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THE INFLUENCE OF HOUSING DENSITY AND URBAN DESIGN ON THE SURFACE ENERGY BALANCE AND LOCAL CLIMATES OF MELBOURNE AUSTRALIA, AND THE IMPACT OF MELBOURNE 2030's VISION

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1. INTRODUCTION

By the year 2003, 47% of the world's 6.3 billion inhabitants were living in urban areas, while in more developed countries, 75% of the population (1.2 billion) lived in urban areas (Population Reference Bureau, 2003). As more and more people make their residencies in the heart of the industrial and commercial world, urbanisation will continue to grow. Alterations to the natural environment due to the physical structure of the city, and its artificial energy and pollution emissions, interact to form distinct urban climates (Bridgeman et al., 1995). These urban climates can often be undesirable causing increases in air pollution and aiding the formation of Urban Heat Islands (UHI). Urban warming can have substantial implications on air quality and human health (Stone and Rodgers, 2001). For instance, the UHI effect can exacerbate hot weather conditions and lead to increases in mortality both directly and indirectly, as seen from the European heat wave event in 2003, which is said to have been compounded by the urban environment, and related to 20,000 deaths (Schar et al., 2004). Those with increased vulnerability include the elderly, low income earners, and residents in high density, older housing stock with limited surrounding vegetation (Smoyer-Tomic et al., 2003). The UHI effect can be mitigated via environmental modification, particularly through controlled and structured urban design measures that can reduce heat stress related illnesses. Unfortunately, despite the obvious existence of UHI's in most cities, few cities have developed comprehensive programs for its mitigation (Stone and Rodgers, 2001).

Important generative factors of the UHI include: emissions of atmospheric pollutants anthropogenic heating; restriction of horizontal airflow due to increased friction; absorption and retention of solar radiation in the urban fabric with high heat capacities; reduced longwave loss due to limited sky view factor (Oke, 1981; 1982 in Stewart, 2000) and reduced evapotranspiration from vegetation removal which is a natural cooling mechanism (Stone and Rodgers, 2001). Urban structure, intensity of development and type of building material can also potentially influence UHI intensity, which suggests that UHI's may be more a product of urban design rather than, as commonly assumed, the density of development (Stone and Rodgers, 2001). Consequently, different settlement structures, such as city centres, parklands, and various suburban residential areas interact in a distinctive manner with the atmospheric boundary layer through alterations in net radiation, heat storage, and sensible and latent heating, resulting in a different local climate from one another (Fehrenbach et al., 2001).

Climate knowledge should be beneficial in the urban planning process, however, "while environmental policy has gained public acceptance in fields like water quality or biodiversity, local climate still is of minor importance for urban and regional planning" (Fehrenbach et al., 2001. pg 5606). Outcomes and knowledge from studies that can potentially improve local climates are often scarcely used in the planning process, or ignored, for reasons such as communication problems, conflicting interests, economy and lack of knowledge (Eliasson, 2000). Additionally, appropriate tools are not available for planning authorities to assess the implications of projected land-use change on local climate (Fehrenbach et al., 2001). Climate knowledge can be very useful in purposefully modifying climates

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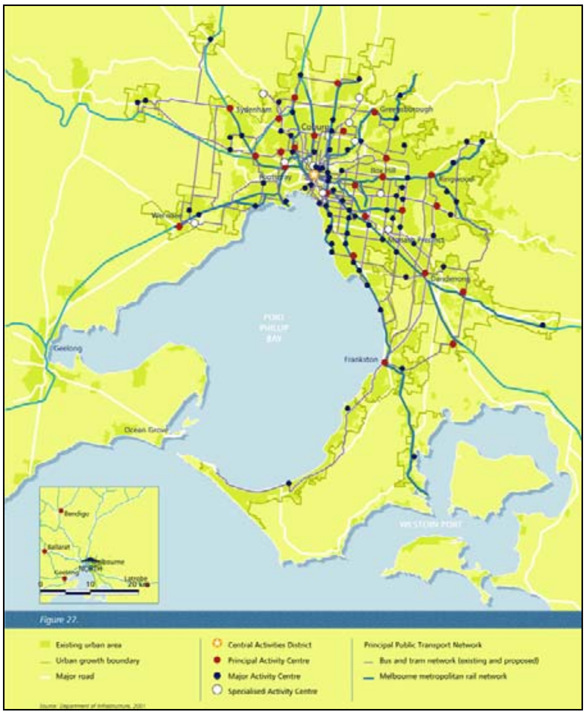
to create more pleasant and beneficial environments for city dwellers to live and work in. Considering such large areas of metropolitan regions are used for housing, and that the design of residential areas can alter the thermal environment and create unique microclimates through alterations in the surface energy balance (Bonan, 2000), it is very important that climate knowledge is used in planning residential neighbourhoods.

Melbourne, Australia, with a population of over 3.5 million is not free from the climatic impacts of urbanisation. In 1992, an automobile transect across the Melbourne region during the evening found a peak warming of 7.1º C in the central business district , with smaller peaks in industrial areas and the medium density terrace housing in the inner Northern suburbs (Torok et al., 2001). Additionally, historical data over the period 1972-1991 from monitoring stations around Melbourne showed a mean annual UHI of 1.13º C averaged at 6am for 20 years. This varied seasonally between summer (1.29º C), spring (1.25º C) autumn (1.02º C) and winter (0.98º C) (Morris et al., 2001). Over the period 1973-1991, daily analysis of 0600 regional climatological temperature data revealed an UHI as high as 6 ºC (Morris and Simmonds, 2000). In order to combat any intensification of the UHI in Melbourne, climate knowledge needs to be incorporated into urban planning strategies.

The Victorian State Government of Australia released a document in 2002 titled ‘Melbourne 2030’ which is the strategic plan to manage growth and change across metropolitan Melbourne and its surrounding region, taking a long term view. The document presents the vision that over the next 30 years “Melbourne will consolidate its reputation as one of the most liveable, attractive and prosperous areas in the world for residents, business and visitors” (DOI, 2002. pg 28). Trends indicate that population growth for Melbourne over the next 30 years could reach 1 million people, leading to an increase of 620,000 households. The Melbourne 2030 plan for achieving this vision includes a number of key directions, one of which is a more compact city. This involves the development of activity centres, which are centres that are built up as a focus for high quality development, activity and living for the community (Figure 1). The approach of Melbourne 2030 is to increase housing in established urban areas, particularly around activity centres, in order to achieve a more compact city that would include forms of higher density housing clustering in and around activity centres (DOI, 2002). In addition, Melbourne 2030 has defined an urban growth boundary to set clear limits to metropolitan Melbourne’s outward expansion, and help facilitate growth in activity centres, resulting in increased urban development.



<u>Figure 1.</u> The locations of Melbourne 2030’s Activity centres and the Urban Growth Boundary (DOI, 2002).

This research investigates the potential impacts on local urban climate that could result from the Melbourne 2030 planning strategy. We hypothesise that a more compact city, incorporating increased housing density and the development of built up activity centres, will intensify the Melbourne UHI. This would in turn conflict with the Melbourne 2030 vision statement. Through the study of the surface energy balance, which governs boundary layer evolution, a better understanding of the impact of land use change can be achieved, and the knowledge used for more informed and efficient land use decisions.

These are to our knowledge the first surface energy balance measurements for an Australian capitol city, and certainly only one of a few studies to simultaneously measure across multiple sites. This provides a new and unique dataset, allowing direct site comparisons.

2. METHODS

Measurements of the surface energy balance were taken using the eddy covariance technique (Baldocchi, 1988) on tall towers over a range of residential housing densities throughout Melbourne, Australia (37º 49’ S, 144º 58’ E) in order to examine the differences in the surface energy balance. Four sites were established throughout the Melbourne region including three urban sites of increasing housing density, and one rural site as a control site where no urban development has occurred (Figure 2). The first of the urban sites was located north of Melbourne (CBD) in Preston, a high-medium density suburban housing area. This site was operated for the entire observational period and was considered as our reference site (Table 1). The second urban site was a high density residential site located south-east of Melbourne in Armadale. The third urban site was a medium density suburban residential site located east of Melbourne in Surrey Hills and was observed to have a higher vegetation fraction than the Preston and Armadale sites. Finally, the rural site was located south-east of Melbourne in Lyndhurst, just outside the main metropolitan region in a cleared grassed area utilizing a Bowen ratio system. All four sites were operating simultaneously for a period of 100 days. The observation period ended in early June, 2004.

Table 1. Details of the operation of each of the sites: the operational period, the measurement system used and the height of instrumentation (m). Sites are listed in decreasing density.

Site	Operation Period	System	Instrument Height
Armadale	Nov 03 - June 04	Eddy Cov.	40
Preston	Aug 03 - June 04	Eddy Cov.	40
Surrey Hills	Feb 04 - June 04	Eddy Cov.	35
Lyndhurst	Nov 03 - May 04	Bowen ratio	7

Each site recorded net radiation (Q^*), sensible heat flux (Q_H) and latent heat flux (Q_E), as well as temperature and humidity. Ground heat flux (ΔQ_S) at the urban sites was not measured due to the number of different types of surfaces, and therefore approximated as a residual from the energy balance equation, while the ground heat flux (Q_G) was directly measured at the Lyndhurst site. Anthropogenic heat flux (Q_F), was assumed to be included implicitly within the other terms of the surface energy balance. All measurements were estimated to have been taken within the constant flux layer where the roughness layer is between 2 to 5 times the height of the roughness elements (Raupach et al., 1991), and sites were selected that showed similar radiative and turbulent flux footprints. In addition, the radiation balance was also measured at the 3 urban sites for calculation of Albedo and longwave emission. Eddy covariance measurements were corrected for oxygen absorption and density effects (Webb et al., 1980), and all data underwent quality control procedures. Housing density was graded through visual observations from both the ground and from the tower, and viewing aerial photography.

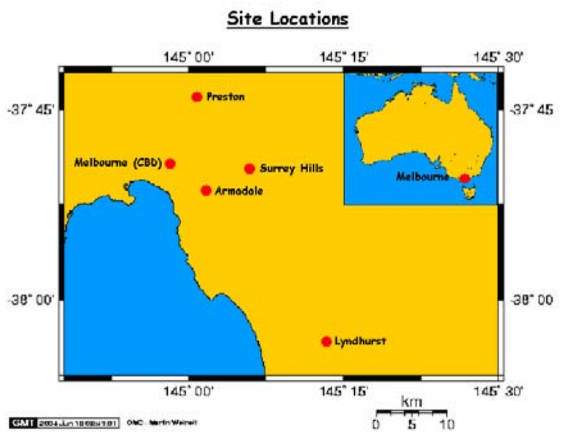


Figure 2. Site locations of Melbourne CBD, and 3 urban sites (Armadale, Preston, Surrey Hills) and 1 rural site (Lyndhurst)

3. RESULTS AND DISCUSSION

The following discussion will encompass the preliminary results of two separate month long periods when all four sites were simultaneously operating. The first period was from the end of

February 2004 to the end of March 2004 (37 days), while the second period extended from the beginning of May 2004 to the beginning of June 2004 (34 days), allowing a good comparison of the differences in the radiative and surface fluxes between the summer and winter climate regimes.

3.1 *Diurnal energy balance*

As an example of the diurnal pattern of the energy balance, the high-medium density site of Preston showed a good contrast between seasons in the partitioning of energy into the surface fluxes (Figures 3a and 3b). The general characteristics of energy partitioning at high-medium density site were very similar to those seen at both the high and medium density sites. During summer periods, available energy was predominantly partitioned into Q_H and ΔQ_S with a small amount partitioned into Q_E (Figure 3a). This is typical of many suburban regions similar in latitude (Grimmond, 1999). The hysteresis pattern often seen in urban areas, where ΔQ_S precedes Q^* by 1-2 hours was also evident, peaking in the late morning, and decreasing in the afternoon as Q_H and Q_E became more predominant (Grimmond and Oke, 1995). During the night, ΔQ_S was largely negative, particularly in the early to late evening, as the energy stored within the canopy was released. This could potentially contribute to the peak UHI seen in the early morning (Torok, 2001) as a result of slower cooling rates compared to surrounding rural areas. This energy release also supported a slightly positive Q_E throughout the night.

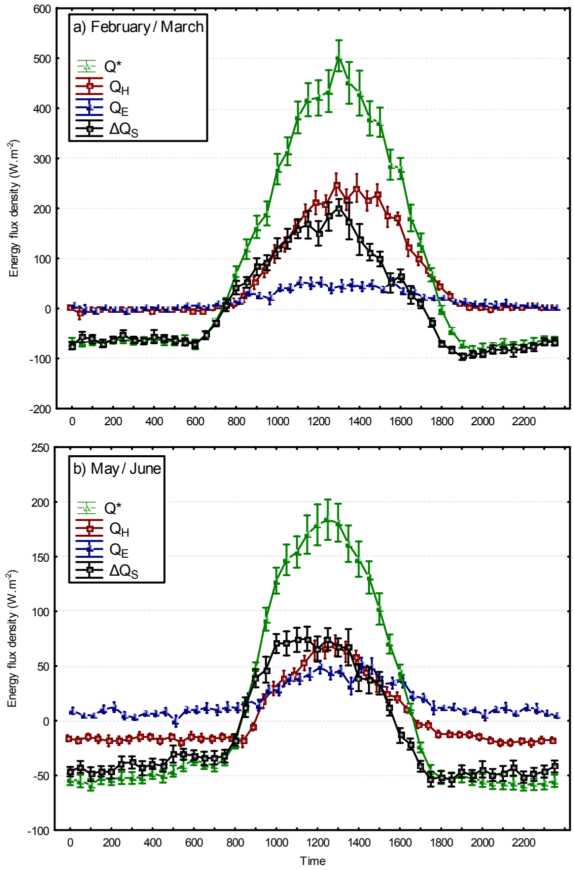


Figure 3. Preston diurnal surface energy balance for a) the period covering February and March (Day 55-91) and b) the period covering May and June (Day 122-154). Note the scale differences.

In winter periods at the high-medium density site (Figure 3b), the relative magnitude of the fluxes reduced following a decrease in Q^*, and the partitioning of energy into Q_H and Q_E became more equal due to limited solar heating and absorption at the urban surface, which also accounted for a less negative ΔQ_S during the night. The storage flux became more dominant during the day in the winter, which is similar to the observations made in Christchurch, New Zealand (Spronken-Smith, 2002). The magnitude of daytime Q_E remained very similar between the seasons. Such results suggest that UHI development in Melbourne is more likely to occur during summer conditions, as seen by Morris *et al.* (2001), when more energy is partitioned into Q_H warming the atmosphere during the day and ΔQ_S releasing heat to the atmosphere during the night.

3.2 *Comparison of surface fluxes between sites during summer*

In order to compare the partitioning of fluxes between the sites of varying density, and between the two climatic stages, the ratios of each of the surface fluxes to Q^* are presented in table 2. Averages of air and surface temperature, and albedo are also given for each of the urban sites. Firstly during the summer period, Q_E was relatively conserved with only a small fraction of Q^* being used in evaporation because there was limited water available during this time. However, there was no difference in evaporative fraction between the high density and medium density sites, despite

Table 2. *Daytime mean observed ratios of surface fluxes to net radiation over the two chosen periods. Mean midday air temperature (eddy covariance measurement height) and surface temperature (from outgoing longwave radiation) and albedo over periods when all 3 urban stations were running simultaneously. Sites are listed in decreasing density.*

	Daytime Ratios ($Q^* > 10$ W.m^{-2})				Midday		
	Q_H/Q^*	Q_E/Q^*	$\Delta Q_S/Q^*$	β	T_{air}	$T_{surface}$	α
February / March (Day 54-91) - Austral summer					(Day 55-68)		
Armadale	0.52	0.15	0.31	3.37	20.85	31.22	0.19
Preston	0.54	0.13	0.30	4.26	20.36	32.17	0.15
Surrey Hills	0.59	0.15	0.23	3.85	21.03	30.54	0.17
Lyndhurst	0.42	0.50	0.11	0.84			
May / June (Day 122-154) - Austral winter					(Day 141-154)		
Armadale	0.38	0.28	0.34	1.36	13.55	18.67	0.19
Preston	0.31	0.29	0.40	1.08	13.02	16.47	0.15
Surrey Hills	0.37	0.29	0.33	1.26	13.36	15.12	0.16
Lyndhurst	0.40	0.45	0.21	0.88			

the higher observed vegetation cover at the medium density site. As well as the hot and dry conditions experienced in summer in Melbourne, recent drought had resulted in the implementation of water restrictions, so additional water availability for Q_E that is sometimes seen in other cities, was not evident here. The high-medium density site showed a slightly lower ratio of Q_E/Q^* of 13%.

At each of the urban sites the majority of available energy was partitioned into Q_H. Therefore, there was a large amount of energy being used in heating the atmosphere. Although, at the medium density site, Q_H was the greatest, accounting for 59% of Q^*, and Q_H was shown to decrease with increasing housing density to the high density site, at 52% of Q^*. Bowen ratios were therefore high in the residential areas of Melbourne during the summer (Figure 4) with the highest observed at the high-medium density site of 4.26, and ratios are higher than those observed in many North American suburban areas where Bowen ratios range from 1.24 to 2.87 across seven different sites around the North American summer (Grimmond and Oke, 1999). These lower Bowen ratios may be attributed to greater water availability as a result of irrigation.

In contrast to Q_H/Q^*, $\Delta Q_S/Q^*$ was the smallest at the medium density site (23%) and increased with increasing housing density to the high density site (31%). At the high-medium and high density sites, energy is absorbed more readily through urban materials such as concrete, asphalt and brick that have high thermal admittance. At the medium density site, as there is less cover of urban materials and a higher vegetation fraction, less energy was partitioned into ΔQ_S, and in conjunction with a low Q_E, lead to the higher Q_H. Therefore, it appears that residential areas with low ΔQ_S, have more energy available for partitioning into Q_H.

It is difficult to draw conclusions about the values observed for surface temperature and albedo, and their relation with ΔQ_S. The high-medium density site showed the lowest albedo, and the higher absorption of energy and ΔQ_S led to higher surface temperatures. The medium density site, had a higher albedo, and may have influenced the resultant low ΔQ_S, leading to a low surface temperature. However, the high density site is not consistent with these trends. The high density site had the highest albedo, however, it also showed a high ΔQ_S. This may be due to the surface geometry of the site or the higher amount of urban materials available for absorbing energy, despite an increase in the amount reflected. The higher surface temperature at the high-medium site could also be due to the slightly lower evaporative fraction, allowing for more surface heating.

Comparing these ratios with those found at the undeveloped rural site, results indicate that there is much less energy being transferred into the ground (11%), due to the lower thermal admittance of the soil. Also, most of the energy was partitioned into Q_E as there was a larger amount of water available, even during the summer, resulting in a Bowen ratio of 0.84. So the urban residential areas showed much more heating of the atmosphere than the rural site. Even during the mid summer month of January, the Bowen ratio at Lyndhurst only reached 1.19, indicating that energy is only slightly preferentially used in heating the atmosphere, rather than in evaporation. So urbanisation in Melbourne produces warm and dry climates compared to surrounding rural areas and results in the generation of the UHI.

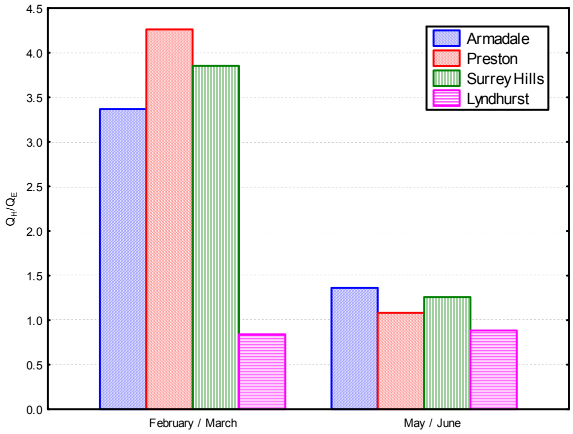


Figure 4. Comparison of mean daytime Bowen ratio ($Q^* > 10\ W.m^{-2}$) between each sites, and between the two periods

3.3 *Comparison of surface fluxes between sites during winter*

During winter, all three sites showed a marked increase in partitioning into Q_E, as more water became available, and again, there was little variation between each of the urban sites. Also, each site showed an increase in ΔQ_S, with the high-medium density site as the greatest (40%). As a result, the high-medium density site showed a smaller fraction of Q_H, which resulted in the lowest Bowen ratio between the urban sites, in comparison to being the highest during the summer (Figure 4). This data again suggests that if energy is readily absorbed into the urban fabric, there is less energy available for sensibly heating the atmosphere, as the partitioning of Q_E is stable between the sites. The pattern in albedo and surface temperatures for the high-medium and medium density sites was similar to the summer period, although the high density site once again showed some discrepancies. Even though the ΔQ_S of the high density site was similar to the medium density site, the surface temperature was much higher, despite the higher albedo. Yet, the ΔQ_S at the high density site was still smaller than that seen at the high-medium density site.

Overall, Bowen ratios were reduced at the urban sites during winter and become more like those seen at the rural site with more energy being partitioned into Q_E, resulting in a much cooler climate. The Bowen ratio at Lyndhurst was slightly higher in winter due to an increase in Q_G from a higher soil moisture content increasing the thermal admittance of the soil. However, the Bowen ratio at the undeveloped site was still lower than the three urban sites, aiding the development of mild UHIs during the winter.

4. CONCLUSION

The influence of housing density on the development of local climates through the surface energy balance does not show a clear pattern that increased housing density will result in warmer and more unpleasant local climates from the area. In fact, during the warmer period, the medium density site showed the highest amount of sensible heating and the high density site showed the lowest Bowen ratio and indicates that the UHI observed in Melbourne may be more a product of urban design than the density of development. It appears that Q_E is very similar at each of the sites, suggesting that there is variation in rates of evaporation in the residential areas of Melbourne, despite observed varying covers of vegetation. Therefore, local climates may be a result of the amount of energy partitioned into the urban fabric, whereby the larger the amount of energy partitioned into ΔQ_S during the daytime, the less is available for partitioning into Q_H. This characteristic was seen during both the summer and winter periods. Nevertheless, the drivers for the development of the UHI observed by (Torok et al., 2001) and (Morris et al., 2001) are identified. The excess heating found in these residential areas during summer could be hazardous, particularly on hot and dry summer days, placing vulnerable residents at risk.

In order to fully address this question of urban design, further analysis is required to identify the exact housing density and vegetation cover of each of the sites through GIS analysis of aerial photography. Detailed site descriptions, source area modelling and ΔQ_S parameterisation also need to be assessed in order to better understand and pinpoint the processes occurring at each of the sites including day to day variability. Additionally, the role of Q_F needs to be investigated, particularly for its contribution to Q_H and UHI development, as well as other factors related to UHI genesis, such as sky view factor and friction. It is important also that these preliminary observations and future observational results, as well as coupled land-atmosphere model simulations achieve the challenging task of incorporation into Melbourne 2030. With improved planning directions involving climatic strategies that work with the key directions of Melbourne 2030, the Victorian State Government can help achieve its vision of Melbourne as one of the most liveable, attractive and prosperous areas in the world for residents, business and visitors.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Bonan, G. B. (2000) The microclimates of a suburban Colorado (USA) landscape and implications for planning and design. *Landscape and Urban Planning*, **49**, 97-114

Baldocchi, D. D., Hincks, B. B. and Meyers, T. P. (1988) Measuring Biosphere-Atmosphere Exchanges of Biologically Related Gases with Micrometeorological Methods (in Special Feature: Gas Exchange in a New Dimension) *Ecology,* **69**, 1331-1340

Bridgeman, H., Warner, R. and Dodson, J. (1995) *Urban Biophysical Environments.* Oxford University Press, Melbourne.

Department of Infrastructure (DOI) (2002) Melbourne 2030: Planning for Sustainable Growth, Melbourne.

Eliasson, I. (2000) The use of climate knowledge in urban planning. *Landscape and Urban Planning,* **48**, 31-44.

Fehrenbach, U., Scherer, D. and Parlow, E. (2001) Automated classification of planning objectives for the consideration of climate and air quality in urban and regional planning for the example of the region of Basel/Switzerland. *Atmospheric Environment,* **35,** 5605-5615.

Grimmond, C. S. B. and Oke, T. R. (1995) Comparison of Heat Fluxes from Summertime Observations in the Suburbs of Four North American Cities. *Journal of Applied Meteorology,* **34**, 873-889.

Grimmond, C. S. B. and Oke, T. R. (1999) Heat storage in urban areas: Local-scale observations and evaluation of a simple model. *Journal of Applied Meteorology,* **38**, 922-940.

Morris, C. J. G. and Simmonds, I. (2000) Associations between varying magnitudes of the urban heat island and the synoptic climatology in Melbourne, Australia. *International Journal of Climatology,* **20**, 1931-1954.

Morris, C. J. G., Simmonds, I. and Plummer, N. (2001) Quantification of the influences of wind and cloud on the nocturnal urban heat island of a large city. *Journal of Applied Meteorology,* **40**, 169-182.

Population Reference Bureau (2003) 2003 World Population Data Sheet of the Population Reference Bureau. Demographic Data and Estimates for the Countries and Regions of the World.Population Reference Bureau. URL: http://www.prb.org/pdf/WorldPopulationDS03_Eng.pdf

Raupach, M. R., Antonia, R. A. and Rajagopalan, S. (1991) Roughwall turbulent boundary layers. *Applied Mechanics Reviews,* **44**, 1-25.

Schar, C., Vidale, P. L., Luthi, D., Frei, D., Harberli, C., Liniger, M. A. and Appenzeller, C. (2004) The role of increasing temperature variability in European summer heatwaves. *Nature,* published online, doi:10.1038/nature02300.

Smoyer-Tomic, K. E., Kuhn, R. and Hudson, A. (2003) Heat Wave Hazards: An Overview of Heat Wave Impacts in Canada. *Natural Hazards,* **28**, 463-485.

Spronken-Smith, R. A. (2002) Comparison of summer- and winter-time suburban energy fluxes in Christchurch, New Zealand. *International Journal of Climatology,* **22**, 979-992.

Stewart, I. D. (2000) Influence of meteorological conditions on the intensity and form of the urban heat island effect in Regina. *Canadian Geographer-Geographe Canadien,* **44**, 271-285.

Stone, B. and Rodgers, M. O. (2001) Urban form and thermal efficiency - How the design of cities influences the urban heat island effect. *Journal of the American Planning Association,* **67**, 186-198.

Torok, S. J., Morris, C. J. G., Skinner, C. and Plummer, N. (2001) Urban heat island features of southeast Australian towns. *Australian Meteorological Magazine,* **50,** 1-13.

Webb, E. K., Pearman, G. I. and Leuning, R. (1980) Correction of flux measurements for density effects due to water vapour transfer. *Quaterly Journal of the Royal Meteorological Society,* **106** 85-100.