Impacts of urban expansion on local and regional climate: from 2D to 3D analysis

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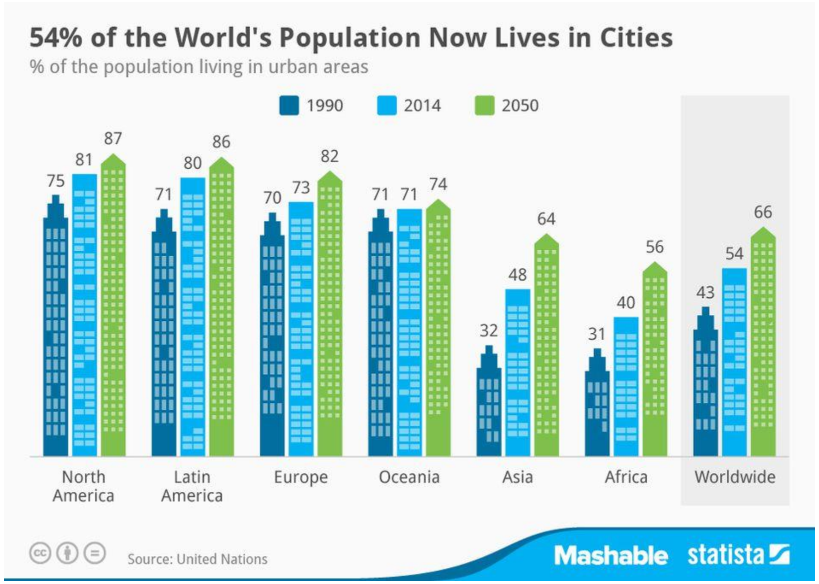
OUTLINE

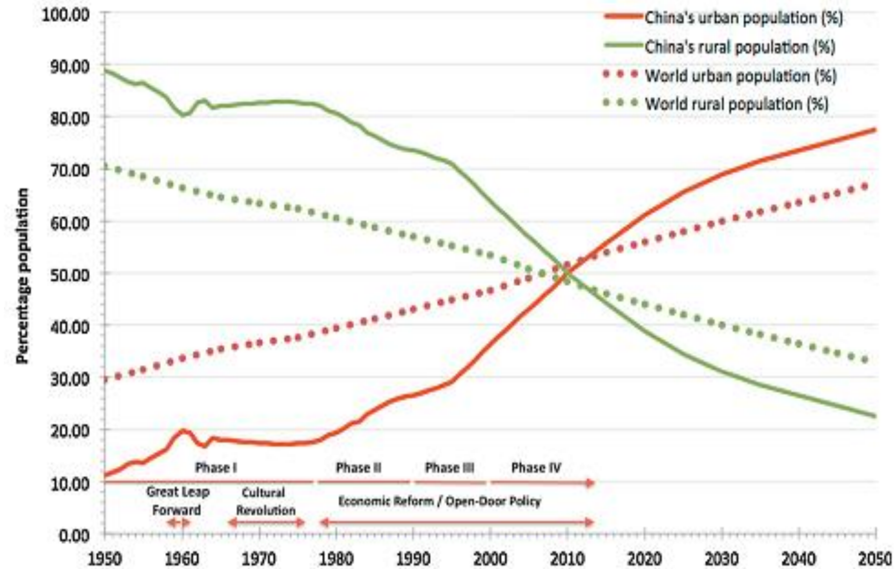
1、Research background

2、Research methods and tools

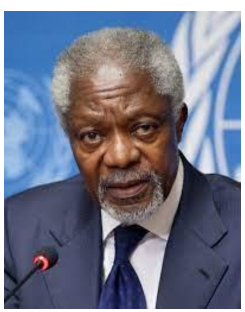
3、Three case studies

4、Conclusions



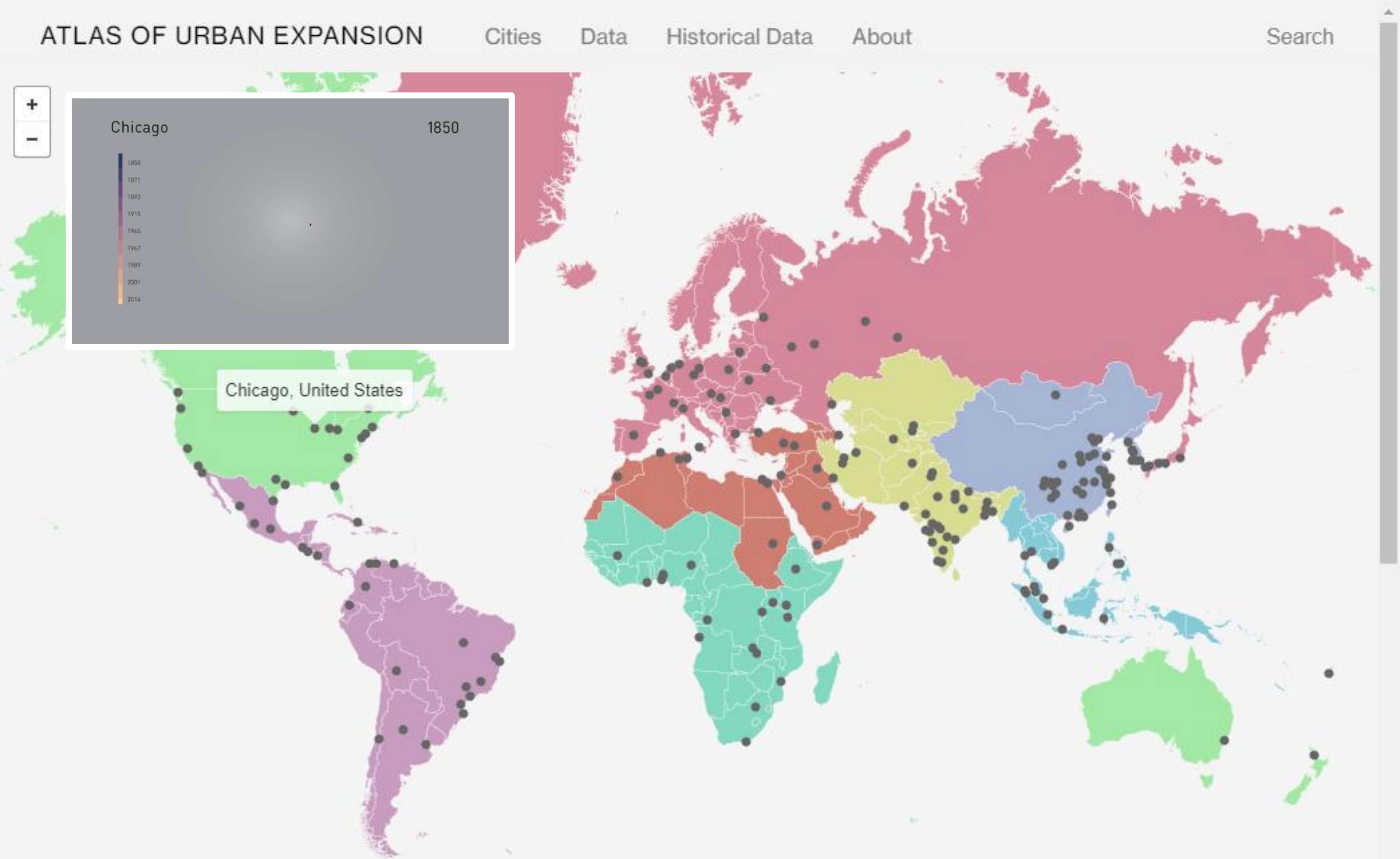


(Wu et al., 2014)



“The future of humanity lies in cities.”

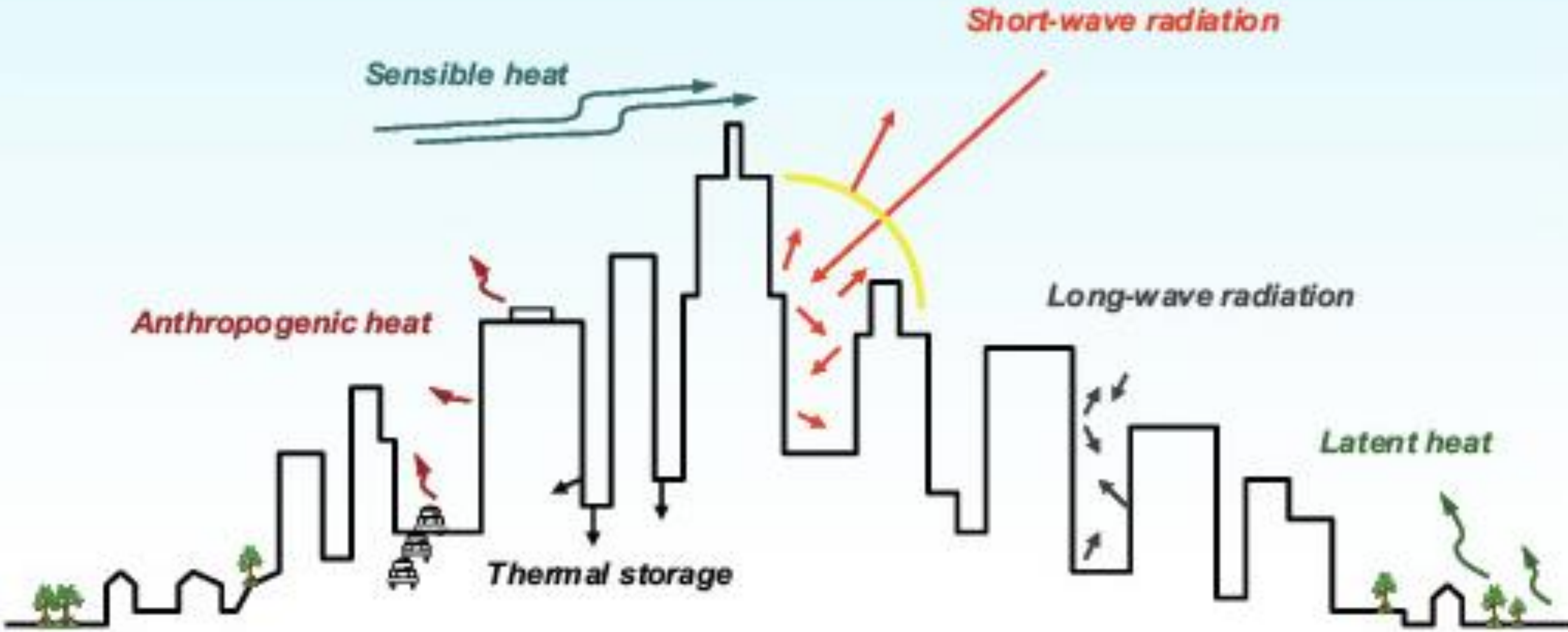
(Kofi Annan, Secretary-general of UN, 2002, UN Press Release SG/SM/8261)



The Atlas of Urban Expansion collects and analyzes data on the quantity and quality of urban expansion in a stratified global sample of 200 cities.

城市热岛

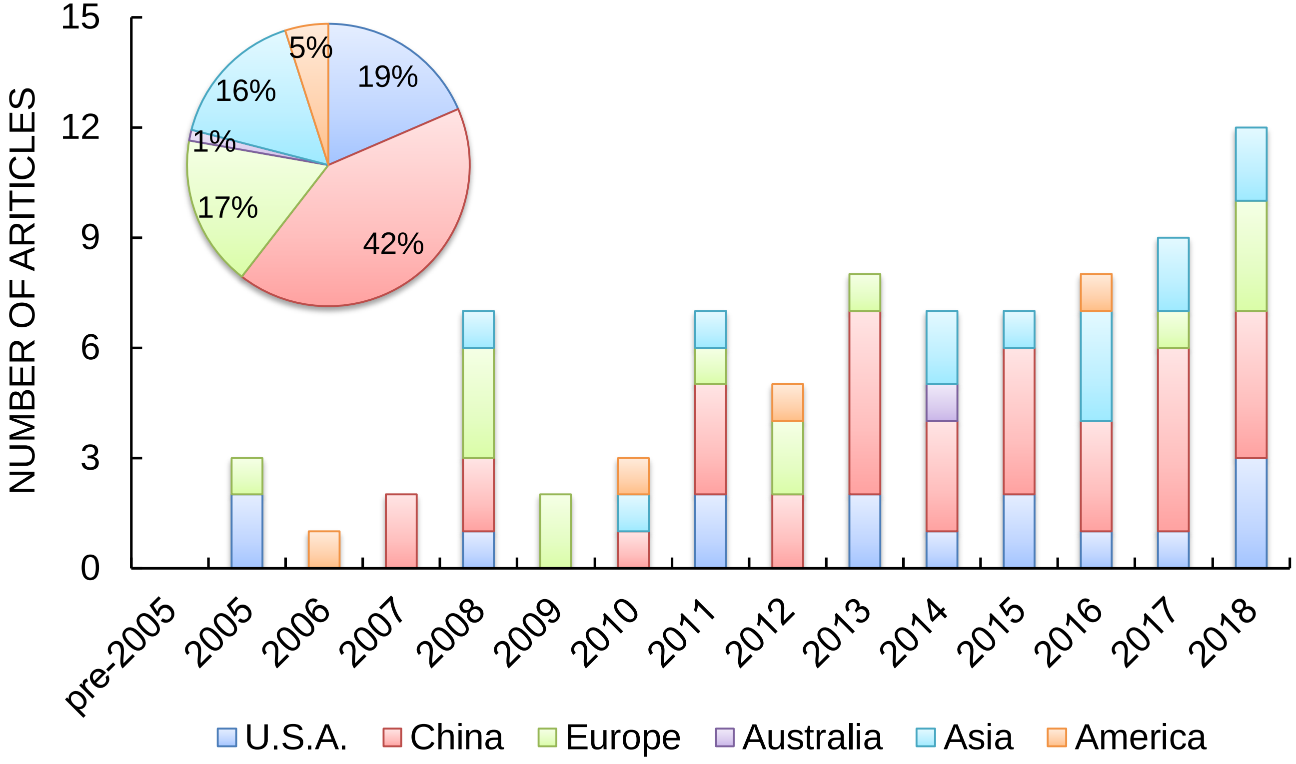
- 下垫面特性（建筑物、道路、绿地）
- 人工热源（工厂生产、交通运输、居民生活）
- 其它因素（大气污染等）



Source: Wong, Hogan, Rosenberg and Denny, US EPA.

城市扩展对降雨、湿度、风场的影响也受到越来越多的关注!

Urbanization impacts on climate



1、China

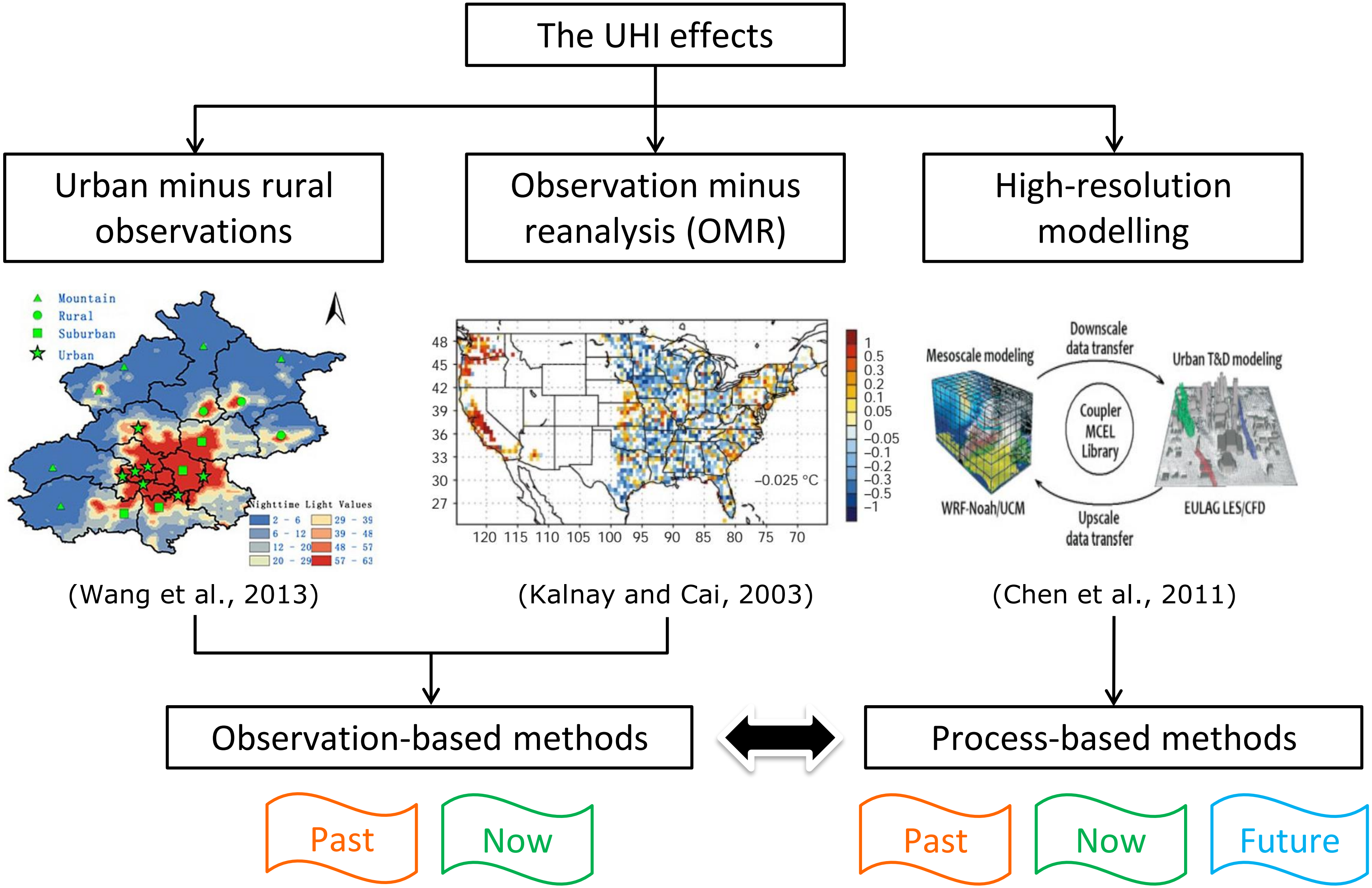
2、U.S.A.

3、Europe

4、Asia

Histogram showing the number of articles published per year that examined the impact of urbanization on climate during 1990 – 2018 (Cao et al., 2020)

OUTLINE

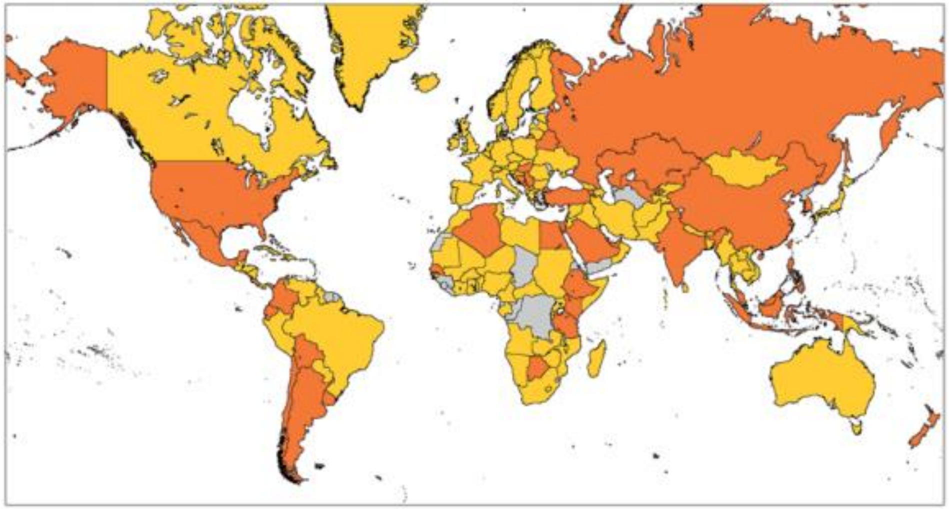


The UHI effects
Urban minus rural observations
Observation minus reanalysis (OMR)
High-resolution modelling
Mountain
Rural
Suburban
Urban
Nighttime Light Values
−0.025 °C
Mesoscale modeling
Downscale data transfer
Urban T&D modeling
Coupler MCEL Library
WRF-Noah/UCM
EULAG LES/CFD
Upscale data transfer
(Wang et al., 2013)
(Kalnay and Cai, 2003)
(Chen et al., 2011)
Observation-based methods
Process-based methods
Past
Now
Past
Now
Future

THE WRF MODELING SYSTEM

The Weather Research and Forecasting (WRF) model is a numerical weather prediction (NWP) and atmospheric simulation system designed for both research and operational applications. WRF development and testing has been a collaborative one headed by the National Center for Atmospheric Research (NCAR).

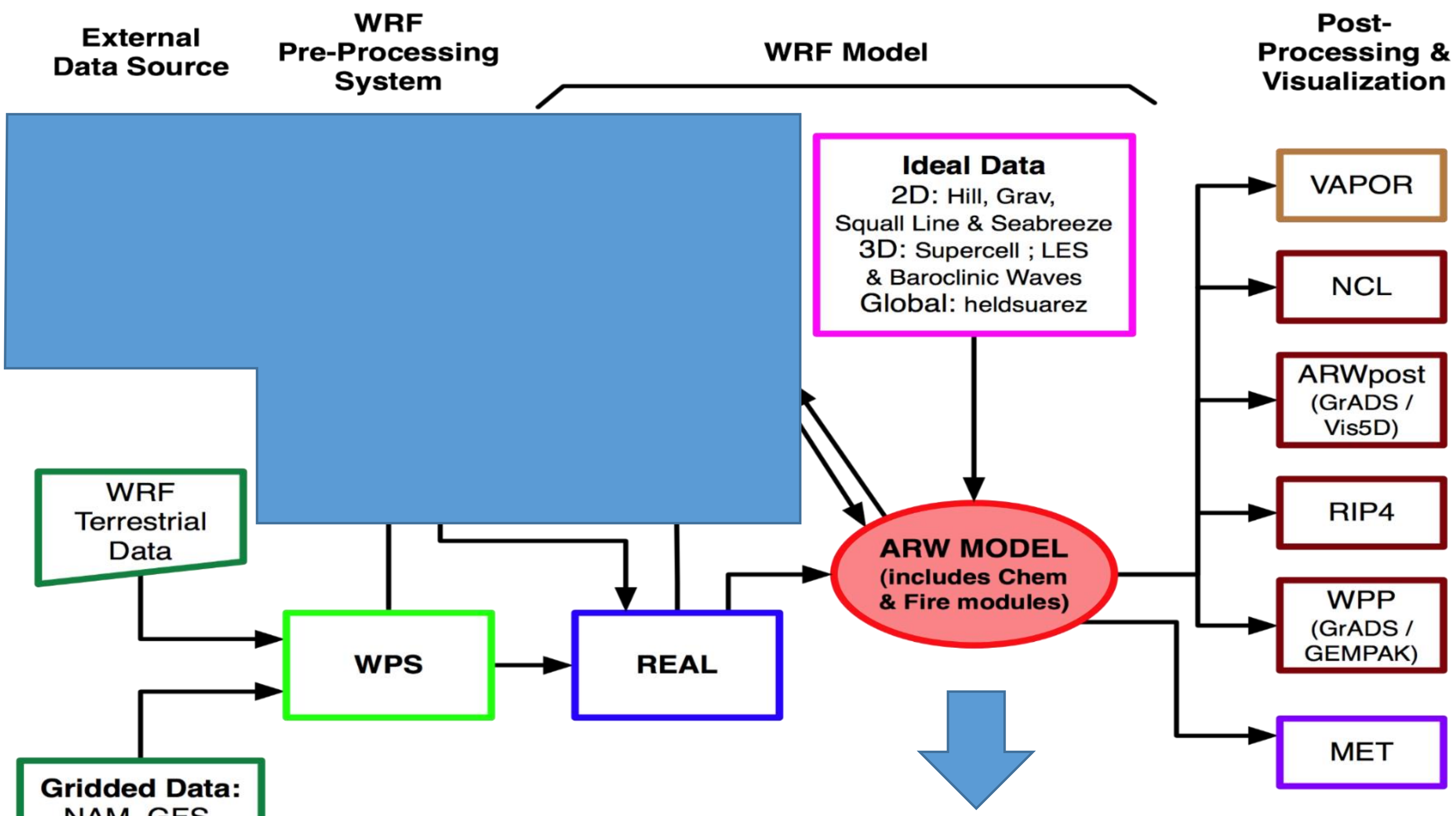
NCAR



- Registered WRF users
- Run WRF operationally

(Powers et al., 2017)

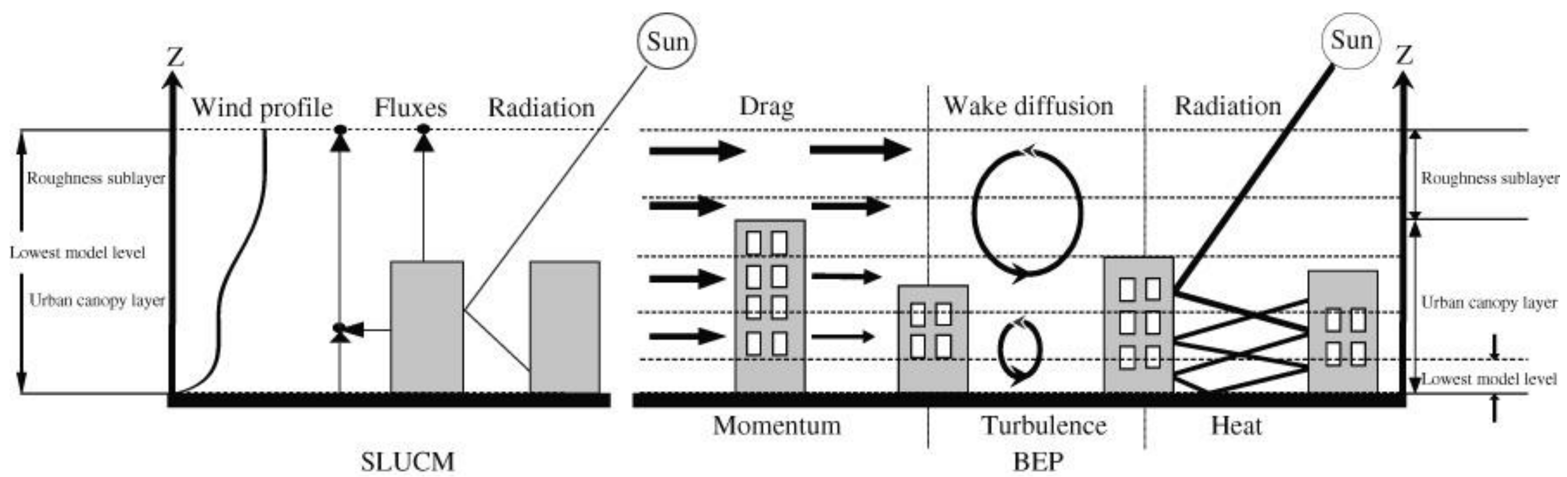
THE WRF MODELING SYSTEM



Dynamic Solver & Physical Parameterizations (microphysics, Land surface processes, radiation, planetary boundary layer, cumulus, etc.)

Urban Canopy Model

1. Single-layer Urban Canopy Model (SLUCM): 2-D urban geometry, street canyons, shadowing from buildings, multi-layer roof, wall and road models. Available in WRF V2.2
2. Multi-layer Urban Canopy Model (BEP): Directly interact with PBL scheme, multiple vertical layers, effects of buildings on momentum and heat fluxes. Available in WRF3.1



(Chen and Dudhia, 2011)

OUTLINE

1、 Research background

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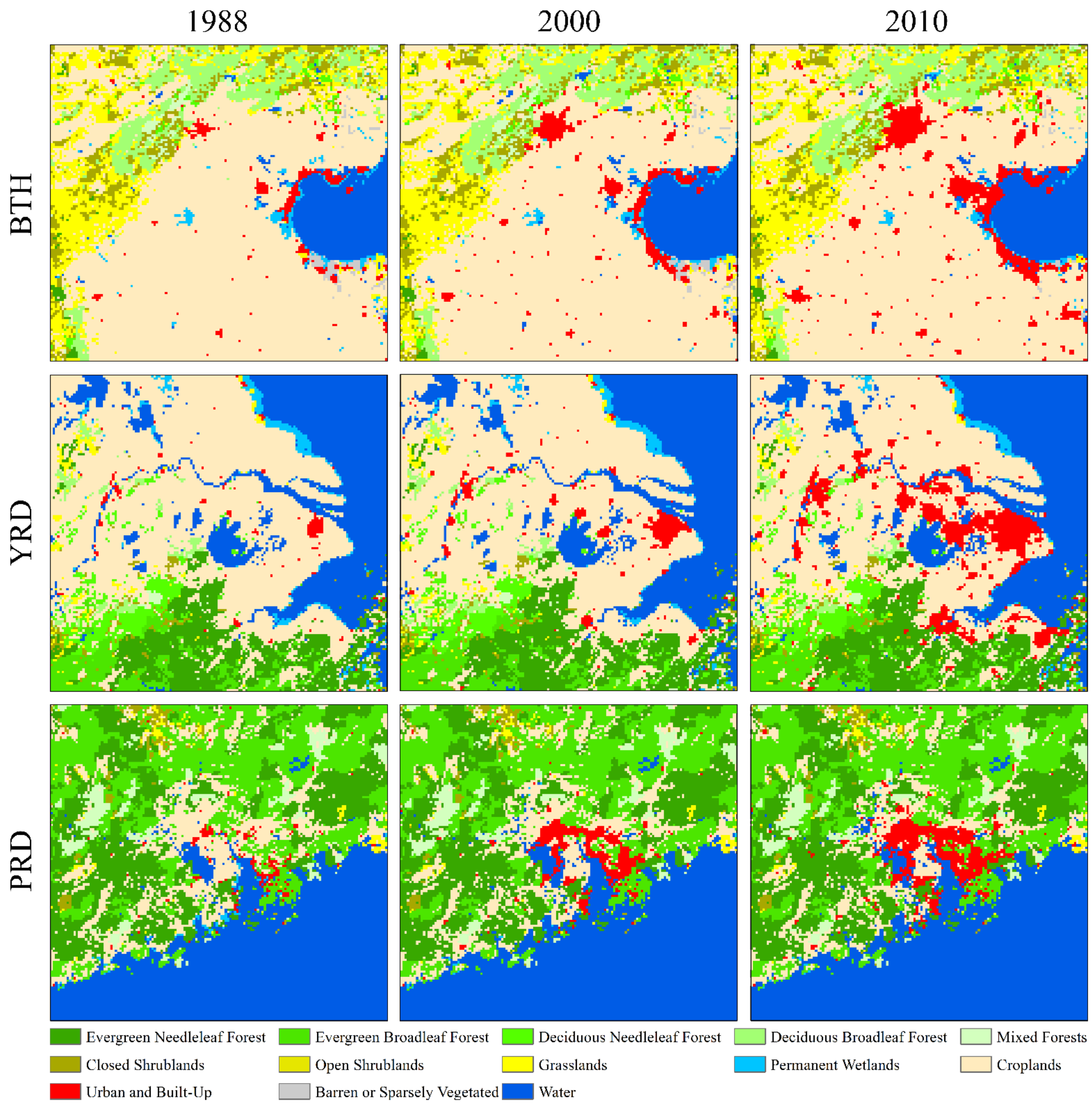
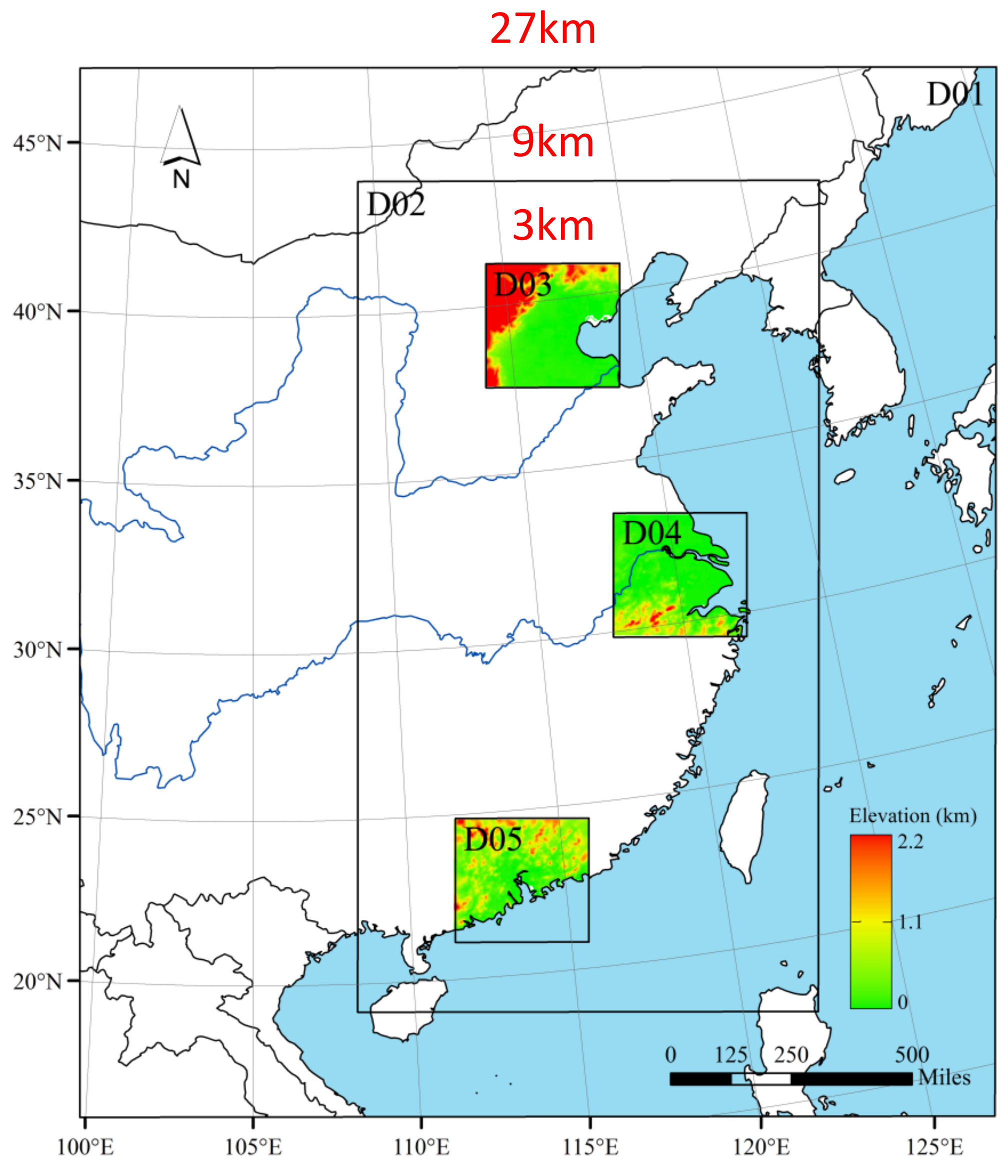
3.1 Impacts of historical urban expansion on climate



Beijing-Tianjin-Hebei
Concentrated aggregations

Yangtze River Delta
Polycentric aggregations

Pearl River Delta
Integrated aggregations

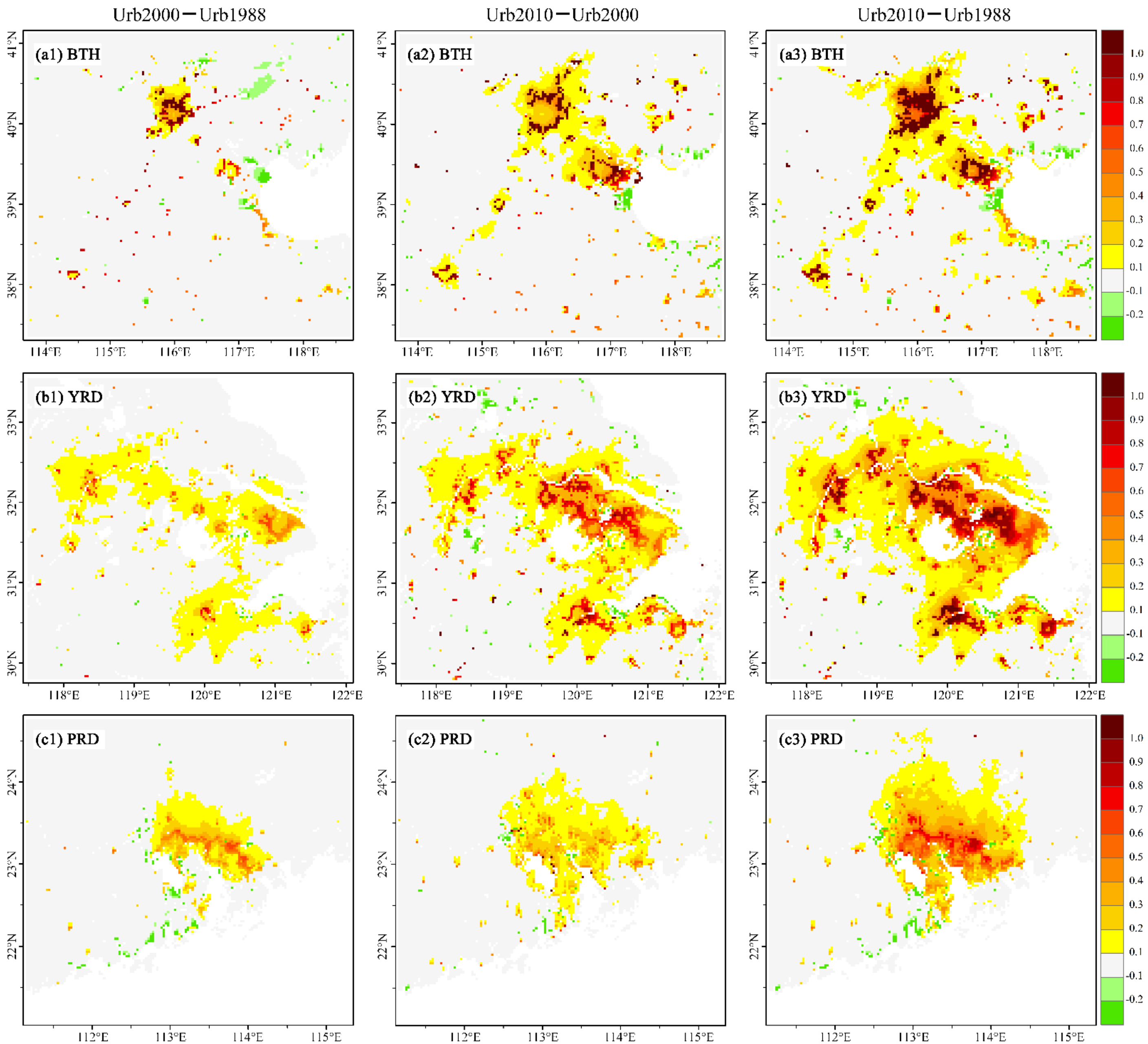


Domain configuration (1:3)

- Beijing-Tianjin-Hebei (D03)
- Yangtze River Delta (D04)
- Pearl River Delta (D05)

Numerical simulation design

Simulations	Spin-up period	Analysis time
Urb1988[a]	May 25 - 31, 2001	Jun 1 - Aug 31, 2001
	May 25 - 31, 2003	Jun 1 - Aug 31, 2003
	May 25 - 31, 2005	Jun 1 - Aug 31, 2005
Urb2000[b]	May 25 - 31, 2001	Jun 1 - Aug 31, 2001
	May 25 - 31, 2003	Jun 1 - Aug 31, 2003
	May 25 - 31, 2005	Jun 1 - Aug 31, 2005
Urb2010[c]	May 25 - 31, 2001	Jun 1 - Aug 31, 2001
	May 25 - 31, 2003	Jun 1 - Aug 31, 2003
	May 25 - 31, 2005	Jun 1 - Aug 31, 2005



1.50 °C

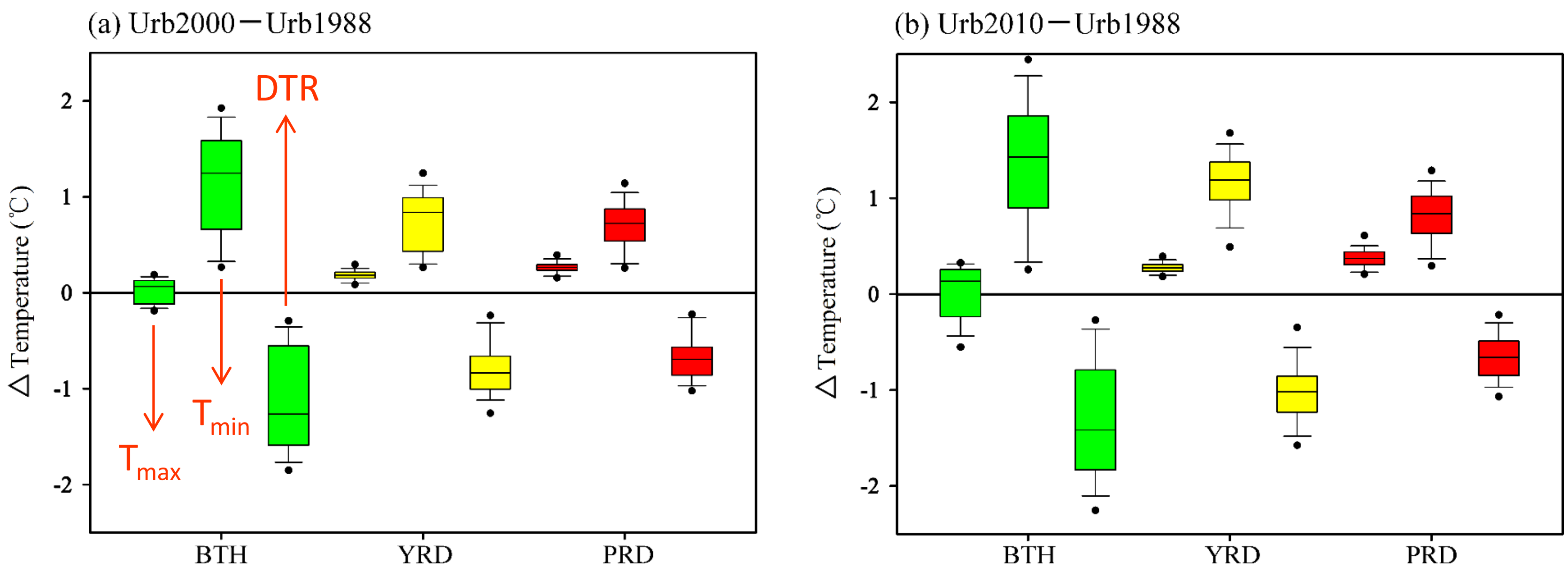
EI=2.7

1.00 °C

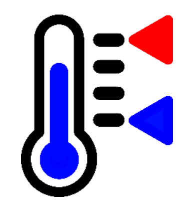
EI=5.0

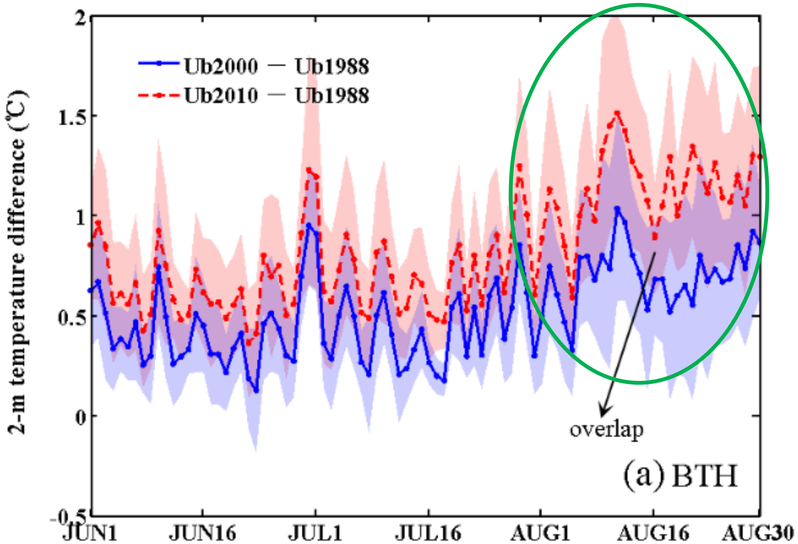
0.80 °C

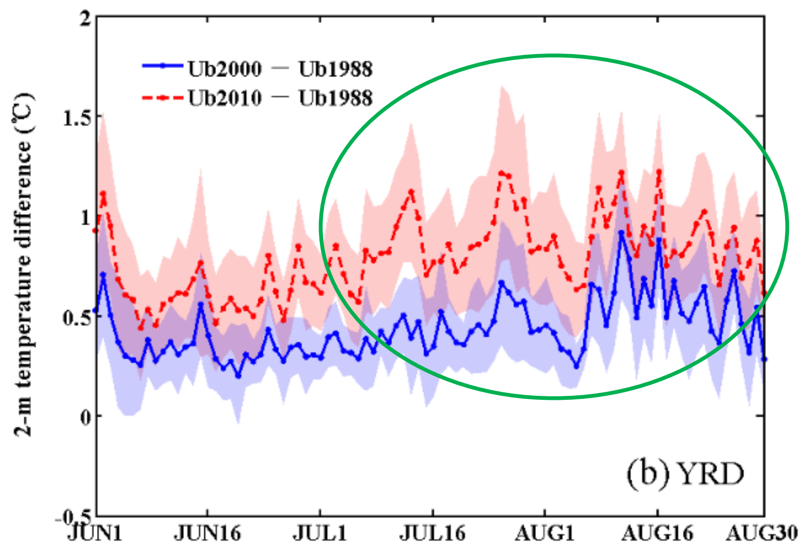
EI=3.6

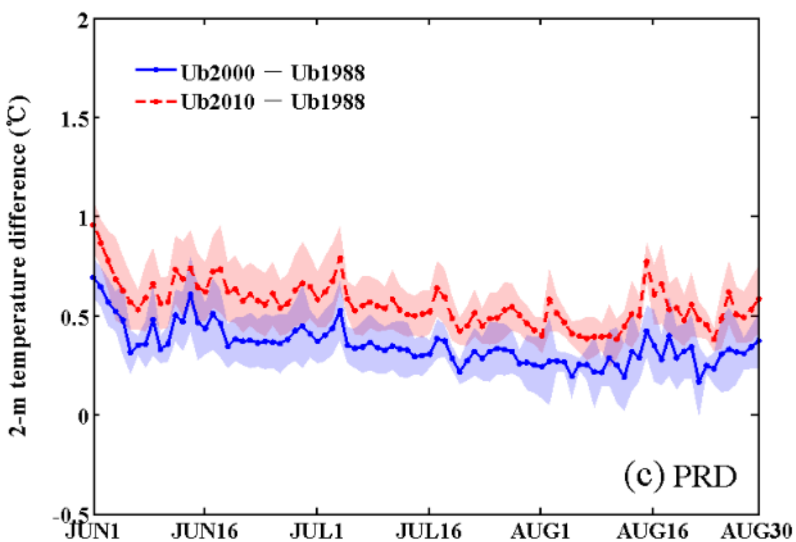


- Magnitude of increases in T_{min} : 1. BTH*, 2. YRD*, 3. PRD*
- Magnitude of increases in T_{max} : 1. PRD*, 2. YRD*, 3. BTH
- Reduced changes in DTR : PRD (2000 — 2010)









Increased T_{avg} of:

- BTH during August
- YRD during July, August
- PRD during summer

3.2 Impacts of future urban expansion on climate

Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools

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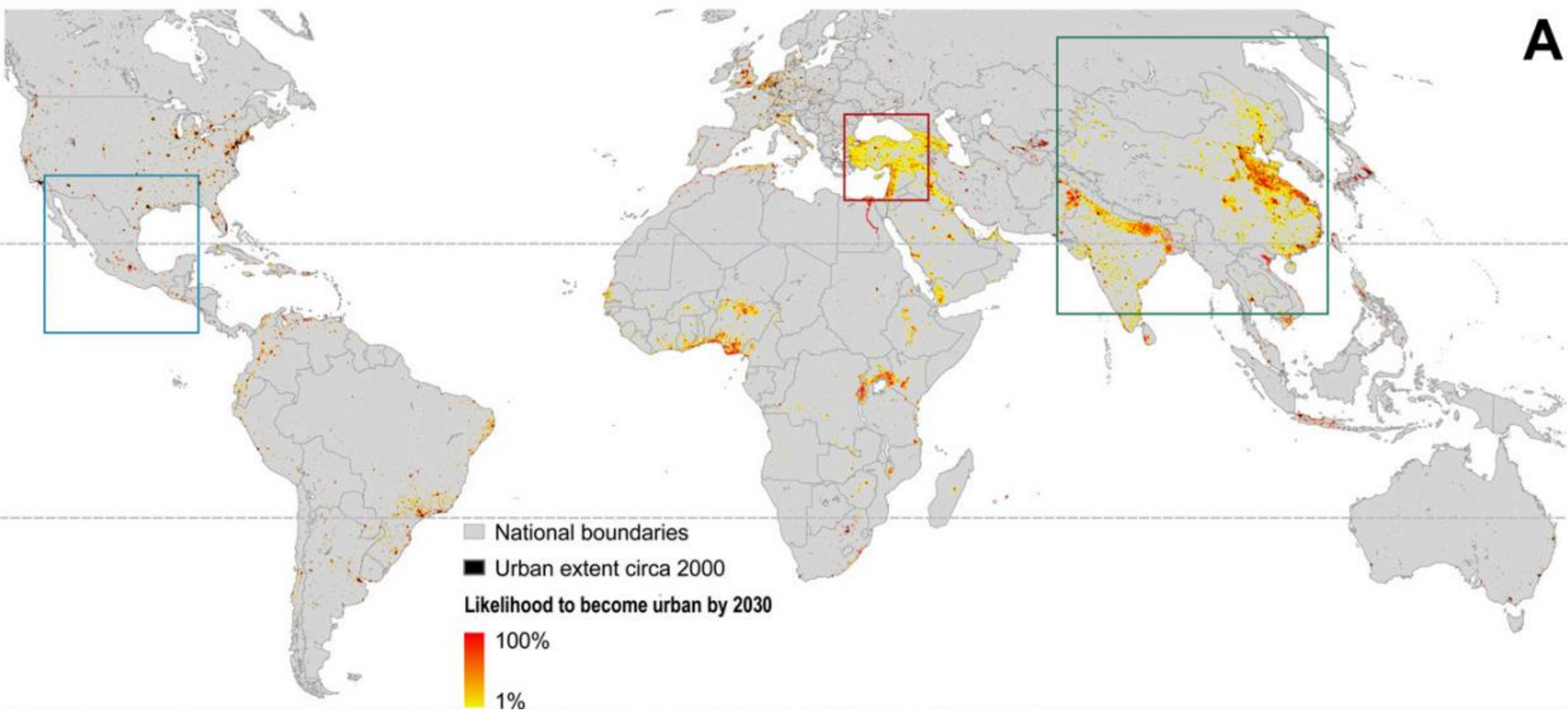
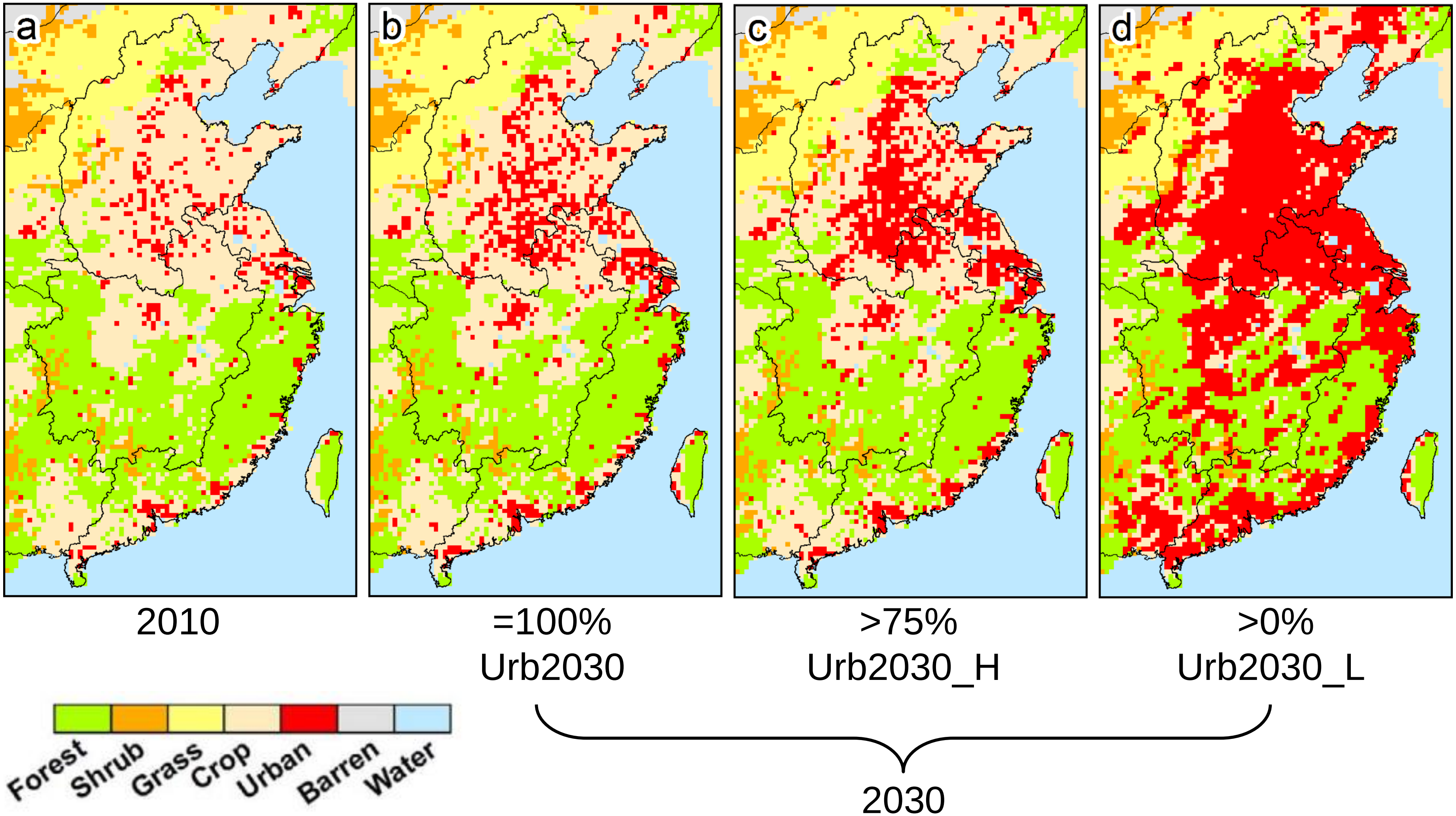
[a]Yale School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511; [b]Department of Geography, Texas A&M University, College Station, TX 77843; and [c]Department of Geography and Environment, Boston University, Boston, MA 02215



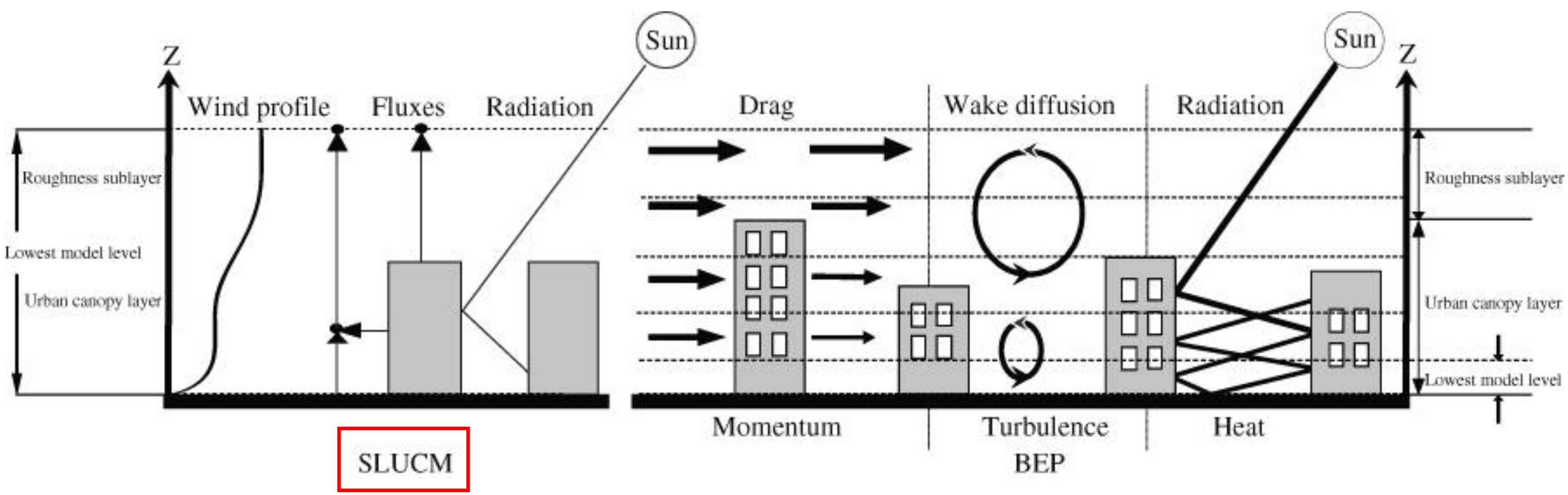
Urban expansion scenarios in eastern China

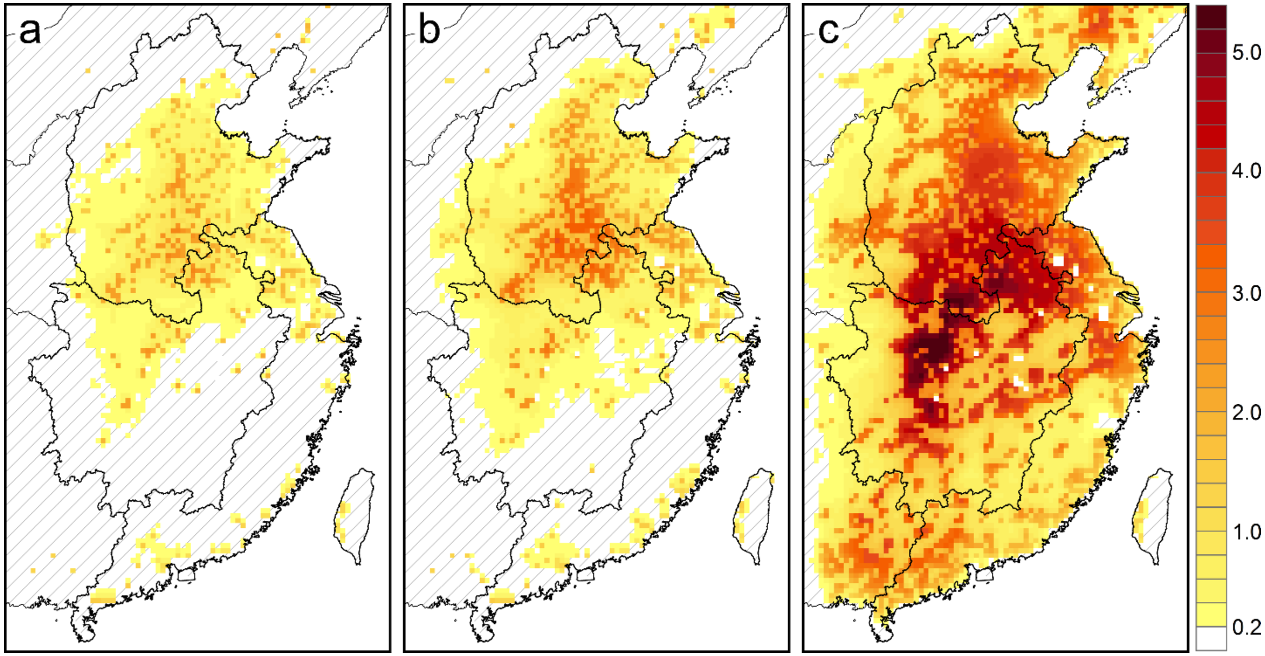


Numerical simulation design

Name convention	Spin-up period	Analysis time
Urb2010	1 Jan – 28 Feb 2009	1 Mar 2009 – 1 Mar 2012
Urb2030	1 Jan – 28 Feb 2009	1 Mar 2009 – 1 Mar 2012
Urb2030_High	1 Jan – 28 Feb 2009	1 Mar 2009 – 1 Mar 2012
Urb2030_Low	1 Jan – 28 Feb 2009	1 Mar 2009 – 1 Mar 2012

夏季: 城市热岛的危害最大 接收的太阳辐射最多 植被的蒸散发最强烈





夏季平均气温变化:

(a) Urb2030 – Urb2010

(b) Urb2030_H – Urb2010

(c) Urb2030_L – Urb2010

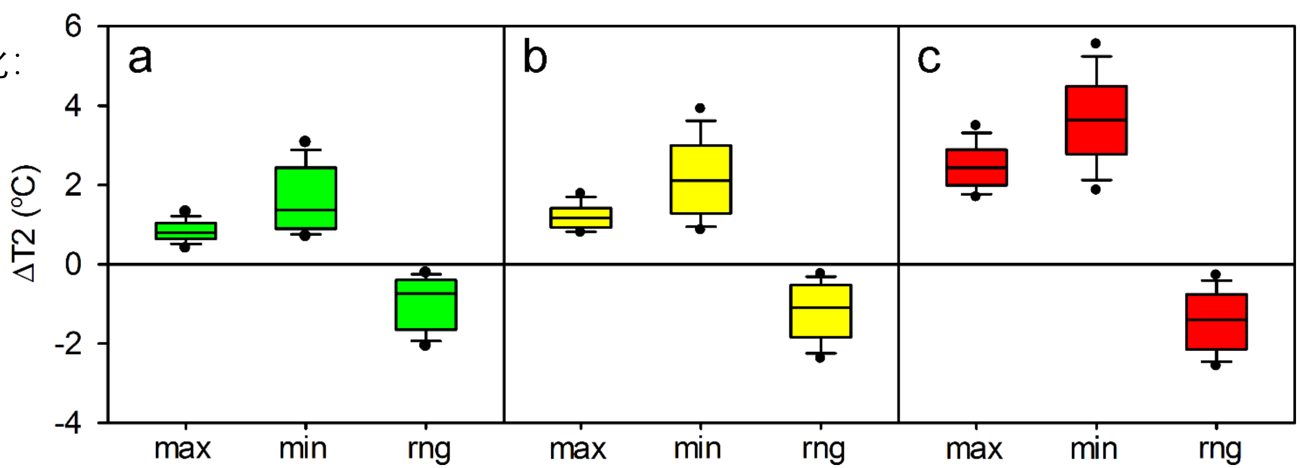
>5°C

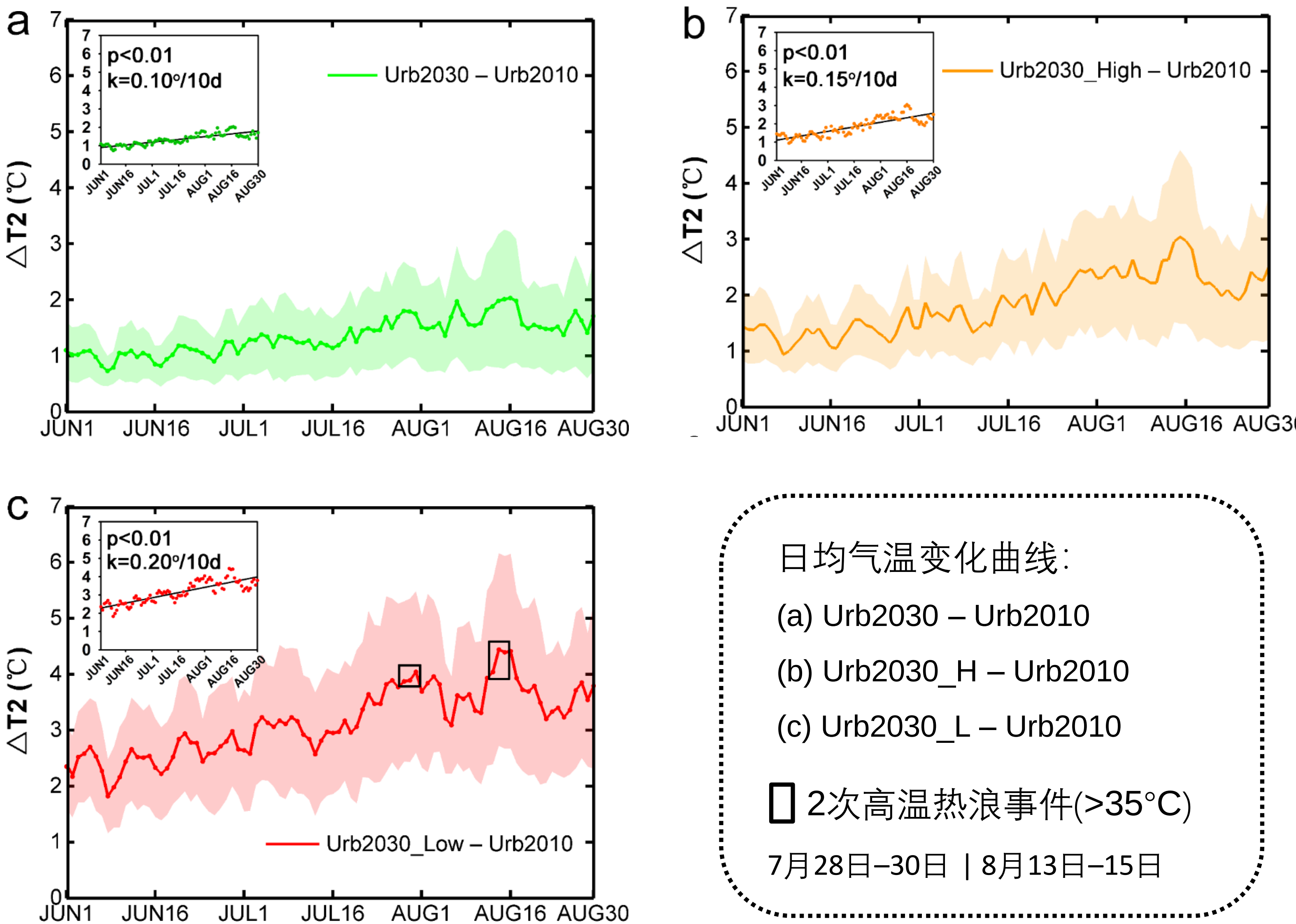
最高温、最低温、日较差变化:

(a) Urb2030 – Urb2010

(b) Urb2030_H – Urb2010

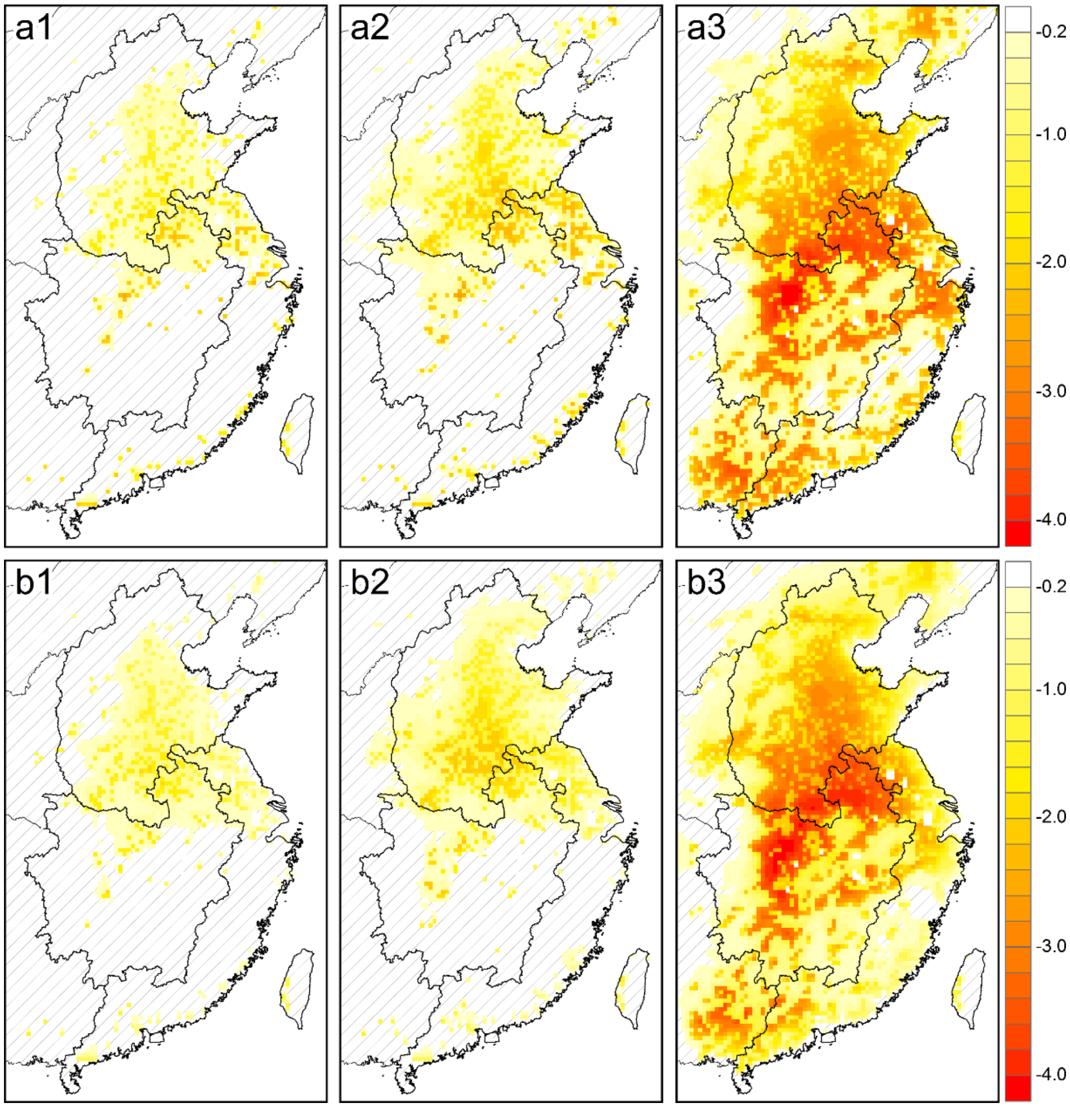
(c) Urb2030_L – Urb2010




a
p<0.01
k=0.10°/10d
Urb2030 – Urb2010
ΔT2 (℃)
JUN1 JUN16 JUL1 JUL16 AUG1 AUG16 AUG30
b
p<0.01
k=0.15°/10d
Urb2030_High – Urb2010
ΔT2 (℃)
JUN1 JUN16 JUL1 JUL16 AUG1 AUG16 AUG30
c
p<0.01
k=0.20°/10d
Urb2030_Low – Urb2010
ΔT2 (℃)
JUN1 JUN16 JUL1 JUL16 AUG1 AUG16 AUG30
日均气温变化曲线:
(a) Urb2030 – Urb2010
(b) Urb2030_H – Urb2010
(c) Urb2030_L – Urb2010
2次高温热浪事件(>35°C)
7月28日–30日 | 8月13日–15日

白天

夜晚



水汽减少量:

- 沿海地区白天大于夜晚
- 内陆地区白天与夜晚相近
- 南部地区大于北部地区

≈ 2-4 g/kg

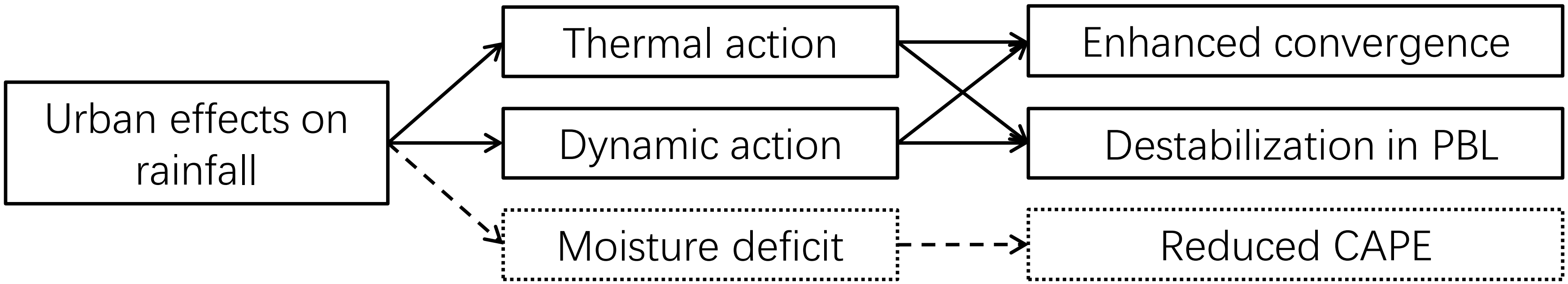
25°且相对湿度50%的空气团的水汽混合比为10g/kg!

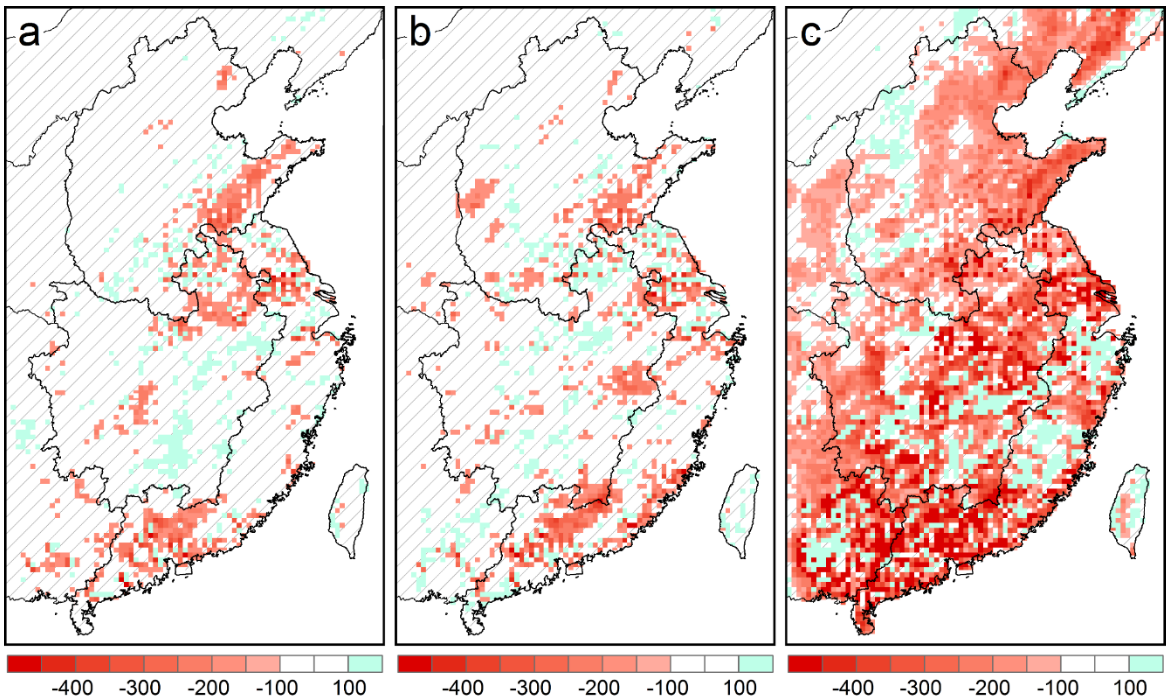
(a1), (a2) Urb2030 – Urb2010

(b1), (b2) Urb2030_H – Urb2010

(c1), (c2) Urb2030_L – Urb2010

Unit: g/kg





(Wang et al., 2012, 2015; Zhang et al., 2017)

a:unchanged rainfall pattern

b:unchanged rainfall pattern

c:changed rainfall pattern

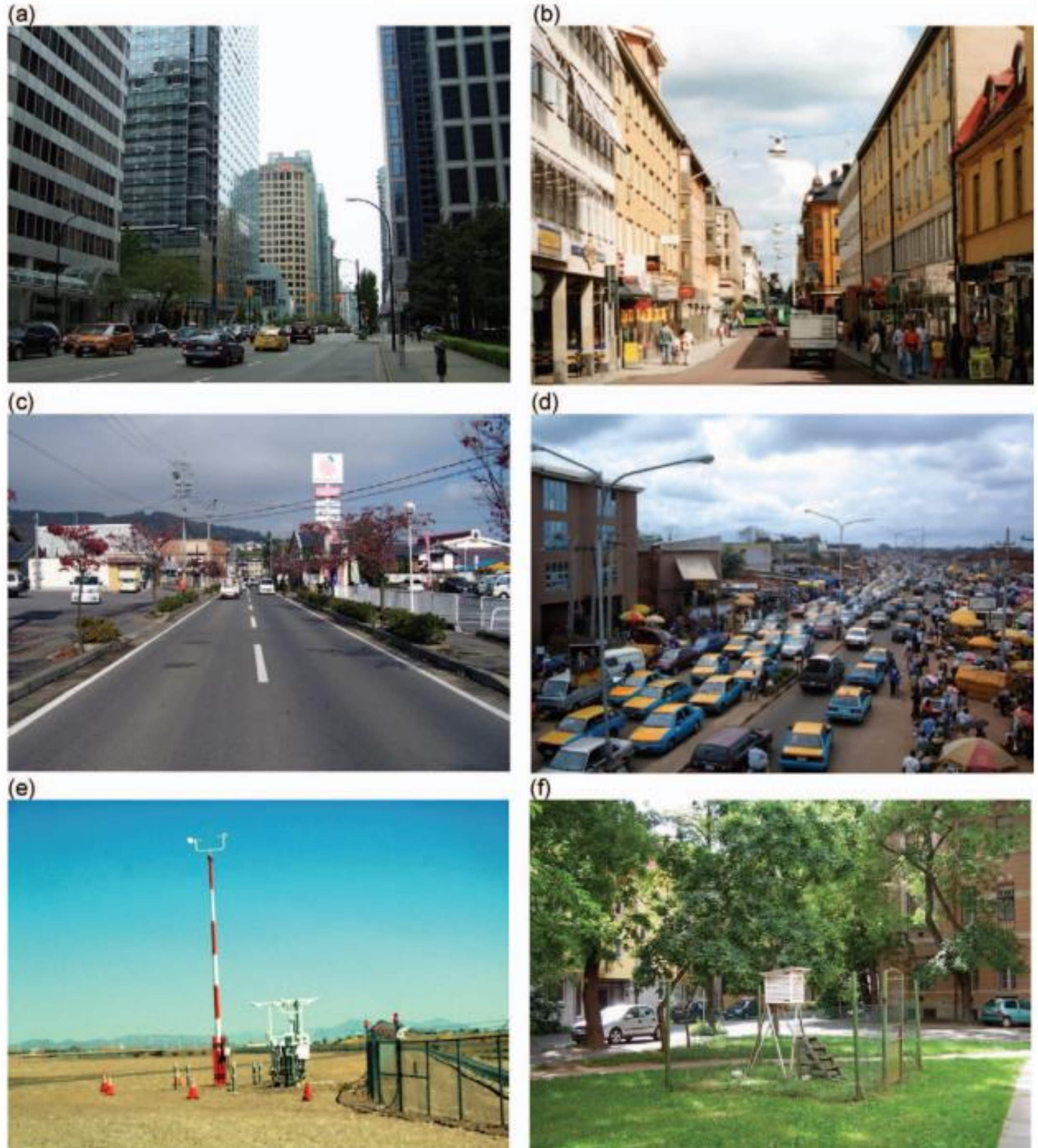
(a) Urb2030 – Urb2010

(b) Urb2030_H – Urb2010

(c) Urb2030_L – Urb2010

Unit: mm

3.3 Impacts 3D urban morphology on microclimate



Vancouver, Canada

Uppsala, Sweden

Toyono, Japan

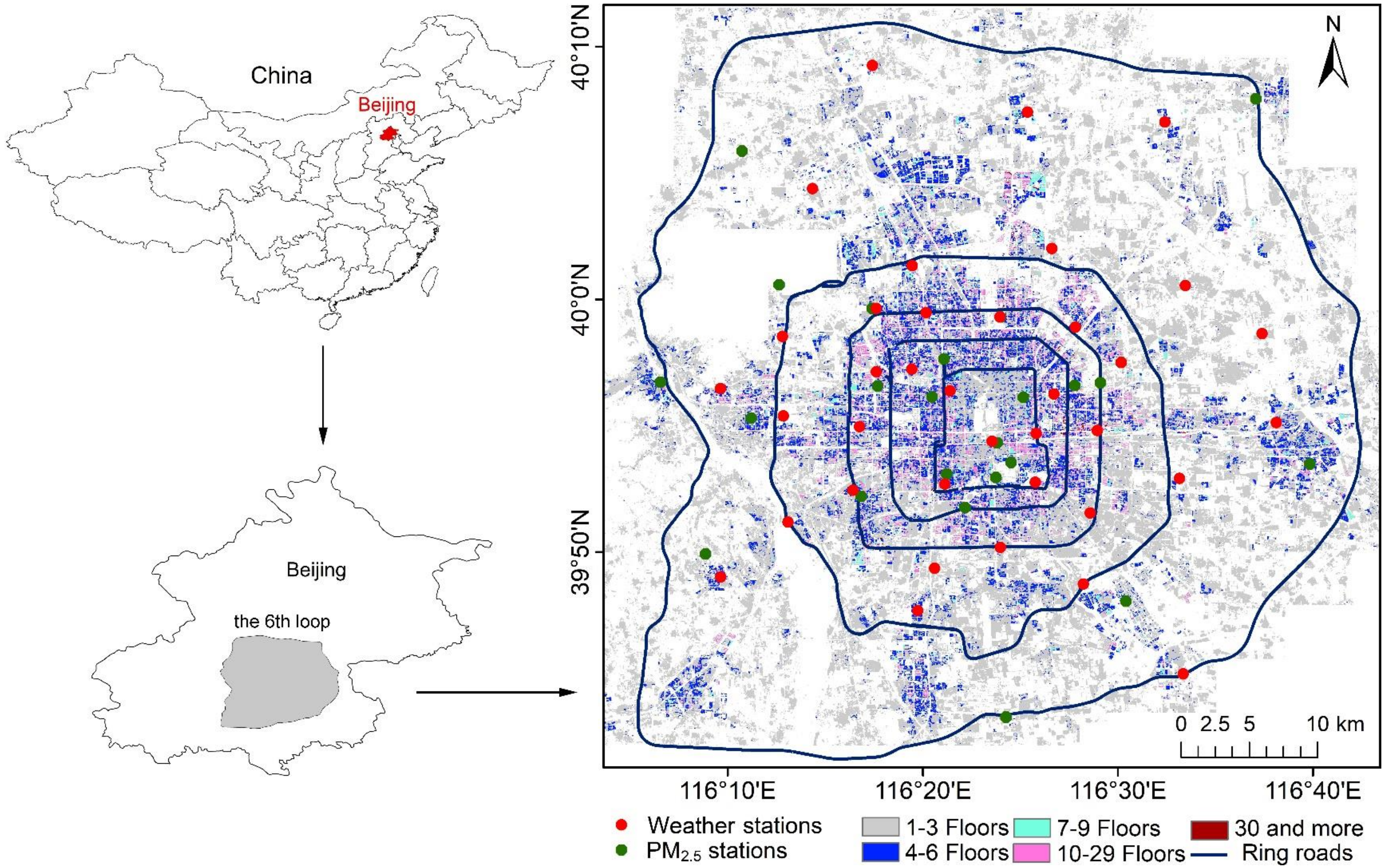
Akure, Nigeria

Phoenix, Arizona

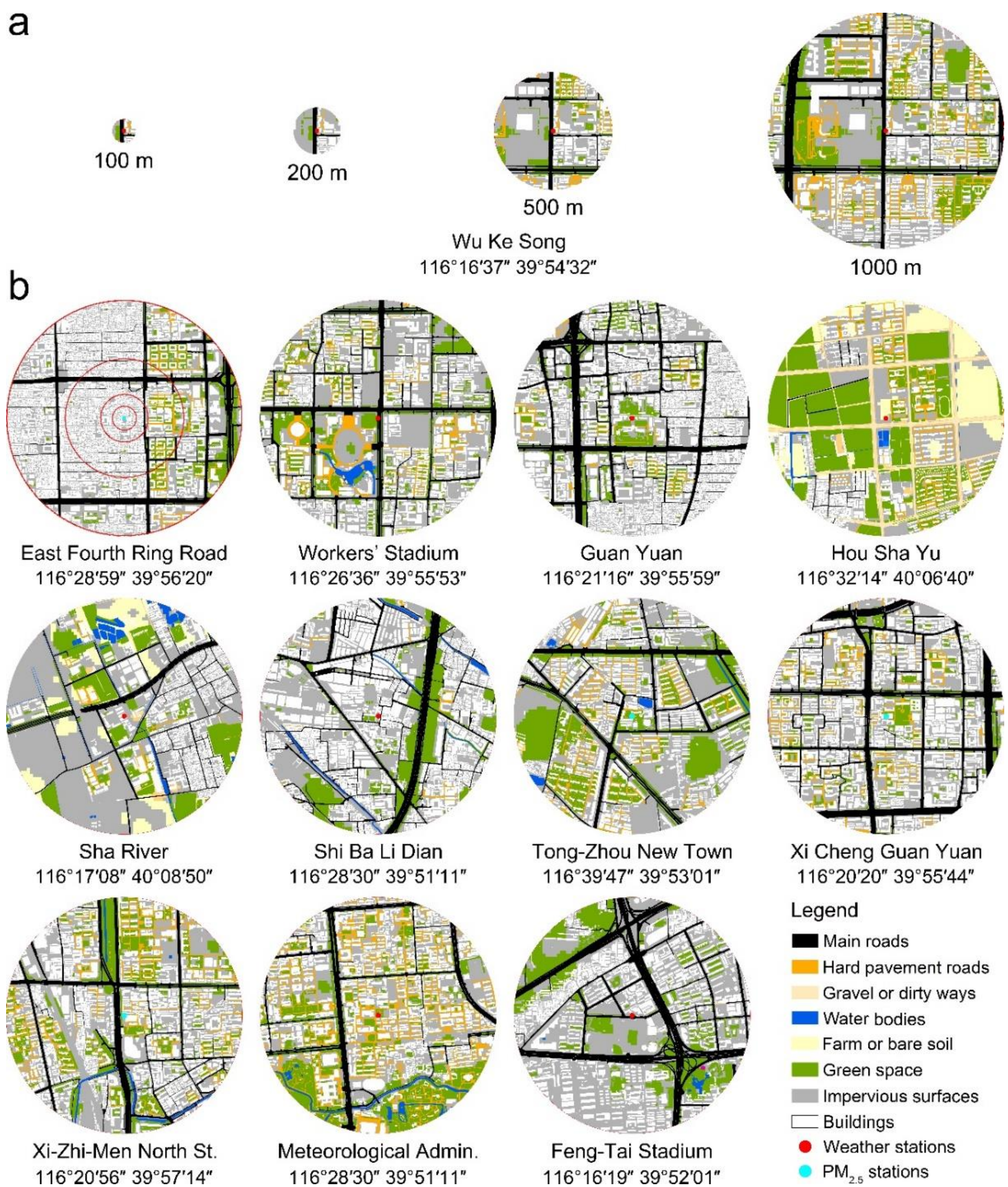
Szeged, Hungary

(Stewart and Oke, 2012; Local climate zones for urban temperature studies)

—Study Area—



On the left: the location of Beijing in China and the 6[th]-loop zone in Beijing. **On the right:** the distribution of buildings categorized by the number of floors in central Beijing, with the 37 weather stations and 24 air quality monitoring stations overlaid



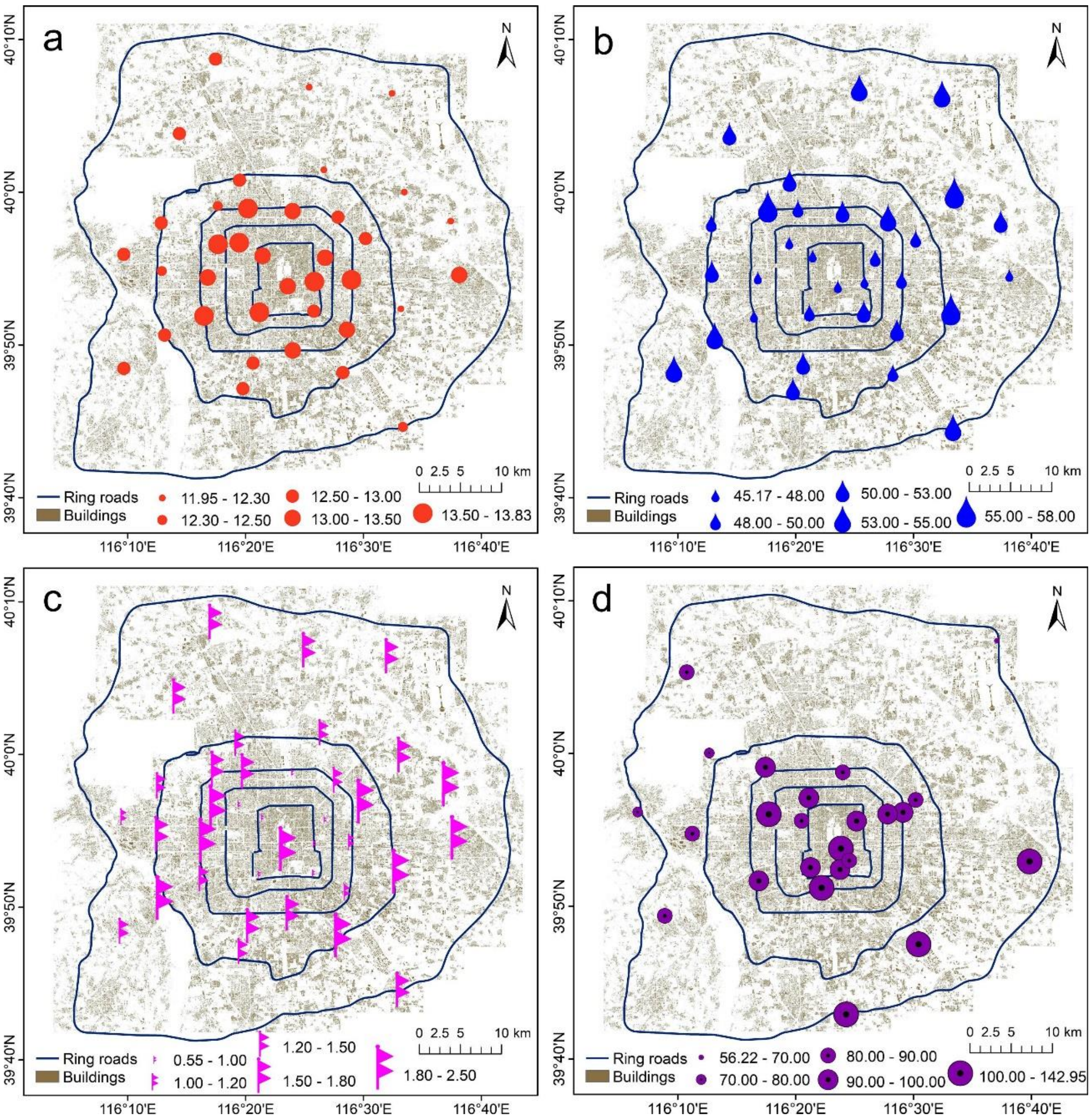
2D Metrics:

percentage of patch (PLAND)
patch area range (PAR)
coefficient of variation (CV)
patch density (PD)
largest patch index (LPI)
aggregation index (AI)

3D Metrics:

building volume density (BVD)
building height range (BHR)
building otherness (BO)
building height density (BHD)
highest building index (HBI)
sky view factor (SVF)

circular buffer zones
100、200、500、1000m



Climate factors:

Air temperature (℃)
Relative humidity (%)
Wind speed (m/s)

37 weather stations

Air quality:

$PM_{2.5}$ ($\mu g/m^3$)

24 monitoring stations

2D/3D建筑形态

相关分析

回归分析

城市大气环境

The effects of building morphology on air temperature

Table 1 The correlation coefficients between the 2D/3D building morphology indicators and air temperature

	Spring				Summer				Autumn				Winter			
	100m	200m	500m	1000m	100m	200m	500m	1000m	100m	200m	500m	1000m	100m	200m	500m	1000m
2D																
PLAND	0.349*	0.412*	0.506**	0.673**	0.405*	0.505**	0.568**	0.607**	0.417*	0.472**	0.551**	0.707**	0.405*	0.447**	0.519**	0.659**
PD	0.349*		0.372*	0.473**	0.347*				0.342*		0.346*	0.446**	0.426**		0.462**	0.575**
AI	0.383*	0.335*				0.440**			0.366*	0.365*			0.360*	0.342*		
3D																
BVD	0.439**	0.498**	0.720**	0.787**	0.510**	0.524**	0.607**	0.636**	0.575**	0.613**	0.708**	0.762**	0.598**	0.650**	0.785**	0.827**
BHR	0.485**	0.567**	0.656**	0.700**	0.524**	0.501**	0.522**	0.565**	0.569**	0.591**	0.599**	0.678**	0.598**	0.585**	0.718**	0.764**
BO	-0.384*	-0.356*			-0.472**	-0.482**	-0.413*		-0.366*	-0.370*			-0.442**	-0.331*		
BHD	0.380*	0.488**	0.558**	0.629**	0.430**	0.456**	0.397*	0.481**	0.466**	0.533**	0.499**	0.566**	0.481**	0.558**	0.637**	0.692**
HBI		-0.351*		-0.380*	-0.400*	-0.479**				-0.347*		-0.337*	-0.365*			
SVF	-0.405*	-0.465**	-0.613**	-0.771**	-0.436**	-0.481**	-0.562**	-0.629**	-0.493**	-0.547**	-0.628**	-0.770**	-0.524**	-0.559**	-0.659**	-0.800**

$^{*}p < 0.05$; $^{**}p < 0.01$ (two-tailed)

- BVD, BHR, BHD, and SVF were significantly correlated with it across all scales and seasons, and the degree of correlation became higher as the sample sites enlarged.
- PLAND was the only 2D building morphology indicator significantly correlated with air temperature across all scales and seasons.

The effects of building morphology on relative humidity

Table 2 The correlation coefficients between the 2D/3D building morphology indicators and relative humidity

	Spring				Summer				Autumn				Winter			
	100m	200m	500m	1000m	100m	200m	500m	1000m	100m	200m	500m	1000m	100m	200m	500m	1000m
2D																
PLAND	-0.399*	**-0.452****	**-0.534****	**-0.457****	-0.398*	-0.435*	**-0.550****	**-0.522****	-0.425*	**-0.465****	**-0.618****	**-0.684****	-0.402*	-0.421*	**-0.575****	**-0.580****
PD											-0.395*	-0.440*			-0.418*	**-0.453****
AI		**-0.455****				**-0.466****			-0.373*	**-0.560****	-0.365*	-0.360*		**-0.555****		
3D																
BVD	**-0.520****	**-0.531****	**-0.478****	**-0.514****	**-0.503****	**-0.504****	**-0.498****	**-0.524****	**-0.581****	**-0.624****	**-0.663****	**-0.706****	**-0.547****	**-0.582****	**-0.655****	**-0.709****
BHR	**-0.527****	**-0.511****		-0.364*	**-0.497****	**-0.456****			**-0.567****	**-0.591****	**-0.452****	**-0.593****	**-0.549****	**-0.588****	**-0.512****	**-0.599****
BO	**0.534****	0.401*	**0.451****		**0.459****		**0.476****		**0.484****	**0.460****	**0.458****		**0.571****	**0.468****	0.441*	
BHD	-0.359*	**-0.456****		-0.351*		-0.393*			-0.382*	**-0.537****		**-0.477****	-0.413*	**-0.537****	-0.401*	**-0.565****
HBI	**0.469****	0.406*			0.374*			0.362*	0.410**	**0.458****			**0.518****	**0.482****		
SVF	0.442*	**0.476****	**0.498****	**0.499****	0.423*	0.429*	**0.496****	**0.515****	**0.510****	**0.561****	**0.646****	**0.723****	**0.476****	**0.511****	**0.615****	**0.683****

$^{*}p < 0.05$; $^{**}p < 0.01$ (two-tailed)

- The strength of correlation between the 3D indicators and relative humidity was higher in autumn and winter than in spring and summer.
- Changes in relative humidity were more influenced by the 3D building morphology within a 200-m radius around the observation stations.

The effects of building morphology on winds and $PM_{2.5}$

Table 3 The correlation coefficients between the 2D/3D building morphology indicators and wind speed

	Spring				Summer				Autumn				Winter			
	100m	200m	500m	1000m	100m	200m	500m	1000m	100m	200m	500m	1000m	100m	200m	500m	1000m
2D																
PD	-0.338*		**-0.443****	**-0.479****				-0.352*			-0.337*	-0.383*	-0.356*	-0.363*	**-0.439****	**-0.497****
3D																
BVD			**-0.533****	**-0.554****			-0.350*	-0.393*			**-0.424****	**-0.462****			**-0.535****	**-0.539****
BHR			**-0.535****	**-0.526****			-0.391*	-0.381*			**-0.462****	**-0.494****			**-0.525****	**-0.540****
BHD			**-0.575****	**-0.542****			**-0.443****	**-0.427****			**-0.500****	**-0.493****			**-0.572****	**-0.528****
SVF			0.348*	**0.441****								0.336*			0.373*	**0.458****

$^{*}p < 0.05$; $^{**}p < 0.01$ (two-tailed)

- The relationship between building morphology and winds was highly scale-dependent, and was weaker in summer compared with the other seasons.

Table 4 The correlation coefficients between the 2D/3D building morphology indicators and $PM_{2.5}$ concentrations

	Spring				Summer				Autumn				Winter			
	100m	200m	500m	1000m	100m	200m	500m	1000m	100m	200m	500m	1000m	100m	200m	500m	1000m
3D																
BHR	0.423*								**0.622****	0.458*						
BHD	0.465*	**0.565****	0.413*						**0.690****	**0.680****	0.464*	0.396*				

$^{*}p < 0.05$; $^{**}p < 0.01$ (two-tailed)

- Only BHR and BHD were significantly and positively correlated with $PM_{2.5}$ concentrations in spring and autumn, especially on 100- and 200-m scales.

Summary

- The 3D building morphology indicators had stronger associations with urban environments than the 2D indicators, and the degree of correlation between building morphology and air temperature was the highest, followed by relative humidity and wind speed.
- BVD had the greatest impact on temperature, and BHD exerted the strongest influence on wind speed.
- The effect of building morphology on urban environments was highly scale- and season-dependent.
    - 500 – 1000 m was the best scale to predict intra-urban air temperature and wind speed variability.
    - The effect of building morphology on urban microclimate was stronger in dry and windy seasons.

OUTLINE

1、 Research background

2、 Research methods and tools

3、 Three case studies

4、 Conclusions

- 城市土地面积占陆地总面积的比例虽然只有不到1%，但是城市化对局地、区域乃至全球气候的影响不容忽视；
- 城市热岛研究不应只局限于城市与郊区之间的对比，城市内部景观格局变化对局地气象要素有重要的影响；
- 激光雷达技术和移动数据处理技术的发展，促进了三维景观格局的分析与应用，未来应更多关注三维城市景观格局对区域大气环境的影响；
- 以景观可持续科学为指导，将研究结论应用到城市规划与设计中，从而建设更加宜居的城市，提高居民福祉。

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RESEARCH ARTICLE

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Impacts of urbanization on summer climate in China: An assessment with coupled land-atmospheric modeling

Qian Cao[1], Deyong Yu[1], Matei Georgescu[2], and Jianguo Wu[1,3]

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Qian Cao[a], Deyong Yu[a,*], Matei Georgescu[b], Jianguo Wu[a,c,**], Wei Wang[d]

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The effects of 2D and 3D building morphology on urban environments: A multi-scale analysis in the Beijing metropolitan region

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