Pre-submission report - (Improved) micro-climate modelling assessment of the influence of water sensitive urban design on human thermal comfort

A thesis submitted for the degree of

Doctor of Philosophy

by

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Abstract

With urban areas facing future longer duration heat-waves and temperature extremes, adaptation strategies are needed. Examining the role that increased tree cover and water availability can have on human thermal comfort (HTC) in urban areas as part of these strategies has been done using observations, but further work requires a modelling tool suited for this task. Sufficient model resolution is needed to resolve variables used to calculate HTC as well as the ability to model the physiological processes of vegetation and their interaction with water. The lack of such a tool has been identified as a research gap in the urban climate area and has impaired our ability to fully examine the use of vegetation and water for improved human thermal comfort.

A new model, VTUF-3D (Vegetated Temperatures Of Urban Facets), addresses this gap by embedding the functionality of the MAESPA tree process model (Duursma & Medlyn 2012), that can model individual trees, vegetation, and soil components, within the TUF-3D (Krayenhoff & Voogt 2007) urban micro-climate model. An innovative tiling approach, allows the new model to account for important vegetative physiological processes and shading effects. It also resolves processes at sufficiently high resolution to calculate HTC and air and surface temperature, humidity, and wind speed across an urban canyon.

Model validations have shown performance improvements of the model and a suitability to use it to examine critical questions relating to the role of vegetation and water in the urban environment. Preliminary scenarios of differing amounts of urban vegetation show differences of UTCI of 1.0°C are possible. Further analysis using this model includes scenarios quantifying the impact each individual tree can have on temperatures in urban canyons as well the optimal arrangement and quantity of trees to maximize temperature moderation effects.

Chapter 1

Introduction (excerpt)

1.2.10 Goals of modelling the benefits of WSUD

Some rough estimates can be drawn about how much cooling can be expected from adding urban greenery. Modelling can be attempted, but as will be shown in the literature review, no modelling tool exists yet to examine a wide variety of WSUD scenarios at a human scale (micro-climate scaled) to determine HTC benefits in urban areas. Observational studies are important to give an understanding of the processes within urban areas and to provide baseline validation data sets for models. However, collecting observational data is time consuming and difficult. More importantly, observations can only be used to study existing urban morphologies. Modelling tools are required to study different scenarios and new variations of features of an urban area (buildings and materials and orientations, vegetation, surface types, and water features) to find optimal arrangements and determine best practice for their usage for HTC benefits in urban areas. Therefore, quantifying the positive climatic impacts of WSUD on HTC in urban areas at a micro-climate level requires a new tool set to be created and validated. After the tool is ready, it can be used in a systematic assessment of scenarios to determine the micro-climatic advantages of different WSUD features in a variety of urban configurations.

1.2.11 Research objectives

In order to achieve this aim, a number of objectives will need to be completed. The key research objectives proposed for this project are:

1. **Preparation of a modelling tool to model specialised requirements of WSUD features for HTC at a micro-scale level.**

   Needs to:

   - Predict climate parameters in 3-D urban environments.
   - Accurate predictions of mean radiant temperatures in complex urban geometry.
   - Capture the processes driving energy and water budgets of urban climates (section **??**) and interactions of the three layers of soil, plants, and atmosphere (section **??**) and their interactions with buildings and urban surfaces.
   - Predict at a sufficient resolution (micro-scaled) to resolve human interactions with their surroundings and supply necessary parameters to calculate human thermal comfort index values.
   - Contain functionality to directly model or parameterise a variety of WSUD features.

2. **Validations and assessments follow to determine level of model improvement** over existing models and the suitability to accurately capture important dynamics of WSUD and assess HTC improvements.

   - Test VTUF-3D's ability to model the Coutts et al. (2007) Preston (Melbourne, Australia) data set, using predicted energy flux comparisons as a measurement of accuracy.
   - Model the three scenarios of White et al. (2012) (George St., Gipps St., and Bourke St.) over a number of representative days using temporal and spatial observed UTCI and Tmrt values as a measurement of accuracy.
   - Use the Motazedian (2015) Lincoln Square transits and observations of Tsfc and UTCI as a validation of VTUF-3D's spatial predictions accuracy.
   - Use the White et al. (2012) observation campaign to study a single isolated tree, a Queensland Brush Box (*Lophostemon confertus*) to validate VTUF-3D's ability to model this widely used street tree.
   - Use the Gebert et al. (2012) tree study campaign data to validate VTUF-3D's ability to model WSUD based tree pits.

3. **Determine the impact of WSUD treatments on HTC comfort at a micro-scale in urban areas.**

   Assess:

   - Modifications of temperatures (air and radiant) as well as HTC indexes (PMV, UTCI, etc), spatially and temporally at a micro-climate scale through the implementation of vegetation and WSUD features.
   - The effectiveness of WSUD features in moderating effects of heat waves and temperature extremes.
   - Optimal arrangements of WSUD features to maximise the cooling benefits at least cost using present and possible future urban morphologies.
   - Synthesise guidelines for WSUD usage to most effectively promote human thermal comfort at a micro-scale in urban areas.

   Run scenarios:

   - Run basic tree cover variation scenarios based on the validation scenarios, examining the impact of varying amounts of tree canopy on HTC in these domains.
   - Conduct sensitivity study using amount of vegetation, location of vegetation, characteristics of vegetation (tree height, leaf area index, number of trees, height, and tree placement), and soil moisture levels to isolate the most important parameters.

Chapter 3

Methodology (excerpt)

3.3 Proposed thesis outline

The thesis will follow the following outline:

Chapter 1 : Introduction

Chapter 2 : Literature review and identification of key modelling processes

Chapter 3 : Methodology

Chapter 4 : Modifications to TUF-3D urban micro-climate model to support assessments of WSUD influences on HTC at a micro-scale in urban canyons.

Chapter 5 : Validation and assessment of improved performance of the VTUF-3D model to model urban areas.

Chapter 6 : A systematic assessment of WSUD scenarios and urban morphologies using newly improved VTUF-3D model in support of HTC at a micro-climate level in urban areas.

Chapter 7 : Discussion.

Chapter 8 : Conclusion.

Chapter 9 : References.

3.4 Progress and timetable

This project is expected to be completed over three and a half years (Table 3.1).

Table 3.1: *Proposed project time-line*

Date	Progress/Events
January 2012	Cities as Water Supply Catchments, Project 3: Green Cities and Micro-climate report, 'Urban climate model selection for modelling WSUD features'
February 2012	7th International Conference on Water Sensitive Urban Design presentation, 'The micro-climate of a mixed urban parkland environment'
April 2012	Official candidature start date
April-October 2012	Literature review and planning
May 2012	Cities as Water Supply Catchments Industry Partner Workshop presentation, 'Urban climate model selection for modelling WSUD features'
August 2012	ICUC8 Conference presentation, 'A consideration of Water Sensitive Urban Design (WSUD) modelling strategies'
October 2012	Confirmation of candidature
February 2014	AMS 2014 conference poster, 'An urban micro-climate model for assessing impacts of Water Sensitive Urban Design'
October 2012-March 2015	'Modifications to TUF-3D urban micro-climate model to support assessments of WSUD influences on HTC at a micro-scale in urban canyons.' (Chapter 4)
July 2014	Mid-candidature
October 2014	An urban micro-climate model for assessing impacts of Water Sensitive Urban Design. In: Water Sensitive Cities Conference 2014. 21-23 October, 2014 - Melbourne, Australia. Poster
July 2015	VTUF-3D: An urban micro-climate model to assess temperature moderation from increased vegetation and water in urban canyons. In: ICUC9 - 9th International Conference on Urban Climate 2015. 20-24 July 2015 - Toulouse, France. Presentation
September 2015	VTUF-3D: An urban micro-climate model to assess temperature moderation from increased vegetation and water in urban canyons. In: 2nd Water Sensitive Cities Conference 2015. 8-9 September 2015 - Brisbane, Australia. Poster / Presentation
March 2015 - October 2015	'Validation and assessment of improved performance of the VTUF-3D model to model urban areas.' (Chapter 5)
October 2015 - December 2015	'A systematic assessment of WSUD scenarios and urban morphologies using newly improved VTUF-3D model in support of HTC at a micro-climate level in urban areas.' (Chapter 6)
October 2015-January 2016	Writing
January 2016	Submission

Chapter 4

Modifications to TUF-3D urban micro-climate model to support assessments of WSUD influences on HTC at a micro-scale in urban canyons (excerpt)

4.2 Design overview

4.2.1 VTUF-3D energy balance modelling with MAESPA tiles

- Modifications to TUF-3D (Krayenhoff & Voogt 2007) to resolve urban canyon radiation flux movement using placeholder vegetation structures which call MAESPA (Duursma & Medlyn 2012) vegetation absorption, transmission, and reflection routines.
- VTUF-3D uses cube shaped structures (as TUF-3D uses to represent buildings) to represent vegetation. These cubes store the surface properties and states and interact with the rest of the VTUF-3D domain.
- The vegetation's true shape is represented in MAESPA and calls underlying MAESPA routines to calculate the vegetation's interactions with the urban canyon and radiation movement (Figure 4.1).

- Using a novel approach, MAESPA tiles replaces VTUF-3D ground surfaces with vegetated MAESPA surfaces and use MAESPA's photosynthesis and water cycle routines to modify VTUF-3D's energy balance calculations.
- Each embedded MAESPA surface calculates a full 3 dimensional tree (along with associated soil and movement of water within the stand) and feeds results back to VTUF-3D ground surface energy balances (Figure 4.2.

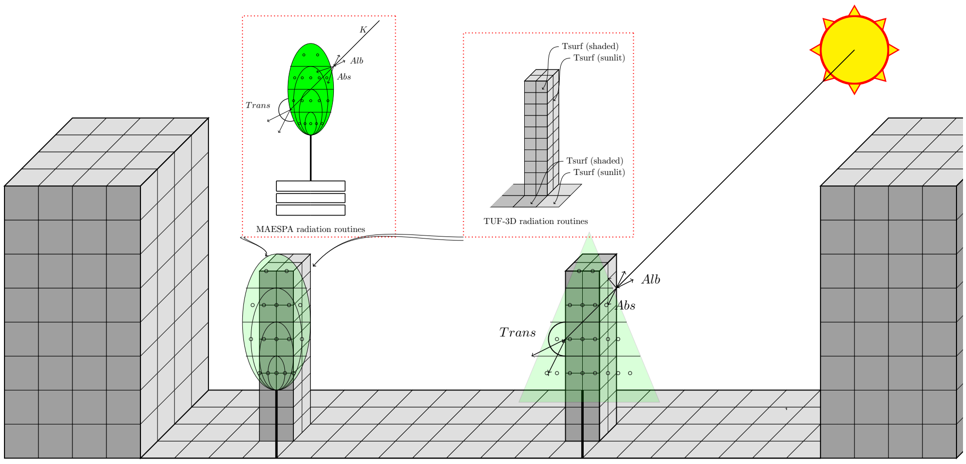

Figure 4.1: *Integration of MAESPA tree model into VTUF-3D radiation fluxes routines*

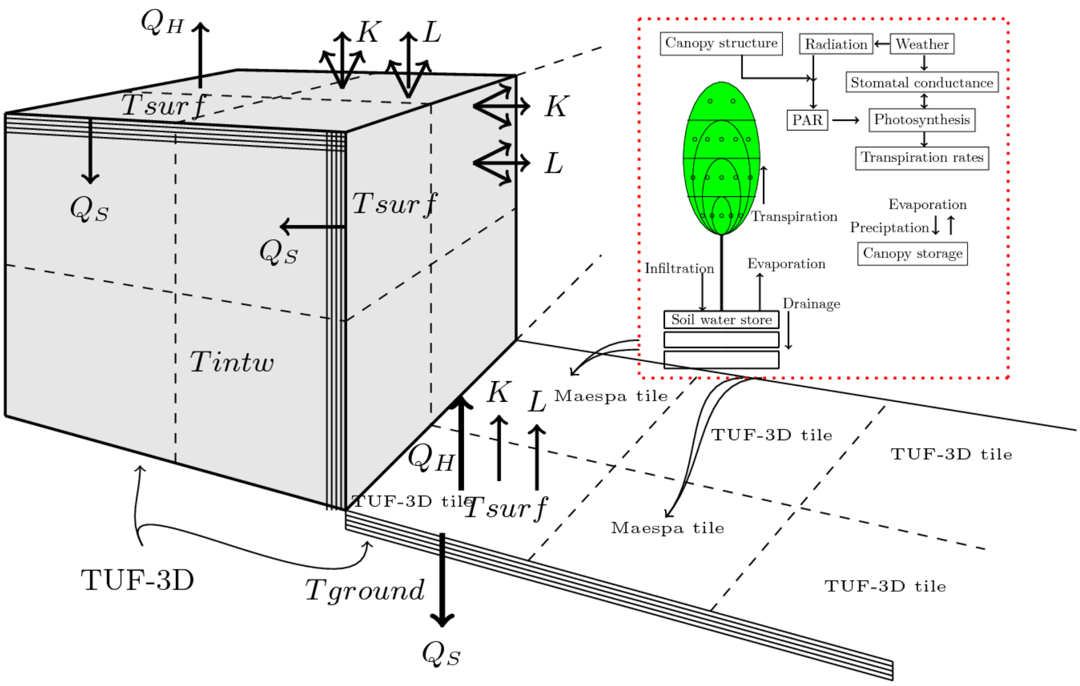

Figure 4.2: *VTUF-3D energy balance modelling with vegetation MAESPA tiles*

Chapter 5

Validation and assessment of improved performance of the VTUF-3D model to model urban areas

5.1 VTUF-3D Validation Details

5.1.1 Overview of validation process

In order to ensure VTUF-3D can make accurate predictions, an extensive validation process was undertaken. A variety of observation data sets allowed validations of a number of different aspects of the model. A validation matrix (Table 5.1) details the specific validations for each data set. These include validations against observations of air temperature (Ta) and canopy temperatures (Tcan), UTCI human thermal index observations (which include Tmrt observations), evapotranspiration (ET) and tree physiological observations, and flux (energy balance) observations.

Items in table cells colored green have completed validation. Those cells colored yellow are still in progress. Cells colored red have not been started and are still awaiting the observations to be finalized.

Table 5.1: *VTUF-3D validation matrix*

Scenario	Ta	Tcan	UTCI	ET	Energy balance
Preston (Coutts et al. 2007)					
Gipps/George St, Melbourne (Coutts et al. 2015)					
Lincoln Sq, Melbourne (Motazedian 2015)					
Hughesdale					
Smith St, Melbourne (Gebert et al. 2012)					

5.1.2 Model testing and validation using Preston dataset

Validations using the Preston data set were undertaken. Preston is a homogeneous, medium density suburb in the northern part of Melbourne, Australia. The data set contains complete flux observations recorded 2003-2004 (Coutts et al. 2007) from a 30 meter flux tower, allowing validation of surface energy balances against modelled predictions.

Figure 5.1: *Preston suburb and modelled area (Google 2015)*

The modelled area (500x500m, Figure 5.2) was chosen to be representative of the overall area observed by flux tower. The mix of vegetation types modelled (Figure 5.4), consisting of grass (18.5%), olive (*Olea europaea*) and brushbox (*Lophostemon Confertus*) trees (7.25%), match closely to published values for data set. Modelled building densities (Figure 5.3), consisting of 46.75% buildings and 27.5% impervious surfaces, also match closely to published data set values. Domain resolution is 5m grids.

Figure 5.2: *Digitization of Preston suburban street. (**1**=building heights, **1**=vegetation heights)*

30 days of simulation were run between the dates 10 February 2004 and 10 March 2004, forced by the observations for those days. Individual fluxes (*Rnet*, *Qh*, *Qg*, *Kdn*, and *Qe*) were aggregated into hourly averages over the 30 days and compared to the observations (Figure

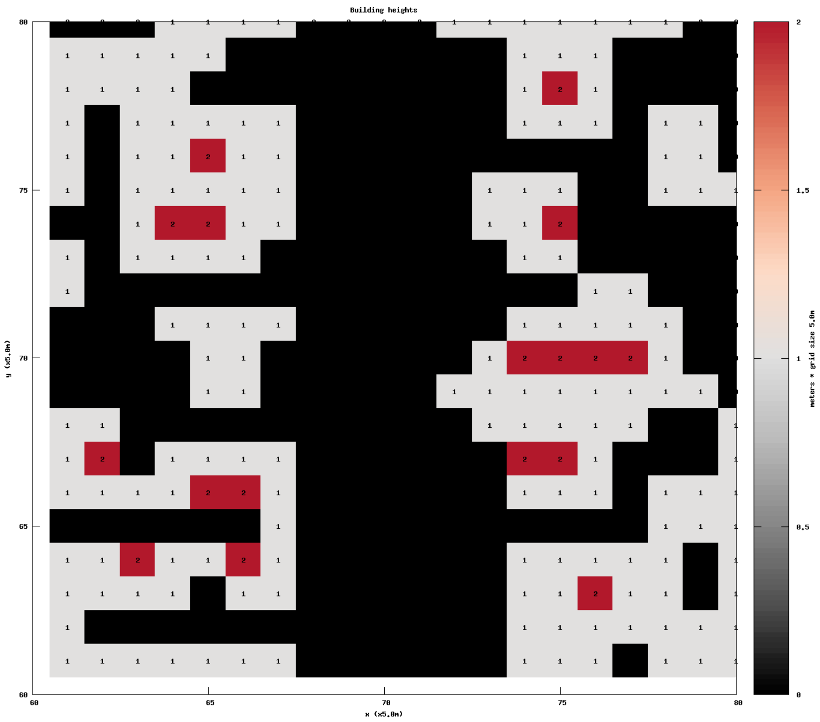

Figure 5.3: *Building heights (0, 5, 10m)*

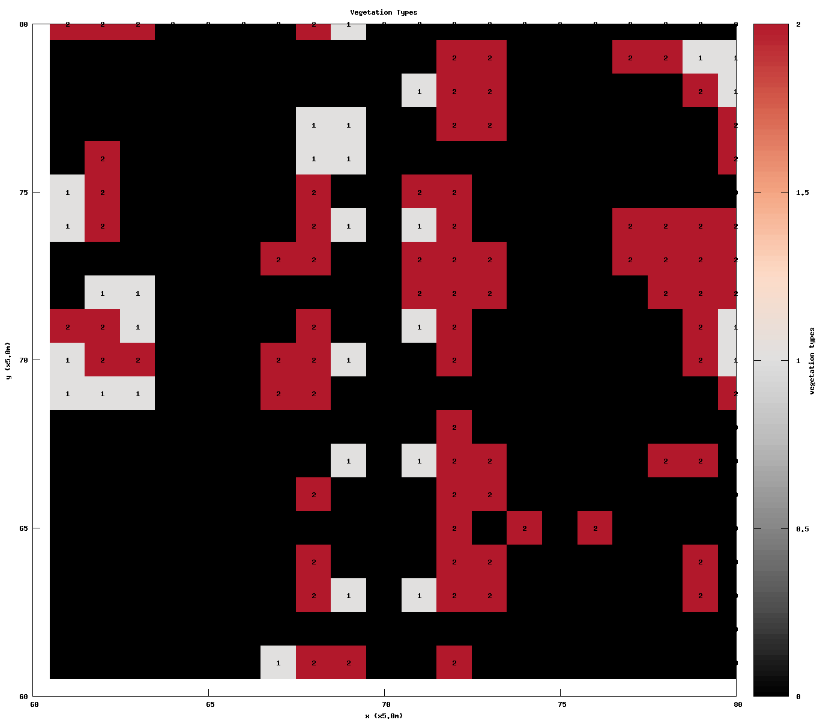

Figure 5.4: *Vegetation heights (0, 5, 10m)*

5.5). All fluxes performed well, except for a slight over prediction of Qe during the afternoons and a slightly large under prediction of Qg during the days and under prediction during the nights. More examination is needed to try and increase the accuracy of these predictions. This open task is noted in Appendix .1.1.

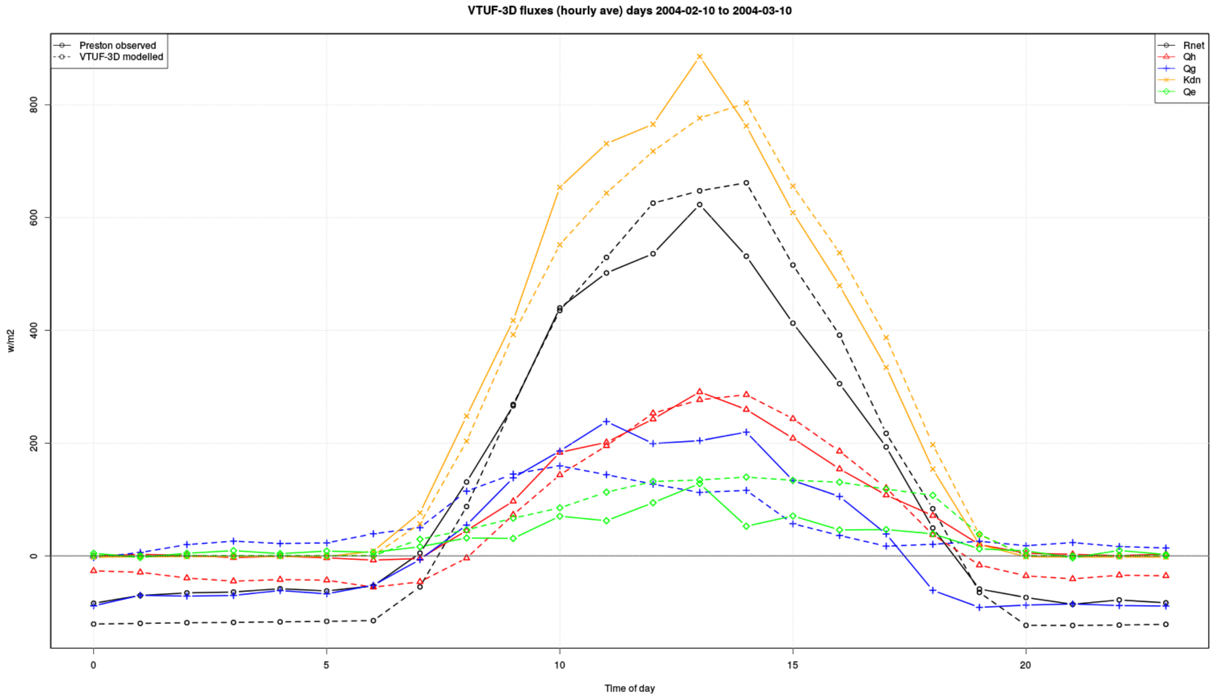

Figure 5.5: *30 day hourly average VTUF-3D flux comparisons to Preston flux observations*

Ground storage observations might be more problematic, as they are calculated as residuals in the observations and contain the sum of all the observational errors (NEED CITE), more work is needed to determine if the model predictions are accurate but just being compared to less accurate observations. Energy closure ($Q* - Qg - Qh - Qe = 0$) for the 30 day run (Figure 5.6) shows a slight energy loss through the run. More examination is needed to improve this as well (Appendix .1.1).

5.1.3 George and Gipps St

Model testing and validation using City of Melbourne, George and Gipps St datasets

A second set of validations was undertaken using observations from George St. and Gipps St. in the City of Melbourne (Coutts et al. 2015). These observations were taken at a number of observation stations, recording air temperature, wind speed, humidity, and incoming short wave, located along the two streets. Observation data set also contains values for Tmrt and UTCI for each observation station.

Station locations, noted on Figure 5.7 as yellow pins (and station name, EM12, EM9, etc.), also shows the modelled domains. Both streets (George St. and Gipps St.) are shallow urban canyons (average building heights 7 and 8m, H:W 0.32 and 0.27) with varying canopy cover (45% and 12%). These domains were configured accordingly (Figure 5.8). The model was run for both streets for the period 1 February 2014 to 1 March 2014. Domain resolution is 5m grids.

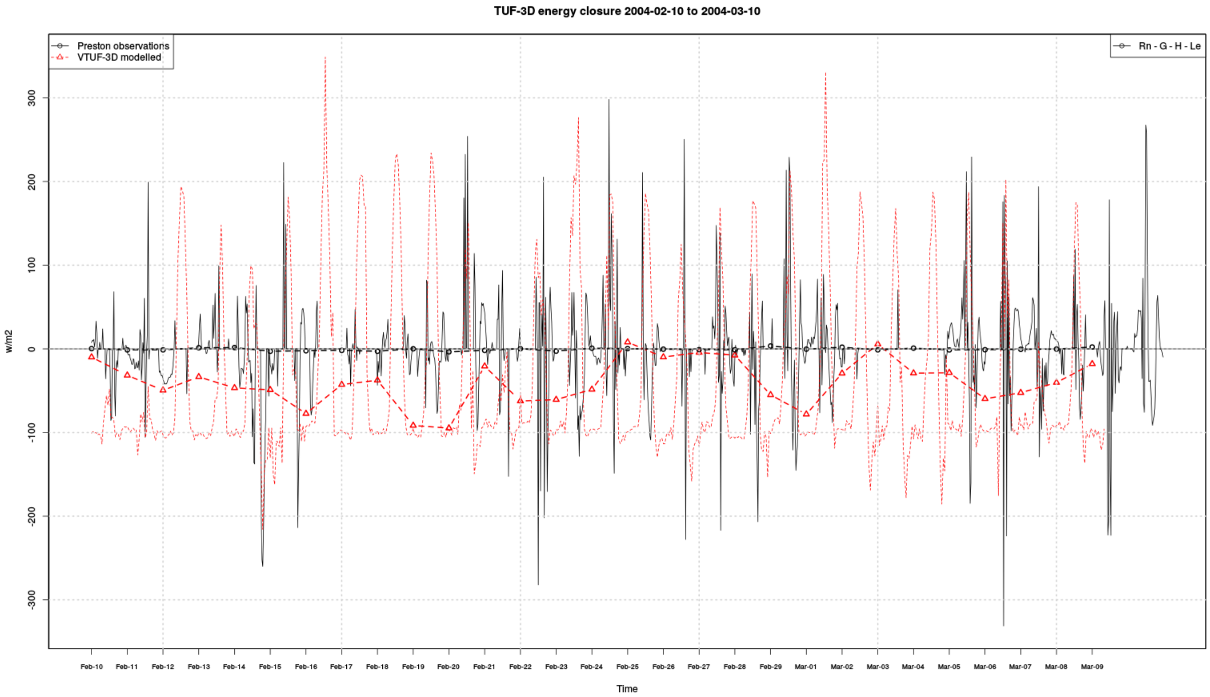

Figure 5.6: *Preston energy closure (VTUF-3D and observations),* $Q* - Qg - Qh - Qe = 0$

Figure 5.7: *George St/Gipps St - Modelled domains with 4 and 3 observation stations located on street*

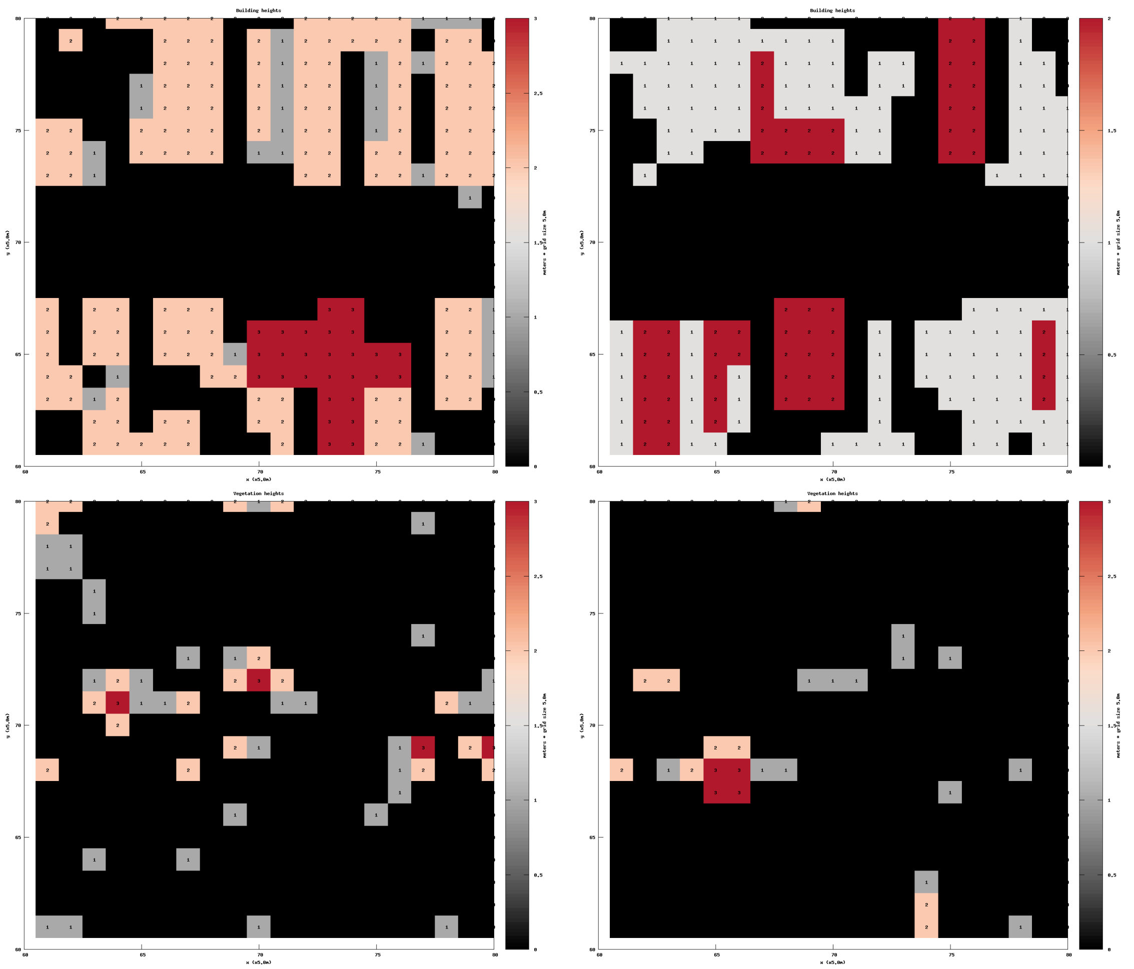

Figure 5.8: *Building heights (top) / Vegetation cover (bottom) - George St (left), Gipps St. (right)*

Energy closure for George St. (Figure 5.9) also shows some energy loss during the modelled period. Further work will address this issue.

The modelled results of Tmrt and UTCI (Figure 5.10) show only the 0m surfaces and remove the building structures. The four observation station values are annotated on these figures, showing the model broadly reproduces the spatial patterns in the urban canyon.

In a point by point comparison, using 30 day hourly averages (Figure 5.11), the model over predicts Tmrt during the day and under predicts it at night. This leads to UTCI, which is calculated from the Tmrt, also reflecting those patterns. More work on improving the Tmrt calculations is another item on the future improvement list (Appendix .1.1).

In the Gipps St. validation, the energy balances (Figure 5.12) are much closer to full closure.

With Gipps St., validations against spatial values of Tmrt and UTCI (Figure 5.13) show broad agreement. Point to point comparisons of 30 day hourly averages (Figure 5.14) show the same patterns as George St. in Tmrt and UTCI.

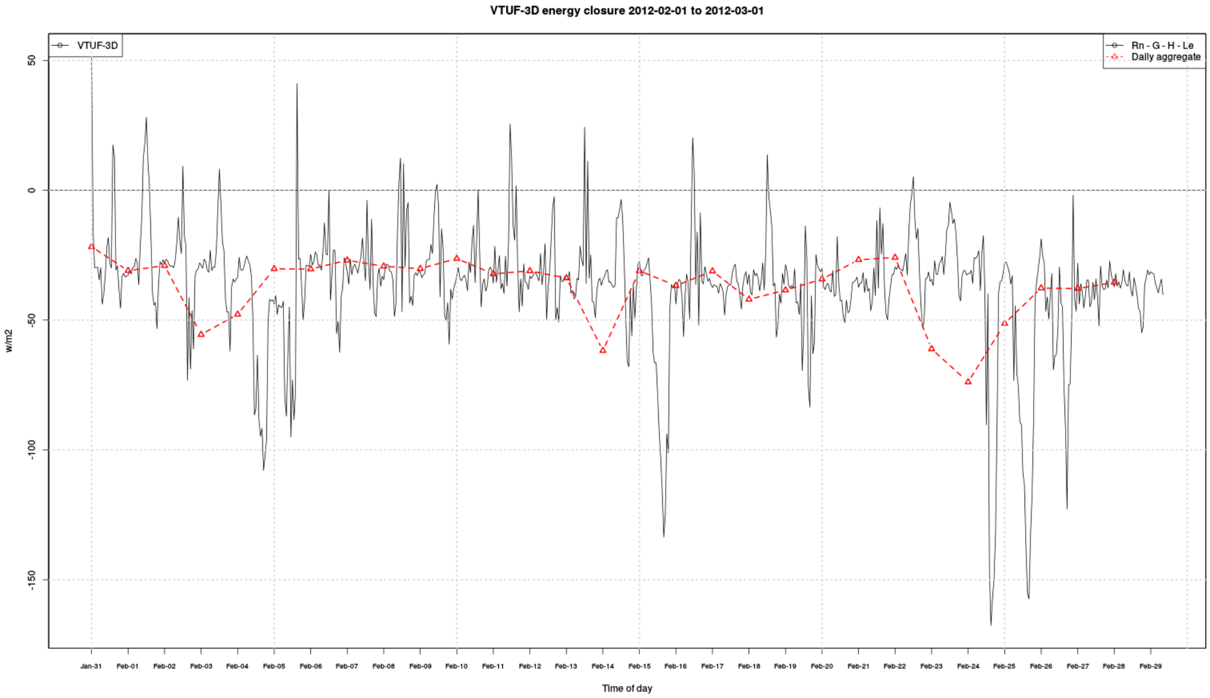

Figure 5.9: *Energy closure of George St*

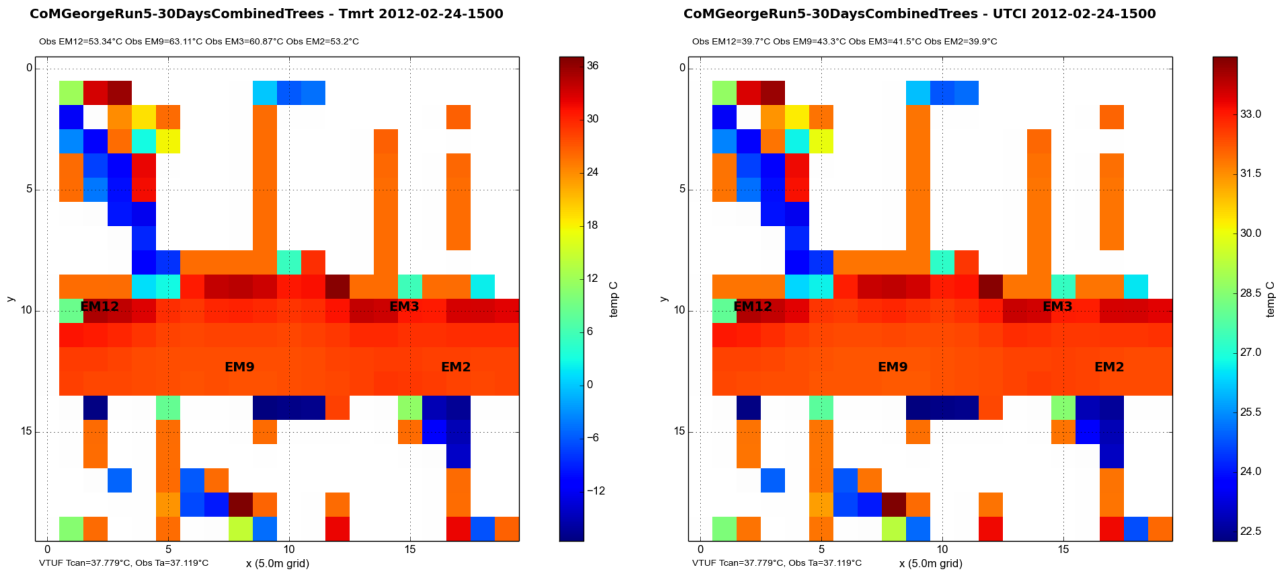

Figure 5.10: *Results of George St. Tmrt and UTCI for 24 February 2014 1500.*

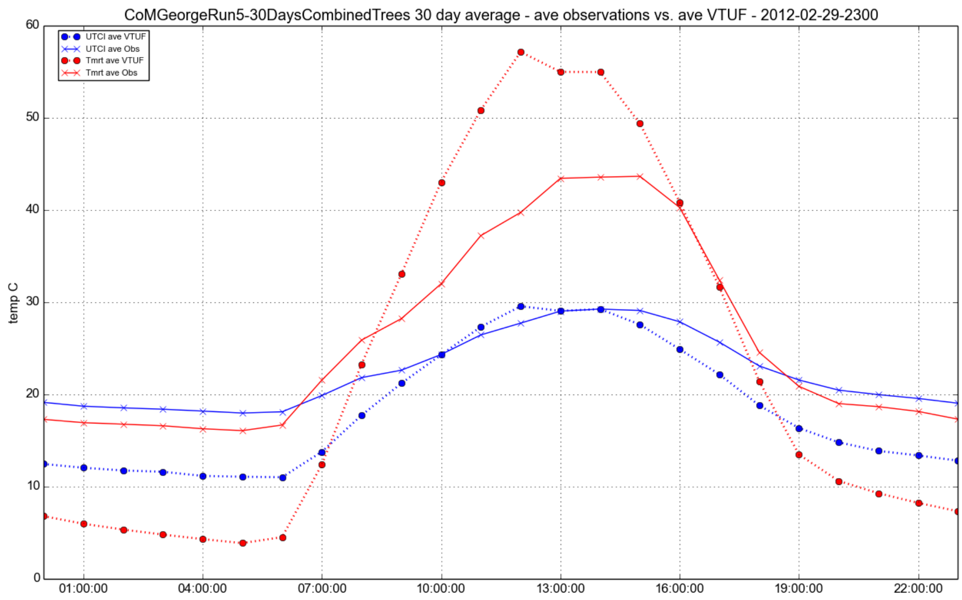

Figure 5.11: *George St. point comparison of 4 averaged observation stations to modelled points*

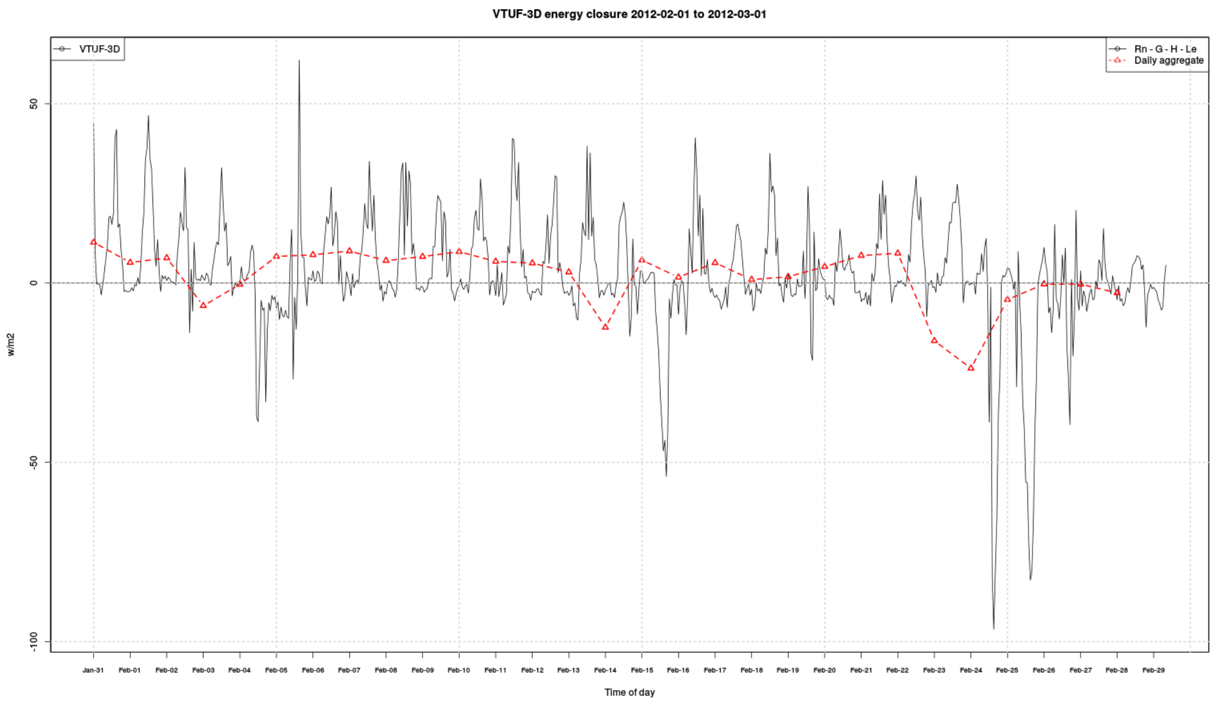

Figure 5.12: *Energy closure of VTUF-3D and observations for Gipps St.*

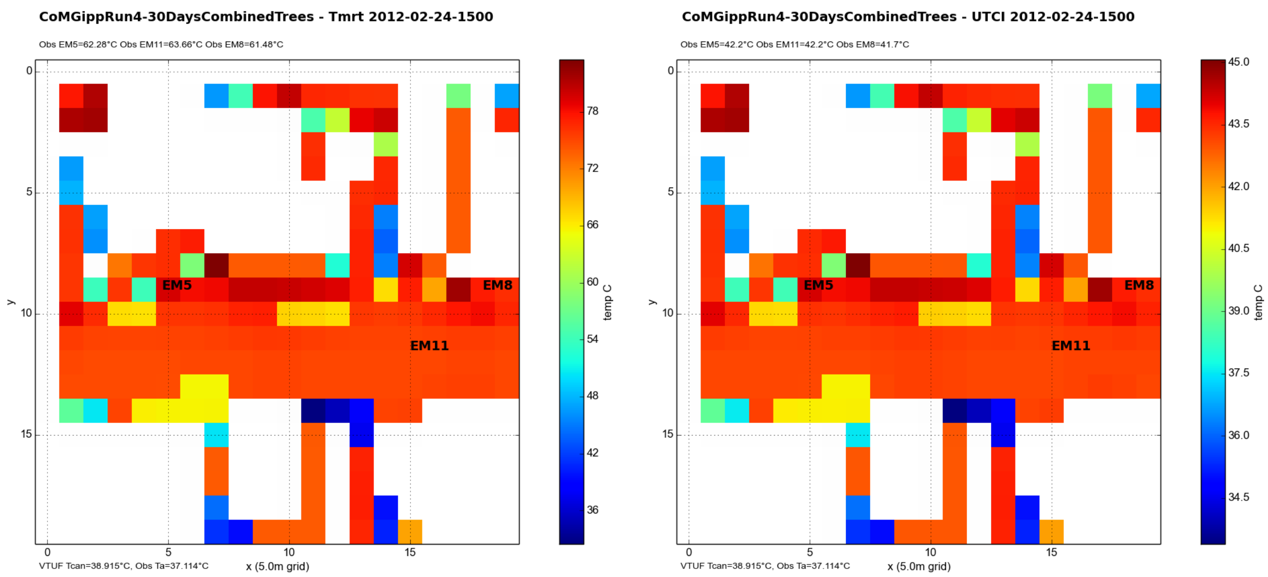

Figure 5.13: *Gipps St. VTUF-3D Tmrt and UTCI for 24 February 2014 1500, annotated with observation values.*

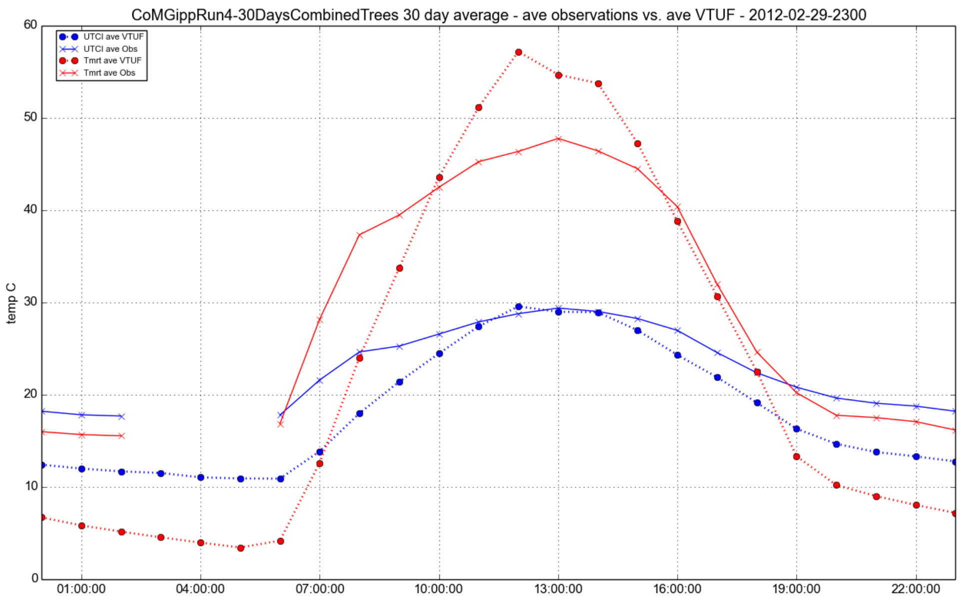

Figure 5.14: *Gipps St. averaged comparison of 3 observations stations to modelled points*

5.1.4 Model testing and validation using Lincoln Sq dataset

A third set of validations was run against the Lincoln Square data set (Motazedian 2015). This is a Melbourne urban square (Figure 5.15) with a mix of open grass and mature trees (Figure 5.17) within a dense urban canyon (Figure 5.16). Domain resolution was 10m grids.

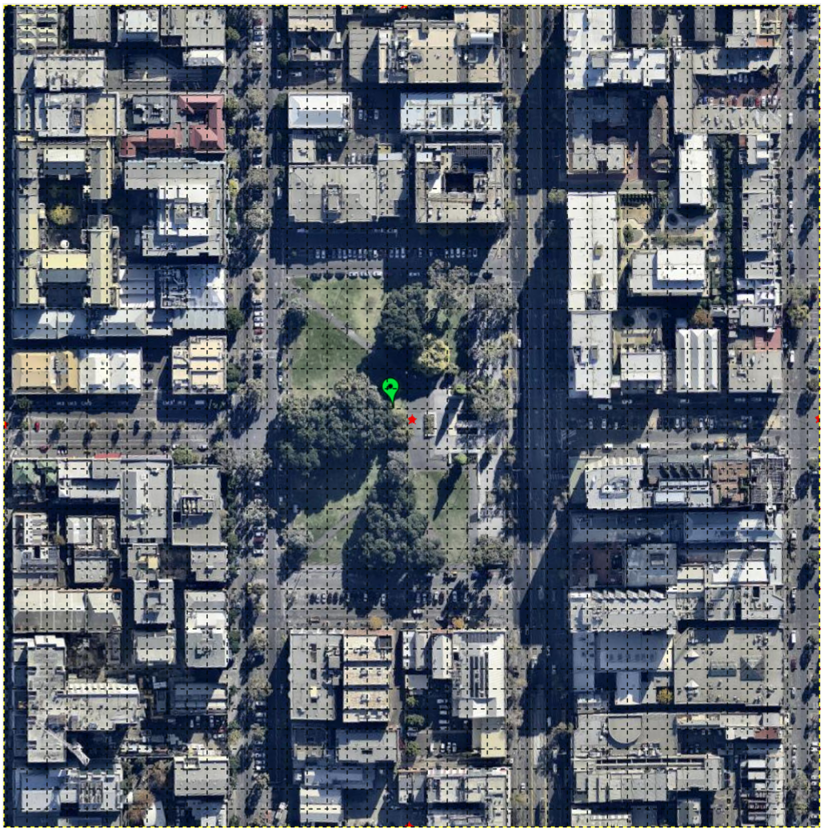

Figure 5.15: *Lincoln Square domain*

The modelled results were compared to transits of Tsfc (Figure 5.18) and UTCI (Figure 5.19) and showed broad agreement with the spatial patterns in the observations.

5.2 Future tasks

5.2.1 Model testing and validation using Hughesdale dataset

Future validations are to be done against the Hughesdale data set. These observations are currently being recorded and finalized. Hughesdale (Figure 5.20) is a medium density homogeneous suburb in the south east of Melbourne, Australia. These observations will include evapotranspiration and other tree physiology observations in addition to climate (air temperature, humidity, shortwave radiation, and wind speed) observations.

5.2.2 Model testing and validation using Smith St dataset

A final set of validations are to be done against the Smith Street data set (Gebert et al. 2012). This is an inner suburb of Melbourne, Australia. This street is a higher density/retail area, with a high percentage of impervious surfaces and very sparse tree cover. Observations were

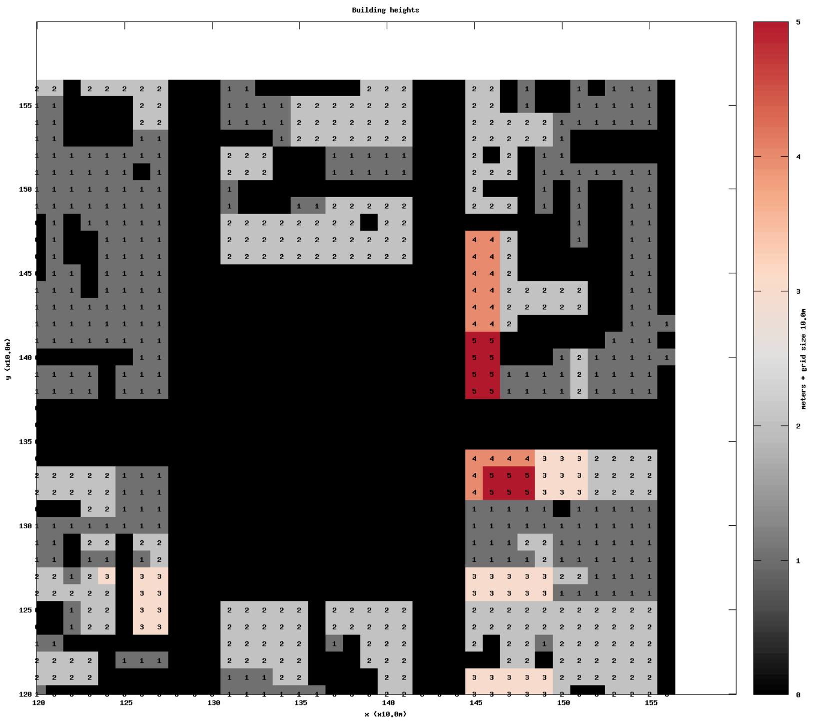

Figure 5.16: *Lincoln Square building heights*

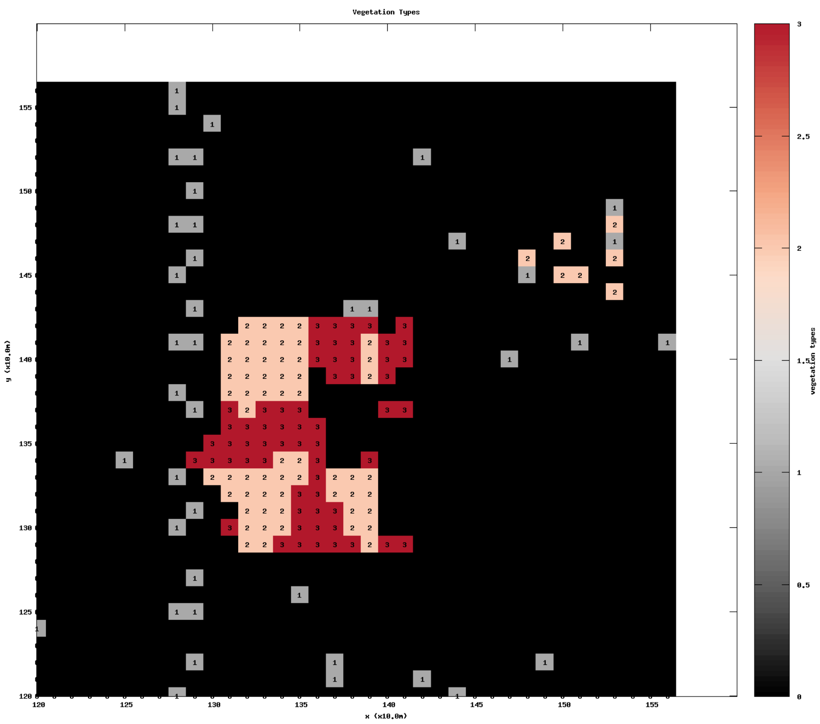

Figure 5.17: *Lincoln Square vegetation heights*

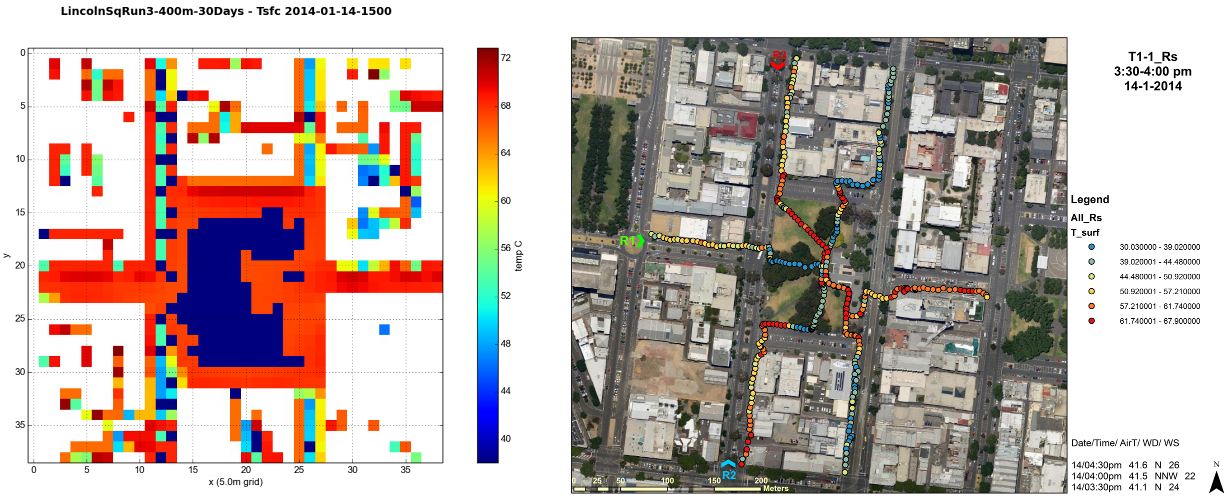

Figure 5.18: *Comparisons of modelled Tsfc to observed transits of Lincoln Sq. on 14 January 2014 3pm*

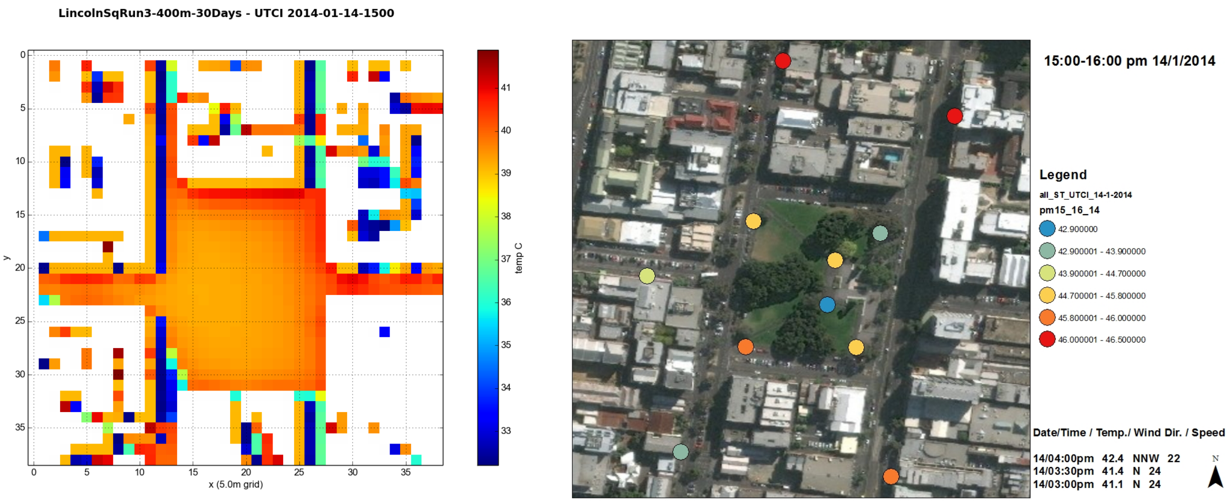

Figure 5.19: *Comparisons of modelled UTCI to observed transits of Lincoln Sq. on 14 January 2014 3pm*

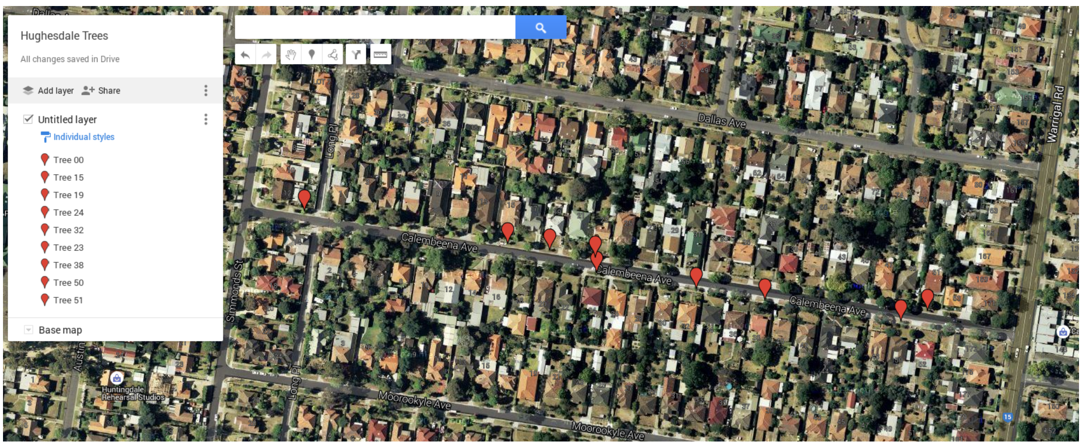

Figure 5.20: *Hughesdale suburb and observation station locations*

done of physiological processes of isolated trees in addition to the regular climate parameters. These validations will compare modelled values of evapotranspiration and photosynthesis to observed values.

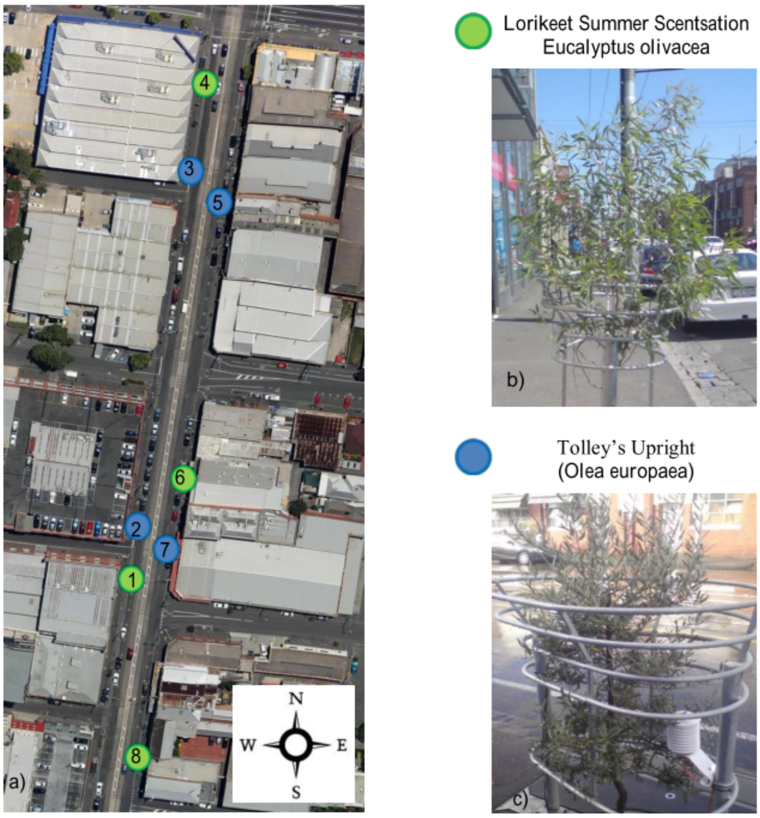

Figure 5.21: *Smith St. contains detailed physiological observations of isolated trees*

Chapter 6

A systematic assessment of WSUD scenarios and urban morphologies using newly improved VTUF-3D model in support of HTC at a micro-climate level in urban areas

6.1 VTUF-3D Scenarios Details

6.1.1 Overview of scenarios

A first group of scenarios were set up, building on the domains from the validations. For each domain, a baseline existing tree cover was used. Then, additional domains were set up with zero trees, half trees, and double trees (as well as quadruple for some domains). The model was run for each variation generating two days of simulation data. Analysis compared UTCI and canopy temperature values to find the differences between the different scenarios.

A second group of scenarios will be set up to conduct a sensitivity study based on an idealized canyon, varying a number of variables to determine their relative importance in influencing HTC in urban areas.

6.1.2 Preston Scenarios

The Preston scenarios were built using the Preston validation domain (Figure 5.1). Three variations from the existing trees cover were designed of zero, half, and double trees (configurations shown in Figure 6.1). The model was run for 13-14 February 2004 using forcing data used in the validation steps.

Post-processing analysis generated Tmrt and UTCI calculations for each surface in the domain. Figures were generated, showing UTCI values for only surfaces at 0m (Figure 6.2, showing 14 February 2004 2pm for each scenario). All 0m UTCI values for 13-14 February 2004 were averaged for each timestep and charted in Figure 6.3 as well as differences between the baseline existing scenario and the other three scenarios.

Finally, canopy temperatures over the modelling period are shown (Figure 6.4), including the Tair forcing air temperature value, as well as differences between the baseline existing scenario and the other three scenarios. Note that canopy temperatures are averaged across the entire domain, while UTCI temperatures are only averaged across 0m surfaces.

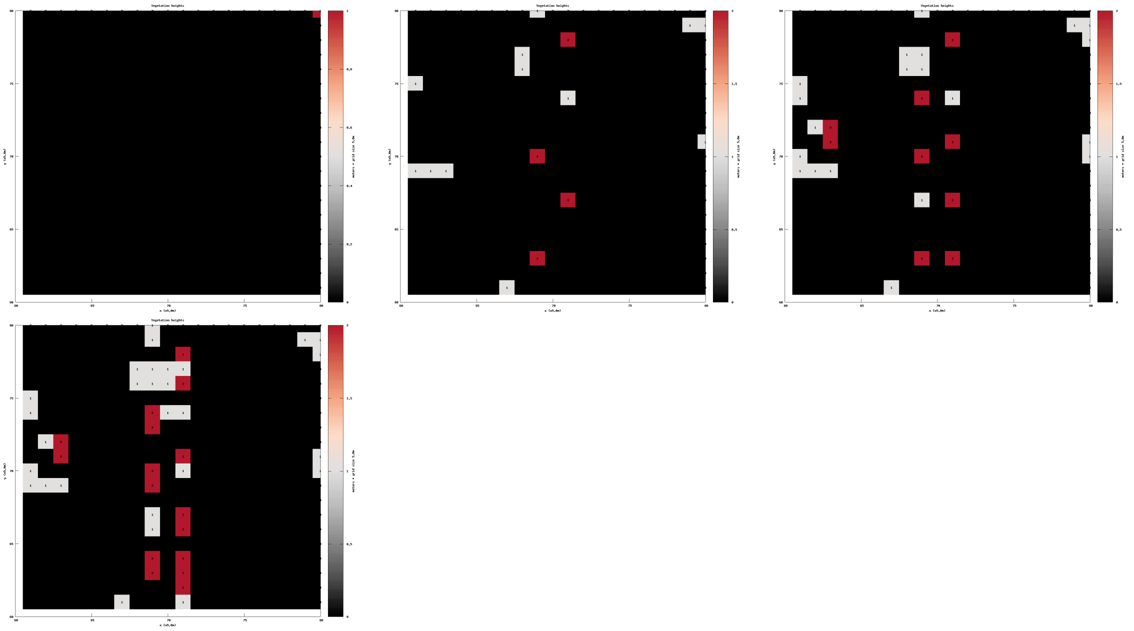

Figure 6.1: *Preston, 4 scenarios of zero trees, half trees, existing Preston tree canopy cover, and double trees*

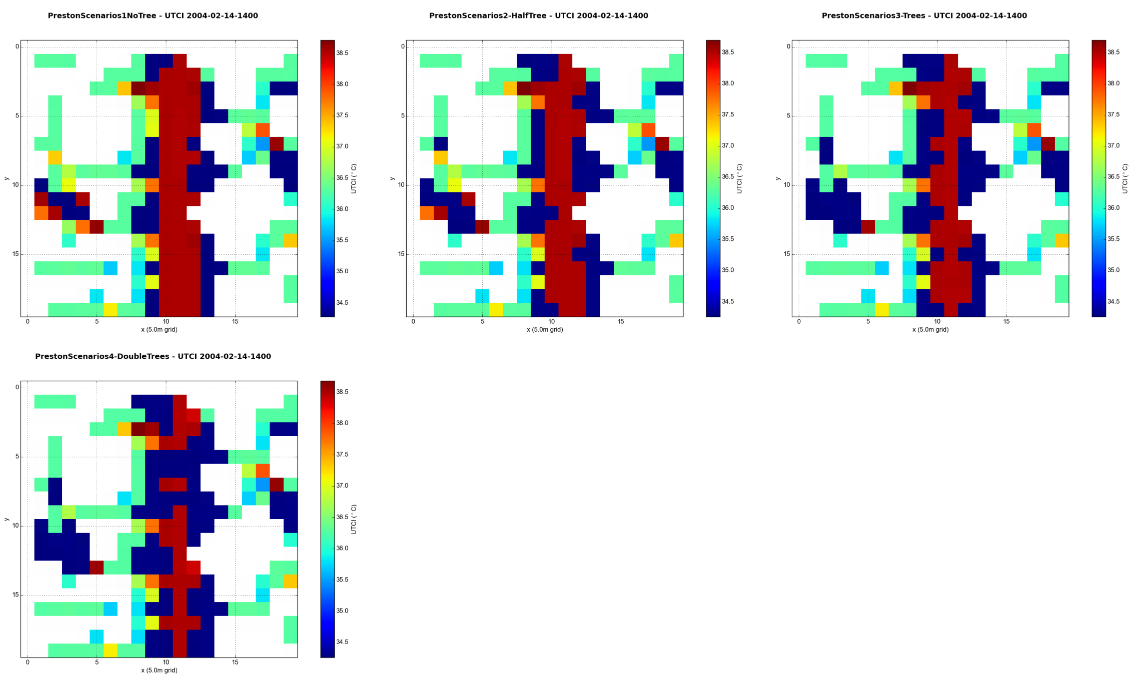

Figure 6.2: *Preston Scenarios-UTCI at 0m for 4 scenarios of zero trees, half trees, existing Preston tree canopy cover, and double trees*

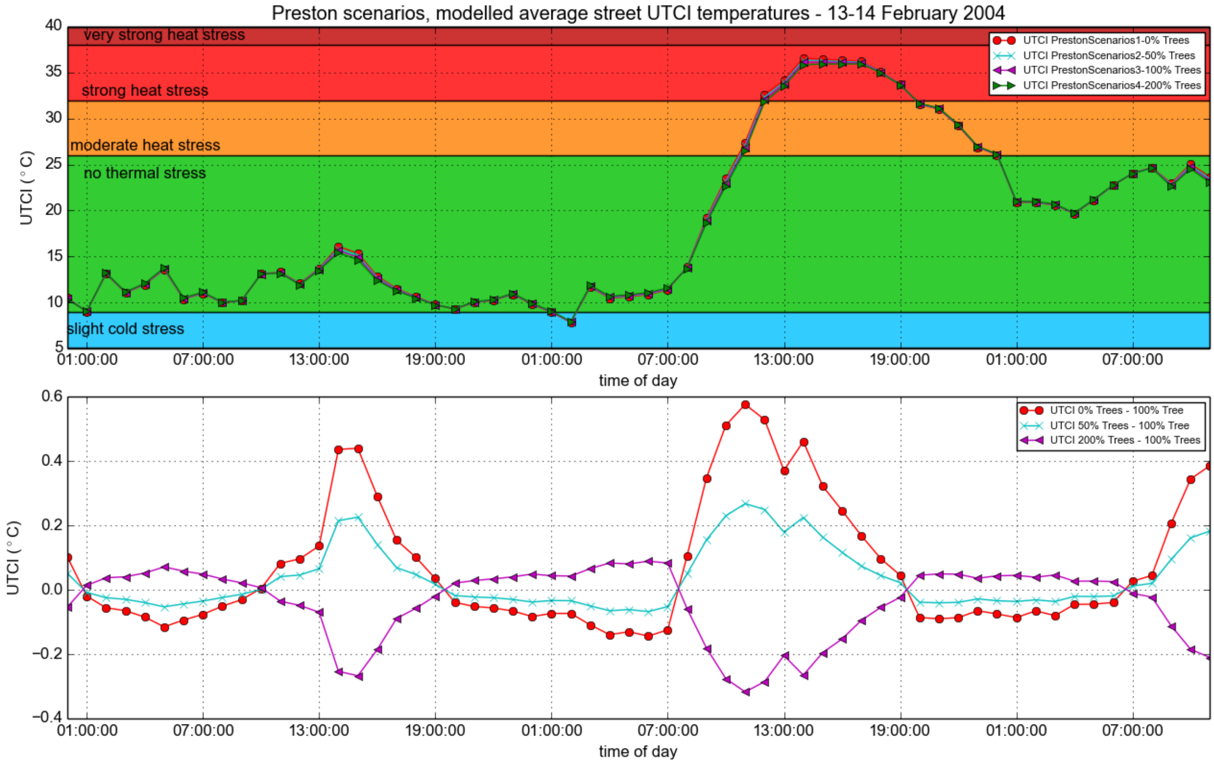

Figure 6.3: *Modelled UTCI of 4 Preston scenarios over 13-14 February 2004 / UTCI differences between baseline existing Preston trees and other scenarios*

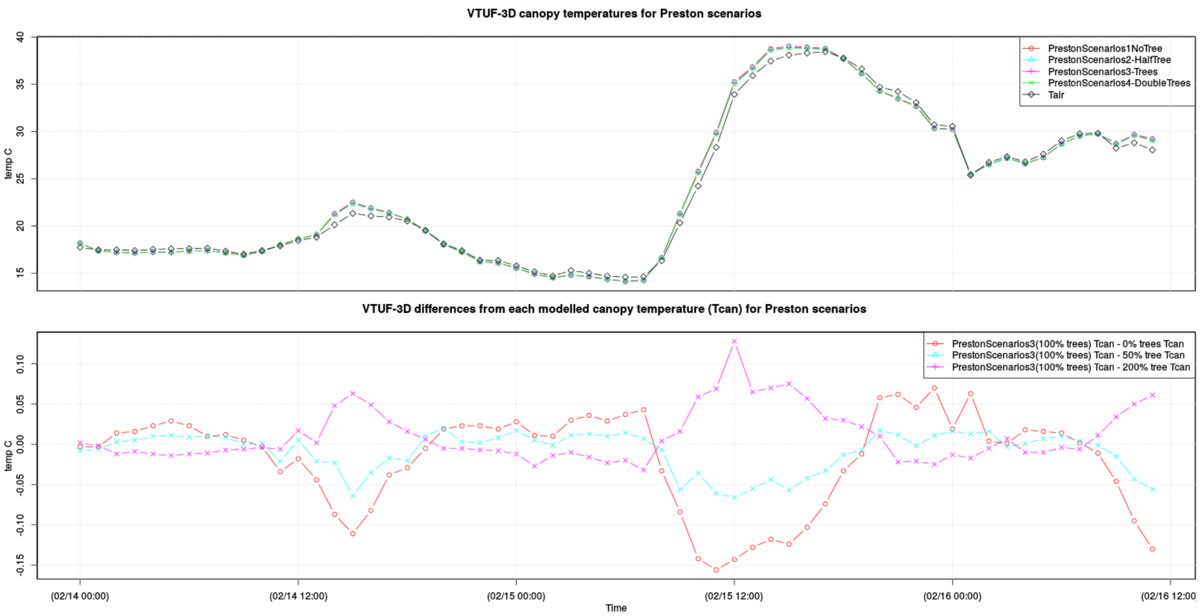

Figure 6.4: *Modelled Tcan of 4 Preston scenarios over 13-14 February 2004 / Tcan differences between baseline existing Preston trees and other scenarios*

The highlights of these scenarios are:

- UTCI (street level, 0m, average) variations of 0.9°C between the no tree scenario and double trees
- Double trees scenario gives 0.3°C UTCI reduction over existing Preston tree canopy
- Preston canopy temperature differences of 0.25°C between the scenarios.

6.1.3 City of Melbourne Gipps St. scenarios

The City of Melbourne Gipps St. scenarios where built using the Gipps St. validation domain (Figure 5.7). Four variations from the existing tree cover were designed of zero, half, double, and quadruple trees (configurations shown in Figure 6.5). The model was run for 23-24 February 2014 using forcing data used in the validation steps.

Post-processing analysis generated Tmrt and UTCI calculations for each surface in the domain. Figures were generated, showing UTCI values for only surfaces at 0m (Figure 6.6, showing 24 February 2014 3pm for each scenario). All 0m UTCI values for 23-24 February 2014 were averaged for each timestep and charted in Figure 6.7, as well as differences between the baseline existing scenario and the other four scenarios.

Finally, canopy temperatures over the modelling period are shown (Figure 6.8), including the Tair forcing air temperature value, as well as differences between the baseline existing scenario and the other three scenarios. Note that canopy temperatures are averaged across the entire domain, while UTCI temperatures are only averaged across 0m surfaces.

The highlights of these scenarios are:

- UTCI (averaged at 0m height) maximum variations of 1.0°C between Gipps St. zero tree scenario and double trees
- UTCI (averaged at 0m height) maximum variations of 2.3°C between Gipps St. zero tree scenario and quadruple trees
- Gipps St. canopy temperature differences range from 0.2°C to 0.4°C between the scenarios.

6.1.4 Sensitivity scenarios

A final set of scenarios will be built to examine the different variables in urban vegetation. These will be built using an idealized urban canyon. In these scenarios, the following variables will be varied to determine their individual impact on HTC:

- tree height,
- leaf area index,
- number of trees,
- tree placement (side of street, grouping or solitary,
- soil moisture.

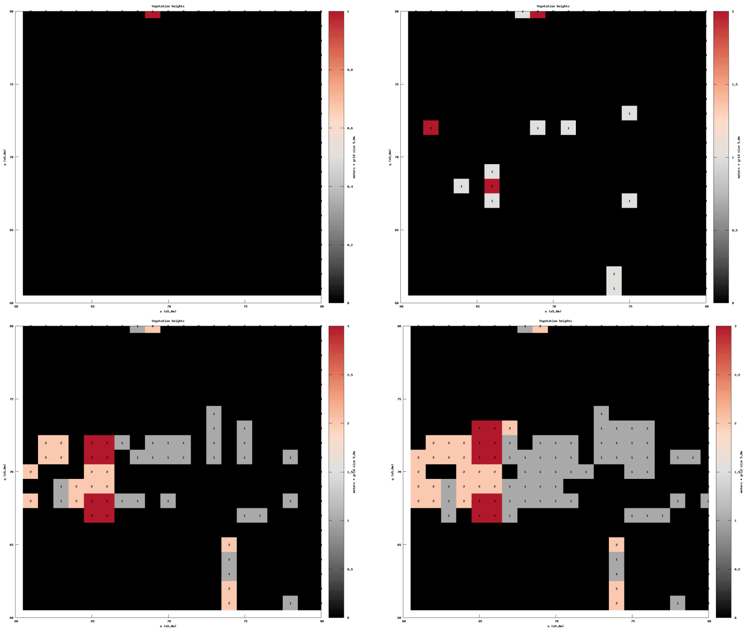

Figure 6.5: *Gipps St. 5 scenarios of zero trees, half trees, existing Gipps St. tree canopy cover, double trees, and quadruple trees.*

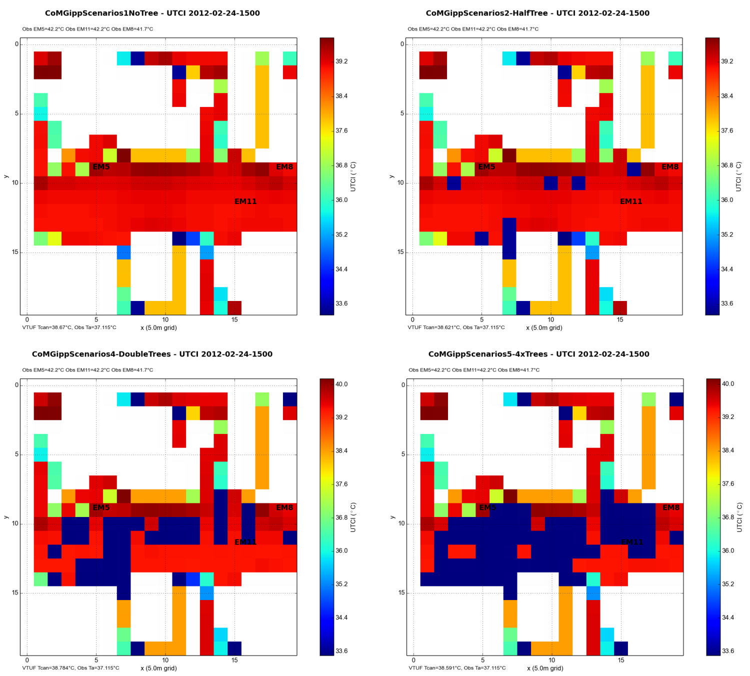

Figure 6.6: *Gipps St. UTCI (averaged at 0m height) of scenarios of zero trees, half trees, existing Gipps St. tree canopy cover, double trees, and quadruple trees.*

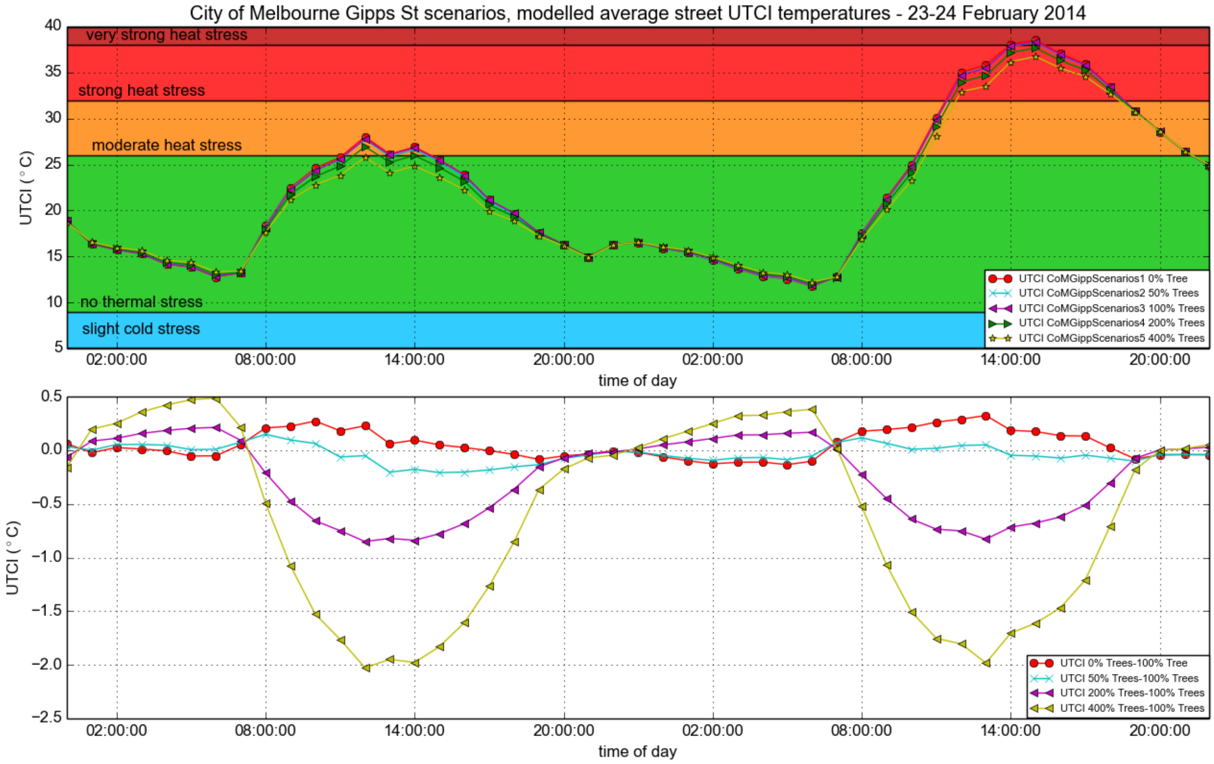

Figure 6.7: *Gipps St. UTCI (averaged at 0m height) for 5 scenarios over 23-24 February 2014 / UTCI differences between baseline scenario and other Gipps St. scenarios*

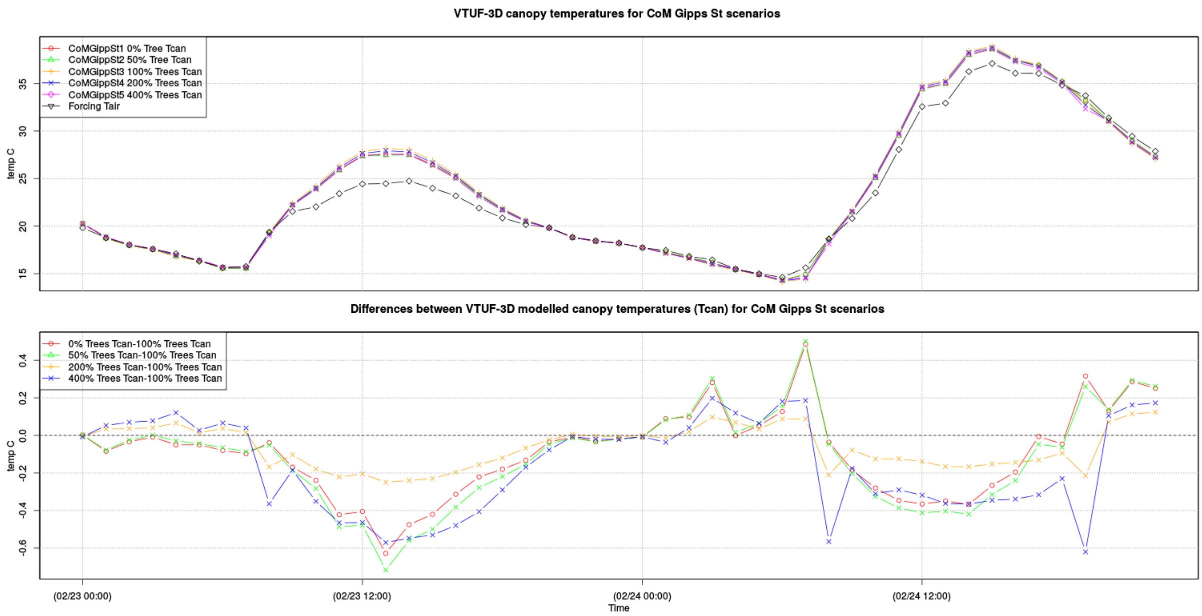

Figure 6.8: *Modelled Tcan of 5 Gipps St. scenarios (and forcing Tair) over 23-24 February 2014 / Tcan differences between baseline existing Gipps St. trees scenario and other scenarios*

Appendices

.1 Open tasks

.1.1 Open task lists

Issues

Model

Storage fluxes? Are they correct? Time of day/night response? Switch to OHM?

Energy balance closures (losing energy for high vegetation configurations).

Revisit how Maespa fluxes are distributed and validate them.

Inner tree shading. All trees are modelled at 100% direct radiation. Interim fix could be to model each tree 3 times, 0%, 50%, and 100% direct radiation. Then use the specific value based on the FBEAM value falling on the tree during the timestep.

Check that Qh actually feeds into Tcan. The calculation of Tcan seems to be very circular in the code.

Finish implementation of tree transmission, absorption, and reflections.

Are Maespa flux values actually needed as they can be calculated from the Tsfc.

There is 0 Maespa transpiration at night. See ICUC9 UCP10 (Linden 2015)

Extend Maespa to model WSUD things (swales, biofiltration, etc).

Configuration GUI (and automated analysis).

OpenFoam air flows

Configuration

Add back in 8 degree rotation.

Are the grass parameterizations correct? Qe should be 35% of net (trees 20-40%) (ICUC9 ICP11 Ngao 2015)

Add in extra tree types.

Is the soil moisture correct?

Configure Maespa to model WSUD things (swales, biofiltration, etc).

Create overall simplified configuration, model running, and analysis toolkit for non-modellers.

Analysis

Are calculations of Tmrt correct? Which then feed into UTCI calculations.

Check energy balance closure at points of interest.

Winter validation?

Sensitivity study: Evaluate tree height, LAI, # of trees, tree placement, soil moisture.