{Q^* - Q_G}{1 + \beta} = \frac{Q^* - Q_G}{1 + \gamma \Delta T / \Delta q},
\]

and sensible heat can be estimated by residual from:

\[
Q_H = Q^* - Q_G - Q_E
\]

The technique has been widely applied, particularly in estimating the SEB at rural locations where fetch requirements are satisfied, and is used at the rural site in Vancouver.
in the present study. In urban applications recent research suggests that this approach may not be as suitable. Roth and Oke (1994) in a study of turbulence at a suburban site in Vancouver, B.C., found that the transfer coefficients for heat and water vapour were dissimilar, particularly in slightly unstable and near neutral conditions. Further, the limited fetch conditions prevailing in most parks again restrict the use of the approach greatly.

**Lysimetry**

An alternative approach to measure $Q_E$ is lysimetry. This technique is not hampered by restrictions of several atmospheric methods. A lysimeter is a cylindrical container in which an undisturbed block of soil and vegetation is isolated and its water budget is carefully monitored. Changes in the mass of the lysimeter (gain due to precipitation, irrigation or dewfall; loss due to evapotranspiration) are monitored by weighing the lysimeter via a sensitive balance installed underneath or a manometer measuring differences of hydrostatic pressure. The dimensions of the lysimeter depend on the type of vegetation, its depth, as well as on the observation time period. Large lysimeters with a surface area greater than 2 m$^2$ are the standard instrument for measuring evapotranspiration (Slatyer and McIlroy, 1961). However they are typically difficult to install, require sophisticated engineering backup and consequently are very expensive.

A recent development is the use of “mini-lysimeters” (diameter < 0.5 m) in field studies (Clark *et al.*, 1984; Dugas and Bland, 1989; Isard and Belding, 1989; Grimmond *et al.*, 1992). As Grimmond and Isard (1992) discuss, mini-lysimeters have the following advantages over large lysimeters:

- they permit measurement of $Q_E$ from small areas;
- they create less disturbance to the environment during installation;
they are considerably cheaper to install and operate.

Because of these characteristics, several mini-lysimeters can be used to study the spatial variability of $Q_E$. Hourly evaporation, $E$ (kg m$^{-2}$ h$^{-1}$), is estimated from:

$$E = \rho(P - \frac{\Delta W}{\rho A})$$

where $P$ is precipitation (m h$^{-1}$), $\Delta W$ is the change in weight (kg h$^{-1}$), $A$ is the surface area (m$^2$) and $\rho$ is the density of water (kg m$^{-3}$) and the fluxes of water mass ($E$) and energy ($Q_E$) are linked by:

$$Q_E = L_v E$$

There are several potential sources of error in estimates of evapotranspiration from these instruments. For example, as the surface area decreases a smaller plant population is sampled and the potential for differences in crop growth between the lysimeter and the field increases. Secondly, errors can occur due to the “bloom effect”, whereby the area of exposed plant canopy exceeds the lysimeter area. Thirdly, the non-vegetated edge between the soil-plant monolith and the surrounding area can increase turbulence in the air immediately above the lysimeter. Fourthly, the walls of the lysimeter may affect the thermal regime of the soil and vegetation. Finally, there may be errors associated with the electronics and mechanics of the weighing device. In general these potential sources of error are inversely proportional to the surface area of the lysimeter (Dugas and Bland, 1989).

Grimmond and Isard (1992) compared the performance of mini-lysimeters with evaporative flux measurements using eddy correlation instrumentation over an extensive homogeneous surface. Their results show that $Q_E$, stomatal resistance and soil moisture measurements from the lysimeters compare favourably to independent measures taken outside the lysimeters.
The mini-lysimeters developed by Grimmond and Isard (1992) are used in this study to measure the spatial variability of evapotranspiration. Each lysimeter consists of a soil monolith, enclosed in a container, that rests upon a load cell which continuously measures its weight (Fig. 3.6). The specifications of the mini-lysimeter are given in Table 3.1.
Table 3.1: Specifications of the mini-lysimeters.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighing mechanism</td>
<td>Interface Inc single point I load cell model SP-I 50</td>
</tr>
<tr>
<td>Internal diameter (m)</td>
<td>0.27</td>
</tr>
<tr>
<td>Surface area (m²)</td>
<td>0.0573</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>0.25</td>
</tr>
<tr>
<td>$E$ resolution (mm h⁻¹)</td>
<td>0.0175</td>
</tr>
<tr>
<td>$Q_E$ resolution @ 20°C (W m⁻²)</td>
<td>11.6</td>
</tr>
</tbody>
</table>

Figure 3.6: Design of the miniature lysimeter (after Grimmond and Isard, 1992).
Chapter 4

Surface Energy Balance of an Urban Park in a Hot Summer Mediterranean Climate – the Sacramento Study

4.1 Observation programme

4.1.1 Physical setting and observation sites

General description

In August 1991, a joint research programme involving research groups from the University of British Columbia, Indiana State University and MacQuarie University, Sydney, studied the surface energy balance of different land–use types in Sacramento, California.

Simultaneous measurements of surface energy balance (SEB) fluxes and other climatic variables were made at a suburban and two rural sites – one wet (irrigated sod farm) and one dry (scrub, grassland) (Fig. 2.1 and Fig. 4.1). A description of the observation programme is presented here; further details are in Grimmond et al. (1993). At the same time, surface energy balance measurements were taken in a small irrigated suburban park.

Continuous measurements of the SEB fluxes were taken from August 19 to 30, 1991 at the suburban and rural sites and from August 22 to 28 at the park site. The average air temperature for August was 22.9°C (compared with a normal 23.7°C), and it was drier than normal with only 0.25 mm rain recorded in the six weeks prior to the measurement period, (compared with an average August precipitation of 1.8 mm).

The synoptic conditions were otherwise typical for the region; cloudless skies prevailed by day with occasional night cloud. A cold front extended into the Sacramento region
Figure 4.1: Photographs of each study site in Sacramento.
on August 25 giving some high cloud, and another front passed through on August 28.

Site descriptions

Park measurements were conducted in Orville Wright Park, a small (3.6 ha) park in the suburb of Mission Oaks. The park is mainly grass with a border of trees (5–10 m high). There is a large sandpit for volley ball and a children’s play area. The neighbourhood is a residential area of predominantly single family dwellings with a well irrigated (mesiscape) vegetation.

The park is heavily irrigated three or four nights per week and the grass is kept cropped at 0.05–0.10 m. The park soils consist of a surface layer of brown, fine sandy loam to a depth of 0.15–0.30 m, below which is a clay hardpan. Consequently permeability is poor, and the park surface can remain damp well into the afternoon following a night of irrigation.

The suburban site was located in the residential neighbourhood of Carmichael, approximately 7 km northwest of Orville Wright Park. The land–use in this suburb is similar to that surrounding the park. Irrigation of private gardens is permitted on alternate days.

The wet rural site was at an irrigated sod farm about 18 km southwest of downtown Sacramento in an area of intensive agriculture. Irrigation at this site occurred every 7–10 days and the surrounding fields (for about 1 km x 1 km) were also regularly irrigated. The grass is maintained at 0.05 m. The dry rural site was about 18 km southeast of downtown Sacramento with a surface cover of tall (0.5 m) unirrigated grass. The topography at each site is generally flat.

Instruments were installed over several days:
- Suburban: August 19, year day, YD, 231
- Dry rural: August 20, YD 232
- Wet rural: August 21, YD 233
- Park: August 22, YD 234.

Continuous measurements were taken at the first three sites until August 29, with the exception of a six hour period on August 26 at the wet rural site, when irrigation was in progress. Three sites were installed in Orville Wright Park on August 22, 1991 with measurements over the following seven days. Whilst there is a complete record for Site 3, Site 2 was later starting due to the need to relocate the lysimeter (a broken irrigation pipe saturated the first lysimeter pit). At Site 1 data were lost on August 26 (YD 236) and the lysimeter failed on August 28 (YD 238). Due to these gaps, and given the essential similarity of conditions over the period, two day averages (August 25 and 27) are derived for the purpose of analysis. While net radiation at the sites showed little variability from the average, the turbulent fluxes could range up to 30% from their average on an hourly basis during the daytime.

4.1.2 Instrumentation

Park Site

The surface energy balance at the park was sampled at three sites along a transect from the edge of the park to its centre. The sites are aligned in a southwesterly direction parallel to the direction of the climatological prevailing wind. Site 1 is at the edge of the park 4 m in from the boundary; site 2 is 27 m from the edge and site 3 is near the centre of the park, 96 m from the boundary (Fig. 4.2).
Figure 4.2: Sampling plan for surface energy balance in Orville Wright Park.
Net all-wave radiation was measured at each site with a Swissteco (model S1) net pyrradiometer mounted 0.8 m above the ground. The ground heat flux was measured at each site with two Middleton soil heat flux plates buried at 0.05 m depth. As no soil temperatures were taken, the divergence of the heat flux between the surface and a depth of 0.05 m was estimated from theory\(^1\) (Leuning et al., 1982). The latent heat flux was measured at the three sites by mini-lysimeters and the sensible heat flux estimated by residual.

Soil moisture is spatially variable in Orville Wright Park, partly due to the variable depth of the hard pan, and also to proximity to the sprinkler heads. The lysimeter monoliths retained a similar amount of moisture to that of the surrounding soil. At the end of the observation period Site 1 had a soil moisture content in the lysimeter of 19% compared with 16% nearby; Site 2 had 17% both in and around the lysimeter; and Site 3 had 24% compared with 20% nearby.

Air temperatures were measured at all sites at a height of about 1.3 m with thermistor probes, and at Site 3 a Vaisala capacitance sensor (model HMP 35C) also measured relative humidity. Wind direction at a height of 1 m was measured at Site 2 during the latter half of the research period. Soil moisture was sampled along the transect every three days. The fluxes and climatic variables were sampled every 20 seconds with 15 minute averages recorded. Hourly averages are derived by averaging the four 15 minute values.

In August 1993 a further two days of measurements were made in Orville Wright Park. Two sites were established – one in the centre of the park and the second over a concrete driveway on a property west of the park. In the park \(Q^*\) was measured with a Swissteco pyrradiometer (model S1), \(Q_H\) was measured by a CSI CA27 one-dimensional

\(^1\)The ground heat flux at the surface is estimated from the ground heat flux at depth by considering the conduction of heat into soil which results from a sinusoidal temperature wave imposed at the surface.
sonic—anemometer–thermometer (SAT) system sampling at 10 Hz with covariances determined over 15 minutes. Wind speed and direction were measured with an R.M. Young Wind Sentry at a height of 1.5 m. At both sites air temperature and relative humidity were measured with a Vaisala capacitance temperature and humidity probe and surface temperature was measured with an Everest 4000A infra-red thermometer. Net radiation and the climatic variables were sampled at 0.1 Hz with 15 minute averages recorded.

Corrections to $Q_H$ were made for density effects (Webb et al., 1980). Kristensen and Fitzjarrald (1984) suggest that in unstable conditions it is not necessary to correct for line–averaging effects down to heights 4–5 times the length of the sonic path. The SAT has a path length of 0.1 m therefore allowing measurement down to 0.4 m. However, in stable conditions $Q_H$ may be underestimated.

This set of measurements had the primary objective of verifying the earlier (1991) estimates of the sensible heat flux (by residual), as well as allowing assessment of the driving forces for park evaporation (surface temperature difference and vapour pressure difference between the park and the adjacent urban air).

Suburban and rural sites

Grimmond et al. (1993) detail the instrumentation used in the observation programme. The following discussion is from their paper. Suburban flux measurements were taken at a height of 29 m. This is judged to be above the roughness layer and in the constant flux layer above the city (Oke et al., 1989). At the rural sites flux measurements were at 1.3 m (wet) and at 1.8 m (dry). Both are considered representative of the microscale. At each site measurements of the turbulent fluxes were made using the eddy correlation approach. Sensible heat was measured with a SAT and $Q_E$ with a CSI KH20 Krypton hygrometer. Air temperature, specific humidity and vertical wind velocity were sampled at 5 Hz with covariances determined over 15 minutes.
Net all-wave radiation was measured using a Swissteco miniature net pyrradiometer at the suburban site and Radiation Energy Balance System (REBS) net pyrradiometers at the two rural sites. Soil heat flux was measured at each site using two REBS soil heat flux plates with a CSI thermocouple system installed above the plates to account for thermal divergence between the plates and the surface. Heat storage at the suburban site is estimated as a residual. Soil moisture was measured daily using a Soil Moisture Equipment Corporation Trase 6000 XI time domain reflectometry system.

Slow response air temperature, relative humidity and wind speed and direction were measured at each site. These were sampled at 0.1 Hz and averaged over 15 minute intervals. The energy balance fluxes and climatological variables are compared using hourly fluxes which represent the average of the four 15 minute values obtained for each hour.

4.1.3 Probable errors in surface energy balance instrumentation

The instruments that were used to measure the same fluxes at different sites were calibrated and/or intercompared prior to installation and appropriate corrections incorporated into the results. The net pyrradiometers were calibrated by comparison with a standard by the Canadian National Radiation Laboratory (Atmospheric Environment Service). They should be accurate to within 3–4% with an even smaller inter-instrument comparison (Latimer, 1972). The mini-lysimeters were calibrated prior to use and checked twice daily through the observation period. Measurements of $Q_E$ from these instruments are precise to within 12 W m$^{-2}$ (Grimmond and Isard, 1992).

It is difficult to assess the actual measurement error associated with eddy correlation estimates of $Q_H$ (Cleugh, 1988). An intercomparison of hourly fluxes from two instruments found a RMSE of 12 W m$^{-2}$ (Cleugh, 1988; Schmid, 1988). Grimmond (1988)
reports that the measurement error is probably less than 10%. The Krypton hygrometers were calibrated by comparison of vapour density measurements with a dew-point generator. Flux corrections were made for oxygen absorption by the hygrometer and for air density (Webb et al., 1980; Tanner and Greene, 1989); and at the suburban site for frequency response and spatial separation of the eddy correlation sensors (S. Grimmond, pers. comm., 1993, and M. Roth, pers. comm., 1992).

Both the sensible heat flux at the park sites and the storage heat flux in the suburban SEB are estimated as residuals. This has the inherent problem of accumulating the measurement errors of the other energy balance components.

4.2 Urban park surface energy balance (SEB)

The August 1993 measurements of surface and air temperatures and humidity both in the park, and over a driveway adjacent to the park, serve to illustrate the surface climate differences. (Figure 4.3).

Air temperature shows little difference between the two sites although the park is consistently cooler during the daytime, but only by 1–1.5°C. The park is always more humid particularly after sunrise when dew is evaporating. The park surface is always cooler than the adjacent paved surface with a maximum difference of 16.6°C occurring at 1500 LAT. This strong contrast in surface temperatures could establish warm air advection over the cooler park.

4.2.1 Energy balance partitioning

Figure 4.4 shows the average (2-day) diurnal surface energy balance at each of the park sites. The energy balance at each is dominated by $Q_E$, and Sites 2 and 3 show similar partitioning of energy. Net radiation peaks at about 530 W m$^{-2}$ and $Q_E$ is very high
Figure 4.3: Differences in diurnal air and surface temperature, $T_a$ and $T_s$ ($^\circ$C), relative humidity, RH (%) in (a), and vapour pressure, $\Delta VP$, in (b), between adjacent park and paved sites at Orville Wright Park, Sacramento.

with a maximum of 400–500 W m$^{-2}$ in the early afternoon. The sensible heat flux peaks near 150 W m$^{-2}$ just before midday, and in the afternoon becomes negative (i.e. directed towards the surface). The ground heat flux is very low; almost negligible. The SEB at Site 1 clearly shows the influence of edge effects. Firstly, the shadows from the nearby trees and hedge create a dip in $Q^*$ at 1300–1500 LAT. Secondly, $Q_E$ is very high – up to 600 W m$^{-2}$ and frequently in excess of $Q^*$. Consequently $Q_H$ is often negative, supplementing $Q^*$ in achieving these high evapotranspiration rates, especially in the afternoon. A statistical summary of the daily and daytime ($Q^* > 0$) fluxes is presented in Table 4.1.

The net all-wave radiant flux density is conservative across the park; each site has a daytime average of approximately 330 W m$^{-2}$. At Site 1, $Q^*$ dips in the early afternoon due to shading. The latent heat flux shows both spatial and temporal differences with increasing fetch over the park. $Q_E$ is greatest at Site 1 due to microscale advection
Figure 4.4: Two-day average surface energy balances at three park sites in Orville Wright Park, Sacramento in August, 1991. The net radiation and sensible heat fluxes measured at Site 3 in August 1993 are also shown for comparison. For the 1991 measurements, net radiation was within 10% of the average on an hourly basis; $Q_E$ within 20% and $Q_H$ and $Q_G$ within 30%. In 1993, $Q^*$ varied less than 4% and $Q_H$ was within 25% of the average on an hourly basis.
Table 4.1: Daily and daytime \((Q^* > 0)\) averages and ratios for energy balance fluxes at sites in Orville Wright Park. All fluxes are in W m\(^{-2}\).

<table>
<thead>
<tr>
<th>Site</th>
<th>(Q^*)</th>
<th>(Q_E)</th>
<th>(Q_H)</th>
<th>(Q_G)</th>
<th>(\frac{Q_E}{Q^*})</th>
<th>(\frac{Q_H}{Q^*})</th>
<th>(\beta = \frac{Q_H}{Q_E})</th>
<th>(\alpha = \frac{Q_E}{Q_{E_0}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) DAILY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>130</td>
<td>196</td>
<td>-61</td>
<td>-5</td>
<td>1.51</td>
<td>-0.47</td>
<td>-0.31</td>
<td>1.99</td>
</tr>
<tr>
<td>2</td>
<td>114</td>
<td>147</td>
<td>-29</td>
<td>-3</td>
<td>1.28</td>
<td>-0.25</td>
<td>-0.20</td>
<td>1.65</td>
</tr>
<tr>
<td>3</td>
<td>119</td>
<td>142</td>
<td>-16</td>
<td>-7</td>
<td>1.19</td>
<td>-0.13(^1)</td>
<td>-0.11</td>
<td>1.52</td>
</tr>
<tr>
<td>b) DAYTIME</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>327</td>
<td>374</td>
<td>-64</td>
<td>16</td>
<td>1.15</td>
<td>-0.20</td>
<td>-0.17</td>
<td>1.67</td>
</tr>
<tr>
<td>2</td>
<td>333</td>
<td>302</td>
<td>16</td>
<td>15</td>
<td>0.91</td>
<td>0.05</td>
<td>0.05</td>
<td>1.30</td>
</tr>
<tr>
<td>3</td>
<td>335</td>
<td>302</td>
<td>26</td>
<td>7</td>
<td>0.90</td>
<td>0.08(^2)</td>
<td>0.09</td>
<td>1.27</td>
</tr>
</tbody>
</table>

across the moist park boundary, supplying an additional energy source to drive evapotranspiration. The peak occurs at 1500 LAT which corresponds to the time of maximum forcing due to surface temperature differentials between the park and the adjacent paved surfaces (see Figure 4.3). Further towards the centre of the park, the magnitude of \(Q_E\) decreases by about 20\% (Table 4.1).

An appreciation of the advective influence can be gained by comparing the measured latent heat flux, \(Q_E\), to the latent heat flux which could occur in the absence of advection, \(Q_{E_0}\), and Priestley and Taylor's (1972) potential evaporation, \(Q_{E_p}\) (if \(\alpha > 1.26\) then \(Q_E > Q_{E_p}\)) (Table 4.1 and Fig. 4.5). Except for a few hours in the morning, evaporation at all sites easily exceeds the equilibrium rate, indicating the influence of mesoscale advection. As \(Q_E > Q_{E_p}\) at all sites in the afternoon, there is evidence of enhanced advective effects. Since evaporation continues through the night daily \(\alpha\) is even higher.
than the daytime ratios. On a daily basis evaporation at the edge of the park is double that of $Q_{Ev}$. This decreases to 1.65 at Site 2 and 1.52 in the centre of the park. The similarity of Sites 2 and 3 suggests that the major influence of fetch is confined to a strip within 25 m of the park edge. The influence of fetch and the contribution of the edge and oasis effects to this advection are considered further in subsection 4.2.2.

In the 1991 park study $Q_H$ was estimated as a residual while in the 1993 observation period it was directly measured by the eddy correlation technique. The diurnal trend and the resulting daytime average of both $Q_H$ and the ratio $Q_H/Q^*$ in 1993 are very similar to those observed in 1991 (see Fig. 4.4 and Table 4.1) and confirm that estimating $Q_H$ by residual is a satisfactory procedure. Sensible heat is positive (into the air) in the morning but as the surface temperature differential increases between the cool park and the warmer neighbourhood in the mid-afternoon, warm air advects over the park and $Q_H$ becomes negative, (directed towards the surface).

The fluxes normalized by $Q^*$ reveal daytime trends in energy partitioning by the park (Fig. 4.6). At Sites 2 and 3, $Q_E/Q^*$ shows a steady increase throughout the daytime. The increase of this ratio suggests that evaporation is not water restricted but is limited by energy availability. Thus it increases in the morning with the net radiation and continues to increase as sensible heat becomes an additional energy source in the late afternoon. The corresponding trend of $Q_H/Q^*$ decreases throughout the day and becomes negative in the afternoon.

The Bowen ratio ($\beta$) for 0800–1600 LAT shows a general decrease at all sites. The low values reflect the dominance of the latent heat flux with $Q_E$ using two to three times as much energy as $Q_H$. At Site 1 the daytime average of $-0.17$ confirms that there is a strong edge effect (Table 4.1). The time of reversal in $\beta$ becomes later further into the park (negative at Site 2 by 1400 LAT, and 1600 LAT at Site 3). On a daytime basis the Bowen ratio at these sites is as small as at an open water site ($< 0.10$).
Figure 4.5: Comparison of the measured $Q_E$ with $Q_{Eh}$ and $Q_{Ep}$ at three sites in Orville Wright Park, Sacramento in August, 1991.
Figure 4.6: Two-day average of the SEB flux ratios for daytime hours at three park sites. To facilitate interpretation, the data for Site 1 near midday are omitted due to shading by nearby trees.
4.2.2 The influence of fetch on $Q_E$

A strong edge effect is observed at the park with very high rates of evaporation near the upwind boundary. The earlier discussion of the spatial variability of $Q_E$ (Section 4.2.1) did not incorporate the true fetch because fixed sites aligned along a transect are not necessarily parallel to the wind direction. Figure 4.7 is a plot of the daytime average $Q_E$ against true fetch for August 27 (YD 239); when wind direction data are available. It shows a decrease in $Q_E$ from the edge of the park to its centre (Fig. 4.7). The similarity of $Q_E$ at Sites 2 and 3 suggests that the edge effect is confined to about 20 m from the upwind edge. At Sites 2 and 3 there is no evidence for an oasis effect as $Q_E < Q_{Ep}$ but evaporation is above the equilibrium rate, indicating some mesoscale advective influence.

While the park does not exhibit a strong oasis effect when averaged on a daytime basis, both the daily average $\alpha$ and the diurnal variation of $Q_H$ indicate that the park experiences both edge and oasis effects (Table 4.1 and Fig. 4.5). From 1600 until at least 2200 LAT, $Q_E$ exceeds $Q_{Ep}$ by up to 330 W m$^{-2}$ at Site 1, 80 W m$^{-2}$ at Site 2, and 100 W m$^{-2}$ at Site 3. Thus during these hours a strong edge effect (130 W m$^{-2}$) is superimposed upon a considerable oasis effect (about 90 W m$^{-2}$).

The evapotranspiration trends in Orville Wright Park agree well with the conceptual model of an exponential decay of $Q_E$ with distance from a leading edge in a well-irrigated park (Fig. 3.1). However, in a park of this size, the oasis effect is only present in the afternoon and evening. There is little evidence of the turbulence regime of the park affecting the decay of $Q_E$. Perhaps Sites 1 and 2 are in a quiet zone, sheltered by the surrounding vegetation and dwellings. There is some evidence to support this contention. Air temperatures are slightly higher at these sites, $Q^*$ is slightly reduced and $Q_G$ is slightly increased. However, evapotranspiration is not reduced at these sites although without the shelter, the eddy diffusivity near the park edge would increase and $Q_E$ could be
4.2.3 Summary of the energetics of a suburban park in a hot summer Mediterranean climate.

In the well-irrigated Orville Wright Park set in a hot climate, the surface energy balance is dominated by evaporation which acts as the main sink for net radiation. The ground heat flux is negligible. Very high rates of $Q_E$ are measured in the park particularly at its upwind edge. The decay of $Q_E$ with increasing fetch generally fits the hypothetical edge effect model, except the vegetated park border may disturb the flow and create a quiet zone in its lee. Sensible heat is a moderate sink for $Q^*$ in the morning however, by early afternoon $Q_H$ turns negative, establishing high rates of $Q_E$ and allowing the park to act as an “oasis”.

Figure 4.7: The variation of average daytime $Q_E$ with distance of fetch from the park edge for August 27 (YD 239). The average wind speed for this period was 2.84 m s$^{-1}$ at the nearby suburban site.
4.3 The urban park in its context – park, suburban and rural comparisons

4.3.1 Energy partitioning in different land–use types

The 2–day average energy balances for each of the four land–use types are given in Figure 4.8 and Table 4.2. The park data refer to Site 3 – the centre of the park. The following analysis compares the energy balance of the park to the others (for comparisons between the suburban and rural sites see Grimmond and Oke, 1993).

At the rural sites it is theoretically possible to achieve energy balance closure, because each flux is measured directly. However, because of measurement errors associated with each flux, few studies ever obtain true closure. Further corrections could be made (e.g. for the frequency response and the spatial separation of eddy correlation sensors) but since the unaccounted residuals are relatively small (5% of \( Q^* \) at the wet site and 1% at the dry site on a daily basis) no corrections were made.

In energetic terms the park is most like the wet rural site (Fig. 4.8 and Table 4.2). Both receive a similar net radiation input and have an energy balance dominated by evaporation; although \( Q_E \) is much higher (140%) in the park. The sensible heat flux for both sites peaks around 100 W m\(^{-2}\) and turns negative in the late afternoon. At both sites \( Q_G \) is negligible. In contrast, the SEB of the suburban site (whose spatial average must include parks) is dominated by \( Q_H \) which peaks near 300 W m\(^{-2}\), whereas \( Q_E \) is much lower at 150 W m\(^{-2}\). The suburban storage flux is positive by day reaching 170 W m\(^{-2}\) in the mid afternoon. The energy balance at the dry rural site is almost completely dominated by \( Q_H \) which peaks around 400 W m\(^{-2}\), \( Q_E \) is negligible and \( Q_G \) plays a more important role, peaking around 80 W m\(^{-2}\).

The 2–day averages of the turbulent fluxes (Table 4.2) show distinct differences in energy partitioning between sites. Daily evaporation in the park is 3.16 times higher than from the nearby suburban neighbourhood. Few studies have reported comparisons
Table 4.2: Daily and daytime 2–day averages and ratios of energy balance fluxes for different land–use types in Sacramento, CA.

<table>
<thead>
<tr>
<th>Site</th>
<th>( Q^* )</th>
<th>( Q_E )</th>
<th>( Q_H )</th>
<th>( Q_G )</th>
<th>( \Delta Q_S )</th>
<th>Res</th>
<th>( \frac{Q_E}{Q^*} )</th>
<th>( \frac{Q_H}{Q^*} )</th>
<th>( \beta )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wm(^{-2})</strong></td>
<td><strong>Wm(^{-2})</strong></td>
<td><strong>Wm(^{-2})</strong></td>
<td><strong>Wm(^{-2})</strong></td>
<td><strong>Wm(^{-2})</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| a) DAILY
| Park       | 119        | 142        | -16        | -7         | 1.19             | -0.13 | -0.11               | 1.52               |
| Wet rural  | 128        | 108        | 17         | -3         | 6                | 0.84 | 0.13                | 0.16               | 1.25       |
| Suburban   | 107        | 45         | 73         | -11        | 0.42             | 0.68 | 1.62                | 0.53               |
| Dry rural  | 110        | 1          | 105        | 2          | 2                | 0.01 | 0.95                | 78                 | 0.02       |
| Park/Suburban | 1.11    | 3.16       | -0.22      | 0.64       |                                 |     |                     |                     |            |
| Park/Wet rural | 0.93  | 1.31       | -0.94      | 2.33       |                                 |     |                     |                     |            |
| b) DAYTIME
| Park       | 335        | 302        | 26         | 7          | 0.90             | 0.08 | 0.09                | 1.27               |
| Wet rural  | 342        | 214        | 52         | 20         | 55               | 0.63 | 0.15                | 0.24               | 1.03       |
| Suburban   | 304        | 89         | 165        | 50         | 50               | 0.29 | 0.54                | 1.85               | 0.49       |
| Dry rural  | 307        | 4          | 253        | 34         | 16               | 0.01 | 0.82                | 57                 | 0.02       |
| Park/Suburban | 1.10   | 3.39       | 0.16       | 0.14       |                                 |     |                     |                     |            |
| Park/Wet rural | 0.98  | 1.41       | 0.50       | 0.35       |                                 |     |                     |                     |            |
Figure 4.8: Average energy balances for different land-use types in Sacramento, CA, based on two days observations in August, 1991. Net radiation is within 10% of the mean on an hourly basis; $Q_E$ within 20%; and $Q_H$ and $Q_G$ within 30%.
of evaporation over moist greenspace compared to the suburban neighbourhood. Oke (1979) in a study of advectively-assisted evapotranspiration from an irrigated lawn in Vancouver, B.C., found evaporation from the lawn was 3.09 times of that in a similar suburban neighbourhood. The differences in the evaporation rates in Sacramento are highlighted in Figure 4.9, which shows the cumulative evaporation for each site. The park has a daily evaporation rate of about 5 mm closely followed by the wet rural site at 4.2 mm. Evaporation from the suburban site is much lower at 1.6 mm and it is negligible at the dry rural site. The dominance of $Q_E$ at the park and wet site is probably a reflection of similar moisture regimes. Both have high soil moisture due to heavy irrigation and are influenced by advective enhancement of evaporation.

The differences in energy partitioning between the sites are clearly seen in an examination of the fluxes when normalized by $Q^*$ (Fig. 4.10 and Table 4.2). The daytime ratio of $Q_E/Q^*$ again shows the dominance of $Q_E$ at the park (90%), followed by the wet
rural site (63%), suburban (32%) and dry rural (1%). The proportion of radiant energy directed into latent heat remains essentially constant at each site until the mid- to late afternoon. Then there is an increase in the ratio at the park and wet sites, corresponding to a decrease in the ratio $Q_H/Q^*$. At these sites the sensible heat flux changes sign in the late afternoon indicating advectively–assisted evaporation that elevates $Q_E$ above $Q^*$. This advective component is most important at the park site where $Q_H$ is negative by 1500 LAT and $Q_E$ exceeds $Q^*$ for the remainder of the afternoon and evening. The advection at this site is sustained by the supply of warm urban air resulting in the park acting as an “oasis”.

The Bowen ratio values ($\beta$) illustrate the interplay between the turbulent sensible and latent heat fluxes at each site. The park and wet rural sites have similar decreasing trends in this ratio throughout the day (Fig. 4.10). The daily averages for $\beta$ are −0.11 for the park and 0.16 for the wet rural site (Table 4.2). This value for $\beta$ for the park is close to that observed by Oke (1979) for an irrigated suburban lawn in Vancouver, B.C. (−0.13).

At the suburban site where $Q_H$ is more dominant in the energy balance, $\beta$ is more variable and has a daily average of 1.62. For a longer averaging period (10 days) at this site Grimmond and Oke (1994) observed a $\beta$ of 1.20. This is comparable to Bowen ratios reported for other cities located in semi–arid environments (eg. 1.33 in Los Angeles and 1.35 in Tucson, (Grimmond and Oke, 1994)).

The ratio $Q_G/Q^*$ is almost negligible at the park and wet rural sites (2% and 6% respectively) although at the dry rural site $Q_G$ is 11% of $Q^*$. The storage heat flux at the suburban site has a daytime average of 16% of $Q^*$. Throughout the day this flux increases in importance and in the afternoon accounts for about 30% of $Q^*$. 
Figure 4.10: Daytime flux ratios for different land-use types in Sacramento, CA. Data are two-day averages. The Bowen ratio for the dry rural site is not shown as it is about 60.
4.3.2 Summary of the urban park surface energy balance compared to other land–use types in a hot summer Mediterranean climate

The irrigated urban park has a surface energy balance most similar to a wet rural site. Both have energy balances dominated by evaporation and consistently negative sensible heat advection in the late afternoon. Soil heat flux at these sites is small. The dominance of $Q_E$ is a direct reflection of the similar soil moisture regimes due to irrigation. However, the park is distinguished from other land–use types by its propensity to act as an "oasis". In a hot dry climate urban parks can have evapotranspiration rates in excess of those at irrigated rural sites. The Sacramento park had a daytime $Q_E$ 1.41 times higher than the irrigated rural site and 3.39 times higher than the suburban value. This elevated evapotranspiration is probably due to oasis–type advection of warm dry urban air over the park supplying additional energy for evapotranspiration. In contrast, the surface energy balance at the suburban and especially the dry rural site, is dominated by $Q_H$. 

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Chapter 5

Surface Energy Balance of an Urban Park in a Cool Summer Mediterranean Climate – the Vancouver Study

5.1 Observation programme

5.1.1 Physical setting and observation sites

General description

In July 1992, simultaneous measurements of the surface energy balance were made over three different land-uses in the Vancouver region. Measurements of the surface energy balance and other climatic variables were made at a park, a suburban and a rural site (Fig. 2.2 and Fig. 5.1). The rural and urban sites were installed in mid July and the park sites on July 20. From July 20 to July 24 a slow-moving low pressure system was located off the coast of British Columbia. A cold front associated with this system passed over Vancouver on July 21 bringing cloudy skies and showers. The showers continued on July 22 with 11 mm of precipitation. Due to this unsettled weather the rural and urban sites were not brought on-line until July 25. By July 27 a high pressure system became established giving mainly sunny skies for the remainder of the study period.

Site descriptions

The park selected for study was Trafalgar Park in the Arbutus district of Vancouver. It is a 4.86 ha open grasssed park with a partial border of mixed deciduous and coniferous trees (about 3–8 m high). Immediately to the west is Trafalgar Elementary School which has
Figure 5.1: Photographs of study sites in Vancouver.
a gravel playing field bordering the park. The park consists of several playing fields and has a childrens playground and a fieldhouse. It is located in a residential neighbourhood of predominantly one- and two-storey dwellings. Two blocks to the west is a small commercial strip. The neighbourhood is in a slight topographic depression.

The park was irrigated until 3 weeks prior to the measurement period. At this time a ban on sprinkling of lawns was implemented, so irrigation of the park ceased. However, 11 mm of precipitation fell on July 22, two days after installing instrumentation in the park. The grass was maintained at approximately 0.05 m height. The park was mown halfway through the observation period.

The suburban site was at “Sunset” in South Vancouver at a location used previously for several energy balance studies (eg. Roth, 1991; Grimmond, 1988; Cleugh, 1988). The neighbourhood consists of predominantly one- and two-storey dwellings. Throughout the measurement period there was a complete ban on irrigation of lawns. Irrigation of gardens was permitted on alternate days.

The rural site was in a mixed agricultural area of Delta, 20 km south of Vancouver. Measurements were conducted over a bush bean crop about 0.5 m high. The upwind fetch for the prevailing southwesterly wind was over beans for approximately 300 m and then over mixed crops. There was no irrigation during the observation period but the site received 7 mm of precipitation on July 22. Bean harvesting began earlier than anticipated on July 29 and was completed by July 31. Measurements of climate variables were made at a nearby tower (3 m high) at the junction of fields containing wheat and corn. The surrounding topography is very flat delta land.
5.1.2 Instrumentation

Park site

In Trafalgar Park, five sites were established in a transect from the southwest side to the centre of the park, aligned in the direction of the prevailing wind. The sites were numbered 1 to 5; 1 being closest to the edge of the park and 5 in the centre (Fig. 5.2).

At Sites 1 and 5, net all-wave radiation, $Q^*$, was measured with a Swissteco net pyrradiometer (model S1) mounted at 1 m and soil heat flux, $Q_G$, with Middleton soil heat flux plates buried at a depth of 0.05 m. Thermocouples were installed above each plate to account for thermal divergence between the surface and the depth of the plates. The latent heat flux, $Q_E$, was measured at all sites using mini-lysimeters as described in Section 3.3.

The sensible heat flux, $Q_H$, was measured at Site 5 only, by a CSI CA27 SAT sampling at a rate of 10 Hz. This instrument, mounted at a height of 1 m, gives an integrated sensible heat flux for the fetch over the park rather than the heat flux of that point. When the prevailing wind is from the southwest there is a fetch of 100 m over the park. Estimates of $Q_H$ at Sites 1–4 were found by residual in the surface energy balance (ie. a point measurement given by $(Q^* - (Q_E + Q_G))$).

At Site 1 air temperature was measured at a height of 1.5 m using a thermistor probe mounted in a radiation shield. Surface temperature was measured using an Everest 4000A infra-red radiation thermometer, precipitation by a tipping bucket raingauge and at Site 4 surface wetness by a Weiss surface wetness sensor (Weiss and Lukens, 1981). At Site 5 air temperature and relative humidity were measured using a Vaisala capacitance temperature–humidity probe mounted in a radiation shield, at a height of 1.5 m. Wind speed and direction were measured at a height of 2 m by an R.M. Young 03001 cup anemometer and wind vane set. Soil moisture was sampled along the transect every
Figure 5.2: Location of sites in Trafalgar Park, Vancouver.
three days for gravimetric analysis.

With the exception of the SAT, all variables were sampled at 0.1 Hz with 15 minute averages recorded by CSI CR21X data loggers. Hourly averages of the energy balance fluxes and climatic variables are derived from an average of the four 15 minute values obtained for each hour.

The mini–lysimeters were installed on July 21 (YD 202) with continuous observations until July 31. Some difficulty was encountered during installation. The high sand content of the park soils resulted in some fragmentation of the lysimeter monoliths causing disturbance. By the end of the observation period soil moisture was depleted in the lysimeters compared to the surroundings. Site 1 had dried out the most (with 11% soil moisture in the lysimeter after 10 days compared to 27% nearby) while Site 5 had the least depletion (20% in the lysimeter compared to 24% nearby).

Since the latent heat flux was both measured (lysimeter) and estimated (SEB residual using $Q_E = Q^* - Q_C - Q_{HEC}$) at Site 5, these data were used to determine if any reduction in evapotranspiration had occurred due to moisture stress by the grass. Evaporation from the mini–lysimeter declined throughout the observation period, whereas that by the residual increased (Fig. 5.3). Therefore it appears the monolith became unrepresentative except for the first few days when the two estimates agree well. This comparison suggests the residual method should be used for Site 5.

To see if the other lysimeters were similarly affected, time trends of the average daytime $Q_E$ at each site are compared (Fig. 5.4). This reveals that sites 1–3 remain approximately in the same relation to the areal (SEB) estimates until after YD 207. But the lysimeters at Sites 4 and 5 show signs of drying out. Therefore data from Site 4 are omitted from analysis and evaporation at Site 5 is estimated by SEB residual, rather than by the lysimeter. Further analysis of elements considers 3–day averages only for the period YD 205–207. Over these days the park is in a drying phase following 11 mm rain
Figure 5.3: A comparison of $Q_E$ as measured by a mini-lysimeter and estimated as the SEB residual for Site 5 in Trafalgar Park.

Rain on YD 203 so there may be considerable variability in the fluxes about their mean. Therefore the results are limited in their generality.

Suburban site

At the suburban site instruments were mounted at two levels on a 33.5 m tower. At the top level (at an effective height of 19 m above zero-plane displacement) the sensible and latent heat fluxes were measured using the same eddy correlation equipment as the suburban Site in Sacramento (i.e. a SAT and a Krypton hygrometer). Signals were sampled at 10 Hz and the covariances determined over 15 minute intervals. Corrections were applied to the resultant fluxes to account for oxygen absorption by the sensor, air density effects and for the frequency response and spatial separation of the sensors. Net all-wave radiation was measured using a Swissteco net pyrradiometer mounted at the
Figure 5.4: Time trend of daytime average $Q_{Ex}/Q_{Eres}$ for Sites 1-5 in Trafalgar Park, Vancouver.

At the lower level (11 m effective height) air temperature and relative humidity were measured with a Vaisala capacitance temperature and humidity probe and wind speed and direction with a Met–One system comprising a wind vane (Met–One 024A) and cup anemometer (Met–One 012A). Precipitation was monitored with a tipping bucket rain gauge and surface wetness with a Weiss wetness sensor placed near the raingauge, on the roof of the trailer, at the base of the tower.

The climate variables were sampled at 0.1 Hz with 15 minute averages recorded on a CSI CR21X data logger. Hourly averages were derived for the energy balance fluxes and the climate variables. Anthropogenic heat was neglected and $\Delta Q_S$ was estimated as the residual in the energy balance (ie. $Q^* - (Q_E + Q_H)$).
Rural site

A CSI Bowen Ratio system was used at Delta to measure the turbulent heat fluxes over the bean crop. Humidity was measured with a cooled mirror dew point hygrometer (Model Dew–10 General Eastern Corp.). Air samples drawn from heights of 1 and 2 m were routed to the cooled-mirror after passing through mixing volumes. The resolution of the dew point temperature measurement is $\pm 0.003^\circ$C over a $\pm 35^\circ$C range. Given the stability of the Dew–10, approximately $0.05^\circ$C, this yields a resolution of better than $\pm 0.001$ kPa in vapour pressure. Every two minutes the air drawn across the cooled-mirror is switched from one measurement level to the other. The mirror is given 40 s to stabilize to the new dew point and an 80 s sample for each level is obtained during each two minute cycle. Dew point temperature is measured every second and vapour pressure is calculated using the equation given by Lowe (1976). Air temperature is measured at 1 and 2 m with chromel-constantan thermocouples. The differential voltage is due to the difference in temperature between the temperatures at heights 1 and 2 m and has no inherent sensor offset error.

This Bowen ratio (BR) system has been compared to others and to eddy correlation systems in the field (Dugas et al., 1991). Four BR systems were compared: one CSI BR system as described above; two using reversing arms with dry- and wet-bulbs; and one with dry- and wet-bulbs on fixed arms. The Bowen ratio ($\beta$) values and calculated $Q_E$ from the 4 BR systems were in close agreement. Differences of $\beta$ were approximately $\pm 0.1$ in the morning and afternoon and $\pm 0.02$ around noon and within 10% for the two days. The eddy correlation value of $Q_E$ was significantly (20–30%), and consistently, less than that from the BR system.

Net all-wave radiation was measured with a Swissteco net pyrradiometer at a height of 2.5 m. The soil heat flux was measured with two Middleton heat flux plates buried
at a depth of 0.05 m; one under a bean bush, the other between rows of beans. Both were corrected for vertical heat flux divergence effects. Surface temperature was measured with an Everest 4000A infra-red thermometer, mounted at 2.5 m. Surface wetness sensors were placed both on the crop and on the bare ground, between the beans. Background climate variables measured at a nearby site (approximately 300 m from the Bowen ratio tower) included air temperature and relative humidity using a Vaisala temperature-humidity probe; wind speed and direction with an R.M. Young 03001-10 wind sentry set; and precipitation using a tipping-bucket raingauge. The sampling rate of these climate variables was 0.1 Hz with 15 minute averages recorded on a data logger. Hourly averages for the energy balance fluxes and climatic variables are later derived.

All instruments were calibrated and/or intercompared before use in the field. For an estimate of errors associated with these instruments see Section 4.1.3.

5.2 Urban park surface energy balance (SEB)

5.2.1 Background climate

Air and surface temperatures increased throughout the observation period as the weather cleared. The 3-day average vapour pressure differences between near-surface and overlying air in the park, together with park-surround surface temperature differences for YD 207, are plotted in Figure 5.5. The surface temperature difference between the park and the adjacent gravel field is available only at three hour intervals. The surface temperature difference which is an important driving gradient for evaporation and advection, peaks in the early afternoon. The vapour pressure difference is generally small and the near-surface park air has a slightly higher vapour pressure from 1000-1600 LAT.

The wind regime in the park is influenced by both synoptic- and local scale systems.
When skies cleared after the frontal disturbance, a land/sea-breeze system became established giving southwesterly winds in the afternoon, with a peak speed near 2 m s⁻¹. At night, very light east or southeasterly breezes were typical.

5.2.2 Energy balance partitioning

The three-day average SEB for Sites 1-3 and 5 in Trafalgar Park are given in Figure 5.6. Table 5.1 is a statistical summary of the daily and daytime fluxes. Due to cloud, the net radiation is less than the maximum possible and asymmetric about solar noon. It varies little across the park, with a daytime average of about 222 W m⁻². The latent heat flux is clearly dominant at all sites peaking near 220–270 W m⁻² and exceeds $Q^*$ for a brief period in the late afternoon. Sites 1, 2 and 5 have similar energy partitioning with 67–71% of $Q^*$ directed into $Q_E$; about 20% going into $Q_H$ and 8–13% into $Q_G$. The
ground heat flux is more important at Site 1, at the expense of $Q_E$. Site 3 is characterized by higher $Q_E$ that accounts for 80% of $Q^*$. Consequently at this Site $Q_H$ is the lowest of the set.

Table 5.1: Daily and daytime ($Q^* > 0$) energy balance fluxes and and ratios for sites in Trafalgar Park. All fluxes are 3-day averages expressed in W m$^{-2}$.

<table>
<thead>
<tr>
<th>Site</th>
<th>$Q^*$</th>
<th>$Q_E$</th>
<th>$Q_H$</th>
<th>$Q_G$</th>
<th>$\frac{Q_E}{Q^*}$</th>
<th>$\frac{Q_H}{Q^*}$</th>
<th>$\frac{Q_G}{Q^*}$</th>
<th>$\beta = \frac{Q_H}{Q_E}$</th>
<th>$\alpha = \frac{Q_E}{Q_{Es}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) DAILY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>110</td>
<td>78</td>
<td>28</td>
<td>4</td>
<td>0.71</td>
<td>0.25</td>
<td>0.03</td>
<td>0.36</td>
<td>1.07</td>
</tr>
<tr>
<td>2</td>
<td>82</td>
<td>25</td>
<td>3</td>
<td>0.74</td>
<td>0.23</td>
<td>0.03</td>
<td>0.31</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>95</td>
<td>14</td>
<td>3</td>
<td>0.85</td>
<td>0.12</td>
<td>0.02</td>
<td>0.14</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>111</td>
<td>84</td>
<td>25</td>
<td>3</td>
<td>0.75</td>
<td>0.22</td>
<td>0.02</td>
<td>0.29</td>
<td>1.13</td>
</tr>
<tr>
<td>b) DAYTIME</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>221</td>
<td>149</td>
<td>44</td>
<td>29</td>
<td>0.67</td>
<td>0.20</td>
<td>0.13</td>
<td>0.30</td>
<td>1.13</td>
</tr>
<tr>
<td>2</td>
<td>155</td>
<td>45</td>
<td>23</td>
<td>0.70</td>
<td>0.20</td>
<td>0.10</td>
<td>0.29</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>178</td>
<td>26</td>
<td>19</td>
<td>0.80</td>
<td>0.12</td>
<td>0.08</td>
<td>0.15</td>
<td>1.29</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>223</td>
<td>158</td>
<td>46</td>
<td>19</td>
<td>0.71</td>
<td>0.21</td>
<td>0.08</td>
<td>0.29</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Although spatially variable, the turbulent fluxes show a similar temporal trend. At all sites $Q_E$ increases rapidly in the morning (probably due to evaporation of dewfall) and peaks around 1500 LAT coincident with the time of maximum net radiation. In the late afternoon $Q_E$ exceeds $Q^*$ for a few hours. In the morning the sensible heat flux is initially low and possibly negative as dewfall is evaporated, but thereafter increases and remains at 70–100 W m$^{-2}$ for several hours in the early afternoon. It then decreases with $Q^*$ and may turn negative for a few hours in the late afternoon, enabling evaporation to exceed net radiation. This effect is the most pronounced at Site 3.

The cumulative evapotranspiration ($E$) has a maximum at Site 3 (Fig. 5.7) where daily average evapotranspiration is close to 3.5 mm. At Sites 2 and 5 cumulative $E$ is
Figure 5.6: Surface energy balance for Sites 1-3 and 5 in Trafalgar Park, Vancouver. Data are three-day averages. There is considerable variability of the fluxes about their mean because the weather was clearing. On an hourly basis the fluxes may vary by up to 30–40% of their mean value.
3 mm, while Site 1 is about 2.8 mm. This trend of an increase in $Q_E$ through Sites 2 and 3 and then a decrease to Site 5 reflects, in part, the turbulent regime of the park (Section 5.2.3).

Analysis of the average daytime flux ratios reveals some diurnal trends (Fig. 5.8). Initially the ratio $Q_E/Q^*$ is high possibly due to the evaporation of dewfall in the early morning. This process would be assisted by the increase in both net radiation and wind speed soon after sunrise. At this time $Q_E$ may exceed $Q^*$ but for the remainder of the day $Q_E/Q^*$ is fairly constant. Due to this high ratio in the morning, $Q_H/Q^*$ is initially low (and possibly negative) but becomes more constant around 0.2 through the day.

On most of the mornings dew was freely available, but by noon this moisture is exhausted and transpiration rather than evaporation drives the moisture flux. Evaporation at all sites exceeds the equilibrium rate, indicating some mesoscale advective influence. However, since $Q_E < Q_{Ep}$ in the centre of the park, there is no evidence of enhanced
Figure 5.8: Surface energy balance flux ratios at sites in Trafalgar Park. Data are three-day averages.
Figure 5.9: The variation of $Q_E$ with distance of fetch from the park edge based on the daytime average for July 24-25, 1992. The average wind speed for this period was 2.19 m s$^{-1}$.

mesoscale advection.

The Bowen ratio is typically low ($< 0.5$), particularly at Site 3 where it remains less than 0.3. The park sites show an increase in $\beta$ throughout the day again indicating the lack of warm air advection over the park. Rather $Q_H$ is an energy sink for most of the day.

5.2.3 The influence of fetch on $Q_E$

Fetch has an influence on evaporation in Trafalgar Park. As outlined in Chapter 3, Section 3.1.2, it is likely that this pattern reflects both the soil moisture and turbulence regimes in the park. Data for the daytime $Q_E$ on both July 24 and July 25, when the wind was from the southwest sector are used for this analysis (Fig. 5.9). This is a typical wind direction so cumulative effects will show up in soil moisture.

While no data were collected on the turbulence regime in the park, a likely scenario
can be hypothesized given the discussion in Chapter 3, Section 3.1.2. In Trafalgar Park, with a southwesterly wind direction it is likely that the flow is disrupted by two features at different scales. The first is the school buildings which are approximately 10 m high, 44 m in the along-wind direction and 110 m wide (perpendicular to the flow) and separated from the park by a gravel field about 78 m wide. The wake shed by this complex is likely to extend into the park with a quiet zone mainly located over the gravel field, but possibly affecting Site 1. The turbulent wake zone shed by the buildings probably influences Sites 1–3, while Site 5 may be in the readjustment zone. The second feature causing flow distortion is the 0.8 m step change from the gravel field to the park. This is likely to effect both Site 1, which is in a quiet zone, and perhaps Site 2, which may be in a readjustment zone from this smaller wake. Given these two features a likely scenario can be sketched for the overall turbulence regime of the park (Fig. 5.10).

Although spatially variable, soil moisture shows an increase with distance from the upwind park edge (Fig. 5.11). This indicates that microscale advection is drying the
soil near the leading edge. Despite this general increase there is considerable variability over small scales. This is partly due to the installation of tile drainage which results in alternating bands of drier and more moist soil (this was evident in late August after several weeks of drying). Also the turbulence regime will impact the trends in soil moisture. Site 1 which is likely in a quiet zone (and hence sheltered from drying), has a soil moisture content of 26%. Site 2 with a low moisture content of about 18% is more exposed (possibly affected by two wakes: at the larger scale, it is probably in the turbulent wake zone shed by the school buildings, however it is also in the readjustment zone shed by the step change in elevation near Site 1). Sites 3 and 5 which are beyond the influence of the smaller wake, have moisture contents of about 25% and 32% respectively. However, given that Site 3 may be in a turbulent wake shed by the school, it is surprising that the moisture content is not lower. Towards the far downwind park edge the moisture content is lower probably due to micro-advection from the adjacent road drying out the soil.

The impacts of both the turbulence and soil moisture regimes are hypothesized as follows. Site 1 is in a quiet zone and is more decoupled from the flow, with a lower $Q_E$ due to reduced eddy diffusivity. Site 2 is affected by two wakes, the smaller of which may counteract the higher diffusivities expected at this Site. Site 3 is in a turbulent wake zone with better coupling to the flow and consequently has an increased eddy diffusivity and hence higher $Q_E$. Site 5 is likely in a readjustment zone with intermediate coupling between Sites 1 and 3. Hence eddy diffusivity is decreased, resulting in a lower $Q_E$. This scenario is a possible explanation of the observed trend in $Q_E$ across the park (Fig. 5.9). However without turbulence measurements within the park it remains speculation only.
5.2.4 Summary of the energetics of a suburban park in a cool summer Mediterranean climate

This analysis of the spatial variability of the surface energy balance in Trafalgar Park occurs over a drying phase. In the moist park, the SEB is dominated by evaporation which uses about 70–80% of net radiation. A strong edge effect with elevated evaporation is not observed. Rather, with distance from the upwind edge, evaporation increases up to about 25 m and then decreases to 100 m. This pattern probably reflects the turbulent regime in the park, due to obstacles at the upwind edge. Sensible heat accounts for 12–20% of net radiation, and may be negative early in the morning and again for a few hours in the late afternoon. This allows evaporation to exceed $Q^*$. However, for most of the day $Q_H$ acts as an energy sink, therefore the park has little propensity to exhibit edge and oasis advective effects. The ground heat flux is small, using 8–13% of net radiation.
5.3 The urban park in its context – park, suburban and rural comparisons

5.3.1 Energy partitioning in different land-use types

This section discusses the differences in energy partitioning between the moist Trafalgar Park and suburban and rural (bush–bean crop) sites. Four days, July 25–28, 1992 (YD 207–210) are selected for comparison with synchronous measurements at all sites (Fig. 5.12 and Table 5.2). Data from Site 5 in the centre of Trafalgar Park are used in this comparison. The energy partitioning at this site is very similar to that observed in the 3–day average for YD 205–207 but there is less variability given the more settled synoptic conditions. Given that Trafalgar Park was not irrigated (as was desired), data from a study by Oke (1979) of evaporation from an irrigated suburban lawn in Vancouver, are included for comparison.

The surface energy balance of the park is most similar to the rural site. Inter–site differences of net–radiation are small (<5% daily and < 10% daytime). Previous studies have shown net radiation at this suburban site exceeds that at a grassed rural site by about 4% (Oke and McCaughey, 1983; Cleugh and Oke, 1986) i.e. comparable to the difference in daily net radiation between the suburban and park sites. While both the park and rural sites receive similar net radiation and are dominated by the latent heat flux, evapotranspiration at the park greatly exceeds that at the rural site. At both sites $Q_E$ exceeds $Q^*$ for a short period in the late afternoon. The sensible heat flux is relatively low at both these sites but especially in the park. The ground heat flux is of minor importance at both sites. On the other hand the suburban SEB is dominated by $Q_H$ with the storage flux playing an important role in the morning.

The average for the turbulent fluxes indicates the dominance of evaporation at the park and rural sites. The daily ratio of evaporation in the park compared to the suburban rate is 2.25 which is lower than the 3.09 observed by Oke (1979) in a comparison of
Figure 5.12: Surface energy balances for the suburban, park and rural sites in Vancouver. Data are four-day averages. On an hourly basis net radiation is within 10% of its average, while the turbulent and storage fluxes may vary up to 20–25%.
Table 5.2: Daily and daytime ($Q^* > 0$) energy balance fluxes and ratios for sites in Vancouver. All fluxes are four-day averages in W m$^{-2}$.

<table>
<thead>
<tr>
<th>site</th>
<th>$Q^*$</th>
<th>$Q_E$</th>
<th>$Q_H$</th>
<th>$Q_G$</th>
<th>$Q_S$</th>
<th>$Q_{RE}$</th>
<th>$Q_{RH}$</th>
<th>$\beta$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) DAILY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suburban</td>
<td>140</td>
<td>44</td>
<td>98</td>
<td>-2</td>
<td>0.31</td>
<td>0.70</td>
<td>2.25</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>Park</td>
<td>135</td>
<td>99</td>
<td>32</td>
<td>3</td>
<td>0.74</td>
<td>0.24</td>
<td>0.33</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td>143</td>
<td>82</td>
<td>56</td>
<td>4</td>
<td>0.58</td>
<td>0.39</td>
<td>0.68</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Park/Suburban</td>
<td>0.96</td>
<td>2.25</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Park/Rural</td>
<td>0.94</td>
<td>1.21</td>
<td>0.57</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Suburban$^1$</td>
<td>156</td>
<td>53</td>
<td>72</td>
<td>31</td>
<td>0.34</td>
<td>0.46</td>
<td>1.34</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Lawn$^1$</td>
<td>95</td>
<td>100</td>
<td>-13</td>
<td>8</td>
<td>1.05</td>
<td>-0.13</td>
<td>-0.13</td>
<td>1.31</td>
<td></td>
</tr>
<tr>
<td>Lawn/Suburban$^2$</td>
<td>1.00</td>
<td>3.09</td>
<td>-0.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b) DAYTIME</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suburban</td>
<td>314</td>
<td>74</td>
<td>181</td>
<td>59</td>
<td>0.23</td>
<td>0.58</td>
<td>2.46</td>
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</tr>
<tr>
<td>Park</td>
<td>282</td>
<td>196</td>
<td>61</td>
<td>24</td>
<td>0.70</td>
<td>0.22</td>
<td>0.31</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td>294</td>
<td>145</td>
<td>114</td>
<td>34</td>
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<td>0.39</td>
<td>0.79</td>
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<tr>
<td>Park/Suburban</td>
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<td>0.34</td>
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<td></td>
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</tr>
<tr>
<td>Park/Rural</td>
<td>0.96</td>
<td>1.35</td>
<td>0.54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^1$Oke, 1979
$^2$To avoid complications from shading, these values are scaled.
evaporation from the lawn and that over the same suburban site. The park site and the lawn from the Oke (1979) study have evaporation rates in excess of equilibrium evaporation but only the irrigated lawn is significantly influenced by sensible heat advection. At the rural site the average daily $\alpha$ is 0.79 indicating the crop is moisture limited. This crop was not irrigated and received less precipitation (6.6 mm) than the park on YD 203. Consequently $Q_E$ is less than $Q_{Eq}$.

A comparison of the flux ratios at each site, clearly demonstrates the different energy partitioning between the land-use types (Table 5.2 and Fig. 5.13). At the park 74% of daily net radiation is directed into evaporation; this is considerably lower than the 105% observed by Oke (1979) for an irrigated lawn. Again this reflects advection of warm air being a more important energy source for the SEB of the lawn when soil water is artificially maintained near field capacity. At the unirrigated rural site only 58% of the available energy is channelled into $Q_E$. At the suburban site only 31% of $Q^*$ is used in evaporation. For the duration of this observation period a sprinkling ban for lawns was in effect resulting in lower external water use by residents. Hence $Q_E$ and $Q_E/Q^*$ for this suburban site are lower than previously observed. In years without an irrigation ban a more typical value is closer to 40%. At all sites the ratio $Q_E/Q^*$ shows an increase throughout the day particularly in the late afternoon as sensible heat at the park and rural sites, and storage at the suburban site, turn negative i.e. act as energy sources.

Due to the larger amount of energy channelled into $Q_E$ at the park and rural sites, the ratio $Q_H/Q^*$ is much lower and has a corresponding decrease in the late afternoon. At the suburban site, due to the drier surfaces, $Q_H$ is the dominant flux and the ratio $Q_H/Q^*$ is much higher and increases throughout the day to as great as 80%.

The ground heat flux is of minor importance in the park and has a small role at the rural site whereas the storage heat flux at the suburban site is substantial, accounting for 60% of $Q^*$ in the morning. Roth (1991) observed a similarly sharp increase in the
Figure 5.13: Daytime fluxes normalized by net radiation for the suburban, park and rural sites in Vancouver. Data are four-day averages.
morning and then an approximately constant rate until afternoon. As \( Q_H \) becomes more
dominant throughout the day, \( \Delta Q_\ast \) declines and is negative by 1600 LAT.

In the park the Bowen ratio is fairly constant at about 0.36 confirming the dominance
of the latent heat flux in the SEB of the park. However as it remains positive there is
no evidence of enhanced mesoscale sensible heat advection. In contrast, Oke (1979)
observed a Bowen ratio of -0.13 over an irrigated lawn, clearly indicating an edge effect.

Why then does the park not exhibit a tendency to behave as an oasis? The sandy
soils and tile-draining in the park may have affected the rate of recovery from recent
rain. This drainage regime, together with the lack of irrigation, meant that the park
soils were relatively dry resulting in a warmer surface which reduces the temperature
differential between the park and urban surfaces. This surface temperature forcing was
clearly illustrated in the thermal images of Vancouver parks which showed substantial
daytime surface temperature differences between irrigated parks and surrounding urban
surfaces while unirrigated parks have temperatures more similar to those of the urban
surface (Section 2.2.2). Hence for unirrigated parks with free draining soils, there is less
propensity for warm air advection that could lead to elevated evaporation rates and edge
and oasis-type behaviour.

At the rural site the Bowen ratio is greater than one in the morning reflecting the
dominant role of sensible heat at this time. The ratio then declines throughout the day
to 0.35 at 1700 LAT. At the suburban site, due to the dominance of the sensible heat
flux, the Bowen ratio is greater than two for most of the day. This ratio is much higher
than that observed in previous studies at this site due to the unusually dry suburban
surface resulting from the sprinkling ban.
5.3.2 Summary of the urban park SEB compared to other land–use types in a cool summer Mediterranean climate

The unirrigated urban park is dominated by the latent heat flux and has a daily average $Q_E$ 20% higher than the rural site and more than twice that of the suburban site. Sensible heat is of secondary importance and there is little enhanced advective influence on evapotranspiration. Consequently the park does not behave as an oasis. It is suggested this is due to the free–draining park soils and a lack of irrigation. The ground heat flux has a minor role.

At the rural site the SEB is again dominated by $Q_E$, but $Q_H$ is more important here accounting for 39% of $Q^*$. Like the park, $Q_G$ has a small role. At the suburban site $Q_H$ dominates the SEB using 70% of $Q^*$. Evaporation is particularly low for this site reflecting lower external water use by the neighbourhood under a sprinkling ban. On a daily basis the storage flux is of minor importance however it is a major component on an hourly basis acting as a sink early in the morning and as a source in the late afternoon.

Although the park was not irrigated, there was heavy rainfall four days prior to this averaging period. Most of the park drying occurred in the four days after the rain. For the duration of the averaging period, evaporation rates had levelled out and daily totals were very similar. This transition phase of the park limits the generality of the results. However, the results do indicate the energetics of a moist park. Similarly, the SEB for the suburban site is also limited in its generality given the unusual case of a city–wide irrigation ban.

5.4 Comparison of park energetics in different climates

The original experimental design aimed to compare the SEBs of parks in different climates to determine the influence of background climate on energy partitioning. Unfortunately
Figure 5.14: Comparison of surface forcing on evaporation between the Sacramento and Vancouver parks and their suburban environs. The surface temperature difference between urban and park surfaces are in (a), while (b) is the vapour pressure difference between the near-surface park air and the overlying air.

The Vancouver study coincided with a city-wide irrigation ban so parks were not irrigated. As a result water status as well as climatic regime differs between the parks. The data used in this comparison are the two-day averages from Orville Wright Park in Sacramento and the four-day averages (for the settled synoptic period, YD 207–210) from Trafalgar Park in Vancouver. In the absence of an irrigated park, data from Oke's (1979) study of the SEB of an irrigated lawn in Vancouver, are used to provide a first order comparison.

A comparison of the surface temperature differences between the parks and nearby paved surfaces in both Vancouver and Sacramento (Fig. 5.14a) shows a much larger difference in Sacramento. The wetter (and hence cooler) park surface in Sacramento increases the park–urban surface temperature difference. Similarly, the vapour pressure difference between the near-surface park air and the overlying air is also much greater in Sacramento (Fig. 5.14b).
A summary of the daily SEB fluxes and ratios of fluxes for Orville Wright and Trafalgar Parks and the irrigated Vancouver lawn is given in Table 5.3. The park SEB fluxes, normalized by their daytime maxima to aid examination of their temporal behaviour in the different locales, are presented in Figure 5.15.

Table 5.3: Comparison of daily energy balance fluxes (W m\(^{-2}\)), and ratios for the Sacramento park (Orville–Wright), Vancouver park (Trafalgar) and an irrigated Vancouver lawn.

<table>
<thead>
<tr>
<th>Surface</th>
<th>(Q^*)</th>
<th>(Q_E)</th>
<th>(Q_H)</th>
<th>(Q_G)</th>
<th>(\frac{Q_E}{Q^*})</th>
<th>(\frac{Q_H}{Q^*})</th>
<th>(\beta)</th>
<th>(\alpha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vancouver park</td>
<td>135</td>
<td>99</td>
<td>32</td>
<td>3</td>
<td>0.74</td>
<td>0.24</td>
<td>0.33</td>
<td>1.08</td>
</tr>
<tr>
<td>Vancouver lawn</td>
<td>95</td>
<td>100</td>
<td>-13</td>
<td>8</td>
<td>1.05</td>
<td>-0.13</td>
<td>-0.13</td>
<td>1.31</td>
</tr>
<tr>
<td>Sacramento park</td>
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<td>142</td>
<td>-16</td>
<td>-7</td>
<td>1.19</td>
<td>-0.13</td>
<td>-0.11</td>
<td>1.52</td>
</tr>
<tr>
<td>Vancouver park/suburban</td>
<td>2.25</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vancouver lawn/suburban</td>
<td>3.09</td>
<td>-0.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sacramento park/suburban</td>
<td>3.16</td>
<td>-0.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The energetics of the two parks are very different. Vancouver, at a higher latitude, has a slightly longer daylength resulting in greater radiant energy input (Table 5.3). Both have negligible ground heat fluxes. This small flux is lagged in the Sacramento park due to the thick grass canopy. \(Q_E\) shows a similar temporal pattern in both parks, but the ratio \(Q_E/Q^*\) reveals that a much higher proportion of net radiation is directed into evaporation in the Sacramento case. The irrigated Vancouver lawn has a SEB similar to that of the Sacramento park with \(Q_E\) exceeding \(Q^*\) on a daily basis. At these irrigated sites evaporation exceeds the potential rate and is thrice that at nearby suburban sites. In contrast, the moist Vancouver Park has a daily evaporation rate well below its potential.

Both irrigated surfaces have the same small negative daily ratio of \(Q_H/Q^*\) whereas
Figure 5.15: Comparison of park SEB fluxes normalized by their maxima (i.e., $Q_x/Q_{x\text{ max}}$). Data are ensemble averages from the Sacramento and Vancouver studies. The normalizing maxima values (in W m$^{-2}$) for Orville Wright Park, Sacramento are: $Q^* = 529$, $Q_E = 435$, $Q_H = 110$, $Q_G = 24$; and for Trafalgar Park, Vancouver: $Q^* = 480$, $Q_E = 311$, $Q_H = 115$, $Q_G = 56$. 
the Vancouver park has a small but positive ratio. This highlights the difference in energetics between the two parks. In the unirrigated Vancouver park the soil is much drier, particularly near the upwind edge where microscale-advection has depleted soil moisture beyond that of the rest of the park (section 5.2.3). Consequently the evaporative forcing is lower than expected for an irrigated park and hence the park has a positive $Q_H$ through most of the day (it is negative for only two hours in the evening). With distance into the park evaporation varies in response to the turbulence regime (an initial increase coinciding with a turbulent wake zone and decrease in the readjustment zone (Fig. 5.9 and 5.10).

In contrast, sensible heat fluxes over the irrigated surfaces (both the Sacramento park and Vancouver lawn) are negative in mid-afternoon, which coincides with the time of maximum evaporative forcing (Fig. 5.14). Thus evaporation from these well-watered surfaces is substantially assisted by advection. In Sacramento both micro- and mesoscale advection are important in the afternoon and evening and sustain high rates of evaporation. In response $Q_E$ shows an exponential decrease with distance into the park. The irrigated Vancouver lawn is small (ca. 75 m$^2$) so microscale advection is likely to have been the most important type involved. Over a more extensive irrigated surface, oasis-type advection might also occur in Vancouver.

In moist or wet urban parks evaporation dominates the SEB and evaporation can exceed the potential rate if surface forcing is sufficient to induce edge and oasis-type advection. The free availability of water, which in summer implies irrigation, appears to be a criterion in order for $Q_E$ to exceed $Q_{Ep}$. In addition there must be a sufficient park-suburban temperature and vapour pressure deficit differential. Given the similarity of the energetics of irrigated surfaces in different climates, it is suggested that soil moisture, rather than background climate, is of greatest importance in determining energy partitioning in parks.
Chapter 6

Scale Model Design for Nocturnal Cooling in Urban Parks

This part of the research aims to gain a better understanding of the controls on park cooling following sunset. A methodology is developed for scale modelling of nocturnal cooling in urban parks.

6.1 Considerations in nocturnal park cooling

The descriptive survey of air and surface temperatures of parks (Chapter 2), showed that except for open, dry grass types, parks are generally cooler than the surrounding neighbourhood throughout the day. For parks with large shade trees the urban–park temperature differential may reach a maximum in the late afternoon. However for most parks, the PCI is best developed at night, soon after sunset for garden and savannah parks, and near sunrise for open grassed parks.

There are several reasons why a park may be a "cool island" relative to the surrounding neighbourhood. By day, the park may have less radiant energy input and/or it may use more of its heat in evapotranspiration or heat conduction to the ground. The turbulent sensible heat transfer and the availability of anthropogenic heat input however, are likely to be less than for the surrounding city. These factors contribute to the park heating up more slowly. At night, in addition to these factors, the park may have greater radiative cooling than the city due to its surfaces possessing higher sky view factors. The research in Sacramento and Vancouver parks (Chapters 4 and 5) provides comparisons of energy balance partitioning in parks and suburban neighbourhoods, and can assist in
determining which of these processes are likely to be important.

For open grassed parks, it is possible for the net radiation to be higher or lower than the suburban value, depending on the albedo of both surfaces. If the park is well treed, net radiation at the surface will be lower because of shade and this will have an important influence by slowing the warming of the park by day, and reducing heat loss at night.

Heat conduction into the ground is much less in the park than in the suburban neighbourhood. Comparison of the two showed that during daytime, the park in Sacramento had about 85% less while in Vancouver the park had 60% less heat conducted to storage than the city (p.90 and p.117). By night the heat release is larger in the city than from the park.

Convective sensible heat transfer is much lower in parks than in the surrounding city, and in fact in some cases the park may act as a sink for $Q_H$ rather than a source. This occurs when the park acts as an “oasis”, often resulting in $Q_E$ exceeding $Q^*$, and a downward flow of sensible heat acting as an extra energy source. This oasis–type behaviour was exhibited in the well–irrigated Orville Wright Park in Sacramento. In Vancouver, probably due to the lack of irrigation, Trafalgar Park did not act as an oasis, however sensible heat in the park was about 70% lower than in the suburban neighbourhood.

By day convective latent heat transfer has the potential to be much higher in a park than in its surrounding city. Certainly in both the Sacramento and Vancouver parks, the latent heat flux from the park is substantially higher than the suburban value. The magnitude of the park–city difference in $Q_E$ depends upon many factors including: soil moisture status of the park relative to the city, the macroscale climate regime, the suburban density and local gardening practices. On the other hand at night $Q_E$ continues at a much reduced rate. By sunset, high rates of evapotranspiration in some well–irrigated parks may establish the park as a cool island. However, at night under calm,
clear conditions when urban–park differences can be large, turbulence is suppressed. This suggests that nocturnal cooling of parks must be due primarily to radiative and conductive processes accentuating the PCI which is already present at sunset.

6.2 Objectives of scale modelling

The aim of the scale modelling portion of this study is to determine the relative magnitude of the controls on nocturnal park cooling. Following the discussion in section 6.1, the objectives are to assess:

- the role of radiative transfer;
- the role of conductive transfer;
- the role of latent heat transfer

in nocturnal cooling. Consideration is restricted to the case of calm and cloudless weather as the park effect is greatest under these conditions. The model simulates the effects of urban and park surface geometry, thermal properties and evapotranspiration.

6.3 Scaling considerations

It is important to state the extent to which model:full scale similitude is preserved. The model simulates cooling after sunset, therefore it is necessary to scale the processes governing heat loss as well as the physical properties of the surfaces which govern the ability to release heat.

The main nocturnal processes are radiation and conduction and the relevant surface properties are radiation geometry and thermal admittance. It is not necessary to scale
the radiative process since all radiative transmission is at the same speed and the characteristic length scale is of negligible dimensions (Oke, 1981). The surface geometry is length scaled.

The model to simulate cooling by conductive transfer manipulates the thermal properties of the "park" relative to the "city". The appropriate property is thermal admittance \((\mu)\) which is related to the thermal conductivity \((k)\) and heat capacity \((C)\) of the surface by:

\[
\mu = (kC)^{\frac{1}{2}}.
\] (6.1)

It is a measure of the thermal response of the surface to the heat flux across the interface. With low values of thermal admittance a surface will readily accept or release heat, but conversely for high \(\mu\) heat is accepted or released slowly. Surfaces of high \(\mu\) exhibit a smaller amplitude temperature wave than those of low \(\mu\). The \(\mu\) value for urban parks may be higher or lower than the city depending mainly on the relative differences in soil moisture content and the nature of the urban fabric. Rather than attempting to approximate real world thermal admittances of park and urban surfaces, the park is constructed of materials that have either higher or lower thermal admittances than the model urban surface. This approach provides a first approximation to the influence on the park cool island, PCI, of the thermal admittance differences between the park and the city.

Scaling evapotranspiration is a complex problem. Simple models of leaves and plant canopies have been used to simulate the flow field and heat and mass transfer (e.g. Schuepp 1972, 1973; Chen et al., 1988a,b; Siegner et al., 1976; Coppin et al., 1986). However the problems surrounding this reductionist approach are immense. Jarvis and McNaughton (1986) and Baldocchi (1989) caution against merely extrapolating from one level to the next and emphasize the central importance of the scale of the phenomenon.
(leaf, plant, canopy, region). Due to important links between plant response and the environment, it is unlikely that physical scale modelling can be applied to study evapotranspiration from a park surface, particularly if results are to be generalized.

Given these difficulties, the "park" is treated as a moist surface with no biological control but, by using an appropriate surface cover, some resistance is provided to free evaporation. Given that plants generally close their stoma at night this approximation, which neglects plant physiological control, is considered acceptable.

6.4 Scale models

To study each park cooling mechanism, three different models are implemented. While such an approach is inherently reductionist and therefore over—simplifies the park system, it gives a first order approximation of the magnitude and extent of cooling to be expected if each mechanism were operating in isolation. Once each mechanism has been studied in isolation, the combined effects of each mechanism are determined through a combination of model designs.

The models are based on hardware scale representations of a "park" surrounded by an "urban environment". The model consists of a base of wood (0.83 m×0.83 m, 37 mm thick Douglas fir) upon which blocks of the same wood (to simulate "buildings") are arranged into canyons. The middle of the model is the "park", which is simulated in various ways depending on the mechanism being investigated. The base is insulated from below by a layer of polystyrene.

A nocturnal cooling cycle is simulated in the following manner. The model is irradiated by nine 500 W halogen lamps. The length of heating is determined by scaling considerations. The thermal diffusivity, \( \kappa \), for the fir base was initially estimated as \( 9.7 \times 10^{-5} \, \text{m}^2 \, \text{s}^{-1} \) (Chapman, 1984). The penetration of a diurnal heat wave into the soil
is represented by:

\[ T(z, t) = \bar{T} + A_0 e^{z/D} \sin \left( \omega t - \frac{z}{D} \right) \]  

(6.2)

where \( T \) is temperature; \( z \) is depth; \( t \) is time; \( \bar{T} \) is the average surface temperature; \( A_0 \) is the amplitude at the surface; \( D \) is the damping depth; and \( \omega \) is the angular frequency of the oscillation (\( \omega = 2\pi \sqrt{\kappa / D^2} \)). An appropriate damping depth is chosen to regulate the diurnal heating and cooling cycle. Given that the model base is 37 mm thick, a damping depth of 10 mm was arbitrarily chosen. This results in: \( \omega = 0.0105 \, \text{s}^{-1} \) which gives a diurnal period, \( P = 2\pi / \omega = 3239 \, \text{s} \) or 54 minutes.

In the real world, soil temperature is approximately isothermal from the surface to the damping depth shortly before sunset. This was achieved by turning the lamps on and off so as to propagate a series of small heat waves. This condition of isothermality has been used as a boundary condition to initiate cooling (Brunt, 1941; Oke, 1981) in prior numerical and scale models of nocturnal cooling at the surface. This boundary condition is hereafter referred to as the model “sunset”. At “sunset” the model is quickly removed from beneath the lamps, a polyethylene tent is placed over it, and it is moved into a small room at a temperature of about 20°C. To create a surface to sky temperature differential for the model that is comparable to that in the real world, the model is heated to be isothermal at about 60°C. This establishes a temperature differential of approximately 40°C between the hot model and the cold “sky” (the ceiling and walls of the room) at room temperature. This temperature differential allows observation of about 15–20°C cooling over a ten minute period. The polyethylene tent avoids convective transfer between the hot model and the air in the room. The surface cooling is monitored for about ten minutes (625 s) following sunset. This corresponds to the time for the model to approach the maximum amount of cooling given the rationale for scaling time. This is slightly less than initially estimated from the time scaling scheme (for a period of
54 minutes the time from a condition of isothermality to the minimum temperature is about 16 minutes. However, the thermal diffusivity of the model base was subsequently determined by differential scanning calorimetry to be $5.25 \times 10^{-7} \text{ m}^2 \text{s}^{-1}$, hence the revised time for cooling.

6.4.1 Simulation of radiative cooling

The model to simulate radiative cooling involves altering the dimensions of the surface geometry to simulate different types of urban park (Fig. 6.1). The “buildings” are arranged in canyons with a height to width ratio of 1:1 to simulate the urban environment. The simplest case of “park” is bare wood for an open grassed park. For the case of parks with trees, model “trees” fashioned from foam rubber are placed in the park to mimic parks with tree borders, savannah parks and garden parks. A more-or-less continuous canopy of foam is placed over the park to simulate a forested park. The dimensions of the surface geometry are scaled to give a 1:625 relation between the model and the real world. Hence “buildings” 40 mm high in the model, represent about 25 m (or 5 storey) buildings in the real world, and the 40–100 mm high “trees” both conical and broad shaped (spherical) in the model represent 25–62.5 m tall trees in the real world. Two sizes of park are simulated. The first is a small 1.6 ha park, approximately 0.20 by 0.20 m in the model; the second is a 5 ha park, approximately 0.36 by 0.36 m in the model. To maintain a constant thermal mass of the model overall, the blocks removed when changing park size, are stored as part of the model base.

6.4.2 Simulation of conductive cooling

The simulation of conductive cooling differences is achieved through manipulation of the thermal properties of the park relative to the city. The background “city” is always constructed of wood (fir) while the “park” is made of different materials (Fig. 6.2). The
Figure 6.1: Scale model design to simulate radiative cooling in different park types. The "grass park" is open with no "trees". The park dimensions are 0.36×0.36 m and the buildings are 40 mm high and wide.
materials used together with their estimated thermal admittance are given in Table 6.1.
The thermal conductivity and specific heat of the fir was determined through differential
scanning calorimetry. Both properties are temperature dependent. The following average
values appropriate for the range of temperatures (20–70°C) in this study are used:
0.265 W m⁻¹ K⁻¹ for thermal conductivity and 1122 J kg⁻¹ K⁻¹ for specific heat (cₐ).
With knowledge of the density (ρ) the volumetric heat capacity (C) is derived:

\[ C = \rho c_a, \]  

(6.3)

and thence thermal admittance (μ) from equation 6.1. Thermal diffusivity (κ) can also be calculated:

\[ \kappa = \left(\frac{k}{\mu}\right)^2. \]  

(6.4)

The thermal admittances of the remaining materials in Table 6.1 are estimated by a
numerical model (see Section 6.6.2) which is validated against the measured Douglas fir.

Table 6.1: Thermal admittance of the materials used in scale modelling

<table>
<thead>
<tr>
<th>Material</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas fir</td>
<td>366</td>
</tr>
<tr>
<td>Plywood</td>
<td>234</td>
</tr>
<tr>
<td>Oriented-strand-board (OSB)</td>
<td>198</td>
</tr>
<tr>
<td>Low density fibre-board (LDF)</td>
<td>147</td>
</tr>
<tr>
<td>Concrete</td>
<td>727</td>
</tr>
</tbody>
</table>

6.4.3 Simulation of evaporative cooling

This model set-up involves a moist “park” surrounded by a dry “city”. The model has a
fir “city” as before with the park section replaced by a moist surface (Fig. 6.3) consisting
initially of a pan of water, and in a subsequent run, by moist blotting paper. In this case the model is heated without the moist park, until the temperature at the 10 mm depth is approximately 60°C. The wet “park” is then placed on the model and after a further period of heating, sunset is initiated and the cooling of the surface is monitored. At sunset the vapour pressure deficit is typically about 1700 Pa.

6.4.4 Combined influences of geometry, thermal admittance and evaporation

The combined influences of surface geometry, thermal admittance and evaporation are assessed in a further set of experiments. Firstly, surface geometry and thermal admittance are combined by adding canyon geometry to the city together with materials of different thermal properties for the park. The addition of surface geometry provides view factor effects as well as changing the thermal admittance of the surface.

Secondly, the combined effects of thermal admittance and evaporation are examined
Figure 6.3: Scale model design to simulate evaporative cooling in urban parks.

in experiments using a flat model with a moist park. However, unlike the parks used in the evaporation experiments, the same materials used in the thermal admittance experiments are soaked for several hours and then inset as a park. This creates both thermal admittance and evaporative differences between the park and the city.

Finally, experiments are run with the combined influences of surface geometry, thermal admittance and evaporation. This is set up as described above for the thermal admittance and evaporation experiments except for the addition of surface geometry on the city. This analysis also examines the behaviour of each park material under different boundary conditions: flat, dry; flat, wet; and for models with urban canyons surrounding a central park – canyons, dry; and canyons, wet.
6.5 Measurements

6.5.1 Surface temperature measurement by thermocouples

The surface temperatures of each model are sampled by an array of thermocouples extending from the edge of the “city” to the centre of the “park”, as well as in “urban canyons”. Thermocouples are also installed to sample temperatures of different facets of the city (ground, canyon wall, canyon roof), of tree canopies (when present) and special spatial coverage across the different park set-ups. Thermocouples also measure “ground” temperatures at various depths (10 mm, 20 mm and 37 mm).

The sensors are 36 awg, copper–constantan thermocouples insulated with teflon coating. They were tested prior to use on the model to determine the inter–sensor precision. The thermocouples were placed in a sealed box in a darkened laboratory for a period of 12 hours. Temperatures were sampled every 30 s and averaged over ten minutes. After 12 hours the standard deviation of the measured temperatures was less than 0.4°C.

The thermocouples are attached to the surface following the method of Fairey and Kalaghchy (1982). This involves the construction of small arcs (approximately 5 mm) between the junction and the insulated wire. The arcs are attached to the surface using a thin layer of tape rather than adhesive to allow the thermocouple positions to be moved.

Seven of the thermocouples in the transect from the city to the centre of the park are sampled at 0.5 Hz while the remaining 13 thermocouples are sampled at 0.1 Hz using a multiplexer. The data are continuously measured on a CSI CR21X data logger. The standard error in temperature measurements is estimated to be 1.03°C. The main sources of error occurring are attributed to the reference temperature within the 21X, thermocouple output and mounting errors (Appendix B). Tests of replicability show the errors are much smaller – typically less than 0.5°C (Section 6.6.5).
6.5.2 Remotely sensed surface temperature measurements

An AGEMA Thermovision scanner is used to remotely sense model surface temperatures. The scanner is placed approximately 1.12 m away from the cooling model, looking down at the model at an angle of about 30° from the horizontal. With the 12° field of view, this results in a viewed area on the model of 0.137 m². This is sufficient to encompass an entire small park and the adjacent city canyon, or half of the large park and its adjacent canyon. The polyethylene tent is extended to the AGEMA lens via a sleeve, so that the scanner is looking directly at the model, hence the transmissivity is approximately 1. Images are recorded at 0.1 Hz. For model runs with a moist park, surface temperatures are digitized from the AGEMA images as the thermocouples do not have good thermal contact when the surface is damp. For the range of temperatures encountered in the modelling, the AGEMA can estimate surface temperature to within 0.5°C (Section 2.1.2).

Figure 6.4 shows a comparison of surface temperature measured by the thermocouple and AGEMA methods. The systems are well correlated but the AGEMA consistently estimates higher surface temperatures than the thermocouples; particularly at temperatures greater than 50°C. This is not of great concern. It is thought that the difference may be mainly due to mounting errors for the thermocouples (approximately 0.4°C).

6.6 Analysis

6.6.1 Corrections

Measurement errors are expected, for example a thermocouple may lift slightly during the run thus giving a lower (air) temperature rather than a true surface temperature. Comparison of the temperatures measured by the two systems is used to detect and correct such a problem. This should require consideration of an emissivity correction to the AGEMA temperatures because a surface emissivity of either unity or 0.97 is assumed.
Figure 6.4: Comparison of surface temperature estimates from the AGEMA and thermocouples. Data are averages for three model runs.
during measurement. The need for correction was checked as follows.

The emissivity of the model materials was determined using the method of Davies et al. (1971). This entailed placing a cone with a polished mylar surface over the material to allow the surface to behave as a blackbody. The temperature of the surface was measured before the cone placement by an Everest 4000A infra–red thermometer to give the apparent surface temperature ($T_r$). Immediately after placing the cone, the true surface temperature ($T_s$) was measured using an infrared thermometer viewing the surface through an aperture in the polished cone. The radiative sky temperature ($T_k$) was measured at several zenith angles and azimuths and averaged. The emissivity of the surface ($\epsilon$) was estimated:

$$\epsilon = \frac{T_r^4 - T_k^4}{T_s^4 - T_k^4} \quad (6.5)$$

Table 6.2 shows the estimated values of emissivity for the model materials. The root mean square error (RMSE) for estimates of emissivity is 0.02 (Appendix B). Sensitivity tests were run to estimate the error incurred by using an assumed $\epsilon$ of 0.97 or 1.0 by the AGEMA system (Fig. 6.5). The following example illustrates the probable error involved. If an emissivity of unity is assumed for the fir, which actually has an emissivity of 0.95, the maximum error in the surface temperature is about 0.4°C at 70°C. The size of the error decreases as the model cools. Given errors of this order, no corrections were made to surface temperatures.

### 6.6.2 Theoretical framework

**Assumptions of modelling**

There are several assumptions both implicit and explicit in the modelling:

- Cooling processes in the model are dominated by radiative and conductive processes, i.e. the model design suppresses convective cooling.
Figure 6.5: Sensitivity tests of the difference between assumed and actual emissivity on derived temperatures from AGEMA images: (a) shows the temperature difference when $\epsilon = 0.97$ is assumed; (b) shows the temperature difference when $\epsilon = 1.0$ is assumed.
Table 6.2: Estimated emissivities for model materials in both their dry and moist states. The means and standard deviations ($\sigma$) are derived from three tests.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\varepsilon$ (dry) $\sigma$ (dry)</th>
<th>$\varepsilon$ (moist) $\sigma$ (moist)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fir</td>
<td>0.967 0.005</td>
<td>0.986 0.002</td>
</tr>
<tr>
<td>Plywood</td>
<td>0.957 0.005</td>
<td>0.988 0.002</td>
</tr>
<tr>
<td>OSB</td>
<td>0.953 0.005</td>
<td>0.986 0.001</td>
</tr>
<tr>
<td>MDF</td>
<td>0.958 0.003</td>
<td>0.988 0.001</td>
</tr>
<tr>
<td>LDF</td>
<td>0.963 0.003</td>
<td>0.989 0.002</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.969 0.004</td>
<td>0.959 0.002</td>
</tr>
<tr>
<td>Blotting paper</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- As all radiative transmission is at the same speed and the characteristic length scale is of negligible dimensions, geometric scaling holds.

- Cooling is proportional to the thermal admittance of model materials.

- Time is scaled according to the thermal properties of the model materials and consideration of the penetration of a sinusoidal heat wave into the base.

- The surface–sky temperature differential at “sunset” is comparable to the real world.

- Anisotropy of the model materials is not considered a problem.

Comparison of scale model cooling with predictions from a numerical model

To determine if the model simulates real world conditions, it is tested against a numerical surface heat island (SHIM) model developed by Johnson et al. (1991). This model
simulates nocturnal cooling of rural and urban surfaces under clear, calm nights and has been carefully validated against field data. The model consists of a system of partial differential equations, hereafter referred to as the SHIM_PDE approach. A full outline of the model is given by Johnson et al. (1991) and numerical details are given in Johnson and Watson (1987, 1988). The urban and rural environments are modelled as layers in which conduction normal to the layer greatly exceeds conduction parallel to it. Heat flow within the layer is modelled by the one-dimensional heat conduction equation,

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} \quad (6.6)$$

where $\kappa$ is the thermal diffusivity ($m^2 \, s^{-1}$) of the layer and $T(x, t)$ is the temperature at distance $x$ from the boundary at time $t$. Heat flow at the surface of a layer is induced through radiative transfer and heat gain at a surface $i$, of absolute temperature $T_i$, when exposed to other surfaces $j$ (where $j = 1, ..., N$), of absolute temperature $T_j$, emissivity $\epsilon_j$, and view factor $\psi_{ji}$, is given by:

$$\epsilon_i \sigma \left[ \sum_{j=1}^{N} \epsilon_j \psi_{ji} T_j^4 - T_i^4 \right] \quad (6.7)$$

where $\epsilon_i$ is the emissivity of surface $i$ and $\sigma$ is the Stefan–Boltzmann constant. Heat flow is modelled within $N$ surface elements by:

$$\frac{\partial T_i}{\partial t} = \kappa_i \frac{\partial^2 T_i}{\partial x^2} \quad i = 1, ..., N, \quad (6.8)$$

with the boundary condition for the interior of this layer given by

$$T_i(0, t) = T_G(t), \quad (6.9)$$

while the boundary condition for all exterior surfaces is

$$k_i \frac{\partial T_i}{\partial x}(D_i, t) = L_i^* \quad i = 1, ..., N, \quad (6.10)$$
where

\[
L_i^* = \epsilon_i \left[ \sum_{j=1}^{N} \sum_{k \neq i}^{N} \psi_{ji} \sigma T_{ij}^4(D_j, t) + \psi_{si} L \downarrow - \sigma T_i^4(D_i, t) \right] + \epsilon_i \sigma \sum_{j=1}^{N} \sum_{k \neq i}^{N} \sum_{l \neq j}^{N} \psi_{ki} (1 - \epsilon_j) \psi_{jk} \epsilon_j T_{ij}^4(D_j, t),
\]

(6.11)
is the net long-wave radiative flux density, using the diffuse-gray assumption. The subscripts \(G\) and \(s\) refer to deep soil, and sky respectively, while \(D_i\) is thickness (m) and \(k_i\) is the thermal conductivity (W m\(^{-1}\) K\(^{-1}\)) of element \(i\) and \(L \downarrow\) is the incoming long-wave radiation. The initial condition for each element is

\[
T_i(x, 0) = f_i(x) \quad 0 \leq x < D_i \quad i = 1, ..., N,
\]

(6.12)

where \(f_i(x)\) are given temperature distributions.

The model is initialized with both a surface and deep soil temperature, incoming long-wave radiation, the constants \(\epsilon, \kappa, k\) and the view factors for each surface. The view factors for each surface are calculated using analyses derived from Steyn and Lyons (1985) and Howell (1982), and also fisheye-lens photography with the method of Steyn (1990). Details are given in Appendix C. The model uses the Crank-Nicholson method to solve equation 6.8 giving temperature of each surface as a function of time.

The SHIM\(_{PDE}\) approach has successfully simulated surface cooling (see Johnson et al., 1991) and is used in this analysis to determine if the scale model can produce realistic results. An ensemble average of surface cooling data from five scale model runs with similar boundary conditions, is used to verify the model. Figure 6.6 shows a comparison of cooling by the scale model with that predicted by the SHIM\(_{PDE}\) model when initialized by scale model data. The numerical model slightly overestimates the cooling in the scale model at lower temperatures, i.e. the latter part of the "night". However, agreement between observed and predicted results is generally good and verifies that the assumptions
in the scale model are valid. Thus the scale model realistically simulates surface cooling.

6.6.3 Derivation of thermal admittance

Given the ability of the SHIM$PDE$ model to simulate both full-scale and scale model cooling, it is used as a tool to determine the thermal admittance of the remaining materials used in the scale model. This is necessary because it was not possible to have all the materials laboratory tested to determine their thermal properties. The observed surface cooling from the scale model is compared iteratively to that predicted by SHIM$PDE$ under different trial values of $k$, $\kappa$ and $\mu$ until good agreement is found.
6.6.4 Calculation of surface temperature park cool islands, PCIₜs

To assess the impact of the chosen experimental variables on cooling, a park effect is calculated for each model run. Despite attempts to evenly heat the model, there is always some spatial variability of surface temperatures at "sunset". To simplify matters spatial averages of surface temperatures are used in the calculation of the park cool island, PCIₜ. Both the average urban surface temperature, $\bar{T}_u$ (averaged from mid-points of canyon floors), and the average park temperature, $\bar{T}_p$, are derived from three points. The PCIₜ is then calculated:

$$ PCIₜ = \bar{T}_u - \bar{T}_p. $$(6.13)

There may be a positive (or negative) $PCIₜ$ present at sunset so this offset is subtracted (or added) to set the $PCIₜ$ equal to zero at sunset. This is hereafter referred to as a "normalized park cool island," $NPCIₜ$. The analysis compares the growth of $NPCIₜ$ through the "night" between the different model set-ups.

6.6.5 Replicability of results

To have confidence in the model, results must be replicable. For the simulations of radiative cooling in larger parks, each set-up was replicated at least three times. Comparison shows that replication errors are generally small for park surface cooling, but errors are larger for cooling in urban canyons. This is illustrated in Figure 6.7 which shows the cooling for urban canyon and park temperatures, and the resultant PCI and associated errors for a "grassed park". The cooling curve for the open park is relatively smooth and possesses a low standard error. The curve for the canyon floor is more variable and has a higher standard error. The variability may be due to convection (buoyant thermals rising from the surface). While there are indications from field research that air within canyons is unstable at night (e.g. Nakamura and Oke, 1988) this phenomenon would be
enhanced at the higher model temperatures. Thus the resulting standard error in a $PCI_s$ may approach about ±0.7°C. Given this variability in the urban reference, analyses of the $PCI_s$ comment on the absolute cooling of the park surface.
Figure 6.7: Test of the replicability of the scale model to simulate cooling in a "grassed park". Average urban and park cooling curves (a) are shown together with the derived $PCI_s$ (b). The averages and their standard errors derived from four replicates.
Chapter 7

Scale Model Results of Nocturnal Cooling in Urban Parks

This chapter presents results from scale modelling of nocturnal cooling in urban parks. Results from the different model designs are given: surface geometry, thermal admittance differences, evaporative effects and combined effects. The combined influence of these mechanisms is discussed in relation to cooling observed in real parks.

7.1 Radiative cooling

7.1.1 Influence of park size

The absolute size (dimension) of a park is an important control on its nocturnal climate. Close to the edge of the open grassed model park there is a sharp decrease in sky view factor, $\psi_s$ (Fig. 7.1). This edge effect is confined mainly to the perimeter of the park. In the case modelled, points from a quarter of the way into the park, to the centre, have view factors greater than 0.85. These view factor effects are reflected in the growth of the PCI$_s$ (Fig. 7.2). Near the edge of the large open grass park ($\psi_s = 0.84$) surface cooling is of a similar magnitude to that for the centre of the small park ($\psi_s = 0.88$). Cooling is greater in the middle of a large park where $\psi_s$ is 0.96. However, for $\psi_s$ from 0.84–0.96, there is a similar rate of increase in PCI$_s$ immediately after sunset. This suggests that smaller parks can attain a significant amount of cooling soon after sunset. To enhance cooling through the night, larger parks are more effective.

The optimum park size mainly depends on the geometry of the urban surroundings.
By estimating $\psi_s$ for the centre of square open grassed parks of different sizes with constant height of the buildings surrounding the park (see method in Appendix C, section C.1), the relation between $\psi_s$ and the ratio of park width : height of the surrounds, is derived. As the ratio of park width to building height (or tree height if there is a tree border) increases beyond about 7.5, there is little gain in terms of radiative cooling (Fig. 7.3). However as the park size increases a larger volume of air is cooled and this increases the potential for advection of cool air into the neighbourhood.

### 7.1.2 Influence of park type

Park type (defined Chapter 1, section 1.2.2) alters the configuration of vegetation and this influences patterns of $\psi_s$ within the park. For the open grassed park there is a strong temperature gradient near the park edge, but little difference between cooling at points in the central area of the park (Fig. 7.4a). The grassed park with the tree border exhibits similar cooling trends to the treeless park, except that cooling near the edge is especially weak, because the tree border reduces $\psi_s$.

Savannah and garden parks (Fig. 7.4c,d) have more spatially-variable surface cooling patterns due to their complex array of sky view factors. However, despite lower $\psi_s$ for the centre of these parks, they still display mid-park cooling comparable to that in open grass parks. This may be due in part to greater surface forcing of cooling with a higher surface to “sky” temperature differential at the time of initialization (or “sunset”).

The forest park (Fig. 7.4e) shows a great range of surface cooling environments. The point on the “ground” a quarter of the way across the park cools little, because the sky is completely obscured. However, both the edge and the centre of the park exhibit considerable cooling, despite $\psi_s$ values of 0.31 and 0.28, respectively. This apparent anomaly may result from the sinking of cooler air from the top of the forest canopy onto the “ground” surface. The top of the canopy has $\psi_s$ about 1.0, and being made from
Figure 7.1: Map of sky view factor for a quadrant of the large open grass park model. The surrounding buildings are 40 mm high. The location of the thermocouples used in the analysis is also shown.
Figure 7.2: The influence of park size on development of the PCI, after sunset.

Figure 7.3: Relation between the ratio park width : building height and sky view factor in the centre of the park. Building height was held constant, but can in practise, vary.
Figure 7.4: Influence of park type on cooling of different facets: (a) open grassed parks; (b) grass parks with tree borders; (c) savannah parks; (d) garden parks and (e) forest parks. Cooling rates in the urban canyon are shown for comparison. The $\psi_s$ for each facet is given in brackets.
foam has very low thermal admittance and almost no contact with the model base.

A general sense of the cooling induced by different park types can be gained from (Fig. 7.5a–e). This shows the surface temperature distributions at the end of each model “night” (after 625 s of cooling). These images have not been normalized for any differences in surface temperatures at sunset, so intercomparisons should be made with caution. Rather, they are used to illustrate spatial patterns. To aid comparison they are plotted with a common temperature scale (and hence some resolution is lost).

The effects of surface geometry are clearly visible. The edges of the park and urban canyons are much warmer than other facets. In the more open parks (grass, and grass with tree border) the mid–park region shows greatest cooling. In the savannah and garden parks, with interspersed trees, cooling is more patchy, and open spaces are distinctly cooler. Where trees are clustered surface temperatures are much higher. The trees themselves are always much cooler (closer to air temperature) and in the forested park the extensive canopy provides an elevated cooling plane which is considerably cooler than any of the surroundings.

The resultant NPCIs at the end of the “night” for the different park types (Fig. 7.6a) range from small (2°C) for the forest park to large (7°C) for the open grass park (Table 7.1). The insulating canopy in the forested park slows “ground” surface cooling resulting in a small increase in the NPCI, by the end of the night. However by “day”, this canopy shades the ground and can produce a substantial cool island which nocturnal cooling slowly accentuates. The increasing NPCI, from open to forested park type is clearly related to greater $\psi$, (Fig. 7.6b).

This effect of surface geometry is comparable to that observed by the numerical simulation (surface heat island model, SHIM) of Oke et al. (1991) which was developed to illustrate the effect of surface geometry on urban heat island development. They found that the presence of canyon geometry (H:W of 1.15) alone, resulted in a 4°C
Figure 7.5: Park surface temperatures at the end of the model "night" (625 s). (a) open grassed parks; (b) grass parks with tree borders; (c) savannah parks; (d) garden parks and (e) forest parks.
Figure 7.6: The influence of park type on: (a) the growth of the PCI, (average $\psi_s$ is shown in brackets) and (b) the relation between the average $\psi_s$ and NPCI.
Table 7.1: The effect of park type on the magnitude of the average PCI₃. All PCI₃s are in Celsius.

<table>
<thead>
<tr>
<th>Park type</th>
<th>ψ₃</th>
<th>PCI₃ at sunset</th>
<th>PCI₃ at end of night</th>
<th>Growth/Decay PCI₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>grass</td>
<td>0.92</td>
<td>-3.5</td>
<td>2.6</td>
<td>6.1</td>
</tr>
<tr>
<td>grass with tree border</td>
<td>0.84</td>
<td>1.3</td>
<td>4.1</td>
<td>5.4</td>
</tr>
<tr>
<td>savannah</td>
<td>0.82</td>
<td>-1.9</td>
<td>3.0</td>
<td>4.9</td>
</tr>
<tr>
<td>garden</td>
<td>0.78</td>
<td>-1.3</td>
<td>2.8</td>
<td>4.1</td>
</tr>
<tr>
<td>forest</td>
<td>0.20</td>
<td>4.8</td>
<td>7.2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

UHI development after sunset. However, they suggested that realistically, if the thermal admittance of the rural area is sufficiently small, the maximum effect of geometry alone is of the order of 7°C; i.e. similar to that observed here in the scale model of open grass parks.

7.2 Thermal admittance effects on park cooling

For the case of the flat, dry park model the magnitude of mid-park cooling is inversely proportional to the thermal admittance, μ. The magnitude of the resultant PCI₃s decreases with increasing μ (Fig. 7.7 and Table 7.2). If μₚark >> μₖiety (e.g. concrete) there is a negative PCI at sunset and it steadily becomes more negative throughout the night. However, if μₚark << μₖiety (e.g. LDF) there is a positive PCI₃ at sunset, and a modest growth through the night (less than 4°C). Materials with μ closer to the background fir (plywood and OSB) show only a small (2°C) PCI₃ after 625 s.

Despite the small range of μ used in this model design, the differences are large enough to create an effect and indicate that in the real world, where these differences
Figure 7.7: PCI₃s for open parks with differing thermal admittances.

Table 7.2: The effect of surface thermal admittance differences (Δμ) upon the PCI₃. The “city” has no canyon geometry and has μ = 366 J m⁻² s⁻¹ K⁻¹. Units of all thermal admittances in J m⁻² s⁻¹ K⁻¹ and all temperatures in Celsius.

<table>
<thead>
<tr>
<th>Park material</th>
<th>Δμ</th>
<th>μ_{park}/μ_{city}</th>
<th>PCI₃ at sunset</th>
<th>PCI₃ at end of night</th>
<th>Growth/Decay PCI₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDF</td>
<td>219</td>
<td>0.40</td>
<td>2.7</td>
<td>6.1</td>
<td>3.4</td>
</tr>
<tr>
<td>OSB</td>
<td>168</td>
<td>0.54</td>
<td>-5.3</td>
<td>-2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Plywood</td>
<td>132</td>
<td>0.64</td>
<td>-0.3</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Fir</td>
<td>0</td>
<td>1.00</td>
<td>-0.8</td>
<td>-0.8</td>
<td>0</td>
</tr>
<tr>
<td>Concrete</td>
<td>-371</td>
<td>2.0</td>
<td>-3.1</td>
<td>-15.8</td>
<td>-12.7</td>
</tr>
</tbody>
</table>
may be large, the thermal admittance differential between a park and city could be of considerable importance in creating PCI$_s$. However, this effect on cooling is established soon after sunset and there is little growth in PCI thereafter.

Dry soils and deserts have thermal admittances as low as 600 J m$^{-2}$ s$^{-\frac{3}{2}}$ K$^{-1}$ while saturated clay soils and dense paved surfaces may be as high as 2200 J m$^{-2}$ s$^{-\frac{3}{2}}$ K$^{-1}$ (Oke, 1987). Therefore, depending on the nature of the urban fabric and the moisture content and soil type of the park, µ differences can be substantial. The SHIM predictions of the effect of µ on UHI development, by Oke et al. (1991) found a heat island of about 4°C developed if $\mu_{rural}/\mu_{city} = 0.42$. This is comparable to the observed NPCI$_s$ when $\mu_{park}/\mu_{city} = 0.40$ (Table 7.2). Oke et al. (1991) suggested that for typical real world values, the effect of µ alone is similar to geometry, and that a 6°C heat island can be generated if $\mu_{rural}$ is very low. Given the results of the scale model here it is possible that PCI$_s$ larger than 3.4°C can be produced if $\mu_{park}$ is much lower than that of the city.

7.3 Evaporative effects on park cooling

The flat, wet model design compares the cooling of both a pan of water, and moist blotting paper over fir, to the cooling of the background fir. At “sunset” the moist blotting paper is 2°C cooler than the water because the latter absorbed the strong heating better. At this time the parks are substantially cooler (by about 24°C) than the surrounding city. After sunset the water “park” with its high heat capacity, cools only by about 3.5°C, while the blotting paper “park”, with lower moisture content, cools by 6°C (Fig. 7.8a). To assess the effect of evaporative cooling as distinct from the thermal admittance effect, a SHIM$_{PDES}$ simulation, initialized with the scale model boundary conditions, was run for the water. This shows that the effect of evaporative cooling was $-1.7^\circ$C, about the same as the effect of thermal admittance.

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In this case, evaporative cooling doubles the effect of thermal admittance and makes the NPCIg less negative i.e. it increases the temperature differential between the park and the city (Fig. 7.8b). Due to these low cooling rates the NPCIg is eroded throughout the night. However, the park is sufficiently cooler than the city at sunset that, despite the slow cooling, it remains a cool island near sunrise.

7.4 Combined effects on park cooling

7.4.1 Radiative and thermal effects

The combined effects of surface geometry and thermal admittance on park cooling were assessed using the model with a dry park and surrounding canyon geometry (canyons, dry park design). Consistent with differences in $\mu$, LDF cools by the greatest amount while concrete cools the least. The AGEMA images (Fig. 7.9) show the warm concrete surface and the very cool LDF surface with visible view factor effects which agree with Figure 7.1. The plywood and OSB cases are similar at the end of the night but the surface temperatures of the OSB park are more patchy, due to the spatially–variable density of this material.

The cooling of points across the different park surfaces is used to illustrate the role of both surface geometry and thermal admittance differences (Fig. 7.10). With increasing sky view factor, surface temperatures are expected to decrease. However, in the warm concrete park, heat is lost by conduction at the edges to the cooler urban surroundings. Hence the reversal in pattern. For the remaining parks with positive differences in $\mu$, as $\psi_s$ increases from about 0.65 to 0.92, the PCI increases by about 6–8°C. Similarly, an increase in $\Delta\mu$ of only about 100 J m$^{-2}$ s$^{-\frac{1}{2}}$ K$^{-1}$ results in a 3–7°C increase in the PCI. Radiative cooling appears to have a dominant role. However, the range of thermal admittance in the model materials (about 150–800 J m$^{-2}$ s$^{-\frac{1}{2}}$ K$^{-1}$) is only 40%
Figure 7.8: Surface cooling (a) and PCIs for parks with evaporating surfaces (b). At sunset both parks had PCIs of about 24°C. Cooling of the water due to evaporation only, is shown by $E$, while cooling due to thermal admittance effects is shown by $\mu$. 

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Figure 7.9: Surface temperatures after 625 s of cooling for parks under the canyons, dry park design: (a) LDF; (b) OSB; (c) plywood; and (d) concrete.
of the range of thermal admittances in the real world (about 600–2200 J m\(^{-2}\) s\(^{-\frac{1}{2}}\) K\(^{-1}\)). Therefore the role of thermal admittance is underestimated by the scale model. If \(\Delta \mu\) were proportionately larger, there is the potential for this process to be as important as radiative cooling.

![Graph](image)

**Figure 7.10:** The maximum intensity of the PCI\(_s\) in relation to the sky view factor, \(\psi_s\) (shown in brackets) of the park surface, and the difference between the thermal admittance of the city and park environments (\(\Delta \mu\)).

Results for the combined effects of geometry and thermal admittance compare closely with the numerical simulations of Oke *et al.* (1991). Firstly, they suggest that as \(\mu_{rural}\) decreases the heat island magnitude increases. This is also observed here; a decrease in \(\mu_{park}\) results in an increase of the PCI\(_s\). Secondly, they note that with large \(\mu_{rural}\) it is not uncommon for small or negative heat islands to form. In the scale model when \(\mu_{park}\) is large (e.g. concrete), a small, negative cool island is produced (the park average PCI\(_s\) at the end of the night is \(-0.6^\circ\)C). Thirdly, they note that the most favourable combination of geometry and thermal properties can cause a heat island of up to \(10^\circ\)C to develop after sunset. For a canyon geometry with H:W of 1.15 and \(\mu_{rural} 40\%\) of \(\mu_{city}\) (most
comparable to scale model for LDF), they found maximum heat island development of 8.5°C—approximately the same as the scale model estimate of 8.3°C for the PCI growth after sunset. Finally, they suggest that the roles of surface geometry and thermal admittance may have similar importance in urban heat island development. The scale model suggests radiative processes are dominant in park cooling, but this is for a limited range of urban–park thermal admittance differences. Given the good agreement between the scale model and numerical simulation for this limited range of Δμ, it is likely that, for large Δμ, the effect on park cooling may be of a similar magnitude to that by radiative transfer.

7.4.2 Relative contribution of processes to park cooling

Three materials (LDF, OSB and plywood) were used in each of the four model designs (flat, dry park; flat, wet park; canyons, dry park; and canyons, wet park). Note that the term “canyons” means the model has surface geometry with urban canyons and an open park in the centre. Their behaviour helps elucidate the combined effects of radiative, thermal and evaporative cooling.

At sunset the absolute magnitude of the PCI is greatest for the canyons, wet park design for all materials (Table 7.3). However, since the model does not try to simulate daytime park heating, these figures can only be used as a rough guide to indicate whether the park is warmer or cooler than the city at sunset.

The growth and decay of the PCI is shown in Figure 7.11. For all three materials the dry model scenarios result in growth of the PCI, particularly if urban canyons are present. In contrast, in the case of all wet model parks, the PCI is either eroded or there is no growth. The OSB park, which can hold more moisture, clearly shows the PCI is reduced in both wet model cases. Despite this erosion, wet parks still maintain the highest PCI at the end of the night. By 625 s, the LDF park, which has low μ,
Table 7.3: Absolute magnitude of the PCIₜ for different model designs. All temperatures are in Celsius and values are rounded to the nearest integral value.

<table>
<thead>
<tr>
<th>Material and model design</th>
<th>PCIₜ at sunset</th>
<th>PCIₜ at end of night</th>
<th>Growth/Decay PCIₜ</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) LDF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>canyons, dry park</td>
<td>2</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>flat, dry park</td>
<td>3</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>canyons, wet park</td>
<td>14</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>flat, wet park</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>b) OSB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>canyons, dry park</td>
<td>-4</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>flat, dry park</td>
<td>-5</td>
<td>-3</td>
<td>2</td>
</tr>
<tr>
<td>canyons, wet park</td>
<td>19</td>
<td>14</td>
<td>-5</td>
</tr>
<tr>
<td>flat, wet park</td>
<td>11</td>
<td>3</td>
<td>-8</td>
</tr>
<tr>
<td>c) Plywood</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>canyons, dry park</td>
<td>2</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>flat, dry park</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>canyons, wet park</td>
<td>12</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>flat, wet park</td>
<td>8</td>
<td>5</td>
<td>-3</td>
</tr>
</tbody>
</table>
almost develops a PCI₃ in the canyons, dry park case, comparable to that achieved under the canyons, wet park design (Table 7.3). This suggests that if a park has low thermal admittance compared to the city, the magnitude of the PCI₃ can approach (or perhaps exceed) that for a moist park.

In summary, after sunset and in the absence of geometry, if \( \mu_{park} << \mu_{city} \) the PCI₃ growth is slow and small (about 2°C). The presence of urban canyon geometry (H:W = 1) around the park, increases the PCI₃ by about 4–5°C for open grassed parks. There is an optimum park width (about 7.5 times the height of the park border) to attain the maximum amount of radiative cooling. However for the park influence to extend beyond the border, it is suggested that larger parks have a greater effect. As the tree cover increases, the NPCI₃ decreases due to reduction of radiative cooling by view-factor effects. The presence of moisture in the park either prevents further growth beyond the sunset value, or results in a decay of the NPCI₃. However, the presence of moisture may have created sufficient evaporative cooling by day, that despite this reduced nocturnal cooling, moist parks still have the highest PCI₃s by sunrise. Parks with low \( \mu \) and high \( \psi \), have the potential to develop PCI₃s comparable in magnitude to those of wet parks. This is due primarily to radiative rather than thermal admittance effects. However, the small range of \( \mu \) possessed by the model materials resulted in an underestimation of the role of thermal admittance in park cooling. With larger urban–park differences in thermal admittance, it is possible that this process is of equal importance to radiative transfer. This conclusion is supported by predictions from SHIM, which suggest that the roles of surface geometry and thermal admittance may have similar importance in urban heat island development. Given the good agreement between the scale model and SHIM results, this numerical model is recommended as a valuable tool for analysis of the effects
Figure 7.11: A comparison of PCIs for different materials: (a) LDF; (b) OSB; (c) plywood; under the different model designs (flat, dry; flat, wet; canyons, dry; canyons, wet). In the “canyons” model designs, the open treeless park is surrounded by canyon geometry.
of surface geometry and thermal admittance on park cooling.

Thus evaporative cooling is critical in establishing the park as a cool island by sunset. However, after sunset moisture retards park cooling. In the limited boundary conditions of the model, radiative transfer dominates nocturnal cooling, but in the real world where urban–park thermal admittance differences are larger, these two processes may be of equal importance.

7.5 Comparison of scale model results with surface cooling observed in Vancouver parks

The scale model results show good agreement with observed nocturnal cooling, at least in a qualitative sense. The model was not designed to simulate real world differences in moisture and thermal admittance, but rather to give a first approximation to the effects of these properties.

As indicated by the modelling, both the presence of tree canopies and moisture, are critical in establishing the park as a cool island by sunset. This is confirmed by daytime observations of surface temperatures in Vancouver parks which showed strong temperature contrasts between well–treed and irrigated parks and built surfaces. As a further indication of the importance of tree canopies by day, the surveys of air temperatures in each city generally found large PCI in parks with extensive tree canopies. These parks may have a PCI that is well established in the afternoon (shade and possibly evaporatively induced). At sunset they have a marked increase in PCI that probably results from a combination of evaporative and radiative cooling. There are probably minimal effects of evaporative cooling in lowering air temperature at ground level by day (due to mixing into the urban boundary layer), but when turbulence and advection decrease near sunset, this cooler air may remain within the park system. This effect is of short
duration though, and the process of radiative cooling continues to cause the PCI to grow through the night.

Field observations show open parks rapidly cool after sunset and the PCI continues to increase through the night. In these open parks, the cooling rate may be similar to that in rural surrounds. However, these parks may be warmer than their urban surrounds by day. Therefore, despite similar rates of cooling between open park and rural surfaces, the nocturnal PCI is less than the UHI.

Scale model results also show that park cooling is similar to the rural case. The good agreement between the scale model results and SHIM simulations indicates that the PCI may in fact be an “inside-out” UHI. However, because open parks may be warmer than their urban surrounds at sunset, the PCI is typically less than the UHI.

Scale modelling confirms that radiative transfer is an important control on park cooling. The modelling shows that moist parks, despite their slower nocturnal cooling, have the highest PCI by sunrise, due to their coolness at sunset. The model also suggests that parks with low \( \mu \), can attain PCI as large as moist parks. Field observations show that open dry parks cool much more than moist parks. The scale model did not attempt to simulate daytime conditions so the role of moisture at sunset may have been overestimated. The range of \( \mu \) in the model is small but sufficient to indicate likely effects. Even small urban–park differences in thermal admittance can double the park cooling. In the real world, where \( \mu \) differences are large, this effect is accentuated and the cooling of parks with lower \( \mu \) surpasses that of moist parks.

As a first approximation to the relative contribution of cooling mechanisms, the scale model performs satisfactorily. The range of model materials limited the applicability of results to real world situations, but they compare well with estimates from numerical simulations. The model also provides an approximate means to assess the influence of moisture on the development of park cool islands.
Chapter 8

Conclusions

This chapter summarizes the major results of the dissertation. This includes conclusions from the survey of the park effect on urban thermal regimes; surface energy balance comparisons of urban parks in different summer climates; and the relative contribution of processes to nocturnal cooling in urban parks. A discussion of these results leads to the development of practical guidelines for planners regarding the manipulation of urban parks to attain maximum climatic benefit.

8.1 Summary of results

- Surveys of the park influence on the thermal regime of two urban areas with different summer climates, both confirms and extends previous studies. The park effect in Vancouver which has a cool summer Mediterranean climate, is typically small (1–3°C) but can approach 5°C under ideal conditions. This is higher than previous estimates, but it is certainly not typical. In hot summer Mediterranean climates, the park effect is enhanced and irrigated greenspace can create cool islands of at least 5–7°C.

- Surface temperature contrasts between irrigated greenspace and the built environment, peak in the afternoon but dry grass parks are not necessarily cooler than urban areas. Shortly after sunset cooling is well established in parks with high sky view factors. By sunrise drier parks, with lower thermal admittance, have cooled
the most. Parks with extensive tree coverage are warmer than open parks at night.

- The park effect on air temperatures is smaller by day, except in parks with substantial shade tree borders. The trend of the park cool island (PCI) through the night suggests that evaporative and radiative cooling processes may be important in creating a large suburban–park temperature differential soon after sunset. With reduced turbulence near sunset, in parks with extensive tree canopies, evaporatively cooled air may remain within the park system, lowering air temperatures. This effect is of short duration and the process of radiative cooling then causes the PCI to grow through the night. Open grass parks with higher sky view factors, are dominated by radiative cooling and have a maximum PCI near sunrise. As the moisture content (and hence thermal admittance) decrease, the park cooling increases.

- Although air temperatures in a park may be considerably cooler than nearby suburban temperatures, the influence of the park is restricted to the neighbourhood within about one park width.

- The surface energy balance of an urban park in a hot, dry summer climate is dominated by evaporation and has consistently negative sensible heat advection in the late afternoon. Soil heat flux is small. While the park has a similar SEB to that of a wet rural site, it is distinguished from other land-use types by its propensity to act as an “oasis”. High rates of evaporation are measured in the park, particularly at its upwind edge. There is an approximately exponential decay of evaporation with distance into the park. In the late afternoon evaporative forcing is sufficient to induce oasis-type advection.
• The SEB of an unirrigated, but moist, urban park in a temperate climate, is also dominated by evaporation. Sensible heat is of secondary importance and there is little enhanced advective influence on evaporation. Consequently the park does not behave as an oasis. It is suggested this is due to the lack of irrigation, because an irrigated suburban lawn in Vancouver does exhibit microscale advection edge effects. Evaporation across the park varies in response to the turbulence and moisture regimes.

• Comparison of the SEB of urban parks in two cities with different summer climates, highlights the role of soil moisture in determining energy partitioning. In moist or wet urban parks, evaporation dominates the SEB and can exceed the potential rate if surface forcing is sufficient to induce edge- and oasis-type advection. Irrigation is thought to be a criterion for this to occur.

• Scale modelling of nocturnal cooling in urban parks provides insight into the relative contribution made by different processes. It suggests that evaporative cooling is critical in establishing the park as a cool island by sunset. However, after sunset, since moisture increases the thermal admittance of the surface, cooling is slowed. With the limited range of model materials, radiation dominated nocturnal cooling with thermal admittance playing a secondary, but important role. However, the modelling suggests that when urban–park thermal admittances are large, this process could be of equal importance to radiative cooling.

• Given the good agreement between the results of the scale model and numerical simulations by the Oke et al. (1991) Surface Heat Island Model (SHIM), this numerical model is recommended as a valuable tool for analysis of the effects of surface geometry and thermal admittance on park cooling.

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The field research and scale modelling show that urban parks may behave more like rural than urban surfaces. Nocturnal cooling in open parks may be at a rate similar to the rural case. However, because open parks may be warmer than their urban surrounds during the day, the park cool island is typically less than the urban heat island at night.

8.2 Implications of research for park design

As discussed in the opening chapter, the design of parks incorporates many factors, both social and physical. The ultimate design involves a trade-off between desired characteristics. One of the main objectives of this dissertation is to develop practical guidelines for planners regarding the manipulation of urban parks to attain the maximum climatic benefit. Consideration is only given to the design of parks to cool neighbourhoods. This is most applicable to cities in warm climates.

Designing a park to achieve the maximum amount of cooling also involves trade-offs. Both daytime and nighttime conditions must be considered. By day the importance of trees in effecting cooling at ground level, has been confirmed. They lower air temperatures at ground level mainly through the provision of shade. Evaporative cooling, is likely to have a negligible impact on air temperatures at ground level as the cool air is rapidly mixed into the urban boundary layer. On the other hand, at night cooling is reduced under a tree canopy because the sky view factor is reduced. Yet this is the critical time when cooling of a few degrees can bring relief to neighbourhood communities. Therefore there must be a trade-off to find an appropriate design that can offer relief from high temperatures in both the day and nighttime.

Observations in parks, together with the scale modelling results, indicate the importance of evaporative cooling in establishing parks as cool islands by sunset. Parks with
substantial tree canopies and well irrigated greenspace show an increase in the PCI soon after sunset. It is suggested that this is partly due to evaporative cooling. This effect lasts only a few hours and unfortunately the presence of moisture (through increasing thermal admittance) and trees (through decreasing the sky view factor), slows cooling.

Therefore the optimum design might be a savannah-type park with loose clusters of trees interspersed by wide open, irrigated grass. The irrigated greenspace contributes to an increase in the PCI at sunset and the open spaces promote rapid radiative cooling to increase the PCI through the night.

The arrangement of trees must be carefully planned. Dense plantings around the park border should be avoided because these impede air movement both into, and out of, the park. Rather, clusters of trees should be interspersed around the edges. Careful attention should be given to the prevailing wind regime on summer evenings. There should be few trees at the prevailing downwind edge of the park to allow advection of cooler air into the neighbourhood.

These guidelines suggest that multi-use parks and golf courses with combinations of trees and open spaces, are among the best park designs. However, golf courses often have dense vegetative borders that restrict airflow into neighbourhoods. Field observations of the park effect in this study, confirm that these parks achieve some of the highest cooling rates of park types and attain maximum cooling soon after sunset, i.e. at the time when lower temperatures are particularly beneficial for neighbouring communities.

The optimum park size depends mainly on the geometry of the urban surrounds. To attain a significant amount of radiative cooling, the park width should be at least 7.5 times the height of the park border. The park effect, however, remains fairly localized influencing only the adjacent neighbourhood up to about one park width away. However as the park size increases, a larger volume of air is cooled which increases the potential for advection of cool air beyond the park boundaries. This suggests the need for many
interspersed neighbourhood parks to attain the maximum cooling benefit.

The central objective of this dissertation is to increase understanding of the energetics and cooling in urban parks. An integrated research approach has contributed to achieving this objective. Knowledge of the park effect on urban temperatures has been increased through detailed spatial and temporal surveys in cities with different climates. The causes of this park cooling have been elucidated through scale modelling which confirms and extends, existing numerical model results. This dissertation also presents the first measurements of the surface energy balance of urban parks. Measurements in parks in two cities with different summer climate, has improved understanding of park energetics. This field component assessed both the spatial variability of the SEB in the parks, as well as placing the park in context with comparisons to energy partitioning in nearby land–use types. Finally, this dissertation provides some practical guidelines to planners suggesting how urban parks should be designed to achieve maximum cooling. This important link between process studies and practical applications, is often neglected.
References


O’Rourke, P.A. and Terjung, W.H. 1981: Urban parks, energy budgets and surface


Appendix A: Survey of the Park Effect in Tucson, Arizona

This appendix presents the results of a pilot survey of the park influence on air temperatures in Tucson, Arizona. Tucson has a very hot dry summer climate (Köppen climate classification BWh – arid desert). The Tucson basin (32° 07'N, 110° 56'W) lies at an elevation of about 730 m and is bounded on three sides by the Santa Catalina, Tucson and Rincon Mountains to the north, west and east, respectively. The Santa Rita Mountains lie about 100 km to the south. The topography is flat or gently rolling with many dry washes. Tucson is located in a desert environment predominantly vegetated by creosote bushes (Larrea divaricata). The population of metropolitan Tucson is approximately 700,000.

Eight traverses measuring air temperature were conducted in May/June, 1990. The synoptic conditions throughout the observation period were controlled by the presence of a thermal low over Arizona. Tucson has a large number of urban parks. The vegetative composition of the parks depends on the amount of irrigation applied; several are natural desert, but most are irrigated. The eighteen parks surveyed range in size from 2 to 140 ha (Fig. A.1). Most of the parks have 50–80% of their surface area in turf, some are fully irrigated and one is a large (111 ha) natural desert park. The majority are multi-use parks with savannah parkland and playing fields – particularly baseball diamonds, which are intensely used especially in the evenings. Four golf courses adjacent to the larger parks, were also surveyed.

Eight traverses around Tucson parks were made in May/June 1990 under mainly clear skies, and a range of wind conditions. Because of breezy conditions only three of the more extensive traverses (through Tucson parks to the desert) were conducted. The
Figure A.1: Location of the fixed sites and the traverse routes for the park surveys in Tucson.
remaining traverses concentrated only on Reid Park. A summary of the PCI and UHI is given in Table A.1. Overall PCI are relatively large. The maximum PCI is 6.8°C. This occurs with high scattered cloud when average wind speed was lowest (1.5 m s\(^{-1}\)). Reid Park (see Fig. A.1), a large (53 ha) multi-use park, consistently exhibits the highest PCI. Lincoln Park, which jointly shares the greatest cool island intensity with Reid Park on June 2, is a similar large (77 ha) multi-use park. The smallest PCI (1.2°C) occurs when the average wind speed is the largest (3.7 m s\(^{-1}\)). This combination of cloud cover and wind suggests that radiation may be less critical than turbulence as a control on the magnitude of the temperature differential. The urban heat island intensity is low, ranging from 1.4°C to 4.6°C.

Table A.1: Summary of the nocturnal thermal climate of parks in Tucson. City-wide traverses only occurred on May 15, May 24 and June 2. The remaining traverses only surveyed Reid Park. All traverses began an hour after sunset.

<table>
<thead>
<tr>
<th>Date</th>
<th>Park</th>
<th>Maximum PCI (°C)</th>
<th>Range PCI (°C)</th>
<th>UHI (°C)</th>
<th>Mean wind speed (m s(^{-1}))</th>
<th>Cloud cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 15</td>
<td>Reid</td>
<td>3.3</td>
<td>0.2–3.3</td>
<td>1.4</td>
<td>2.6</td>
<td>high sct</td>
</tr>
<tr>
<td>May 19</td>
<td>Reid only</td>
<td>1.2</td>
<td></td>
<td></td>
<td>3.7</td>
<td>clear</td>
</tr>
<tr>
<td>May 20</td>
<td>Reid only</td>
<td>2.7</td>
<td></td>
<td></td>
<td>2.1</td>
<td>clear</td>
</tr>
<tr>
<td>May 22</td>
<td>Reid only</td>
<td>6.8</td>
<td></td>
<td></td>
<td>1.5</td>
<td>high sct</td>
</tr>
<tr>
<td>May 23</td>
<td>Reid only</td>
<td>1.5</td>
<td></td>
<td></td>
<td>3.4</td>
<td>mid brkn</td>
</tr>
<tr>
<td>May 24</td>
<td>Reid</td>
<td>3.0</td>
<td>0.2–3.0</td>
<td>4.6</td>
<td>2.7</td>
<td>clear</td>
</tr>
<tr>
<td>June 1</td>
<td>Reid only</td>
<td>3.3</td>
<td></td>
<td></td>
<td>3.2</td>
<td>clear</td>
</tr>
<tr>
<td>June 2</td>
<td>Reid, Lincoln</td>
<td>1.9</td>
<td>0.7–1.9</td>
<td>2.6</td>
<td>2.8</td>
<td>clear</td>
</tr>
</tbody>
</table>

Temperature traverses on calm, clear nights, show higher temperatures in the commercial and downtown regions (Fig. A.2). The warmest area was a commercial route northeast of the city centre. In the suburbs temperatures steadily decline towards the
surrounding desert except for even cooler spots in urban parks.

Observations show that concentrated human activity, such as a large baseball game, can offset park cooling. The largest PCI was observed on nights without such activity. The Reid Park traverse on May 22 (Fig. A.3) was repeated three times (in consecutive runs) to verify the almost startling results. A large temperature difference of nearly 7°C was observed between the nearby commercial strip along Speedway Boulevard, and the centre of the greenspace consisting of Reid Park and Randolph Golf Course. The light westerly winds can be seen to advect cooler air to the east of the park. The warmer areas to the north and southeast, are associated with commercial strips.

The magnitude and extent of nocturnal cooling in urban parks in Tucson exceeds that commonly observed in mid-latitude temperate cities. On the other hand, the magnitude of the urban heat island shortly after sunset is relatively small compared to that of mid-latitude cities of comparable population in similar conditions. Continuous measurements of air temperature at a suburban (Treat) and a desert site (Houghton) (Fig. A.1) for 20 days in May/June 1990, showed that Tucson’s UHI was small (< 1°C) and often negative by day, and peaked at 4–5°C sometime between midnight and sunrise (Grimmond and Oke, pers. comm.).
Legend:
1. Reid Park (multi-use)
2. Randolph Golf Course
3. Freedom Park (multi-use)
4. Lincoln Park (multi-use)
5. Santa Rita Park (multi-use)
6. De Anza Park (multi-use)

Figure A.2: Air temperatures for the downtown to desert traverse an hour after sunset, May 24, 1991.
Figure A.3: Isotherm map for Reid Park, May 22. Arrows indicate the direction of traverse and the spots are check-points for the traverse.
Appendix B: Errors in Scale Modelling

B.1 Introduction

The probable error analysis presented by Fritschen and Gay (1979) is used as a framework to estimate errors in measured variables for the scale modelling. The absolute error $\Delta Y$, of a function $Y$ consisting of variables $x_1, x_2, ..., x_n$ is estimated:

$$\Delta Y = \frac{\Delta x_1 \partial Y}{\partial x_1} + \frac{\Delta x_2 \partial Y}{\partial x_2} + \frac{\Delta x_n \partial Y}{\partial x_n} \quad (B.1)$$

where $\Delta x_i$ are the absolute errors of each of the variables. This provides a “worst case” estimate of the errors assuming that all the errors act in the same direction. It is more likely that the errors about $x_1$ are normally distributed and there is some probability that errors in different variables may offset each other to a limited degree. The probable error in $Y$, $\delta Y$, can be estimated by combining the individual errors through a least squares approach:

$$\delta Y = \left[ \left( \delta x_1 \frac{\partial Y}{\partial x_1} \right)^2 + \left( \delta x_2 \frac{\partial Y}{\partial x_2} \right)^2 + \cdots + \left( \delta x_n \frac{\partial Y}{\partial x_n} \right)^2 \right]^{\frac{1}{2}}. \quad (B.2)$$

The differentials of $Y$ with respect to each of the $x_i$ are substituted into (B.2) and typical values of the variables are used to generate $\delta Y$. The values of $\delta x_i$ are the errors in the variables, typically the root mean square error (RMSE), and are obtained from component instrument errors, or estimated by other means.

B.2 Surface temperature errors

In the scale modelling there are several potential errors associated with measurement of surface temperature by thermocouples. These include errors due to the thermocouple
wire, the use of the 21X micrologger to measure the voltage and linearize the data, and mounting errors (Table B.1).

Table B.1: Summary of errors in surface temperature measurement by thermocouples.

<table>
<thead>
<tr>
<th>Type of error</th>
<th>Amount of error (°C)</th>
<th>% of total error (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference temperature</td>
<td>0.8</td>
<td>61</td>
</tr>
<tr>
<td>Thermocouple output</td>
<td>0.5</td>
<td>24</td>
</tr>
<tr>
<td>Voltage measurement</td>
<td>0.07</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Reference linearization</td>
<td>0.001</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Output linearization</td>
<td>0.001</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Mounting</td>
<td>0.4</td>
<td>15</td>
</tr>
<tr>
<td>Sum</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td>1.03</td>
<td></td>
</tr>
</tbody>
</table>

The main sources of error are the reference temperature, thermocouple output, and mounting errors. The reference temperature error results from a combination of errors in the reference thermistor (± 0.5°C in the range 20–70°C) and when there is a difference between the thermistor and the actual reference junction (the channel to which the thermocouple is attached). This latter error has a maximum of 0.3°C in field situations (CSI manual, 1991) but is likely to be less in a laboratory situation.

The thermocouple output error is given by the manufacturers standard for type–T thermocouple wire. The mounting error includes radiation and conduction errors which result from the attachment of the thermocouple to the model surface. An estimate of the error is made using the range of differences between temperature measured by the thermocouples and by the AGEMA.

The voltage measurement error is generally 0.05% of the full scale range used to
measure thermocouple voltage. On the 5 mV range used, this results in a temperature error of 0.05–0.07°C for the range of temperatures encountered. The reference and output linearization errors result from approximations used in the conversion of voltage to temperature and are negligible.

The combined errors give a RMSE of 1.03°C in surface temperature measurement by the thermocouples.

B.3 Emissivity errors

The emissivity (ε) of the model surface was estimated by the method of Davies et al. (1971):

\[
\epsilon = \frac{T_r^4 - T_k^4}{T_s^4 - T_k^4} \tag{B.3}
\]

where \(T_r\) is the apparent surface temperature; \(T_s\) is the true surface temperature (measured while covered with a polished aluminium cone) and \(T_k\) is the apparent radiative sky temperature. These temperatures were measured with an Everest 4000A infra-red thermometer and logged onto a CR21X data-logger. The associated errors are 0.5°C for the infra-red thermometer and 0.03°C for the voltage measurement on the data-logger. This gives a RMSE of 0.50°C.

The probable error in emissivity estimates is given by:

\[
\delta \epsilon = \left[ \left( \frac{\partial \epsilon}{\partial T_r} \right)^2 + \left( \frac{\partial \epsilon}{\partial T_s} \right)^2 + \left( \frac{\partial \epsilon}{\partial T_k} \right)^2 \right]^{\frac{1}{2}} \tag{B.4}
\]

with partial errors:

\[
\frac{\delta \epsilon}{\delta T_r} = \frac{4T_r^3}{(T_s^4 - T_k^4)} \tag{B.5}
\]

\[
\frac{\delta \epsilon}{\delta T_s} = \frac{4T_s^3(T_r^4 - T_k^4)}{(T_s^4 - T_k^4)^2} \tag{B.6}
\]

\[
\frac{\delta \epsilon}{\delta T_k} = \frac{4T_k^3(T_r^4 - T_k^4)}{(T_s^4 - T_k^4)^2} \tag{B.7}
\]
Typical values of $T_r$, $T_s$ and $T_k$ (285.67, 286.87 and 244.18 K respectively) were substituted into equation B.4 giving a probable error of 0.020 in the surface emissivity when the errors of $T_r$, $T_s$ and $T_k$ are set to 0.5 K.
Appendix C: Sky View Factor Calculations

This appendix outlines three methods used to estimate sky view factors ($\psi_*$) for locations in the scale model. The first, derived from Steyn and Lyons (1985), is used to estimate $\psi_*$ for canyon and park geometries in the absence of vegetation. For simple park geometries (e.g. grass parks with "deciduous tree" borders), a method from Howell (1982) is used to estimate $\psi_*$. Finally, for more complex arrangements of vegetation (savannah, garden and forest parks), $\psi_*$ is calculated from fisheye-lens photography using the method of Steyn (1980).

C.1 Calculation of $\psi_*$ for locations in grass parks and canyons.

In the simplest case with no vegetation, $\psi_*$ is calculated from an analysis derived from Steyn and Lyons (1985) and Steyn, (pers. comm.):

$$\psi_* = 1 - \sum_{n=4} \psi_w \tag{C.1}$$

where $\psi_w$ is the view factor for a wall, calculated from:

$$\psi_w(x, y) = \frac{1}{2\pi} \left\{ \tan^{-1} \left( \frac{\frac{b}{2} - x}{y} \right) + \tan^{-1} \left( \frac{\frac{b}{2} + x}{y} \right) - \frac{y}{\sqrt{h^2 + y^2}} \right\} \tag{C.2}$$

$$\left[ \tan^{-1} \left( \frac{\frac{b}{2} - x}{\sqrt{h^2 + y^2}} \right) + \tan^{-1} \left( \frac{\frac{b}{2} + x}{\sqrt{h^2 + y^2}} \right) \right]$$

and $b$ is the length of wall and $h$ is the height of wall as shown in Figure C.1.

This method, together with the dimensions of the scale model, is used to calculate $\psi_*$ for each thermocouple location. By repeating calculations for points over the model a map of view factors can be produced.
Figure C.1: Definitions of elements and coordinate system for calculating the view factor of a wall for a given point $P$ on the ground.
C.2 Calculation of $\psi_s$ for locations in grass parks with tree borders

The presence of model "trees" complicates the derivation of the view factors. Spheres are used to approximate the shape of deciduous trees and the formula presented by Howell (1982) is used to determine the view factor of tree ($\psi_t$):

$$\psi_t = \frac{H}{2(1 + D^2)} \left\{ \frac{X}{[X^2 - 4R^2(1 + D^2)]^{1/2}} - 1 \right\}$$  \hspace{1cm} (C.3)

where $H = x/l$, $R = r/l$, $D = y/l$ and $X = R^2 + D^2 + H^2 + 1$ with the elements $x, y, l, r$, given in figure C.2. The sky view factor is then calculated:

$$\psi_s = 1 - \left( \sum_{i=1}^{n} \psi_t + \sum_{i=1}^{n} \psi_w \right).$$  \hspace{1cm} (C.4)

Figure C.2: Definitions of elements and coordinate system for calculating the view factor of a deciduous tree for the point P.
C.3 Calculation of $\psi_s$ in savannah, garden and forest parks

To estimate $\psi_s$ for savannah, garden and forest parks, fisheye–lens photographs were taken at specific locations across the park surface. The images were then projected onto polar graph paper and $\psi_s$ was derived using the method of Steyn (1980).