LOW CARBON LIVING CRC

Preliminary design of a smart climatic road in Phillip St. Parramatta

Final report

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- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2007),

and provided constructive feedback which was considered and addressed by the author(s).

Contents

LOW CARBON LIVING CRC

1. GLOSSARY OF TERMS

Glossary

Albedo: Albedo is a measure of reflectivity of a surface; i.e. the proportion of the incoming solar radiation that is reflected by the surface back into the atmosphere. It is determined by a value between 0 and 1.

Anthropogenic Heat Flux: is the heat flux resulting from vehicular emissions, space heating and cooling of buildings, industrial processing and the metabolic heat release by people.

Aerial Survey: it refers to the measurements performed with a drone (DJI S900 Hexacopter) flying over the city. It is equipped with a fully radiometric high-resolution thermal camera (WIRIS 640 by Workswell).

Bureau of Meteorology (BoM) Stations: BoM weather stations that record a variety of weather phenomena.

Cooling Degree Days (CDD): Cooling degree days are a measure of how much (in degrees), and for how long (in days), the outside air temperature is above a certain level (base temperature). They are the summation (or integral) of the differences between outdoor temperatures and a defined base temperature. CDD are good indicator of the severity of the climate and the cooling needs of buildings.

Cooling Parramatta Tool: an online platform to visualise the data generated by the WRF simulations. It is a dynamic assessment tool to forecast the detailed characteristics of the Urban Overheating in Parramatta under the present and future climatic and land use conditions, and to optimise the implementation of mitigation technologies to amortize urban overheating.

Cool materials: materials (roofing and/or paving) that are characterized by high solar reflectance and high thermal emittance

Cool pavements: materials used in various surfaces of the urban fabric (e.g. roads, parking lots, sidewalks etc.) that are characterized by high solar reflectance and high thermal emittance.

Cool roofs: roofing materials that are characterized by high solar reflectance and high thermal emittance.

EnergyBus: it is UNSW mobile lab which is equipped to record the meteorological data.

ENVI-met: a three-dimensional microclimate model designed to simulate the surface, plant and air interactions in an urban environment. This computer program is an accurate tool to simulate the distribution of the main climatic parameters in the urban environment. More information can be found at: http://www.envi-met.com/

Global Horizontal Irradiance (GHI): it is a measure of the rate of total incoming solar energy (both direct and diffuse) on a horizontal plane at the Earth's surface.

Heat Wave: a heat wave day is a period of excessively hot weather. In this report, the heat wave day in 2017 corresponds to the extreme condition (+10 °C above long-term average temperature).

Heat related mortality or excess deaths: number of additional deaths observed in the population attributable to heat.

Heating degree Days (HDD): HDD is the number of degrees that a day’s average temperature is below the base temperature, which is the temperature below which buildings need to be heated.

Local Government Area Level (LGA Level): calculations aiming to estimate the impact that a mitigation scenario would have on the whole LGA. These calculations are performed using statistical data (e.g. total building floor area, population etc.) that refer to the whole LGA.

Microscale climate model: is used to assess heat mitigation strategies based on micro-scale modelling with ENVI-met (Bruse and Fleer, 1998). This model works at the street or neighbourhood scale with higher resolution compared to mesoscale modelling (grid size was 6 x 6 m). In this study, local heat mitigation strategies include: use of greenery, cool roofs and pavements, water-based technologies, combination of greenery and water-based technologies, and combination of cool roofs and pavements and water-based technologies in a neighbourhood scale. Result of microclimate simulations is used to generate weather data to compute building energy consumption and health impacts analysis.

Mean Absolute Error (MAE): MAE measures the average magnitude of the errors in a set of predictions. It is the average of the absolute differences between prediction and actual observation.

Mean maximum ambient condition: refers to a day that the maximum temperature is equal to the average temperature of the month.

Median: median of a set of data is the middle number in a sorted list of numbers.

NARCliM climate model: The NSW and ACT Regional Climate Model (NARCliM) is comprised of a twelve models ensemble. Three configurations of the Weather Research and Forecasting (WRF) regional climate model (RCM) have been used to downscale projections from four global climate models (GCMs) providing a total of 12 models. This ensemble approach is used to ensure robust climate projections that are at the regional scale span the likely future climate.

New Weather File: weather file that represents the weather profile of an area considering that a specific mitigation scenario has been implemented. The new weather files were developed by modifying the weather profiles given by the BoM station, considering the calculated mitigation factors, for each one of the mitigation scenarios under the present climate.

Outliers: an observation that seem to differ by a substantial amount from the rest of the data. For this study outliers are defined as points that are beyond the quartiles by one-and-a-half Interquartile Range (IQR), where the IQR is the difference between the between the upper quartile (Q3) and the lower quartile (Q1) (defined as the 25th and 75th percentiles).

Percentile: is a measure used in statistics indicating the value below which a given percentage of observations in a group of observations fall. For example, the 25th percentile is the value (or score) below which 25% of the observations may be found.

PMV (Predicted Mean Vote): is an index which predicts the mean response of a larger group of people on the a seven-point thermal sensation scale. It is an empirical fit to the human sensation of thermal comfort.

Reference Case: it represents the existing situation, where no mitigation solutions have been considered. The terms reference case and unmitigated scenario are used interchangeably in the report.

Terrestrial Survey: measurements performed from the ground surface including measurements with fixed air temperature stations, measurements with the EnergyBus at 1.5 m and 10 m above the ground, and measurements with local measurements at multiple locations with portable stations.

Thermal comfort: is the condition of mind that expresses satisfaction with the thermal environment.

Total mitigation strategies: see global mitigation strategies

Urban Heat Island (UHI): is a phenomenon in which urban areas exhibit higher temperatures than the surrounding rural areas. Urban Heat Island is the result of the positive thermal balance of cities caused mainly by the increased absorption of solar radiation and heat storage, high anthropogenic heat and reduced heat losses.

Urban heat island intensity (UHII): it is an important metric used in measuring Urban heat island (UHI) effect. The UHI magnitude is the temperature difference of an urban and rural area ($DT_{urban-rural}$)

Unmitigated Scenario: see Reference Case

Whisker-box plot diagrams: the box plot is a standardized way of displaying the distribution of data based on the five-number summary: minimum, first quartile, median, third quartile, and maximum. In the simplest box plot the central rectangle spans the first quartile to the third quartile (the interquartile range or IQR); the likely range of variation. A segment inside the rectangle shows the median and "whiskers" above and below the box show the minimum and maximum.

WRF (Weather Research and Forecasting) model: WRF is a next-generation mesoscale numerical weather prediction system developed by the National Center for Atmospheric Research (NCAR). It has been one of the world most widely used numerical weather prediction models. The WRF Model is an atmospheric model designed both research and numerical weather prediction (NWP).

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2. INTRODUCTION

Scope of the Study

The present study is aiming to pre-design and optimize a smart climatic street in Parramatta, named Phillip st., exhibiting high climatic, environmental, and energy performance.

The specific objective of the study is to propose, investigate, and optimize the combination of advanced thermal mitigation and smart technologies to improve thermal comfort and mitigate the urban overheating in the area.

Methodology of the Study

To satisfy the above described objective, he whole study involves the following research phases:

Phase 1: Aerial monitoring of the surface temperatures using drone technologies. Use of the mobile Energy Bus to measure the temperature distribution in the whole area.

Phase 2: Identification of the climatic conditions and hot spots in the area and development of preliminary mitigation scenarios.

Phase 3: Preliminary climatic evaluation of the proposed mitigation scenarios and final selection of the technologies and systems to be implemented.

Phase 4: Detailed thermal study and optimization of the proposed mitigation scenarios.

3. LOCAL CLIMATE MEASUREMENTS IN THE AREA OF Phillip ST. PARRAMATTA

Introduction

Built environment interacts with the atmosphere and vice versa in a spatial and temporal scale. Urban climatology, as discipline of climatology, investigates these continuous interactions [1].
Understanding the effect that the built environment produces on the local climate and how the local climate affects the urban environment and people is of fundamental importance [2].
Our cities and outdoor spaces are facing the Urban Heat Island phenomenon and the overheating due to climate change during summer season. Several studies are registering the problem of overheating and heatwaves and investigating mitigation strategies to improve outdoor thermal comfort [3].

Before proposing solutions with cooling potential, it is necessary to make a diagnosis of the urban area of interest to understand the intensity of the problem and where to intervene. For this reason, comprehensive and continuous local monitoring campaigns are a prerequisite that allow to elaborate reliable microclimate simulations and propose adequate countermeasures for specific hot spots. Unfortunately, available data from BoM weather stations [4] are not enough to identify the local microclimate and its interaction with each component of the built environment. At the same time, continuous monitoring is often not economically feasible and requires an important data cleaning and data analysis. As a compromise, it is possible to perform measurement campaigns during specific summer days under peak conditions and still get significative results useful for urban climate mapping and validation of microscale models [5].

Through microclimate simulations it is then possible to test different mitigation strategies and a combination of them in order to identify the optimal solution considering different key factors [6].

In this section, we document two monitoring campaigns conducted in the area of Phillip St. in Parramatta. The first one has been performed mainly to measure the spatial and temporal distribution of the air temperature within Phillip St. and his close surrounding, while the second one has been performed mainly to map the surface temperature by means of the aerial monitoring.

Data and methods

The scope of the two monitoring campaigns in Phillip St., Parramatta is to identify the most relevant hotspots along Phillip St. and then propose specific mitigation strategies for the identified hotspots. To achieve this goal, we employed multiple measurement techniques, so as to gather a comprehensive picture of the local microclimate in Phillip St. during warm-hot days. The measurements have been performed in two different days and consist of:

- A terrestrial survey, performing measurements at multiple locations at pedestrian level for a variety of climate parameters, including ambient air temperature and relative humidity, wind speed and direction, incoming solar radiation, and surface temperatures; and
- An aerial survey, with an Unmanned Aerial Vehicle (UAV), such as a drone equipped with a high-resolution thermal camera. This activity provides the surface temperatures of the urban surfaces along a section of Phillip St. where flight is allowed by the Civil Aviation Safety Authority (CASA). The UAV flights have been performed in safety conditions.

The terrestrial survey has been performed from 9:30 am to 3:30 pm (local solar time) on the 2nd December 2018 in Phillip St., Parramatta, and surrounding area, while the aerial survey has been carried out from 12:30 pm to 2:30 pm on the 3rd February 2019 along a section of Phillip St that goes from Horwood Pl. to Charles St., close to Parramatta river.
Both monitoring campaigns have been performed in the central hours of sunny days to provide an average spatial distribution in peak conditions. Measurements have been collected at least twice at the same location at different times to ensure redundancy.

Instruments and measurement techniques

Terrestrial Survey - Instruments and measurement techniques

The terrestrial survey was composed by the following elements:

- Measurements with the EnergyBus at 10 m from 10:30 am to 12:25 pm and at 5 m from 12:30 pm to 3:30 pm of incoming solar radiation, air temperature, relative humidity, pressure, wind speed and direction. The height of the EnergyBus's must had to be reduced due to excessive wind (max 14.68 m/s) for safety reasons;
- Measurements of air temperature, relative humidity, pressure, wind speed and direction with a station mounted in a tripod at 1.5 m located at the same location of the EnergyBus for the entire duration of the monitoring campaign (9:30 am until 3.30 pm, solar time);
- Spot measurements taken at multiple locations along Phillip St. with a portable station collecting air temperature, relative humidity, pressure, wind speed and direction and a thermal camera collecting information on the surface temperatures;
- Spot measurements taken at multiple locations in the surrounding area of Phillip St. with two portable stations collecting air temperature, relative humidity, and wind speed and a thermal camera collecting information on the surface temperatures;
- Thermal images of vertical surfaces taken along the entire Phillip St. with a drone equipped with a high-resolution thermal camera installed on the roof rack of a UNSW car.

The local climate measurements of incoming solar radiation, air temperature, relative humidity, wind speed and direction have been performed with the EnergyBus (Figure 1). A set of sensors has been installed on the mast of the vehicle elevated to 10 m in the morning and to 5 m in the afternoon. These include:

- A net radiometer (NR01 by Hukseflux), which provided the incoming solar radiation, by means of ISO 9060 second class pyranometers (Table 1);
- A weather station (MetPak Pro with an integrated WindSonic ultrasonic wind sensor by Gill Instruments, Table 2).

The EnergyBus has been positioned in an open area in proximity of the intersection between Phillip St. and Smith St. to prevent the excessive influence of high buildings. The area surrounding the EnergyBus has been delimited and secured as much as possible for safety reasons.
The sampling rate for the MetPak Pro weather station and the pyranometer was set to 1 s, averaged and recorded over 30 s by means of a datalogger (DT85 by Lontek).

Figure 1. The EnergyBus in Phillip St. with the monitoring station mounted on the mast at 10 m from the ground.

Table 1. Technical characteristics of the used pyranometers.

Parameter	Value
ISO classification (ISO 9060: 1990)	second class pyranometer
Response time (95 %)	18 s
Zero offset a (response to 200 W/m2 net thermal radiation)	< ± 15 W/m^2 unventilated
Zero offset b (response to 5 K/h change in ambient temperature)	< ± 4 W/m^2
Non-stability	< ± 1 % change per year
Non-linearity	< ± 1 % (100 to 1000 W/m^2)
Directional response	< ± 25 W/m^2
Spectral selectivity	< ± 5 % (0.35 to 1.5 x 10^{-6} m)
Temperature response	< ± 3 % (-10 to 40 °C)
Tilt response	< ± 2 % (0 to 90° at 1000 W/m^2)

Table 2. Technical characteristics of the used pyranometers.

Quantity	Parameters	Value
Wind	Wind Speed Range	0-60m/s
	Wind Speed Accuracy	±2% @12m/s
	Wind Speed Resolution	0.01m/s
	Wind Direction Range	0 to 359º - No dead band
	Wind Direction Accuracy	±3º @12m/s
	Wind Direction Resolution	1º

Temperature	Air Temperature	Pt100 1/3 Class B
	Range	-50ºC to +100ºC
	Accuracy	±0.1ºC
	Resolution	0.1ºC
Barometric pressure	Range	600-1100hPa
	Accuracy	±0.5hPa
	Resolution	0.1hPa
	Units of measure	hPa, mbar, mmHg, inHg
	Compensated for temp. dependency	-30ºC to +70ºC
	Range	600-1100hPa
Dew Point	Resolution	0.1ºC
	Accuracy	±0.15ºC (23ºC ambient temp @20ºC dew point)

A MetPak Pro weather station (Figure 2) has been installed at 1.5 m on a tripod located in proximity of the EnergyBus (distant from specific objects). Also in this case, the sampling rate for the MetPak Pro weather station was set to 1 s, averaged and recorded over 30 s by means of a datalogger (DT85 by Lontek).

Figure 2. The MetPak Pro weather station in Phillip St. mounted on a tripod at 1.5 m from the ground.

Another MetPak Pro weather station (Figure 3) has been installed at 1.5 m on a cart to collect spot measurements of air temperature along Phillip St. at different instants of time. A 2-people team collected measurements following the Track M with the cart and a thermal camera T540 by FLIR. The measurements along Track M were performed for approximately 10 minutes per collection point and are high accuracy measurements and they have been carried out about three times per location.

Figure 3. The MetPak Pro weather station in Phillip St. mounted on a cart at 1.5 m from the ground used for spot measurements in Track M.

The spot measurements at multiple locations in the surrounding area of Phillip St. were performed with instruments mounted on a cart at 1.5 m. Two carts were equipped with RH85 sensors (by Omega Engineering, Figure 4 and Table 3) with a white radiation shield and TG54 infrared thermometers by FLIR. The two people using these carts collected the measurements along the Track A and P simultaneously. These measurements along Track A and P provide an estimation of the thermal boundary conditions and were performed multiple times per location, for 8 minutes per location.

Figure 4. The cart used for spot measurements in Track A on the left, the RH85 sensor and the and TG54 infrared thermometers integrated in the cart, respectively in the middle and on the right.

Table 3. Technical characteristics of the RH85 sensors.

Parameter	Value
Temperature range	-20 to 60°C
Temperature resolution	0.1°C
Temperature accuracy	±0.5°C from 0 to 45°C
Relative humidity range	0% to 100%
Relative humidity resolution	0.1 %

Relative humidity accuracy	±2.5% @ 25°C, 10%-90% RH, ±5% @ 25°C, 0%-10% RH, 90%-100% RH
Response time for 90% of total range	60 s

Due to flight restrictions and safety regulations within the area of study, it was not possible to perform the aerial survey with the drone to create the thermal video useful to identify the hottest surfaces along the street. As alternative solution, a terrestrial survey has been performed by mounting the drone of the High Performance Architecture group of UNSW Built Environment on the roof rack of a UNSW car (Figure 5). High quality images of the vertical north-facing side of Phillip St. have been taken at 2.5 m over the street level, while the car was moving slowly from the start to the end of Phillip St. repeatedly, thanks to a fully radiometric high-resolution thermal camera (WIRIS 640 by Workswell) integrated in the drone. The drone is a DJI S900 Hexacopter (Figure 6). The resolution of the thermal camera is of 640 x 540 pixels, the accuracy of ± 2%, the spectral range of 7.5 – 13.5 µm and the field of view equal to 51° x 51°.

A series of photos - in the above-mentioned thermal wavelength range - has been collected and later unified in a thermal video. The position of the images is determined by means of the GPS antenna on the drone. In this case the thermal camera was kept orthogonal to the vertical facades along the north-facing side of Phillip St.. The thermal images and image postprocessing have been performed by Geraldo Sansone of SkyMonkey for UNSW.

Figure 5. A car used for the terrestrial survey, equipped with the UNSW drone.

Figure 6. The drone and thermal camera of the HPA group of UNSW Built Environment used for the thermal survey.

Aerial Survey - Instruments and measurement techniques

The aerial survey has been performed with the drone of SkyMonkey (Figure 7). The drone is equipped with the DJI Zenmuse X5S camera, the currently very best drone camera.
Because of the flight regulation and safety reasons, only part of Phillip St., from Horwood Pl. to Charles St., has been covered by the drone to create a 3D thermal model of the street.
The flights and image postprocessing have been performed by Geraldo Sansone of SkyMonkey for UNSW.
In parallel, a MetPak Pro weather station (Figure 8) has been installed at 1.5 m on a cart to collect continuous high accuracy measurements of air temperature in a fixed spot located at the intersection of Smith St. and Phillip St., to have a reference for the local thermal conditions during the aerial survey. The sampling rate for the MetPak Pro weather station was set to 1 s, averaged and recorded over 30 s by means of a datalogger (DT85 by Lontek).

Figure 7. The drone and thermal camera of SkyMonkey used for the aerial survey.

Figure 8. The MetPak Pro weather station in Phillip St. mounted on a cart at 1.5 m from the ground and the flying drone in the sky.

Measurement locations

The area of interest for the monitoring campaign is the entire Phillip St., from Marsden St. to Charles St., and its surrounding in Parramatta. The exact location of the measurement points was defined based on one preliminary inspections on site guided by members of the Council of Parramatta.

The measurements locations of the terrestrial survey are shown in Figure 9.

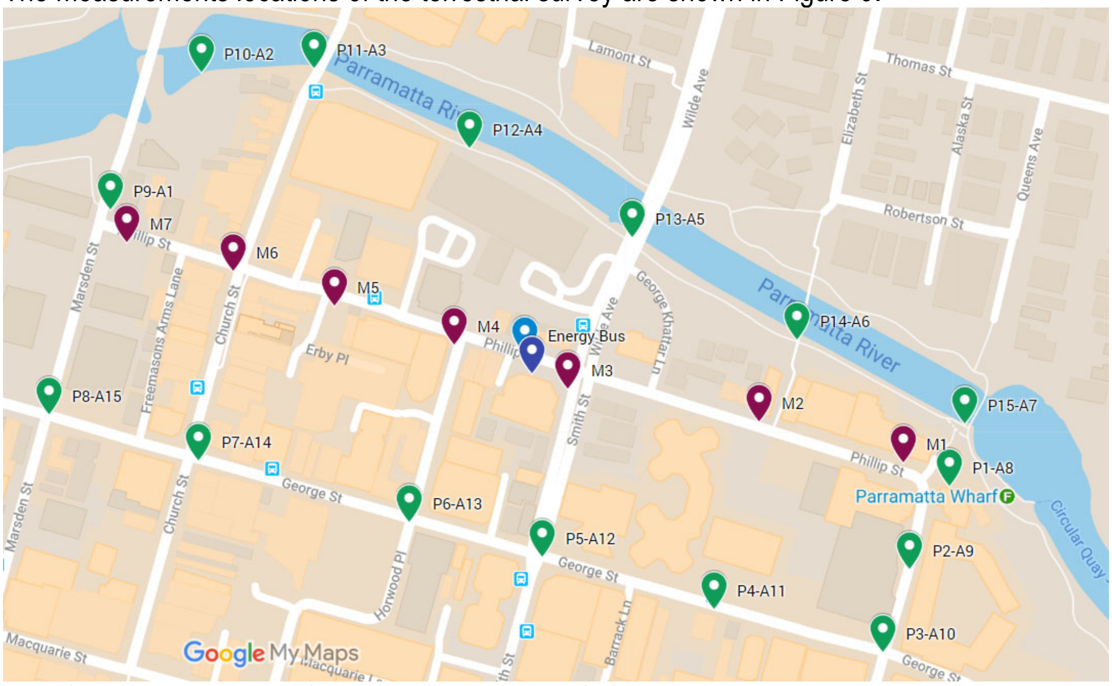


Figure 9. Measurement locations of the terrestrial survey in Phillip St. (EnergyBus and standing MetPak Pro weather station in the light and dark blue pins, respectively - Track M in the purple pins) and surrounding area (Track A and P in the green pins).

Table 4. Geographic coordinates of the measurement locations.

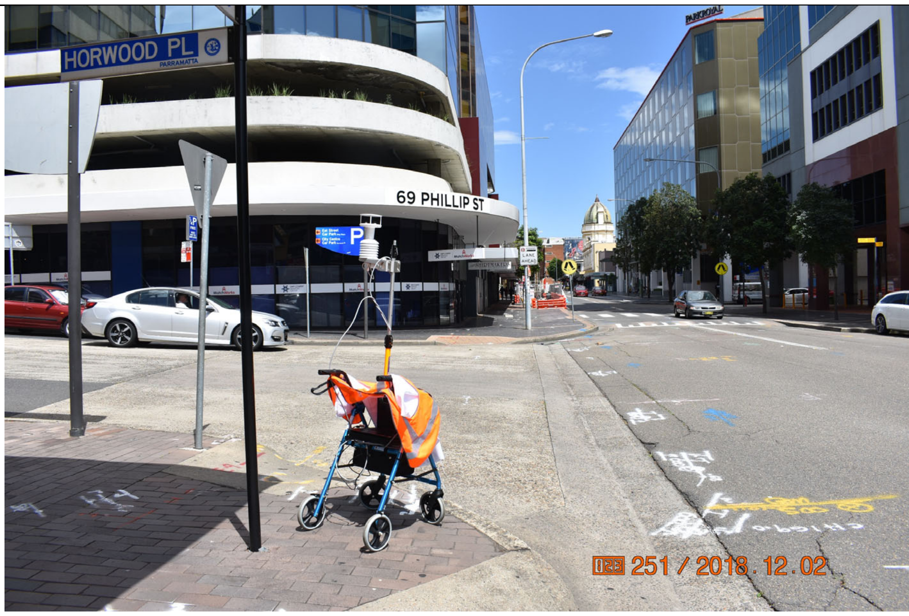
Measurement location name	Latitude	Longitude
Energy Bus_10 m	-33.81288	151.00622
Fix station_1.5 m	-33.81292	151.00623
M1	-33.81366	151.00971
M2	-33.81331	151.00818
M3	-33.813	151.00653
M4	-33.81278	151.00562
M5	-33.8125	151.00462
M6	-33.81226	151.00377
M7	-33.81198	151.00271
P1-A8	-33.81368	151.00973
P2-A9	-33.81433	151.00945
P3-A10	-33.81491	151.00922
P4-A11	-33.81461	151.00781
P5-A12	-33.81424	151.00637
P6-A13	-33.814	151.00525
P7-A14	-33.81357	151.00348
P8-A15	-33.81326	151.00222
P9-A1	-33.81193	151.00263
P10-A2	-33.81087	151.0035
P11-A3	-33.81085	151.00444
P12-A4	-33.8114	151.00575
P13-A5	-33.81202	151.00711
P14-A6	-33.81274	151.0085
P15-A7	-33.81332	151.0099

The EnergyBus (light blue pin in Figure 9) and the MetPak Pro weather station installed in the tripod (dark blue pin in Figure 9) have been positioned in a space centred with respect to Phillip St. length and at the intersection with Smith St.

Trak M (purple pin in Figure 9) has been defined to collect detailed air temperature measurements at pedestrian height in 7 spots located at the main intersections of Phillip St. (Figure 10).

Then in the surrounding area, air temperature measurements have been collected at pedestrian height in 15 locations (green pins, Trak A and P, in Figure 9).

M1	
M2	

M3	251 / 2018.12.02
M4	HORWOOD PL PARRAMATTA 69 PHILLIP ST 251 / 2018.12.02

M5	TABLE 30 RESTAURANT PARKROYAL 251 / 2018.12.02
M6	MAD MEX MILLE UNO NO RIGHT TURN 251 / 2018.12.02

M7	

Figure 10. MetPak Pro weather station on the cart at each measurement locations of Track M.

The aerial survey was conducted along half part of Phillip St., between Horwood Pl. and Charles St., over the area delimited by Parramatta River (Figure 11). The SkyMonkey's drone flew and took pictures over the buildings looking at the street and the buildings' facades of Phillip St. facing Parramatta River. The MetPak Pro weather station has been located in close proximity of the position where the EnergyBus was parked during the terrestrial survy (dark blue pin M in Figure 11).

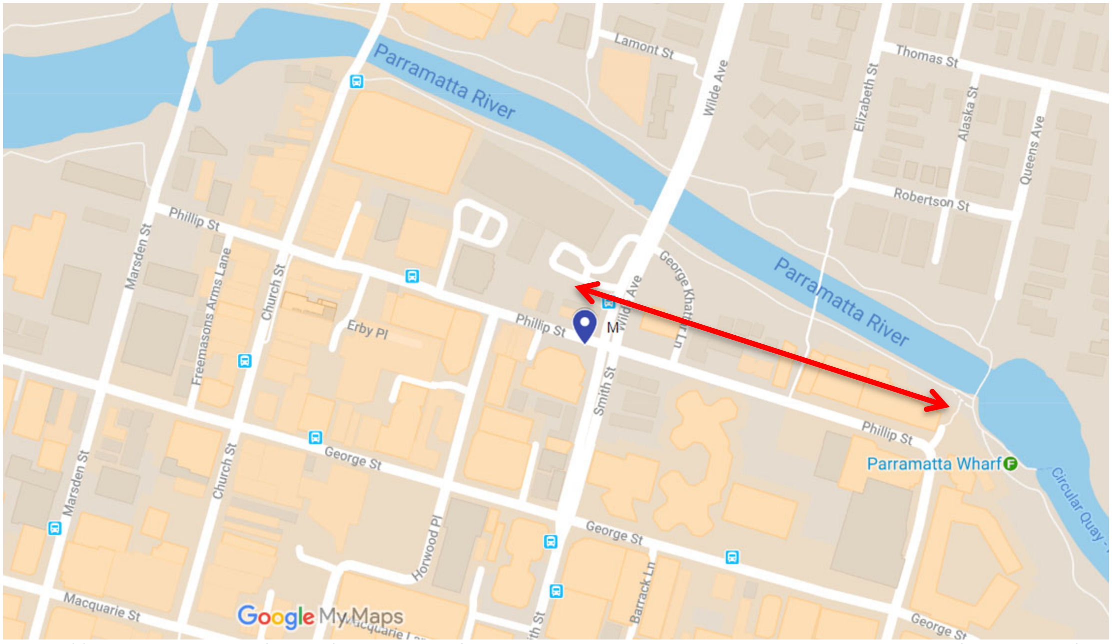


Figure 11. Aerial survey path (red line) along Phillip St., Parramatta, and MetPak Pro weather station location (dark blue pin).

Phillip St. Results and discussion

Results of the Terrestrial Survey

The reference air temperature profiles chosen for Phillip St., Parramatta, are provided by the EnergyBus and the close stationary MetPak Pro weather station (Figure 12).
The EnergyBus recorded all the available environmental data at 10 m height from 10:30 am to 12:25 pm. For safety reason, from 12:30 pm to 3:30 pm the EnergyBus recorded data at 5 m height because

around 12:10 pm the wind began to reach excessive speed values (up to a maximum of 14.68 m/s at 12:34 pm). In the middle of the afternoon (i.e., at 3.30 pm), since the wind speed from the river continued to increase, the entire monitoring campaign was suspended.
Owing to the little influence of the urban environment at 10 m height, the first part of the day is characterized by an average air temperature difference of 0.4°C, calculated as difference between the temperature recorded at pedestrian level (at 1.5 m) by the stationary weather station and the temperature recorded at 10 m by the EnergyBus station. The average air temperature difference decreased up to 0.1°C, once the temperature was recorded at 5 m, where the influence of the urban environment that accumulate and release heat become higher. The temperature profiles monitored at 1.5 m and at 5 m are almost the same both in trend and intensity, while the temperature profiles monitored at 1.5 m and at 10 m are similar in the trend and not in intensity, where the temperature measured at pedestrian level shows consistently higher values.

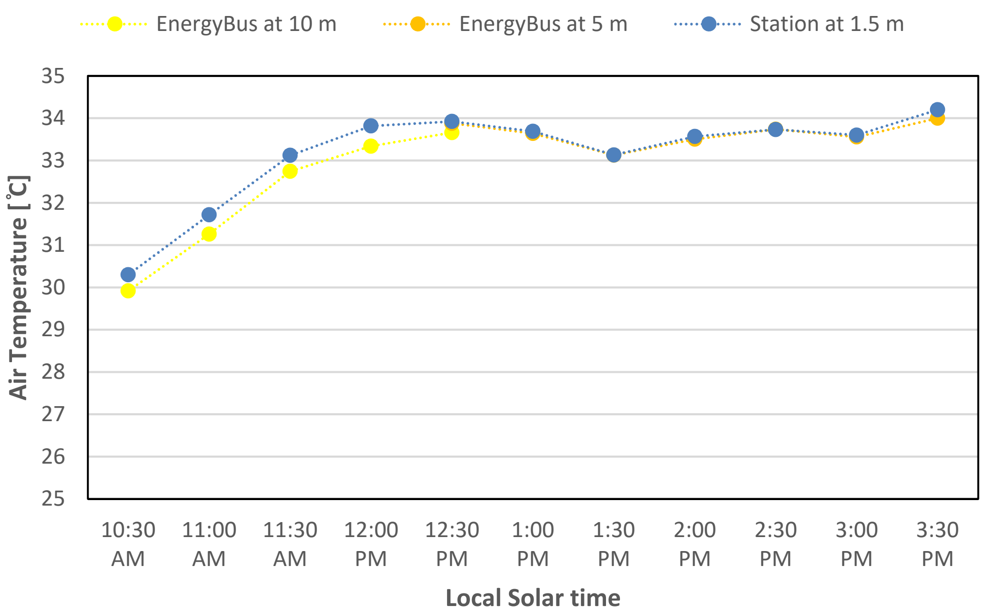


Figure 12. Air temperature profiles by EnergyBus and MetPak Pro weather station on 03/12/2018 (30 min averages).

Figure 12 shows the air temperatures averaged over 30 minutes for the sake of clarity, but at the EnergyBus we recorded with higher frequency. Considering data averaged every 5 minutes (Figure 13), we still see a consistent temperature trend, with a small vertical gradient from 1.5 m to 10 m, not exceeding 0.7°C, and an almost inexistent vertical gradient from 1.5 m and 5 m during the measurement period.

All the other measured environmental parameters describe a typical summer day, with clear sky alternated by frequent cloudiness moments (especially in the morning), relatively low relative humidity, and variable wind speed (Figure 14 - 17). The average wind speed of 3.3 m s^{-1} and 3.7 m s^{-1}, and absolute maximum wind speed of 12.8 m s^{-1} and 15.3 m s^{-1}, calculated respectively at 10 m and 5 m, indicate the presence of forced convection (Figure 15). The wind speed sensor of the MetPak Pro weather station stopped recording at 12:14 pm after the station fall caused by the strong wind. The data recorded before the station fall show lower speed value at pedestrian level with respect to the data registered at 10 m, due to the presence of obstacles (such as trees and buildings) that slow down the wind flow.

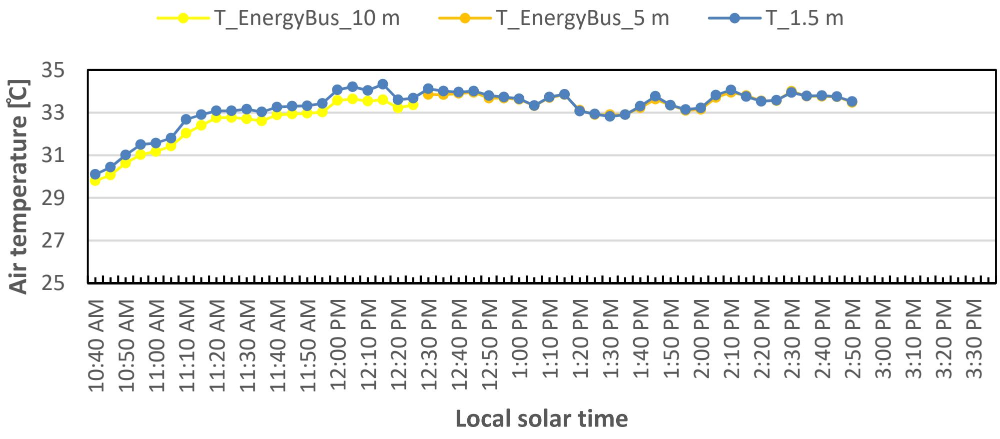


Figure 13. Air temperature (5 min averages) at 10 m (up to 12:25 pm)/5 m (from 12:30 pm) and 1.5 m.

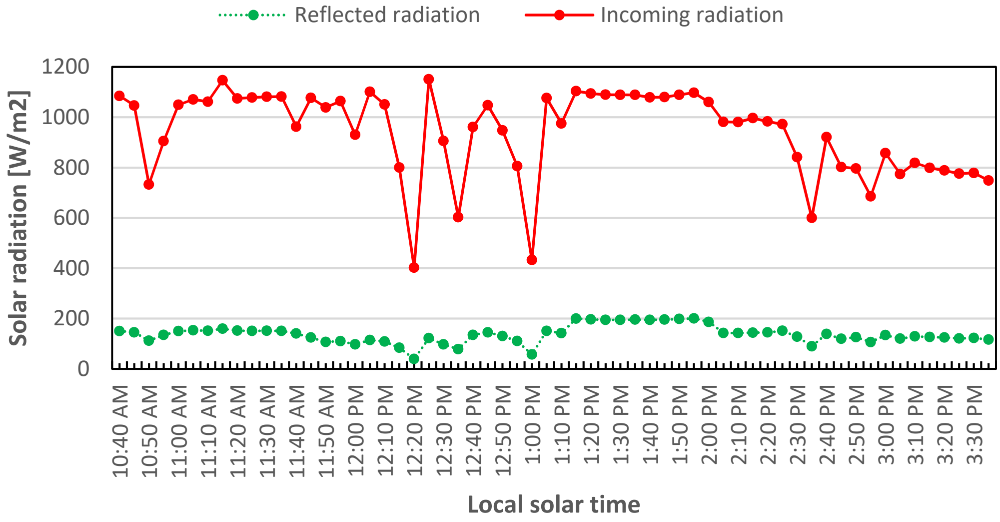


Figure 14. Incoming and reflected solar radiation (5 min averages) monitored by the EnergyBus at 10 m up to 12:25 pm and 5 m from 12:30 pm.

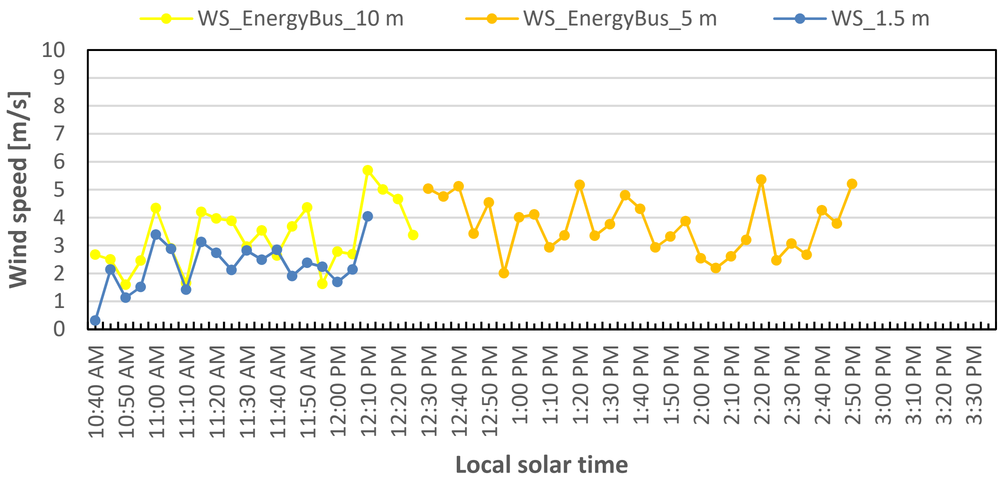


Figure 15. Wind speed (5 min averages) at 10 m (up to 12:25 pm)/5 m (from 12:30 pm) and 1.5 m.

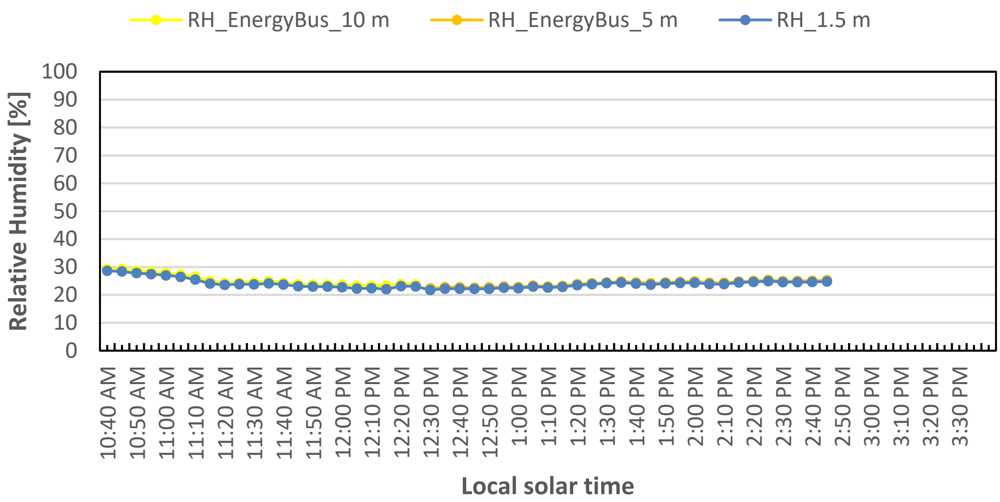


Figure 16. Relative humidity (5 min averages) at 10 m (up to 12:25 pm)/5 m (from 12:30 pm) and 1.5 m.

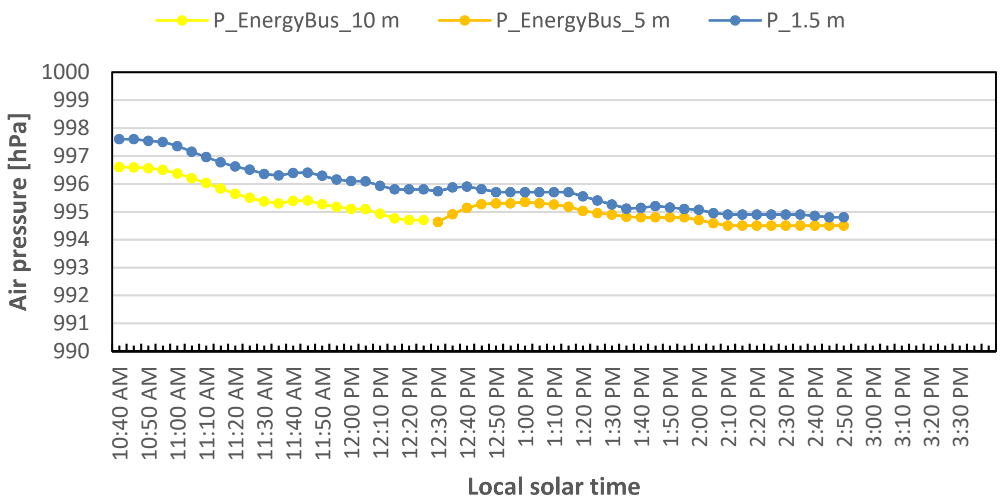


Figure 17. Air pressure (5 min averages) at 10 m (up to 12:25 pm)/5 m (from 12:30 pm) and 1.5 m.

These figures completely describe the boundary conditions of the measurement period, but do not provide an understanding of the spatial distribution of temperature along Phillip St. and its urban surrounding, which can be captured with the results of the spot measurements taken following tracks A, P, and M. The spatial representation of the spot measurements performed at pedestrian level helps us to identify the hot spots within the area of investigation.

These spot measurements are affected by uncertainty related to the position and accuracy of the instruments. With the collection of data in multiple points (some measured twice or more) and the use of multiple instruments we aimed to provide a robustness climate map. Redundant records have been averaged. The spot measurements have been performed during the central portion of the day and in sunlit portions of the urban fabric, excluding the locations affected by shadows (verified considering the street surface temperature measured with an infrared thermometer) with exception of the point M5 shaded by trees located in the small plaza nearby. The results have been then georeferenced and plotted with a GIS tool, producing a climate map for Phillip St. at 12 pm in summer conditions (Figure 18). Considering as reference point the measurements taken with the EnergyBus

at 10 m height, in a central position with respect to the street length and where there is less influence from the built environment and less urban heat island effect, the climate map shows the temperature differences between the average spot temperatures (taken along track A, P, and M) and the reference temperatures at 10 m.
As mentioned above, the temperatures recorded at 10 m result lower than the temperature recorded at pedestrian level, therefore, the temperature differences showed in the climate map are always positive.
High air temperature, low air relative humidity, and high wind speed enounce the temperature difference between the North-East area surrounded by Parramatta river (cooler area by means of the evapotranspiration) and the South-West area of the investigated area (hotter area) [7]. In particular, in correspondence of the green pin P7-A14 (South-West of Phillip St.), the air temperature has resulted 2.8 ºC and 2.4 ºC higher than in the central area of Phillip St., in correspondence of the EnergyBus at 10 m and the stationary station and 1.5 m, respectively. Along the river banks, the maximum temperature difference has been recorded in correspondence of the green pin P11-A3 (e.g., 1.1 ºC and 0.7 ºC in correspondence of the EnergyBus at 10 m and the stationary station and 1.5 m, respectively). It is confirmed, that the presence of the river and the breeze from the Parramatta river penetrating in Phillip St. from North-East contribute to mitigate the overheating of the area in the proximity of the river and in the Eastern part of Phillip St.
Overall, the Western part of Phillip St. is on average warmer by 1 °C than the Eastern part.

The interpolation in GIS has shown clear boundaries of the temperature contours, without inconsistent patterns also if compared with previous monitoring studies.
Moreover, we observed consistent high wind speeds also in the surrounding area of Phillip St., in the range between 0.4 and 17 m s^{-1} with an average speed of 3.5 m s^{-1}.

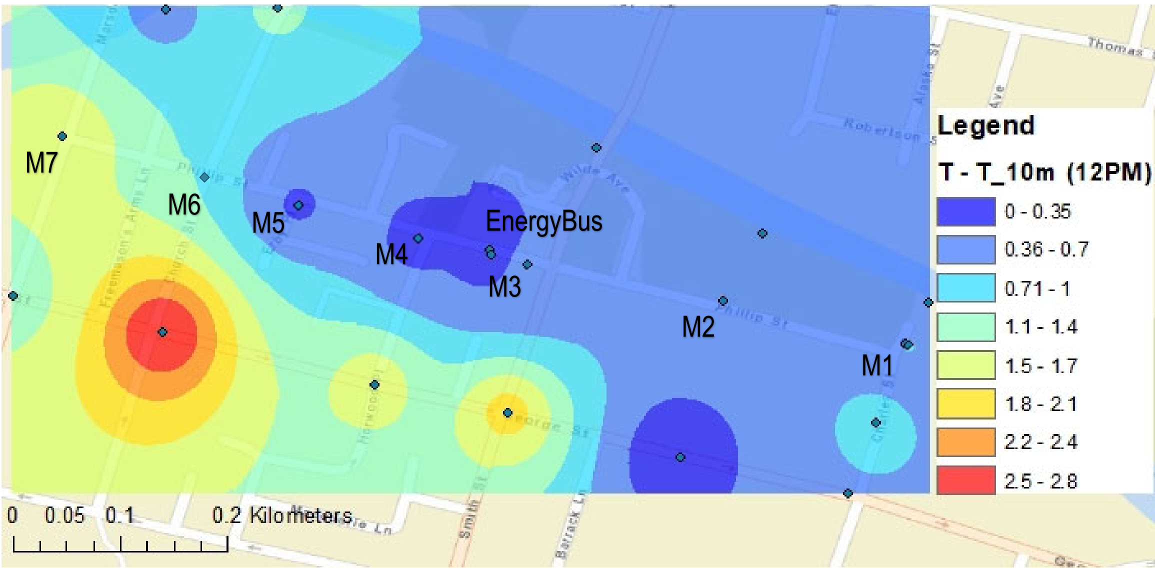


Figure 18. Climate map of Phillip St. and its surrounding obtained at 12 pm with respect to the EnergyBus (10 m) measurements in °C.

From the terrestrial survey also surface temperature of asphalt, pavements and sidewalks, and roof coverings in Phillip St. have been collected thanks to the thermal camera and the infrared thermometers (Figure 19 – 24).

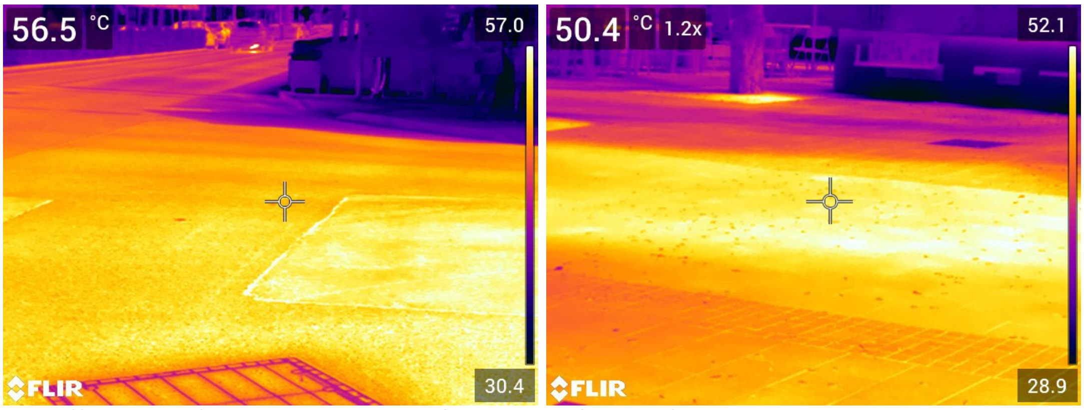


Figure 19. Asphalt surface temperatures in Phillip St., Parramatta (IR images).

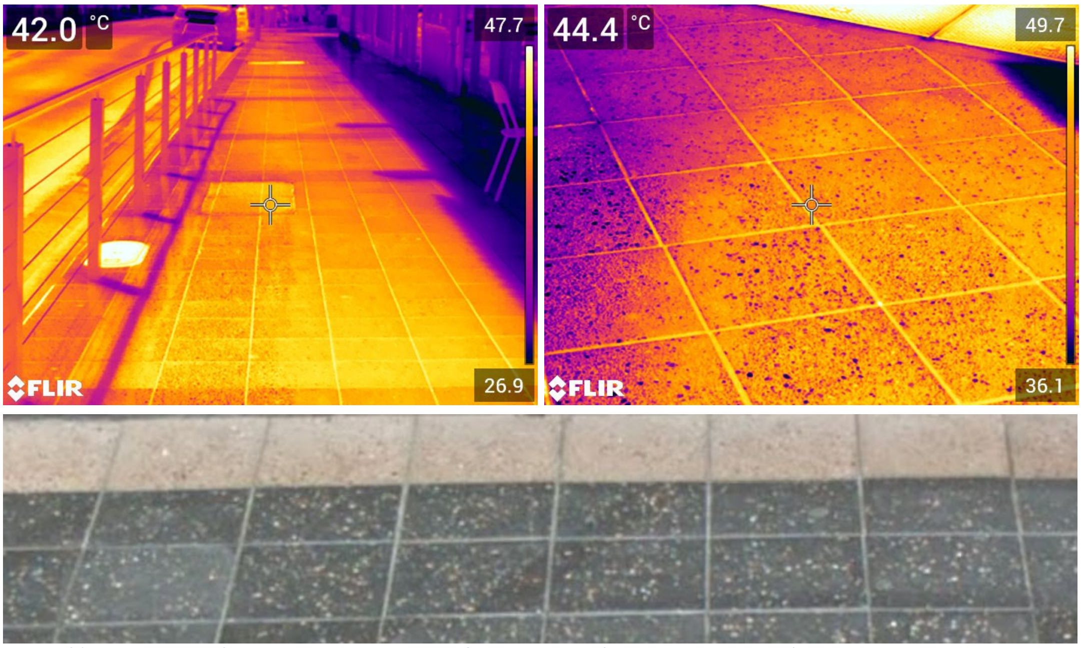


Figure 20. Pavement surface temperatures in Phillip St., Parramatta (IR and visible images).

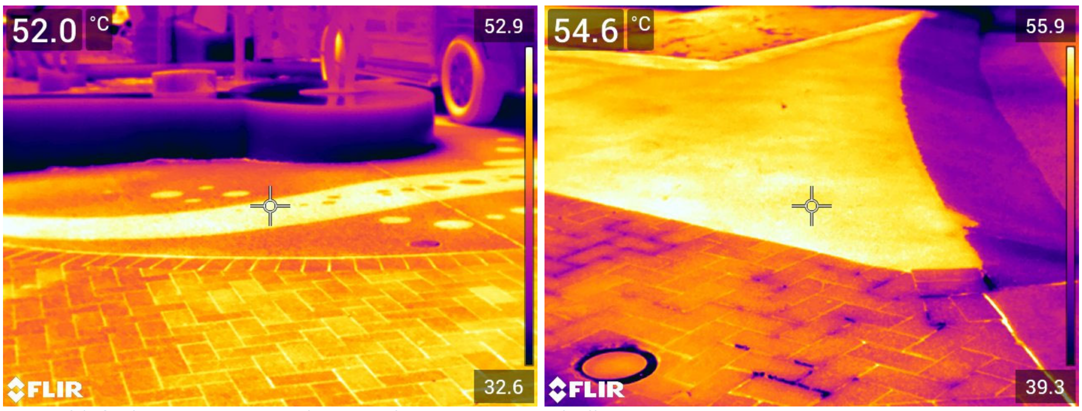


Figure 21. Surface temperatures of portion of sidewalks made of different materials.

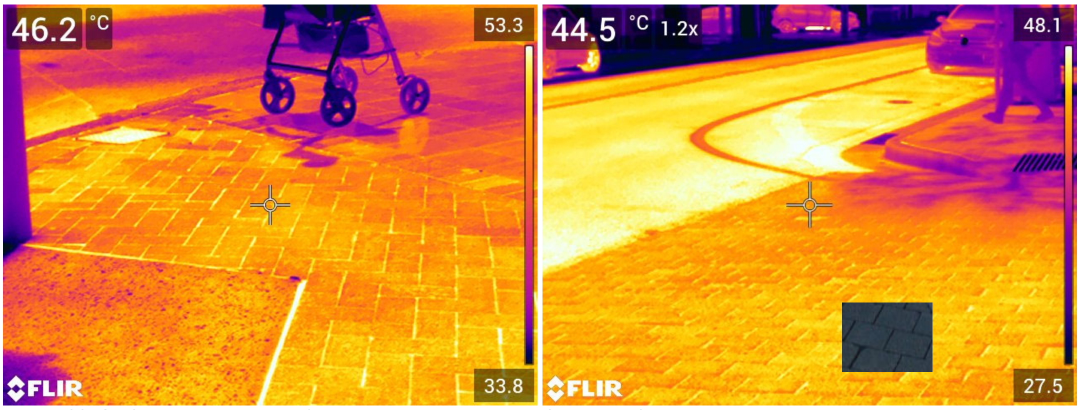


Figure 22. Surface temperatures of low albedo terracotta tiles (IR images).

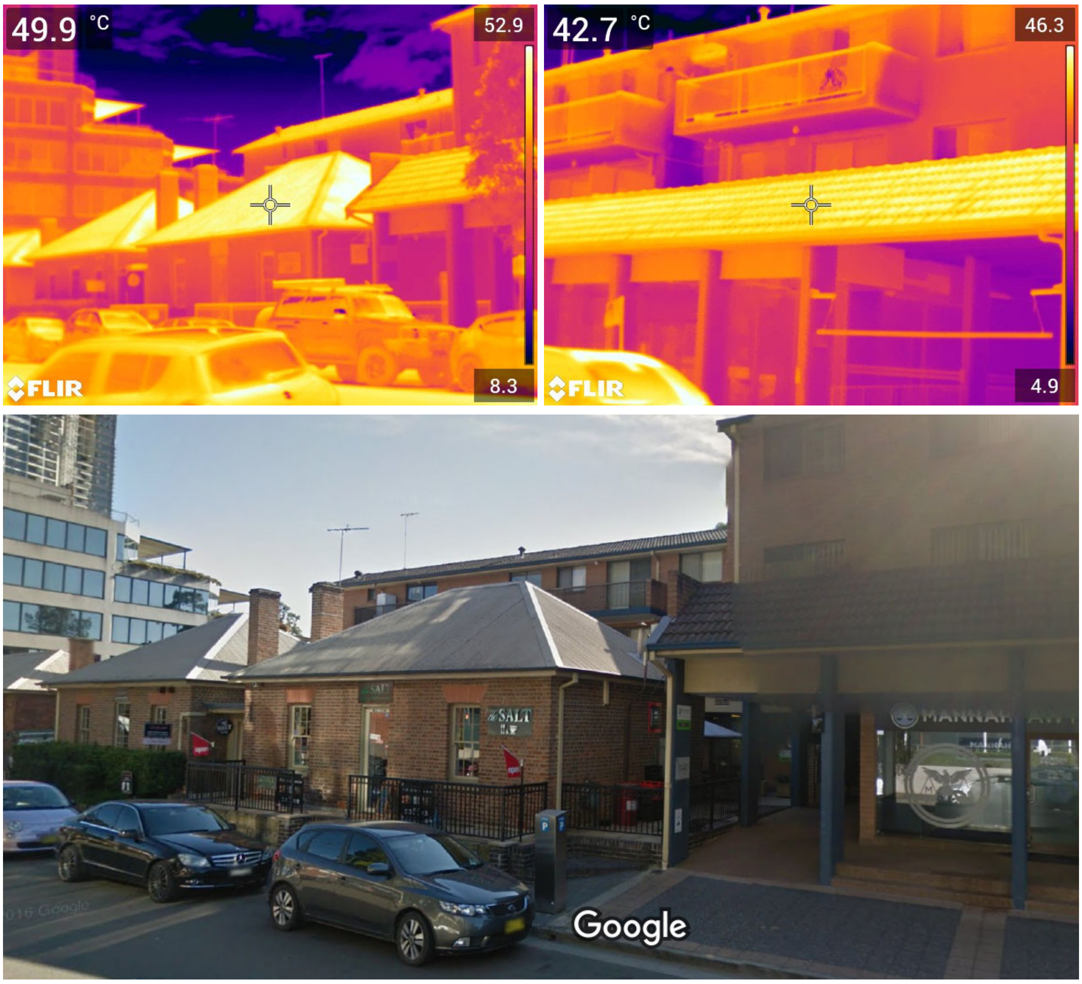


Figure 23. Roof surface temperatures of roofs facing Phillip St., Parramatta (IR and visible images).

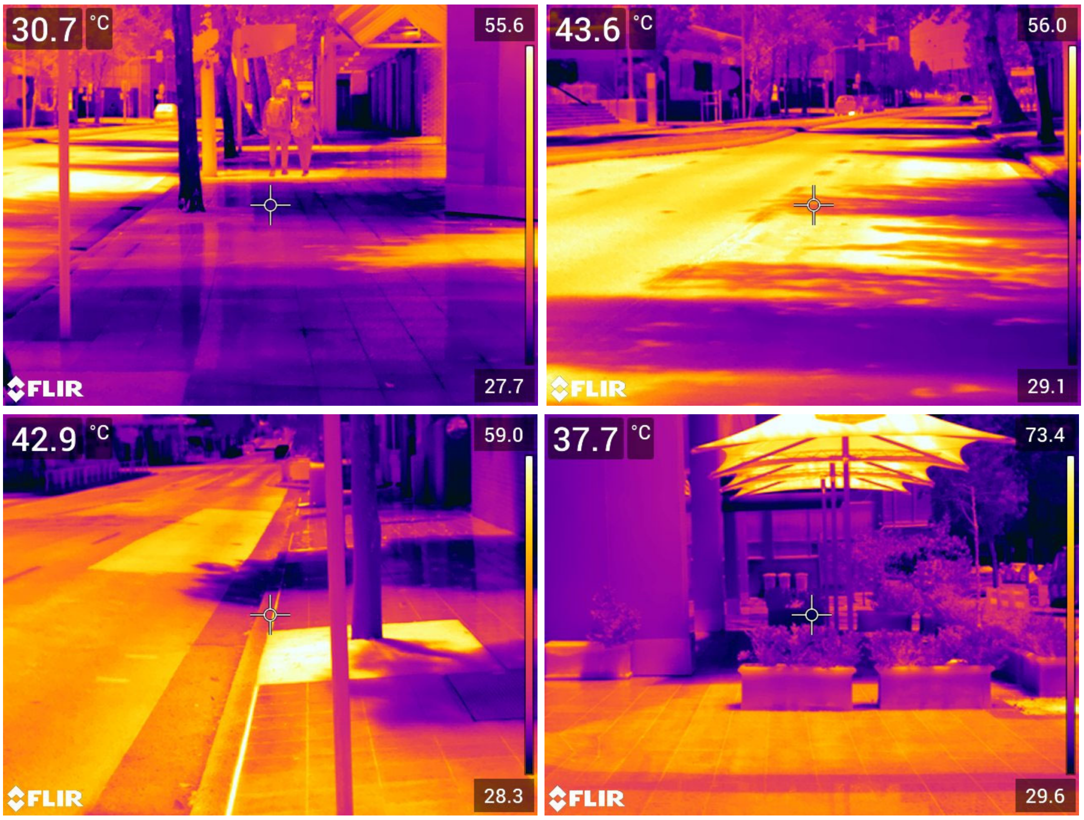
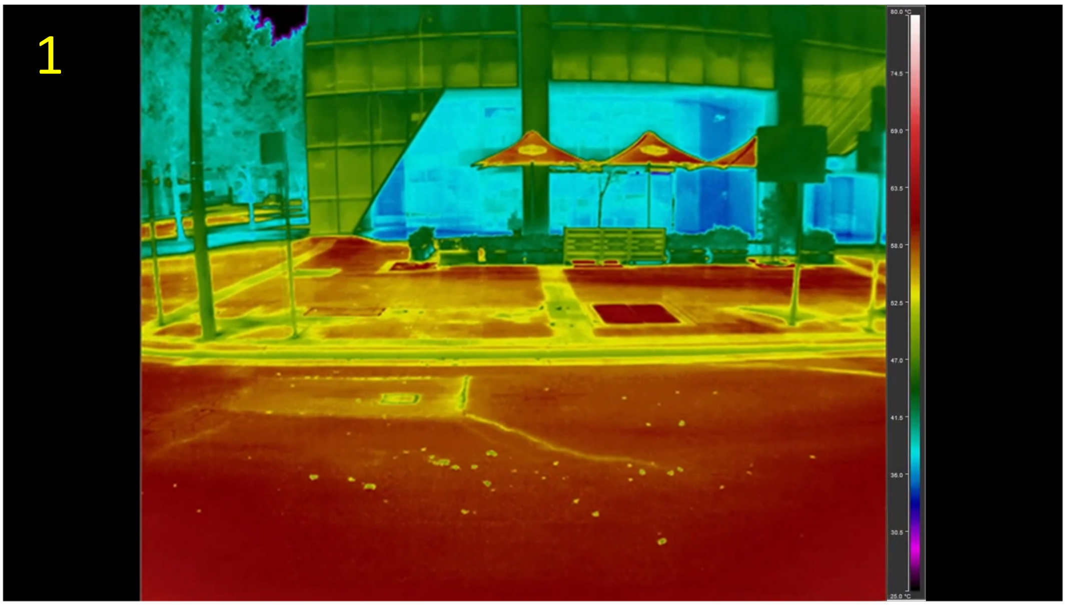
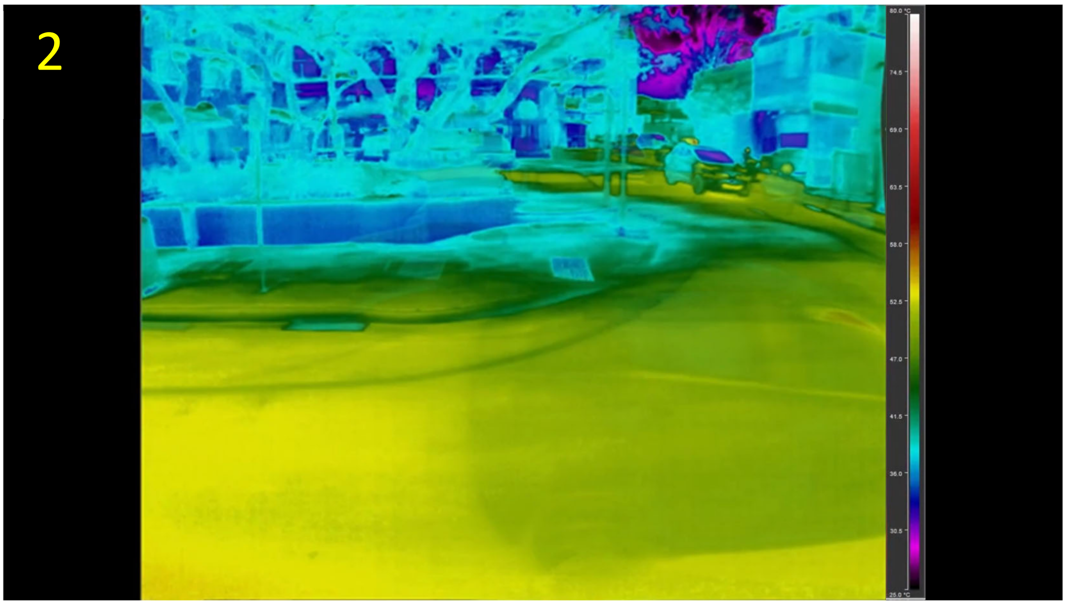


Figure 24. Surface temperatures in shaded and unshaded areas (IR images).

The thermal images show low albedo asphalt exceeding 50°C of surface temperature, low albedo and terracotta tiles exceeding 40°C, and a few roof coverings exceeding 42°C.
As expected, lower surface temperatures are recorded in shaded areas (Figure 24), given the absence of high-performance materials.

Thanks to the terrestrial survey of Phillip St., Parramatta, performed with the UNSW drone mounted on the roof racks of a car, a slow motion time-lapse thermal video was elaborated by SkyMonkey. The video captures information about the surface temperatures of both horizontal and vertical surfaces during the central hours of the 2nd December 2018.
Figure 25 shows a few thermal images used to compose the terrestrial thermal video.


1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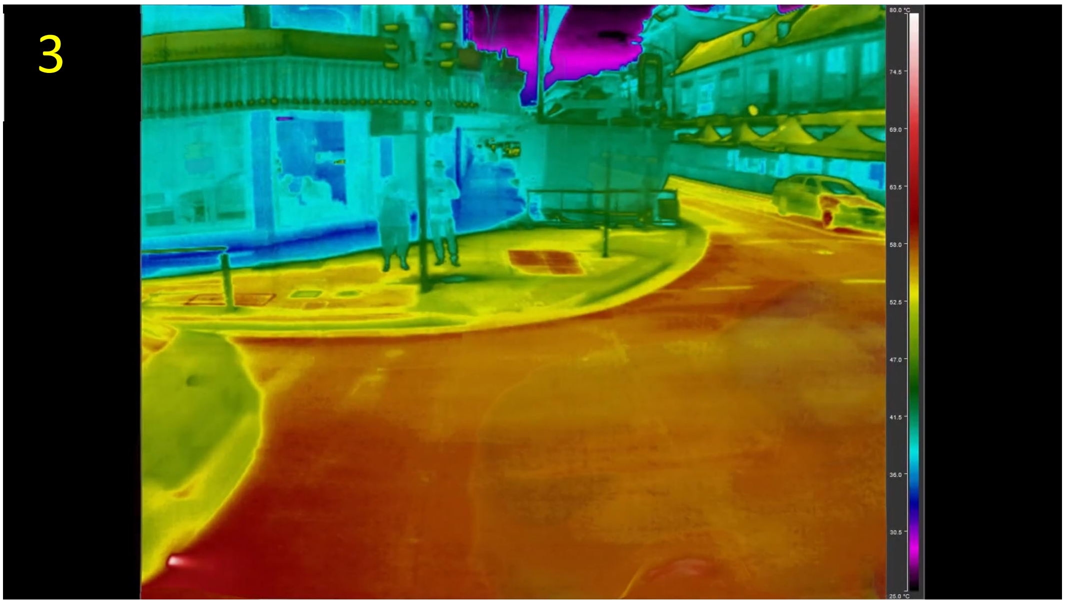

Figure 25. Images of the slow motion time-lapse thermal video, facing South while moving along Phillip S.t[1]. On the right the temperature scale is in °C.

From the three thermal images of Figure 25 and from the entire video, it is evident that the hot spot is the aged asphalt concrete (albedo of approximately 0.15) with high surface temperature ranging between 55°C and 65°C [8], with exception for the second thermal image where the surface temperature of the pavement results a bit lower due to the shading provided by trees of the small plaza.

Results of the Aerial Survey

The aerial survey of Phillip St., Parramatta, has been done to create a 3D thermal model of the street and the facades facing Parramatta river (Figure 26). This aerial survey provides qualitative information about the surface temperature for both land and vertical surfaces.
The drone's flight has been performed in a sunny day with adequate wind speed and under clear sky conditions to maximize the radiative response. The 3D thermal model shows the spatial distribution of the surface temperature for the 3rd of February 2019 around 1:30 pm and it is possible to navigate along the model under virtual reality.
The higher surface temperatures are visible in some rooftops and on the street asphalt that has high solar access, while lower surface temperatures are visible in the green areas. Due to the uncertainty in the thermal emittance value of building facades and roofs materials it is not possible to extrapolate quantitative results from the 3D model, but it is possible to identify the hot surfaces that wort attention. Anyway, the 3D model and the thermal video show how the facades are more reflective and with lower solar access, thus absorbing less solar radiation and not exceeding 45°C, on average.

The average air temperature measured by the MetPak Pro weather station during the aerial campaign was 32,7 °C, with a maximum and minimum air temperature of 33,4°C and 32,3°C, respectively. The maximum wind speed was 4 m/s.

The aerial survey confirms the observations of the terrestrial survey, especially the results obtained from the thermal images, showing high surface temperatures for the asphalt, often exceeding 50 °C (red and yellow colour in Figure 26).

[1] Slow-motion thermal video: https://www.youtube.com/watch?v=nZFHzI26EEs&feature=youtu.be

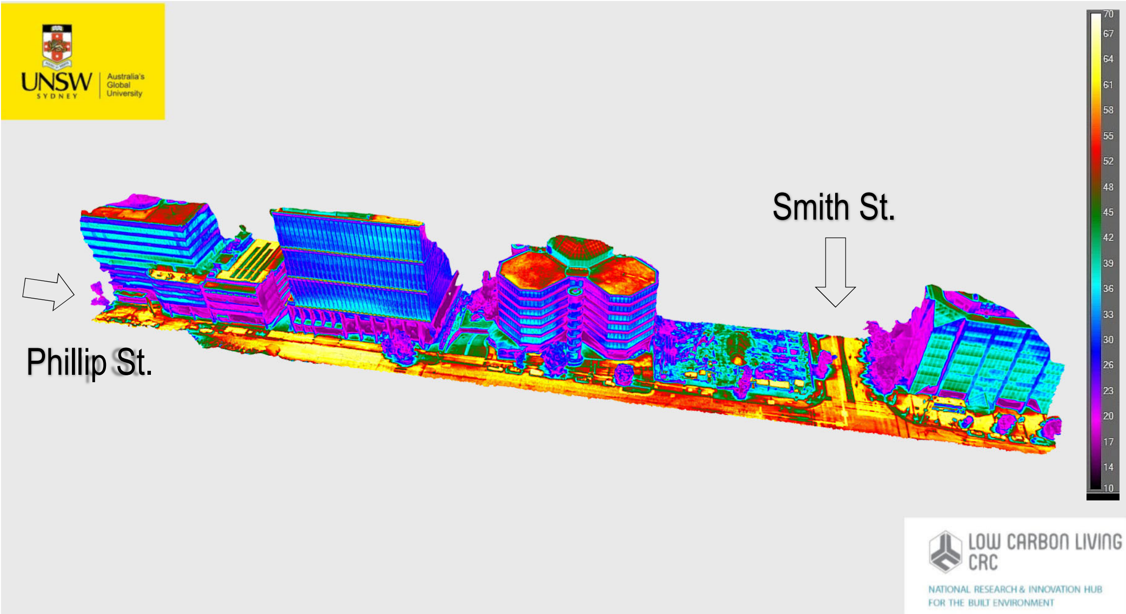

Figure 26. 3D thermal model of Phillip St., Parramatta (03/02/2019 at 1:30 pm)[2].

Conclusions

This chapter present the results of two monitoring campaigns performed in two summer days (e.g., terrestrial survey on the 02/12/2018 and aerial survey on the 02/02/2019) with the aim to assess the local microclimate and the impact of the microclimate on the built environment in Phillip St., Parramatta, and its surrounding. In both cases, the measurements have been performed during the central hours of the day to account for the peak conditions. One of the main results, is the average temperature difference of 1°C, registered between the two extremes of Phillip St. (e.g., the hotter Western part and the cooler Eastern part) at same instants of time. Regarding the surface temperatures of the urban environment in Phillip St., it has been found that the maximum values (above 50°C) are reached by the aged asphalt concrete that constitutes the entire street and that identifies the hot spot that require the higher attention.

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LOW CARBON LIVING CRC

4. SIMULATION OF THE CLIMATIC SCENARIOS- ASSUMPTIONS

Introduction

Urban heat island (UHI) and global warming increase the near surface ambient temperature in cities [1,2]. Urban heat island can affect the energy performance of buildings located in densely built areas as these buildings undergo several UHI effects such as higher external air temperatures, lower wind speeds and reduced energy losses during the night period. These effects have a significant impact especially on cooling energy consumption [1]. Research studies have identified and tested a wide range of counter measures to urban overheating, including the use of reflective materials, greenery [3]. The potential of mitigation technologies to lower ambient temperatures has been evaluated through a large number of mitigation projects from various parts of the world and various climatic conditions, demonstrating they can lower average peak temperatures by 2°C [4]. Lowering ambient temperatures by the large-scale use of UHI mitigation strategies such cool materials or greenery results in reducing the needs for cooling [5,6].

This section presents the analysis of microclimate in Phillip Street located in the City of Paramatta CBD. This investigation has been built on two different simulation approaches for analysis:

1. Microscale modelling for simulations of the reference and all mitigation scenarios
2. Mesoscale modelling under current climate and land use to derive climatic input data

Using microscale modelling, we simulated and assessed the unmitigated scenario as existing (S0) and planned developments (building height-S00) and maximum potential buildings heights and density (S000). The selected heat mitigation strategies for microscale modelling are as follows: S1) Cool pavement, S2) Greenery and tree, S3) Shading (shading cloth), S4) Spray system, S5) Cool roof, S6) Combination of cool pavement, greenery, shading, spray system, cool roof, S7) Combination of cool pavement and greenery, S8) Radiative Cooling-shading, S9) the City of Parramatta Council implementation plan, S10) Improvement of the City of Parramatta Council implementation plan. The details and assumptions of the mitigated and unmitigated scenarios are described in Table 1.

Methodology

Inputs and assumptions of the simulation model

Simulations of the unmitigated and mitigated scenarios under current climate have been performed using the software ENVI-met V4.1.3. This program is a three-dimensional microclimate model designed to simulate the surface, plant and air interactions in an urban environment. This computer program is an accurate tool to simulate the distribution of the main climatic parameters in the urban environment. For evaluating the urban microclimate effects, ten mitigation scenarios have been developed and considered in the model. We also modelled and analysed the future microclimate condition in the City of Parramatta CBD considering the increase of building height and density. The year chosen for the simulation of current climate was 2017-2018.

The City of Parramatta CBD was selected and modelled for a representative day during summer heatwave, summer mean maximum condition, and winter. The climate input data (24 hr) for the mean maximum and heatwave conditions was selected based on COOLING PARRAMATTA tool which visualises the data generated by the WRF simulations (HTTP://147.27.33.179:8083). The temperature, wind speed and wind direction were selected based on current climate and land use. Since winter is not included in the climatic conditions in COOLING PARRAMATTA tool, we used the hourly climatic data from the Sydney Olympic Park AWS BoM station [7] (ID: 066212, Lat: -33.8338, Lon:151.0718, Height: 4 m above the sea level, located 6.5 Km from Parramatta CBD) for winter period simulations.

We mainly focus on the simulation of Phillip street; however, the whole City of Parramatta CBD was modelled to consider a comprehensive interaction of built environment. The simulation was performed for 24 hours of the day starting before sunrise. The unmitigated model has been made applying the standard values of the urban environment, especially regarding radiative properties of buildings; the albedo of the building surface materials (roofs and walls) was selected as 0.2 in the actual (base case) scenario. The model has been created with the Area Input file editor of the ENVI-met® rotated 15.5° out of grid north, according to the main direction of development of the roads. The spatial resolution used in the simulations is 3 m horizontally. The area has been rendered with a 270 × 264 × 30 (x-y-z) cells, with the following size: dx = 3 m, dy = 3 m, and base dz = 0.3 m. The grid at the z axis is telescopic (factor of %20) with a thicker cell near the ground, allowing a better accuracy for edge effects. The obtained results of the simulation are presented in the following sections.

Evaluation of comfort

Thermal comfort was assessed using ENVI-met BioMet to evaluate the effect of mitigation technologies on outdoor urban microclimate and examine thermal comfort at pedestrian level, calculate potential heat stress reduction with each microclimatic scenario, and identify the microclimatic zones where the mitigation technologies ameliorate the urban biometeorological conditions. For the evaluation of outdoor thermal comfort, we calculated two comfort indices using ENVI-met Biomet: Universal Thermal Climate Index (UTCI) and Physiological Equivalent Temperature (PET). For the thermo-physiological parameter of human body, we assumed a typical male (35 years old, 1.75 tall, weight 75) with clothing values of 0.5 and 0.9 (corresponding to summer and winter business suits) and an activity level of 1.4 MET.

UTCI is a state-of-art human energy balance model that quantifies outdoor thermal comfort by integrating thermo-physiological effects of four environmental (air temperature (T_a), mean radiant temperature (MRT), relative humidity (RH), wind speed (v)), and two personal parameters, clothing insolation (clo), and activity (w). UTCI is a multi-node model of human thermoregulation [8] incorporating an adaptive clothing algorithm [9] related to outdoor thermal conditions. UTCI above 46 °C indicates extreme heat stress, values comprised between 38 °C and 46 °C identify very strong heat stress, moderate heat stress between 26 °C and 38 °C, and no heat stress between 9 °C and 26 °C. In ENVI-met, the calculation of UTCI is based on a 6th order polynomial regression function estimating UTCI from wind speed, air temperature, mean radiant temperature and air vapour pressure. This approach has two limitations: 1) UTCI as used in the software is limited to a wind speed range of 0.5 to 17 m/s related to 10 m Height. 2) UTCI is related to wind speed at 10 m height while the biometeorological parameters are normally define between 1.5 and 2 m. Due to these restrictions, areas outside the official bounds of UTCI are not calculated by BioMet and marked with “No Data”. Thus, in urban areas the lower limit of 0.5 m/s can create a number of white “No Data” areas in the maps. UTCI in the regression-based version based on using pedestrian level wind speeds extrapolated to 10m. However, in a complex urban environment, wind speeds at pedestrian level are unique and cannot be related to some above-roof general quantity. Therefore, we also assessed comfort using the application of a pure physically-based approach (i.e. PET) as recommended.

The Physiological Equivalent Temperature (PET) is a thermal comfort index that is based on a prognostic model of the human energy balance that computes the skin temperature, the body core temperature, the sweat rate and the clothing temperature. It is generally based on the 2-node model proposed by Gagge et al. [10] and was compiled and extended by Höppe [11]. PET is defined as “the physiologically equivalent air temperature at any given place (outdoors or indoors) and is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of a human body is maintained with core and skin temperatures equal to those under the conditions being assessed” [11]. It corresponds to the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed [11]. PET expresses the thermal comfort of a human body using the skin and core temperature as reference indicators. Thus, all incoming and outgoing fluxes at the human body are defined, a skin and a core temperature, that matches all the calculated fluxes are calculated, the person is transposed into an indoor environment, then it reset all data that are not available in an indoor environment (direct solar radiation, forced wind movement), and search for an indoor air temperature (as only parameter) that results in the same skin temperature and core temperature as the outdoor setting. This theoretically calculated indoor temperature is called PET.

The PMV Model (Predicted Mean Vote Model) is the best know human thermal comfort model especially for indoor applications. It is based on Fanger’s [12] comfort model and relates the energy balance of the human body with the human thermal impression using a straight empirical function. PMV was originally developed for steady-state indoor situations, but by extending the energy flux related parts of the model with solar and longwave radiation and allowing wind speeds above an indoor room situation, PMV can also be applied (with limits) to outdoor situations. PMV scale is defined between -4 (very cold) and +4 (very hot) where 0 is the thermal neutral (comfort) value. Applying the PMV equation to outdoor conditions in summer heat stress situations can easily produce PMV values high above +4 (+8 and more). While this result is numerically correct, it violates the range of the original PMV system.

Description of the mitigation scenarios

Table 1 summarises the mitigation technologies used in this investigation. We modelled and simulated the unmitigated scenario without implementation of the mitigation strategies in three conditions (Figure 1 to Figure 3): the reference model as existing in present form (S1); the model which incorporates planned developments and proposed building heights (S00); the model which shows the maximum potential buildings heights (S000).

Table 1. Description of the unmitigated case and the mitigation scenarios in Phillip street

No	Scenario	Description
S0	Existing/unmitigated scenario	Albedo of walls and roofs=0.2, Asphalts Albedo=0.05, Concrete pavements Albedo=0.20, Loamy soil Albedo=0.15
S00	Planned height/Future	Same as S0- increased building height
S000	Potential height/Future	Same as S0- increased building height
S1	Cool pavement	Increased albedo of pavements to 0.5, and albedo of streets to 0.4
S2	Greenery and tree	Increased urban greenery by planting of 82 mature trees in the area
S3	Shading (shading cloth)	Use of shading device covering 75% of Phillip St with albedo of
S4	Spray system	0.5 Use of evaporative cooling techniques with 22 misting
S5	Cool roof	systems Increased albedo of building roof adjacent to Phillip St to
S6	Combination of S1 to S5	0.85 Combination of cool pavement, greenery, shading, spray system, cool roof
S7	Combination of cool pavement and greenery	Increased albedo of pavements and streets to 0.5 and 0.4, and increased urban greenery by planting of 82 mature trees
S8	Radiative cooling-shading	Use of radiative cooling material as the shading device
S9	Parramatta council implementation plan	Proposed design by the City of Parramatta Council-(albedo of concrete pavement: 0.15, albedo of streets: 0.05 Asphalt, Tree:8m Solkova)
S10	Parramatta council optimised design	Use of cool pavement in the proposed design by the City of Parramatta i.e., Tree:8m Solkova

Figure 1 to Figure 3 show the present and future models without implementation of the mitigation strategies. The specific details each scenario is discussed in the following section.

Reference model-City of Parramatta CBD

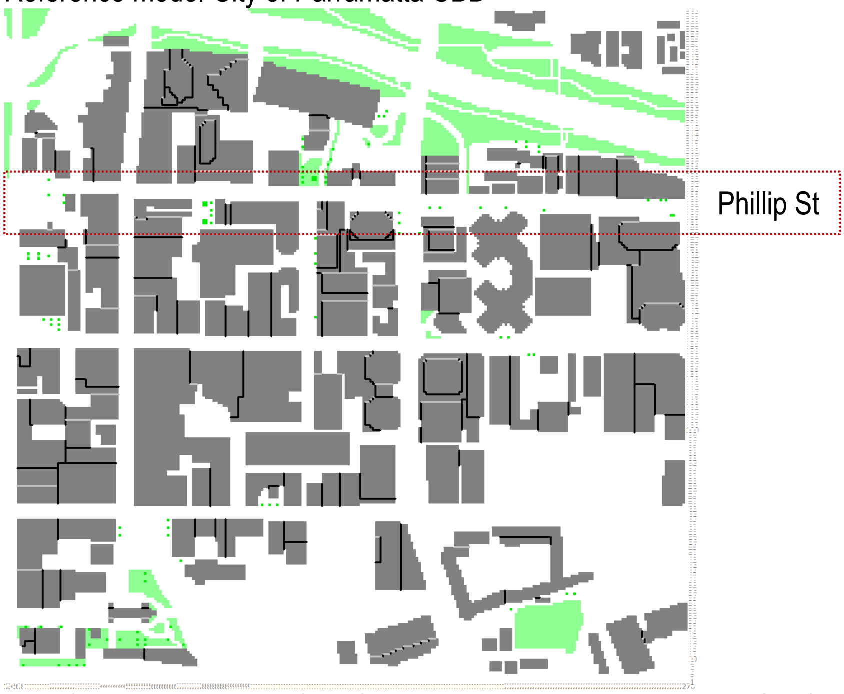


Figure 1. The simulation domain of the reference model representing existing condition-City of Parramatta CBD and Phillip Street

Planned building height model- City of Parramatta CBD

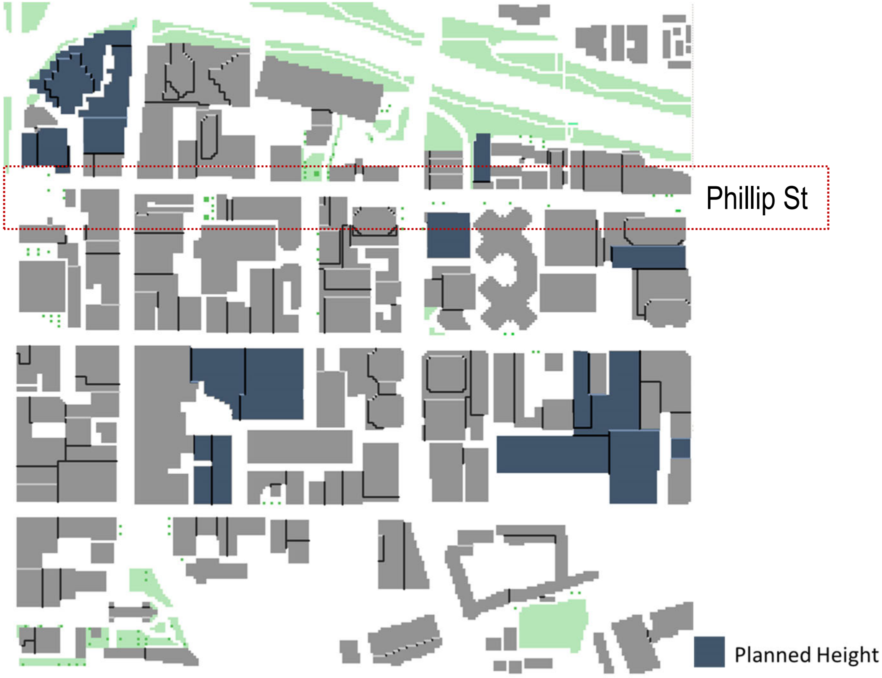


Figure 2. The simulation domain of the planned building height model representing future condition-City of Parramatta CBD and Phillip Street

Potential building height model- City of Parramatta CBD

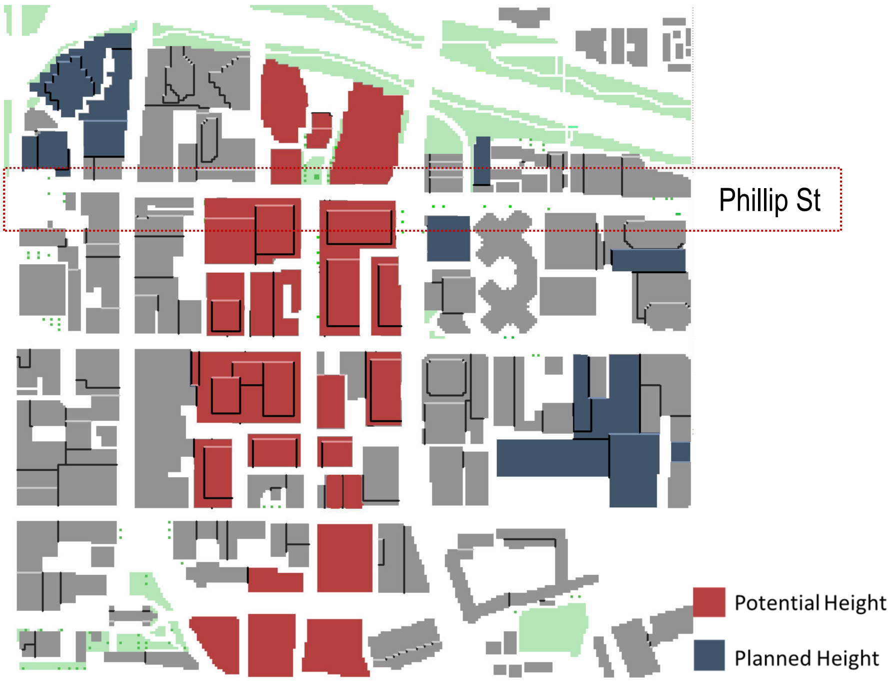
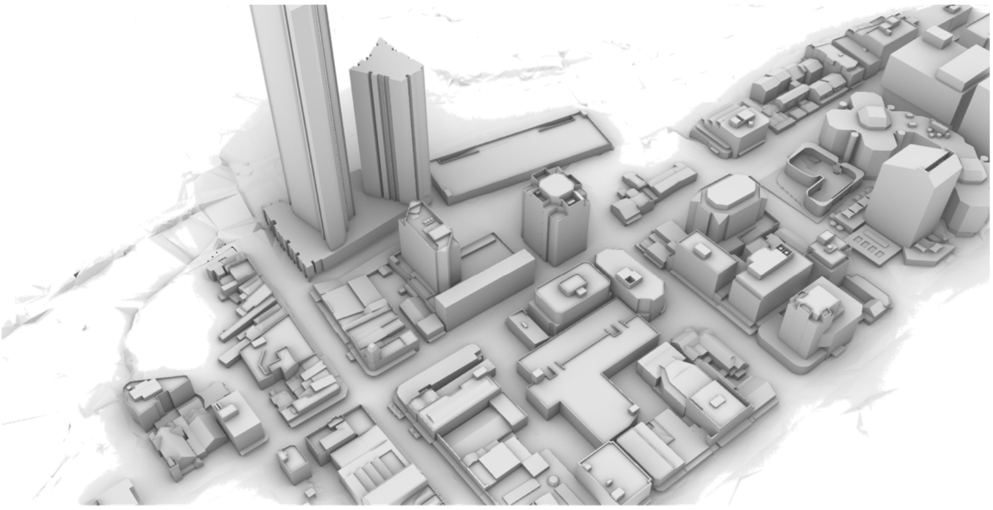


Figure 3. The simulation domain of the maximum building height model representing future condition-City of Parramatta CBD and Phillip Street

S0- Existing/unmitigated scenario

The unmitigated scenario corresponding to the existing condition was modelled as a reference case to compare with the mitigated scenarios and assess the cooling potential of mitigated ones against the existing condition. In the reference scenario, the albedo of material used in the model is as follows: building walls and roofs material is 0.2, asphalt surface is 0.05, concrete pavement is 0.20, and loamy soil is 0.15. The information about building heights and horizontal surfaces were extracted from Google and Near maps. For the modelling of the vegetation in the whole City of Parramatta CBD, two different plant types have been employed: deciduous and evergreen trees with different height from 3m to14m, very dense foliage, distinct crown layer, and grass with average density.

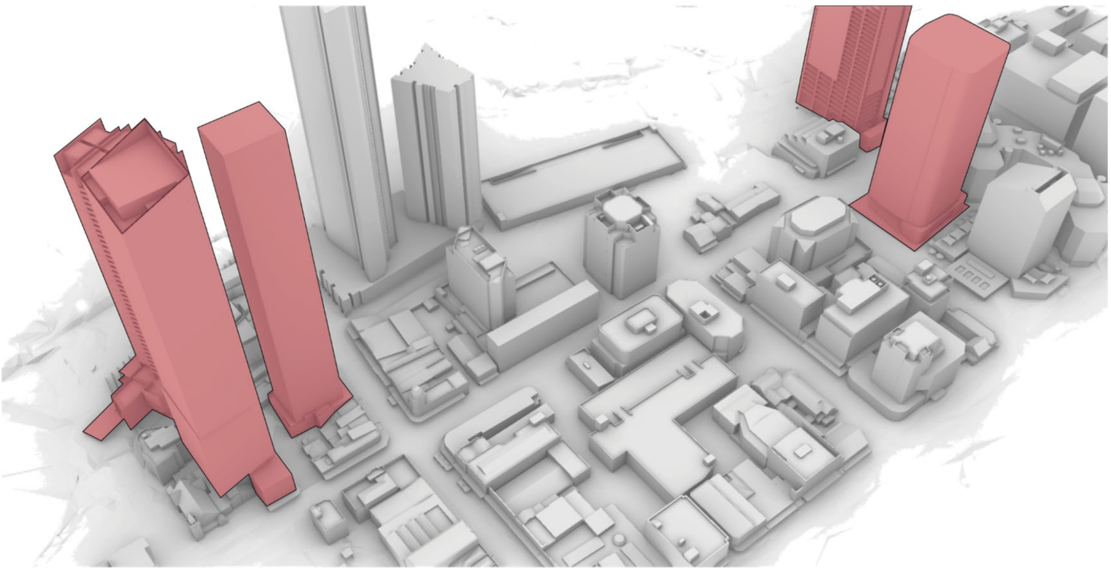


0 - Existing/unmitigated

Figure 4. Schematic 3-D view of the Phillip Street mitigation interventions-existing condition (S0)

S00-Planned height/Future

The scenario of future built form is designed to investigate the impacts of new buildings and development plan in the microclimate of Parramatta CBD and Phillip street. The properties of building material and urban surfaces are kept consistent with the reference existing scenario.

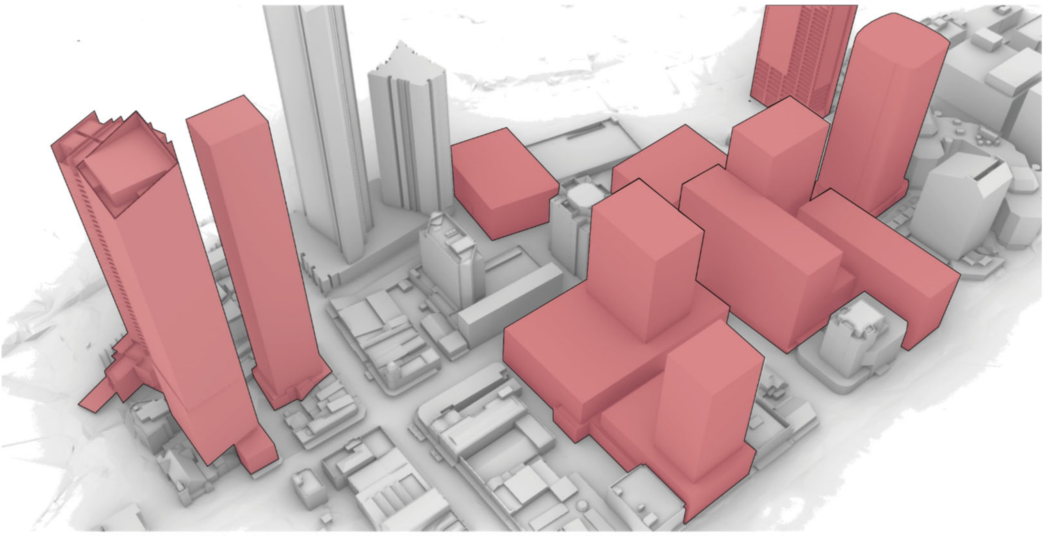


00 - Planned/future case

Figure 5. Schematic 3-D view of the Phillip Street mitigation interventions-future condition (S00)

S000-Potential height/Future

This scenario implements future changes in the built form and increased building heights in the City of Parramatta CBD and Phillip Street. The assigned building heights range between 55 to 240m. Building alignments, height and setbacks were considered based on Civic Link proposed strategy (2-Storey street wall and pedestrian path). This scenario is designed to understand the effect of building height in outdoor microclimate of Parramatta CBD. The properties of building material and urban surfaces are kept consistent with the reference case (existing scenario).

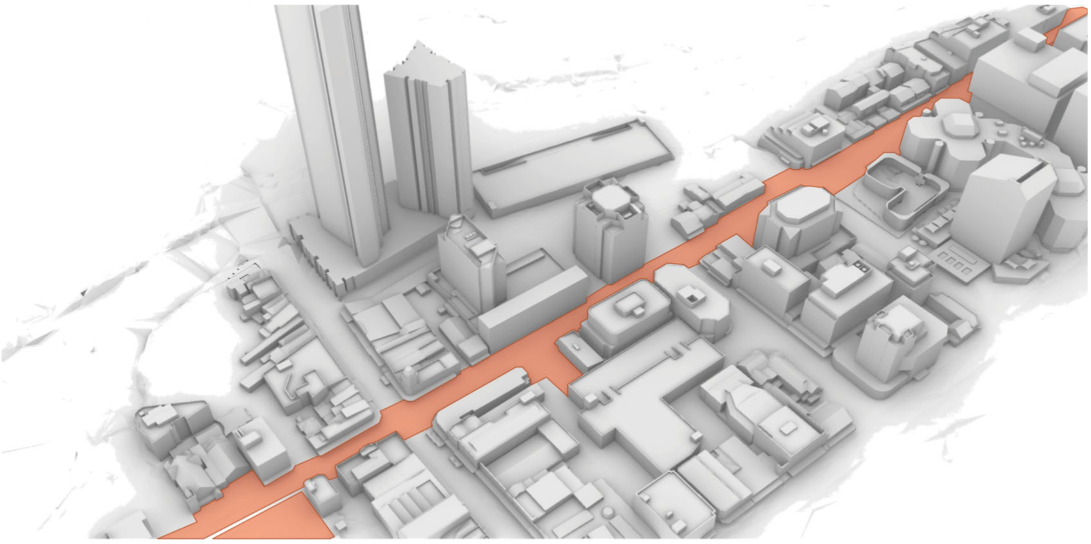


000 - Potential future built form

Figure 6. Schematic 3-D view of the Phillip Street mitigation interventions-future condition (S000)

S1-Cool pavement:

The effects of reflective pavements have been assessed by increasing the albedo of horizontal surfaces; i.e., albedo of pavements was increased to 0.5, and the albedo of streets was changed to 0.4. The corresponding values in the unmitigated model were 0.20 and 0.05, respectively. The changes have been implemented to the whole Phillip street, and other streets in the Parramatta CBD were kept unchanged as existing.

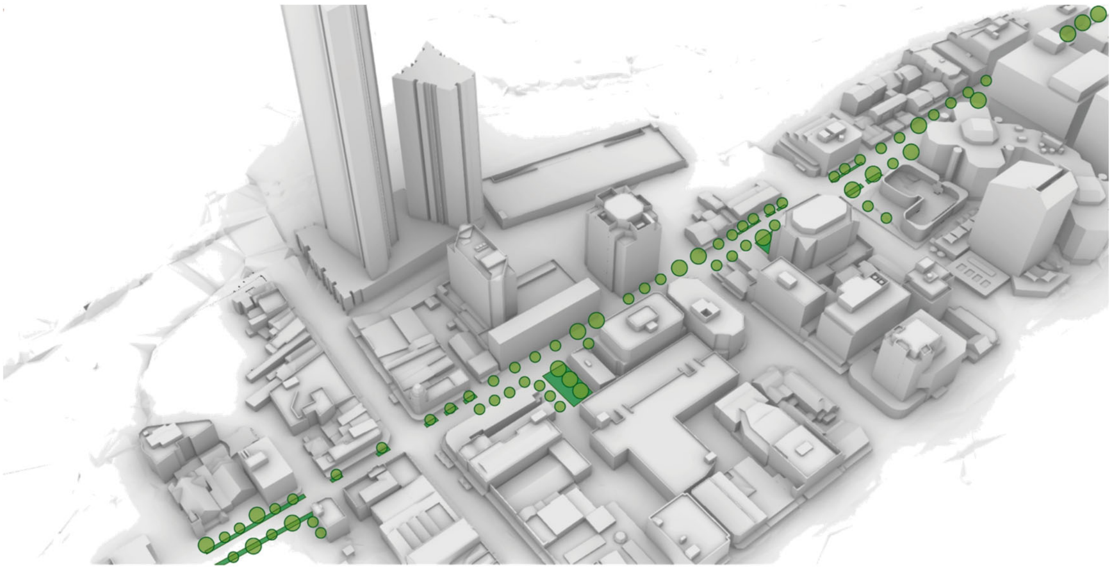


1 - Cool pavements

Figure 7. Schematic 3-D view of the Phillip Street mitigation interventions-cool pavement (S1)

S2- Greenery and tree

This scenario focuses on the effects of increased urban greenery in the microclimate condition of the Phillip street. We applied the changes in the existing unmitigated scenario by planting of 82 mature irrigated trees and raingardens in the area. Both deciduous and evergreen trees were planted with the height of 6m. A few 8meter high trees were also considered in the model.

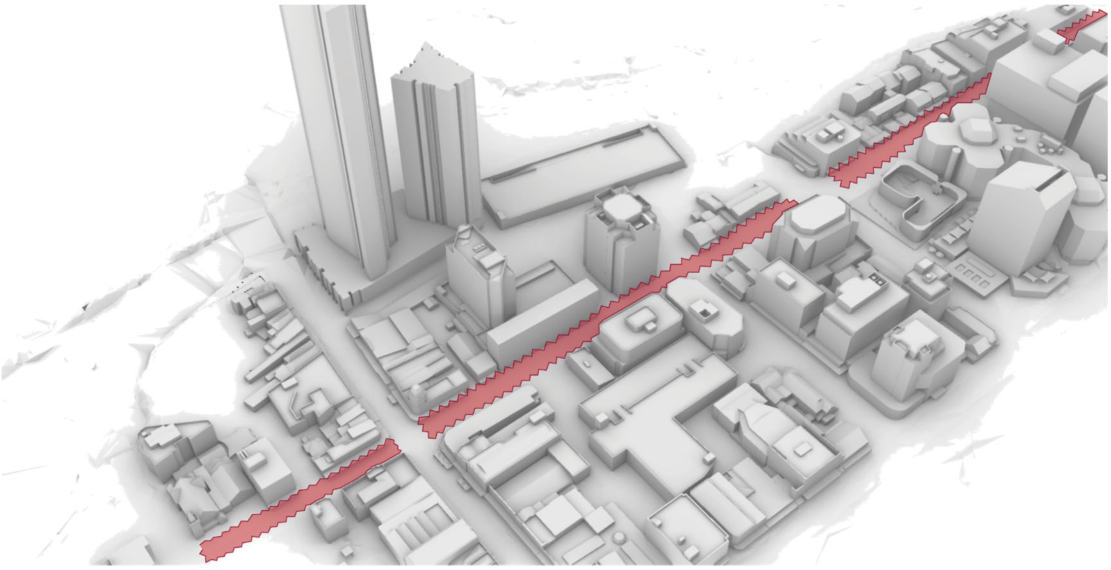


2 - Greenery and trees

Figure 8. Schematic 3-D view of the Phillip Street mitigation interventions-greenery and trees (S2)

S3-Shading (shading cloth)

Solar control has been shown to be an effective strategy to improve outdoor thermal comfort. This scenario investigates the use of shading device covering 75% of Phillip St.. For this assessment, shading cloth with an albedo of 0.5 is selected and located at the height of 10m above the ground. The following input has been applied to the property of the selected material: reflection: 0.5, absorption:0.5, and transmission: 0.

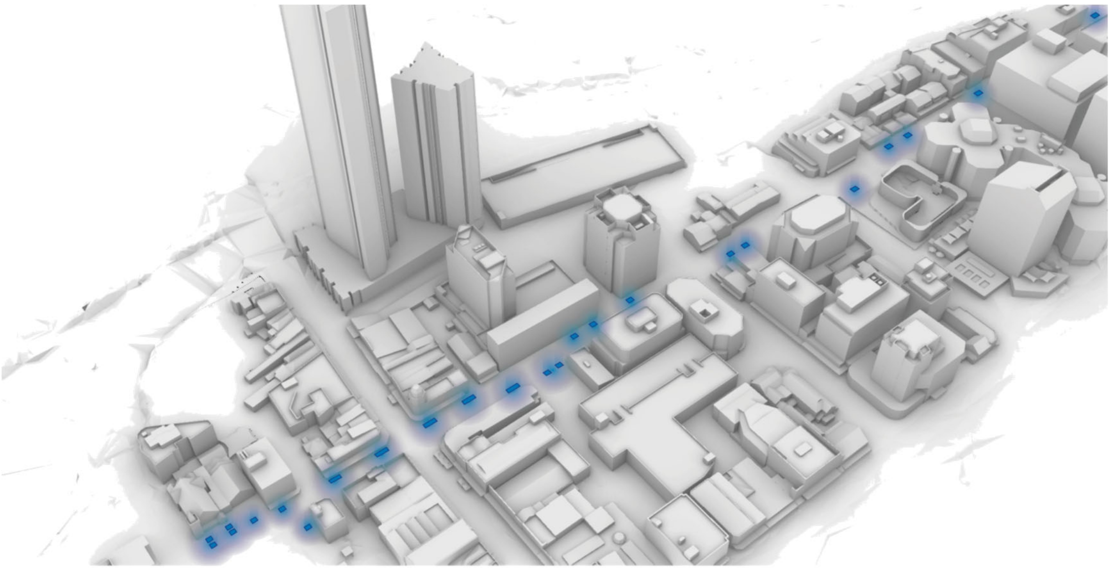


3 - Shading structure

Figure 9. Schematic 3-D view of the Phillip Street mitigation interventions-solar control with shading cloth (S3)

S4-Spray system

We investigated the effects of evaporative cooling techniques in improving the microclimate of the Phillip Street. We implemented 22 misting systems with the size of 3m×3m and the height of 4m.

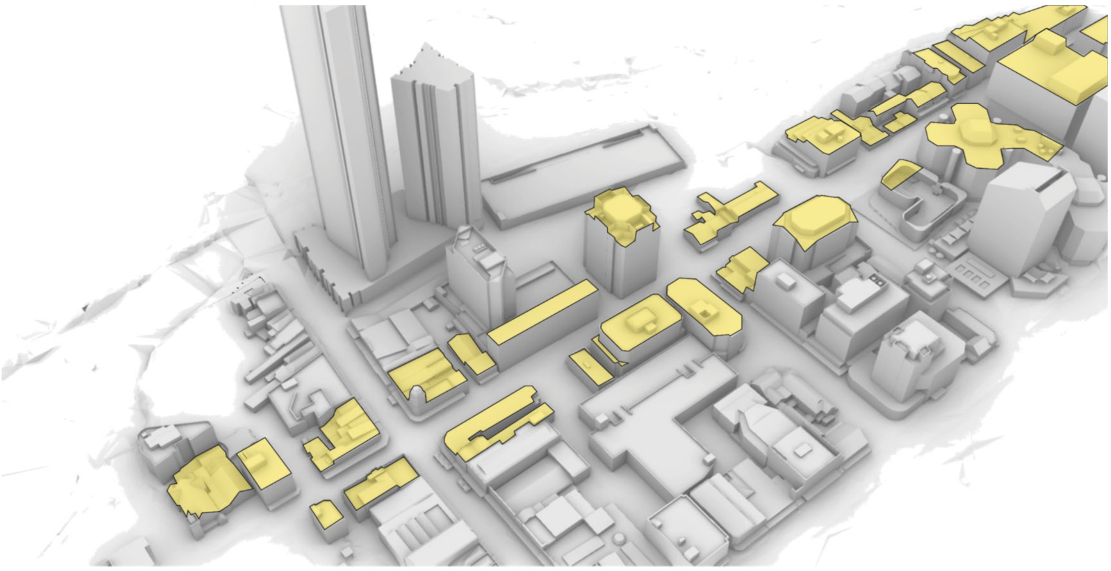


4 - Spray system/Water

Figure 10. Schematic 3-D view of the Phillip Street mitigation interventions-water misting system (S4)

S5-Cool roof

The effects of highly reflective building roof material have been evaluated int his scenario/ We increased the albedo of building roof adjacent to Phillip Street to 0.85. Building wall were kept unchanged.

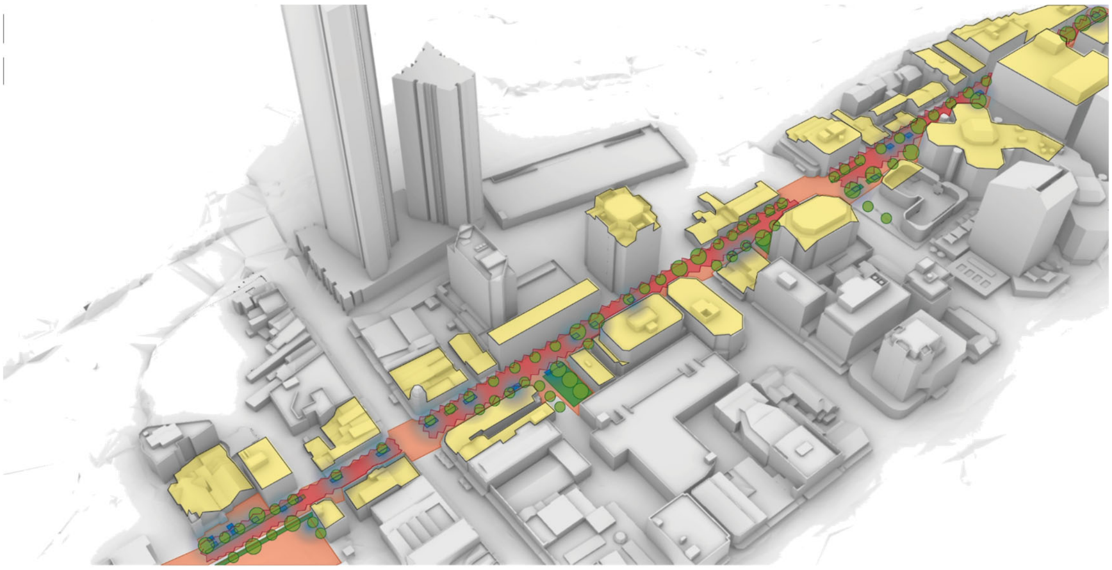


5 - Cool roofs

Figure 11. Schematic 3-D view of the Phillip Street mitigation interventions-cool roof (S5)

S6-Combination of S1 to S5

The combination of cool pavement, greenery, shading, spray system, cool roof was assessed in the scenario 6. The existing model were changed to incorporate all technologies mentioned above.

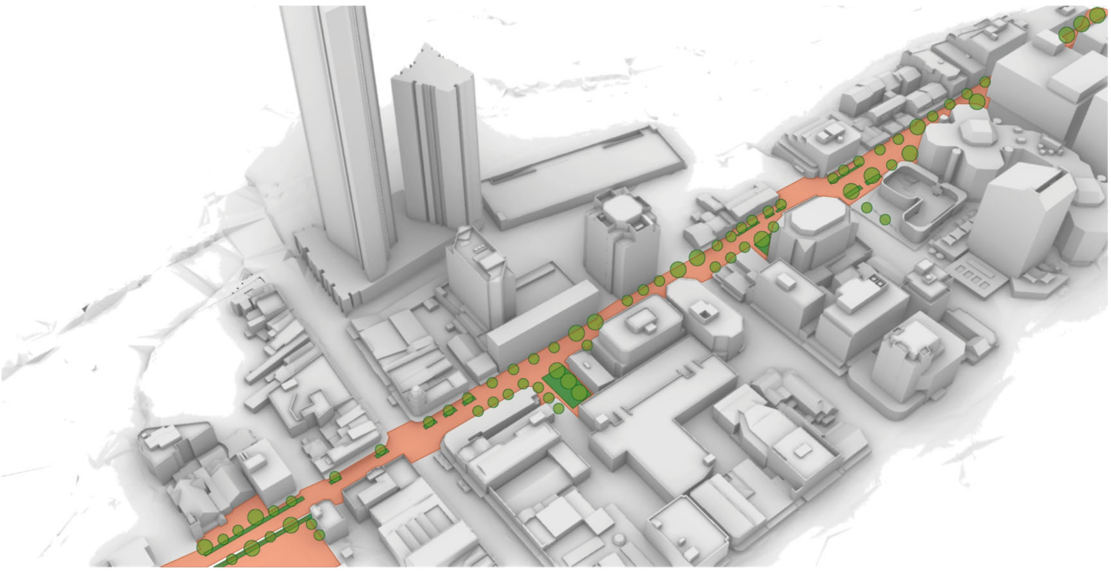


6 - Combined 1-5

Figure 12. Schematic 3-D view of the Phillip Street mitigation interventions-combination of five strategies (S6)

S7-Combination of cool pavement and greenery

We combined the two scenarios of cool pavement (scenario 1) and urban greenery (scenario 2) to investigate the combined effect of cool material and greenery. These are the most feasible strategies, which can be implemented with less complications. We increased albedo of pavements and streets to 0.5 and 0.4 and planted of 82 irrigated mature trees in the Phillip Street.



7 - Combined 1 & 2

Figure 13. Schematic 3-D view of the Phillip Street mitigation interventions-combination of cool pavement and greenery (S7)

S8-Radiative cooling-shading

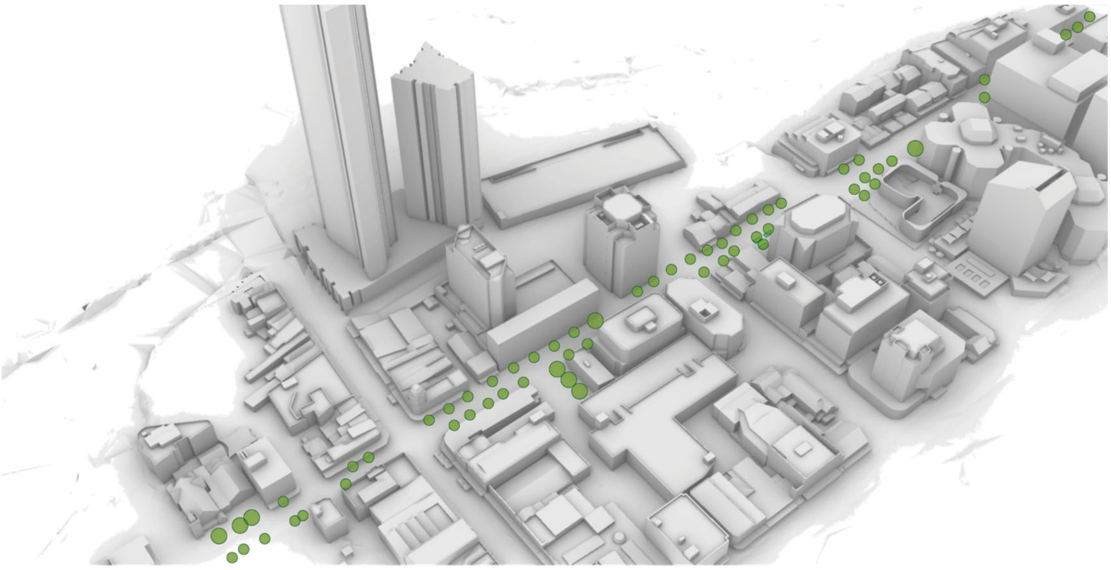
We use radiative cooling material in the shading device located at the height of 10m. The solar control device covers 75% of Phillip Street (same location and height as scenario 3). The following inputs have been applied to the property of the selected material: reflection: 0.9, absorption:0.1, and transmission: 0.

8 - Radiative cooling + Shading

Figure 14. Schematic 3-D view of the Phillip Street mitigation interventions-solar control with radiative cooling (S8)

S9-Parramatta council implementation plan

Scenario 9 evaluate the proposed design by the City of Parramatta Council. We considered the reflectivity of the proposed material for pavement (0.15) and streets asphalt (0.05). We modelled the horizontal surfaces based on the measured data. The proposed greenery is 8m mature Solkova tree which was modelled in line with the City of Parramatta Council implementation plan.



9 - Parramatta implementation plan

Figure 15. Schematic 3-D view of the Phillip Street mitigation interventions-Council design (S9)

The reflectance of the two samples of materials namely Adelaide black and LightGrey were measured in HPA lab at UNSW. The results are presented in Figure below.

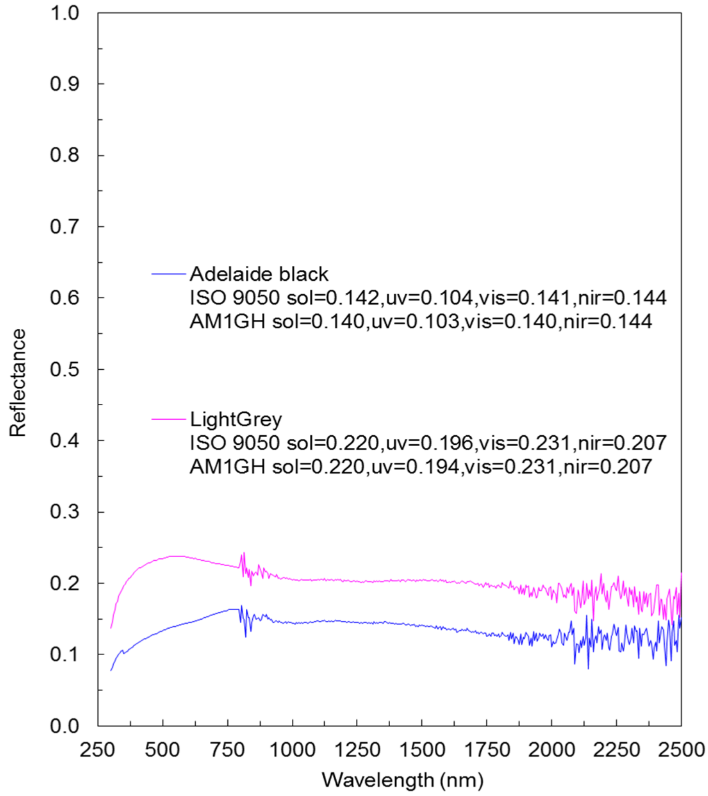
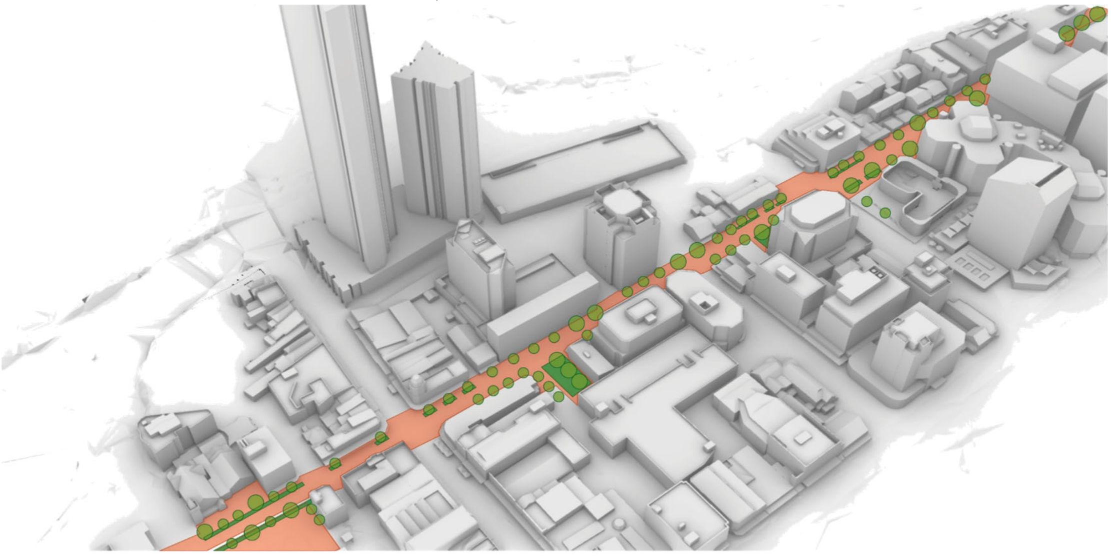


Figure 16. Reflectance of proposed pavement material by the City of Parramatta

S10-Parramatta Council optimised design

To further improve the microclimatic condition of Phillip Street, we used reflective material for street and pavements in the Parramatta Council implementation plan and modelled the proposed greenery (8m mature Solkova tree) combined with the cool pavement (increased albedo of pavements and streets to 0.5 and 0.4).



10 - Parramatta optimised design

Figure 17. Schematic 3-D view of the Phillip Street mitigation interventions-Council design improvement (S10)

Simulation results

We performed the simulation for three different conditions: summer mean maximum, heatwave and winter representative day, which are presented in the following sections. In each climatic condition, reference scenario and the two future development scenarios (planned and potential building height) are followed by the mitigated scenarios and council implementation plan. This section summarised the results of simulations at the peak time of the day 13:00 and at the height of 1.9 m above the ground.

Mean maximum condition

The climatic input data for the mean maximum condition was derived from the Cooling Parramatta tool (HTTP://147.27.33.179:8083). In the mean maximum condition, the initial wind speed considered in the simulations is 4.5 m/s, and wind direction is from south west. The minimum and maximum ambient temperatures of the simulation day are 19.2 °C and 32.9 °C, respectively.

Reference scenario

Reference scenario: existing condition

Scenario 0

Temperature in Phillip Street, in the existing form, ranges from 30.7 °C to 35.1 °C during the mean maximum summer condition. The temperature distribution map shows the area between Marsden Street and Church Street and Horwood Pl represents warmer conditions than eastern side of Phillip Street (Figure 18). The corner of Marsden Street reveals the hottest spot in Phillip Street exceeding 34 °C. Simulation results show the north eastern and northern part of the City of Parramatta CBD present cooler ambient temperatures than western and southern areas.

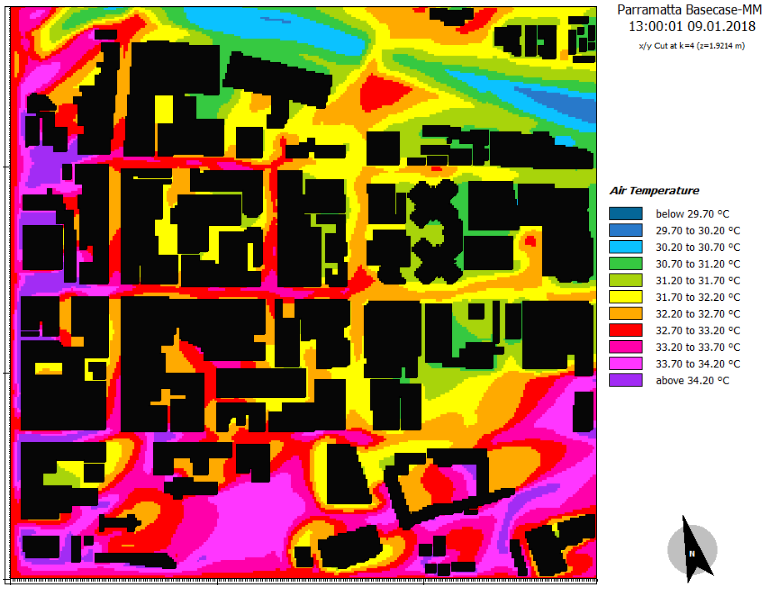


Figure 18. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 0, mean maximum condition - 13:00

Figure 19 shows the surface temperature distribution in the City of Parramatta CBD and Phillip Street in the existing condition (reference scenario). The surface temperature reaches 57 °C in the City of Parramatta CBD. Parramatta river and surrounding areas illustrate lower surface temperatures. The surface temperature in Phillip Street mainly ranges between 40.30 °C and 51.5 °C. Corner of Marsden Street, Church Street, and Smith Street in Phillip Street present very high surface temperatures.

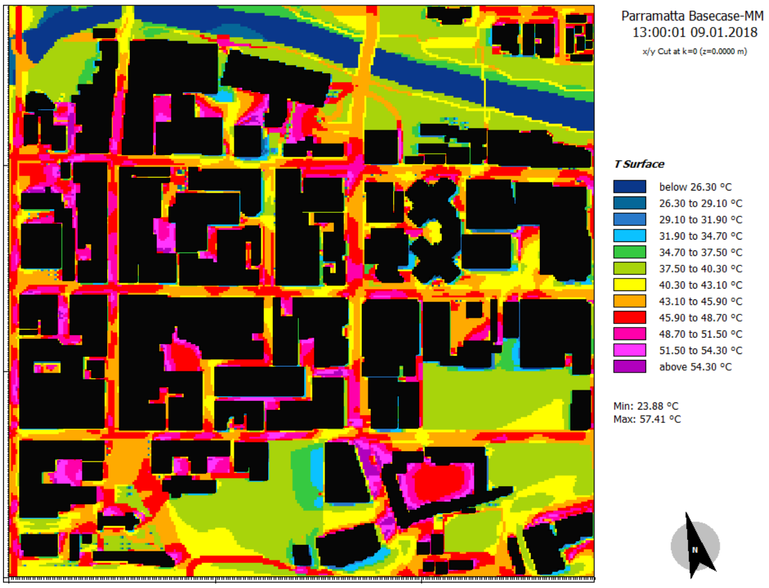


Figure 19. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 0, mean maximum condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 20. As presented, wind speed varies between 0 m/s and about 6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 4m/s in Phillip Street. The areas around the corner of Church Street and Smith Street illustrate lower wind speed values below 2 m/s. The western part of Phillip street presents higher wind speeds which affects advection mechanism in that area.

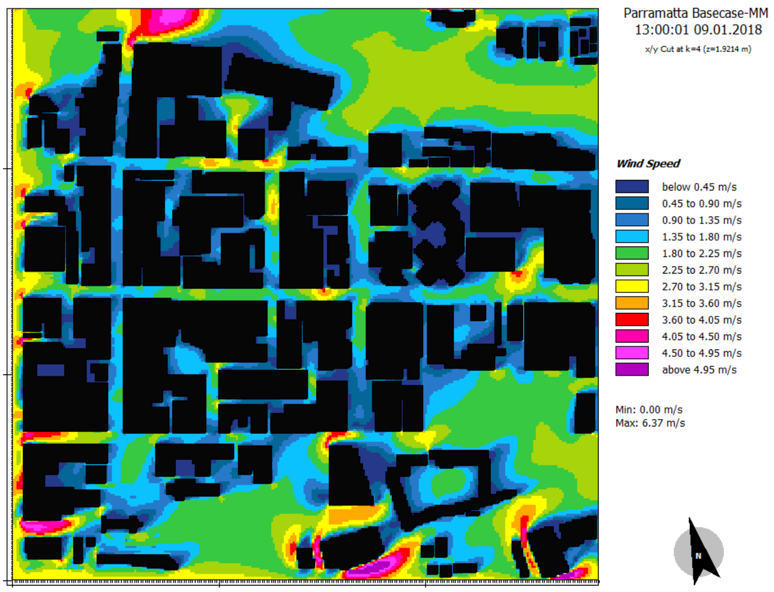


Figure 20. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 0, mean maximum condition - 13:00

We performed analysis of comfort in the Parramatta CBD using different comfort indices. Figure 21 provides the distribution of comfort indices (i.e. UTCI and PET). This analysis shows the western side of the City of Parramatta CBD experiences heat stress and warmth discomfort during mean maximum condition. Phillip Street in general indicates moderate to strong heat stress in most of the areas. The Universal Thermal Climate Index (UTCI) is showing strong heat stress (38-40 °C) mainly in the areas between Marsden Street and Church Street and the corner of Smith Street. UTCI as used in the software is limited to a wind speed range of 0.5 to 17 m/s at 10 m Height. Thus, the areas with very low wind speed below 0.5 m/s have no calculated data and presented in white colour. PET is consistent with UTCI indicating areas out of comfort range. It mostly varies from about 40 °C to 46 °C in Phillip street.

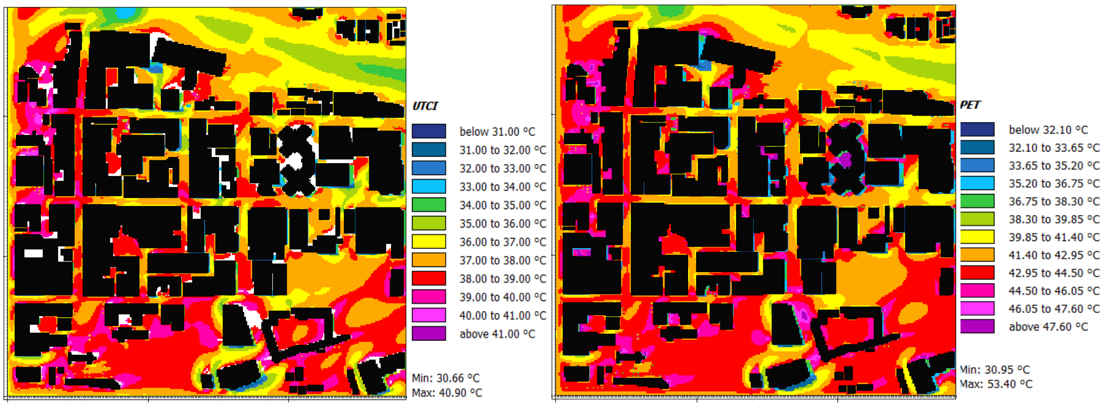


Figure 21. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 0, mean maximum condition - 13:00: UTCI (left), PET (right)

Future scenarios

Future scenarios: future development

Scenario 00

Temperature in Phillip Street under future development plan (planned height), ranges from 30.6°C to 34.9°C during the mean maximum summer condition. The temperature distribution map shows the area between Marsden Street and Horwood Pl represents much warmer conditions than eastern side of Phillip Street (Figure 22). The corner of Marsden Street, Church Street and Horwood Pl reveal the hottest spots in Phillip Street exceeding 32.7°C. Future building height and form affect the wind speed and solar access where new buildings were implemented.

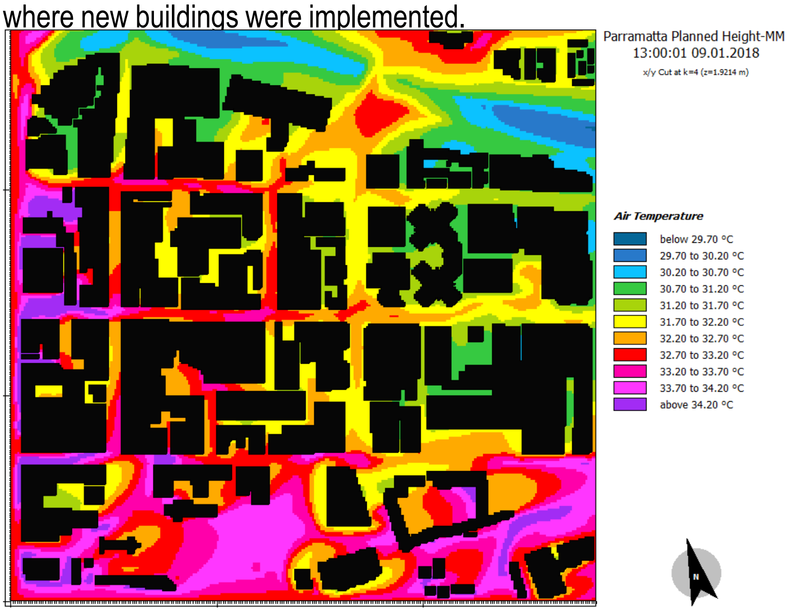


Figure 22.Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 00, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 23) shows temperature reduction in the street when new buildings were added, or height was changed. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and this scenario in the same spot. Due to the advection and shading provided by new buildings, areas close to new development have lower temperatures compared to the unmitigated scenario.

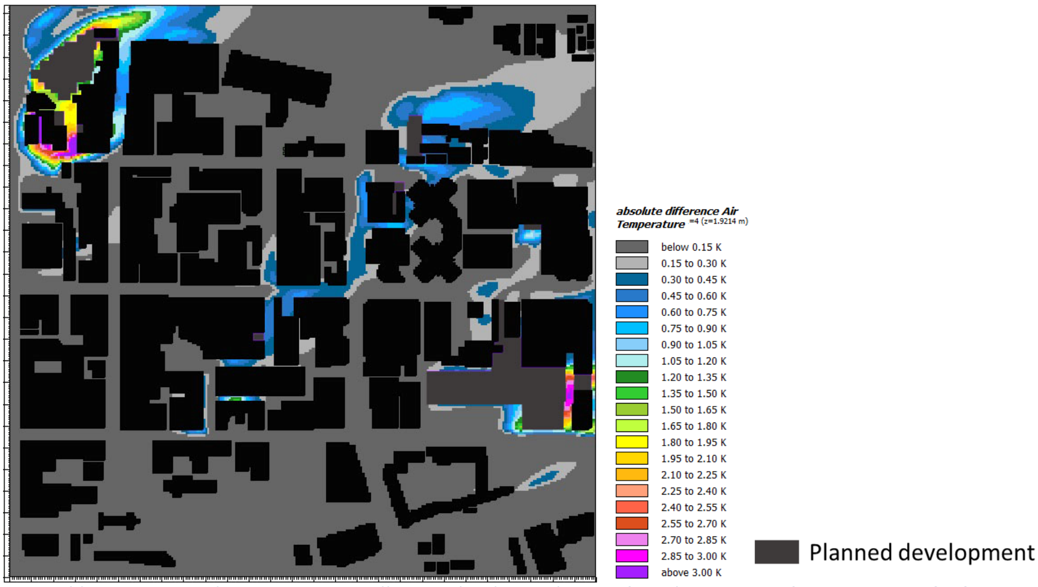


Figure 23. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 00, mean maximum condition - 13:00

Figure 24 illustrates the surface temperature distribution considering planned development (scenario 00). The surface temperature reaches 58°C in the City of Parramatta CBD. Dark coloured pavements show higher surface temperatures; however, western part of Phillip street shows lower surface temperatures compared to the reference scenario (scenario 0) because of the shading provided by new high-rise buildings. The maximum surface temperature is observed in the corner of Phillip Street and Smith Street which exceeds 50°C.

Figure 24. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 00, mean maximum condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 25. As presented, wind speed varies between 0 m/s and about 6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed exceeds 5m/s in western part of Phillip Street where new high-rise buildings were implemented. The corner of Marsden Street, Horwood Pl, Smith Street, and Church Street illustrate higher wind speed values than eastern part of Phillip Street. The wind speed distribution pattern affects advection mechanism in Phillip street.

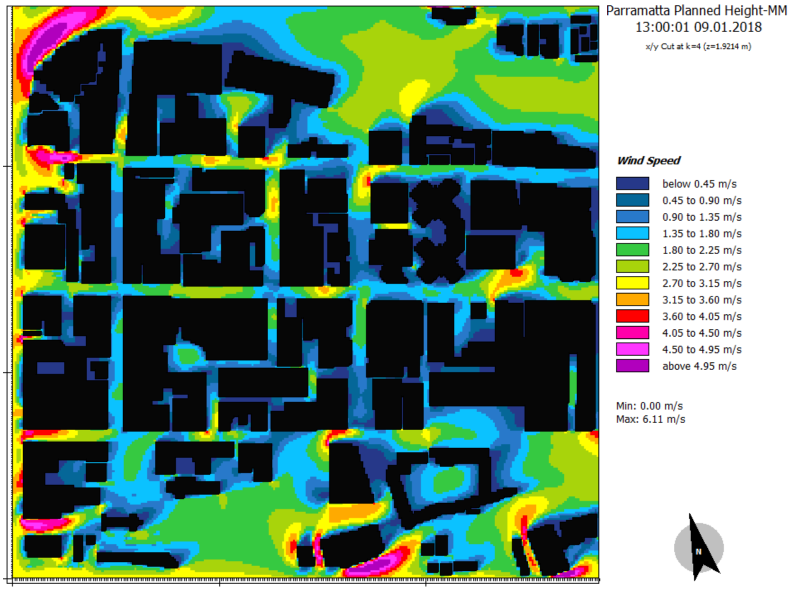


Figure 25. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 00, mean maximum condition - 13:00

Figure 26 provides the distribution of comfort indices (i.e. UTCI and PET). Phillip Street in general indicates moderate to strong heat stress. However, this analysis shows thermal comfort is improved in the western side of Phillip street (areas around Church Street and Marsden Street and between Church Street and Horwood Pl) which is explained by the effects of shading and changes in wind speed. The Universal Thermal Climate Index (UTCI) is mostly ranging from 36°C to 38°C in Phillip street during mean maximum condition. The corner of Smith Street still presenting strong heat street during the mean maximum condition. PET is consistent with UTCI indicating areas out of comfort range.

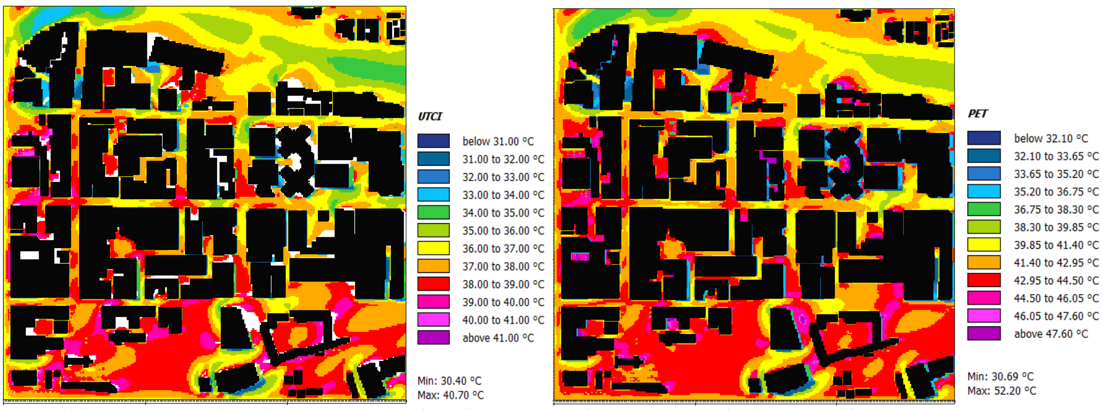


Figure 26. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 00, mean maximum condition - 13:00: UTCI (left), PET (right)

Scenario 000

The ambient temperature ranges from 30.6°C to 34.9°C in Phillip Street when development plan is considered together with hypothetical future building height and density in the central part of the City of Parramatta CBD. Implementing future building height and form highly affect the wind speed, solar access and pattern of temperature distribution. The temperature distribution map shows the area between Marsden Street and Horwood Pl in Phillip street still represents much warmer conditions than eastern side of Phillip Street (Figure 27) with temperatures exceeding 32.7°C.

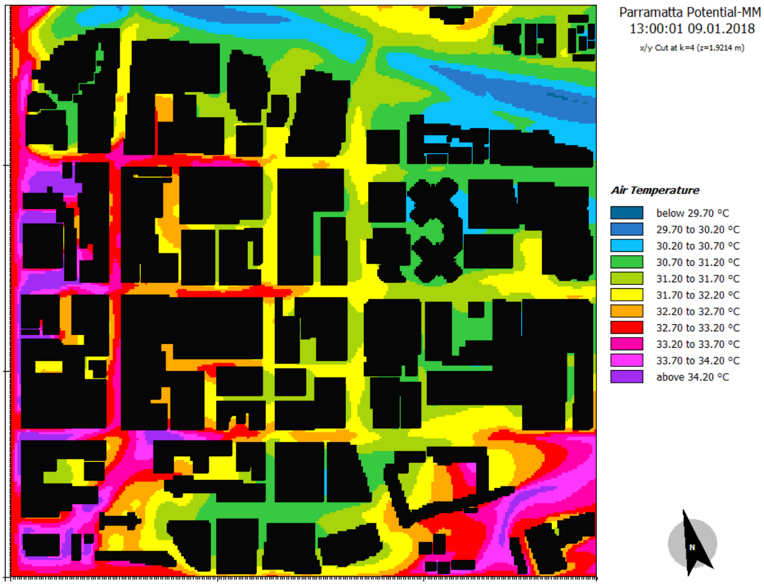


Figure 27. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 000, mean maximum condition - 13:00

Figure 28 shows the temperature difference between the future scenario and the reference in the same spot. Changes in wind speed distribution and shading provided by new buildings lead to lower temperatures in areas nearby new development compared to unmitigated scenario.

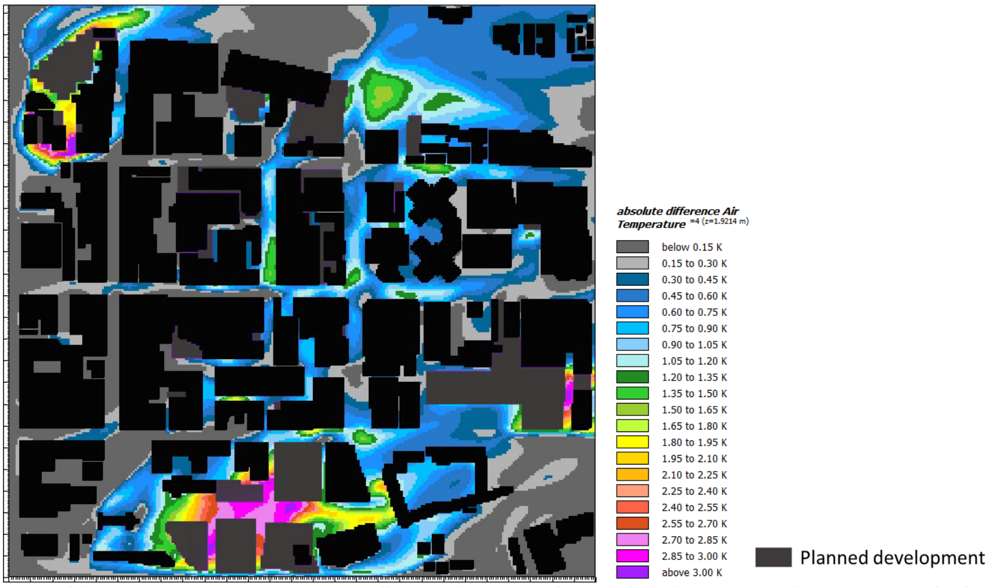


Figure 28. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 000, mean maximum condition - 13:00

The surface temperature distribution in the City of Parramatta CBD is shown in Figure 29 considering new development with maximum building height and density (scenario 000). The surface temperature reaches 57°C in the City of Parramatta CBD. Horizontal surfaces covered with asphalt show higher surface temperatures; however, areas shaded by new high-rise buildings show lower surface temperatures compared to the existing condition (scenario 0). The surface temperature in the corner of Phillip Street and Smith Street exceed 50°C and presents the highest surface temperature in Phillip Street when potential building height was considered.

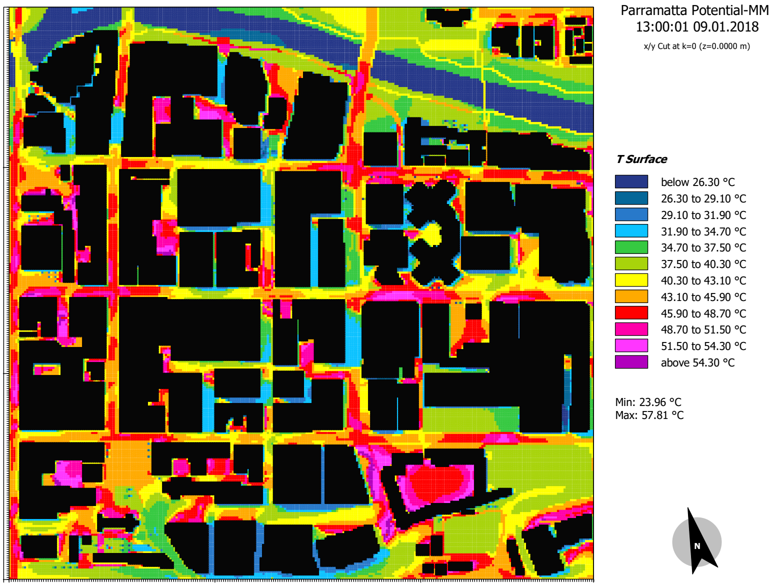


Figure 29. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 000, mean maximum condition - 13:00

As presented in Figure 30, wind speed reaches to about 12 m/s in Parramatta CBD. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed exceeds 5m/s in north western part of Phillip Street and southern part of the CBD where new high-rise buildings were implemented. The eastern parts of Phillip Street illustrate lower wind speed values compared to the western parts.

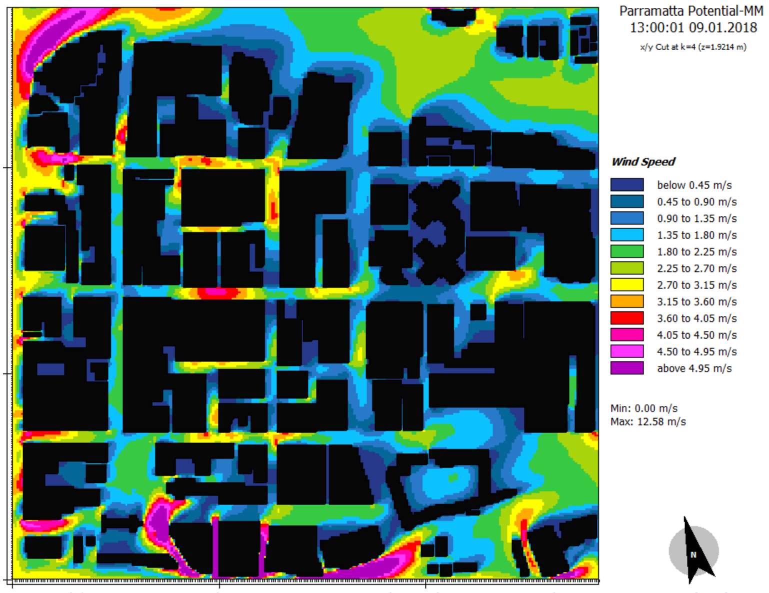


Figure 30. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 000, mean maximum condition - 13:00

Figure 31 shows the distribution of comfort indices (i.e. UTCI and PET). Phillip Street in general indicates moderate heat stress. The Universal Thermal Climate Index (UTCI) is mostly ranging from 34°C to 38°C in Phillip street during mean maximum condition under potential building height scenario. The corner of Smith Street and Phillip street is still presenting moderate to strong heat street – uncomfortable condition during the mean maximum condition. PET is consistent with UTCI indicating areas out of comfort range.

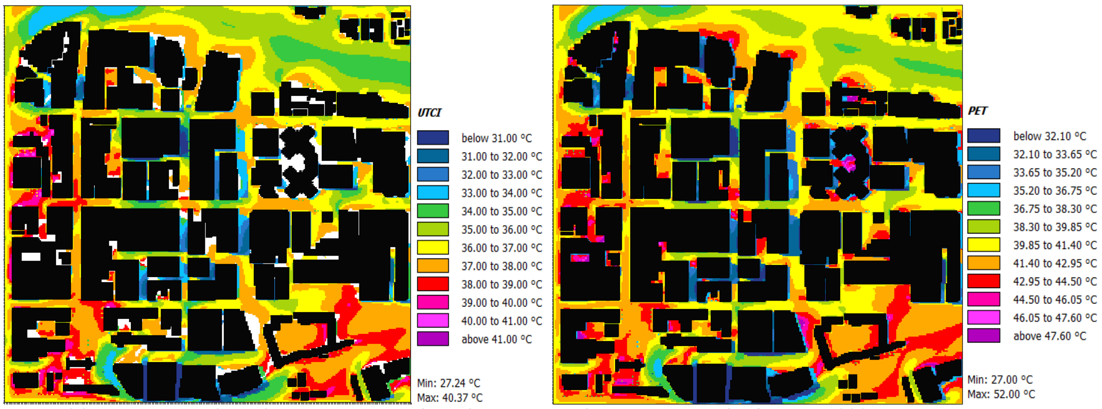


Figure 31. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 000, mean maximum condition - 13:00: UTCI (left), PET (right)

Mitigation scenarios

Mitigation scenarios

Scenario 1

Ambient temperature ranges from 30.6°C to 34.3°C in Phillip Street when cool pavement is implemented (scenario 1). Cool pavement is used in the whole Phillip Street and the car park located at the corner of Marsden Street. Despite higher ambient temperatures in western part of Phillip Street, the air temperature distribution map (Figure 32) shows that air temperature in the Phillip Street is reduced by the use of cool pavement compared to the reference scenario.

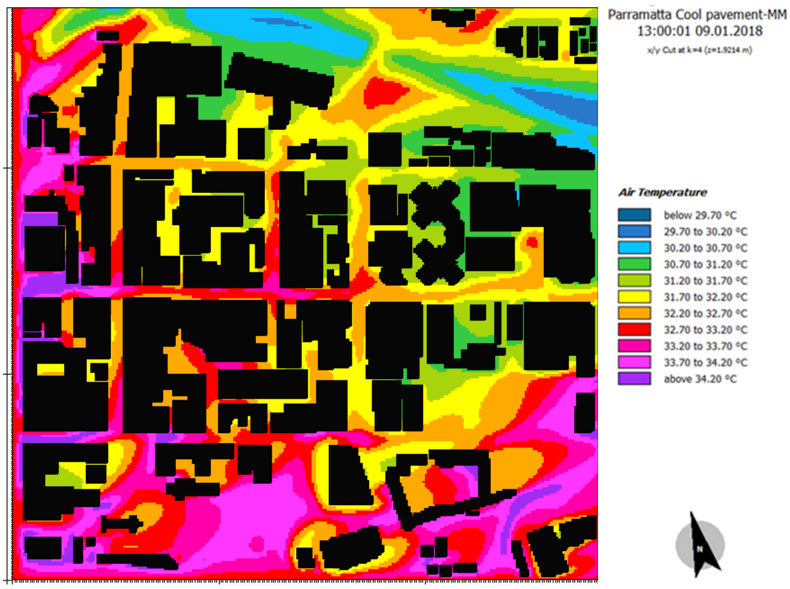


Figure 32.Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 1, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 33) shows temperature reduction in the street where mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the cool pavement scenario in the same spot. As shown in Figure below, the local temperature reduction ranges from 0 to 1.4°C and the average temperature reduction in the whole Phillip St. is 0.4°C.

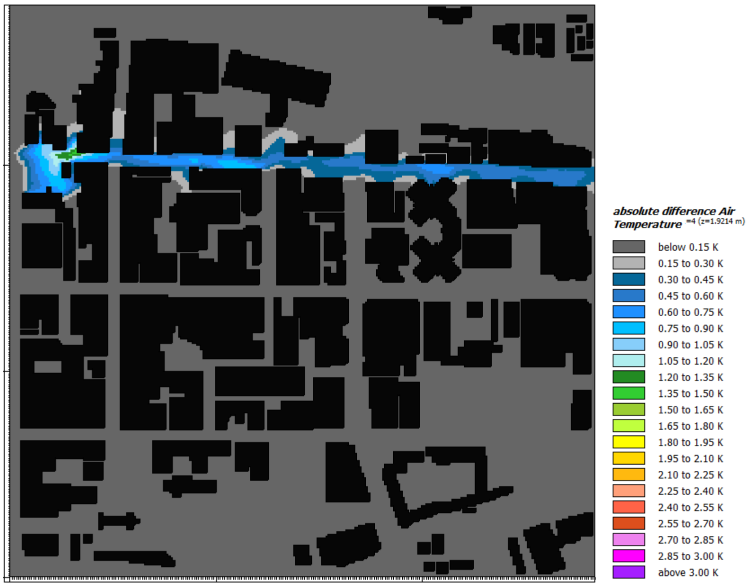


Figure 33. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 1, mean maximum condition - 13:00

The surface temperature distribution is shown in Figure 34 when cool pavement is implemented in Phillip St. The surface temperature is significantly reduced in scenario 1 compared to that in the reference scenario. The surface temperature varies from 29.1°C to 45.9°C in Phillip St. and reaches 56.9°C in the City of Parramatta CBD. It ranges between 37.5°C and 43.1°C in most parts of Phillip St.

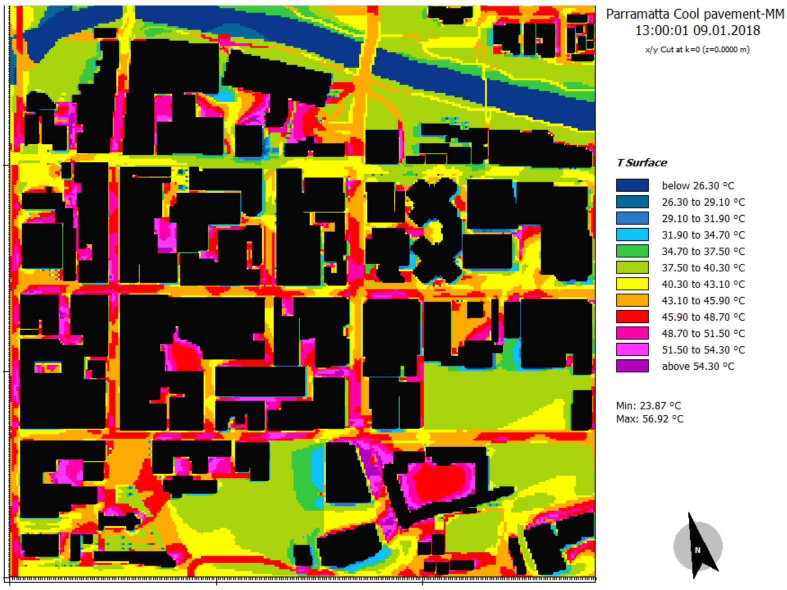


Figure 34. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 1, mean maximum condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 35. As presented, wind speed varies between 0 m/s and about 6.3 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 and about 4m/s in Phillip St. The areas around the corner of Church Street and Smith Street illustrate lower wind speed values below 2 m/s, while the corner of Marsden street and the areas between Church Street and Horwood Pl presents higher wind speeds which affects advection mechanism in those areas. Since there was no change in physical configuration of the model, wind speed is the same as reference scenario.

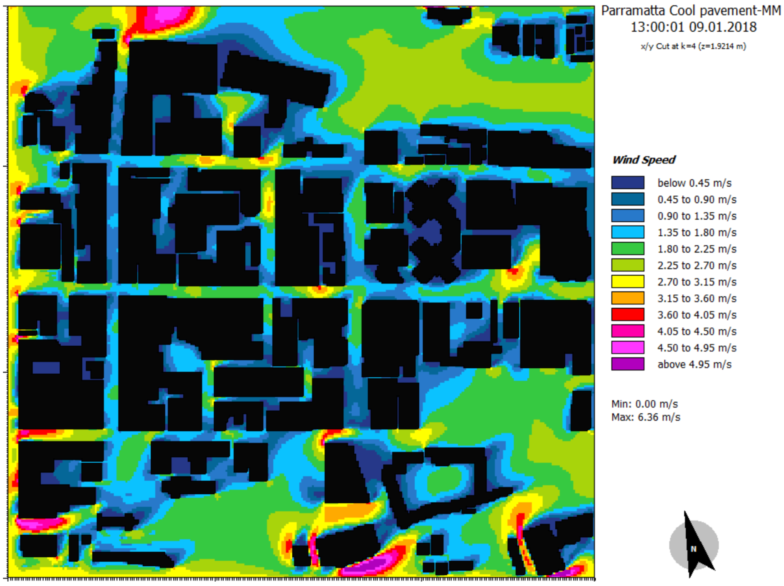


Figure 35. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 1, mean maximum condition - 13:00

Figure 36 shows the distribution of comfort indices (i.e. UTCI and PET). Phillip Street in general indicates moderate heat stress. The Universal Thermal Climate Index (UTCI) is mostly ranging from 34°C to 40°C in Phillip St. during the mean maximum condition under cool pavement scenario. The area between Marsden Street and Church Street, and the corner of Smith Street present moderate to strong heat street. PET distribution is consistent with UTCI indicating areas out of comfort zone.

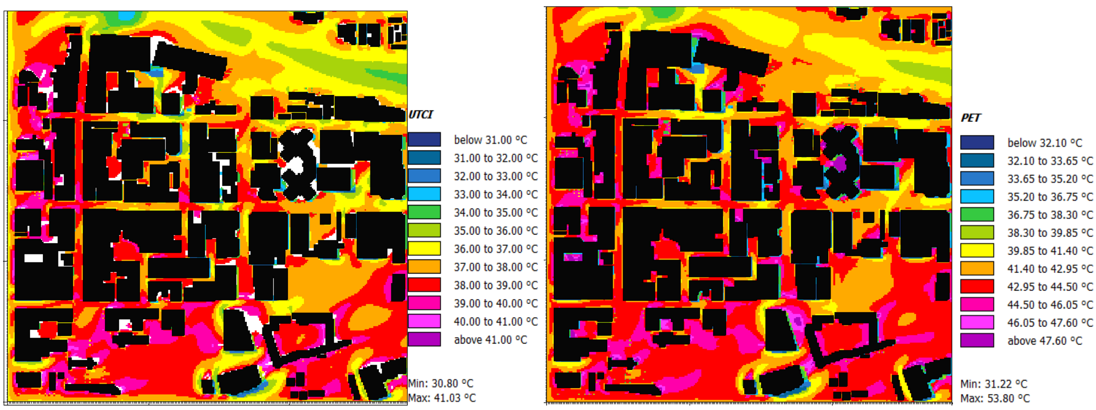


Figure 36. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 1, mean maximum condition - 13:00: UTCI (left), PET (right)

Scenario 2

The ambient temperature ranges from 30.7°C to 34.9°C in Phillip St. when 82 irrigated trees and greenery were implemented (scenario 2). New mature irrigated trees (both deciduous and evergreen) were planted in the whole Phillip St. The ambient temperature distribution map shows that air temperature in Phillip St. is lower than the reference scenario where new trees were planted (Figure 37).

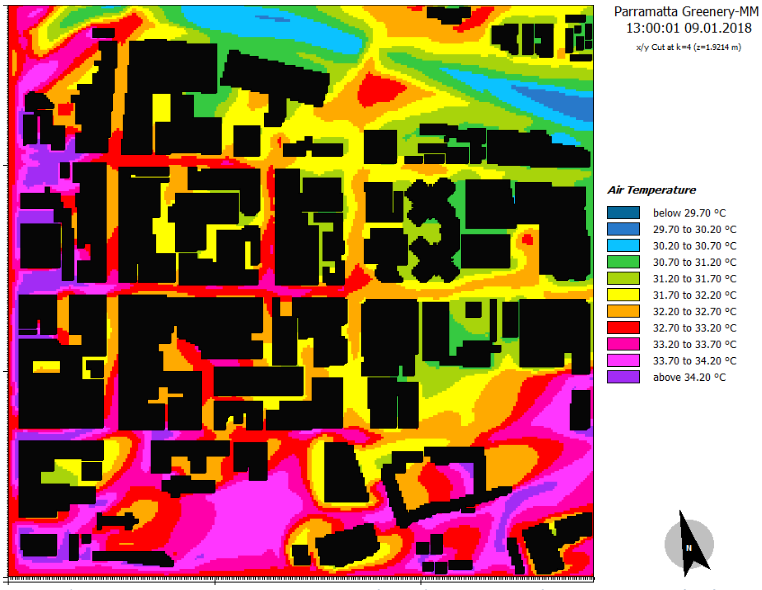


Figure 37. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 2, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 38) shows temperature reduction in the street where the mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the greenery scenario in the same spot. Temperature difference distribution map shows the local temperature reduction in Phillip street where trees were planted. The maximum local temperature reduction is about 0.7°C in scenario 2.

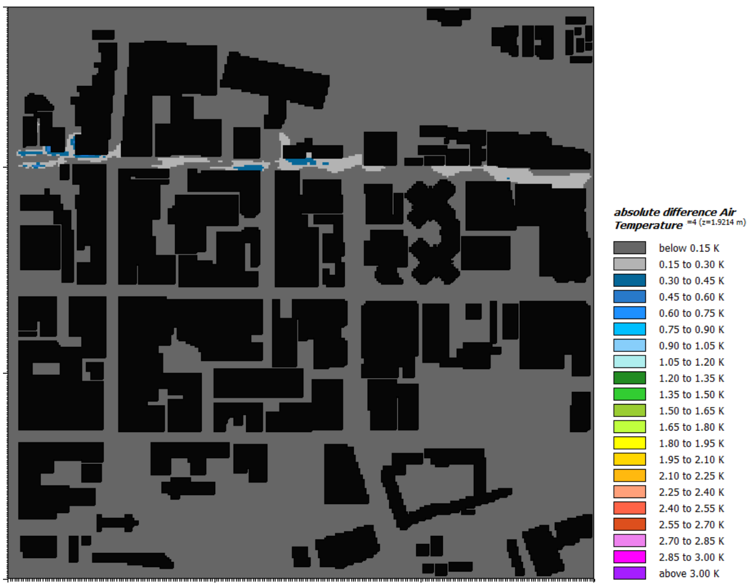


Figure 38. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 2, mean maximum condition - 13:00

The surface temperature distribution is shown in Figure 39 when 82 mature trees (mostly 6m high, both evergreen and deciduous) were planted and raingarden was implemented in Phillip street. The surface temperature is significantly reduced in scenario 2 (where trees are planted) compared to the same spot in the reference scenario. The surface temperature in Phillip street was reduced by 20-26°C under the tree shading and reduced by about 10°C where raingarden was implemented. The temperature of horizontal surfaces generally varies from 22.7°C to 57.4°C in the City of Parramatta CBD.

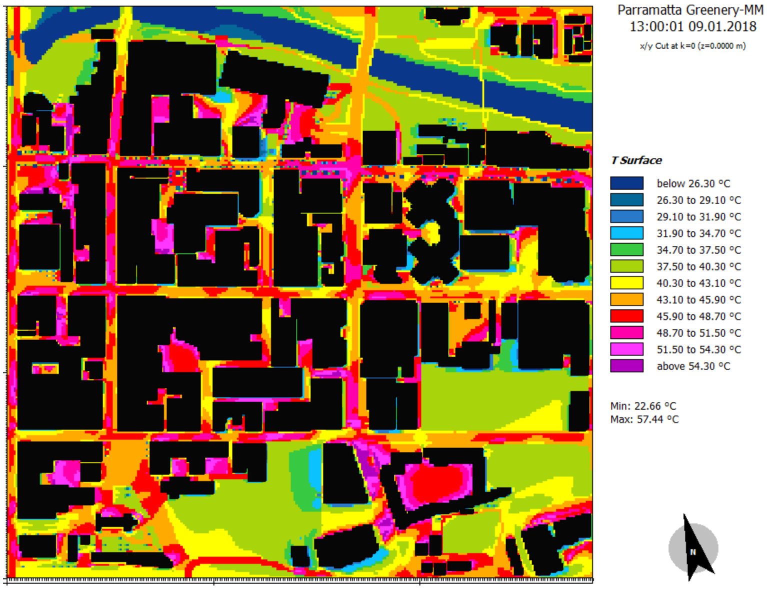


Figure 39. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 1, mean maximum condition - 13:00

The wind speed distribution (Figure 40) shows wind speed varies between 0 m/s and about 6 m/s in the City of Parramatta CBD. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 3m/s in Phillip Street. It is lower where trees were planted compared to the same spots in the reference scenario.

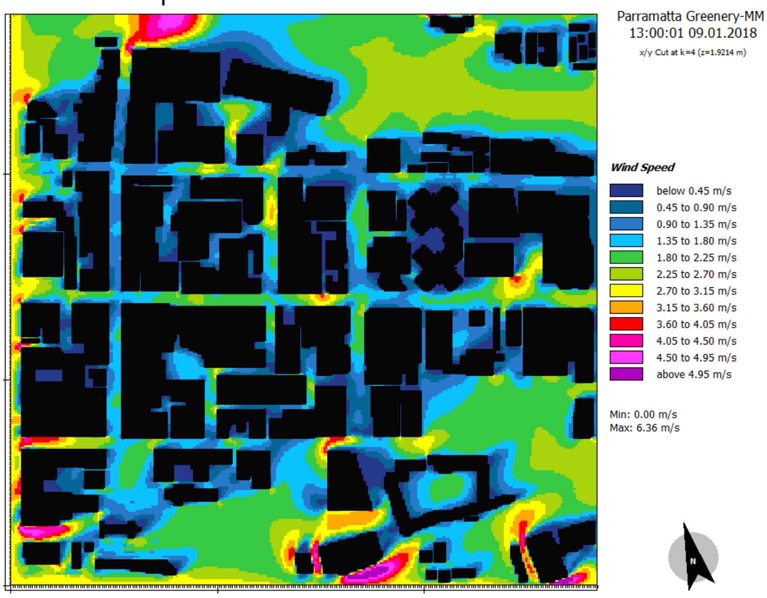


Figure 40. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 2, mean maximum condition - 13:00

Figure 41 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street in general indicates strong heat stress under scenario 2 ranging from 36°C to 40°C during mean maximum condition. However, under the shades from the trees, comfort is improved to moderate heat stress (UTCI below 36°C). UTCI and PET distribution maps are consistent indicating the local effects of trees to improve thermal comfort in Phillip Street.

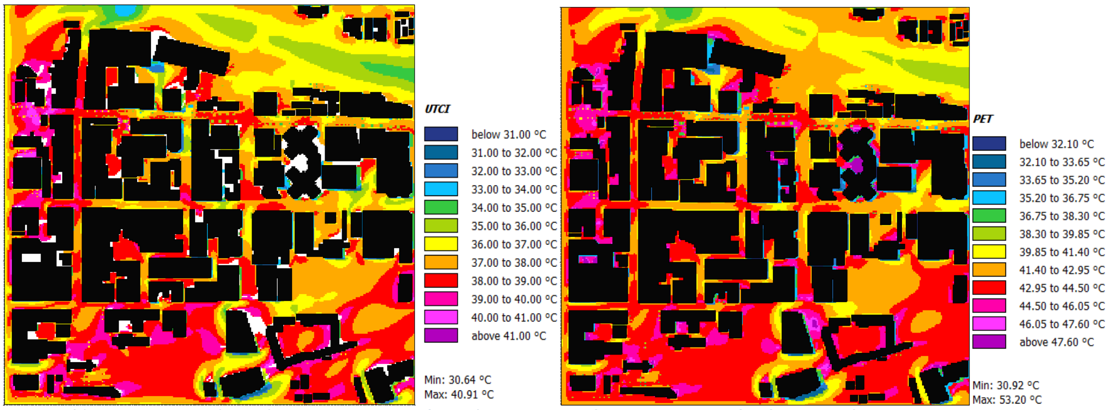


Figure 41. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 2, mean maximum condition - 13:00: UTCI (left), PET (right)

Scenario 3

The ambient temperature ranges from 30.6 °C to 34.3 °C in Phillip Street when shading cloth was used to cover 75% of the street (scenario 3). We have shown that shading is an effecting strategy reducing the temperature by 2.2 °C compared to the reference scenario. The ambient temperature distribution map shows that the air temperature in Phillip Street is lower than the reference scenario where solar control was employed (Figure 42).

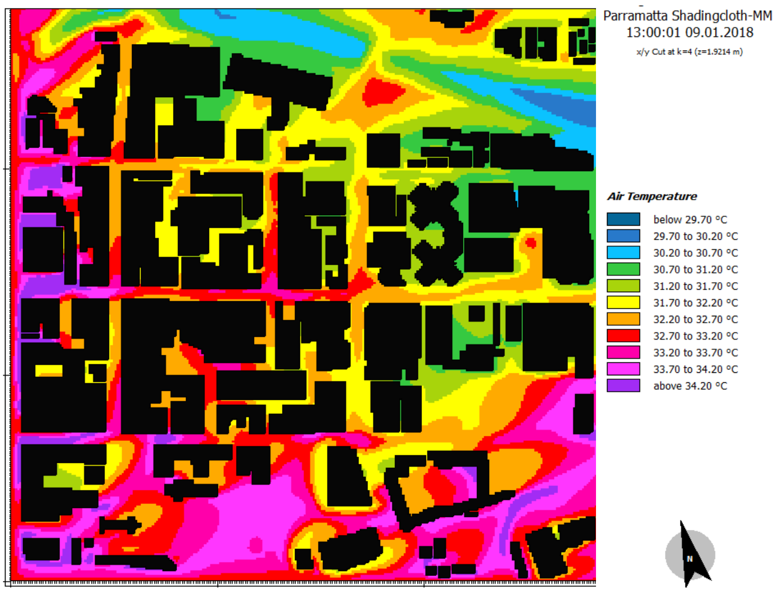


Figure 42. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 3, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 43) shows temperature reduction in the street where the mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the shading scenario in the same spot. Temperature difference distribution map shows the local temperature reduction in Phillip street where shading cloth was used. The maximum local temperature reduction is 2.2°C and the average is 0.4°C. Due to the effects of advection, surrounding areas also have lower temperatures compared to unmitigated scenario. As shown, use of solar control device helps to reduce the temperature of western part of Phillip Street and the area between Church Street and Horwood Pl over 1.2°C.

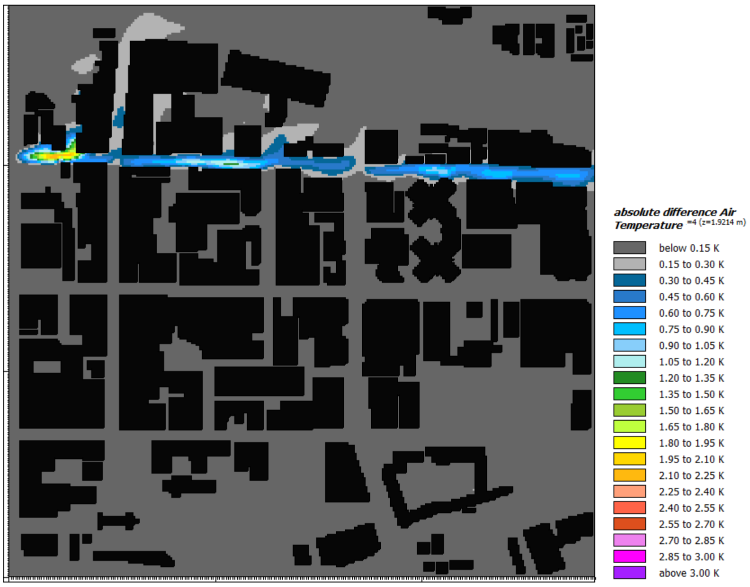


Figure 43. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 3, mean maximum condition - 13:00

The surface temperature distribution is shown in Figure 44 when solar control devices were used in Phillip Street. The surface temperature is significantly reduced in scenario 3 compared to the same spot in the reference scenario. The surface temperature reduction in Phillip street was between 11.6°C and 20°C and recached to 24°C in the shaded areas. The surface temperature generally varies from 23.7°C to 57.4°C in the City of Parramatta CBD and mostly ranges between 29.1°C and 34.7°C in Phillip street (except unshaded areas which reached 51.5°C).

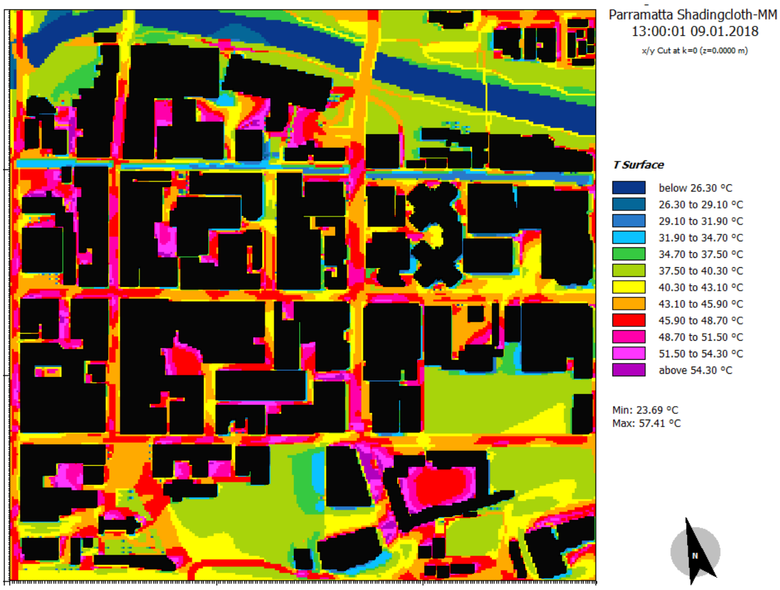


Figure 44. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 3, mean maximum condition - 13:00

Figure 45 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 4m/s in Phillip Street. Due to the height of shading device, there was a small effect on the wind speed distribution at pedestrian level.

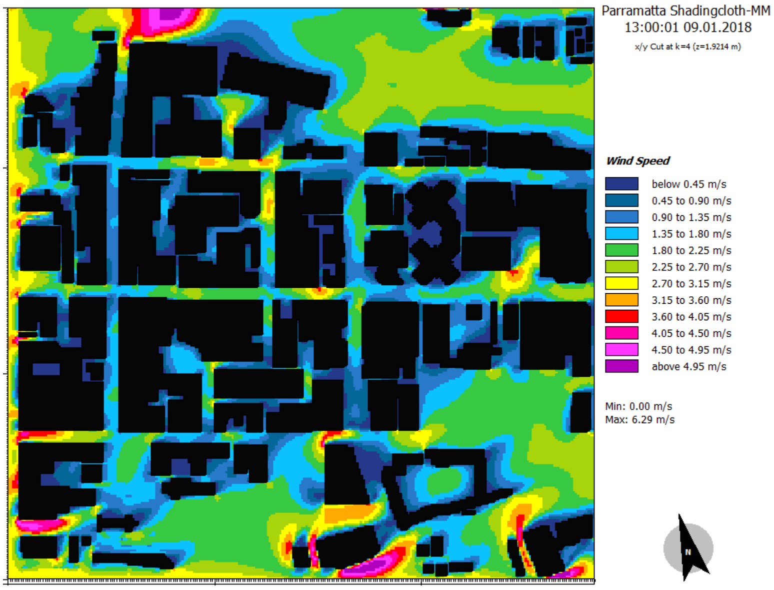


Figure 45. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 3, mean maximum condition - 13:00

Figure 46 shows the distribution of comfort indices (i.e. UTCI and PET) in the city of Parramatta CBD. Phillip Street indicates moderate heat stress under scenario 3 with UTCI ranging from 31°C to 35°C during mean maximum condition. This reveals that shading device is an effective strategy to improve thermal comfort in the area. UTCI and PET distribution maps are consistent indicating the effects of solar control to improve comfort in Phillip Street. Results show that heat stress for humans in urban areas can be significantly reduced by providing shading and, at the same time, not reducing wind speed too much. Due to the effects of advection comfort level is enhanced in the whole street; however, the effects are much higher under the shaded area.

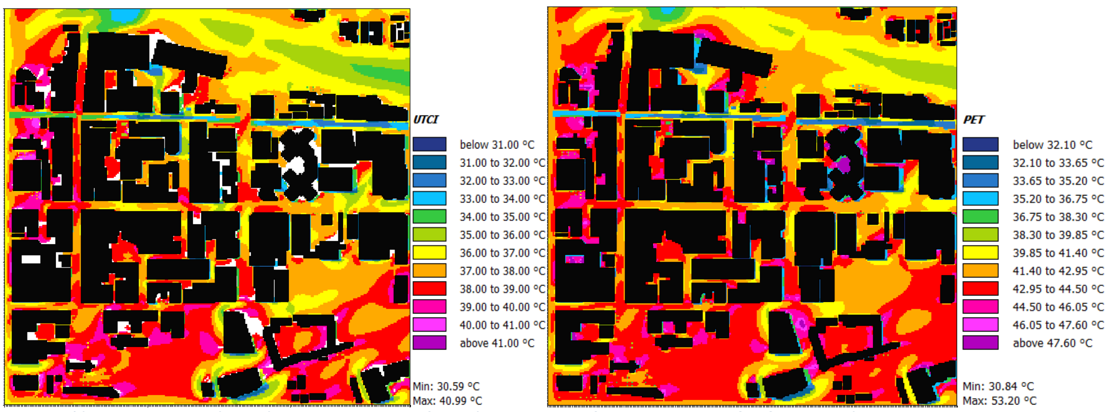


Figure 46. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 3, mean maximum condition - 13:00: UTCI (left), PET (right)

Scenario 4

The ambient temperature ranges from 30.2 °C to 33.8 °C in Phillip Street when we used 22 evaporative cooling systems with the height of 4m (scenario 3). Misting system is an effective strategy reducing the temperature by 5.1 °C. The ambient temperature distribution map shows that air temperature in Phillip Street is significantly lower than the reference scenario where misting systems were used (Figure 47).

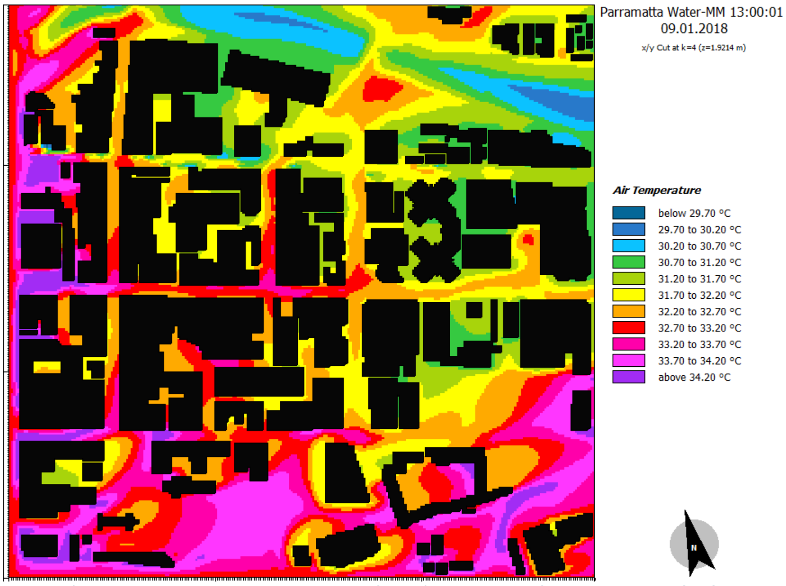


Figure 47. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 4, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 48) shows temperature reduction where the mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the scenario of evaporative system in the same spot. The local temperature reduction ranges from 0.15°C to 5.1°C and the average temperature reduction is 0.5°C. The temperature difference map shows the local effects of spray systems and the effects of advection to reduce the temperature of the nearby areas.

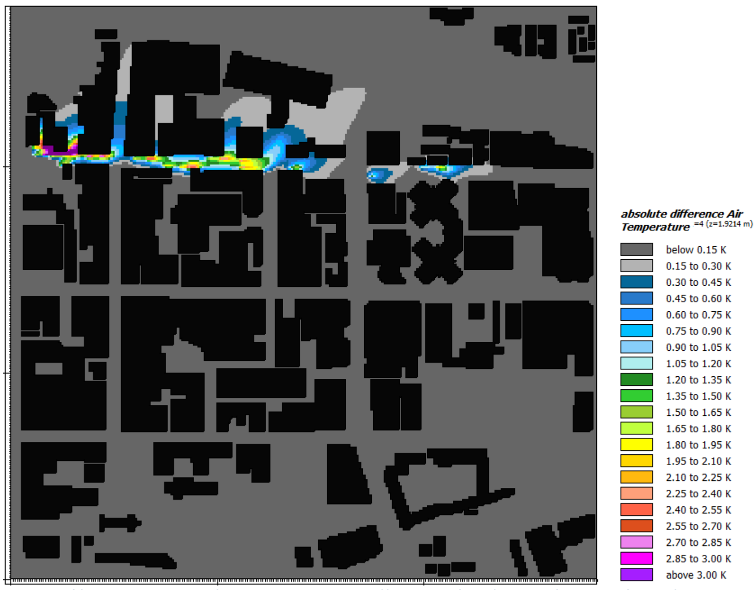


Figure 48. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 4, mean maximum condition - 13:00

The surface temperature distribution is shown in Figure 49 when misting systems were used in Phillip Street. The surface temperature is significantly reduced locally in scenario 4 compared to the same spot in the reference scenario. Other parts of Phillip Street were not affected. The surface temperature generally varies from 23.7°C to 57.4°C in the City of Parramatta CBD.

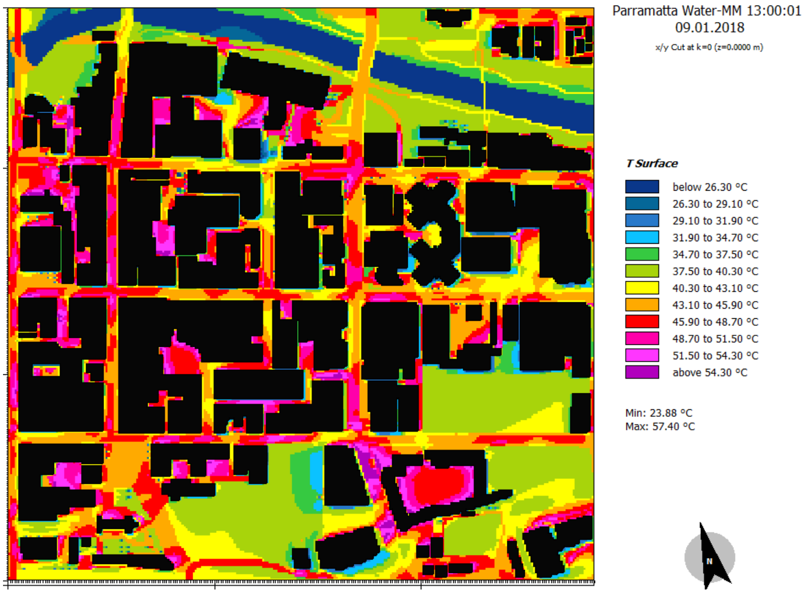


Figure 49. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 4, mean maximum condition - 13:00

Figure 50 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 4m/s in Phillip Street. Misting system does not change the wind speed distribution in the street.

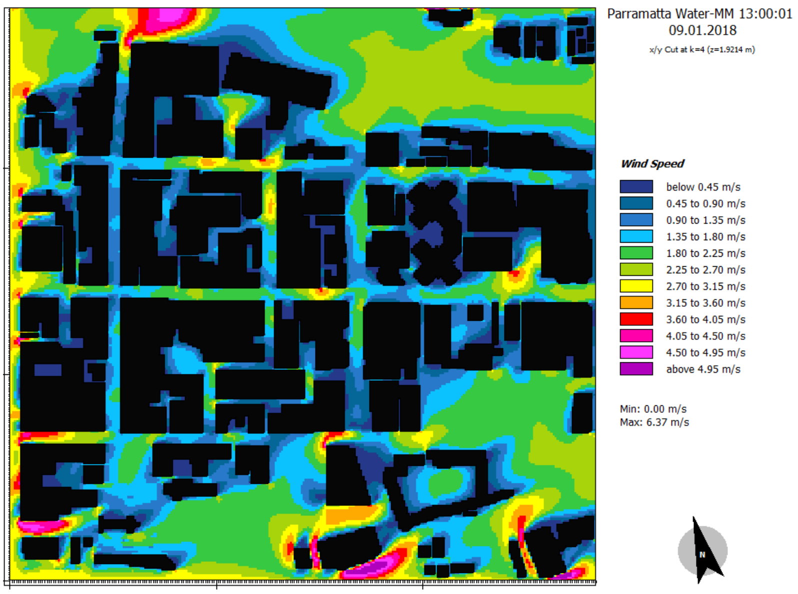


Figure 50. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 4, mean maximum condition - 13:00

Figure 51 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates moderate heat stress with UTCI ranging from 32°C to 34°C during mean maximum condition. UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street. Heat stress for humans in urban areas can be significantly reduced by the use of misting system. However, it has only local effects.

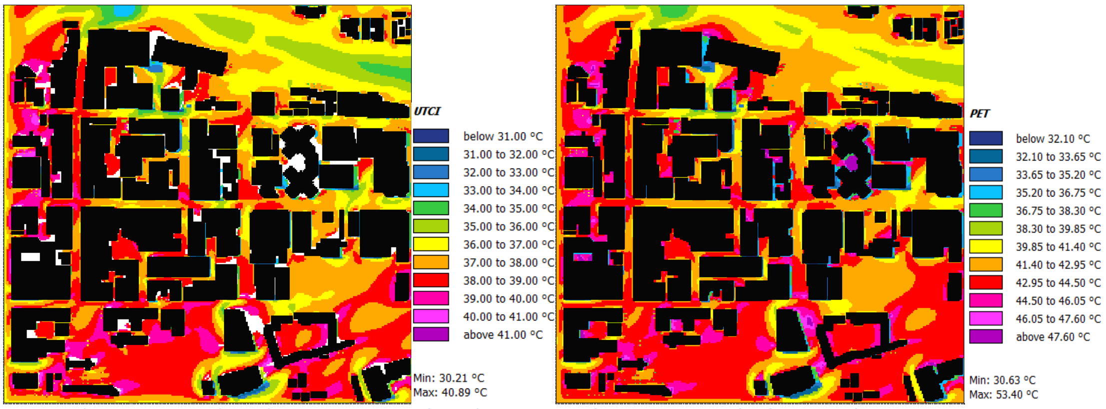


Figure 51. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 4, mean maximum condition - 13:00: UTCI (left), PET (right)

Scenario 5

The ambient temperature ranges from 30.5°C to 35°C in Phillip Street when we used cool roof in the buildings adjacent to Phillip Street (scenario 5). Area between Marsden Street and Church Street and Horwood Pl represent warmer conditions than eastern side of Phillip Street. Due to the height of building, cool roof has insignificant effect in reducing the ambient temperature at pedestrian level in Phillip Street (Figure 52).

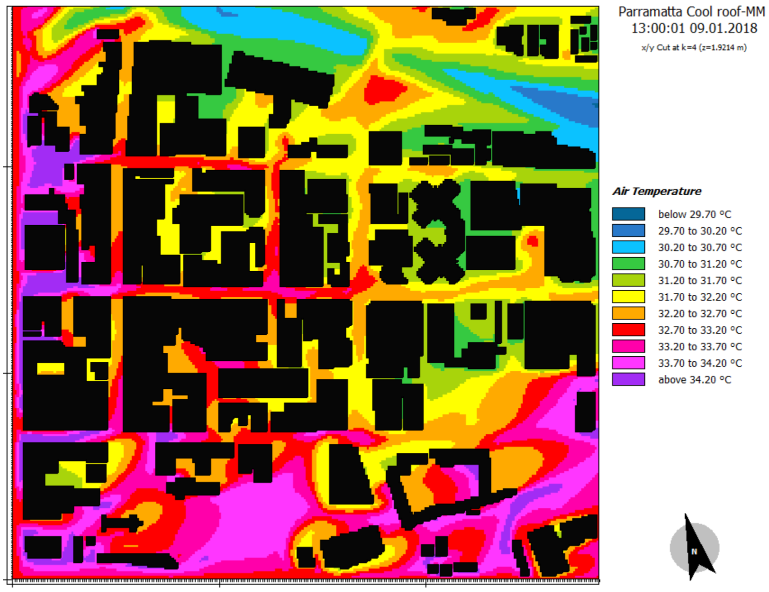


Figure 52. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 5, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 53) shows temperature reduction where the mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the scenario of cool roof in the same spot. Temperature difference distribution map shows the effects of cool roof is minimal by 0.3°C in the pedestrian level (1.9 m above the ground). Due to the effects of advection (south westerly winds), the cooling effect is mostly seen in the northern side of Phillip Street and buildings with lower heights.

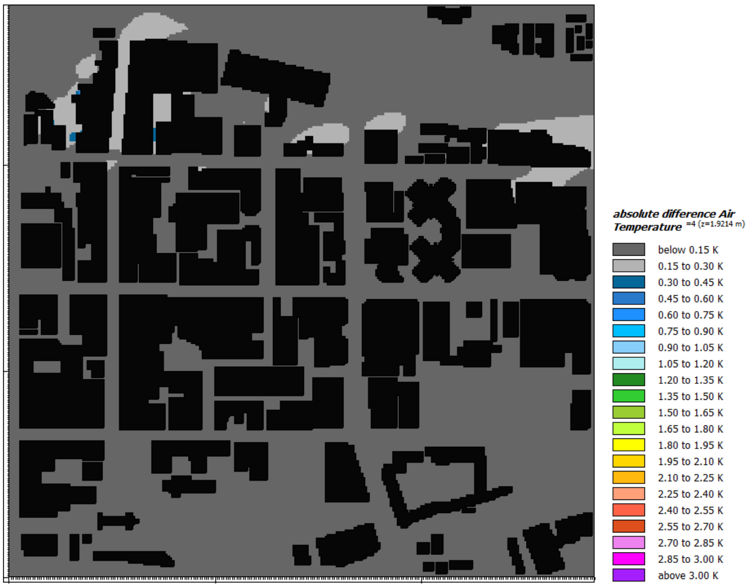


Figure 53. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 5, mean maximum condition - 13:00

The surface temperature distribution is shown in Figure 54 when cool roofs were used in Phillip Street. The surface temperature varies from 23.7°C to 57.4°C in the City of Parramatta CBD. The surface temperature in Phillip Street is not affected by the implementation of cool roof.

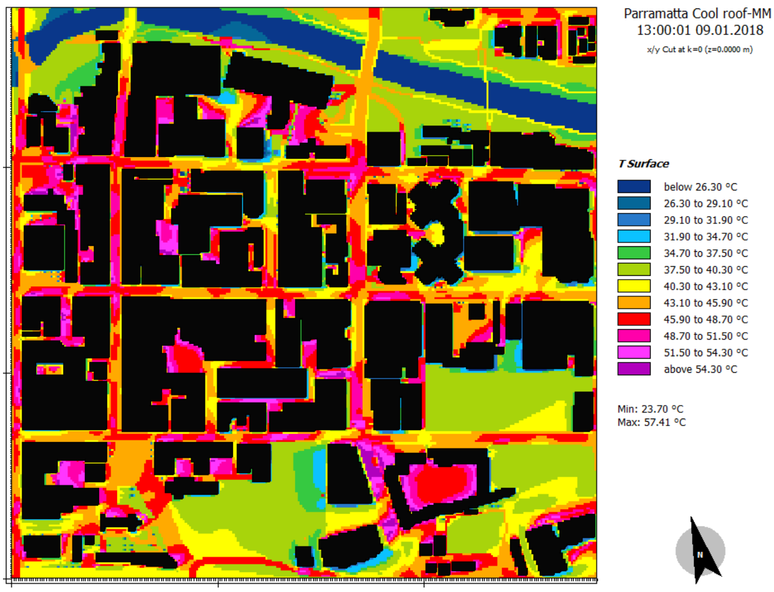


Figure 54. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 5, mean maximum condition - 13:00

Figure 55 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 6 m/s. Different building heights, spaces between buildings and street orientation, lead to variation of the wind speed from one area to another. The wind speed ranges between 0 to about 4m/s in Phillip Street and is not impacted by the use of cool roof.

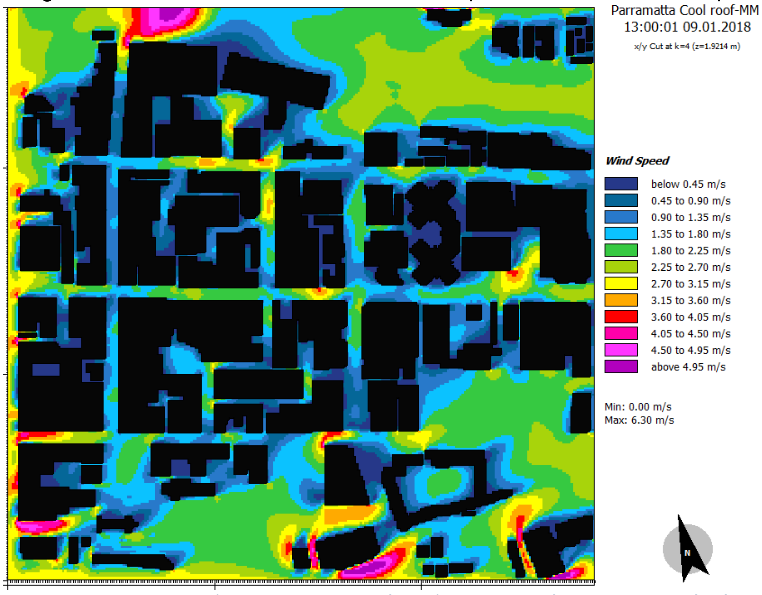


Figure 55. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 5, mean maximum condition - 13:00

Figure 56 shows the distribution of comfort indices in the City of Parramatta CBD. Phillip Street indicates moderate heat stress with UTCI ranging from 32°C to 34°C, which is similar to that in the reference scenario. UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street when cool roof was used.

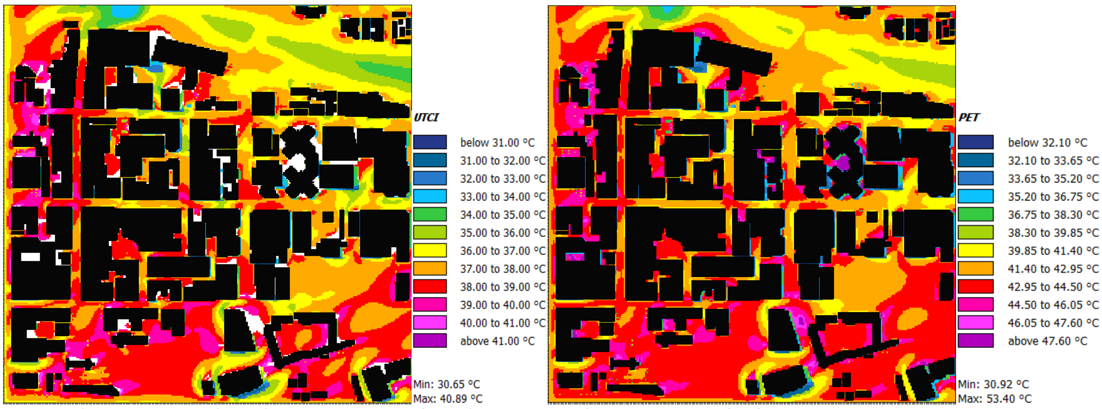


Figure 56. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 5, mean maximum condition - 13:00: UTCI (left), PET (right)

Scenario 6

The ambient temperature ranges from 29.2°C to 33.2°C in Phillip Street when we used a combination of mitigation technologies, i.e., cool pavement, greenery, shading, spray system, and cool roof (scenario 6). The effect of combined scenario is very significant in reducing temperature in the whole street (Figure 57).

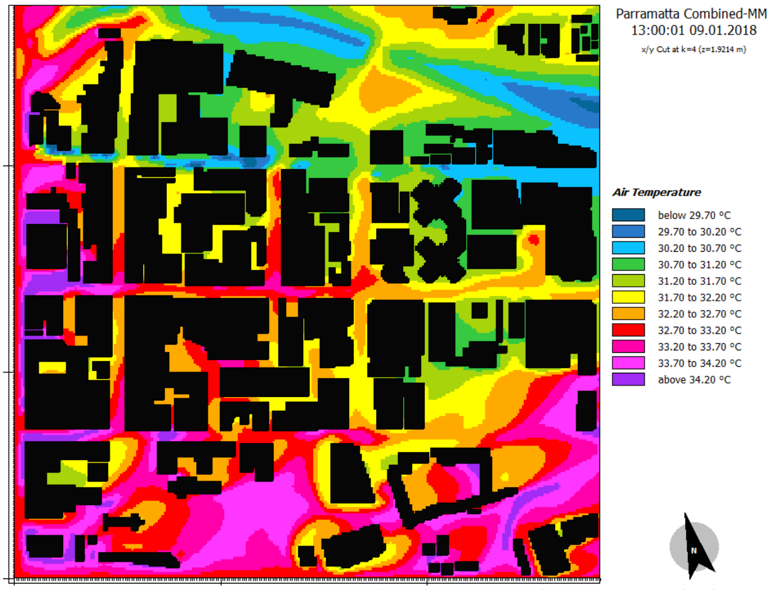


Figure 57. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 6, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 58) shows the achieved air temperature reduction where mitigation technologies were implemented (combination of cool pavement, greenery, shading, spray system, and cool roof). The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the combined scenario in the same spot. Under the scenario 6, the maximum local temperature reduction is 6.4°C and the average is 1.3°C. The achieved air temperature reduction in the most parts of Phillip Street between Marsden Street and Horwood Pl ranges from about 1.2°C to 6.4°C.

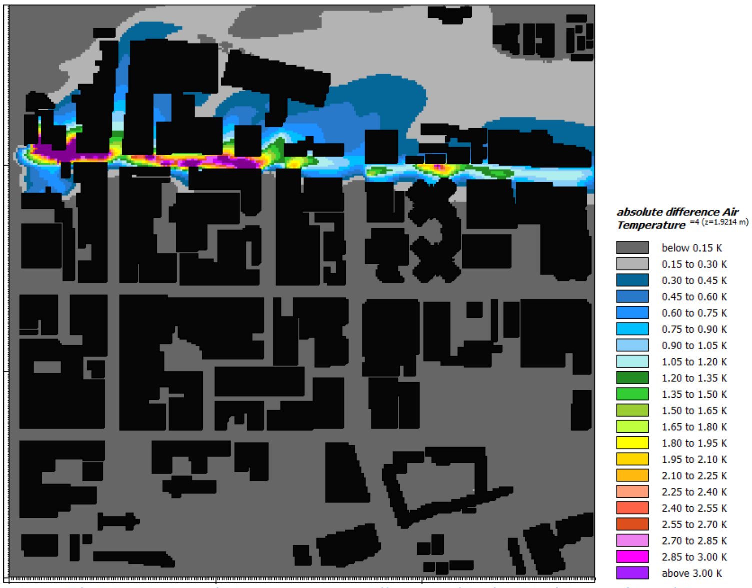
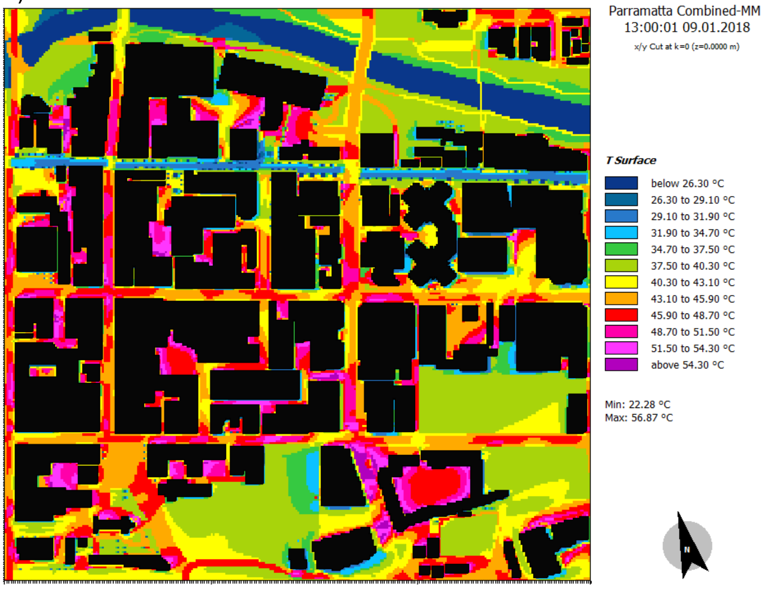


Figure 58. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 6, mean maximum condition - 13:00

The surface temperature distribution is shown in Figure 59 when a combination of strategies was used in Phillip Street. The surface temperature generally varies from 22.3°C to 56.9°C in the City of Parramatta CBD. In Phillip Street, the surface temperature mostly falls below 32°C (Figure 59 a). The surface temperature is significantly reduced in scenario 6 compared to the same spot in the reference scenario. The surface temperature reduction achieved under the combined scenario varies from 8.4°C to 19.6°C under the shading device and between 22.4°C and 27°C under the shading provided by the trees (Figure 59 b).

a)



b)

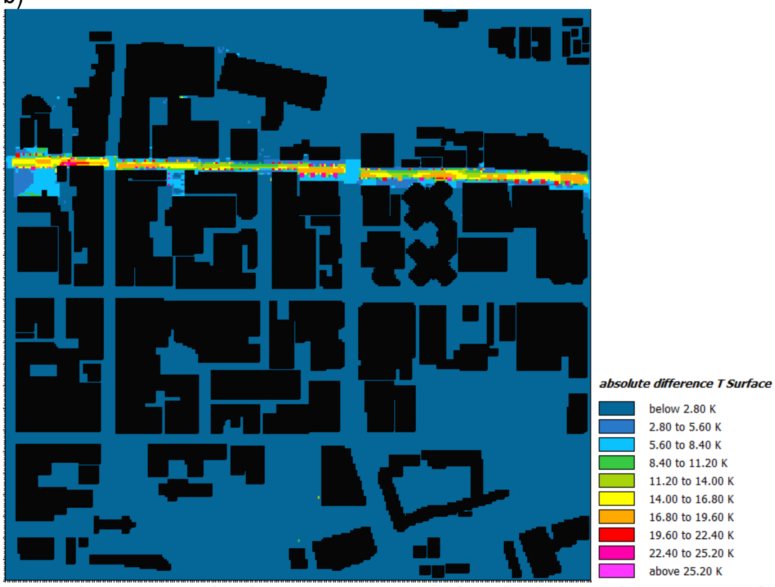


Figure 59. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 6, mean maximum condition - 13:00 (a), surface temperature difference ($T_{surace, ref} - T_{surface, mit}$) (b)

Figure 60 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 6 m/s. Wind speed varies from one area to another due to different building heights, spaces between buildings and street orientation. The wind speed ranges between 0 to about 3m/s in Phillip Street and is mostly impacted by the trees.

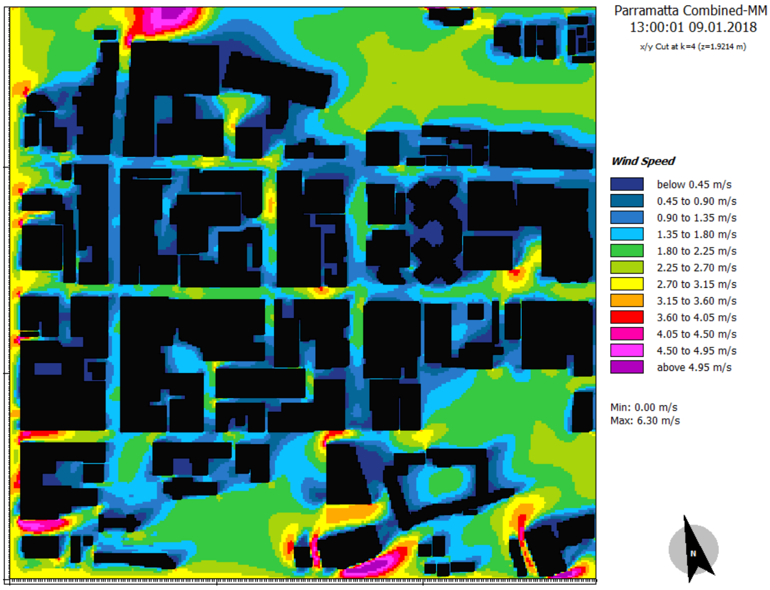


Figure 60. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 6, mean maximum condition - 13:00

Figure 61 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates moderate heat stress with UTCI mostly ranging from 32°C to 34°C during mean maximum condition. This can be compared with Phillip street (reference scenario) and Church street (existing condition) where UTCI falls above 38°C. UTCI and PET distribution maps are consistent in presenting hot spots and areas with improved thermal comfort in Phillip Street. As shown here, heat stress for humans in urban areas can be significantly reduced with the implementation of the combined strategies.

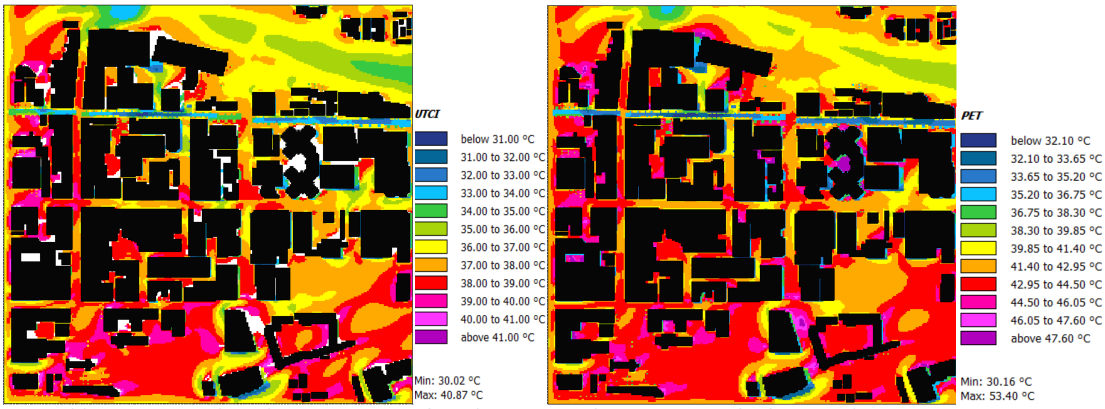


Figure 61. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 6, mean maximum condition - 13:00: UTCI (left), PET (right)

Scenario 7

As shown in Figure 62, the ambient temperature ranges from 30.6°C to 34.2°C when new trees and greenery were implemented, and cool pavements were used in Phillip Street (scenario 7). New mature irrigated trees (both deciduous and evergreen) were planted in the whole Phillip Street and cool pavements were used (combination of scenario 1 and scenario 2). The ambient temperature distribution map shows that air temperature in Phillip Street is lower where mitigation technologies were implemented than the same spots in the reference scenario (Figure 62).

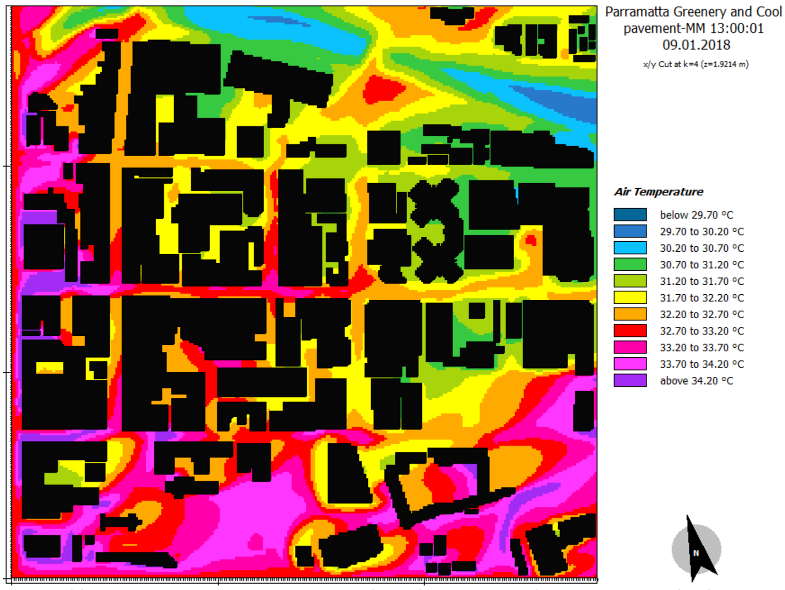


Figure 62.Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 7, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 63) shows temperature reduction where the mitigation technology is implemented (combination of cool pavement and greenery). The local air temperature drop is defined as the temperature difference between the reference scenario and the mitigated scenario in the same spot. Under the scenario 7, the maximum local temperature reduction reaches to 1.6°C and the average temperature reduction is 0.5°C.

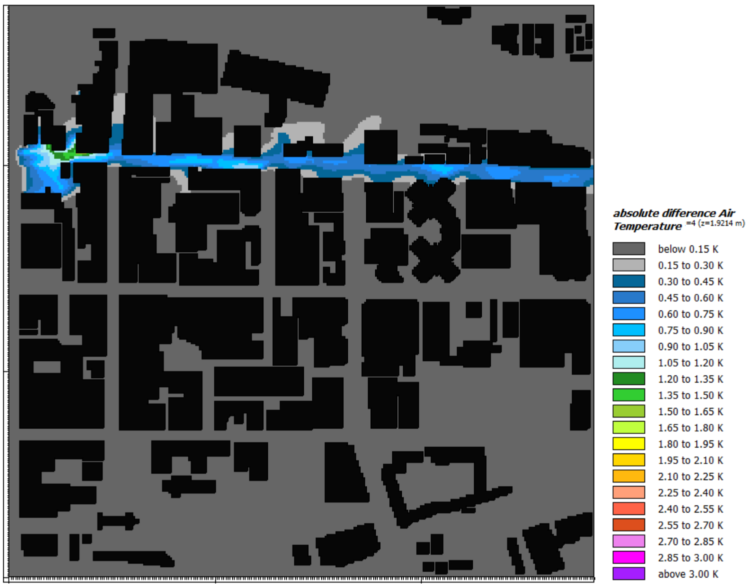


Figure 63. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 7, mean maximum condition - 13:00

The surface temperature distribution is shown in Figure 64 when a combination of strategies was used in Phillip Street. The surface temperature generally varies from 22.6°C to 56.9°C in the City of Parramatta CBD. In Phillip Street, the surface temperature mostly ranges from 37.5°C to 43.1°C (Figure 64). The surface temperature is significantly reduced under the trees where temperature falls below 26.3°C in the map (Figure 64).

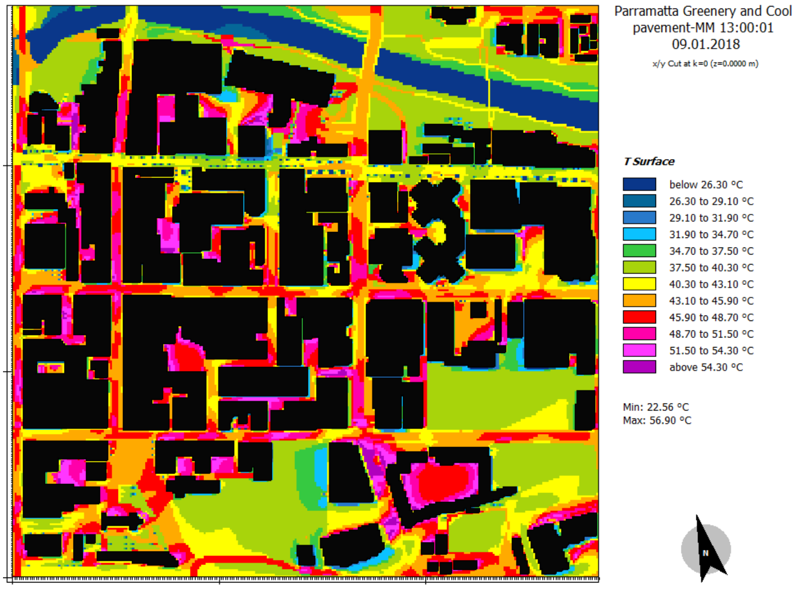


Figure 64. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 7, mean maximum condition - 13:00

Figure 65 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 6 m/s. Wind speed varies from one area to another due to different building heights, spaces between buildings and street orientation. The wind speed ranges between 0 to about 3m/s in Phillip Street. Near the trees, wind speed at pedestrian level is reduced compared to the refence scenarios.

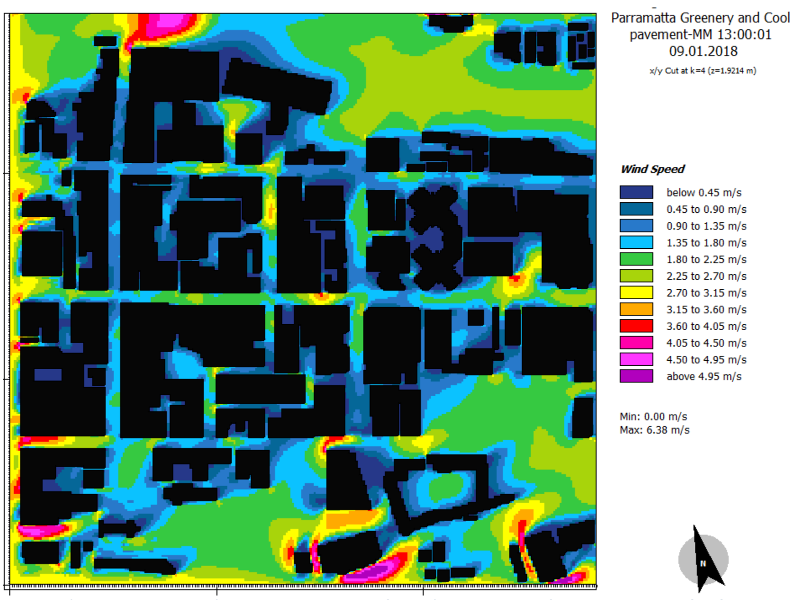


Figure 65. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 7, mean maximum condition - 13:00

Figure 66 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates moderate to strong heat stress with UTCI mostly ranging from 36°C to 40°C during mean maximum condition. UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street. As shown in Figure 66, tree shading helps to reduce the heat stress for humans in urban areas where UTCI reduces to about 34-35°C. Thus, the most comfortable conditions can be found below the trees. They are providing shade and are hardly causing wind speed reductions at the pedestrian level. Other areas do not show improved comfort due to wind speed reductions by the trees.

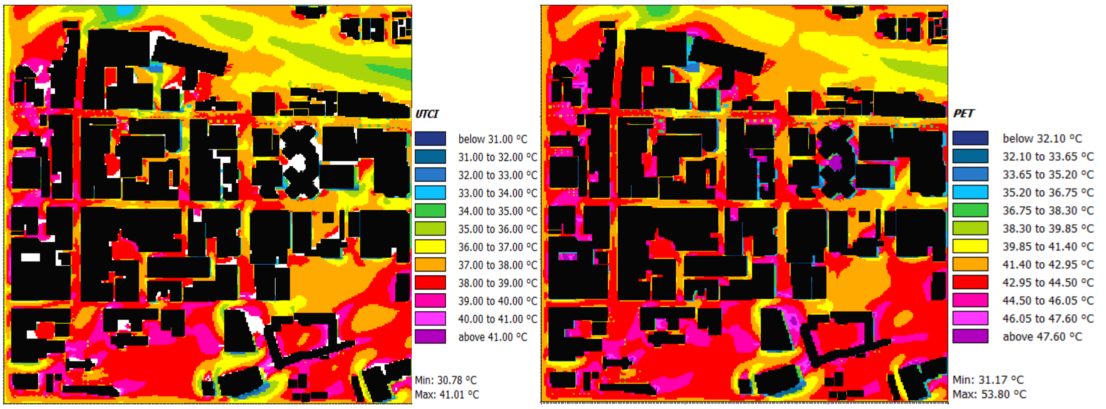


Figure 66. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 7, mean maximum condition - 13:00: UTCI (left), PET (right)

Scenario 8

The ambient temperature ranges from 30.5 °C to 34.3 °C in Phillip Street where radiative cooling material is used (scenario 8). Same structure (surface area) as shading device (scenario 3) is implemented covering about 75% of the street. This approach maximises emission of infrared thermal radiation through the atmospheric window for releasing heat and minimises absorption of incoming atmospheric radiation. These simultaneous processes can lead to the shading device temperature substantially below the ambient temperature [13]. We have shown that shading with radiative cooling is an effecting strategy reducing the temperature by 2.4°C compared to the reference scenario. The ambient temperature distribution map shows that the air temperature in Phillip Street is lower than the reference scenario where solar control with radiative cooling material was employed (Figure 67).

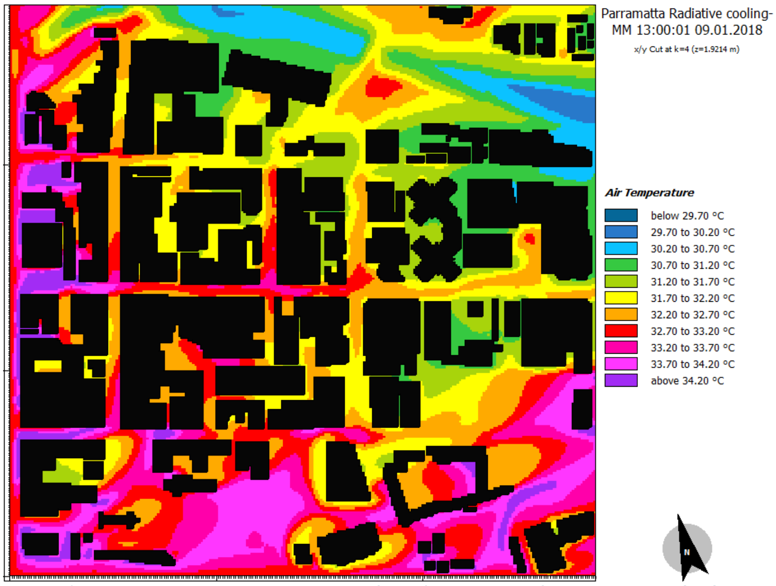


Figure 67. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 8, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 68) shows the temperature reduction where the radiative cooling technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the mitigated scenario in the same spot. Under the scenario 8, the maximum local temperature reduction is 2.4°C and the average is 0.5°C.

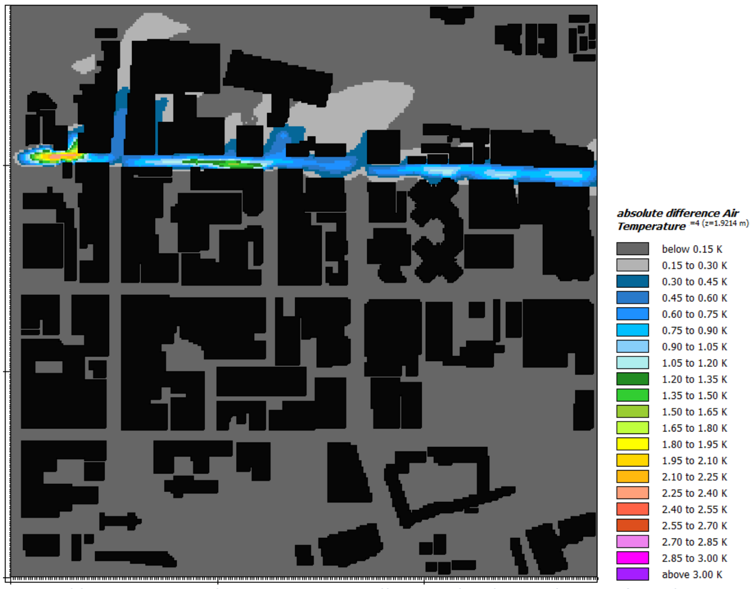


Figure 68. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 8, mean maximum condition - 13:00

The surface temperature distribution is shown in Figure 69 when radiative cooling material was used for the shading device in Phillip Street. In Phillip Street, the surface temperature mostly falls below 32°C under the shaded area (Figure 69). The surface temperature is significantly reduced in scenario 8 compared to the same spot in the reference scenario. The achieved surface temperature reduction mostly varies from 8.4°C to 19.6°C under the shading device with radiative cooling and reaches to a range of 20-24°C between Church and Marsden Streets.

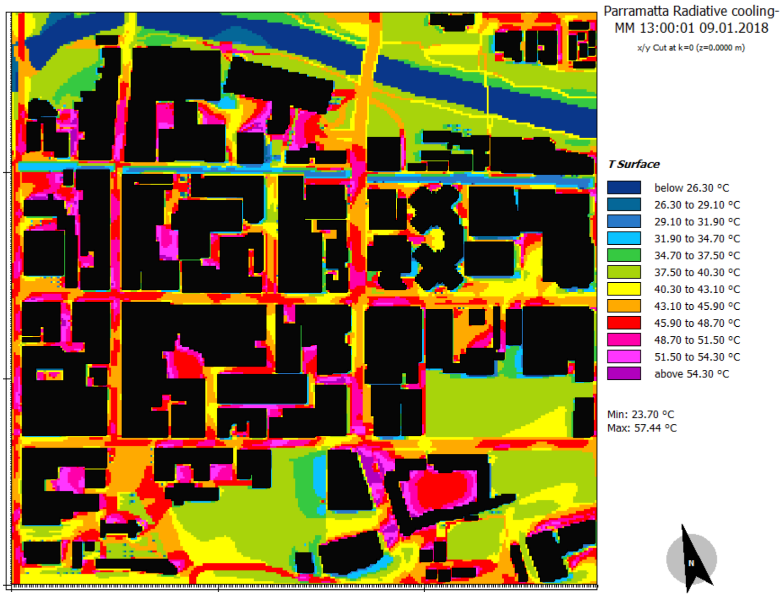


Figure 69. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 8, mean maximum condition - 13:00

Figure 70 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 4m/s in Phillip Street. Due to the height of shading device, there was a small effect on the wind speed distribution at pedestrian level near the corner of Church Street and Smith street.

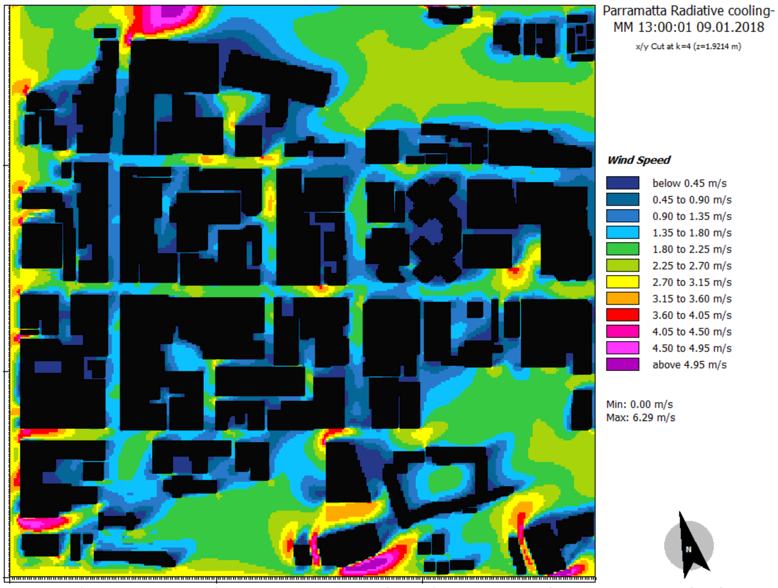


Figure 70. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 8, mean maximum condition - 13:00

Figure 71 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates moderate heat stress with UTCI mostly ranging from 32°C to 35° C during mean maximum condition. This can be compared with Phillip street (reference scenario) and Church street (existing condition) where UTCI falls above 38 °C. UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street. PET varies between 32.1 °C and 36.7 °C under the shaded area (scenario 8), while the same spots fall above 39.9 ° C and reaches 44.5 °C in the reference scenario. Due to the effects of advection comfort level is also enhanced in the whole street; however, the effects are much higher under the shaded area

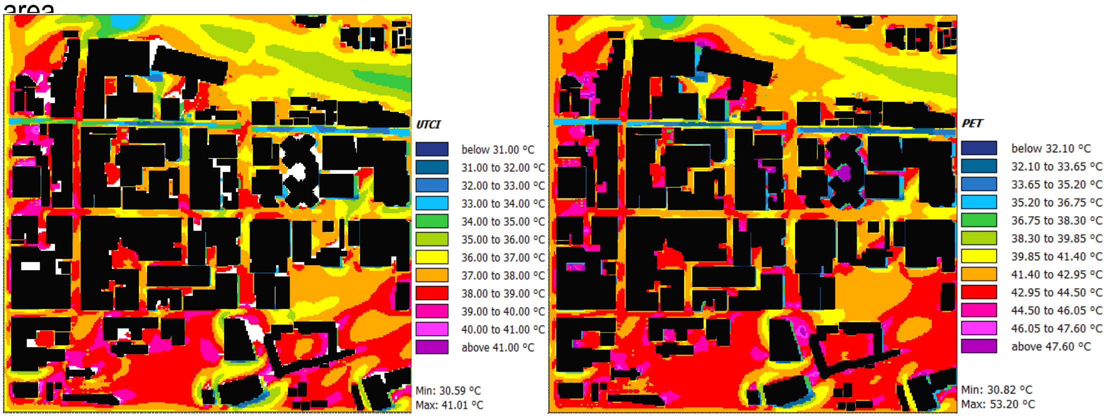


Figure 71. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 8, mean maximum condition - 13:00: UTCI (left), PET (right)

Scenario 9

The air temperature ranges from 30.6°C to 34.8°C when we implemented the proposed trees and pavements by the City of Parramatta Council in Phillip Street (Figure 72). New trees were planted and proposed pavement materials with proper reflectivity were used in Phillip Street based on the Council implementation plan. The air temperature in Phillip Street is not significantly influenced by the City of Parramatta Council implementation plan. However, Phillip Street presents lower temperatures compared to the reference scenario where new trees were planted.

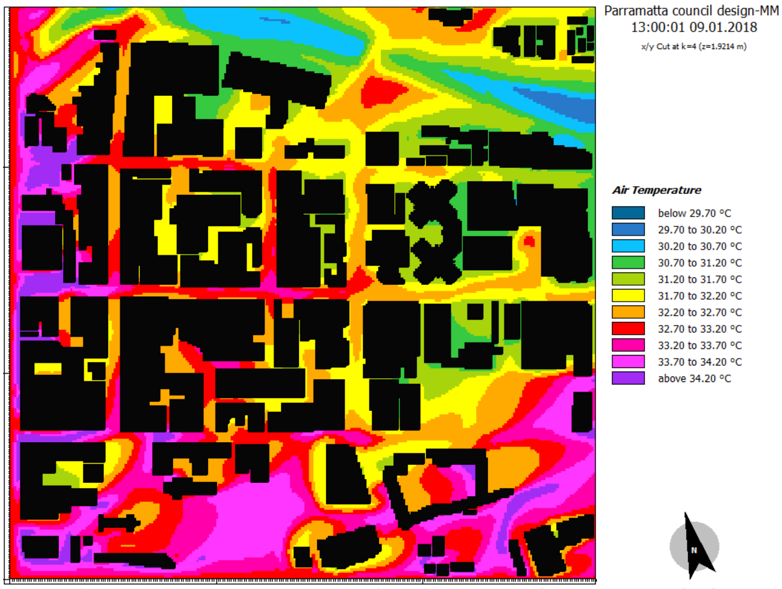


Figure 72. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 9, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 73) shows temperature reduction in the street where the implementation plan by the City of Parramatta Council is used. The local air temperature drop is defined as the temperature difference between the reference scenario and this scenario. The maximum local temperature reduction is about 0.7°C.

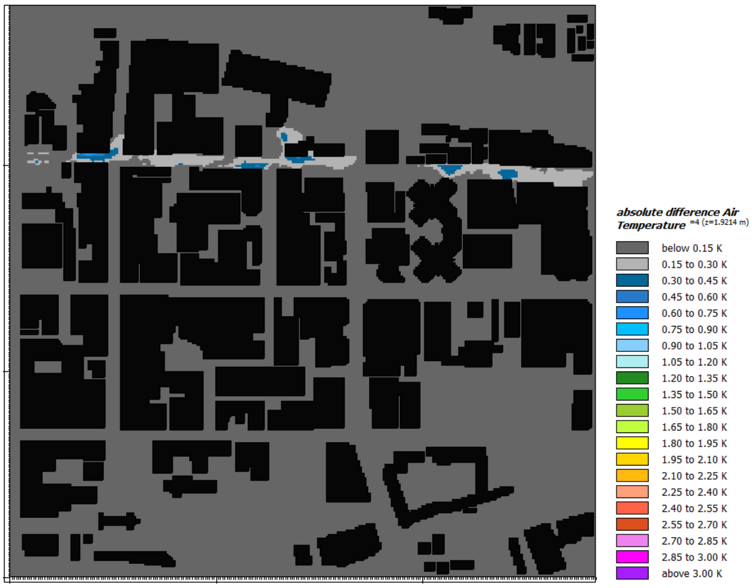


Figure 73. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 9, mean maximum condition - 13:00

The surface temperature distribution is shown in Figure 74 when the City of Parramatta Council plan was implemented in Phillip Street. The surface temperature is significantly reduced where trees are planted compared to the same spot in the reference scenario. The surface temperature in Phillip street was reduced by 20-26 °C in the areas shaded by the trees compared to the same areas in the reference scenario. The temperature of horizontal surfaces generally varies from 23.9 °C to 57.5 °C in the City of Parramatta CBD and mostly falls above 43.1 °C in Phillip Street.

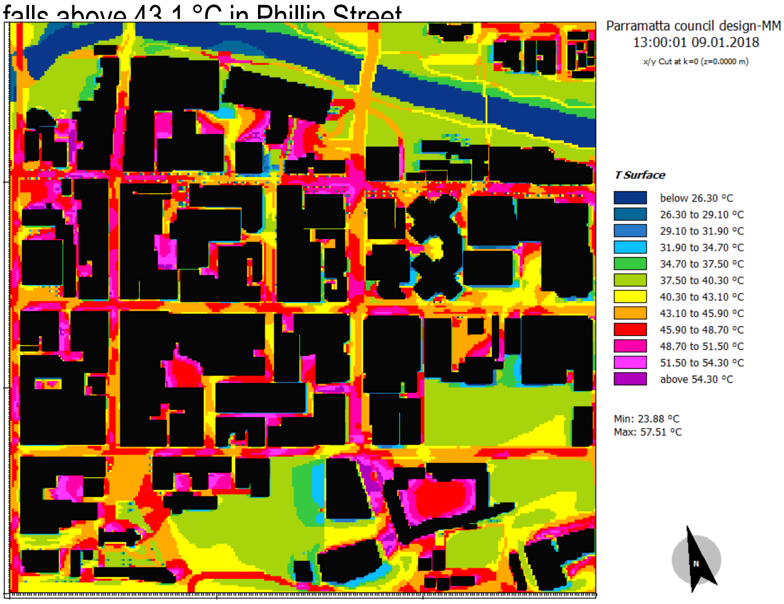


Figure 74. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 9, mean maximum condition - 13:00

Figure 75 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 3m/s in Phillip Street. New trees reduce the wind speed at pedestrian level in Phillip Street.

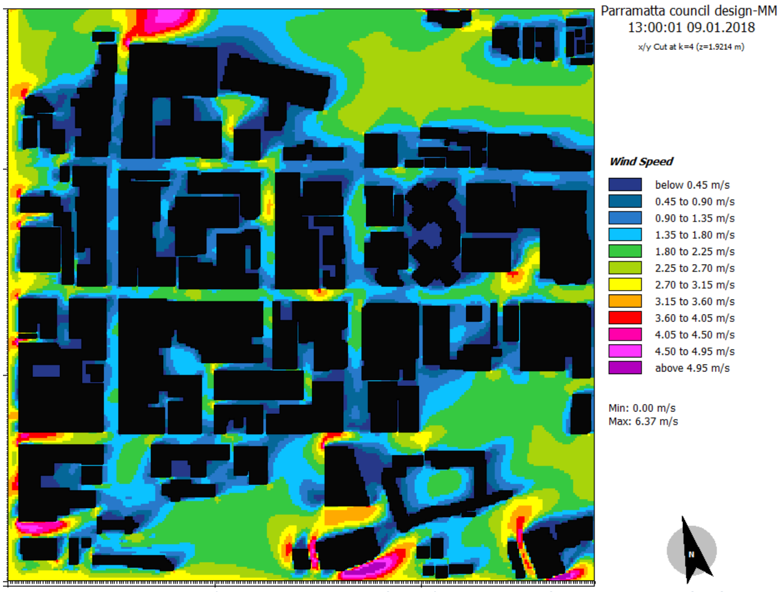


Figure 75. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 9, mean maximum condition - 13:00

Figure 76 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates moderate heat stress with UTCI mostly ranging from 36°C to 41°C during mean maximum condition (scenario 9). UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street. PET varies between 41.4 °C and 46 °C. Planting 8 m Solkova trees helps to improve comfort condition locally. UTCI shows reduction of heat stress in the areas where trees were planted with a range of 35-37°C.

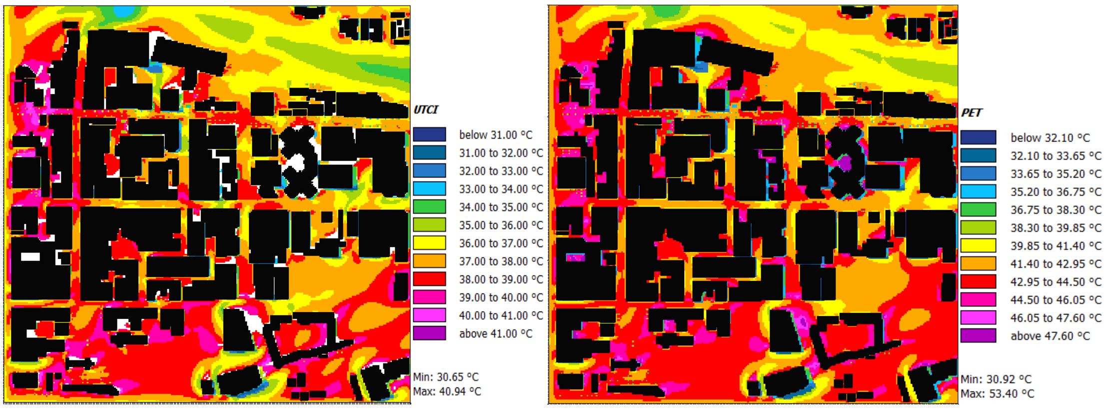


Figure 76. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 9, mean maximum condition - 13:00: UTCI (left), PET (right)

Scenario 10

The air temperature ranges from 30.6 °C to 34.1 °C when we implemented Solkova trees proposed by the City of Parramatta Council and used cool material instead of Adelaide black and black asphalt in Phillip Street (Figure 77). By using cool pavement, areas between Church Street and Horwood Pl represent by 1.2°C lower temperatures than the same locations in the City of Parramatta Council implementation plan.

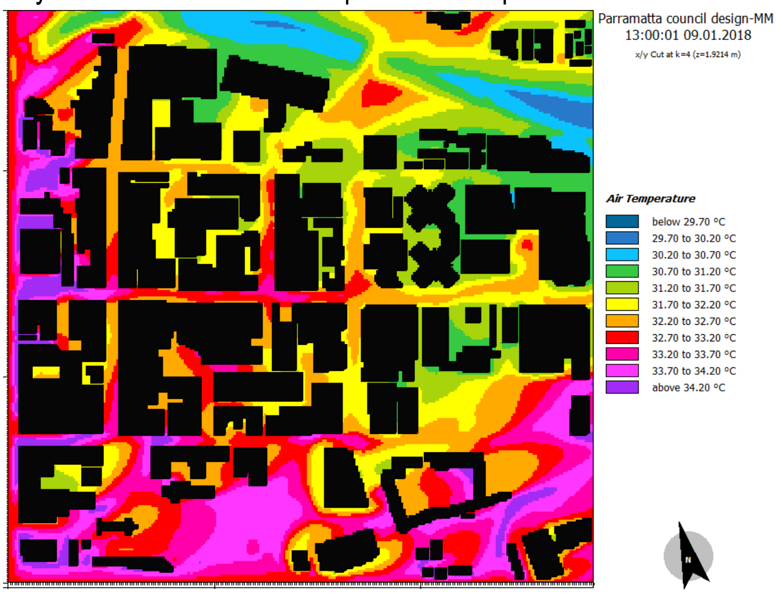


Figure 77. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 10, mean maximum condition - 13:00

The ambient temperature difference distribution map (Figure 78) shows temperature reduction in the street when mitigation techniques were used to improve the City of Parramatta Council implementation plan. The local air temperature drop is defined as the temperature difference between the reference scenario and this scenario in the same spot. Temperature difference distribution map illustrates the temperature reduction in the street where cool pavements were implemented in addition to the greenery (solkova tree) in council implementation plan. The local temperature reduction achieved ranges from 0 to 1.4°C in Phillip St. (scenario 10). The average air temperature reduction is 0.4°C.

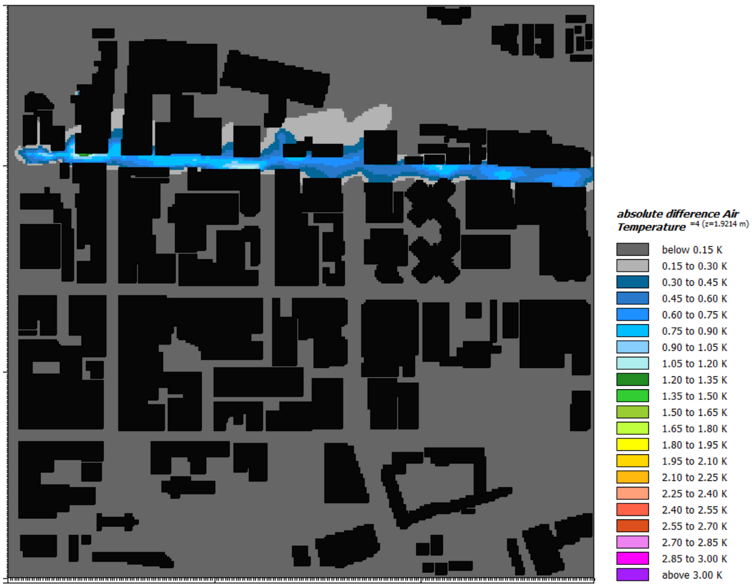


Figure 78. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 10, mean maximum condition - 13:00

The surface temperature distribution is shown in Figure 79 when cool pavement was used to improve the City of Parramatta Council implementation plan. The surface temperature is significantly reduced in scenario 10 compared the reference scenario (scenario 0) and the City of Parramatta Council implementation plan (scenario 9). The surface temperature mostly ranges between 37.5°C and 45.90 in Phillip Street, and falls below 26.3 °C in the areas shaded by Solkova trees.

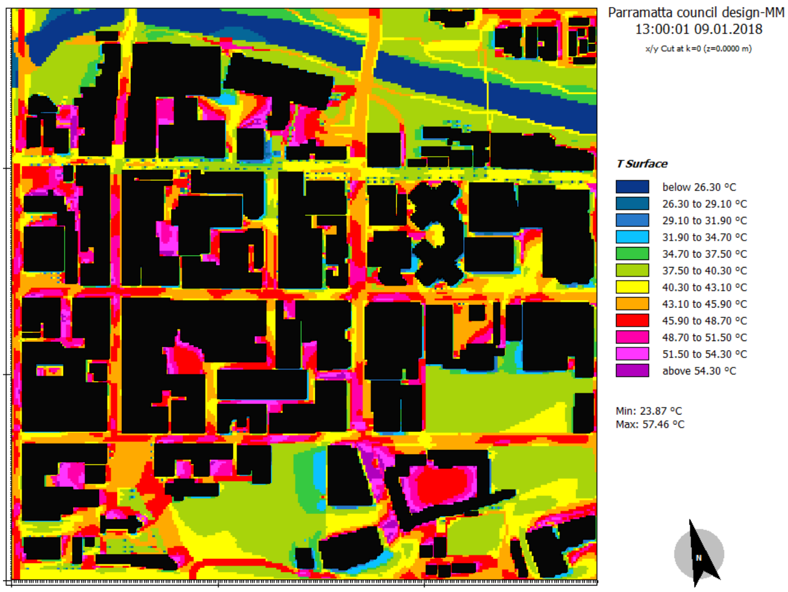


Figure 79. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 10, mean maximum condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 80 where the wind speed varies between 0 m/s and about 6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 3 m/s in Phillip Street. New trees reduce the wind speed at pedestrian level in Phillip Street.

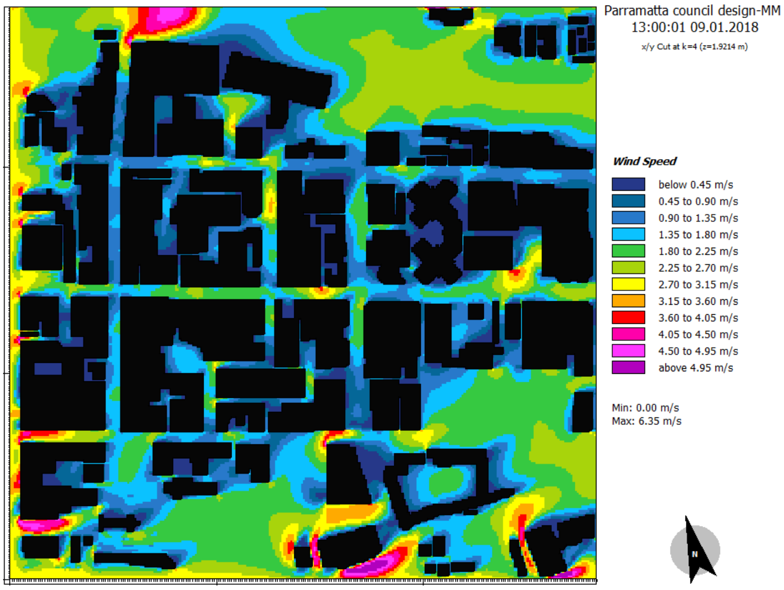


Figure 80. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 10, mean maximum condition - 13:00

Figure 81 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates moderate to strong heat stress with UTCI and PET mostly fall above 36°C and 41.4, respectively, during mean maximum condition. UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street. Planting 8 m Solkova trees helps to improve comfort condition locally. UTCI shows reduction of heat stress in the areas where trees were planted with a range of 35-37°C. The most comfortable conditions can be found below the trees. They are providing shade and are hardly causing wind speed reductions at the pedestrian level. Other areas do not show improved comfort due to wind speed reductions by the trees.

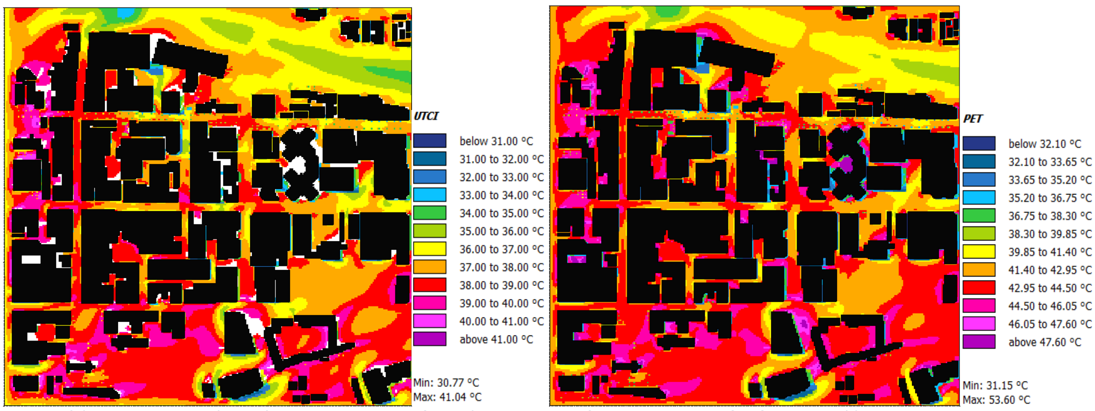


Figure 81. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 10, mean maximum condition - 13:00: UTCI (left), PET (right)

Heatwave condition

The climatic input data for the heatwave condition was derived from the Cooling Parramatta tool (HTTP://147.27.33.179:8083) which was developed based on WRF modelling. In the heatwave condition, the initial wind speed considered in the simulations is 3 m/s, and wind direction is from north west. The minimum and maximum ambient temperatures of the simulation day are 19.7°C and 43.9°C, respectively. The following sections provide details of simulation results for each scenario.

Reference scenario

Reference scenario: existing condition

Scenario 0

The ambient temperature in Phillip Street, in the existing form (reference scenario), ranges from 36.4°C to 43°C during the heatwave condition. The temperature distribution map shows that the area between Marsden Street and Horwood Pl represents warmer conditions than eastern side of Phillip Street (Figure 82). The ambient temperature in the western part of Phillip Street exceeds 38.7°C. Simulation results indicate the eastern part of the City of Parramatta CBD presents cooler ambient temperatures than western and southern areas.

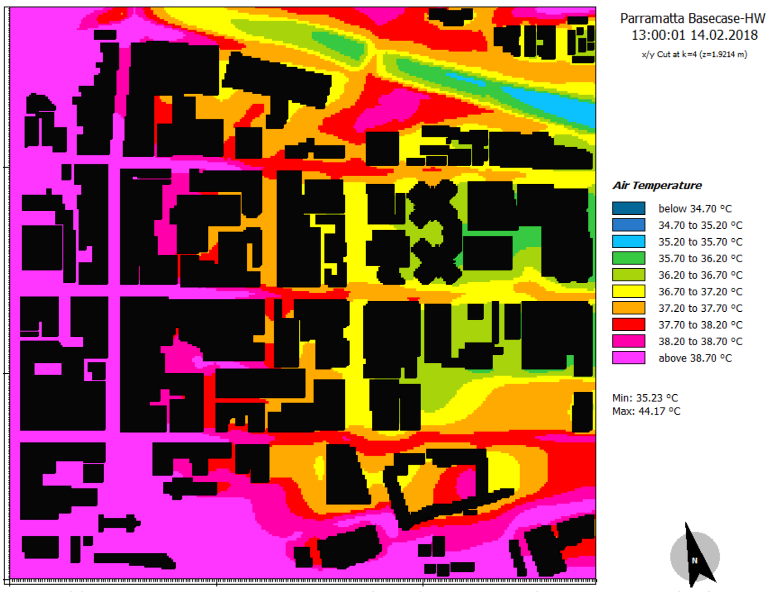


Figure 82.Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 0, heatwave condition - 13:00

Figure 83 shows the surface temperature distribution in the City of Parramatta CBD and Phillip Street in the existing condition (reference scenario). The surface temperature reaches 62.6°C in the City of Parramatta CBD. Parramatta river and surrounding areas illustrate lower surface temperatures. The surface temperature in Phillip Street mainly ranges between 45.9°C and 61.7°C being higher in the western parts. The area between Marsden Street and Church Street in Phillip Street present very high surface temperatures exceeding 55°C. The area between Church Street and Horwood Pl shows a temperature range of about 34.7°C to 53.6° C.

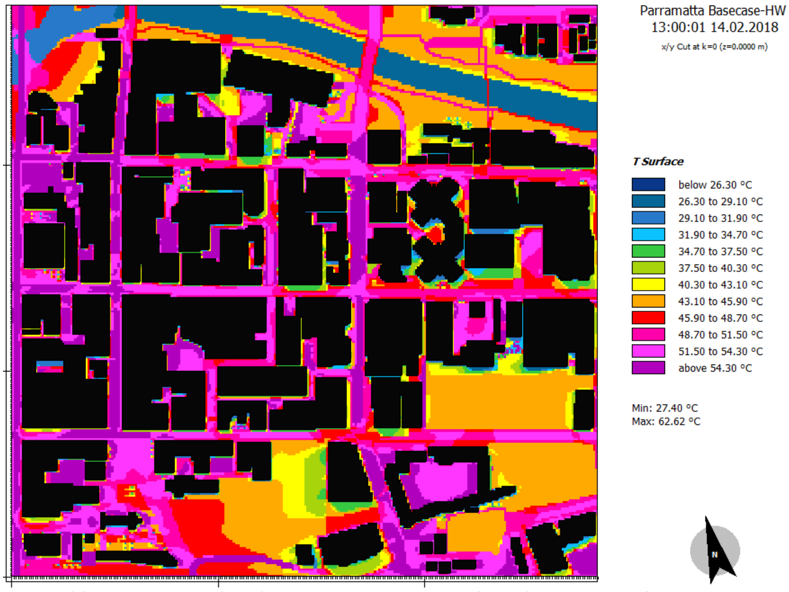


Figure 83. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 0, heatwave condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 84, where wind speed varies between 0 m/s and about 5.3 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 1.3 to about 1.8 m/s in the eastern part of Phillip Street. It is slightly higher between Church Street and Horwood Pl (about 2 m/s). Since initial wind direction is from northwest, a lower wind speed is obtained at the pedestrian level in Phillip street. The wind direction and pattern of wind speed distribution affects advection mechanism in that area.

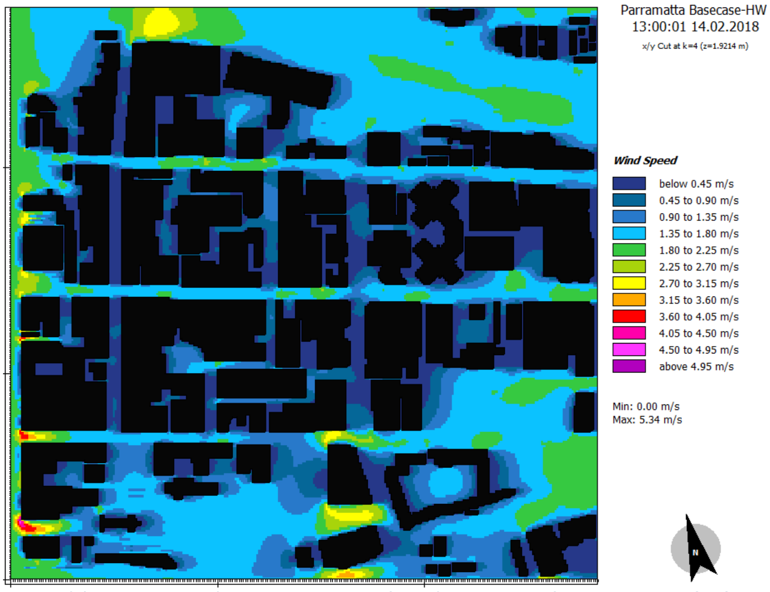


Figure 84. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 0, heatwave condition - 13:00

We performed analysis of comfort in the Parramatta CBD using different comfort indices. Figure 85 provides the distribution of comfort indices (i.e. UTCI and PET). This analysis shows the western side of the City of Parramatta CBD experiences extreme heat stress and warmth discomfort during heatwave condition. Phillip Street in general indicates a very strong heat stress. The Universal Thermal Climate Index (UTCI) is showing strong heat stress mainly ranging from 42 to 50 °C. In the areas between Marsden Street and Church Street the condition is extremely uncomfortable during heatwave condition. UTCI as used in the software is limited to a wind speed range of 0.5 to 17 m/s at 10 m Height. Thus, the areas with very low wind speed below 0.5 m/s have no calculated data and presented in white colour.

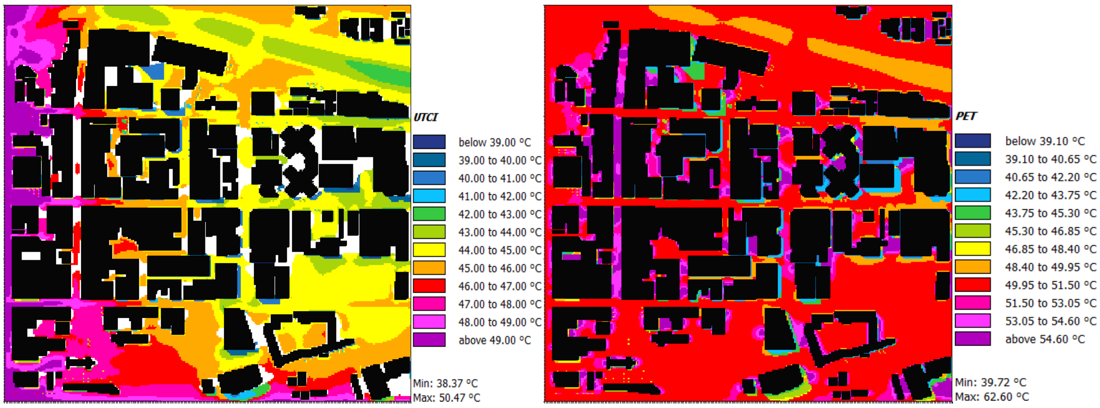


Figure 85. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 0, heatwave condition - 13:00: UTCI (left), PET (right)

Future scenarios

Future scenarios: future development

Scenario 00

Temperature in Phillip Street, under future development plan (planned height), ranges from 36.5 °C to 43.7 °C during the heatwave condition. The area between Marsden Street and Horwood Pl represents much warmer conditions than eastern side of Phillip Street (Figure 86). Future building height and form affect the wind speed and solar access where new buildings were implemented. The area between Marsden Street and Horwood Pl reveals the hottest spot in Phillip Street exceeding 38.7 °C.

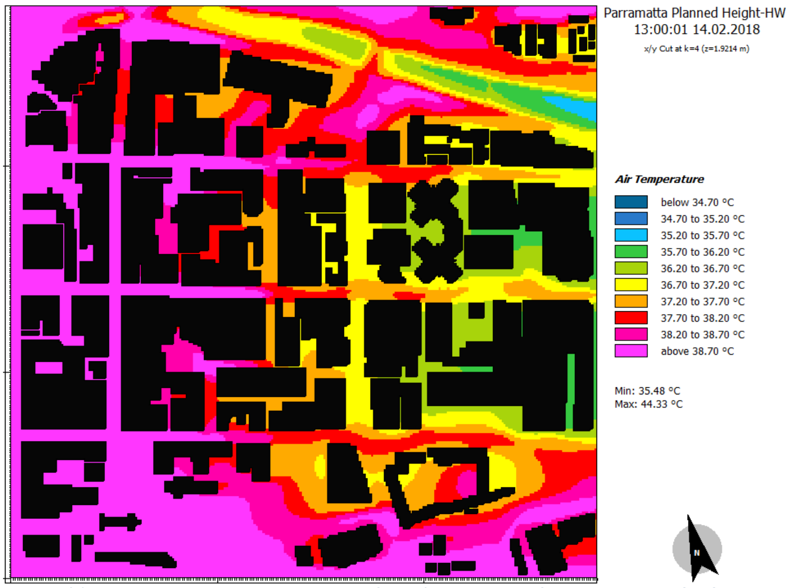


Figure 86. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 00, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 87) shows temperature reduction in the street when new buildings were added, or height was changed. The local air temperature drop is defined as the temperature difference between the reference scenario and the development plan scenario in the same spot. Areas nearby new development mostly present lower temperatures compared to the same spots in the unmitigated scenario due to advection and shading provided by new the high-rise buildings.

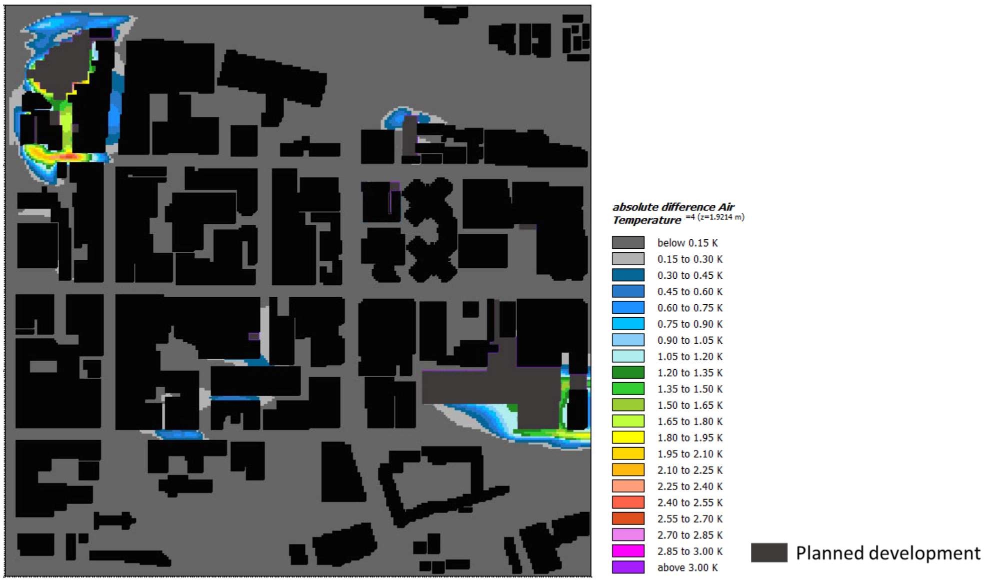


Figure 87. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 00, heatwave condition - 13:00

Figure 88 illustrates the surface temperature distribution in the City of Parramatta CBD considering planned development (scenario 00). The surface temperature reaches 63 °C in the City of Parramatta CBD. Dark coloured pavements show higher surface temperatures; however, western part of Phillip street shows lower surface temperatures compared to the reference scenario because of the shading provided by new high-rise buildings. The surface temperature in the corners of Church Street and Smith Street in Phillip Street exceed 54 °C.

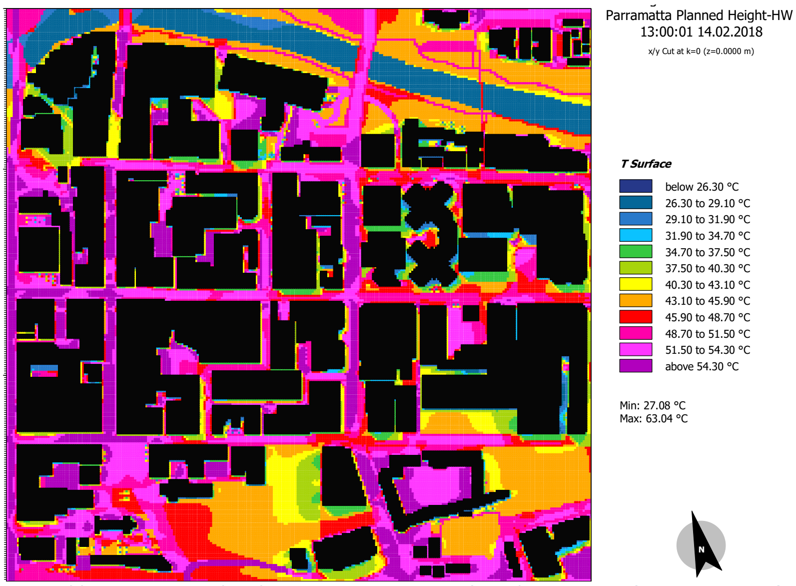


Figure 88. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 00, heatwave condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 89. As presented, wind speed varies between 0 m/s and about 5.3 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed exceeds 4m/s in western part of Phillip Street where new high-rise buildings were implemented. The corner of Phillip Street and Marsden Street illustrates highest wind speed values.

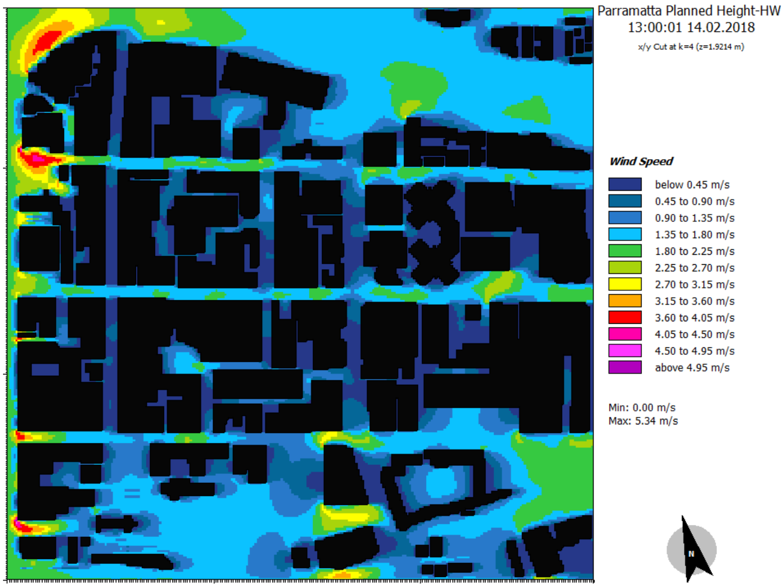


Figure 89. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 00, heatwave condition - 13:00

Figure 90 provides the distribution of comfort indices (i.e. UTCI and PET). Phillip Street in general indicates strong heat stress. However, this analysis shows thermal comfort is improved in the western side of Phillip street which is explained by the effects of shading by new high-rise buildings and changes in wind speed. The Universal Thermal Climate Index (UTCI) is mostly ranging from 42°C to 49°C in Phillip street during heatwave condition. The corner of Marsden Street is still presenting strong heat street during heatwave condition. PET is consistent with UTCI indicating areas out of comfort range and areas where comfort is improved.

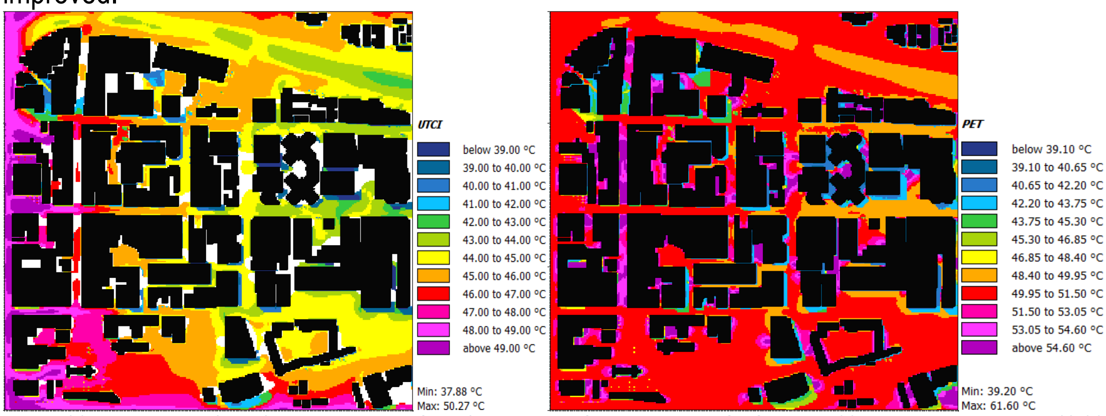


Figure 90. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 00, heatwave condition - 13:00: UTCI (left), PET (right)

Scenario 000

Ambient temperature ranges from 36.3 °C to 43.7 °C in Phillip Street when development plan is considered together with hypothetical future building height and density in the central part of the City of Parramatta CBD. Implementing future building height and form highly affect the wind speed, solar access and pattern of temperature distribution. The temperature distribution map shows the area between Marsden Street and Horwood Pl in Phillip street still represents much warmer conditions than eastern side of Phillip Street (Figure 91) with temperatures exceeding 38.7 °C. The temperature in the City of Parramatta CBD varies between 35.1 and 44.1°C.

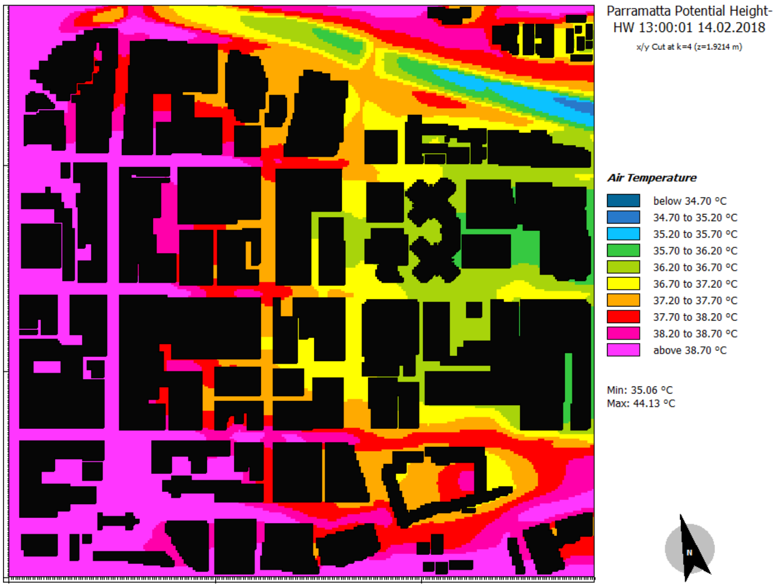


Figure 91.Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 000, heatwave condition - 13:00

Figure 92 shows the temperature difference between the future development scenario and the reference scenario in the same spot. Changes in wind speed and shading by buildings lead to lower temperatures in areas nearby new development compared to unmitigated scenario.

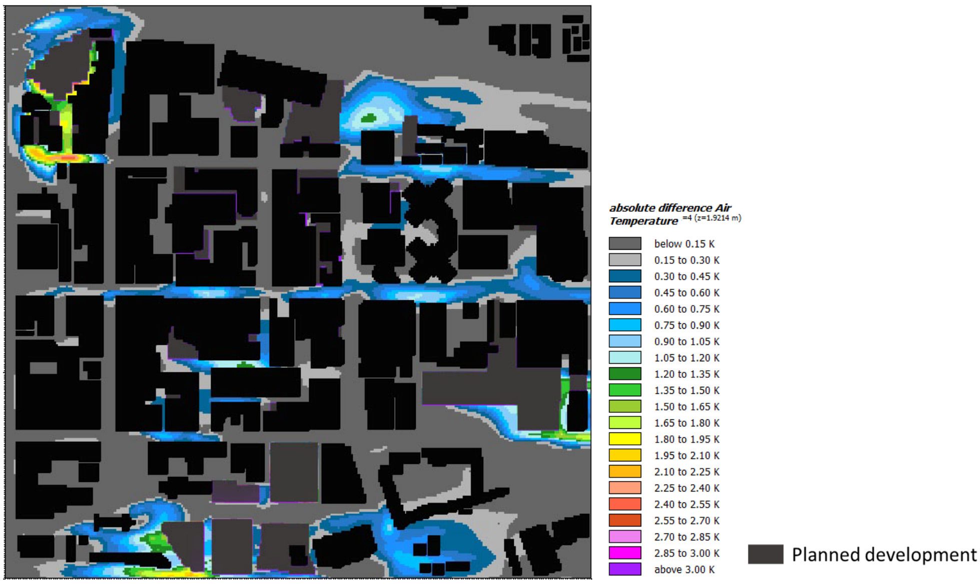


Figure 92. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 000, heatwave condition - 13:00

The surface temperature distribution in the City of Parramatta CBD is shown in Figure 93 considering new development with maximum building height and density (scenario 000). The surface temperature reaches 62.7 °C in the City of Parramatta CBD. Horizontal surfaces covered with black asphalt show higher surface temperatures; however, areas shaded by new high-rise buildings show lower surface temperatures compared to the existing condition (scenario 0). The surface temperature in the corner of Phillip Street and Smith Street exceed 54.3 °C and presents the highest surface temperature in Phillip Street when potential building height was considered.

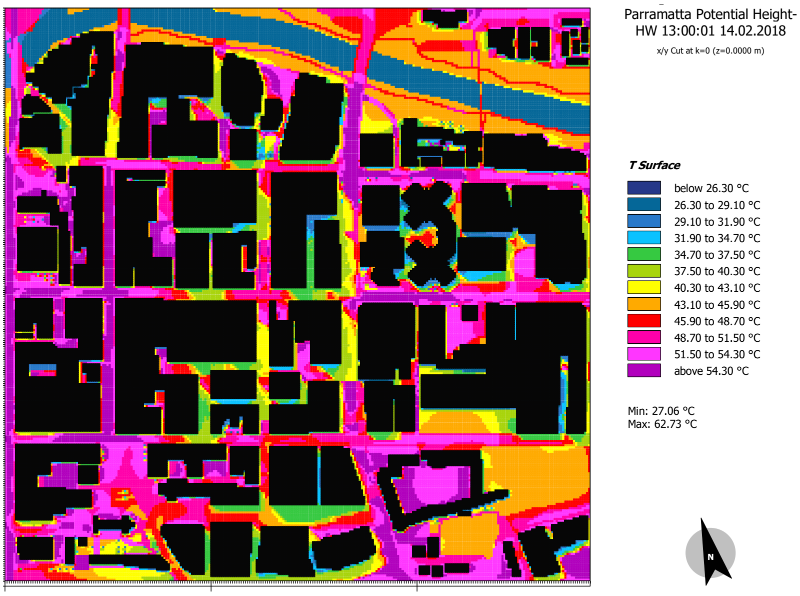


Figure 93. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 000, heatwave condition - 13:00

As presented in Figure 94, wind speed reaches to about 5 m/s in Parramatta CBD. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed exceeds 5m/s in north western part of Phillip Street and southern part of the CBD where new high-rise buildings were implemented. Eastern parts of Phillip Street illustrate wind speed values below 1 m/s while western parts exceed 3m/s.

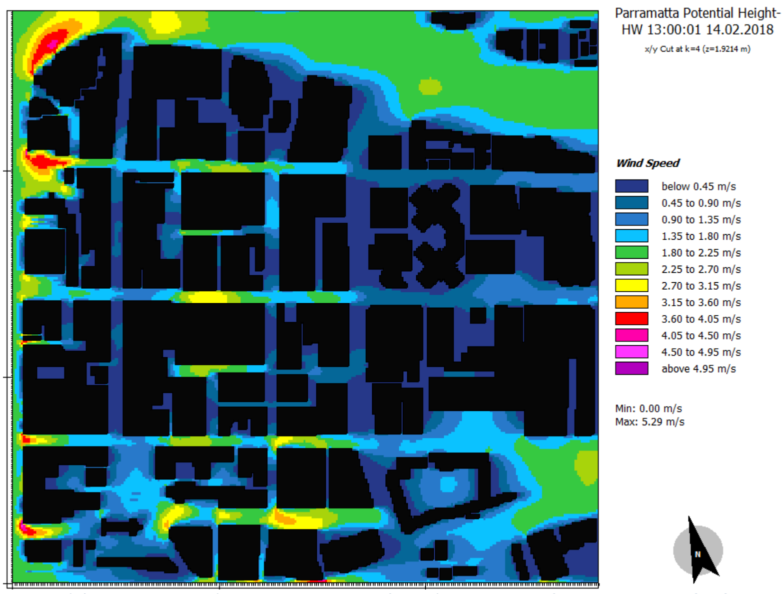


Figure 94. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 000, heatwave condition - 13:00

Figure 95 shows the distribution of comfort indices (i.e. UTCI and PET). Phillip Street in general indicates very strong heat stress. The Universal Thermal Climate Index (UTCI) is mostly ranging from 40°C to 48°C in Phillip street during heatwave condition under future scenario with potential building height and density. Thermal comfort is slightly improved in the areas shaded by new buildings (e.g. corner of Marsden street and Phillip street) compared to the reference scenario.

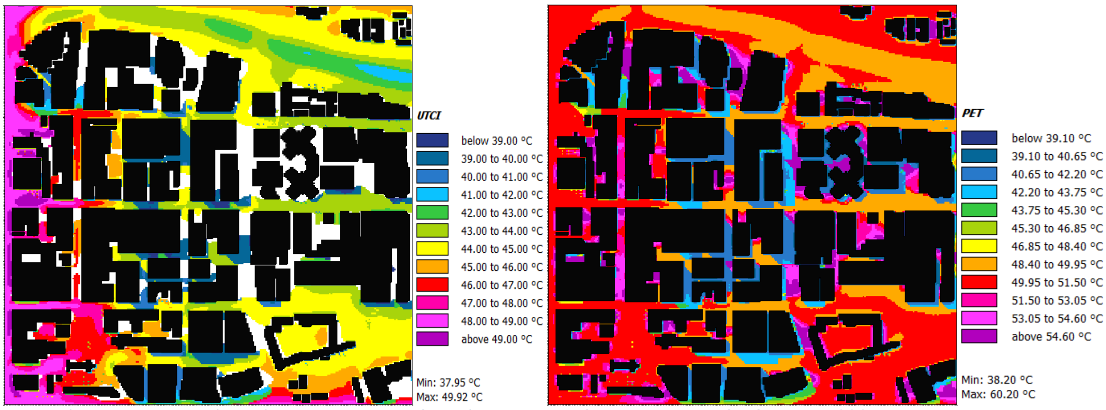


Figure 95. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 000, heatwave condition - 13:00: UTCI (left), PET (right)

Mitigation scenarios

Mitigation scenarios

Scenario 1

Ambient temperature ranges from 36.0°C to 42.7°C in Phillip Street when cool pavement is implemented (scenario 1). Cool pavement is used in the whole Phillip Street and the car park located at the corner of Marsden Street. Despite higher ambient temperatures in western part of Phillip Street, the air temperature distribution map (Figure 96) shows that air temperature in the Phillip Street is reduced by the use of cool pavement compared to the reference scenario. The air temperature ranges between 35.2°C to 44.1°C in the city of Parramatta CBD.

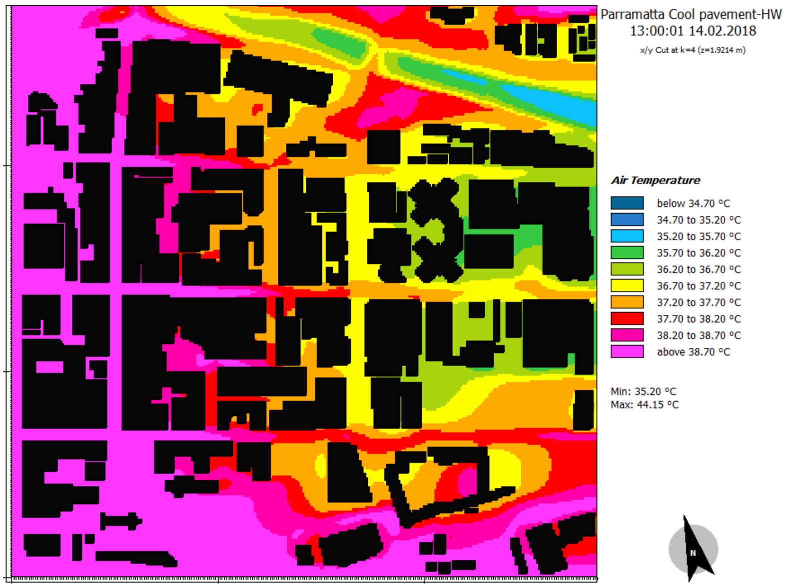


Figure 96. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 1, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 97) shows temperature reduction in the street where mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the cool pavement scenario in the same spot. As shown in Figure 97 below, the local temperature reduction ranges from 0.02 to 1.2°C and the average temperature reduction in the whole Phillip St. is 0.4°C.

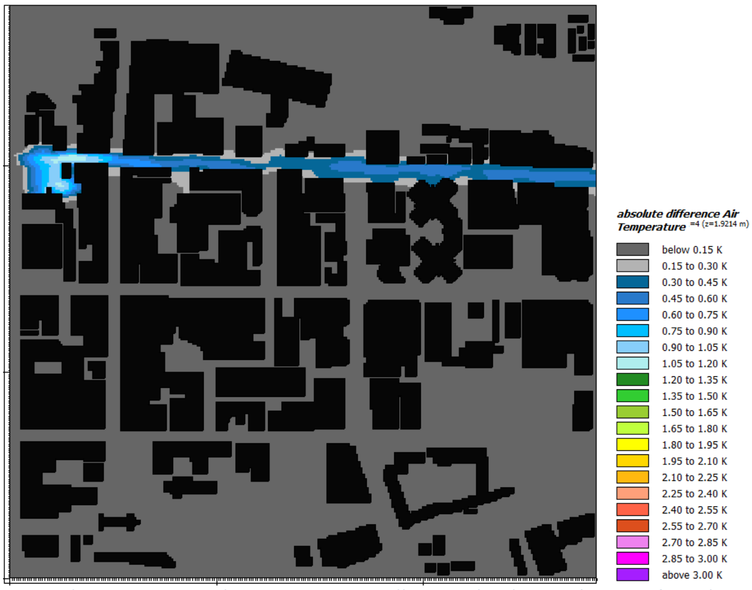


Figure 97. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 1, heatwave condition - 13:00

The surface temperature distribution is shown in Figure 98 when cool pavement is implemented in Phillip Street. The surface temperature is significantly reduced in scenario 1 compared to that in the reference scenario. The temperature of horizontal surfaces varies between 34.7 °C and 51.5 °C in Phillip Street. It reaches 61.9 °C in the City of Parramatta CBD.

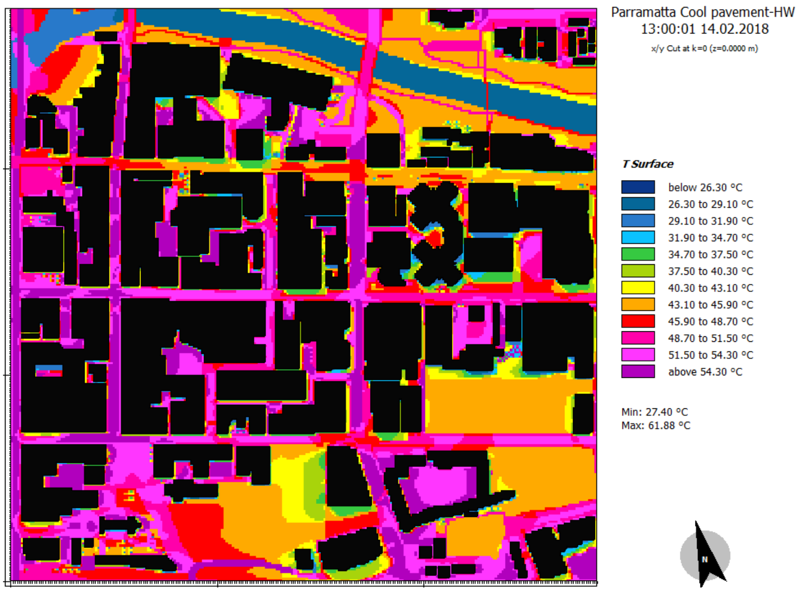


Figure 98. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 1, heatwave condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 99. As presented, wind speed varies between 0 m/s and about 5.3 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 1 to about 2.2 m/s in Phillip Street and mostly fall below 1.8 m/s. The areas between Church Street and Horwood Pl presents slightly higher wind speeds (1.8-2.25 m/s) which affects advection mechanism in those areas. Since there was no change in physical configuration of the model, wind speed is the same as reference scenario.

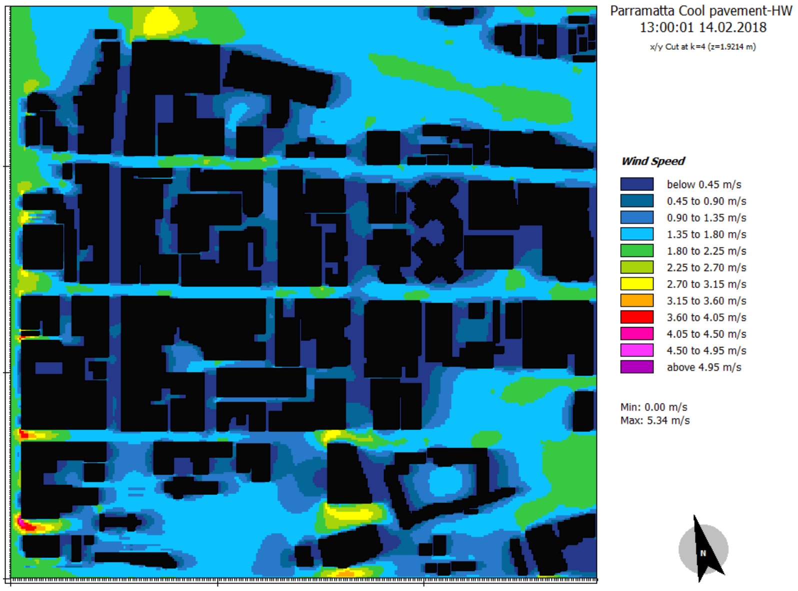


Figure 99. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 1, heatwave condition - 13:00

Figure 100 shows the distribution of comfort indices (i.e. UTCI and PET). Phillip Street in general indicates very strong heat stress. The Universal Thermal Climate Index (UTCI) is mostly ranging from 42°C to 49°C in Phillip street during heatwave condition under cool pavement scenario. The corner of Marsden Street and Phillip street and areas near Church Street is presenting extreme heat street while eastern parts of Phillip street have slightly lower UTCI. PET distribution is consistent with UTCI indicating areas out of comfort zone.

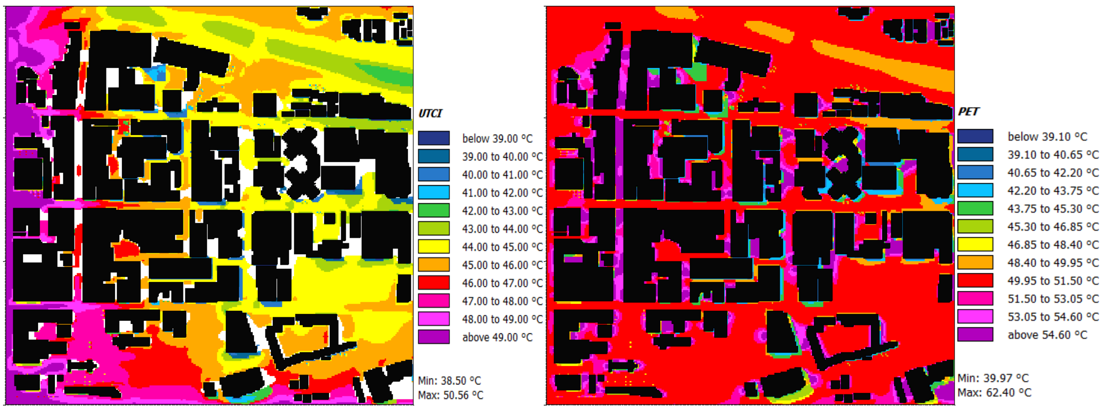


Figure 100. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 1, heatwave condition - 13:00: UTCI (left), PET (right)

Scenario 2

Ambient temperature ranges from 36.4 °C to 43.0 °C in Phillip Street when 82 irrigated trees and greenery were implemented (scenario 2). New mature irrigated trees (both deciduous and evergreen) were planted in the whole Phillip Street. The ambient temperature distribution map shows that air temperature in Phillip Street is lower than the reference scenario where tress where planted (Figure 101).

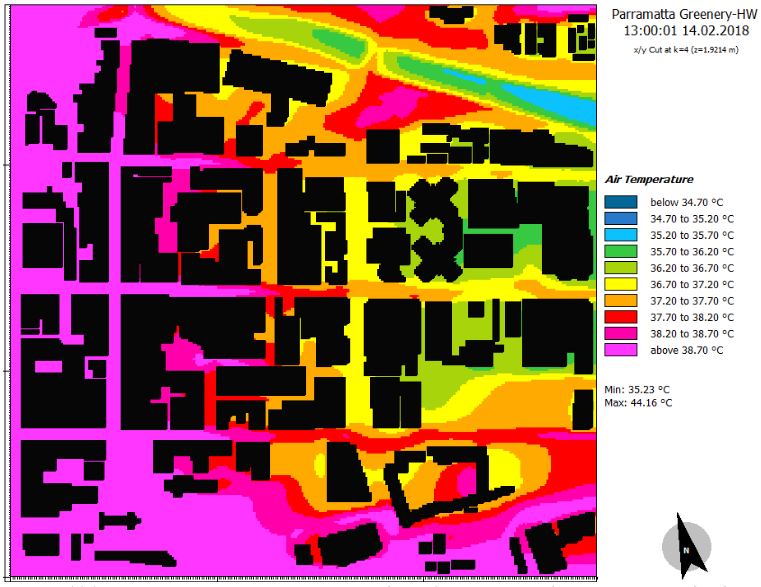


Figure 101. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 2, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 102) shows temperature reduction in the street where the mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the greenery scenario in the same spot. Temperature difference distribution map shows the local temperature reduction in Phillip street where trees were planted. The maximum local temperature reduction is about 0.8°C in scenario 2.

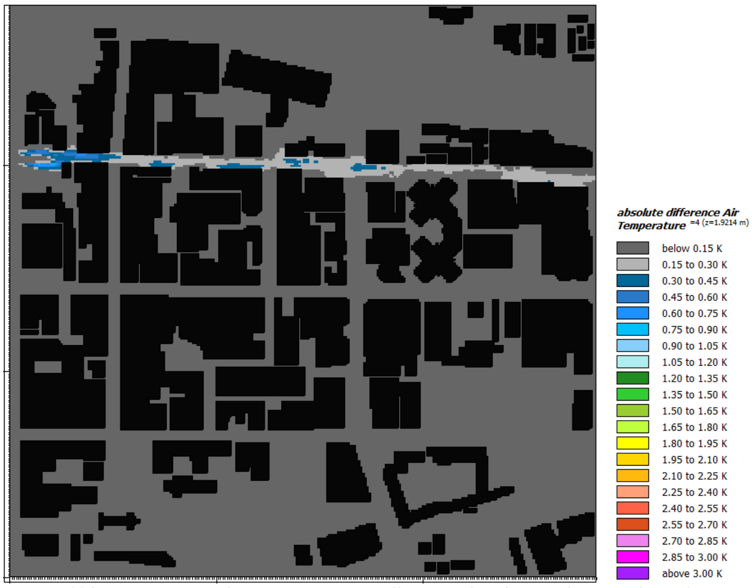


Figure 102. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 2, heatwave condition - 13:00

The surface temperature distribution is shown in Figure 103 when 82 mature trees (mostly 6m high, both evergreen and deciduous) were planted and raingarden was implemented in Phillip street. The surface temperature is significantly reduced in scenario 2 (where trees are planted) compared to the same spot in the reference scenario. The surface temperature in Phillip street was reduced by 22-28°C in the areas shaded by the trees and reduced by about 10°C where raingarden was implemented. The temperature of horizontal surfaces generally varies from 25.2°C to 62.6°C in the City of Parramatta CBD.

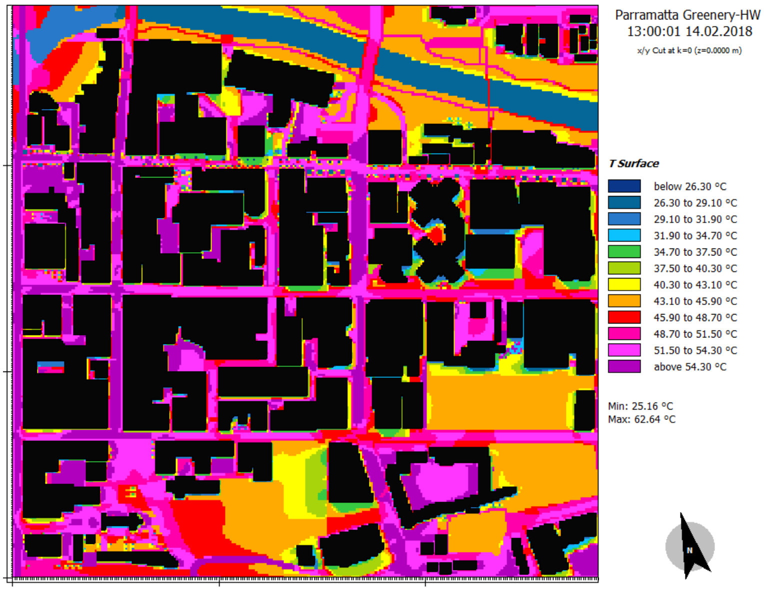


Figure 103. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 2, heatwave condition - 13:00

The wind speed distribution (Figure 104) shows wind speed varies between 0 m/s and about 5 m/s in the City of Parramatta CBD. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed mostly ranges between 0.45 and about 1.8 m/s in Phillip Street. However, wind speed is reduced where trees were planted compared to the same spots in the reference scenario.

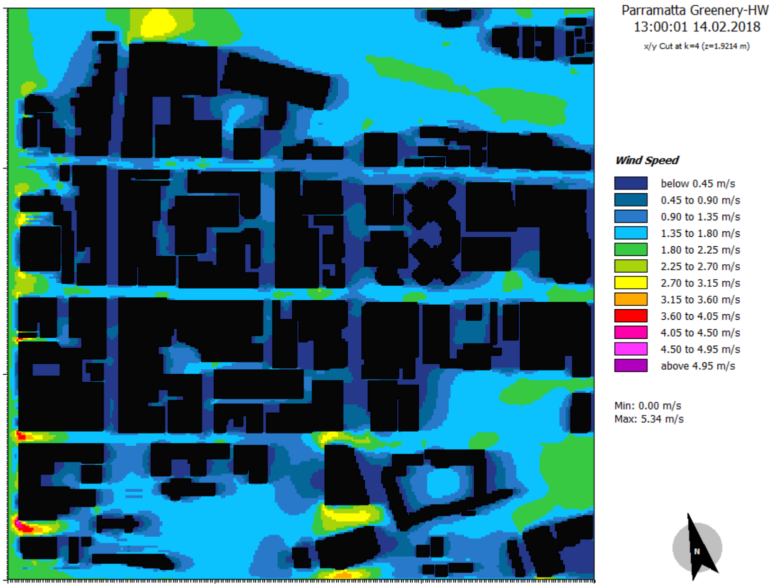


Figure 104. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 2, heatwave condition - 13:00

Figure 105 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street in general indicates extreme heat stress under scenario 2 ranging from 40°C to 49°C during heatwave condition. However, under the shades from the trees, comfort is slightly improved (UTCI below 39°C in the eastern side of Phillip Street). UTCI and PET distribution maps are consistent indicating the local effects of trees to improve comfort in Phillip Street.

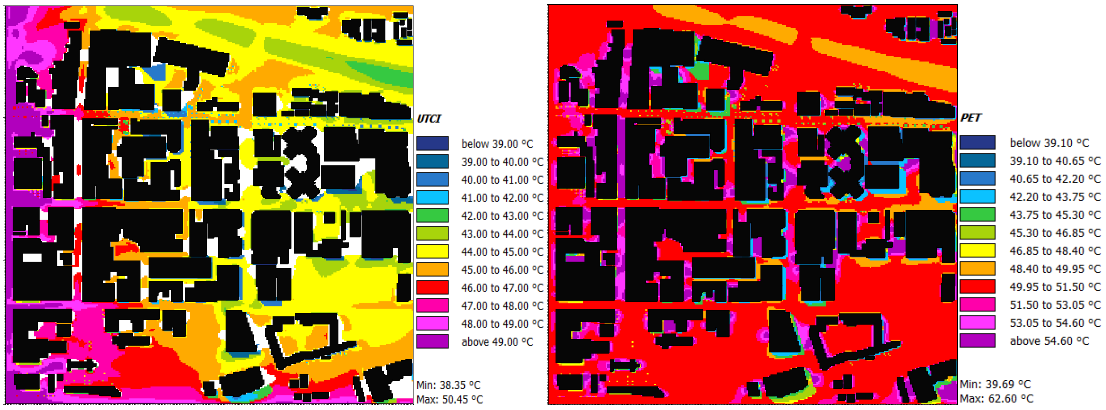


Figure 105. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 2, heatwave condition - 13:00: UTCI (left), PET (right)

Scenario 3

Ambient temperature ranges from 36.2°C to 43.1°C in Phillip Street when shading cloth was used to cover 75% of the street (scenario 3). We have shown that shading is an effecting strategy reducing the temperature by 1.9°C compared to the reference scenario. The ambient temperature distribution map shows that air temperature in Phillip Street is lower where solar control device was implemented compared to the reference scenario (Figure 106).

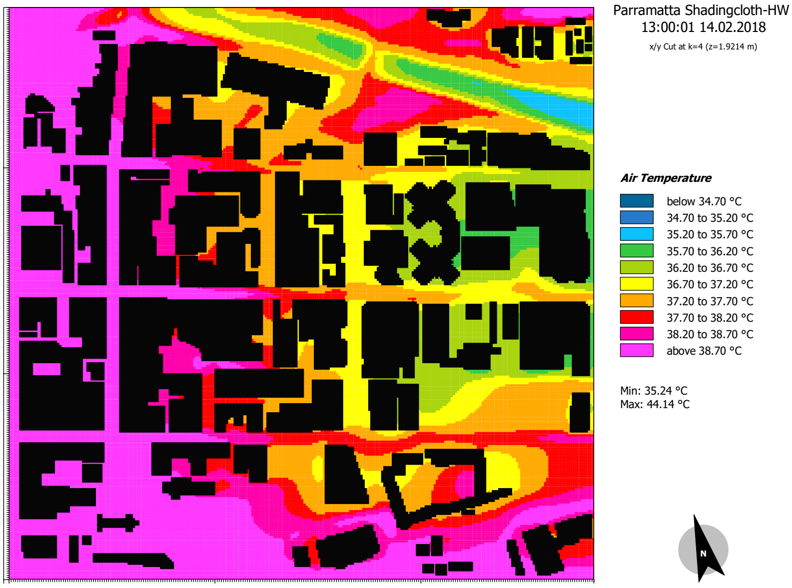


Figure 106. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 3, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 107) shows temperature reduction in the street where the mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the shading scenario in the same spot. Temperature difference distribution map shows the local temperature reduction in Phillip street where shading cloth was used. The maximum local temperature reduction is 1.9°C and the average is 0.3°C. Due to the effects of advection, surrounding areas also have lower temperatures compared to unmitigated scenario. As shown, use of solar control device reduces the temperature about 1.0°C in the area between Church Street and Horwood Pl and about 1.9 in the area between Marsden Street and Church Street.

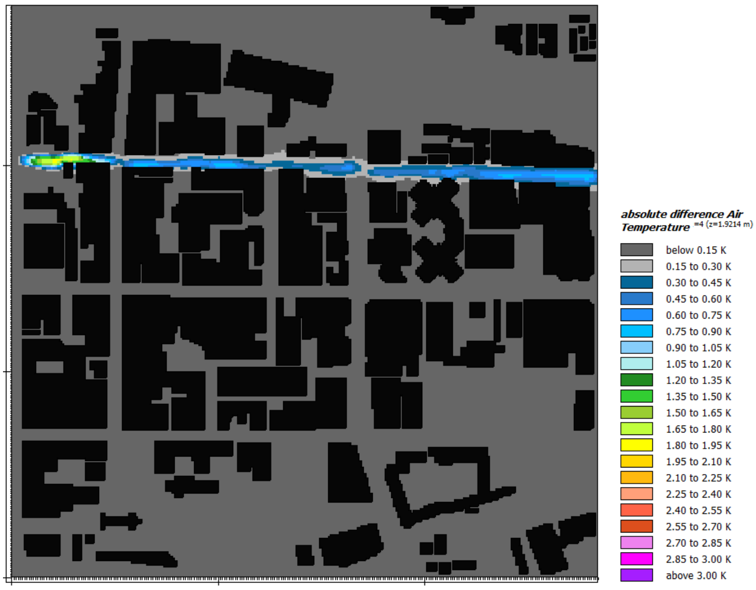


Figure 107. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 3, heatwave condition - 13:00

The surface temperature distribution is shown in Figure 108 when solar control device was used in Phillip Street. The surface temperature is significantly reduced in scenario 3 compared to the same spot in the reference scenario. The surface temperature reduction in Phillip street was between 11.6°C and 20°C and recached to 24°C in the shaded areas. The surface temperature generally varies from 27.2 °C to 62.4°C in the City of Parramatta CBD and mostly ranges between 34.7°C and 51.5°C in Phillip street (except unshaded areas which exceed 54.3°C).

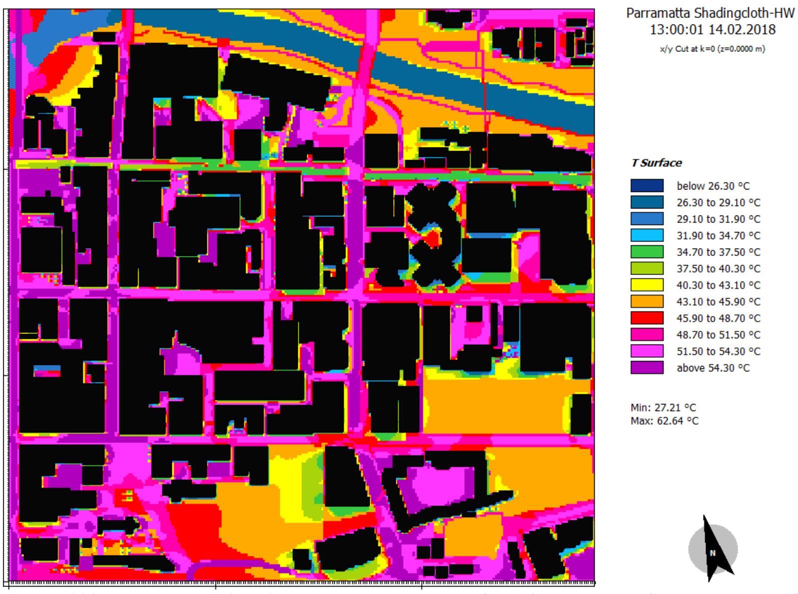


Figure 108. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 3, heatwave condition - 13:00

Figure 109 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0.45 and about 2.2 m/s in Phillip Street. Due to the height of shading device, there was a small effect on the wind speed distribution at pedestrian level.

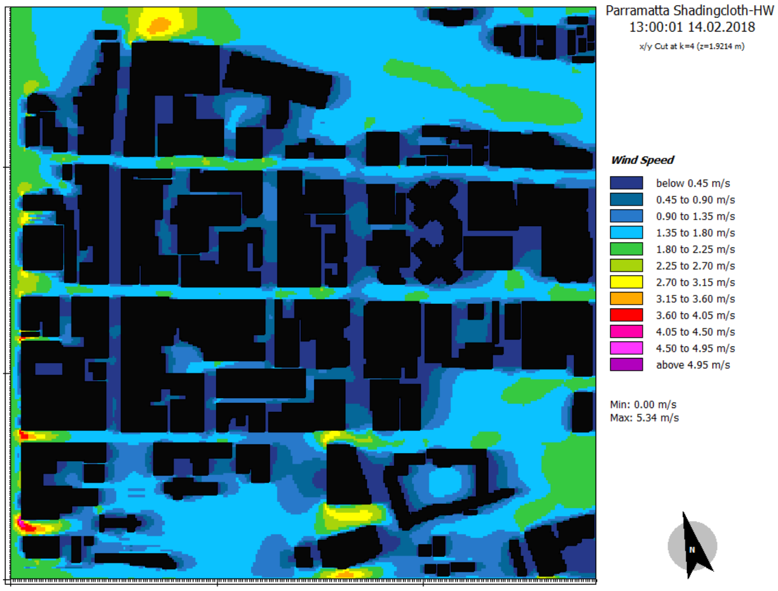


Figure 109. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 3, heatwave condition - 13:00

Figure 110 shows the distribution of comfort indices (i.e. UTCI and PET) in the city of Parramatta CBD. Phillip Street indicates extreme heat stress with UTCI ranging from 38°C to above 49° C during heatwave condition. UTCI under shading device varies between about 38 to 45°C. This reveals that shading device is an effective strategy to improve thermal comfort in the area. UTCI and PET distribution maps are consistent indicating the effects of solar control to improve comfort in Phillip Street; PET reduces from 48.4-51.5 °C to 40.7-50°C. Results show that heat stress for humans in urban areas can be reduced by providing shading and, at the same time, not reducing wind speed too much. Due to the effects of advection comfort level is enhanced in the whole street; however, the effects are much higher under the shaded area. Despite reducing heat stress by providing shading, Phillip Street presents uncomfortable conditions during heatwave.

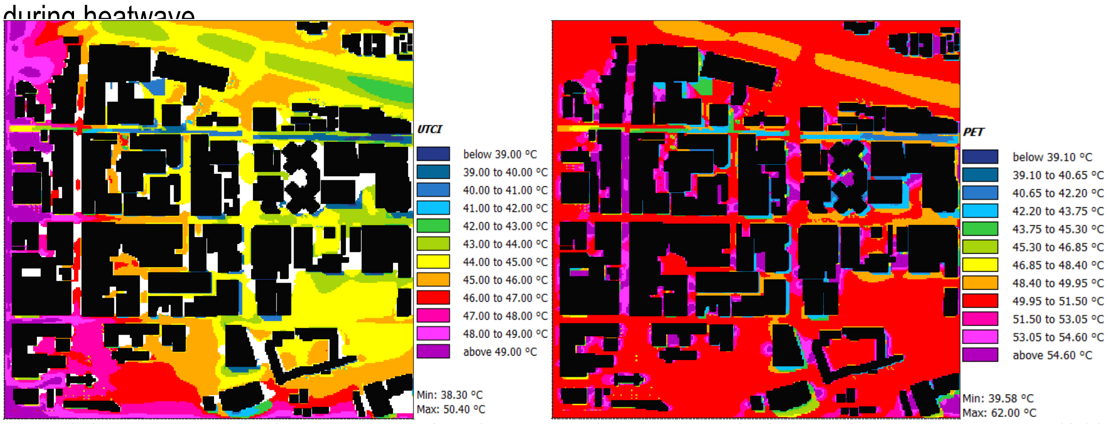


Figure 110. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 3, heatwave condition - 13:00: UTCI (left), PET (right)

Scenario 4

Ambient temperature ranges from 35.5 °C to 40.2 °C in Phillip Street when we used 22 evaporative cooling systems with the height of 4m (scenario 3). Misting system is an effective strategy reducing the temperature by 5.4 °C. The ambient temperature distribution map shows that air temperature in Phillip Street is significantly lower than the reference scenario where misting systems were used (Figure 111).

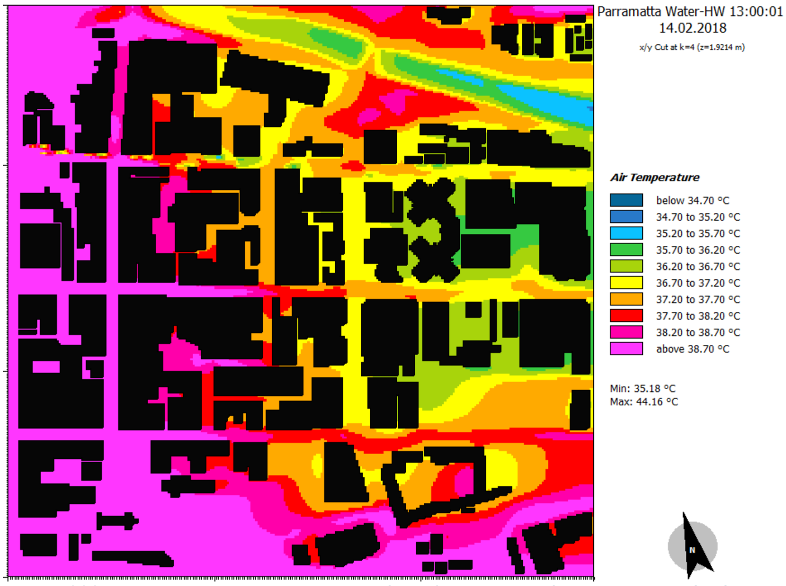


Figure 111. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 4, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 112) shows temperature reduction in scenario 4. The local air temperature drop is defined as the temperature difference between the reference scenario and the scenario of evaporative system in the same spot. The local temperature reduction ranges from 0 to 5.4°C and the average temperature reduction is 0.6°C. The temperature difference map shows the local effects of spray systems and the effects of advection to reduce the temperature of the nearby areas.

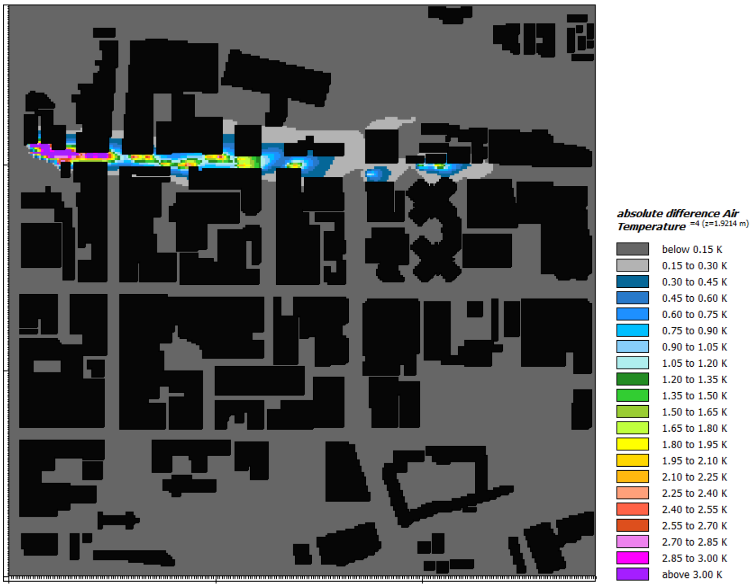


Figure 112. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 4, heatwave condition - 13:00

The surface temperature distribution is shown in Figure 113 when misting systems were used in Phillip Street. The surface temperature is reduced by 4°C near water spray systems (scenario 4) compared to the same spot in the reference scenario. Other parts of Phillip Street were not affected. The surface temperature generally varies from 27.4 °C to 62.6 °C in the City of Parramatta CBD.

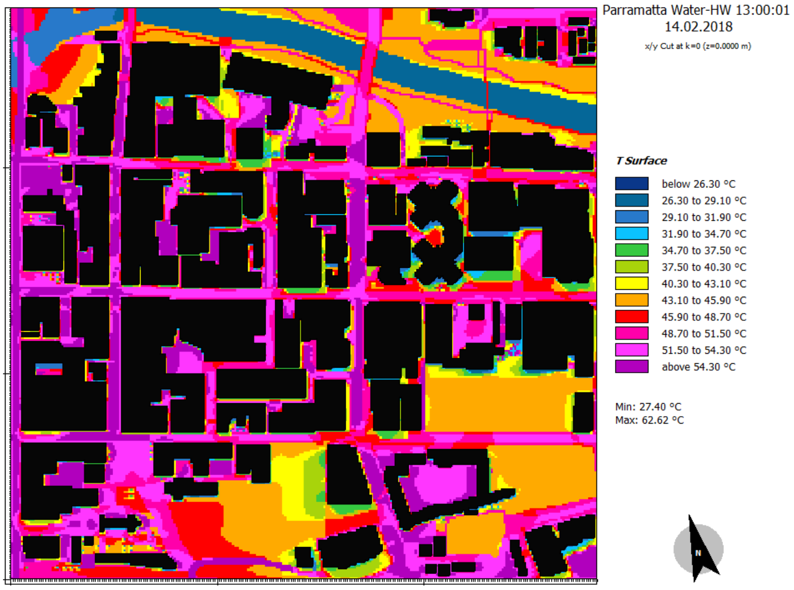


Figure 113. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 4, heatwave condition - 13:00

Figure 114 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed mostly ranges between 0.45 and about 2m/s in Phillip Street. Misting system does not change the wind speed distribution in the street.

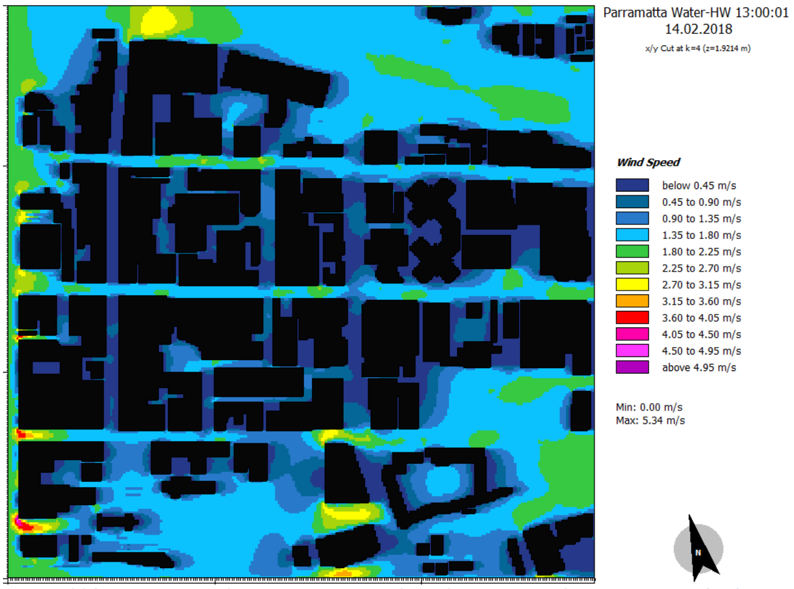


Figure 114. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 4, heatwave condition - 13:00

Figure 115 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates extreme heat stress with UTCI ranging from 43°C to above 49°C during heatwave condition. UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street. Heat stress for humans in urban areas can be reduced (by 2-5°C) by misting system. However, this the cooling effects is only applied locally where misting systems are used.

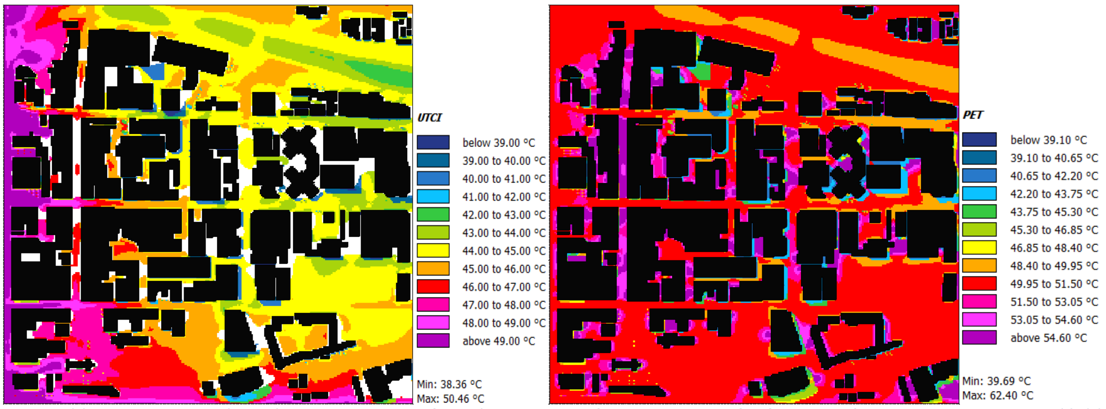


Figure 115. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 4, heatwave condition - 13:00: UTCI (left), PET (right)

Scenario 5

Ambient temperature ranges from 36.3 °C to 42.8 °C in Phillip Street when we used cool roof in the buildings adjacent to Phillip Street (scenario 5). Area between Marsden Street and Church Street and Horwood Pl represent warmer conditions than eastern side of Phillip Street. Due to the height of buildings, cool roof has insignificant effect in reducing the ambient temperature at pedestrian level in Phillip Street (Figure 116).

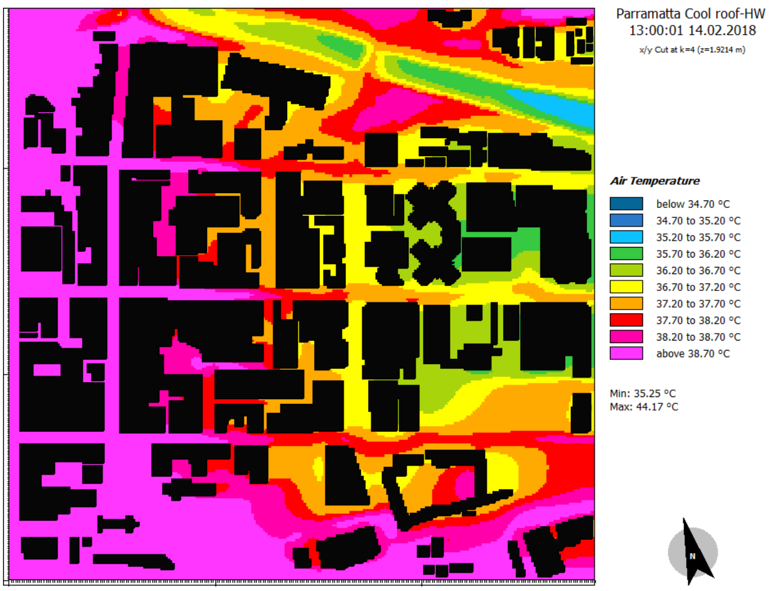


Figure 116. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 5, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 117) shows temperature reduction where the mitigation technology is implemented. The local air temperature drop is defined as the temperature difference between the reference scenario and the scenario of cool roof in the same spot. Temperature difference distribution map shows the effects of cool roof is minimal (below 0.15°C) in the pedestrian level (1.9 m above the ground).

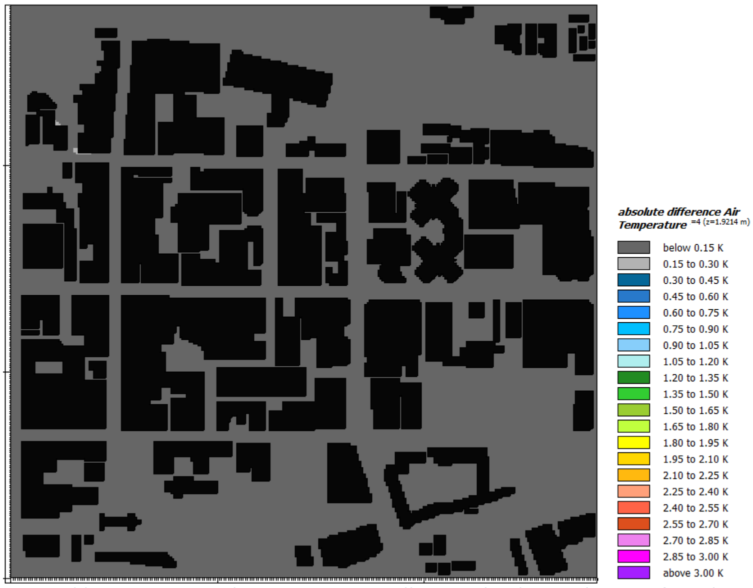


Figure 117. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 5, heatwave condition - 13:00

The surface temperature distribution is shown in Figure 118 when cool roofs were used in Phillip Street. The surface temperature varies from 27.2 °C to 62.6°C in the City of Parramatta CBD. The surface temperature in Phillip Street is not affected by the implementation of cool roof.

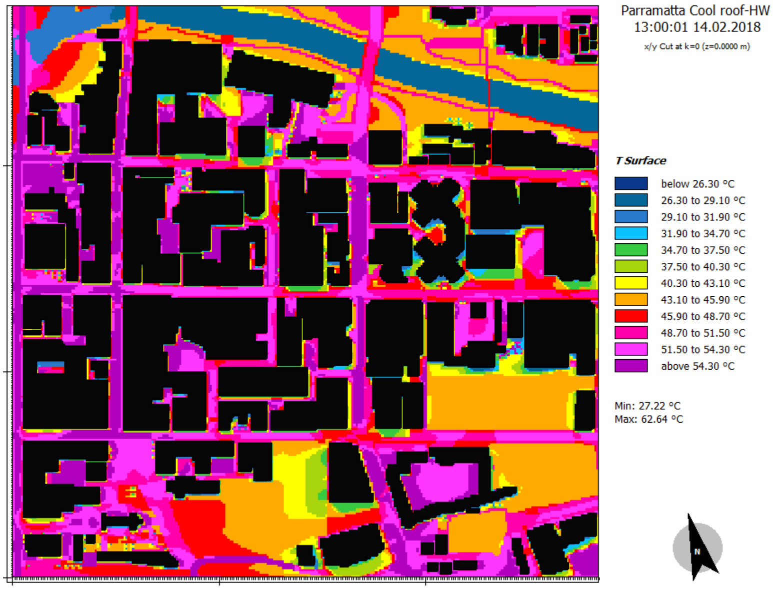


Figure 118.Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 5, heatwave condition - 13:00

Figure 119 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and 5.3 m/s. Different building heights, spaces between buildings and street orientation, lead to variation of the wind speed from one area to another. The wind speed mostly varies from 0.45 to about 2 m/s in Phillip Street and is not impacted by the use of cool roof.

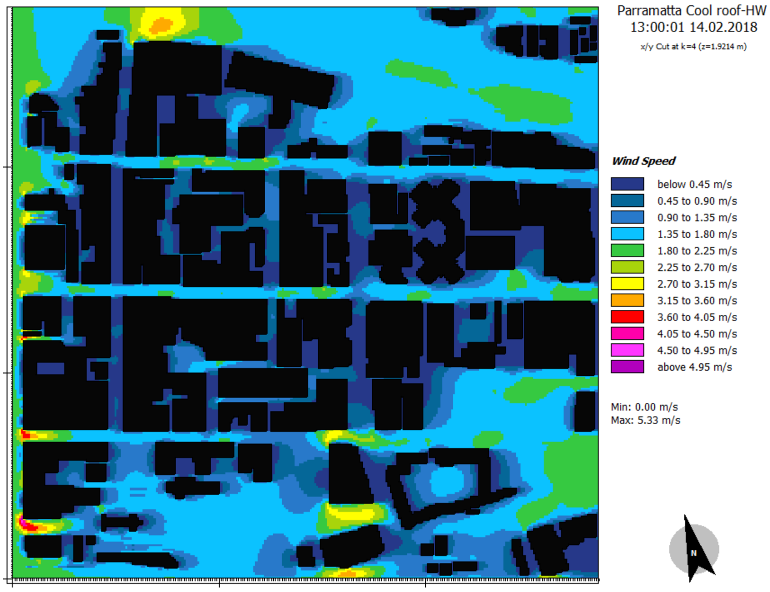


Figure 119. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 5, heatwave condition - 13:00

Figure 120 shows the distribution of comfort indices in the City of Parramatta CBD. Phillip Street indicates extreme heat stress with UTCI ranging from 39°C to above 49°C, which is similar to that in the reference scenario. UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street when cool roof was used.

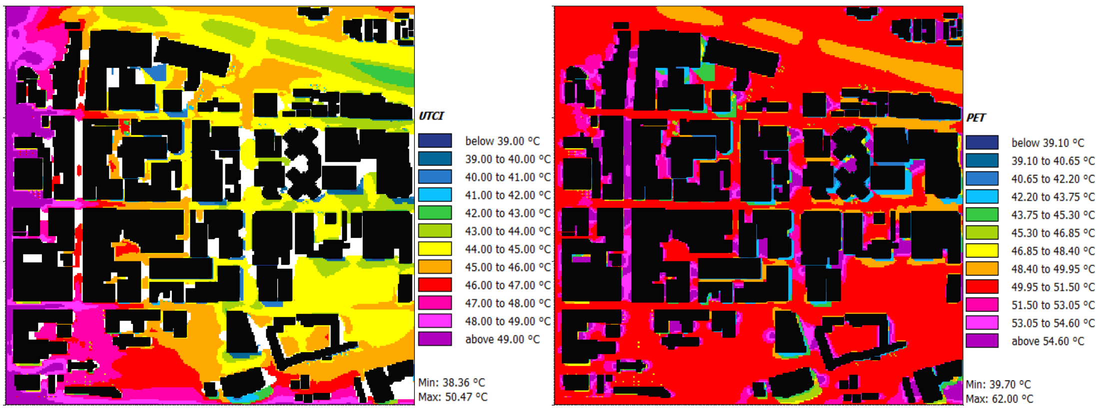


Figure 120. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 5, heatwave condition - 13:00: UTCI (left), PET (right)

Scenario 6

Ambient temperature ranges from 35 °C to 39.9 °C in Phillip Street when we used a combination of mitigation technologies, i.e., cool pavement, greenery, shading, spray system, and cool roof (scenario 6). The effect of combined scenario is very significant in reducing the ambient temperature in the whole Phillip street (Figure 121).

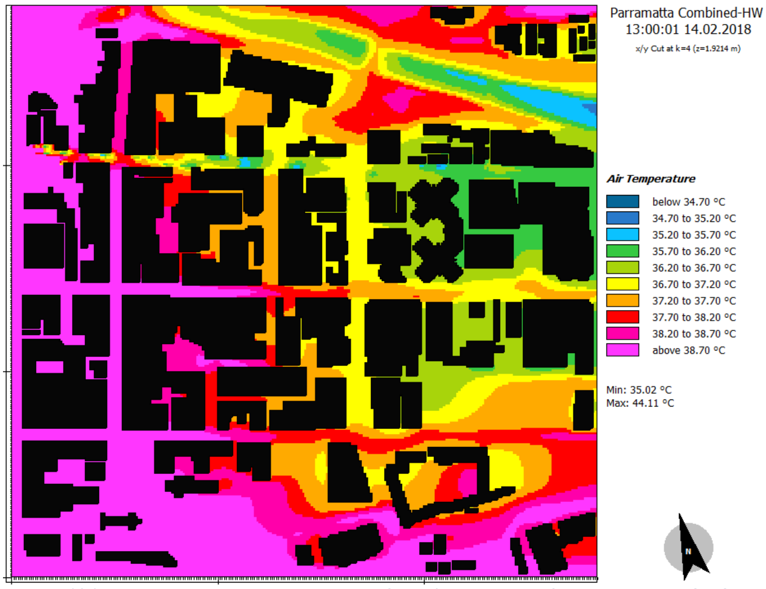


Figure 121. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 5, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 122) shows the achieved temperature reduction where mitigation technologies were implemented (combination of cool pavement, greenery, shading, spray system, and cool roof). The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the combined scenario in the same spot. Under the scenario 6, the maximum local temperature reduction is 6.7°C and the average is 1.3°C. The temperature reduction achieved in the most parts of Phillip Street between Marsden Street and Horwood Pl ranges from about 1.2°C to 6.7°C.

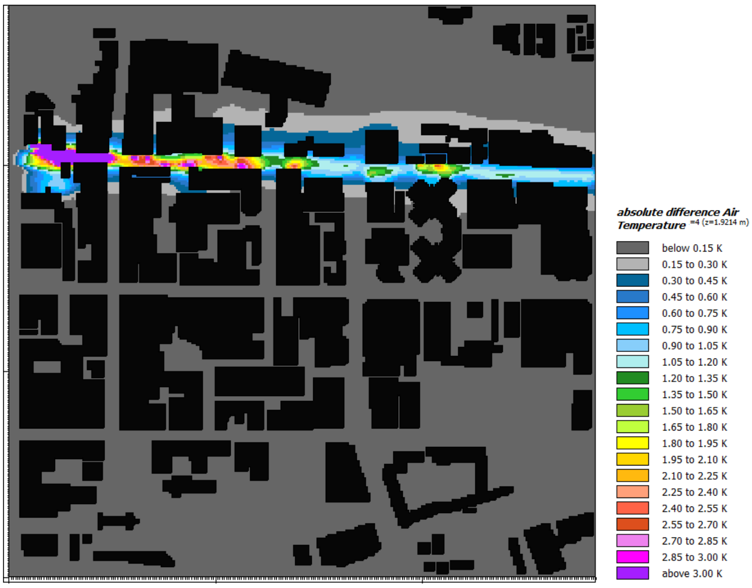
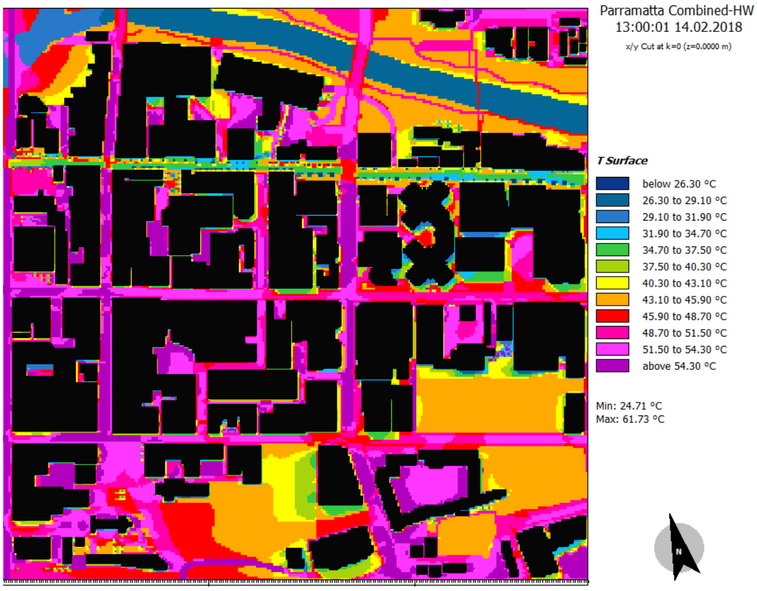


Figure 122. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 6, heatwave condition - 13:00

The surface temperature distribution is shown in Figure 123 when a combination of strategies was used in Phillip Street. The surface temperature generally varies from 24.7 °C to 61.7 °C in the City of Parramatta CBD. In Phillip Street, the surface temperature mostly falls above 31.9 °C and below 48.7 °C (Figure 123 a). The surface temperature is significantly reduced in scenario

6 compared to the same spot in the reference scenario. The surface temperature reduction achieved under the combined scenario varies from 8.4°C to 19.6°C under the shading device and exceeds 25.2°C under the shading provided by the trees (Figure 123 b).

a)



b)

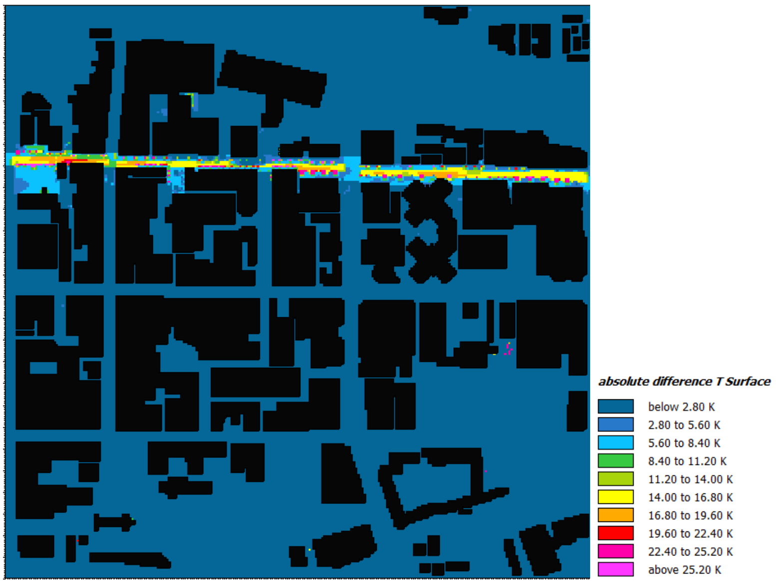


Figure 123. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 6, heatwave condition - 13:00 (a), surface temperature difference ($T_{surace, ref}$ – $T_{surface, mit}$) (b)

Figure 124 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5.2 m/s. Wind speed varies from one area to another due to different building heights, spaces between buildings and street orientation. The wind speed is reduced in Phillip street compared to the reference scenario. It mostly ranges between 0.45 and about 1.8 m/s in Phillip Street. The wind speed value and distribution are impacted by the trees.

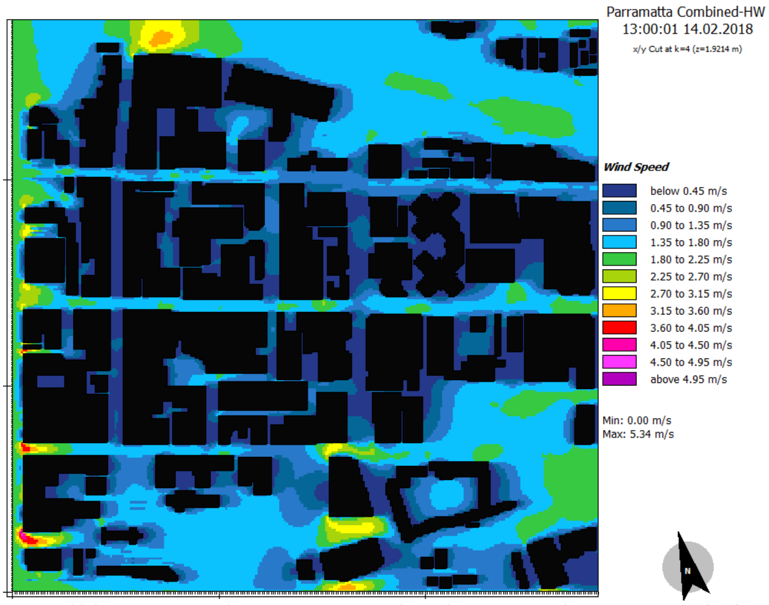


Figure 124. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 6, heatwave condition - 13:00

Figure 125 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD during heatwave condition. Phillip Street indicates very strong heat stress with UTCI and PET ranging from 38 °C to 45°C and 39.1 °C to 48.4 °C, respectively. This can be compared with Phillip street (reference scenario) and Church street (existing condition) where UTCI falls above 46 °C and PET exceeds 50 °C. UTCI and PET distribution maps are consistent in presenting hot spots and areas with improved thermal comfort in Phillip Street. As shown here, heat stress for humans in urban areas can be significantly reduced with the implementation of the combined strategies.

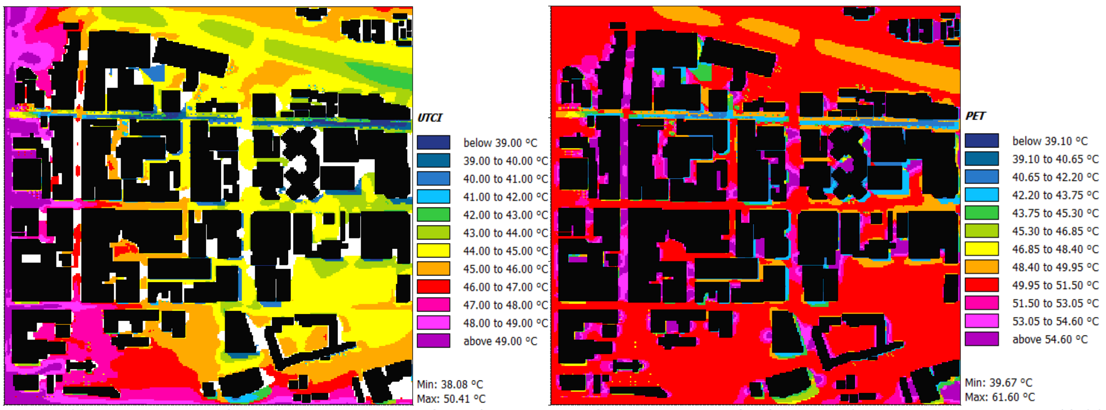


Figure 125. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 6, heatwave condition - 13:00: UTCI (left), PET (right)

Scenario 7

As shown in Figure 126, the ambient temperature ranges from 36.4 °C to 42.9 °C when new trees and greenery were implemented, and cool pavements were used in Phillip Street (scenario 7). New mature irrigated trees (both deciduous and evergreen) were planted in the whole Phillip Street and cool pavements were used (combination of scenario 1 and scenario 2). The ambient temperature distribution map shows that air temperature in Phillip Street is lower where mitigation technologies were implemented than the same spots in the reference scenario (Figure 126).

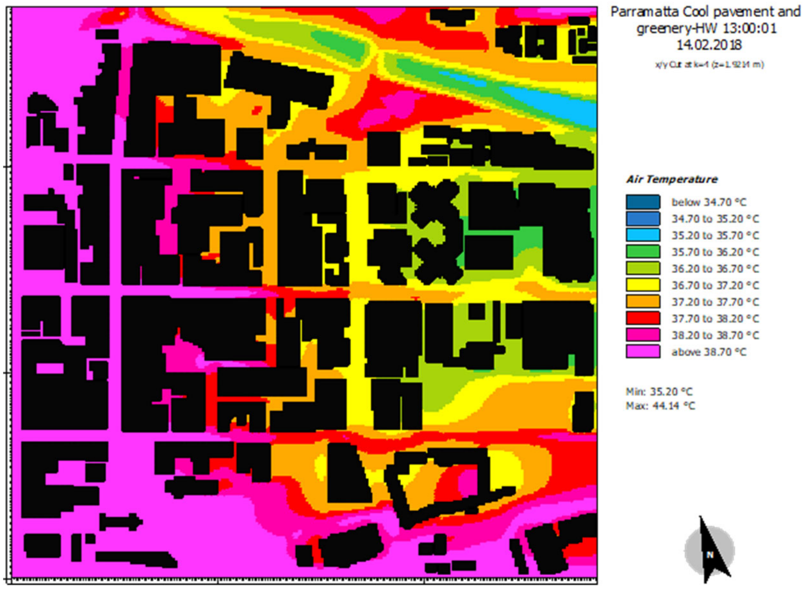


Figure 126. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 7, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 127) shows temperature reduction where the mitigation technology is implemented (combination of cool pavement and greenery). The local air temperature drop is defined as the temperature difference between the reference scenario and the mitigated scenario in the same spot. Under the scenario 7, the local temperature reduction reaches to 1.5°C and the average temperature reduction is 0.5°C.

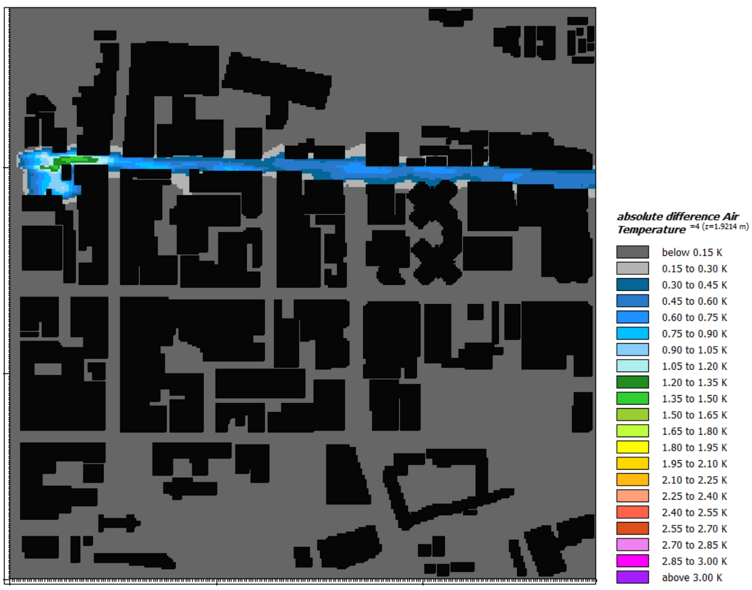


Figure 127. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 7, heatwave condition - 13:00

The surface temperature distribution is shown in Figure 128 when a combination of strategies was used in Phillip Street. The surface temperature generally varies from 25.1°C to 61.9°C in the City of Parramatta CBD. In Phillip Street, the surface temperature mostly ranges from 43.1°C to 51.5°C (Figure 128). The surface temperature is significantly reduced under the trees where temperature falls below 26.3°C (Figure 128).

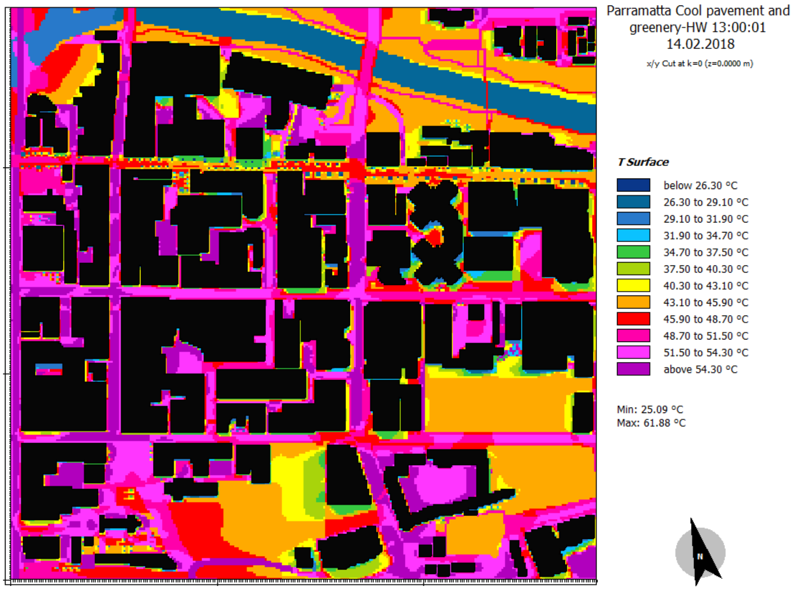


Figure 128. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 7, heatwave condition - 13:00

Figure 129 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5.3 m/s. Wind speed varies from one area to another due to different building heights, spaces between buildings and street orientation. The wind speed ranges between 0.45 and about 1.8 m/s in Phillip Street. Near the trees, wind speed at pedestrian level is reduced compared to the refence scenarios.

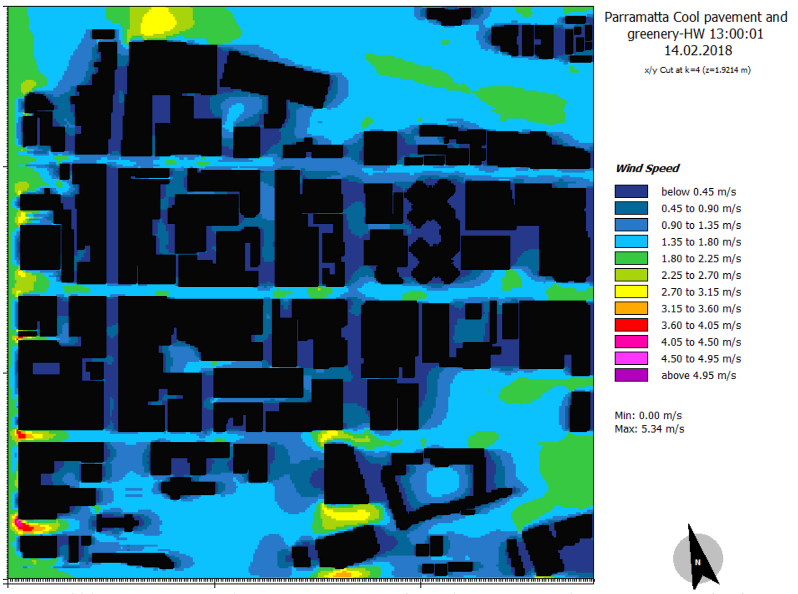


Figure 129. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 7, heatwave condition - 13:00

Figure 130 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates very strong heat stress with UTCI mostly ranging from 42°C to above 49°C during heatwave condition. UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street. As shown in **Error! Reference source not found.**, tree shading helps to reduce the heat stress for humans in urban areas where UTCI is mostly reduced to below 42-43°C. Thus, the most comfortable conditions can be found below the trees. They are providing shade and are hardly causing wind speed reductions at the pedestrian level. Other areas do not show improved comfort due to wind speed reductions by the trees.

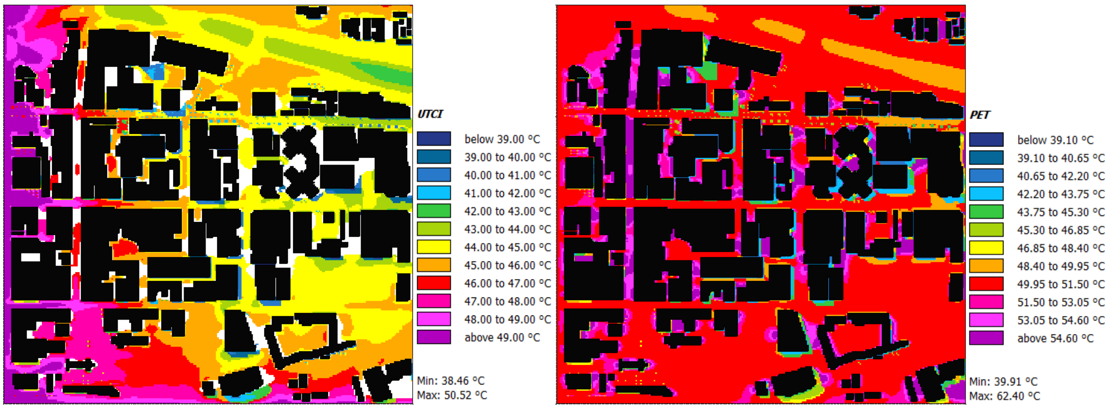


Figure 130. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 7, heatwave condition - 13:00: UTCI (left), PET (right)

Scenario 8

The ambient temperature ranges from 36°C to 43.1°C in Phillip Street where radiative cooling material is used (scenario 8). Same structure (surface area) as shading device (scenario 3) is implemented covering about 75% of the street. This approach maximises emission of infrared thermal radiation through the atmospheric window for releasing heat and minimises absorption of incoming atmospheric radiation. These simultaneous processes can lead to the shading device temperature substantially below the ambient temperature [13]. We have shown that shading with radiative cooling is an effecting strategy reducing the temperature by about 1.8°C compared to the reference scenario. The ambient temperature distribution map shows that the air temperature in Phillip Street is lower than the reference scenario where solar control with radiative cooling material was employed (Figure 131).

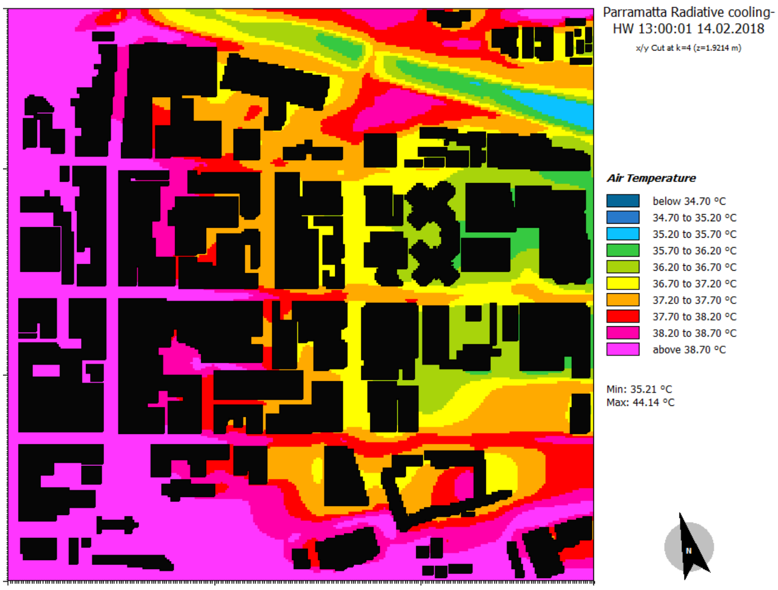


Figure 131. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 8, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 132) shows the temperature reduction where the radiative cooling technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the mitigated scenario in the same spot. Under the scenario 8, the maximum local temperature reduction is 1.8°C and the average is 0.4°C.

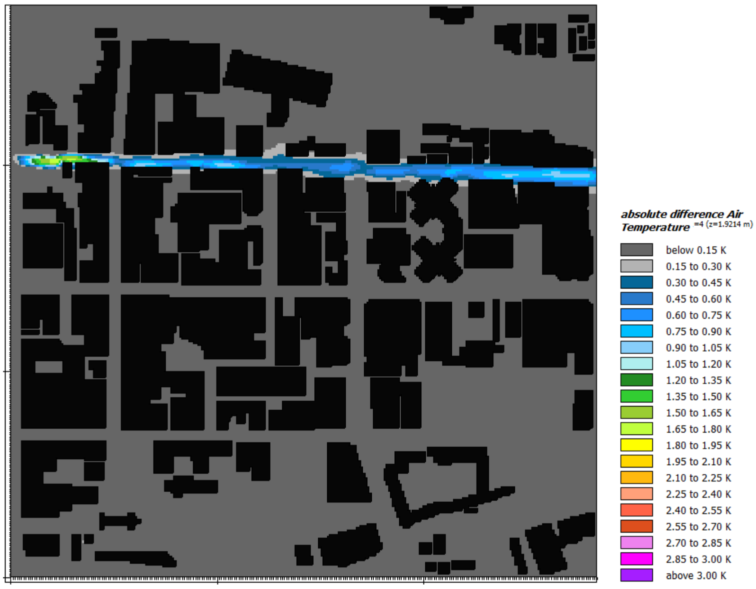


Figure 132. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 8, heatwave condition - 13:00

The surface temperature distribution is shown in Figure 133 when radiative cooling material was used for the shading device in Phillip Street. In Phillip Street, the surface temperature mostly falls below 37.5 °C under the shaded area (Figure 133). The surface temperature is significantly reduced in scenario 8 compared to the same spot in the reference scenario. The achieved surface temperature reduction varies from 8.4 °C to 19.6 °C under the shading device with radiative cooling and reaches to about 20 °C between Church and Marsden Streets.

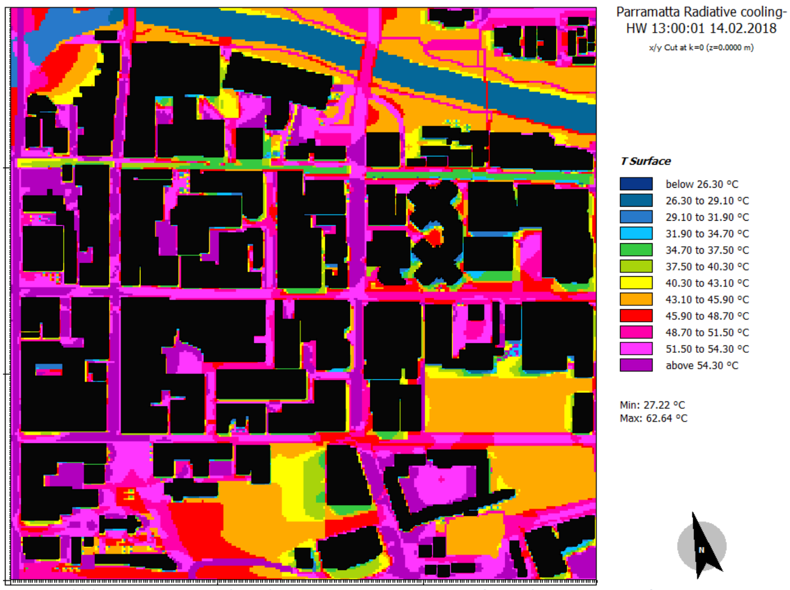


Figure 133. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 8, heatwave condition - 13:00

Figure 134 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5.3 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0.9 and about 2.2 m/s in Phillip Street. Due to the height of shading device, there was a small effect on the wind speed distribution at pedestrian level near the corner of Church Street and Smith street.

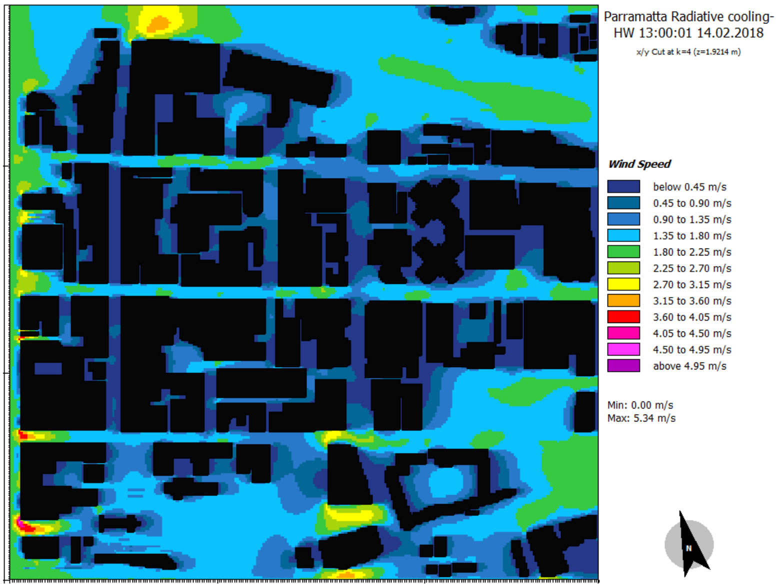


Figure 134. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 8, heatwave condition - 13:00

Figure 135 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates very strong heat stress with UTCI mostly ranging from about 39°C to above 49°C during heatwave condition. This can be compared with Phillip street (reference scenario) and Church street (existing condition) where UTCI falls above 46 °C. UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street. PET mostly varies between 39.1 °C and 48.4 °C under the shaded area (scenario 8), while the same spots fall above 50 °C in the reference scenario. Due to the effects of advection comfort level is also enhanced in the whole street; however, the effects are much higher under the shaded area.

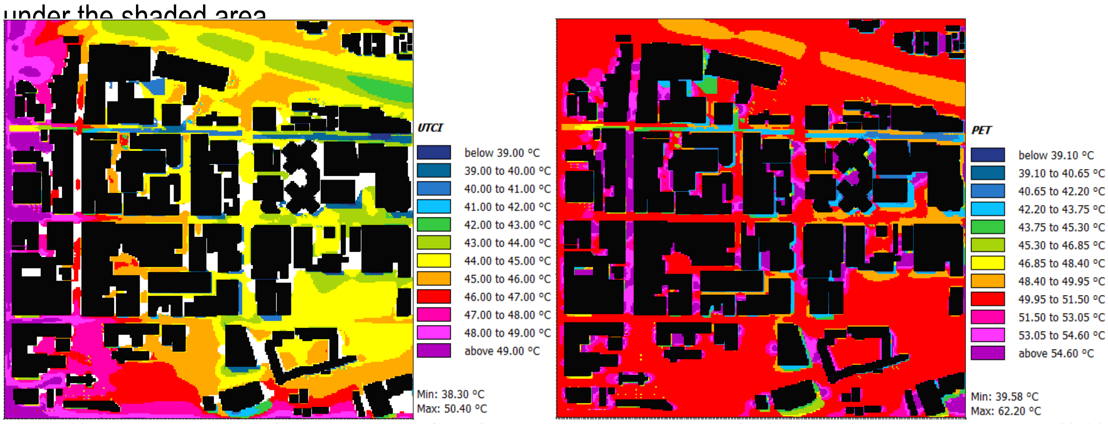


Figure 135. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 8, heatwave condition - 13:00: UTCI (left), PET (right)

Scenario 9

The air temperature ranges from 36.4 °C to 42.9 °C when we implemented the proposed trees and pavements by the City of Parramatta Council in Phillip Street (Figure 136). New trees were planted and proposed pavement materials with proper reflectivity were used in Phillip Street based on the Council implementation plan. The air temperature in Phillip Street is not significantly influenced by the City of Parramatta Council implementation plan. However, Phillip Street presents lower temperatures compared to the reference scenario where new trees were planted.

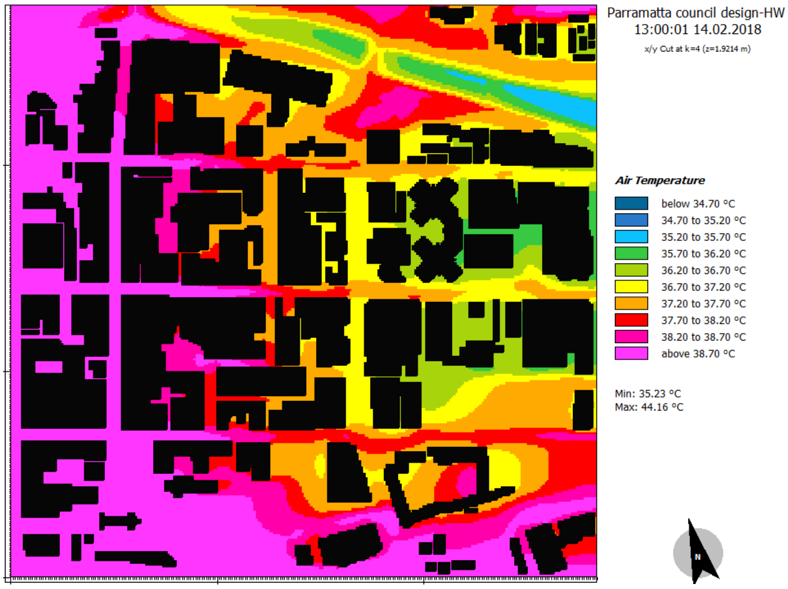


Figure 136. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 9, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 137) shows temperature reduction in the street where the implementation plan by the City of Parramatta Council is used. The local air temperature drop is defined as the temperature difference between the reference scenario and this scenario. The maximum and average local temperature reduction is about 0.6°C, and 0.14°C, respectively.

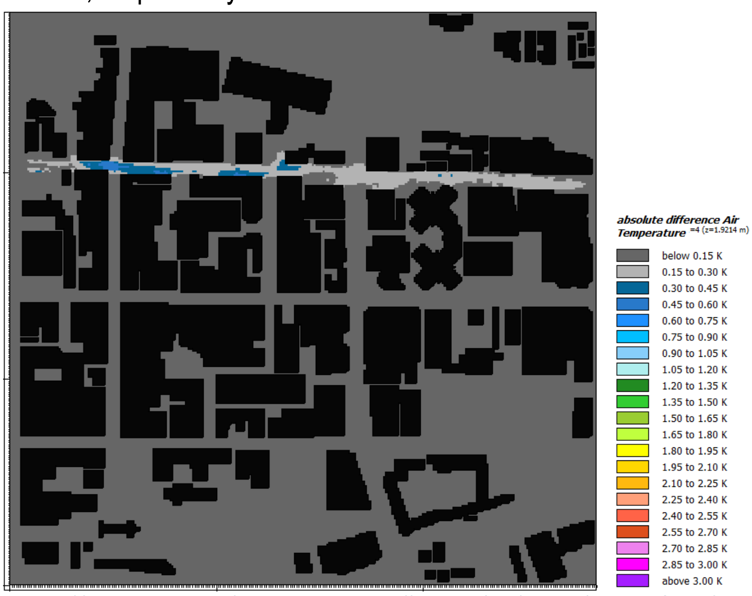


Figure 137. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 9, heatwave condition - 13:00

The surface temperature distribution is shown in Figure 138 when the City of Parramatta Council plan was implemented in Phillip Street. The surface temperature is significantly reduced where trees are planted compared to the same spot in the reference scenario. The surface temperature in Phillip street was reduced by about 20 °C in the areas shaded by the trees compared to the same areas in the reference scenario. The temperature of horizontal surfaces generally varies from 27.4 °C to 62.6 °C in the City of Parramatta CBD and mostly falls above 48.7 °C in Phillip Street.

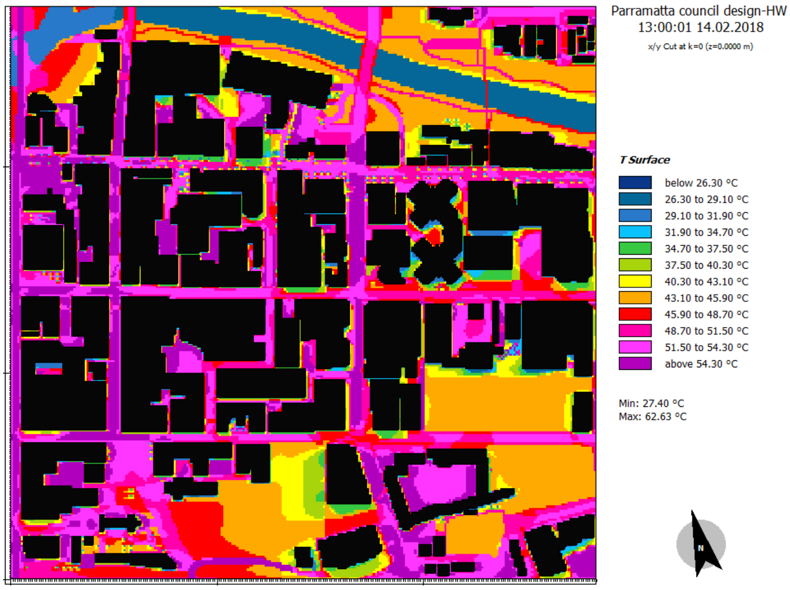


Figure 138. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 9, heatwave condition - 13:00

Figure 139 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5.3 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0.45 and about 2 m/s in Phillip Street. New trees reduce the wind speed at pedestrian level in Phillip Street.

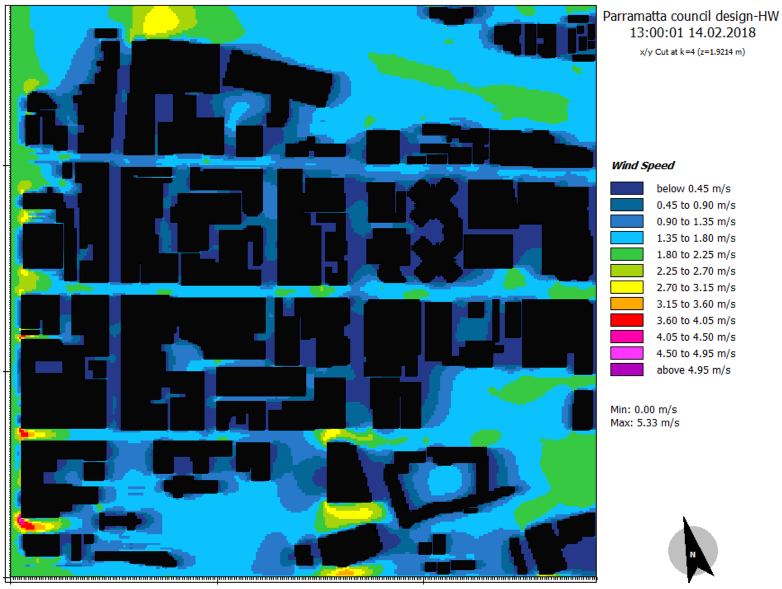


Figure 139. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 9, heat wave condition - 13:00

Figure 140 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates extreme heat stress with UTCI and PET mostly ranging above 43 °C and 48.4 °C, respectively, during heatwave condition (scenario 9). UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street. Planting 8 m Solkova trees helps to improve comfort condition locally. UTCI helps to reduce heat stress in the areas where trees were planted to a range of 38-42°C in eastern part of Phillip Street and between 43°C to 47°C in western part.

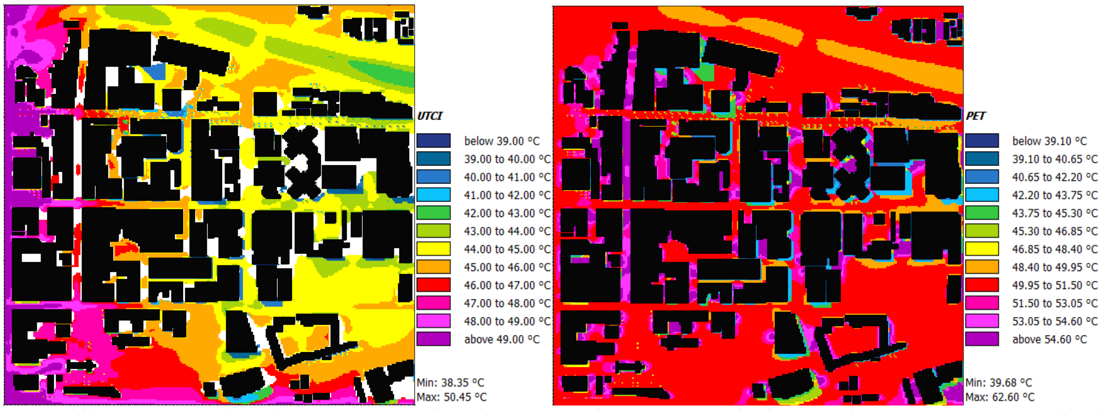


Figure 140. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 9, heatwave condition - 13:00: UTCI (left), PET (right)

Scenario 10

The air temperature ranges from 36.2 °C to 42.5 °C when we implemented Solkova trees proposed by the City of Parramatta Council and used cool material instead of Adelaide black and black asphalt in Phillip Street (Figure 141). By using cool pavement, areas between Church Street and Horwood Pl represent up to 1.2°C lower temperatures than the same locations in the City of Parramatta Council implementation plan.

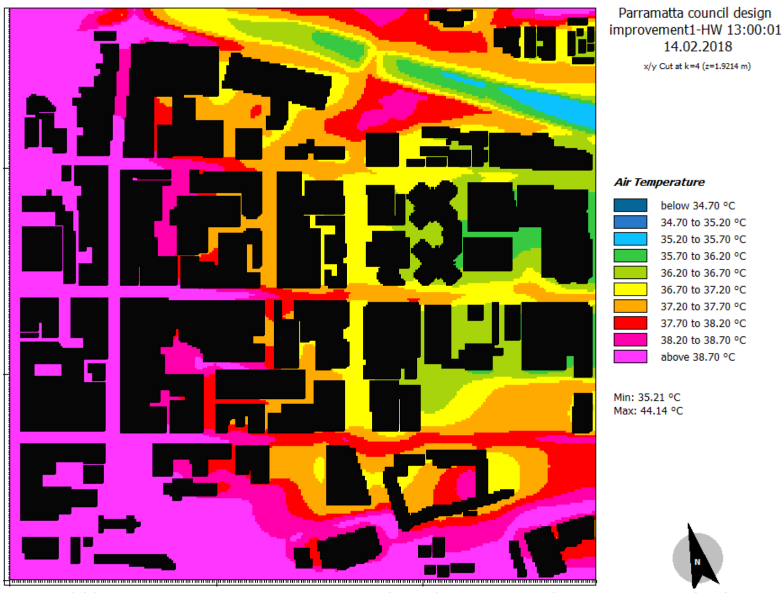


Figure 141. Temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 10, heatwave condition - 13:00

The ambient temperature difference distribution map (Figure 142) shows temperature reduction in Phillip street when cool pavements were used to improve the City of Parramatta Council implementation plan. The local air temperature drop is defined as the temperature difference between the reference scenario and this scenario in the same spot. Temperature difference distribution map shows temperature reduction in the street where cool pavements were implemented in addition to greenery in council implementation plan (scenario 9). The local temperature reduction reaches to 1.2°C and the average temperature reduction is 0.4°C.

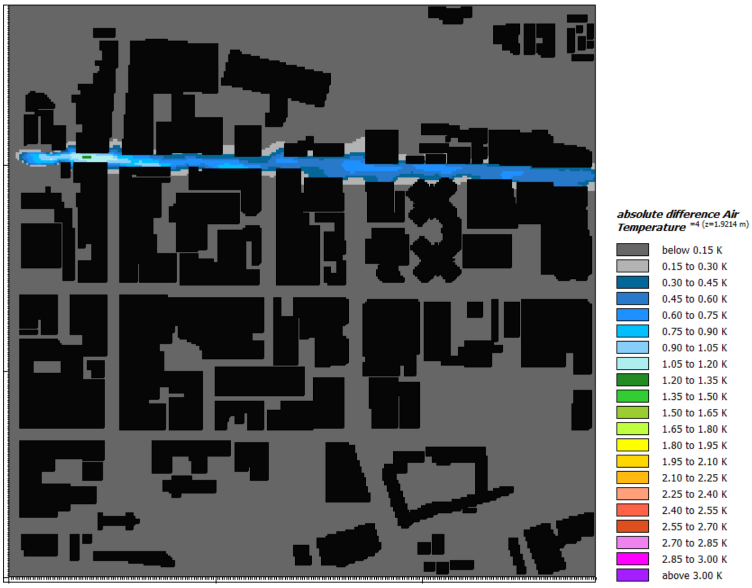


Figure 142. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 10, heatwave condition - 13:00

The surface temperature distribution is shown in Figure 143 when cool pavement was used to improve the City of Parramatta Council implementation plan. The surface temperature is significantly reduced in scenario 10 compared the reference scenario and the City of Parramatta Council implementation plan. The surface temperature mostly ranges between 43.1°C and 48.7°C in Phillip Street and falls below 26.3 °C in the areas shaded by Solkova trees.

Figure 143. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 10, heatwave condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 144 where the wind speed varies between 0 m/s and about 5.3 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed falls below 2.7 m/s in Phillip Street. New trees reduce the wind speed at pedestrian level in Phillip Street.

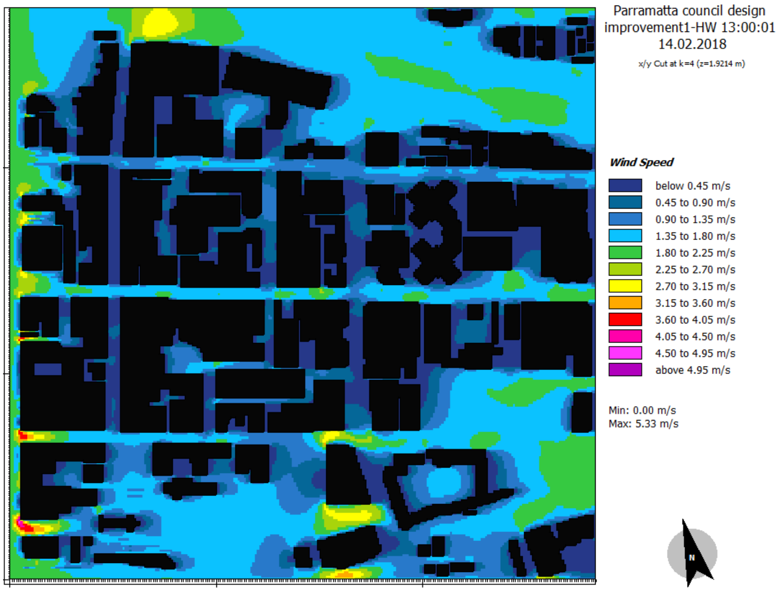


Figure 144. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 10, heat wave condition - 13:00

Figure 145 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates strong heat stress when UTCI and PET mostly fall above 42°C and 48.4 during heatwave condition, respectively. UTCI and PET distribution maps are consistent in presenting hot spots in Phillip Street. UTCI helps to reduce local heat stress in the areas where 8 m Solkova trees were planted to a range of 38-42°C in eastern part of Phillip Street and between 43°C to 47°C in western part. Trees are providing shade and are hardly causing wind speed reductions at the pedestrian level.

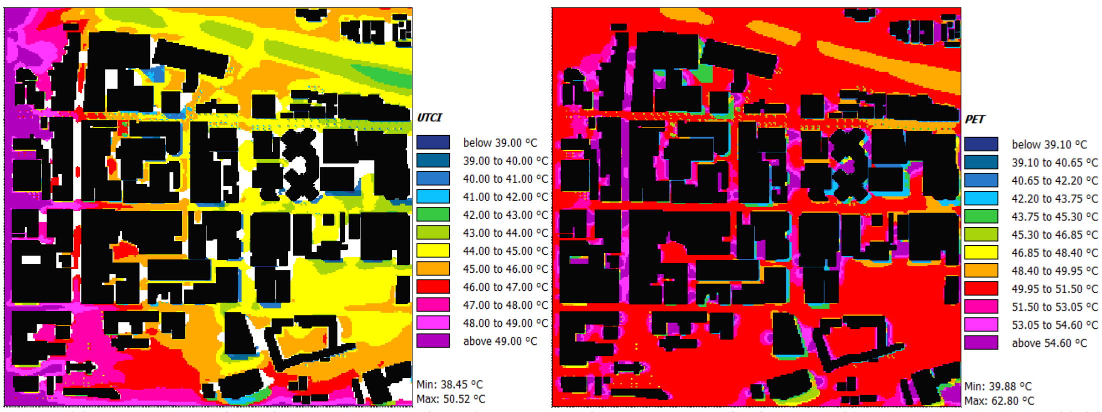


Figure 145. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 10, heatwave condition - 13:00: UTCI (left), PET (right)

Winter condition

Winter condition

The climatic input data for the winter condition was derived from Sydney Olympic Park AWS BoM station [8] (ID: 066212, Lat: -33.8338, Lon:151.0718, Height: 4 m above the sea level), located 6.5 Km from Parramatta CBD. In the winter condition, the initial wind speed considered in the simulations is 3 m/s, and wind direction is from north west. The minimum and maximum ambient temperatures of the simulation day are 6 °C and 18.9 °C, respectively.

Reference scenario

Reference scenario: existing condition

Scenario 0

The ambient temperature in Phillip Street, in the existing form, ranges from 14.9 °C to 18.2 °C during the winter condition. The temperature distribution map shows the area between Marsden Street and Horwood Pl and the corner of Smith Street represent warmer conditions than eastern side of Phillip Street (**Error! Reference source not found.**Figure146). The corner of Marsden Street reveals the warmest spot in Phillip Street exceeding 17.2 °C. Simulation results show the eastern part of the City of Parramatta CBD present cooler ambient temperatures than western areas.

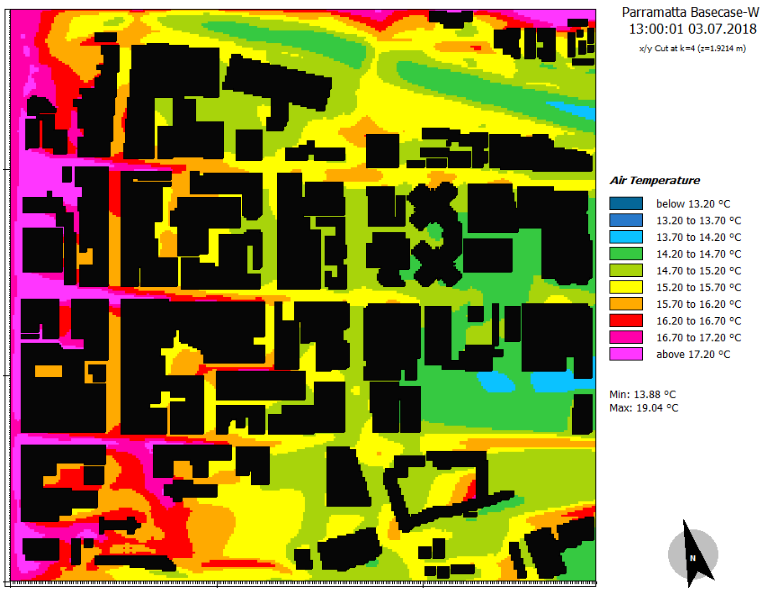


Figure 146. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 0, winter condition - 13:00

Figure 147 shows the surface temperature distribution in the City of Parramatta CBD and Phillip Street in the existing condition (reference scenario). The surface temperature reaches 34 °C in the City of Parramatta CBD. Parramatta river and surrounding areas illustrate lower surface temperatures below 17 °C. The surface temperature in Phillip Street mainly ranges between 14.1 °C and 28.1 °C. Corner of Marsden Street, Church Street, and Smith Street in Phillip Street present higher surface temperatures than other parts of the street.

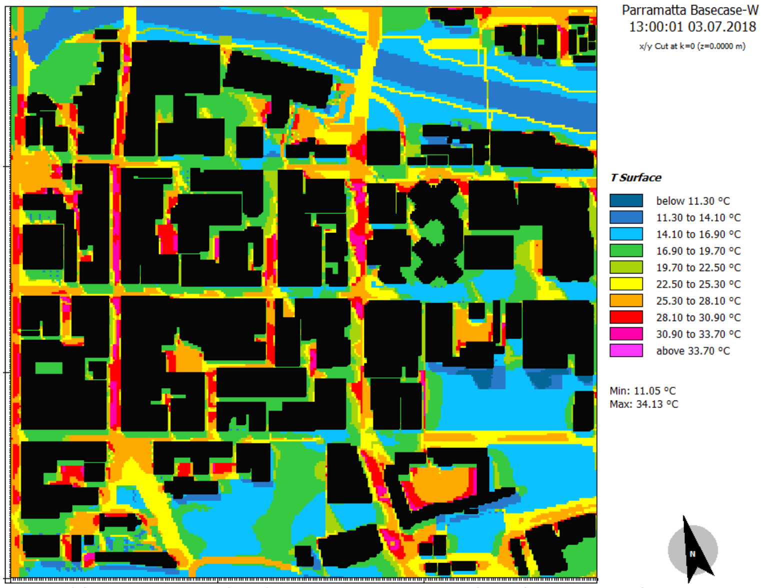


Figure 147. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 0, winter condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 148. As presented, wind speed varies between 0 m/s and about 5.6 m/s in the CBD. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed falls below 2.25 m/s in Phillip Street. The areas between Smith Street and Charles Street illustrate lower wind speed values mostly below 1.8 m/s. The western part of Phillip street and the areas between Church Street and Horwood Pl presents higher wind speeds which affects advection mechanism in that area.

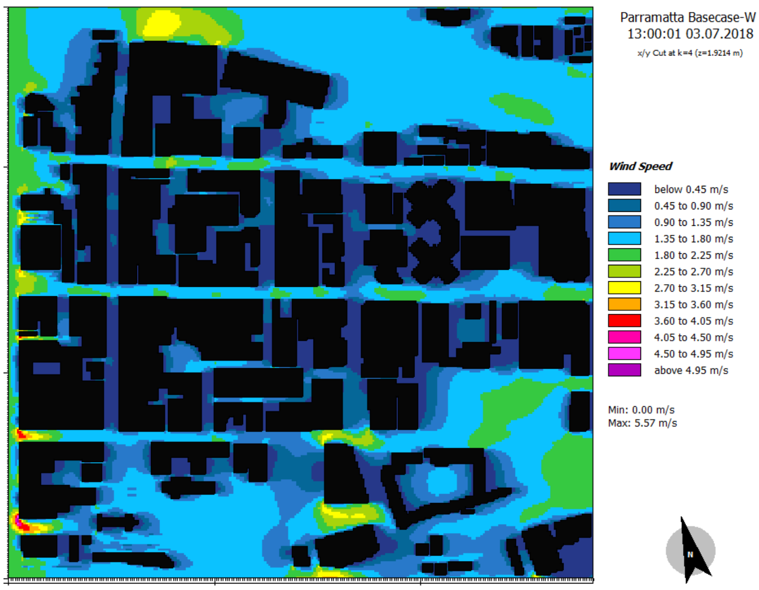


Figure 148. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 0, winter condition - 13:00

We performed analysis of comfort in the Parramatta CBD using different comfort indices. Figure 149 provides the distribution of comfort indices (i.e. UTCI and PET). This analysis shows the City of Parramatta CBD and Phillip Street experience no heat stress during winter condition. The Universal Thermal Climate Index (UTCI) mostly falls below 14.65 °C between Church Street and

Horwood Pl and areas between Smith Street and Charles Street. UTCI in the other parts of Phillip Street mainly varies between 24.9 and 27.4 °C. UTCI as used in the software is limited to a wind speed range of 0.5 to 17 m/s at 10 m Height. Thus, the areas with very low wind speed below 0.5 m/s have no calculated data and presented in white colour. PET is consistent with UTCI indicating areas with no heat stress and areas out of comfort range. It mostly varies from about 22.3 °C to 27.4 °C in Phillip street and falls below 14.65 °C between Church Street and Horwood Pl.

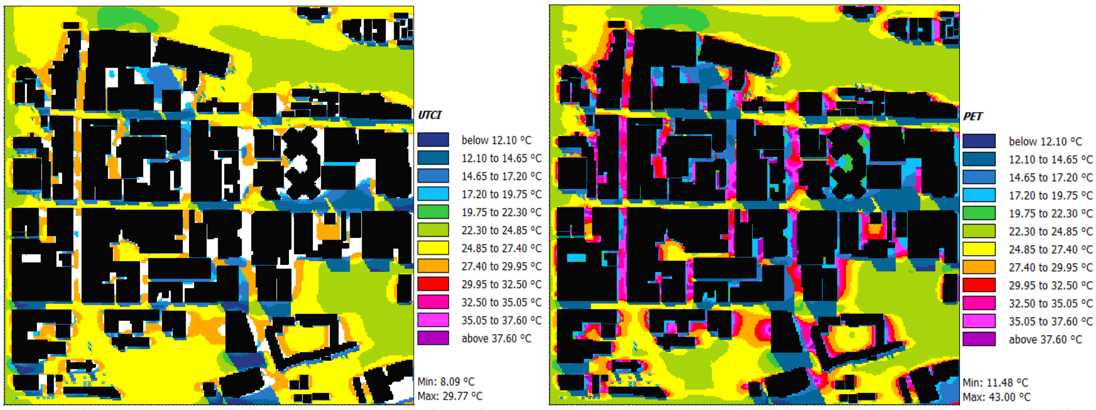


Figure 149. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 0, winter condition - 13:00: UTCI (left), PET (right)

Future scenarios

Future scenarios: future development

Scenario 00

Temperature in Phillip Street under future development plan (planned height), ranges from 14.8°C to 17.3°C during the winter condition. The temperature distribution map shows the area between Marsden Street and Church represents and the corner of Smith street warmer conditions than other parts of Phillip Street (Figure 150). The corner of Marsden Street and Phillip reveal the warmest spots in Phillip Street exceeding 17.2 °C. Future building height and form affect the wind speed and solar access where new buildings are implemented.

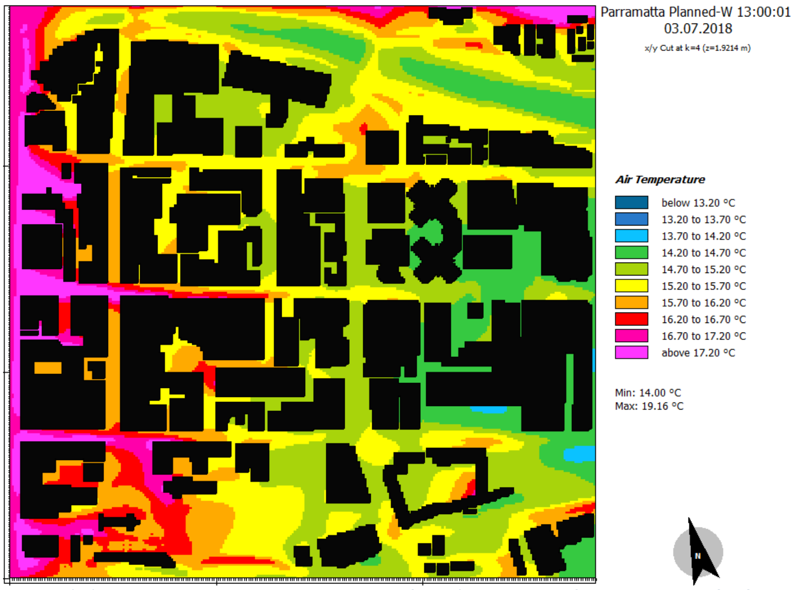


Figure 150. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 00, winter condition - 13:00

The ambient temperature difference distribution map (Figure 151) shows temperature reduction in the street when new buildings were added, or height was changed. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and this scenario in the same spot. Due to the advection and shading provided by new buildings, areas close to new development have lower temperatures compared to the unmitigated scenario. The maximum temperature reduction under this scenario is 2 °C.

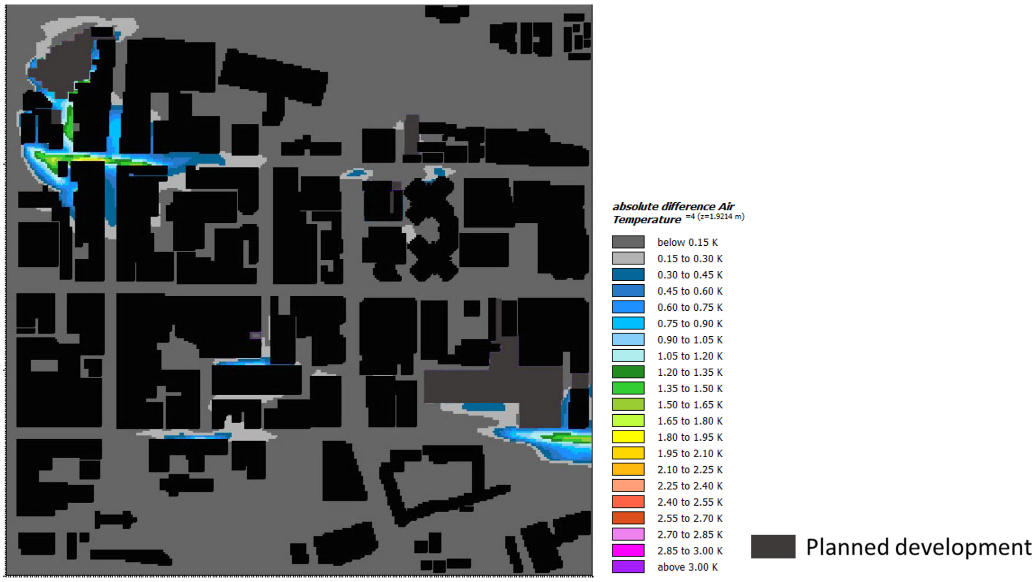


Figure 151. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 00, winter condition - 13:00

Figure 152 illustrates the surface temperature distribution considering planned development (scenario 00). The surface temperature reaches 34 °C in the City of Parramatta CBD. Phillip street shows lower surface temperatures compared to the reference scenario (scenario 0) because of the shading provided by new high-rise buildings. This is more apparent in the area between Marsden street and Horwood Pl. The maximum surface temperature is observed in the corner of Phillip Street and Smith Street which exceeds 25.3 °C.

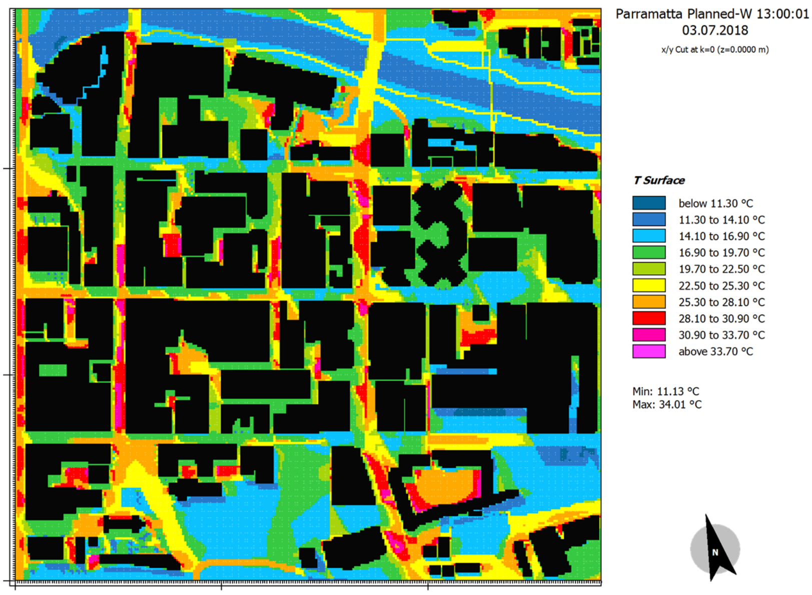


Figure 152. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 00, winter condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 153. As presented, wind speed varies between 0 m/s and about 5.6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed exceeds 3.6 m/s in western part of Phillip Street where new high-rise buildings were implemented. The corner of Marsden Street, Horwood Pl, Smith Street, and Church Street illustrate higher wind speed values than other part of Phillip Street. The wind speed distribution pattern affects advection mechanism in Phillip street.

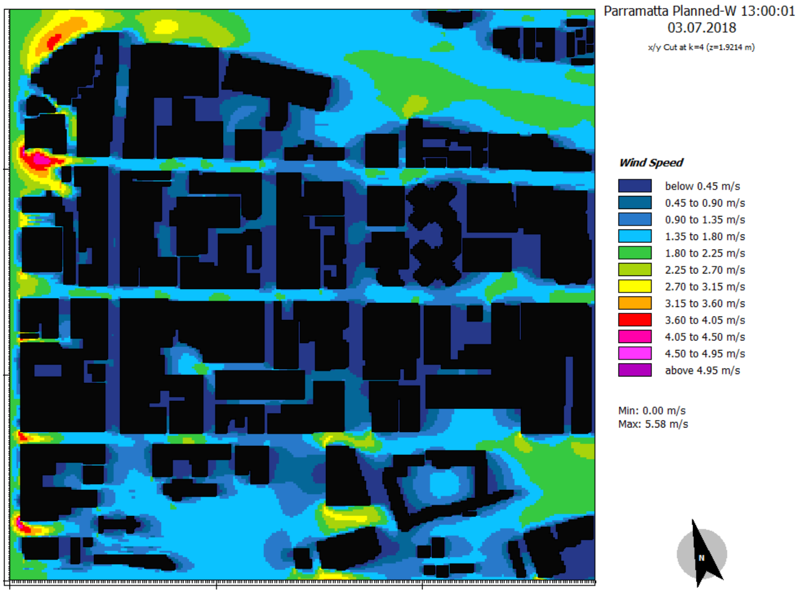


Figure 153. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 00, winter condition - 13:00

Figure 154 provides the distribution of comfort indices (i.e. UTCI and PET). Phillip Street in general indicates no heat stress during winter. This analysis shows thermal comfort is affected in the western side of Phillip street (areas around Church Street and Marsden Street) which is explained by the effects of shading and changes in wind speed due to new high-rise buildings. The Universal Thermal Climate Index (UTCI) is ranging from 6°C to 29°C in Phillip street during winter condition under this scenario. The corner of Smith Street is presenting warmer than othe areas during the winter condition. PET distribution is consistent with that of UTCI.

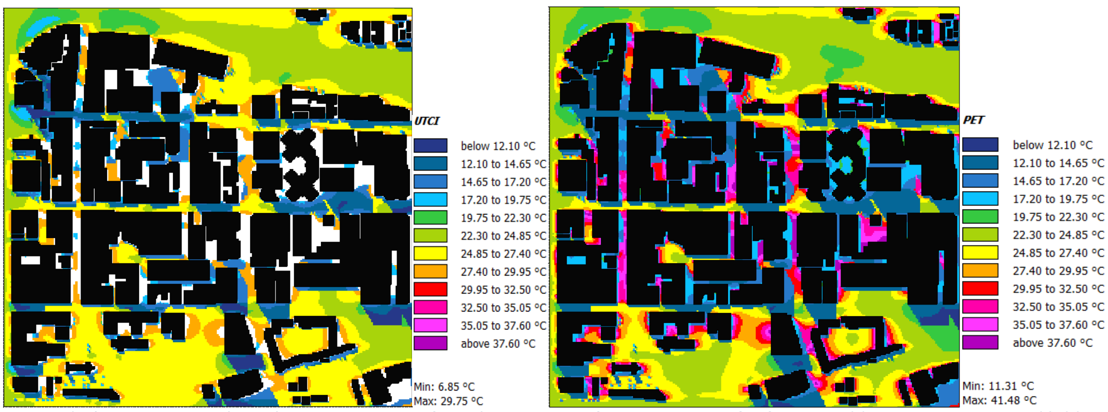


Figure 154. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 00, winter condition - 13:00: UTCI (left), PET (right)

Scenario 000

The ambient temperature ranges from 14.8 °C to 16.8 °C in Phillip Street when development plan is considered together with hypothetical future building height and density in the central part of the City of Parramatta CBD. Implementing future building height and form highly affect the wind speed, solar access and pattern of temperature distribution. The temperature distribution map shows the area between Marsden Street and Horwood Pl in Phillip street represents warmer conditions than eastern side of Phillip Street (Figure 155) with temperatures exceeding 15.7 °C.

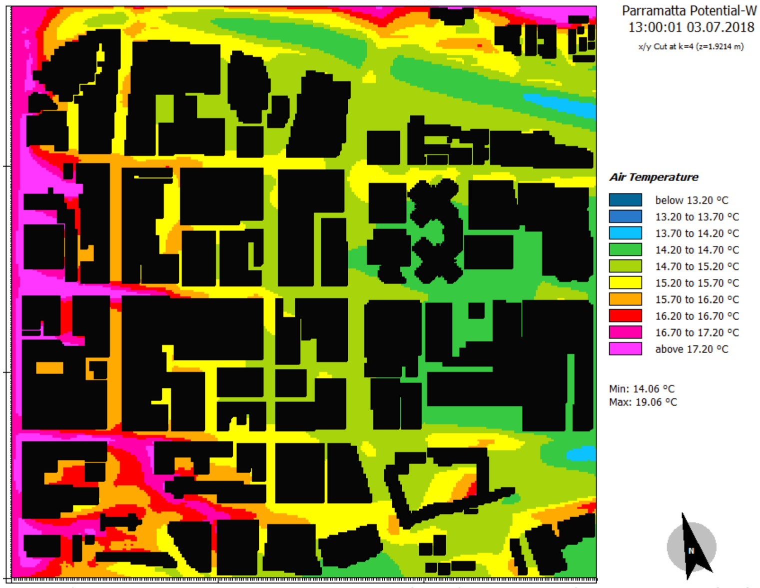


Figure 155. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 000, winter condition - 13:00

Figure 156 shows the temperature difference between the future scenario and the reference one in the same spot. Changes in wind speed distribution and shading provided by new buildings lead to lower temperatures (up to about 2 °C) in areas nearby new development compared to unmitigated scenario.

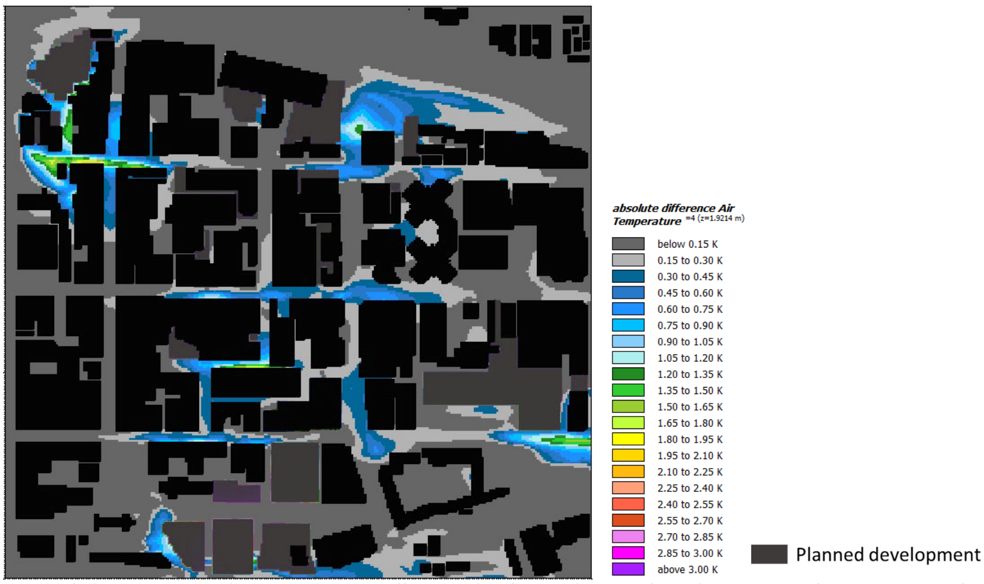


Figure 156. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 000, winter condition - 13:00

The surface temperature distribution in the City of Parramatta CBD is shown in Figure 157 considering new development with maximum building height and density (scenario 000). The surface temperature reaches 33.8 °C in the City of Parramatta CBD. Areas shaded by new high-rise buildings show lower surface temperatures compared to the existing condition (ranging between 14.1 °C and 19.2 °C). The surface temperature in the corner of Phillip Street and Smith Street exceed 25.3°C and presents the highest surface temperature in Phillip Street when potential building height was considered during winter.

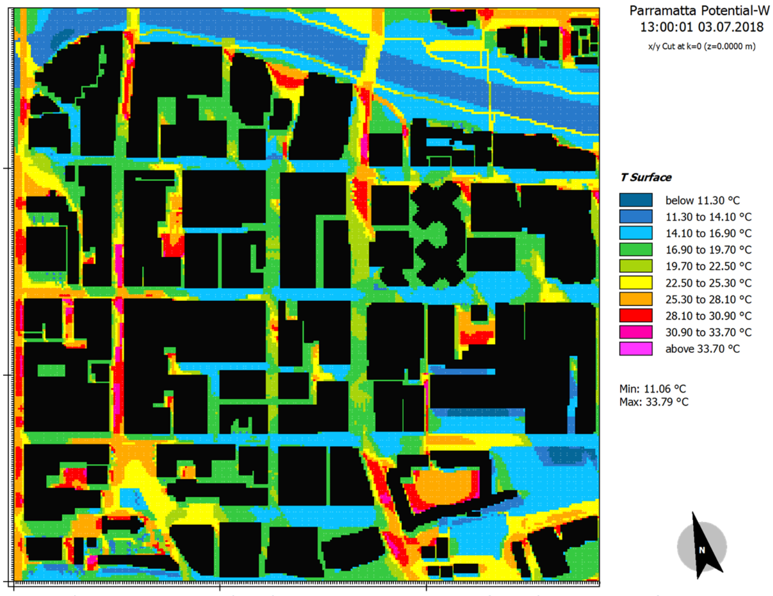


Figure 157. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 000, winter condition - 13:00

As presented in Figure 158, wind speed reaches to about 6 m/s in Parramatta CBD. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed exceeds 4m/s in north western part of Phillip Street where new high-rise buildings were implemented. The eastern part of Smith Street illustrates slightly lower wind speed values compared to the western parts.

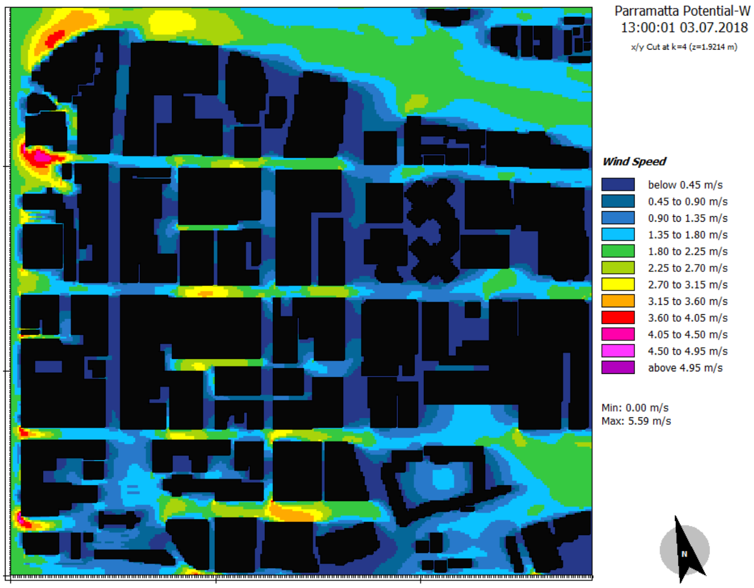


Figure 158. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 000, winter condition - 13:00

Figure 159 shows the distribution of comfort indices (i.e. UTCI and PET). Phillip Street in general indicates no heat stress. The Universal Thermal Climate Index (UTCI) and PET mostly fall below 14.65°C in Phillip street during winter condition under potential building height scenario. The corner of Smith Street and Phillip street is presenting warmer condition during winter compared to other parts of Phillip Street.

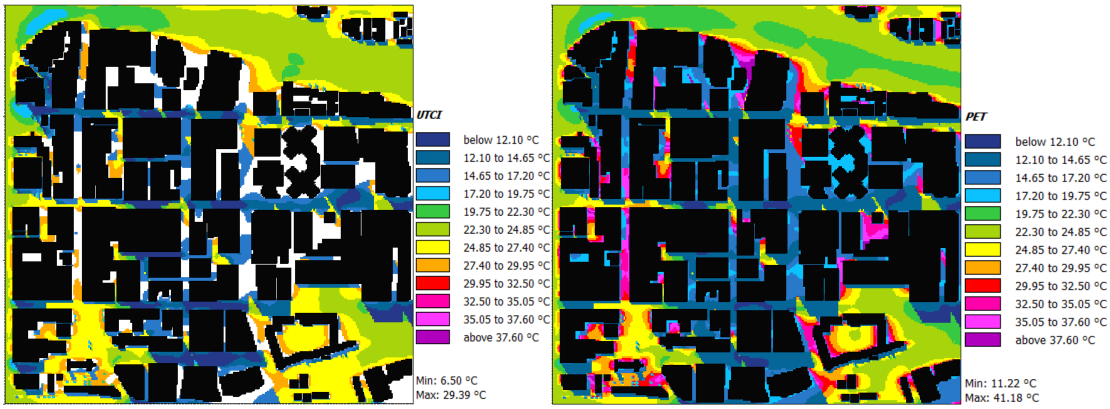


Figure 159. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 000, winter condition - 13:00: UTCI (left), PET (right)

Mitigation scenarios

Mitigation scenarios

The ambient temperature ranges from 14.8 °C to 17.9 °C in Phillip Street when cool pavement is implemented (scenario 1). Cool pavement is used in the whole Phillip Street and the car park located at the corner of Marsden Street. Despite higher ambient temperatures in western part of Phillip Street, the air temperature distribution map (Figure 160) shows that air temperature in Phillip Street is slightly reduced by the use of cool pavement compared to the reference scenario (scenario 0).

Scenario 1

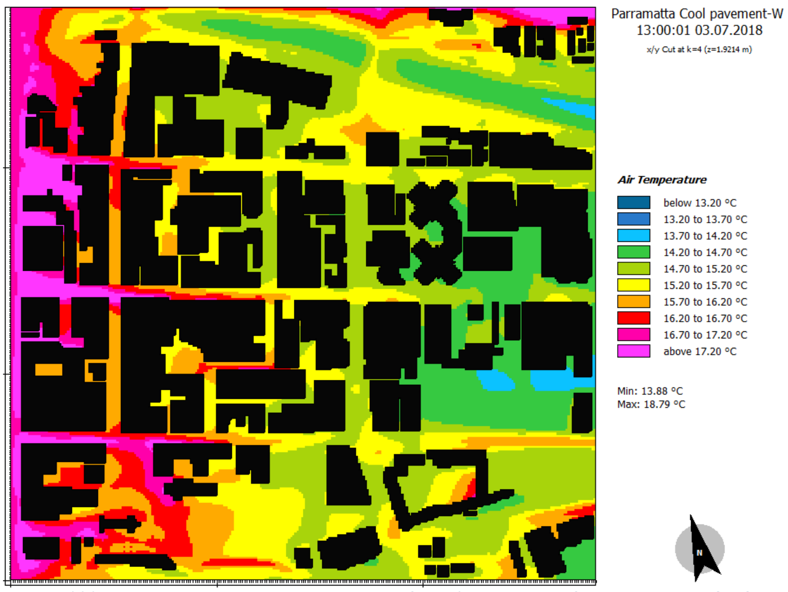


Figure 160. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 1, winter condition - 13:00

The ambient temperature difference distribution map (Figure 161) shows temperature reduction in the street where mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the cool pavement scenario in the same spot. As shown in Figure below, the local temperature reduction ranges from 0 to 0.8°C and the average temperature reduction in the whole Phillip Street is 0.2°C.

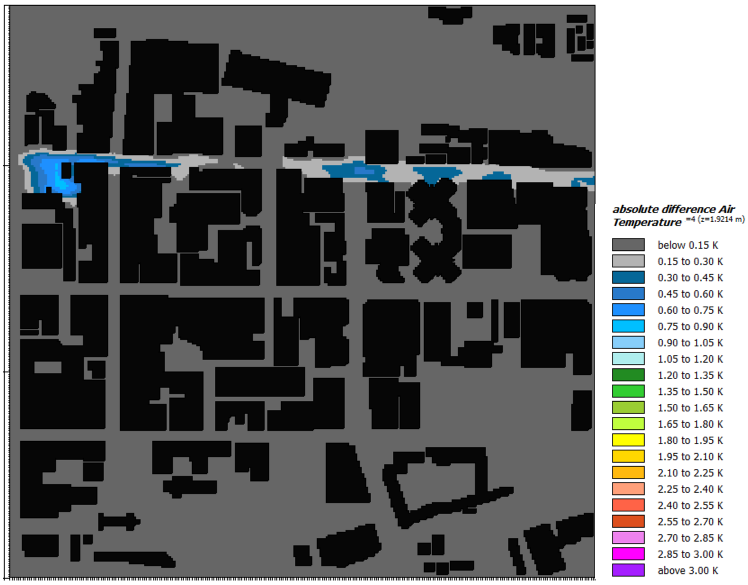


Figure 161. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 1, winter condition - 13:00

The surface temperature distribution is shown in Figure 162 when cool pavement is implemented in Phillip Street. The surface temperature is reduced in scenario 1 compared to that in the reference scenario. The temperature of horizontal surfaces varies from 14.1°C to 25.3 °C in Phillip Street while it reaches to about 34 °C in the City of Parramatta CBD. The surface temperature ranges between 14.1°C and 22.5°C in most parts of Phillip Streets.

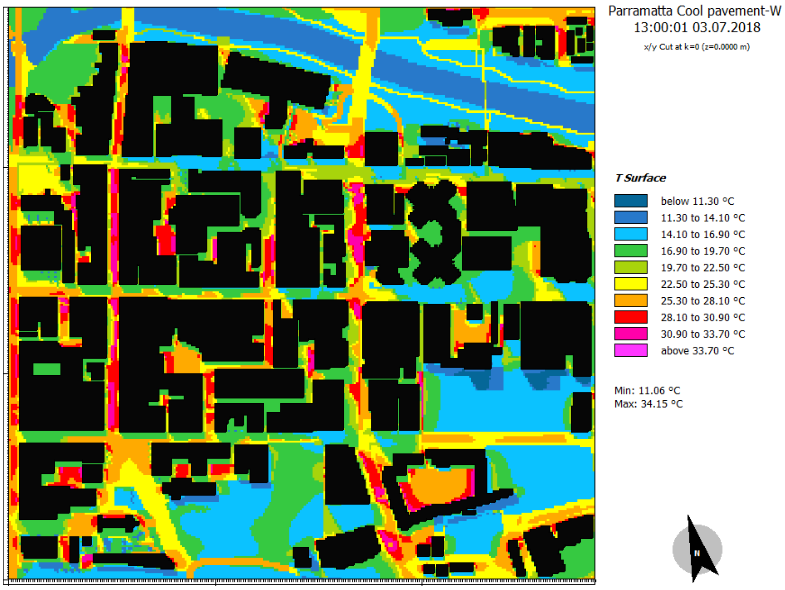


Figure 162. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 1, winter condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 163. As presented, wind speed varies between 0 m/s and about 5.6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed mostly ranges between 0.45 and about 2.25 m/s in Phillip Street. The corner of Marsden street and the areas between Church Street and Horwood Pl presents slightly higher wind speeds than other areas which affects advection mechanism in the street. Since there was no change in physical configuration of the model, wind speed is the same as reference scenario.

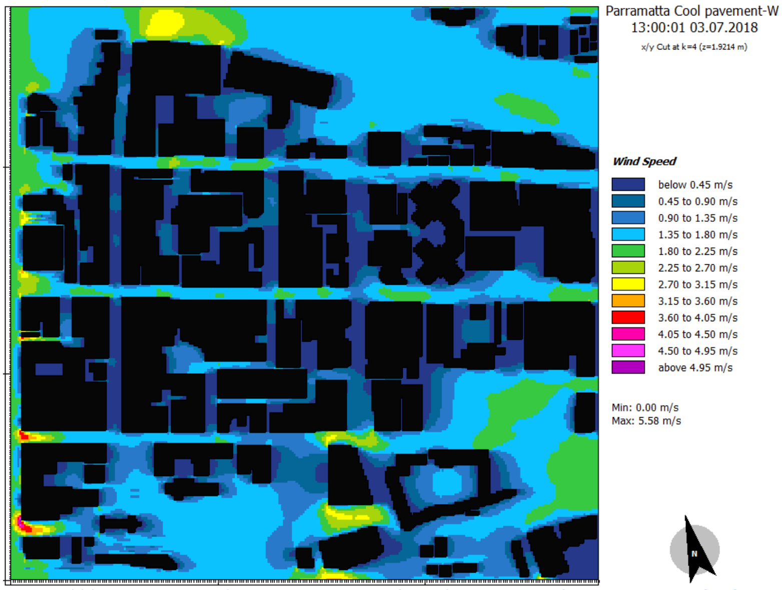


Figure 163. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 1, winter condition - 13:00

Figure 164 shows the distribution of comfort indices (i.e. UTCI and PET). Phillip Street in general indicates no heat stress during winter. UTCI and PET mostly falls below 27.4°C in Phillip street during winter condition under cool pavement scenario. The areas near Church Street and Smith Street present warmer thermal conditions.

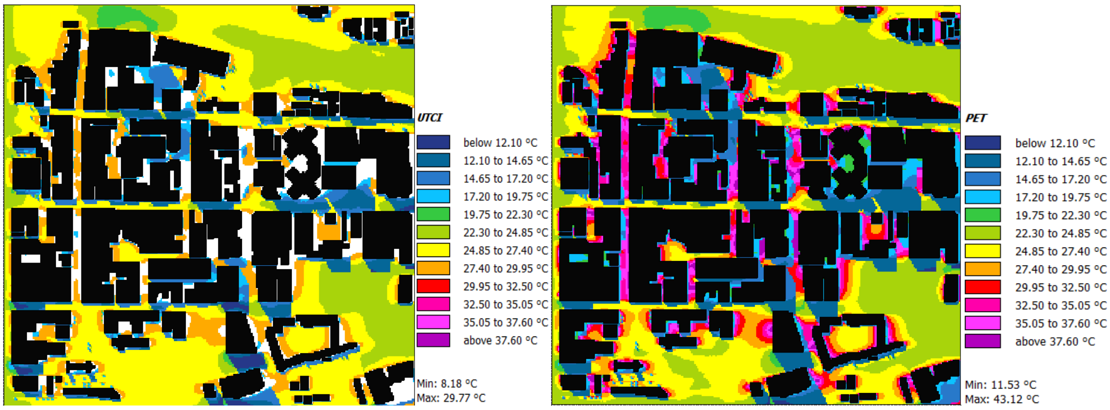


Figure 164. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 1, winter condition - 13:00: UTCI (left), PET (right)

Scenario 2

The ambient temperature ranges from 14.9 °C to 17.8 °C in Phillip Street when 82 irrigated trees and greenery were implemented (scenario 2). New mature irrigated trees (both deciduous and evergreen) were planted in the whole Phillip Street. The ambient temperature distribution map shows that air temperature in Phillip Street is very similar to that in the reference (Figure 165).

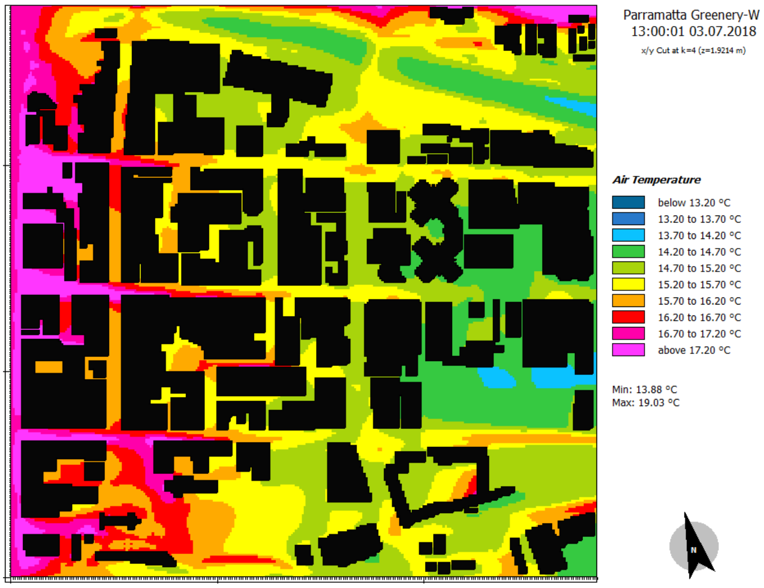


Figure 165. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 2, winter condition - 13:00

The ambient temperature difference distribution map (Figure 166) shows temperature reduction in the street where the mitigation technology is implemented. The local air temperature drop is defined as the temperature difference between the reference scenario and the greenery scenario in the same spot. Temperature difference distribution map shows the local temperature reduction in Phillip street near planted trees. The maximum and average local temperature reduction is about 0.6°C and 0.1 in scenario 2, respectively.

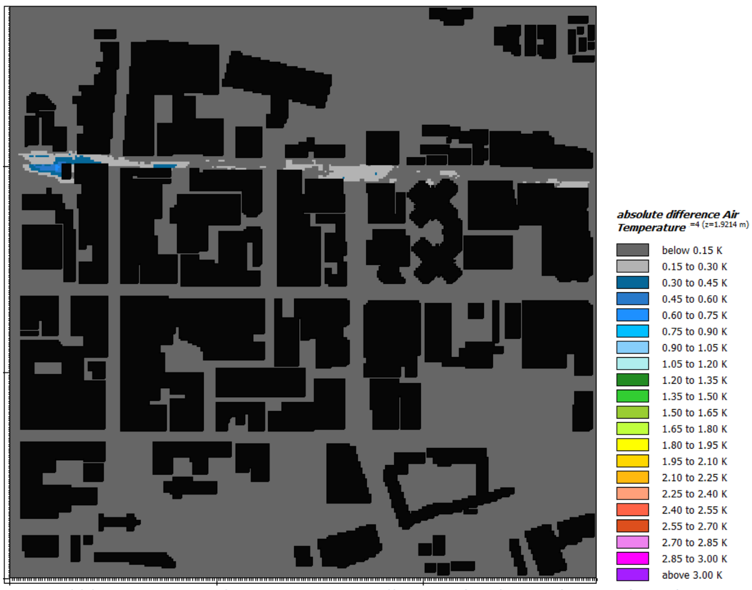


Figure 166. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 2, winter condition - 13:00

The surface temperature distribution is shown in Figure 167 when 82 mature trees (mostly 6m high, both evergreen and deciduous) were planted and raingarden was implemented in Phillip street. The surface temperature is reduced in scenario 2 where trees are planted compared to the same spot in the reference scenario. The surface temperature in Phillip street was reduced in the areas shaded by the trees, and where raingarden was implemented (mostly falling below 16.9°C). The temperature of horizontal surfaces generally varies from 10.6 °C to 34.1 °C in the City of Parramatta CBD.

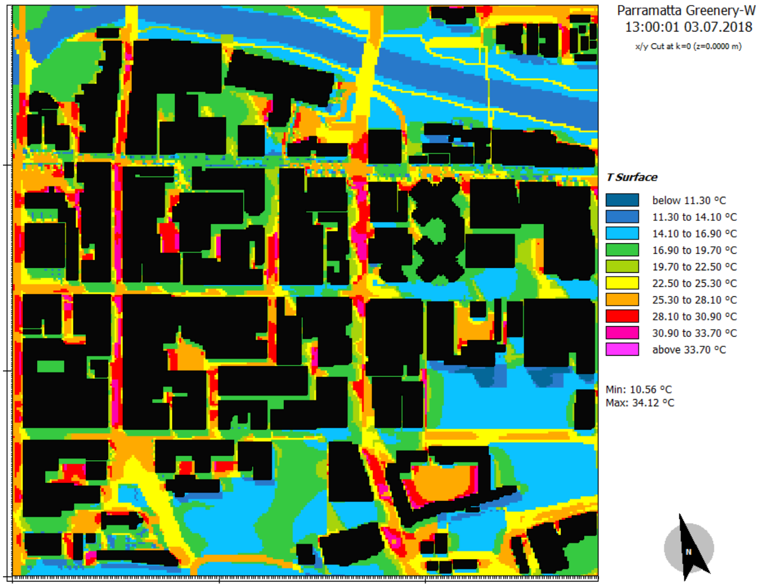


Figure 167. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 2, winter condition - 13:00

The wind speed distribution (Figure 168) shows wind speed varies between 0 m/s and about 5.6 m/s in the City of Parramatta CBD. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 1.8 m/s in Phillip Street. Wind speed is lower where trees were planted compared to the same spots in the reference scenario.

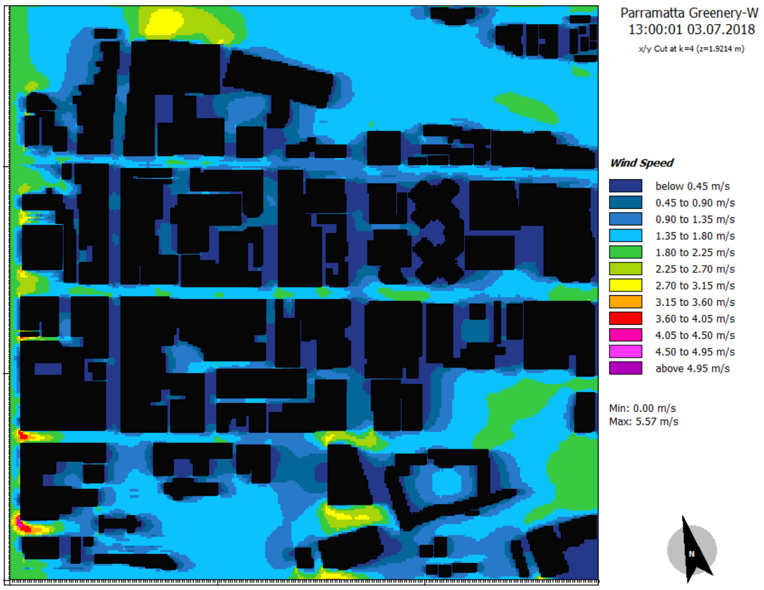


Figure 168. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 2, winter condition - 13:00

Figure 169 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip St. in general indicates no heat stress under scenario 2 during winter condition. However, under the shades from the trees, UTCI and PET mostly fall below 17.2 C°. UTCI and PET distribution maps are consistent indicating the local cooling effects of trees in Phillip Street.

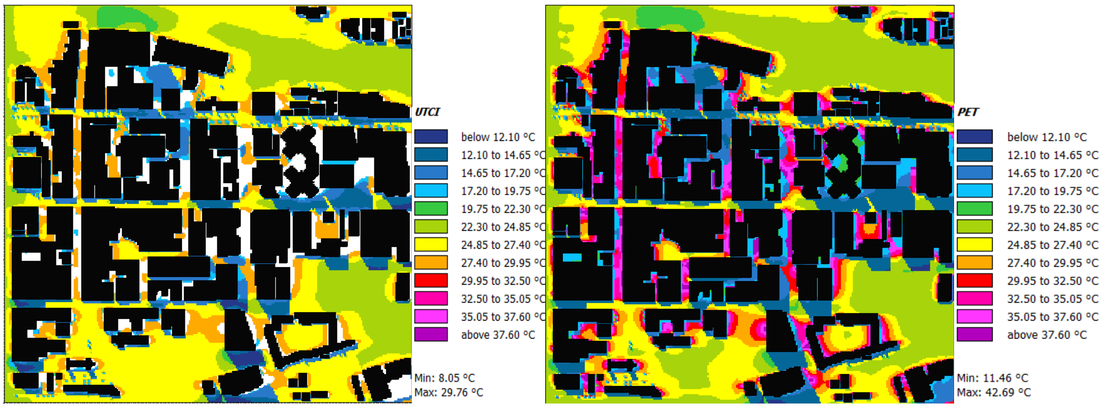


Figure 169. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 2, winter condition - 13:00: UTCI (left), PET (right)

Scenario 3

The ambient temperature ranges from 14.7 °C to 18.3 °C in Phillip Street when shading cloth was used to cover 75% of the street (scenario 3). We have shown that shading is reducing the temperature by a maximum of 1.1 °C compared to the reference scenario during winter. The ambient temperature distribution map shows that the air temperature in Phillip Street is slightly lower than the reference scenario where solar control was employed (Figure 170).

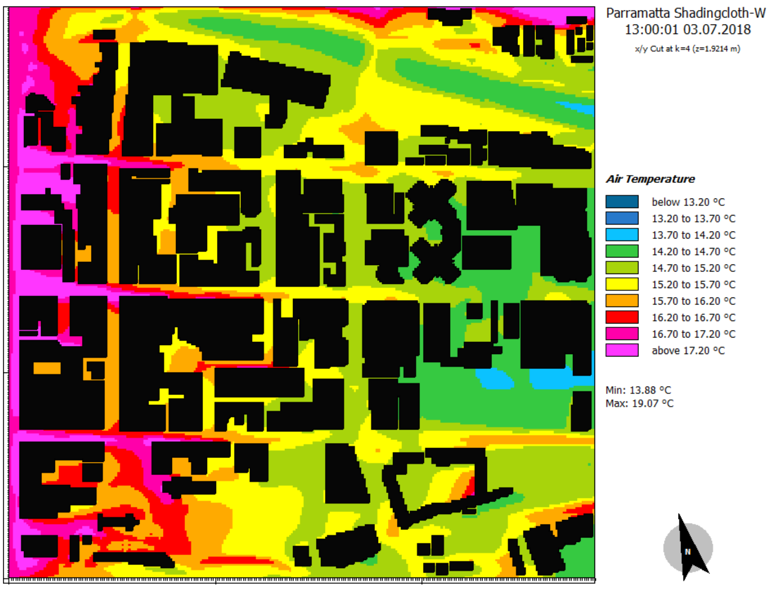


Figure 170. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 3, winter condition - 13:00

The ambient temperature difference distribution map (Figure 171) shows temperature reduction in the street where the mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the shading scenario in the same spot. Temperature difference distribution map shows the local temperature reduction in Phillip street where shading cloth was used. The maximum local temperature reduction is 1.1 °C and the average is 0.1 °C. Due to the effects of advection, surrounding areas also have lower temperatures compared to unmitigated scenario. As shown, use of solar control device has negligible effect in the area between Church Street and Horwood Pl.

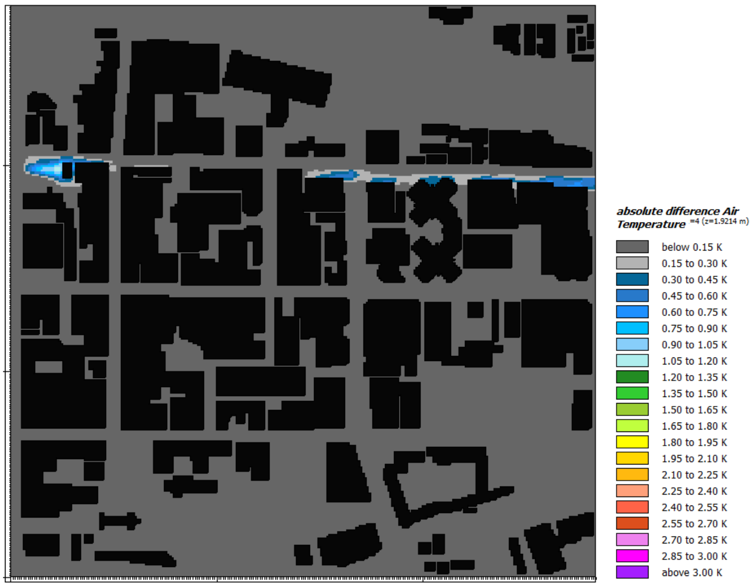


Figure 171. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 3, winter condition - 13:00

The surface temperature distribution is shown in Figure 172 when solar control devices were used in Phillip Street. The surface temperature is significantly reduced in scenario 3 compared to the same spot in the reference scenario. The surface temperature in Phillip street mostly varies between 14.1°C and 28.1 °C. The surface temperature ranges from 11.0 °C to 34.0 °C in the City of Parramatta CBD.

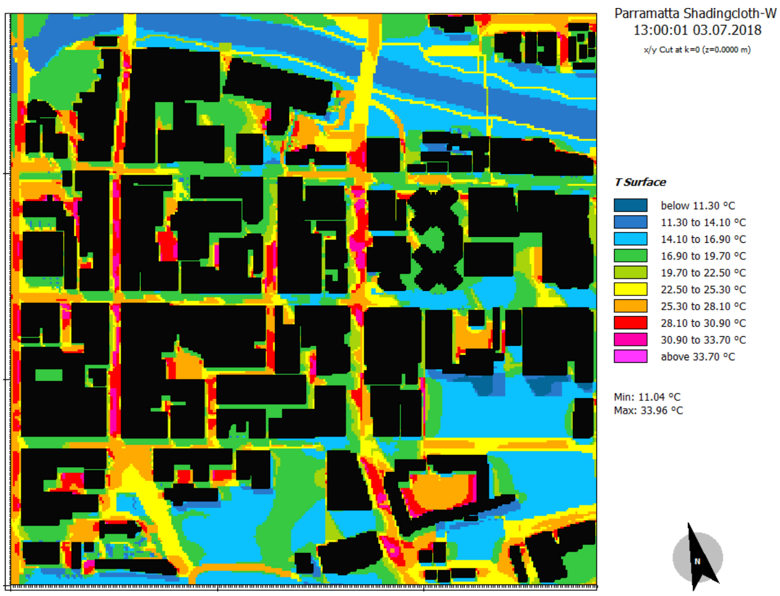


Figure 172. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 3, winter condition - 13:00

Figure 173 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5.6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 and about 2.2 m/s in Phillip Street. Due to the height of shading device, there was a small effect on the wind speed distribution at pedestrian level.

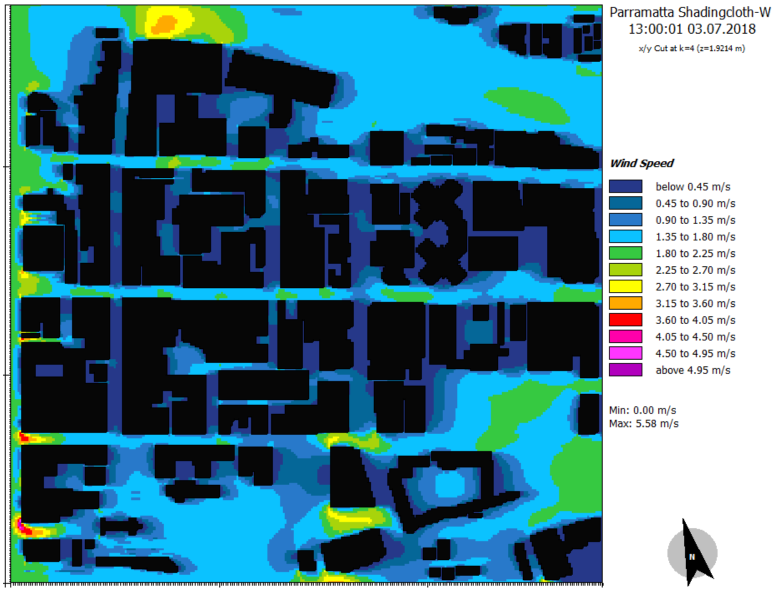


Figure 173. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 3, winter condition - 13:00

Figure 174 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates no heat stress under scenario 3 with UTCI and PET falling below 27.4 °C during winter condition, respectively. Results show that pedestrian in urban areas may feel slightly cooler in the eastern part of Phillip Street when shading is used.

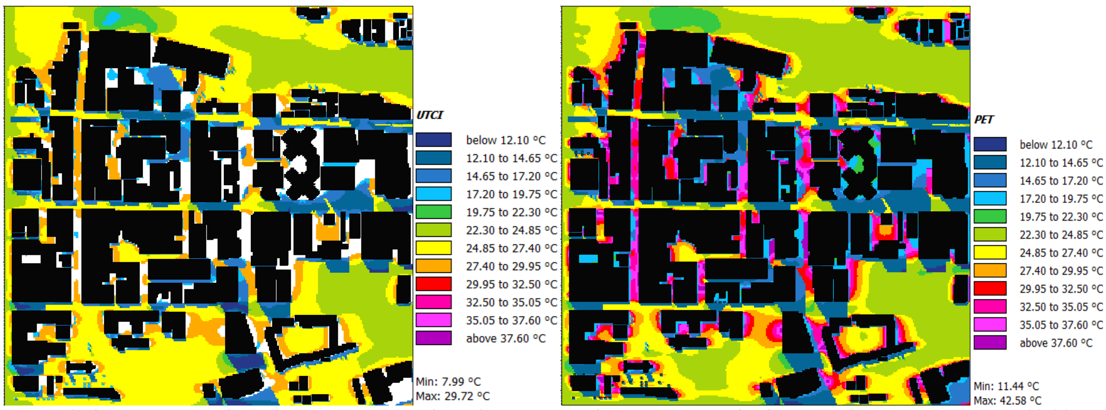


Figure 174. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 3, winter condition - 13:00: UTCI (left), PET (right)

Scenario 4

The ambient temperature ranges from 13.4 °C to 16.6 °C in Phillip Street when we used 22 evaporative cooling systems with the height of 4m (scenario 3). Misting system is reducing the temperature by a maximum of 3.9 °C during winter. The ambient temperature distribution map shows that air temperature in Phillip Street is lower than the reference scenario where misting systems were used (Figure 175). The is more apparent in the area between Marsden street and Horwood Pl.

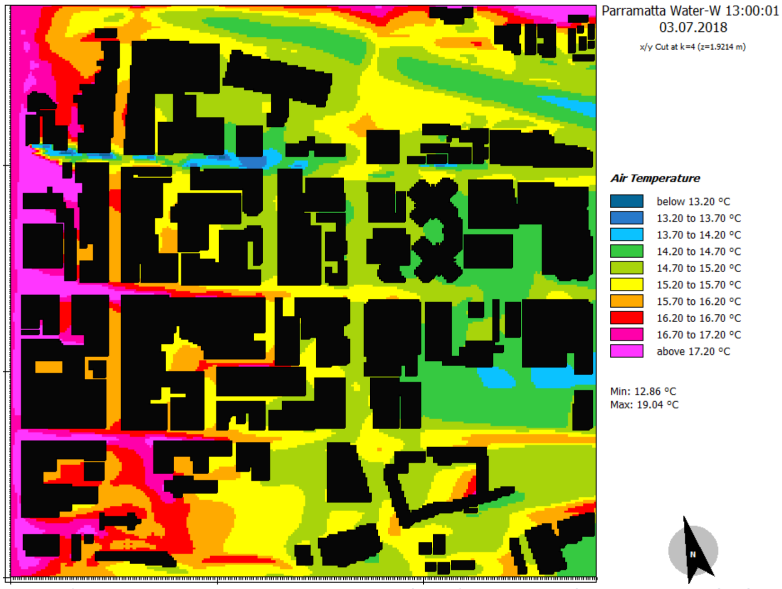


Figure 175. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 4, winter condition - 13:00

The ambient temperature difference distribution map (Figure 176) shows temperature reduction where the mitigation technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the scenario of evaporative system in the same spot. The local temperature reduction ranges from below 0.15 to 3.9°C and the average temperature reduction is 0.8°C. The temperature difference map shows the local effects of spray systems and the effects of advection to reduce the temperature of the nearby areas.

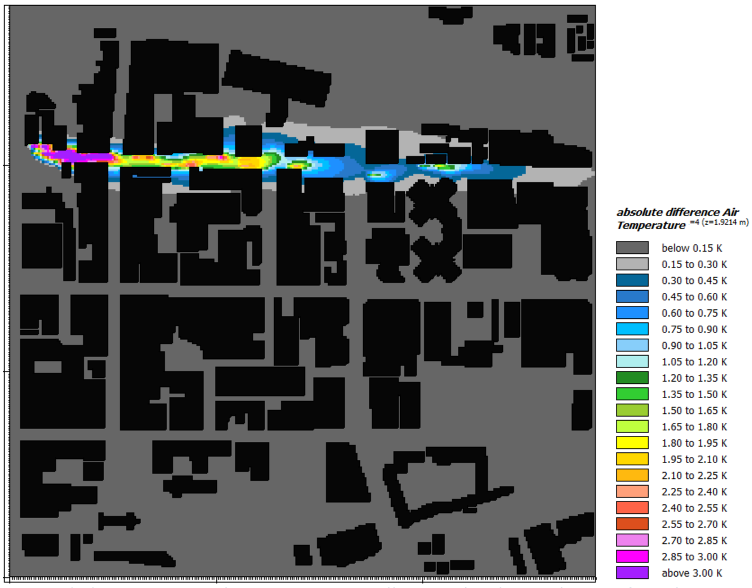


Figure 176. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 4, winter condition - 13:00

The surface temperature distribution is shown in Figure 177 when misting systems were used in Phillip Street. The surface temperature is significantly reduced locally in scenario 4 compared to the same spot in the reference scenario. The surface temperature generally varies from about 11 °C to 34.1 °C in the City of Parramatta CBD and ranges between 14.1 and 28.1°C in Phillip Street.

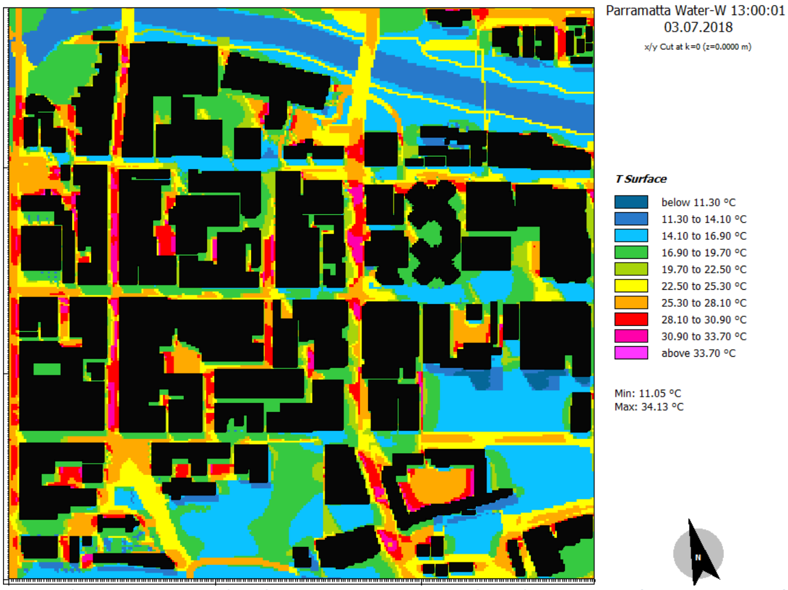


Figure 177. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 4, winter - 13:00

Figure 178 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5.6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 2.25 m/s in Phillip Street. Misting system does not change the wind speed distribution in the street compared to the reference scenario.

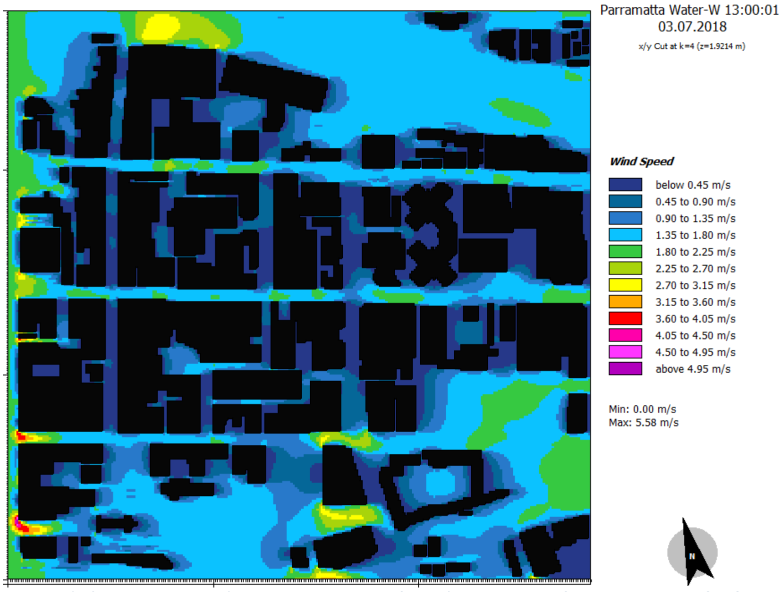


Figure 178. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 4, winter condition - 13:00

Figure 179 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates no heat stress with UTCI and PET falling below 27.4 °C during winter condition. Spray system has as a local effect in reducing comfort indices down to below

12.1 °C. UTCI and PET distribution maps are consistent in presenting cool and warm spots in Phillip Street. It is shown that the area between Horwood Pl and Church street presents cooler part in Phillip Street.

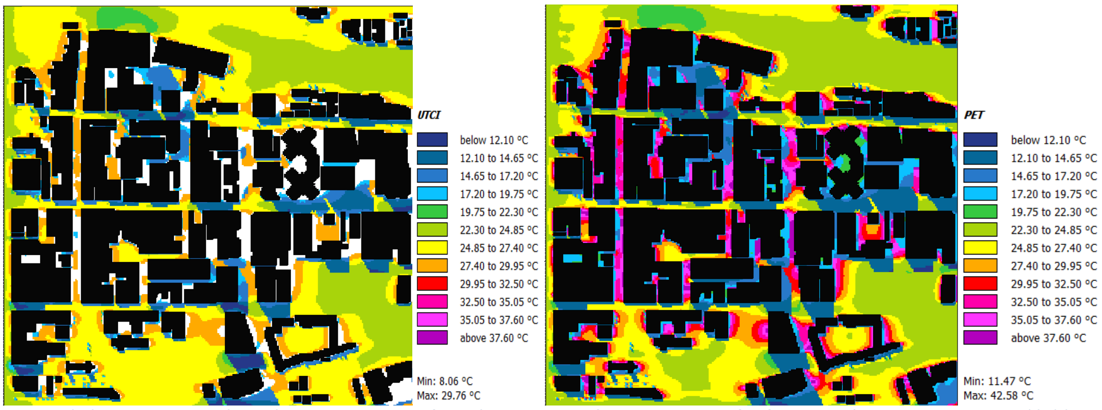


Figure 179. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 4, winter condition - 13:00: UTCI (left), PET (right)

Scenario 5

The ambient temperature ranges from 14.7 °C to 17.8 °C in Phillip Street when we used cool roof in the buildings adjacent to Phillip Street (scenario 5). The area between Marsden Street and Church Street and Horwood Pl represent warmer conditions than eastern side of Phillip Street. Due to the height of building, cool roof has insignificant effect in reducing the ambient temperature at pedestrian level in Phillip Street (Figure 180).

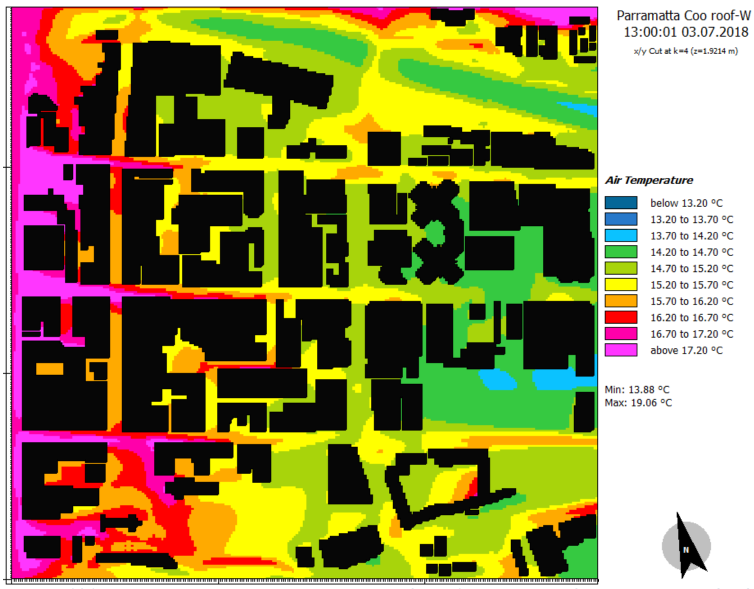


Figure 180. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 5, winter condition - 13:00

The ambient temperature difference distribution map (Figure 181) shows temperature reduction where the mitigation technology is implemented. The local air temperature drop is defined as the temperature difference between the reference scenario and the scenario of cool roof in the same spot. Temperature difference distribution map shows the effects of cool roof is minimal by 0.2°C in the pedestrian level (1.9 m above the ground).

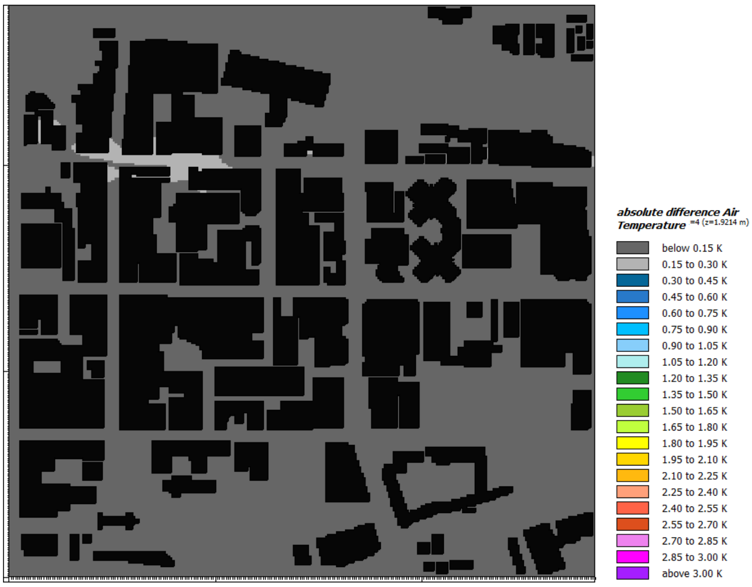


Figure 181. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 5, winter condition - 13:00

The surface temperature distribution is shown in Figure 182 when cool roofs were used in Phillip Street. The surface temperature varies from 11.1 °C to 34 °C in the City of Parramatta CBD. The surface temperature in Phillip Street is not affected by the implementation of cool roof.

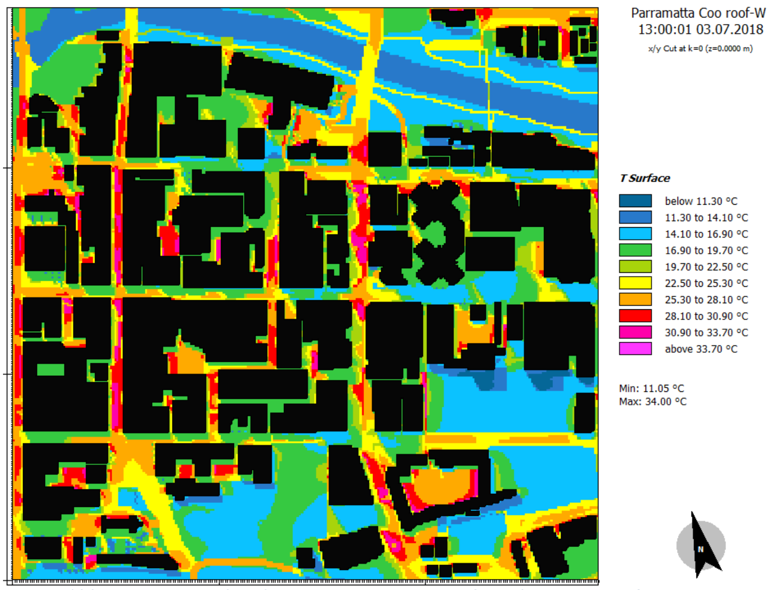


Figure 182. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 5, winter condition - 13:00

Figure 183 shows the wind speed distribution in the City of Parramatta CBD. Different building heights, spaces between buildings and street orientation, lead to variation of the wind speed from one area to another. The wind speed falls below 2.7 m/s (mostly within a range of 1 m/s to 1.8 m/s) in Phillip Street and is not impacted by the use of cool roof.

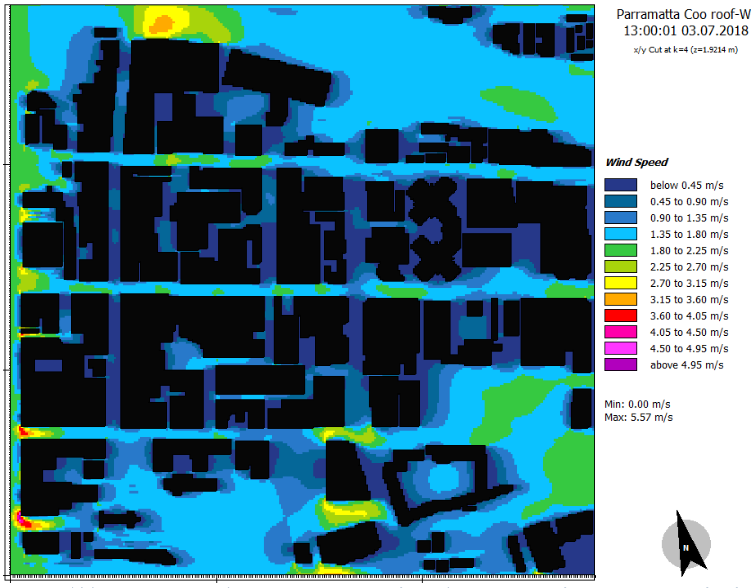


Figure 183. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 5, winter condition - 13:00

Figure 184 shows the distribution of comfort indices in the City of Parramatta CBD. Phillip Street indicates no heat stress with UTCI and PET ranging from about 12 °C to 27.4°C, which is similar to that in the reference scenario (scenario 0). UTCI and PET distribution maps are consistent in presenting warm and cool spots in Phillip Street when cool roof was used (scenario 5).

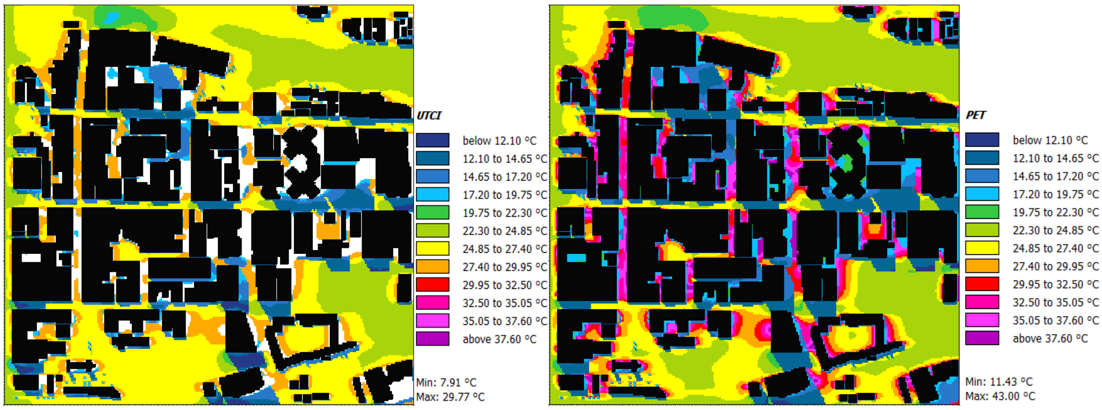


Figure 184. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 5, winter condition - 13:00: UTCI (left), PET (right)

Scenario 6

The ambient temperature ranges from 13.4 °C to 15.7 °C in Phillip Street when we used a combination of mitigation technologies, i.e., cool pavement, greenery, shading, spray system, and cool roof (scenario 6). The combined scenario has the most significant effect in reducing temperature in the whole street (Figure 185).

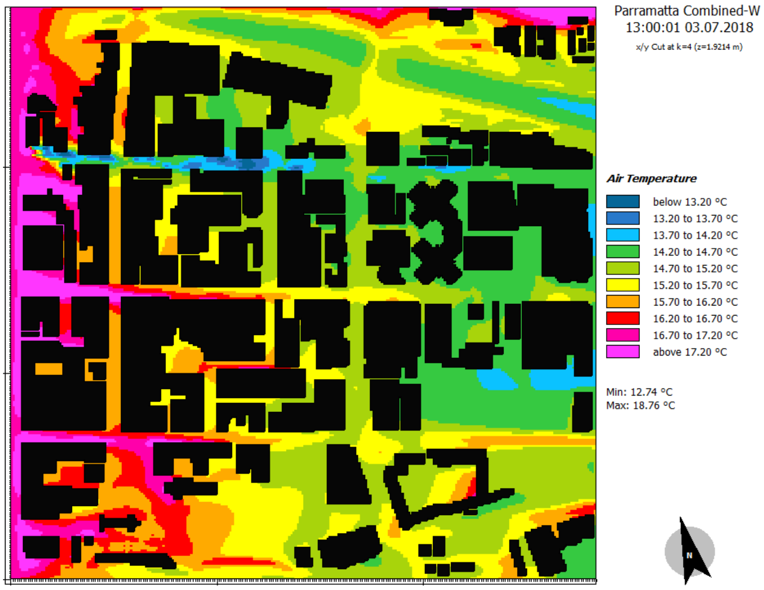


Figure 185. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 6, winter condition - 13:00

The ambient temperature difference distribution map (Figure 186) shows the achieved air temperature reduction where mitigation technologies were implemented (combination of cool pavement, greenery, shading, spray system, and cool roof). The local air temperature drop is defined as the temperature difference between the reference scenario and the combined scenario in the same spot. Under the scenario 6, the maximum local temperature reduction is 4.4°C and the average is 1.2°C.

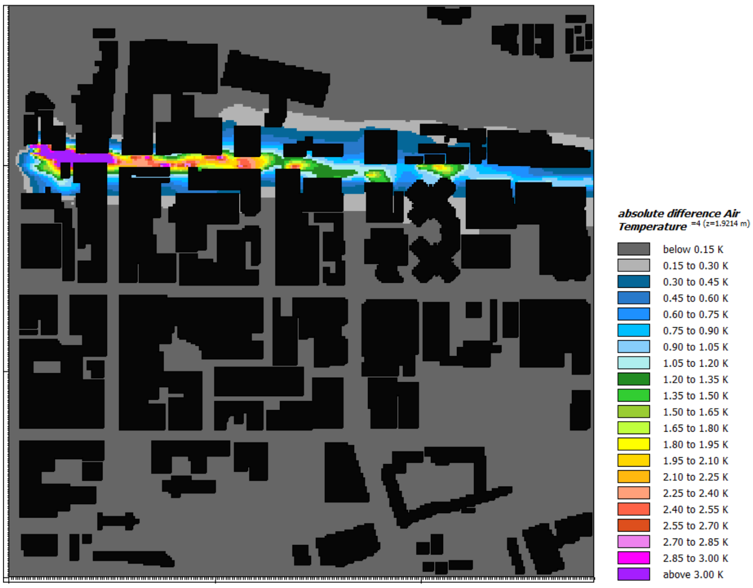
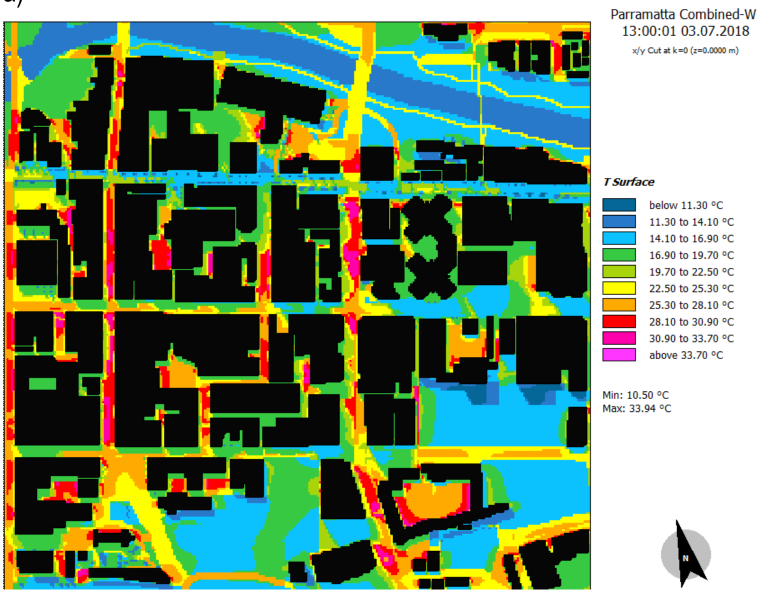


Figure 186. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 6, winter condition - 13:00

The surface temperature distribution is shown in Figure 187 when a combination of strategies was used in Phillip Street. The surface temperature generally varies from 10.5 °C to 34 °C in the City of Parramatta CBD. In Phillip Street, the surface temperature mostly falls below 22.5 °C (Figure 187 a). The surface temperature is significantly reduced in scenario 6 compared to the same spot in the reference scenario. The surface temperature is reduced under the combined scenario by 16.8 °C (Figure 187 b).

a)



b)

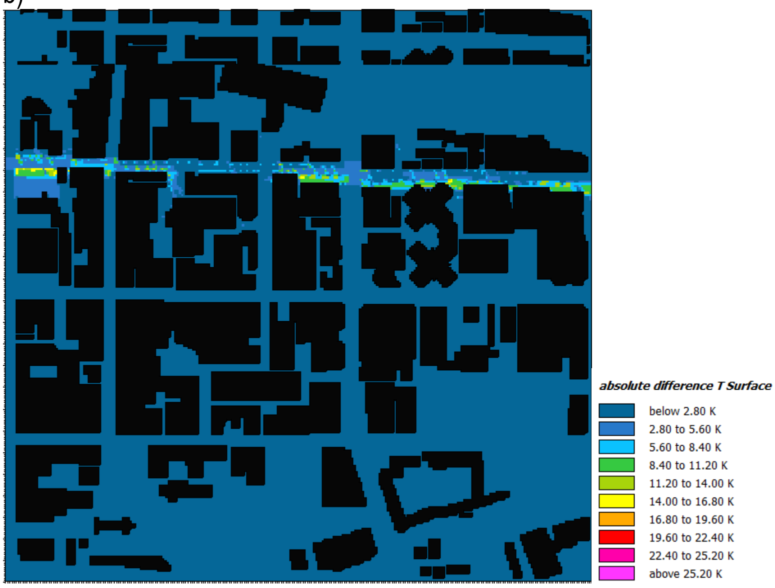


Figure 187. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 6, winter condition - 13:00

Figure 188 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5.6 m/s. Wind speed varies from one area to another due to different building heights, spaces between buildings and street orientation. The wind speed is reduced under the combined scenario which ranges between 0 and about 2 m/s in Phillip Street. The wind speed distribution is mostly impacted by the trees.

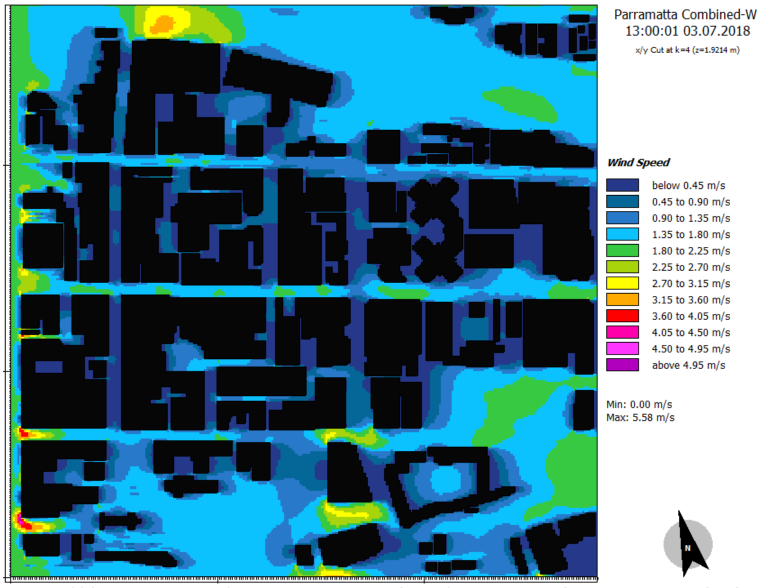


Figure 188. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 6, winter condition - 13:00

Figure 189 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates no heat stress with UTCI and PET mostly falling below 27.4 °C during winter condition. These comfort indices are reduced under the combined scenario to lower values below 17.2°C due to the impacts of mitigation technologies employed. UTCI and PET distribution maps are consistent in presenting warm and cool spots in Phillip Street.

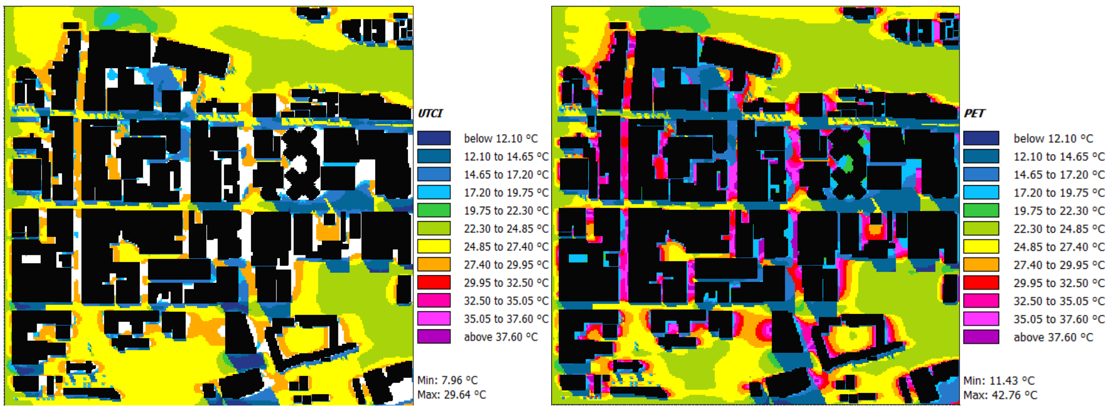


Figure 189. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 6, winter condition - 13:00: UTCI (left), PET (right)

Scenario 7

As shown in Figure 190, the ambient temperature ranges from 14.8 °C to 17.8 °C when new trees and greenery were implemented, and cool pavements were used in Phillip Street (scenario 7). New mature irrigated trees (both deciduous and evergreen) were planted in the whole Phillip Street and cool pavements were used (combination of scenario 1 and scenario 2). The ambient temperature distribution map shows that air temperature in Phillip Street is lower where mitigation technologies were implemented than the same spots in the reference scenario (Figure 190).

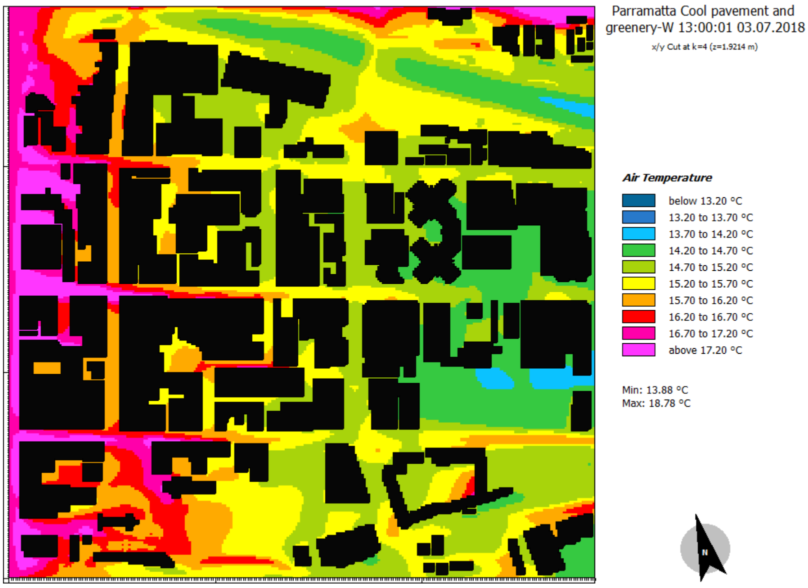


Figure 190. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 7, winter condition - 13:00

The ambient temperature difference distribution map (Figure 191) shows temperature reduction where the mitigation technology is implemented (combination of cool pavement and greenery). The local air temperature drop is defined as the temperature difference between the reference scenario and the mitigated scenario in the same spot. Under the scenario 7, the maximum local temperature reduction reaches to 1.1°C and the average temperature reduction is 0.3°C.

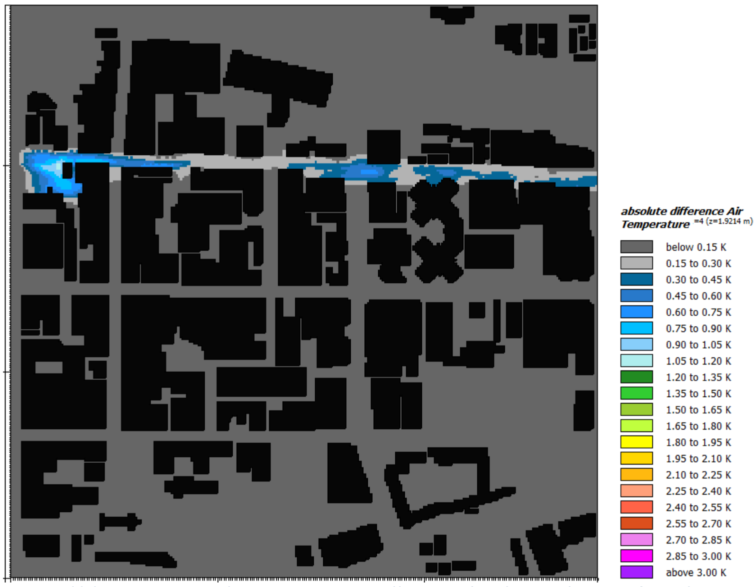


Figure 191. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 7, winter condition - 13:00

The surface temperature distribution is shown in Figure 192 when a combination of strategies was used in Phillip Street. The surface temperature generally varies from 10.5°C to 34.1°C in the City of Parramatta CBD. In Phillip Street, the surface temperature mostly falls below 25.3°C (Figure 192). It is further reduced under the trees where the surface temperature falls below 14.1°C.

Figure 192. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 7, mean maximum condition - 13:00

Figure 193 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5.6 m/s. Wind speed varies from one area to another due to different building heights, spaces between buildings and street orientation. The wind speed ranges between 0 to about 2 m/s in Phillip Street. Near the trees, wind speed at pedestrian level is reduced compared to the refence scenarios.

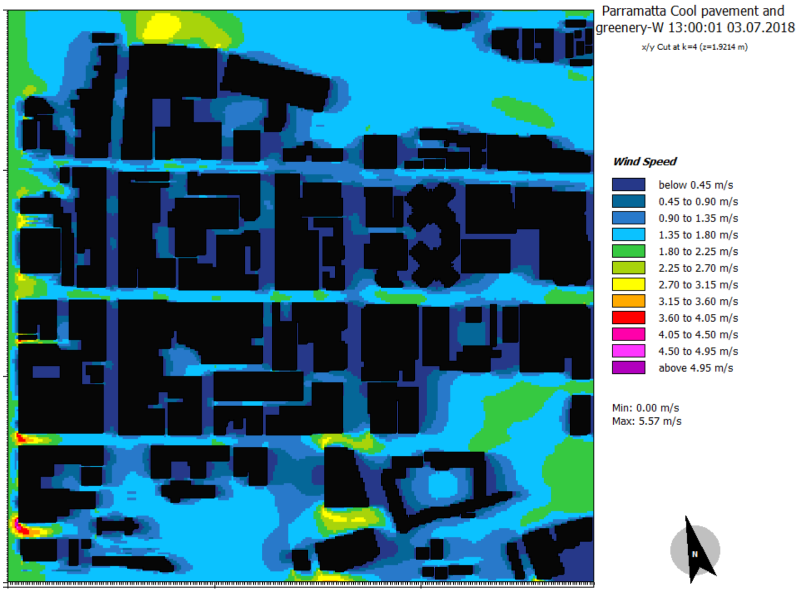


Figure 193. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 7, winter condition - 13:00

Figure 194 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates no heat stress with UTCI mostly ranging from 12°C to 27.4°C during winter condition. UTCI and PET distribution maps are consistent in presenting warm and cool spots in Phillip Street. As shown in Figure 194, tree shading reduces the heat stress for humans in urban areas where UTCI and PET fall below 17.2°C.

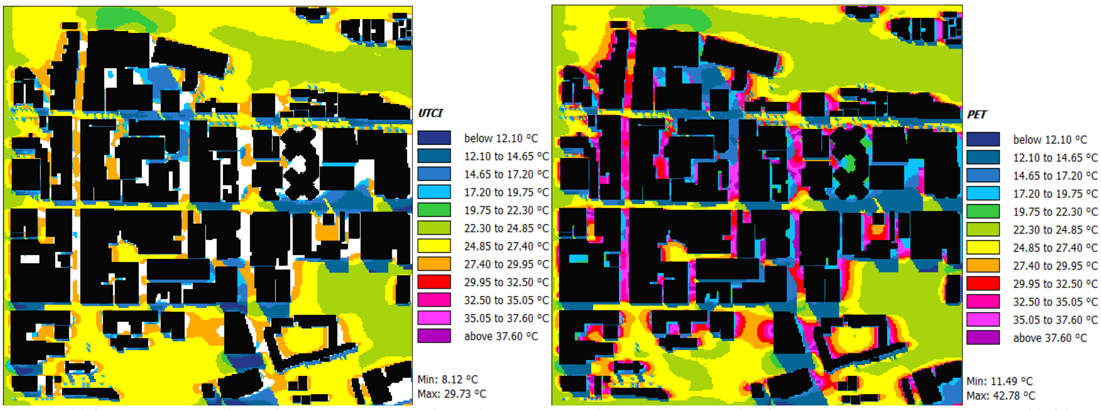


Figure 194. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 7, winter condition - 13:00: UTCI (left), PET (right)

Scenario 8

The ambient temperature ranges from 14.6 °C to 18.3 °C in Phillip Street where radiative cooling material is used (scenario 8). Same structure (surface area) as shading device (scenario 3) is implemented covering about 75% of the street. This approach maximises emission of infrared thermal radiation through the atmospheric window for releasing heat and minimises absorption of incoming atmospheric radiation. These simultaneous processes can lead to the shading device temperature substantially below the ambient temperature. Shading with radiative cooling is reducing the temperature by about 1°C compared to the reference scenario. The ambient temperature distribution map shows that the air temperature in Phillip Street is slightly lower than the reference scenario where solar control with radiative cooling material was employed (Figure 195).

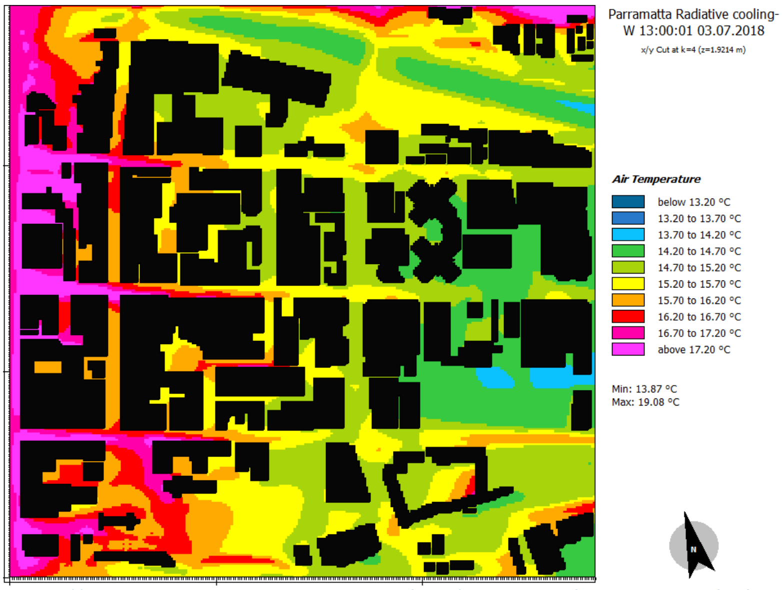


Figure 195. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 8, winter condition - 13:00

The ambient temperature difference distribution map (Figure 196) shows the temperature reduction where the radiative cooling technology is implemented. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the mitigated scenario in the same spot. Under the scenario 8, the maximum local temperature reduction is 1.0°C and the average is 0.2°C.

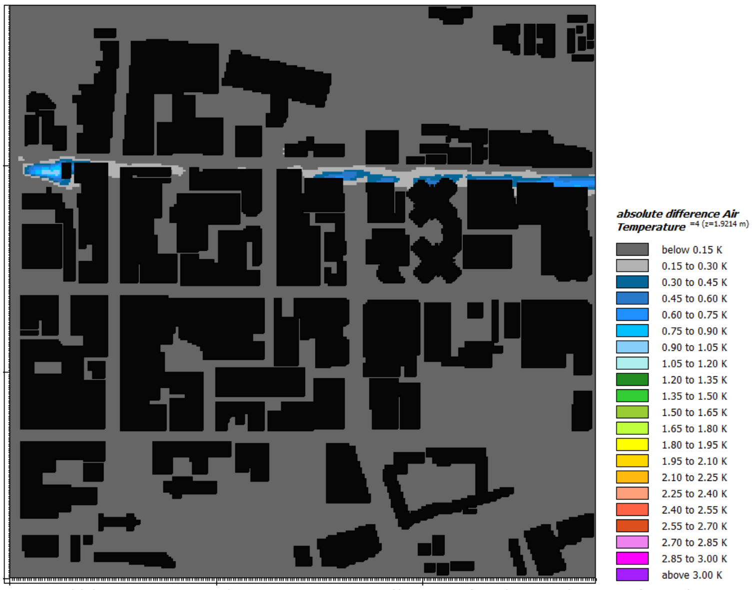


Figure 196. Distribution of air temperature difference (Tref – Tmit) in the City of Parramatta CBD and Phillip St: Scenario 8, winter condition - 13:00

The surface temperature distribution is shown in Figure 197 when radiative cooling material was used for the shading device in Phillip Street. In Phillip Street, the surface temperature mostly falls below 19.7°C under or near the shaded area (Figure 197). The surface temperature is reduced in scenario 8 compared to the same spot in the reference scenario. The achieved surface temperature reduction mostly varies from 5.5°C to 11°C near the shading device.

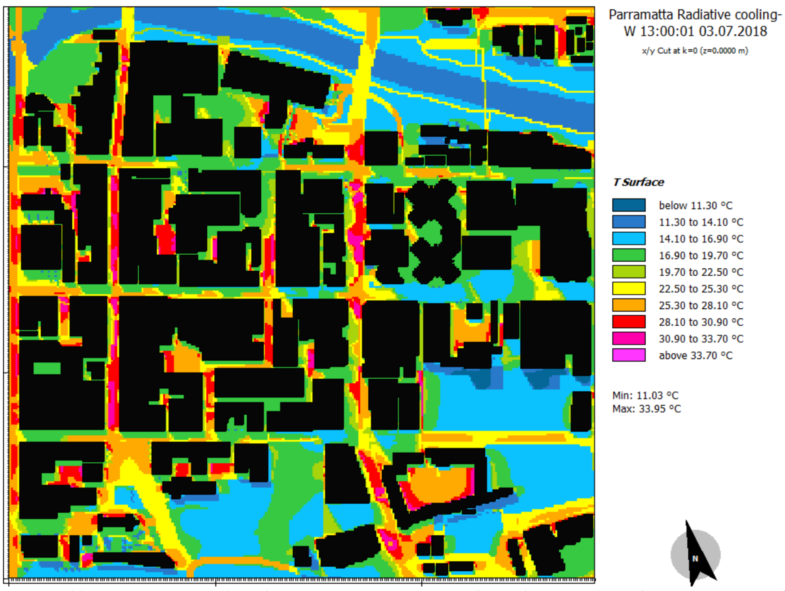


Figure 197. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 8, winter condition - 13:00

Figure 198 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5.6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 2.25 m/s in Phillip Street. Due to the height of shading device, there was a small effect on the wind speed distribution at pedestrian level near the corner of Smith street. Eastern part of Phillip Street shows lower wind speed values compared to the western parts.

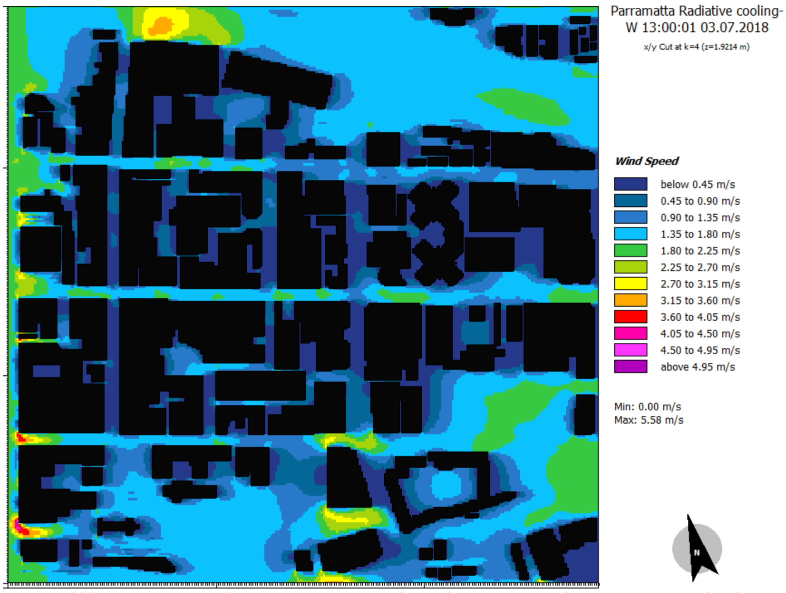


Figure 198. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 8, winter condition - 13:00

Figure 199 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates no heat stress with UTCI mostly ranging from 12°C to 27.4°C during winter condition. This can be compared with Phillip street (reference scenario) and Church street (existing condition) where UTCI falls above 27.4 °C. UTCI and PET distribution maps are consistent in presenting warm and cool spots in Phillip Street. These comfort indices fall below 17.2 °C near the shaded area (scenario 8).

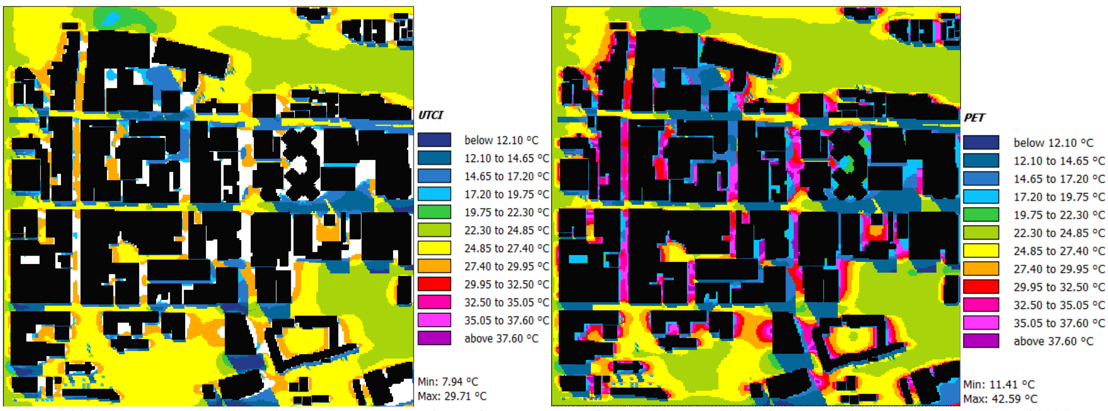


Figure 199. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 8, winter condition - 13:00: UTCI (left), PET (right)

Scenario 9

The air temperature ranges from 14.8 °C to 18 °C when we implemented the proposed trees and pavements by the City of Parramatta Council in Phillip Street (Figure 200). New trees were planted and proposed pavement materials with proper reflectivity were used in Phillip Street based on the Council implementation plan. The air temperature in Phillip Street is not significantly influenced by the City of Parramatta Council implementation plan. However, Phillip Street presents slightly lower temperatures compared to the reference scenario where new trees were planted.

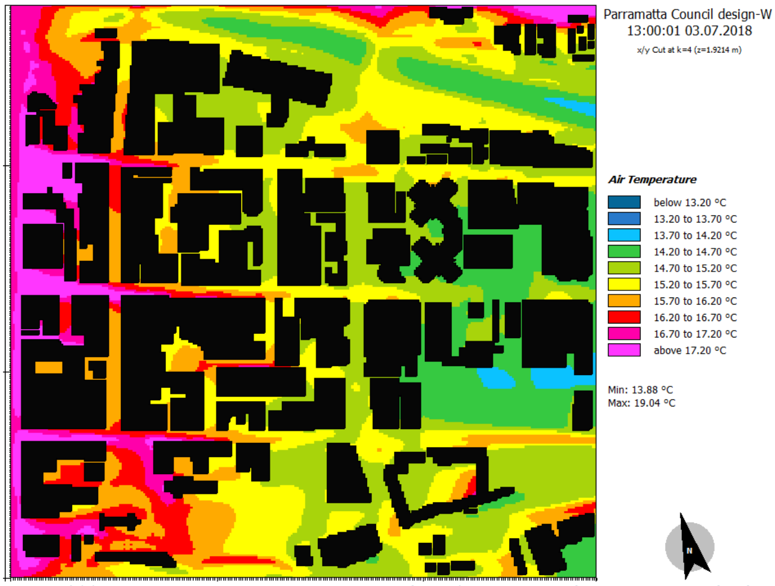


Figure 200. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 9, winter condition - 13:00

The ambient temperature difference distribution map (Figure 201) shows temperature reduction in the street where the implementation plan by the City of Parramatta Council is used. The local air temperature drop is defined as the temperature difference between the reference scenario and this scenario. The maximum local temperature reduction is about 0.4°C.

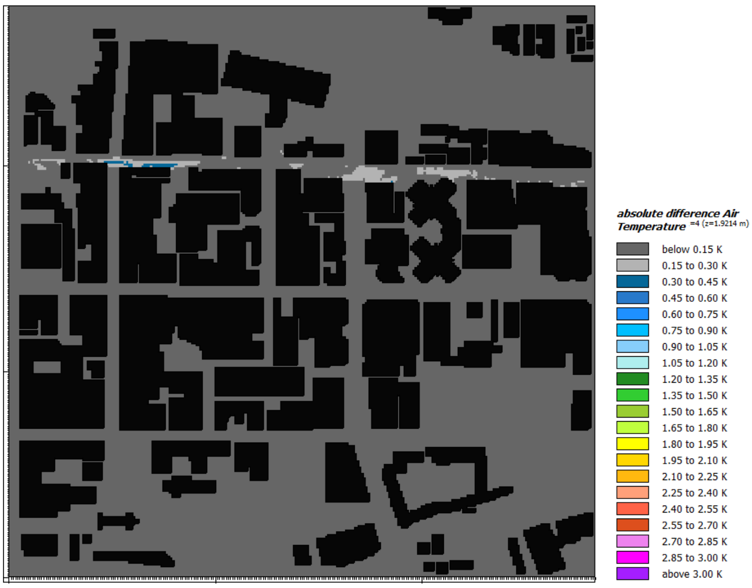


Figure 201. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 9, winter condition - 13:00

The surface temperature distribution is shown in Figure 202 when the City of Parramatta Council plan was implemented in Phillip Street. The surface temperature is reduced where trees are planted compared to the same spot in the reference scenario. The temperature of horizontal surfaces generally varies from 11 °C to 34.1 °C in the City of Parramatta CBD and mostly falls above 14.1 °C and below 28.1 °C in Phillip Street (except areas shaded by trees). The surface temperature in Phillip street was reduced by 8 °C in the areas shaded by the trees compared to the same areas in the reference scenario.

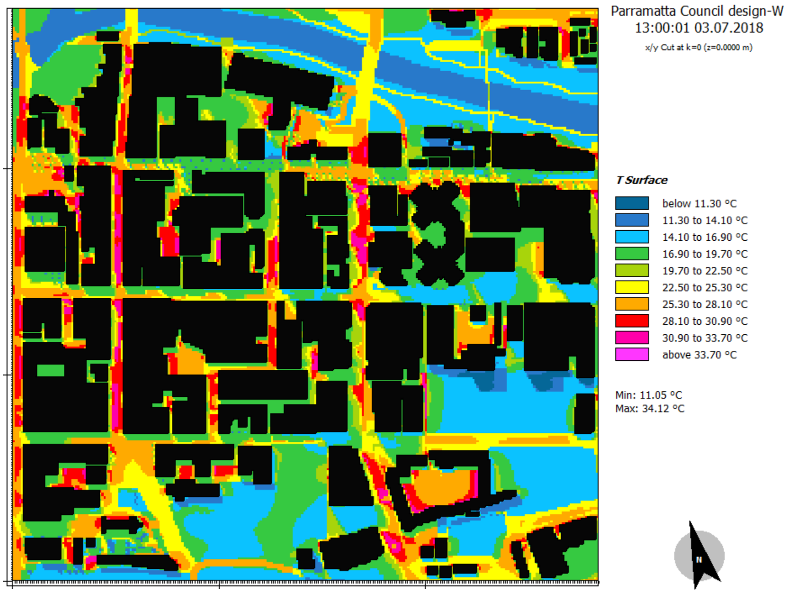


Figure 202. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 9, winter condition - 13:00

Figure 203 shows the wind speed distribution in the City of Parramatta CBD where the wind speed varies between 0 m/s and about 5.6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 2 m/s in Phillip Street. New trees reduce the wind speed at pedestrian level in Phillip Street.

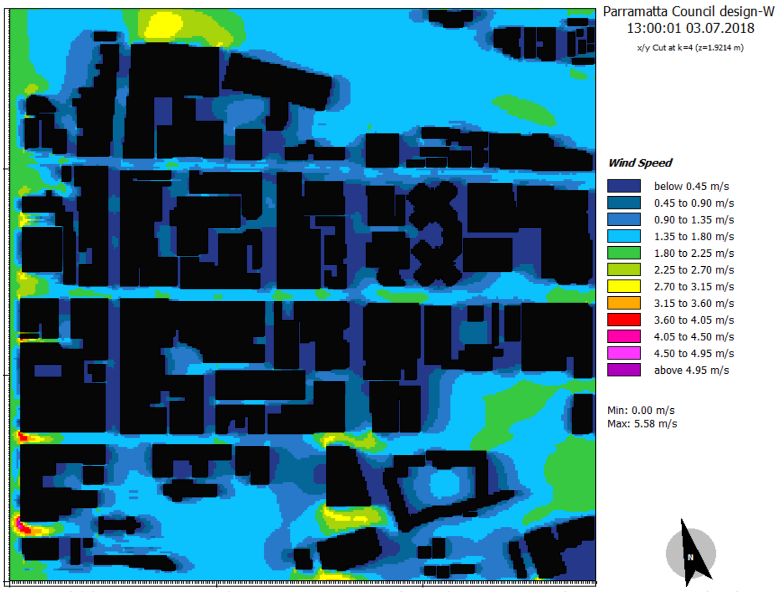


Figure 203. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 9, winter condition - 13:00

Figure 204 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates no heat stress with UTCI and PET mostly falling below 27.4 °C and 30 °C during, respectively, winter condition (scenario 9). UTCI and PET distribution maps are consistent in presenting warm and cool spots in Phillip Street. Solkova trees with 8 m height reduce the comfort indices and providing cooler environments locally.

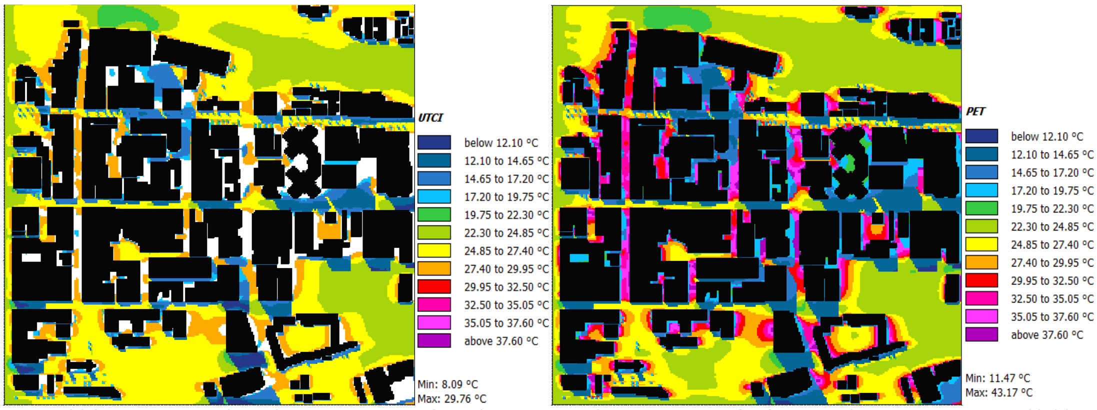


Figure 204. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 9, winter condition - 13:00: UTCI (left), PET (right)

Scenario 10

The air temperature ranges from 14.8 °C to 17.8 °C when we implemented Solkova trees proposed by the City of Parramatta Council and used cool material instead of Adelaide black and black asphalt in Phillip Street (Figure 205). By using cool pavement, areas between Church Street and Horwood Pl represent lower temperatures by about 1.0°C than the same locations in the City of Parramatta Council implementation plan.

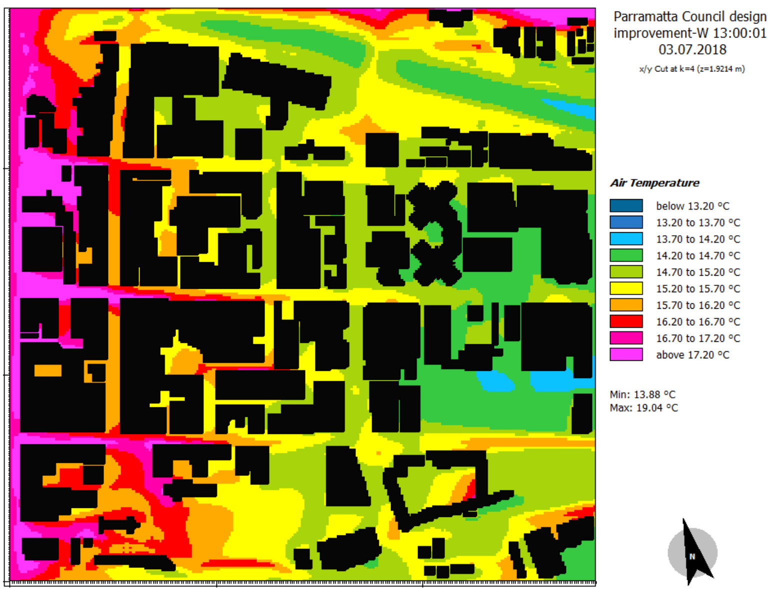


Figure 205. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 10, winter condition - 13:00

The ambient temperature difference distribution map (Figure 206) shows temperature reduction in the street when mitigation techniques were used to improve the City of Parramatta Council implementation plan. The local air temperature drop is defined as the temperature difference between the reference scenario and this scenario in the same spot. Temperature difference distribution map shows temperature reduction in the street where cool pavements were implemented in addition to greenery in council implementation plan (scenario 9). The local temperature reduction ranges from 0 to 0.8°C and the average temperature reduction is 0.2°C.

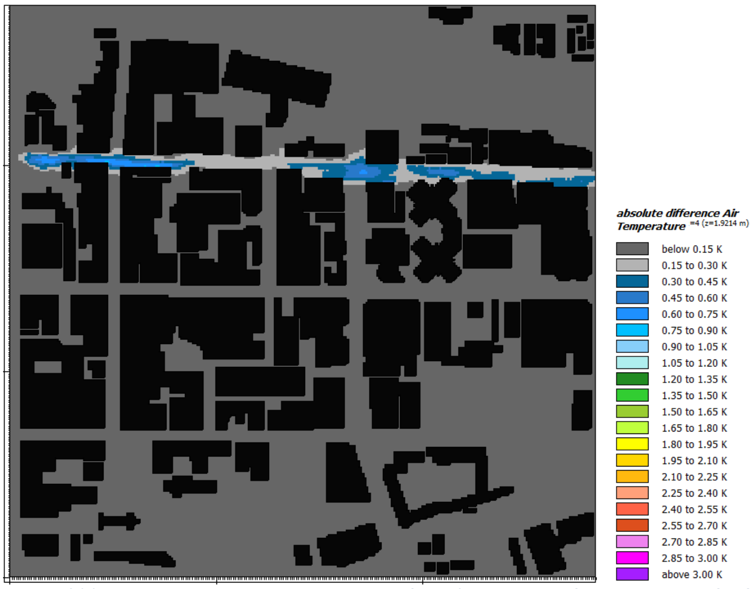


Figure 206. Air temperature distribution in the City of Parramatta CBD and Phillip St: Scenario 10, winter condition - 13:00

The surface temperature distribution is shown in Figure 207 when cool pavement was used to improve the City of Parramatta Council implementation plan. The surface temperature is reduced in scenario 10 compared the reference scenario and the City of Parramatta Council implementation plan. The surface temperature mostly ranges between 14.1°C and 25.3°C in Phillip Street and falls below 19.7 °C in the areas shaded by Solkova trees.

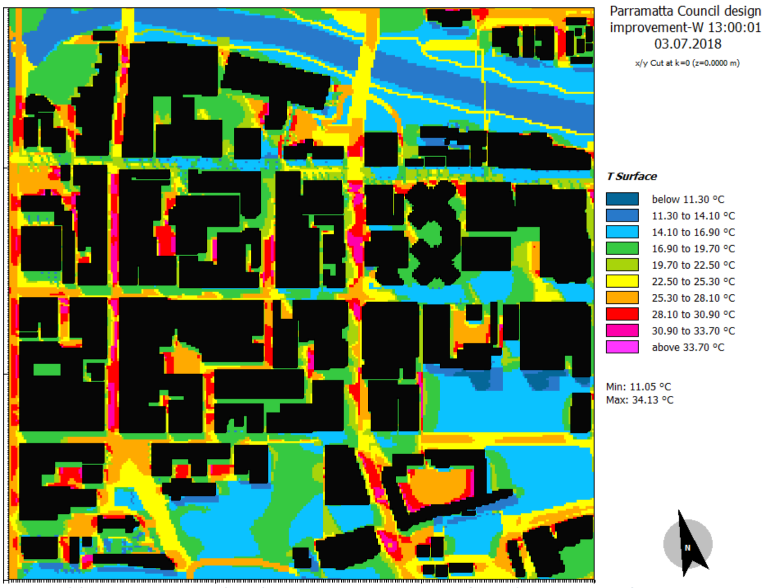


Figure 207. Distribution of surface temperature in the City of Parramatta CBD and Phillip St: Scenario 10, winter condition - 13:00

The wind speed distribution in the City of Parramatta CBD is shown in Figure 208 where the wind speed varies between 0 m/s and about 5.6 m/s. Due to the differences in building heights, spaces between buildings and street orientation, the wind speed varies from one area to another. The wind speed ranges between 0 to about 2 m/s in Phillip Street. New trees reduce the wind speed at pedestrian level in Phillip Street.

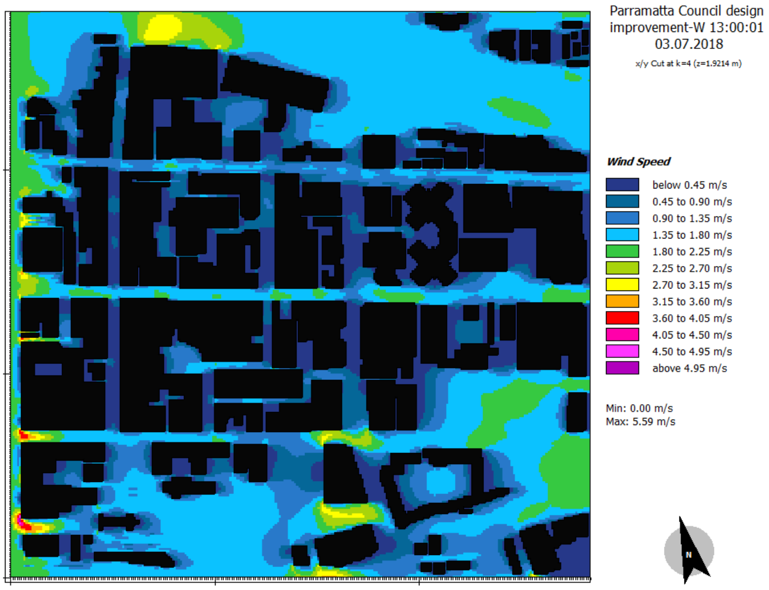


Figure 208. Distribution of wind speed in the City of Parramatta CBD and Phillip St: Scenario 10, winter condition - 13:00

Figure 209 shows the distribution of comfort indices (i.e. UTCI and PET) in the City of Parramatta CBD. Phillip Street indicates no heat stress with UTCI and PET mostly falling below 27.4°C during winter condition. UTCI and PET distribution maps are consistent in presenting cool and warm spots in Phillip Street.

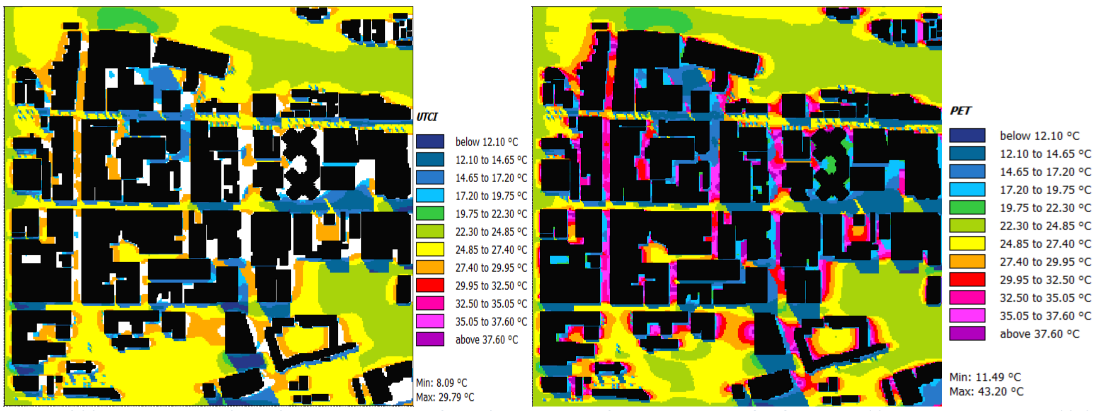


Figure 209. Distribution of comfort indices in the City of Parramatta CBD and Phillip St: Scenario 10, winter condition - 13:00: UTCI (left), PET (right)

Chapter summary

We assessed the impacts of different mitigation technologies in three different conditions: Mean maximum, heatwave and winter conditions. Figure 210 shows box plots of ambient temperature and compares the results of simulations in each climatic condition.

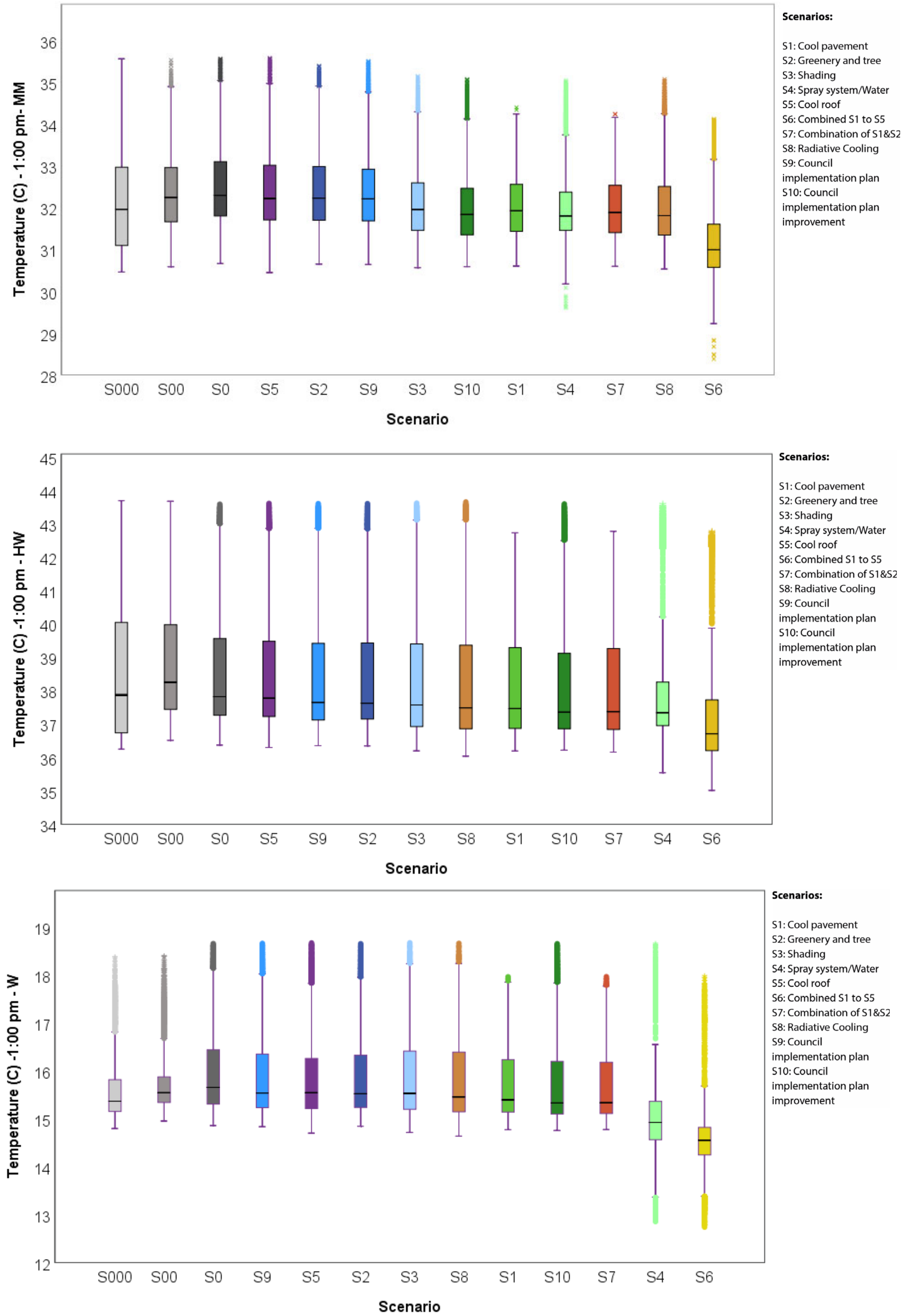


Figure 210. Box plots of ambient temperature during three different conditions mean maximum (MM), heatwave (HW), and winter (W) at 1:00 pm.

In all investigated conditions, western part of Phillip street presents higher ambient temperatures than eastern parts. The mitigation potential of the strategies varies as a function of prevailing wind direction and speed. In general, most of mitigation technologies help to decrease the air temperature during the warm season without deteriorating environmental condition during the cool season. Solar control, cool pavements, and greenery are effective technologies to reduce ambient heat during the warm season. Despite their efficiency during summer mean maximum and heatwave, these strategies have insignificant cooling impact during winter. As shown above, the combination of different scenarios (cool pavement, greenery, shading, spray system, and cool roof) reduces ambient temperature in all climatic conditions. The maximum reduction of ambient temperature achieved under combined scenario (scenario 6) is 6.4°C, 6.7°C, 4.4°C during mean maximum, heatwave and winter conditions, respectively. Misting system has also a strong local effect and reduces the minimum and average ambient temperature in all climatic conditions.

Mean maximum condition

Table 2 and Figure 211 illustrate the maximum, minimum and average ambient temperature in Phillip Street for each scenario during summer mean maximum condition. The average ambient air temperature for the reference scenario (unmitigated) in Phillip Street during mean maximum condition was 32.6 °C and the maximum and minimum temperatures were 35.1 °C and 30.7 °C, respectively. By applying proper mitigation technologies, the average, maximum and minimum air temperature may be reduced to 31.3 °C, 33.2 °C, and 29.2 °C, respectively.

Table 2. Average, minimum and maximum temperature in Phillip St. for each scenario- mean maximum condition

Scenario	**Temperature** (°C) Max, T_{max}	**Temperature** (°C) Min, T_{min}	**Temperature** (°C) Average, T_{avg}
S000 Potential height/Future	35.6	30.5	32.1
S00 Planned height/Future	34.9	30.6	32.4
S0 Existing/unmitigated	35.1	30.7	32.6
S1 Cool pavement	34.3	30.6	32.1
S2 Greenery and tree	34.9	30.7	32.4
S3 Shading (shading cloth)	34.3	30.6	32.1
S4 Spray system	33.8	30.2	32.1
S5 Cool roof	35.0	30.5	32.5
S6 Combination of S1 to S5	33.2	29.2	31.3
S7 Combination of S1 and S2	34.2	30.6	32.1
S8 Radiative cooling-shading	34.3	30.5	32.0
S9 Parramatta Council implementation plan	34.8	30.6	32.4
S10 Parramatta Council design improvement	34.1	30.6	32.1

Solkova trees proposed by the City of Parramatta Council and council's new pavement material (e.g. Adelaide black) were used to assess the Parramatta Council implementation plan (scenario 9). Results show that the average, maximum and minimum air temperature may be reduced to 32.4°C, 34.8°C, and 30.6°C, respectively. Compared to the reference scenario (unmitigated condition), there is a slight reduction in the average temperature of Phillip Street (0.2°C). The maximum ambient temperature in the street may also be reduced by 1.0 °C. When we used reflective material for pavements to improve the City of Parramatta Council implementation plan (scenario 10), the average, maximum and minimum air temperature were reduced to 32.1°C, 34.1°C, and 30.6°C, respectively. The maximum local temperature reduction in scenario 10 reached to 1.4°C, while the achieved maximum local temperature drop in scenario 9 is 0.7°C (Figure 212).

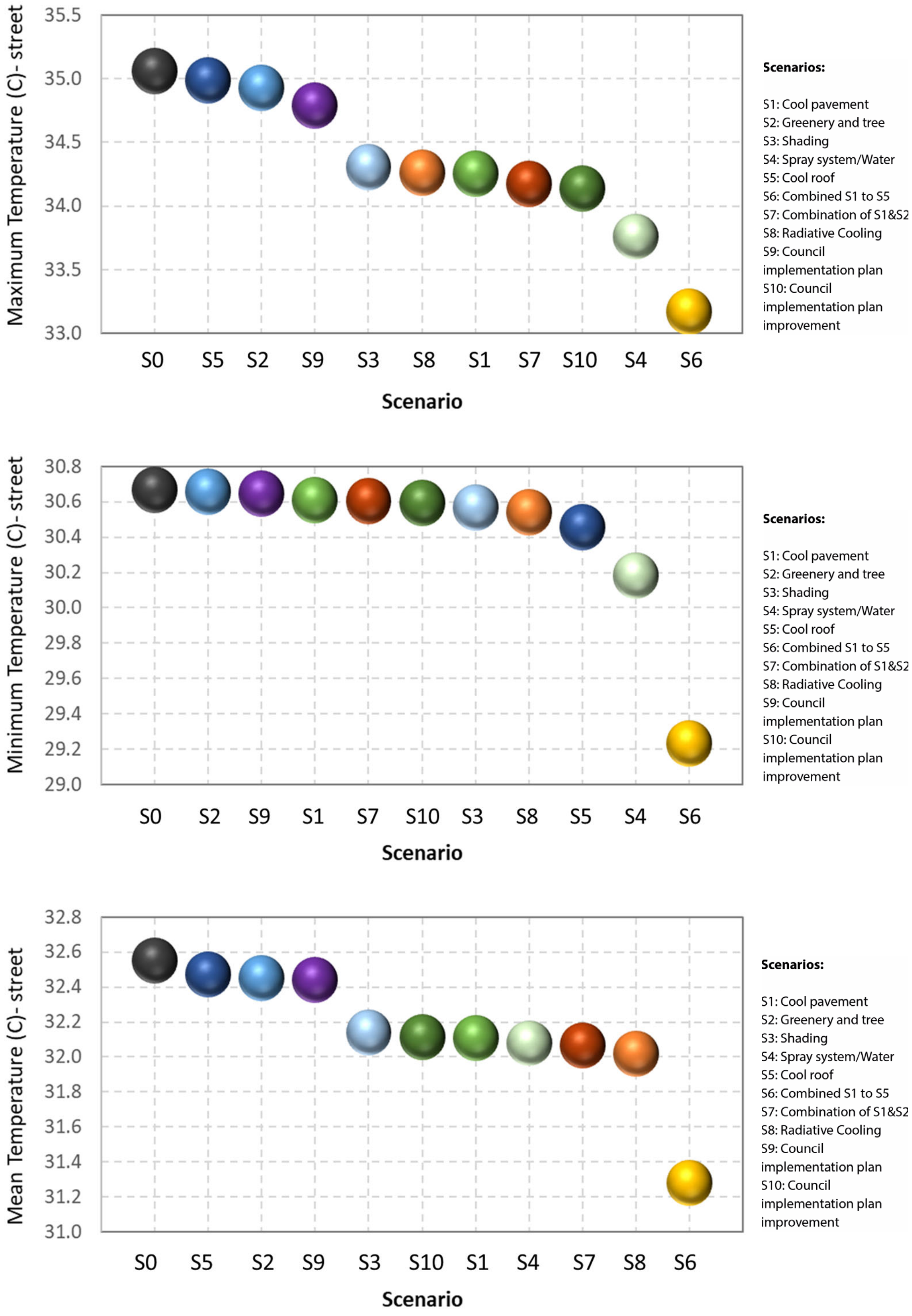


Figure 211. Maximum, minimum and mean temperature in Phillip Street per scenario- summer mean maximum condition

Figure 212 shows the local average and maximum heat mitigation potential in Phillip St. for each scenario during mean maximum condition. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the mitigated scenario in the same spot. The maximum local air temperature reduction ranges between 0.3°C for cool roof and 6.4°C for the scenario of combining cool pavement, greenery, shading, spray system, and cool roof. The average air temperature reduction reaches to 1.3°C for the combined scenario during summer mean maximum condition. Water has strong local effect and lead to a maximum reduction of 5.1°C during mean maximum condition. We assessed the effects of trees and greenery in scenario 2 (tree and raingarden) and scenario 9 (Parramatta Council implementation plan). We have shown greenery is the second less efficient strategy compared to the other investigated technologies. Temperature difference distribution maps show the local temperature drop in Phillip St. where trees were planted. The maximum local temperature reduction is about 0.7°C with planting trees.

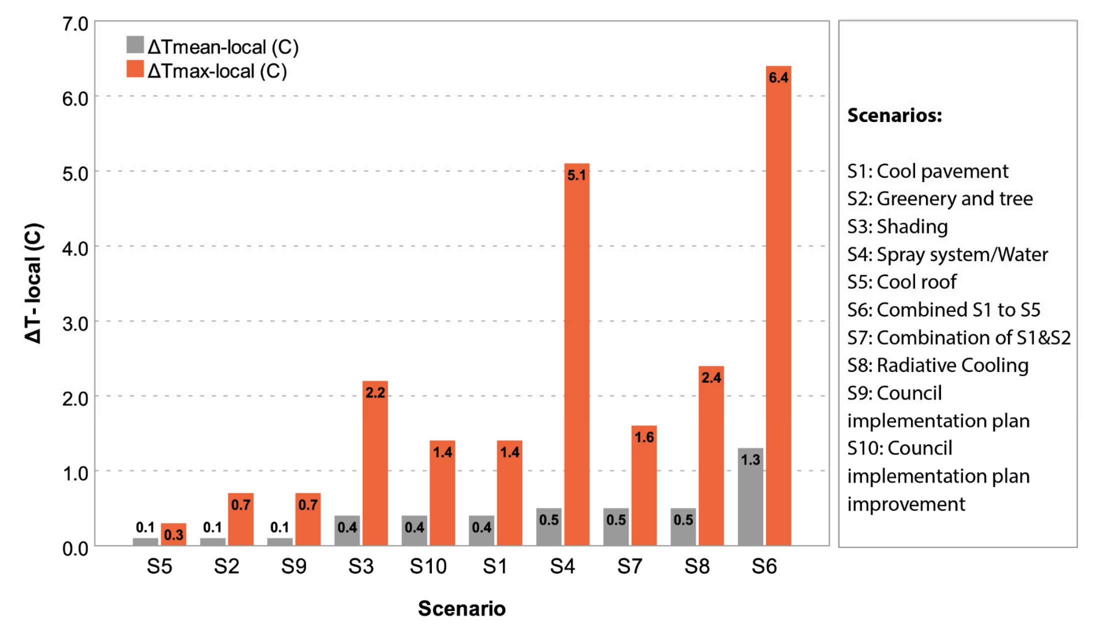


Figure 212. Average and maximum mitigation potential in Phillip St. per scenario- summer mean maximum condition: (ΔT local = TRef - TMit)

Use of shading devices (shading cloth and radiative cooling material), tree shading, and cool pavement are very effective in reducing surface temperature of the street and pavements. Our simulations show that with the combination of cool pavement, greenery, shading, spray system, and cool roof, the surface temperature in Phillip St. mostly falls below 32°C. The surface temperature reduction achieved under the combined scenario varies from 8.4°C to 19.6°C under the shading device and between 22.4°C and 27°C under the shading provided by the trees. It should be noted that the surface temperature generally varies from 22.3°C to 56.9°C in the City of Parramatta CBD.

The wind speed varies from one area to another due to different building heights, spaces between buildings and street orientation, and is impacted by the trees in Phillip St.

Analysis of comfort indices is shown in the box plots of Figure 213. The Universal Thermal Climate Index (UTCI) is showing moderate to very strong heat stress in Phillip Street. UTCI is ranging from 38-40°C in the areas between Marsden Street and Church Street and the corner of Smith Street. PET is consistent with UTCI indicating areas out of comfort range. It mostly varies from about 40°C to 46°C in Phillip street.

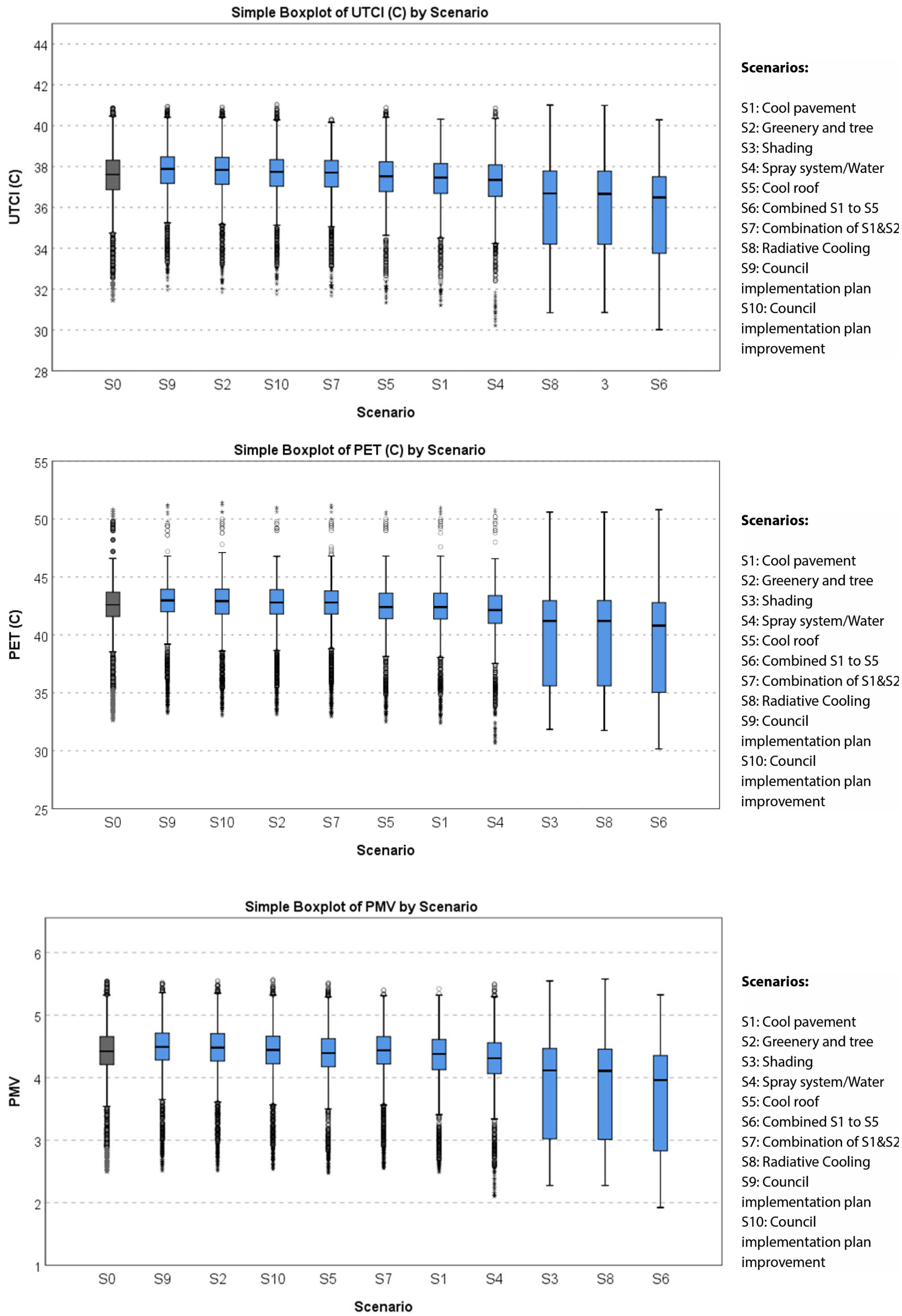


Figure 213. Boxplots of different comfort indices in Phillip Street per scenario- summer mean maximum condition

We also compared the results of UTCI and PET, presented earlier, with those of PMV (predicted mean votes). PMV represents the subjective evaluation of comfort and the warmth feeling on a subjective scale from extremely hot to extremely cold and neutral in the middle. As shown here, all comfort indices are consistent and suggest cool pavement, shading (solar control), water technologies (misting system), and combination of different strategies are the most effective solutions to improve comfort in Phillip St. during summer mean maximum condition. Tree shading helps to reduce the heat stress for humans in urban areas. Thus, the most comfortable conditions can be found below the trees. They are providing shade and are hardly causing wind speed reductions at the pedestrian level. Other areas in the street do not show improved comfort due to wind speed reductions by the trees. Figure 214 compares the distribution of UTCI and PET in Phillip street under unmitigated scenario (scenario 0) and combined mitigation scenario (scenario 6) during mean maximum condition. As shown here, heat stress for humans in urban areas can be significantly reduced with the implementation of the combined strategies.

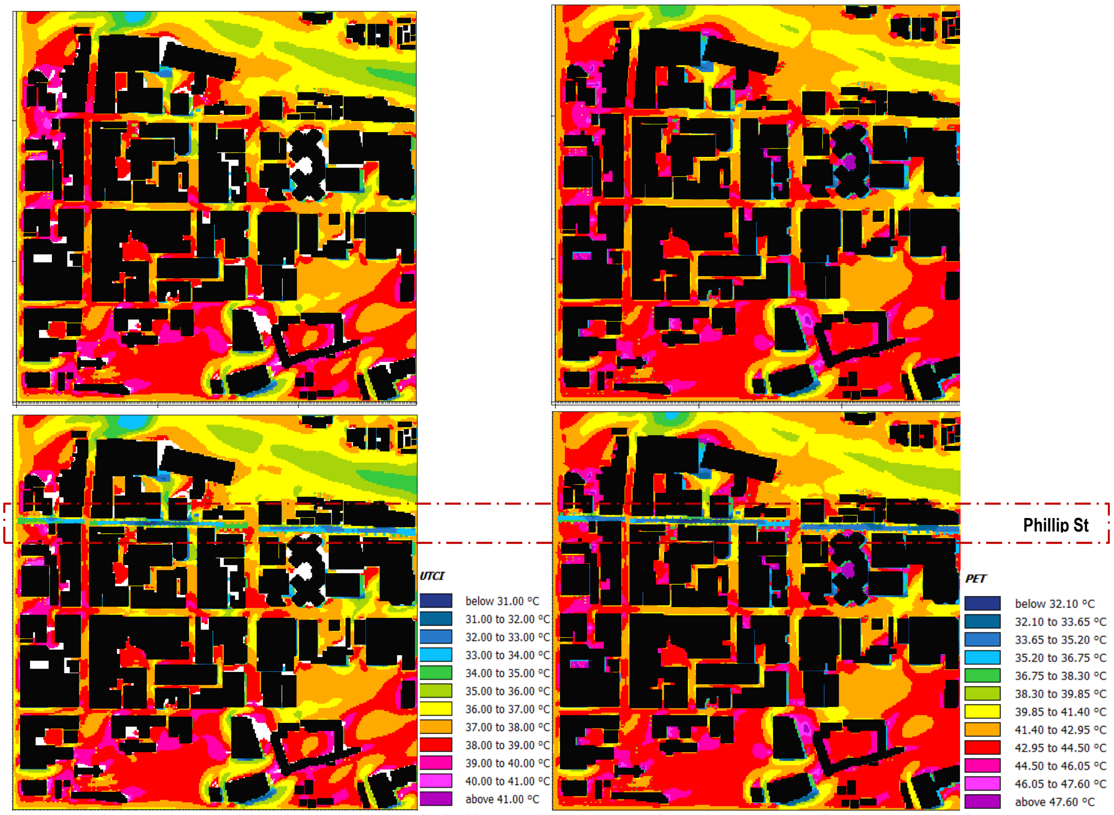


Figure 214. Distribution of comfort indices, UTCI (left), PET (right), in the City of Parramatta CBD and Phillip St during summer mean maximum condition: unmitigated scenario (top) and combined scenario 6 (bottom)

Heatwave Condition

Table 3 presents statistical summary of average, minimum and maximum temperature in Phillip St. for each scenario during heatwave condition. The local maximum and average reduction of ambient temperature in Phillip St. are provided in Table 4. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the mitigated scenario in the same spot.

The average ambient air temperature for the reference case was 38.7°C in Phillip St. during heatwave condition, and the maximum and minimum temperatures were 43.0°C and 36.4°C, respectively. The maximum local air temperature reduction ranges between 0.2°C for cool roof, and 6.7°C for the scenario of combining cool pavement, greenery, shading, spray system, and cool roof. The average air temperature reduction reaches to 1.3°C for the combined scenario. Water has strong local effect and lead to a maximum reduction of 5.4°C during heatwave condition. Table 3 suggests that shading strategies, misting system, cool pavements are more effective technologies to reduce the average ambient temperature during heatwave condition.

Table 3. Average, minimum and maximum temperature in Phillip St. for each scenario- Heatwave condition

Scenario	**Temperature** (°C) Max, T_{max}	**Temperature** (°C) Min, T_{min}	**Temperature** (°C) Average, T_{avg}
S000 Potential height/Future	43.7	36.3	38.6
S00 Planned height/Future	43.7	36.5	38.9
S0 Existing/unmitigated	43.0	36.4	38.7
S1 Cool pavement	42.7	36.2	38.4
S2 Greenery and tree	42.9	36.4	38.6
S3 Shading (shading cloth)	43.0	36.2	38.4
S4 Spray system	40.2	35.5	38.2
S5 Cool roof	42.9	36.3	38.7
S6 Combination of S1 to S5	37.4	35.0	39.9
S7 Combination of S1 and S2	42.8	36.2	38.3
S8 Radiative cooling-shading	43.0	36.0	38.4
S9 Parramatta Council implementation plan	42.9	36.4	38.6
S10 Parramatta Council design improvement	42.5	36.2	38.3

Table 4. Average and maximum temperature difference between each mitigation scenario and the reference scenario for Phillip Street – Heatwave condition

Scenario	MAX ΔT(°C) mitigation -ref	Avg ΔT (°C) mitigation -ref
S1 Cool pavement	1.2	0.4
S2 Greenery and tree	0.8	0.1
S3 Shading (shading cloth)	1.9	0.3
S4 Spray system	5.4	0.6
S5 Cool roof	0.2	0.0
S6 Combination of S1 to S5	6.7	1.3
S7 Combination of S1 and S2	1.5	0.5
S8 Radiative cooling-shading	1.8	0.4
S9 Parramatta Council implementation plan	0.6	0.1
S10 Parramatta Council design improvement	1.2	0.4

We have shown increasing greenery is the second less efficient strategy (after cool roof) in Phillip street compared to the other investigated technologies. The maximum local temperature reduction is about 0.6 °C in the City of Parramatta implementation plan (scenario 9) and 0.8 °C in the greenery scenario (scenario 2) while the local average temperature drop is about 0.1 °C. Results show that the average and maximum air temperature in Phillip Street may be reduced by 0.1°C by the City of Parramatta implementation plan (scenario 9), and 0.5°C by applying cool pavements as a strategy to improve scenario 9 (i.e. scenario 10).

Under heatwave condition, the surface temperature in Phillip Street mainly ranges between 45.9°C and 61.7°C being higher in the western parts. The area between Marsden Street and Church Street in Phillip St. presents very high surface temperatures exceeding 55°C, and the area between Church Street and Horwood Pl shows a temperature range of about 34.7°C to 53.6°C. By applying the combination of strategies (scenario 6), the surface temperature reduction achieved in Phillip St. varies from 8.4°C to 19.6°C under the shading device and exceeds 25.2°C under the shading provided by the trees. The surface temperature in Phillip street under the combined scenario mostly falls above 31.9°C and below 48.7°C.

The Universal Thermal Climate Index (UTCI) shows a very strong to extreme heat stress mainly ranging from 42 to 50°C. When we applied the combination of cool pavement, greenery, shading, spray system, and cool roof, UTCI and PET mainly varied from about 38°C to 45°C and 39.1°C to 48.4°C, respectively.

Winter Condition

Table 5 presents statistical summary of average, minimum and maximum temperature in Phillip St. for each scenario during winter condition. The local maximum and average reduction of ambient temperature in Phillip Street are provided in Table 6. The local air temperature drop (ΔT_a) is defined as the temperature difference between the reference scenario and the mitigated scenario in the same spot.

Table 5. Average, minimum and maximum temperature in Phillip Street for each scenario- Winter

Scenario	**Temperature** (°C) Max, T_{max}	**Temperature** (°C) Min, T_{min}	**Temperature** (°C) Average, T_{avg}
S000 Potential height/Future	16.8	14.8	15.7
S00 Planned height/Future	16.7	15.0	15.8
S0 Existing/unmitigated	18.1	14.9	16.0
S1 Cool pavement	17.9	14.8	15.8
S2 Greenery and tree	18.0	14.9	15.9
S3 Shading (shading cloth)	18.3	14.7	15.9
S4 Spray system	16.6	13.4	15.2
S5 Cool roof	17.9	14.7	15.9
S6 Combination of S1 to S5	15.7	13.4	14.8
S7 Combination of S1 and S2	17.8	14.8	15.7
S8 Radiative cooling-shading	18.3	14.6	15.8
S9 Parramatta Council implementation plan	18.0	14.5	15.9
S10 Parramatta Council design improvement	17.8	14.8	15.8

The average ambient air temperature for the reference case was 16.0 °C in Phillip St. during winter condition, and the maximum and minimum temperatures were 18.1°C and 14.9°C, respectively. During winter condition, the average temperature of the street is mostly reduced by 0.1 to 0.3°C by applying the investigated mitigation technologies. Combined scenario and water misting system are the only strategies that reduce average air temperature of Phillip St. to 14.8°C and 15.2°C respectively. The future development (building height and density) lead to lower ambient temperatures compared to the existing scenario (scenario 0). This can be explained by the overshading of the streets by high-rise buildings in the City of Parramatta and Phillip Street. Further, wind speed and direction affect the microclimate condition of the street during winter.

The maximum local air temperature reduction ranges between 0.2 °C for cool roof, and 4.4 °C for the scenario of combining cool pavement, greenery, shading, spray system, and cool roof. Cool roof followed by greenery, cool pavement, and shading have minimal impacts on lowering the ambient temperature during winter. Misting system has a strong local effect and reduces the minimum and average air temperatures by 1.5 °C and 0.7 °C, respectively. The maximum reduction of the local ambient temperature reaches to 4 °C by applying water-based system.

Table 6. Average and maximum temperature difference between each mitigation scenario and the reference scenario for Phillip Street – Winter condition

Scenario	MAX ΔT(°C) mitigation -ref	Avg ΔT (°C) mitigation -ref
S1 Cool pavement	0.8	0.2
S2 Greenery and tree	0.6	0.1
S3 Shading (shading cloth)	1.1	0.1
S4 Spray system	4.0	0.8
S5 Cool roof	0.2	0.1
S6 Combination of S1 to S5	4.4	1.2
S7 Combination of S1 and S2	1.1	0.3
S8 Radiative cooling-shading	1.0	0.2
S9 Parramatta Council implementation plan	0.4	0.1
S10 Parramatta Council design improvement	0.8	0.2

Under winter condition in the unmitigated scenario, the surface temperature in Phillip St. mainly ranges between 14.1°C and 28.1°C. Corner of Marsden Street, Church Street, and Smith Street in Phillip St. present higher surface temperatures than other parts of the street. The wind speed falls below 2.25 m/s in Phillip St. The areas between Smith Street and Charles Street illustrate lower wind speed values mostly below 1.8 m/s. the City of Parramatta CBD and Phillip St. experience no heat stress during winter condition. The Universal Thermal Climate Index (UTCI) mostly falls below 14.65°C between Church Street and Horwood Pl and areas between Smith Street and Charles Street. UTCI in the other parts of Phillip St. mainly varies between 24.9°C and 27.4°C.

After application of the combined scenario (scenario 6), the surface temperature in Phillip Street mostly falls below 22.5°C and above 10.5°C. Phillip Street indicates no heat stress with UTCI and PET mostly falling below 27.4°C during winter condition. These comfort indices are reduced under the combined scenario to lower values below 17.2°C due to the impacts of mitigation technologies.

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LOW CARBON LIVING CRC

5. CONCLUSIONS

Conclusions

In the following the main conclusions of the study are summarised.

Local climate measurements in the area of Phillip St., Parramatta

1. The results obtained by the terrestrial and aerial survey have been used to assess the microclimate of Phillip St. and its close surrounding and to identify hot spots in the area.
2. On the 02/12/2018, the air temperature registered at 10 m height for the entire duration of the terrestrial survey and in the central area of Phillip St. produces the following results:
    - Maximum temperature equal to 34°C around 12:30 pm and 3:30 pm;
    - Average temperature equal to 33°C;
    - Minimum temperature equal to 30°C around 10 am.

   In the same location, at 1.5 m height, higher value of air temperature (of approximately 0.4°C) are recorded due to the influence of the close surfaces of the built environment that store and release the accumulated heat in the air.
3. An average albedo of 0.15 has been calculated for the asphalt in the proximity of the EnergyBus thanks to the monitored incoming and reflected solar radiation.
4. On the 02/12/2018, the average wind speed of 3.3 m s^{-1} and 3.7 m s^{-1}, and absolute maximum wind speed of 12.8 m s^{-1} and 15.3 m s^{-1}, have been calculated respectively at 10 m and 5 m in the central area of Phillip St., Parramatta. The data recorded at 1.5 m show lower speed value with respect to the data registered at 10 m, due to the presence of trees and buildings that slow down the wind flow.
5. On the 02/12/2018, low values of relative humidity, ranging between 20% and 30%, have been recorded at 10 m height in the central area of Phillip St., Parramatta.
6. During the summer day 02/12/2018, the Eastern part of Phillip St. showed, up to 1.0 °C in average, higher temperature than the Western part during the peak hours of the day. This is mainly due to the presence of Parramatta river that can cool down its surrounding for evapotranspiration. Possibly, an additional influence can be the refreshing sea breeze in the Eastern part of Parramatta, and the impact of possible warm Western winds in the Western part of the city.
7. The surface temperature of low albedo asphalt used to cover the entire Phillip St. reaches to above 50 °C in unshaded areas.
8. The surface temperature of low albedo tiles and terracotta tiles used to cover pavement areas of Phillip St. reaches to above 40 °C in unshaded areas.
9. The slow-motion thermal video (for the 02/12/2018) and the 3D thermal model (for the 03/02/2019) confirm the same observations about the surface temperature of the urban surfaces of Phillip St., Parramatta.

Simulation of the climatic scenarios-assumptions

1. From all simulations performed under three different conditions, such as mean maximum, heatwave and winter conditions, it emerges that Western part of Phillip St., Parramatta, presents higher air temperatures than Eastern part, confirming the monitoring results.
2. Ten mitigation scenarios have been simulated under the three conditions above and most of them (e.g., solar control, cool pavements, and greenery) demonstrated a positive cooling potential during the warm season and negligible effect during the cool season.

3. The maximum reduction of ambient temperature achieved under combined scenario (e.g., combination of cool pavement, greenery, shading, spray system, and cool roof) is 6.4°C, 6.7°C, 4.4°C during mean maximum, heatwave, and winter conditions, respectively.
4. Under the mean maximum condition, the average ambient air temperature for the unmitigated scenario in Phillip St. was 32.6 °C and the maximum and minimum temperatures were 35.1°C and 30.7°C, respectively. By applying proper mitigation technologies, the average, maximum and minimum air temperature may be reduced to 31.3°C (e.g., combined scenario), 33.2°C (e.g., combined scenario), and 29.2°C (e.g., combined scenario), respectively.
5. Under the mean maximum condition in summer, the combining scenario (e.g., combination of cool pavement, greenery, shading, spray system, and cool roof) produces the maximum values for both the average and maximum air temperature reduction (e.g., 1.3°C and 6.4°C, respectively), followed by the scenario with the implementation of spray systems and water (e.g., 0.5°C and 5.1°C).
6. Under the mean maximum condition in summer, cool pavement, shading (solar control), water technologies (misting system), and combination of different strategies are the most effective solutions to improve comfort in Phillip St.
7. Under the heatwave condition, the average ambient air temperature for the unmitigated scenario in Phillip St. was 38.7°C and the maximum and minimum temperatures were 43.0°C and 36.4°C, respectively. By applying proper mitigation technologies, the average, maximum and minimum air temperature may be reduced to 38.2°C (e.g., water scenario), 37.4°C (e.g., combined scenario), and 35.0°C (e.g., combined scenario), respectively.
8. Under the heatwave condition, the combining scenario (e.g., combination of cool pavement, greenery, shading, spray system, and cool roof) produces the maximum values for both the average and maximum air temperature reduction (e.g., 1.3°C and 6.7°C, respectively), followed by the scenario with the implementation of spray systems and water (e.g., 0.6°C and 5.4°C).
9. From the comfort analysis, Phillip St. presents from a moderate to very strong heat stress under the mean maximum condition in summer and from a very strong to extreme heat stress under the heatwave condition.
10. Under the winter condition, the average ambient air temperature for the unmitigated scenario in Phillip St. was 16.0°C and the maximum and minimum temperatures were 18.1°C and 14.9°C, respectively. By applying proper mitigation technologies, the average, maximum and minimum air temperature may be reduced to 14.8°C (e.g., combined scenario), 15.7°C (e.g., combined scenario), and 13.4°C (combined scenario and water scenario), respectively.
11. The combined scenario is very effective in reducing surface temperature of the street and pavements under the three investigated conditions.

Further investigations

In the following section are listed further investigations that worth to be done.

1. A continuous microclimate monitoring in several key spots along Phillip St. will help to fully understand the local microclimate in real-time and its influence on the pedestrians' thermal comfort.
2. A smart continuous monitoring will allow to better understand the local microclimate, but also to interact with the daily decisions of pedestrians by producing useful real-time information and advices customized specifically for Phillip St. Thanks to the use of apps specifically developed to increase awareness on the impact produced by the

thermal discomfort and inform people on adaptation, mitigation strategies, and heat safe habits, pedestrians will be protected from the more frequent heat waves and extreme climate events.

3. The real implementation of the combined scenario or of a combination of specific mitigation strategies in the identified hot spots will help to improve the thermal comfort for pedestrians especially under predicted future climate conditions.
4. A thermal survey carried out along Phillip St. under different weather conditions and instants of time along the day could provide real data regarding the pedestrians' thermal sensation and useful feedbacks for improvement.
5. An increase of the shaded area (thanks to the implementation of vegetation or shading devices), especially in correspondence of the hot spots along the Phillip St., will improve the thermal comfort and the livability of the area significantly.
6. The integration of shading devices combined with radiative cooling materials and greenery along the sidewalks, public squares, and pedestrian areas will improve furthermore the thermal comfort for pedestrians that will use the public space with more pleasure, spending more time outside and preferring local business activities.
7. Cool asphalt even in the same color than the traditional asphalt, should be implemented along the entire Phillip St. The recommended albedo for a new asphalt product is 0.4, that corresponds to an average albedo of 0.15-0.2 after the use.
8. New and existing trees or green coverage need to be continuously maintained and, more important, well irrigated to guarantee a cooling effect.
9. Intervene in Phillip St. by applying cooling strategies, together with smart monitoring, and innovative technologies, especially in the prospective to redevelop the surrounding area, will enhance the importance of the area allowing more truism and economic interest.
10. Phillip St. has the potential to become a climate demonstration project from where to collect microclimatic data, test new climate technologies and mitigation strategies, and monitored the progress achieved in terms of climatic performance. This information can be used to promote climate adaptation in outdoor space through an education and information system specifically for the City of Parramatta.
11. Developing other climate demonstration projects in open spaces all around the City of Parramatta is an important step to promote the climate adaptation and prevent the current and future negative implications produced by the urban overheating, climate change and extreme heat events.