The urban heat island in Melbourne: drivers, spatial and temporal variability, and the vital role of stormwater

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Abstract. Urban stormwater managers and water sensitive urban design practitioners are becoming increasingly aware of the benefits of retaining water in the urban environment to mitigate the effects of the Urban Heat Island (UHI). Research in Melbourne has investigated the influence urban density, vegetation cover and pervious surface area on the form and intensity of the UHI. Research demonstrates that water availability is especially important in influencing temperatures and creating urban-rural contrasts, while within city variability is largely a result of street and building design. There are benefits in utilising available stormwater to limit UHI intensity and reduce vulnerability to daily heat stress.

1 Introduction

The Urban Heat Island (UHI) is a phenomenon whereby temperatures in urban areas are warmer than the surrounding rural countryside, often by several degrees (Figure 1). This phenomenon is most obvious during the evening and night as rural areas cool more rapidly than urban areas. Urban areas – with their dense networks of streets and urban canyons, dense building materials of concrete and steel, lack of vegetation and rapid removal of water – are able to capture and store more daytime energy than their rural counterparts. This energy is then slowly released at night, resulting in differential surface cooling rates and driving the generation of the UHI (Figure 1). Urban areas also release large amounts of waste heat (from vehicles and buildings) that support additional warming not seen in rural areas.

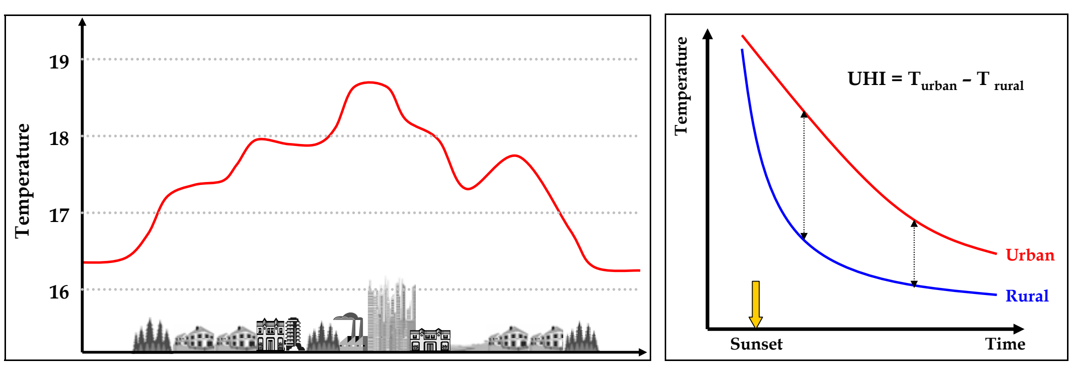

Fig. 1. A generalised description of the UHI (left panel) and a generalised description of the differential cooling rates between urban and rural areas that result in the UHI (right panel). The intensity of the UHI is given by the difference in urban and rural temperatures.

Numerous studies in Melbourne demonstrate the occurrence of an UHI (Morris & Simmonds 2000; Torok et al. 2001; Walker 2004) ranging from a mean of around 2 ºC to 4 ºC, with daily peaks as high as 7 ºC, depending on location and time of day and year. The UHI is particularly important from a human health perspective as high urban temperatures place urban inhabitants under heat stress (especially in combination with heat waves) and the UHI restricts night time recovery from daily heat stress. Research has shown an increase in the numbers of excess deaths (increases of 19–21% over expected death rate) occur when daily minimum temperatures exceed 24°C (Nicholls et al. 2008).

Spatial and temporal variability in the UHI intensity is in response to different surface characteristics influencing the partitioning of energy and generation of local climates. Vegetation has been said to have the ability to act as a natural cooling mechanism (Stone and Rodgers, 2001) by supporting higher rates of evapotranspiration which limit the amount of energy that is available to be stored in the urban fabric within walls, roofs, the ground and air space, (and later generate the UHI) or available to heat the atmosphere. This is known as the surface energy balance and governs the climate of a site. Previous studies have indicated that as urban green-space and vegetation cover increases, evapotranspiration increases (Christen and Vogt 2004; Grimmond et al. 1996). As such, a common mitigation measure is to increase urban vegetation and open space.

This paper outlines research conducted in Melbourne aimed at demonstrating the temporal and spatial variability of the UHI across the city and identifying the specific drivers that cause this variability. In particular, research investigated whether the UHI increases with increasing urban density and the role of vegetation cover and pervious surface area (and other surface characteristics) on evapotranspiration and the UHI. Evapotranspiration is a particular focus as it is influenced by the amount of water in the urban environment – which is partly controlled by stormwater management.

2 Methods

In order to characterise the urban surface and its influence on energy partitioning in the urban environment, four research sites were established in Melbourne – three urban sites of increasing urban density (dwelling density per km^2: high density – 1495; medium density – 1248; low density – 1113), and one rural control site (Coutts et al. 2007). At each urban site, surface characteristics of vegetation cover, impervious surface cover, albedo, and height to width ratios (urban canyon shape) were examined (Table 1). The surface energy balance was also measured at each site to examine local climate and UHI development including: available energy (net radiation); evapotranspiration; heat storage; and atmospheric heating. All four sites were operating simultaneously for three months from March 2004 to May 2004. The evapotranspiration component of the surface energy balance is the focus of this paper. Surface temperatures were also measured for the urban sites at approximately 40 m above the surface using a long-wave radiometer. This gave a picture of the mean radiative temperature of the built environment close to where urban residents reside.

In order to characterise the spatial variability of the UHI, a series of four automobile transects were completed across the city of Melbourne at 1am on 23rd March, 2006 from the rural outskirts of the city – into the central business district – and out again to the rural outskirts. Satellite data was also collected for land surface temperature and the normalised difference vegetation index (NDVI) (representing vegetation cover) at a similar time to determine whether there were any relationships.

3 Results and Discussion

3.1 Evapotranspiration in the urban environment

The availability of moisture in the urban environment for evapotranspiration is controlled by rainfall, runoff, infiltration and irrigation. Comparing evapotranspiration between the sites in March and May shows a strong contrast between the urban sites and rural site. As the natural landscape is replaced with hard, dry impervious surfaces, runoff increases as water is rapidly removed through the stormwater network, and infiltration is restricted – significantly reducing evaporation. Normally, some of this exported water is replaced with imported irrigation water however, Melbourne was under Stage 1 water restrictions at this time in 2004.

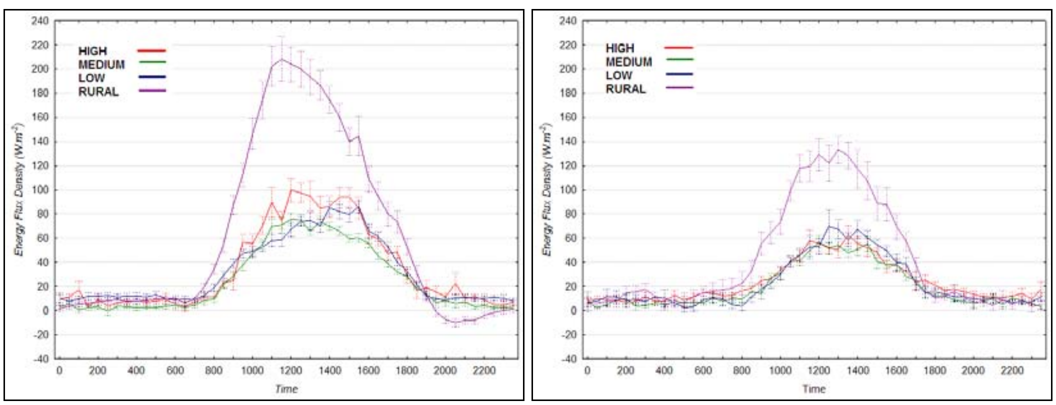

Fig. 2. Mean diurnal evapotranspiration rates at each site for both March and May 2004.

In addition, there is little water in the landscape available for trees to draw on and transpire to the atmosphere. Transpiration from vegetation is a by-product of photosynthesis. When trees become stressed, the stomata of the leaves shut down (increased stomata resistance) in order to prevent moisture loss. This means photosynthesis and hence transpiration stops, and the leaves shrivel and die.

The result is a very dry urban landscape and means that more energy is partitioned into either heating the atmosphere (which drives hot and dry conditions), or into heat storage (which drives the night time UHI). The effects are likely to be further exaggerated now under current Stage 3a water restrictions and following five additional years of drought.

When comparing the three urban sites, results showed that there was not a significant response in rates of evapotranspiration to changes in vegetation cover or impervious surface area. No matter whether it was a built up site, or a more open and vegetated site – rates of evapotranspiration were low across the entire urban landscape. Because the pervious surface areas (particularly the grassed areas) were so dry, they effectively function in a similar manner to impervious surface areas – because the surface is hard and sheds water quickly and there is little sustained infiltration. Variability in evapotranspiration rates in March are not a direct result of vegetation and pervious surface cover, and are more likely due to local rainfall or irrigation patterns. The high density site in fact showed a slightly higher evapotranspiration rates in March, despite what should be higher runoff and lower infiltration, and was likely attributed to slightly higher local rainfall or irrigation.

Figure 3 presents one of the transects across Melbourne at 1am, 23rd March 2006, in combination with a corresponding transect from satellite images of land surface temperature and NDVI. The UHI is clearly evident in both land surface and air temperatures – measuring around 4 ºC from the automobile transect data. There appears to be no clear relationship between vegetation cover and temperature. Temperatures increase rapidly upon entering the urban environment as a result of dry nature of the urban landscape.

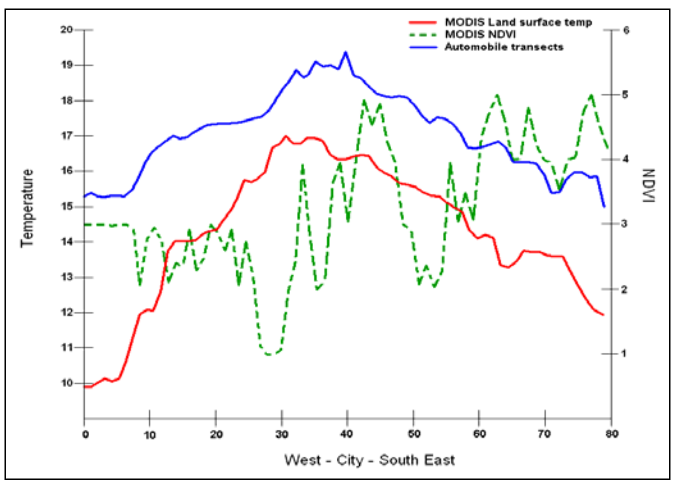

Fig. 3. A transect from the west of Melbourne to the south-east of Melbourne, via the city, demonstrating temperature from the automobile transects and land surface temperature (left axis) and NDVI (vegetation cover) (right axis).

So, under current urban layouts, once the natural landscape is replaced with even low density development, evapotranspiration is significantly reduced and increase the availability of energy for heat storage and atmospheric heating leading to a baseline increase in UHI intensity. Low rainfall or poorly irrigated areas are more susceptible to additional heat storage and atmospheric heating.

3.2 Surface characteristics and UHI intensity

Given the similar evapotranspiration rates observed at the urban sites, it is likely that the intra-city spatial and temporal variability across the landscape of the night time UHI intensity is dominated by the balance between the ability of the landscape to absorb and retain heat and energy. The amount of heat adsorbed during the day and retained in the landscape is controlled by a complex combination of variables including: the 3D urban morphology; type of surface materials; albedo; impervious surface cover; and water availability. Mean radiant surface temperatures are presented for March and May 2004 in Figure 4 and show the diurnal variability for the urban sites. Generally, mean radiant surface temperatures increase with increasing housing density. This pattern is clearly evident in May, and also holds true for the early morning hours in March.

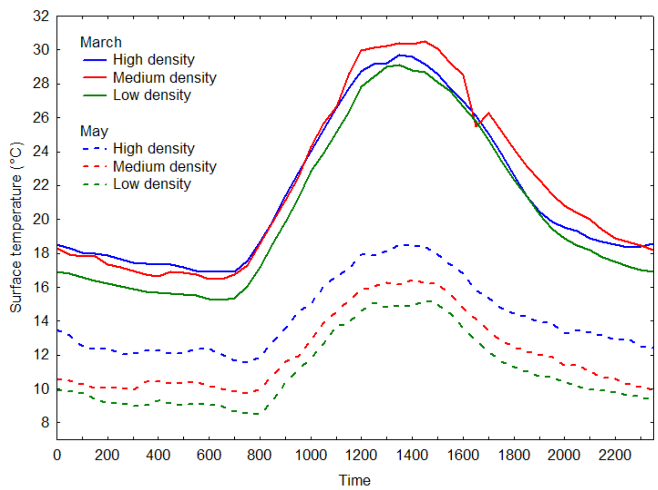

Fig. 4. Mean diurnal surface temperatures measured at each of the three urban sites for both March and May 2004.

Looking at the surface characteristics for each of the sites (Table 1) results suggest that the dominant surface characteristic that influences intra-city variations in local UHI intensity is the morphology of the landscape (the height to width ratio), particularly in controlling heat retention. As the complexity of landscape increases with narrower, deeper urban canyons, the more difficult it is for heat to escape – keeping temperatures warm throughout the night and creating the differential cooling rates that produce the UHI.

Tab. 1. Surface characteristics for each of the observational sites (Coutts et al. 2007).

Density	High	Medium	Low	Rural
Vegetation cover (trees) (%)	20	23	29	100
Impervious surface area (%)	67	62	53	0
Height to width ratio (H:W)	0.56	0.42	0.41	-
Albedo	0.19	0.15	0.17	-

The low albedo (0.15) and lower water availability meant that a large amount of intense summertime solar radiation was adsorbed by the local landscape, increasing radiant surface temperatures during the day in March. However, by the early hours of the morning, radiant surface temperatures at the medium density site returned to below those at the high density site (Figure 4). Shading can also be an important factor, whereby deeper urban canyons prevent direct solar radiative energy reaching all the canyon surfaces.

In May 2004, the pattern of increasing mean radiant surface temperatures with increasing density becomes more evident, despite the medium density site showing the highest heat storage flux during the day. During this time of the year when daytime solar radiation is less intense, the higher density sites with more complex urban morphology and high 3D surface area (Table 1) continued to efficiently trap and retain heat and become an even more dominant feature.

The other feature that is likely to influencing mean radiant surface temperature pattern in May is higher water availability. The magnitude of evapotranspiration decreases in May compared to March (due to suppressed solar driven evaporation and photosynthesis in May), but the proportion of total energy used for evapotranspiration increases (from around 18% to around 30%). While the evapotranspiration in May remained similar at each of the sites, the moisture in the environment delivers cooler local landscapes – and the pervious surfaces stop functioning like impervious surfaces. The saturated pervious surfaces aid to disperse heat into the ground, and requiring more energy to heat up than impervious surface materials. So while more energy is going into the urban fabric at the medium density site, it is not effectively heating the surface. Vegetation can also play a role in limiting surface heating by shading buildings, roads and other impervious surfaces (Wong et al 2003), but in order to be effective, vegetation needs water which became more available in May.

3.3 Re-integrating water back into the landscape

The climate of a site is fundamentally governed by the local surface energy balance and that by increasing evapotranspiration in the urban environment, we can help reduce the amount of energy available for the heat storage and UHI generation.

There are a range of mitigation measures that are available to minimise the intensity of the night time UHI including: water sensitive urban design; increased vegetation and open space; high albedo and thermal emittence surfaces; street design (control height to width ratios) and energy efficiency. In contrast to previous studies, evapotranspiration rates and surface temperatures are not simply aligned with vegetation cover but rather water availability. Therefore, increased vegetation cover to mitigate the UHI must be accompanied by water retention strategies in order enhance the effectiveness of vegetation.

However, water retention strategies through water sensitive urban design, stormwater capture and reuse are particularly beneficial. While high albedos and changes in street design can limit heat storage – water retention strategies (especially those that support vegetation) can both limit heat storage (and limit UHI intensity) and encourage evapotranspiration. The result is both cooler night time temperatures (through mitigation of the UHI) and daytime temperatures (through reduced atmospheric heating). This is most important in the context of climate change. By 2070, climate change is projected to increase the number of hot days over 35 ºC from nine to 14, and hot days over 40 ºC from one to three under a medium climate change scenario (CSIRO & BoM 2007). In 2009, Melbourne has already experienced four days over 40 ºC. These projections do not include additional warming from increasing urban development.

4 Conclusions

The UHI is predominantly a night time phenomenon caused by differential cooling rates between urban and rural areas. From the energy balance study in 2004, results showed that there are large differences in evapotranspiration between urban and rural areas that lead to baseline differences in UHI intensity between the two environments because more energy is partitioned into atmospheric heating and heat storage – driving development of the UHI. There was not a significant response in rates of evapotranspiration to changes in vegetation cover or impervious surface area within the urban environment because the whole landscape is dry during summer. Evapotranspiration rates were more likely to be influenced by localised rainfall or irrigation rates.

Within city variability in the urban heat island at night is dependant on the balance between the ability of the landscape to absorb <u>and</u> retain heat. Despite variations in vegetation cover and impervious surface area, each of the local landscapes studied were basically acting in the same way in summer. Therefore, the morphology of the landscape is particularly important in controlling heat retention.

Water in the environment helps to reduce heat adsorption by: encouraging evaporation and transpiration; keeping pervious surfaces cool; and enhancing the effectiveness of vegetation for shading. Retention of urban water, and even the re-integration of water back into the landscape, is essential in order to minimise heat stress from both extreme temperature events, but also the urban heat island. Rather than rapidly exporting water away from the urban landscape, approaches need to be developed to; encourage slower removal of water; investigate options for stormwater storage; enhance deep soil infiltration, deliver fit for purpose water use in the landscape for stormwater and other alternative water sources. There are significant benefits in terms of health and social wellbeing that can be delivered with cost-effective approaches to re-integrate water back into the urban landscape.

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