Introducing the TUF-3D/MAESPA urban micro-climate model

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Work made possible through assistance of:

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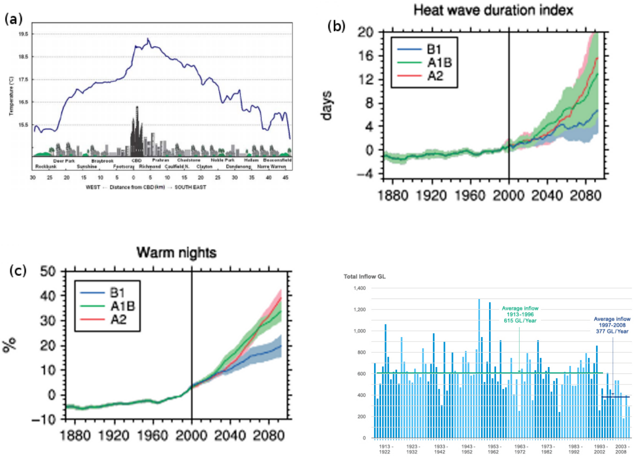
- Jason Beringer (Supervisor)
- Andrew Coutts (Supervisor)
- Scott Krayenhoff (TUF-3D model)
- Remko Duursma (MAESPA model)

Outline



Urban heat island effects; predicted increasing extremes for Australia; Melbourne's water supply

(Coutts et al. 2010; Alexander & Arblaster 2009; Melbourne Water 2008)

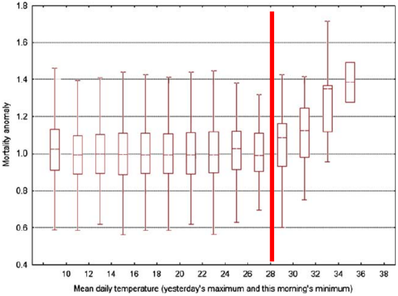
Increasingly vulnerable Australian demographics

- **Population growth** - In 2007, 21.0 million people
  30.9 to 42.5 by 2056
  33.7 and 62.2 by 2101.
- **Ageing population** - Median age, 36.8 years in 2007
  38.7 to 40.7 years in 2026
  41.9 to 45.2 years in 2056.
  In 2007, 13% of population 65 years and over
  23% to 25% in 2056
- **Increased urbanisation** - In 2007, 64% lived in a capital city.
  By 2056, increase to 67%.

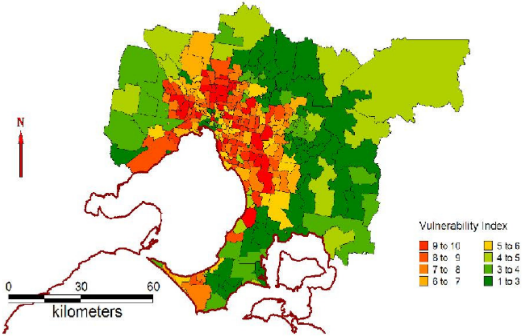
(http://www.abs.gov.au/Ausstats/abs@.nsf/mf/3222.0)

Melbourne heat index thresholds and spatial vulnerability of high risk populations during hot weather

Melbourne: Daily mean temp. 28 °C threshold

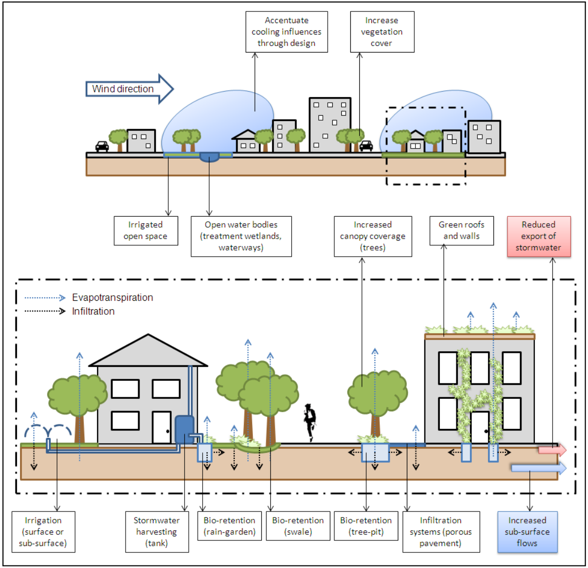


(Nicholls et al. 2008; Loughnan et al., 2009)



Melbourne vulnerability index based on UHI, land use, urban form, demographics (age, medical conditions, socio-economic, social isolation)

CRC for Water Sensitive Cities research overview

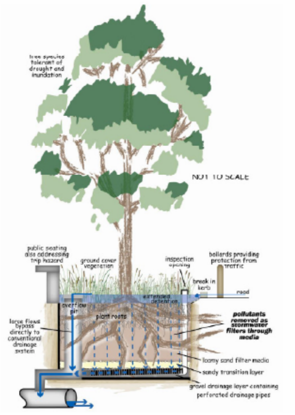


(Coutts 2012)

Project B3.1 Green Cities and Microclimate, and B3.2 The Design of the Public Realm to Enhance Urban Microclimate

- Meet challenges of drought & water restrictions, poor vegetation health, strained water supplies, degraded stream health
- Integrating Water Sensitive Urban Design features throughout the urban landscape as a natural cooling mechanism and UHI mitigation strategy
- Increasing vegetation in the landscape AND providing water for vegetation health
- Enhanced infiltration and evapotranspiration

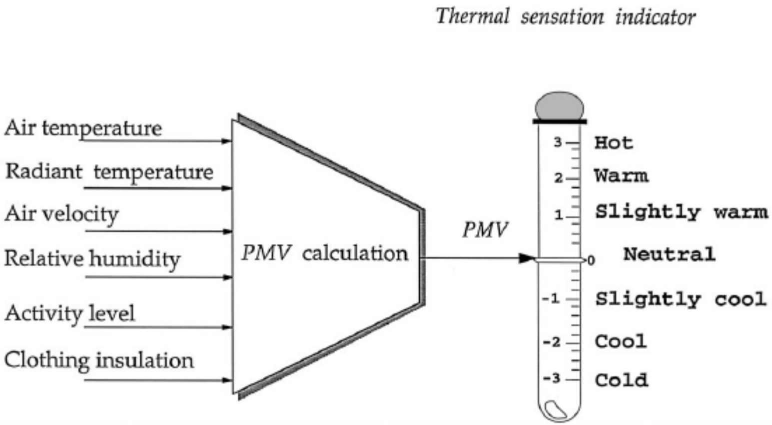
Are there positive climatic impacts on human thermal comfort?



Design of a tree-pit (FAWB, 2009)

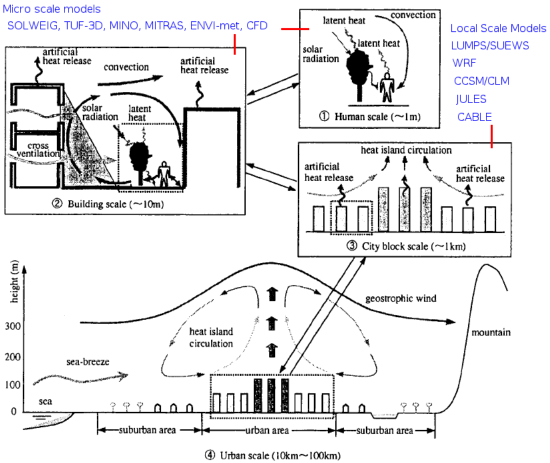
Tree pits and other WSUD features in urban areas.
(FAWB 2009; FAWB 2008)

Required inputs to model Human Thermal Comfort (HTC)



PMV and thermal sensation (Hamdi et al. 1999)

Observations can only examine what already exists. Modelling is needed to examine a wider range of scenarios, technologies, and climatic benefits at a variety of scales.



(Adapted from Murakami et al. 1999)

Outline

Computatial fluid dynamics (CFD) methods

Navier-Stokes Equations
3 – dimensional – unsteady

Glenn Research Center

Coordinates: (x,y,z)
Velocity Components: (u,v,w)

Time : t
Density: ρ
Total Energy: Et

Pressure: p
Stress: τ

Heat Flux: q
Reynolds Number: Re
Prandtl Number: Pr

Continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X – Momentum:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right]$$

Y – Momentum:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right]$$

Z – Momentum

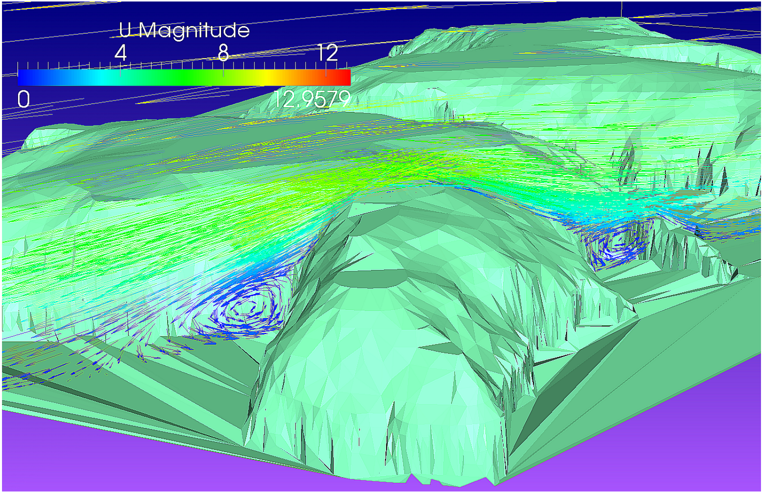
$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right]$$

Energy:

$$\frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right]$$

$$+ \frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\,\tau_{xx} + v\,\tau_{xy} + w\,\tau_{xz}) + \frac{\partial}{\partial y}(u\,\tau_{xy} + v\,\tau_{yy} + w\,\tau_{yz}) + \frac{\partial}{\partial z}(u\,\tau_{xz} + v\,\tau_{yz} + w\,\tau_{zz})\right]$$

Navier-Stokes Equations, relating the velocity, pressure, temperature, and density of a moving fluid. (Nasa 2013)



CFD study of Air Flow over Complex Terrain
(Fabre et al. 2012)

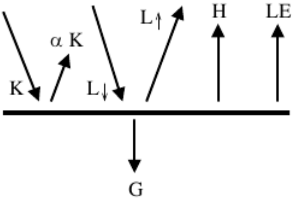
Micro scaled urban models - CFD based

- MIMO (Kunz 2000), MITRAS (Mikroskaliges Chemie, Transport und Strömungsmodell) (Hinneburg et al. 2003), CFD frameworks such as OpenFOAM (OpenFOAM 2011) or STAR-CD (CD-adapco 2011), or ENVI-met (Bruse 1999)
- Very technically challenging to set up and run and extremely computationally intense.
- Originally designed for particle dispersion studies, concern over accuracy of added energy balance components.

Energy balance models partition known quantities of shortwave and longwave radiation into energy balance budget components.

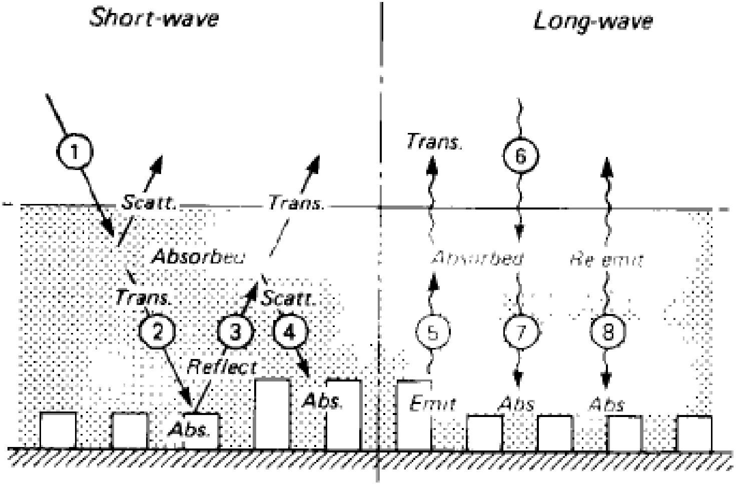
$$(1-\alpha)(Ksf+Kdf)+\varepsilon L\downarrow - L\uparrow - G - H - LE = 0$$

A less intensive approach (compared to CFD), often used by local and micro-scaled models.



Schematic of the energy balance for a surface. The direction of the arrows indicate the direction of positive flux densities.
(Harman 2003)

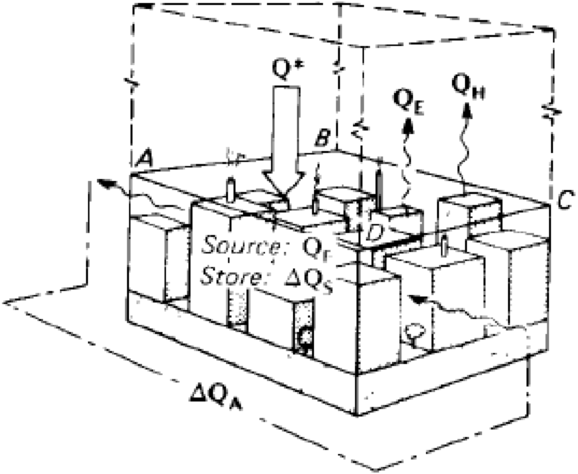
Urban surface radiation budget



Surface Radiation Budget : $Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow$

($Q*$ net radiation, K shortwave up/down, L longwave up/down)
(Oke 1988)

Urban surface energy budget

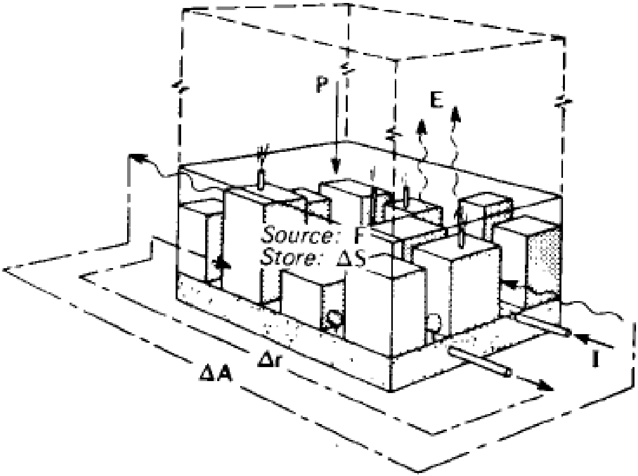


Surface Energy Budget :

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

($Q*$ net radiation, Qf anthropogenic heat, Qh sensible heat, Qe latent energy, Qs storage heat, Qa advected heat) (Oke 1988)

Urban surface water budget



Surface Water Budget :

$$p + F + I = E + \Delta r + \Delta S + \Delta A$$

(p precipitation, F released from combustion, I urban water supply, E evaporation, r runoff, S storage, A advection) (Oke 1988)

Micro scaled models

- TUF-3D (Krayenhoff & Voogt 2007) - 3D raster model, simulates energy balances, modelling radiation, conduction, and convection in order to predict fluxes of sensible heat, conduction, and radiation fluxes.
- Currently doesn't support vegetation or latent energy fluxes. More detail on these enhancements soon.

Outline

TUF-3D model structure

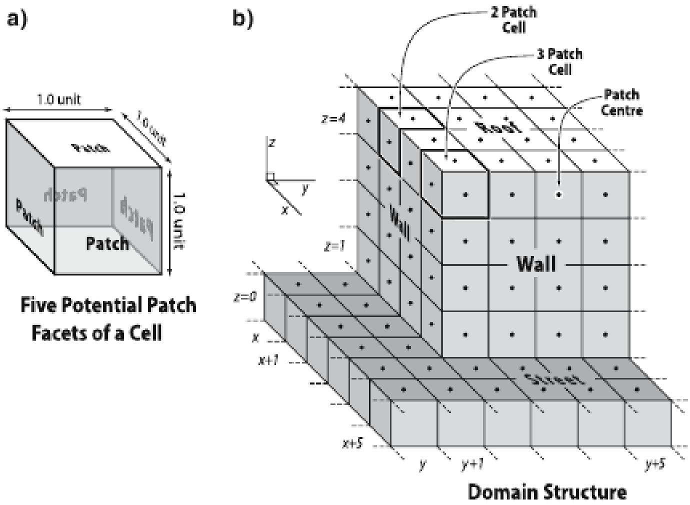


Fig. 1 Basic cubic cell and surface patch structure of TUF-3D

(Krayenhoff & Voogt 2007)

TUF-3D domains

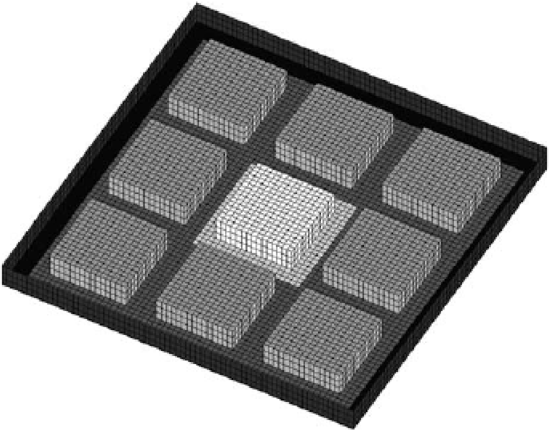
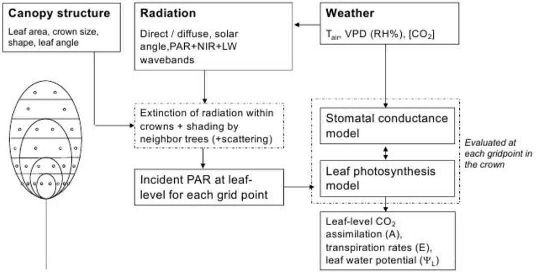
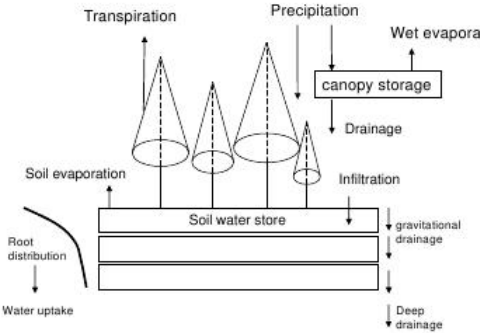


Fig. 2 An example TUF-3D domain with a bounding wall and the sub-domain S_d (chosen to coincide with the central urban unit) in lighter shades

(Krayenhoff & Voogt 2007)

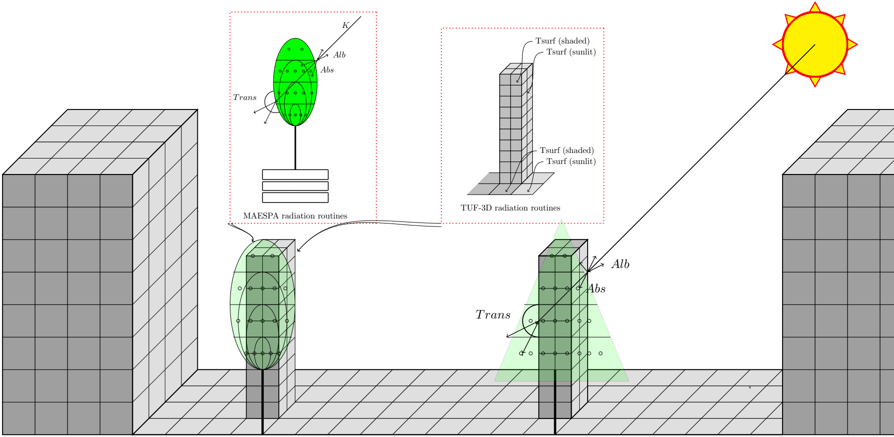
MAESPA tree model





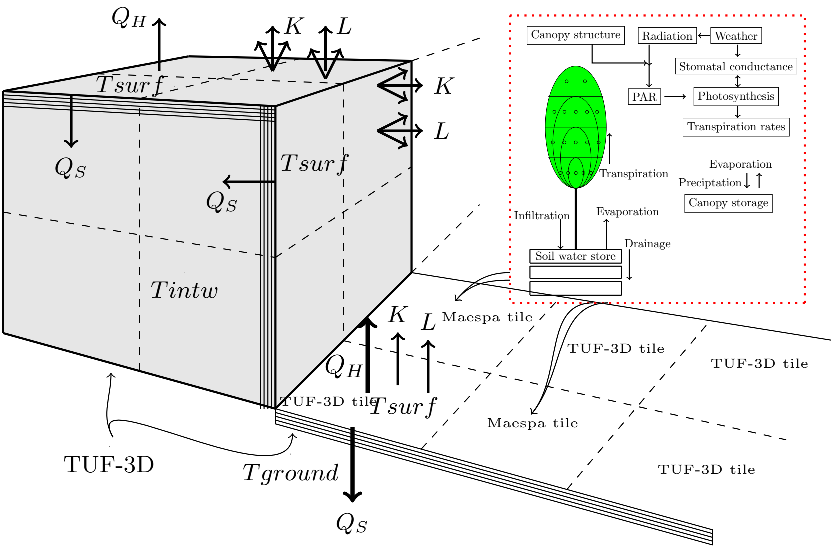
Process and water balance flowcharts (Duursma & Medlyn 2012)

Additions to TUF-3D, modifications to radiation modelling



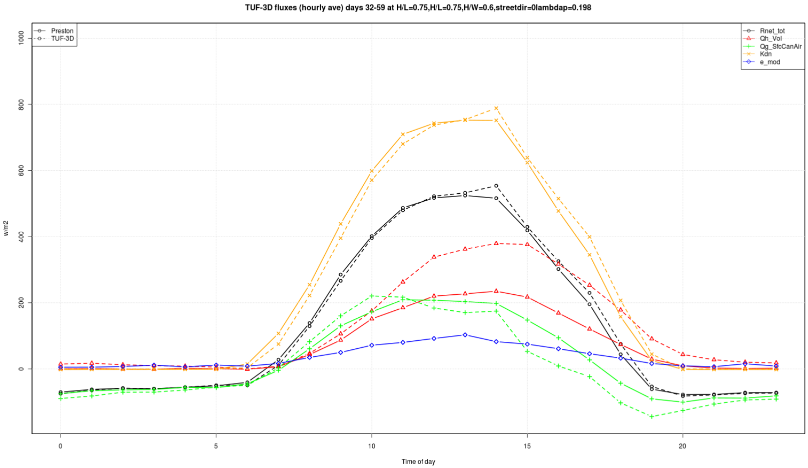
Integration of MAESPA tree model in the TUF-3D model

Additions to TUF-3D, embedding MAESPA tree model



TUF-3D energy balance modelling with MAESPA tiles

Additions to TUF-3D, increasing accuracy



Unmodified TUF-3D energy balances validated against Preston data set (Coutts 2007). Improvements needed in *QH* and *QE* predictions.

Future work

- Completion of coding
- Validations
- Running comprehensive set of WSUD scenarios