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Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments

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Abstract Urban street trees provide many environmental, social, and economic benefits for our cities. This research explored the role of street trees in Melbourne, Australia, in cooling the urban microclimate and improving human thermal comfort (HTC). Three east–west (E–W) oriented streets were studied in two contrasting street canyon forms (deep and shallow) and between contrasting tree canopy covers (high and low). These streets were instrumented with multiple microclimate monitoring stations to continuously measure air temperature, humidity, solar radiation, wind speed and mean radiant temperature so as to calculate the Universal Thermal Climate Index (UTCI) from May 2011 to June 2013, focusing on summertime conditions and heat events. Street trees supported average daytime cooling during heat events in the shallow canyon by around 0.2 to 0.6 °C and up to 0.9 °C during mid-morning (9:00–10:00). Maximum daytime cooling reached 1.5 °C in the shallow canyon. The influence of street tree canopies in the deep canyon was masked by the shading effect of the tall buildings. Trees were very effective at reducing daytime UTCI in summer largely through a reduction in mean radiant temperature from shade, lowering thermal stress from very strong (UTCI>38 °C) down to strong (UTCI>

32 °C). The influence of street trees on canyon air temperature and HTC was highly localized and variable, depending on tree cover, geometry, and prevailing meteorological conditions. The cooling benefit of street tree canopies increases as street canyon geometry shallows and broadens. This should be recognized in the strategic placement, density of planting, and species selection of street trees.

1 Introduction

Street trees are an important part of the urban landscape, with the potential to improve amenity, provide stormwater quantity and quality benefits, and reduce building energy use (McPherson et al. 2011). Street trees can also help reduce high urban temperature through key vegetative processes of shading and transpiration (Bowler et al. 2010). Several studies suggest that an increase in vegetation can help mitigate the urban heat island (UHI) (Loughner et al. 2012), while others promote vegetation as a way of modifying urban microclimates and human thermal comfort (HTC) (Shashua-Bar et al. 2010b). However urban street trees face significant challenges including development and infrastructure pressures, maintenance issues, and poor water availability at times that can compromise their ability to mitigate urban heat and improve HTC. In Melbourne, and across southeast Australia, an extended drought period was experienced from 1997 to 2009 leading to the implementation of water restrictions that resulted in detrimental effects on Melbourne's tree health (May et al. 2013). The combination of drought, water restrictions, and rapid export of stormwater away from the urban environment leaves the urban landscape water-starved and can constrain tree transpiration (Coutts et al. 2013). Urban climatic conditions of higher temperature and vapor pressure deficit (Peters et al. 2010) resulting from urban development

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including extensive imperviousness, removal of vegetation, increased rainfall runoff, and heat trapping by canyon geometry can compound the effects of heat events. This can further stress urban vegetation, even leading to significant defoliation of tree canopies (May et al. 2013) which therefore compromises tree shading. Maintaining healthy street trees during such adverse conditions requires tree management and expense that need to be outweighed by the potential benefits including urban heat mitigation and improved HTC.

Evidence from observational studies suggests that air temperature under trees is lower than in the open during the day (Bowler et al. 2010). Souch and Souch (1993) observed that maximum air temperature under canopies of individual trees and clumps of trees was reduced by 0.7–1.3 °C in the early afternoon for a variety of tree species. Lin and Lin (2010) found that air temperature below tree canopies was 0.64–2.52 °C lower than in the open at midday in a subtropical park. Others have shown that variables, such as the tree species, size, and characteristics, influence their cooling effects (Georgi and Zafiriadis 2006). In one of the few experimental urban tree studies, Berry et al. (2013) placed large trees adjacent to single room dwellings and observed a reduction in air temperature of up to 1.0 °C between the tree canopy and building wall. While trees in more open areas may result in a discernable temperature reduction, the cooling potential of trees does not solely depend on the attributes of the tree or tree stand but also the nature of the surrounding urban environment such as surface materials, geometry, building height, and density (Shashua-Bar et al. 2010a). Souch and Souch (1993) found that street trees were less effective than individual trees or clumps of trees located in open areas, only cooling by 0.1 °C in the early afternoon. Shashua-Bar and Hoffman (2000) observed cooler air temperatures of 1.3–4.0 °C in green areas such as streets and courtyards with trees, compared with nearby reference sites. While street trees can provide a benefit during the day, numerous studies observe that nocturnal air temperature beneath tree canopies can be slightly higher than nearby open sites (Bowler et al. 2010) due to reduced sky view factor (SVF) inhibiting longwave cooling at night. Again, Souch and Souch (1993) observed that air temperature was 0.5 °C warmer under canopies than at their open reference station due to longwave radiation that was emitted from the ground being absorbed and reemitted by the canopy. Clearly, there is some variability in the magnitude of temperature effects of trees in urban areas that will vary with aspects of urban geometry and background climate and thereby modulate any HTC benefits.

HTC considers not only air temperature effects on the human body but also other microclimatic factors of humidity, wind, and shortwave and longwave radiation (Johansson 2006). Indices of HTC, such as the physiological equivalent temperature (PET) or the Universal Thermal Comfort Index (UTCI), more accurately describe the human thermal sensation at the microscale. Lee et al. (2013) found that street trees reduce mean radiant temperature, and hence PET, under warm, sunny daytime conditions. Trees directly absorb or reflect solar radiation and reduce adjacent ground surface temperature through shading. Souch and Souch (1993) and Zhang et al. (2013) observed higher humidity (vapor pressure) below tree canopies, while ventilation (wind speed) may also be reduced below the tree canopy (Park et al. 2012), both of which can adversely affect HTC. At night, trees tend to restrict longwave radiation loss and cooling, as well as restricting ventilation beneath the canopy that can result in slightly higher air temperature and a negative effect on HTC under warm summer conditions (Charalampopoulos et al. 2013; Spronken-Smith and Oke 1998). Understanding the effects of street trees on microclimate and how they influence HTC is important to help provide guidance on their placement, protection and maintenance. Demonstrating the benefits on HTC can help to convince authorities to invest in street trees, and quantifying improvements in HTC can aid local authorities develop cost–benefit analysis.

This study sought to determine how effective street trees are at reducing canyon air temperature and improving HTC under a 'Mediterranean' style climate of warm, dry summers. The study also sought to determine how effective street trees are under different street canyon geometries. Three streets were selected within the City of Melbourne, Australia: a wide shallow street canyon with trees; a wide shallow street canyon without trees; and a narrow, deep street canyon with trees. The aims of the study were (1) to quantify the effects of street trees on the overall canyon air temperature and HTC of three streets of varying tree cover and canyon morphology and (2) to quantify the effects of street trees on air temperature and HTC within individual streets by comparing microclimates directly below tree canopies and microclimates in more open areas. As such, this is a unique study in that it was capable of observing both interstreet and intrastreet air temperature and HTC differences because of the large number of monitoring stations installed in the streets (20 total). Few studies have been undertaken representing these Mediterranean style climates, and many temperate cities may experience such warm summer conditions and heat events under projected climatic changes. Particular focus is given to extreme heat events, as urban communities, infrastructure, and services are placed under significant pressures during such conditions. Melbourne also presents its own unique urban form and design, while an extended drought period has left vegetation in a depleted state over recent years. Given that the City of Melbourne maintains around 70,000 trees that have an estimated amenity value of around Australian $700 million (CoM 2012), this research is valuable for the ongoing management of the urban forest.

2 Methodology

To quantify the effects of street trees on both the interstreet and intrastreet air temperature and HTC under changing geometries, three contrasting streets in terms of tree canopy coverage and canyon morphology were selected (Table 1). We chose: (1) a deep urban canyon oriented ENE–WSW in the Central Business District with moderate vegetation cover (CBD); (2) a shallow urban canyon oriented E–W in nearby East Melbourne that was open, with very little tree canopy cover (Open: OPN); and (3) a shallow urban canyon oriented E–W in East Melbourne with dense tree canopy cover (Treed: TRD) (Fig. 1). These streets provide three contrasting street environments. Several monitoring stations were installed in each street to capture both interstreet and intrastreet microclimate variability: ten in the CBD (four in the west section of the CBD and six in the east section of CBD), five in OPN, and seven in TRD (Fig. 2) to achieve a representative cover. In TRD and CBD, some stations were placed directly below tree canopies, while others were in the open. The stations provide for the observation of within canyon microclimatic differences, particularly due to tree canopies. The East Melbourne streets were located in the same block as one another, approximately 1.5 km east of the CBD site. E–W–oriented streets were selected for the study as trees are more effective at cooling in E–W streets (Ali-Toudert and Mayer 2007a). The trees in the CBD street canyon were *Platanus* × *acerifolia* and *Platanus occidentalis* (Plane family) with median planting heights of 16.9 m and crown diameters of 13.0 m. At TRD, the trees were uniformly *Ulmus parvifolia* (Chinese Elm), with median heights of 9.5 m and crown diameters of 9.6 m. The CBD trees had a trunk height to the base of canopy of approximately 4.8 m while the trunk height at TRD was approximately 3.4 m. At CBD, the trees were located on the sidewalk and emerged from small pervious areas surrounding the trunk of 1.2 m^2 at CBD. At TRD, the trees were located within the road area, adjacent to the sidewalk with a small surrounding pervious area of 1.2 m^2. Aside from the small area surrounding the tree trunks, the rest of the street canyon floor was impervious (e.g., pavement, asphalt) (Fig. 1). At

OPN, the few trees were also *U. parvifolia*. Lin and Lin (2010) examined the effects of different characteristics of shade trees on below canopy air and surface temperature (including *U. parvifolia*). They found four characteristics that influenced cooling in order of importance: leaf color, leaf area index, leaf thickness, and leaf texture. *U. parvifolia* generally has a greater leaf area index than *Platanus* × *acerifolia* (Lin and Lin 2010; USDA 2002), suggesting that less solar radiation will be transmitted through the canopy at TRD.

Several monitoring stations were located in each street using scientific grade instrumentation in a comprehensive network. Each monitoring station measured air temperature (t_a) and relative humidity (HMP155A, Campbell Scientific), wind speed (014A, Met-One), solar radiation (SI-212, Apogee Instruments), and black globe temperature (sensor constructed using an Omega 44031 precision thermistors and a 0.15 m-diameter copper float painted black). Stations were mounted on existing light poles at a height of between 3.5 and 4.0 m to avoid vandalism. Poles were selected in order to best represent each street canyon environment, by selecting poles on both the north and south sides of the street, under canopy and in the open, and under building shade for the CBD site. Poles were selected for the installation of stations in order to obtain an accurate representation of the pedestrian microclimatic experience in the street. Pole selection was constrained by existing fixtures on poles, condition of the poles, and permission based on weight loadings, but we believe a representative cover was achieved due to the high number of stations. Previous studies have not had such high spatial coverage of sites adopted here, and some studies attempt to represent the urban canyon microclimate using a single site. Thus, this was a comprehensive network of stations capable of accurately capturing the microclimate. More stations were placed in TRD (seven) than OPN (five) because of the increased street complexity in TRD due to street tree presence, and more stations again were placed in CBD (10) as the street section was longer and the street complexity considerable due to variable building heights. The total sky view factor (SVF) was documented at each site, along with the contribution from buildings to the SVF, and the contribution from trees to SVF over and above that contributed by

Table 1 Characteristics of each street: Bourke St. comprises two sections (West and East) with varying characteristics

	Bourke St. (W–E)	Gipps St.	George St.
Site description	CBD	Open (OPN)	Treed (TRD)
No. of stations	10 (4–6)	5	7
Minimum building height (m)	5	4	4
Maximum building height (m)	133	14	11
Average building height (m)	22	7	8
Street width (m)	29	25	25
Mean H:W	0.76 (1.06–0.54)	0.27	0.32
Plan area canopy cover (%)	31 (20–42)	12	45

Fig. 1 Location and photos of each street: Bourke St. (*CBD*) (East and West), Gipps St. (*OPN*), and George St. (*TRD*)

buildings (Table 2). SVF was calculated using fish-eye photographs processed in RayMan Pro 2.1 (Matzarakis et al. 2010).

The measurement height in this study was higher than the suggested pedestrian level experience of HTC of 1.1 m. As such, t_a during the day may be slightly underestimated, while wind speed may be slightly overestimated. Oke (2004) suggests relaxing the requirement of measurements at standard observational heights (between 1.25 and 2 m) in part to avoid

sensor damage in urban areas. Oke (2004) also points out that taking temperature measurements between 3 and 5 m should not lead to significant measurement bias and are little different from standard height because t_a measurements show very slight gradients through most of the urban canopy layer. The CBD stations were installed for around 12 months from May 2011 to May 2012, while the East Melbourne stations OPN and TRD were installed for 21 months, from October 2011 to June 2013. Data were logged every 10 s (CR211 data logger,
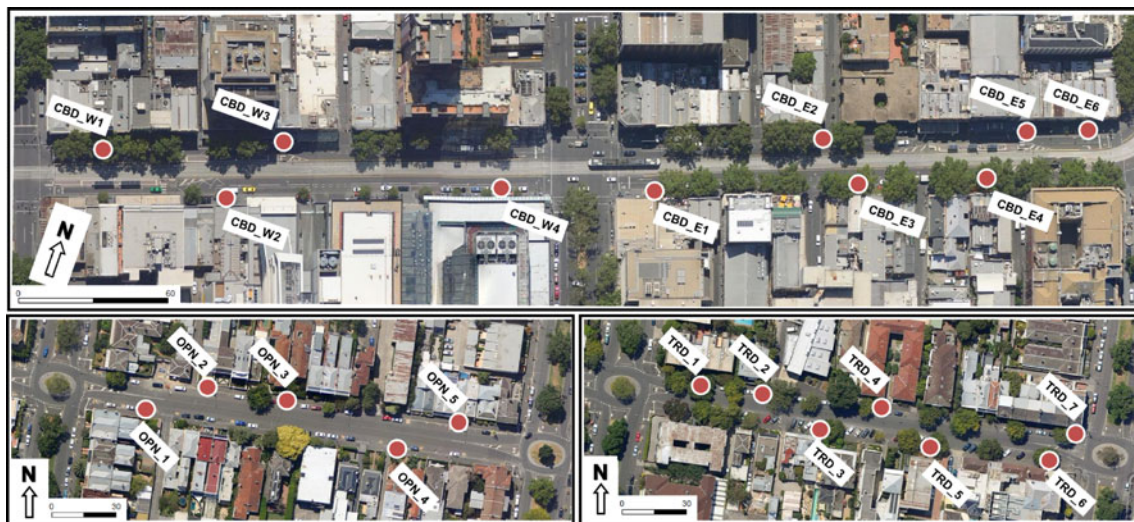

Fig. 2 Aerial view of the streets highlighting individual station locations and tree canopy coverage in Bourke St. (*CBD*), Gipps St. (*OPN*), and George St. (*TRD*)

Table 2 Sky view factor (SVF) at each monitoring site

Site	SVF		
	Total	Build.	Trees
TRD			
TRD_1	0.13	0.68	0.55
TRD_2	0.22	0.85	0.63
TRD_3	0.17	0.70	0.53
TRD_4	0.66	0.81	0.15
TRD_5	0.18	0.71	0.53
TRD_6	0.09	0.52	0.43
TRD_7	0.47	0.74	0.27
Mean	0.27	0.72	0.44
OPN			
OPN_1	0.76	0.77	0.01
OPN_2	0.78	0.79	0.01
OPN_3	0.63	0.81	0.18
OPN_4	0.86	0.94	0.08
OPN_5	0.77	0.78	0.01
Mean	0.76	0.82	0.06
CBD			
CBD_W1	0.02	0.43	0.40
CBD_W2	0.33	0.40	0.07
CBD_W3	0.29	0.31	0.02
CBD_W4	0.28	0.40	0.12
CBD_E1	0.25	0.46	0.21
CBD_E2	0.20	0.59	0.39
CBD_E3	0.18	0.56	0.38
CBD_E4	0.08	0.50	0.42
CBD_E5	0.39	0.43	0.03
CBD_E6	0.45	0.48	0.03
Mean	0.25	0.45	0.21

Presented is the total SVF (resulting from buildings and trees) at each site; the reduction in SVF as a result of buildings only (Build.) and the reduction in SVF as a result of trees in addition to that resulting from buildings

Campbell Scientific) and averaged to 10 min; from 16 May 2012, data were averaged to 30 min. The response time of the black globe thermometer (t_g) varies with the mass of the globe. Suggested time periods for black globe thermometers to reach equilibrium vary between studies, from 10 min for a thin sphere (0.015 in.) (Graves 1974) to 25 min for a standard globe thermometer to attain equilibrium when a resolution of 0.1 °C is required (Vincent 1939). We averaged t_g over 30 min. Statistical analysis involved t tests for independent variables.

Mean radiant temperature (t_{mrt}) was calculated using the black globe thermometers and accounting for the effects of convection and conduction on the black globe given by (Kántor and Unger 2011):

$$t_{mrt} = \sqrt[4]{\left(t_g + 273.15\right)^4 + \frac{h_{c_g}}{\varepsilon d_g^{0.4}}\left(t_g - t_a\right)} - 273.15$$

where t_g is the globe temperature, h_{Cg} is the mean convective coefficient ($1.10 \times 10^8 v^{0.6}$ where v is wind velocity [m s^{-1}]), d_g

is the globe diameter (m), ε is the globe emissivity (0.95), and t_a is air temperature. Prior to installing the black globe thermometers, we compared the constructed globes with direct measurements of the mean radiant flux density (S_{str}), considering shortwave and longwave radiation from the six cardinal directions using three all-wave radiometers (CNR1, Kipp and Zonen) and accounting for angular and absorption factors of a sphere (Thorsson et al. 2007). All the black globe thermometers and radiometers were set up in a residential back yard along with t_a and v, for 5 days from 28 January 2011 to 1 February 2011 (excluding the dawn and dusk periods 0745–1000 and 1620–1745 h when nearby structures caused differential shading of sensors). Conditions were predominantly warm with clear skies, with t_a ranging between 11 and 40 °C. The t_{mrt} from the black globe thermometers was overestimated compared to the direct radiation observations of t_{mrt} for a sphere, so we corrected the mean convection coefficient h_{Cg} to $0.65 \times 10^8 v^{0.53}$, which resulted in good agreement between the approaches. Finally, we use the recently developed Universal Thermal Climate Index (UTCI) as a thermal index of HTC (Bröde et al. 2012) that calculates the physiological response to meteorological input based on a multimodal model of human thermoregulation. From a comparison of several thermal indicies, Blazejczyk et al. (2012) concluded that the UTCI can represent bioclimatic conditions and their relevance to human thermal stress under a range of climatic conditions, making the index universal in nature, and represented the temporal variability of thermal conditions better than other indices. The UTCI was calculated using RayMan Pro 2.1 (Matzarakis et al. 2010) for a 35-year-old male, with a clothing factor of 0.9 and activity rate of 80 W. UTCI equivalent temperature was then compared with the assessment scale of thermal stress (Bröde et al. 2012), where the UTCI range +9 to +26 °C indicates no thermal stress, +26 to +32 °C moderate heat stress, +32 to +38 °C strong heat stress, +38 to +46 °C very strong heat stress, and above +46 °C indicates extreme heat stress.

3 Results and discussion

3.1 Interstreet variability under summertime conditions

We sought to explore the influence of trees on the street canyon microclimate under warm summer time and extreme heat conditions because that is when the cooling benefit provided by trees will be of greatest benefit. The dense network of monitoring stations within each street provided a more representative picture of canyon microclimate than a single station. This allowed the opportunity to quantify the effects of street trees on the overall canyon air temperature and HTC of three streets of varying tree cover and canyon morphology. We first

compare interstreet variability between TRD and OPN and then TRD and CBD under average summertime conditions.

During January 2012, mean canyon t_a during the day was very similar for all streets, with OPN being marginally greater than TRD by 0.2 °C (Fig. 3a), but was not statistically significant. While differences in t_a were subtle, the mean conditions during January 2012 showed clear differences in t_{mrt}, wind speed, and UTCI between all the streets. Figure 3 presents the individual environmental components that contributed to HTC for January 2012 averaged across all the monitoring stations in each street. OPN displayed greater t_{mrt} during the day compared to TRD (Fig. 3b) where the extensive tree canopy shading reduced t_{mrt} by blocking solar radiation. At night, the reverse occurred as the wide, shallow canyon of OPN allowed longwave radiative cooling, while the tree canopy at TRD inhibited longwave radiative cooling from the surface (Park et al. 2012). The trees also absorb and (re)emit longwave radiation which further contributes to greater t_{mrt} at night at TRD. Trees also acted as surface roughness elements in TRD leading to reduced wind speed in the urban canyon compared to OPN (Fig. 3c). Finally, vapor pressure (e) was slightly greater (nonsignificant) at TRD compared to OPN and was

likely due to transpiration from the trees in the street canyon because the street canyon floor was almost entirely impervious at both sites (Fig. 3d).

The individual environmental components of HTC (t_a, t_{mrt}, v, and e) were all modified by the presence of trees, having either positive or negative effects on HTC as determined using the UTCI. The mean UTCI for each street from January 2012 data is presented in Fig. 4a and shows that OPN supported a slightly greater UTCI and level of heat stress than TRD. As outlined in previous research (Ali-Toudert and Mayer 2007b; Shashua-Bar et al. 2010b), t_{mrt} is the dominant driver of HTC under warm sunny conditions. Trees reduce the SVF, providing shade during the day at TRD and substantially reduced the street canyon t_{mrt} which limited heat stress levels. This is demonstrated in Fig. 4b where there was a clear relationship between SVF and UTCI during the day for individual stations across all three sites in January 2012. While the overall street canyon UTCI at OPN was not drastically different from TRD, UTCI was variable throughout TRD and dependent on SVF. Figure 4b also suggests that street canyons that have a SVF> 0.5 should be prioritized for tree planting and canopy cover increase. At night, t_{mrt} remained a strong influence at TRD,

Fig. 3 Environmental components influencing human thermal comfort for each street, averaged across all monitoring stations: January 2012 mean diurnal values for **a** air temperature, **b** mean radiant temperature, **c** wind speed, and **d** vapor pressure. Error bars are 95 % confidence interval
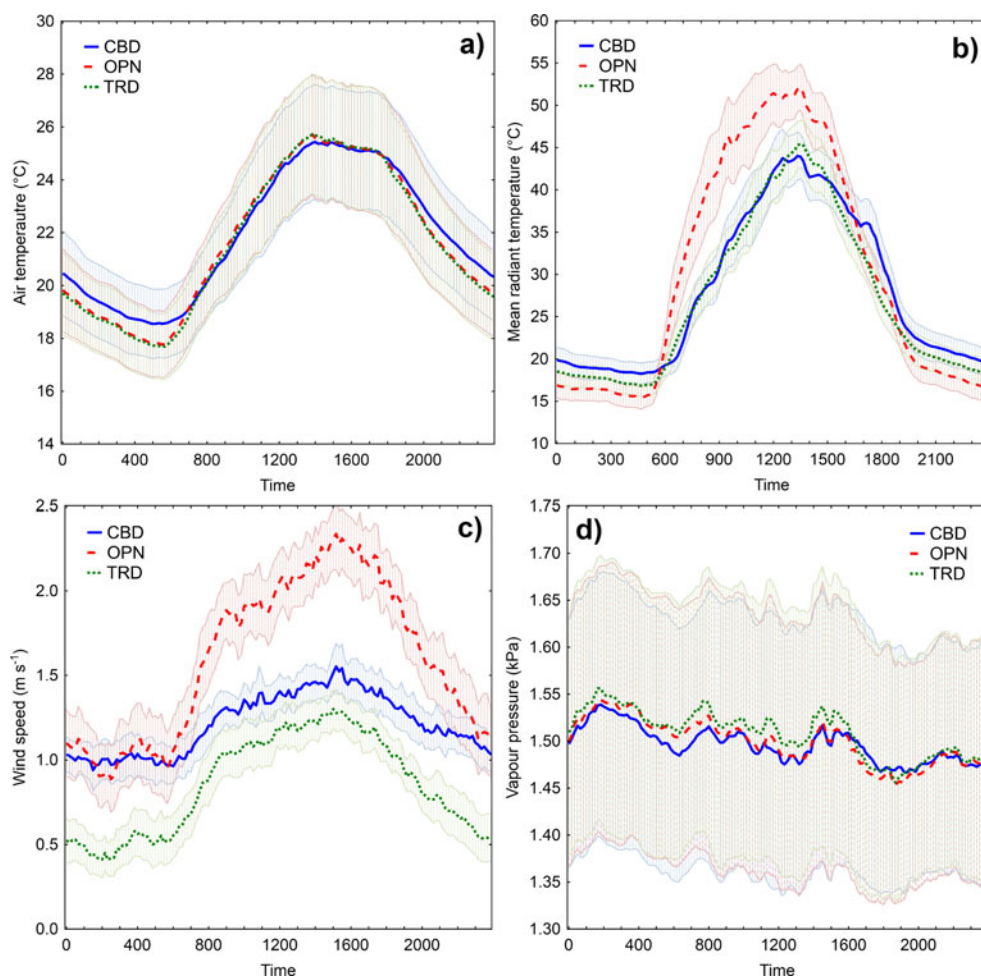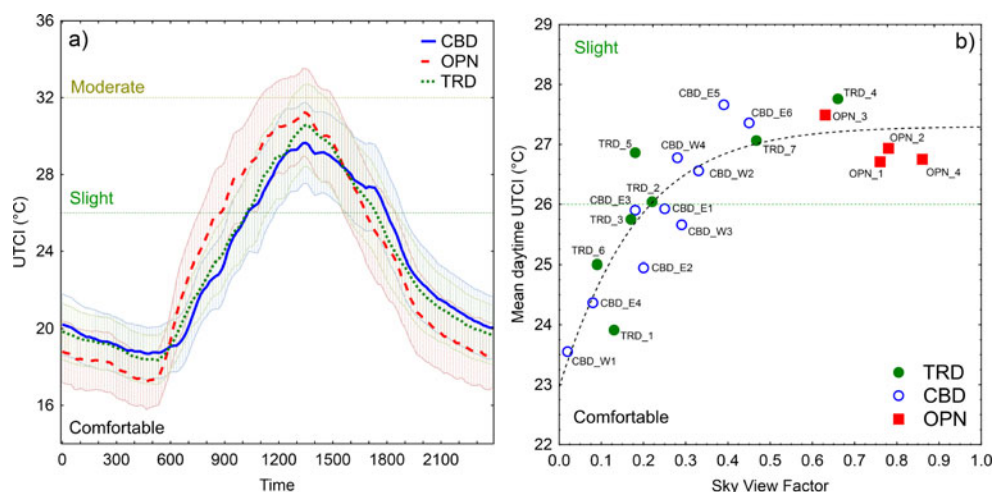
Fig. 4 **a** Mean Universal
Thermal Climate Index (*UTCI*)
for each street, averaged across all
monitoring stations in January
2012. Error bars are 95 %
confidence interval. The levels of
thermal stress from the associated
assessment scale are also
presented; **b** relationship between
sky view factor (*SVF*) and mean
daytime UTCI in January 2012

and in combination with a reduced wind speed, resulted in a higher UTCI than at OPN where there were few trees. Under these average summer month conditions, the trees in TRD did not significantly reduce ambient t_a below that measured in OPN, but did improve HTC during the day by reducing heat stress levels. While the tree canopy did increase UTCI overnight, the thermal sensation at night was comfortable, so an increase in UTCI was not as problematic. In summary, under these average summer month conditions, the trees in TRD did not provide large amounts of cooling of ambient t_a below that measured in OPN, but did improve HTC during the day by reducing heat stress levels.

Comparing TRD with the more built-up CBD site, there was a clear difference in canyon t_a of up to 0.8 °C at night which was statistically significant ($p<0.05$) (Fig. 3a). This was due to the higher amounts of imperviousness at CBD and the higher H:W. The deep urban canyon of the CBD cooled slowly in comparison to the shallow urban canyon of TRD due to the retention of radiation that was absorbed during the day within the large impervious surface cover and reduced longwave radiative cooling. Anthropogenic heat (waste heat produced by human activities) from vehicles and buildings may also have served to warm the CBD street canyon. It is interesting to note that this difference in night time t_a was evident despite a similar total SVF at CBD and TRD, although a greater proportion of the reduced SVF at CBD resulted from buildings (Table 2). This suggests that a reduced SVF resulting from buildings has a greater impact on heat retention than reduced SVF resulting from the tree canopy. The tall solid buildings restrict the loss of longwave radiation from the street canyon to a greater extent than the porous tree canopies, and the warmer buildings also reemit greater amounts of stored longwave radiation into the street than the cooler tree canopies. The greater t_a at CBD was also despite a higher amount of ventilation (wind speed) compared to TRD. At night, wind speed at CBD remained high and may be due to channeling and/or drainage of airflow along the street canyon. The greater tree canopy cover at TRD (Table 1)

also contributed to a reduced wind speed. At CBD, e was reduced despite a 31 % tree cover and may reflect a lower background e in the central city area, in general, due to high imperviousness. Finally, t_{mrt} was similar between CBD and TRD due to shading from either buildings or trees and follows that the total SVF was similar as the sites (Table 2). As a result, despite the lower tree canopy cover at CBD, the level of HTC during the day based on the UTCI was similar to TRD. The buildings at CBD reduced the SVF providing additional shading in conjunction with the trees (Fig. 4). In summary, the buildings at CBD appear to have a greater influence on t_a, and overwhelm the influence of trees, and as such the trees were less effective in reducing UTCI at CBD because shading was already being provided by buildings.

3.2 Temperature and HTC during heat events

The 2011–2012 summer in Melbourne was relatively mild compared to previous summers, such as 2008–2009, when the city experienced its highest ever recorded maximum temperature of 46.4 °C on 9 February 2009. Australia was experiencing La Niña conditions during 2011–2012. The most intense heat events over this summer occurred on 2 January 2012 when maximum temperature peaked at 40.0 °C and on 24 and 25 February 2012 when maximum temperature reached 37.1 °C on both days (observed at the Melbourne Regional Office weather station). The mean daily temperatures (the mean of yesterday's maximum temperature and this morning's minimum temperature) were 31.8 °C on 2 January 2012, and 30.7 and 31.1 °C on 24 and 25 January, respectively. Corresponding minimum temperatures following the high maximum daytime temperatures were 23.6, 24.2, and 25.0 °C. According to Nicholls et al. (2008), when the mean daily temperature in Melbourne exceeds 30 °C, there is a 15–17 % increase in mean average daily mortality for >65 year olds. Furthermore, when the minimum overnight temperature exceeds 24 °C, the mean average daily mortality for >65 year olds increases by 19–21 %.

Temperatures on all these selected days exceeded one or both of these thresholds and therefore represent periods of increased risk of mortality in vulnerable populations.

Under these heat events, the differences in street canyon microclimate were more pronounced and street trees had a greater influence on t_a. TRD was generally cooler than OPN during the day as the tree canopy absorbed solar radiation and shaded surrounding urban surfaces (Fig. 5). The daytime differences were around 0.2–0.6 °C and peaked at 0.9 °C during mid-morning (9:00–10:00) when OPN heated up rapidly, while the tree canopy in TRD delayed heating of that urban canyon. However, the differences in mean t_a between OPN and TRD were not statistically significant. OPN remains slightly warmer into the evening (e.g., through to around midnight) before OPN and TRD became similar in the early hours of the morning. Regarding HTC, the UTCI over the heat event followed the same pattern as throughout January 2012 but reached very strong heat stress levels during the day (Fig. 5),

with OPN showing the highest level of heat stress. Wide and shallow canyon streets without street trees present the most unfavorable conditions during the day (high t_a and high UTCI).

Comparing the deep canyon CBD site to the shallow TRD site, the most striking feature was the higher overnight t_a at CBD (Fig. 5), with differences of up to 4.8 °C prior to dawn. This further highlights the restricted longwave cooling from reduced SVF because of buildings at CBD that is known as a strong driver of the canopy layer UHI. Similarly, this highlights the increased frequency of threshold minimum night temperatures of 24 °C at CBD, above which increased mortality in vulnerable communities can be expected. However, the CBD site was slightly cooler during the day by as much as 2.0 °C, as a result of the reduced SVF from the buildings making up the deep canyon and to a lesser extent from the trees, along with the absorption of solar radiation by urban materials. These influences are sometimes listed as drivers of the daytime urban cool island. The lower daytime t_a at the
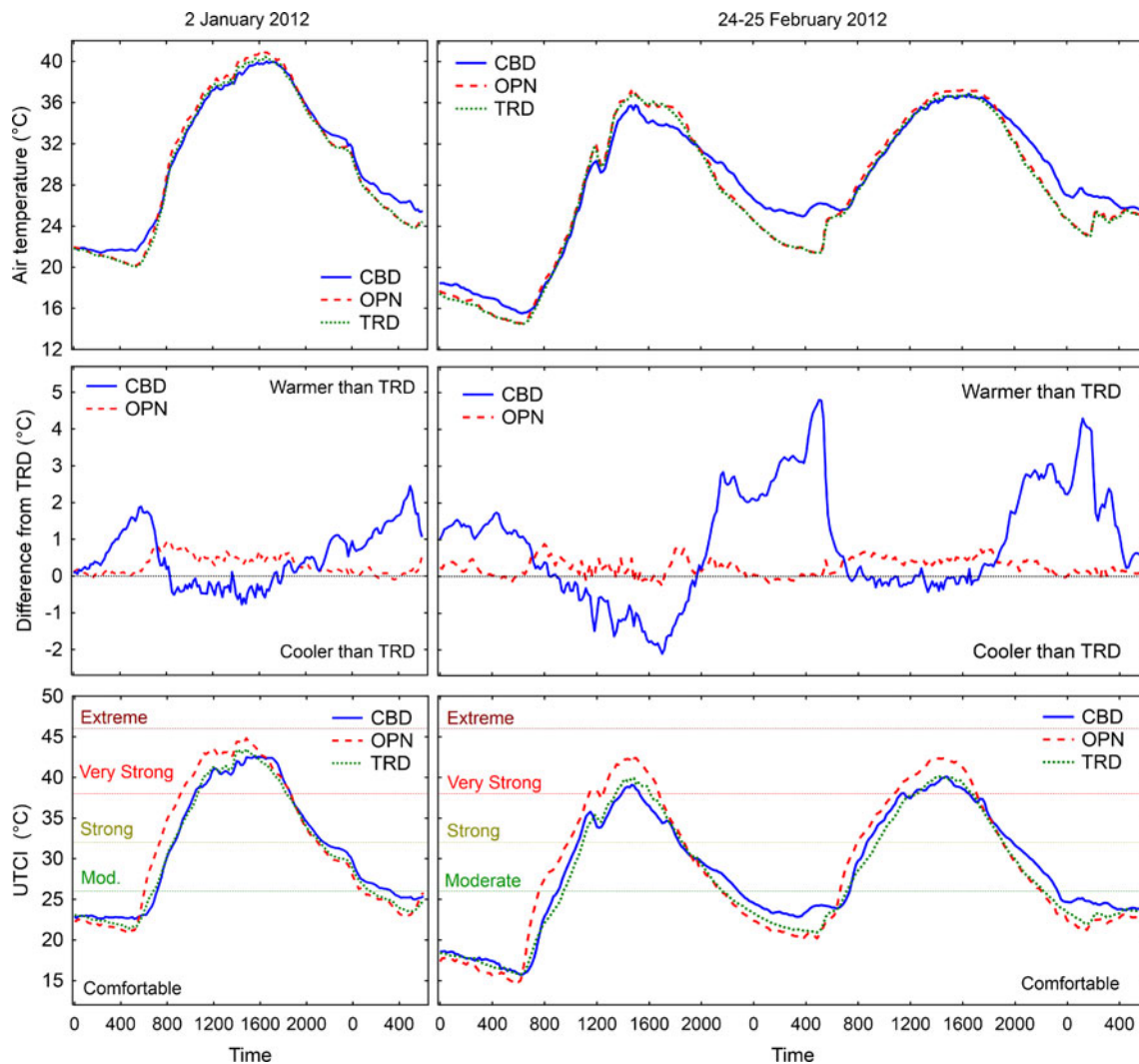

Fig. 5 Mean air temperature for each street during heat events on 2 January 2012 and 24–25 February 2012, differences in air temperature for CBD and OPN in comparison with TRD (*Difference from TRD*), and UTCI for each site and the corresponding grades of heat stress

CBD site occurs despite a lower vegetation cover and lower leaf area index of the trees and further emphasizes that at the CBD, the building morphology of the area overwhelms the influence of street trees on t_a. For HTC, the low SVF also results in a reduction in UTCI during the day through shading (Fig. 5). This demonstrates that during the day, shading from either buildings or trees can reduce UTCI and contribute to improve HTC under warm sunny conditions. However at night, deep street canyons are the most unfavorable as the retention of heat results in a poorer HTC (high t_a, and high UTCI). Thus, the street trees in TRD provide a more thermally comfortable environment during the day, but without a strong detrimental impact on HTC at night.

The summer of 2012–2013 had higher average monthly summer temperature than the summer of 2011–2012, with a larger number of heat events. Summertime conditions actually extended into March 2013 (autumn) in Melbourne with a prolonged heat event extending from 4 to 12 March with nine consecutive days exceeding 32 °C, due to a near stationary 'blocking' high pressure system situated over the Tasman Sea bringing warm northerly air from the continental interior to Melbourne (BoM 2013). This has been the longest period of days over 30 °C or above in Melbourne for any month since records began in 1855 and led to record high overnight temperature minimums for any month, with seven consecutive nights above 20 °C (7–13 March) (BoM 2013). The monitoring stations in OPN and TRD were in place during this period and provide a good representation of the influence of the tree canopy at the microscale during prolonged warm conditions (Fig. 6). During the day, OPN heated rapidly in the morning,
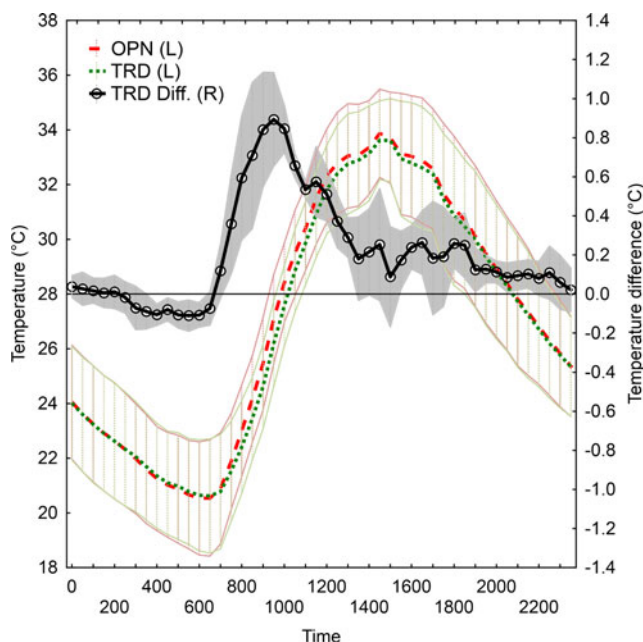

Fig. 6 Mean air temperature in OPN and TRD during the 4–12 March 2013 heat event and the difference (*TRD Diff.*) between the two streets. Error bars are 95 % confidence interval

while the tree canopy at TRD delayed canyon heating leading to an average temperature reduction of 0.9 °C, but by as much as 1.5 °C. As the day progressed, TRD began to warm but still remained cooler than OPN by between 0.2 and 0.6 °C. Shashua-Bar and Hoffman (2000) observed air temperature reductions of up to 2.5 °C within a well-treed avenue in Tel-Aviv as compared to a reference site outside the avenue. After dusk, TRD and OPN were similar, until trapping of heat at TRD by the tree canopy resulted in a slightly warmer t_a after midnight. Nocturnal t_a was warmer in TRD, which was similar to that observed by Souch and Souch (1993). While the tree canopy may inhibit nocturnal longwave radiative cooling within the street canyon (microscale), the daytime contribution of shading and transpiration from high tree canopy cover is likely to reduce the amount of heat storage in the landscape across the neighborhood (local scale) (Coutts et al. 2007), thereby reducing potential nocturnal t_a.

3.3 Microscale variability in air temperature

Closer examination of the 4–12 March 2013 data revealed that there was a large amount of microscale variability in t_a with differences of up to 3.1 °C among the seven stations in TRD during the March 2013 heat event. Ali-Toudert and Mayer (2007b) observed t_a that was 3.0 °C warmer on the sun-exposed side of a street at 17:00 of an E–W-oriented street in Freiburg, Germany. The variability of t_a in this study was greater in the more 'complex' TRD street, where the trees and buildings strongly influenced microscale variations in t_a (Fig. 7). OPN displayed a spatially more consistent t_a during the day, while the trees in TRD reduced mean daytime t_a of individual monitoring stations by up to 1.0 °C (Fig. 7). However, during this period, only OPN_2 and TRD_2 were significantly different during the day ($p<0.01$). This variability in t_a was partly due to shading, as the tree canopy reflects and absorbs solar radiation. The mean daytime temperature was plotted against the average daily amount of solar radiation received at each station (Fig. 8), and this demonstrates the influence of solar radiation on microscale t_a within the canopy. Several studies that have considered microscale street climate have highlighted the major role of tree canopy shading, although these studies also note that the effects are obviously localized (Lin and Lin 2010; Shashua-Bar and Hoffman 2000). Another driver of t_a variability within TRD may be the reduced wind speeds that reduce vertical mixing between air within and air above the street canyon (Park et al. 2012). While the differences in t_a between OPN and TRD (Fig. 7) were relatively small, if trees were present throughout the neighborhood, the benefit of lowering local-scale t_a could be substantial (Lynn et al. 2009).

Considering again the January 2012 period, we compared the variability in mean daytime t_a between individual stations in OPN with those in TRD during all conditions. It was

Fig. 7 Mean daytime
temperature for individual
stations at OPN and TRD during
the heat event over 4–12 March
2013. A spatial surface was
derived using inverse distance
weighted interpolation tool in
order to aid visualization
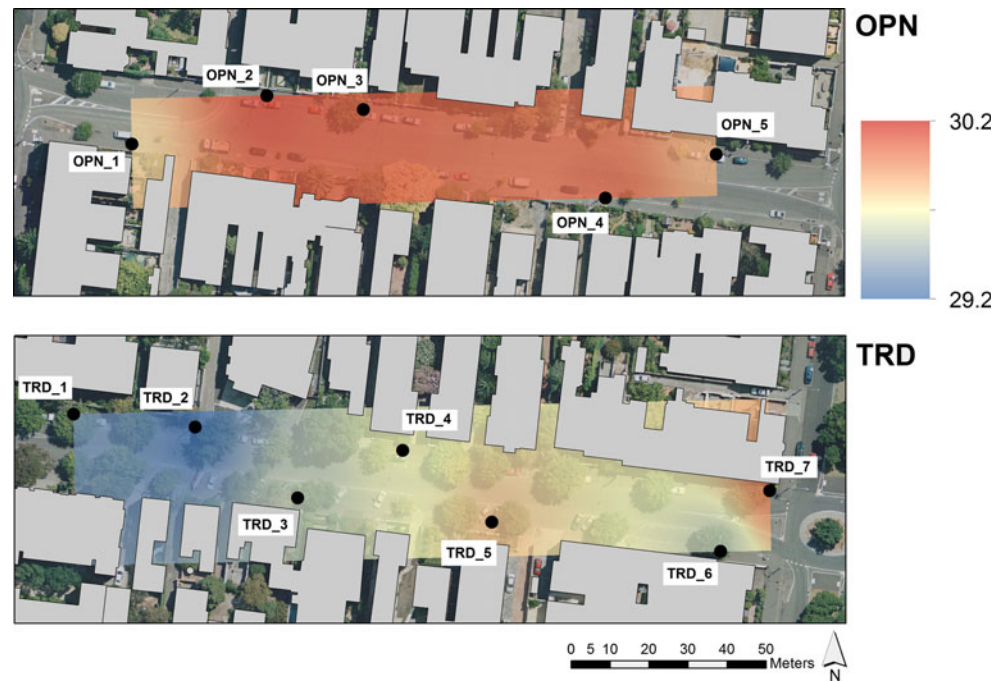
apparent that t_a of some individual stations in TRD was significantly different from others in OPN ($p<0.05$), namely, those stations below the tree canopy (e.g., TRD_1 and TRD_2), indicating that the trees influence the street microclimate. There are many drivers that influence the climate at the microscale, and as Park et al. (2012) suggest, determining the influence of vegetation on microclimate is susceptible to other local and microscale influences such as geometry, urban

Fig. 8 Scatterplot of mean daytime air temperature and average total daily solar radiation at each monitoring site in OPN and TRD for 4–12 March 2012

materials, and background meteorology. It was apparent here that the influence of trees on microscale variability in t_a varied with wind direction, just as Lin and Lin (2010) noted that the cooling effect of trees depends on the meteorological conditions at the time. The patterns in mean daytime t_a for January 2012 both within and between streets TRD and OPN are presented as schematic diagrams in Fig. 9. We found that under northerly wind conditions that bring warm air from the continental interior, t_a was generally lower in TRD than OPN, especially on the shaded side of the street (similar to patterns presented in Fig. 7). However, only station OPN_6 was significantly different during the day compared to the stations in TRD, suggesting more uniform t_a across the two streets. In contrast, under southerly wind conditions that bring cool maritime air, several stations in TRD were significantly different than others in OPN. We found that stations on the northern, shaded side of TRD were cooler than those in OPN, but the stations on the southern, sun-exposed side of TRD (TRD_3 and TRD_7) were warmer than those in OPN. Further, at an intrastreet scale under southerly conditions, stations on the south side of the TRD were often significantly ($p<0.05$) warmer than stations on the north side of TRD.

Overall, we suggest that within-canyon variability in t_a for OPN and TRD depends on the presence of trees, surface heating from solar radiation, geometry, and flow conditions (schematic Fig. 9). Offerle et al. (2007) showed that geometry strongly influences the flow and temperature distribution in urban canyons when they observed surface temperature and sensible heat fluxes above and within a street canyon (H:W=2.1) in central Gothenburg, Sweden. Offerle et al. (2007) describes how sensible heat fluxes depend on whether
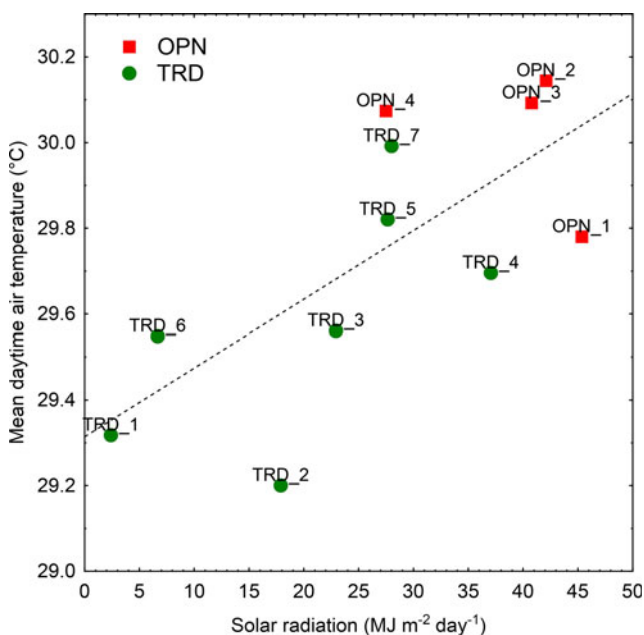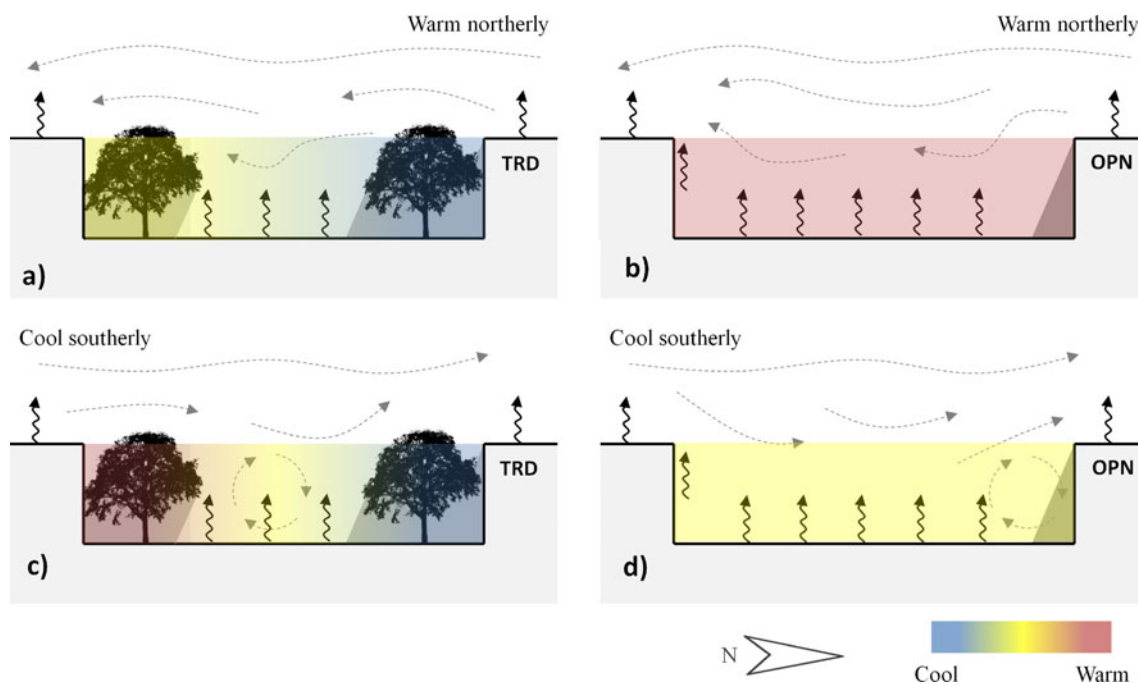
Fig. 9 Relative differences in mean daytime air temperature in TRD (**a** and **c**) and OPN (**b** and **d**) during January 2012 under northerly (**a** and **b**) and southerly (**c** and **d**) wind directions. The sun is to the north

the sunlit (heated) wall is either the windward or leeward wall of the urban canyon. When the windward wall is heated, there is an enhancement of turbulent heat fluxes and mixing due to interaction of buoyancy and vortex circulation, as well as the entrainment of cooler air; when the leeward side is heated, heat transfer is concentrated near the wall and transported vertically (Offerle et al. 2007). Such interactions are consistent with the distributions of t_a observed in our study (Fig. 9). Under warm northerly wind conditions, the north side of the street remains relatively cool due to shading from trees and buildings, creating a zone of relatively cool air. The trees on the south side of the street also provide shade, but surface heating in the street warms the southern side of the street floor and wall, and buoyancy transports heat vertically (Fig. 9a). Under cool southerly wind conditions, a zone of relatively warm air is created on the south side of the street from surface heat and heat trapping by the canopy. This enhances the heat transfer and mixing from buoyancy and canyon vortex and the entrainment of cooler air (from the northern side of the street) (Fig. 9c). In contrast, the treeless canyon of OPN was more exposed to the prevailing northerly/southerly wind conditions and geometry was less influential in modifying air temperature distributions within the canyon (Fig. 9b and d). Salmond et al. (2012) observed turbulent fluxes of heat and momentum using scintillometry across the top of a canyon and noted that the observations were influenced by a combination of variability in urban structure, materials, radiative heating, and wind-dependent microscale advection of turbulent kinetic energy and sensible heat. Hence, with these complex drivers, spatial and temporal variability in t_a at the microscale can be

substantial, and these general patterns need to be confirmed using more detailed observations and documentation of turbulence characteristics within the canyons or with the use of microscale modeling.

3.4 Microscale variability in HTC

The UTCI averaged for each street during the heat events (Fig. 5) were similar in that they all reached very strong heat stress levels. However, microscale differences in UTCI were largely due to the variability in t_{mrt} due to shading. Those stations experiencing shade showed substantial reductions in t_{mrt} and UTCI (Fig. 10). During peak daytime heating, tree shade could reduce the level of heat stress from 'very strong' to 'strong', while over the course of the day, the overall level of heat stress was much lower (e.g., TRD_1 and CBD_E4). Shade from buildings was even more efficient than shade from trees at reducing UTCI during the day (e.g., CBD_W3), because trees allow some transmittance of solar radiation through the canopy. Figure 4b in Section Interstreet variability under summertime conditions highlighted the relationship between SVF and UTCI at individual stations and was a result of reductions in t_{mrt}. Stations in CBD and TRD that were located adjacent to tree canopies and were not shaded in the afternoon (e.g., TRD_3, CBD_E1) actually showed a higher UTCI than stations that were completely sun-exposed which was likely due to the reduced wind speed below and adjacent to the tree canopy. Figure 10 highlights the large amount of variability in HTC at the microscale, simply due to the variable amount of shade. During another heat event on 4 January 2013, when the

Fig. 10 Universal Thermal Climate Index (*UTCI*) and human thermal comfort (HTC) at selected stations over the 24–25 February 2012 heat event for **a** TRD in comparison with UTCI (± max and min) observed at OPN and **b** selected stations for CBD
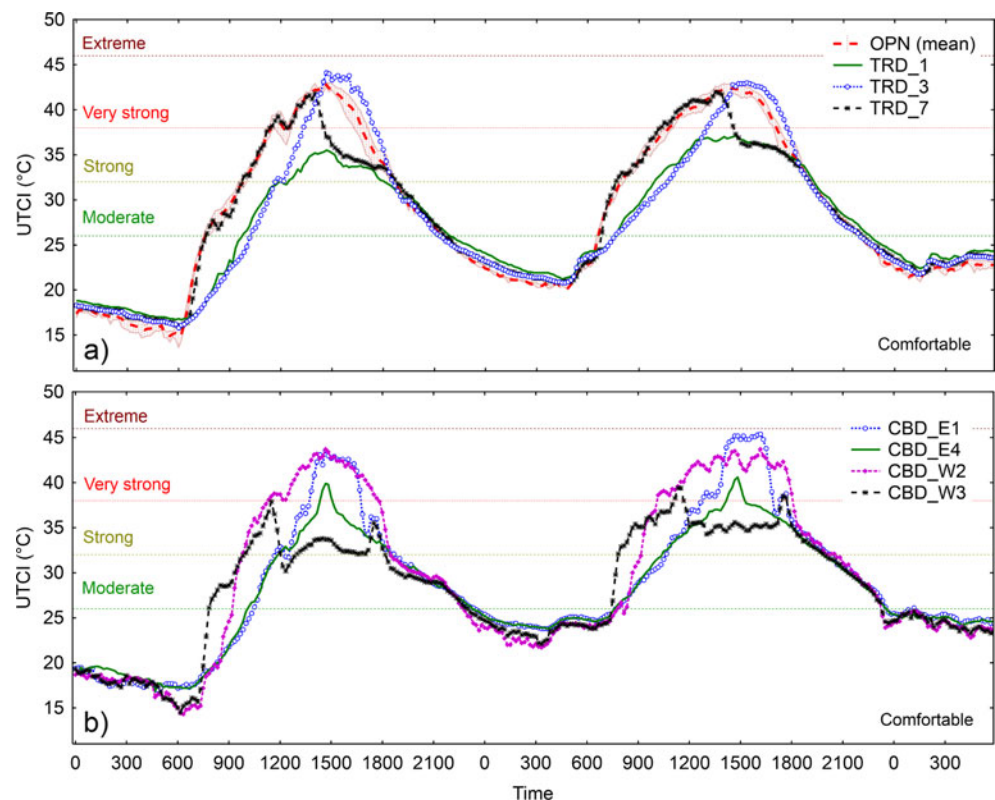
maximum air temperature reached 41.1 °C, unshaded stations at OPN and TRD exceeded the 'extreme' heat stress level (UTCI>46 °C), while the shaded stations were limited to 'very strong' heat stress. At night, individual stations were warmer than OPN due to the reduced longwave cooling due to the presence of trees and buildings and radiance from these structures. While UTCI was slightly elevated at night, the HTC levels remained 'comfortable', and the substantial reduction in UTCI during the day is likely to outweigh any minor increase in UTCI at night. To reduce the harmful effects of urban heat events, it is critical that shading is provided to pedestrians at street level during the day, especially in streets with low H:W ratios and high solar exposure potential and in streets with high pedestrian activity and therefore high human exposure potential.

4 Conclusions

Protecting and maintaining urban street trees in warm temperature and Mediterranean cities are crucial to realize the microclimate benefits they can provide. Tree canopy cover contributes to microclimate benefits by reducing daytime t_a during heat events and thereby improving daytime HTC during hot conditions. This justifies the argument for increased investment in tree planting, maintenance, and protection by local councils. The City of Melbourne has set a target of increasing

canopy cover from the current 22 % up to 40 % by 2040 (CoM 2012). From the findings of this study, this ambitious target will help achieve a more attractive, thermally comfortable, and sustainable urban environment. However, we have observed that the cooling and HTC benefits of street trees are localized and highly variable both spatially and temporally. Given this variability, precisely quantifying the benefit of street trees on t_a at the individual tree or whole street level is difficult. The magnitude of daytime tree cooling depends on the amount of shading, street geometry, and the local meteorological conditions, all of which influence the air temperature variations within and between urban canyons. Adding trees to an urban canyon alters both the overall air temperature and the range and distribution of air temperatures in that canyon by modifying surface heating and air flow under the prevailing weather conditions at the time. Street trees are more effective in influencing the street microclimate in more open, shallow street canyons, whereas in narrow, deep canyons, the building morphology tends to overwhelm the influence of trees and dominates the air temperature levels and distribution within the canyon. Depending on their position in the street canyon, the prevailing conditions, and time of day, trees can have either a cooling or warming effect. Critically though, under summertime conditions during heat events, trees play a vital role in mitigating high urban air temperature.

Because of the variable and localized nature of street tree cooling, trees should be distributed throughout the streetscape

for overall cooling and HTC. During heat events, street trees can lower the level of heat stress through the day, largely through a reduction in t_{mrt} from tree canopy shading. Distributed tree canopies, placed strategically where pedestrians are likely to be exposed to high levels of solar radiation during the day (such as city squares, transport corridors, walking routes, and public services like schools and hospitals) will help deliver a more climate-sensitive city with reduced levels of daytime heat stress in summer. Strategic tree placement also recognizes the sometimes limited budgets of local councils and the need to achieve the largest benefit for the cost of investment and maintenance. Trees should be placed on the sun-exposed side of E–W-oriented streets, targeting streets of low H:W. Strategic placement of trees is also critical at night. The tree canopy cover led to a slightly higher UTCI at night from reduced longwave radiative cooling in the canyon and lower wind speeds that restricted ventilation. Therefore, trees should be strategically placed to maximize their shade area yet spaced sufficiently to allow some nocturnal longwave cooling and ventilation, although daytime improvements in HTC from street trees far outweighs any detrimental impacts on UTCI at night.

As air temperature is highly variable at the microscale in treed street canyons, an intensive microscale measurement program as presented in this study is required for a robust assessment of urban canyon warming and cooling. We suggest that short duration measurement studies and studies that use a single monitoring station to represent a whole urban canyon will not sufficiently capture the microscale climate that is crucial to understanding HTC at an individual pedestrian scale. Scale was also an important consideration in this study with the focus being on understanding canyon climate from the street-scale to the microscale. If tree canopy cover were increased in the City of Melbourne to 40 % by 2040, this would likely lead to local-scale daytime cooling greater than that observed here (e.g., 0.2 to 0.6 °C, and up to 0.9 °C during mid-morning) in this study during heat events. Increased transpiration from an extensive tree canopy will increase local-scale latent heat fluxes leading to lower daytime t_a, and increased canopy shading will reduce local-scale storage heat fluxes, helping to mitigate the nocturnal UHI (Coutts et al. 2007). A multiscale modeling approach would help to elucidate the benefits of a widespread increase in street trees at the microscale. To further justify the expense of maintaining an increased urban forest canopy, the monetary benefits delivered through cooling and improved HTC need to be recognized alongside the other benefits such as building energy savings, transport efficiency savings, productivity and human health. Finally, ensuring adequate water is available for street trees is paramount to ensure they remain healthy, with full canopies for shade and sufficient soil moisture for transpiration in what can be a harsh urban environment.

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