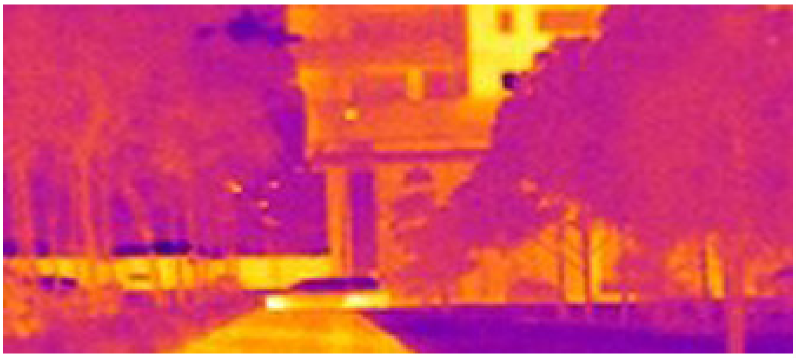

Final Report

Micro-Urban-Climatic Thermal Emissions: in a Medium-Density Residential Precinct

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Sydney 2010

National Library of Australia Cataloguing-in-Publication entry

Title: Micro-urban-climatic thermal emissions : in a medium-density residential precinct / Robert Samuels ... [et al.]

ISBN: 9781740440387 (pbk.)

Subjects: City planning--Climatic factors
Urban climatology--New South wales--Victoria Park.
Urban heat island--New South wales--Victoria Park.
Victoria Park (N.S.W.)--Climate--Observations.

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Dewey Number: 551.525091732

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FINAL REPORT

MICRO-URBAN-CLIMATIC THERMAL EMISSIONS:
IN A MEDIUM-DENSITY RESIDENTIAL PRECINCT

ACKNOWLEDGEMENTS

This pilot research was undertaken on behalf of the
City Futures Research Centre
and
HASSELL (Sydney).

Principal Researcher and Report author, Dr Robert Samuels
acknowledges the crucial input, insights and critique
from colleagues associated with the research

From the FBE:
Professor Bill Randolph, Associate Dean Research
and Director of the CFRC
and
Dr Peter Graham, Acting Disciplinary Head, Architecture and Design
and UNEP Associate

From HASSELL:
Tony McCormick, Principal
and
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Thanks also to Chairman Professor Ken Maher
who supported and funded the research.

CITY FUTURES RESEARCH CENTRE

City Futures is a University Research Centre dedicated to developing a better understanding of our cities, their people, the policies that manage their growth, the issues they face, and the impacts they make on our environment and economy.

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Executive Summary

A pilot research program evaluating the thermal emissivity of elements in the designed environment and their transience to the urban air was carried out in the summer of 2010 in the Victoria Park medium-density residential precinct, Sydney. At question is the degree to which components of the built environment and associated urban landscapes contribute waste heat to the urban climate and heat island. The intention is to contribute knowledge of thermal performance at a micro-urban scale - to design decisions: aimed at adaptively counteracting global and urban warming phenomena, and mitigating noxious consequences by cooling urban environments.

Although generic sustainability rating schemes are in use, and basic thermal mass insights are acknowledged – and urban climatologists undertake a raft of complex simulation studies – practical application in the ‘cool’ design of city buildings and precincts is minimal. Empirical insights are lacking; and the emphasis is on energy - essential but insufficient in itself to affect the excess heat stored in the built form and transferred to the urban air mass. Critically, it is heat which changes the carbon cycle and climate, rather than the gases themselves. This research aims to fill that paradigm gap.

Moreover, acknowledging that greenhouse gases are present in the atmosphere at concentrations likely to persist for a century and more, the only logically realistic resolution appears to be: to take the heat out of the equation.

The methodology followed in this research was to obtain thermal imagery of radiant emissivity at micro-urban-climatic scale, at different times of day and night and on different facade orientations in a case study site - by means of a hand-held thermal camera. Ambient conditions were logged simultaneously, and correlated with the radiant emissions.

The results have been tabulated in a Thermal Performance Index representing the *transience contribution of elements*, ranked from hottest to coolest (radiators to coolers); where maximum and minimum radiant emissions are associated, and interpreted as rules of thumb.

Although the thermal imagery indicates that albedo reflects heat and cool coloured elements apparently contribute less heat, and water stores heat as expected, unless the thermal energy is *transformed*, essentially, by living, vegetative greenery the dilemma of excess heat in the urban environment and climate persists. This is a conceptual interpretation drawn from this research – and demands further research.

This thermal imaging technique can be readily applied in urban environments of any scale – since the metric is micro-urban climatic. To undertake evaluations of designed environments - from the CBD via medium-density to outer suburban configurations - is a next logical step.

Key Findings

Key findings from the pilot research program include conceptual and methodological developments, and results.

Proviso: the results reflect summer conditions in Sydney; and derive from a medium-density medium-rise residential precinct, with considerable tree cover and open grass parkland. Specific locations and proximate structures and activities are expected to affect the thermal performance of elements; thus further study of urban settings and climates is necessary to develop the rule-of-thumb findings into substantive guidelines.

Conceptual Understanding

The key concept is the relationship between the urban climate and the *thermal transience* performance of the designed environment; in other words, heat transfers between the built-and-landscaped environment, the urban-heat-island beneath the building canopies and the regional climatic boundary-layer above the skyline.

Research Method

Thermal transience is evaluated via visualisation and empirical measurement of radiant emissivity, by means of a thermal imaging camera.

Outcome

Micro-climatic thermal contributions of elements of the designed environment to the urban climate; presented in the format of a matrix of thermal performance indicators.

Key Research Findings:

Generics

1. Radiant absorption & emissivity are in constant flux in the designed environment:

- highest during peak sunshine hours – and lowest at dawn, when elements have returned to Ambient equivalent temperatures

  differences between diurnal maximum and minimum

  radiant temperatures are indicative of the relative transient contribution

  of each element to the urban thermal environment

- vary by building Orientation

2. High Reflectivity/Albedo cools building elements

- at question is the extent to which this cools the urban climate.

Specifics

Coolers

1. **Walls**: White & South-Facing Façades
   1-3^{O}C transient contribution over diurnal cycle
   ie *transience*

   Resulting from Albedo and Orientation and Tree Shading in combination

2. **Trees**: Shade & Leaf Canopy in Grass Park
   3-4C transience

   &

   Shade on Light-Coloured Paving & on White Walls
   7-8C transience

   Vegetation cools by transformation ie evapotranspiration/latent heat phase change; and shading.

3. **Water:** Shallow, running down concrete steps, daytime only, & located at edge of grassy park
   7C transience

   Water is a cooler: a thermal sink, and reflector; transforming heat at the surface nexus with the atmosphere.

4. **Swales:** Reed beds (dry, here) and (young) eucalyptus trees
   6-9C transience

   Swales located along dark tarred roads seem less effective coolers [9C transience] than along a light coloured/non-porous concrete path at park's edge [6C].

5. ***Un*shaded Grass in Park:**
   12C transience

   Grass is radiating at 34^{O}C in full sunshine
   and 22^{O}C at dawn

   Transition point between coolers and radiators: where $\boldsymbol{T_R = T_A}$

Radiators

1. **Inadvertent:**
    - **gas water-heater exhaust**
      radiating at 150^{O}C
    - **air conditioner exhaust**
      radiating at 47^{O}C

2. **Vehicles:**
    - **truck - exposed engine**
      radiating at 65^{O}C
    - **heat shadow under truck**
      30C transience
    - **car body**
      28C transience
    - **car - engine, tyres, exhaust**
      17C transience

3. **Roads**

   29C transience

   Tarred/Grey-Black/unshaded

4. **Walls**

   18 to 21C transience

   Concrete Brown & Black painted (balcony walls)
   Western orientation = hottest, then East = North

5. **Paths**

   15 to 20C transience

   Concrete Pavers: grey-coloured - non-porous/unshaded.

Humans:

Radiate at 32-36^{O}C

Clothing & hair insulate, exercise exacerbates

= urban climate contribution.

Introduction

Cities are incubators of greenhouse gas and thermal emissions - a potent climate-changing combination. Because urban environments are thermally massive and thus heat-sensitive, absorbing and re-emitting heat in a continuous cycle, urban heat islands (UHI) are generated. A range of challenging consequences emerges. Extreme urban-climate weather events are visited upon cities; and a significant quantity of fossil-fuelled energy is expended to cool buildings (and vehicles) in order to mitigate the negative effects of this thermal exaggeration - entraining corresponding emissions of greenhouse gases. And the health and wellbeing of urbanites is also seriously impacted, via heatwaves and intensified air pollution, more thunderstorms and flooding; and by thermal discomfort which diminishes the liveability of cities.

The focus of contemporary climatic concerns is concentrated on energy – essentially and necessarily; but heat – the actual climate-changing agent, absorbed by the thermally receptive greenhouse gases – has gone largely unheralded. The designed environment - the built environment in its landscaped setting - is a major culprit in this equation. Cooling cities is thus the most essential strategy necessary to accompany energy generation, consumption and emission resolutions. Although urban climatologists recognize that cities overheat, this appreciation is rarely transmitted to urban design practitioners and city regulators and decision-makers, in practice.

Consequently, a pilot research program has been devised to empirically investigate this urban thermal paradigm at micro-climatic level, develop a methodology which can be deployed in later research of a more substantial nature, and produce a thermal performance visual index. To this end, the Urban Observatory at the City Futures Research Centre in the FBE@UNSW has collaborated with HASSELL Architects (Sydney).

During the summer months of 2009-2010 a micro-urban precinct was nominated in the Victoria Park (Zetland, Sydney) medium-density residential neighbourhood and its micro-climatic thermal emissions measured and mapped – by means of a thermal camera.

The Results reported here as Table 1, is an Index intended to represent Thermal Performance Indicators in the Victoria Park precinct; with possibly wider potential application. It is a metric that indicates thermal *emissivity and transience* between elements of the designed environment and the urban atmosphere, and is scaled from those elements contributing the most heat to the urban heat island (the 'radiators') to those providing the most effective cooling (the 'coolers'). The break-even or threshold point between the radiators and coolers is when they are radiating at ambient temperature.

The intention is that this thermal performance indicator might serve as a basic rule-of-thumb directory to begin to inform designers and decision-making processes, in the first instance, and that the TPI might be developed and the research concept and methodology integrated into larger research frameworks, aimed at evaluating climate change adaptive capacity in cities – at micro-urban-climatic scale.

The research Report, below, is structured as follows: discussions of the Victoria Park research methodologies and results, particularly the ‘Transient Emissivity: Designed Environment to Urban Climate’ matrix - the core thermal performance metric.

Two examples of an evolving ‘Visual Performance Index’ are presented, to indicate the methodology from which the matrix is constructed - the full development of which is proposed as a future research endeavour.

This section of the Report concludes with a Future Research extrapolation.

The Literature Review follows, as Appendix I, tailored to this specific pilot research program, covering generic methods briefly and then focusing on specific thermal imagery methodologies and resolutions. This ranges from hand-held thermography, via satellite imagery and simulation modelling – to cooling from greenery and apparent cooling from reflectivity, urban form interventions for cooling, and relationships between these new urban metrics and urban sustainability rating systems that accredit UHI cooling.

Research Methodologies

Urban climates and urban heat islands are well researched and documented, with a plethora of methodologies directed at understanding and resolving these phenomena, the very great majority of which are: remote sensing, simulation modelling and nocturnal urban traverses to measure conditions in cities and parks.

Recently a range of urban sustainability rating schemes have been developed, some few of which refer to the UHI and accredit 'points' for taking it into account in a design. LEED (2009) (Leadership in Energy and Environmental Design), in its Neighbourhood Development component, for instance credits high reflectance and vegetative cover, including on roofs, and tree-shaded streets – critical components in the urban cooling paradigm (See Appendix II; and later elaboration on Ratings).

Hand-held thermal imagery at micro-climatic and micro-urban scale is a recent development, and as yet few researchers appear to be utilizing infra-red (IR) cameras. Those who do, it seems, use them to support aerial photography or validate simulation estimations, or as add-ons to their suite of other measuring techniques - or simply to illustrate temperature differentials in a generic fashion (cooler park, hotter road). In the Victoria Park research a hand-held IR camera is used as the central method to envisage the thermal embodiment and emissivity of the designed environment. It appears to be the first to attempt to index elements in these settings in a visual thermal performance matrix; ranging from radiators - those that absorb and re-emit large amounts of heat, exacerbating the UHI - to coolers, those that absorb and emit less, and are more ecologically benign.

Everything contains heat, even ice. There are literally hundreds of elements in the designed environment that are involved in the thermal transience interaction, each with its own characteristics. From the VP research method it becomes possible to envisage, say, a tree radiating at dawn, when, even though its emissivity temperature might be much the same as ambient temperature, it is still relatively warm, in itself - albeit functioning as a cooler. And although a tree's shadow in a park is cooler than its shadow on a paved path, it is nevertheless warm; while water, a great absorber of heat - withdrawing it from the atmosphere to which is it intimately connected and retaining it for long periods - and radiating at ambient at dawn on a 25C dawning day: it is warm too. The principle is simple: when the atmosphere is warmer than the elements in the designed environment they absorb some of that warmth, and when they are radiating at higher temperatures than the ambient air, they transfer some of their heat to it. The UHI generates in the wake of these transient interactions.

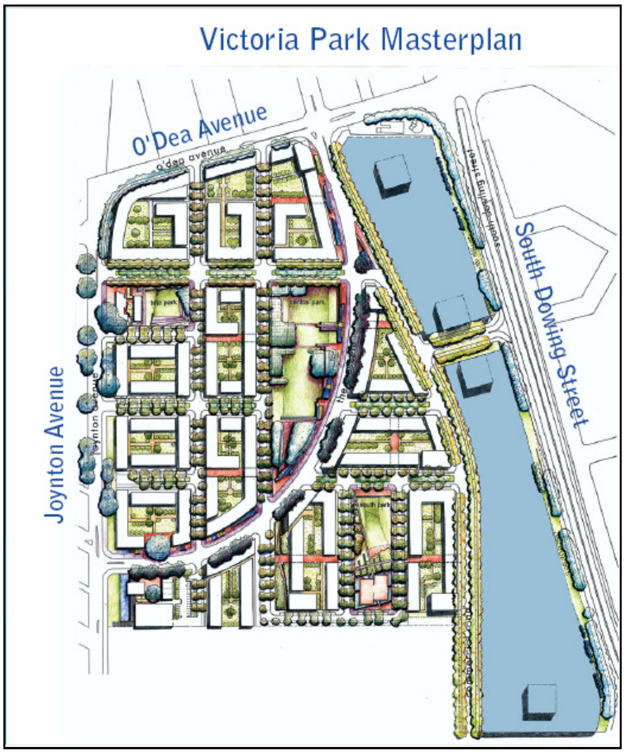
Thermal imagery as a technique can readily render these situations and elements visible, in any designed environment setting; and thus open them to scientific analysis and comparison – from which urban, architectural and landscape design guidelines can be inferred. The aim of the research is thus to clarify which elements and combinations of elements are contributing most and which least to the urban heat island, itself a phenomenon not measured here.[1]

The implications for design from these simple parameters can be quite complex.

Victoria Park Methodology

The Site: Victoria Park is a recently developed (and still developing) 25-hectare medium-density residential precinct, with a range of non-residential functions, located on a regenerated inner-city brown-field site in the industrial area of Zetland, 4kms south of the Sydney CBD. Various architectural firms were engaged to design the buildings within the parameters of the Masterplan framework set by LandCom architectural and urban planning consultants Cox/Richardson and as revised by Hassel. This included environmentally sustainable parameters. In particular, the water sensitive design appreciates that the area is a catchment zone, and a network of retention swales collect, filter and feed stormwater to underground collection tanks, which supply recycled water for irrigation and the public art water–step features. Moreover, 3.5 hectares of parklands, open space and courtyards were designated, to preserve the natural environment and enhance the life quality of the residents.

Figs 1 & 2: Victoria Park - Location and Masterplan (Source: www.landcom.com.au)

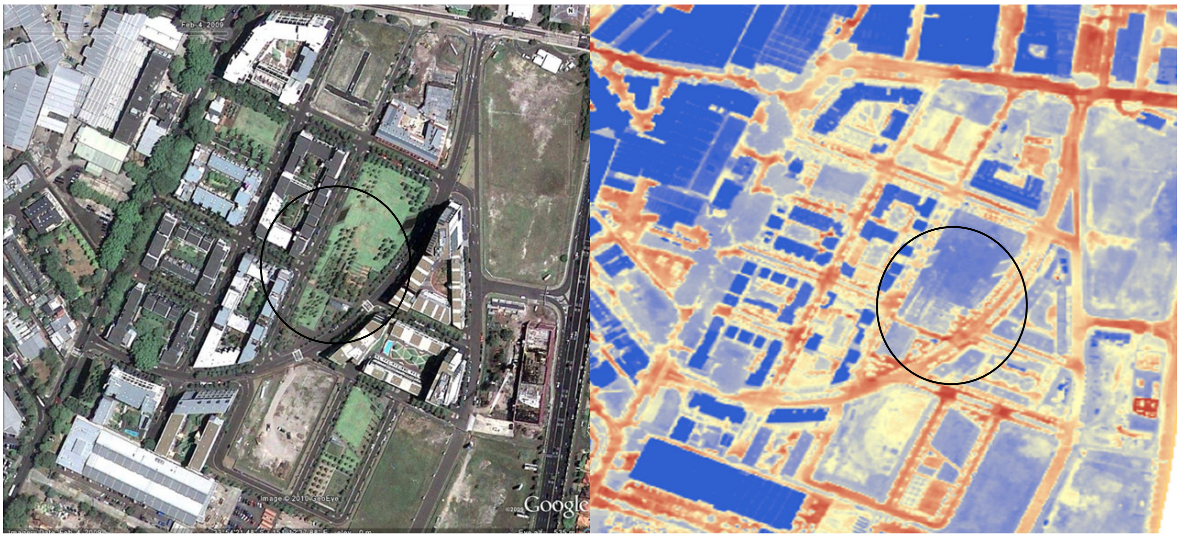


[1] *The City of Sydney seems to have a 2-3C UHI (measured at Observatory Hill) – when compared to minimum ambient temperatures in a much more rural setting (Badgerys Creek) (See later discussion)*

The specific focus of the investigation was the ‘ESP’ gateway building (Figs 3 & 4) - an urban block of contiguous buildings ranging from a 20-storey high-rise tower to 8-storey perimeter buildings clustered around an internal courtyard, encircled by faded-black tarred roads and light-coloured impervious-pavedfootpaths; adjacent to Joynton Park. This site embodies a broad range of vertical and horizontal built and natural micro-urban elements; and was agreed upon as an appropriate setting - after the area and its adjacent surrounds were observed and recorded during the daytime with a digital camera, and with a FLIR B250 thermal camera afterdark (measuring long-wave radiation in the 7-13 microns [700-1300 nanometre] range at a resolution of 320x240 pixels).

The research model adopted was to record the diurnal fluctuations in both radiant and ambient temperatures in the setting, over a 24-hour period, during heat-island promoting weather conditions on a typical summer day in Sydney. This survey was initially conducted during four one-hour periods: at midday (12am-1pm) when solar radiation was at its maximum, between 8 and 9pm, at midnite (12pm-1am) and again at dusk (6-7am) when temperatures are at their minimum just before sunrise.

A portable digital data logger, shielded from the sun during the day, was transported around by the researcher, measuring ambient temperature and humidity (at one-minute intervals), and later downloaded to a computer.

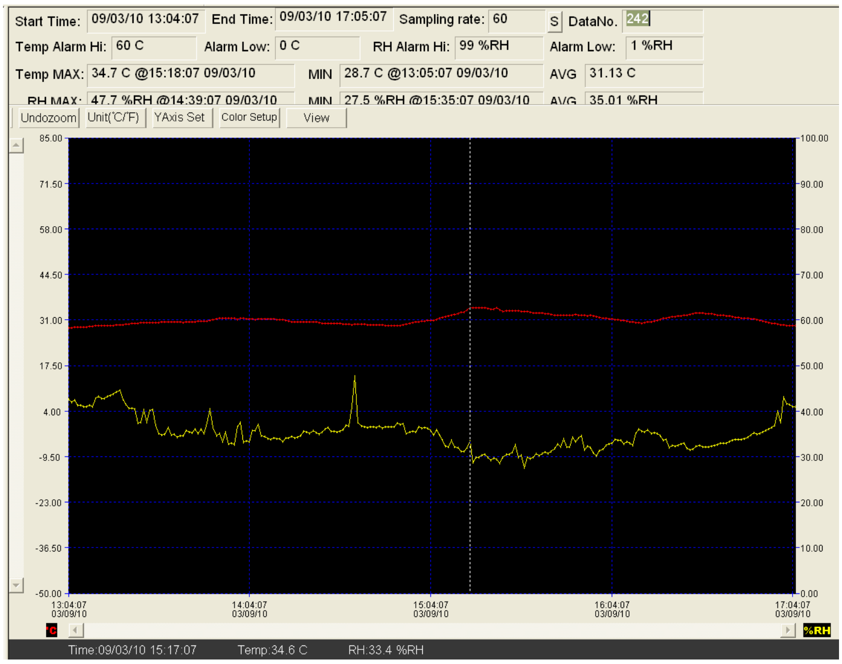


Figs 3 & 4: Google Image of Victoria Park (before completion) and enlarged Thermal Image, excerpted from the City of Sydney Image (see later) - at similar scale. Circled area is the research site.

Fig 5: ESP - East, North and Western facades

Fig 6: South (Eastern edge) with swale roadway

Fig 7: Log of maximum ambient and humidity readings, Western orientation.



The later realization that maximum daytime temperatures would be at their maximum at mid to late afternoon on the western facade, resulted in a secondary excursion on a day of similar ambient temperatures to the primary survey (when the temperature reached 35C on the western edge of the precinct – 3 degrees more than at midday). The thermal images were then correlated with the logger data and adjusted accordingly in the camera software settings (which allow for temperature, humidity, emissivity, reflectivity and distance adjustments); and then classified and sequenced by orientation and time. Thus, four images were selected representing the transient emissivity of elements in a particular setting at the different times.

Given that there are a multitude of possible elemental aspects in every micro-setting, this resulted in a range of these 'quadruple sequences' being examined for each building orientation, and for each street and pavement, and in the adjacent park with its water-step feature – to come to an average metric. This process was elaborate and time-consuming. However, during the analysis phase, it became apparent that the radiant emissions had decreased by 8-9pm (not unexpectedly) and continued to progressively emit less and less until by dawn they had more or less returned to ambient temperature levels – give or take a few exceptions, where the temperatures were either just above or just below ambient. This led to the realization that in future research only the maximum and minimum temperatures need to be measured; which would increase the efficiency and rapidity and reduce the complexity of the process considerably. This model was retested during a further excursion, when only maximum and minimum readings were made, during a relatively cooler day (24C) and night, producing a similar result. As a consequence, the thermal indicator matrix produced has been refined into a table that fundamentally indicates maximum and minimum radiant emissions ranked by their contributory roles as radiators or coolers.

This thermal performance indicator is composed of elements themselves an amalgam of averaged measurements. This is an inevitable consequence of the multitude of facets recorded in each image. A segment pattern may contain building materials of varying colours and mass, a variety of metals, glazing of different characteristics, and have contours and angles, and variable solar and shading regimes, and of course both vertical and horizontal elements; as well as be affected by passing or parked cars which radiate intensely and affect the generic radiant climate; not to mention the movement of people or even dogs each of which has a thermal signature which can be detected by the camera. Moreover, a vast array of varying natural conditions can impact on the apparent temperatures in designed environment settings, including: humidity in the air, wind fluctuations, cloud movements, and thermal sinks and reflective radiators in the vicinity. It is thus necessary to examine a range of images of the same setting, from a variety of angles, and average out the radiant emissions of any particular element under scrutiny. The result is a rule of thumb indicator, based on empirical metrics, but nonetheless an amalgam of readings.

Moreover, the aim is not to measure absolute temperatures but to be able to distinguish between relative emissivity contributions from different elements in the designed environment. And, the fact that a black wall on a western facade (in the given conditions) is radiating at 47C at its peak and 23C at its nadir and thus delivering 21 degrees of heat to the urban air is not diminished by an instrumental error reading of a half or even one degree.

Such metrics are useful in the generation of performance-based policy-informing designed environment strategies for adapting to and mitigating climate change impacts.

Fig 8: Illustration of micro-climatic differentials of designed environment elements

In order to validate the camera readings, a thermocouple was employed. The expectation is that the camera manufactured by FLIR, the dominant company supplying the international market, would be reliable. And this proved to be the case. At a distance of 50 metres the disparity in readings between it and the thermocouple was in the region of 0.5C, which is an insignificant margin of error – given the vast range of elements which can affect a reading. The aspect which seems to produce most variation is angle: due to the transmission of the radiance through the atmosphere; here varying up to 1-2C, on average. The more acute the angle, the greater the impact, so the best results are obtained by face-on imagery.

The Anticipated Outcome

From documenting the thermal emissions from the urban landscape and the medium density housing precinct, derive an initial, empirical metric of urban thermal emissions (sources/radiators and sinks/coolers) in the form of a rule-of-thumb Thermal Performance Index - indicative of transient emissivity between the designed environment and the urban climate.

To reiterate: the ultimate purpose of this pilot research programme was aimed at informing urban design policy and practice to enhance the sustainability and resilience of the city system to global climate warming, and reduce the vulnerability of the population to injurious urban-climate and heat island affects, *by cooling the urban realm*.

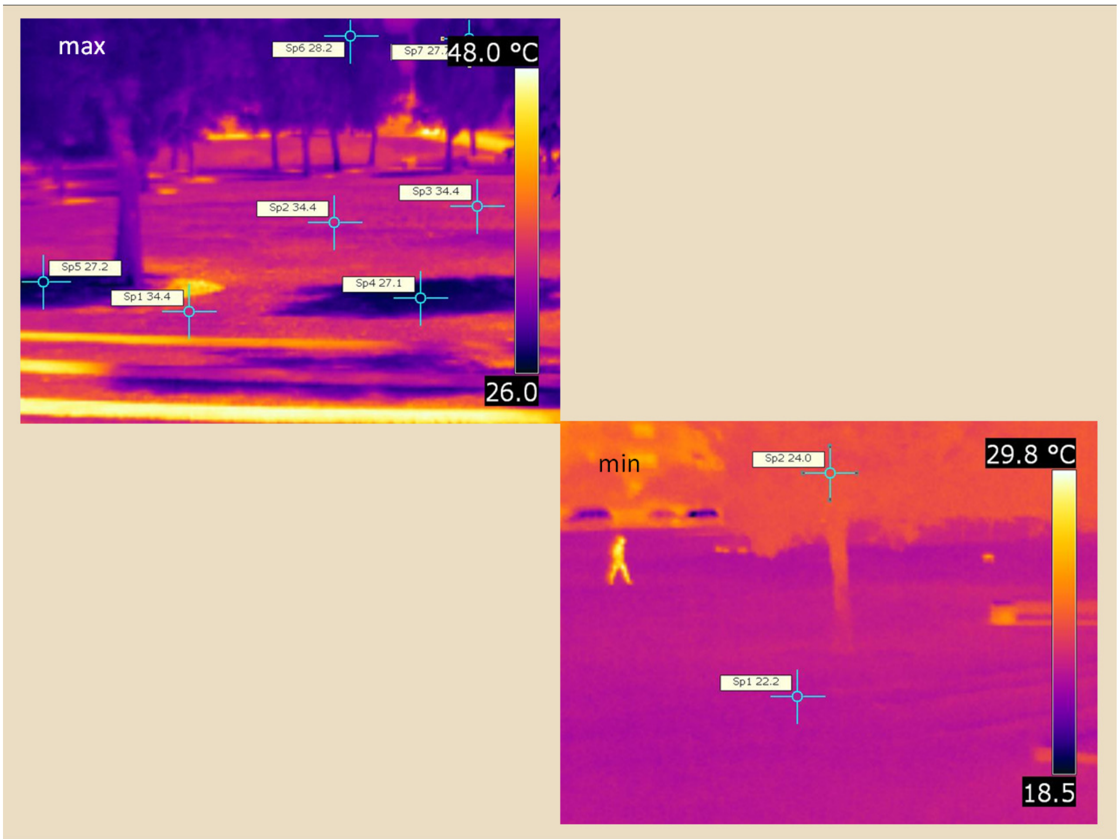
RESULTS of the Pilot Study

Besides the generic interpretations made from the data, and the development and refinement of the methodology, the distinct purpose was to create a rule-of thumb Thermal Performance Index (TPI: Table 1), indicating transience emissivity from the designed environment to the urban climate – via the urban heat island.

A separate set of matrices indicate the temporal transience of selected major elements for each orientation, over the diurnal period (See: Appendix III)

Below is one set of (hundreds of potential) representative thermal images, from which the TPI can be generated.

Fig 9: Trees & grass in Joynton Park, in full sunshine (max) and at dawn (min)



Figs 10 & 11: Tree shade on wall and path (here 5C cooler than sun-exposed portions @ maximum ambient)

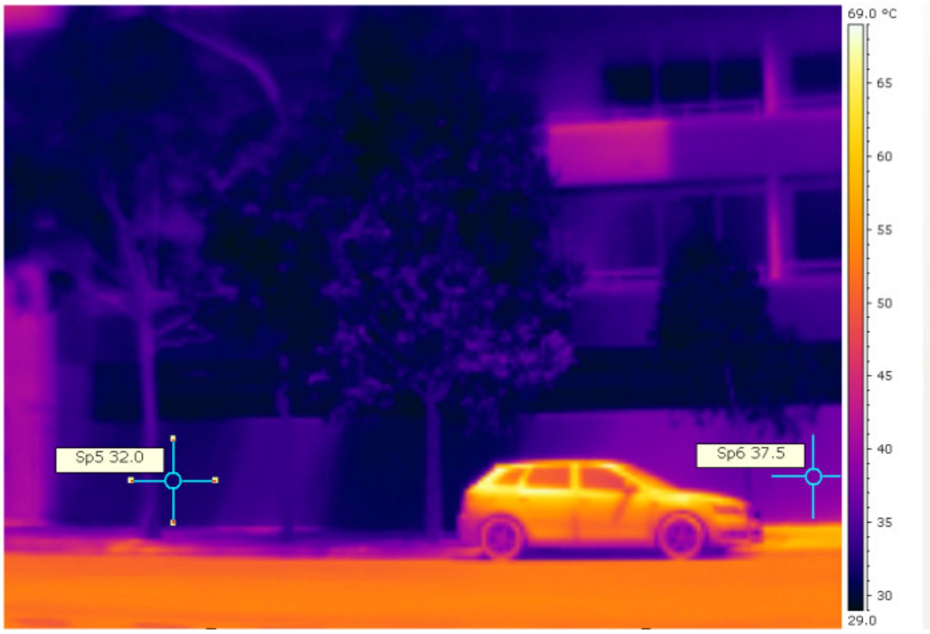


Table 1 (over) indicates the extent to which elements in this setting emit and transmit heat to the urban air, over a diurnal cycle, from maximum to minimum ambient.

Table 1: Thermal Performance Index (TPI):
Thermal transience from the designed environment to the urban climate

Transient Emissivity: Designed Environment ⇔ Urban Climate							
Rank	Max - Min	MAX	MIN		Elements	Orient	Rank
Hot	**ΔT_R**	**RadT C***					*Cool*
Ambient Temperature C^o: Maximum = 35 Minimum = 24							
1st		150			gas water-heater exhaust	W	*22nd*
2		65			moving truck: exposed engine	g	*21*
3	**30**	58	28		heat shadow: under truck	g	*20*
4	**29**	52	23		road (grey/black)	g	*19*
5	**28**	53	25		car body: in sun	E	*18*
6		47			air conditioner exhaust	g	*17*
7		46			generator motor	g	*16*
8	**21**	47	26		wall/black	W	*15*
9	**20**	46	26		concrete paving (light grey colour)	W	*14*
10	**19**	45	26		wall/brown	W	*13*
10	**19**	44	25		wall/black	E	*13*
11	**18**	43	25		wall/black	N	*12*
11	**18**	43	25		concrete column/grey	W	*12*
12	**17**	41	25		car: moving at night/parked @dawn	g	*11*
13	**15**	38	23		concrete adjacent water-steps (light)	W	*10*
14	**12**	40	28		heat shadow: under car	W	*9*
14	**12**	35	23		grass in park: (max in sun)	W	*9*
15	**9**	32	23		swale: dry reeds under spindly trees	S	*8*
16	**8**	32	24^{+}		tree shade on white wall	E	*7*
16	**8**	32	24		wall/white	N W E	*7*

17	**7**	31	24+		tree shade on paving	W	*6*
17	**7**	29	23#		water on water-steps	W	*6*
18	**6**	30	24		tree trunk & leaves	W	*5*
18	**6**	30	24		reeds along path (dry): edge park	W	*5*
18	**6**	30	24		wall/grey	S	*5*
19	**4**	28	24		shade beneath shade-tree: on paving	W	*4*
19	**4**	28	24		tree canopy/leaves: in park	g	*4*
20	**3**	27	24		concrete base bench: in park	g	*3*
20	**3**	27	24+		shade of tree: in park	g	*3*
21	**2**	26	24		wall/white	S	*2*
21	**1**	27	26		concrete slabs: corrugated/vertical gloss grey-**white** paint	S	*2*
22nd		-	22		stony rooftops: tower and medium-rise insulated - at night	g	*1st*

+ Estimate = Minimum Ambient **** Mean/Rounded***	***g Generic Orientation***	***# water does not run at night***

	Thermocouple	Thermal Image			REFLECTIVITY	O	Amb
	26	26			water steps - Victoria Park: shallow - day #	W	26
	25 / 25	26 / 26			fountain – Martin Place: still/falling-foaming - nite	W	26
	27 / 27	26 / 26			water feature – AGL site: still/spouting - night	g	26
	24	24	23	22	glazing: house & tree & sky reflections - day	N	24
		24-32 / 12-15			metallic roof - industrial sheds: sarking & skylights - day/night	g	

Table 1 (TPI) - should be interpreted as follows:

The principle information relates to radiant temperature differentials (in degrees Centigrade) indicative of relative contributions of elements to the urban atmosphere (represented by the symbol $\mathbf{\Delta T_{R)}}$**.** Maximum and minimum radiant temperatures of elements are ranked from Hot (in descending order) to Cool (in ascending order).

The threshold point between radiator and cooler elements is where the maximum transience of an element is equivalent to the ambient temperature of the air. For instance, in Table 1, the 14^{th} radiator – also the 9^{th} cooler (grass in Western afternoon sunlight) – is emitting radiant heat at 34C at its maximum, which equates to the maximum air temperature on that day, at that season: 35C. On the TPI, before that point, thus, elements are considered radiators; after that point, they are coolers.

A range of places need to be researched, at different ambient temperatures and seasons, and in different regional climates - to generate a comprehensive Index, and validate this one. Logically, radiator elements will be radiators and coolers will be coolers in whatever climate and ambient setting – given their thermal nature - but to a greater or lesser extent.

The maximum and minimum ambient temperatures recorded in the diurnal cycle during the field experimental day are also indicated – for comparative evaluation.

Humidity is known, but not recorded in the matrix (lowest at maximum temperatures and highest at the dawn minimum).

The orientation of the element is also indicated, as an aid to building design; a ‘g’ indicates that the orientation is a generic direction (cars on roads in sunshine, for instance).

The Table distinguishes between elements not only in terms of their thermal contributions to the urban air mass, but also between elements on various facade orientations.

Walls, for instance: black and white walls perform differently depending on their spatial location, too. Black or dark brown walls on the West absorb and emit more heat than those on the North and East, and are far more thermally intensive and intrusive than, say, a grey wall on the South (no south-facing black walls in this site). A white wall on the South, again, is less intensive an emitter than one on the other three orientations. In fact, it is virtually the coolest element in this particular precinct – with a clear advantage in design for climate-change terms. It shares first place as a cool element with a concrete wall painted gloss-grey on the South, with *maximum* daytime radiant temperatures only at ambient (25C here), and only cooling further by one degree at dawn.

These elements are even more effective than the shade of a tree in a sun-exposed park. On the other three orientations, a white wall is about equivalent in effectiveness to a reedy lightly-shaded swale on the South, or shallow running water on the water steps on the West.

The shade of a tree in the grassy park appears to be the most effective *natural* cooling stratagem emerging from this research.

Cars and roads give up their invisible secrets too, showing up as major thermal polluting elements; with potentially enormous urban design and lifestyle implications for urban resilience. Air conditioners on buildings are about as potent thermally as cars and roads. And heating water with gas, usually considered environmentally less noxious than with oil or electricity reveals its enormous thermal footprint, albeit tiny in terms of comparative quantities emitted.

Furthermore, park-grass in sunshine is not cool; and the soil beneath it is a major absorber of heat too. Although it does cool to even below ambient (to 22-23C in this setting), it contributes 12 degrees of heat to the air mass during the diurnal cycle. It would be much more benign if it were extensively shaded. The leaves in the tree canopy are radiating at much the same temperature as the trunk, a slab of wood, but still considerably cooler relative to the grass in the sunlight.

Surprisingly, the emissivity factor of a dark green eucalypt leaf is the same as that of concrete; which might help explain this otherwise apparent anomaly.

Reflectivity and albedo are phenomena now widely considered as panaceas for urban warming, yet the question of what happens to the heat reflected remains to be resolved (see discussion, later). In any event, the thermal camera is surprisingly accurate even when measuring radiant heat in a reflective element, like moving water in sunlight. With glazing, the issue is more complex, since reflections themselves are radiating at different temperatures depending on the object they are reflecting (see discussion later).

Table 2: Transience over Time, North & East Orientations

Temporal Transience/Emissivity Indicators: Summer Season 2010

TIME	Road	Car	Walls				corrugated		Column	Paving		Swale South	Trees eucalypt		broadleaf	Grass		Water		Ambient	Humidity
	black		black	white	brown	grey	grey-white W	S	grey	sun	shd/N		sun	shd/N	shd/N	sun	shd/N	D	N	C°	%
ELEMENT																					
NORTH																					
midday	52		43	31					42				32			36	28			***28***	*63*
20h	29		26	26					26					25			24			***27***	*66*
midnite	27		26	26					26					25			24			***27***	*72*
dawn	23		24	24					25					23			22			***25***	*81*
ΔTr	29		19	7					*15*				9			*14*	4			*-3*	*+18*
EAST																					
midday	52	50		30	46	40				54	35		31							***30***	*57*
20h	29	28		25	26	26					28			26						***27***	*66*
midnite	29	28		25	26	26					28			25						***27***	*72*
dawn	25	23		24	25	24					26			24						***25***	*86*
ΔTr	27	27		6	21	*16*				28	9		7							*-5*	*+29*

All figures averaged, and rounded (.5+ ↑)

These transience tables (see Appendix III for a further example) were constructed from diurnal readings, and contain a metric indicative of the passage of heat from a maximum at midday to dawn, where every element has given off its heat to the urban air and is now basically radiating in equivalence with the ambient temperature; and gearing up to go through the whole cycle once more. Ultimately, however, the formation of the UHI depends on favourable synoptic weather conditions, since strong cyclonic activity can eliminate it, rain temporarily removes it (via evaporative cooling perhaps) and winds diminish it considerably, moving it to other locations and cooling it at the same time (via a wind-chill factor, perhaps). Again, maximum and minimum emissivity contributors to the urban climate can be read off the above table.

As previously explained, all metrics indicated in all the matrices have been averaged, by examining several images of the same setting from different perspectives; and rounded (.5> and above going up; <.5 down). The figures indicate relative rather than absolute differences.

These tabulated matrices accompany and advance insights gleaned from other research methodologies related to adapting and mitigating urban environments to climate change and urban climate warming; and complement sustainable design guideline rating tools which include a UHI factor, such as LEED (US/GBC) in particular, and MIST (US/EPA).

The rooftop of the ESP tower was accessed and photographed, and was found to be cool at night (see TPI). It has white pebbles as a surface, and will undoubtedly be insulated. No green roofs are included in the Victoria Park precinct.

Opposite the precinct, the roofs of the industrial buildings/sheds are very cool at night – radiating at just 12–15 degrees centigrade. Some cursory investigation was also made into the roof temperatures of the building opposite the ESP across the park, where the City of Sydney thermal imagery revealed inconsistencies ie white roof areas radiating at different temperatures (see discussions, later).

In the two visual performance matrices of radiant transience (see: Figures 12 and 13, over: indicators of wall and paving elements), relevant LEED factors have been specifically incorporated. Suffice it to say here that LEED Neighbourhood Development accredits both 'non-roof' interventions to ameliorate UHI - via tree-lined streets and shading, or reflective/green roofs; while LEED New Construction accredits shade/albedo/porosity or underground/shaded/porous parking spaces (see discussion, later).

RADIANT TRANSIENCE (C^0)	ΔT_R	TPI Thermal Rank	ELEMENT: WALL Concrete Prefabricated/Balcony
	18^0	11^{th} radiator	Black
	7^0	7^{th} cooler	White
Season: Summer 2010 **Place:** Victoria Park, Sydney			**Orientation:** North

INTERPRETATION (temperatures averaged & rounded) (TPI = Thermal Performance Index: Rank 1 = prime effect)

North-facing 18-storey tower (residential)

Midday: Black Walls
= 12 warmer than White
= 14 warmer than Ambient
Dawn: Black & White Walls = Ambient

ΔT_R - Diurnal Radiant Emissions: to UHI
Black: 18 White: 7

UHI Micro-Climatic Guide:
White Walls on the North
= lower urban thermal load than Black

LEED: Accredits White: Albedo/Reflectivity

Midday Temperatures
Ambient: 29 (H: 63%)

Radiant:-
- Black Wall: 43
- White Wall: 31

- Black/Grey Road: 51
- Grey Column: 40
- Tree/West: 32

(East: Brown Walls warmer than White)

Dawn Temperatures
Ambient: 25 (H: 81%)

Radiant:-
- Black Wall: 25
- White Wall: 24

- Black/Grey Road: 23
- Grey Column: 25
- Tree/West: 24

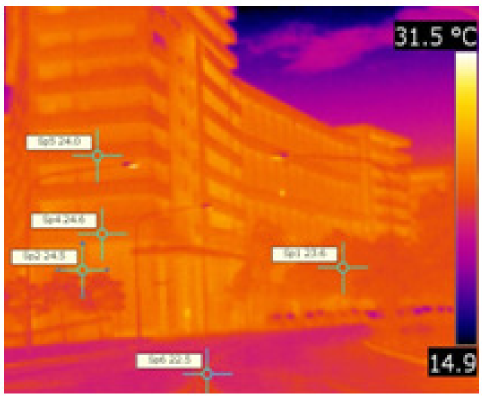


Figure 12: Towards a Visual Performance Index: Radiant Transience - Wall Element

RADIANT TRANSIENCE (C^{o})	ΔT_R	TPI Thermal Rank	ELEMENT: PAVING Cement Tiles/Light-Grey/Impervious
	20^{o}	9th radiator	Sunshine
	5^{o}	5th cooler	Shade
Season: Summer 2010 **Place:** Victoria Park, Sydney			**Orientation:** West
INTERPRETATION (temperatures averaged & rounded) (TPI = Thermal Performance Index: Rank 1 = prime effect)			

Paved Pathway adjacent to Joynton Park

Midday: Sunlit = 17 warmer than Shaded
= 11 warmer than Ambient
: Shaded = 6 cooler than Ambient
Dawn: Sunlit = 2 warmer than Ambient
: Pre-Shaded = Ambient

ΔT_R - Diurnal Radiant Emissions: to UHI
Sunlit: 20^{o} Shaded: 5^{o}

UHI Micro-Climatic Guide:
Shaded pavements
= lower urban thermal load than Sunlit

LEED: Accredits - Shaded Paving

Midday Temperatures
Ambient: 35 (H: 53%)

Radiant:-
- Sunlit Paving: 46
- Shaded Paving: 29

- Reeds under Trees 30

Dawn Temperatures
Ambient: 24 (H: 87%)

Radiant:-
- Sunlit Paving: 26
- Pre-Shaded Paving: 24

- Reeds under Trees 24

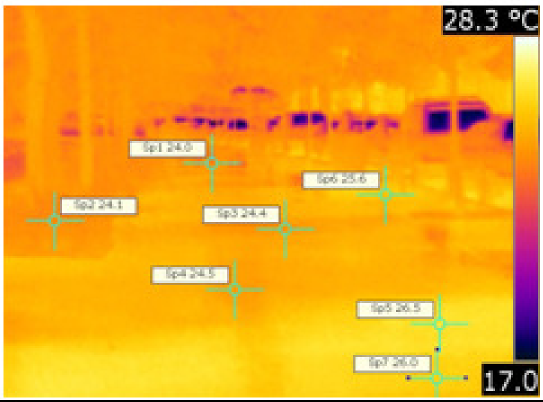


Figure 13: Towards a Visual Performance Index: Radiant Transience - Paving Element

Future Research

Extrapolating from the Victoria Park pilot program, and scaling up to urban and regional levels, future research into Urban Climate can be envisaged.

Best practice would suggest a substantive research program informed by both aerial imagery and hand-held micro-urban metrics.

From an analysis of hot and cool places at the generic spatial scale, a focused evaluation of thermo-spatial patterns at elemental scale can proceed. From such research the radiators and coolers which constitute this environment can be identified, and indexed, and ranked. Consequently, knowledge garnered from designed environment elements investigated at micro-climatic and micro-urban scales, could have great utility in helping plan mitigations and future adaptations to climate change thermal stress scenarios.

An intra-urban evaluation study could be devised, for Sydney by way of example, ranging from high-rise high-density CBD scale to low-rise low density Western Sydney suburbs, via medium-rise medium density precincts – with Victoria Park as the first of those. Measures of seasonal variations - from a maximum in mid-summer to a minimum in mid-winter - would complement that understanding.

In terms of related experimental research, a useful future laboratory experiment could simulate the impact of green, living vegetative surfaces, in comparison black, white and retroreflective surfaces, advancing the research on reflectivity cited in the report.

And research into the feasibility of harvesting waste heat at air-conditioner outlets, recycling it to mass storage water systems and withdrawing it from the urban heat island air could be devised and economically implemented on a CBD building rooftop.

During this summer season evaluation, it became evident that designed environment elements (inclusive of trees and grassy parks...) absorb radiant heat from direct sunshine and the ambient environment up to a maximum sometime around midday, and then progressively emit less and less until by dawn they have returned to ambient temperature levels, in general.

In terms of methodology, this led to the realization that in future research only the maximum and minimum temperatures need to be measured; which will increase the efficiency and rapidity of the hand-held thermal imaging process and reduce the complexity of measuring diurnal changes at four or more time-periods.

Also, to adequately measure CBD radiant building temperatures it will be necessary to photograph facades face-on at varying heights (from, eg, balconies of residential towers interspersed in the CBD).

Essentially, face-on imagery is best practice. This will minimize angular distortion of measurements. Where angular imagery is inevitable, a range of reading can help establish an average metric for that element, a road or building facade, as instances. And, the error is minimal – somewhere in the vicinity of 0.5 to 1.5^{O}C. This can either be ignored, or used to normalise the range.

Thermal sinks and sources are possibly better understood if conceived as thermal ‘radiators’ contributing to the UHI, or ‘coolers’ - which nonetheless do contribute but to a lesser degree. Water storage complexities arise here, for instance. And, advocating the role of living vegetation in ‘transforming’ heat via a range of extraordinary interactive mechanisms as best practice should be researched in greater depth.

Reflectivity and albedo warrant further reflection and until some resolution in terms of heat deflection is understood and integrated, a question mark should be placed over sustainability rating schemas which accredit white roofs and roads with cooling the urban heat island – unless set in urban forests. The urban climate should be understood as constituting both the UHI beneath the urban canopy and the urban boundary layer above the rooftops. Sky-view calculation is an essential tool to add into the research strategy, but needs to be appreciated in the light of this urban climate holistic concept too.

Finally, given that the Thermal Performance Index (Table 1) is derived from the comparative thermal imagery of radiant emissions transmitted from elements to the urban environment, the logical next step is to generate a Visual Performance Index, suitably designed to simply represent these complex relationships. This could become a micro-climatic tool to help inform decisions made about the designed environment at any scale.

In Conclusion

Resolutions aimed at the adaptation of the designed environment and the re-framing of its mitigating resilience to climate change can be readily elaborated and tested by means of thermal imagery. The by-now standardized cooling responses: parks and vegetation, trees and vines, strategic shading of walls and paving and parking lots, green roofs, albedo and reflectivity, paving porosity and evaporative stormwater runoff, thermal materiality and building and site orientation, and land-use distribution generally - can be evaluated via thermogarphy. In terms of their relative thermal transience to the ambient climate, impacts or ameliorations can then be extrapolated to the urban heat island, and the urban climate; and the global climate, by implication. Urban geometry parameters such as canyon configurations and density/massing/contiguity (aided by remote IR sensing and 3-D GIS mapping), ventilation valleys and sky view contributions to the ambient urban atmosphere, can also be similarly elaborated and indexed. The emissivity of the CBD with its particular urban pattern language and high rise residential blocks can be appreciated relative to the low-rise low-density Western suburbs, where the majority of Sydney's population growth is occuring, for instance.

Implications for thermal comfort and urban liveability, walkability, and health and mental wellbeing, UV protection, as well as reduced air pollution, and decreased energy consumption (and GHG emissions) required for cooling buildings and vehicles - go hand in hand with the advantages of cooling the overheating atmosphere at every level: micro, precinct, urban, regional and global.

APPENDICES

Appendix I: Literature Review

Generics

Every city creates its own climate, in an urban heat island dome. The materials in buildings and the urban infrastructure absorb solar radiation and anthropogenic heat and in conjunction with the loss of natural thermal sinks and transformers (trees especially) can cause the temperature of urban air to range up to 10C warmer than the surrounding countryside (www.NASA) – even up to 16C warmer in Athens (Santamouris, 2001).

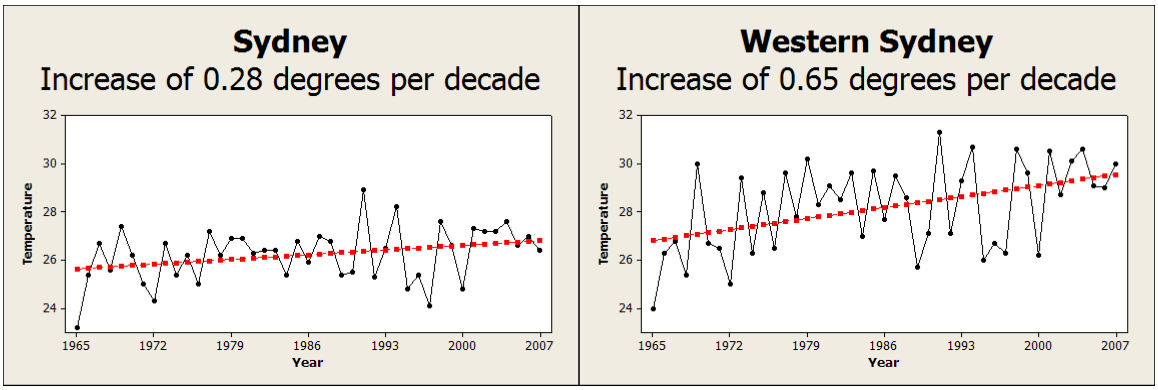
This UHI has been traditionally understood as the difference between urban and rural settings ($\boldsymbol{\Delta}T_{u\text{-}r}$). The utility of such a measure is doubtful, though. Unless one knows the inter-elemental disparities, or at least the intra-urban variations, there is little practical guidance that can be gleaned from the information.

The development of the urban heat island (Oke, 1982, 1987; Arnfield, 2003) is one of the most evident phenomena associated with urban settlements. In general terms, the UHI intensifies as city size increases; and further deranges weather patterns (Changnon *et al*., 1996, Rosenfeld *et al*., 1998, Konopacki and Akbari, 2002, Rizwan *et al*., 2007).

Furthermore, it is necessary to appreciate that the UHI is measured by the minimum temperature differences at night, not the maximums during the day.

There is a CSIRO/Greening Australia heat stress study (Urban Heat Stress and Opportunities for Climate Adaptation in Australian Cities) currently reporting that the hottest *days* in Western Sydney are 4-6C degrees warmer since the 1960s, interpreted from daytime maximum readings - but attribute this to a UHI.

Fig 14: indicates that the January mean maximum temperatures for Western Sydney have increased more than twice the rate experienced by coastal suburbs. It is also more than twice the rate expected from global warming (Greening Australia – www.ga.org.au)



This is more likely to be a regional inland condition which is being further exacerbated (by tree removal and impervious surface increase, as stated) but not a UHI (especially since the thermal mass in the suburbs is many times inferior to that of the CBD). Bureau of Meteorology records indicate that the

West is indeed hotter during the day, but is cooler at night. From the Observatory Hill weather station records used for the Sydney CBD, the mean *maximum* ambient temperature in 2009 was 22.9C ie some 2 to 3 degrees *less* during the day than say Parramatta or Penrith or Richmond; but at night the minimum is 15.1C, some 3 to 4 degrees *warmer* – the urban heat island, to wit. This is consistent with expectations. The mass in the city absorbs heat from the urban air during the day, and together with the shading of the setting by the structures, relatively cools, but re-emits this thermal load at night, when the ambient drops below radiative temperatures. While in the West, the relatively low amount of mass absorbs less during the day (the air is hotter) and emits that faster during the night, cooling to around 11 to 12C, some 3 degrees cooler than in the city.

Fig 15: Sydney, 2009 Maxima & Minima Ambient Temperatures (Source: http://www.bom.gov.au/climate/current/annual/nsw/sydney.shtml)

Summary statistics for 2009

	Maximum temperatures (°C)				Minimum temperatures (°C)			
	Mean for 2009	Diff from average	Highest for 2009		Mean for 2009	Diff from average	Lowest for 2009	
Sydney (Observatory Hill)	22.9	+0.9	40.9	24 Jan	15.1	+1.4	5.9	9 Aug
Bankstown Airport AWS	23.9	+0.8	41.5	20 Nov	12.5	+0.5	1.3	9 Aug
Camden Airport AWS	24.6	+1.0	43.1	17 Dec	10.7	+0.6	-2.8	9 Aug
Liverpool	24.6	+1.4	42.0	17 Dec	11.6	0.0	-1.2	9 Aug
Parramatta North	24.1	+0.8	41.8	17 Dec	12.9	+0.8	2.4	9 Aug
Penrith Lakes AWS	25.3		43.3	15 Jan	12.6		1.5	6 Jul
Richmond RAAF	24.7	+1.0	42.1	17 Dec	11.6	+0.6	-2.4	11 Jun
Terrey Hills AWS	22.1		39.2	24 Jan	13.6		3.1	6 Jul

Nonetheless, the resolution of urban and suburban warming, whether day or night is no less crucial for this interpretation.

Waste heat emission can be physically moderated in a variety of known ways through intelligent design: via the evaporative cooling capacity of the natural environment (trees and parklands are natural coolers) and built environment (porous pavements), greening of buildings and use of lightweight materials in construction. The deployment of light-coloured albedo materials and reflective surfaces is more relevant in reflecting shortwave solar radiation away from the built environment (See discussion on Reflectivity, later).

Waste heat emissions can also be addressed through broader passive measures such as: urban reforestation, and changing the form and scale of cities. Building geometry and surface thermal properties have been shown to have the largest effect on the magnitude of the UHI (Oke, 1982, 1987). Measurement of building geometry includes building height/canyon width (H/W) ratio and sky view factor, the proportion of sky seen from an outdoor point in space (Grimmond *et al*., 2001), and a compactness index, which is the ratio of building surface area to the surface area of a cube which has the same volume as the building (Unger, 2004; Emmanuel and Fernando, 2007). The variance here is infinite, but there are different liveability and sustainability implications for urban climates in compact medium-density medium-rise cities and in high-rise canyon-cities – the latter playing a major role in the warming of the urban climate (Bosselman *et al*, 1995; Golany, 1996, *inter alia*).

Other causal factors of the UHI include anthropogenic heat release from buildings in use, and from vehicles on hot roadways, waste heat emissions from air conditioners, loss of evapo-transpiration due to reduced vegetation and latent heat transfer; and the loss of wind within the built environment to transport heat out of the city (Oke, 1988).

And humidity is a silent toxin: in combination with heat its effects can be devastating. In the chart below, the apparent temperature *ie* sensible experience of 95F/**35C** heat (often considered to be indicative of a heatwave) and 75% humidity is the equivalent of 130F/**55C** – well above all measures of heatwave presence. Water vapour is a potent and underrated greenhouse gas; all warming, global and urban, generates more humidity - from ocean, river and vegetative evapo-transpiration.

Fig 16: Temperature and Humidity interrelationships with Heat Stress Experience (Source: Heat Index Chart: http://www.tvweather.com/awpage/heat_index_chart.htm)

Heat Index Chart

Temperature	% Relative Humidity: 15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
110	108	112	117	123	130											
105	102	105	108	113	117	122	130									
100	97	98	102	104	107	110	115	120	126	132						
95	91	93	95	96	98	100	104	106	109	113	119	124	130			
90	86	87	88	90	91	92	95	97	98	100	103	106	110	114	117	121
85	81	82	83	84	85	86	87	88	89	90	92	94	96	97	100	102
80	76	77	78	78	79	79	80	81	82	83	84	85	86	87	88	89

Legend

80-89 degrees	Fatigue is possible with prolonged exposure and/or physical activity.
90-104 degrees	Sunstroke, heat cramps and heat exhaustion are possible with prolonged exposure and/or physical activity.
105-129 degrees	Sunstroke, heat cramps and heat exhaustion are likely. Heat stroke is possible with prolonged exposure and/or physical activity.
130+ degrees	Heatstroke/sunstroke is highly likely with continued exposure.

The impacts of urban heat islands on urban climate are various and considerable, disturbing city and regional weather in a multitude of ways (WMO, 1997). Wind movement and precipitation patterns are relentlessly distorted, and thunderstorms, hail and violent winds are all exacerbated (Eliasson, 1996; Bornstein & Lin, 1999; Burian *et al*, 2004), even downwind of urban hotspots. Humidity, cloud-cover, fog and snow are also impacted. Simulations of Sydney's urbanization and deforestation impacts on the weather also indicate that the biggest storms form over the CBD (SMH, Oct 2005) – *ie* where thermal mass concentrations are greatest. As an aside, the belief that cold climate cities should benefit from waste heat emissions and an urban heat island effect is ecologically fallacious: since winter conditions are also pushed to extremes where the urban climate is disrupted, and ice storms, snow storms, rain storms, wind storms increase in intensity and frequency and uncertainty. Whatever heat might be added to a city environment in winter is also likely to rise above the level of pedestrian activity in any event, and add nothing to their comfort at street level.

Specific Methodologies and Resolutions

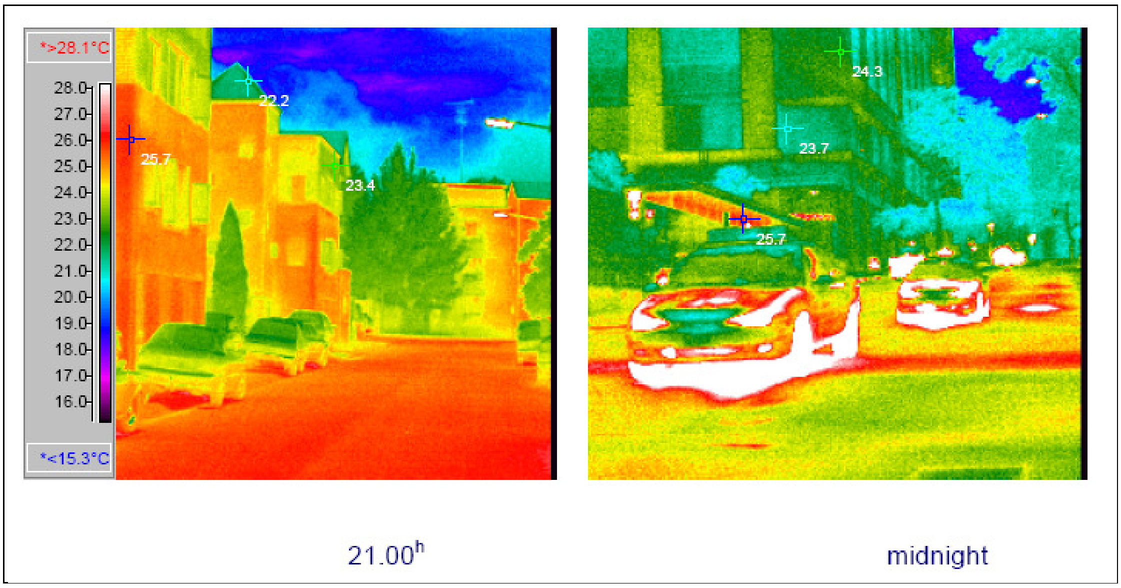
Urban Climate Conferences (ICUC 99 [Sydney] in November 1999; ICUC 5 [Lodz, Poland] in 2003; ICUC 6 [Goteborg, Sweden] in 2006; and ICUC 7 [Japan]) in 2009; Urban Climate News (the newsletter of the International Association for Urban Climate (www.urban-climate.org); and conferences on Climate Change related to Urban Design (2008) and Countermeasures to UHI (2009); *inter alia*, have been specifically mined for possible similar research programs *ie* studies using thermal imagery, of any nature, to develop performance indicators as design rules of thumb. No such study has been unearthed.

Hand-held Thermography

While infrared thermography has been taken from the air in previous studies (Voogt and Oke, 1997; Ben-Dor and Saaroni, 1997; inter alia), the use of hand-held infrared thermography for microscale UHI studies is a more recent technique. This is most likely due to recent improvement in resolution and portability of thermal cameras.

In 2000, Samuels published the two thermal images of Sydney City, in a peer-reviewed paper ('Urban Climate Experience') presented at an International Association of People in their Surroundings Conference in Paris. Here the focus was on making visible the invisible, exposing thermal signatures hidden in the built environment, and also the waste heat emitted by motor cars – an awareness raising exercise, important in the pursuit of urban sustainability.

Fig 17: Sydney City Thermal Imagery, Summer 1999 (Source: Samuels, 2000)



Again, a few years later, these same two exemplar images (selected from many hundreds) served to illustrate two further papers by the same author, making the same point about urban sustainability and the management of waste heat, and promoting the case for the thermal study of urban environments via IR imagery. These were: *'Perennial Old-City Paradigms' (2002) and 'Urban Heat*

Islands' - a submission to the Australian Government's House of Representatives "Sustainable Cities 2025 Enquiry" (2003).

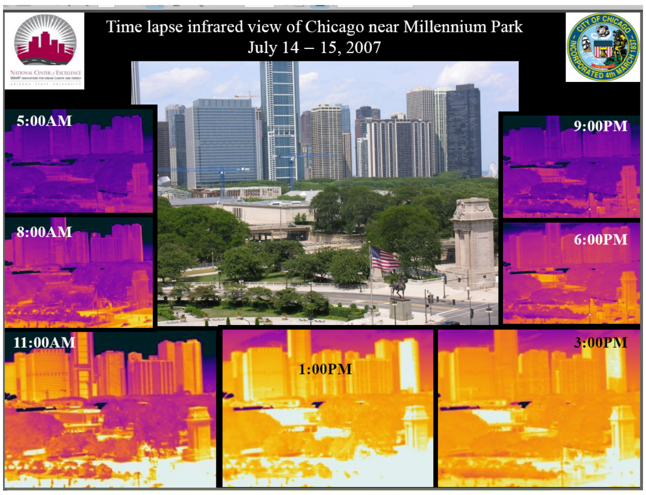
These three earlier papers were precursors to the Victoria park research, albeit only materializing in 2010, a decade later.

There are a handful of other studies generating hand-held thermal imagery as addendums to standard urban traverses and infrared measurements with radiometers (of individual elements). These do not analyse the imagery in any detail at all; using it, rather, as descriptors of variations in thermal emissions. Notwithstanding, they are salient reflectors of the Victoria Park research. Curiously, they all seem to have emerged from Arizona and have Phoenix as their focus.

Carlson (2005) studied the thermal properties of surfaces, principally pavements - at Sky Harbor International Airport, measuring diurnal temperature patterns with an IR camera. Overlaying GIS land cover data helped to locate and understand micro-scale surface temperature distributions at the airport.

Kamil Kaloush, of the National Centre of Excellence for Smart Innovations, Arizona State University, showed so-called 'time-lapse' infrared views of Chicago and its Millennium Park, taken in summer of 2007 in a presentation at the Sustainable Communities Conference, Dallas, Texas.

Fig 18: Time-lapse views – Chicago



This study is closest in methodology to the Victoria Park pilot - an advance towards an urban design database indicative of the thermal absorption and emissivity of elements in the designed environment. But a detailed micro-climatic approach across a range of scales is necessary to supplement this set of images - given the atmospheric attenuation effect which must be appreciated in imagery at this scale if a robust metric is to be evolved.

In 2009, two papers were delivered at the *Eighth Symposium on the Urban Environment, Arizona,* both focused on a study on the Phoenix UHI, specifically the micro-meteorological effects of built elements (Di Sabatino *et al*, 2009; Hedquist *et al*, 2009).

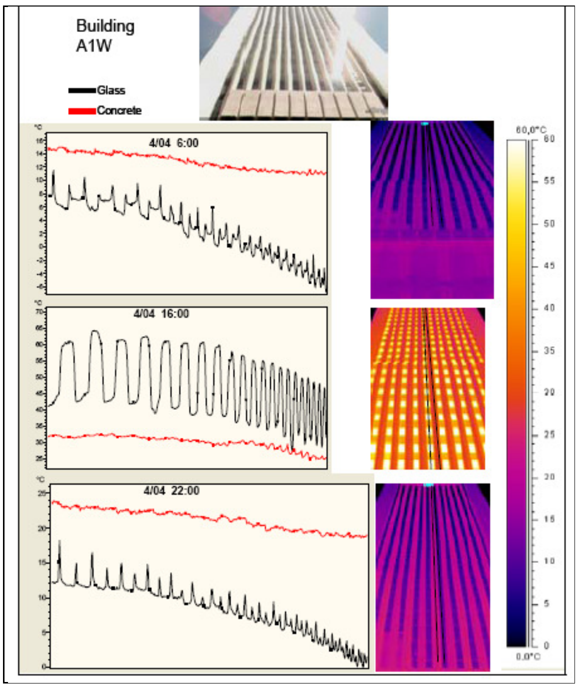
Their focus was on temperature patterns at the scale of individual buildings in street canyons in the downtown CBD. *Inter alia*, infrared thermography was used for surface mapping. Ambient and radiant temperatures were recorded during one diurnal period, which data were compared with simulations from a three-dimensional microclimate numerical model ENVI-Met model (www.envi-met.com; Bruse, 2007).

The simulations replicated the highest UHI a few hours after sunset, but under-predicted the 24-hour maxima and minima.

The use of thermal images, nonetheless, allowed for an understanding of temperature distributions at a fine resolution. Building façades, for instance, reached averages of 40C. As in the Victoria Park study, there is an appreciation of the importance of measuring temperature distributions where buildings and streets intersect, crucial in designing for outdoor human comfort. At night, air temperature was found to correlate well with surface temperature. In Victoria Park, radiant temperatures were seen to decline from the daytime maximum to a dawn minimum when they matched ambient temperatures in almost all cases.

A creative research technique - being transported through the city in a bicycle taxi - allowed them to move easily through the traffic from one location to the other; Several images of the same building façade were captured at several heights; and later assembled into one with the software; from which mean radiant temperatures were assessed (the average of all temperature readings on the entire building façade). Concrete and dark glazing are the major components making up the desert-climate urban setting (see Fig 19, below). Many variations were unearthed, resulting from orientation, exposure, materials, height. But air temperature rising within the CBD as building façades cooled is good evidence for UHI exacerbation.

Figure 19: Comparison of mean radiant temperatures of dark glass and concrete in a downtown Phoenix building



One critique of their methodology must be made. Some of their measurements are claimed to showed an intense temperature peak at the base of buildings (correctly) which are then said to decrease linearly with elevation. More likely, this would be an effect of angularity and transmission through the atmosphere. To adequately measure CBD radiant building temperatures it will be necessary to photograph facades face-on at varying heights (from, eg, balconies of residential towers interspersed in the CBD); a technique which could be part of a future research program.

The Phoenix research also obtained high-resolution IR images of surface radiant temperatures from a helicopter 300m above the ground, at approximately the same time (1400, 1900, and 2200) as the mobile vehicle was travelling through the canyon.

Even prior to the Arizona research, the Japanese Government in 2004 created an ‘Outline of the Policy Framework to Reduce Urban Heat Island Effects’ - in recognition of the social and urban impact of heat islands: from heat strokes, atmospheric pollution and energy emissions to regional downpours. Countermeasures suggested include the reduction of artificially-generated exhaust heat, increased land cover, improvement in urban formats and lifestyles, reinforced monitoring and management systems...and investigative studies.

Two later studies, cited in the industry journal, Urban Green Tech (2007) employed hand-held thermal photography. In both cases, as comparative illustrations in which the variety of temperatures can be readily envisaged; but neither takes the next step - and accumulates these into a thermal index.

The first, by Mochida & Kikuchi is focused on a “Comprehensive Assessment System for Building Environment Efficiency on Heat Island Relaxation”, and uses measurements of a roadside tree setting in the central city area of Sendai City. It is also reported in The Seventh International Conference on Urban Climate, 2009.

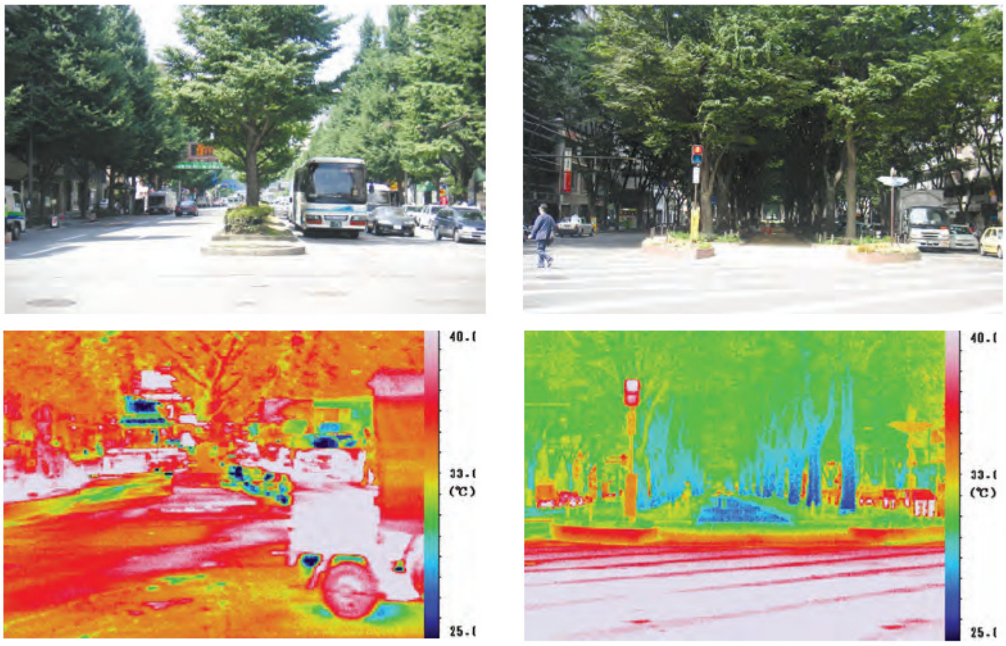
The research aimed to investigate the effects of roadside trees and moving automobiles on airflow distribution, turbulent diffusion of air pollutants, ventilation efficiency and thermal environments within street canyons. Field measurements were carried out at two streets with different densities of roadside trees and traffic volume in the central part of Sendai city, Japan. A series of ‘computational fluid dynamics’ (CFD) analyses were also carried out.

It was shown that the high density roadside trees decreased the flow rate of the street canyon and *increased* the contaminant concentration near the ground level. To investigate ways to improve this situation, the ventilation efficiencies within street canyons with different conditions of roadside trees were evaluated based on the results of CFD analyses. In the case where the roadside trees near the building walls were pruned (in the software), the flow rate from the upside was increased and thus the ventilation efficiency was improved.

From these, extrapolations are made of the effects of trees on urban environments; concluding that simply raising greenery ratios is not the solution. The issue is more complex; each place is different, and building design is a critical variable.

The images (below) were taken in daylight, on a summer day.

Fig 20: Thermal and Digital Imagery of Streets in Sendai City, Japan

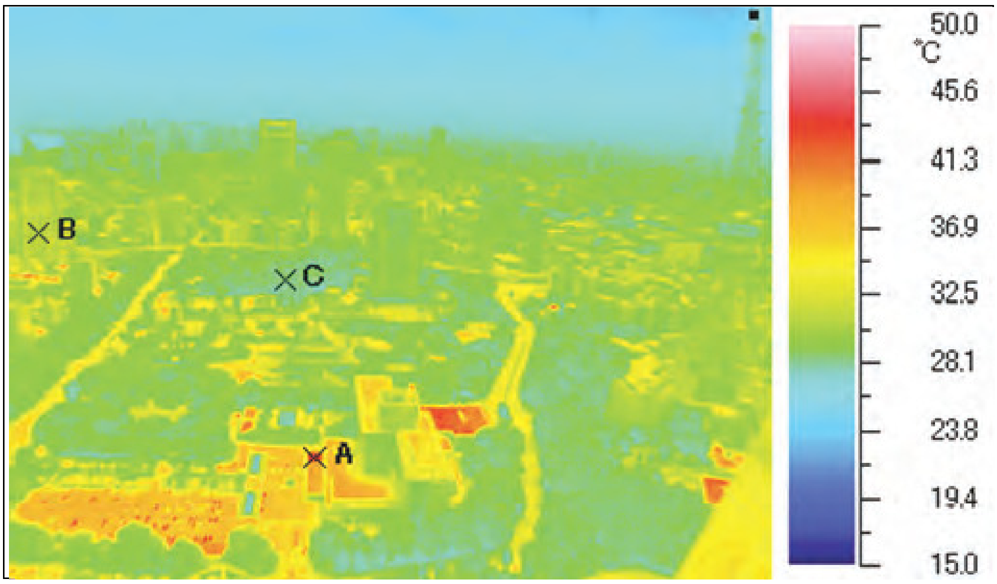


Conditions at Hirose-Dori (left) and Jozenji-Dori (left), in Sendai city, and their thermal images (10 Aug. 2006, 2:30 p.m.)
(Source) Akashi Mochida, Aya Kikuchi P. 19

The second study (Handa *et al*, 2007) highlights the need for comprehensively creating and preserving green areas, in addition to other strategies such as conservation of resources and energy.

Their methodology included hand-held imagery but was basically an urban scale simulation using the so-called Klima Atlas (climate map) tool; and measures of sensible temperature and "green" volume as indicators of thermal improvement. In the image (below) the relative values of a roof, wall and woodland can be detected. Large scale city shots, nonetheless, are abstractions not a robust metric, since the apparent heat fall-off due to atmospheric distance is substantial.

Fig 21: Comparison of surface temperatures: A (structure roof), B (structure wall), C (woodland) (July 2006, 12:50 pm)
(Source: Mariko Handa, Kazutaka Imai, Migiwa Matsui, 2007)



Thermal Research via Other Methodologies: In Brief

IR Satellite Imagery

In urban climatic research thermal imagery is frequently utilized, yet virtually exclusively in the form of aerial remote sensing from satellites and helicopters

Fig 22: Satellite Imagery - Excerpt from ASU online

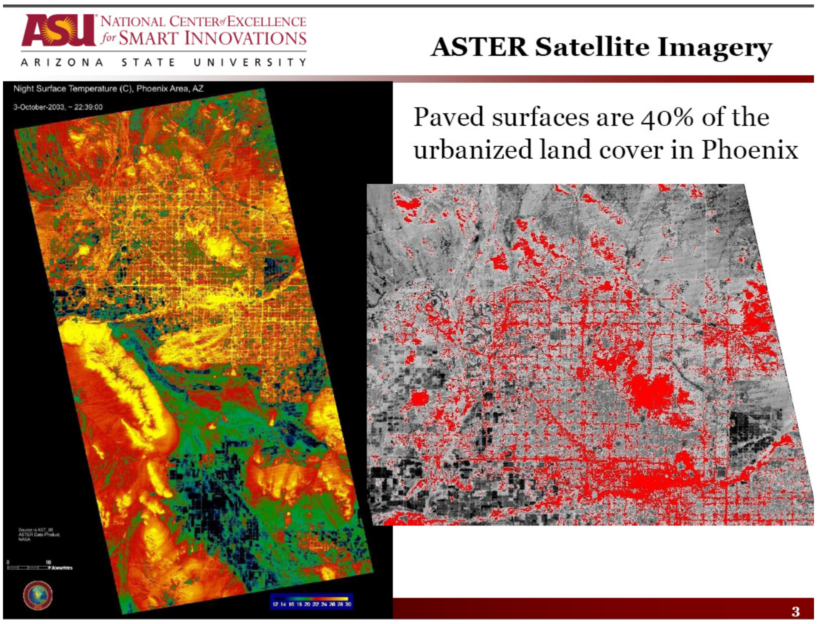
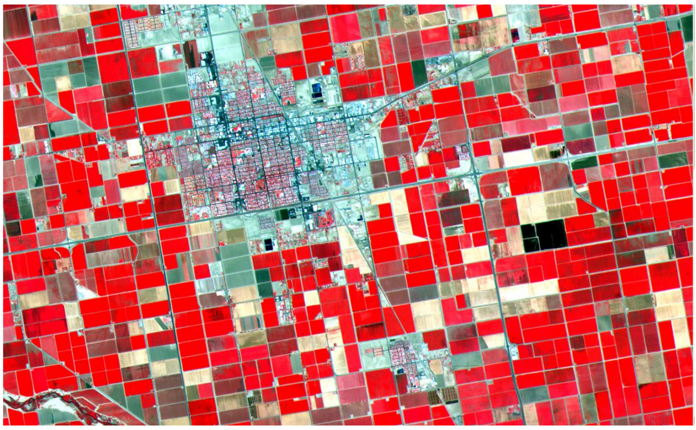


Fig 23: Example of ASTER Image @ resolution 90metres



Aerial thermography/remote sensing (Aster, Landsat, Geosat, NASA...) is a long established tradition to visualize the heat signatures of urban and green spaces. This methodology provides a gross overview but not the micro-climatic differential built-in to the designed environment.

The usual major utility of IR remote sensing is the detection of heat loss from buildings in winter (related, for instance, to insulation programs). Now, thermal emissions to the urban heat island are being linked with an exaggeration of urban climatic extremes.

Importantly, aerial imagery represents only horizontal surfaces only; although one study attempted to compensate for this (Voogt & Oke, 2003) where a camera was set at an angle of 45 degrees, which would pick up on a reasonable measure of verticality. The issue of angle distortion through the atmosphere, however, needs to be accounted for. The Victoria Park research shows clearly how thermal imagery measurements are affected by angle (to a degree), rather than by distance. So, reliable temperatures can be achieved from satellite and helicopters because they are set perpendicular to the ground.

Tanaka Takahiro *et al* (2006) used geo-referenced **airborne** thermal sensor images to represent radiative temperatures, during the daytime and at night; appreciating how radiative temperatures differ between surface temperatures due to the influence of the atmosphere, and again focused on generic relative differences.

Dousset & Gourmelon (2006) reflected on the 2003 heatwave which killed thousands of people in Paris, from satellite imagery both visible and IR. They detected a strong relationship of surface temperature to built density, particularly at night; and a large night-time heat island, up to 8C in the city centre, and even more, up to 11C scattered in suburban industrial areas. It is said that this lack of relief at night, rather than high daytime temperatures, puts people at risk - of heat stress and heat death.

Combining the high spatial resolution SPOT and IR AVHRR data, these researchers identified the regions of the Paris metropolitan area that are most vulnerable to heat stress, at very least allowing for public health safety alerts in future heat-wave situations to be communicated more effectively.

Solis, Cardoso & Cueto (2008) reported - at the Climate Change and Urban Design Congress of the Council for European Urbanism - on comprehensive research conducted in an industrialized area of Mexico City, aimed at to characterizing the thermal gradient of the site, in relation to urban structure. Their proposals for environmental design to diminish this impact confirm the general understanding in the urban climate community - asphalt exposed to solar radiation represents a higher temperature that that on a shaded concrete sidewalk, or surfaces covered with vegetation. This research measured radiation behaviour of horizontal and vertical surfaces using an infrared thermometer; and to distinguish between the urban thermal zones, satellite imagery was used, accompanied by information from weather stations distributed in the city. Data showed that vertical surfaces (walls) have a different thermal behaviour depending on their orientation; walls facing north-northeast reached 113F, whereas those located south-southwest only 89.6F. The Victoria Park research generally confirms these observations.

Suggestions from this research for UHI amelioration include: reducing waterproof surfaces, especially those with a low albedo; increasing the albedo in rooftops, and increasing urban vegetable coverage (see also: Akbari *et al*, 1992); Scott *et al.,* 1999).

Methodologically, the satellite images show spatial thermal distributions at regional level, fixed stations show the distribution of isotherms at urban level, while mobile station monitoring at site level and the use of an infrared thermometer allow a precise evaluation of the site materials related to their orientation.

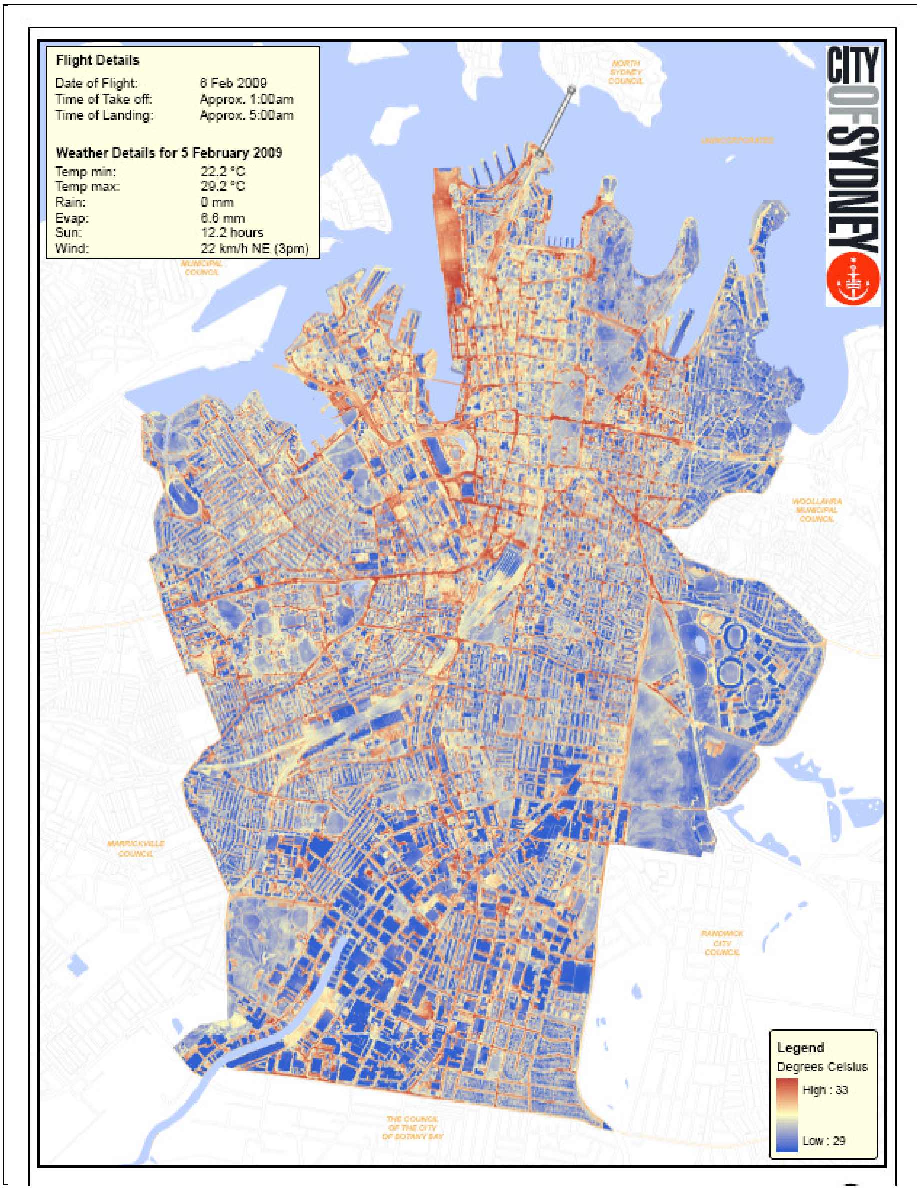
Future research in the Sydney region should be informed by aerial imagery certainly, also allowing for the focus of the micro-scale work to be directed logically to both hot and cool places, urban and suburban, to understand better the thermo-spatial interrelationships.

Recently, the City of Sydney commissioned a midnight-to-dawn thermal imaging flyover (see Figure 24) in which the radiant relevance of roads is clearly visible, and the warmer high-rise canyon CBD region can be detected. The range of radiant temperatures over the period was 33 to 29C, and the ambient temperature ranged from around 29 maximum to 22C at dawn. In the image, the parks appear as cooler, but their blue colour is deceptive *ie* the 'cool' spots are only 4C less that the 'hot' spots, and still radiating at 29 degrees at dawn. This means these places are emitting heat equivalent to the maximum daytime ambient (on that day) even when it has dropped to around 22 degrees at dawn.

Moreover, it is probable that the overflights began over the CBD, at midnight when the radiant temperature is still relatively high and terminated at dawn in the south when the minimum ambient is reached, again distorting the relative contributions of the elements and places to the urban heat dome.

Nonetheless, the salience of roads (and the concrete wharf at the Barangaroo redevelopment site) and rooftops to thermal emissivity is obvious. Interestingly, the roofs of the industrial zones in the south of the city are radiating at a similar temperature to the parkland. A typical industrial shed has sarking foil and uninsulated skylights, and whatever heat is accumulated inside the structure on a sunny day is quickly lost to the urban air sink at night. In other words, the apparent UHI advantage of these cool roof zones is an illusion: they have simply returned their thermal load to the night sky more quickly than more solid and better insulated residential rooftops.

Fig 24: Thermal Image of Sydney, Summer - 2009) (Source: Sydney Morning Herald, 15/02/2010)



Interpretations are complex. Roads in Woolloomooloo and Darlinghurst are hotter than those of Potts Point, Kings Cross and Elizabeth Bay, which have higher rise buildings. Possibly mutual shading of buildings and of roads is involved; as it is in the CBD – evident in the Google.com spatial configuration map (Fig 25, over; ie the black interstices). Clearly, cooler parks and ovals are apparent. It would be salient to examine this thermal map at micro-urban scale: by means of a hand-held IR camera.

Now that generic spatial aspects have been highlighted, hot and cool spots and the designed environment elements of which they are constituted can be investigated with facility; and great utility for planning mitigations and future adaptations to climate change thermal stress scenarios.

Fig 25: City of Sydney - Spatial Configuration (Source: Googlemaps)

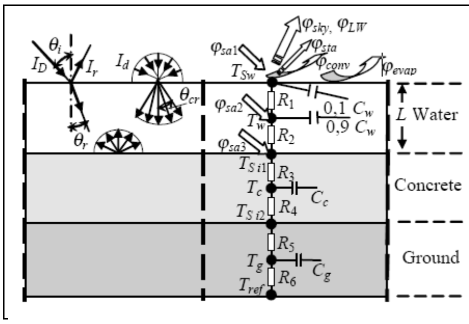
Simulation and Modelling

The KLIMES research project simulates microclimatic urban conditions under global climate change (www.klimes-bmbf.de), and recognizes two dominant factors: mean radiant temperature and wind speed. Higher wind speed in particular is apparently negatively perceived by people living in moderate climates but positively perceived in warmer climates. But, in any event, urban ventilation needs to be taken into account in urban planning (RUROS, 2004).

Urban climatologists have proposed water ponds for cooling by evaporation in summer (Givoni & La Roche, 2000); and Robitu *et al* (2003) modelled the radiative properties of a pond and its influence on microclimate. In spite of its importance, the quantitative estimation of this relationship between water and atmosphere is poorly understood, due to the complexity of the phenomenon and the difficulty of obtaining rigorous and reliable physical models.

Computational Fluid Dynamics (CFD) and mathematically based methods provided the image below, for the information of the illuminated.

Fig 26: Radiative properties of a water pond (Source: Robitu el, 2003)



$$\frac{C_w}{10}\frac{dTs_w}{dt} = \varphi_{sa1} - \varphi_{sta} - \varphi_{conv} - \varphi_{evap} - \varphi_{LW} - \varphi_{sky} - \frac{1}{R_1}(T_{Sw} - T_w)$$

$$\frac{9C_w}{10}\frac{dT_w}{dt} = \varphi_{sa2} + \frac{1}{R_1}(T_{Sw} - T_w) - \frac{1}{R_2}(T_w - T_{Si1})$$

$$\varphi_{sa3} + \frac{1}{R_2}(T_w - T_{Si1}) - \frac{1}{R_3}(T_{Si1} - T_c) = 0$$

$$C_c\frac{dT_c}{dt} = \frac{1}{R_3}(T_{Si1} - T_c) - \frac{1}{R_4}(T_c - T_{Si2})$$

$$\frac{1}{R_4}(T_c - T_{Si2}) - \frac{1}{R_5}(T_{Si2} - T_g) = 0$$

$$C_g\frac{dT_g}{dt} = \frac{1}{R_5}(T_{Si2} - T_g) - \frac{1}{R_6}(T_g - T_{ref})$$

Complexities include: solar radiation reaching the water surface, amount reflected and varying position of the sun and angle of incidence, site location, possible presence of shading and atmospheric conditions – besides aspects like the spectral distribution of water, the depth of the water and air flow near the water surface.

There is simultaneously a heat transfer due to the temperature variation between water and air, and a mass transfer due to the gradient of the specific humidity of water vapour in the air. Latent heat transfer necessary for evaporation accompanies this mass transfer.

The Victoria Park research begins to specifically examine this phenomenon, measuring the storage and transience effect of the water steps, and of ponds in a neighbouring precinct (AGL site), at the water fountain in Martin Place in the heart of Sydney City, and in a swimming pool near the coast – thermal imagery useful in any future Visual Performance Index development.

Sasaki *et al* (2003) affirm the replanting strategy being implemented in urbanized areas, especially roof planting, and also urban tree planting in some major cities; and note that although urban forestry has decreased air temperatures there has been a corresponding increase in air humidity. Humidity is a factor vital in thermal comfort experience. Additionally, flow and turbulent diffusion fields in urban area have changed. This study investigated the impact of urban tree planting on the urban climate in Tokyo, proposing a new concept: the “Thermal Metabolism Model” to evaluate urban thermal structures and the environmental impacts of countermeasures to heat islands. The heat budget in the urban area was calculated using numerical data provided by meso-scale climatic modelling. It appears that the sensible heat stored in the urban atmosphere would not be much decreased by urban planting, although the sensible heat from ground surfaces would decrease greatly. Simultaneously, however, the increased outgoing latent heat from the surface, stored in the atmosphere would be greater during the daytime after urban planting. Self-evidently, greening is not a simple panacea.

Ihara *et al* (2009) invoke the Japanese government’s Outline of Countermeasures to Urban Heat Island of 2004, and caution against forgetting the increase in CO_2 emissions caused by energy consumed to implement countermeasure interventions. This is especially relevant since, to meet Japan’s Goals of the Kyoto Protocol Target Achievement Plan of 2005, there should be no significant increase in CO_2 emissions, generally. This study evaluated both the changes in the urban air temperature and life cycle CO_2 emissions resulting from the installation of various UHI countermeasures (photocatalysts, solar reflective paint, and greening) using annual meteorological and building energy models (AIST-MCBM) and the life cycle inventory analysis.

They found that all the countermeasures mitigated the urban air temperature during summer; and all affected CO_2 emissions. The annualized life cycle CO_2 emissions from the construction and the operation of photocatalysts was highest, then came rooftop greening and sidewall greening; and best of all was the solar reflective paint.

Krayenhoff et al (2009) employed a meso-scale meteorological model and land cover data to simulate Toronto's low-level air temperature during a fair weather period in the summer of 1997. While both green roofs and white roofs are generally proposed as urban design strategies to reduce low-level air temperatures, green roofs partition more solar energy into latent as opposed to sensible heat, while white roofs increase reflection of solar radiation, they report. Preliminary results suggest green roof and white roof modifications reduce the air temperature by less than 0.1 centigrade.

It seems true to say, in sum, that the complexity of the environmental-atmospheric interface and the wide range of complex models simulating varying conditions are informative but the level of uncertainty accompanying them makes it unlikely that design-policy decisions will be based on them. Moreover, these results are rarely communicated to designers of the built and landscaped environment, and if so, not in a format that suits their requirements.

Natural Coolers and Greening

The importance of actively including cooling mechanisms both designed and natural into the urban thermal environment cannot be overstated. The results from the Victoria park pilot indicate this empirically.

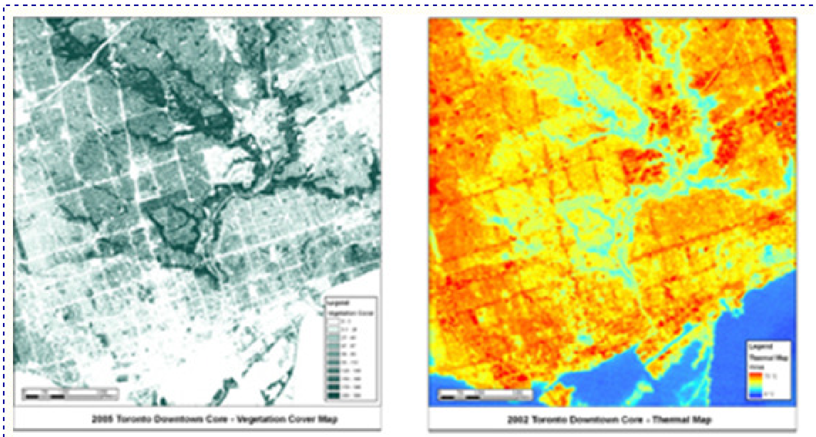
Many other recent studies have come to the same conclusion, via different methodologies; briefly outlined below.

An interesting study of the cool island effect in the large Shinjuku Gyoen Park in the centre of Tokyo identified a ‘park breeze’ (Honjo *et al*, 2003). Spatial distributions of temperature and humidity were mapped. Not only was a cool island effect detected but there was also ‘gravitational’ air flow to the surrounding urban area on clear calm nights – measured via 3-D ultrasonic anemometer-thermometers.

Walz (2007) depicted how road-side large trees ameliorate urban heat by creating barriers between solar radiation and pavements. With satellite images (Landsat Thematic Mapper) and localized infrared measures the influence of vegetation on local temperatures in Huntington, West Virginia was assessed. The vegetation was mapped in spring and summer to indicate the varying extent of canopy shading of sealed surfaces. ‘Not surprisingly a highly significant inverse relationship exists between vegetation proportion and surface temperature’...while...‘large buildings and parking lots in otherwise vegetated residential neighbourhoods form clearly detectable hotspots’. This technique of combining high resolution satellite data with relatively coarse thermal information to identify cool and hot spots in cities, the researcher suggests, could be adapted by city planners in order to ameliorate environmental quality in cities, and to identify gaps in urban forests.

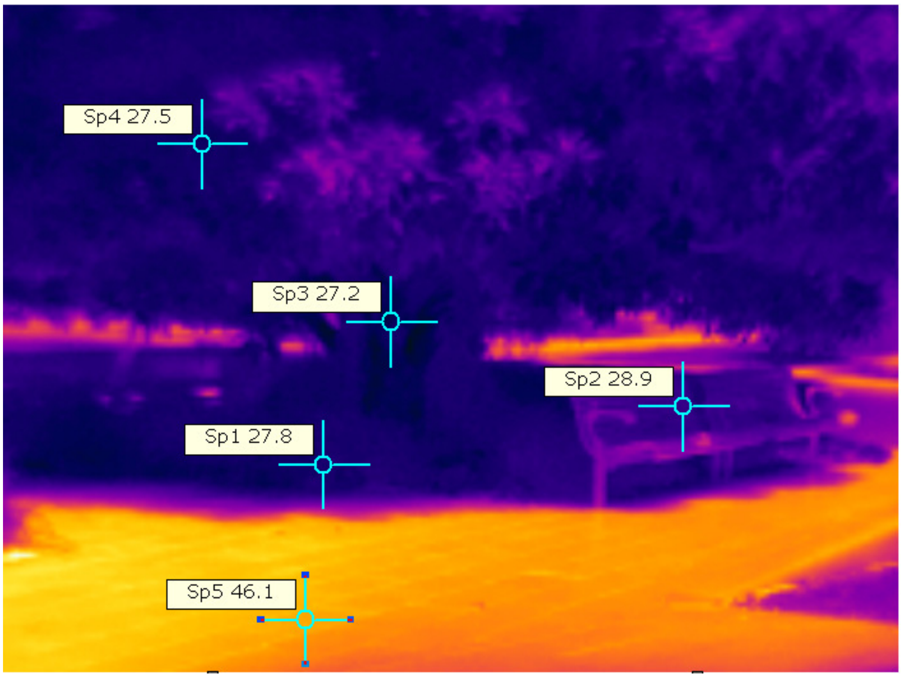
The relationship between vegetation and heat island formation is far from self-evident, however. Not only the amount but the type of plant, and geographic placement and adjacency, play major roles – besides seasonal climate. A green leaf coverage ratio (percentage cover:land) or canopy cover are usually used as generic indicators – via Quickbird satellite imagery for instance, and geographic information system data and/or field measurements. This can also identify potential future tree planting sites.

Fig 27: Quickbird Vegetation cover (darker areas) compared with surface temperature; indicating cooling effect of landscaping (Source: http://ess.nrcan.gc.ca/ercc-rrcc/proj2/theme1/act5_e.php)



Hand-held thermal imagery at scales varying from a single tree to a grove of trees can now be readily indexed, providing an empirical metric. The image below indicates the enormous daytime difference (about 18C) between the average radiant temperature of a impervious light-coloured paved walkway and the shade under a broadleaf shade tree in Victoria Park– where the shaded canopy understorey is much the same temperature as the shade on the ground (also evident in previous figures).

Fig 28: Tree shade metrics



The metabolic relationship between trees and the environment is highly sophisticated. During the photosynthetic cycle (in the presence of daylight and/or sunlight) CO_2 is absorbed and reacts with H_2O, breaking down into sugars to harvest chemical energy used for maintenance and growth, with the O_2 expelled and the carbon sequestered. The respiration cycle, which occurs both day and night, is like photosynthesis in reverse: CO_2 and water are released, the water allowing for evapo-transpiration from leaves and thus for cooling to occur (over and above the simple cooling effect of shading from solar radiation).

Paradoxically, urban green spaces in the form of lawns do not necessarily help counteract greenhouse gas emissions (as distinct from thermal emissions). Research from the University of California, Irvine reports that although turf-grass lawns are sinks that help remove carbon dioxide from the atmosphere through photosynthesis and sequester it as organic carbon in soil, greenhouse gas emissions from fertilizer production and nitrous oxide released from soil after fertilization, mowing and leaf blowing (so-called 'lawn grooming practices') are four times greater than the amount of carbon stored by 'ornamental' grass in parks - besides the 'environmental costs' of irrigation (Townsend-Small & Czimczik, 2010).

Green Roofs

The literature on the benefits of green roofs is very extensive and cannot be elaborated here. Reference should be made to the 'Reducing Urban Heat Island Compendium of Strategies' prepared and published by the Climate Protection Partnership Division in the U.S. Environmental Protection Agency's Office of Atmospheric Programs – specifically for green roof development (Green Roofs Heat Island Effect: US EPA). Over 50 references are cited there; and cost/benefit analyses are undertaken (see also: Clark et al, 2008). To cite but one salient study, Liu and Baskaran (2003) highlight how, on a hot summer day, the surface temperature of a green roof can be cooler than air temperature, whereas the surface of a conventional rooftop can be up to 90F (50C) warmer.

Suffice it to say that the EPA Heat Island Site lists the following benefits:

- *Reduced energy use:* Green roofs absorb heat and act as insulators for buildings, reducing energy needed to provide cooling and heating.
- *Reduced air pollution and greenhouse gas emissions:* By lowering air conditioning demand, green roofs can decrease the production of associated air pollution and greenhouse gas emissions. Vegetation can also remove air pollutants and greenhouse gas emissions through dry deposition and carbon sequestration and storage.
- *Improved human health and comfort:* Green roofs, by reducing heat transfer through the building roof, can improve indoor comfort and lower heat stress associated with heat waves.
- *Enhanced stormwater management and water quality:* Green roofs can reduce and slow stormwater runoff in the urban environment; they also filter pollutants from rainfall.
- *Improved quality of life:* Green roofs can provide aesthetic value and habitat for many species.

About 8.5 million square feet (790,000m^2) of green roofs had been installed or were in progress as of June 2008 in the USA alone (http://www.greenroofs.com/projects/plist.php).

Fig 29: Chicago City Hall green roof measures almost 89F (40C) cooler than an adjacent conventional roof (Source: http://www.epa.gov/heatisland/resources/pdf/GreenRoofsCompendium.pdf)

Albedo and Reflectivity

Albedo is the percentage of radiation reflected. Increasing the solar reflectance of urban surfaces and of architectural elements reduces their solar heat gain and lowers their temperatures. But to decrease the outflow of infrared radiation to space beyond the 11 kilometres of tropospheric atmosphere is more complex (see Dilemma discussion, later).

Certainly, cool roofs reduce cooling-energy use in air-conditioned buildings and increases comfort in unconditioned buildings; while cool roofs and cool pavements mitigate summer urban heat islands, also improving outdoor air quality (Akbari *et al*, 2001 & 2005; Levinson *et al,* 2005).

Akbari *et al* (2008) reviewed the literature for the solar reflectance of many standard and reflective paved surfaces, and report that the solar reflectance of freshly installed asphalt pavement is about 0.05. Aged asphalt pavements have a solar reflectance of 0.10 - 0.18, depending on the type of aggregate used in the mix. A light-colour concrete can have an initial solar reflectance of 0.35 - 0.40 that will age to about 0.25 - 0.30. They recommend using cool pavement materials in urban areas to increase the solar reflectance of paved surfaced by about 0.15 (Pomerantz and Akbari, 1998; Pomerantz *et al,* 1997).

Dark flat roofs reflect only 10 to 20% of sunlight. Akbari *et al* (2008) have shown that resurfacing conventional dark roofs with a cool white material that has a long-term solar reflectance of 0.60 or more increases its solar reflectance by at least 0.40.

Using white materials for flat roofs in California has been a requirement for non-residential buildings since 2005. However, the demand for white sloped roofs is limited in North America for aesthetic reasons. California has compromised by requiring only “cool coloured” surfaces for sloped roofs, starting in January 2010.

But these only achieve about half the reflectance of white surfaces.

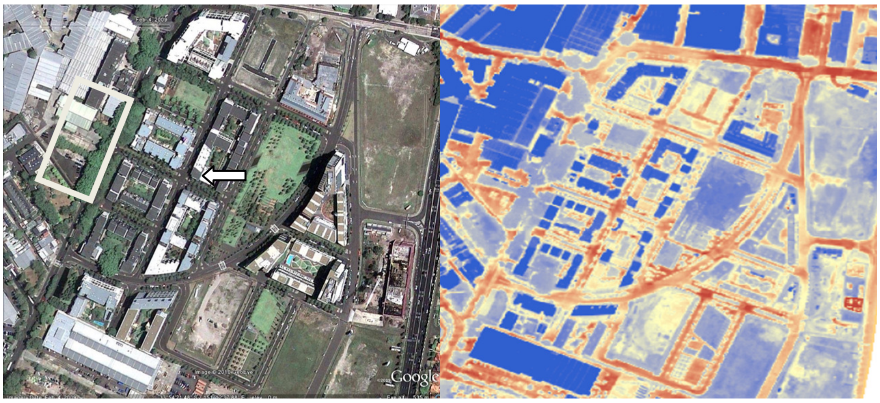
In Europe, the EU Cool Roof Council (EU-CRC) organized its first meeting to promote and provide support for installation of cool roofs in 2009; while in Brazil a “One Degree Less” movement (ODL 2009) has been pioneered, via cool roofs and heat island mitigation - to help combat global warming.

The first study to simulate the impacts of white roofs on urban areas worldwide suggests that painting roofs white has the potential to significantly cool cities and mitigate some impacts of global warming, in theory at least. The research team from the National Center for Atmospheric Research in Boulder, Colorado, cautions that there are still many hurdles between the concept and actual use of white roofs to counteract rising temperatures – including dust and weathering, density and location. Issues of glare discomfort and even risk (‘blinding’ motorists) – and not excluding a distaste for this aesthetic, say, in European cities with their traditional warm red tile roofs, will also presumably play a role.

The Colorado study team used a new urban canyon model that simulates temperature changes in abstract city landscapes, capturing such factors as the influence of roofs, walls, streets, and green spaces on local temperatures. The model has also been linked to a simulation of worldwide climate, the NCAR-based Community Climate System Model, enabling researchers to study interactions between global climate change and urban areas. The simulation suggests that if every roof were painted white, world-wide the urban heat island effect could be reduced by 33 percent; cooling the world's cities by an average of about 0.7F. Results of the research are due for publication in the American Geophysical Union (AGU) journal *Geophysical Research Letters* (see also

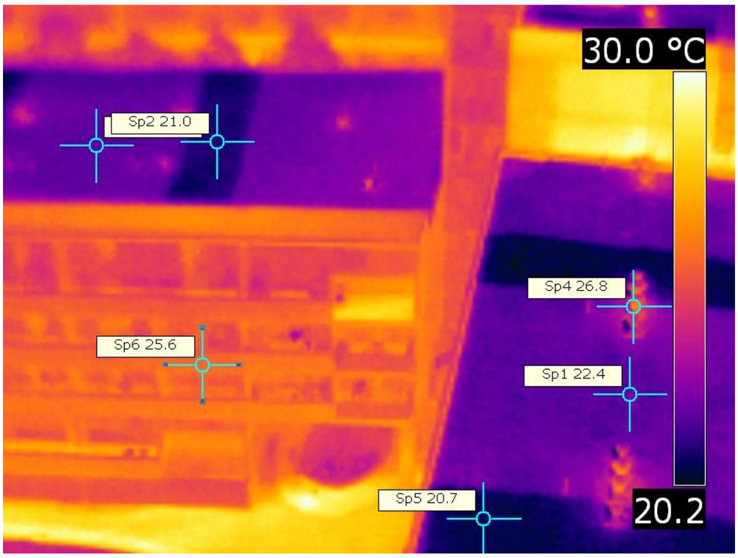
Noria Corporation Newsletter: “Reliable Plant”, no date) & (see Dilemma discussion, later).

Victoria Park has neither green roofs nor green walls; but some roofs are painted white, others are shades of grey. The tower rooftop (arrow) of the ESP building is covered in white pebbles. From the Google image and the City of Sydney thermal image below (see Figs 3 & 4, earlier) both the tower section and the lower-rise perimeter building rooftops appear to be radiating at a similar temperature, around 30C (recall: hot-roads are 33C, the ‘cool blue’ is thus deceptive).



Contradictory evidence, however, comes from the thermal images of the ESP rooftops, all indicating a temperature of around 22C @9pm.

Fig 30: Lower-rise ESP perimeter buildings around internal courtyard



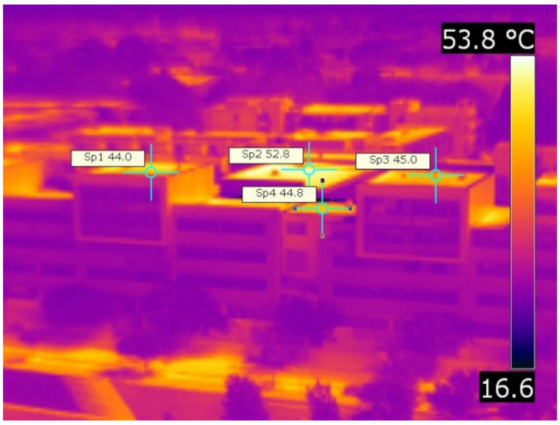
The 4-storey buildings facing the ESP across the park (grey rectangle) have grey and white rooftops, but appear on the aerial thermal image with the white roofs noticeably warmer than the grey. The tall structure in the top corner of Victoria Park, however, has a white roof and here it is as cool as the grey-tops.

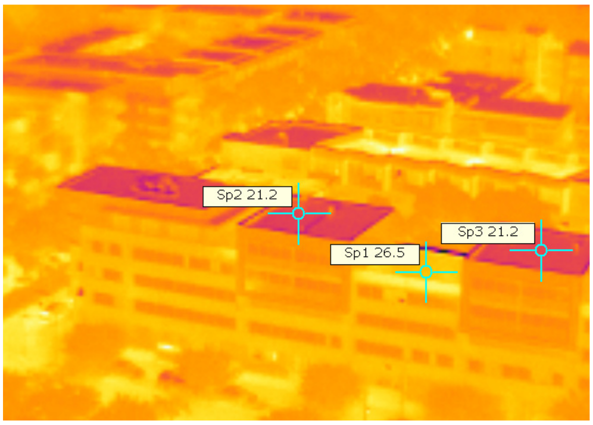
From the hand-held thermal imagery the grey rooftops are hot - ranging from 43C to 53C - when the ambient is at a maximum: yet each segment is radiating at a different rate; while at night some have cooled to 21C, others to only 26.5C.

Some other factors must be at work. It is not a simple issue at all.

Fig 31: Grey rooftops of 4-storey building facing the ESP across the park

Fig 32: Thermal Images: hot daytime; and
Fig 33: cool at night





Reflectivity Dilemma

Despite the understanding of the localized cooling benefits of reflectivity, there does not appear to be a comprehensive discussion of where the reflected heat ends up. Logic suggests that although reflectivity might be favourable for specific buildings under the urban canopy layer, the rejected heat is likely to bounce around, particularly in the urban canyon, being absorbed by other elements and/or until finally transmitted above the building rooftops into the urban boundary layer. This city-wide climate zone is replete with heat absorbing greenhouse gases emitted from the conurbation - and thus affects the urban, regional and ultimately the global climate. Certainly, reflected heat will impinge negatively on adjacent or proximate buildings that are not albedo-treated. Reflected heat will also be likely to impact on the thermal comfort of pedestrians at the base of the urban canyon. The urban multiplier thus complicates the building-scale albedo advantage since heat energy is not eliminated or even transformed by these interventions.

Two apparent resolutions appear feasible. First, in a setting with trees and living vegetation - interspersed between and amongst the heat reflecting elements – with their capacity to *transform* heat, the reflective situation could be beneficial, generically. At the edges of the urban canopy and urban boundary layer, green roofs, particularly if shaded, might well perform the same task.

Secondly, there is an **infrared sky window** in the atmosphere, where IR radiation in the narrow wavelength range from 8 to 14 µm or micrometers (of the electromagnetic spectrum) passes through unimpeded, from the sun to the earth - and back to space, without warming the atmosphere (Smith & Granqvist, 2010; Smith, 2007; (www.ipac.caltech.edu/Outreach/Edu/Windows/irwindows.html; *inter alia*). This window mechanism functions best when the atmosphere is dry (which has implications for places with high or rising humidity). At wavelengths shorter than 8 µm, H_2O and NH_3 absorb IR. At wavelengths longer than 14 µm, CO_2 and CH_4 absorb the heat. These are greenhouse gases distributed in the urban climate and global atmosphere alike – which will absorb emitted and reflected heat alike.

Radiative paints and surfaces, thus, need to be manufactured with both high albedo and high emissivity characteristics, and which function in that particular IR window range - to be effective urban climate coolers. It would appear that a standard white paint will not have this capacity.

A simple experiment conducted at Osaka City University, indicated in the diagrams below, shows the absorption and reflectivity characteristics of black and white paint and a retroreflective surface (reflecting light back in the direction it came). Other surfaces simulated represent the road and an adjacent building. The reflected heat (specular [down to the ground], diffuse [across to other surfaces] and retroreflective) raises the temperature of its surrounds; *and* this is more evident from the white and reflective surface than from the absorbent black (until darkness falls).

A useful future experiment could simulate the impact of green, living vegetative surfaces, in comparison. Theory suggests this would be the best resolution.

Fig 34: Simulated Urban Canyon Experiment #1 (Source: http://heatisland2009.lbl.gov/docs/211450-sakai-ppt.pdf)

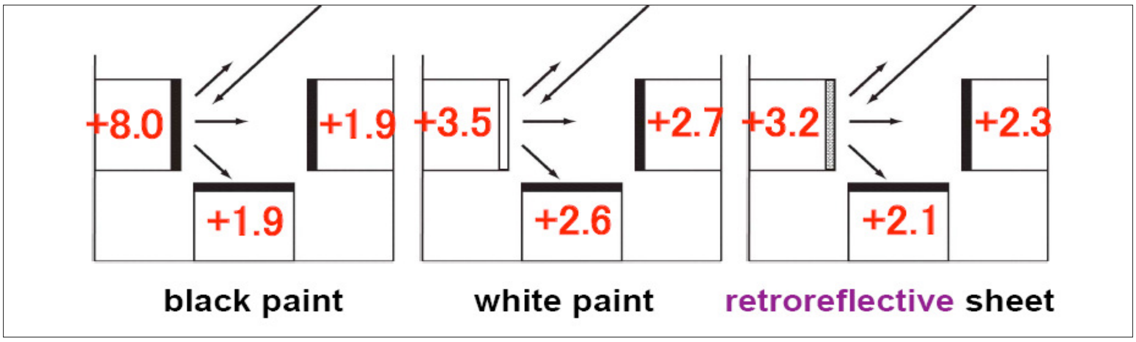
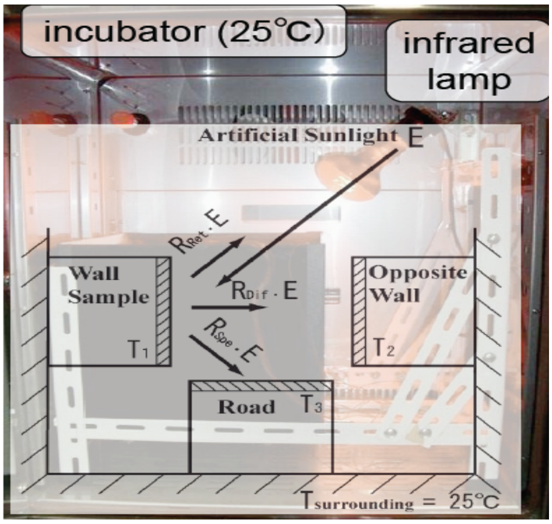
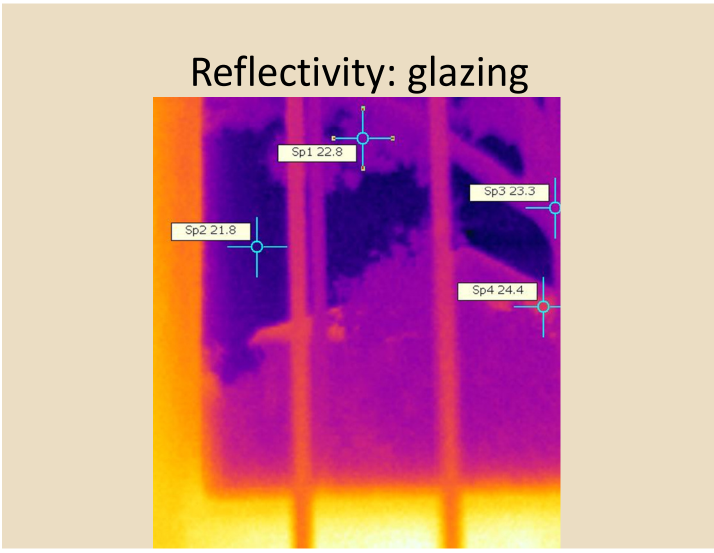


Fig 35: Simulated Urban Canyon Experiment #2



The complexity of the issue is symbolized in the thermal image below, where reflections themselves are radiating at different temperatures depending on their materiality – a realization possibly unrecognized in the literature to date.

Fig 36: Reflections of a tree, leaves, house and sky – all radiating at different temperatures



Urban Form Evaluations (in brief)

Urban geometry is implicated in urban heat island development (Oke 1981; Bärring *et al* 1985; Eliasson 1996). Urban form impacts significantly on the sky view-factor – affecting heat loss potential to the cool sky sink, at night in particular (Svensson 2002; Upmanis 1999); and canyon street geometry characterized by height/width (Grimmond & Oke 1999) and linearity/sinuosity ratios is also highly salient in the thermal performance equation.

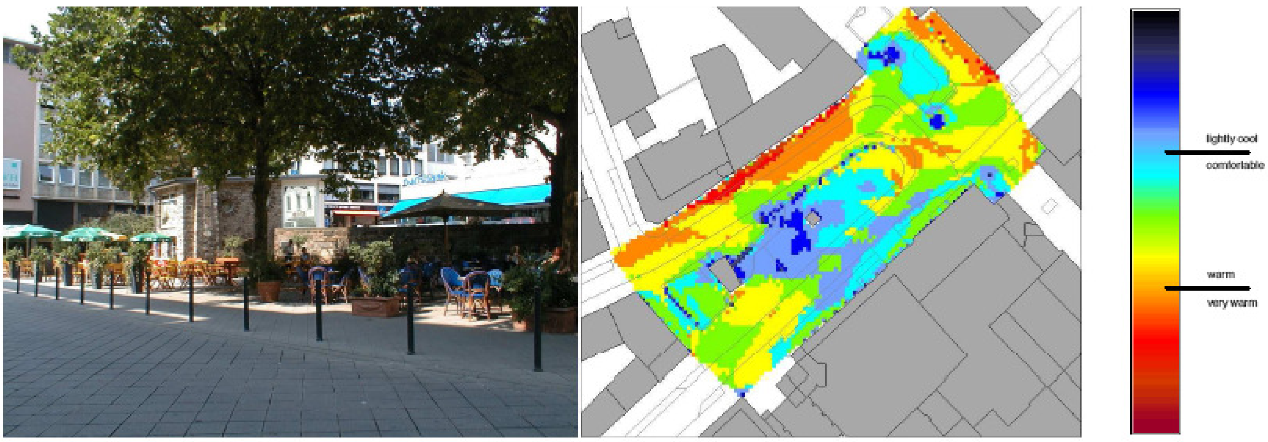
An indirect method to research the effect of form is to measure the difference in heat island intensity in varying parts of an urban setting. For instance, measurements of ambient air via digital thermometers, mounted on cars, showed the existence of heat islands in Debrecen, Hungary, one in the dense city centre and another in the belt of housing estates bordering the centre. The ratio of artificial surfaces in the city centre is high (70-80%), but consists of 4-5 storey buildings in the main; while in the housing belt, where the ratio of artificial surface cover is still relatively high (over 50%), there are also large vertical surface 10-14 storey buildings. The forest of the Nagyerdő in the North is the coolest part of the city (Szegedi & Kircsi, 2003).

Baker *et al.* (2003) suggested - for Phoenix – both high albedo materials for roads and roofs and more green areas between buildings; as well as the redesign of the city to reduce urban heating through narrower streets – a classic Old City European paradigm.

Lindberg *et al* (2003) measured intra urban temperatures in the dense urban structure of central Göteborg in Sweden, with its typically narrow street canyons but also large green areas and water bodies. A 3D GIS database was correlated with air and surface temperatures obtained from automobile traverses three hours after sunset. *Building Intensity* - a summation of building volume by area and building height - was calculated from the GIS data base for two different areas; and fish-eye photographs were taken and sky view-factor calculated. They reported surface street temperatures varying up to 6.9C but considerably smaller air temperature variations (up to 2.5C). The variations are suggested to be due to elevation (reducing the influence of advection) and uneven heating during the daytime depending on exposure to solar radiation.

In 2006, Erell, Williamson & Blaustein carried out meteorological measurements in two urban street canyons in central Adelaide and at two reference sites in a suburban location and at an exposed site near the middle of the city - for a period of nearly a year. Substantial differences were noted between air temperatures in the urban street canyons and both reference sites. Although, as expected, a nocturnal urban heat island was noted in the canyons, there was also a frequent occurrence of a weak daytime cool island during summer. Both phenomena they attribute to the increase in surface area participating in energy exchanges with the atmosphere in an urban street canyon compared to a typical rural site, and hence in an increase in effective thermal mass *ie* both storing and re-emitting heat, at different times. The effect of street and mutual building shading is also likely to be implicated.

Fig 37: Urban microclimatic conditions in an urban square (Source: Katzscher & Thorsson. 2009)



Even more recently, in Paranhos, Portugal, Balkeståhl *et al* (2008) found correlations between street geometry and building density in terms of their thermal signatures, with the urban heat island most evident in densely built up areas with a low sky-view factor.

And in 2009, Katzschner and Thorsson mapped out the geometry of an urban square in the city of Kassel, Germany using a variety of measures including surface radiation flux. They noticed a strong shadow effect on their instruments, where mean radiant temperature dropped significantly due to the decrease in short-wave radiation when shaded.

Chen-Yi Sun *et al* (2009) found air temperature in urban street canyons correlated strongly with three factors: street H/W ratio, vegetation, and building density; demonstrating that increasing vegetation **and** decreasing building density are important strategies to diminish street warming and to create a thermally comfortable environment in urban street canyons. Moreover, higher densities can have implications for air circulation.

Contemporary planning notions, in Australia (and elsewhere), however, advocate higher densities in more compact forms. Where such developments are perimeter blocks with good sky views, internal courts and/or green roof-spaces and/or green walls, the thermal budget can be tipped in favour of cooling despite the greater thermal massing; and orientation to prevailing breezes can be influential too. It is not simply an issue of form.

3D GIS-based urban modelling can now map occupancy and other parameters vertically as well as horizontally (as per the ongoing UNSW/FBE/City Futures Research Centre/UrbanIT Project).

In any event, adding to the strategy of measuring ambient temperatures to distinguish the UHI – with a radiant emissivity metric via thermography – advances the understanding.

Urban Sustainability Rating Systems: UHI Cooling

Several built environment sustainability rating systems are currently available, nationally and internationally: MIST (EPA) and LEED (US/GBC) in the US, BREEAM (UK), the Sustainable Building Council Certificate System and the Assessment Matrix (Germany), and Australian sustainability codes like BASIX, GreenStar (GBC) and PRECINX (Landcom). Note: they deal primarily with horizontal rather than vertical surfaces.

This is not the place to review their relevance, but only to comment on whether or not they contain credits for UHI cooling. Of primary relevance is the suite of the LEED rating schemes (see Appendix II).

LEED-Neighborhood (ND) addresses city-related climate change issues – including buildings, vehicle travel and land use change – in terms of their microclimatic heat island effect. The categories are:

I. Smart Location & Linkage (30 points)

II. Neighborhood Pattern & Design (39 points)

III. Green Construction & Technology (31 points)

IV. Innovation & Design Process (6 points)

LEED ND Credit 14 – affords 1 point for each parameter: tree lined streets AND shaded streets - (total of 2 points available).

LEED ND Credit GIB 9 - affords 1 point for implementing one of 3 options(no extra points for 2 or more options): nonroof measures such as shading an impervious site by structures or tree canopies OR pervious or high reflectance cool paving OR high reflectance or vegetated green roofs, OR a mix of measures.

In addition, LEED-ND offers a credit for solar orientation: either orienting blocks north-south or buildings east-west.

LEED New Construction Sustainable Sites Credit 7.1 – affords 1 point for implementing one of the 2 options: any combination covering 50% of the site of the nonroof parameters listed in LEED ND Credit 14 (shade/albedo/porosity) OR a minimum of 50% of parking spaces under cover (no extra points for both options).

LEED Version 2.2 (2005) uses Solar Reflectance Index (SRI) - rather than solar reflectance, thermal emittance or the US Energy-Star™ compliance - to qualify a cool pavement. LEED requires a cool pavement to have a minimum SRI 29. Energy Star requires that low-sloped roofing products have initial and three-year-aged solar reflectance of not less than 0.65 and 0.50, respectively; while steep-sloped roofing products must have initial and three-year-aged solar reflectance of not less than 0.25 and 0.15, respectively.

Further, since 1999, several widely used building energy-efficiency standards, including ASHRAE 90.1, ASHRAE 90.2, the International Energy Conservation Code, and California's Title 24 have adopted cool-roof credits or requirements.

The Mitigation Impact Screening Tool (MIST) is a recent US Environmental Protection Agency 'Heat Island Effect' software tool - for American cities - that estimates the impacts of urban heat island mitigation strategies on urban air temperatures, ozone and energy consumption (www.epa.gov/hiri/resources/index.htm).

MIST demonstrates generically how heat island mitigation strategies can be deployed at the city scale to achieve local temperature reductions. It deals with large scale albedo modification, and vegetation modification and combinations of the two to help ameliorate UHI. Variations can for instance range between -0.5 to +0.5.

Many assumptions are made, and acknowledged, including the simplification where MIST applies any temperature change uniformly across the city and throughout the year. Certainly, the tool deals with some crucial factors, but it is uncertain that robust design-policy decisions could be made based on simulations at this generic scale.

Moreover, the MIST claim is made that "On a clear, dry summer day, up to 80% of the solar heat reflected by cool roofs (ie long waves) passes back through the atmosphere and out into space, and does not heat the air in the city", (see Dilemma discussion, earlier).

Also, from 1998, five US cities participated in the EPA's Urban Heat Island Pilot Project, the basic purpose of which was to assist cities in their efforts to evaluate and adopt and heat island reduction strategies and programs; also related to ground-level ozone pollution (affected by light and heat). Here The Department of Energy's Lawrence Berkeley National Laboratory (LBNL) conducted land use characterizations of the cities to further help them identify target areas for change. LBNL also modelled the potential air temperature, energy, and air quality impacts from wide-scale adoption of heat island reduction strategies (see: http://www.epa.gov/hiri/pilot/index.htm).

In (NSW) Australia, BASIX - the Building Sustainability Index - takes energy and water efficiency into account particularly at individual house level; while other site specific rating tools such as NABERS and Green Star (GBCA) are also aimed at improving sustainability. Yet none of these three tools addresses urban heat island and city cooling.

Pitched at the broader precinct scale (large–scale residential), the PRECINX sustainability planning and design diagnostic tool has been recently introduced by Landcom (in 2010). It addresses GHG energy and emissions, embodied carbon in materials, water, stormwater, transport options and housing diversity.

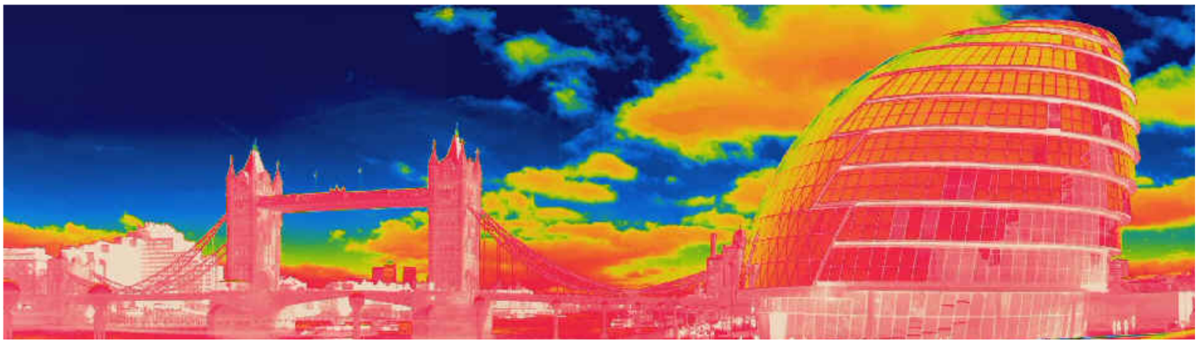
It makes no mention, however, of strategies to ameliorate the UHI. Neither does it address landscaping and shading and trees as potential precinct coolers.

The lack of scientifically verified data on the measurable environmental benefits of trees or other landscape components (particularly in the Australian context) on the reduction of local temperatures has been suggested as possibly why, in a review of the tool (by Ingrid Mather, landscape architect). The Victoria Park research goes some of the way towards ameliorating this issue.

The addition of a micro-urban scale thermal index can add flesh to these bones. It can indicate any number of relationships not itemized in LEED. For instance, the temporally varying influence of the shade of a tree in a park (compared to that on a paved surface), or the thermal mass properties of water over a diurnal cycle, or the comparative effect of a concrete and wooden bench set on paving or in a park. And, of course, the albedo/emissivity characteristics of any surface, coloured from black to white; and the emissivity impact and radiant contribution of roads, and cars and air conditioners and other energy equipment to the localized ambient temperature...and of people in the public realm.

Fig 38: London's Tower Bridge and City Hall (Source: Thermalcities.com)

Thermal imagery is also just fun!



Appendix II: UHI Excerpts from: LEED 2009 for Neighborhood Development (Leadership in Energy and Environmental Design)

GIB Credit 9: Heat Island Reduction

1 point

Intent

To reduce heat islands to minimize effects on the microclimate and human and wildlife habitat.

Requirements

OPTION 1. Nonroof Measures

Use any combination of the following strategies for 50% of the nonroof site hardscape (including roads, sidewalks, courtyards, parking lots, parking structures, and driveways):

a. Provide shade from open structures, such as those supporting solar photovoltaic panels, canopied walkways, and vine pergolas, all with a solar reflectance index (SRI) of at least 29.

b. Use paving materials with an SRI of at least 29.

c. Install an open-grid pavement system that is at least 50% pervious.

d. Provide shade from tree canopy (within ten years of landscape installation).

OR

OPTION 2. High-Reflectance and Vegetated Roofs

Use roofing materials that have an SRI equal to or greater than the values in Table 1 for a minimum of 75% of the roof area of all new buildings within the *project*; or install a vegetated ("green") roof for at least 50% of the roof area of all new buildings within the project. Combinations of SRI-compliant and vegetated roofs can be used provided they collectively cover 75% of the roof area of all new buildings (use the equation in Option 3).

Table 1. Minimum solar reflectance index value, by roof slope

Roof slope	SRI
Low (≤ 2:12)	78
Steep (> 2:12)	29

OR

OPTION 3. Mixed Nonroof and Roof Measures

Use any of the strategies listed under Options 1 and 2 that in combination meet the following criterion:

$$\frac{\text{Area of Nonroof Measures}}{0.5} + \frac{\text{Area of SRI Roof}}{0.75} + \frac{\text{Area of Vegetated Roof}}{0.5} \geq \text{Total Site Hardscape Area} + \text{Total Roof Area}$$

NPD Credit 14: Tree-Lined and Shaded Streets

1–2 points

Intent

To encourage walking, bicycling, and transit use and discourage excessive motoring speeds. To reduce urban heat island effects, improve air quality, increase evapotranspiration, and reduce cooling loads in buildings.

Requirements

OPTION 1. Tree-Lined Streets (1 point)

Design and build the *project* to provide street trees on both sides of at least 60% of new and *existing streets* within the project and on the project side of bordering streets, between the vehicle travel way and walkway, at intervals averaging no more than 40 feet (excluding driveways and utility vaults).

AND/OR

OPTION 2. Shaded Streets (1 point)

Trees or other structures provide shade over at least 40% of the length of sidewalks on streets within or contiguous to the project. Trees must provide shade within ten years of landscape installation. Use the estimated crown diameter (the width of the shade if the sun is directly above the tree) to calculate the shaded area.

AND

FOR ALL PROJECTS INVOLVING STREET TREE PLANTINGS

Obtain a registered landscape architect's determination that planting details are appropriate to growing healthy trees, taking into account tree species, root medium, and width and soil volume of planter strips or wells, and that the selected tree species are not considered *invasive* in the project context according to USDA or the state agricultural extension service.

Appendix III:
Temporal Transience by Element and Orientation

Temporal Transience/Emissivity Indicators: Summer Season 2010

ELEMENT

NORTH

TIME	Road	Car	Walls				corrugated		Column	Paving		Swale South	Trees eucalypt		broadleaf	Grass		Water		Ambient	Humidity
	black		black	white	brown	grey	grey-white W	S	grey	sun	shd/N		sun	shd/N	shd/N	sun	shd/N	D	N	C°	%
midday	52		43	31					42				32			36	28			**28**	*63*
20h	29		26	26					26					25			24			**27**	*66*
midnite	27		26	26					26					25			24			**27**	*72*
dawn	23		24	24					25					23			22			**25**	*81*
ΔTr	*29*		*19*	*7*					*15*				*9*			*14*	*4*			*-3*	*+18*

EAST

TIME	Road	Car	Walls black	white	brown	grey	corrugated W	S	Column	Paving sun	shd/N	Swale	Trees sun	shd/N	broadleaf shd/N	Grass sun	shd/N	Water D	N	Ambient	Humidity
midday	52	50		30	46	40				54	35		31							**30**	*57*
20h	29	28		25	26	26					28			26						**27**	*66*
midnite	29	28		25	26	26					28			25						**27**	*72*
dawn	25	23		24	25	24					26			24						**25**	*86*
ΔTr	*27*	*27*		*6*	*21*	*16*				*28*	*9*		*7*							*-5*	*+29*

All figures averaged, and rounded (.5+↑)

Temporal Transience/Emissivity Indicators: Summer Season 2010

ELEMENT

SOUTH

TIME	Road	Car	Walls				corrugated		Column	Paving		Swale South	Trees eucalypt		broadleaf	Grass		Water		Ambient	Humidity
	black		black	white	brown	grey	grey-white W	S	grey	sun	shd/N	dry	sun	shd/N	shd/N	sun	shd/N	D	N	C°	%
midday	47	53	29	26		30		27			28	32		30						**32**	*54*
20h				26				27												**26**	*72*
midnite				26				26												**26**	*79*
dawn	24	25	25	24		24		26			25	24		24						**24**	*87*
ΔTr	*23*	*28*	*4*	*2*		*6*		*1*			*3*	*8*		*6*						*-8*	*+33*

WEST

TIME	Road	Car	Walls black	white	brown	grey	corrugated W	S	Column	Paving sun	shd/N	Swale	Trees sun	shd/N	broadleaf shd/N	Grass sun	shd/N	Water D	N	Ambient	Humidity
MidArvo	54	55	46	32	45	32	36		43	45	30	32	31		28	34		29		**35**	*29*
20h																				**26**	*72*
midnite																				**25**	*74*
dawn	25	25	25	24	25	25	26			25		23		24	24		22		23	**24**	*87*
ΔTr	*29*	*30*	*21*	*8*	*20*	*7*	*10*			*20*		*9*	*7*		*4*	*12*		*6*		*-11*	*+58*

All figures averaged, and rounded (.5+↑)

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