How do Green Roofs Mitigate the Thermal Stress under Heat Waves?

Ting Sun[1,2*], Sue Grimmond[2], Guangheng Ni[1]

1: IHWR, Tsinghua University
2: Dept. of Meteorology, University of Reading

23 July 2015

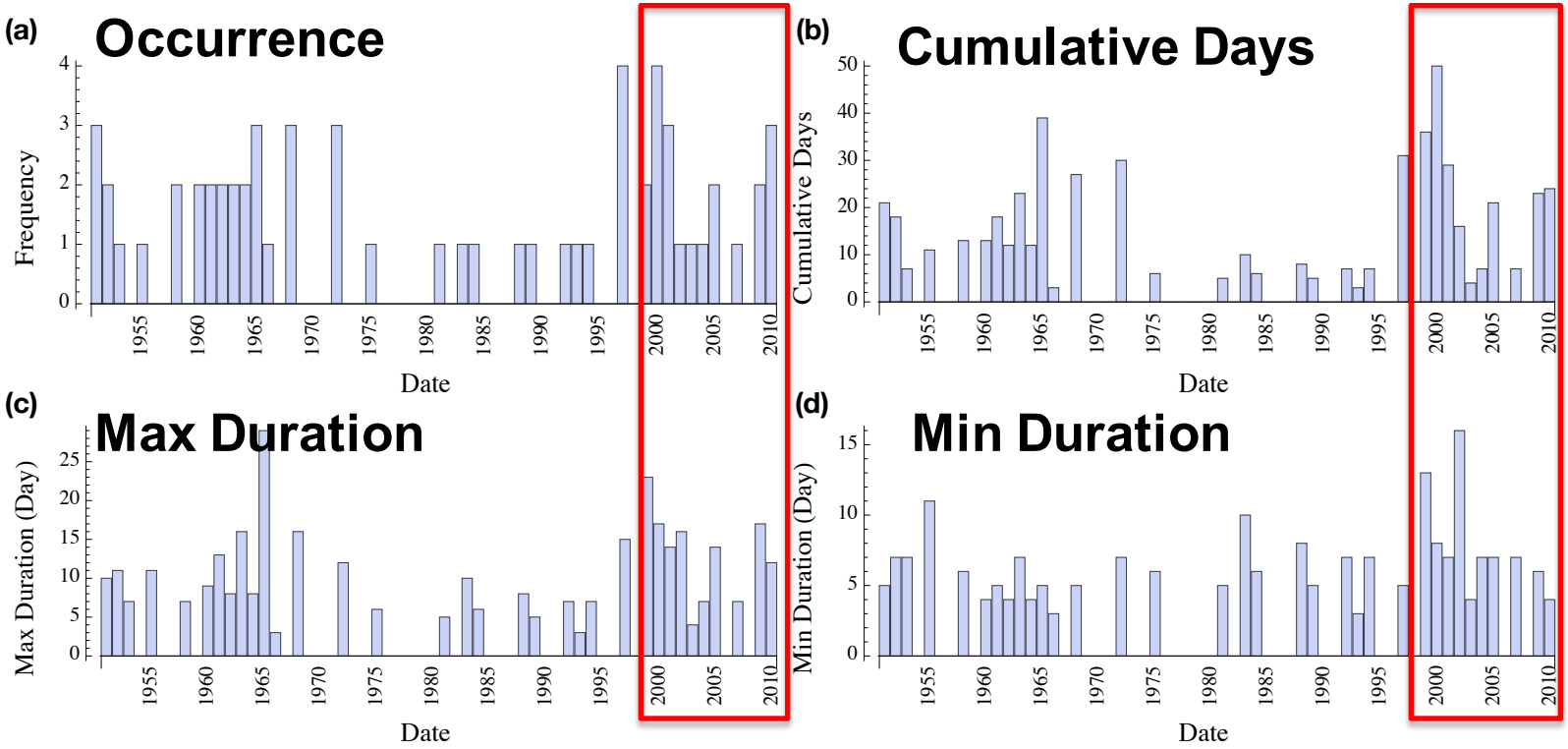
Contents

1 Introduction

Heat Wave: Extreme Natural Hazard

- A period lasting for several days with air temperature much higher than normal condition
  - ✓ Mortality risk increases 4.5% for every 1 ºC increase in air temperature and 0.5% for every 1 day increase in duration (Anderson and Bell, 2011)
  - ✓ Synergetic impact with UHI effect on micro-climatogical conditions in urban areas (Li and Bou-Zeid, 2013)

Heat Waves in Beijing



What Are Green Roofs?

Extensive Green Roof

Intensive Green Roof

Source: Earth Pledge(2005)

GR Site at Tsinghua

Motivations

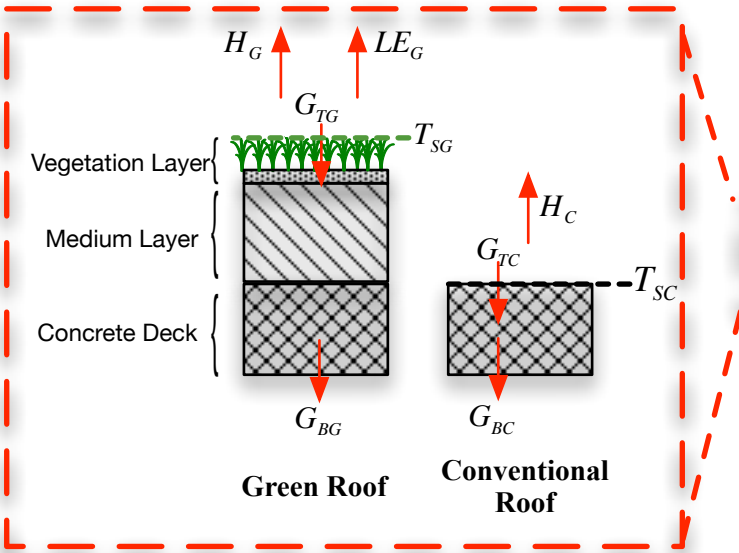
- What are the city-scale impact of GRs on the UHI effect, especially under heat waves?

- How do GRs mitigate thermal stress under heat waves?

2 Model Setup and Evaluation

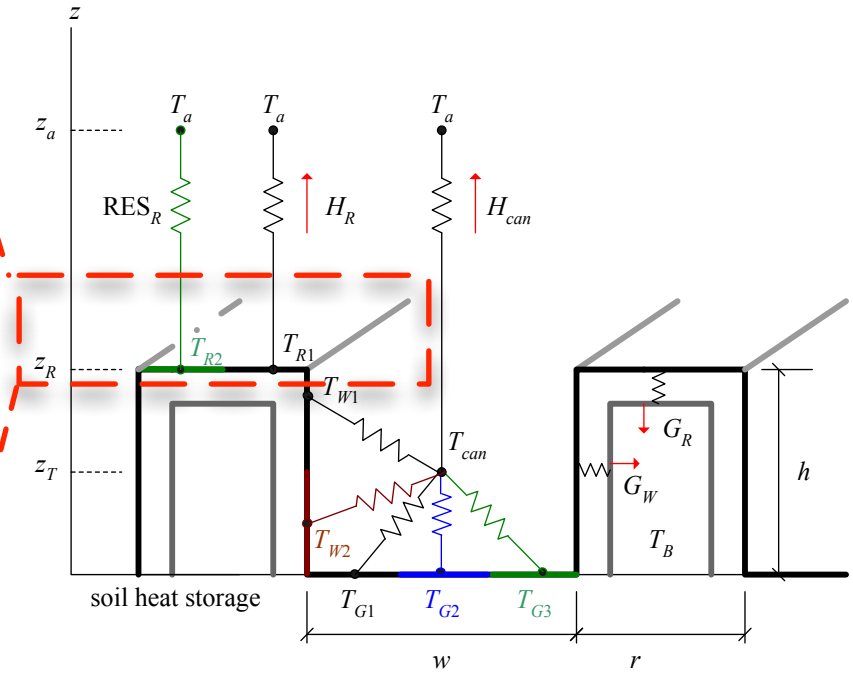
WRF-PUCM

Princeton ROof Model (PROM)



Sun et al. (2013, 2014)

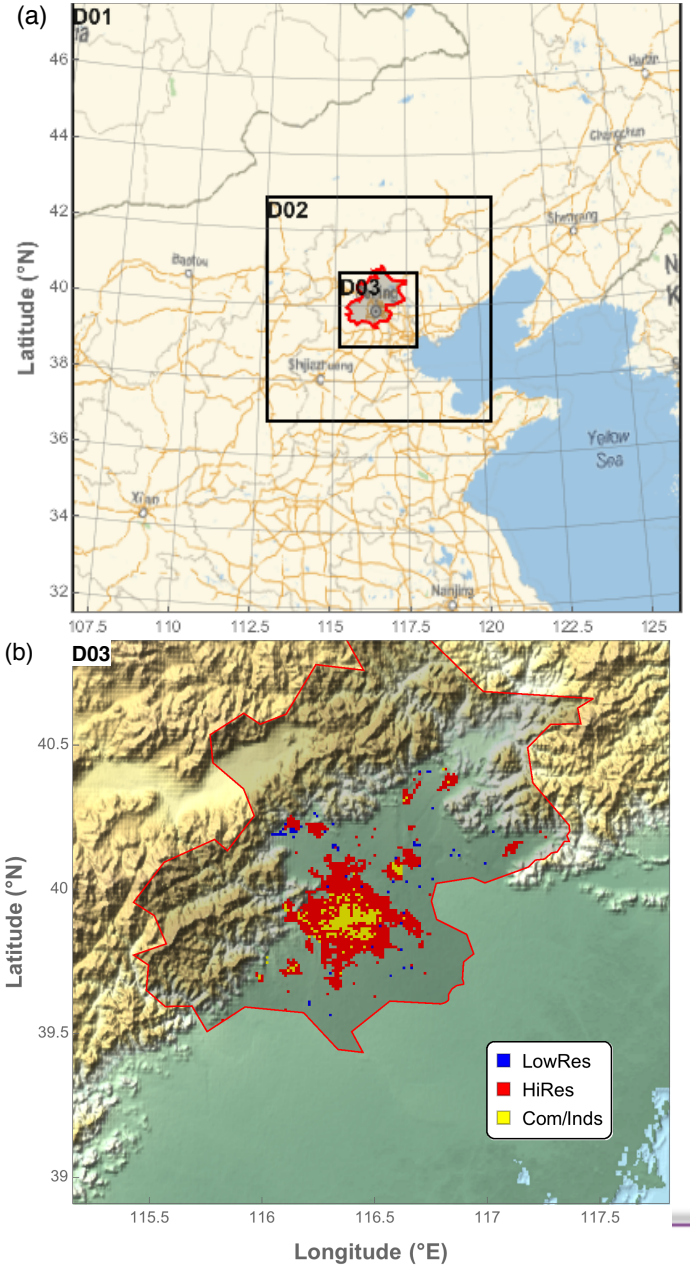
Princeton Urban Canopy Model (PUCM)



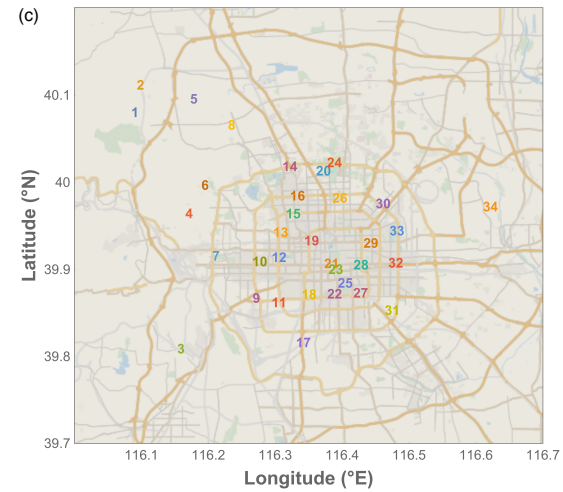
Wang, Bou-Zeid and Smith (2013)
Yang et al. (2014)

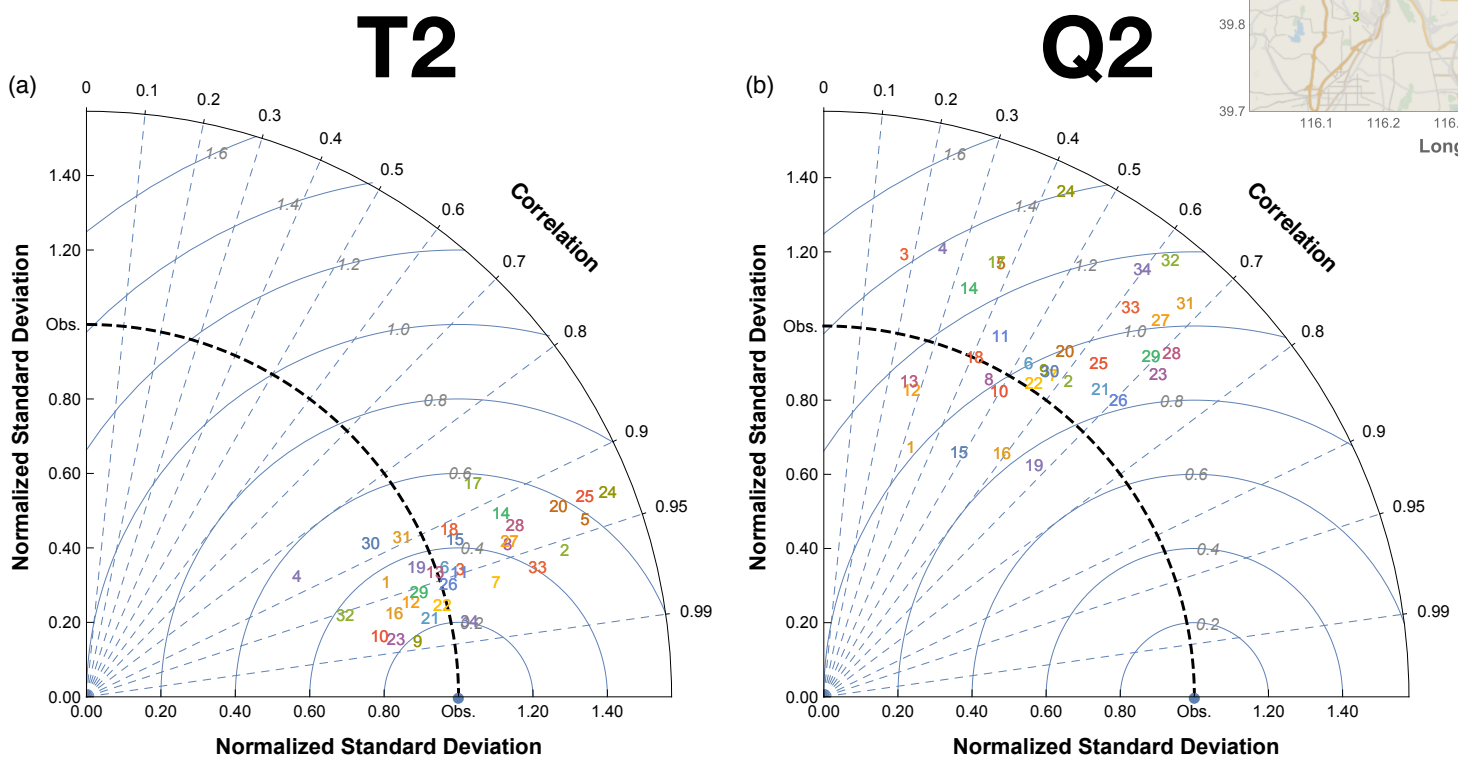
Model Setup

- Simulation period:
  - ✓ July 4 –7, 2010 (a HW period)
- Grid settings:
  - ✓ One-way nesting:
    - 3 nested domains: 9 km, 3 km, 1 km
    - d03 covers the whole Beijing area
  - ✓ Three different urban settings
- Simulation scenarios:
  - ✓ default scenario (**DFT**): all conventional roof coverage
  - ✓ green roof scenario (**GR**)
    - Varying GR coverage: 10%, 20%, 50%, 80%, **100%**



Model Evaluation

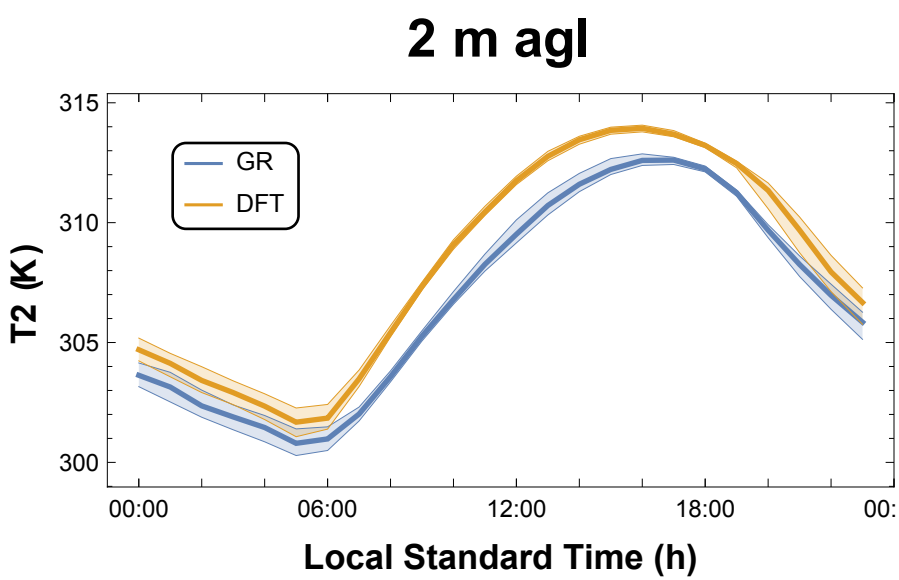


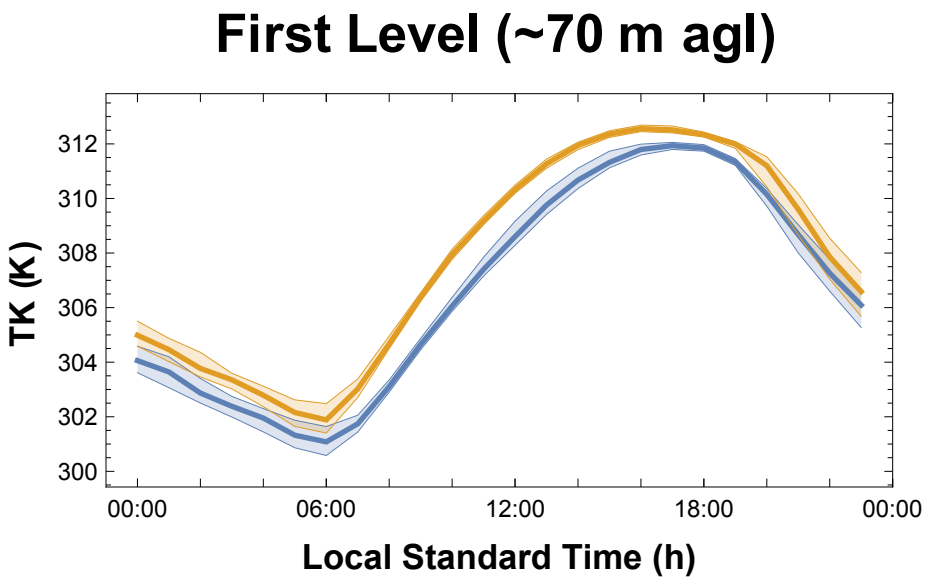


- Observations collected from 34 met stations are used.
- Better performance is found in T2.

3 Impact on Micro-meteorological Factors by GRs

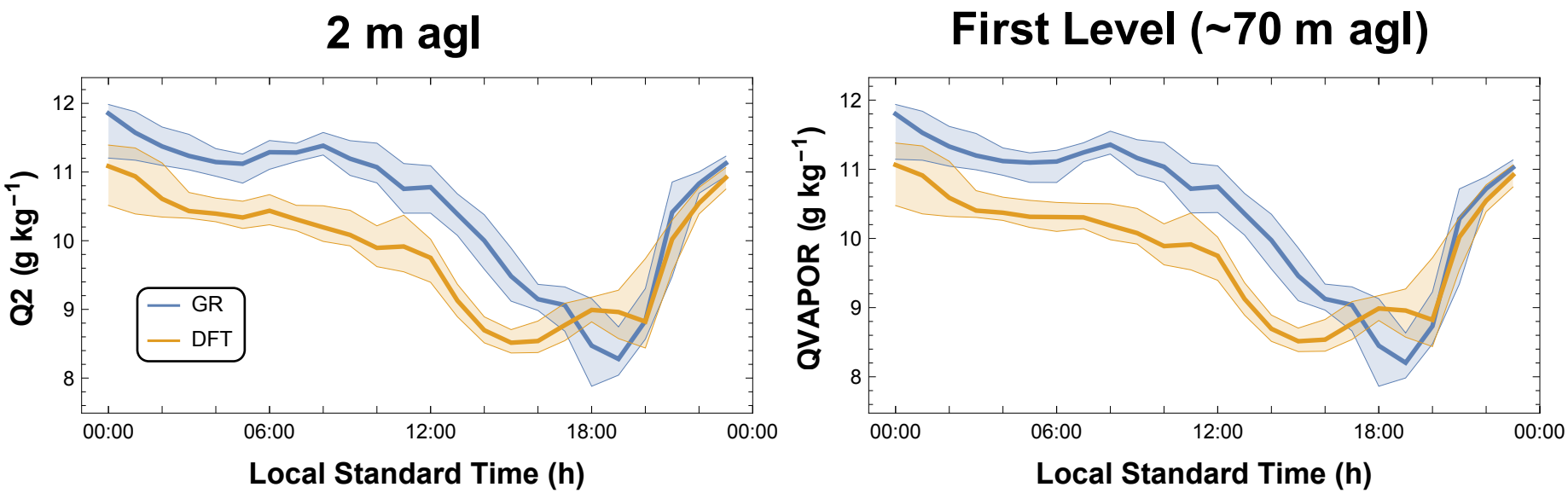
Air Temperature





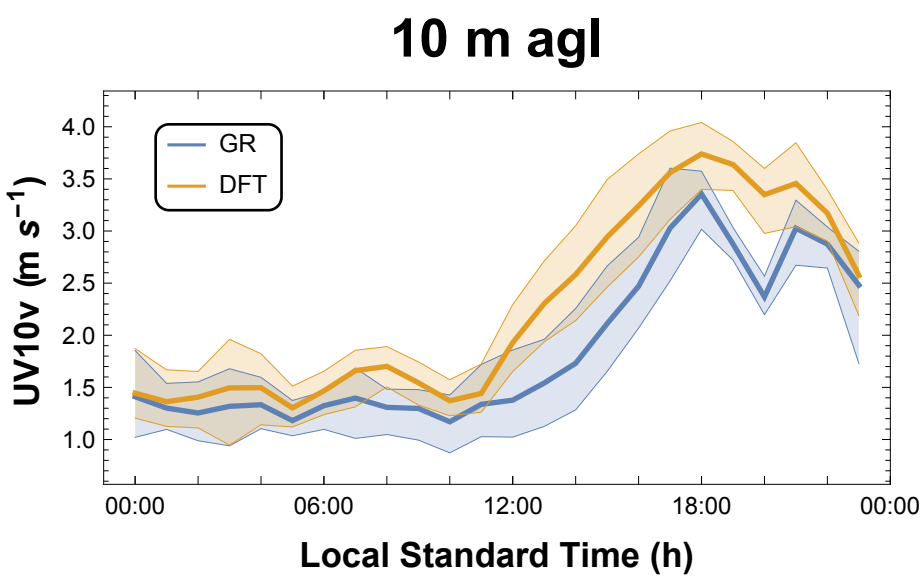
- Green roofs decrease air temperature by as much as 4 ºC

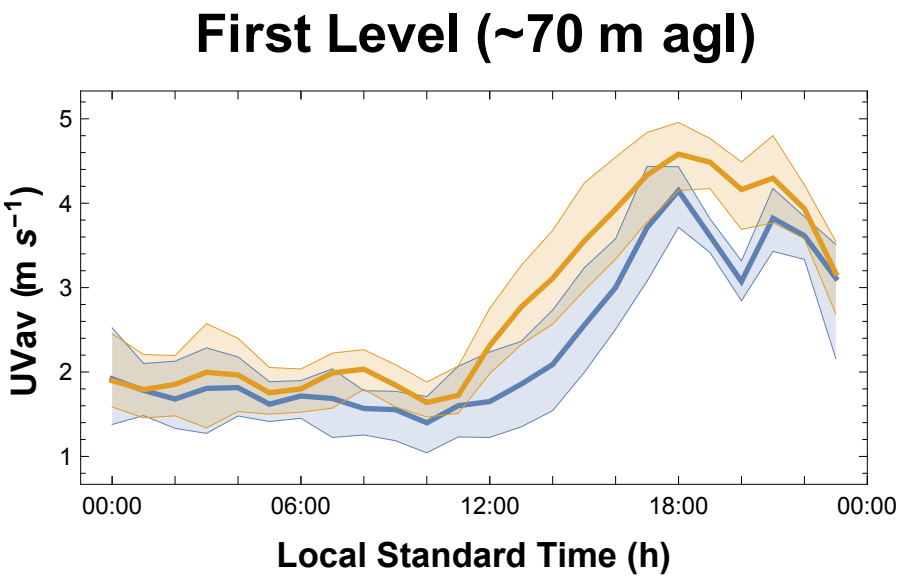
Air Humidity



- Green roofs increase air humidity by as much as 3 g kg^{-1}

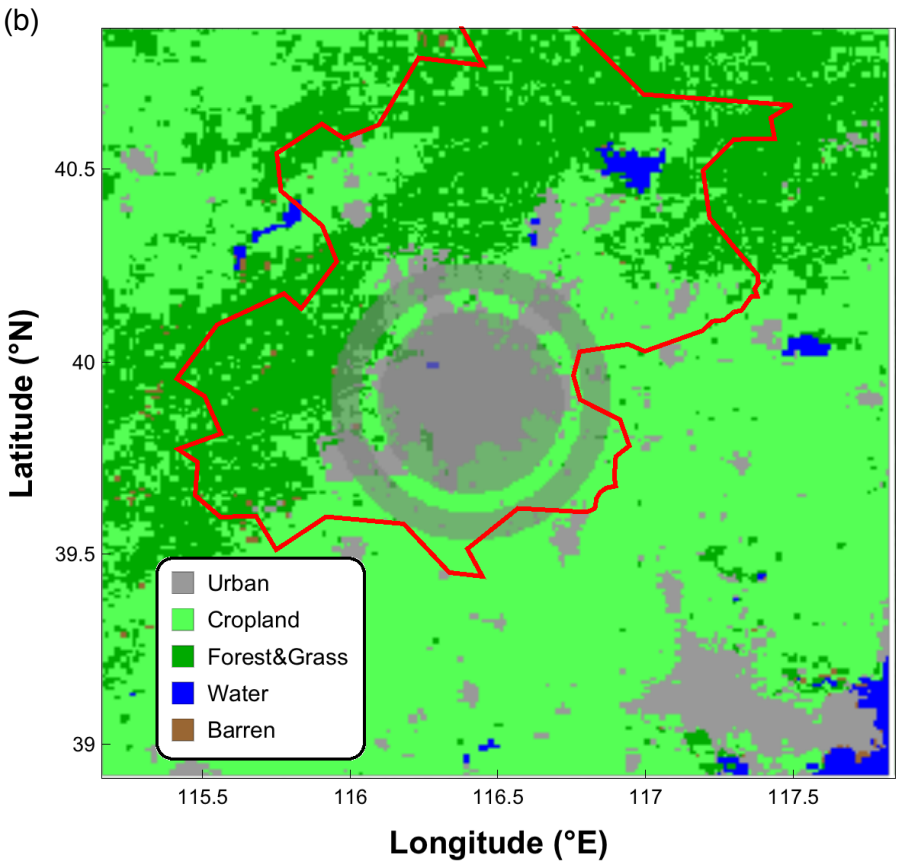
Wind Speed





- Green roofs decrease wind speed by as much as 2 m s^{-1}

UHI Effect

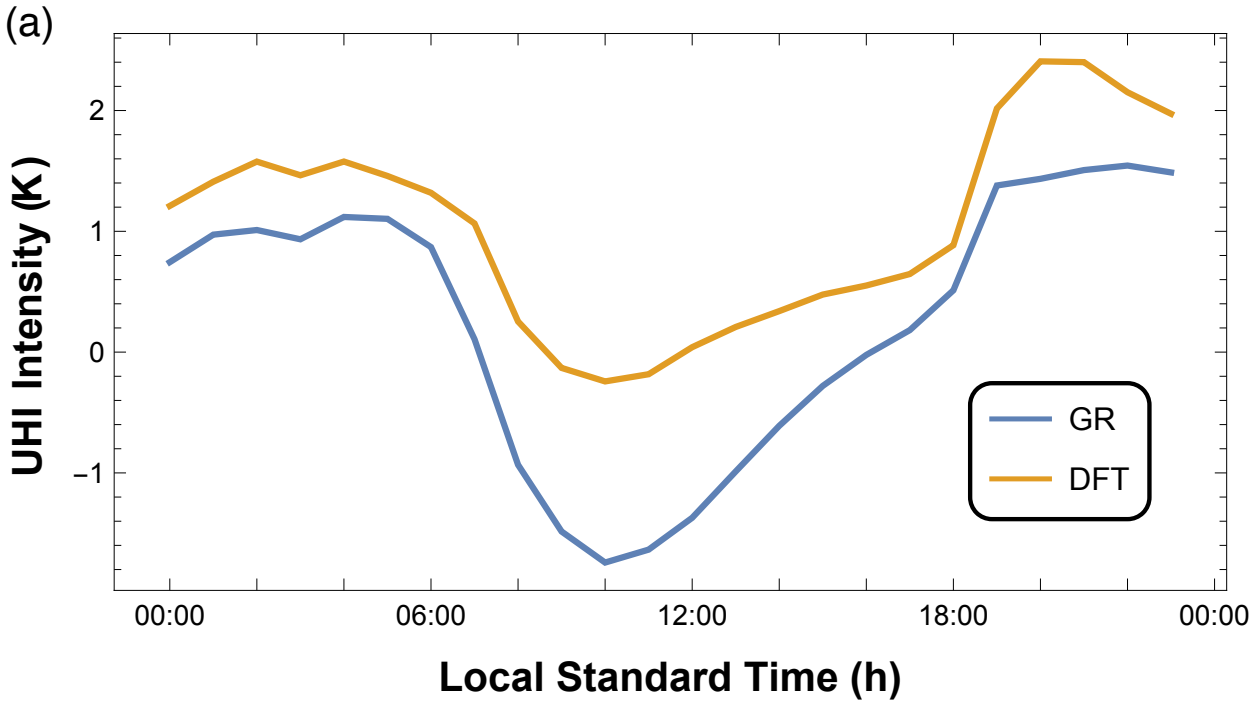


- UHI intensity:

$$UHI = T2_{urban} - T2_{rural}$$

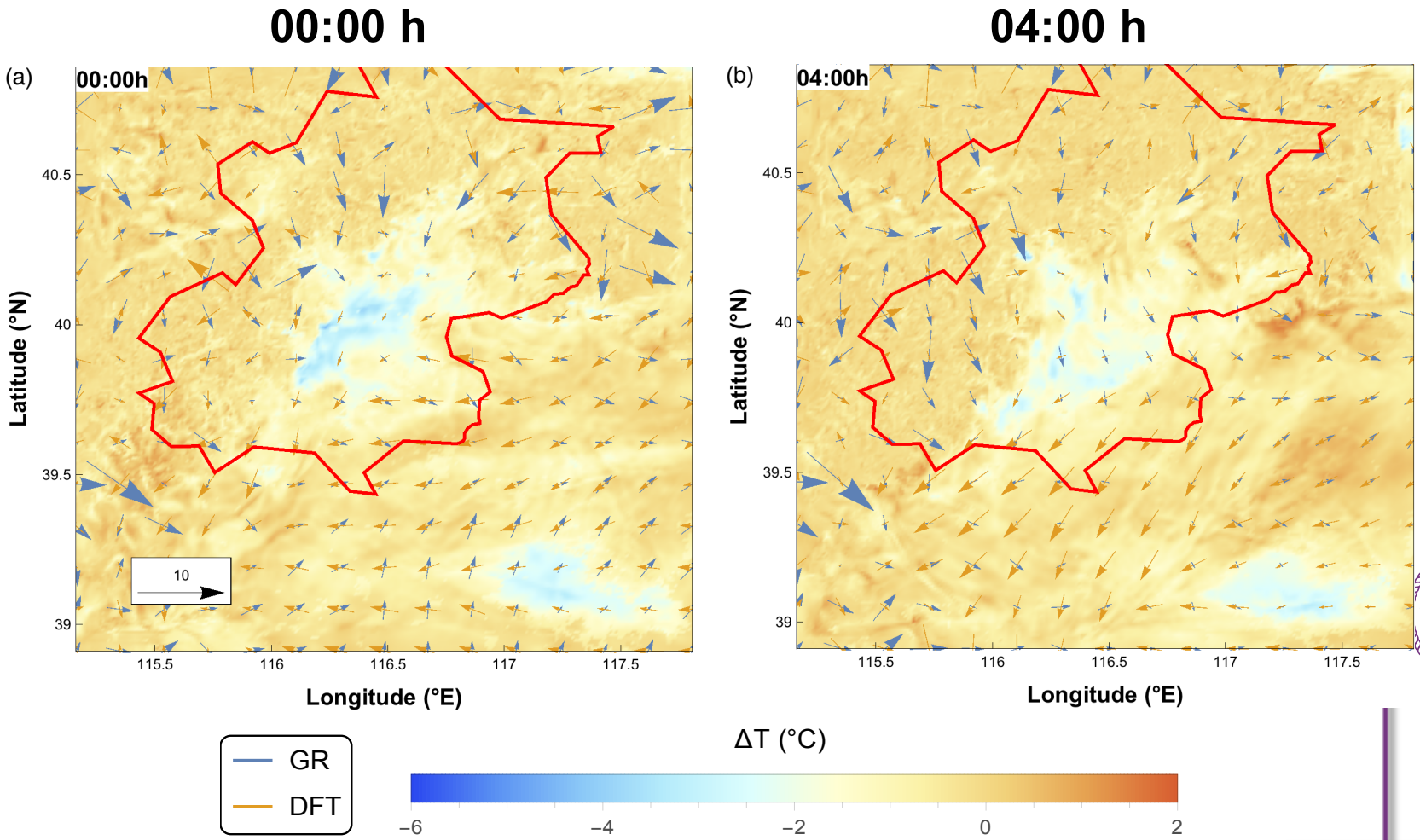
- ✓ Urban grids:
  - Landuse: urban and built-up
  - Area: disk
- ✓ Rural grids:
  - Landuse: cropland
  - Area: annulus

UHI Effect

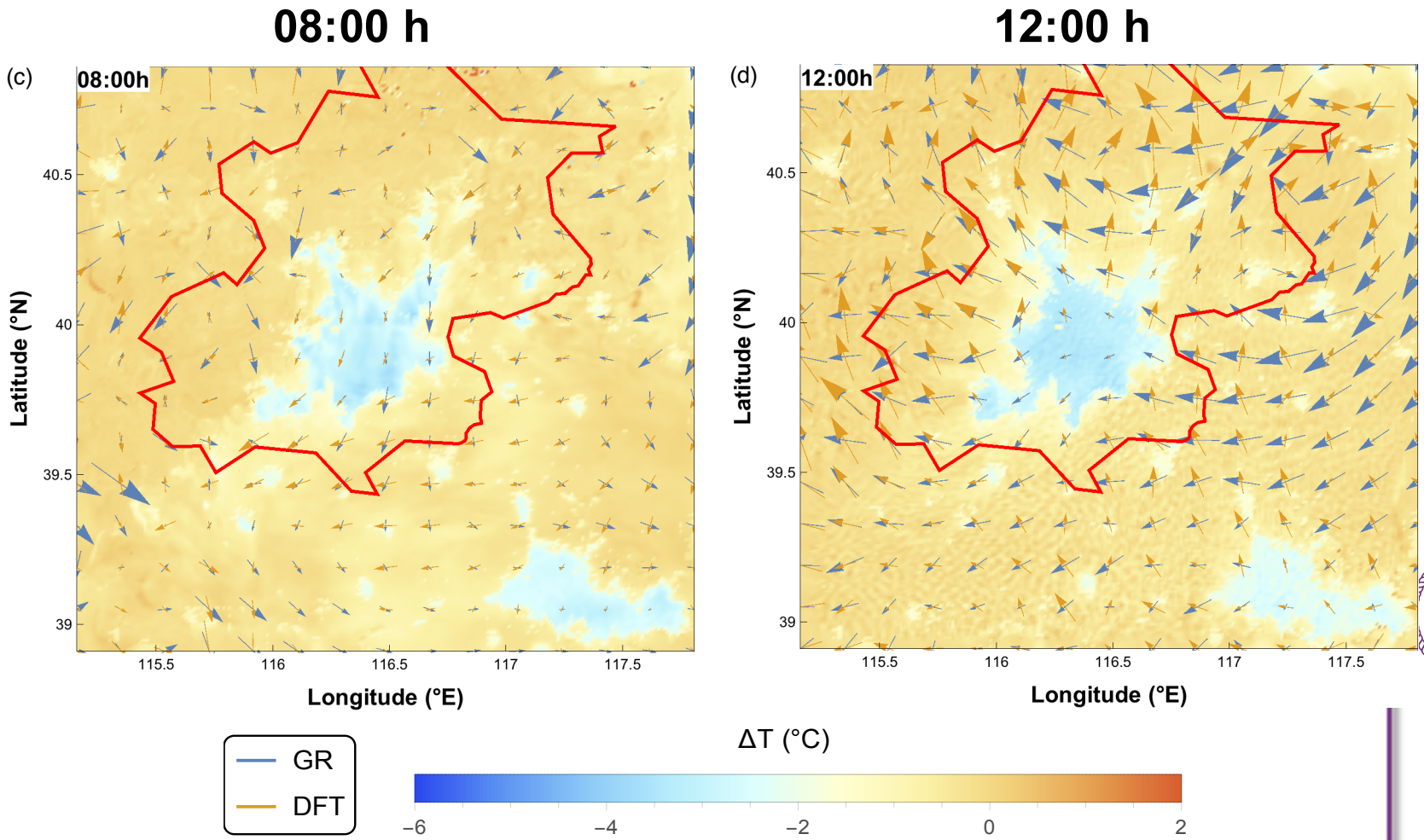


- Evident decrease is observed during daytime.
  - ✓urban heat island → urban "cool island"

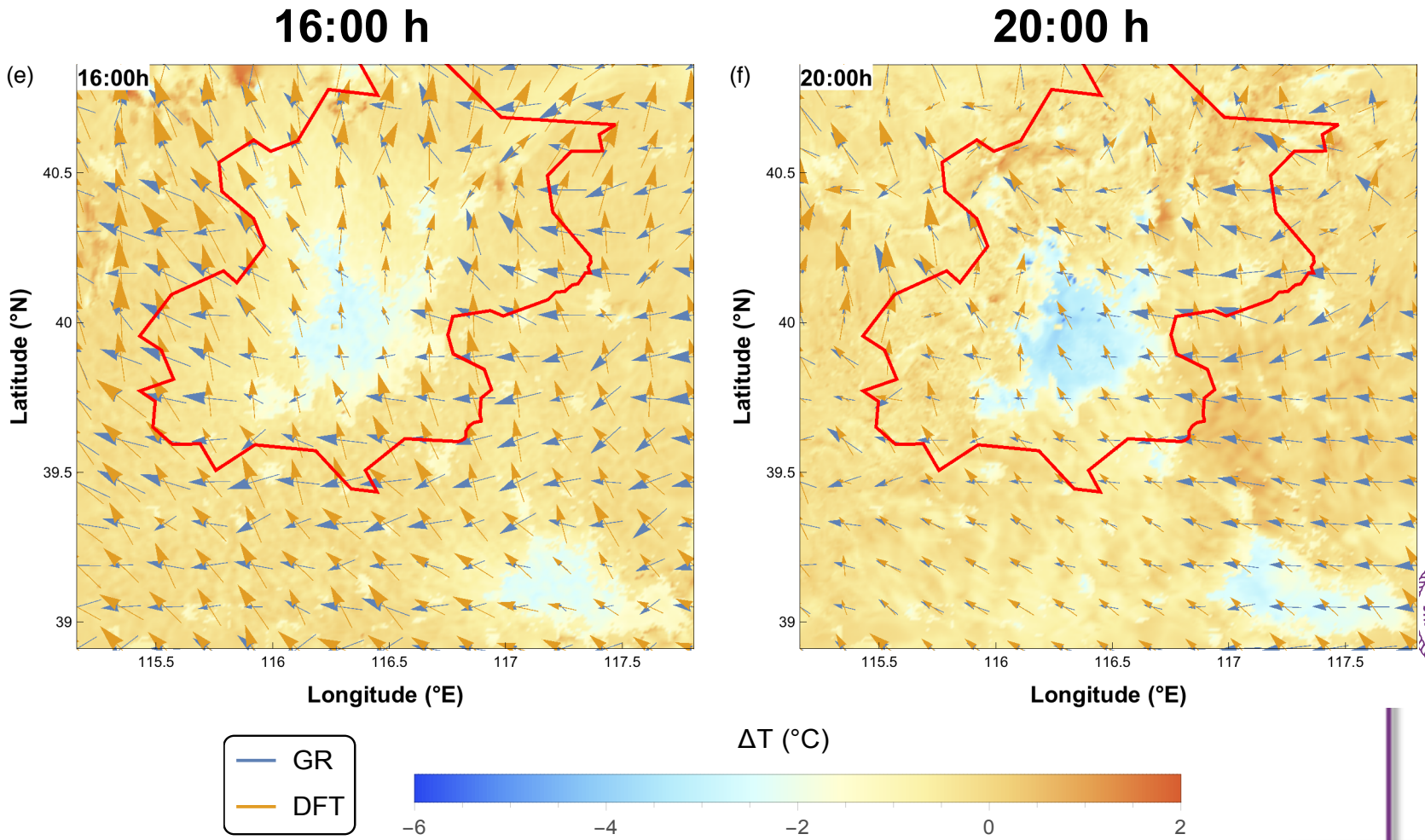
Regional Circulation



Regional Circulation



Regional Circulation



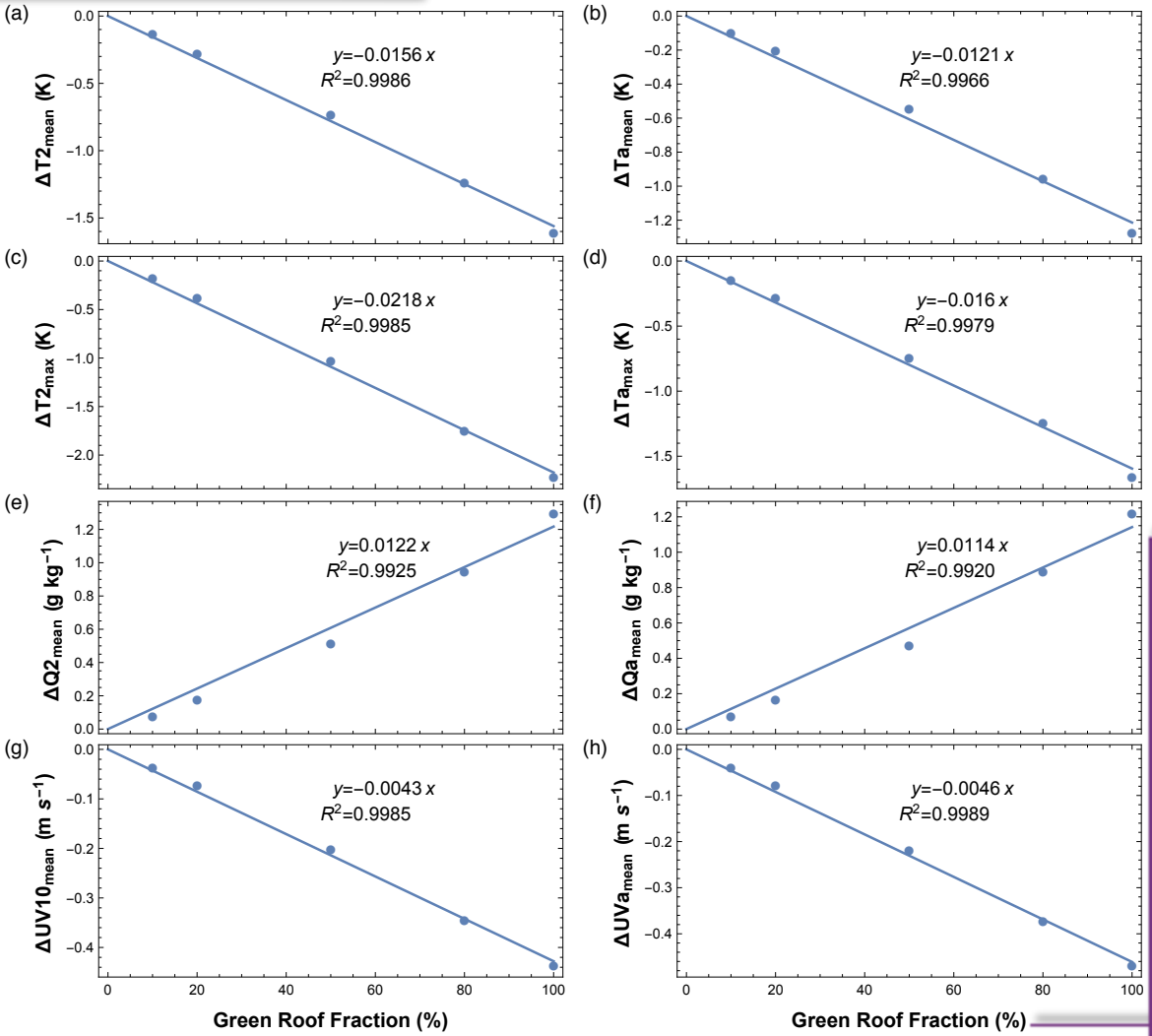
Green Roof Fraction

Decrease in Mean Air Temperature

Decrease in Max Air Temperature

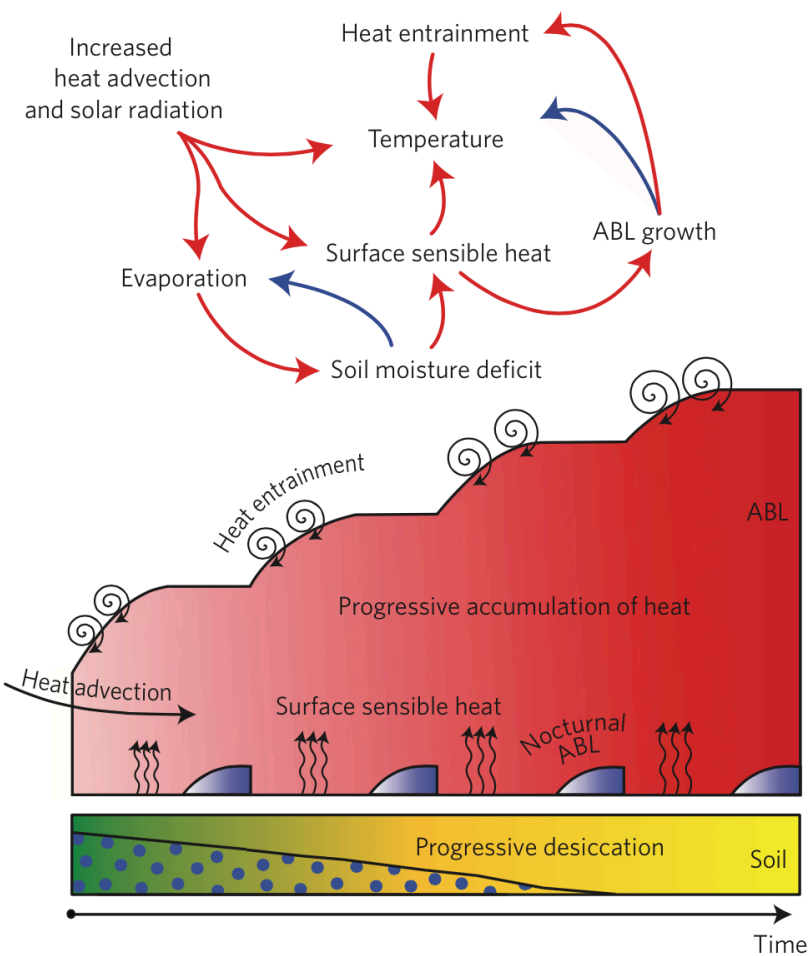
Increase in Mean Air Humidity

Decrease in Mean Wind Speed



4 Mitigation Mechanism of GRs against the Thermal Stress

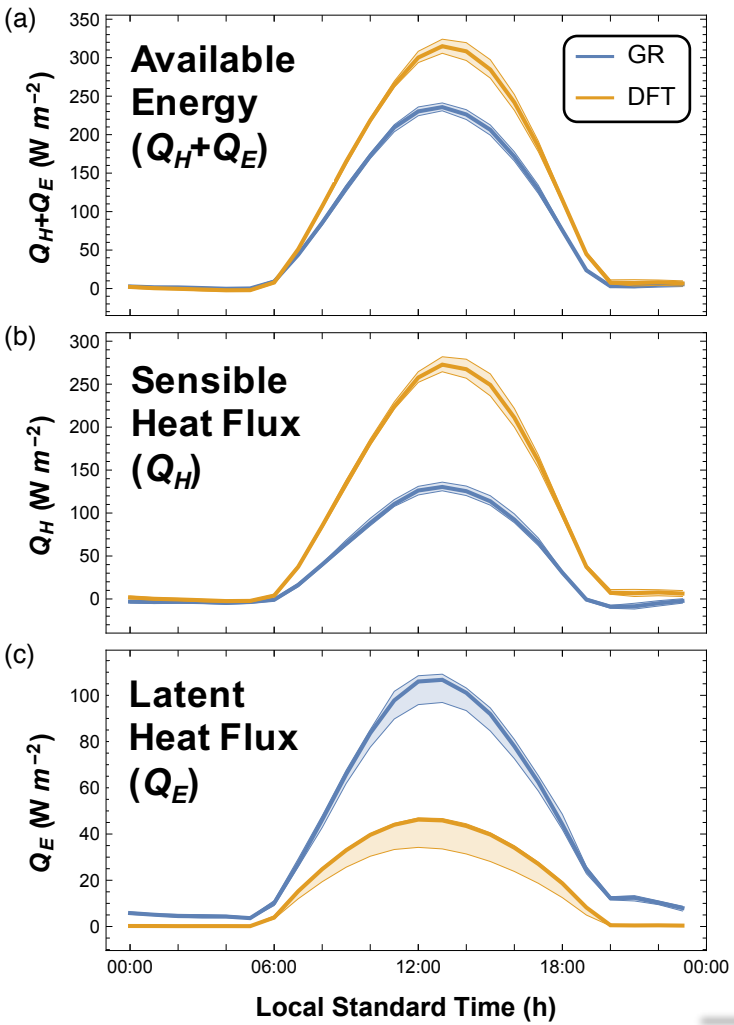
Heating Mechanism of Heat Waves



- According to Miralles et al.(2014):
  - ✓ soil moisture deficit→ higher sensible heat
  - ✓ more buoyancy → higher PBL → more entrainment
  - ✓ hotter and hotter!

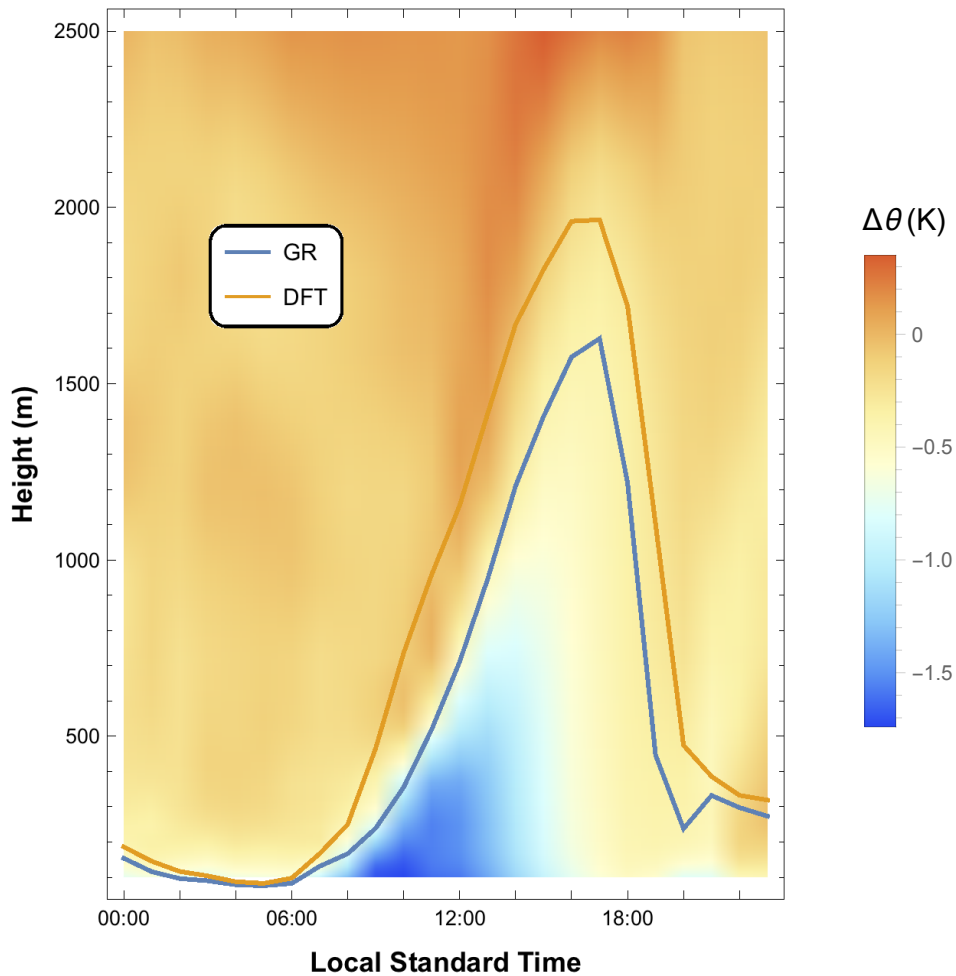
Surface Energy Budgets

- Changes in surface heating from sensible heat flux between DFT and GR:
  - ✓ Total turbulent fluxes are decreased;
  - ✓ Peak Q_H is decreased by more than 50%;
  - ✓ More turbulent fluxes are dissipated as Q_E .



Boundary Layer Characteristics

- PBL height:
  - ✓ Maximum height will decrease from 2000 m to 1600 m.
- Difference in θ :
  - ✓ Decreases propagate to higher PBL as PBL develops;
  - ✓ Maximum decrease can be 1.8 K.



5 Concluding Remarks

Concluding Remarks

- WRF-PUCM demonstrates appealing ability in capturing the micro-meteorological dynamics in urban contexts.
- GRs prove encouraging effect in mitigating UHI effect under heat wave scenarios.
- The mitigation against UHI relies in a two-way cooling mechanism:
  - ✓ Bottom: GRs alter the SEB by enhancing the wetness condition and thus decrease the heating from sensible heat;
  - ✓ Top: GRs cause a shallower PBL that dampens the heating from entrainment at the PBL top.

Thank You!

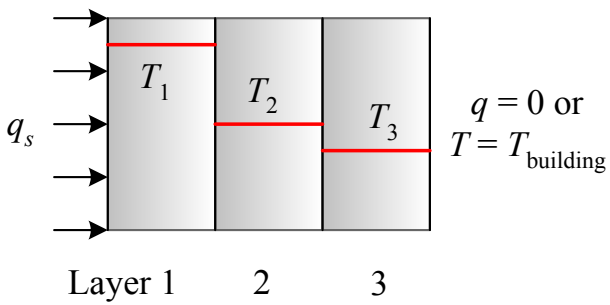
References

- WRF-PUCM:
  - ✓ Wang, Z.-H., E. Bou-Zeid, and J. A. Smith (2012), A coupled energy transport and hydrological model for urban canopies evaluated using a wireless sensor network, *Q.J.R. Meteorol. Soc.*, *139*(675), 1643–1657, doi:10.1002/qj.2032.
  - ✓ Yang, J., Z.-H. Wang, F. Chen, S. Miao, M. Tewari, J. A. Voogt, and S. Myint (2014), Enhancing Hydrologic Modelling in the Coupled Weather Research and Forecasting–Urban Modelling System, *Boundary-Layer Meteorol.*, 1–23, doi:10.1007/s10546-014-9991-6.
  - ✓ Sun, T., E. Bou-Zeid, and G.-H. Ni (2014), To irrigate or not to irrigate: Analysis of green roof performance via a vertically-resolved hygrothermal model, *Build. Environ.*, *73*, 127–137, doi:10.1016/j.buildenv.2013.12.004.
  - ✓ Sun, T., E. Bou-Zeid, Z.-H. Wang, E. Zerba, and G.-H. Ni (2013), Hydrometeorological determinants of green roof performance via a vertically-resolved model for heat and water transport, *Build. Environ.*, *60*, 211–224, doi:10.1016/j.buildenv.2012.10.018.
- Heat Waves:
  - ✓ Li, D., and E. Bou-Zeid (2013), Synergistic Interactions between Urban Heat Islands and Heat Waves: The Impact in Cities Is Larger than the Sum of Its Parts*, *J Appl Meteorol Clim*, *52*(9), 2051–2064, doi:10.1175/JAMC-D-13-02.1.
  - ✓ Miralles, D. G., A. J. Teuling, C. C. van Heerwaarden, and J. V.-G. de Arellano (2014), Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation, Nature Geosci, 7(5), 345–349, doi:10.1038/ngeo2141.
  - ✓ Anderson, G. B., and M. L. Bell (2010), Heat Waves in the United States: Mortality Risk during Heat Waves and Effect Modification by Heat Wave Characteristics in 43 U.S. Communities, Environ Health Perspect, 119(2), 210–218, doi:10.1289/ehp.1002313.

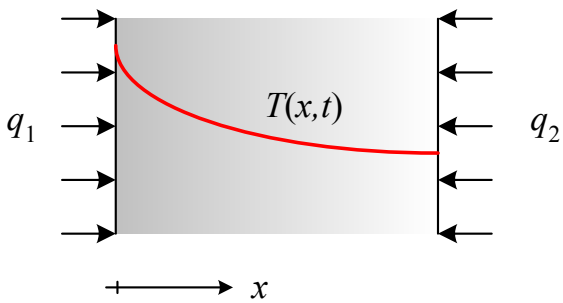
How to Identify Heat Waves

- According to Meehl and Tebaldi (2004), a heat wave period can be identified by:
  - ✓ Define T_1 and T_2 as the 97.5% and 81% percentiles in the maximum daily temperature series $\{T_{\max}\}$, respectively;
  - ✓ $\min\{T_{\max}\} > T_2$
  - ✓ $\mathrm{avg}\{T_{\max}\} > T_1$
  - ✓ $\mathrm{length}\{T_{\max} \mid T_{\max} > T_1\} > 3$

Multi-layer Heat Transfer Scheme



Discrete model



Analytical model

Green's function-based solution for one layer:

$$T_t = T_i + \int_0^t Q_1 \, dG_1 + \int_0^t Q_2 \, dG_2$$

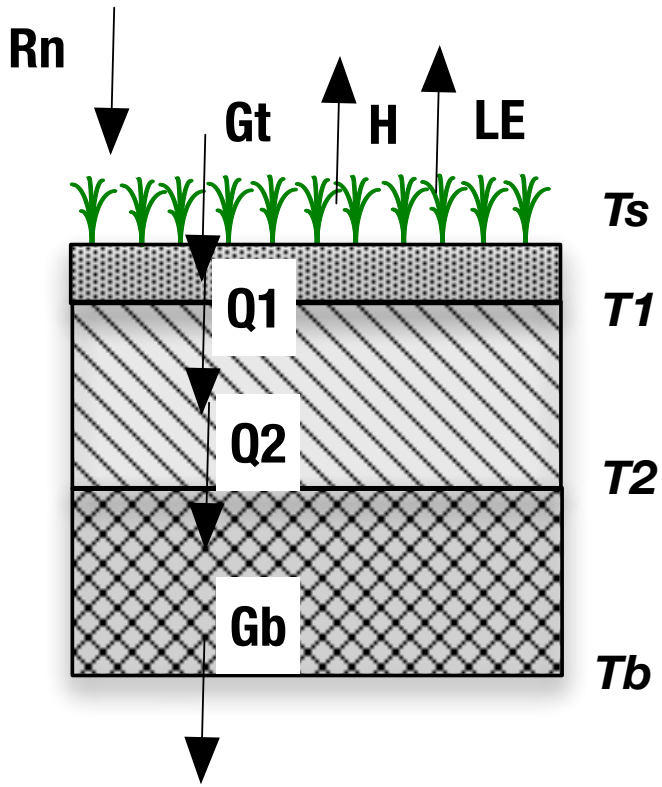
$$Q_G = -k \frac{\partial T}{\partial z} = -k \left(\int_0^t Q_1 \, dG_1' + \int_0^t Q_2 \, dG_2' \right)$$

Key advantage:

The ability to capture a more accurate temperature gradient between interfaces of different media.

Wang, Z., Bou-Zeid, E., & Smith, J. A. (2011).

Multi-layer Heat Transfer Scheme



Green's function-based solution for one layer:

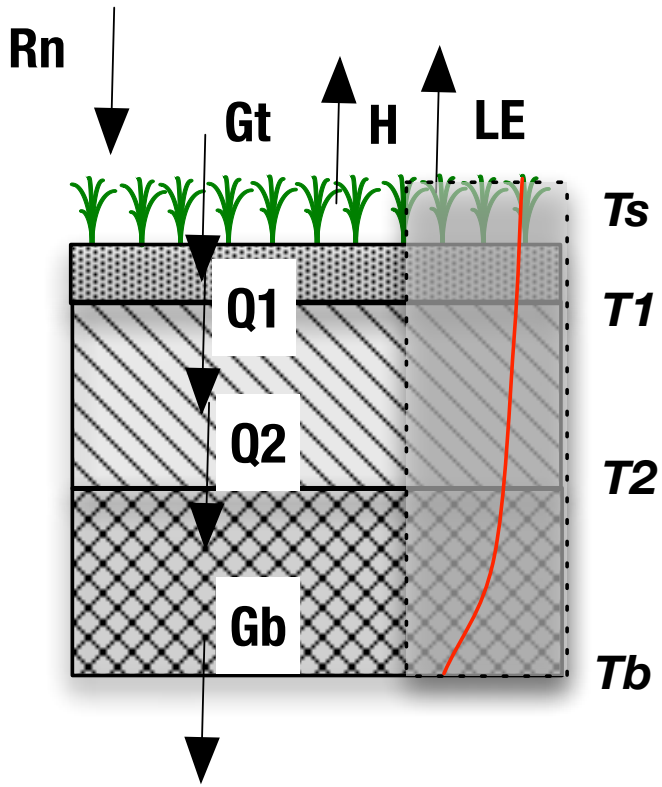
$$T_t = T_i + \int_0^t Q_1\, dG_1 + \int_0^t Q_2\, dG_2$$

$$Q_G = -k\frac{\partial T}{\partial z} = -k\left(\int_0^t Q_1\, dG_1^{'} + \int_0^t Q_2\, dG_2^{'}\right)$$

Key advantage:

The ability to capture a more accurate temperature gradient between interfaces of different media.

Multi-layer Heat Transfer Scheme



Green's function-based solution for one layer:

$$T_t = T_i + \int_0^t Q_1\, dG_1 + \int_0^t Q_2\, dG_2$$

$$Q_G = -k\frac{\partial T}{\partial z} = -k\left(\int_0^t Q_1\, dG_1^{'} + \int_0^t Q_2\, dG_2^{'}\right)$$

Key advantage:

The ability to capture a more accurate temperature gradient between interfaces of different media.

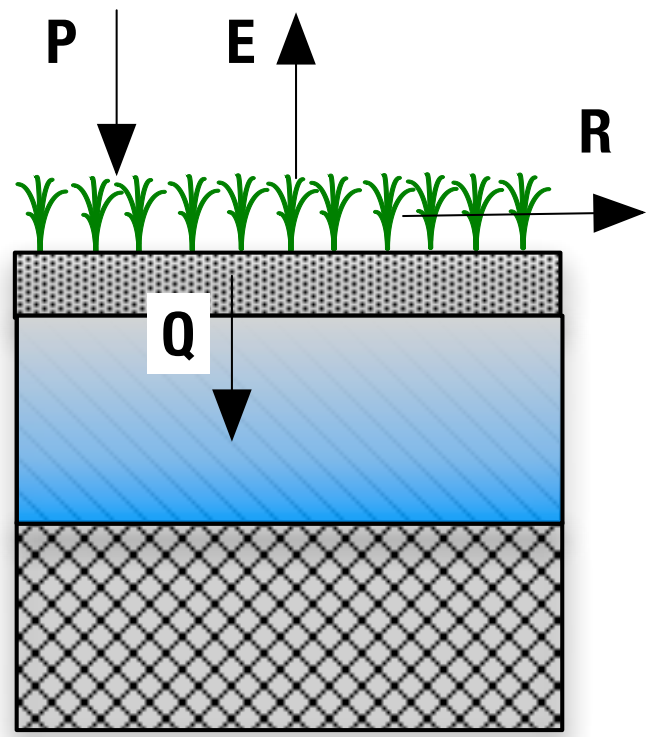
Hydrologic Module

Richards' equation-based solution:

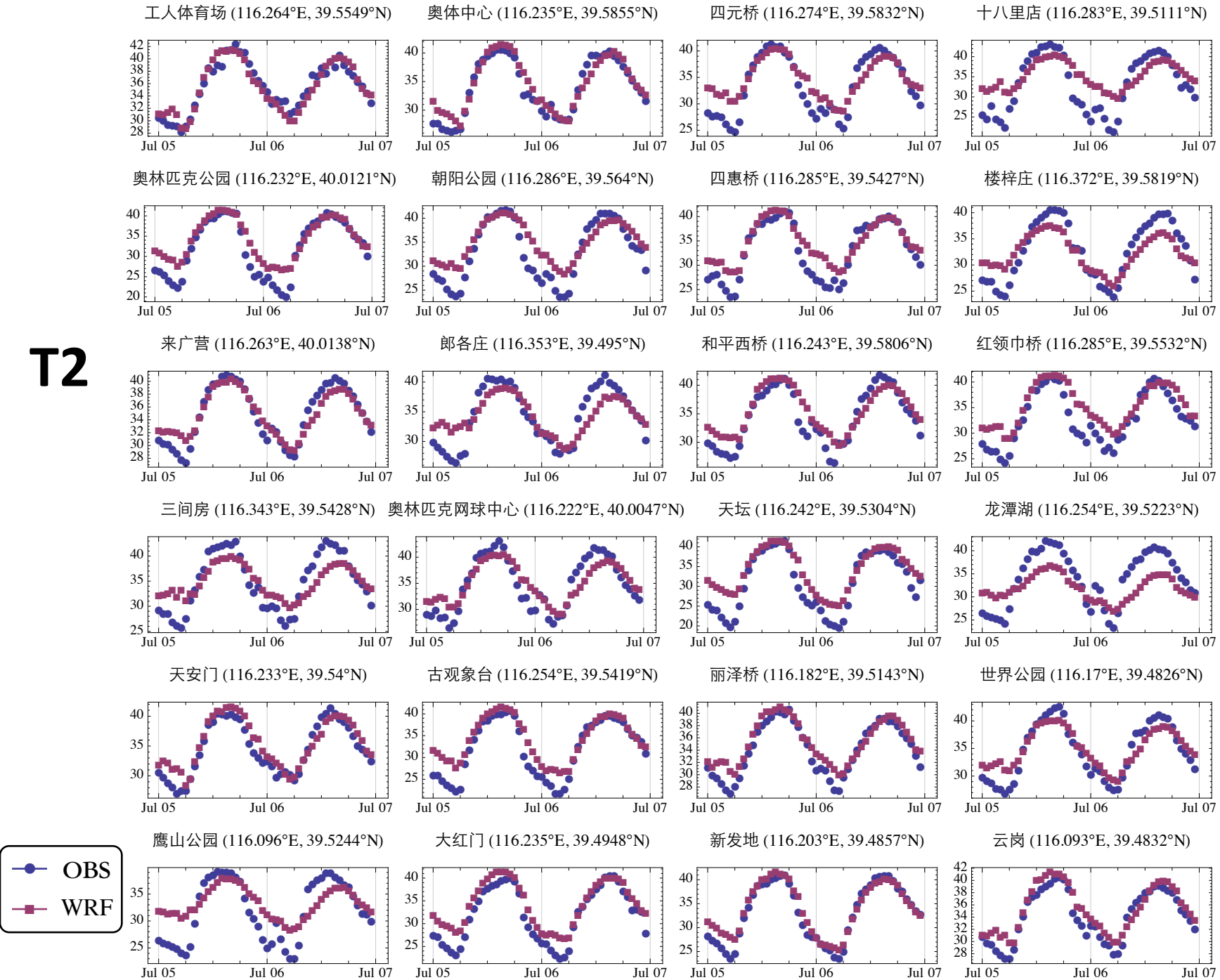
$$\frac{\partial \theta_k}{\partial t} = \begin{cases} \frac{1}{d_1}\left[P - E\left(\theta_1\right) - R - Q_{w,1\to 2}\right], & k = 1 \\ \frac{1}{d_k}\left[Q_{w,k-1\to k} - Q_{w,k\to k+1}\right], & k > 1 \end{cases}$$

$$Q_{w,k\to k+1} = \bar{D}_{k,k+1}\frac{\theta_k - \theta_{k+1}}{d_k + d_{k+1}} + \bar{K}_{k,k+1}$$

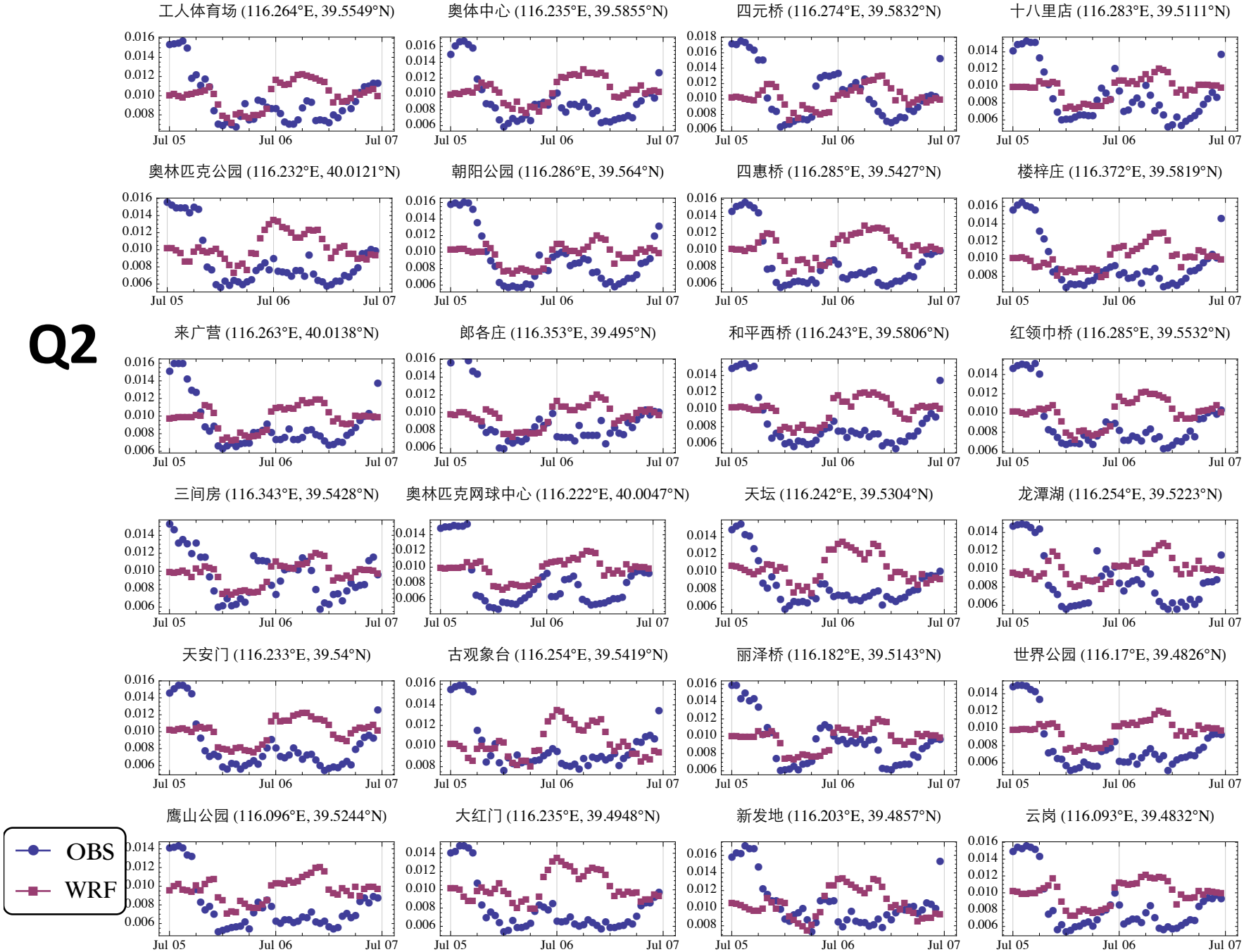
$$E = \beta_e\left(\theta\right)\frac{\rho_a\left(q_s^* - q_a\right)}{R_a + R_s}$$



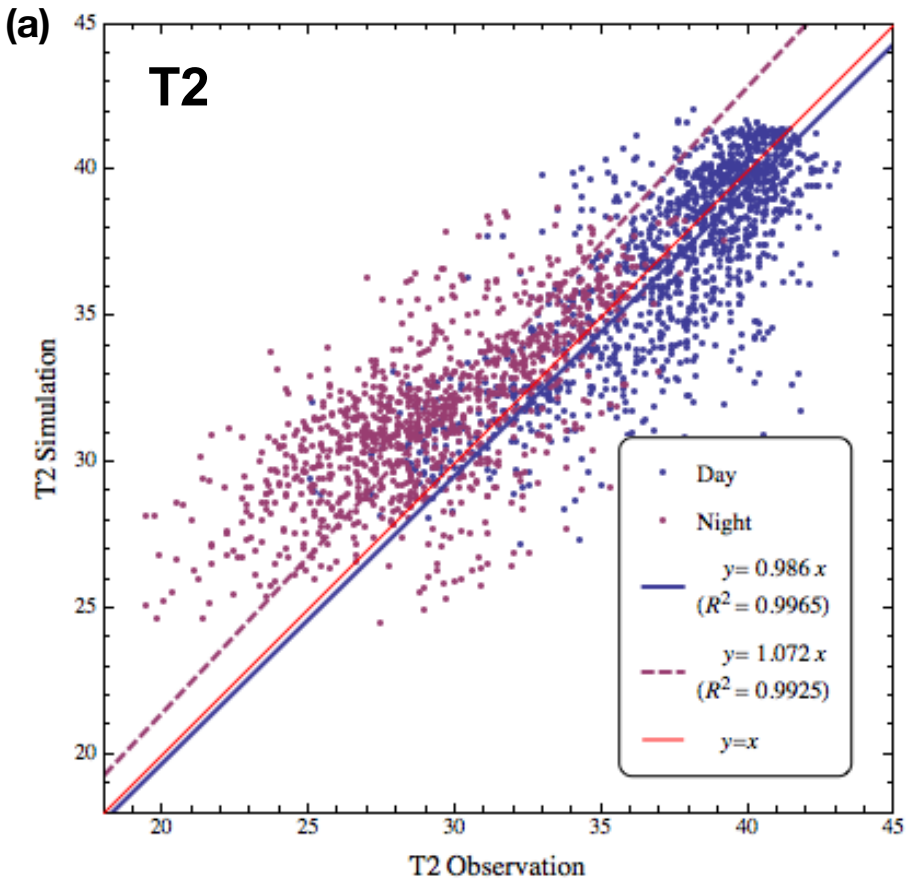
T2

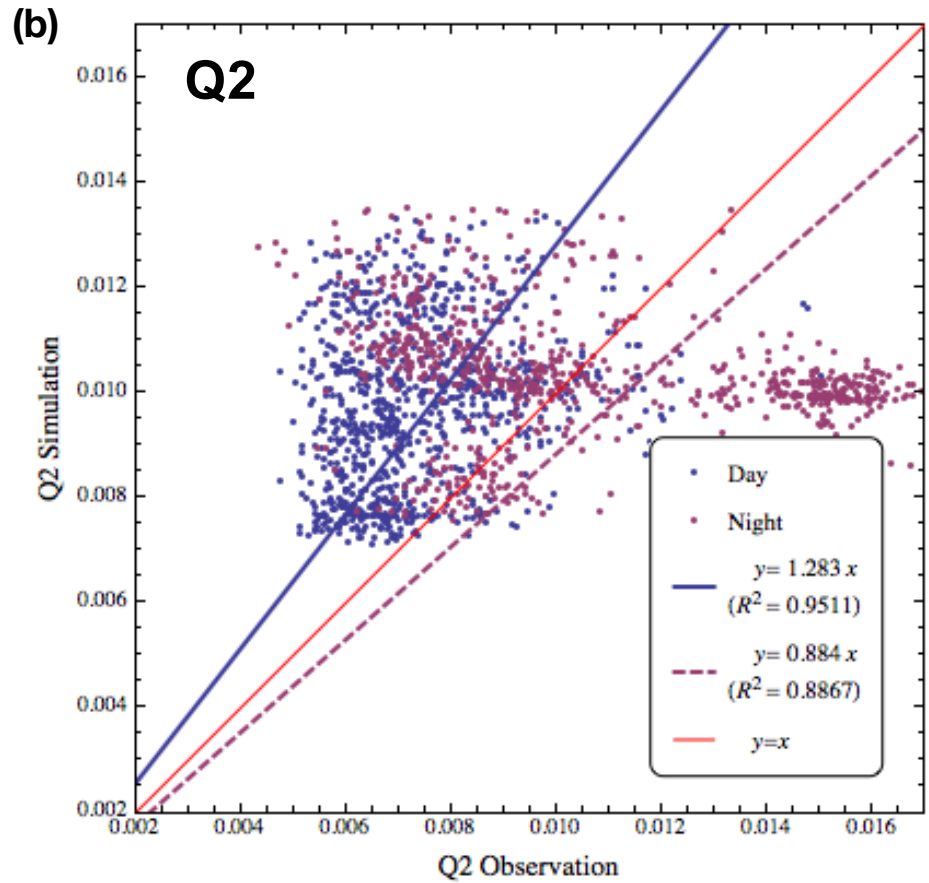

工人体育场 (116.264°E, 39.5549°N)
奥体中心 (116.235°E, 39.5855°N)
四元桥 (116.274°E, 39.5832°N)
十八里店 (116.283°E, 39.5111°N)
奥林匹克公园 (116.232°E, 40.0121°N)
朝阳公园 (116.286°E, 39.564°N)
四惠桥 (116.285°E, 39.5427°N)
楼梓庄 (116.372°E, 39.5819°N)
来广营 (116.263°E, 40.0138°N)
郎各庄 (116.353°E, 39.495°N)
和平西桥 (116.243°E, 39.5806°N)
红领巾桥 (116.285°E, 39.5532°N)
三间房 (116.343°E, 39.5428°N)
奥林匹克网球中心 (116.222°E, 40.0047°N)
天坛 (116.242°E, 39.5304°N)
龙潭湖 (116.254°E, 39.5223°N)
天安门 (116.233°E, 39.54°N)
古观象台 (116.254°E, 39.5419°N)
丽泽桥 (116.182°E, 39.5143°N)
世界公园 (116.17°E, 39.4826°N)
鹰山公园 (116.096°E, 39.5244°N)
大红门 (116.235°E, 39.4948°N)
新发地 (116.203°E, 39.4857°N)
云岗 (116.093°E, 39.4832°N)
Jul 05
Jul 06
Jul 07
OBS
WRF

Q2

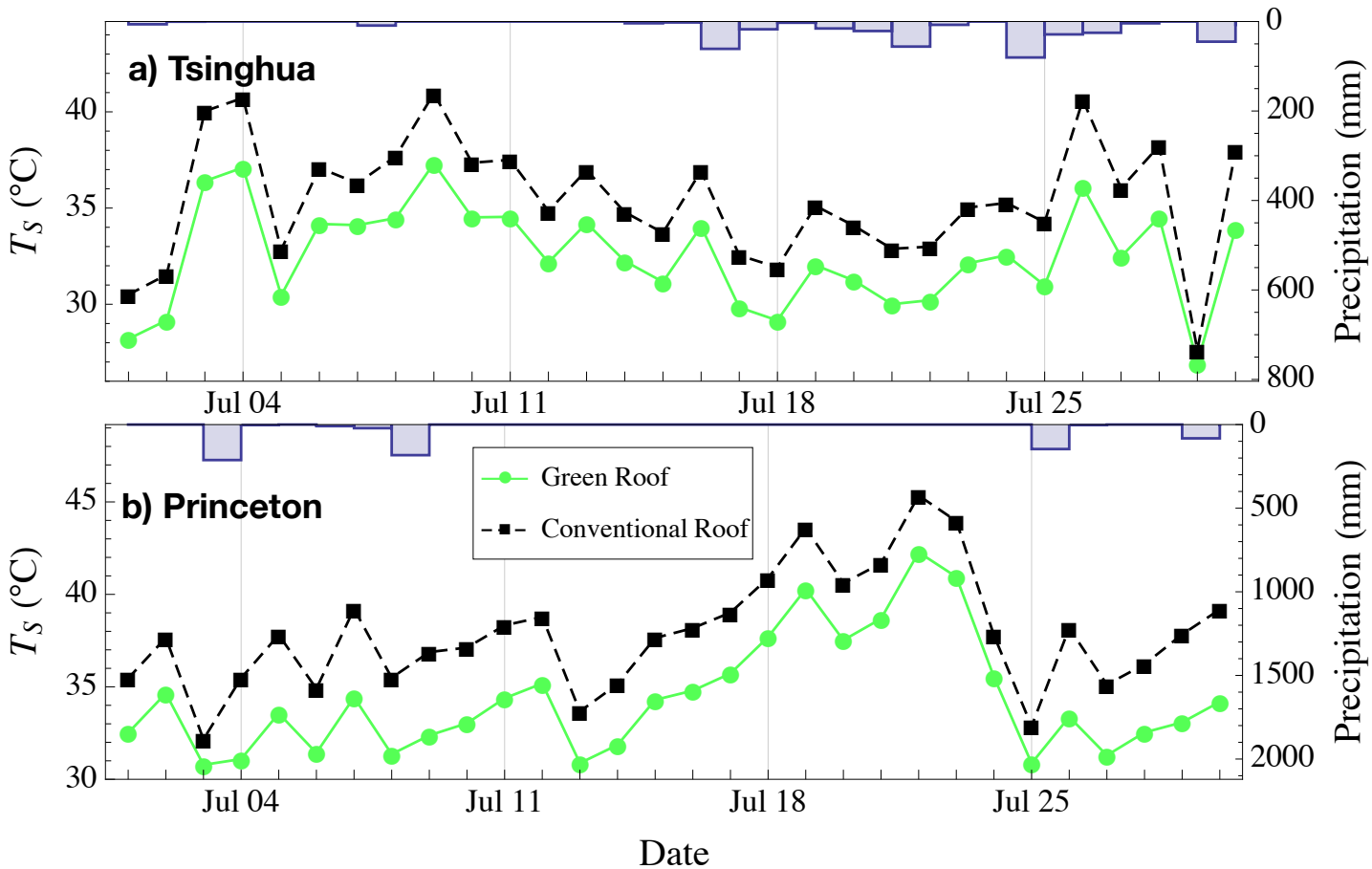

工人体育场 (116.264°E, 39.5549°N)
奥体中心 (116.235°E, 39.5855°N)
四元桥 (116.274°E, 39.5832°N)
十八里店 (116.283°E, 39.5111°N)
奥林匹克公园 (116.232°E, 40.0121°N)
朝阳公园 (116.286°E, 39.564°N)
四惠桥 (116.285°E, 39.5427°N)
楼梓庄 (116.372°E, 39.5819°N)
来广营 (116.263°E, 40.0138°N)
郎各庄 (116.353°E, 39.495°N)
和平西桥 (116.243°E, 39.5806°N)
红领巾桥 (116.285°E, 39.5532°N)
三间房 (116.343°E, 39.5428°N)
奥林匹克网球中心 (116.222°E, 40.0047°N)
天坛 (116.242°E, 39.5304°N)
龙潭湖 (116.254°E, 39.5223°N)
天安门 (116.233°E, 39.54°N)
古观象台 (116.254°E, 39.5419°N)
丽泽桥 (116.182°E, 39.5143°N)
世界公园 (116.17°E, 39.4826°N)
鹰山公园 (116.096°E, 39.5244°N)
大红门 (116.235°E, 39.4948°N)
新发地 (116.203°E, 39.4857°N)
云岗 (116.093°E, 39.4832°N)
Jul 05
Jul 06
Jul 07
OBS
WRF

Model Validation



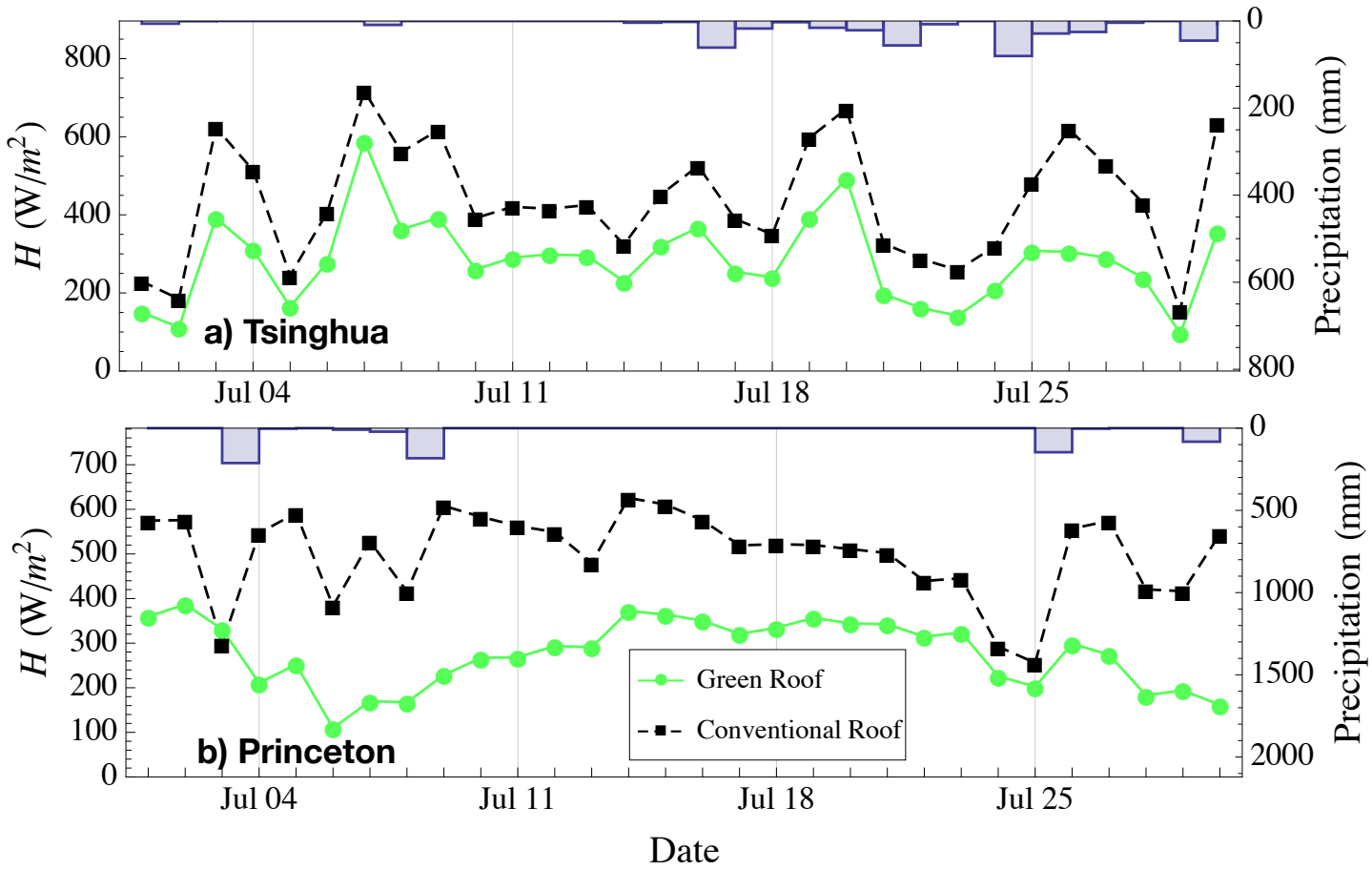


Surface Temperature



Green Roofs significantly reduces surface temperature.

Sensible Heat Flux



Sensible heat flux can be greatly reduced by green roofs.