



The Air-temperature Response to Green/blue-infrastructure Evaluation Tool (TARGET v1.0): an efficient and user-friendly model of city cooling.

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Abstract.

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The adverse impacts of urban heat and global climate change are leading policy-makers to consider green and blue infrastructure (GBI) for heat mitigation benefits. Though many models exist to evaluate the cooling impacts of GBI, their complexity and computational demand leaves most of them largely inaccessible to those without specialist expertise and computing facilities. Here a new model called **The Air-temperature Response** to **Green/blue-infrastructure Evaluation Tool** (TARGET) is presented. TARGET is designed to be efficient and easy to use, with fewer user-defined parameters and less model input data required than other urban climate models. TARGET can be used to model street level air temperature at fine spatial scales

- (e.g. 30 m), meaning it can be used at the street, precinct, or city scales. The model aims to balance realistic representation of physical processes and computation efficiency. An evaluation against two different datasets shows that TARGET can reproduce
 the magnitude and patterns of both air temperature and surface temperature within suburban environments. To demonstrate the utility of the model for planners and policy-makers, the results from two precinct-scale heat mitigation scenarios are presented. TARGET will be made available to the public and ongoing development, including a graphical user interface, is planned for
 - future work.

1 Introduction

- 15 Policy and decision-makers are increasingly aware of the cooling potential of green and blue infrastructure (GBI). Recent examples of this include the Australian Federal Government's 20 Millon Trees Program (Commonwealth of Australia, 2017) and Singapore Green Plan (Singapore Ministry of Environment and Water Resources, 2012). Governments and urban planners wish to evaluate the cooling effects of design and planning options. Urban climate models are becoming more complex, allowing more complete representation of urban physics. However, the complexity of urban climate models renders them inac-
- 20 cessible to consultants (Elasson, 2000), who typically work for designers and planners. Commonly used urban climate models, such as the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) and ENVI-met (Bruse, 1999) require trained research scientists and significant computational resources to run. As a result, consultants usually provide generic and unsubstantiated estimates of cooling magnitudes. Consequently, there is a need for simple, computationally efficient, and scientifically-defensible urban climate models that can be used by consultants to provide reliable estimates of cooling to gov-
- 25 ernmental planners and policy-makers.

There are a number of existing micro-to-local scale urban models capable of modelling GBI. The most complex models are primary based on computational fluid dynamics (CFD) techniques. These include ENVI-met, hand-coded CFD models (such as OpenFOAM (OpenFOAM, 2011) or STAR-CD (CD-adapco, 2011)), and other CFD based approaches (Bailey et al., 2014, 2016; Kunz et al., 2000; Schlünzen et al., 2011; Yamada and Koike, 2011; Bruse, 1999). ENVI-met is the most commonly used

30 urban microclimate model. However, numerous ENVI-met studies have reported concerns with model accuracy, particularly for representation of vegetation (Ali-Toudert and Mayer, 2006; Krüger et al., 2011; Acero and Herranz-Pascual, 2015; Spangenberg and Shinzato, 2008). In addition, the complexity of configuration and computational intensity of all CFD based models (i.e. 24 hours of simulation requiring 24 hours of computation time) puts their usage out of the reach of non-specialized users.





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A second group of commonly used models, such SOLWEIG (Lindberg et al., 2008) and RayMan (Matzarakis et al., 2007, 2010), focus around radiation fluxes in urban areas. These models have been used to assess GBI cooling, especially tree shading. However, the limitations of these models may not allow a complete assessment of GBI cooling because the effects of evapotranspiration are neglected. The Temperatures of Urban Facets in 3D (TUF-3D) model (Krayenhoff and Voogt, 2007) and a vegetated derivative (VTUF-3D) (Nice et al., 2018), provide a precise representation of urban canyon physical processes. However, TUF-3D and VTUF-3D require a high level of computer power, modeling experience, and parameter setup.

The canyon air temperature (CAT) model (Erell and Williamson, 2006) shows potential as a computationally efficient model that calculates air temperatures using urban building and vegetation geometry and moisture availability. However, the lack of surface temperature prediction makes it difficult to derive human thermal comfort indexes. The Town Energy Balance

- 10 (TEB) model (Masson, 2000) has emerged as a popular urban area parameteristion scheme. The TEB-Veg (Lemonsu et al., 2012; Redon et al., 2017) variation includes urban vegetation and provides functionality to assess cooling impacts of GBI. However, the TEB-Veg model configuration and application requires a level of modelling skill normally outside the capability of environmental consultants.
- While not an air temperature model, the Local-Scale Urban Meteorological Parameterization Scheme (LUMPS) (Grimmond and Oke, 2002) has been widely used to assess the impacts of GBI on surface energy balance (SEB). The Surface Urban Energy and Water Balance Scheme (SUEWS) (Järvi et al., 2011), a superset of LUMPS with added urban water balance functionality, provides a means to assess vegetation (and associated soil) transpiration impacts at local scales. SUEWS shows good performance in SEB evaluations for Vancouver and Los Angeles (Järvi et al., 2011), Helsinki (Järvi et al., 2014), and Singapore (Demuzere et al., 2017). Due to the success and simplicity of LUMPS, we use it as a key component of this model.
- The lack of an efficient yet accessible tool for assessing GBI has been identified as a research gap. Here we introduce and evaluate a new model called **The Air-temperature Response** to **Green/blue-infrastructure Evaluation Tool** (TARGET). TARGET is a simple modelling tool that calculates surface temperature and street level (below roof height) air temperature in urban areas. TARGET is designed to make quick and accurate assessments of urban microclimate and blue/green infrastructure cooling with minimal input data. TARGET is formulated to be applied at the micro-to-local-scales (street-to-precinct scales);
- 25 meaning it can be used to assess the cooling benefits of small scale interventions (e.g. a single street or small urban park) to suburb scale greening projects. The computational efficiency of the model is such that a user (with 1–2 hours of training) could calculate in minutes the 30 m horizontal resolution cooling effects, on a normal desktop computer, across an entire suburb/local-government area or neighbourhood.

The main aims of this paper are the following: (1) to provide a technical description of TARGET; (2) to provide detailed evaluation of model performance; and (3) to provide proof of concept, and illustrate how the model could be operationalized by a consultants and practitioners.





2 Model description

2.1 Model overview

As outlined in Fig. 1, TARGET treats each model grid point as an idealized urban canyon with roofs, walls, and ground-level facets. Roof width (W_{roof}) , building height (H), tree width (W_{tree}) , and street width (W) are used to define the geometry

- 5 of the canyon. The thermal and radiative characteristics of roofs and walls are considered to be uniform. At street level, the surfaces can be defined as: concrete, asphalt, grass, irrigated grass, and water. Trees are represented at roof height and the surfaces beneath trees are considered to be representative of the ground level surfaces. Additionally, water bodies are treated separately to all other surfaces using an independent module. More details about the model process is shown in Fig. 2. For each grid point, the average surface characteristics are used to calculate an aggregated surface temperature (T_{surf}) . T_{surf} is
- 10 converted to an average canopy layer air temperature (T_{ac}) , using a estimated canopy wind speed (U_{can}) , and above canopy air temperature (T_b) . A uniform T_b for all grid points is diagnosed for each timestep using reference meteorological variables.



Figure 1. Schematic of TARGET urban canyon setup. T_{ac} = canopy layer air temperature and T_b = above canopy air temperature, which is a uniform value across the whole domain. W_{roof} is the roof width, W_{tree} is the tree width, W is canyon width, and $W * = W - W_{tree}$. The surface beneath trees is assumed to be representative of canyon ground-level surfaces.







Figure 2. Overview of approach used in TARGET microclimate module. T_{ac} is street level (urban canopy layer) air temperature (°C), T_b is the air temperature above the urban canopy layer (°C), $T_{surf,i}$ is the surface temperature for surface type i, $K \downarrow$ is incoming shortwave radiation (W m⁻²), $L \downarrow$ is incoming longwave radiation (W m⁻²), T_a is reference air temperature (°C), R_n is net radiation (W m⁻²), RH is relative humidity (%), F_i is fraction of land cover type i (%), $Q_{H,i}$ is sensible heat flux for surface i from LUMPS (W m⁻²), $Q_{G,i}$ is storage heat flux for surface type i from LUMPS (W m⁻²), U_z is reference wind speed (m s⁻¹), H is average building height (m), W is average street width (m), r_s is resistance from surface to canopy (s m⁻¹), and r_a is resistance from urban canopy to the atmosphere (s m⁻¹). $*T_b$ is a homogeneous value for the whole domain, which is diagnosed by the processes laid out in Sect. 2.7.





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2.2 Input data requirements

2.2.1 Land cover

TARGET uses simple data inputs that are intended to be easily accessible. The model requires the user to define the plan area of buildings (A_{roof}) , concrete (A_{conc}) , asphalt (A_{asph}) , grass (A_{gras}) , irrigated grass (A_{igrs}) , tree (A_{tree}) , and water (A_{watr}) . These land cover categories are self-explanatory and describe most of the surfaces present in urban areas. Local governments

- often have geographical information system (GIS) datasets of land cover and/or land-use that can be used for land cover input data. Further, we intend to develop a graphical user interface (GUI) that allows users to easily input land cover datasets and define the model domain. This feature will allow users to convert and upload GIS data (e.g. shape and raster files) directly into the model. The W_{roof} , W_{tree} , W, W*, and wall area (A_{wall}) are calculated from plan area land cover inputs. However,
- 10 average building height (m) must be user defined or set to a domain average value. If detailed land cover data are not available, input data can be defined from existing land-use look-up tables or from databases such as the World Urban Database and Portal Tool (WUDAPT) (Mills et al., 2015; Ching et al., 2018). See Wouters et al. (2016) for an example of how the WUDAPT data could be integrated.

2.2.2 Meteorological data

15 TARGET requires reference meteorological data to drive the model and calculate microscale urban air temperature. The following meteorological variables are required: incoming shortwave (solar) radiation (K↓), incoming longwave (terrestrial) radiation (L↓), relative humidity (RH), reference wind speed (typically at 10 m) (Uz), and air temperature (Ta). The user must define the height above ground of reference Uz and Ta. Ideally, meteorological data should be representative of a nearby urban site. However, the nearest airport weather station will suffice. At a minimum, reference meteorological data should
20 conform to World Meteorological Organization guidelines (Oke, 2007).

2.3 Radiation calculation

The net radiation of the *ith* surface type $(R_{n,i})$ is calculated using the following:

$$R_{n,i} = \left(K \downarrow (1 - \alpha_i) + \epsilon_i \left(L \downarrow -\sigma T_{surf,i,[t-2]}^4 \right) \right) SVF_i$$
(1)

where α_i is surface albedo, ϵ_i is surface emissivity, and σ is the Stefan-Boltzmann constant (5.67 × 10⁻⁸ W m⁻²K⁻⁴). The 25 α_i and ϵ_i values are predefined for each surface (see Table 1). The right hand side of the equation accounts for net longwave radiation. The modelled $T_{surf,i,[t-2]}$ from 2 time steps (t) previously is used to calculate $L \uparrow$. This is necessary to avoid circular logic in model calculations; modelled $T_{surf,i,[t-2]}$ is calculated using the storage heat flux ($Q_{G,i}$), which takes R_n from the previous time step. The time lag does not significantly affect calculations when a 30 minute time step is used. The average sky view factor (SVF_i) is included to broadly represent the interception of incoming and outgoing short and longwave radiation

30 by buildings and trees on the radiation balance. Addition of SVF restricts the net radiation exchange of each facet to its total





view factor occupied by sky. It assumes that walls and ground surfaces have similar longwave emission relative to the sky, and that solar radiation receipt can be approximated by SVF, on average. This simplification means that the model makes no distinction between lit and unlit buildings walls. SVF_i for ground-level, wall, and roof facets is defined as (Sparrow and Cess, 1978):

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$$SVF_{ground} = \left[1 + \left(\frac{H}{W*}\right)^2\right]^{\frac{1}{2}} - \frac{H}{W*};$$
 (2)

$$SVF_{wall} = \frac{1}{2} \left(1 + \frac{W*}{H} - \left[1 + \left(\frac{W*}{H} \right)^2 \right]^{\frac{1}{2}} \right);$$
(3)

$$SVF_{roof} = 1$$
 (4)

The $R_{n,i}$ is then used to calculate a $Q_{G,i}$ for each surface type.

2.4 Storage heat flux (Q_G) calculation

10 The storage heat flux $(Q_{G,i})$ for the *i*th land cover class is calculated using an adapted version of the objective hysteresis model (OHM) (Grimmond and Oke, 2002):

$$Q_{G,i} = R_{n,i}a_{1,i} + \left(\frac{\partial R_{n,i}}{\partial t}\right)a_{2,i} + a_{3,i}$$
(5)

where \$\frac{\partial R_{n,i}}{\partial t}\$ = 0.5(\$R_{n,i,(t-1)} - \$R_{n,i,(t+1)}\$) and the three \$a\$ coefficients are defined using cited values for each surface (see Table 1). The \$a\$ coefficients capture the hysteresis pattern commonly observed between the \$R_n\$ and \$Q_{G,i}\$ in urban areas. See
15 Grimmond and Oke (1999) for a full description of the OHM and the role of the \$a\$ parameters in \$Q_{G,i}\$ calculations. The \$Q_{G,i}\$ is then used to calculate the \$T_{surf}\$ for each land cover type using the force-restore method.

2.5 Surface temperature calculation ('force-restore')

The force-restore method is an efficient method for calculating surface temperature (Bhumralkar, 1975; Deardorff, 1978), and is an alternative to multilayer conduction approaches used in other climate models. The force-restore method is used to ensure that the model remains computationally efficient. The ground layer is conceptually divided into two layers with uniform vertical temperature: a thin surface layer and deep soil layer. The forcing term, which is driven by $Q_{G,i}$, heats the surface layer. The restore term, driven by deep soil temperature, dampens the forcing term. The change in surface temperature T_{surf} for surface *i*, with respect to time (*t*), is calculated as (Jacobs et al., 2000):

$$\frac{\partial T_{surf,i}}{\partial t} = \frac{Q_{G,i}}{C_i D} - \frac{2\pi}{\tau} \left(T_{surf,i,[t-1]} - T_{m,i,[t-1]} \right) \tag{6}$$





	Roof &	Asphalt	Water	Soil (wa-	Concrete	Dry grass	Irrigated	Tree
	wall‡			ter)*			grass	
α	0.15 ¹	0.08^{1}	0.10 ¹	N/A	0.20^{1}	0.19 ³	0.19 ³	0.10 ¹
ϵ	0.90^{1}	0.95^{1}	0.97^{1}	N/A	0.94 ¹	0.98^{2}	0.98^{2}	0.98^{1}
$C(\times 10^{6})$	1.25^{2}	1.94 ¹	4.18 ¹	3.03 ¹	2.11^{1}	1.35 ³	2.19 ³	N/A
$\kappa (\times 10^{-6})$	0.05†	0.38 ¹	0.14^{1}	0.63 ¹	0.72^{1}	0.21 ³	0.42^{3}	N/A
T_m	25.0	26.0	25.0	25.0	26.0	20.0	20.0	N/A
	(28.2)	(29.0)	(24.5)	(24.5)	(27.9)	(22.4)	(21.5)	
OHM $[a_1, a_2, a_3]$	[0.12,0.24,-	[0.36,0.23,-	N/A	N/A	[0.67,0.31,-	[0.21,0.11,-	[0.27,0.33,-	N/A
	4.5] ³	19.3] ^{4,5}			31.45] ^{4,5}	16.10] ⁶	21.75] ^{6,7}	
S	0.0	0.0	N/A	N/A	0.0	0.2	1.0	N/A
β	3	3	3	3	3	3	3	N/A

Table 1. Parameter setup for all TARGET simulations in this article.

¹ Oke (1987)

² Stewart et al. (2014)

³ Järvi et al. (2014)

⁴ Narita et al. (1984)

⁵ Asaeda and Ca (1993)

⁶ Grimmond et al. (1993)

⁷ Doll et al. (1985)

 α = surface albedo

 ϵ = surface emissivity

C = volumetric heat capacity (J m⁻³ K⁻¹) (×10⁶)

 κ = thermal diffusivity (m² s⁻¹) (×10⁻⁶)

 T_m = average soil (ground) temperature (°C)

 α_{pm} = LUMPS empirical parameter (alpha parameter) - relates to surface moisture

 β = LUMPS empirical parameter (beta parameter) T_m bracketed values were used in Mawson Lakes suburb simulations — derived from 1 month spin-up. *soil layer beneath water layer.

† the traditional force-restore method is not well suited to urban surfaces (e.g. roof and walls) — we use an artificially low thermal diffusivity to represent a

thin layer. This is discussed further in Sect. 2.5.

 \ddagger roof and wall layers are represented with the same model parameters.





where C_i is the volumetric heat capacity (J m⁻³ K⁻¹), τ is the period (86400 seconds), D is the damping depth of the diurnal temperature wave $D = 2\kappa/\omega 0.5$, $\omega = 2\pi/\tau$, and κ represents thermal diffusivity. The average soil (ground) temperature (°C) (T_m) is calculated using:

$$\frac{\partial T_{m,i}}{\partial t} = \frac{\Delta Q_{G,i}}{C_i D_y} \tag{7}$$

5 where $D_y = D\sqrt{365}$, the damping depth for the annual temperature cycle (m).

The force-restore method, which assumes two layers each of uniform temperature, cannot be applied to more complex surfaces such as water, trees, walls, or roofs. For roofs we set C at realistic value and use κ as a tuning parameter to represent layers of thermally active mass characteristic of most building roofs, which are often thinner than ground level surfaces. This approach produces accurate $T_{surf,roof}$ results (see Sect. 3.2), but ongoing work is needed to represent roofs in a physically realistic and efficient manner. For simplicity, the wall surfaces are assumed to have the same thermal properties as roofs. For trees, we assume that $T_{surf,tree}$ is equal to T_a (see Fig. 13 for justification), and a simple water body model is used to calculate

 $T_{surf,watr}$.

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2.6 Simple water body model

The water model is used for modelling small inland water bodies, such as lakes and wetlands. The water model in TARGET is 15 based on a single water layer, overlaying a soil layer. Essentially, the force-restore surface temperature model is implemented, and is overlain by a homogeneous mixed water layer (i.e. neglecting thermal stratification) representing a water body of depth d_{watr} (m). The model is designed to apply to water bodies of 0.1–1.0 m depths. The water model is based on the pan evaporation model of Molina Martínez et al. (2006), which closely follows that of the lake model of Jacobs et al. (1998). The water body model also determines the surface energy balance of the water surface. The energy balance model for the water layer is given 20 by Molina Martínez et al. (2006):

$$S_{ab} + L_n + Q_{H,watr} - Q_{E,watr} - Q_{G,watr} - \Delta Q_{S,watr} = 0$$

$$\tag{8}$$

where S_{ab} is absorbed shortwave radiation (W m⁻²), L_n , the net longwave radiation (W m⁻²), $Q_{G,watr}$ is the convective heat flux at the bottom of the water layer and into the soil below (W m⁻²), and $\Delta Q_{S,watr}$ is the change in heat storage of the water layer (W m⁻²). Solar radiation penetrates the water surface and is absorbed as described by Beer's Law (Molina Martínez et al., 2006):

$$S_{ab} = K_n \left[\beta_k + (1 - \beta_k))(1 - e^{-\eta}) \right]$$
(9)





where K_n is the net shortwave radiation (W m⁻²), β_k is the amount of shortwave radiation immediately absorbed by the water layer (set to 0.45) (Molina Martínez et al., 2006), and η the extinction coefficient. Here, η is given the following from Subin et al. (2012), for the water layer with depth d_{watr} (m):

$$\eta = 1.1925 d_{watr}^{-0.424} \tag{10}$$

5 A correction factor for the solar path length zenith angle is often applied to Eq. (9) (Molina Martínez et al., 2006) but this has been omitted from TARGET to reduce complexity.

The $Q_{G,watr}$ into the soil at the base of the water layer is given by Molina Martínez et al. (2006):

$$Q_{G,watr} = -C_{watr}\kappa_{watr}\frac{\Delta T}{\Delta d_{watr}} \tag{11}$$

where C_{watr} is the volumetric heat capacity of water (4.18×10⁶ J m⁻³ K⁻¹), κ_{watr} is the eddy diffusivity of water (m² s⁻¹),
and the change in depth Δd_{watr} = d_{watr} (the depth of the water layer). κ_{watr} is a complex function accounting for thermal stratification of water and surface friction velocity. To reduce complexity and assuming a mixed homogeneous water layer, a constant κ_{watr} has been selected based on shallow lakes reported in Salas De León et al. (2016). The change in temperature ΔT (°C) is the difference between the water temperature T_{surfwatr} (°C) and the soil temperature beneath the water layer T_{soil} (°C). T_{soil} is calculated using the force-restore model where Q_{G,watr} is equivalent to Q_{G,i} in Eq. (6):

15
$$\frac{dT_{soil}}{dt} = \frac{(Q_{G,watr} + (K_n - S_{ab}))}{C_{watr}D} - \frac{2\pi}{\tau} (T_{soil,[t-1]} - T_{m,[t-1]})$$
(12)

To represent the radiation that is not absorbed by the water, but is absorbed by the underlying soil layer, $K_n - S_{ab}$ is added to $Q_{G,watr}$.

The latent heat flux $(Q_{E,watr})$ (W m⁻²) is given by Arya (2001):

$$Q_{E,watr} = \rho v L_v h_v U_z (q_s - q_a) \tag{13}$$

20 where ρv is the density of moist air (kg m⁻³), L_v is the latent heat of vaporisation (=2.43 MJ kg⁻¹), h_v is bulk transfer coefficient for moisture (1.4×10⁻³) (Hicks, 1972; Jones et al., 2005), U_z is the reference wind speed, q_s the saturated specific humidity at $T_{surfwatr}$, and q_a is the specific humidity of the air for the given T_a .

The sensible heat flux above the water surface is given by Molina Martínez et al. (2006):

$$Q_{H,watr} = \rho_a C_p h_c U_z (T_a - T_{surf,watr}) \tag{14}$$

25 where ρ_a is the density of dry air (=1.2 kg m⁻³), C_p the specific heat of air (1013 J kg⁻¹ K⁻¹), and h_c the bulk transfer coefficient for heat ($h_c = h_v$).





Returning to Eq. (9), net long wave radiation $L_n = R_n - K_n$, leaving $\Delta Q_{S,watr}$ from the energy balance equation, which is defined as (Molina Martínez et al., 2006):

$$\Delta Q_{S,watr} = C_{watr} d_{watr} \frac{\Delta T_{surf,watr}}{\Delta t} \tag{15}$$

where Δt is change in time (seconds) and C_{watr} is the volumetric heat capacity of water (J m⁻² K⁻¹). Solving for $\Delta T_{surf,watr}$ 5 and adding the change in temperature to the previous time step ($T_{surf,watr[t+1]} = T_{surf,watr,[t]} + \Delta T_{surf,watr}$) gives the new water layer temperature.

2.7 Calculation of urban canopy layer air temperature (T_{ac})

To calculate T_{ac} we first calculate a domain T_b for each timestep. Assuming air temperature at 3 times building height (3H) is consistent between the neighbourhood of interest and the reference weather station location, we extrapolate reference air

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temperature at measurement height to 3H assuming a constant flux layer and using a bulk Richardson number-based approximation (Mascart et al., 1995). Through this simple calculation we define a domain constant T_b with basic representation of atmospheric stability in TARGET.

The canyon air temperature is then calculated using a modified version of the canopy air temperature equation from the Community Land Model Urban (CLMU) (Oleson et al., 2010):

$$(T_{surf,asph}c_{s}F_{asph}) + (T_{surf,conc}c_{s}F_{conc}) + (T_{surf,gras}c_{s}F_{gras}) + (T_{surf,irgs}c_{s}F_{irgs}) + (T_{surf,tree}c_{s}F_{tree}) + T_{surf,wall}c_{s}F_{wall}) + (T_{surf,watr}c_{s}F_{watr}) + \left[\frac{T_{surf,roof}}{\left(\frac{1}{c_{s}} + \frac{1}{c_{a}}\right)}F_{roof}\right] + (T_{b}c_{a}W)$$

$$(16)$$

$$T_{ac} = \frac{(c_{s}F_{asph}) + (c_{s}F_{conc}) + (c_{s}F_{gras}) + (c_{s}F_{tree}) + (c_{s}F_{wall}) + (c_{s}F_{asph}) + (c_{s}F_{watr}) + \left[\frac{F_{roof}}{\left(\frac{1}{c_{s}} + \frac{1}{c_{a}}\right)}\right] + (c_{a}W)$$

$$\left[\frac{F_{roof}}{\left(\frac{1}{c_{s}} + \frac{1}{c_{a}}\right)}\right] + (c_{a}W)$$

where F_i is the 2-D fractional coverage of surface *i* in the canyon, c_s is the conductance from surface to urban canopy layer (m s⁻¹), and c_a is the conductance from urban canopy to the above canopy surface layer (m s⁻¹). In Eq. 16 we assume roofs are connected to the canyon via two resistances in series, thus representing the additional impediment to transfer of heat from a rooftop into the canyon. The c_a is calculated following Masson (2000) and using the stability coefficients from Mascart et al. (1995). The c_s term is from Masson (2000):

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$$c_s = \frac{\rho_a C_p}{11.8 + 4.2U_{can}} \tag{17}$$



where $c_s = \frac{1}{r_s}$ and U_{can} is the wind speed in canyon (m s⁻¹) (Kusaka et al., 2001):

$$U_{can} = U_{top} exp\left(-0.386\frac{H}{W}\right) \tag{18}$$

where U_{top} is the wind speed at the top of the canyon (m s⁻¹). U_{top} is estimated at the top of the UCL based on U_z using a logarithmic relationship.

5 3 Methods and data

3.1 Overview

As part of the model evaluation, we conducted a range of simulations that test model performance for both T_{surf} and T_{ac} . These validation experiments are focused on clear sky summertime conditions. Clear sky conditions were chosen because the local-cooling effects of GBI are most notable during warm, clear-sky, summer conditions. First, we tested the model's ability

10 to simulate T_{surf} for each land cover type that can be prescribed in TARGET (i.e. dry grass, asphalt etc.), using ground-based observations of T_{surf} (Sect. 3.2). These simulations by land cover type, provide a detailed assessment of model parameters, and the underlying energy balance dynamics and resulting T_{surf} for each land cover class. Second, we conducted suburb scale simulations of Mawson Lakes, Adelaide, for which we have high resolution remotely sensed T_{surf} observations and in situ T_{ac} data (Sect. 3.3). The suburb scale simulations reflect the way the model is intended to be used by practitioners.

15 3.2 Land cover simulations

To test model performance at simulating T_{surf} of different land cover classes and perform sensitivity analysis on a number of model parameters, we used ground-based observations of T_{surf} from the Melbourne metropolitan area. Coutts et al. (2016) deployed infrared temperature sensors (SI-121 - Apogee), during February 2012, across a range of land cover types including: asphalt, concrete, grass, irrigated grass, steel roof, and water. The conditions during this period represented near-typical sum-

20 mertime conditions in Melbourne; including a number of days (15th, 24th, and 25th February) where air temperature exceeded 30° C (see Fig. 11). These hotter days were characterised by northerly winds, which bring hot and dry air from Australia's interior, and often result in heatwave conditions in Melbourne. Additionally, there was at least one cloudy day where incoming shortwave radiation ($K \downarrow$) dropped significantly and negligible amount of rainfall occurred (17th February).

3.3 Suburb scale simulations (Mawson Lakes)

In addition to the land cover category testing, we also conducted suburb scale simulations of T_{surf} and T_{ac} for Mawson Lakes, Adelaide (Fig. 3). The suburb scale simulations used observational data from the Mawson Lakes field campaign, conducted 13-18th February 2011, which represented average summertime conditions in Adelaide (Broadbent et al., 2017b). For these simulations, the model was run on a 30 m grid over the Mawson Lakes suburb for the period 13th–18th February (Fig. 12).





Remotely sensed land cover data from the campaign were used to define land cover, and building morphology was defined using LiDAR data (see Broadbent et al. (2017b)). The Mawson Lakes simulations used the same parameter setup as above (summarised in Table 1), and were forced with meteorological data from the Kent Town Bureau of Meteorology (ID 023090) weather station. Modelled T_{surf} was validated using observed remotely sensed T_{surf} (night - 15th February and day - 16th February), which was resampled to 30 m resolution (Broadbent et al., 2017b). To validate T_{ac} , we use data from 27 automatic

5 February), which was resampled to 30 m resolution (Broadbent et al., 2017b). To validate T_{ac} , we use data from 27 automat weather station (AWS) that were also deployed during the Mawson Lakes field campaign (see Fig. 3 for AWS locations).

4 Model evaluation results and discussion

4.1 Land cover simulations

- The surface temperature for each land cover class was simulated for a 14 day period during February 2012. The results show
 that modelled surface temperature for all 3 impervious surfaces (concrete, asphalt, and roof) were reasonably well predicted with mean bias errors (MBE) of 0.88, -0.22, and -1.16°C, respectively (Fig. 4a–f). The root mean square error (RMSE) values for impervious surfaces were around 3.5–4°C. These RMSE values represent about 15% of diurnal T_{surf} variation, which implies good model skill given the simplicity of the approach.
- The night of the 16 February was not well captured at the concrete and asphalt sites. The $T_{surf,conc}$ and $T_{surf,asph}$ were 15 under-predicted (up to 5°C cooler than observations) on the night of 16 February, which may have been caused by warm air advection. The TARGET approach cannot account for the effects of warm air advection on surface temperature, as there is not feedback between T_{ac} and T_{surf} . Despite this limitation, the broad timing and magnitude of heating and cooling was well captured for all three impervious land cover types.

Model performance for $T_{surf,watr}$ had a low MBE of 0.91°C but the r^2 value of 0.76 suggests the model captured diurnal 20 $T_{surf,watr}$ variation less accurately than other surfaces (Fig. 4g–h). In particular, daily maximum $T_{surf,watr}$ were underpredicted on hotter days (e.g. 14th February). TARGET uses a different module for water bodies (see Sect. 2.6). This simple module treats water as a single layer overlying soil.Despite the under-prediction on 14 February, the simple water body model can reproduce $T_{surf,watr}$ to an acceptable standard.

Modelled $T_{surf,irgs}$ had a MBE (-1.56°C) comparable to that of impervious surfaces (Fig. 4i–j). However, the RMSE for 25 irrigated grass (3.69°C) represents approximately 20% of diurnal $T_{surf,igrs}$ variation, suggesting model error is slightly higher than for the impervious surfaces. Generally $T_{surf,igrs}$ was slightly over-predicted at night and under-predicted at the daily maxima. This skewing of the scatter plot suggests that thermal inertia is too high in the model. Overall, the model was skillful enough to capture the timing and amplitude of $T_{surf,igrs}$.

Dry grass had a small MBE error (0.06°C), but the largest RMSE of the surfaces tested (4.38°C). However, this RMSE only
equated to approximately 10–15% of diurnal T_{surf,gras} variability (Fig. 4k–l) as dry grass had the largest amplitude of surface temperature variability. Dry grass exhibited the same skewing in the scatterplot as irrigated grass, with a general over-prediction of night-time temperatures and under-prediction of daytime maxima.







Figure 3. Mawson Lakes suburb with weather station locations. The numbers indicate individual weather stations while the color coding specifies groups of sites with statistically similar thermal characteristics. The names of each cluster indicate the average land surface characteristics: urban sites with nearby water (TA-1[Urb+Wtr]), mixed land-use with nearby water (TA-2[Mxd+Wtr]), urban mid-rise type sites (TA-3[Urb+Mid]), urban residential sites (TA-4[Urb+Res]), natural grass dominated sites (TA-5[Nat+Grs]), and a single outlier site (TA-6[outlier]) (Broadbent et al., 2017b). 14













4.1.1 Suburb scale simulations (Mawson Lakes)

Surface temperature

In addition to the land cover simulations we conducted suburb scale modelling of the Mawson Lakes suburb. These simulations reveal how the TARGET model can be operationalised by practitioners who want to assess the cooling benefits of blue

- 5 infrastructure or greening initiatives. Suburb scale simulations were conducted using the same parameters as above (Table 1). Fig. 5 shows the predicted T_{surf} (30 m average) for the Mawson Lakes domain plotted against observed T_{surf} (30m). The Mawson Lakes simulations revealed the initial conditions of the T_m parameter (which represents the average temperature in the ground layer) are important for good model performance. A spin-up period (1 month) had to be used to obtain initial T_m values for each surface type. This can be quickly and easily achieved by running the force-restore module for a single point for
- 10 each surface type. A future version of the model will automatically spin-up initial T_m values. The model output also shows that some of input land cover is poorly categorised, resulting in population of grid points where modelled T_{surf} is over-predicted. Additionally, errors in the observed T_{surf} caused by heterogeneity of roof emissivity, also contribute to apparent inaccuracies of modelled T_{surf} . In general, the daytime T_{surf} was slightly over-predicted and the complexity of spatial variability was not fully captured. However, this is a positive result given only 8 land cover classes are represented in the model. Overall, the
- 15 daytime T_{surf} was well predicted with the range and magnitude of T_{surf} captured by the model.

The results suggest that night-time T_{surf} was under-predicted by model. The range of modelled nocturnal T_{surf} variability (c. 8°C) was much smaller than observed variability (c. 18°C). This under-prediction of variability could reflect the fact that some processes that dictate the rate of nocturnal cooling are not fully accounted for in this approach. Nevertheless, the general spatial patterns of T_{surf} are captured well. Further, given that the range of T_{surf} is smaller at night, this under-prediction is

of minimal consequence for modelled T_{ac} . The nocturnal T_{surf} of impervious surfaces was also under-predicted in the land cover simulations (i.e. Sect. 4.1) under warm advection conditions. Although warm advection conditions were not observed during the Mawson Lakes campaign, it is worthwhile further investigating this phenomenon, in future work, to negate its effect and improve nocturnal T_{surf} accuracy.

Air temperature

- 25 Spatial plots of modelled 3 am and 3 pm T_{ac} are shown in Fig. 6. The lack of advection representation in TARGET means no horizontal mixing of heat, which exaggerates the spatial variability of simulated T_{ac} . However, the general patterns of T_{ac} are reasonable and as expected. We also extracted modelled T_{ac} from the grid points where the 27 AWS were located (grid points were centred at the AWS) for a 2 day period (15-16th February 2011) (Fig. 7). The T_{ac} was generally well predicted (Fig. 7), with a RMSE of 2.0 °C. These results are about the same accuracy as simulations, from the same site, conducted using a
- 30 more sophisticated and computationally expensive urban climate model called SURFEX (Broadbent et al., 2017a). Although a simple model, TARGET appears as accurate as more complex models. Additionally, TARGET does not require the user to provide above canyon forcing data (e.g. T_b), which is needed for other models and is not easily obtained. TARGET tended to over-predict average T_{ac} at all urban sites (Fig. 8). Residential sites (TA-4_[Urb+Res] cluster [red]) were too warm during the







Figure 5. Mawson Lakes observed (a & d) T_{surf} and modelled (b & e) T_{surf} for day (TOP) and night (BOTTOM). Areas where land cover is categorized as 'other' were not simulated. Note: T_{surf} here does not include $T_{surf,wall}$ for comparison with horizontally averaged aerial imagery observations.





day. This over-prediction is likely due to the uniform wall and roof thermal parameters used, which are not representative of residential areas. Further, the lack of horizontal mixing may have exacerbated warmer temperatures in these areas. By contrast, the TA-5_[Nat+Grs] cluster is too cool at night. The model predicts the formation of a stable layer with cool air trapped near the surface. Overall, the diurnal range and average T_{ac} are well captured by the model.

Finally, there is some hysteresis in Fig. 6, indicating that modelled T_{ac} is slightly out-of-sync with observed T_{ac}. This could be due to the approach used to diagnose T_b, which assumes a constant Ri in the surface layer, and therefore heats up too quickly during the morning. Improvement in the T_b term is an area for future model development. However, we believe it is important to calculate T_b, as this makes the model much more accessible to non-expert users. Given the simplicity and computational efficiency of the model approaches used, TARGET shows good skill for predicting urban T_{ac}. Overall, the air temperature
evaluation shows we can have confidence in the accuracy of the model and its potential for application by practitioners.



Figure 6. Spatial map of modelled T_{ac} (30 m) for (a) day (3 pm) and (b) night (3 am) in Mawson Lakes domain. Points with $F_{roof} > 0.75$ are excluded.

5 Heat mitigation scenarios

To demonstrate how TARGET can be used by practitioners to predict GBI cooling impacts, two simple heat mitigation scenarios are presented: (1) a doubling of existing tree cover ($^{2}\times$ TREE') (Fig. 9) and (2) all dry grass is converted to irrigated grass ('IRRIGATION') (Fig. 10). The $^{2}\times$ TREE' scenario assumes a maximum tree coverage of 75%. The results presented here







Figure 7. Modelled T_{ac} vs observed T_{ac} for Mawson Lakes weather stations (15–16th February 2011, 30 minute data). The numbers and colors correspond to individual stations and clusters shown in Fig. 3.







Figure 8. Boxplot of modelled T_{ac} (grey) vs observed T_{ac} (black) for Mawson Lakes with average, min, and max T_{ac} shown. Boxplots were generated from 30 minute data from period 15–16th February 2011. The numbers and colors (x-axis) correspond to individual stations and clusters in Fig. 3.

represent the local spatial maximum cooling potential of GBI. In reality, the cooling local magnitude will be decreased by advection, which TARGET does not represent.

The 2×TREE scenario shows maximum cooling of 3.15° C during the day and smaller effect (< 0.25° C) at night (Fig. 9). The IRRIGATION scenarios suggests that increasing irrigation can have a small warming effect (< 0.75° C) at night, and cooling of up to 1.75° C at 3 pm (Fig. 10). The amount of land cover change differs in each scenario. As such, we calculate the cooling sensitivity (γ) as:

$$\gamma = \left(\frac{\Delta T_{ac}}{\Delta LC}\right) \tag{19}$$

where ΔLC is the average land cover change (%) (Table 2). Model results suggests that trees are about 1.5 times more effective at providing cooling at 3 pm (Table 2). Over the course of a day, trees are predicted to be 4 times more effective at cooling

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than irrigation. The results for both heat mitigation simulations are within the expected magnitudes based on previous heat mitigation modelling studies (Grossman-Clarke et al., 2010; Middel et al., 2015; Daniel et al., 2016; Broadbent et al., 2017a). These simulations demonstrate that TARGET not only reproduces observations accurately, but can be used with confidence to efficiently assess the efficacy of heat mitigation measures.





Table 2. Summary of domain average cooling impacts (°C) for BGI heat mitigation scenarios.

Scenario	ΔT_{ac} 3 am	γ 3 am	ΔT_{ac} 3 pm	γ 3 pm	ΔT_{ac} daily	γ daily
2×TREE	0.00	0.000	-0.58	-0.036	-0.24	-0.018
IRRIGATION	0.41	0.015	-0.71	-0.025	-0.07	-0.003



Figure 9. The ΔT_{ac} (°C) for IRRIGATION – BASE at (a) 3 am and (b) 3 pm for Mawson Lakes domain.



Figure 10. The ΔT_{ac} (°C) for 2×TREE – BASE at (a) 3 am and (b) 3 pm for Mawson Lakes domain.





6 Limitations of the model

As discussed above, TARGET aims to be a simple and accessible urban climate model that provides scientifically defensible and accurate urban temperature predictions. To achieve simplicity the model necessarily makes some assumptions and omissions that users should be aware of. TARGET is primarily intended to model urban microclimate characteristics during clear sky conditions. The model does not simulate rainfall and therefore should not be used for periods containing significant pre-

5 sky conditions. The model does not simulate rainfall and therefore should not be used for periods containing significant precipitation. Further, the model can be used to simulate urban microclimate for days to weeks (i.e. a heatwave), but has not been tested or validated for longer scale simulations (i.e. months to years).

For computational efficiency, the model assumes no horizontal advection (inside or above) the UCL. In general, advection reduces the microscale impacts (i.e. cooling directly adjacent the cooling intervention) of GBI due to atmospheric mixing, and

10 therefore we expect TARGET to provide estimates of near maximum microscale cooling benefits. In reality, microscale cooling effects will be diminished by advection, especially during the day and during high wind conditions.

As mentioned, the force-restore method is used for roof and wall surfaces with an artificially reduced κ value. Although this approach generally performed well, it is our intention to develop and integrate a more realistic formula for modelling roof and wall $Q_{G,i}$. A conduction model, although more computationally expensive, would allow more flexibility as different types of roof (which do vary significantly) could be represented. Furthermore, wall surfaces are treated the same as roofs in TARGET,

which is unrealistic. Improved representation of walls and roofs are key areas for future model development.

In addition, the $Q_{G,i}$ (hence the heat transfer between the urban canopy atmosphere, as the residual) is parametrized according to R_n and the building parameters. This means that the dependency on the other atmospheric conditions, such as air temperature, wind speed, and humidity, is neglected in TARGET. However, given that the OHM (used to calculate $Q_{G,i}$) was

20 developed based on observational data collected during summertime clear sky conditions, we are confident that TARGET will provide reasonable results during summer. Ongoing testing is needed to ascertain the limitations of the use of the OHM in TARGET.

A resistance formulation is used to calculate the $Q_{H,i}$ over water bodies (see Eq. (14)), whereas $Q_{H,i}$ for the non-water surfaces is calculated as a residual (and not temperature and wind-speed dependent). Although testing has not revealed any unexpected behavior, these different model formulations may lead to artificial non-physical discrepancies. Ongoing testing and

improvement of the water body model is needed.

7 Conclusions and future work

This paper has presented TARGET; a simple and user-friendly urban microclimate model that is designed to be accessible to urban planners and policy makers. The model contains a number of key limitations that are outlined above. However, despite

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these caveats, rigorous testing suggests TARGET shows excellent potential for modelling the cooling effects of GBI projects.We believe this novel model is well balanced between complexity and accuracy. The computational efficiency of the model and the reduced amount of input data required ensures that non-skilled users could use the model to ascertain reliable urban





cooling estimates. Ongoing work will be done to improve TARGET, including the creation of GUI, the addition of human thermal comfort indices, and the improvements to model physics outlined above.

8 Code availability and licensing

TARGET is distributed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 Generic (CC BY-NC-SA
4.0). TARGET code cannot be used for commercial purposes. It is available in two versions, Python or Java. The Python code can be downloaded from https://doi.org/10.5281/zenodo.1300023 or Java code is available here https://zenodo.org/record/1310138. We recommend using the Java version as it runs faster than the Python code.

9 List of Symbols

- a_1 Objective hysteresis model (OHM) parameter
- 10 a_2 Objective hysteresis model (OHM) parameter

 a_3 - Objective hysteresis model (OHM) parameter

 A_{asph} - land cover asphalt plan area (m²)

 A_{conc} - land cover concrete plan area (m²)

 A_{gras} - land cover grass plan area (m²)

15 A_{igrs} - land cover irrigated grass plan area (m²)

 A_{tree} - land cover tree plan area (m²)

- A_{roof} land cover building plan area (m²)
- A_{wall} land cover wall plan area (m²)
- A_{watr} land cover water plan area (m^2)
- 20 C volumetric heat capacity (J m⁻³ K⁻¹)
 - C_{watr} volumetric heat capacity of water (J $\rm m^{-2}~K^{-1})$
 - c_a conductance from urban canopy to the above canopy surface layer (m s⁻¹)
 - c_s conductance from surface to urban canopy layer (m s⁻¹
 - C_{watr} volumetric heat capacity of water (4.18×10⁶ J m⁻³ K⁻¹)
- 25 C_p specific heat of air (1013 J kg⁻¹ K⁻¹)
 - d_{watr} depth of water body (m)
 - D_y damping depth for the annual temperature cycle (m)
 - η extinction coefficient
 - F_i fraction of land cover type i (%)
- **30** H average building height (m)
 - h_c bulk transfer coefficient for heat ($h_c = h_v$)





- h_v bulk transfer coefficient for moisture (=1.4 × 10⁻³)
- K_n net shortwave radiation (W m⁻²)
- $K\downarrow$ incoming shortwave radiation (W m $^{-2})$
- L_n net longwave radiation (W m⁻²)
- 5 $L \downarrow$ incoming longwave radiation (W m⁻²)
 - $L\uparrow$ outgoing longwave radiation (W m⁻²)
 - L_v latent heat of vaporisation (=2.43 MJ kg⁻¹)
 - $Q_{E,watr}$ latent heat flux for water surface (W m⁻²)
 - $Q_{G,i}$ storage heat flux for surface type *i* from LUMPS (W m⁻²)
- 10 $Q_{G,watr}$ convective heat flux at the bottom of the water layer (and into the soil below) (W m⁻²)

 $Q_{H,i}$ - sensible heat flux for surface *i* from LUMPS (W m⁻²)

- $Q_{H,watr}$ sensible heat flux for water surface (W m⁻²)
- r_a resistance from urban canopy to the atmosphere (s m⁻¹)
- RH relative humidity (%)
- 15 *Ri* Richardson number
 - R_n net radiation (W m⁻²)
 - S_{ab} absorbed shortwave radiation (W $\rm m^{-2})$
 - SVF sky view factor
 - r_s resistance from surface to canopy (s m⁻¹)
- 20 T_a reference air temperature (°C)

TARGET - CRC for Water Sensitive Cities microclimate toolkit model

- T_{ac} street level (urban canopy layer) air temperature (°C)
- T_b the air temperature above the urban canopy layer (°C)
- T_m average soil (ground) temperature (°C)
- 25 T_{high} upper level temperature for Richardson number calcuation (°C)
 - T_{low} lower level temperature for Richardson number calcuation (°C)

 T_{soil} - soil temperature (°C)

 T_{surf} - surface temperature from the force-restore model (°C)

- U_{can} wind speed in canyon (m s⁻¹)
- 30 U_{top} wind speed at the top of the canyon (m s⁻¹)

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U_z - reference wind speed (m s<sup>-1</sup>)
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- W average street width (m)
- W* average street width minus tree width (m)
- W_{tree} tree width (m)
- 35 W_{roof} roof width (m)



 α - surface albedo

 α_{pm} - LUMPS empirical parameter (alpha parameter) - relates to surface moisture

- β LUMPS empirical parameter (beta parameter)
- β_k amount of shortwave radiation immediately absorbed by the water layer (set to 0.45)

 $\Delta Q_{S,watr}$ - change in heat storage of the water layer (W m⁻²)

 ϵ - surface emissivity

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 κ - thermal diffusivity (m² s⁻¹)

 κ_{watr} - eddy diffusivity of water (m² s⁻¹)

 λ_C - the plan area ground level surfaces (m²)

- 10 ρ_a density of dry air (=1.2 kg m⁻³)
 - ρv density of moist air (kg m⁻³)

 σ - Stefan-Boltzmann constant (5.67 \times $10^{-8}~{\rm W}~{\rm m}^{-2}{\rm K}^{-4})$

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30 Appendix A

A1 Meteorological conditions during validation periods

As outlined in Sect. 3, we conducted model validation experiments during two different periods. A summary of the meteorological conditions for land cover [Melbourne] (Fig. 11) and suburb scale [Mawson Lakes] (Fig. 12) simulations are provided below.





Figure 11. Meteorological conditions during land cover validation period. Data source: Melbourne Airport Bureau of Meteorology (ID 086282) weather station.



Figure 12. Meteorological condition during the Mawson Lakes field campaign. Data source: Bureau of Meteorology Parafield Airport (ID: 023013) and Kent Town (ID: 94675) weather stations, Adelaide.







Figure 13. Observed air temperature vs. observed tree T_{surf} .

A2 Tree surface temperature

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To assess T_{tree} we obtained observational data from a tree experiment conducted in Melbourne, which including T_{surf} observations of the tree canopy (collected during February 2014). We also obtained a BoM meteorological forcing data for the 2014 case study period. This period (not shown) was very similar to the February 2012 period (Fig. 11) used above. The tree data confirms that T_a is excellent predictor or T_{tree} .