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Weekly cycles in peak time temperatures and urban heat island intensity

Nick Earl[1], Ian Simmonds[1] and Nigel Tapper[2]

[1] School of Earth Sciences, The University of Melbourne, Parkville, Melbourne, Victoria, 3010, Australia
[2] School of Earth, Atmosphere and Environment, Monash University and Cooperative Research Centre for Water Sensitive Cities, Clayton, Melbourne, Victoria, 3800, Australia

E-mail: nearl@unimelb.edu.au

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Abstract

Regular diurnal and weekly cycles (WCs) in temperature provide valuable insights into the consequences of anthropogenic activity on the urban environment. Different locations experience a range of identified WCs and have very different structures. Two important sources of urban heat are those associated with the effect of large urban structures on the radiation budget and energy storage and those from the heat generated as a consequence of anthropogenic activity. The former forcing will remain relatively constant, but a WC will appear in the latter. WCs for specific times of day and the urban heat island (UHI) have not been analysed heretofore. We use three-hourly surface (2 m) temperature data to analyse the WCs of seven major Australian cities at different times of day and to determine to what extent one of our major city's (Melbourne) UHI exhibits a WC. We show that the WC of temperature in major cities differs according to the time of day and that the UHI intensity of Melbourne is affected on a WC. This provides crucial information that can contribute toward the push for healthier urban environments in the face of a more extreme climate.

1. Introduction

Regular diurnal and weekly cycles (WCs) of meteorological parameters provide valuable insights into the consequences of human activities (e.g. industrial activity, generating electricity, biomass burning and powering motor vehicles, which commonly change at weekends), particularly in urban areas. Such insights are possible because many human activities follow fairly regular diurnal and weekly schedules. Since Ashworth (1929) 'accidentally' discovered a weekly Sunday minimum when investigating rainfall in the industrial town of Rochdale, England, the concept of humans affecting their surroundings on a daily scale inspired many WC studies as summarised by Sanchez-Lorenzo *et al* (2012).

Different locations experience a wide range of identified WCs, and these are often contradictory in nature. Many researchers have found significant WCs in various meteorological parameters in and around urban/industrial areas (Fujibe 1987, 2010, Simmonds and Keay 1997, Cerveny and Balling 1998, 2005, Forster and Solomon 2003, Shutters and Balling 2006, Gong *et al* 2006, 2007, Bell *et al* 2008, Laux and Kunstmann 2008, Bell *et al* 2009, Sitnov 2010, Rosenfeld and Bell 2011, Gruzdev 2013, Farias *et al* 2014, Georgoulias *et al* 2015) while others found that the observed signals are no stronger than the background variability (DeLisi *et al* 2001, Barmet *et al* 2009, Hendricks Franssen *et al* 2009, Stjern 2011). Daniel *et al* (2012) suggest that a wide variety of statistical tests are often used inappropriately and this is at least partly responsible for the contradiction. Anthropogenic activity linked to WCs can be thought of as due to human heat generation and the release of atmospheric pollution (Simmonds and Keay 1997), with the accompanying emission of moisture also affecting the urban energy budget (Sailor 2011). The three major sources of anthropogenic heat, closely related to energy consumption, are transportation, buildings and industry, as explained by Sailor (2011). However, atmospheric dynamics, aerosol and moisture release complicate the observed surface air temperature relationship with anthropogenic activity. Aerosol and moisture interaction with solar radiation (direct effect) and aerosols altering clouds characteristics and thermodynamics (indirect effect) vary greatly with time of year, surface land use and a wide range of other influences (e.g. city size, location, types of local circulations; Bell and Rosenfeld 2008). Therefore, the net effect of aerosol on surface temperature is highly variable and under debate.

The presence and/or strength of WCs in urban areas are related to the driving forces for the anthropogenic use of energy. These include population, character of industrial activity, patterns and intensity of vehicular traffic, typical synoptic patterns (and implications for, e.g., ventilation), physical geography of the city, proximity of the city to large water bodies and their direction in relation to the prevailing winds, frequency of inversions (and their implications for convection and for trapping of heat) and typical rain-producing mechanisms of the area. The relative importance of these factors differs between cities, strongly influenced by background climate.

Diurnal rhythms also present perspectives on anthropogenic influences. The typical diurnal warming and cooling regime of high-density urban areas is very different from that of rural or low-density urban areas. After nightfall, urban sites cool relatively slowly due to a number of anthropogenic causal mechanisms, discussed in detail by Oke (1982). This steady decline continues throughout the night, whereas rural areas cool fast soon after sunset and then more slowly later as radiation emission decreases. After sunrise, the rural sites warm faster, catching up with the urban locations and generally both reach a temperature peak in mid-afternoon. This rural warming can lead to an early morning urban 'cool island' in some cities due to the atmospheric boundary layer being deeper over the urban area, reducing the apparent early morning heating compared to the rural environment (Oke 1982, Theeuwes *et al* 2015). However other factors including shading in urban canyons, leading to a smaller surface area of accessible insolation, greater total urban surface area (compared to flat surface) and enhanced early morning absorption of radiation by urban materials (e.g. concrete and asphalt) may also be involved. This means that the urban heat island (UHI) intensity undergoes a marked diurnal variation with the largest difference typically 3–5 h after sunset and smallest, which may sometimes be negative, from early morning to mid-afternoon. For reasons similar to those discussed above, the diurnal evolution of the UHI can differ significantly with location. The diurnal cycle, combined with the WC, provides us with the opportunity to examine when anthropogenic activity has the largest influence on the environment. This is the first major focus of the paper.

There is a range of postulated causes of urban heat (Oke 1982). Two of the more important sources of urban heat are those associated with the effect of large urban structures on the radiation budget and energy storage and from the heat generated from anthropogenic activity (Rizwan *et al* 2008). The former forcing will remain relatively constant, but a WC will appear in the latter. The nature (including the diurnal progression) and intensity of the UHI changes with city characteristics (size, density, industrial activity, traffic intensity, amount of green space etc; Stewart and Oke 2012), latitude, time of day (e.g. Kolokotroni *et al* 2006), background climate (e.g. Zhao *et al* 2014) and weather types (e.g. Lowry 1977, Morris and Simmonds 2000). This means that the UHI in cities in tropical areas may contrast with those in temperate regions. With Australia possessing cites with a range of climates, it is an ideal location for this study. Lowry (1977) provides a conceptual framework that highlights the difficulties in defining and measuring the UHI, with factors including background climate, local topography and effect of local urbanisation. Understanding the characteristics of the UHI is of considerable importance due to the rises in urban population (table S1). UHIs have a profound effect on the lives of urban residents and the health impact of heatwaves is one factor that motivates the growing efforts to mitigate UHI (Tapper *et al* 2014, Zhao *et al* 2014).

One aspect of UHIs yet to be comprehensively studied is how it varies on a WC. Furthermore, surface observation based WC temperature studies are essentially based on daily mean temperature (Bäumer and Vogel 2007, Laux and Kunstmann 2008, Fujibe 2010), maximum or minimum temperatures (Simmonds and Keay 1997, Laux and Kunstmann 2008, Kim *et al* 2009) or daily temperature range (Forster and Solomon 2003, Gong *et al* 2006, Bäumer and Vogel 2007, Laux and Kunstmann 2008, Kim *et al* 2009, Kim *et al* 2010), not at specific times of day. Therefore, there are two main questions this paper aims to answer, once WCs have been identified as expected for at least the largest cities: How does the surface temperature WC of Australian major cities differ with time of day? Is the UHI intensity of a major city, Melbourne, affected on a WC?

2. Data and method

In order to investigate the temperature WCs for different times of day, three-hourly surface (2 m) observation (dating as far back as 1943) data from the Australian Bureau of Meteorology are utilised. These give eight separate local times of day from which the WCs are analysed from 0000 to 2100 h. We use data from seven major Australian cities (see table S2) including Melbourne, which is also the focus of the UHI analysis, together with three additional sites to represent the surrounding rural area. The study utilises data on vehicular traffic that is a major source of anthropogenic heat release and generally acts as a good proxy for indicating when peak times occur with regard to anthropogenic activity. To test whether WCs are statistically significant, we use a Monte Carlo based method (Earl *et al* 2015).

2.1. Station temperature data

The meteorological stations are located at sites that are near the centres of the urban areas, and hence significantly affected by anthropogenic activities (table S2). Included in the analysis is every state capital, as well as the reasonably densely populated regional centre of Cairns in Queensland, due to its long record and tropical location. Territory capitals will not be analysed due to Canberra's station being moved many times and Darwin's station being located too far from the urban area.

2.2. Melbourne UHI station data

The three non-urban sites, to be compared with the Melbourne CBD site, include the stations located at Melbourne Airport, Moorabbin Airport and Laverton Airport (table S3). We use the same period of 1973–2013 for the analysis, as this is an epoch when all three non-urban sites have good data coverage. These sites were used by Morris and Simmonds (2000) in their study of Melbourne's UHI, and they provide further site description details. These sites are located between 17 and 23 km away, in different directions from Melbourne's centre (see figure 3) and are at similar altitudes. We did not average the non-urban sites, because of the varying microclimatic effects at each specific location; some important signals would likely be smoothed out. Some sites are 'more urban' than others, depending on wind direction and are not ideal locations for rural representation, falling under the category of 'urban affected' (see Lowry 1977), but are the best available.

2.3. Vehicular traffic peak times

Traffic data provided by Vic Roads (www.vicroads.gov.au) for a typical junction located approximately 1 km from the CBD of the major Australian city of Melbourne are utilised. We use the traffic volume data (every 15 min total) from October 2014, which can be considered as a representative month.

2.4. Statistical testing

The temperature data are run through the daily divergence from a 31 d running mean (Bäumer and Vogel 2007, Earl *et al* 2015) filter to remove the effects of interannual and intraannual cycles, with each time of day treated as a separate time series. We use a Monte Carlo test based on the range between the days of the week with the minimum and maximum temperature anomalies. We randomly remove 5% of the data (run 10 000 times), retaining the order of the remaining components of the time series and therefore effectively retaining the autocorrelation of the data, which is important when analysing temperature data due to the memory, meaning that independence cannot be assumed. The WC temperature anomalies are calculated and the maximum-to-minimum range taken from each simulated WC (WCR), creating a Monte Carlo based PDF (of range in temperature) (Earl *et al* 2015). To test whether the weekends differ from the weekdays, we take the average Monday–Friday temperature minus the average Saturday–Sunday temperature from the original data and compare that to each of the 10 000 Monte Carlo based WCs (WD-WE). This is also done with mean Monday–Saturday minus Sunday alone (WD-S). Mondays at 0000, 0300 and 0600 h are considered as representing Sunday nights for this statistical test due to being influenced by the (lack of) Sunday night urban activity.

3. Results and discussion

In Australian cities (and in developed nations throughout the world), there tends to be two peaks when most people travel to and from work, take children to school etc. These occur during working weekdays (Monday to Friday) in the morning (typically running from 7–9 am) and there is a less pronounced afternoon/evening peak (4–7 pm). At the weekend these peaks do not occur, so there is a large difference in anthropogenic activity between weekday and weekend activity at these times, especially in the morning. Traditionally there is less total traffic seen in cities like Melbourne on Saturdays and especially Sundays (Simmonds and Keay 1997). During these times on weekdays other human activities also occur in city centres, such as the use of air conditioning units or heating systems, and further afield with electricity generation and biomass burning (Earl *et al* 2015), producing additional waste heat and aerosols. In western cultures, with Saturdays and Sundays being days off work for a significant proportion of the population, Friday and Saturday evenings have become popular with people going to restaurants, pubs, theatres etc. This means that there are anthropogenic activities in the city centres on these evenings through to the early hours of the following day. This activity does not include typical industrial activities seen during weekday daytimes, e.g. biomass burning, but increased usage of patio heaters or air conditioning units and perhaps even metabolic heat from the increased number of people in the area (Quah and Roth 2012).

3.1. Typical traffic volumes

Figure 1 displays the traffic volume of a typical road junction near the Melbourne CBD. A similar pattern was found on a suburban arterial road 10 km southeast of the CBD (www.vicroads.gov.au), indicating that this activity is not confined to inner Melbourne. It highlights the difference between the weekdays and weekend (figure 1(a)) showing the general nocturnal

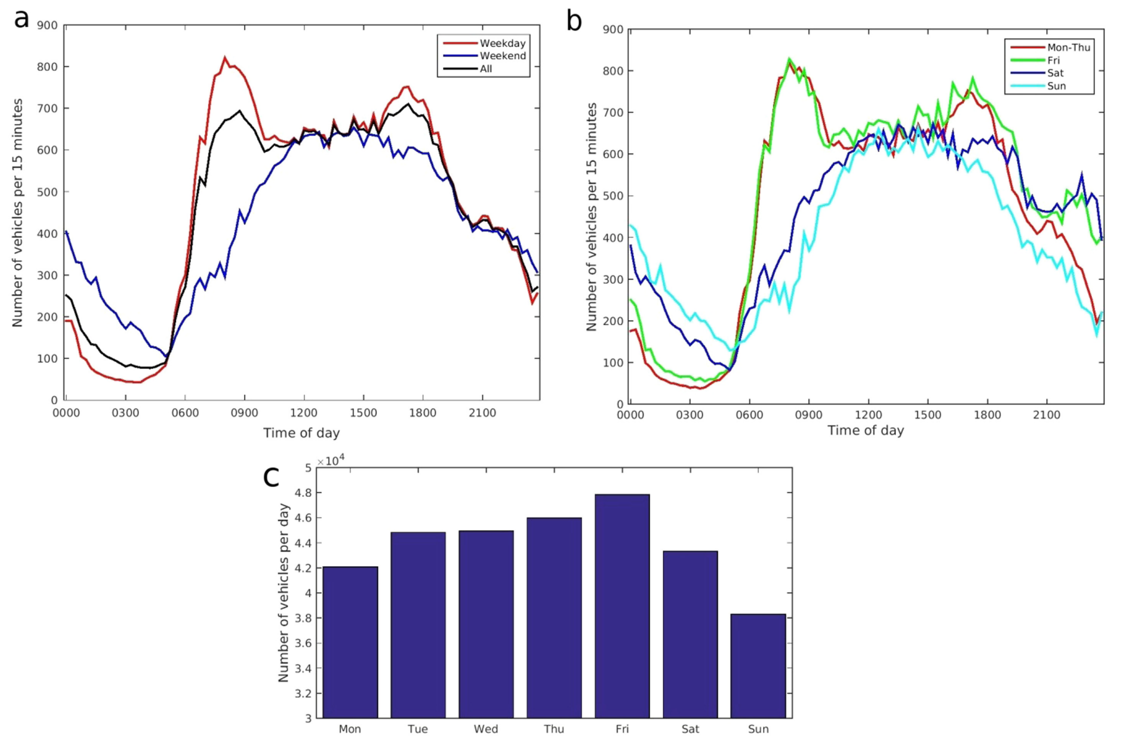

Figure 1. Mean four-week, 1st October–28th October 2014, traffic volume at a typical junction in central Melbourne (300 m from meteorological station). (a) Average weekday, weekend and overall (per 15 min). (b) Average Monday–Thursday volumes with Friday, Saturday and Sunday (per 15 min). (c) Total vehicles (per day).

increase and morning reduction at weekends com pared with the weekdays. There is a distinct morning and afternoon peak with the weekend showing a less extreme single peak during the middle of the day. When comparing the averaged Monday–Thursday and Friday, Saturday and Sunday volumes (1b), the Friday and Saturday night activity is highlighted. The weekend nocturnal increase is comparable to the weekday evening peak hour volume. Friday follows the weekday (Monday–Thursday) pattern until 2100 h where activity is increased into Saturday night, similar to Saturday evening and Sunday night. Figure 1(c) displays the weekend dip in traffic volume, especially Sunday, with Friday being a weekday and weekend night, possessing the most traffic. Monday has slightly less total traffic than Saturday, due to the high volumes in the early hours of Saturday and the fact that Monday has slightly lower traffic volumes throughout the day than the other weekdays (not shown).

3.2. Morning peak time

In the diurnal cycle of an average day, the morning peak occurs the time at which the atmosphere is in the transition between nocturnal and diurnal conditions, which means that the incoming solar radiation is only beginning to warm the surface and start the processes of mixing in the lower troposphere (Oke 1982). At this time there will often be a more stable surface layer or even a temperature inversion relatively close to the surface, which may act to trap the anthropogenic waste heat, which will build up more than later in the day, especially during winter in certain stable weather types (Morris and Simmonds 2000). Also, this is the time when the weekday to weekend anthropogenic activity differential is at its maximum. This means that we would expect a strong WC of surface temperature during the morning peak, especially in the larger cities. This time provides the clearest insight into the short-term effects of anthropogenic activity.

Figure 2 shows that Australia's largest cities have lower 0900 h temperatures on the weekend, with a signal well above the statistical noise level. The strength of the Melbourne and Sydney signals is surprising because they include all times of the year and all synoptic weather types, not just those which are favourable. Both cities have signals that are strongly statistically significant both in the WCR and WD-WE (figure 2(a)). The Melbourne signal displays a WC sinusoidal pattern, peaking on Thursday with a Sunday minimum. Sydney has a less coherent pattern, peaking on Friday, with a Sunday minimum. Brisbane's old monitoring site (1955–1972) also displays a statistically significant WD-WE, but not for WCR, and not as strongly as Melbourne's probably because of site characteristics (it is located in the City Botanic Gardens, close to the river and further from the source of heat, though still clearly affected by the morning anthropogenic activity). Adelaide does not display a strongly statistically significant signal, except for when Sunday alone is compared to weekdays (WD-S) as

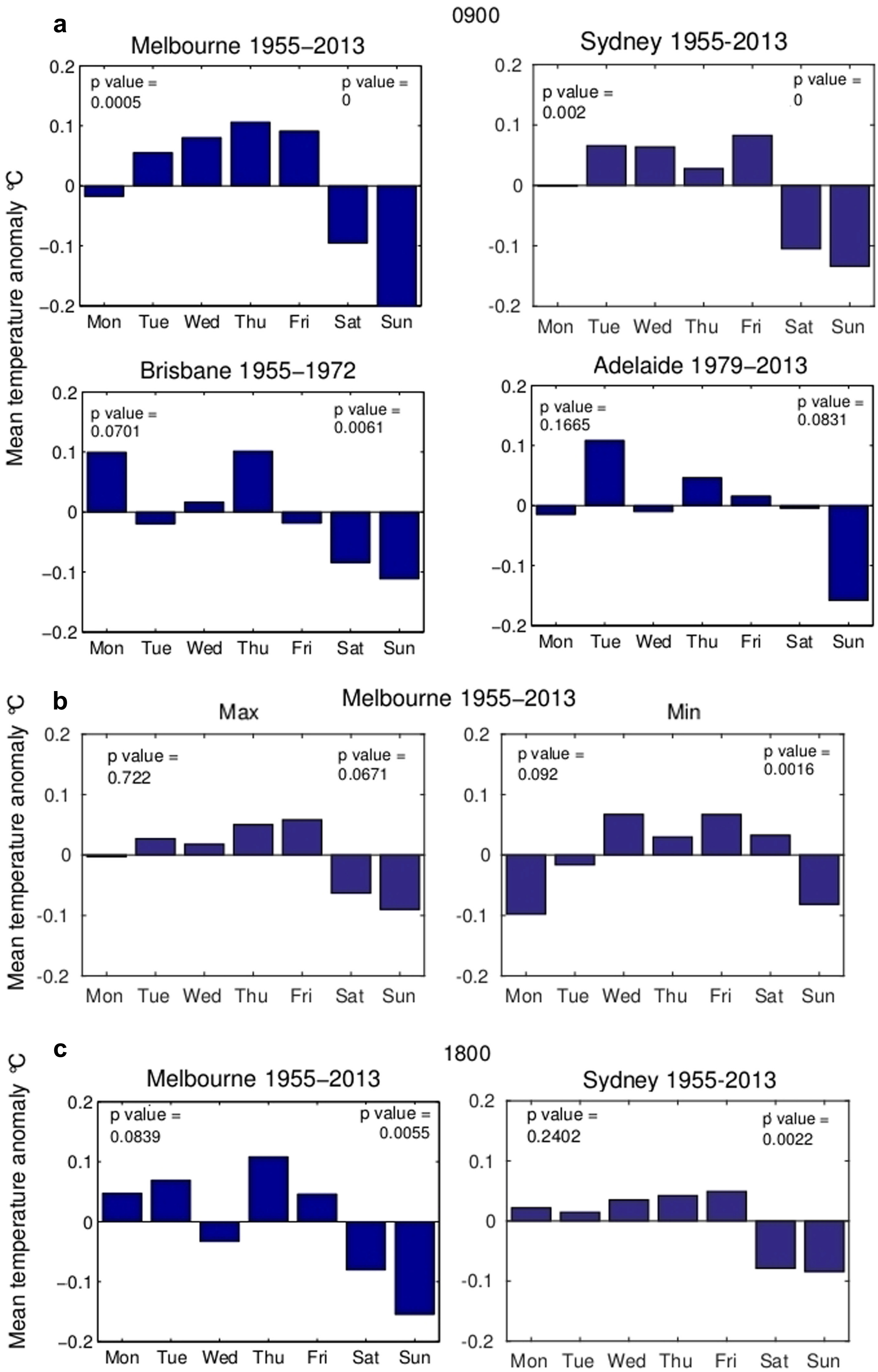

Figure 2. (a) Major Australian city 0900 h temperature weekly cycles. WCR test *p*-value (left) and WD-WE (right). (b) Melbourne maximum and minimum temperature weekly cycles WCR test *p*-value (left) and WD-WE (right), WE considered as Sunday and Monday for minimum temperature. (c) As with (a) but for 1800 h.

discussed below. The signals in the other cities did not have statistically significant WCs at 0900 h, probably because these are not large or busy enough to produce a signal above the statistical noise level. Fujibe (2010) also found this in daily mean temperature minimum for major Japanese cities. However, these Australian patterns are different from German cities, studied by Bäumer and Vogel (2007) and Laux and Kunstmann (2008), most of which had a Wednesday (or Thursday) peak and Saturday minimum. These studies are not sufficiently similar to ours for any robust comparison due to them using mean temperature rather than 0900 h temperature.

The Melbourne 0900 h signal is stronger statistically than any of the Melbourne maximum and minimum seasonal temperature analyses carried out by Simmonds and Keay (1997). The 0900 h signal is also stronger than the updated Melbourne maximum and minimum temperature WCs (figure 2(b)). This displays the Monday–Friday working week, which has a similar pattern to the 0900 h, though not as amplified or as strong statistically and with a Friday maximum. The minimum Melbourne temperature WC (figure 2(b)) is very different from the 0900 h, with a clear Sunday and especially Monday minimum, with again smaller amplitude and is less strong statistically. The Sunday night (Monday morning) minimum is apparent (discussed below).

3.3. Evening peak time

In summer, especially in temperate cites, the weekday evening peak time occurs before or soon after sunset, so urban areas have a positive convective sensible heat flux with significant mixing occurring in the unstable lower atmosphere (Oke 1982). During winter however, the Sun has already set at this time and nocturnal processes have begun. Like the morning, the increased volume of traffic (figure 1) and relatively stable atmospheric conditions, waste heat and aerosols can build up. This means that we would expect to see a WC during the evening peak, though not as pronounced as for the morning.

Australia's two largest cities display lower temperatures on the weekend than during the week, at 1800 h (figure 2(c)), statistically significant for WD-WE, but not as strong as for 0900 h and the WCR was not significant. The Melbourne signal is not sinusoidal as for the morning, though does display a Thursday peak and Sunday minimum. The 1800 h temperature does not correspond particularly closely with maximum temperature as seen for Melbourne (figures 2(b) and (c)), though is likely to be more similar during summer, with the maximum temperature often occurring around this time. The Sydney 1800 h also show a Friday maximum and Sunday minimum, similar to the 0900 h results. The other cities did not display statistically significant WCs at this time due to the daytime processes causing a great deal of mixing hence inhibiting the build-up of heat in these smaller cities.

3.4. Night life effect

Anthropogenic activity during the night that creates any waste heat is more likely to produce a WC signal due to the more stable lower atmosphere during the night, especially on calm nights. This means that we would expect a Saturday and Sunday 0000 h and 0300 h maxima rather than the minima seen at 0900 and 1800 h.

There is a statistically significant 0000 h WC in Melbourne and the new Brisbane site in the WCR test (table 1). The WE-WD test is also significant but at the end of the other tail (compared to 0900 and 1800 h analysis), weekends are warmer than weekdays as expected. Sydney does not display a Saturday and Sunday maxima, the reason for which is unclear, however we can speculate that the location of the Sydney site is on relatively high ground, especially compared to the adjacent highway, so perhaps the site is relatively unaffected by the nocturnal anthropogenic heat island and is also well ventilated. Table 1 indicates that the 0300 h temperatures do not show strong statistically significant patterns seen at 0000 h for any location, other than Melbourne when Sunday is compared to the rest of the week.

All cities have a noticeable Monday morning (Sunday night) minimum, statistically significant in the WD-S test for Sydney, Melbourne and Brisbane's new site, and close to significance in Perth (old site), Hobart and Cairns as shown in table 1. This may be due to aerosol loading during the week, with Sunday night being the longest time (over two days) since the last aerosol-producing weekday. This means that these city sites may be relatively clean, cloud free and better ventilated on Monday morning, allowing for more efficient cooling (e.g. Cerveny and Balling 2005). Simmonds and Keay (1997) found a sharp Sunday drop in aerosols in Melbourne and other studies have found a similar pattern (Cerveney and Balling 1998, Kim *et al* 2009), so this could be the causal mechanism. Kim *et al* (2009) found for Korean cities that there was often a Tuesday/Wednesday minimum in minimum temperature and a Saturday peak, which may occur for a similar reason, with urban activities occurring on Saturday night, though the authors link the peak to increased cloud cover from aerosol interaction. It could also be due to less Sunday urban activity as figure 1 shows with fewer vehicles on the roads throughout the day, meaning less build-up of waste heat. This pattern is not seen in Europe for minimum temperature (Laux and Kunstmann 2008), though this does not always correspond to 0000 h temperature.

3.5. Other times of the day

The table 1 column for Melbourne indicates that the site displays a WC in temperature at all times of day

Table 1. Summary of statistical WC tests[a].

Time	Sydney (1955–2013)	Melbourne (1955–2013)	Brisbane (1955–1972)	Brisbane (2000–2013)	Perth (1964–1991)	Perth (1995–2014)	Adelaide (1979–2013)	Hobart (1995–2014)	Cairns (1979–2013)
Weekly cycle range									
0000		** Sa M		** Sa M					
0300									
0600						* W Sa			
0900	*** F Su	*** Th Su	* Th Su						* Th F
1200						** Mo Th			
1500						*** M Th			** Th F
1800		* Th Su				** M Th			* Th F
2100		* Th Su							
Weekday minus weekend									
0000		−−−		−−−		+			
0300		−		−					
0600						++			+
0900	+++	+++	+++		+		+		
1200				−			+		
1500		+		−		−			
1800	+++	+++							+
2100	++	++						+	
Monday–Saturday minus Sunday									
0000	++	+++	+	++	+			+	+
0300	+	++						+	
0600		++						++	
0900	+++	+++	++				++		
1200		+				−−	++		
1500						−−	++	++	
1800	++	+++		+		−−	++		
2100	+	+++		++		−−	+	+	

[a] Tests include WCR, WD-WE and WD-S (see section 2.4) for each city (in order of population) station. * Indicates significance in the WCR test and the day of maximum (left) and minimum (right), + indicates a significant positive difference and—a significant negative difference. The number of *, + or − shows significance level, one is to the 10% level, two the 5% level and three to the 1% level.

except at mid-afternoon 1200 and 1500 h. This is to be expected as this is the time when the atmosphere is at its most energetic and maximum mixing occurs (Oke 1982), not allowing near surface heat build-up from anthropogenic activities. The afternoon is the time when the anthropogenic activity weekday to weekend difference is at a minimum (figure 1). Also, weekday build-up of aerosols during the morning may be reducing the amount of shortwave irradiance reaching the surface (e.g. Georgoulias *et al* 2015) reducing the effect of any increased waste heat. The times of day that Sydney exhibits a WC are 0900, 1800 and 0000 h as discussed above. With the site relatively exposed, as mentioned, any signal from other times of day may be overcome by advection of heat out of the area, along with the anthropogenic activity being more similar at these times on weekends and weekdays. The Brisbane sites have differing WCs, with the new site having a strong WD-WE negative anomaly at 0000 h and the old site a strong positive anomaly at 0900 h as mentioned above. This is likely to be due to a change in lifestyle and Brisbane's weekend nocturnal anthropogenic activity, with Brisbane's population more than doubling during the two time periods (table S1) and many parts of the inner city becoming gentrified, leading to more nocturnal weekend activity and less weekday industrial activity. It could also be due to the change in location to a site closer to anthropogenic activity and further from the moderating effects of the Brisbane River. The original Perth station does not show any significant WC signal though it has a weak positive WD-WE and WD-S at 0900 h and 0000 h respectively. The new site has a very different WC pattern (also from all other Australian urban stations) with Thursday minima and Monday maxima in the afternoon and evening, along with negative Sunday anomalies at these times. This is due to the sites having very disparate source areas, with the old site located to the west of the city centre, upstream of the urban centre from the prevailing south-west winds and the new site located north-east of the urban centre, next to a golf course, which is often irrigated at mandated times and days (www.watercorporation.com.au). This highlights the dangers of interpreting long-term micro-scale data when site changes are involved (Stewart and Oke 2012), especially with variable site characteristics. Adelaide and Hobart only have a WC signal for WD-S, indicating that Sunday is the only day where anthropogenic activity in these urban centres is low enough to produce a signal. The only significant WC signal in Cairns is a Thursday maximum and Friday minimum for the WCR test. It is unclear why this occurs.

These results show, for the first time, how there are temperature WCs that occur at different times of day and that vary in character. This is highly significant because understanding the temperature characteristics of the urban environment is becoming more important due to the rise in global urban population and heat-health implications.

3.6. Melbourne UHI WC

Melbourne is a growing metropolis and has increased in population by 65% from 1973 to 2014 (table S1). It has a WC for almost all times of the day (table 1), so we can expect the UHI to also display a WC, assuming that the surrounding rural areas do not display a WC as strongly.

The Melbourne UHI peaks between 2100 and 0000 h and is at its minimum between 0900 and 1500 h, depending on the day of the week and which location is used to represent the rural environment (figure 3). This is generally similar to the typical UHI diurnal cycle described by Oke (1982) with the Melbourne CBD—Laverton anomaly on weekdays the most similar to Oke's cycle. The weekend 0900 h dip is the main contrast with the classic diurnal UHI cycle, but is in agreement with the result of Theeuwes *et al* (2015), and is likely to be masked by averaging in non-WC UHI studies. The weekend CBD 0900 h anomalies compared to all rural sites contrast strongly with the other days of the week, the extent of which is highlighted by the divergence from the mean graphs in figure 3. The 0900 h WCs are all highly significant for both the WCR and WD-WE tests. This is of no surprise when we consider the weekday to weekend difference in the morning peak in vehicular activity (figure 1), which is likely to be less extreme in the more rural areas. UHI are often associated with the changes in energy budgets of the surface materials, however this confirms that the anthropogenic activity within these areas also makes an important contribution, with the reduction of the UHI especially at 0900 h on Sunday. The Sunday 0900 h minimum in the CBD is so extreme that there is a slight urban 'cool island' when compared to Moorabbin airport. This may be partly due to the fact that the Moorabbin site has some urban characteristics compared with Laverton and especially Tullamarine. The 1800 h UHI is not as extreme as the 0900 h one but is also statistically significant at each site for the WD-WE test but not for the WCR. This is to be expected since the anthropogenic activity weekday to weekend evening peak difference is not as extreme as during the morning. The Saturday and Sunday 0000 h anomalies have the opposite sign for the WD-WE test, with the weekend morning (Friday and Saturday nights) UHI anomaly significantly higher than during the rest of the week as expected. The line graphs display how the Saturday and Sunday UHI anomalies transition from being the highest at 0000 h, to the lowest by 0900 h when compared to each location. This is consistent with the change in traffic volumes (figure 1) representing anthropogenic activity, also displaying the extreme weekday versus weekend anomalies being at 0900 h.

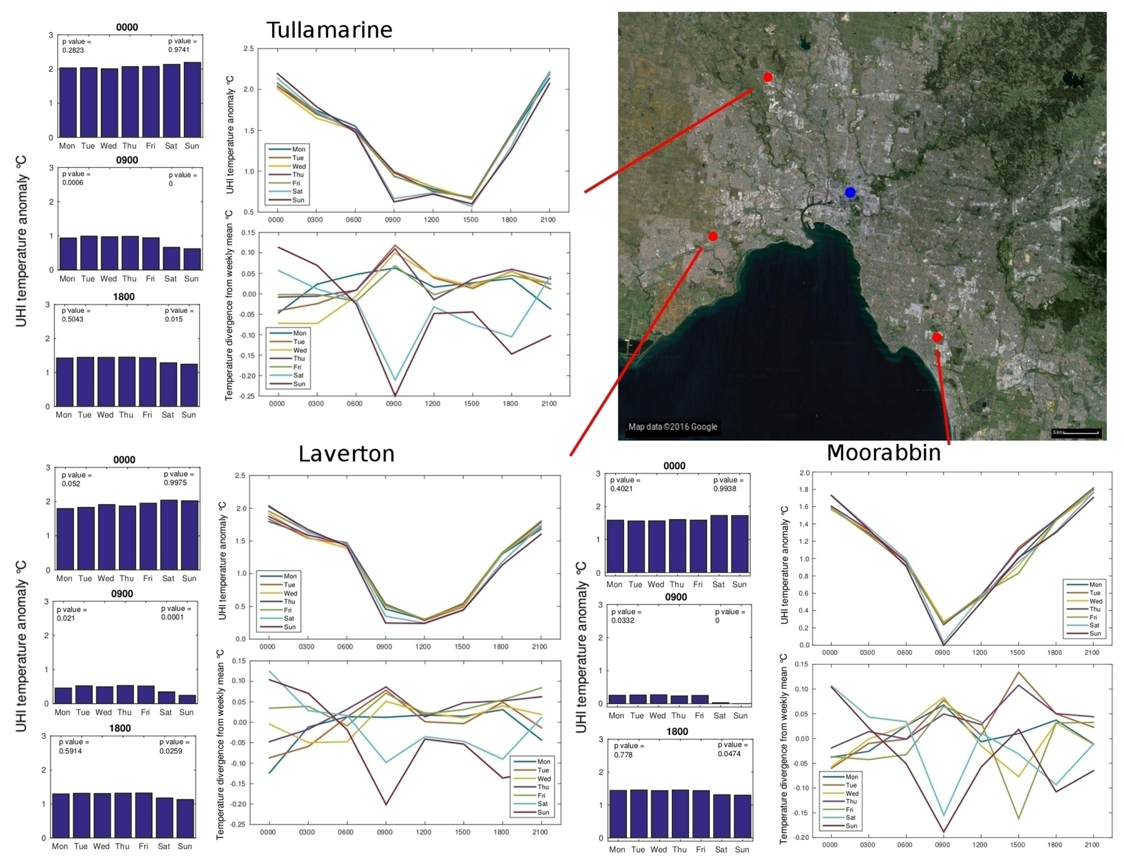

Figure 3. Temperature anomalies from the Melbourne site (blue dot in the centre of the map) minus the three airport site (red dots) temperature weekly cycles with the test *p*-value for (left) the WCR and (right) WD-WE. The top line graphs represent the diurnal temperature anomalies for each day. The lower graphs plot the divergence from the mean for each observation time.

These results show that the UHI of a major city can have a WC, especially at 0900 h, but also at 1800 and 0000 h, while it is not significant at other times of day (not shown). This result gives us an indication of the influence of anthropogenic activity in enhancing the UHI significantly, confounding the effect of the urban surface characteristics that produce the UHI by changing the local energy budgets.

4. Conclusions

These results show, for the first time, that the WC of temperature in major cities differs according to the time of day and that the UHI intensity of a major city is affected on a WC. This has profound implications during extreme heatwaves, showing that humans have the capability to manage anthropogenic heat flux by changing the activities to the characteristics of a weekend day, and vice versa for the night. With the number and severity of heatwaves set to increase (Cowan *et al* 2014), this could have significant implications for the health of urban populations. Recent work for Melbourne (Nicholls *et al* 2008, Tapper *et al* 2014) has shown distinct threshold temperatures above which human mortality greatly increases. Advance warning of extreme heat events provides opportunities to better manage (e.g., incentives for drivers to avoid using their cars at the warmest part of the day) human activity that will add to the heat. Australian government concern with the need to create cooler, greener and more liveable cities in the face of climate change is evidenced in the recent (January 2016) ministerial statement on cities. Clearly the results reported here provide further important information that can contribute to this push for healthier urban environments in the face of a more extreme climate.

Introducing the concepts of WCs at different times of day and identifying a WC in the UHI were the key aims of the study. Planned future work will address the important questions of seasonality, weather typing (e.g. Morris and Simmonds 2000), normalising the Sunrise and sunset times (e.g. Fortuniak *et al* 2006) and the impact of windspeed (e.g. Morris *et al* 2001) to the WC signals.

Acknowledgments

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shtml) and traffic data from Vic Roads (www.vicroads.gov.au).

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