Adequately and Efficiently Representing Heat Conduction and Storage for Urban Surfaces

Never Stand Still

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ARC CENTRE OF EXCELLENCE FOR CLIMATE SYSTEM SCIENCE

Climate Change Research Centre

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Melissa Hart | UNSW
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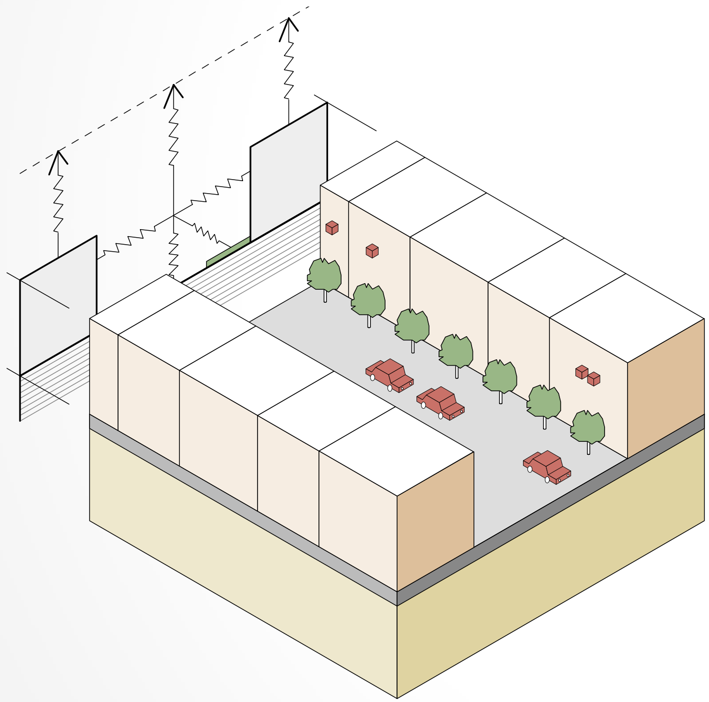
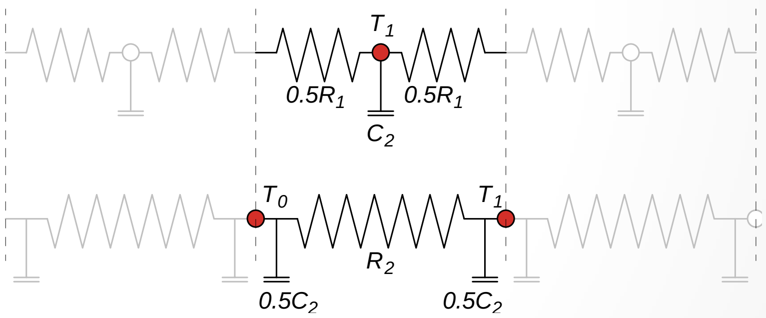
1. The Australian Town Energy Budget scheme (aTEB)



2. Interface heat storage/conduction scheme



Introductions

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Melissa Hart | UNSW
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- aTEB to be coupled with mesoscale climate models:
  - can not slow down climate scale runs
  - must be as efficient as surrounding land surface tiles
- Researchers want a flexible model to assess climate impacts in various cities:
  - urban geometry/ materials
  - vegetation (lawn, trees, roofs)
  - anthropogenic heat flux
  - air flow / dispersion

SIMPLE <- - - - - - - - - - - - - - - - -> REALISTIC

(bulk surface properties)

(distinct surface properties)

ADEQUATE?

Model Aims

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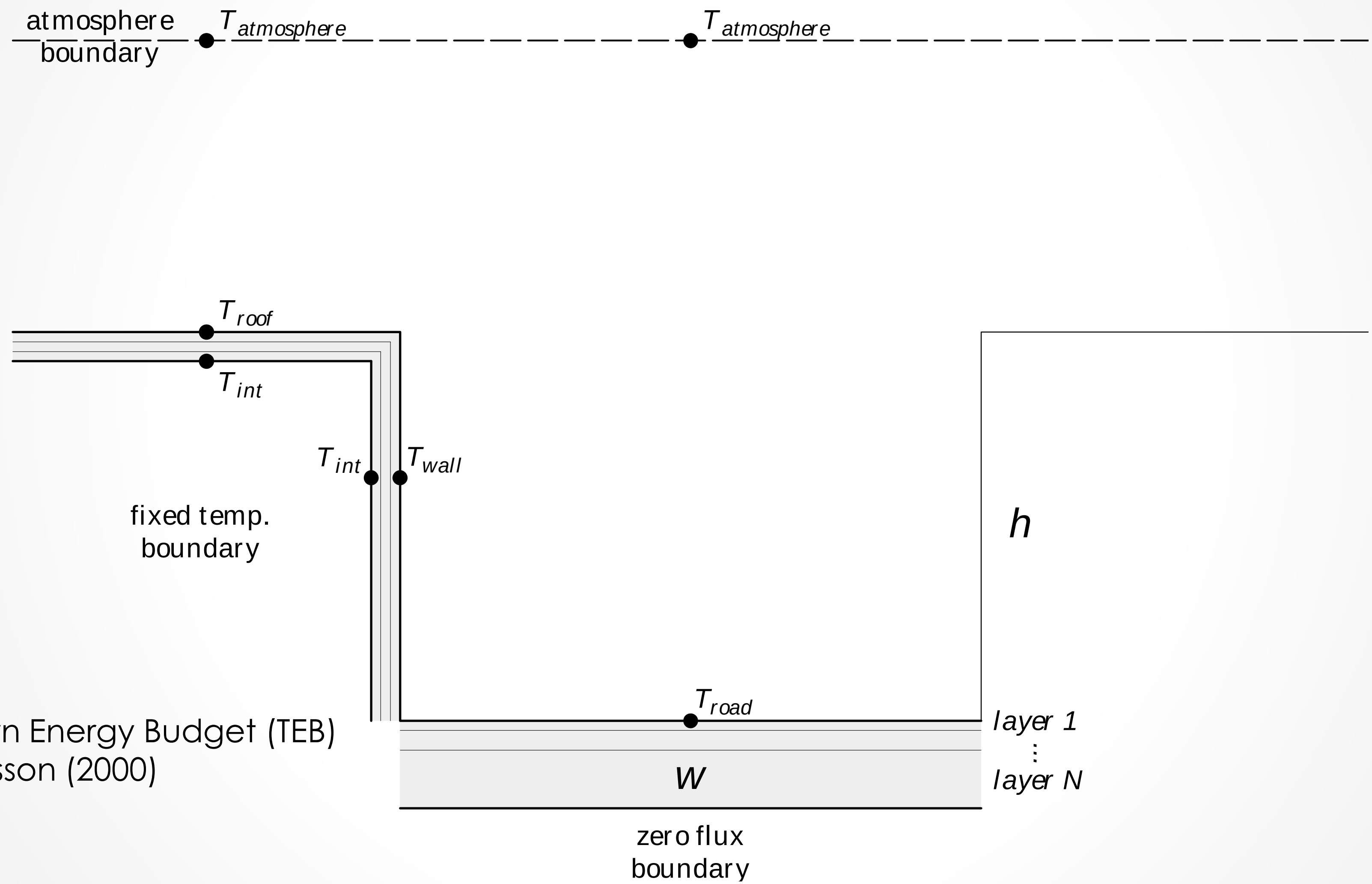

Town Energy Budget (TEB)
Masson (2000)

Town Energy Budget (TEB) Approach

Adequately and efficiently representing heat conduction and storage for urban surfaces

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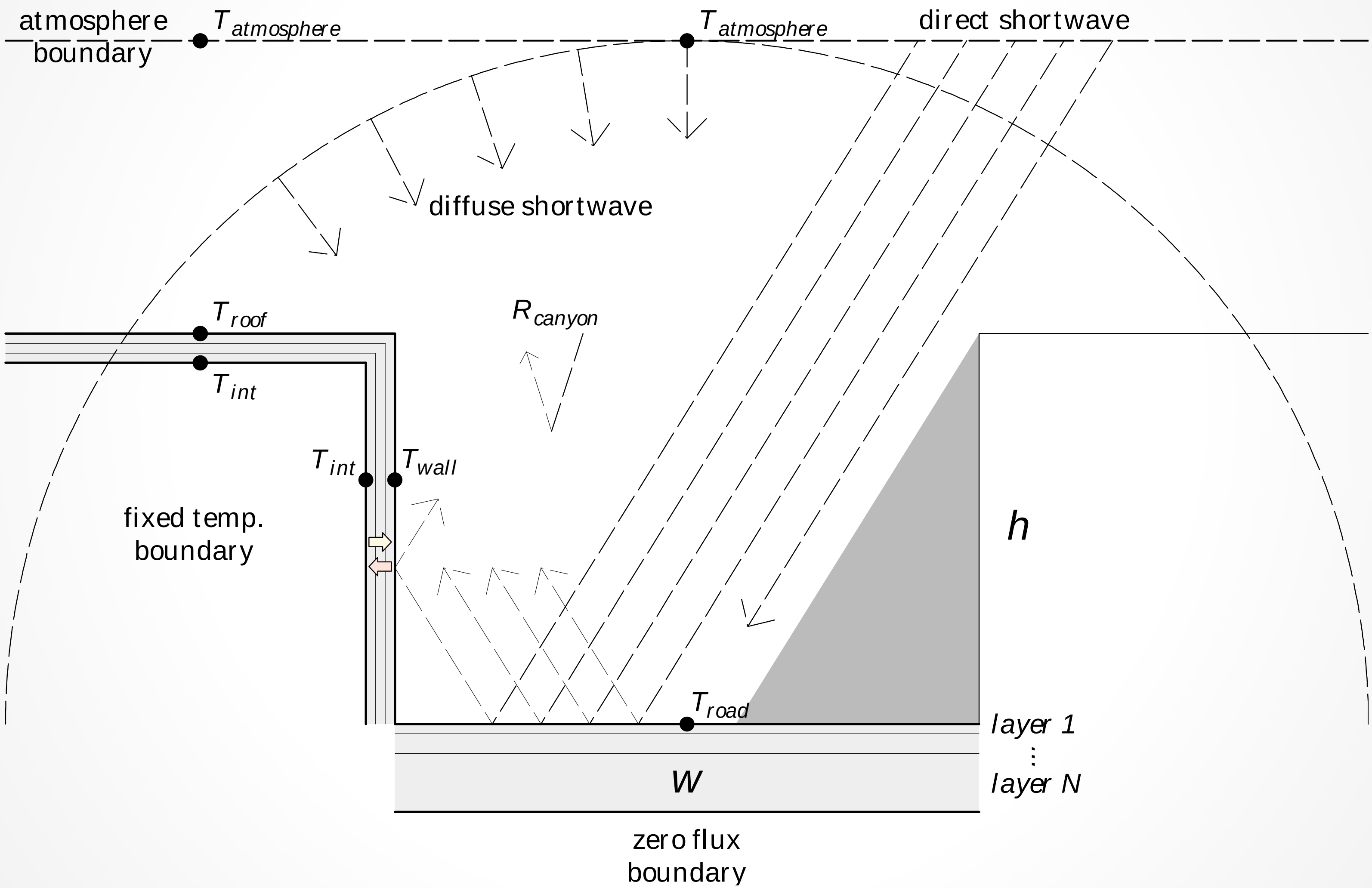

Town Energy Budget (TEB) Approach

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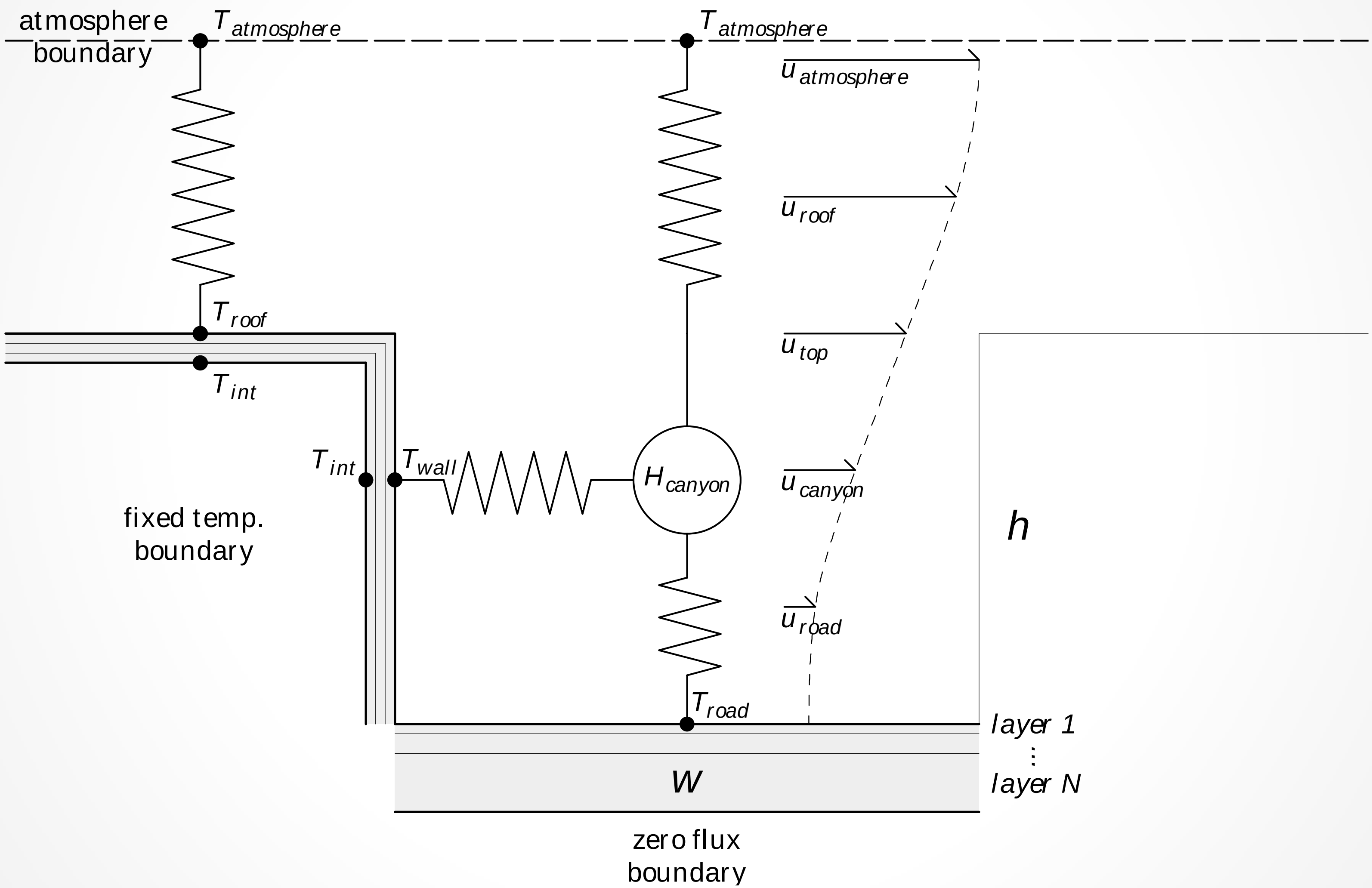

Town Energy Budget (TEB) Approach

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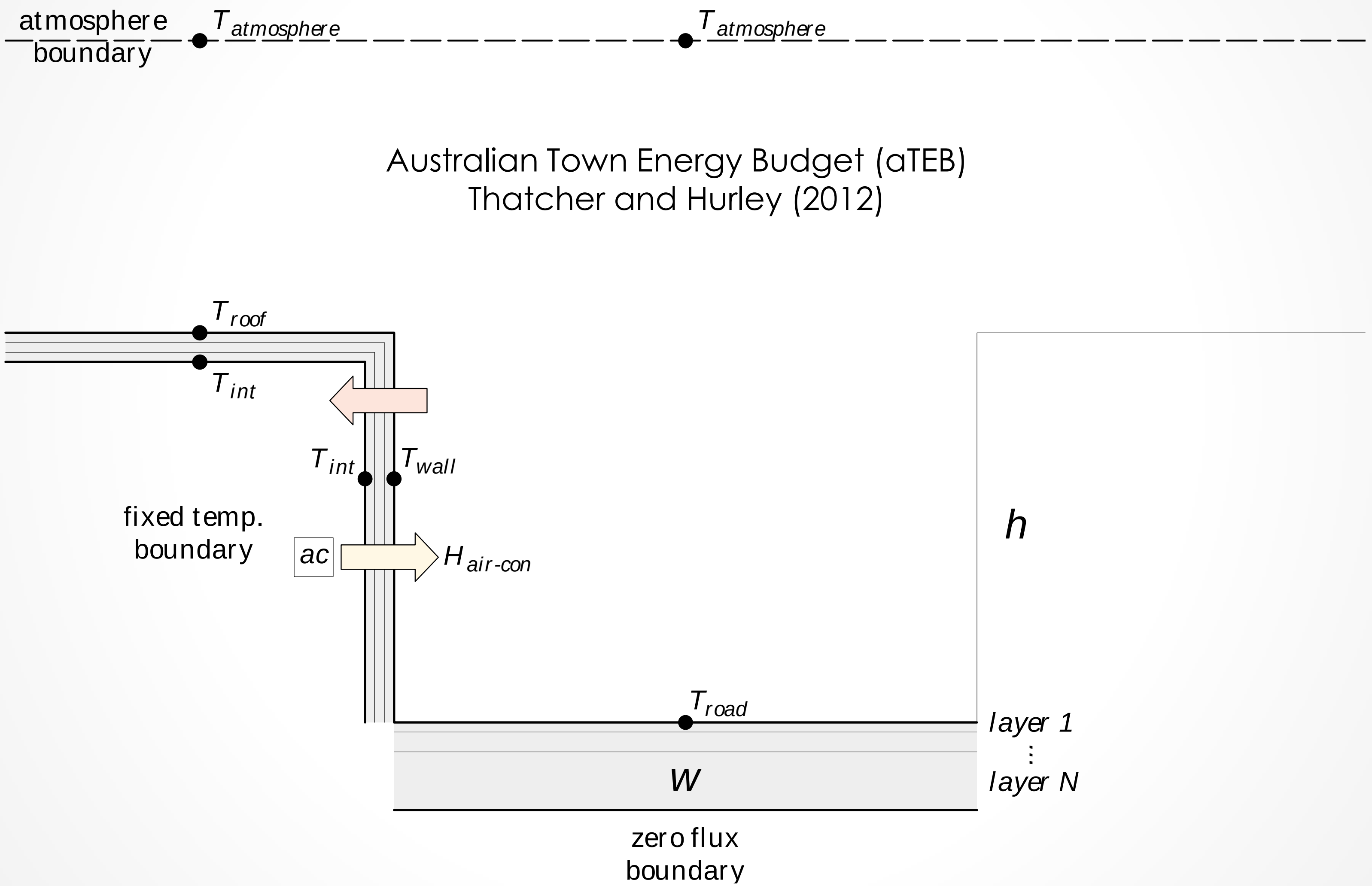

How aTEB is Different: Air Conditioning

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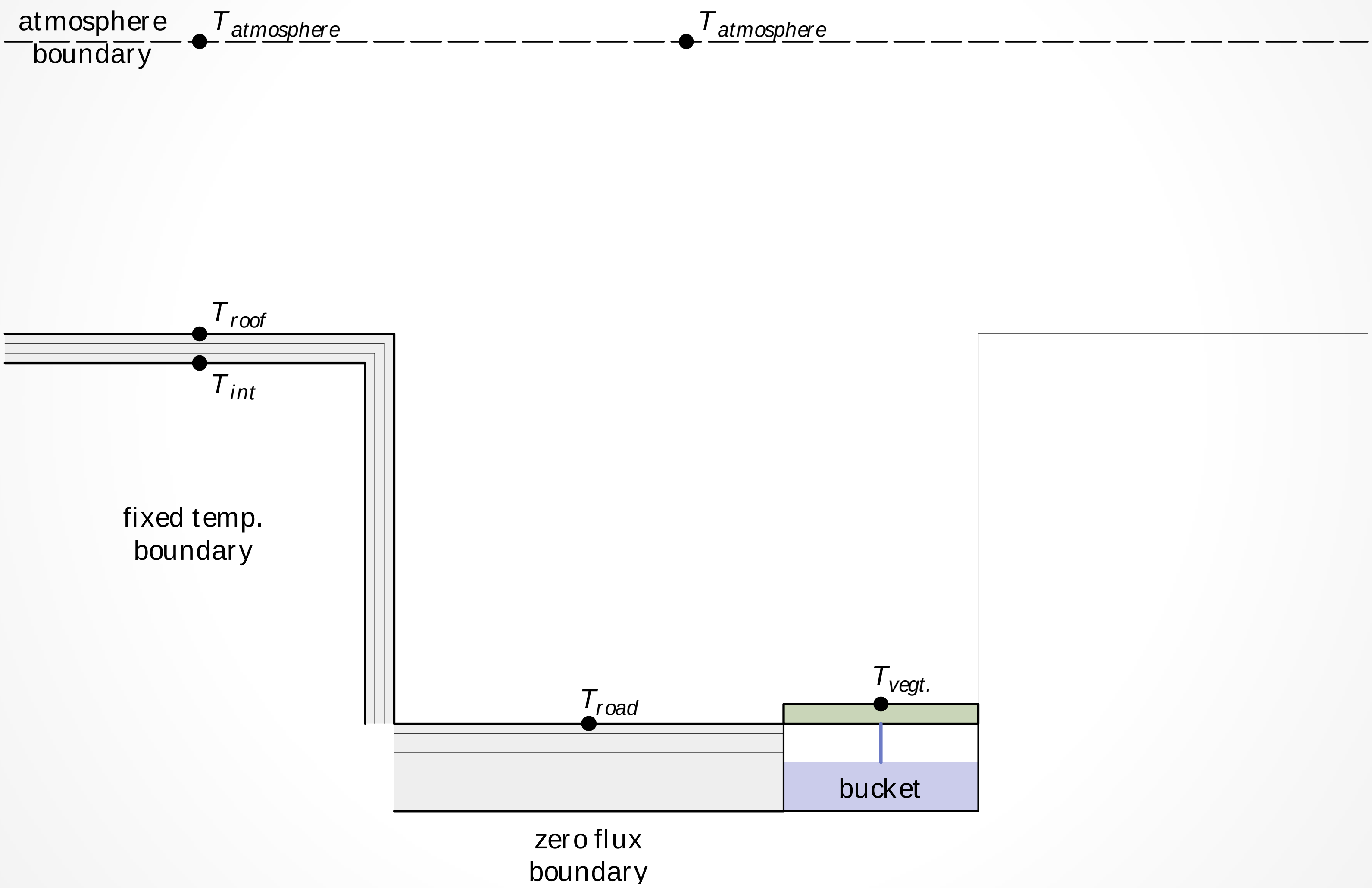
Melissa Hart | UNSW
Marcus Thatcher | CSIRO



How aTEB is Different: In-canyon Vegetation

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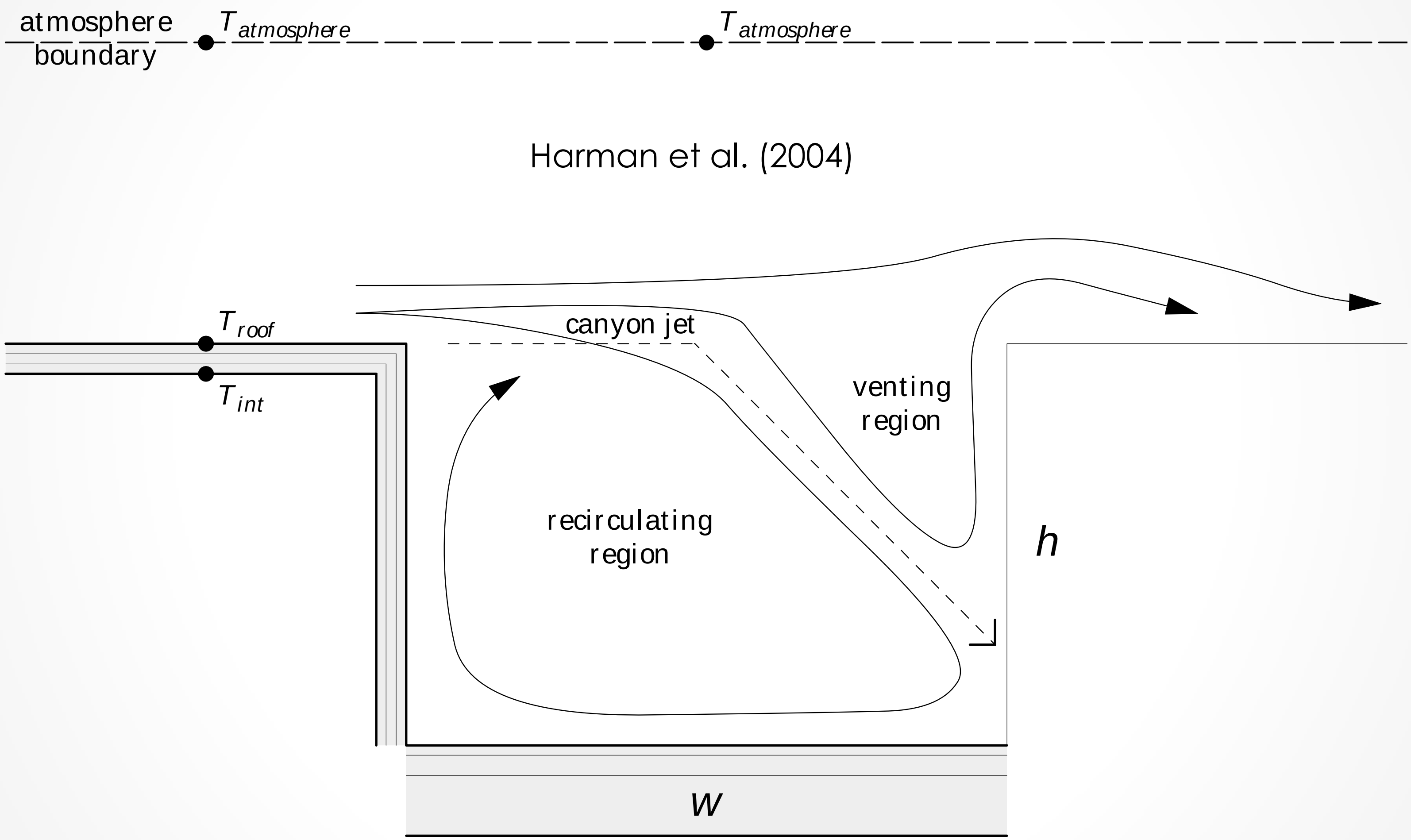

Harman et al. (2004)

How aTEB is Different to TEB: Wind

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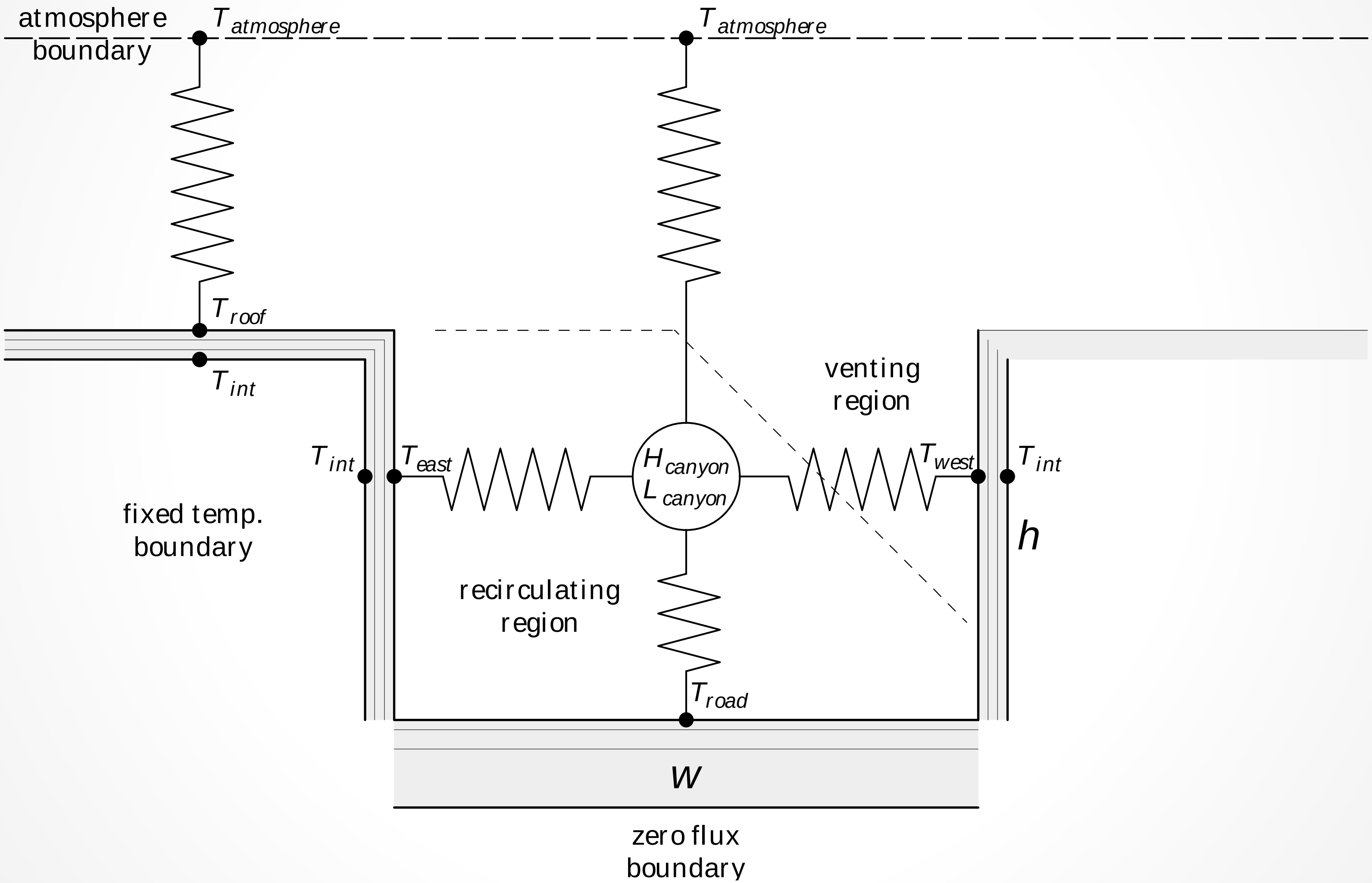

How aTEB is Different: 4 Facets

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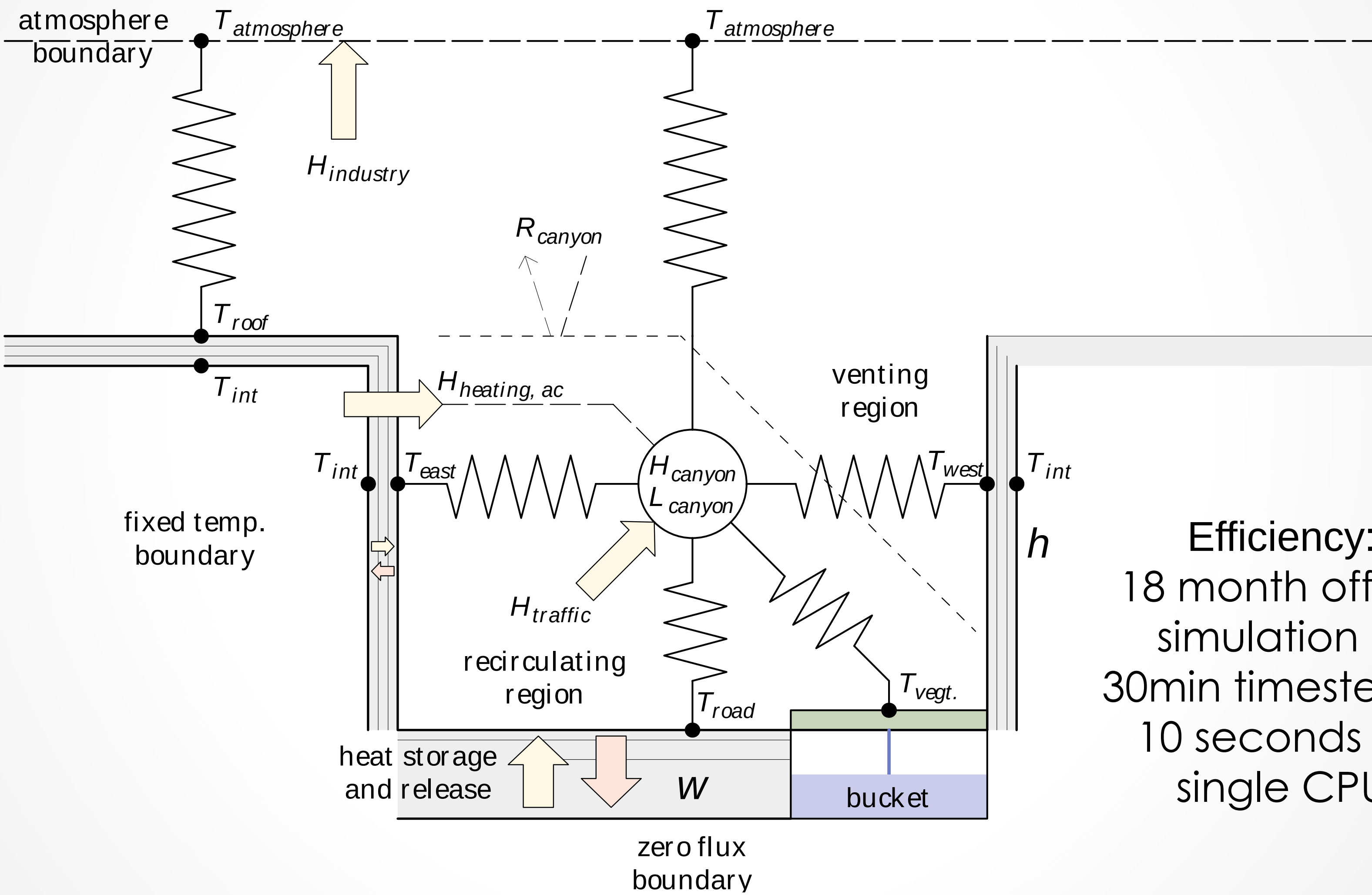

Efficiency:
18 month offline simulation @ 30min timesteps ~ 10 seconds on single CPU

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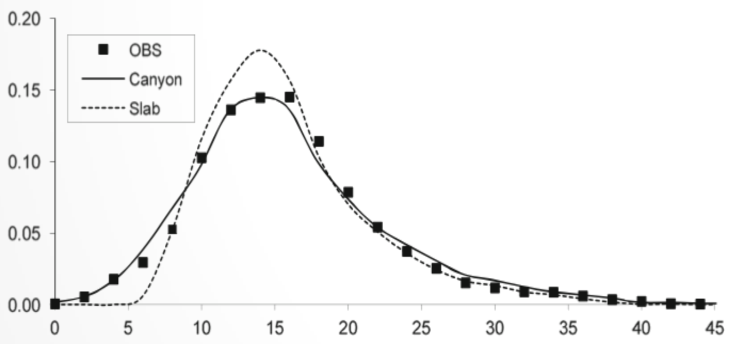
- Thatcher and Hurley (2012)
  - Obs: Melbourne 2003-2004 (Coutts et al. 2007)
- Luhar et al. (2014)
  - Obs: Basel 2002 (BUBBLE) (Rotach et al. 2005)

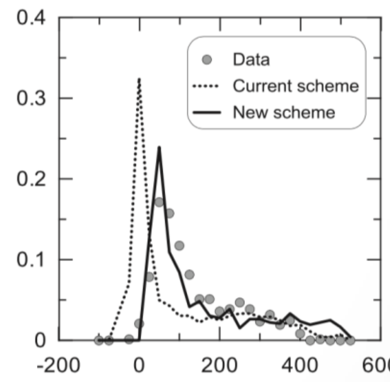
Temperature PDF

Probability



2m Temperature (°C)

Sensible Heat PDF



Flux Density (W/m^2)

Improvement over existing slab scheme

Adequately and efficiently representing heat conduction and storage for urban surfaces

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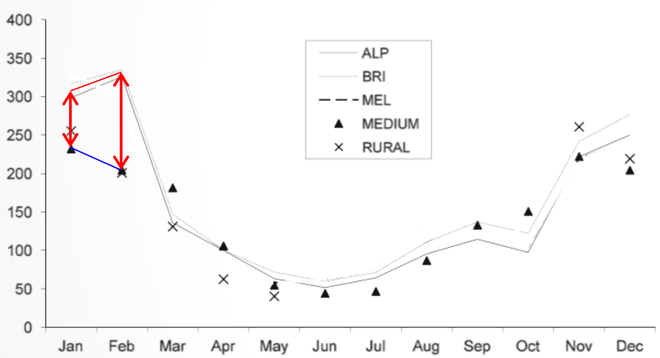
- Thatcher and Hurley (2012)
- Luhar et al. (2014)

Sensible Heat Flux

Sensible Heat Flux (W/m^2)



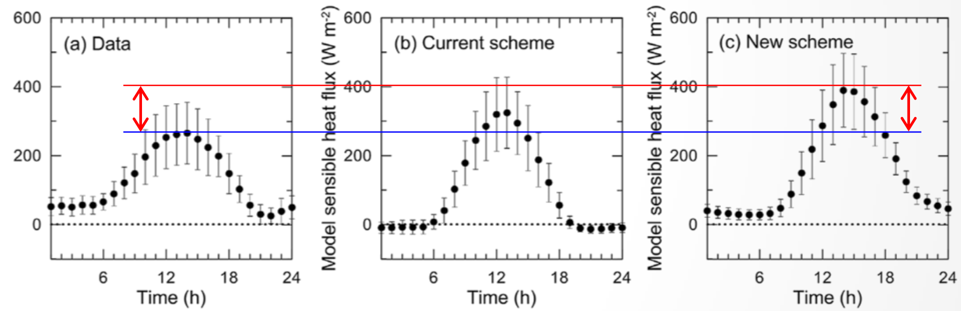
Annual Cycle

Sensible Heat Flux

Obs

Slab

Canyon



Diurnal Cycle

Overestimation of peak sensible heat flux

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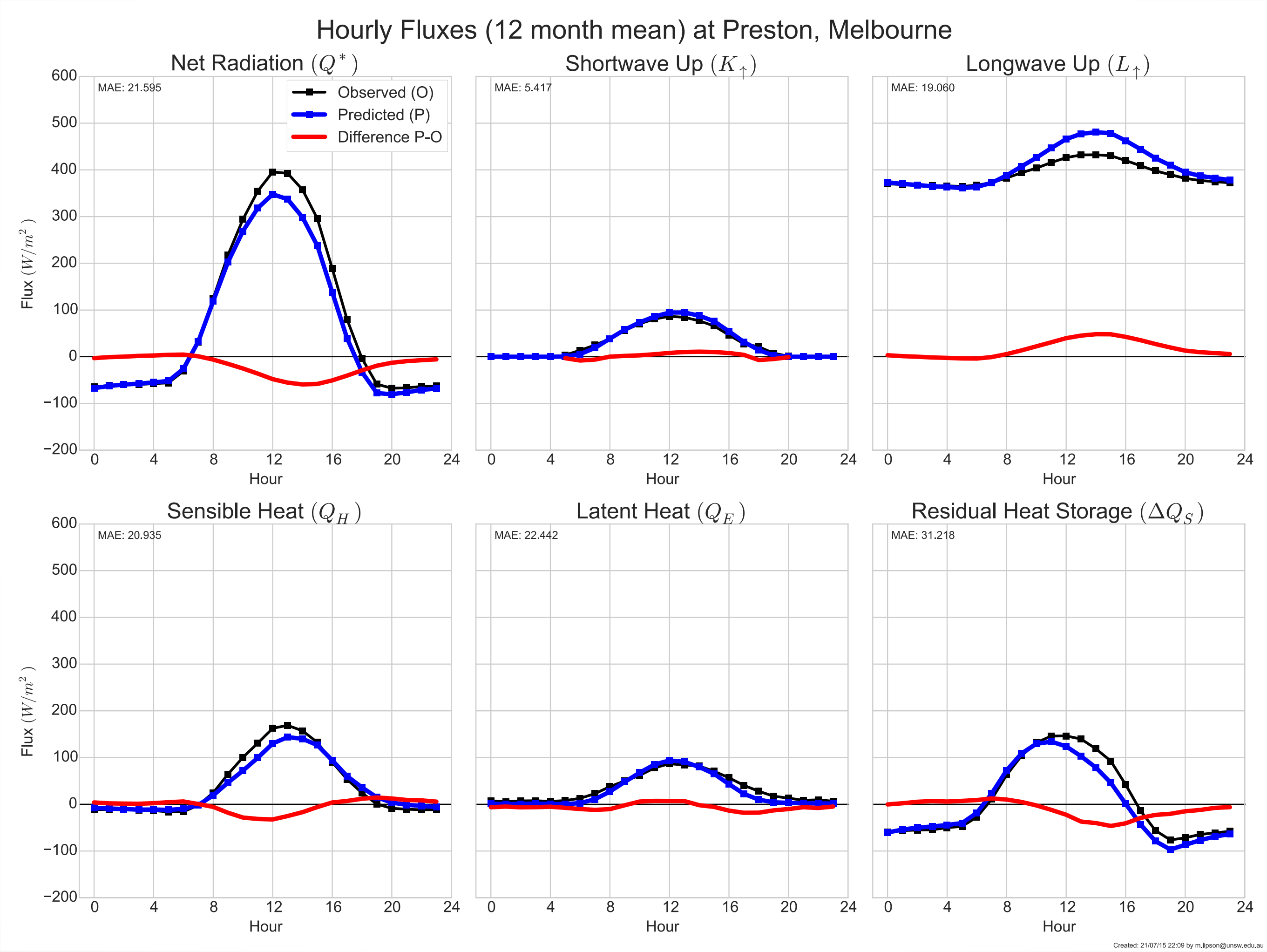

Default parameters

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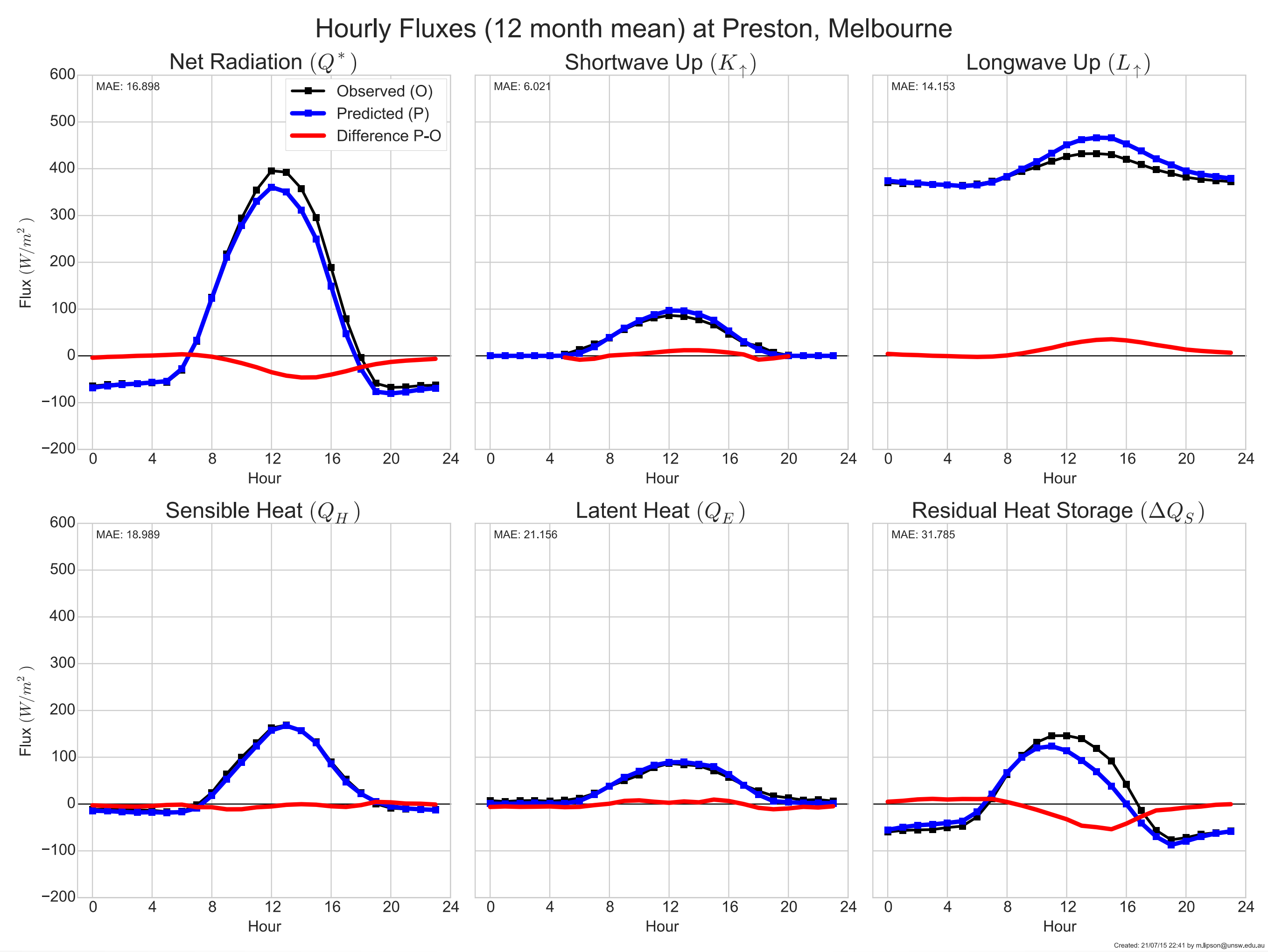

Even when tuned, heat storage an issue

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Storage heat flux:

- often regarded as the key process in the genesis of urban heat island (Grimmond and Oke 1999)
- but is difficult to measure, therefore often calculated as a residual, so errors from other fluxes accumulate
- notwithstanding measurement uncertainty, 31/32 models participating in the urban intercomparison phase 2 had negative bias for storage heat flux; ensemble mean absolute error was largest of the fluxes (Grimmond, pers. comms)

Broader implications?

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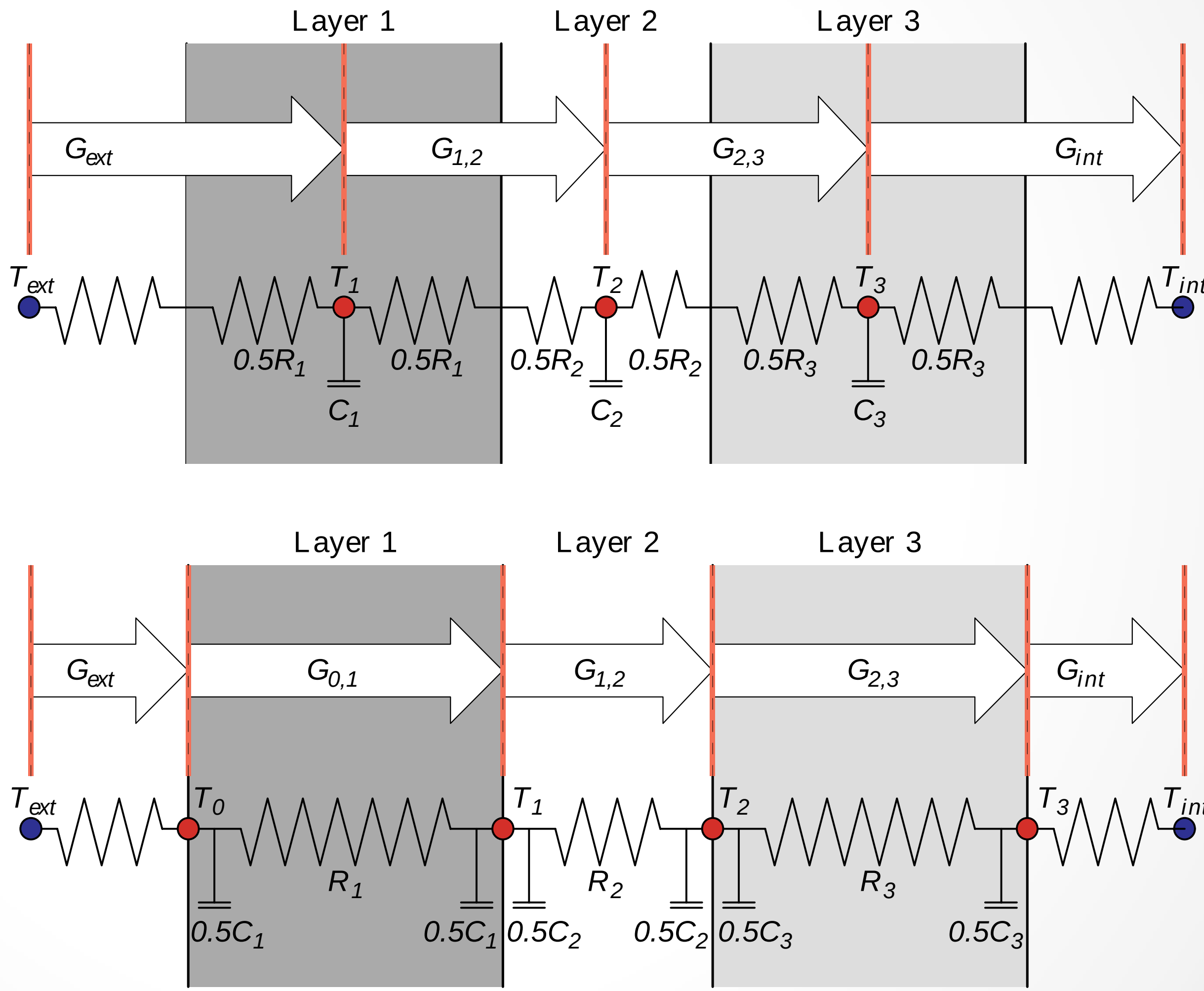
Discretised 1D heat diffusion equation (lumped capacitance model)

Half-layer scheme
Current aTEB
(R-C-R)

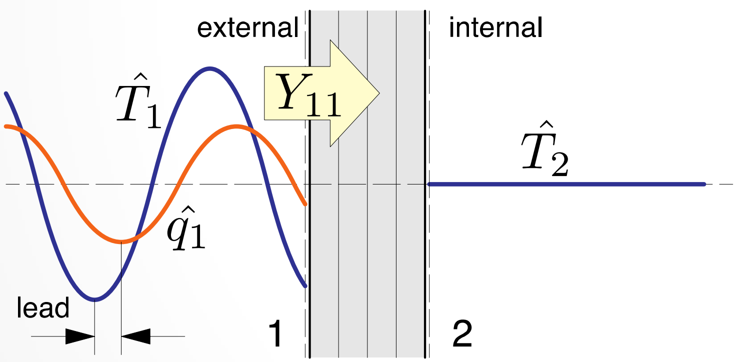
Interface scheme
Proposed
(C-R-C)



Comparing models

- Assumptions:
  - 24 hr periodic temperature forcing on one side
  - Fixed temperature on the other, average of forcing
  - Fixed external and internal surface heat transfer coefficients
  - Planar heat transfer (homogenous layers, no cavities, no thermal bridges)

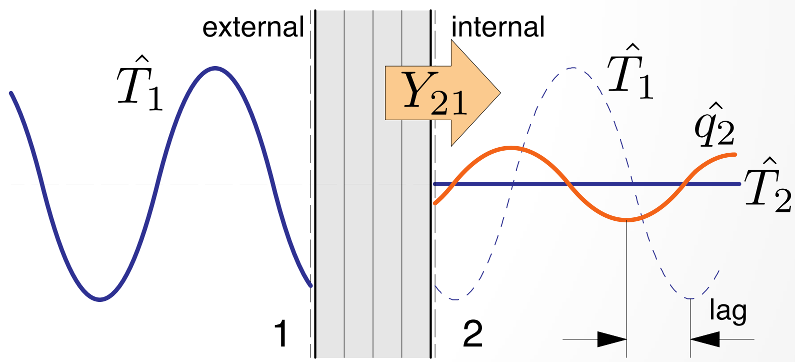
Periodic Thermal Admittance



Temperature
Heat flux density

$$Y_{11} = \frac{\hat{q}_1}{\hat{T}_1}$$

Periodic Thermal Transmittance



Temperature
Heat flux density

$$Y_{21} = -\frac{\hat{q}_2}{\hat{T}_1}$$

Comparing models

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Test our discretised models against an exact solution

- Numerical Method (as in aTEB):
  - Tridiagonal solver for N layer system (Thomas Algorithm)

where $a_1 = 0$ and $c_n = 0$.

$$\begin{bmatrix} b_1 & c_1 & & & 0 \\ a_2 & b_2 & c_2 & & \\ & a_3 & b_3 & \ddots & \\ & & \ddots & \ddots & c_{n-1} \\ 0 & & & a_n & b_n \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ \vdots \\ d_n \end{bmatrix}.$$

- Analytical Method:
  - 'Admittance procedure' calculates exact solution to heat transfer in a composite system of homogenous layers, including surface resistances.
  - Temperature and heat flux of each side is related via heat transfer matrix.
  - Method documented in ISO13786:2007.

$$\begin{pmatrix} \hat{T}_2 \\ \hat{q}_2 \end{pmatrix} = \overbrace{\begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix}}^{\boldsymbol{Z}_{\text{system}}} \cdot \begin{pmatrix} \hat{T}_1 \\ \hat{q}_1 \end{pmatrix}$$

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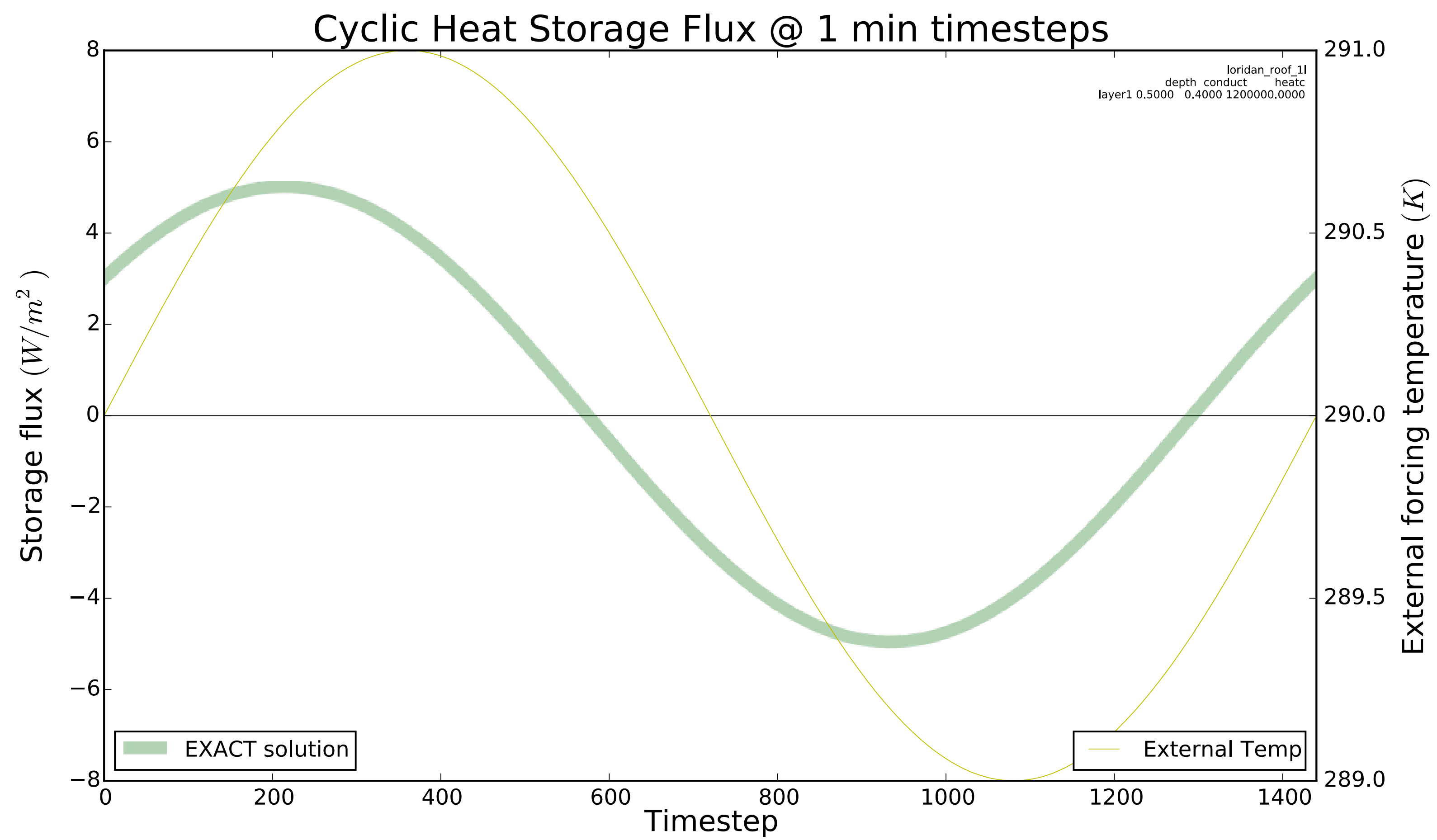

Discetisation in space of homogenous wall

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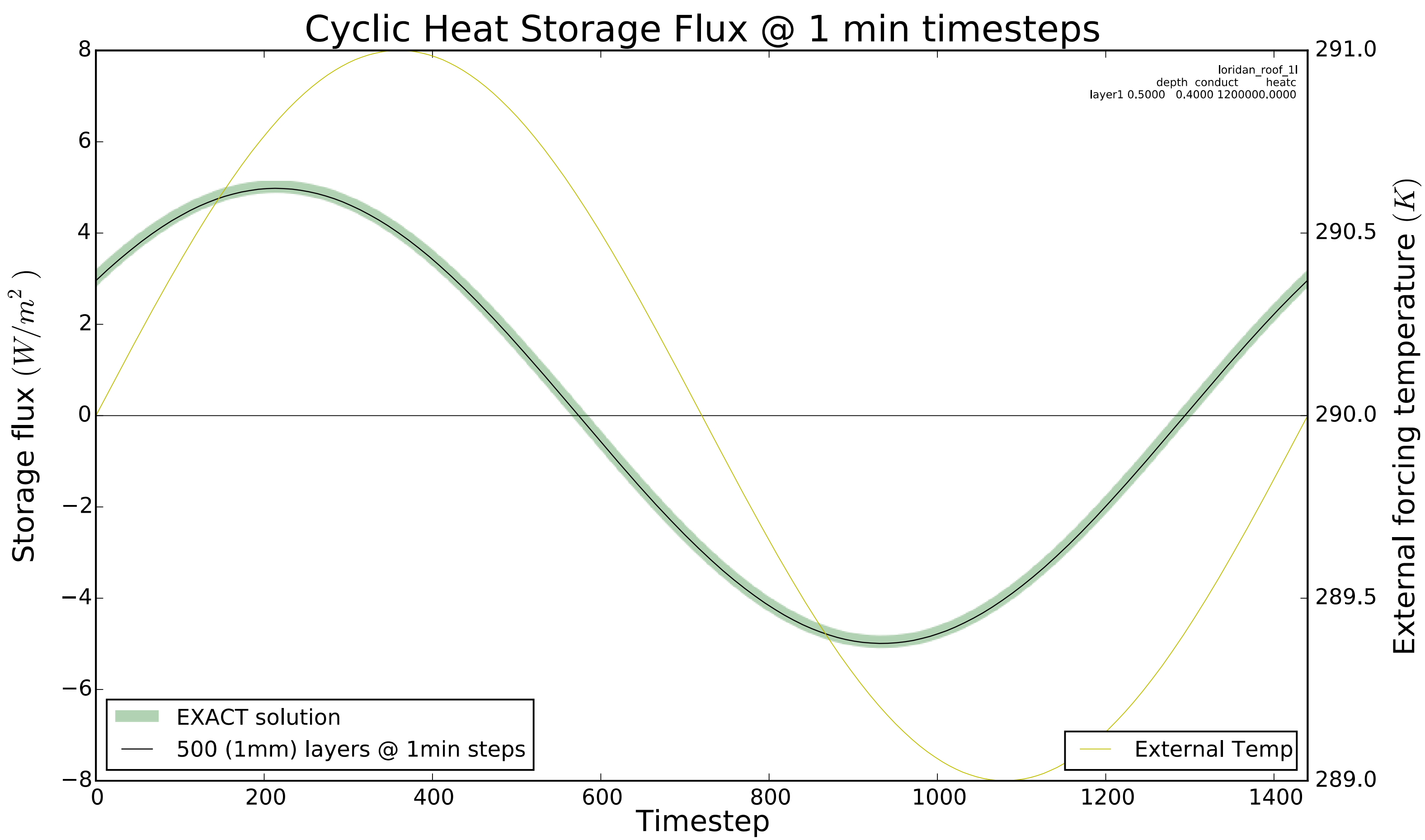

Discetisation in space of homogenous wall

Adequately and efficiently representing heat conduction and storage for urban surfaces

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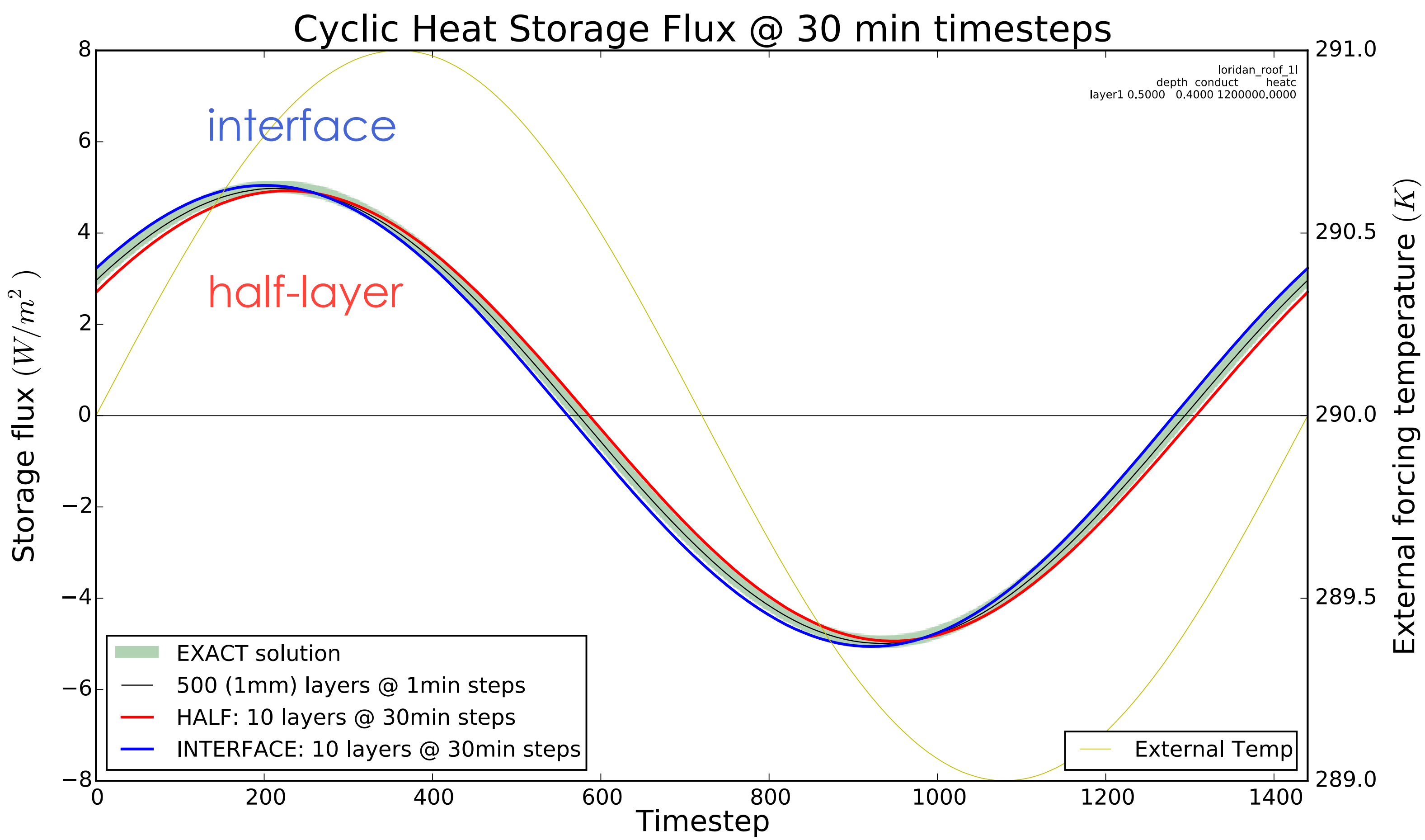

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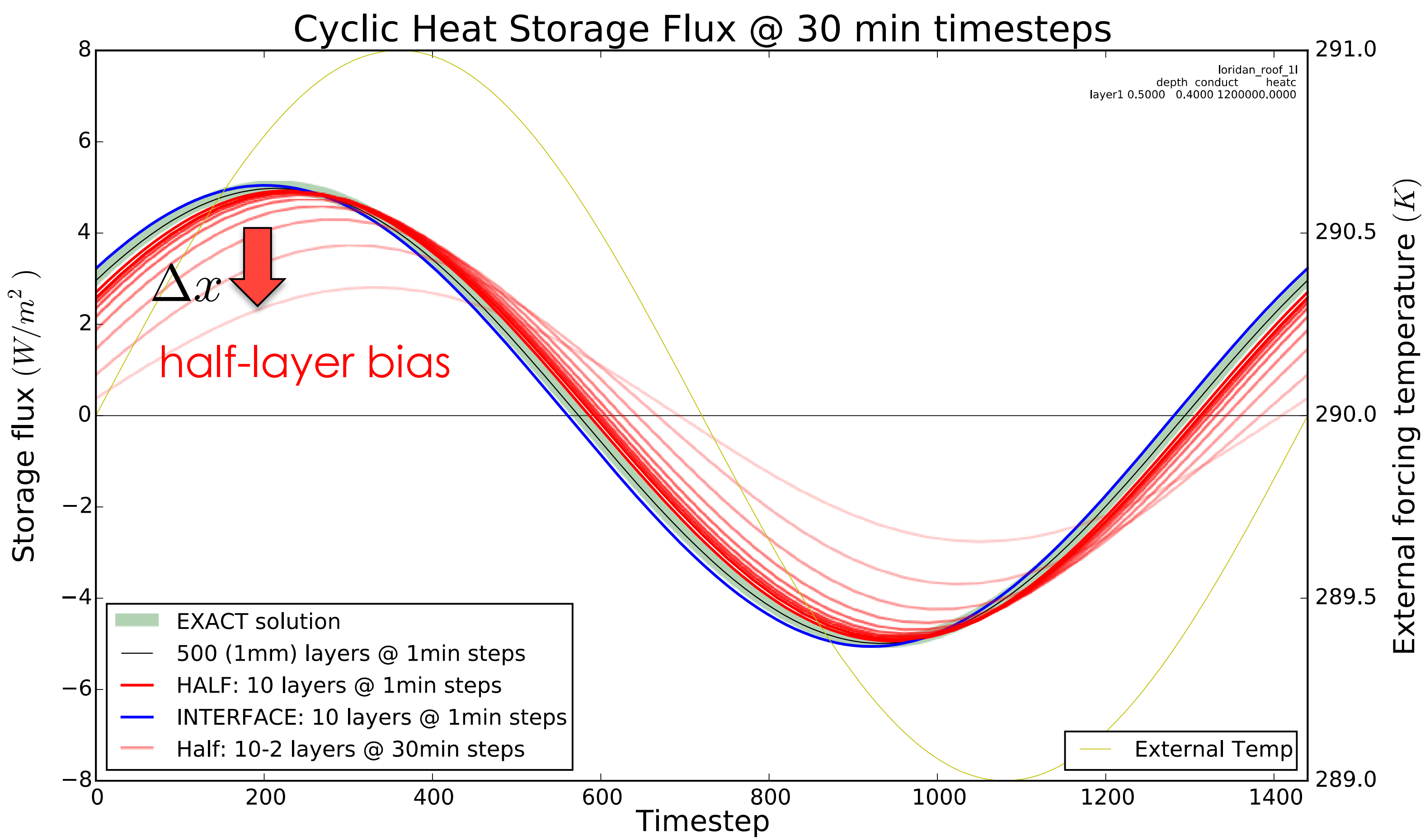

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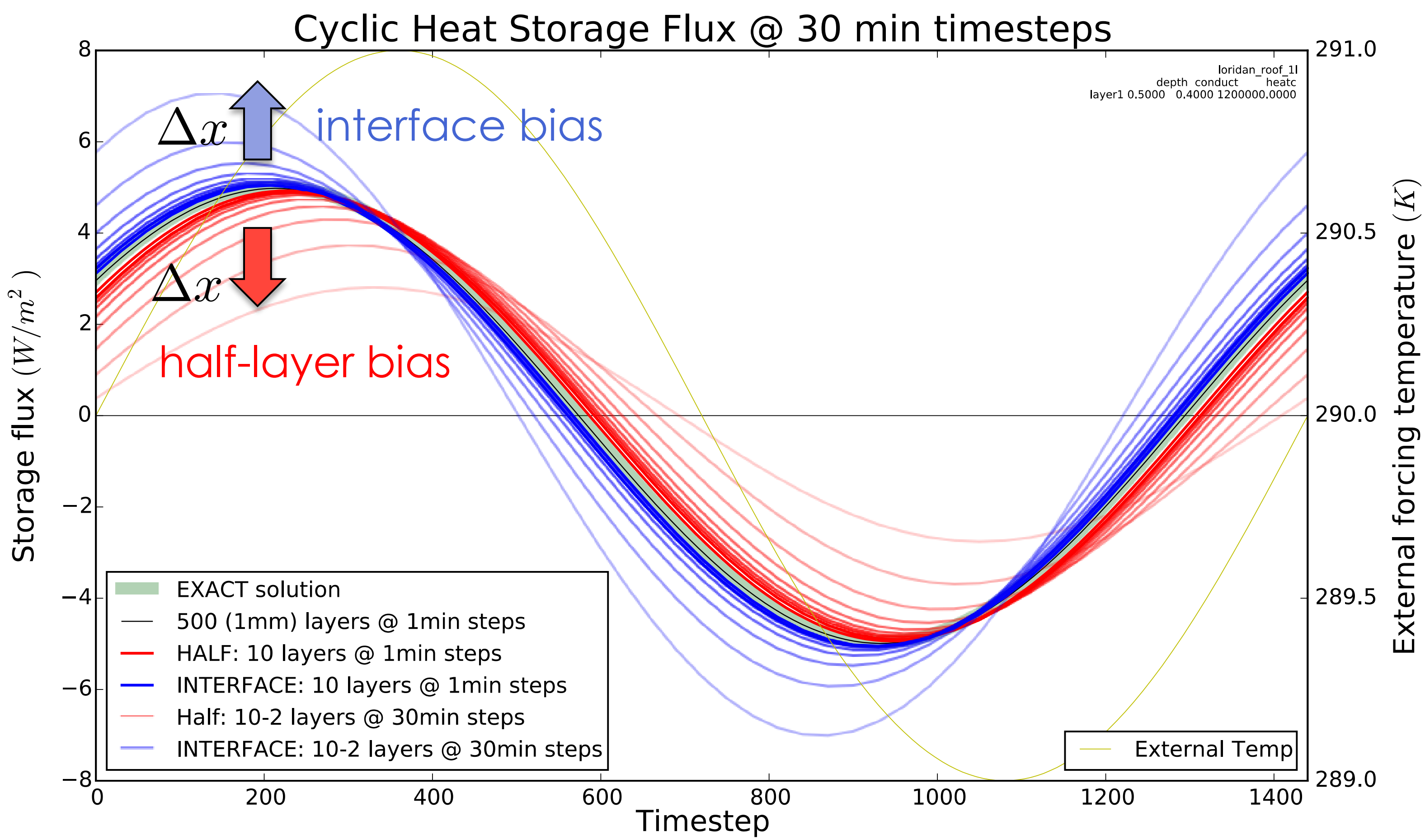

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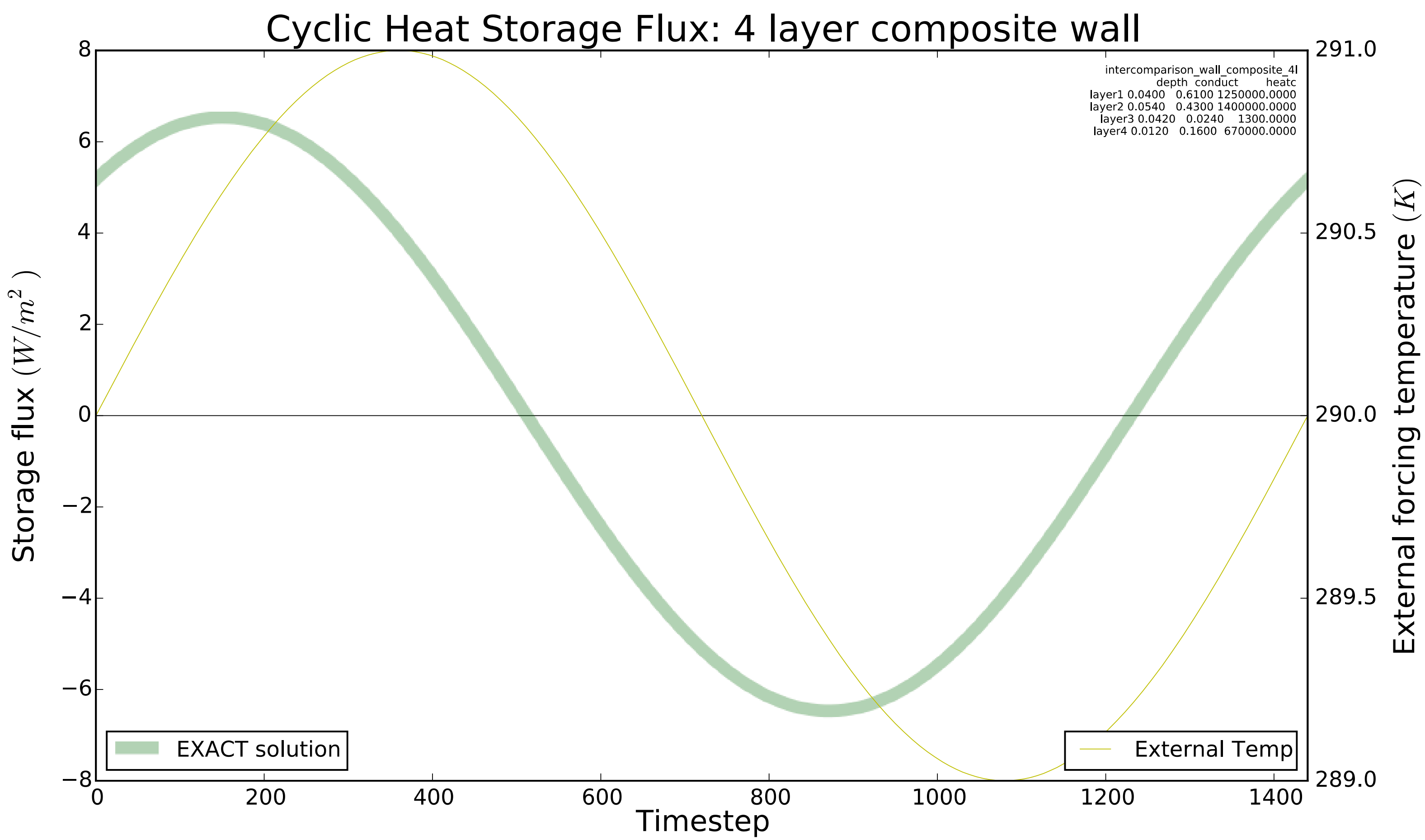

Discetisation in time of composite wall

Adequately and efficiently representing heat conduction and storage for urban surfaces

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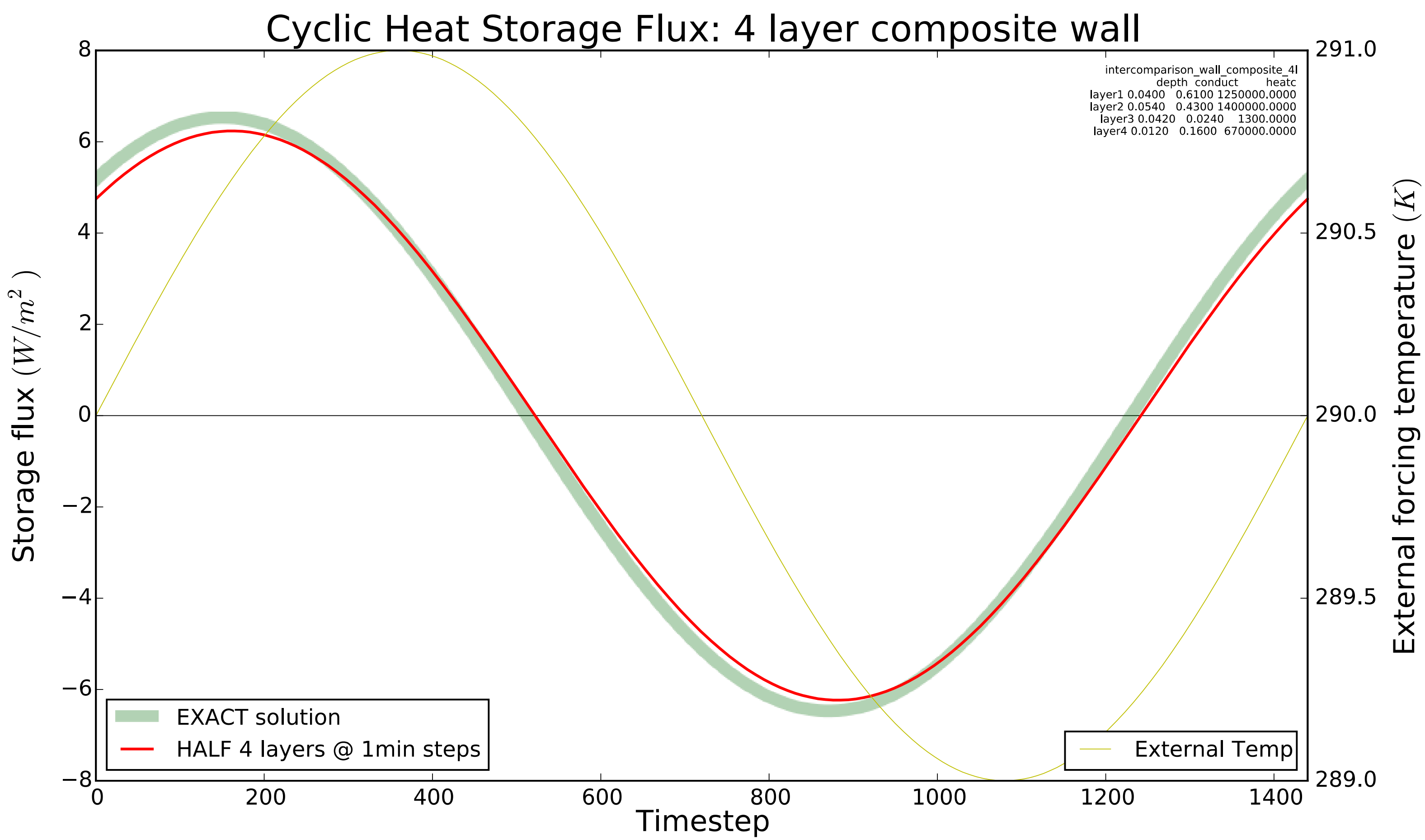

Discetisation in time of composite wall

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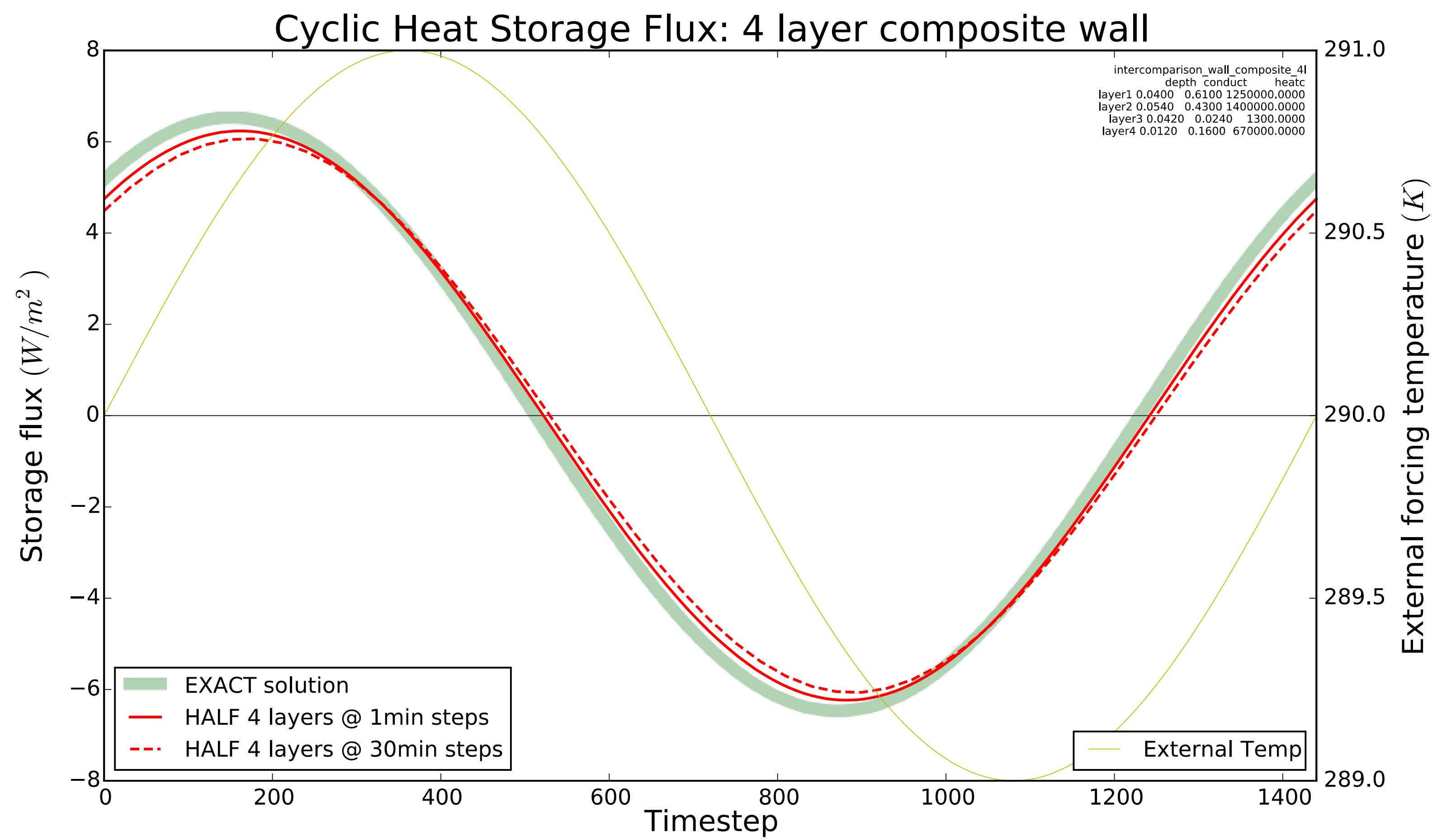

Discetisation in time of composite wall

Adequately and efficiently representing heat conduction and storage for urban surfaces

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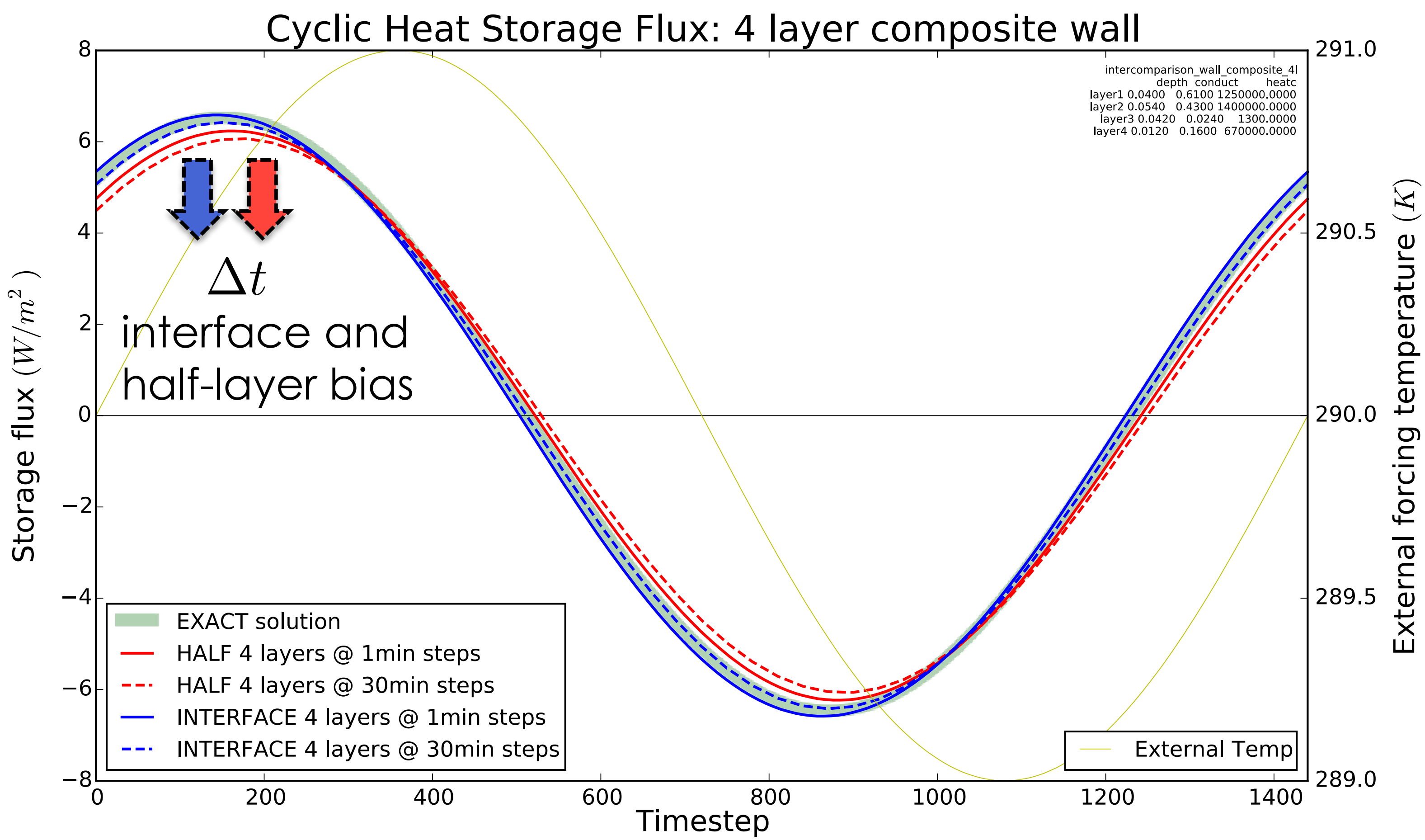

Discetisation in time of composite wall

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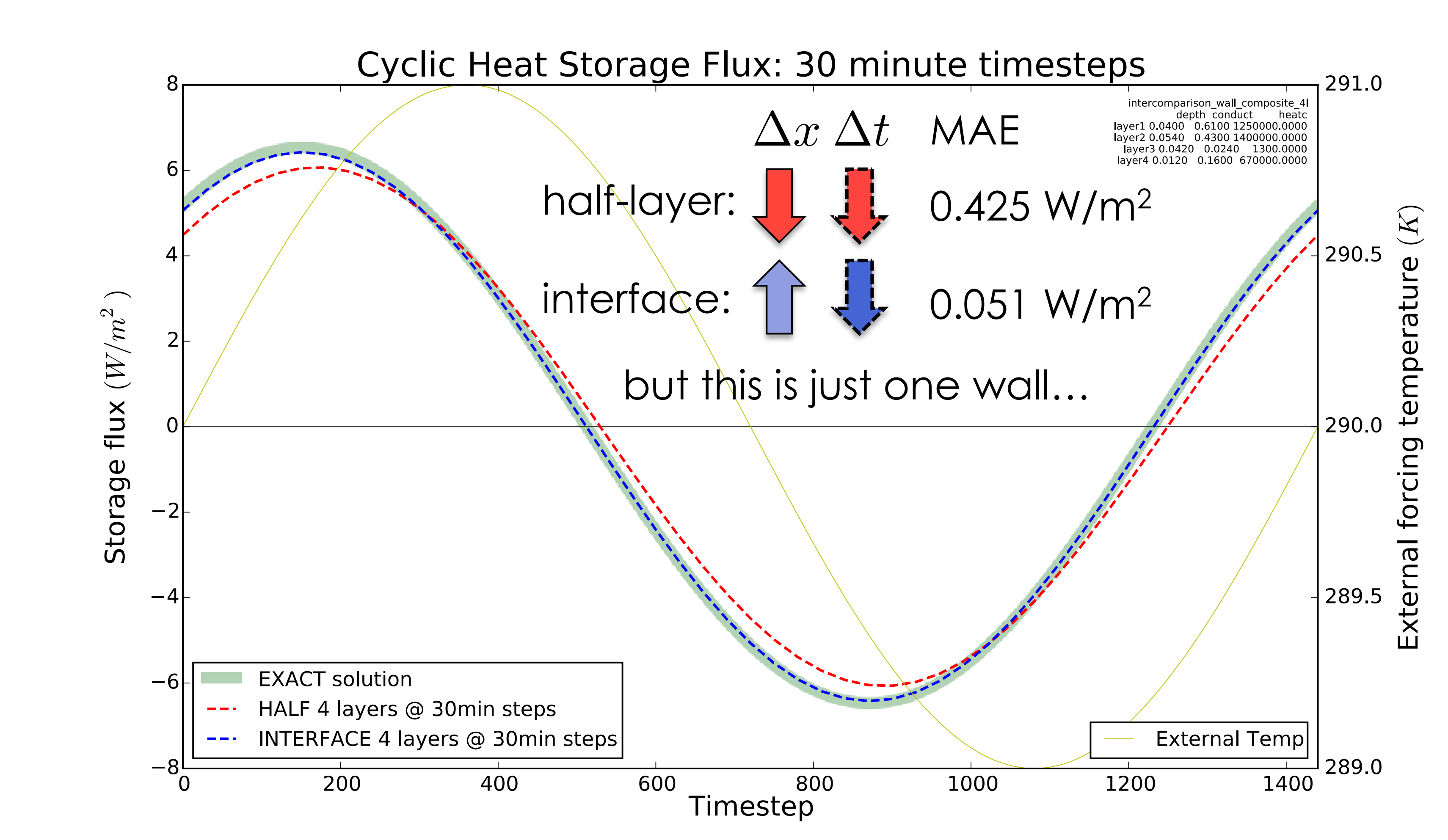

Discetisation used in aTEB (4 layer, 30 min)

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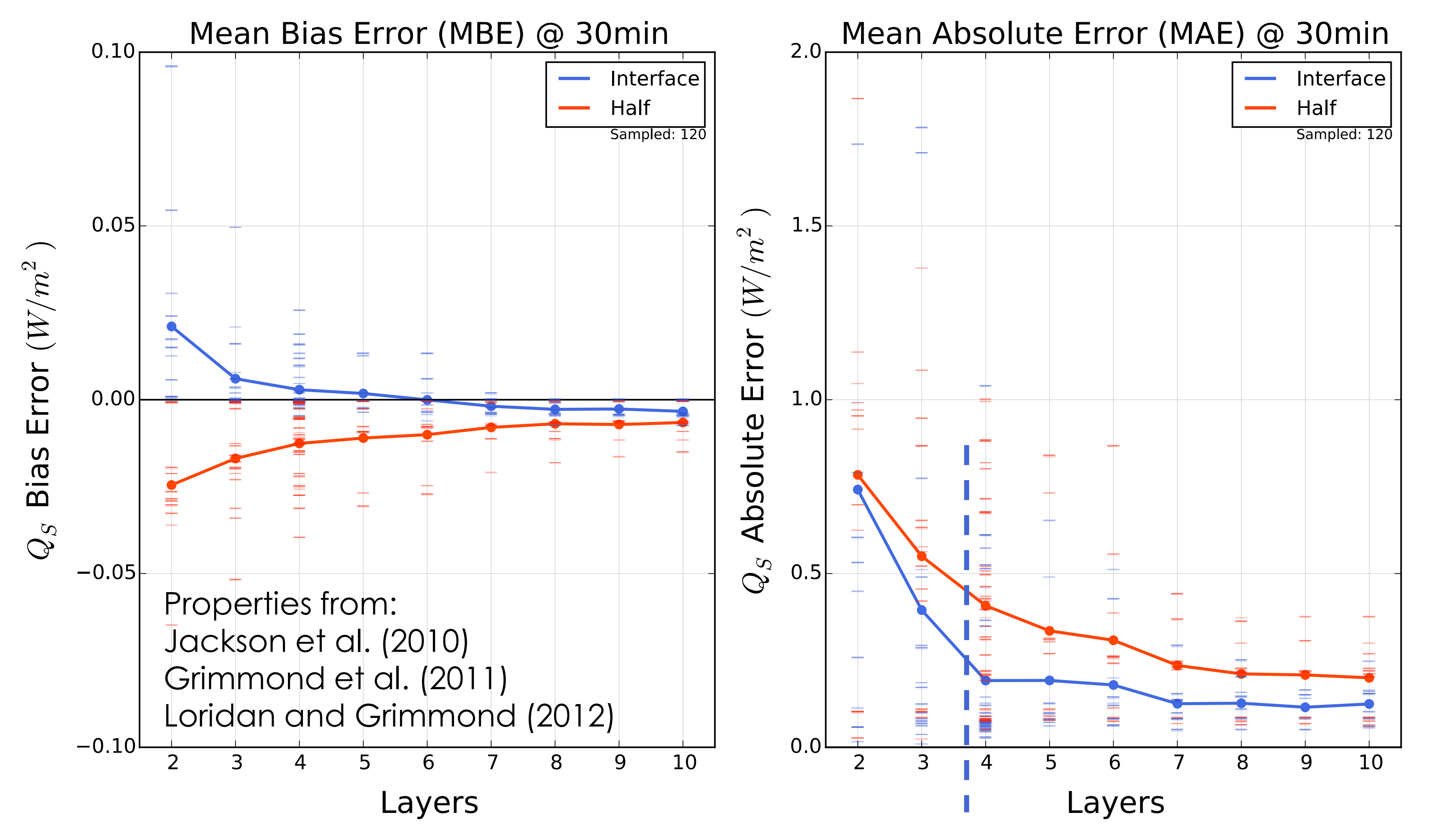

Comparing schemes: average errors

Conclusions:

- although heat storage not evaluated as often as other fluxes, (because of observational uncertainty) getting heat storage right is critical in simulating the important urban processes
- aTEB's current scheme, along with other models, generally underestimate storage heat flux, affecting other fluxes
- interface conduction scheme is closer to exact solution with chosen assumptions – yet to see impact in full model

~4 layers

SIMPLE <- - - - - - - - - - - - - - - - -> REALISTIC

↑

ADEQUATE

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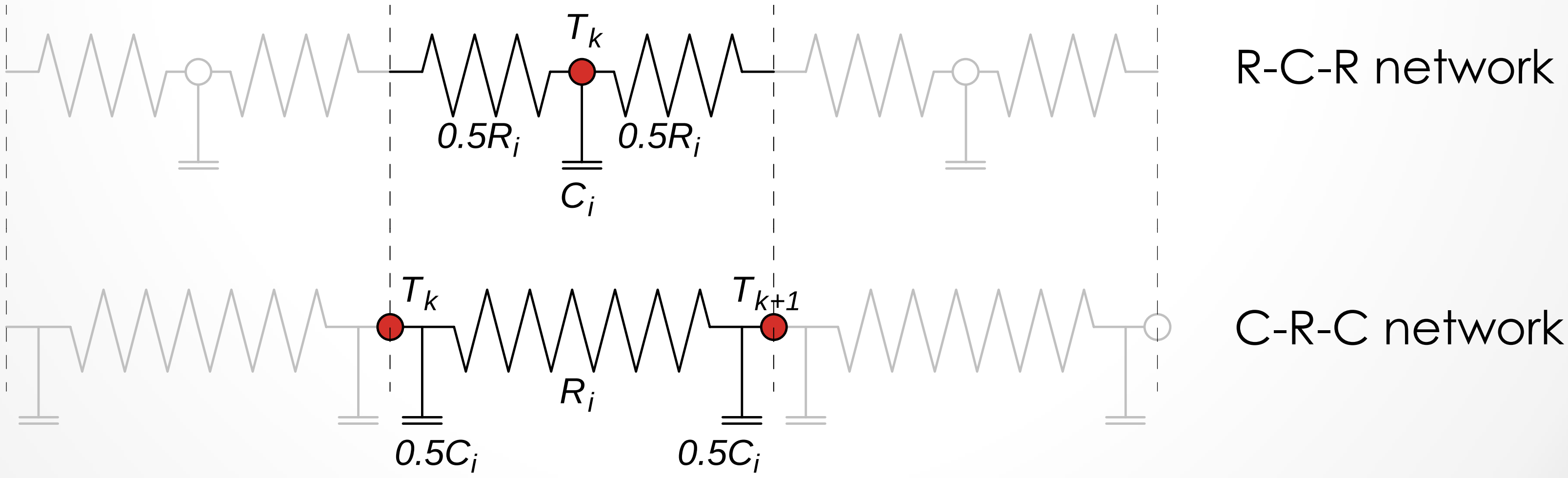
Discretised 1D heat diffusion equation (lumped model)

$$G = -\lambda \frac{\partial T}{\partial x} \qquad \Longrightarrow G_{\rightarrow} = \lambda \frac{(T_k - T_{k+1})}{\Delta x}$$

$$C \frac{\partial T}{\partial t} = \frac{\partial G}{\partial x} \qquad \Longrightarrow C_i \Delta x \frac{T_k^{t+1} - T_k^t}{\Delta t} = G_{in} - G_{out}$$

Resistance and capacitance



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Heat transfer matrix:
(ISO13786:2007)

$$\begin{pmatrix} \hat{T}_2 \\ \hat{q}_2 \end{pmatrix} = \overbrace{\begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix}}^{\boldsymbol{Z}_\mathrm{i}} \cdot \begin{pmatrix} \hat{T}_1 \\ \hat{q}_1 \end{pmatrix}$$

$$\boldsymbol{Z}_\mathrm{system} = \begin{pmatrix} 1 & -R_{se} \\ 0 & 1 \end{pmatrix} \cdot \boldsymbol{Z}_N \cdot \boldsymbol{Z}_{N-1} \cdots \boldsymbol{Z}_2 \cdot \boldsymbol{Z}_1 \cdot \begin{pmatrix} 1 & -R_{si} \\ 0 & 1 \end{pmatrix}$$

Layer heat transfer matrix elements:

$$Z_{11} = cosh(\tfrac{d}{\delta})cos(\tfrac{d}{\delta}) + j sinh(\tfrac{d}{\delta})sin(\tfrac{d}{\delta}) = Z_{22}$$

$$Z_{12} = -\frac{\delta}{2\lambda}\left\{sinh(\tfrac{d}{\delta})cos(\tfrac{d}{\delta}) + cosh(\tfrac{d}{\delta})sin(\tfrac{d}{\delta}) + j\left[cosh(\tfrac{d}{\delta})sin(\tfrac{d}{\delta}) - sinh(\tfrac{d}{\delta})cos(\tfrac{d}{\delta})\right]\right\}$$

$$Z_{21} = -\frac{\delta}{\lambda}\left\{sinh(\tfrac{d}{\delta})cos(\tfrac{d}{\delta}) - cosh(\tfrac{d}{\delta})sin(\tfrac{d}{\delta}) + j\left[sinh(\tfrac{d}{\delta})cos(\tfrac{d}{\delta}) + cosh(\tfrac{d}{\delta})sin(\tfrac{d}{\delta})\right]\right\}$$

where periodic penetration depth: $\delta = \sqrt{\frac{\lambda T}{\pi \rho c}}$

Analytical solution to periodic heat transfer

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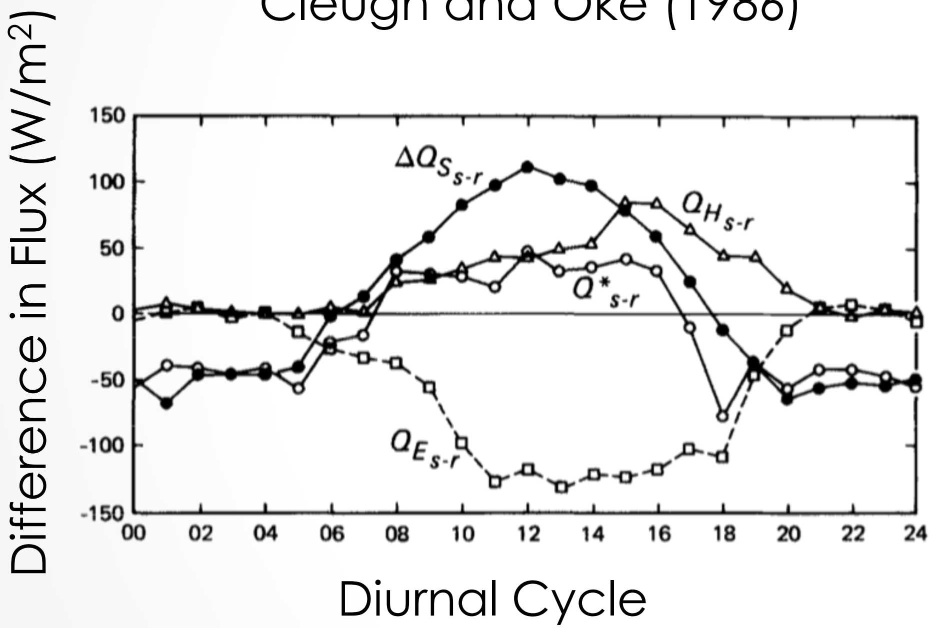
- Storage heat flux (G or ΔQ_s): rural and urban site observations

Cleugh and Oke (1986)



Grimmond and Oke (1999)

"The storage heat flux … is a significant component of the energy balance"

"Often regarded as the key process in the genesis of urban heat islands"

Importance of heat storage in urban sites

- Thatcher and Hurley (2012)
  - Obs: Melbourne 2003-2004 (Coutts 2007)
  - Focus on canopy temperature, wind and partitioning of fluxes

Boundary-Layer Meteorol (2012) 142:149–175
DOI 10.1007/s10546-011-9663-8

ARTICLE

Simulating Australian Urban Climate in a Mesoscale Atmospheric Numerical Model

Marcus Thatcher · Peter Hurley

Received: 21 December 2010 / Accepted: 6 October 2011 / Published online: 29 October 2011

Abstract We develop an urban canopy scheme coupled to a mesoscale atmospheric numerical model and evaluate the simulated climate of an Australian city. The urban canopy scheme is based on the Town Energy Budget approach, but is modified to efficiently represent the predominately suburban component of Australian cities in regional climate simulations. Energy conservation is improved by adding a simple model of air-conditioning to prevent the urban parametrization acting as an energy sink during the Australian summer. In-canyon vegetation for suburban areas is represented by a big-leaf model, but with a largely reduced set of prognostic variables compared to previous approaches. Although we have used a recirculation/venting based parametrization of in-canyon turbulent heat fluxes that employs two canyon wall energy budgets, we avoid using a fixed canyon orientation by averaging the canyon fluxes after integrating over 180° of possible canyon orientations. The urban canopy scheme is evaluated by simulating the climate for Melbourne, Australia after coupling it to The Air Pollution Model. The combined system was found to predict a realistic climatology of air temperatures and winds when compared with observations from Environmental Protection Authority monitoring stations. The model also produced a plausible partitioning of the urban energy budget when compared to urban flux-tower studies. Overall, the urban canyon parametrization appears to have reasonable potential for studying present and predicting changes in future Australian urban climates in regional climate simulations.

- Luhar et al. (2014)
  - Obs: Basel 2002 (BUBBLE)
  - Focus on flow and dispersion in the urban boundary layer

Atmospheric Environment 88 (2014) 47–58

Contents lists available at ScienceDirect

Atmospheric Environment

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ATMOSPHERIC ENVIRONMENT

Evaluating a building-averaged urban surface scheme in an operational mesoscale model for flow and dispersion

CrossMark

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HIGHLIGHTS

- A building-averaged urban canyon scheme in a mesoscale model is evaluated.
- This scheme simulates the observed near-neutral to weakly unstable conditions at night.
- In contrast, the original slab scheme predicts weakly stable conditions at night.
- A better representation of the observed dispersion by the building-averaged scheme.
- Computational efficiency of the canyon scheme is on par with the slab scheme.

ARTICLE INFO

Article history:
Received 9 October 2013
Received in revised form
22 January 2014
Accepted 24 January 2014

Keywords:
Air pollution dispersion
BUBBLE data
TAPM model
Town energy balance
Urban boundary layer
Turbulent fluxes
Mesoscale modelling

ABSTRACT

A recently developed building-averaged urban surface scheme as coupled to an operational mesoscale model, TAPM, is evaluated for both flow and tracer dispersion using data from the 2002 Basel UrBan Boundary Layer Experiment (BUBBLE) conducted in the city of Basel, Switzerland. This scheme is based on the so-called town energy balance (TEB) approach and simulates turbulent fluxes using a generic canyon geometry to resolve energy balances for walls, roads and roofs. Air conditioning to close the building energy budget, in-canyon vegetation, and the effects of recirculation and venting of air within the canyon on turbulent fluxes are included. Comparison is also made with the original urban surface scheme of TAPM based on a simple slab approach with separate urban and vegetation–soil tiles and a specified anthropogenic heat flux. The results show that the new scheme leads to an overall improvement in the prediction of surface fluxes, and is able to reproduce the observed near-neutral to weakly unstable conditions at night, which is a feature of urban meteorology. In contrast, the slab scheme predicts stable conditions at night. The observed concentration fields from the tracer experiments are better simulated using the new scheme, but because there were no nighttime tracer releases, the capability of the new scheme under full diurnal conditions could not be demonstrated. For the applications considered here, the computational efficiency of the new scheme in TAPM is on par with the slab scheme.

Adequately and efficiently representing heat conduction and storage for urban surfaces

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Melissa Hart | UNSW
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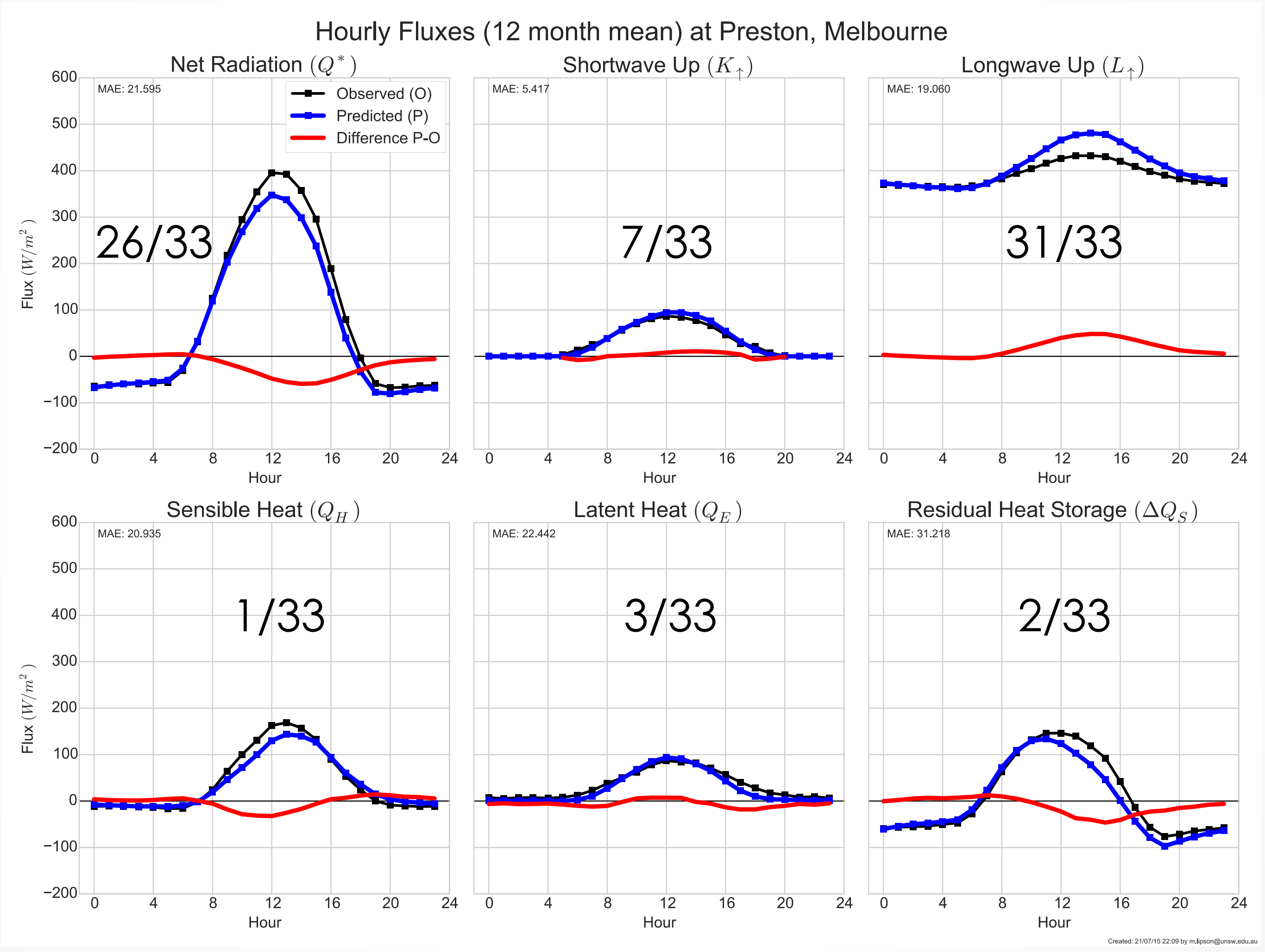

Default parameters

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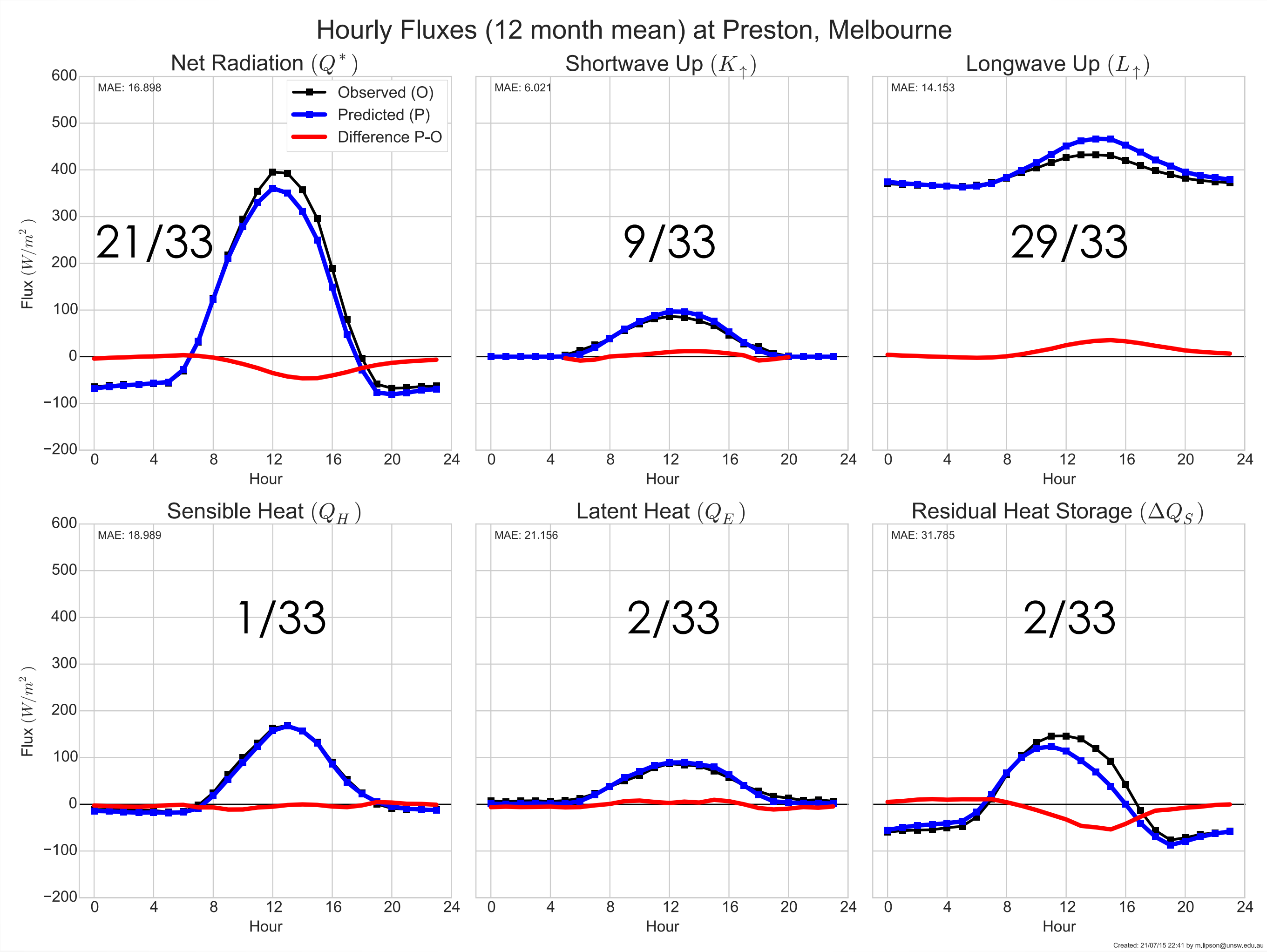

Even when tuned, heat storage an issue

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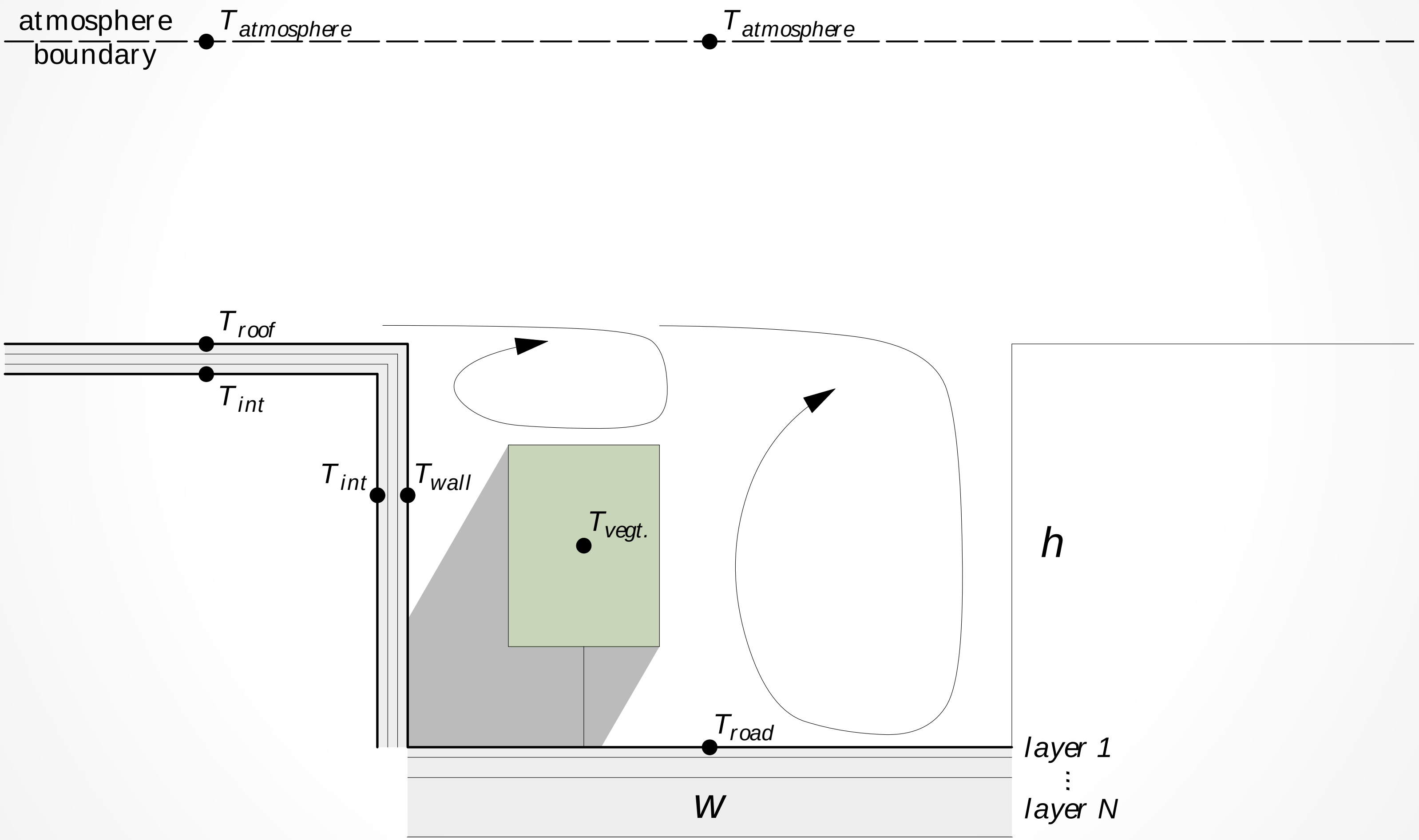

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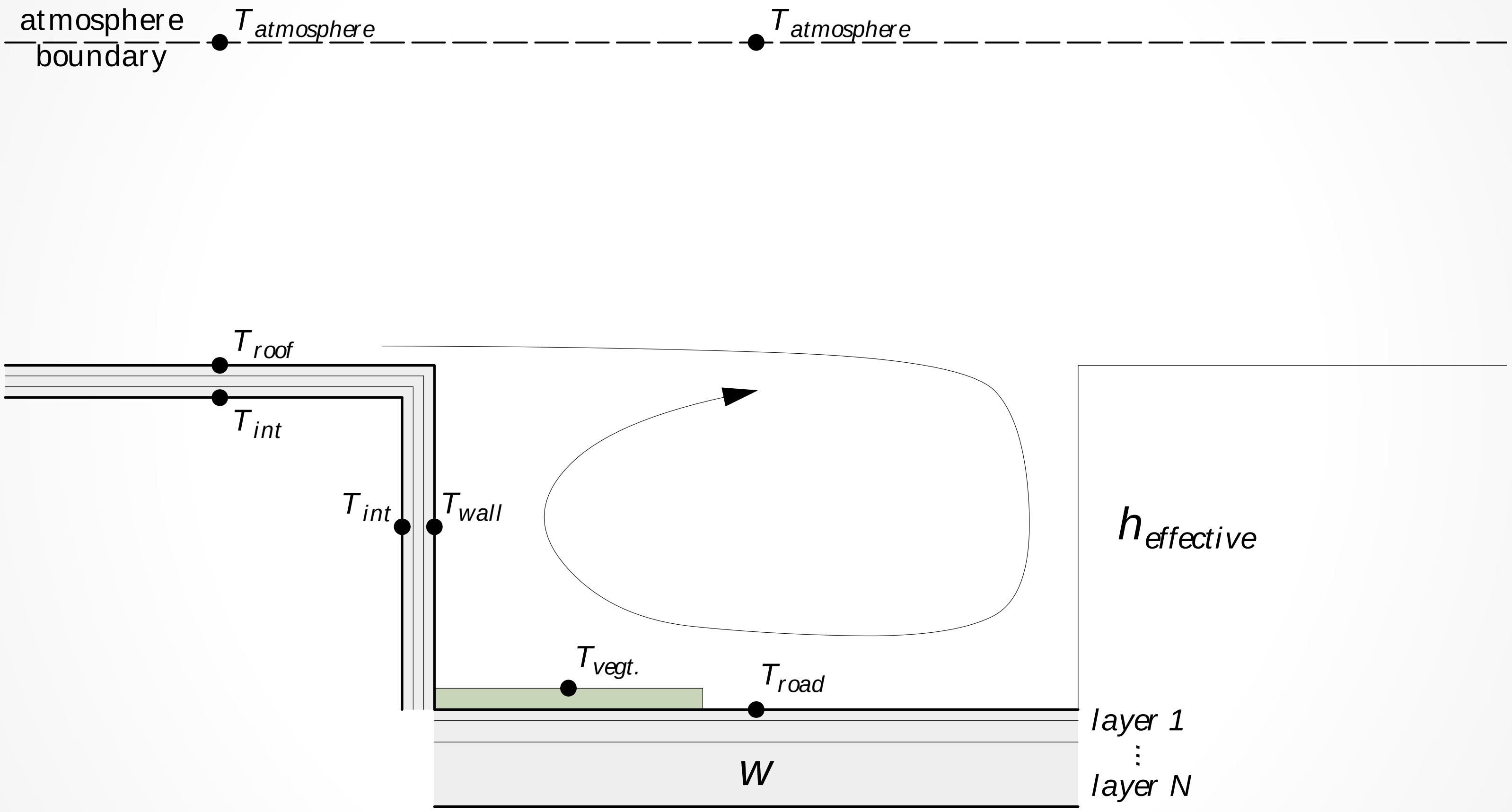

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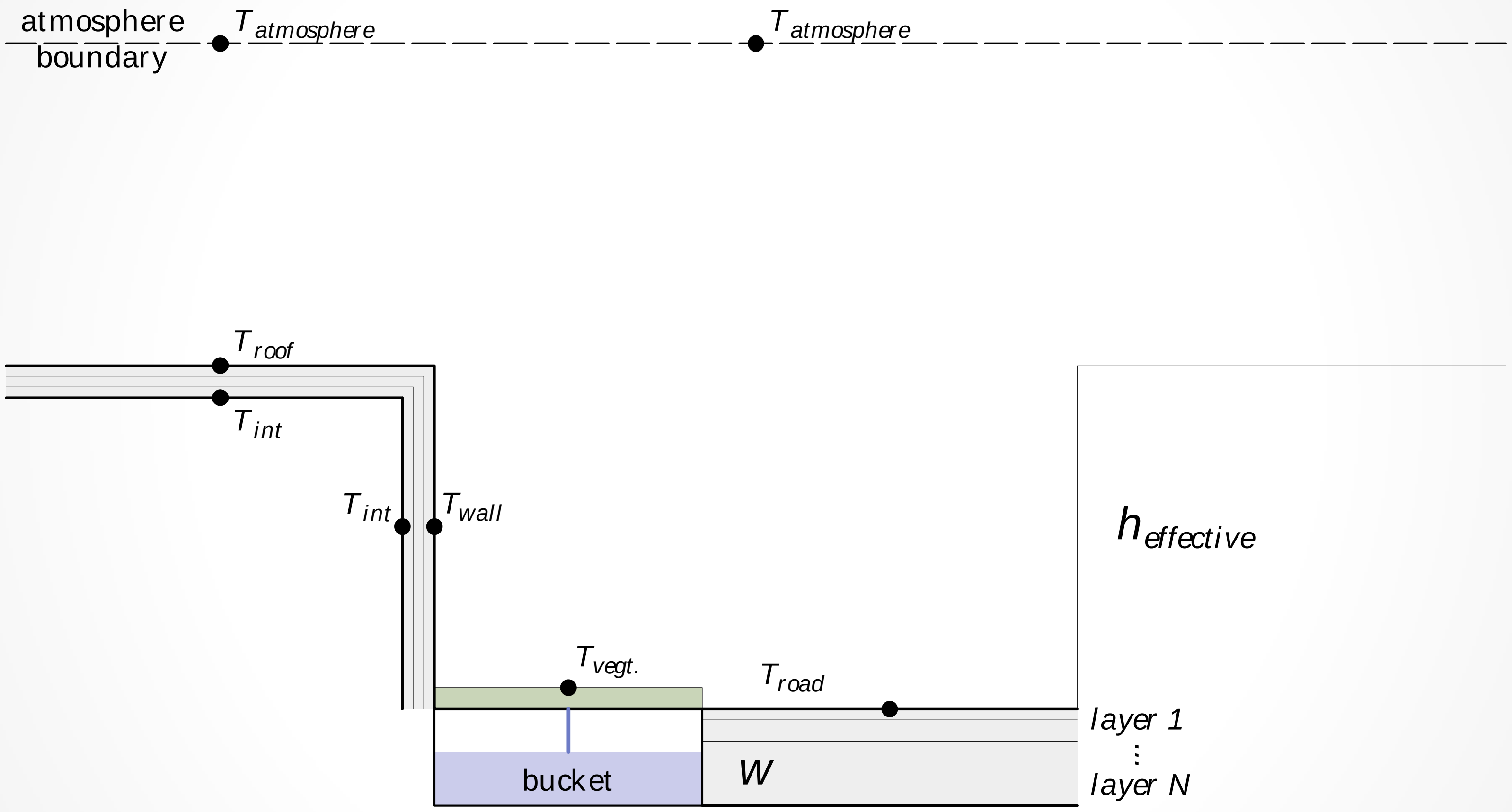

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