



南京信息工程大学

Modeling impacts of urbanization and urban heat island mitigation on boundary layer meteorology and air quality in Beijing under different weather conditions

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(Chen et al., 2018JGR)

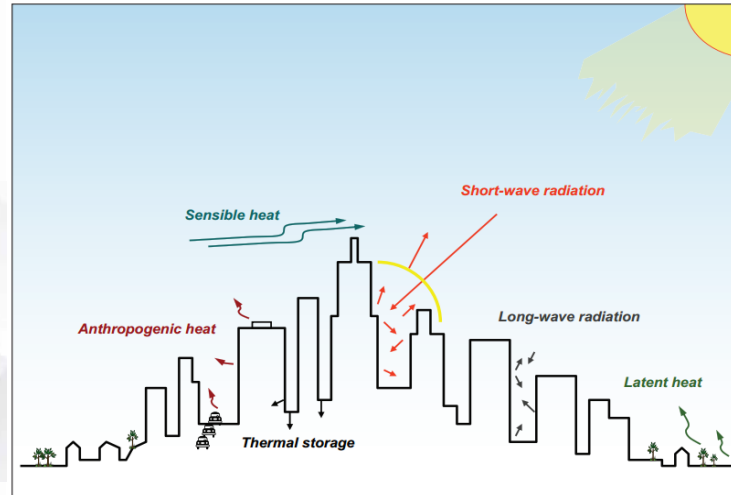


Outline

- **Background**
- **Objective**
- **Model description**
- **Model evaluation**
- **Results**
- **Conclusions**



Background



natural vegetation → **artificial construction**

Albedo

Vegetation fraction

Sky view factor/radiation trap

Thermal storage/conductivity

Roughness



Anthropogenic heat

Anthropogenic aerosol



Boundary layer meteorology and air quality in urban areas

Background

- **Beijing is the capital of China.** Its **population** has been over 21 million since the end of 2015, and the **population density** in built-up areas ranks fourth in China.
- Due to a large number of rural population flocking to the Beijing metropolitan region, **the urban built-up areas in Beijing significant increase** with an average annual growth rate of 11.6% since 2000.



Background

- Most previous modeling studies on urbanization impacts over China mainly focus on the Yangtze River Delta (YRD) region and the Pearl River Delta Region (PRD) region, **but few analyze the impacts over the North China Plain, especially in the densely populated Beijing metropolitan area.**
- Heat waves (HWs) will become more frequent and last longer in the late 21st century, and the North China Plain has been suffering from severe haze pollution with fine particulate matter reaching unprecedentedly high levels. **But few studies quantify the synergies between HWs and urban heat island (UHI), and the synergies between aerosols and UHI.**

The most well-known urban climate feature caused by urbanization is UHI, which means the urban area is obviously warmer than its surrounding rural areas.

- Urbanization can cause significant urban heat island intensity, and numerous studies have been carried out to research the efficient mitigation technologies to reduce UHI intensity. **However, few researches focus on the impacts of UHI mitigation strategies on urban air quality.**

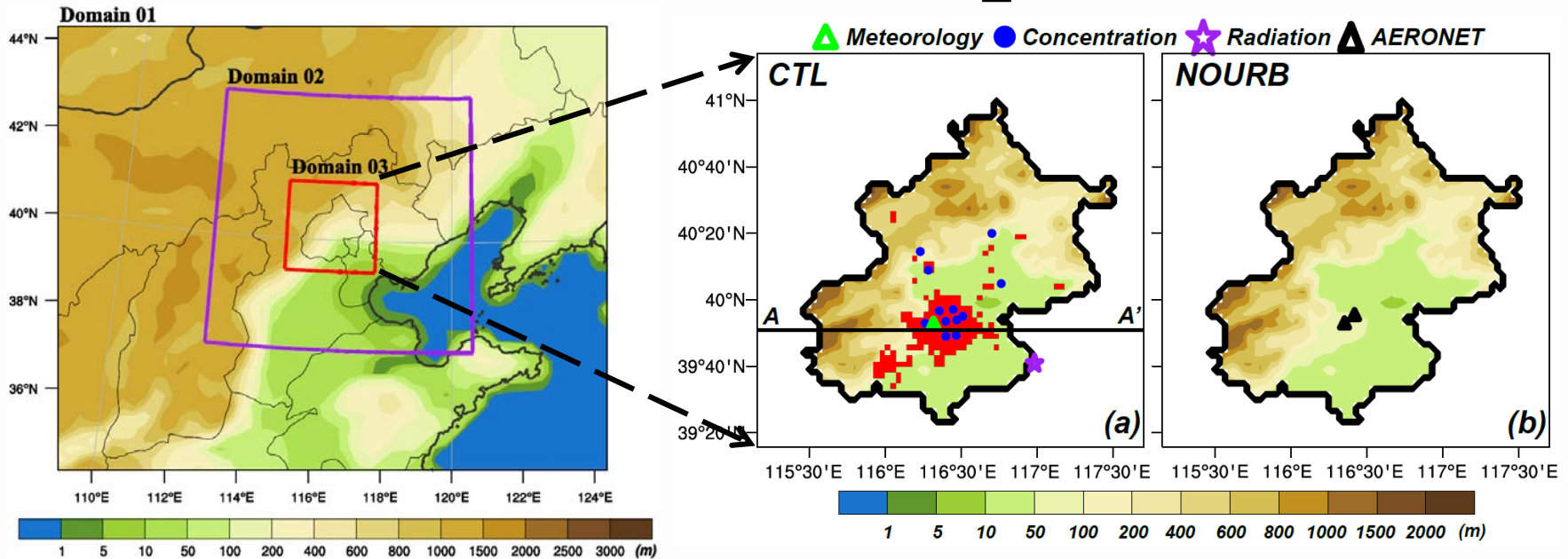


Objective

- This study aims to **quantify the impacts of urbanization on regional climate and air quality, and the influence of UHI mitigation measures on air quality in Beijing**, with special attention on the impacts under different weather conditions (i.e., heat waves in summer and polluted days in winter).
- Try to provide helpful suggestions for policy makers in both city planning and climate change mitigation.



Model Description



WRF-Chem v3.7

● Simulation period:

✓ 26 June ~ 31 July 2015 (as summer) && 16 November ~ 21 December 2015 (as winter)

● Simulation area:

- ✓ Three nested domains at 27 km, 9 km, and 3 km horizontal resolution, respectively.
- ✓ An inner region of the third domain (39.41°N–41.18°N, 115.19°E–117.52°E) with 68 × 68 grid points are analyzed.
- ✓ 29 sigma levels from the surface to 50 hPa with the lowest 12 layers below 1 km.

Data inputs

- Anthropogenic emissions are based on the MIX inventory for the year 2010.
- Biogenic emissions are calculated online using MEGANv2.04.
- Biomass burning emissions are taken from GFEDv3.1.
- NCEP Final reanalysis data is used as initial meteorological fields and boundary condition.
- MOZART output data is used as the chemical initial and boundary condition.

Parameterization schemes

Options	WRF-Chem
Microphysics option	Purdue Lin Scheme
Longwave radiation option	RRTMG Scheme
Shortwave radiation option	RRTMG Scheme
Surface layer option	Revised MM5 Monin–Obukhov Scheme
Land surface option	Unified Noah land–surface model
Urban canopy model	Single–layer UCM Scheme
Boundary layer option	YSU Scheme
Cumulus option	Grell 3D ensemble Scheme
Photolysis scheme	Fast–J
Dust scheme	Shao_2004
Chemistry option	CBMZ
Aerosol option	MOSAIC
Analysis nudging	On (including grid nudging and surface nudging)

Numerical experiments

Case Description	Urban Scenarios	Urban Albedo
CTL	Modis Urban (2015)	0.2
NOURB	No Urban	0.2
ALBEDO	Modis Urban (2015)	0.85

- **CTL:** The control case represents the land-use condition in 2015 retrieved from MODIS satellite observation data
- **NOURB:** Same as CTL, but all urban grids are replaced by irrigated cropland.
Irrigate cropland is the most common land cover type in and around Beijing, and is often used to represent the pre-urbanization land cover type (Wang et al., 2012JGR; Wang et al., 2014JAMC)
- **ALBEDO:** Same as CTL, but the albedo within urban grids is modified from **0.2** to **0.85**, following Wang et al. (2013TAC) and Vahmani et al.(2016ERL).
The albedo of 0.85 represents an ideal highly reflective white paint (Fallmann et al., 2016AE)

CTL vs. NOURB: analyze the impacts of urbanization on boundary layer meteorological parameters and air pollutant concentrations

CTL vs. ALBEDO: quantify the effects of UHI mitigation (increasing urban albedo) on air quality

Model evaluation

➤ Meteorological parameters:

- Temperature
- Relative Humidity
- Wind Speed
- Wind Direction

➤ Surface-layer concentrations:

- O₃
- PM_{2.5}

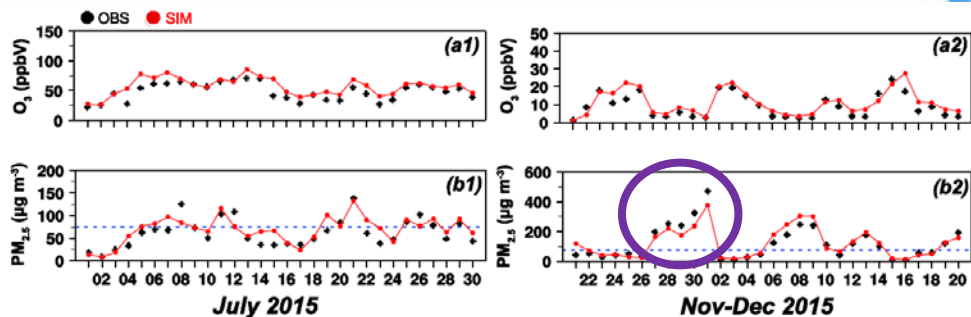
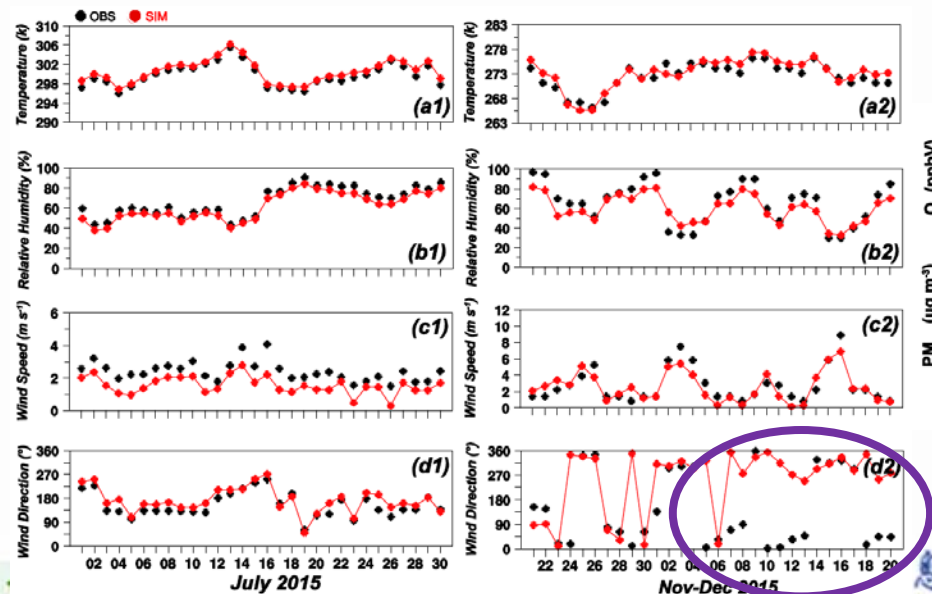


Statistics of comparisons between OBS and SIM

Variables	Summer					Winter				
	\overline{OBS}^a	\overline{SIM}^b	MB ^c	RMSE ^d	R ^e	\overline{OBS}^a	\overline{SIM}^b	MB ^c	RMSE ^d	R ^e
Temp (K)	299.8	300.6	0.79	0.85	0.97	272.5	273.2	0.66	1.4	0.92
RH (%)	66.9	61.8	-5.1	5.4	0.92	65.8	59.9	-5.9	10.7	0.94
WS ($m s^{-1}$)	2.39	1.56	-0.84	0.90	0.83	2.75	2.54	-0.21	1.1	0.87
WD (°)	154.4	172.2	17.8	24.6	0.93	143	250.1	107.1	183.1	0.31
O ₃ (ppbV)	48.2	56.9	8.7	11.8	0.84	9.1	11.1	2.0	3.6	0.90
PM _{2.5} ($\mu g m^{-3}$)	62.0	68.4	6.4	19.8	0.80	120	121.7	1.6	40.3	0.93

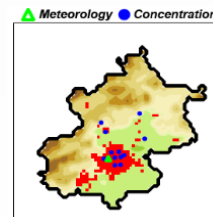
R ≥ 0.80

R ≥ 0.85



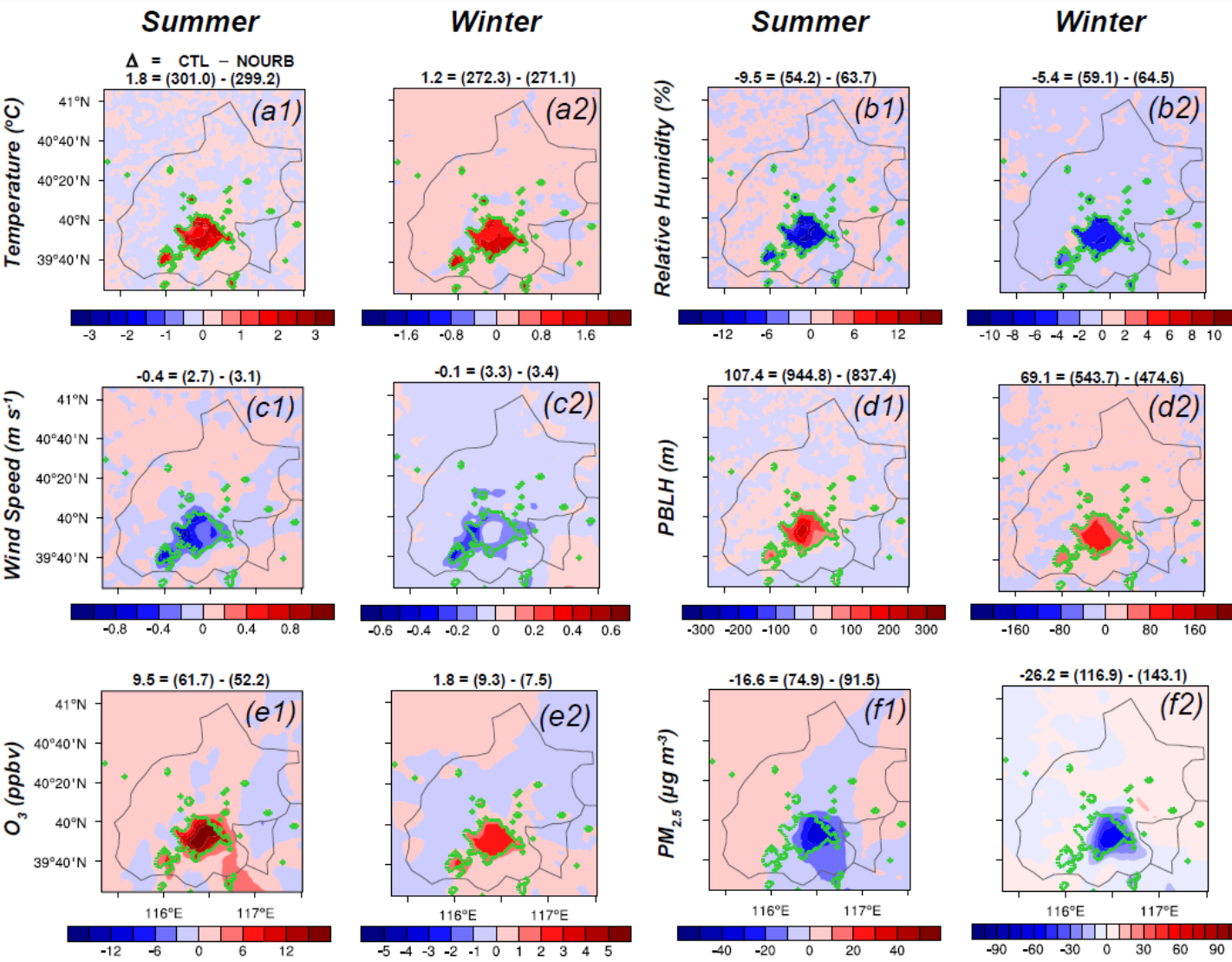
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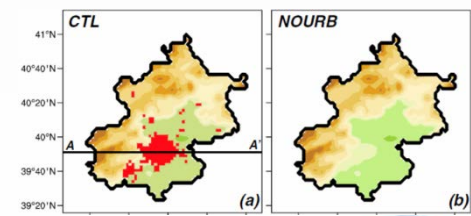


Result 1: Impacts of Urban Sprawl

CTL vs. NOURB

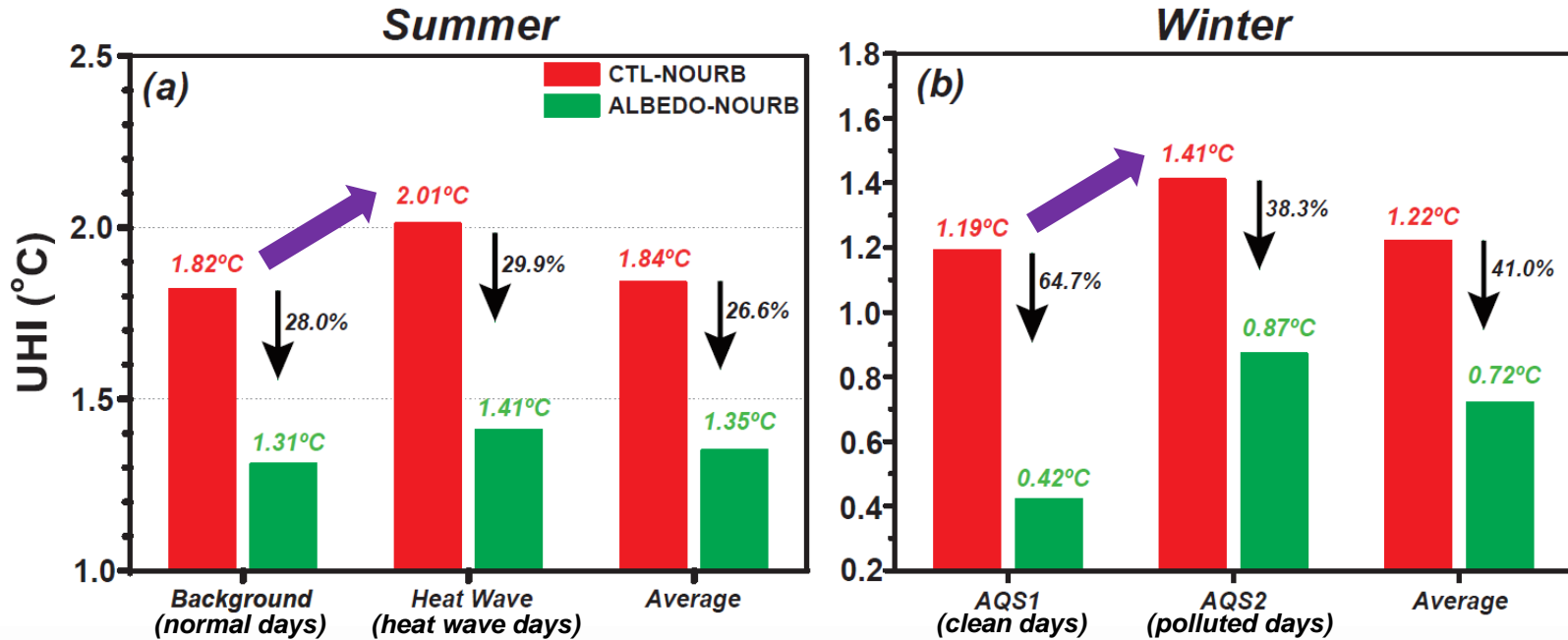


Temp \uparrow 1.2~1.8 k
 RH \downarrow -9.5~-5.4%
 WS \downarrow -0.1~-0.4m s⁻¹
 PBLH \uparrow 69.1~107.4m
 O₃ \uparrow 1.8~9.5ppbv
 PM_{2.5} \downarrow -26.2~-16.6 $\mu\text{g m}^{-3}$



Result 2: Impacts of UHI mitigation

CTL vs. ALBEDO



In summer, a day with the daily mean temperature averaged over urban areas in Beijing larger than 35°C is defined as a **heat wave day**

In winter, a day with the daily mean $\text{PM}_{2.5}$ concentration averaged over urban areas in Beijing larger than $75\ \mu\text{g m}^{-3}$ is classified as a **polluted day**

When the urban albedo is increased from 0.2 to 0.85:

- the UHI intensity is **decreased** by **28.0%** in normal days and by **29.9%** in hot days during summer
- the UHI intensity is **decreased** by **64.7%** in clean days and by **38.3%** in polluted days during winter

Increasing urban albedo is an effective mitigation strategy to reduce UHI intensity especially during HW days and clean days

Species	Weather condition	Summer (01 to 30 July 2015)						Winter (21 November to 20 December 2015)					
		Daily Maximum			Daily Average			Daily Maximum			Daily Average		
		ALBEDO	CTL	Delta	ALBEDO	CTL	Delta	ALBEDO	CTL	Delta	ALBEDO	CTL	Delta
PM _{2.5} ($\mu\text{g m}^{-3}$)	Type1 ^a	124.2	114.9	9.3	84.5	75.1	9.4	37.1	34.0	3.1	24.6	21.7	2.9
	Type2 ^b	140.4	113.4	27.0	89.6	72.5	17.1	200.5	192.1	8.5	184.6	176.6	8.0
	Avg	125.8	114.8	11.1	85.1	74.9	10.2	136.3	128.8	7.5	123.0	116.9	6.1
O ₃ (ppbV)	Type1 ^a	100.0	99.6	0.38	55.9	59.5	-3.5	28.3	31.9	-3.7	16.9	19.1	-2.2
	Type2 ^b	156.4	143.7	12.8	80.4	81.9	-1.6	15.6	17.7	-2.2	4.6	5.2	-0.6
	Avg	105.5	103.7	1.8	58.4	61.7	-3.3	19.4	21.9	-2.5	8.3	9.3	-1.0

When the urban albedo increases from 0.2 to 0.85:

- Both the daily maximum and the daily average PM_{2.5} concentrations are **increased** in summer and winter
- Compared with normal days (clean days), the increase in PM_{2.5} concentrations is **larger** under HWs during summer (in polluted days during winter);
- The daily mean O₃ concentrations are **decreased** both in summer and winter
- However, the daily maximum O₃ concentration in summer is **increased**, and the increase is larger under HWs (12.8 ppbv) than in normal days (0.38 ppbv).

Conclusions

- The modification of rural land–use into urban impervious surface significantly **increases T_2 and PBLH**, but **decreases RH_2 and WS_{10}** in urban Beijing
- Urbanization leads to the **increase in surface-layer O_3 concentrations** of 9.5 ppbv in summer and 1.8 ppbv in winter, and the **decreases in $PM_{2.5}$ concentrations** of $16.6 \mu\text{g m}^{-3}$ in summer and $26.2 \mu\text{g m}^{-3}$ in winter.
- Although **increasing urban albedo is an effective mitigation strategy to decrease UHI intensity**, it can **worsen the urban air quality**. When the urban albedo is increased from 0.2 to 0.85:
 - **Daily average $PM_{2.5}$ concentrations are increased** by 10.2 (6.1) $\mu\text{g m}^{-3}$ in summer (in winter)
 - **Daily maximum O_3 concentrations are increased** by 12.8 ppbv under heat waves in summer.





Thank You





Background

- **Beijing is the capital of China.** Its **population** has been over 21 million since the end of 2015, and the **population density** in built-up areas ranks fourth in China.
- Due to a large number of rural population flocking to the Beijing metropolitan region, **the urban built-up areas in Beijing significant increase** with an average annual growth rate of 11.6% since 2000.
- **Beijing has been suffering from serious air pollutions during recent years.** The annual concentration of PM_{2.5} in Beijing is ~80 μg m⁻³ in 2015, nearly eight times higher than the WHO guideline, including 26 days under heavy pollution (daily PM_{2.5} concentration >150 μg m⁻³).



Background

Li et al. (2015ERL) pointed out that heat waves (HWs) in summer could not only increase the ambient temperature in urban and rural regions, but also enhance the urban heat island (UHI) intensity which is caused by urbanization, implying the synergies between HWs and UHI.

Cao et al. (2016NC) revealed that the haze pollution could enhance UHI in China, especially over densely populated metropolises, implying the synergies between aerosol and UHI.



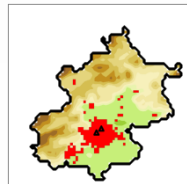
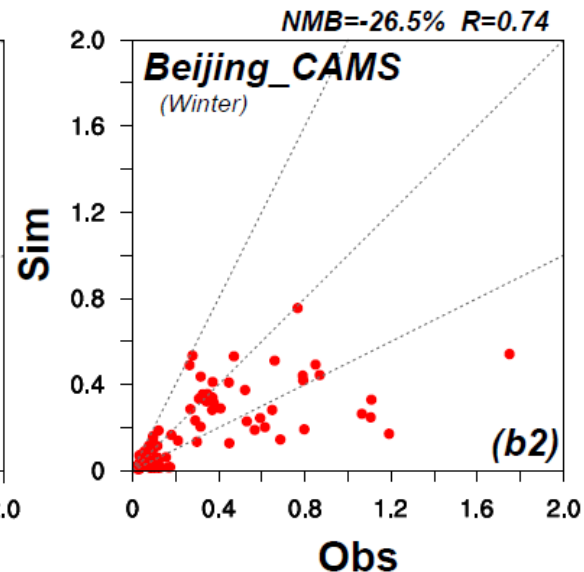
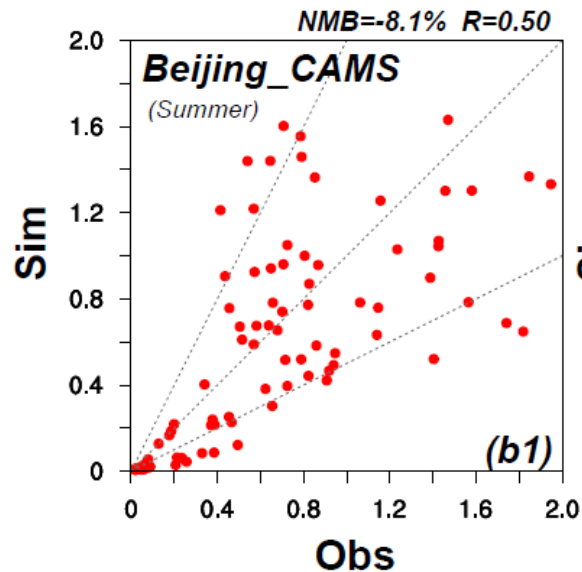
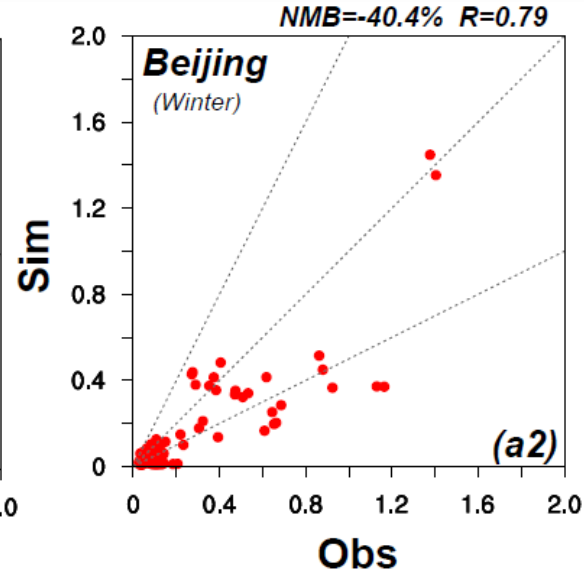
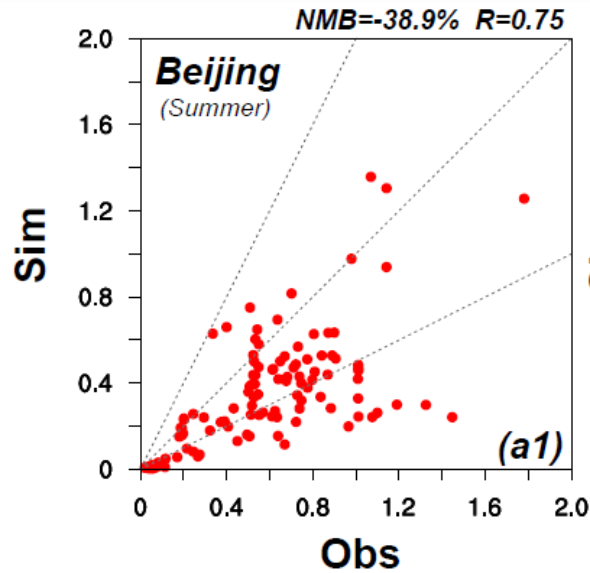
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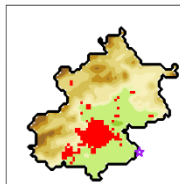
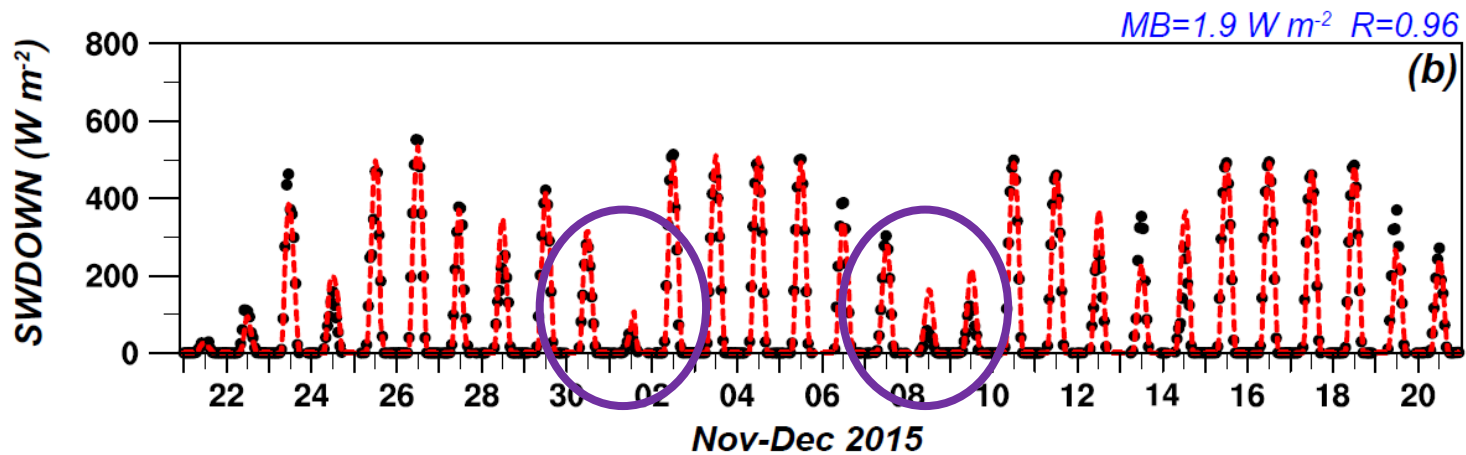
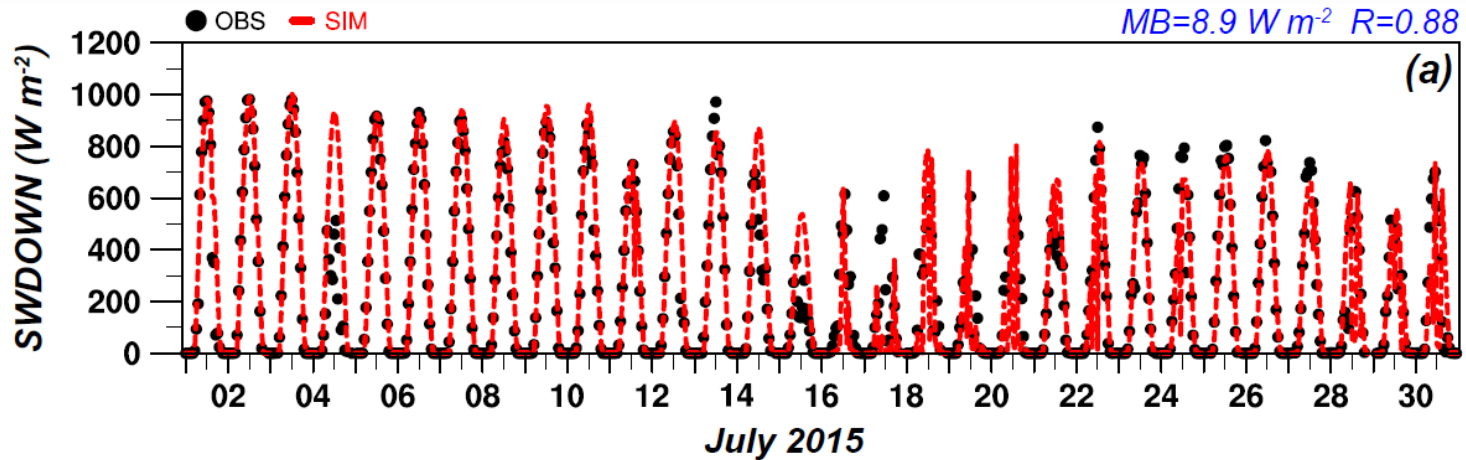
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Urbanization can cause significant urban heat island intensity, and numerous studies have been carried out to research the efficient mitigation technologies to reduce UHI intensity. **However, few researches focus on the impacts of UHI mitigation strategies on urban air quality.**

Scatter plots of hourly AOD



Time series of hourly solar downward radiation flux



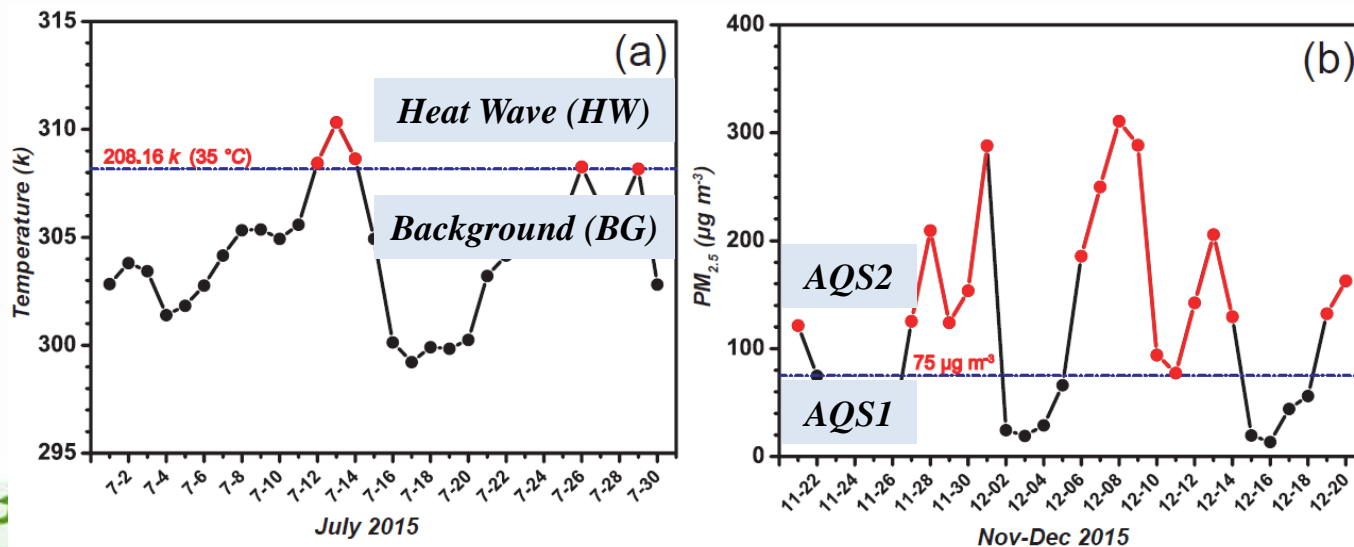
Results

- Impacts of **urbanization** on boundary layer meteorological fields and air pollutants
- Impacts of **UHI mitigation strategy** (increasing urban albedo) on urban air quality



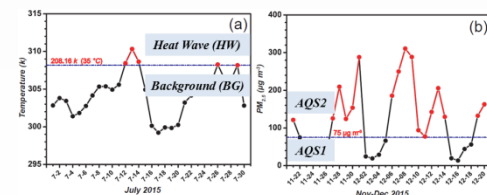
To better understand the effects of urbanization on boundary layer meteorology and air quality over Beijing **under different weather conditions**, we highlight heat wave days in summer and polluted days in winter:

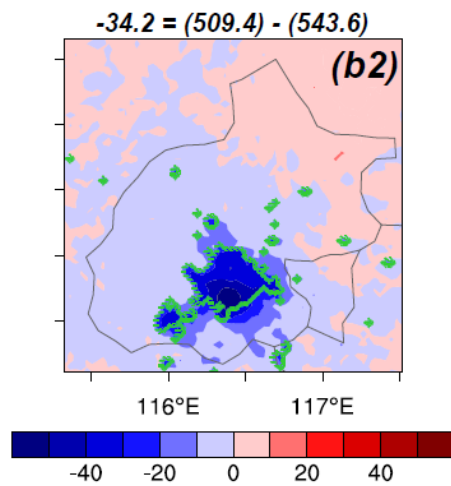
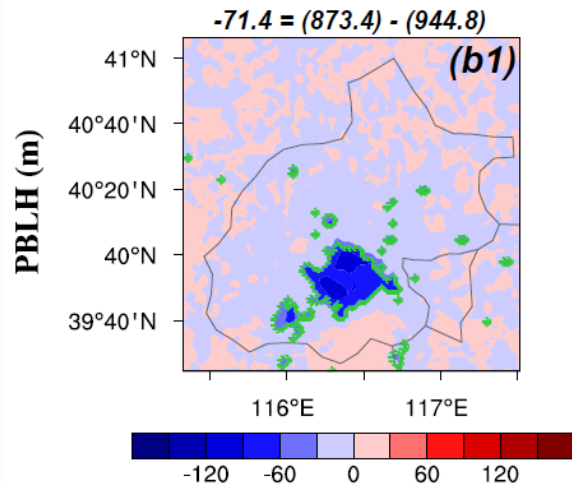
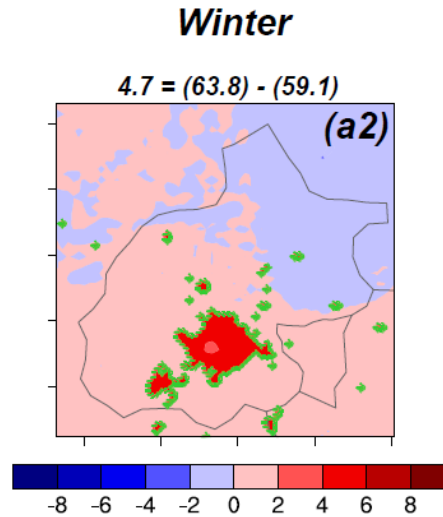
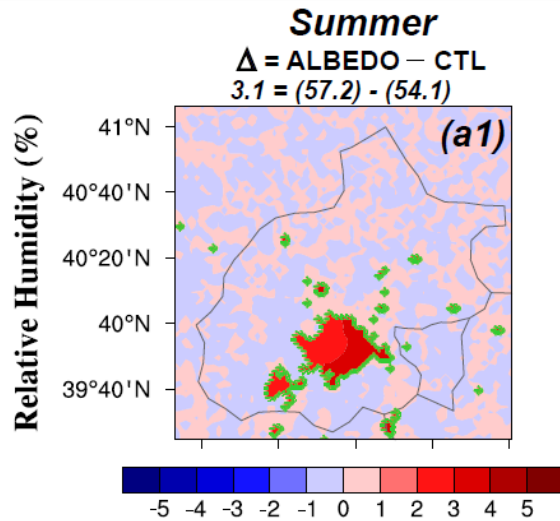
- In summer, a day with the daily mean temperature averaged over the urban areas in Beijing **larger than 35 °C** is defined as a **heat wave day**. (following Tan et al., 2007IJB; Smith et al., 2013CC)
- In winter, a day with the daily mean PM_{2.5} concentration averaged over the urban areas in Beijing **larger than 75 μg m⁻³** is classified as a **polluted day**. (see the Grade II standard defined by the National Ambient Air Quality Standards of China)



Period	Weather condition	Temp (K)			RH (%)			PBLH (m)			O ₃ (ppbv)			PM _{2.5} (μg m ⁻³)		
		CTL ^e	NOURB ^f	Delta ^g	CTL	NOURB	Delta	CTL	NOURB	Delta	CTL	NOURB	Delta	CTL	NOURB	Delta
Summer (01 to 30 July 2015)	BG ^a	303.4	301.6	1.8	55.6	65.3	-9.6	922.4	815.7	106.7	59.5	49.7	9.8	75.1	91.5	-16.3
	HW ^b	308.8	306.8	2.0	41.0	49.2	-8.3	1146.3	1033.1	113.3	81.9	75.0	7.0	72.5	91.8	-19.4
Winter (21 November to 20 December 2015)	AQS1 ^c	271.0	269.8	1.2	46.2	54.6	-8.4	757.4	667.8	89.5	19.1	15.5	3.5	21.7	27.5	-5.8
	AQS2 ^d	273.6	272.1	1.4	65.9	71.4	-5.5	456.5	389.8	66.7	5.2	3.9	1.3	176.6	216.1	-39.5

- Compared with normal days (clean days), UHI intensity is enhanced by 11.1% during heat waves in summer (by 16.7% during polluted days in winter)
- The decreases in relative humidity induced by urbanization are smaller in hot days and polluted days.
- The increases in PBLH due to urbanization are larger during heat waves in summer but smaller during polluted days in winter.
- Urbanization can increase the surface-layer O₃ concentrations over the urbanized areas both in summer and winter, but the impacts are reduced during HWs and polluted days
- The decreases in surface-layer PM_{2.5} concentrations induced by urbanization are larger in hot days and polluted days





RH ↑ 3.1~4.7%
PBLH ↓ -71.4~-34.2m