VTUF-3D: An urban micro-climate model to assess temperature moderation from increased vegetation and water in urban canyons

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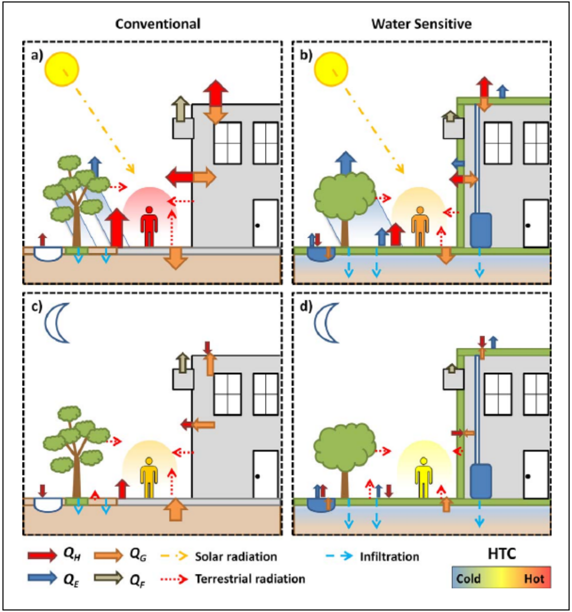
Outline

- Aim of research
- Design overview
- Validation process
- Next steps



(Coutts et al., 2013)

Project B3.1 - Cities as Water Supply Catchments - Green Cities and Microclimate

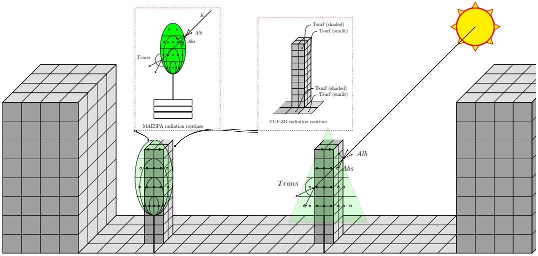
The aim of this project is to identify the climatic advantages of stormwater harvesting/reuse and water sensitive urban design at building to neighbourhood scales.

- To determine the micro-climate processes and impacts of decentralised stormwater harvesting solutions and technologies at both household and neighbourhood scales.
- To assess the impacts of these solutions on human thermal comfort and heat related stress and mortality.
- To provide stormwater harvesting strategies to improve the urban climate and benefit the carbon balance of cities.
- To project the likely impact of climate change on local urban climate, with and without stormwater resuse as a mitigation strategy.

(CRC for Water Sensitive Cities, 2015)

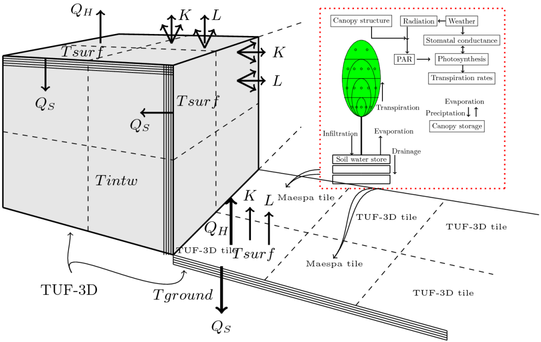
VTUF-3D energy balance modelling with MAESPA tiles

- Modifications to TUF-3D (Krayenhoff and Voogt, 2007) to resolve urban canyon radiation flux movement using placeholder vegetation structures which call MAESPA (Duursma and 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.



Integration of MAESPA tree model into VTUF-3D radiation fluxes routines

- 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.



VTUF-3D energy balance modelling with vegetation MAESPA tiles

MAESPA tree parameterization

- Stomatal conductance - Ball-Berry-Opti model (Medlyn et al., 2011)
- nolay = 6 (Number of layers in the crown assumed when calculating radiation interception.)
- pplay = 12 (Number of points per layer)
- nzen = 5 (Number of zenith angles for which diffuse transmittances are calculated.)
- naz= 11 (Number of azimuth angles for which the calculation is done.)

MAESPA olive tree (*Olea europaea*) parameterization

- Tree dimensions for 5x5m grid (rescale for taller/shorter):
  crown radius = 2.5m, crown height = 3.75m
  trunk height = 1.25m, leaf area index=2.48
  crown shape = round, zht=4.0, zpd=1.6, z0ht=3.0
- Leaf reflectance 3 wavelengths 0.082, 0.49, 0.05 (Baldini et al 1997)
- Minimum stomatal conductance g0 = 0.0213 (From Smith St. data)
- Slope parameter g1 = 3.018 (From Smith St data)
- # of sides of the leaf with Stomata = 2
- Width of leaf (metres) = 0.0102
- CO2 compensation point = 46 (Sierra 2012) (56 @ Smith St.)
- Max rate electron transport=135.5 (135.5 @ Sierra 2012) (134 @ Smith St.)
- Max rate rubisco activity = 82.7 (82.7 @ Sierra 2012) (94 @ Smith St.)
- Curvature of the light response curve =0.9 (Sierra 2012)
- Activation energy of Jmax = 35350 (Diaz-Espejo et al 2006)
- Deactivation energy of Jmax = 200000 (Medlyn et al 2005)
- XX Entropy term = 644.4338
- Quantam yield of electron transport = 0.2
- Dark respiration= 1.12 (Sierra 2012) (1.79 @ Smith St.)
- Specific leaf area=5.1 (3.65=Villalobos et al 1995;5.1=Mariscal et al 2000)

MAESPA brushbox tree (*Lophostemon Confertus*) parameterization

- Tree dimensions for 5x5m grid (rescale for taller/shorter):
  crown radius = 2.5m, crown height = 3.75m
  trunk height = 1.25m, leaf area index =2.0
  crown shape = round, zht=4.0, zpd=1.6, z0ht=3.0
- Leaf reflectance 3 wavelengths 0.04, 0.35, 0.05 (Fung-yan 1999)
- Minimum stomatal conductance g0 = 0.01 (Determined from Melbourne Cemetery Tree)
- Slope parameter g1 = 3.33 (Determined from Melbourne Cemetery Tree)
- # of sides of the leaf with Stomata = 1 (Beardsell and Consodine)
- Width of leaf (metres) = 0.05
- CO2 compensation point = 53.06 (CO2 curves)
- Max rate electron transport=105.76 (CO2 curves)
- Max rate rubisco activity = 81.6 (CO2 curves)
- Curvature of the light response curve =0.61 (PAR curves)
- Activation energy of Jmax = 35350 (Bernacchi et al 2001)
- Deactivation energy of Jmax = 200000 (Medlyn et al 2005)
- XX Entropy term = 644.4338
- Quantam yield of electron transport = 0.06 (PAR curves)
- Dark respiration= 1.29 (PAR curves)
- Specific leaf area=25.3 (25.3=Wright and Westoby 2000)

MAESPA grass parameterization

- Stomatal conductance - Ball-Berry-Opti model (Medlyn et al., 2011)
- Dimensions for grass vegetation for 5x5m grid
  - crown shape = box
  - crown radius = 2.5m
  - crown height = 0.1m
  - trunk height = 0.1m
  - leaf area index=1.47 (Bremer and Ham 2005)
- nolay = 6 (Number of layers in the crown assumed when calculating radiation interception.)
- pplay = 12 (Number of points per layer)
- nzen = 5 (Number of zenith angles for which diffuse transmittances are calculated.)
- naz= 11 (Number of azimuth angles for which the calculation is done.)

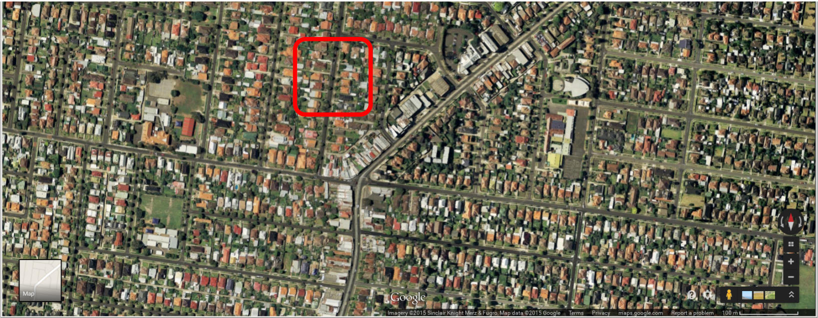
VTUF-3D validation matrix

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)					

A variety of observation data allows validations of a number of different aspects of the model

Model testing and validation using Preston dataset

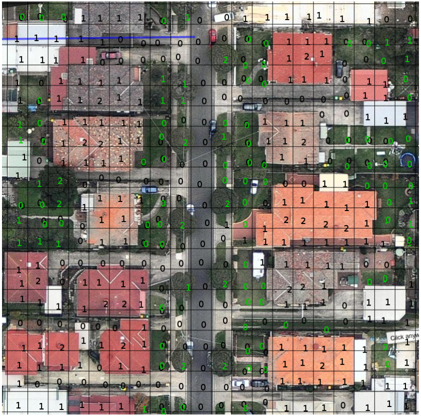
- Preston - homogeneous, medium density.
- Data set contains complete flux observations recorded 2003-2004, allowing validation of surface energy balances
- Modelled area (500x500m) chosen is representative of overall area observed by flux tower



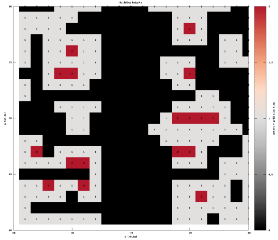
(Google 2015)

Model testing and validation using Preston dataset

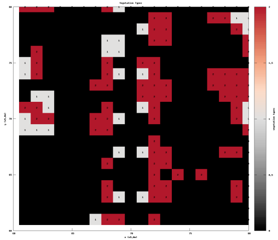
Mix of vegetation types: grass (18.5%), olive and brushbox trees (7.25%). Medium density area (46.75% buildings). 27.5% impervious surfaces.



Digitization of Preston suburban street.
(1=building heights, 1=vegetation heights)



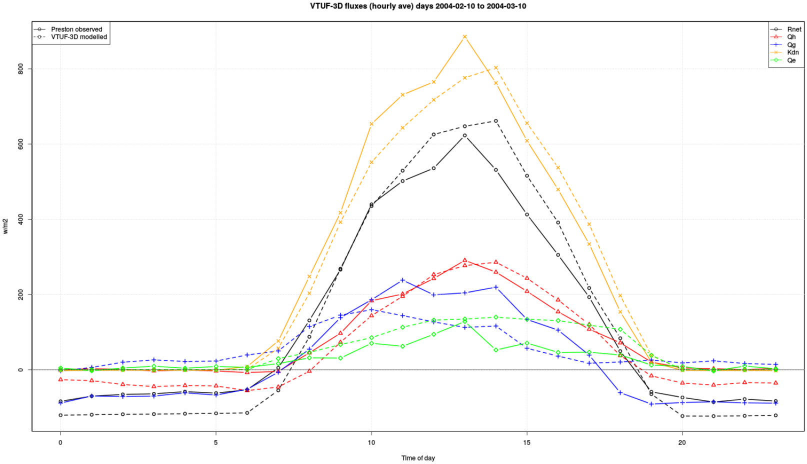
Building heights (0, 5, 10m)



Vegetation heights (0, 5, 10m)

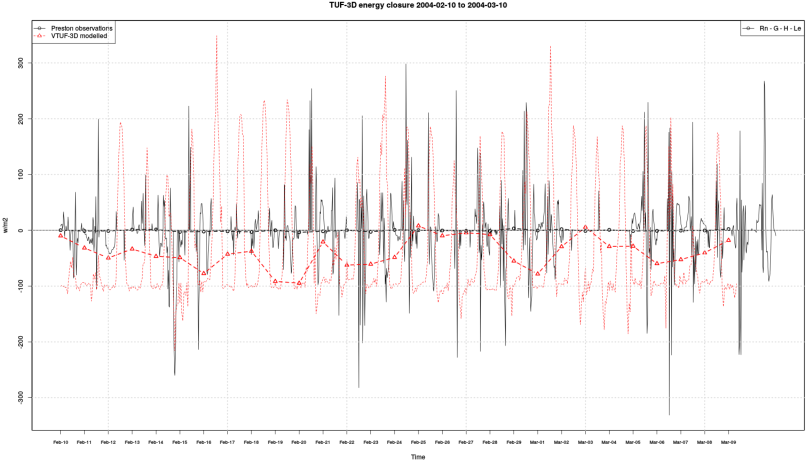
Model testing and validation using Preston dataset

30 day hourly average flux comparisons to Preston flux observations



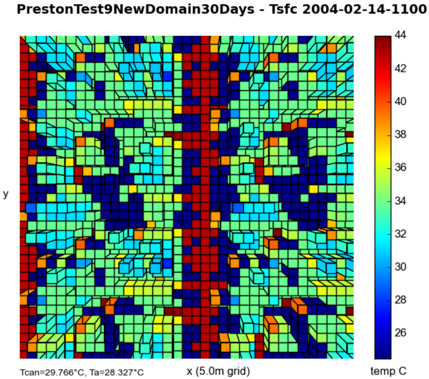
Model testing and validation using Preston dataset

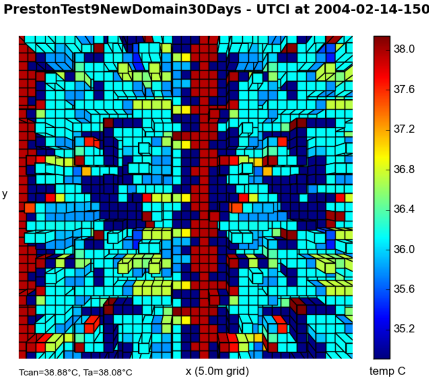
Energy closure, $Q* - Qg - Qh - Qe = 0$



Model results using Preston dataset

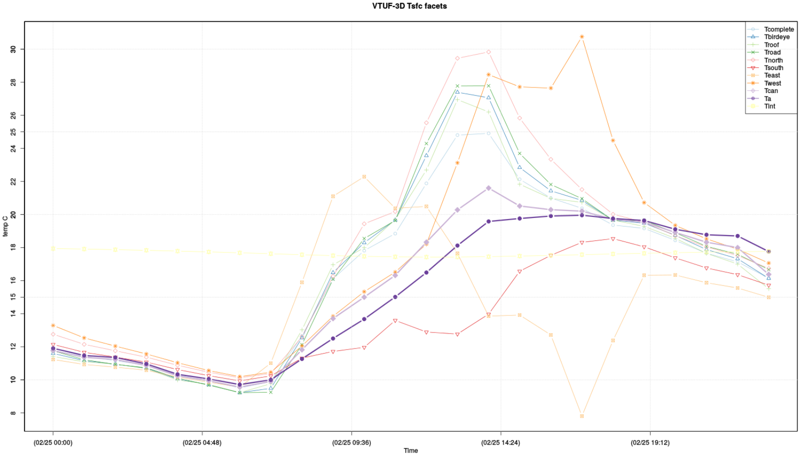
Hourly results for Tsfc and UTCI for 14 Februrary 2004





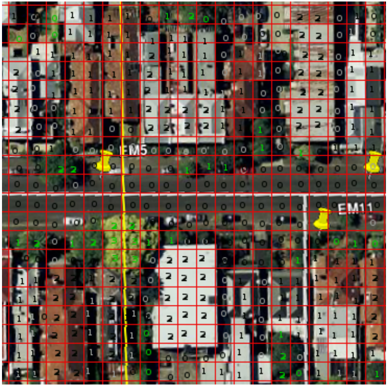
Model results using Preston dataset

Canyon temperatures for 25 Feburary 2004, predicted canyon air temperature along with various canyon surface temperatures



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

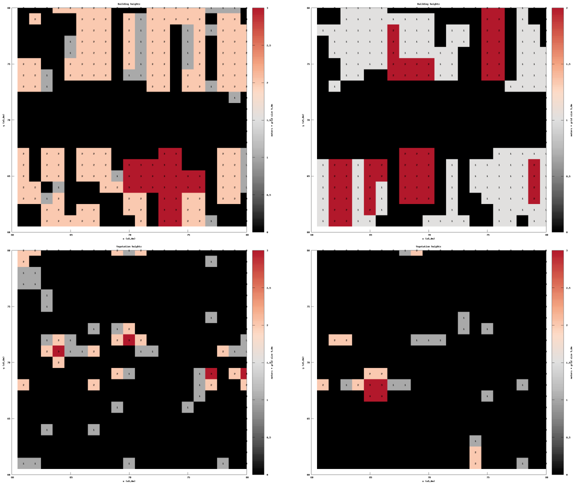
Shallow urban canyons (ave building heights 7 and 8m, H:W 0.32 and 0.27) with varying canopy cover (45% and 12%)



Validation against 4 and 3 observation stations located on street

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

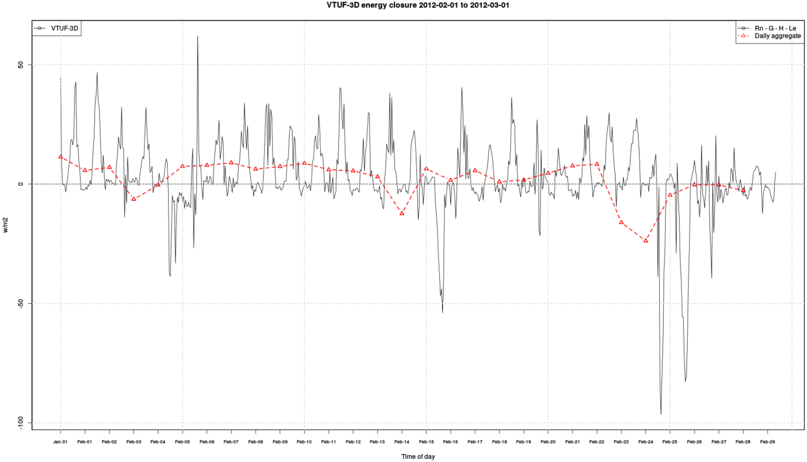
Building heights - George St, Gipp St



Vegetation cover - George St, Gipp St

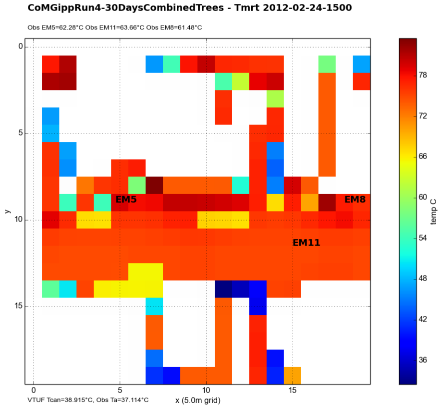
Model testing and validation using City of Melbourne, George and Gipp St datasets

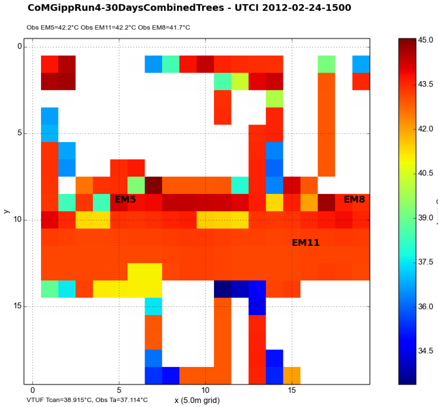
Energy closure of Gipp St



Model testing and validation using City of Melbourne, Gipp St dataset

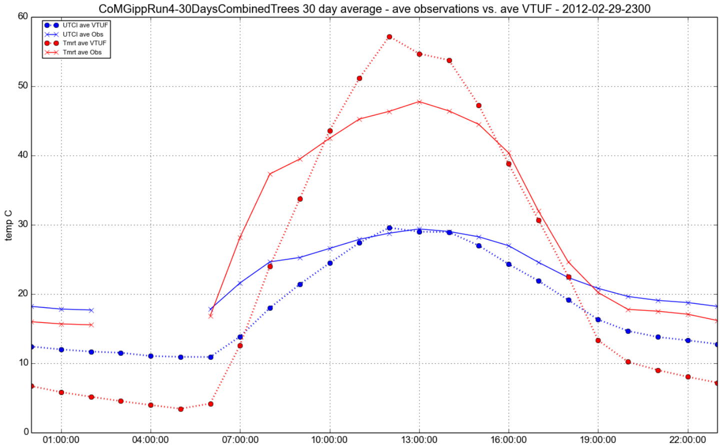
Results of Tmrt and UTCI for 24 February 2014 1500.



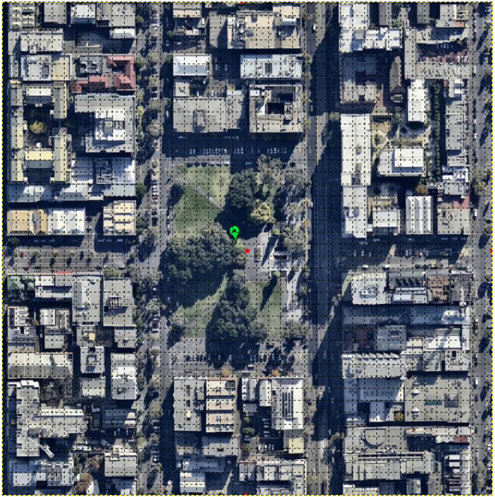


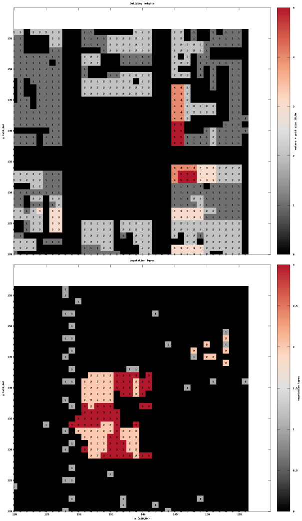
Model testing and validation using City of Melbourne, Gipps St dataset

Averaged comparison of 3 observations stations to modelled points



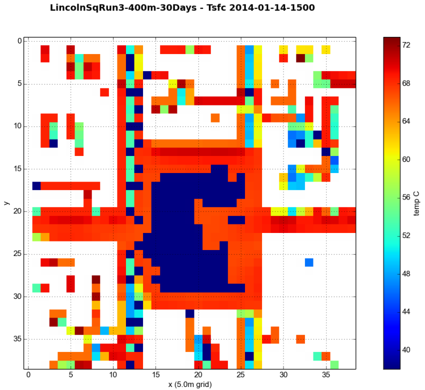
Model testing and validation using Lincoln Sq dataset





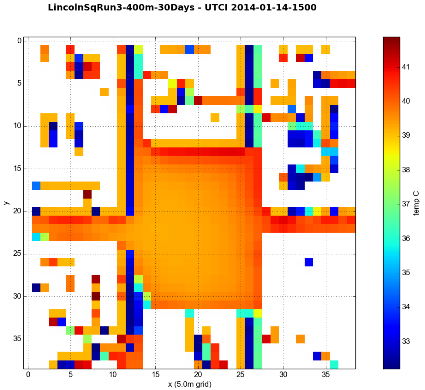
Melbourne urban square, mix of open grass and mature trees within dense urban canyon

Model testing and validation using Lincoln Sq dataset



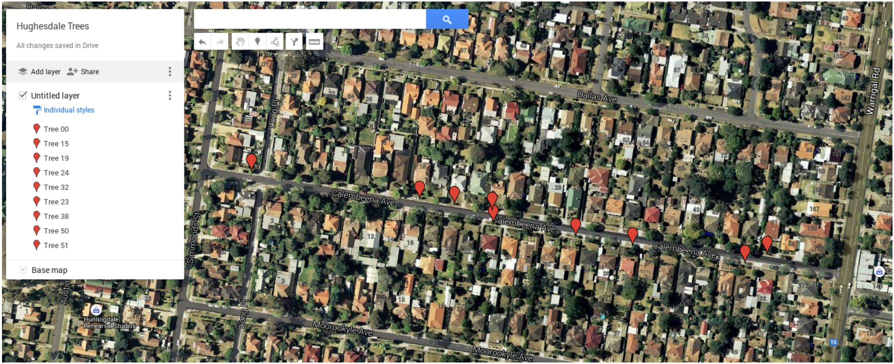
Comparisons of modelled Tsfc to observed transits

Model testing and validation using Lincoln Sq dataset



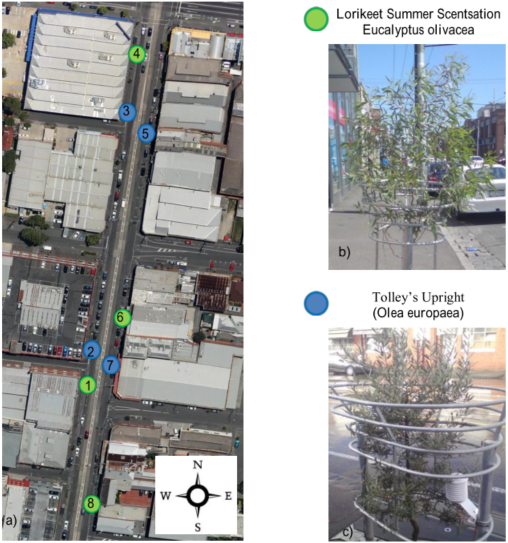
Comparisons of modelled UTCI to observed transits

Model testing and validation using Hughesdale dataset



Validations in medium density urban area using tree physiology data

Model testing and validation using Smith St dataset



Validations using isolated tree physiology data (Gebert et al., 2012)

Future work

- Completion of vegetation parameterizations (grass as well as a variety of common street trees, in addition to the olive and brushbox parameterizations)
- Completion of validation scenarios
  - Hughesdale
  - Smith St
- Sensitivity study building on and adding variations of validation scenarios to examine impact to human thermal comfort of placement and quantity of trees in urban areas

Bibliography

Coutts, A.M., Beringer, J. and Tapper, N.J. (2007), Impact of Increasing Urban Density on Local Climate: Spatial and Temporal Variations in the Surface Energy Balance in Melbourne, Australia. *Journal of Applied Meteorology and Climatology*, 46(4):pp. 477–493.

Coutts, A.M., Daly, E., Beringer, J. and Tapper, N.J. (2013), Assessing practical measures to reduce urban heat: Green and cool roofs. *Building and Environment*, 70:pp. 266–276.

Coutts, A.M., White, E.C., Tapper, N.J., Beringer, J. and Livesley, S.J. (2015), Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments. *Theoretical and Applied Climatology*:pp. 1–14.

CRC for Water Sensitive Cities (2015), Project B3 - Water Sensitive Urban Design and Urban Micro-climate. http://watersensitivecities.org.au/programs-page/water-sensitive-urbanism-program-b/project-b3/.

Duursma, R.A. and Medlyn, B.E. (2012), MAESPA: a model to study interactions between water limitation, environmental drivers and vegetation function at tree and stand levels, with an example application to [CO2] x drought interactions. *Geoscientific Model Development*, 5(4):pp. 919–940.

Gebert, L., Coutts, A. and Beringer, J. (2012), Response of trees to the urban environment. Technical report, Monash University.

Krayenhoff, E.S. and Voogt, J.A. (2007), A microscale three-dimensional urban energy balance model for studying surface temperatures. *Boundary-Layer Meteorology*, 123(3):pp. 433–461.

Medlyn, B.E., Duursma, R.a., Eamus, D., Ellsworth, D.S., Prentice, I.C., Barton, C.V.M., Crous, K.Y., De Angelis, P., Freeman, M. and Wingate, L. (2011), Reconciling the optimal and empirical approaches to modelling stomatal conductance. *Global Change Biology*, 17(6):pp. 2134–2144.

Motazedian, A. (2015), Observations from Lincoln Sq, Melbourne.

Thank you. Questions?