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A Vegetated Urban Canopy Model for Meteorological and Environmental Modelling

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Boundary-Layer Meteorol (2008)

Reporter：Zhang Lei

Introduction

slab model
Myrup, 1969; Atwater1977; Seaman et al. 1989

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single-layer urban canopy
Oke.et al, 1991; Deardorff, 1978; Walko.et al, 2000

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multi-layer urban canopy model
Brown, 2000; Ca.et al, 2002; Martilli.et al. 2002; Dupont.et al, 2004

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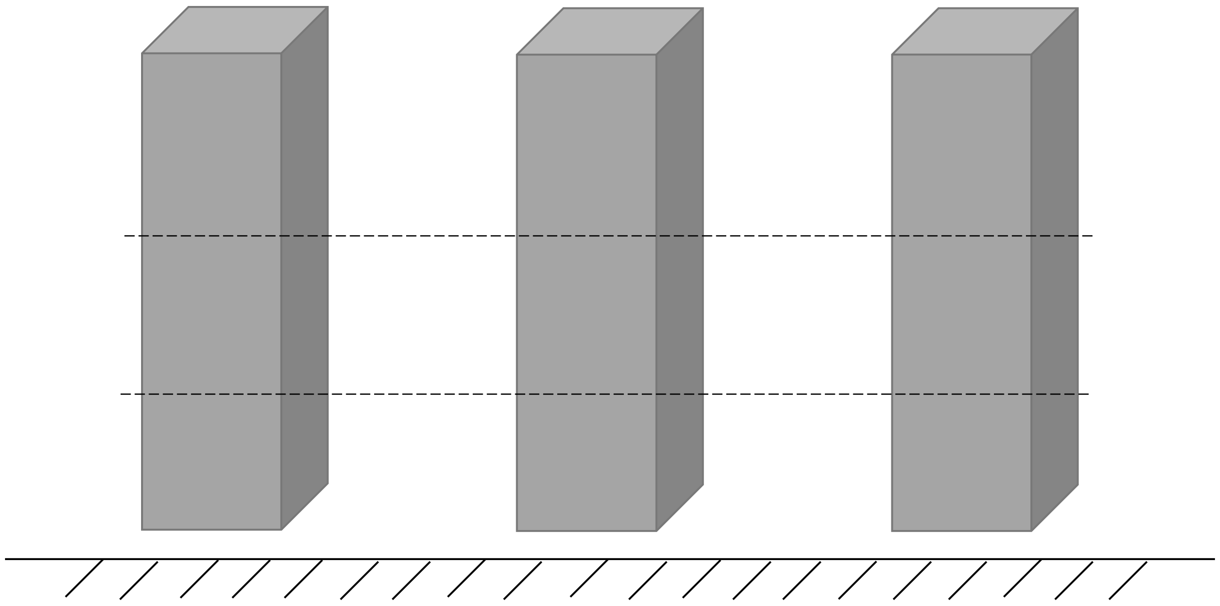


Why a new model should be developed?

omitting the canyon vegetation planted within the urban street canyon

- urban surface temperature
- air temperature and humidity
- surface energy balance

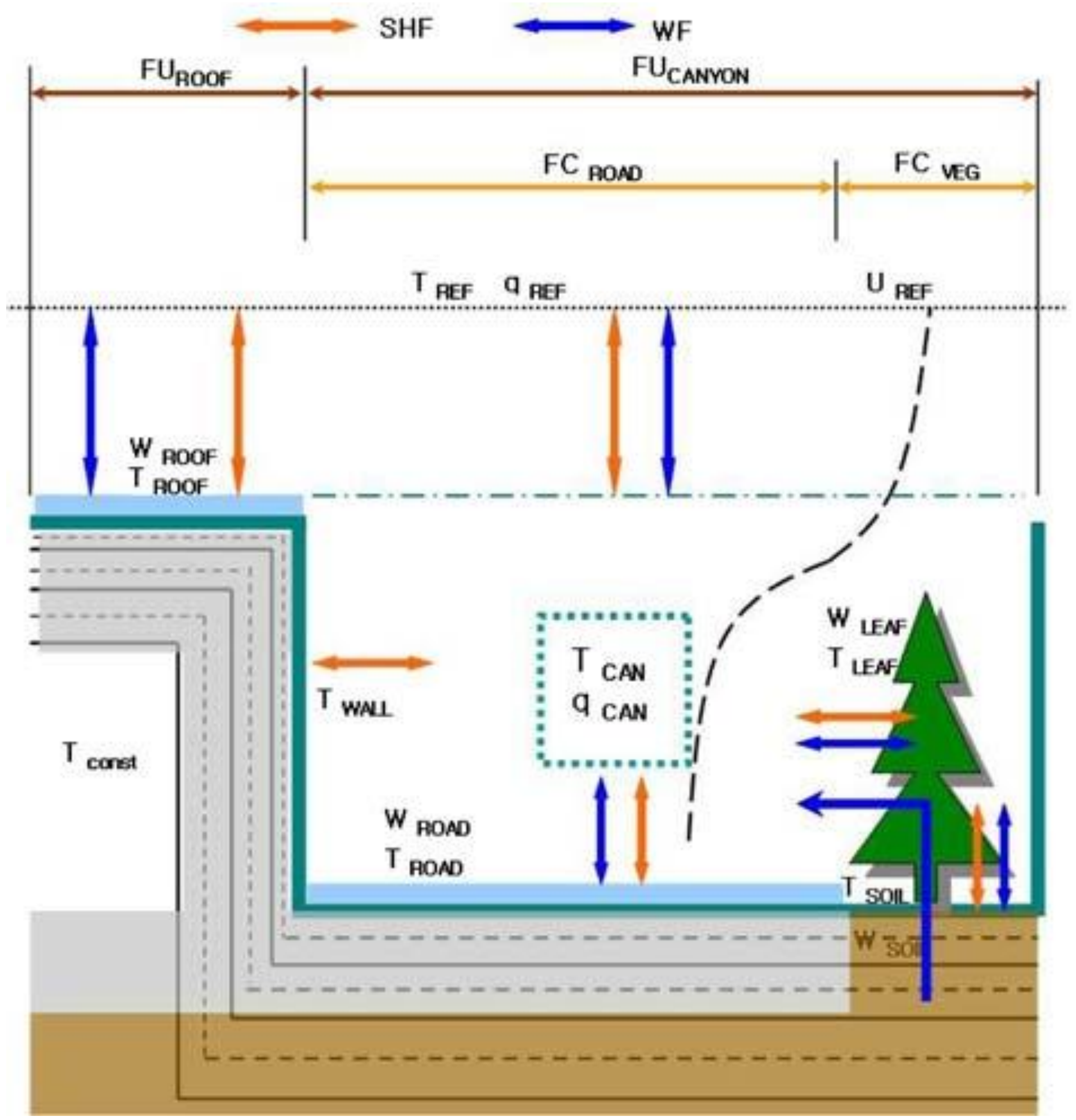
Solution:

In this study, the Vegetated Urban Canopy Model (VUCM) is developed on the basis of a single-layer model for realistic representation of urban surfaces.

Model Description

Fig. 1 The schematic diagram of VUCM. Light and dark arrows indicate the pathways of heat and moisture, respectively.

Take five types of surfaces in consideration : roof, wall, road, vegetation and soil, respectively.



Model Description

- Surface Temperatures

Artificial Surfaces: Roof, Wall, and Road

The energy fluxes at the top surface (n + 1 layer) can be estimated from:

$$F_{i,n+1} = S_i^{\downarrow\uparrow} + L_i^{\downarrow\uparrow} - H_i - \lambda E_i$$

Natural Surfaces: Vegetation and Soil

Energy budget at the soil top is given by:

$$F_{s,top} = S_s^{\downarrow\uparrow} + L_s^{\downarrow\uparrow} - H_s - \lambda E_s$$

The energy balance on the vegetation surface (or leaf surface) is given by:

$$C_l \frac{\partial T_l}{\partial t} = S_l^{\downarrow\uparrow} + L_l^{\downarrow\uparrow} - H_l - \lambda(E_l + E_{root})$$

$$<C_l = 4186LAI>$$

Model Description

- Water Budget on the Surfaces

The precipitation (on a rainy day) and dewfall (on a clear night) are considered in VUCM as water sources for the surfaces.

The water budget equation on each surface:

$$\frac{\partial W_i}{\partial t} = P_i + E_i$$

precipitation rate (P_i)   evaporation/dewfall rate (E_i)

Model Description

- Canopy Air Energy Budget

The energy balance equation for the canopy air temperature:

$$\rho c_p \Delta V_C \frac{dT_C}{dt} = \left[\frac{2h}{w} H_w + \overline{H}_g + H_{AHF} + \sigma_l H_l - H_C\right] \Delta A_C$$

The water mass balance equation for the specific humidity of the canopy air (q_C):

$$\rho \Delta V_C \frac{dq_C}{dt} = \left[\overline{E}_g + \sigma_l E_l - E_C\right] \Delta A_C$$

Model Description

- Shortwave Radiation Budget

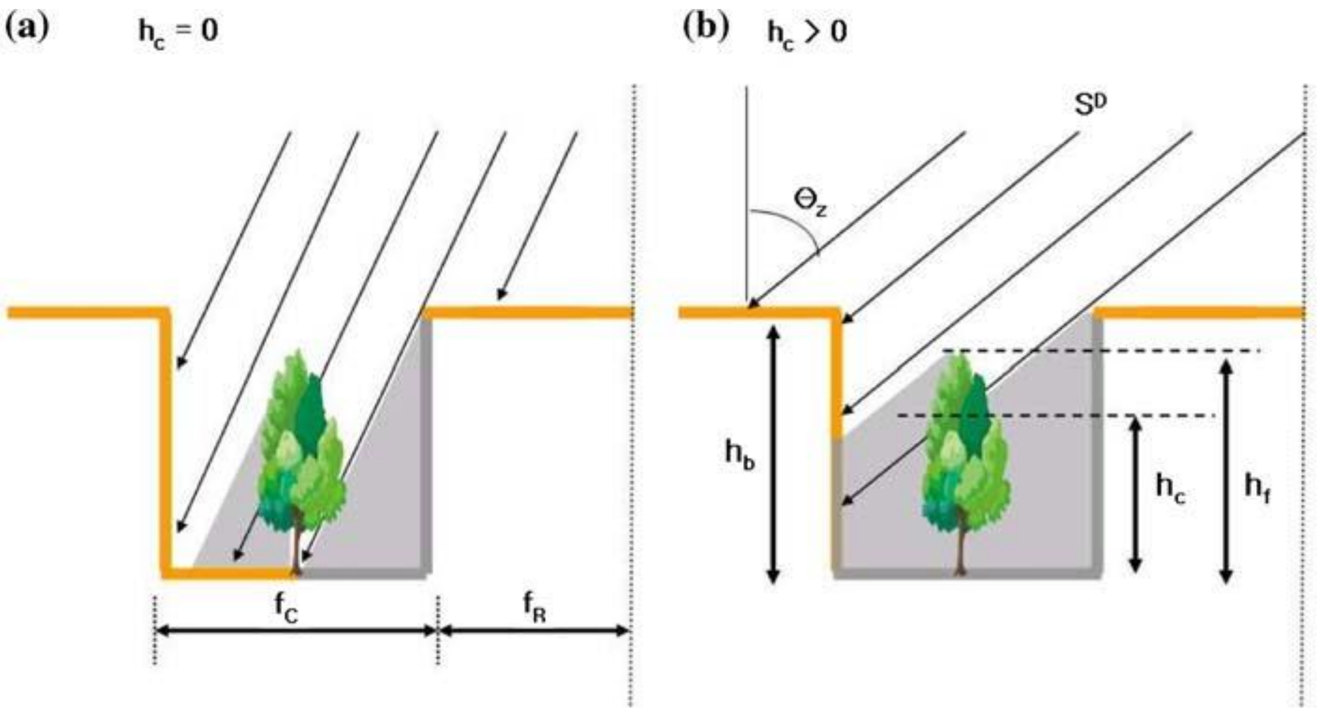


Fig. 3 The direct solar radiation received by the urban surfaces and vegetation in the cases of (a) high solar altitude angle ($\theta z <$ arctan (w/ h)) and (b) low solar altitude angle ($\theta z \geq$ arctan (w/ h)); f_R and f_C are fractions of roof and canyon. hc represents the shaded height of urban trees due to buildings.

The conservation equation for the total incoming shortwave radiative energy:

$$S^{T\downarrow} = \frac{2h}{w} S_w^{\downarrow\uparrow} + S_g^{\downarrow\uparrow} + \sigma_l S_l^{\downarrow\uparrow} + S_{atm}^{\uparrow}$$

$$\alpha_C = \frac{S_{atm}^{\uparrow}}{S^{T\downarrow}}$$

Model Description

- Longwave Radiation Budget

Assumed
- the atmospheric radiation from the sky ($L^{atm\downarrow}$) is isotropic
- the reflecting surface is Lambertian
- the emissivity of the surface for the longwave radiation is high

Model Description

- Wind Profile within the Canyon

The canyon wind speed needs to be estimated to calculate the heat and moisture fluxes between the surfaces (wall, road, vegetation, and soil) and the surrounding canopy air.

The wind profile within the canyon U_C is given by:

$$U_C = U_{h_b} exp\left[-0.386\frac{h}{w}\right] exp(-v f_v \Gamma_l LAI)$$

Model Description

- Turbulent Fluxes

The turbulent fluxes between the canopy air and the overlying atmosphere, as well as the fluxes on the roof and road surfaces, are estimated using the Monin–Obukhov similarity theory.

When the leaf surface is wet:

$$E_l = \sigma_w \rho \frac{q^{sat}(T_l) - q_c}{r_b} LAI^*$$

When the leaf is dry:

$$E_{root} = (1 - \sigma_w) \rho \frac{q^{sat}(T_l) - q_c}{r_b + r_c} LAI^*$$

$$< LAI^* = 2.5[1 - exp(-0.4LAI)] >$$

Validation of VUCM and Sensitivity Tests

- Vancouver, British Columbia

The observation site is located in a north-south oriented canyon 79 m long and 7.54 m wide, and the heights of the east and west walls are 7.31 and 5.59 m, respectively. The canyon floor is composed of a 30–50 mm layer mixed with gravel and sandy clay while the walls are made of concrete blocks painted white. The weather was continuously clear during the measurement period, wind speeds in the canyon were less than $2ms^{-1}$ in daytime and less than $1ms^{-1}$ during the night.

Validation of VUCM and Sensitivity Tests

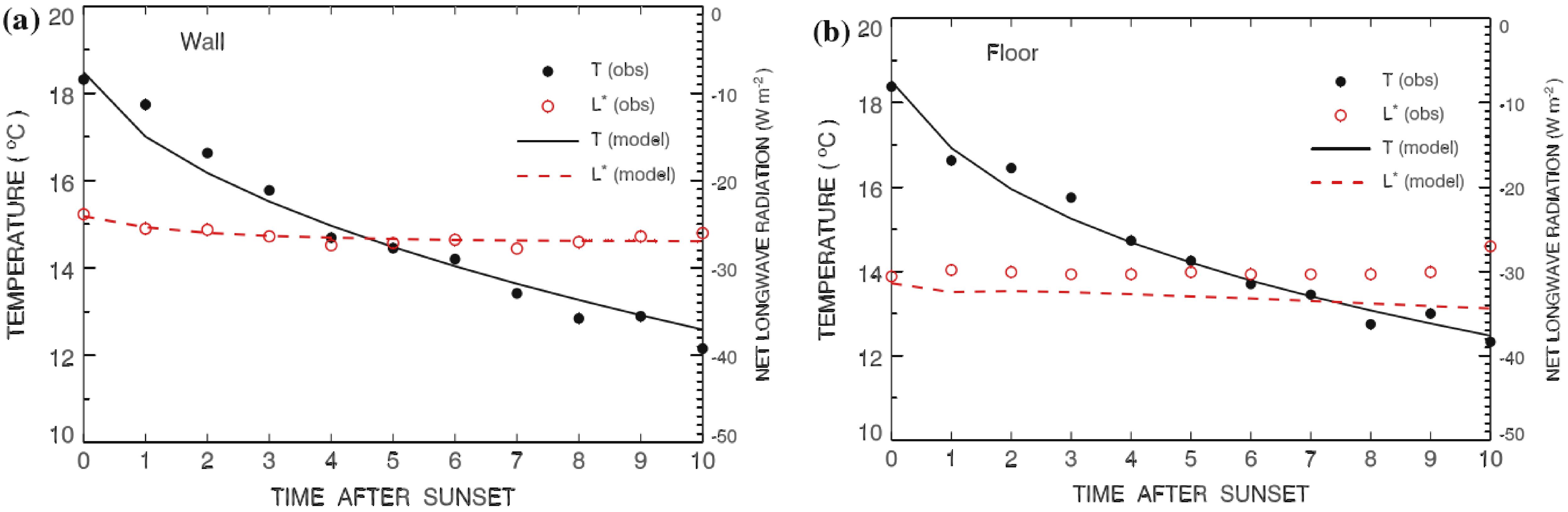


Fig. 4 Comparisons of the observed (the open circle for the net longwave radiation flux and the solid circle for the surface temperature) and the simulated net longwave radiation flux (dashed line) and the simulated surface temperature (solid line) at the (a) wall and (b) floor.

Validation of VUCM and Sensitivity Tests

- Marseille, France

The artificial surface covers about 86% of total urban surfaces and the natural vegetated area takes about 14%. The average height of the buildings and the canyon aspect ratio are 15.6 and 1.63 m, respectively. The urban vegetation height is assigned to be 10 m with the LAI of 3, and it is also assumed that the maximum leaf area density is found at the height of $0.8h_f$. Soil textural class for the vegetated area is assumed to be sandy clay loam type.

In this paper, the period from 18 June to 11 July (24 days) is simulated and compared with the observations.

Validation of VUCM and Sensitivity Tests

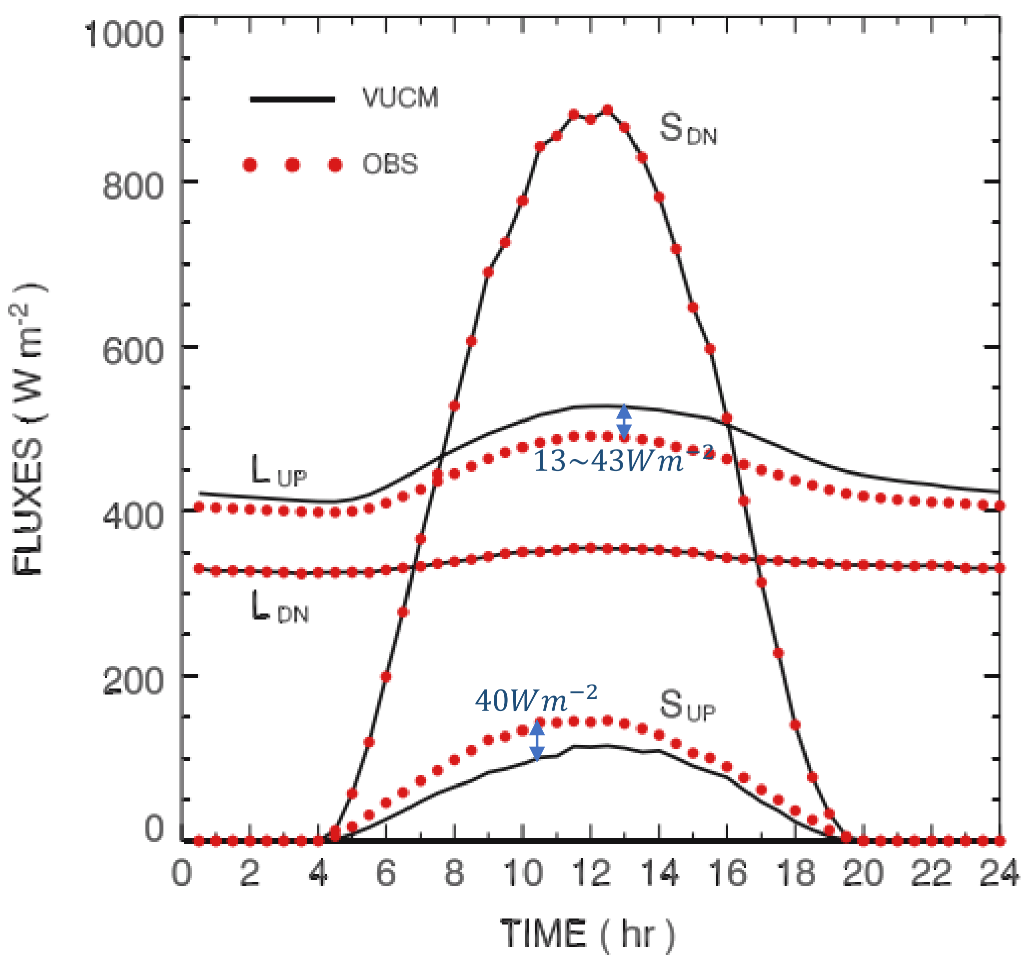


Fig. 5 Mean diurnal variations of the observed (solid circle) and the simulated (solid line) radiative fluxes. S_{DN}、S_{UP}、L_{DN}、L_{UP} represent downward and upward shortwave radiation, downward and upward longwave radiation fluxes, respectively. All fluxes are averaged for 24 days

Validation of VUCM and Sensitivity Tests

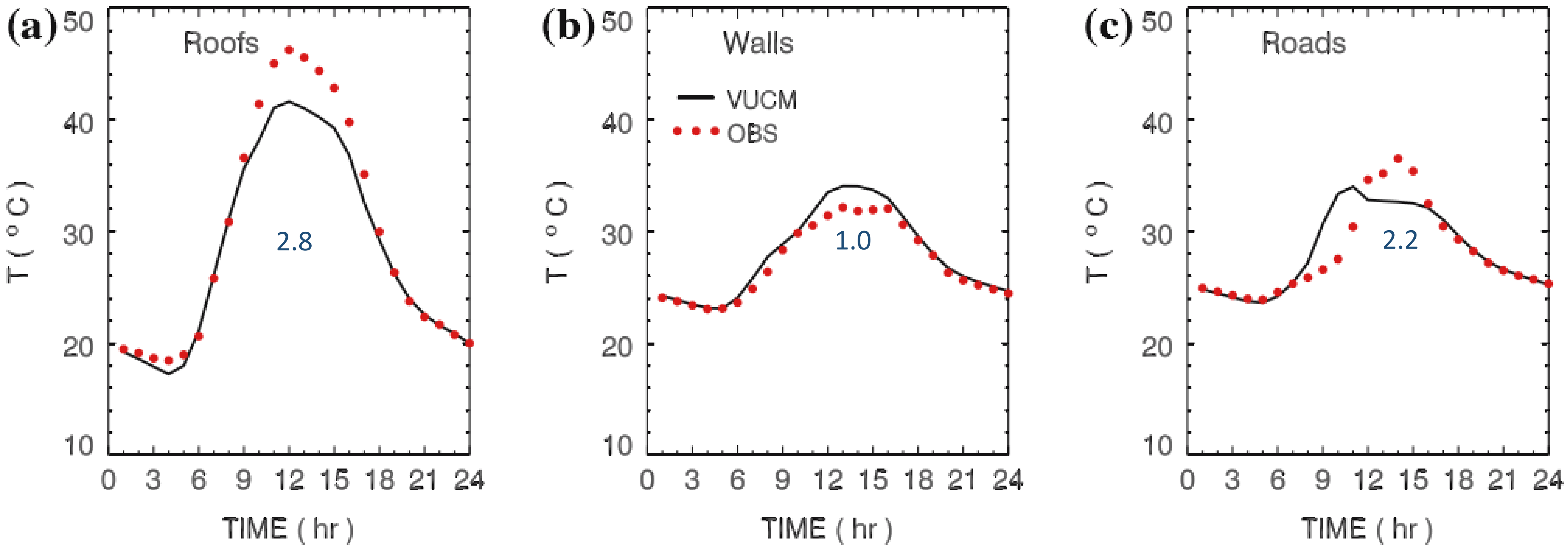


Fig. 6 Mean diurnal variation of the observed (solid circle) and the simulated (solid line) surface temperature. Roof temperature is averaged for five days from 7 July to 11 July. Road and wall temperatures are averaged for 16 days from 26 June to 11 July.

Validation of VUCM and Sensitivity Tests

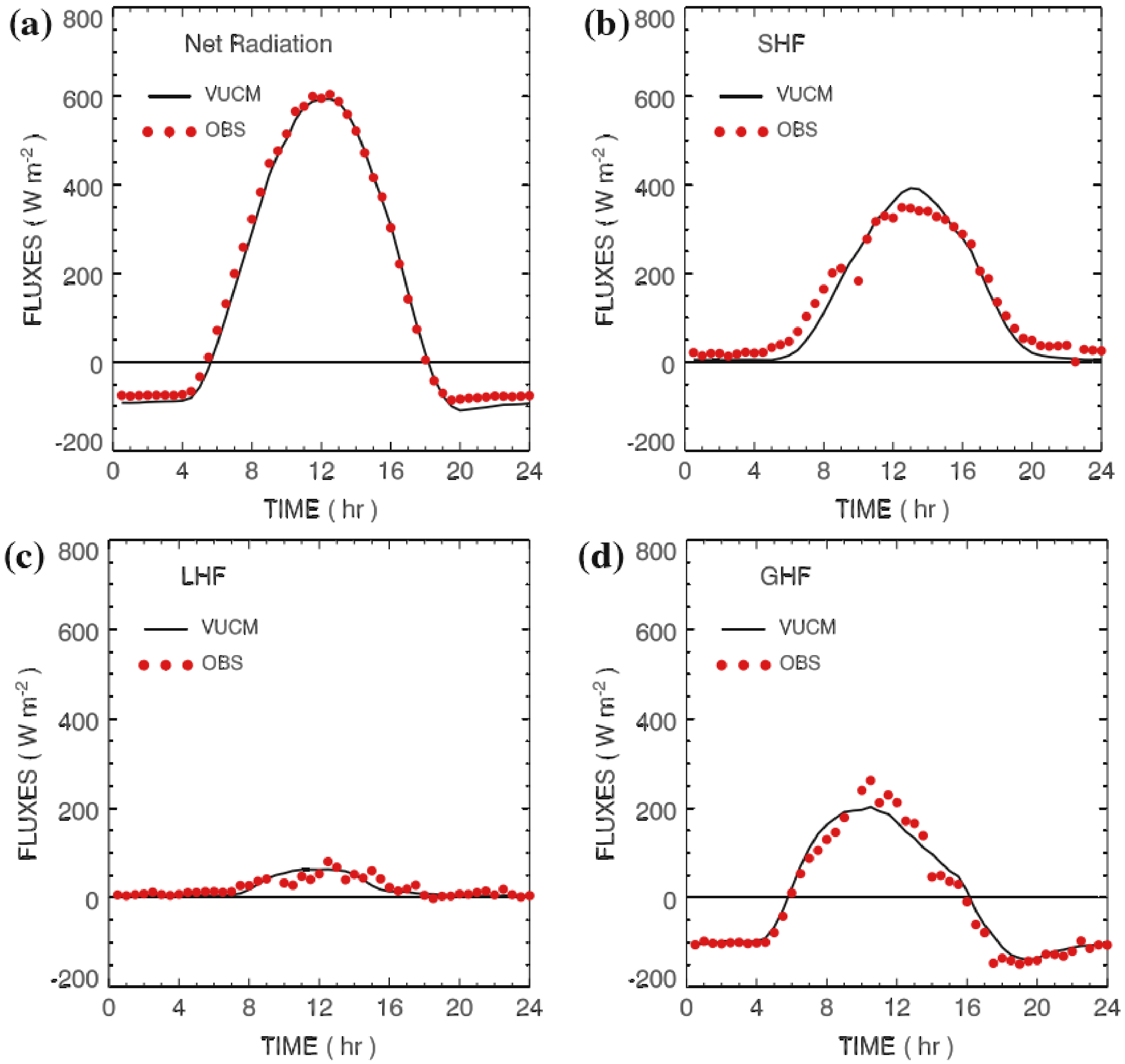


Fig. 8 Observed (solid circle) and simulated (solid line) 24-day mean diurnal variation of the (a) net radiation, turbulent (b) sensible and (c) latent heat fluxes, and (d) storage heat flux.

Validation of VUCM and Sensitivity Tests

Table 6 Performance statistics for net radiation (Q^*), turbulent sensible heat (Q_H) and latent heat (Q_E)fluxes, and storage heat flux (Q_S)

		Q^*	Q_H	Q_E	ΔQ_S
Total period	OBS	163	150	24	−11
	VUCM	151	130	20	0
	MBE	−13	−19	−4	12
	RMSE	27	54	39	64
Daytime 08:00~16:00	OBS	465	304	42	114
	VUCM	460	299	44	118
	MBE	−5	−5	1	3
	RMSE	32	78	61	99
Nighttime 21:00~03:00	OBS	−76	25	8	−108
	VUCM	−93	6	5	−104
	MBE	−17	−19	−3	5
	RMSE	19	26	16	24

$< 20 W m^{-2}$

Validation of VUCM and Sensitivity Tests

- Impacts of the Canyon Vegetation

Sensitivity tests are conducted to investigate effects of canyon vegetation on radiative and turbulent fluxes released into the atmosphere as well as canyon thermal and moisture environment.

Table 7 Cases for the sensitivity test of VUCM: Case 1 for the control run, Case 2 for the non-vegetated canyon, Case 3 for the reduced soil moisture, and Case 4 for the reduced leaf area index

Parameter	Case 1	Case 2	Case 3	Case 4
f_r	0.66	1.0	0.66	0.66
f_v	0.34	0.0	0.34	0.34
LAI	3.0	–	3.0	1.0
η	0.3	–	0.2	0.3

Validation of VUCM and Sensitivity Tests

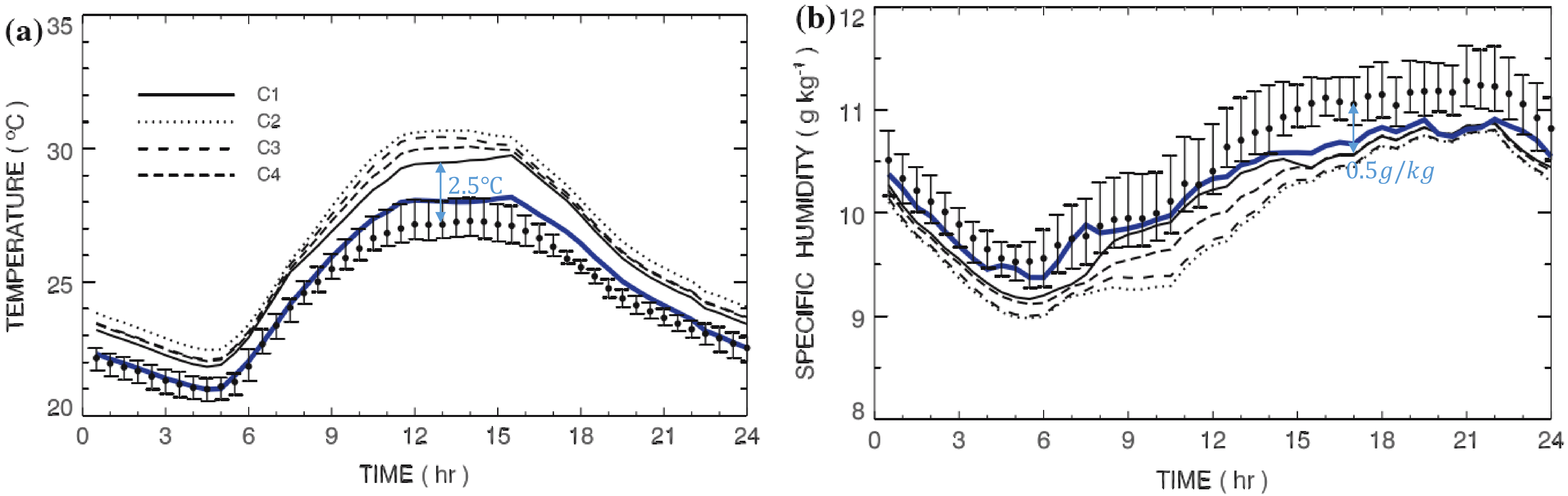


Fig. 9 Simulated 24-day mean diurnal variation of the canopy air (a) temperature and (b) specific humidity for four different cases. Solid circles are the observed mean temperature and specific humidity from five in canyon stations around the city centre. Vertical bars indicate the maximum deviation of temperature and specific humidity in the observed stations. Thick solid lines represent the simulated canopy air temperature and specific humidity with the modified urban geometry and vegetation.

Summary and Conclusions

- The model well reproduces the observed characteristics such as nocturnal radiative cooling, temperature evolutions of artificial surfaces, canopy air temperature and specific humidity, momentum flux, and surface energy balance.
- Temperatures of the artificial surfaces in the vegetated canyon decrease due to the absorption of solar radiation by trees.
- The canopy air temperature decreases but the specific humidity increases by vegetation, especially during the daytime.
- The canyon vegetation causes a reduction of sensible heat flux release into the overlying atmosphere with an increase of the latent heat flux but little change of storage heat flux.
- Surface energy balance can be affected by soil moisture content and LAI as well as the fraction of vegetation.

The thinking of myself

slab model
Myrup, 1969; Atwater1977; Seaman et al. 1989

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Hydrologic Modelling

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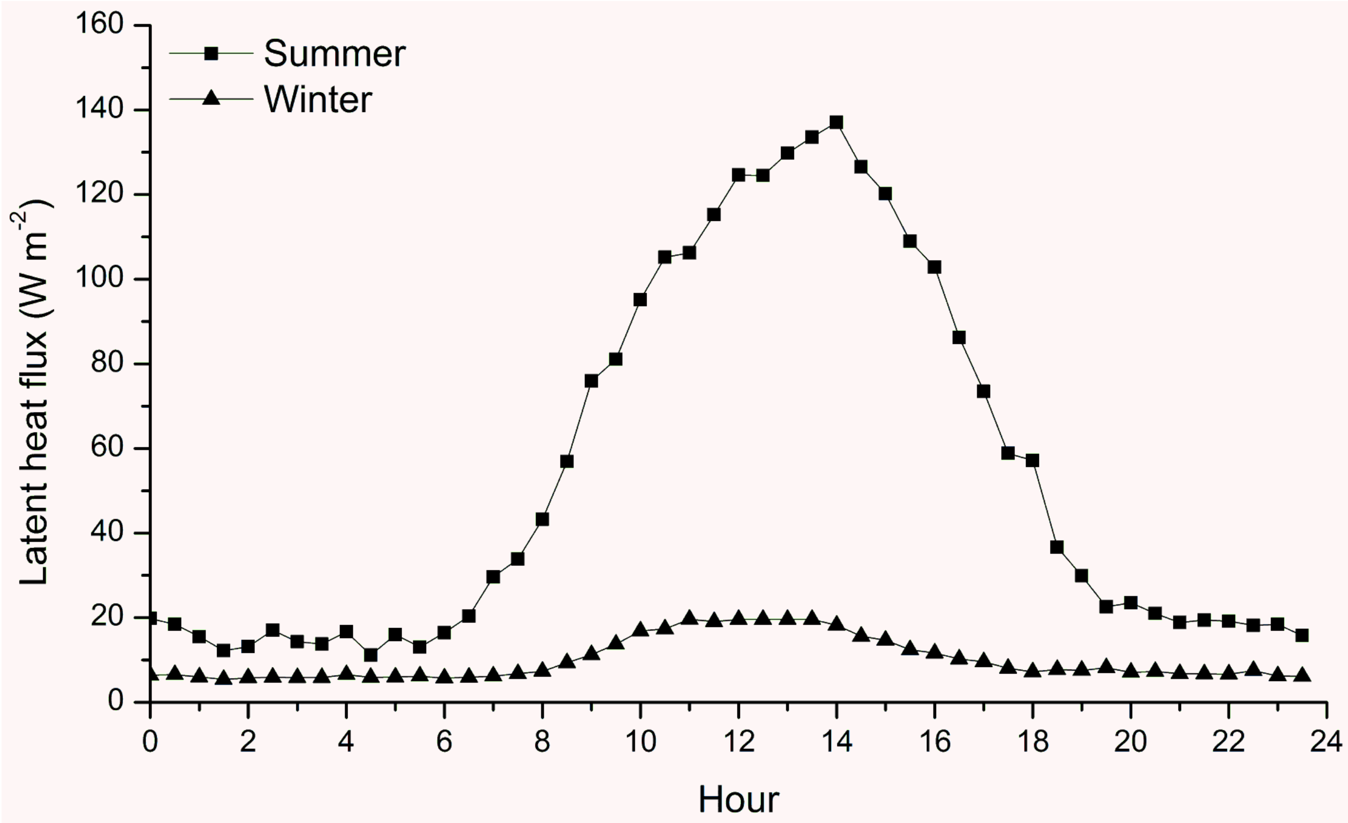

Liu.et al
Site: Beijing 325-m meteorological tower

Thanks!