Evaluation of an urban canopy model in a tropical city: The role of tree evapotranspiration

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Manuscript submitted to Environmental Research Letters

Received: April 6, 2017

Revised: June 26, 2017

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Abstract

A single layer urban canopy model (SLUCM) with enhanced hydrologic processes, is evaluated in a tropical city, Singapore. The evaluation was performed using an 11-month offline simulation with the coupled Noah land surface model/SLUCM over a compact low-rise residential area. Various hydrological processes are considered, including anthropogenic latent heat release, and evaporation from impervious urban facets. Results show that the prediction of energy fluxes, in particular latent heat flux, is improved when these processes were included. However, the simulated latent heat flux is still underestimated by ~40%. Considering Singapore’s high green cover ratio, the tree evapotranspiration process is introduced into the model, which significantly improves the simulated latent heat flux. In particular, the systematic error of the model is greatly reduced, and becomes lower than the unsystematic error in some seasons. The effect of tree evapotranspiration on the urban surface energy balance is further demonstrated during an unusual dry spell. The present study demonstrates that even at sites with relatively low (11%) tree coverage, ignoring evapotranspiration from trees may cause serious underestimation of the latent heat flux and atmospheric humidity. The improved model is also transferable to other tropical or temperate regions to study the impact of tree evapotranspiration on urban climate.

Key Words: Energy balance; Hydrological; Urban canopy model; Tropical; Tree evapotranspiration
1. Introduction

Due to the accelerated worldwide urbanization since the late 20th century, large expanses of natural surfaces have been converted to urban landscapes with implications for albedo (usually lower), surface roughness (higher), evaporation (less), transpiration (less), heat storage capacity (higher) and anthropogenic heat emissions (higher). These changes of underlying surface properties have led to more complex surface energy distribution in urban areas. In addition to impact the local and regional climate (Grimm et al., 2008), they may further bring adverse effects to human health (Patz et al., 2005).

The urban canopy layer (UCL) is the layer between the surface and the mean height of buildings and trees. Its characteristics are dominated by the energy and mass exchange between individual surface facets and the canyon air (Oke, 1976). With the recognition of the important roles played by urban areas in surface energy balance (SEB), various numerical models have been developed to investigate the energy exchange over cities, as well as the transfer of momentum and moisture between UCL and the overlying atmosphere. One type of such models is the physically based urban canopy models (UCM), which explicitly consider the impacts of urban building morphology when calculating the SEB. The UCMs can be further categorized into two types (Fernando, 2012): single-layer (Kusaka et al., 2001) and multilayer (Martilli, 2002) schemes. The single-layer urban canopy model (SLUCM) simply represents the urban geometry as two-dimensional street canyons with infinite length but considers the three-dimensional nature of urban morphologies, the shadowing from buildings, and reflection of radiation in the canopy layer. These models calculate the prognostic variables such as surface skin temperature and heat fluxes produced from urban facets (i.e., building roofs, walls and roads). Chen et al. (2004) and Miao et al. (2009) have coupled SLUCM into mesoscale atmospheric models (e.g., Weather Research and Forecasting, WRF model) to offer feasible lower boundary conditions to the overlying atmosphere. The coupled WRF/SLUCM system
has been successfully applied in various cities around the world (Chen et al., 2011) for studying various microclimatic phenomena such as the urban heat island effect (e.g., Miao et al., 2009, Li et al., 2013, Li et al., 2016).

The SLUCM has achieved satisfactory performance in predicting net radiation and sensible heat flux but is still inadequate in predicting latent heat flux (e.g., Loridan et al., 2010, Li et al., 2013). Comparing 33 urban SEB models, Grimmond et al. (2011) concluded that the underestimation of latent heat flux exists not only in SLUCM but also in most other urban land surface schemes. This mainly results from the uncertain mechanism of complex water vapor transport and the inadequate representation of urban hydrological processes, urban vegetation and soil properties. The underestimation of latent heat flux usually leads to overestimation of sensible heat flux and surface skin temperature, which ultimately jeopardizes the SLUCM’s accuracy. In order to improve the simulation accuracy of latent heat flux, Loridan et al. (2010) assessed the fitness of a coupled Noah land surface model/SLUCM parameterization scheme and suggested that a vegetation class like ‘cropland/grassland mosaic’ or ‘grassland’ with a low stomatal resistance could help improve the insufficient representation of urban evaporation in the SLUCM. Miao and Chen (2014) and Yang et al. (2015) included several additional urban hydrological processes (i.e., the anthropogenic latent heat, urban irrigation, evaporation from paved surfaces, and the urban oasis effect) in the coupled Noah/SLUCM to enhance the urban evaporation components. Their evaluation of the model performance in Beijing, Phoenix, Vancouver and Montreal showed that the latent heat flux simulated by the new model improved substantially.

The latent heat flux is especially important since it impacts soil moisture dynamics, surface runoff, and the overlying atmosphere (Koster, 2015). Accurate information about the latent heat flux and evapotranspiration is essential for estimating urban ecosystem water requirements and stress regimes, which is of utmost importance during a draught. However,
urban latent heat flux and evapotranspiration measurement and estimates are sparse in both
time and space (Gentine et al., 2016). Accurate prediction of latent heat flux will therefore
widely benefit the scientific community, urban designers and policy-makers (e.g., Mitchell et
al., 2008). It has been demonstrated that including vegetation effects in urban SEB models is
crucial to obtain accurate prediction of the sensible and latent heat fluxes (Best and Grimmond,
2015, 2016). In previous urban SEB models, the urban vegetation was usually represented by
‘grassland’ and the impact of urban trees was neglected in UCMs. Lee and Park (2008)
included trees in their SLUCM but did not consider sub-surface moisture transport. Krayenhoff
et al. (2014, 2015) incorporated trees into a multilayer UCM and added tree-building
interaction, but they did not fully take the evaporative impact of trees into account. Ryu et al.
(2016) included the hydrothermal processes associated with trees in SLUCM and adequately
incorporated the interaction of trees, ground and walls. Their simulation results in three
urban/suburban sites in Basel, Switzerland showed improved prediction performance of latent
heat flux. The abovementioned models with tree effects revealed the important role of urban
trees in SEB modeling, especially in simulating latent heat flux.

In the light of previous studies and the need of accurate prediction of latent heat flux
for urban climate modeling, we will conduct an evaluation study in a tropical city Singapore
using the coupled Noah/SLUCM model with physically-based urban hydrological processes
and tree evapotranspiration. Some previous evaluation studies have been carried out in
Singapore (Harshan, 2015, Demuzere et al., 2017), but neither evaluated the role of tree
evapotranspiration. The aims of our study are: (1) evaluate the performance of Noah/SLUCM
in a tropical residential neighborhood; (2) improve the capability of this model with urban
hydrological processes and tree evapotranspiration; and (3) assess the importance of urban trees
in the urban surface energy balance in Singapore.
2. Methods

2.1 Local climate and data collection

Singapore is a tropical city state located at the southern tip of the Malay Peninsula. It is a highly urbanized coastal city with a very high population density of 7821 persons per km$^2$. As a ‘City in the Garden’, about half of its land is covered by managed vegetation and young secondary forest (Yee et al., 2011). Because of its geographical location near the equator, Singapore has a typical equatorial wet climate characterized by perennial high temperature, high humidity and abundant precipitation. Alternating northeast and southwest monsoon winds blowing throughout the island divides its annual climate into a northeast monsoon season (usually December to early March of the following year), a southwest monsoon season (usually June to September) and two inter-monsoon periods (Fong and Ng, 2012).

A 23.7 m high eddy-covariance (EC) flux tower is located in Telok Kurau (1°18’51.46”N, 103°54’40.31”E, elevation: \(\sim\)10 m a.s.l), a low-density residential area in Southeast Singapore. The study area corresponds to ‘compact low-rise’ or Local Climate Zone 3 according to Stewart and Oke (2012). Given a mean building height of 9.86 m, the sensors are expected to be located with the inertial sublayer (above 2-5 times the height of the surface roughness according to Roth, 2000) where fluxes are constant with height and representative of the underlying surface. Within a 1 km radius of the tower, 39% of the plan area is covered by mainly 2-3 story high residential buildings, 12% roads, 34% other impervious surfaces and 15% vegetation (including 11% tree crowns and 4% grassland) with little directional variation (Fig. S1 in Velasco et al., 2013). Average flux footprints, which encompass the area on the ground which contributes to the measurement, extended to between 400 m (daytime) to 1000 m (nighttime) from the tower (Fig. S7 in Velasco et al., 2013, Fig. 1 in Roth et al., 2017). Under most atmospheric conditions the measured fluxes therefore represent the local area of interest.

Individual variables were sampled at 10 Hz by EC sensors installed at the top of the tower.
Fluxes were calculated for 30-min periods following standard correction and data quality assurance. A detailed description of the instrumentation and flux post-processing are provided in Velasco et al. (2013) and Roth et al. (2017). The dataset used in the present study was gap-filled (Harshan, 2015) and used in other studies to evaluate urban land surface models (LSM) to predict SEB fluxes (Harshan, 2015, Demuzere et al., 2017).

2.2 Coupled Noah/SLUCM model

The coupled Noah/SLUCM is utilized in this study. The heat fluxes associated with the different urban facets (building roofs and walls, roads and other impervious surfaces) are simulated by SLUCM, while those from the vegetation fraction are handled by the Noah LSM (Chen and Dudhia, 2001). The urban SEB equations are (Oke, 1988)

\[
Q^* = K_1 - K_1 + L_1 - L_1, \tag{1}
\]

\[
Q^* + Q_E = Q_H + Q_E + \Delta Q_S, \tag{2}
\]

where \(K_1\) and \(K_1\) are upwelling and downwelling shortwave radiation, \(L_1\) and \(L_1\) are upwelling and downwelling longwave radiation; \(Q^*\) is net radiation, \(Q_E\) is anthropogenic heat flux, \(Q_H\) is sensible heat flux, \(Q_E\) is latent heat flux and \(\Delta Q_S\) is heat storage. More details of the coupled Noah/SLUCM model can be found in Chen et al. (2011).

This coupled Noah/SLUCM model was run off-line driven by the 30-minute meteorological and radiation data collected from the EC flux tower, including wind speed, air temperature, relative humidity, ambient pressure, precipitation, downward shortwave and longwave radiation. Other input parameters of urban geometry, building materials and anthropogenic heat used in this study are given in Table 1.

Table 1. Input parameters for the coupled Noah/SLUCM model in this study.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Units</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban category</td>
<td>-</td>
<td>Low-density residential</td>
<td>(Roth et al., 2017)</td>
</tr>
</tbody>
</table>
Impervious fraction % 85 (Velasco et al., 2013)
Tree fraction % 11 (Velasco et al., 2013)
Building height m 9.86 (Velasco et al., 2013)
Tree height m 7.26 (Velasco et al., 2013)
Maximum anthropogenic heat $Q_{AHMAX}^a$ W m$^{-2}$ 13 (Quah and Roth, 2012)
Roof albedo - 0.20 (Li et al., 2013)
Wall albedo - 0.10 (Li et al., 2013)
Road albedo - 0.10 (Li et al., 2013)
Road width m 5 (Li et al., 2013)
Leaf area index of tree - 3 (Tan and Sia, 2010)

- Estimated using a combination of top-down and bottom-up modelling approaches of energy consumption applied to the study area.

2.3 Enhanced hydrological processes

In order to mitigate the deficiency in modeling the latent heat flux in urban LSM models, Miao and Chen (2014) and Yang et al. (2015) proposed to include some enhanced hydrological processes in the coupled Noah/SLUCM model. These processes are (1) anthropogenic heat flux release, (2) the urban oasis effect (a phenomenon that patchy vegetation in urban areas has higher rates of potential evapotranspiration than large area vegetation in the natural environment, Hagishima et al., 2007), (3) urban irrigation and (4) a modified evaporation scheme over urban impervious surfaces. Because the oasis effect is location specific and there is no routine urban irrigation in Singapore, these two processes are not considered in the present study. Instead, a sensitivity study of the oasis effect will be conducted in the supplementary material (Section S3). Considering the other hydrological processes, the latent heat flux can be calculated from two combined sources, urban and non-urban, according to Yang et al. (2015), as

$$ Q_E = f_{urb}(Q_{urb} + Q_{ALH}) + f_{veg}Q_{Eveg}, \quad (3) $$

$$ Q_{Eveg} = C_hE_p, \quad (4) $$

where $f_{urb}$ is the urban (impervious) fraction, $f_{veg}$ is the vegetation fraction, $Q_{urb}$ is the latent heat flux from the urban sources calculated by the original SLUCM, $Q_{Eveg}$ is the latent...
heat flux produced by non-urban sources. $C_H$ is the exchange coefficient, $E_p$ is the potential evaporation rate, $Q_{ALH}$ is anthropogenic latent heat flux, which is calculated as (Yang et al., 2015)

$$Q_{ALH} = Q_{ALH MAX} f_{ALH},$$

$$\frac{Q_{ALH MAX}}{Q_{ASH MAX}} = \beta \frac{\Delta}{\gamma},$$

$$Q_{ALH MAX} + Q_{ASH MAX} = Q_{AH MAX},$$

where $\Delta$ is the slope of the saturation vapor pressure curve (kPa K$^{-1}$), $\gamma$ is the psychrometric constant (66.1 Pa K$^{-1}$), $\beta$ is the moisture availability parameter (a value of 1.5 is used here following Yang et al., 2015). $Q_{ALH MAX}$, $Q_{ASH MAX}$ and $Q_{AH MAX}$ are daily maximum anthropogenic latent, sensible and total heat flux, respectively. $f_{ALH}$ is the diurnally-varying coefficient of anthropogenic sensible and latent heat. $Q_{AH MAX}$ and $f_{ALH}$ are both taken from Quah and Roth (2012) and Li et al. (2013).

Many studies have demonstrated that urban impervious surfaces can partly store precipitation and supply evaporation over a given period of time (e.g., Kawai and Kanda, 2010, Ramamurthy and Bou-Zeid, 2014). The default evaporation scheme for impervious surfaces only considers the evaporation on the ground surface during precipitation, but excludes water availabilities from ponded surface water due to impeded drainage after precipitation. Based on the hypothesis that water availabilities in road, roof and wall exponentially decrease to 0 in 24 hours since last precipitation, Miao and Chen (2014) proposed a new evaporation scheme over urban impervious surfaces in calculating $Q_{Eur b}$ (referred to as the new impervious evaporation scheme hereafter). It is noteworthy that this new impervious evaporation scheme is only applicable in the cases of consecutive precipitation and poor drainage, and therefore in this study we only apply it during the early NE monsoon season.

2.4 Tree evapotranspiration

To account for the tree evapotranspiration effect, a new term is added to Eq. (3):
\[ Q_E = f_{urb}(Q_{Eurb} + Q_{ALH}) + f_{veg}Q_{Eveg} + f_{tree}Q_{Etree}, \]  
(8)

where \( f_{tree} \) is the tree fraction and \( Q_{Etree} \) is the latent heat flux produced by trees, which is calculated using the Penman-Monteith equation (Bosveld and Bouten, 2001, Ballinas and Barradas, 2016)

\[ Q_{Etree} = \lambda_v ET = \frac{\Delta Q^* + \rho C_p VPD}{\Delta + \gamma(1 + \frac{r_C}{r_A})}, \]  
(9)

where \( \lambda_v \) is latent heat of vaporization of water (J kg\(^{-1}\)), \( ET \) is the mass water evapotranspiration rate (kg s\(^{-1}\) m\(^{-2}\)), \( \rho \) is the density of air (kg m\(^{-3}\)), \( C_p \) is the specific heat capacity of air at constant pressure (J kg\(^{-1}\)K\(^{-1}\)), \( VPD \) is the vapor pressure deficit (kPa), \( r_A \) is the bulk surface aerodynamic resistance for water vapor (s m\(^{-1}\)), and \( r_C \) is the canopy surface resistance (s m\(^{-1}\)). The vapor pressure deficit is calculated by

\[ VPD = e_s - e_a = e_s(1 - RH), \]  
(10)

where \( e_s \) and \( e_a \) are saturation vapor pressure (kPa) and vapor pressure (kPa), respectively, and \( RH \) is relative humidity. The bulk surface aerodynamic resistance \( r_A \) is calculated according to Allen et al. (1998) as

\[ r_A = \frac{1}{k^*u} \ln \left( \frac{z_m - d}{z_{om}} \right) \ln \left( \frac{z_h - z_d}{z_{oh}} \right), \]  
(11)

where \( k \) is the von Karman’s constant (= 0.41), \( u \) is the wind speed at height \( z_m \) (m s\(^{-1}\)), \( z_m \) is the height of wind measurement (m), \( z_h \) is the height of humidity measurement (m), \( z_d \) is the zero plane displacement height (m), \( z_{om} \) is the aerodynamic roughness length for momentum transfer (m) and \( z_{oh} \) is the aerodynamic roughness length for the transfer of heat and vapor (m). The zero-plane displacement height \( z_d \) is estimated as 0.67\( z_r \), where \( z_r \) is the canopy height (m). In this study, \( z_{oh} \) is calculated as 0.1\( z_{tree} \), where \( z_{tree} \) is the mean height of trees (m), while \( z_{om} \) is calculated as 0.1\( z_{oh} \). The canopy surface resistance \( r_C \) is calculated following Chen and Dudhia (2001).
2.5 Numerical experiment design

The impact of different processes on the performance of the coupled Noah/SLUCM model was evaluated through three numerical experiments (*Table 2*). Sim_1 used the original model without any additional effects. Sim_2 considered the enhanced hydrological processes including (1) anthropogenic latent heat release, and (2) the evaporation from impervious surfaces (Miao and Chen, 2014). Sim_3 further included the tree evapotranspiration in addition to those enhanced hydrological processes considered in Sim_2.

**Table 2.** Designs of numerical simulations to evaluate the importance of hydrological processes.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Enhanced hydrological process</th>
<th>Tree evapotranspiration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Anthropogenic latent heat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Evaporation on impervious</td>
<td></td>
</tr>
<tr>
<td></td>
<td>surfaces</td>
<td></td>
</tr>
<tr>
<td>Sim_1</td>
<td>No</td>
<td>Default scheme</td>
</tr>
<tr>
<td>Sim_2</td>
<td>Yes</td>
<td>The new impervious</td>
</tr>
<tr>
<td></td>
<td></td>
<td>evaporation scheme for early NE monsoon season</td>
</tr>
<tr>
<td>Sim_3</td>
<td>Yes</td>
<td>The new impervious</td>
</tr>
<tr>
<td></td>
<td></td>
<td>evaporation scheme for early NE monsoon season</td>
</tr>
</tbody>
</table>

3. Model evaluation

3.1 Study period

The study period spans 11 months from 18 May 2013 to 19 Apr 2014 (‘Entire period’ hereafter).

Considering the climate characteristics of Singapore, two seasons were identified following the monsoon season partitioning in 2013-2014 according to NEA annual weather report (MSS, 2014): southwest monsoon season (‘SW monsoon’ hereafter) and early northeast monsoon season (‘Early NE monsoon’ hereafter). Detailed seasonal division is shown in *Table 3*. In southwest monsoon season, this island experiences dry wind southerly to southeasterly, resulting in less rainfall comparing to other months of the year. While in the early northeast monsoon season (usually the wettest months within the year), northeast monsoon surges often
bring consecutive and widespread heavy rainfalls. Another season is an unusually prolonged dry period (‘Dry period’ hereafter), during which Singapore suffered the longest dry spell since the beginning of its official records in 1929 (McBride et al., 2015). During this period, the climate station located at Changi airport only recorded 0.2 mm rainfall, while 2.2 mm rainfall was observed at Telok Kurau. Through conducting the simulations during these seasons which represent Singapore’s year-round climate conditions, we attempt to evaluate this coupled Noah/SLUCM model and its modified versions at an equatorial tropical site. In the following sections, the daytime refers to 0800 – 1800 LT, and nighttime refers to 2000 – 0600 LT every day.

Table 3. Seasonal division for the study period.

<table>
<thead>
<tr>
<th>Code</th>
<th>Period</th>
<th>Number of days</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire period</td>
<td>18 May 2013 – 19 Apr 2014</td>
<td>337</td>
<td></td>
</tr>
<tr>
<td>SW monsoon</td>
<td>01 Jun 2013 – 15 Oct 2013</td>
<td>137</td>
<td>Southwest monsoon</td>
</tr>
<tr>
<td>Early NE monsoon</td>
<td>16 Nov 2013 – 12 Jan 2014</td>
<td>58</td>
<td>Early northeast monsoon</td>
</tr>
<tr>
<td>Dry period</td>
<td>13 Jan 2014 – 15 Mar 2014</td>
<td>62</td>
<td>Prolonged dry spell</td>
</tr>
</tbody>
</table>

3.2 Radiation and SEB validation

3.2.1 Upwelling radiation $K_\uparrow$ and $L_\uparrow$

Figure 1 compares the observed and simulated upwelling radiation for each experiment and season. Since the additional processes included in Sim_2 and Sim_3 do not alter the albedo of the underlying surfaces, no variations of the simulated $K_\uparrow$ are observed between the three experiments. In general, the simulated $K_\uparrow$ all agree well with the corresponding observations. Only a slight overestimation in the early NE monsoon season is observed, possibly due to the water accumulation over paved surfaces resulted from consecutive rainfalls in this season. This
surface wetness change leads to a lower albedo, while the model albedo is keeps constant for all cases.

Figure 1 Averaged diurnal profiles of observed (symbols) and simulated (lines) $L_\uparrow$ and $K_\uparrow$ for the (a) entire period, (b) SW monsoon, (c) early NE monsoon, and (d) dry period. The definitions of different seasons are detailed in Table 3.

The simulated $L_\uparrow$ is generally overestimated during daytime (by about 10%) while slightly underestimated just before sunrise (Figure 1). It is generally more complex in modeling $L_\uparrow$ than $K_\uparrow$ since $L_\uparrow$ depends strongly on the surface temperature, which in turn is difficult to reproduce given the heterogeneity of materials and geometries within the urban fabric (Grimmond et al., 2011). In Sim_3, the error of the simulated $L_\uparrow$ during daytime decreases by about 20% compared with the other two experiments, suggesting a better performance after considering tree evapotranspiration effects, although the simulated $L_\uparrow$ is still overestimated.
during daytime. This suggests that the tree evapotranspiration contributes more to the reduced surface temperature than the other hydrological processes considered.

![Figure 2 Same as Figure 1 but for $Q^*$](image)

3.2.2 Net radiation $Q^*$

The net radiation $Q^*$ is calculated by Eq. (1), while the downwelling components are from the input forcing data, i.e., the measured data from the EC flux tower. Due to the aforementioned overestimation of $L_1$, $Q^*$ is always underestimated. The simulation performance of $Q^*$ is generally excellent in terms of the statistic metrics and the performance does not vary much across different seasons (Figure 2). The index of agreement (IOA) remains in the interval of 0.97-0.99 during the entire day and during daytime, but decreases slightly during nighttime (Table S1). Although the effect is only marginal, the introduction of the hydrological processes and tree evapotranspiration leads to a continuous reduction of root-mean-square error (RMSE),
indicating their positive role in improving the simulated $Q^*$. It is noteworthy that the reduction of the systematic RMSE (RMSEs, Table SI) suggests an improvement in the model’s prediction skills after considering the tree effect.

![Image of Q_e plots](image)

Figure 3 Same as Figure 1 but for $Q_E$.

3.2.3 Latent heat flux $Q_E$

$Q_E$ is usually the least well-modelled energy flux component in existing urban SEB models (Grimmond et al., 2011). The same situation can also be noticed in this study. The original model (Sim_1, see Table SI) gives a RMSE of 52.65 W m$^{-2}$ and an IOA as low as 0.52 during the entire period.

Incorporating urban hydrological processes into the coupled Noah/SLUCM model has achieved satisfactory results with improving modeling accuracy of $Q_E$ in many cities such as
Beijing, Phoenix and Montreal in previous studies (Miao and Chen, 2014, Yang et al., 2015). In our case, after considering hydrological processes in our study, though an increased average value of 12.68 W m$^{-2}$ and a reduction of RMSE to 51.07 W m$^{-2}$ are achieved during the entire period (Sim_2, see Table SI), there is still a notable discrepancy between the modeled and observed $Q_E$. This situation may be explained by the different geography locations of the tropic city Singapore and mid-latitude cities. The mid-latitude cities are located in relatively dry areas with a high atmospheric demand and limited water available at the surface, whereas in Singapore the atmospheric demand is lower, while water in the urban fabric is more abundantly available.

In previous coupled Noah/SLUCM model simulations, the vegetation part of an urban site is generally represented by grassland without considering trees. In our case, the addition of tree evapotranspiration in Sim_3 sees a marked improvement in the accuracy of simulated $Q_E$. During the entire period, the RMSE and mean biased error (MBE) drop to 38.71 W m$^{-2}$ and -11.99 W m$^{-2}$, respectively, and the IOA increases to 0.75 (Table SI). From Sim_1 to Sim_3, the systematic RMSE (RMSEs) reduces continuously (Table SI), manifesting the improved model skills by including the tree evapotranspiration.

The model performance in predicting $Q_E$ has a strong dependence on the seasonality. Sim_1 and Sim_2 give the poorest simulation results in the dry period, with the mean value of 2.54 W m$^{-2}$ and 4.84 W m$^{-2}$, respectively, compared with the observed value of 34.39 W m$^{-2}$ (Table SI). $Q_E$ is usually highly impacted by precipitation. Though there was only 2.2 mm precipitation during the dry period, the mean value of observed $Q_E$ was still as high as 78% of that in other seasons (44.14 W m$^{-2}$ in SW monsoon season, and 44.11 W m$^{-2}$ in early NE monsoon season). There should be other processes contributing to $Q_E$ during the dry period. One such process is the tree evapotranspiration, which has been demonstrated in Sim_3 (Figure 3d). With added tree evapotranspiration, the RMSEs of $Q_E$ decreases from 46.94 W m$^{-2}$ (Sim_1)
to 20.55 W m$^{-2}$ (Sim_3), indicating that the systematic error has been greatly reduced and most of the discrepancy between the simulated and observed $Q_E$ can be explained by random processes (e.g., due to uncertainties from input parameters). Another possible process is the urban irrigation. Although no regular urban irrigation is conducted in Singapore, in extremely dry period, it is reasonable to assume that some manual, sporadic irrigations may be carried out by local residents to mitigate the absence of water.

![Graphs showing QH vs. local time for different simulations and observations.](image)

Figure 4 Same as Figure 1 but for $Q_H$.

3.2.4 Sensible heat flux $Q_H$

The simulated $Q_H$ exhibits a consistent performance during all seasons (Figure 4). The RMSE of $Q_H$ in Sim_1 is more than 35 W m$^{-2}$. With the added hydrological processes (Sim_2), the model performance improves accordingly. Nevertheless, $Q_H$ is still overestimated until the tree
effect is considered in Sim_3. The model shows notable improvement in Sim_3 in the early NE monsoon season (Figure 4c), with RMSE reducing to 29.92 W m$^{-2}$ from 34.87 W m$^{-2}$ and 33.97 W m$^{-2}$ in Sim_1 and Sim_2, respectively (Table S1). The RMSEs and RMSEu also decrease with added hydrological processes and tree evapotranspiration, although RMSEs is still higher than RMSEu (Table S1).

A consistent lag in the simulated $Q_H$ is found in all the seasons. Hysteresis starts from 0800 LT with peak value at 1300 to 1330 LT, slightly later than the observed peak at 1230 LT. This phenomenon is not typical as the long-term (2006-2013) average $Q_H$ of Singapore peaks at 1300 LT, and 1400 LT for dry seasons (Roth et al., 2017). The diurnal cycle of predicted $Q_H$ corresponds more to the long-term statistics rather than the period under investigation here. Since the major goal of this study is to improve the prediction of $Q_E$, no efforts were made to fine tune the parameters related to $Q_H$. The observed lag in $Q_H$ needs further investigation, but it is beyond the scope of the current study.

3.2.5 Heat storage flux $\Delta Q_S$

As both the simulated and observed $\Delta Q_S$ are calculated as the residual of the net radiation and the other energy components (see Eq. 2), i.e., $(Q^* + Q_F) - (Q_H + Q_E)$, and no direct measurements are available for comparison, the modeling uncertainties of all other variables in Eq. (2) accumulate in $\Delta Q_S$. The time shift resulting from $Q_H$ leads to the time shift in $\Delta Q_S$, and the negative and positive biases of $Q^*$, $Q_H$ and $Q_E$ offset each other. No appreciable difference between the three simulations can be observed, except a slight difference in Sim_3 near noon and sunset (1900 LT). The simulated results in all seasons show an overestimation before noon while underestimation during the second half of the day.
Figure 5 Same as Figure 1 but for $\Delta Q_S$

3.3 Further analysis of $Q_E$

3.3.1 Taylor diagram

Figure 6 shows normalized Taylor diagrams for $Q^*$, $L_1$, $Q_H$ and $Q_E$ for all simulations, observations and seasons. Observations are indicated by the star symbol at (1.0, 1.0, 0.0), correlation coefficients are plotted on polar axes, normalized standard deviations on y-axes and normalized RMSE are given by the inner grey circles.
Figure 6 Normalized Taylor diagrams for $Q^*$, $L_1$, $Q_H$ and $Q_E$ for all simulations (symbols) and seasons (colors).

The performance of $Q^*$ shows no visible difference across all simulations, while the predicted $L_1$ is sensitive to the seasonality, with the best performance during the dry period and worst during the early NE monsoon season. The correlation coefficients of $Q_H$ are in a narrow range from 0.9 to 0.95, with small variability in normalized standard deviation and normalized RMSE. A wide range of model performance is evident for $Q_E$. Correlation coefficients for all simulations are less than 0.7 except for Sim_3 during the dry period (indicated by the green circle symbol). The normalized standard deviations are scattered from 0.0 to 0.8 and RMSE values are around 0.8 except for Sim_3 during the dry period (indicated by the green circle symbol, which is below 0.7). Overall, taking the tree evapotranspiration into account greatly improves the model performance in predicting $Q_E$. It can be seen from the diagram that the model with the tree evapotranspiration generally has the best performance during the dry period.
and early NE monsoon season with the new impervious evaporation scheme (indicated by the green and red circle symbols, respectively). During the dry period (green circle symbol), the simulated $Q_E$ shows the highest correlation and lowest RMSE, while during early NE monsoon season (red circle symbol) the standard deviation of the simulated $Q_E$ is the closest to the observational data.

3.3.2 Model performance during dry period

As revealed by the Taylor diagrams (Figure 6), the $Q_E$ simulation during the dry period with added tree evapotranspiration shows best performance. To examine $Q_E$ simulation improvement during the dry period in detail, Figure 7 compares the daily averaged $Q_E$ from both observations and simulations during the daytime (Figure 7a) and nighttime (Figure 7b). An evident increase of all values is noted in Sim_3 during daytime with a magnitude 3 times larger than that in Sim_2, which suggests that urban tree evapotranspiration dominants the dry period’s latent heat release. However, during nighttime, the model performance of Sim_3 is as bad as that of Sim_2, since no solar radiation is available for evapotranspiration at that time.
4. Conclusions and discussions

This study evaluated the performance of the coupled Noah/SLCUM model in a tropical suburban site during a 11-month period. Some urban hydrological processes (anthropogenic latent heat flux and evaporation from urban impervious surfaces) as well as the tree evapotranspiration were implemented in the model to improve the prediction skills of latent heat flux $Q_E$. Comparisons with the field measurements showed that the added hydrological processes can help improve the accuracy in predicting $Q_E$. However, there still remained much discrepancy between the simulated and observed $Q_E$ until the tree evapotranspiration was included in the model. The inclusion of the tree evapotranspiration had been shown to greatly reduce the MBE and RMSE of simulated $Q_E$, particularly leading to much lower systematic RMSE, an indication of the improved prediction skills. During an unusual dry spell in early 2014 when there was little contribution from precipitation, the tree evapotranspiration was found to contribute most of $Q_E$. The improved model demonstrated little effect during nighttime, when the solar radiation needed for transpiration is missing. The results demonstrated that tree evapotranspiration plays a very important role in latent heat flux in an urban environment like Singapore, and ignoring the tree effect will result in underestimation of latent heat flux.

Similar studies in Vancouver, Canada (Krayenhoff et al., 2014, Krayenhoff et al., 2015) and Basel, Switzerland (Ryu et al., 2016) have demonstrated the role of trees in improving latent heat flux prediction. It is therefore expected that the proposed improved model from the present study can be transferred to other tropical and temperate urban environments to produce improved latent heat flux prediction. For neighborhoods without the necessary observational data as input to the model (which is very common), the online simulation with the well-calibrated coupled WRF/UCM can be performed instead. The improved model can be applied to better predict a variety of important real-world issues facing urban dwellers, such as urban
heat island mitigation, outdoor thermal comfort, building energy usage (when coupled with a
building energy model), or water usage management during draught conditions (Vahmani and
Ban-Weiss, 2016).

Acknowledgments

This research is supported by the National Research Foundation Singapore (NRF) under its
Campus for Research Excellence and Technological Enterprise (CREATE) programme. The
Center for Environmental Sensing and Modeling (CENSAM) is an interdisciplinary research
group of the Singapore-MIT Alliance for Research and Technology (SMART). We thank Mr.
YANG Jiachuan and Dr. WANG Zhihua at Arizona State University for providing the source
code and their valuable suggestions.

References

ALLEN, R. G., PEREIRA, L. S., RAES, D. & SMITH, M. 1998. Crop evapotranspiration-
Guidelines for computing crop water requirements-FAO Irrigation and drainage paper
56. FAO, Rome, 300, D05109.

BALLINAS, M. & BARRADAS, V. L. 2016. The urban tree as a tool to mitigate the urban
heat island in Mexico City: a simple phenomenological model. Journal of
Environmental Quality, 45, 157-166.

Land Surface Model Comparison Project. Bulletin of the American Meteorological
Society, 96, 805-U18.

Urban Sites with Varying Vegetation Cover. Journal of Hydrometeorology, 17, 2537-
2553.


CHEN, F. & DUDHIA, J. 2001. Coupling an advanced land surface-hydrology model with the
Penn State-NCAR MM5 modeling system. Part I: Model implementation and


