P. Rajagopalan, V. Soebarto and H. Akbari (Eds.), *6th International Conference on Countermeasures to Urban Heat Islands (IC2UHI)*, pp. 265-274. ©2023, RMIT University, Melbourne, Australia

Mitigating Heat Islands and Simulating Efficacy in Future Climate Scenarios

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ABSTRACT

While there are several methods proposed for quantifying Urban Heat Islands, they focus mainly on air temperature or sky exposure, as they are used in the context of evaluating impact on building cooling loads and demand for air conditioning. Furthermore, these metrics identify the problem at a macro level and tend to focus on identifying current patterns rather than evaluating future scenarios within the context of a changing climate. This paper aims to evaluate the impact of heat islands on human health and habitability, focusing on occupants in the public realm, their experience of heat stress and how these spaces might be adapted using local interventions to maintain comfort in future years.

This study proposes to use the metric of Universal Thermal Climate Index, to account for the impact of physiological and local environmental factors on the experience of thermal stress. This approach will undertake annual hourly simulations for a typical public space in Sydney using the Microclimate tool developed by Virtual Climate, to evaluate comfort distribution across the space throughout the year and identify how often comfort thresholds are exceeded. These simulations will be rerun with passive mitigation measures for a comparative analysis to quantify the impact of interventions and evaluate the efficacy of these measures in the future, using predicted weather files developed by the Commonwealth Scientific and Industrial Research Organisation.

Keywords: Adaptation, Microclimate, Pedestrian comfort, Annual CFD.

Introduction

Various methods have been proposed to quantify Urban Heat Islands (UHI), ranging from Land Surface Temperature (LST) based on satellite observations (Cheval and Dumitrescu 2008), to Sky View Factor (SVF) as a proxy (Dirksen et al. 2019). While these methods identify the issue at a macro level, evaluating the overall built form, they fail to provide effective solutions since existing buildings cannot be summarily modified. Furthermore, they merely reveal current patterns rather than predicting future trends in a changing climate. We are already living through the impacts of climate change, and they will intensify over the coming decades. This highlights the need to implement targeted adaptation measures for the habitable public realm, to improve long term resilience.

Addressing the impact of heat islands on human health and comfort requires a metric that considers physical and environmental factors beyond air and surface temperature. This study proposes the use of the Universal Thermal Climate Index, or UTCI (Blazejczyk et al. 2013) to account for the impact of solar radiation, temperature, humidity, local air speed,

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urban morphology, clothing and activity levels on the experience of thermal stress. Additionally, pedestrian wind comfort will be evaluated using the Dutch standard NEN 8100.

This paper undertakes annual hourly analyses for Martin Place in Sydney using the Microclimate tool developed by Virtual Climate. The climate in Sydney is largely temperate, with mild winter temperatures ranging from 8-17°C and average summer temperatures ranging from 20-30°C. However, over the past 20 years, summer temperatures have frequently exceeded 30°C with peak temperatures reaching 40°C on multiple occasions. This can impact the usability of public spaces, particularly in the city centre. Martin Place was selected because it is fully paved and surrounded by tall buildings and hard surfaces, which reflects and re-radiates heat and can exacerbate warm discomfort.

The first iteration establishes a baseline using recent meteorological data from 2007 – 2021, to establish the UTCI distribution across the space throughout the year and identify how often comfort thresholds are exceeded. These simulations are subsequently rerun with the inclusion of passive mitigation measures, to quantify the impact of these measures.

The final iteration will evaluate the efficacy of these mitigation measures in the future, i.e., the extent of increase in heat stress hours, using predicted weather files for 2030 and 2050 developed by CSIRO (Chen et al. 2020).

Methodology

The analyses described in this paper use a cloud-based microclimate analysis tool that combines a range of open-source software such as Radiance for radiation distribution, OpenFOAM for the Computational Fluid Dynamics (CFD) and ParaView for data analysis and visualisation as outlined in a previous paper (Baliga et al. 2018). This tool delivers dynamic hourly analyses for solar radiation, wind, and thermal comfort distribution via a plugin for SketchUp. This enables analyses for any time of year, and for any 'area of interest' in the 3D model, allowing us to explore granular variations in microclimate conditions.

Figure 1. Model used for analysis showing area of interest in red (left and centre) and satellite overview (right).

The area of interest for this analysis – highlighted in red in Figure 1 – focuses on the eastern end of Martin Place with Elizabeth St. on the left and Macquarie St. on the right. The model and satellite images show the density of buildings and ubiquity of hardscape surfaces. The analysis results are mapped at a height of 1m above the ground.

Data used in the model are from publicly available datasets. The 3D geometry was sourced from OpenStreetMap, terrain data from Elvis – Elevation and Depth – Foundation Spatial Data, and weather files in EPW format for present and future conditions from ClimateOneBuilding and CSIRO's AgData Shop respectively.

The weather file used to represent present-day conditions is a Typical Meteorological Year (TMY) file based on measured data from 2007-2021 at Sydney Observatory Hill. For future weather conditions in 2030 and 2050, files for Representative Concentration Pathway

(RCP) 2.6 were used, since this has been the reference emissions pathway targeted by most governments.

Annual analysis was undertaken for likely ‘habitable’ hours of 8am – 10pm, for 365 days. Simulations were undertaken for the options outlined below and representative geometries for relevant options are shown in Figure 2.

Baseline

The surface paving was modelled as the current bluestone paving with a reflectivity or albedo of 0.35. The baseline was modelled as entirely unshaded, and simulation was undertaken only for present-day weather data.

High Albedo

For this option, the geometry was the same as the baseline, but the surface paving was modelled with a high reflectivity or albedo of 0.75, similar to that of concrete with white Portland cement. While albedos in this range would be considered highly reflective for streetscapes, the aim was to represent potential solutions being tested globally, such as the cool pavements initiative in Los Angeles, which involves painting streets white to combat UHIs. The area of interest was modelled as entirely unshaded and was simulated only with present-day weather data.

Baseline with Shading

The analysis focused on outdoor seating at either end of the area of interest; these habitable spaces were the focus of improvement measures for comfort. Since the main source of warm / hot discomfort in the unshaded baseline is direct radiant gain, this option modelled shading over both seating areas – the central image in Figure 2 – including trees present next to Elizabeth St. and built-up shading on the Macquarie St. side. The surface properties of the ground are the same as the baseline, and this option was simulated with present-day weather to calculate improvement in comfort compared to the unshaded baseline. It was also simulated for 2030 and 2050 to review if, and how often, comfort conditions are achieved.

Baseline with Shading and Wind Breaks

Issues with wind comfort were identified in one of the future scenarios. This option – baseline with shading in 2050 – was re-evaluated with wind breaks in the form of topiary potted plants with wide canopies (image on the right in Figure 2).

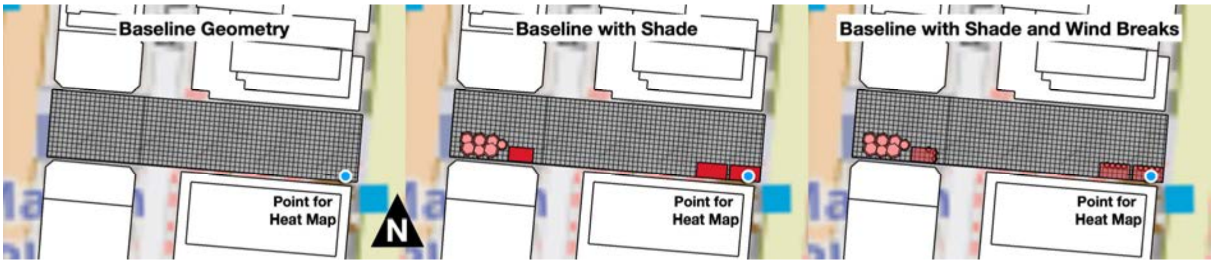

Figure 2. Representative geometries modelled for area of interest with seating areas at either end.

Results and Discussion

An overview of thermal and wind comfort results for each of the options simulated is described below in the context of the metrics used.

The thermal comfort 'band' for UTCI ranges from 9 – 26 indicating no thermal stress, with values < 9 indicating cold stress and values > 26 indicating hot stress. The NEN-8100 wind comfort standard defines comfort for sedentary or low activity spaces, as those where wind speeds exceed 5 m/s for less than 5% of hours annually.

Baseline

Figure 3 provides an overview of baseline heat stress; the images on the left show how often the area analysed experiences heat stress; UTCI > 26, and strong heat stress; UTCI > 30 across the entire year. The images on the right show the same results for the warmer months of spring and summer. In line with the temperate climate experienced in Sydney, occupants in the area analysed experience heat stress for less than 15% of annual hours. Due to the higher sun angles and ubiquity of hardscape areas, hot discomfort is prevalent in spring and summer. Figure 3 results on the right, show that in the warmer seasons, occupants would experience heat stress for 16% - 24% of occupied hours.

This translates to a maximum of 649 hours of heat stress across spring and summer. A subset of the overall heat stress, includes 193 hours with the UTCI > 30, indicating strong heat stress. Allowing for 14 hours of occupancy per day, this equates to over 46 days overall, where occupants experience heat stress for each of the 14 hours, including 13.7 days where they experience strong heat stress. The rest of this paper will refer to these equivalent 14-hour days with UTCI > 26 as 'hot' days, and UTCI > 30 as 'very hot' days.

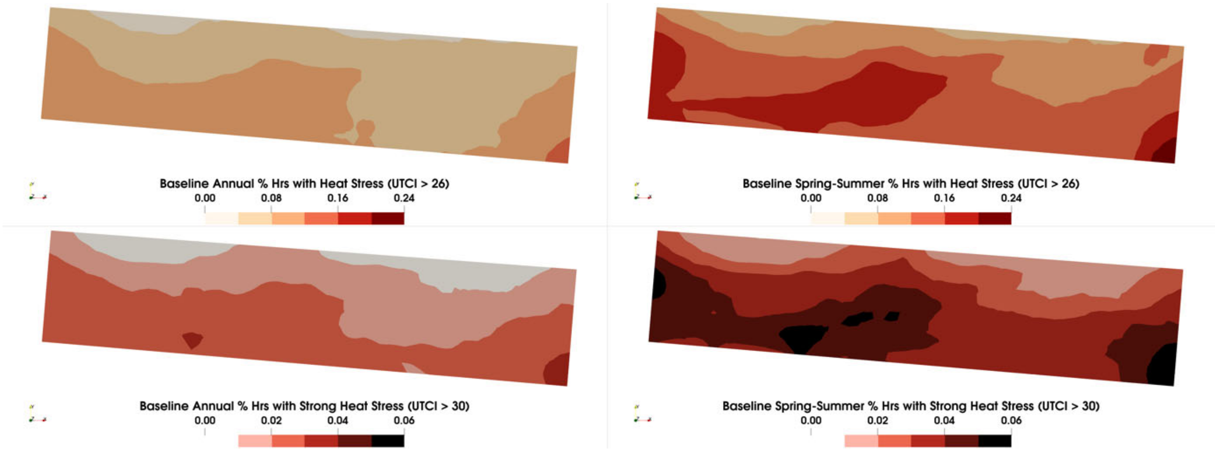

Figure 3. Baseline – heat stress distribution across the year (left) and in the warmer months (right).

The annual average wind speed – shown to the left in Figure 4 – is higher on the eastern end adjacent to Macquarie Street, forming a wind funnel. The wind comfort results – on the right in Figure 4 – show that high wind speeds occur between 10 – 20% of annual hours. While the wind comfort is within acceptable limits for part of the seating area on the eastern end, the street access to Martin Place would be better used as a transitory space and would not be ideal for prolonged use.

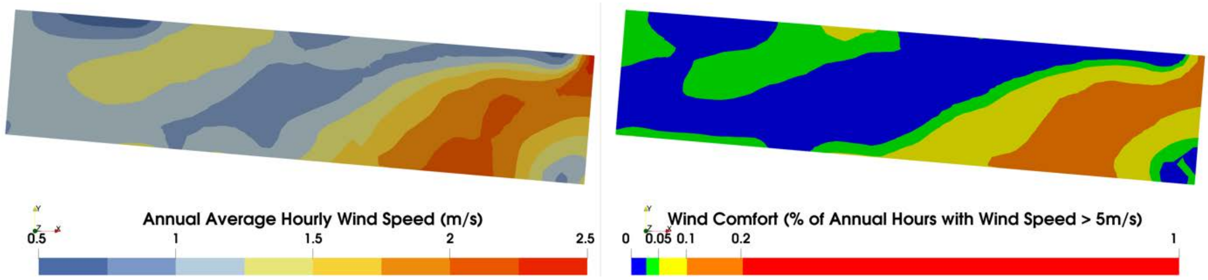

Figure 4. Baseline – annual average wind speed (left) and annual wind comfort (right).

High Albedo

A typical approach to ameliorating heat islands is reducing surface temperatures by increasing reflectivity of hardscape surfaces. However, this was observed to worsen comfort conditions compared to the baseline during the warmer times of the year. Overall, this resulted in 775 hours of heat stress, or over 55 equivalent ‘hot’ days in the warmer months. Of the additional 9 ‘hot’ days compared to the baseline, 7.4 days are ‘very hot’ with UTCI > 30, indicating that the increase is primarily in strong heat stress.

The expected impact of increased reflectivity is lower surface temperatures, since less incident radiation is absorbed. A comparison between the ground surface temperatures for the baseline and high albedo option shown in Figure 5 indicates that the surface temperature is indeed reduced. However, the impact on human comfort is still detrimental. This result can be explained by the fact that the radiant impact of lower surface temperatures is overshadowed by the impact of increased reflected radiation onto occupants, due to higher albedo. This aligns with observations by others (Erell, Pearlmutter, and Boneh 2012) that higher albedo can negatively impact human thermal comfort due to increase in reflected radiant gain. Incidentally, this pattern has also been observed in buildings where increased reflectivity in adjacent external paving has resulted in higher cooling loads (Kleissl and Yaghoobian 2012).

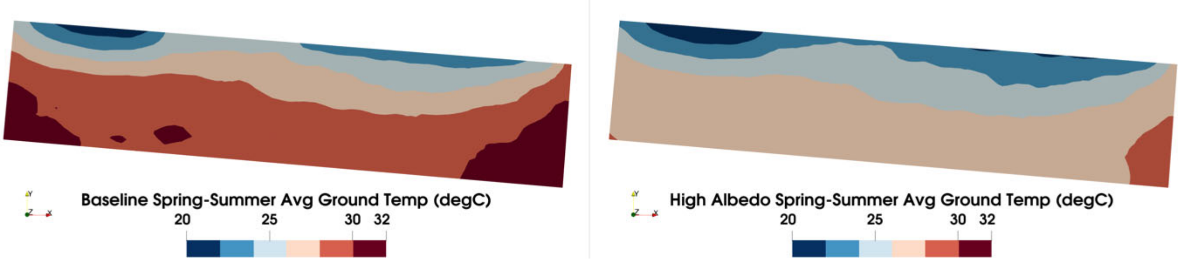

Figure 5. Baseline (left) vs high albedo (right) – average ground temperature comparison.

Baseline with Shading

The inclusion of shading reduces the maximum number of heat stress hours to 227, or 16.2 ‘hot’ days. This is a 65% reduction compared to the baseline. The occurrence of strong heat stress with UTCI > 30 is also reduced to 36 hours per year, or 2.6 ‘very hot’ days; a reduction of over 80%. As expected, the inclusion of shading addresses the key factor affecting hot discomfort by meaningfully reducing direct radiation on people.

The remaining hot discomfort hours were further interrogated to identify other causal factors. In most cases, heat stress was caused either by direct solar gain in the morning hours when the sun angle is low enough to get below the shade – shown on the left in Figure 6 – or due to lack of air movement with the wind speed being low or zero – shown on the right – occasionally a combination of both.

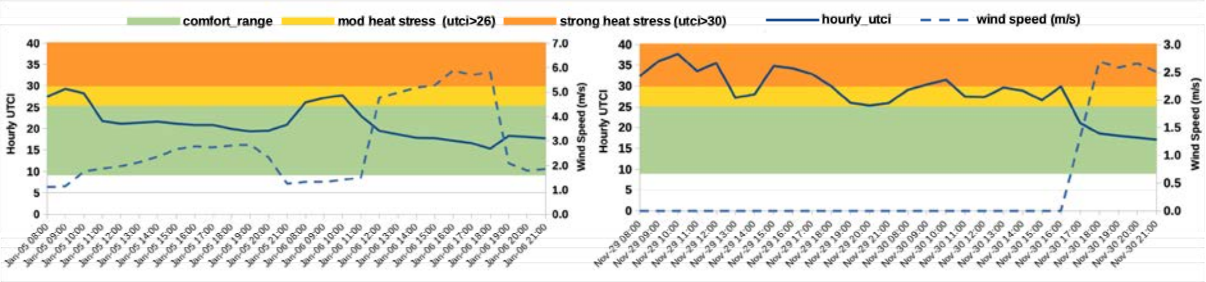

Figure 6. Examples of hot discomfort due to solar gain in January (left) and low wind speed in November (right).

Baseline with Shading (2030)

The inclusion of overhead shading alone produced a meaningful reduction in hot discomfort, rendering the seating spaces comfortable for over 91% of hours in spring and summer under current climate conditions. When the performance of this solution was further evaluated for future weather conditions in 2030, the overall number of discomfort hours stays in the same range as the present-day results. Overall, heat stress was experienced for 222 hours, or 15.9 'hot' days in the warmer seasons. The occurrence of strong heat stress with UTCI > 30 was also reduced to 27 hours per year, or 1.9 'very hot' days.

The minor reduction in hot discomfort for the 2030 simulation can be explained by the weather data, where the higher temperatures in 2030 are offset by far fewer hours with stagnant air, having a wind speed of 0. The present-day CFD results show the air being stagnant for 50% of occupied hours as opposed to 1% of the time in 2030 results.

Baseline with Shading (2050)

When the shaded option is tested with 2050 weather data, heat stress was experienced for 250 hours or 17.9 'hot' days, with strong heat stress occurring for 42 hours or 3 'very hot' days. While these results indicate a minor increase in thermal discomfort compared to the present-day, the overall results are promising. When interrogating these results further, it was observed that the 2050 weather data showed not only fewer hours with stagnant air, but also noticeably higher wind speeds compared to the present-day weather data. This is borne out by a comparison between wind comfort results in Figure 7, which shows wind speeds high enough to cause safety and comfort issues next to the street entrance.

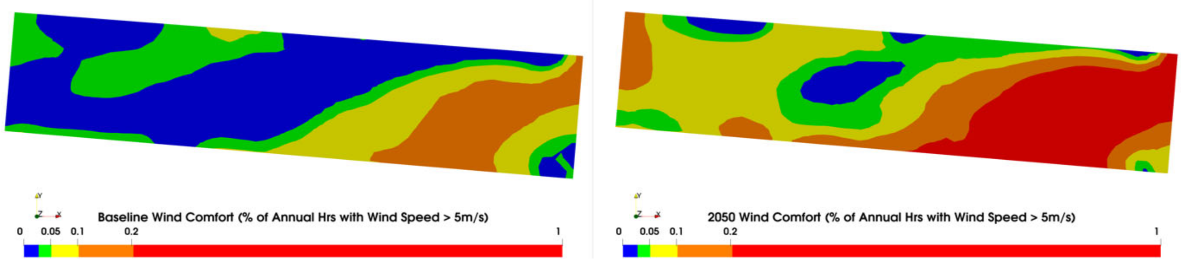

Figure 7. Present-day (left) vs 2050 (right) – annual wind comfort comparison.

Baseline with Shading and Wind Breaks (2050)

As a result of the wind comfort results discussed above, this option was re-evaluated with wind breaks around the seating area to review the impact on local air speeds, wind comfort and thermal comfort. The wind speed was reduced in part of the eastern seating area as shown in both images in Figure 8, but in the rest of the traversable area on the Macquarie St. end, the wind speed remains high enough to compromise wind comfort and safety.

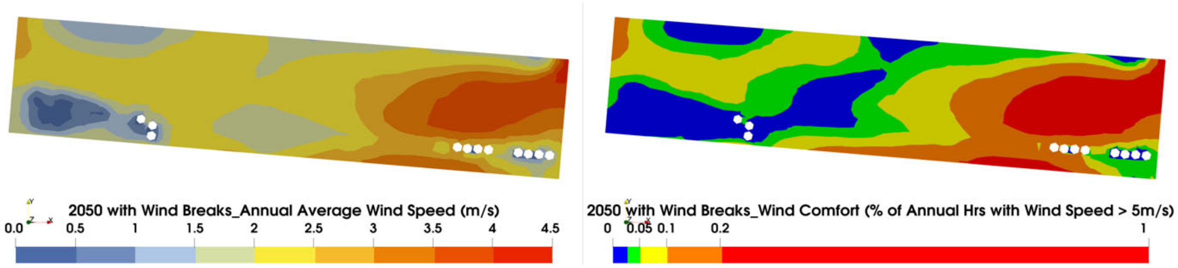

Figure 8. 2050 with wind breaks – annual average wind speed (left) and annual wind comfort (right).

In terms of thermal comfort, the overall heat stress amounted to 265 hours, or 18.9 'hot' days, with strong heat stress occurring for 49 hours or 3.5 'very hot' days. This represents only a minor increase in thermal discomfort, without a significant increase in strong heat stress.

Depending on the focus, further improvements can be targeted towards the seating areas or the overall traversable area, by including a larger wind break across the Macquarie St. entrance to Martin Place. These results demonstrate that trying to ameliorate thermal stress resulting from heat islands may require a trade-off between thermal comfort, wind comfort and safety, and urban planners and decision makers need to weigh the effectiveness of future decisions based on their priorities.

Summary of Results

Figure 9 shows a comparative visual summary of hot discomfort results in warmer months, for each of the options tested. These distribution maps show the number of hours when occupants experience heat stress across the area of interest.

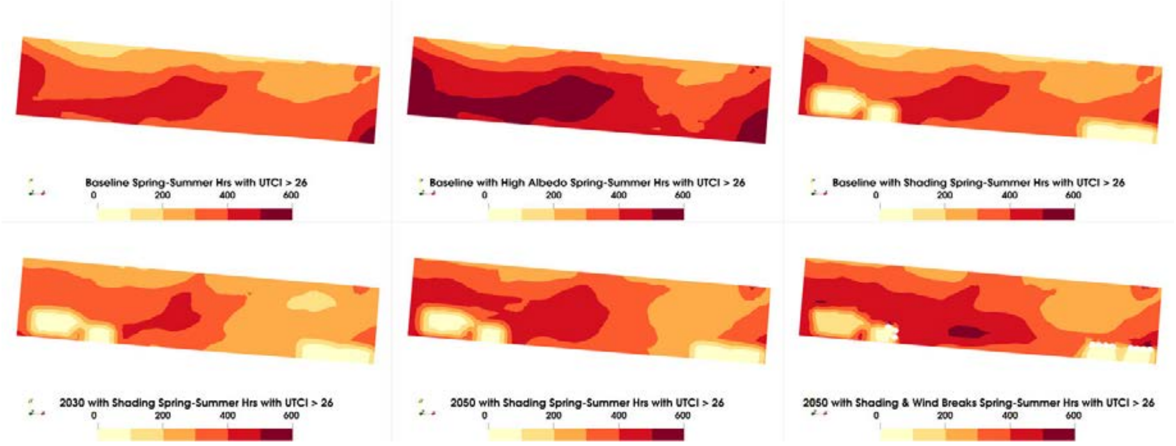

Figure 9. Distribution maps showing hours of heat stress in warmer months for all options modelled.

While the baseline calculation relied on measured weather data, this study did not have an opportunity to retrieve detailed measurements from the actual site. However, since this is a comparative analysis, a primary insight gained from the study is the relative impact of a range of interventions on heat stress. Even with changes to the baseline, the effectiveness of the solutions tested will remain consistent relative to each other. The number of summer heat stress hours might change but the pattern of increase or decrease in heat stress would remain consistent.

A granular hourly view of thermal comfort in the form of heat maps for each option modelled, is shown in Figure 10. In these heat maps, the x-axis represents the day of the year, and the y-axis shows the time of day. In the colour legend for hourly UTCI, the values outside the comfort range are represented as dark blue for UTCI < 9 denoting cold stress, and dark red > 26 denoting heat stress.

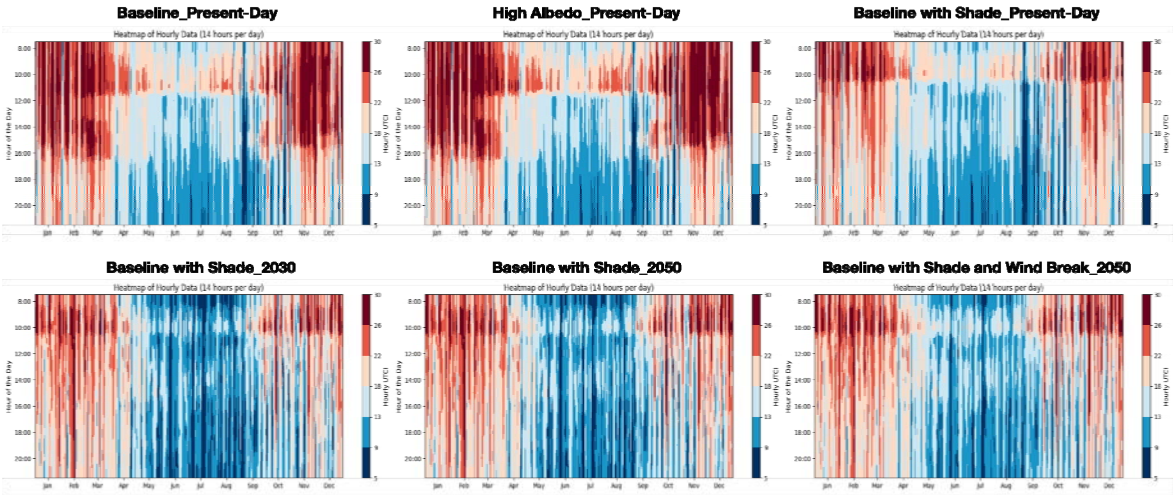

Figure 10. Annual hourly heat maps for all options modelled.

A tabular summary of the heat maps is outlined in Table 1.

Table 1. Summary of Hot Discomfort Results for All Option Modelled

Options Modelled	Hours with UTCI > 26	Hours with UTCI > 30	Change in Discomfort
Baseline	649	193	n/a
High albedo	775	297	+19.41%
Baseline with shade	227	36	– 65.02%
Baseline with shade (2030)	222	27	– 65.79%
Baseline with shade (2050)	250	42	– 61.48%
Baseline with shade and wind breaks (2050)	265	49	– 59.17%

Observations on Future Weather Data

Over the course of this analysis, it was observed that the weather data based on RCP 2.6, which limits projected warming to 2°C, appears to be an optimistic option in terms of future temperatures and emissions scenarios. The present-day data set from 2007-2021 shows higher peak temperatures than the projected weather data for 2030 or 2050 and the future weather data rarely exceeds the nominal skin temperature of 34°C.

A comparison of the dry bulb temperatures (DBT) from the three weather files used, is shown in Table 2.

Table 2. Dry Bulb Temperature (DBT) Comparison for Weather Files

	DBT (2007-2021)	DBT (2030 RCP 2.6)	DBT (2050 RCP 2.6)
Minimum (°C)	5.3	6.1	6.6
Maximum (°C)	40.8	38.3	39.6
Average (°C)	19.6	20.4	20.8
90th Percentile (°C)	25.3	26.3	26.6
No. of Hours > 34°C	25	23	30

RCP 2.6, projections are based on carbon emissions gradually starting to decline from 2020. Since this has not been achieved, the current rate of emissions and the comparison shown in Table 2 indicate that the predicted weather files might be optimistic, and that eventual weather data for 2030 and 2050 will likely be warmer than the pathway projected by RCP 2.6.

Conclusions

Heat islands need to be addressed differently depending on whether the aim is to reduce surface temperatures or address human comfort and liveability. Conventional mitigation strategies such as increased reflectivity for hard surfaces might not be a panacea and may in fact have a detrimental impact on outdoor thermal comfort.

In most warm climates, an effective way to mitigate heat islands is to include significant shading, from built-up structures and vegetation. Breaking up continuous hardscape surfaces with vegetation or water bodies can vary the ‘texture’ of the urban form and more effectively address the radiant gain that leads to UHIs. This can also help modulate the local wind environment to enhance safety and comfort.

The current study outlined how the inclusion of shading could reduce the occurrence of heat stress even in the context of a warming climate. Future iterations of this study could look at improving wind safety in the eastern access to Martin Place, which would likely lead to an increase in heat stress. Addressing this heat stress would require evaluation of additional strategies not covered in this paper, such as the use of evaporative cooling or spill air from neighbouring conditioned buildings. This could also include local weather measurements at several points within the site, to generate UTCI values to test and validate the baseline results.

This paper outlines an approach that allows decision makers to identify potential problem areas and quantify the impact of proposed interventions in the present-day and evaluate their efficacy in the future. This is applicable to most countries with warm climates, but particularly meaningful in a nation like Australia, that prioritises time spent outdoors.

Refurbishments of public spaces are not frequent and the proposed approach allows cities and local councils to virtually test proposed adaptation strategies to confirm that they will be viable over the coming decades, de-risking their monetary and labour investment.

This would be of particular importance to streetscapes created to encourage walkability. By quantifying thermal comfort for pedestrian areas and cycling routes, urban planners can test solutions to minimise discomfort hours and incentivise walking as a form of transport. This approach can also help identify optimal routes to promote the use of cycling lanes or pedestrian-only zones.

One of the outcomes of this study is that there is unlikely to be a standard solution that applies across the board. However, requiring some form of performance assessment for new and existing external spaces, focused on liveability and occupant comfort, would greatly benefit the quality of the public realm. This approach would be analogous to internal environment quality standards currently implemented for building design.

Implementing such performance requirements for the public realm, followed by post-occupancy evaluation, can form the basis for creating habitable cities that are liveable now and into the future.

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Sydney Terrain Data https://elevation.fsdf.org.au

UHI2023
6th International Conference on
Countermeasures to Urban Heat Islands
4 - 7 December 2023 | Melbourne, Australia

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ISBN 978-0-646-88538-4