Urban Climate and Smart City Development

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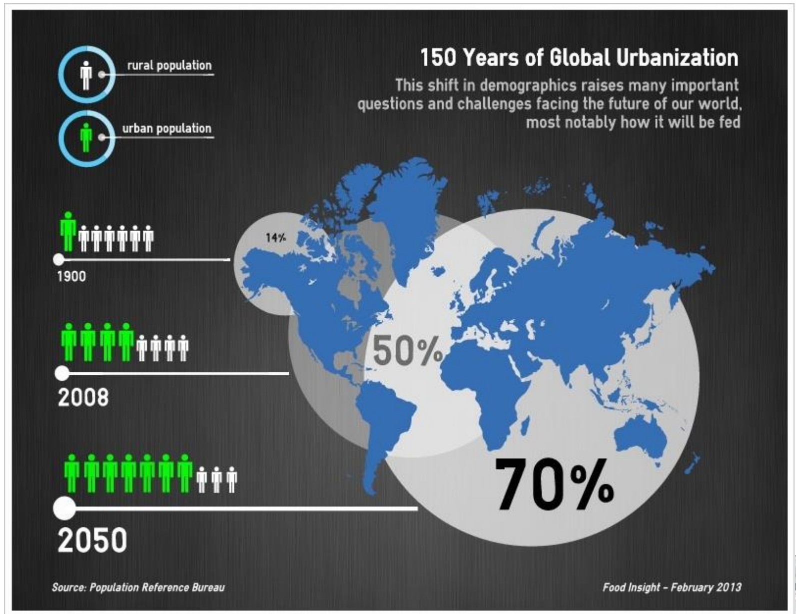
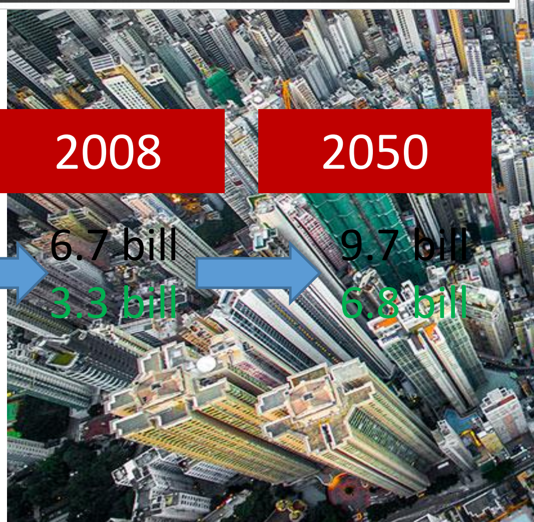
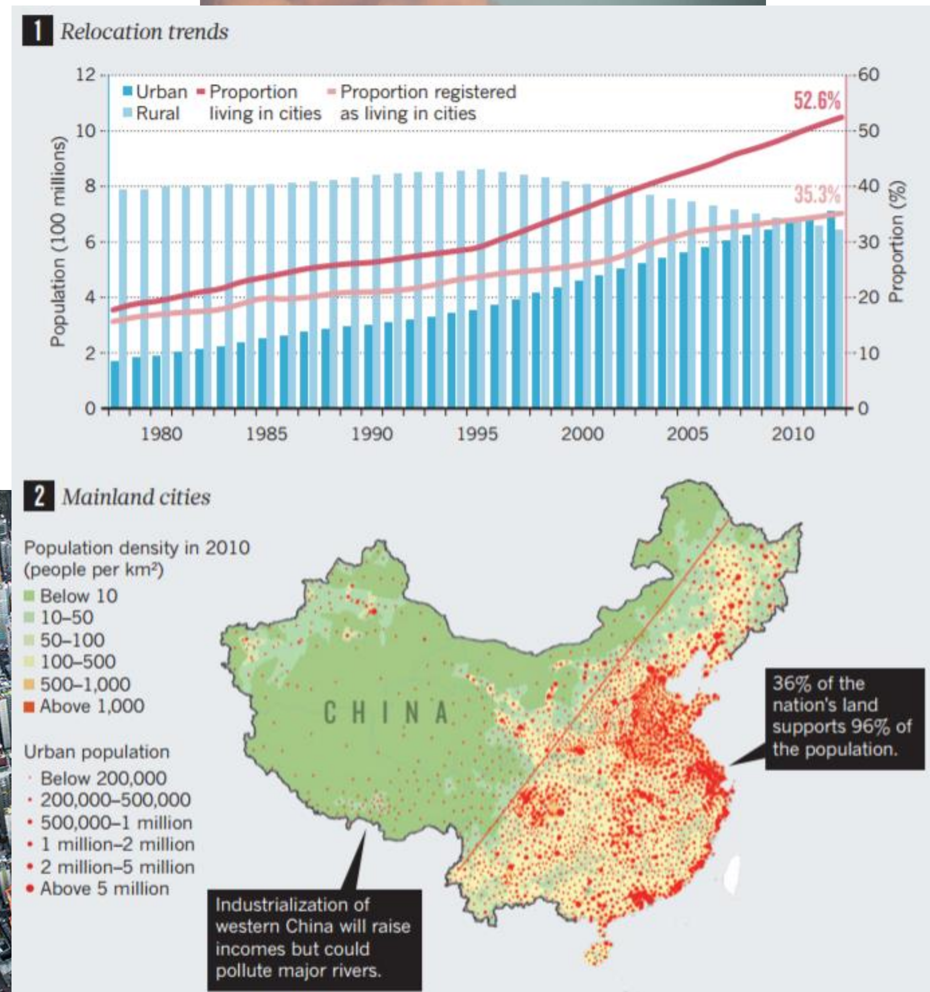
Ongoing Urbanization



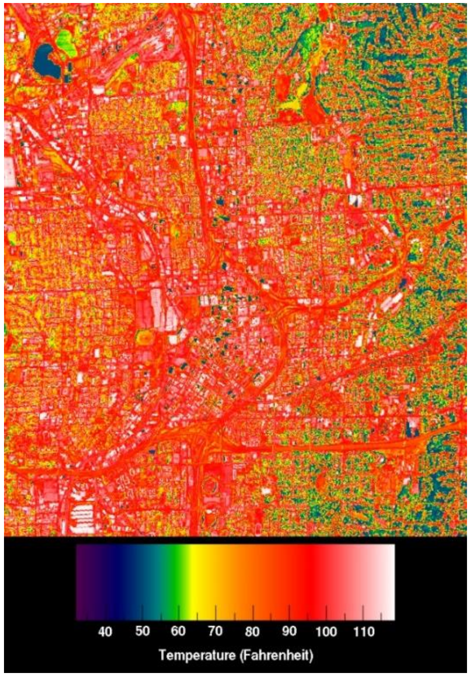


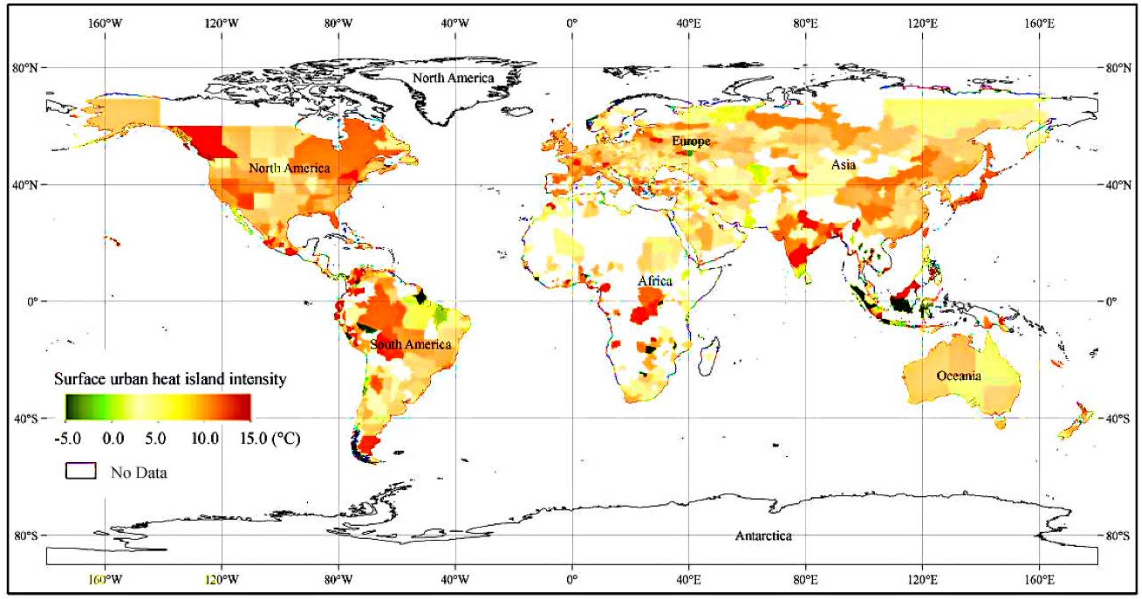


1900	2008	2050
1.6 bill	6.7 bill	9.7 bill
0.2 bill	3.3 bill	6.8 bill

Source: http://www.museumofthecity.org/project/urban-air-pollution-in-chinese-cities/
https://agnux.wordpress.com/2009/06/22/ecofasa-turns-waste-to-biodiesel-using-bacteria/
http://environment.nationalgeographic.com/environment/photos/urban-threats/

Urban Heat Island (UHI)

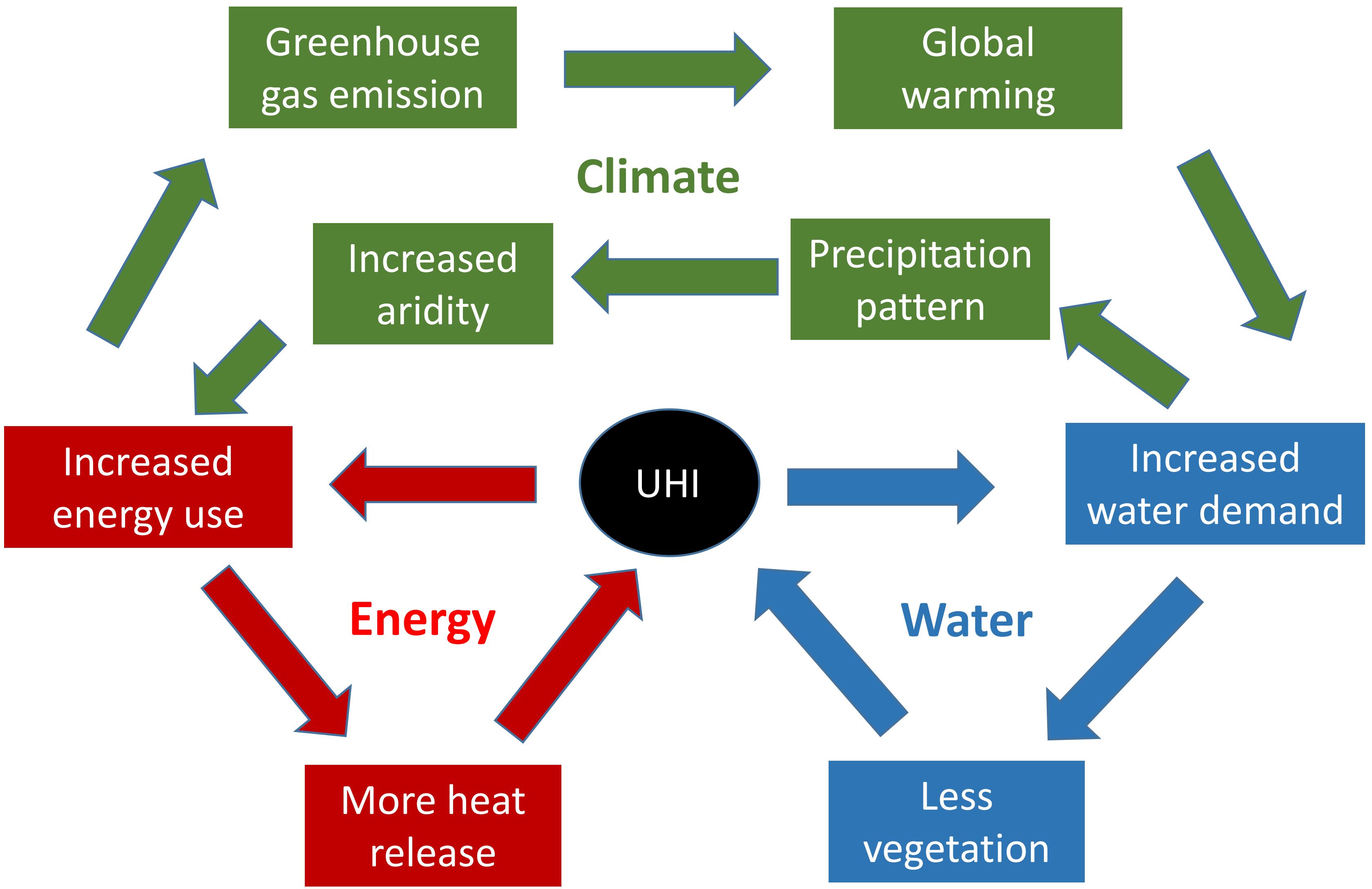




❖ From 1979-2003, excessive heat exposure causes more deaths than hurricanes, lightning, tornadoes, floods, and earthquakes in U.S. (Center for Disease Control and Prevention, 2006)

http://environment.nationalgeographic.com/environment/photos/urban-threats/
http://www.mdpi.com/2071-1050/8/8/706

Water-Energy-Climate Feedback



Urban Heat Mitigation

Urban heat island	Technology → Policy	**Smart cities**
➢ Large heat storage in engineering materials	→	➢ Novel engineering material
➢ Reduced evaporative cooling due to small vegetative cover	→	➢ Urban green landscape
➢ Built-up landscape traps radiation and inhibits advective cooling	→	➢ Resilient urban form design
➢ Waste heat released from anthropogenic activities	→	➢ Green and renewable energy, efficient energy use

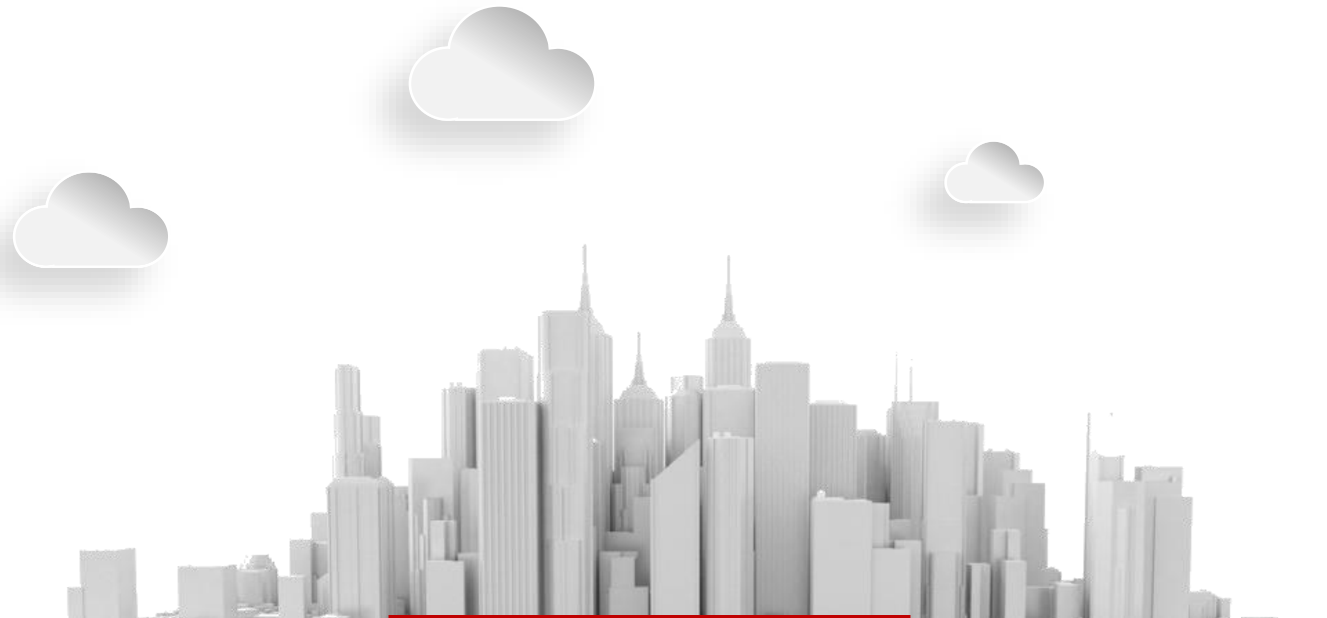
Research Question

How to manage the water-energy-climate nexus to develop smart cities under global change?

- What needs to be done?
  Investigate the impact of potential adaptation/mitigation technology and policy on complex urban water-energy-climate nexus

- How? A synthesis of experimental and numerical approaches

Scale issue **Complex processes**



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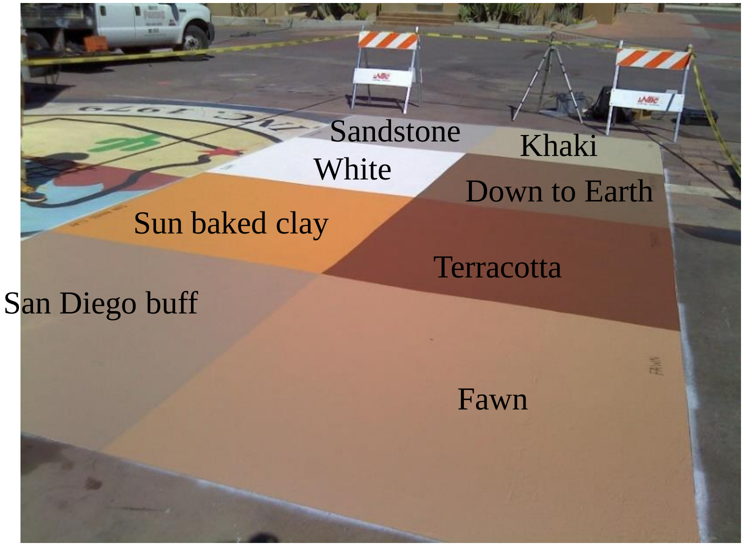
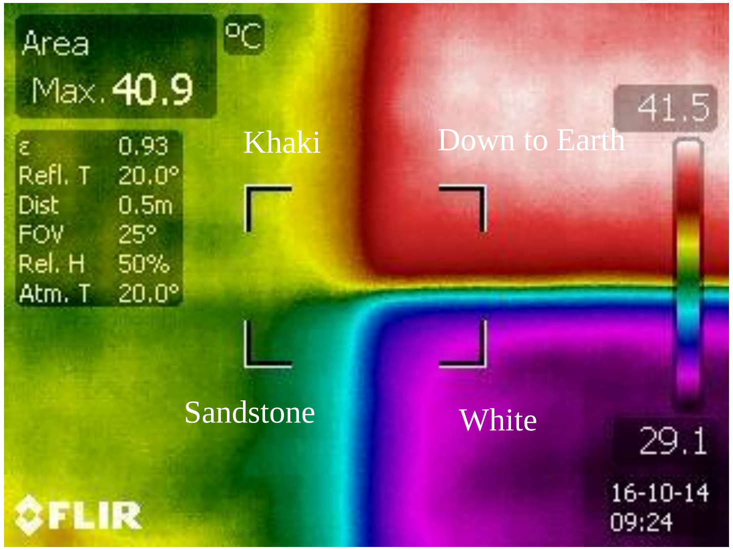
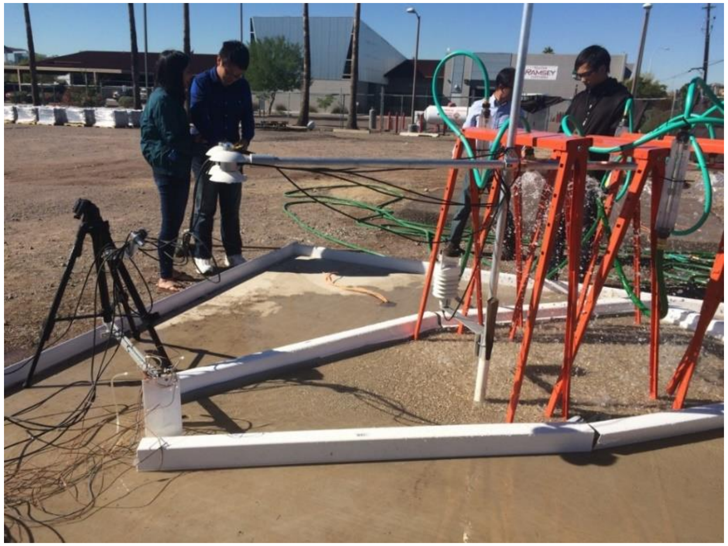
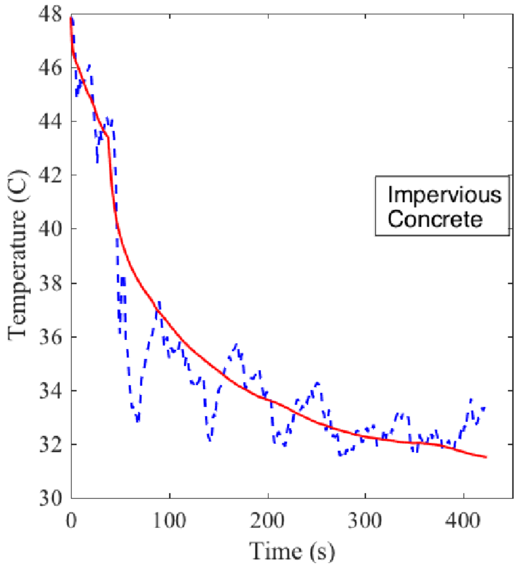
Sensing Engineering Materials









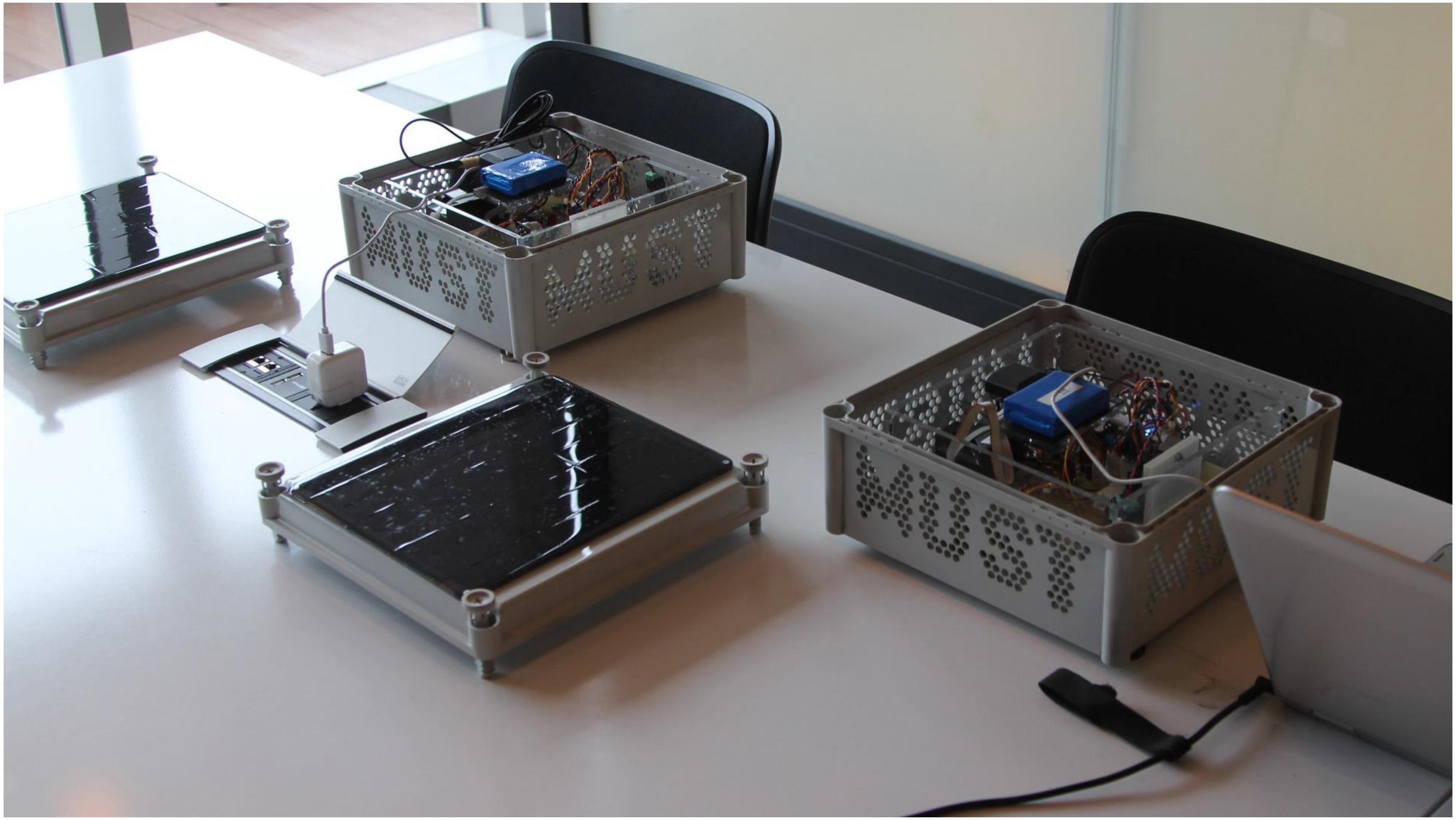
Omidvar, Song, **Yang** et al. *Water Resour. Res.* 2018

Sensing the Campus

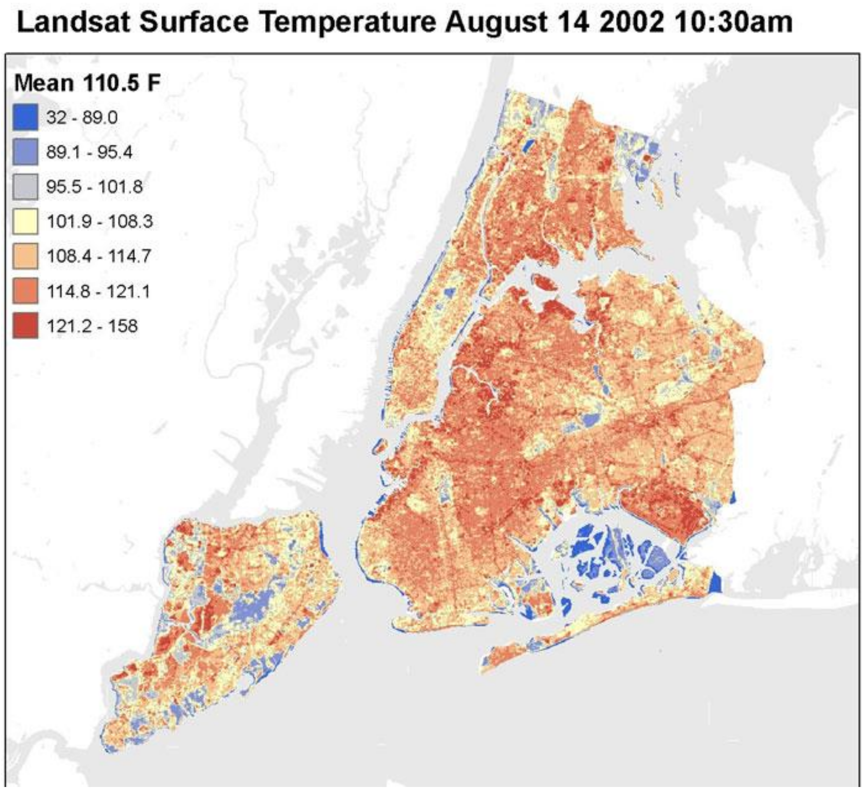
Wireless Sensor Network


Mobile Urban Sensing Technologies (MUST)

Led by Maider Llaguno-Munitxa



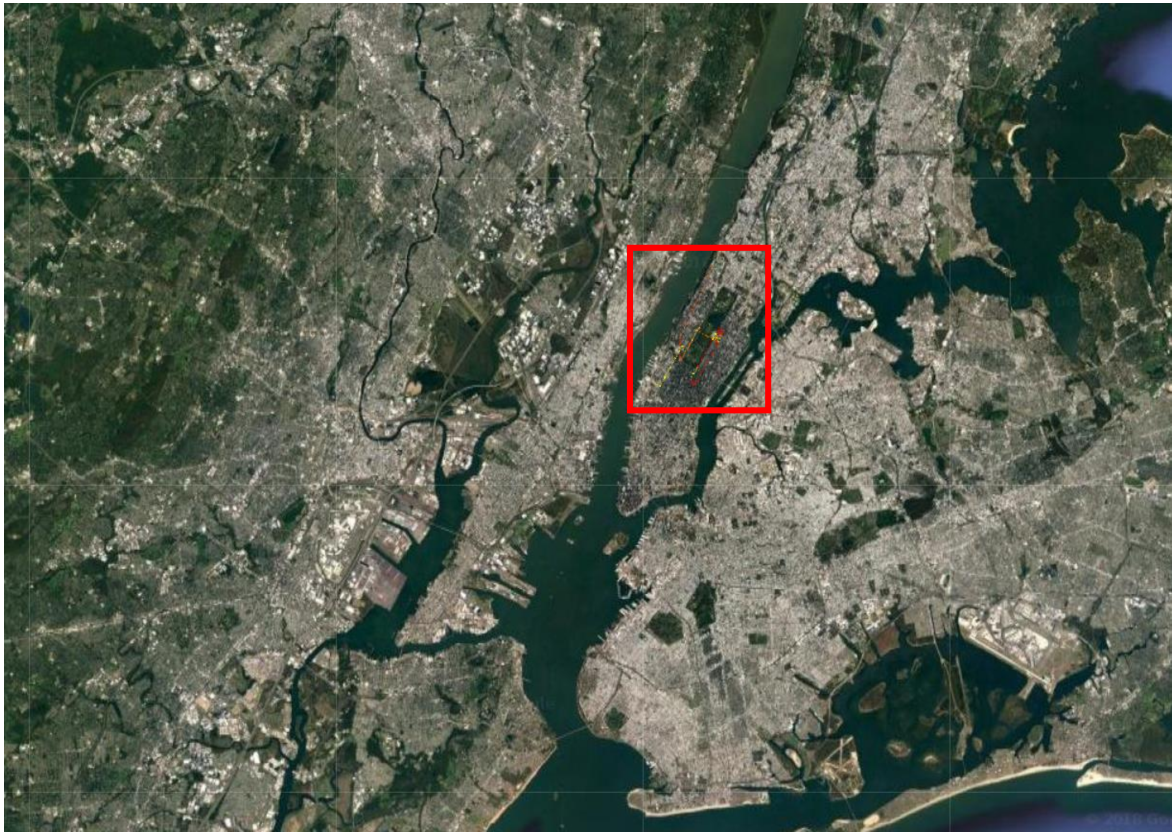
Heterogeneous Urban Environment



Spatiotemporal temperature variability

https://www.nasa.gov/centers/goddard/news/topstory/2005/nyc_heatisland.html

How many stations (mobile/fixed) do we need?



New York City

Spatial

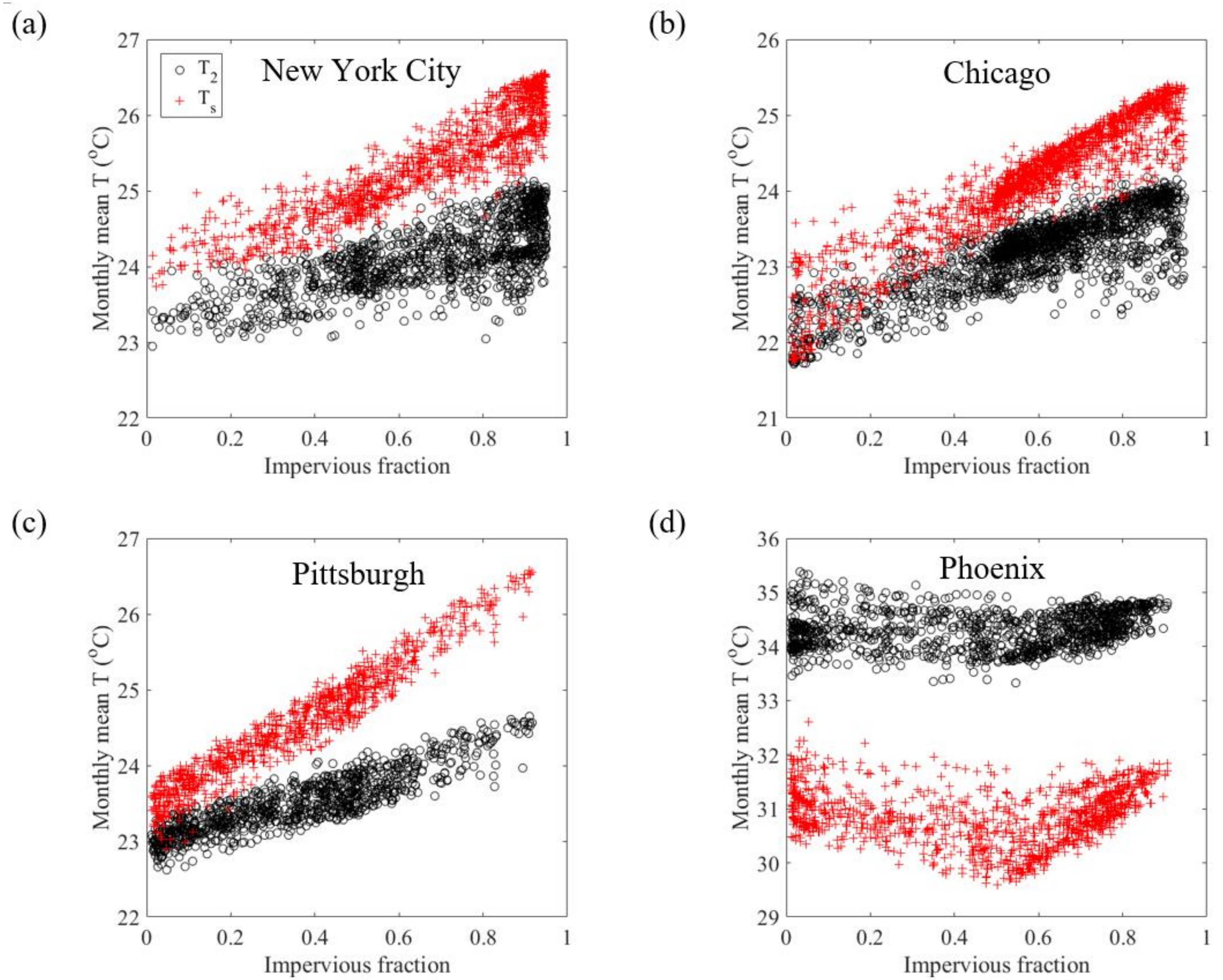
42880 grids (500 m x 500 m)

Temporal

1440 time (30-min interval)

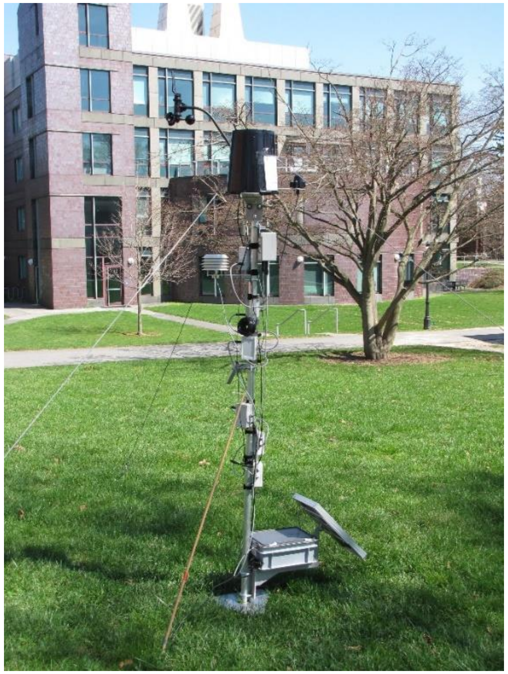
61,747,200

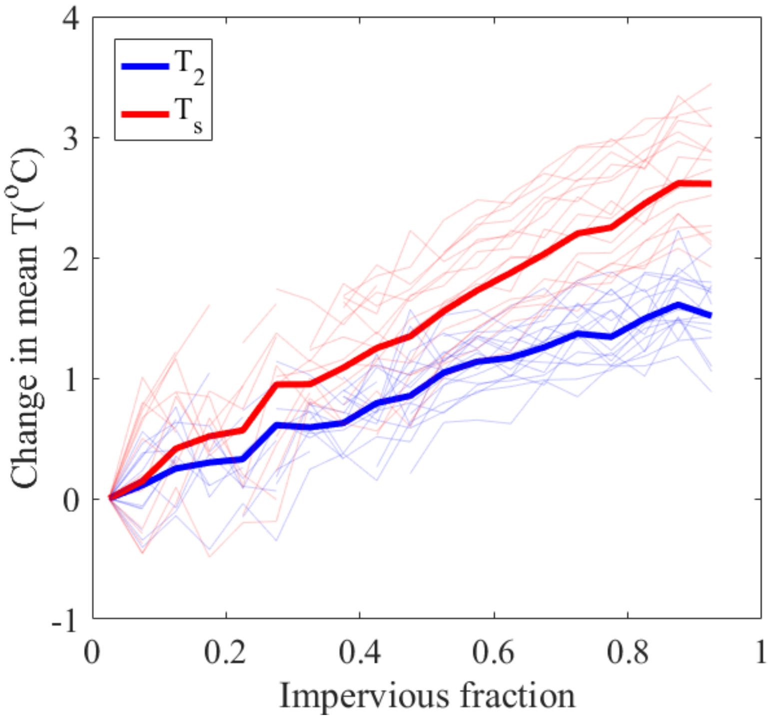
Monthly Mean Temperature



Sensor Network Design

<u>Measurement network A:</u>
randomly distributed fixed (RDF) sensors assuming no prior knowledge of the urban land use

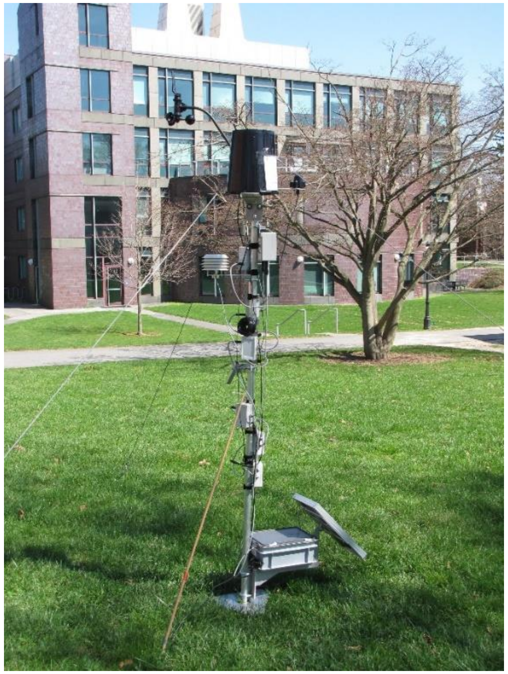


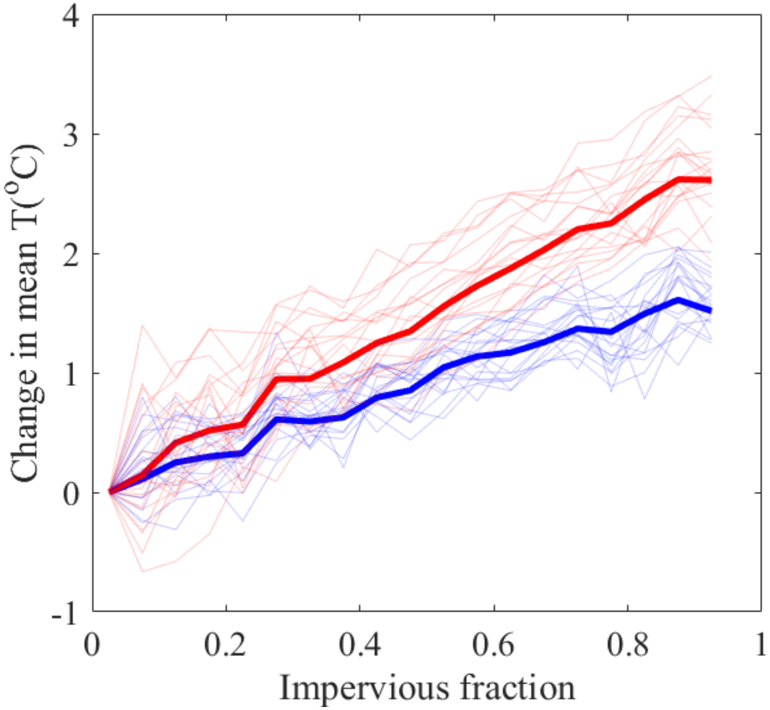


Yang and Bou-Zeid, *Environ. Res. Lett.* 2019

Sensor Network Design

<u>Measurement network B:</u>
evenly distributed fixed (EDF) sensors with equal measurements over each bin of impervious fractions

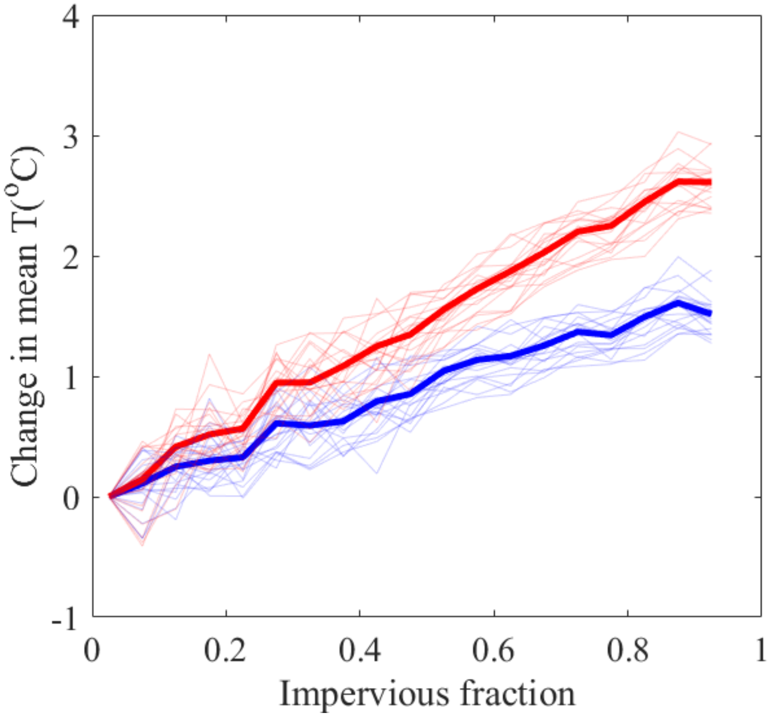




Yang and Bou-Zeid, *Environ. Res. Lett.* 2019

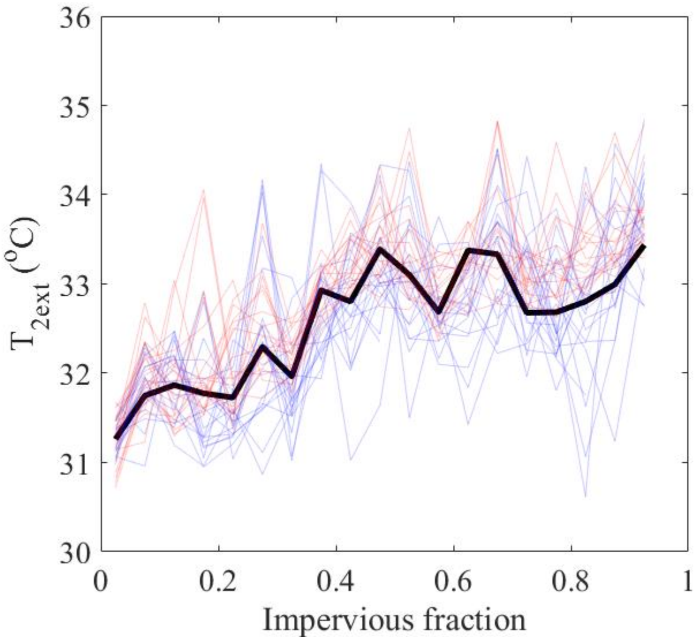
Sensor Network Design

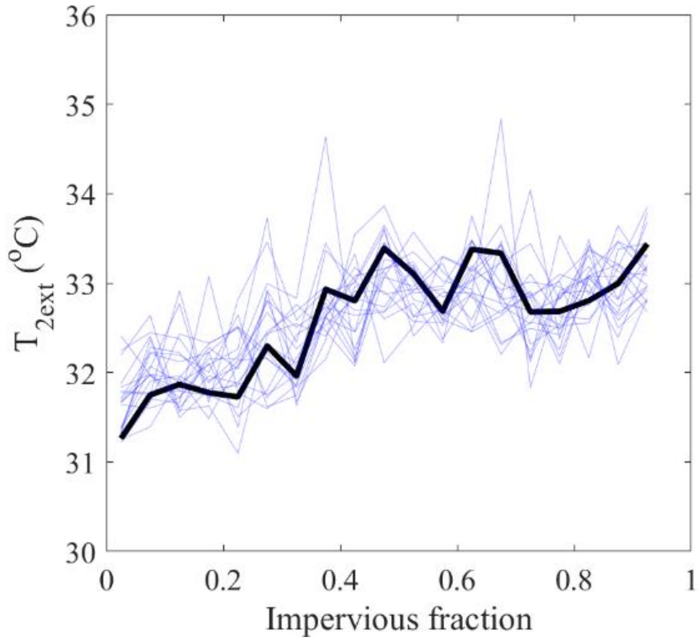
<u>Measurement network D:</u>
mobile measurement network (MMN) with sensors moving randomly within the studied area



Yang and Bou-Zeid, *Environ. Res. Lett.* 2019

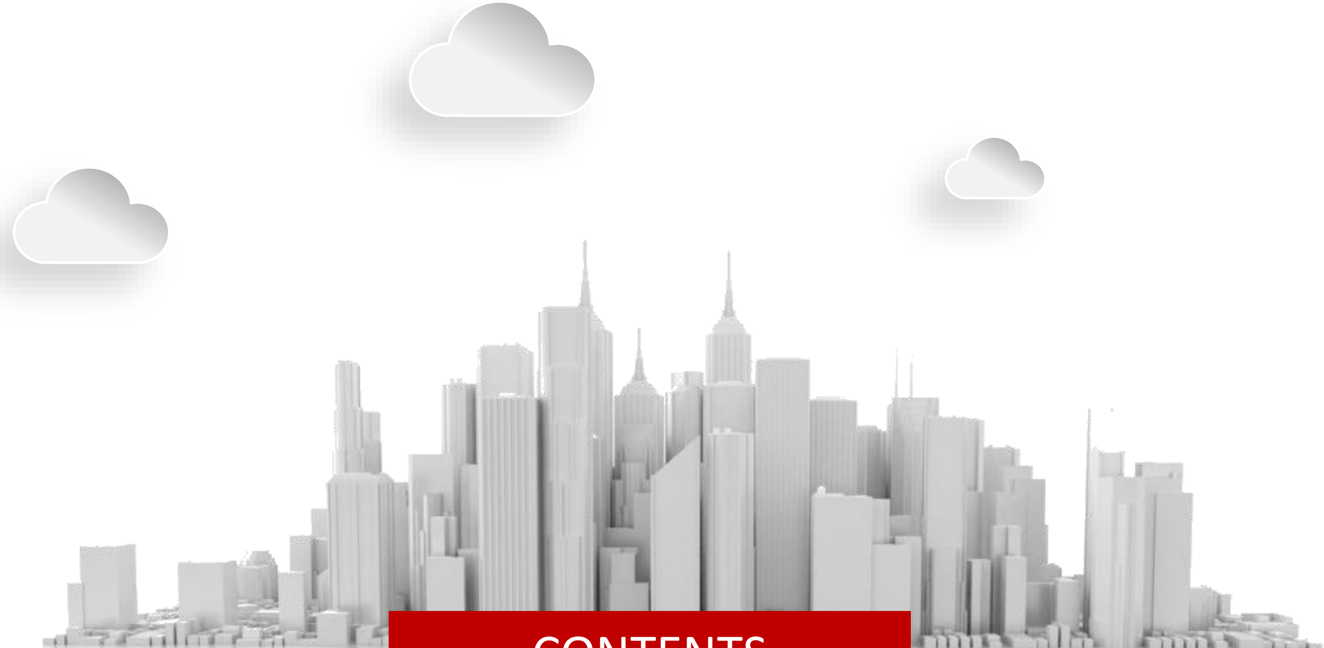
How about extreme temperatures?





Yang and Bou-Zeid *Environ. Res. Lett.* 2019

Optimal sensing strategy by combing mobile and fixed stations



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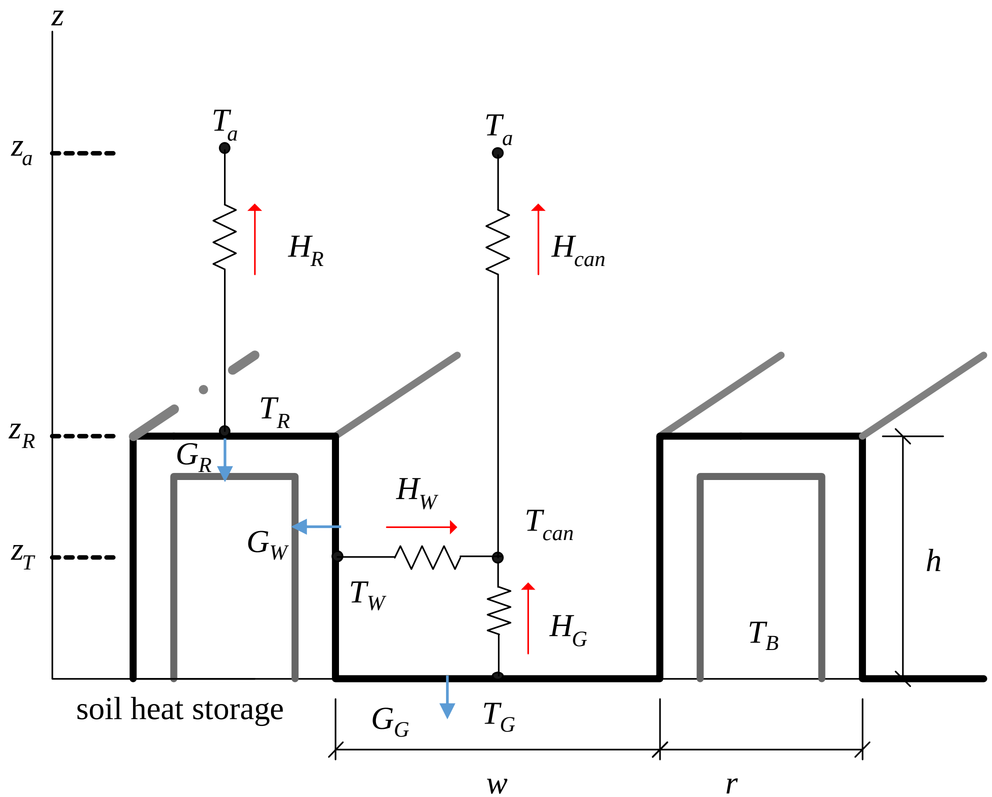
Urban Canopy Model

Urban surface energy balance: $R_n + Q = H + LE + G$

R_n is the net radiation, Q is the anthropogenic heat, H is the sensible heat flux, LE is the latent heat flux, G is the storage heat flux



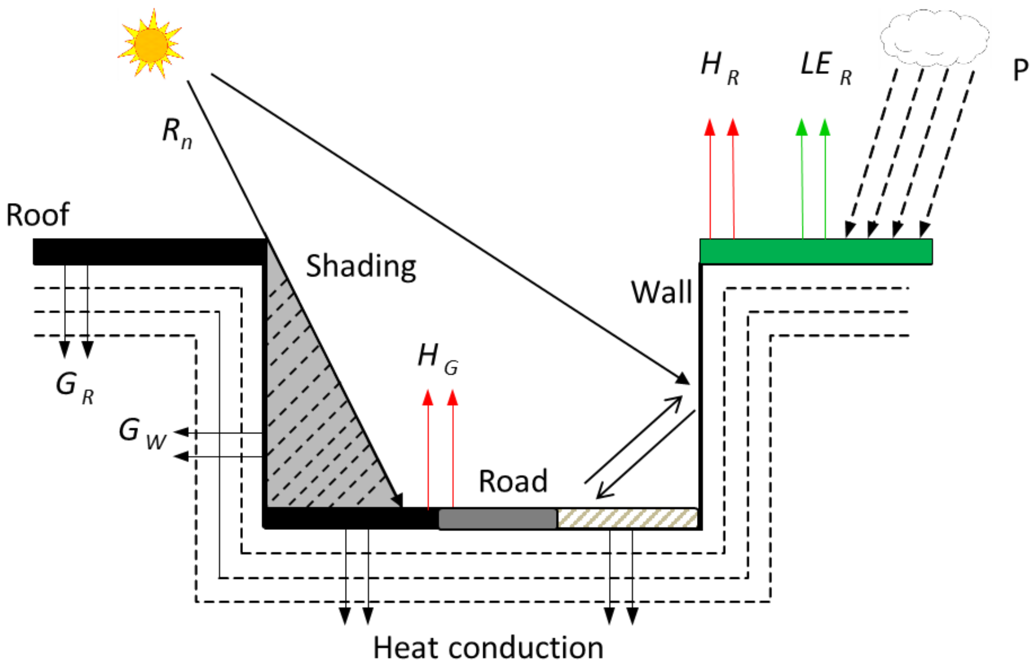
Kusaka et al. *Boundary-Layer Meteorol.* 2001

- Urban vegetation
- Hydrological modeling
- Sub-surface heterogeneity

Urban Hydrological Modeling

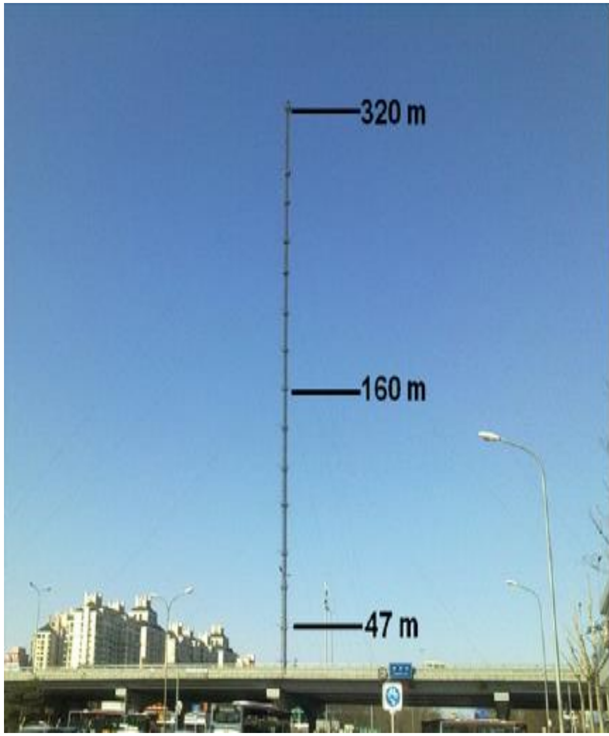
Current modeling system needs to be enhanced via a better representation of urban hydrological processes:

- <u>Outdoor irrigation</u>
- <u>Anthropogenic latent heat</u>
- <u>Oasis effect</u>
- <u>Evaporation over engineering materials</u>



Yang et al. *Boundary-layer. Meteorol.* 2015

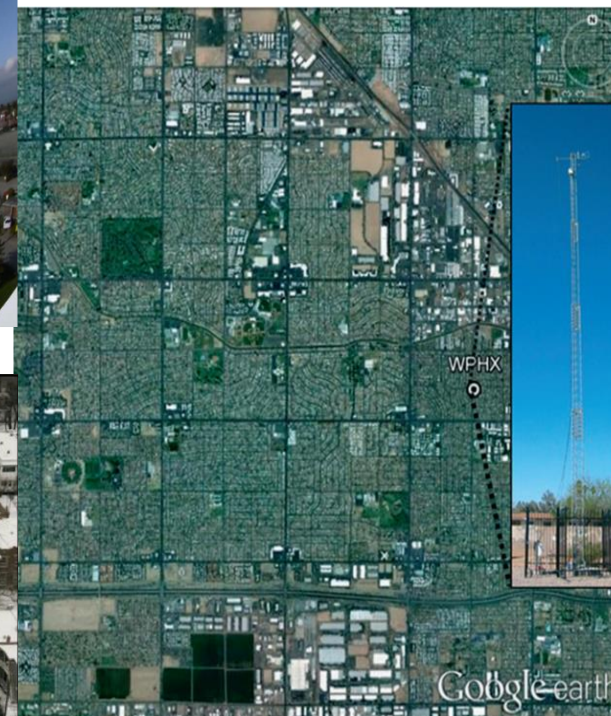
In-situ Data Collection



Beijing 325-m tower
(Song and Wang 2012)

Vancouver 29-m tower
(Crawford et al. 2013)

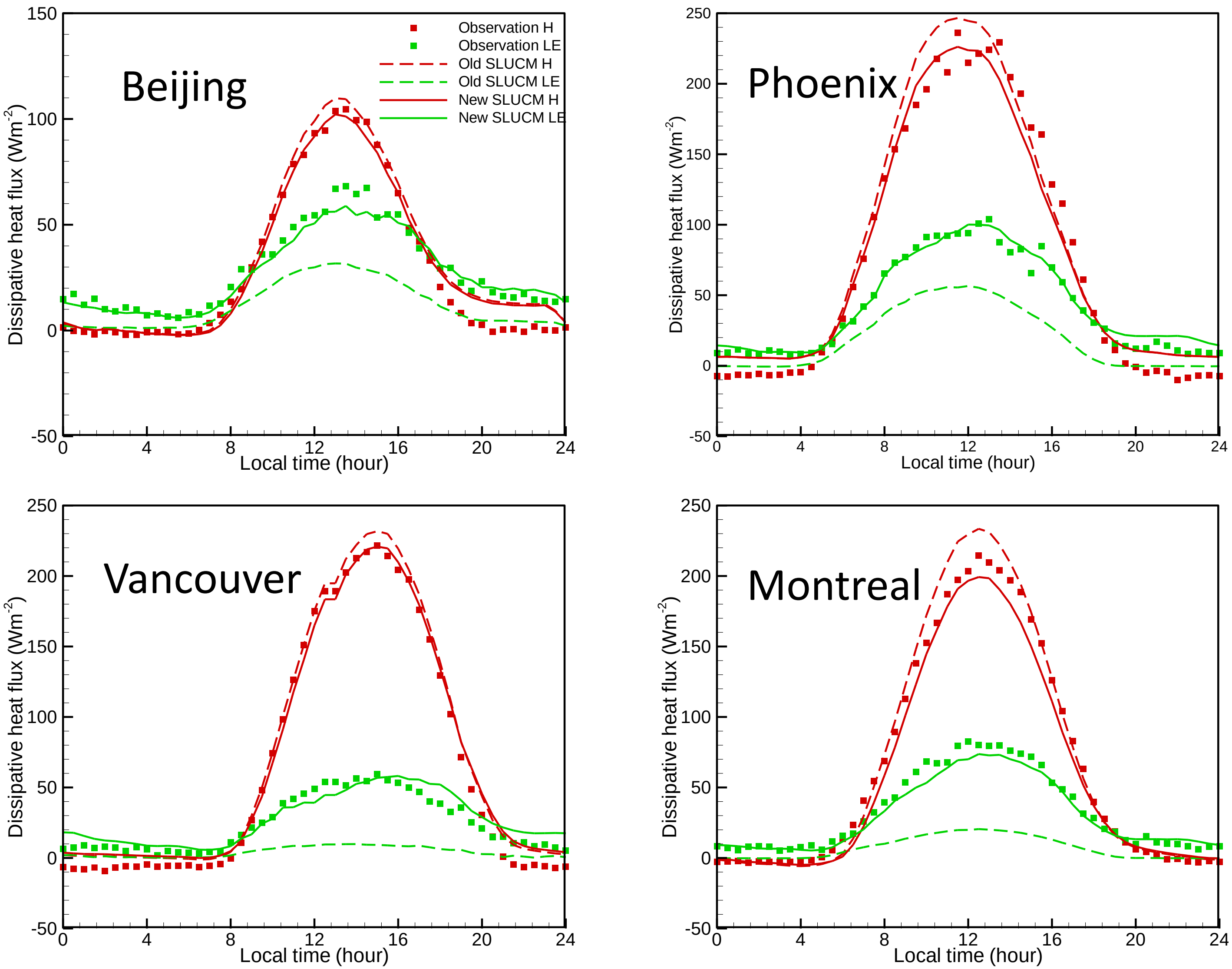
Montreal 25-m tower
(Leroyer et al. 2011)



Phoenix 22-m tower
(Chow et al. 2014)

Urban canopy parameters for each site is estimated based on field measurements and remote sensing technique.

Model Evaluation at 4 Cities



Yang et al. *Boundary-layer. Meteorol.* 2015

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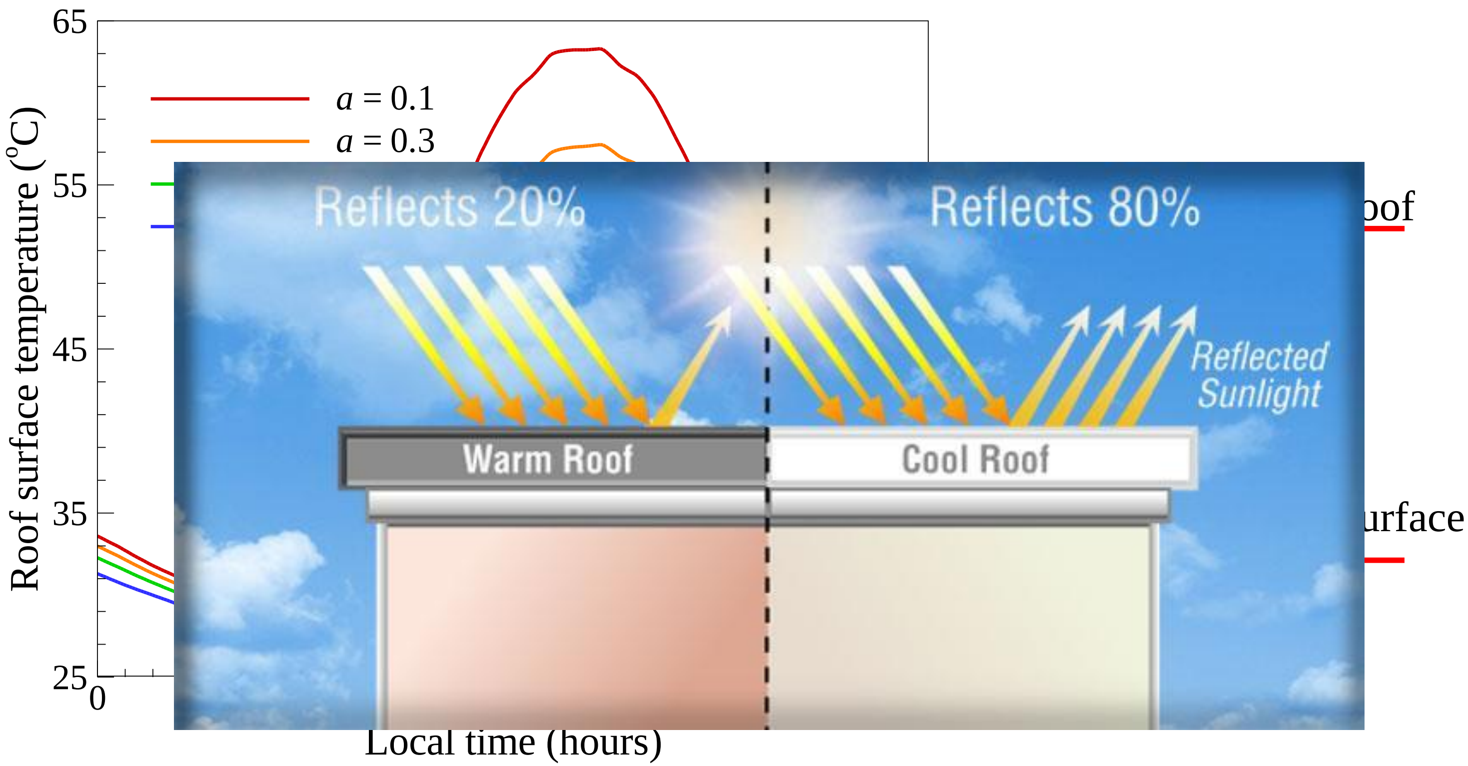
- Background and Motivation
- Experimental Investigation
- Urban Canopy Model
- **Smart City Development**
  - **Neighborhood Scale**
- Future Work

Built Urban Jungle

Paved surfaces, including roads, parking areas and sidewalks, covers about 36-45% of urban surfaces for a variety of metropolitan areas (Gray & Finster, 2009)

Source: http://www.scmp.com/magazines/post-magazine/short-reads/article/2059543/drone-photos-hong-kong-andy-yeungs-unique
https://www.phoenix.gov/waterservicessite/Documents/Landscape%20Watering%20Guidelines.pdf

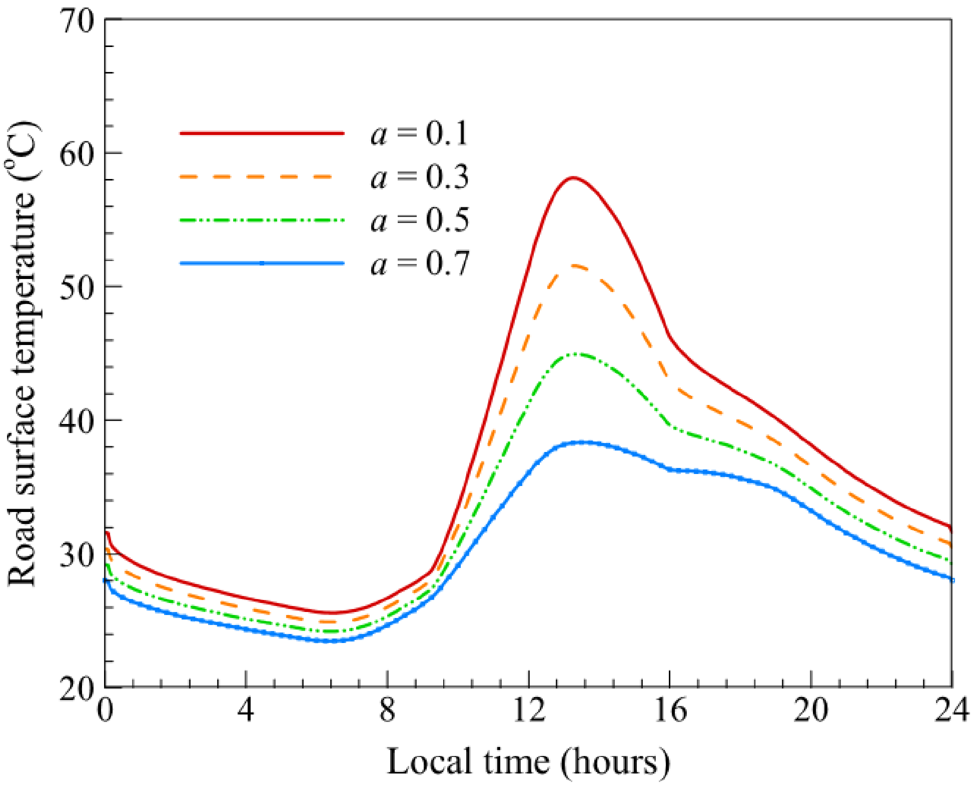
Reflective Materials



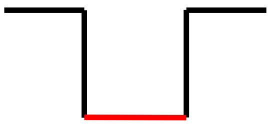
Yang et al. *Build. Environ.* 2016

Source: http://newscenter.lbl.gov/2011/11/03/cool-roofs-really-can-be-cool/

Reflective Materials

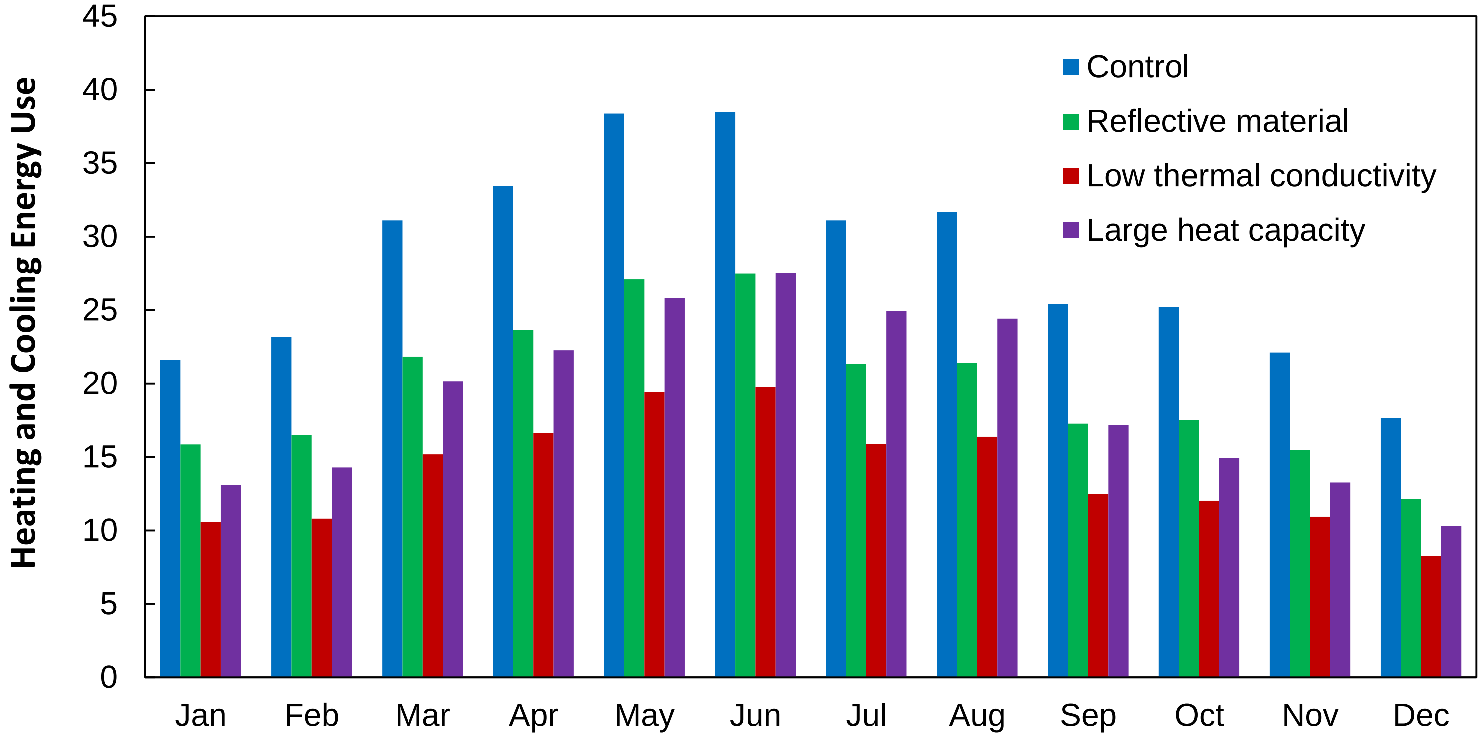


Yang et al. *Build. Environ.* 2016



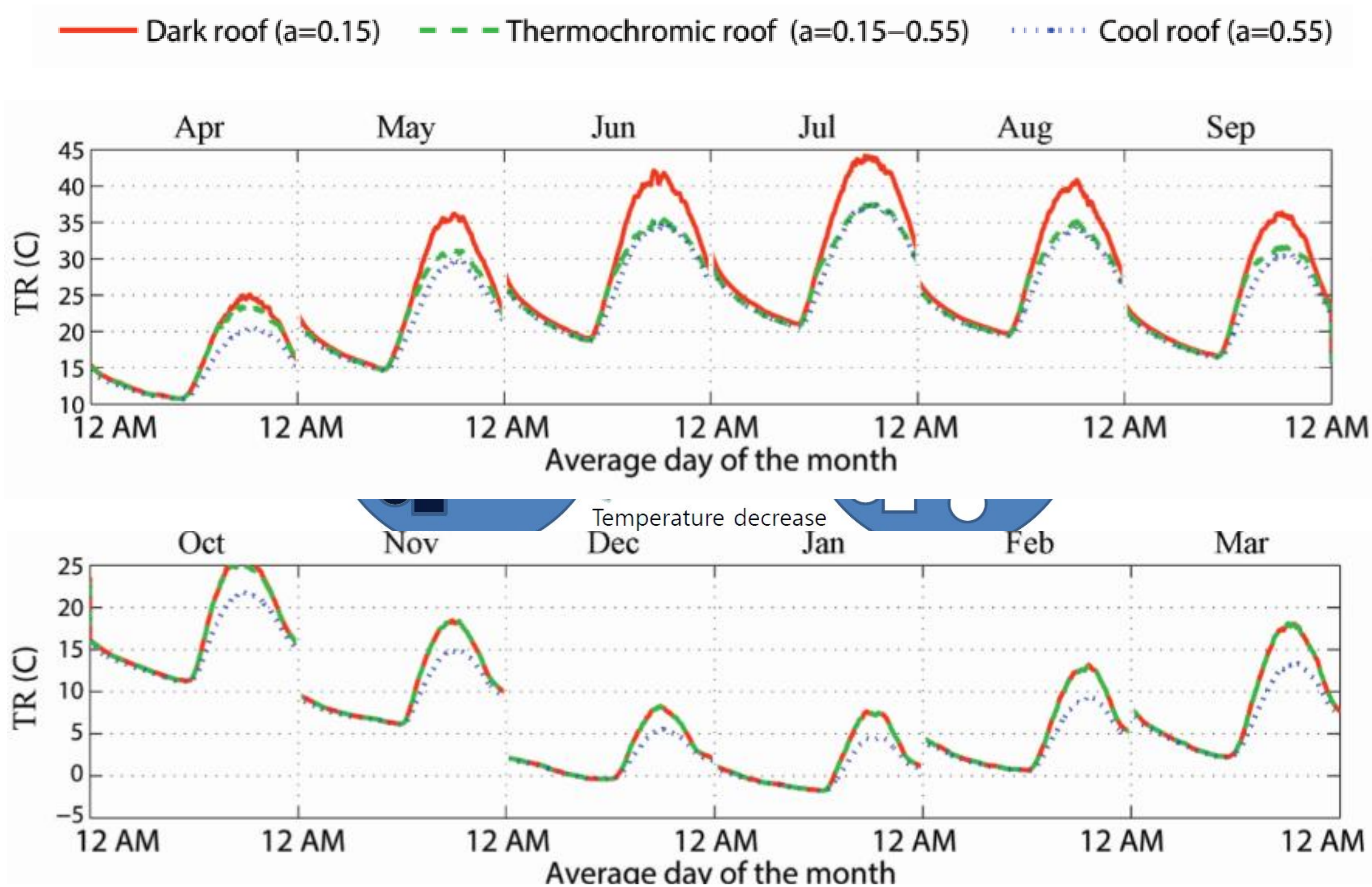
Building height = street width

Impact of Material Thermal Property



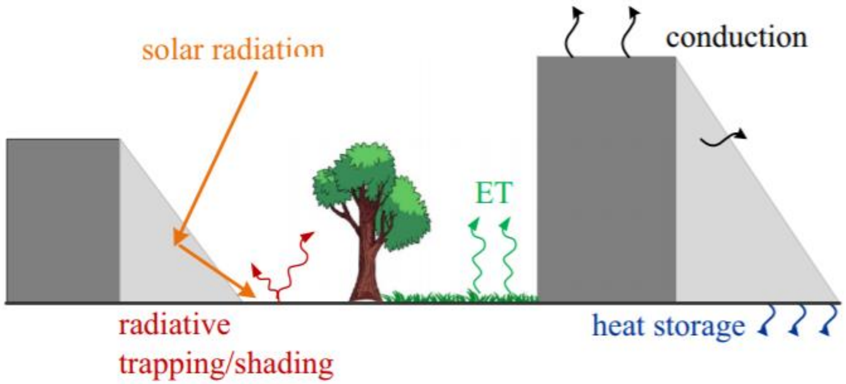
	Reflective material	Material of low thermal conductivity	Material of large heat capacity
Building energy efficiency enhancement	24.07%	40.30%	25.20%

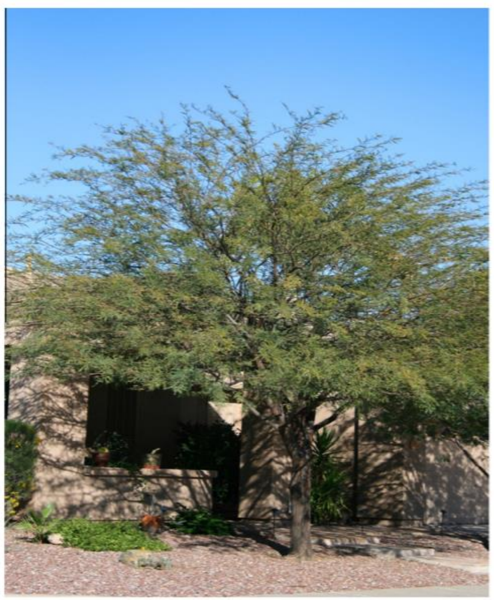
Novel Engineering Materials

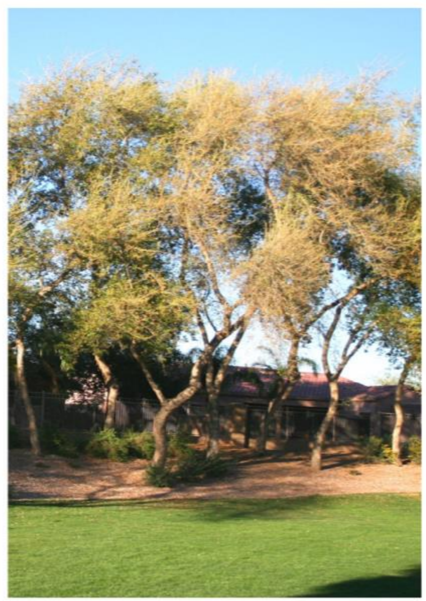


Fabiani, Pisello, Bou-Zeid, **Yang** et al. *Appl. Energy* 2019

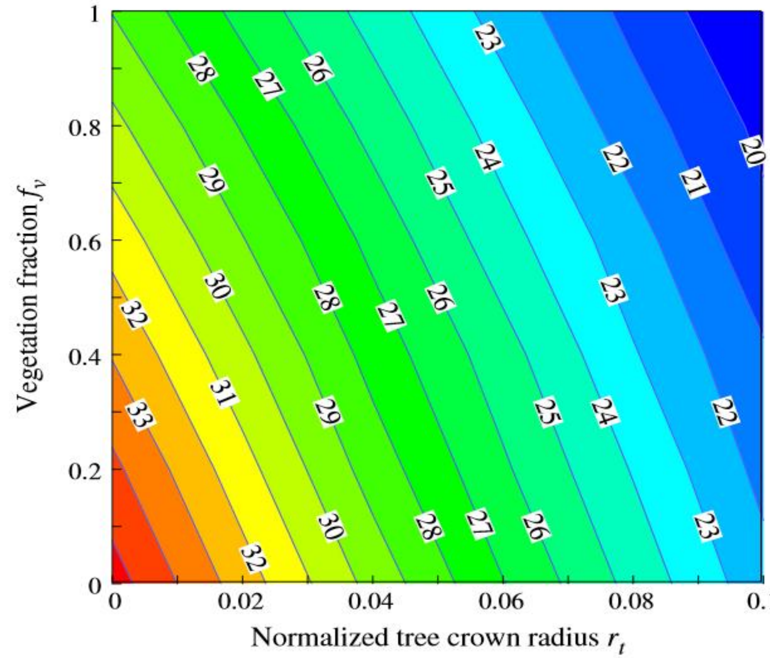
Urban Green Landscape



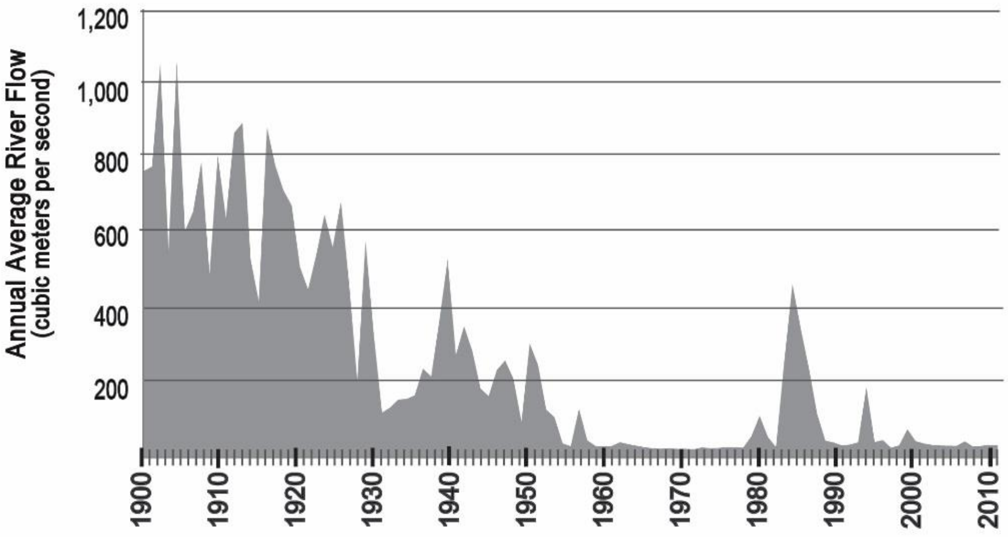




Wang, Zhao, **Yang** and Song *Appl. Energy* 2016



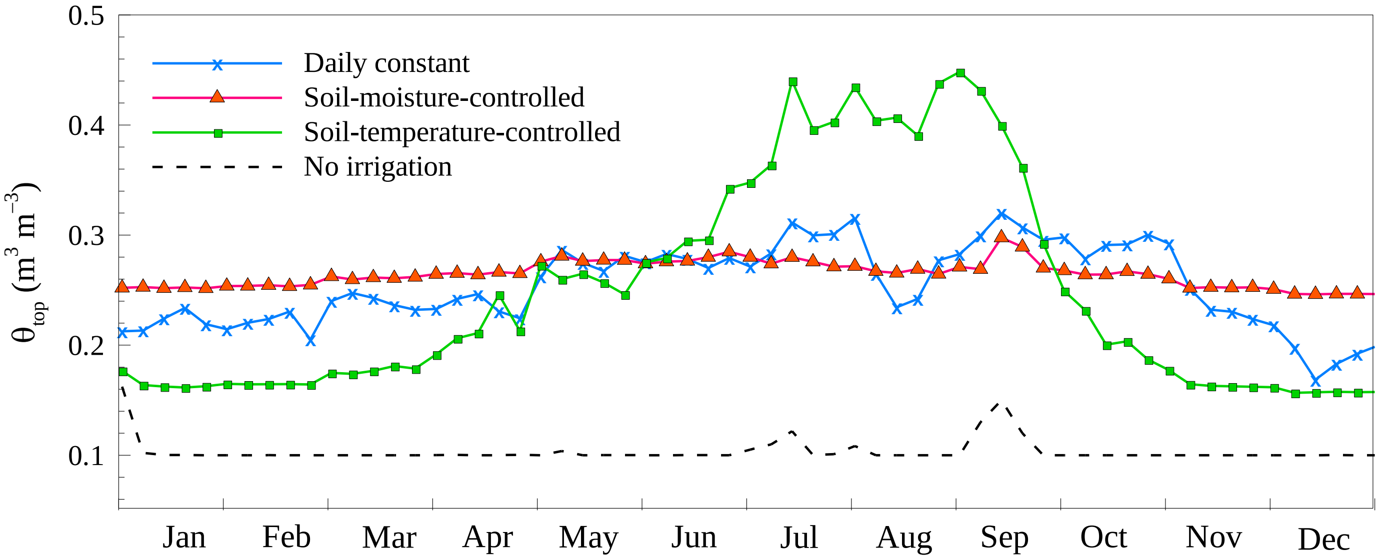
"Smart" Irrigation Schemes

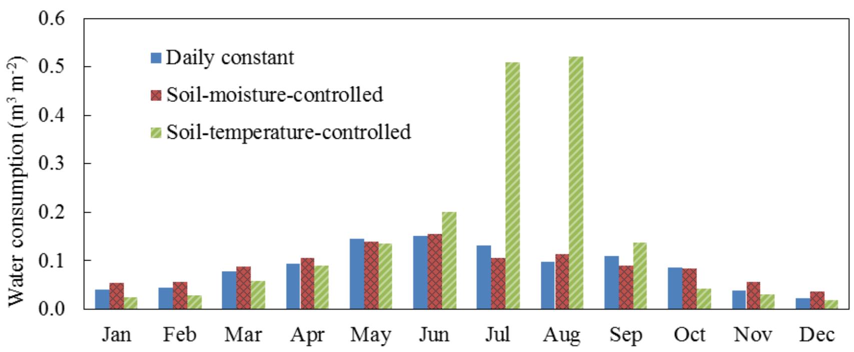


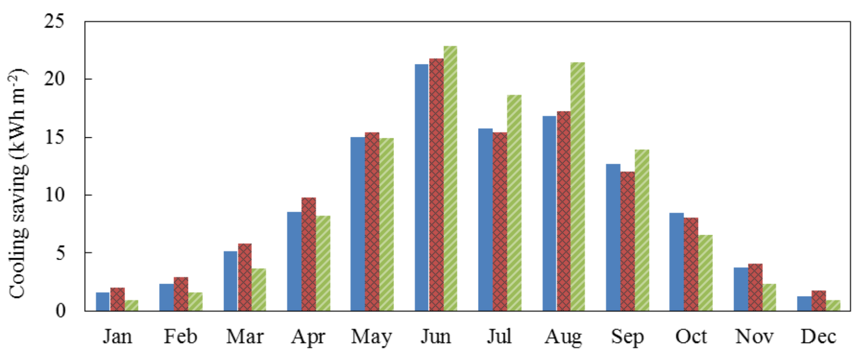
How can we better design outdoor irrigation for a desert city?

- Daily constant: based on irrigation practice in Phoenix (8 pm local time)
- Soil-moisture-controlled: meet plant need (wilting point ~ 0.24)
- Soil-temperature-controlled: meet threshold temperature of 22 ^{o}C, but maintaining residual soil moisture of 0.10

“Smart” Irrigation Schemes



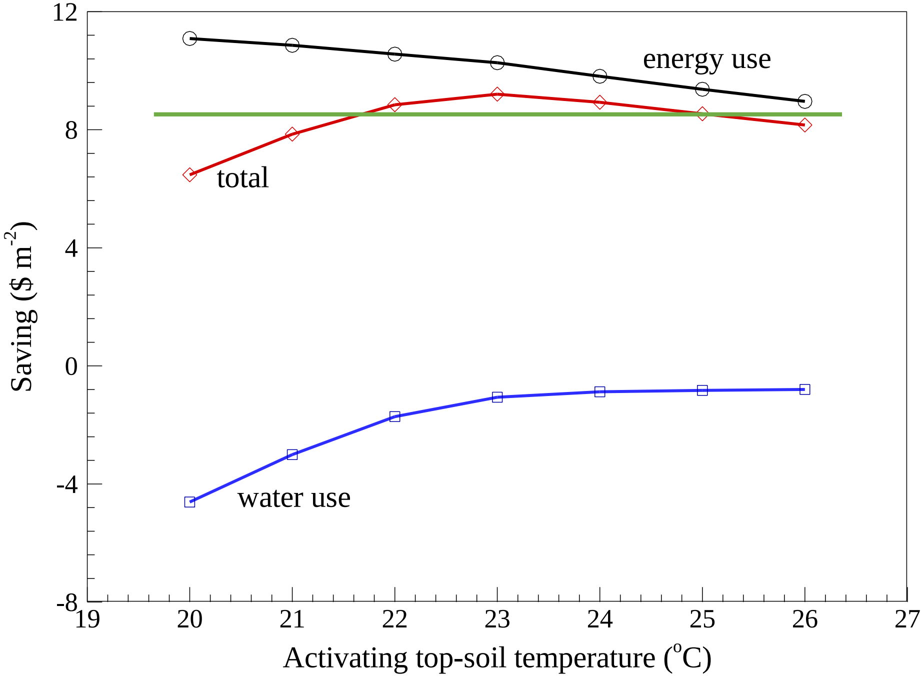




Yang and Wang, 2015 Energy Build.

Energy-Water Tradeoff

Is there an optimal temperature that can maximize the combined saving of energy and water resources?



Yang and Wang, 2015 Energy Build.

The activating soil temperature needs to be carefully determined in order to achieve the optimal irrigation scheme

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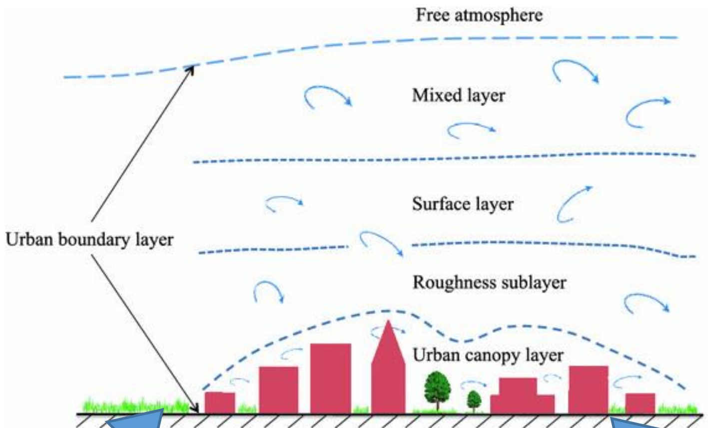
- Experimental Investigation
- Urban Canopy Model
- Smart City Development
  - Regional Scale
- Future Work

Coupled Atmosphere-Urban Modeling

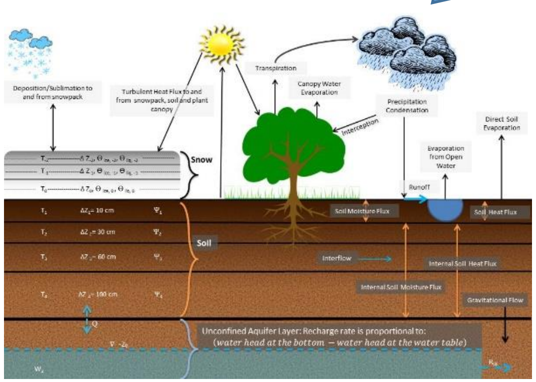
Upscaling the neighbourhood-scale results brings uncertainty:

- Spatial heterogeneity of land surfaces
- Lack of land-atmosphere interactions

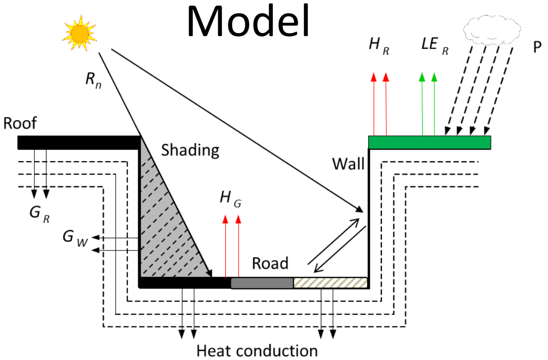


Weather Research and Forecasting Model

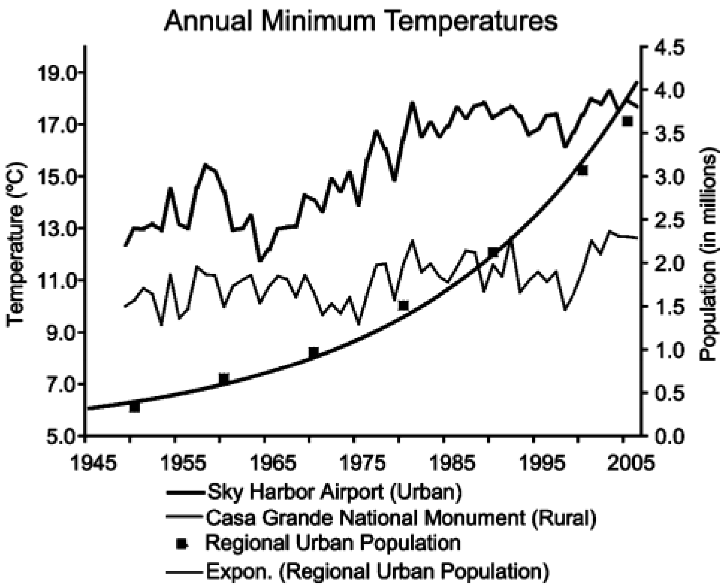
Land Surface Model



Urban Canopy Model



Planning for a Growing Desert City



(Golden, 2004)

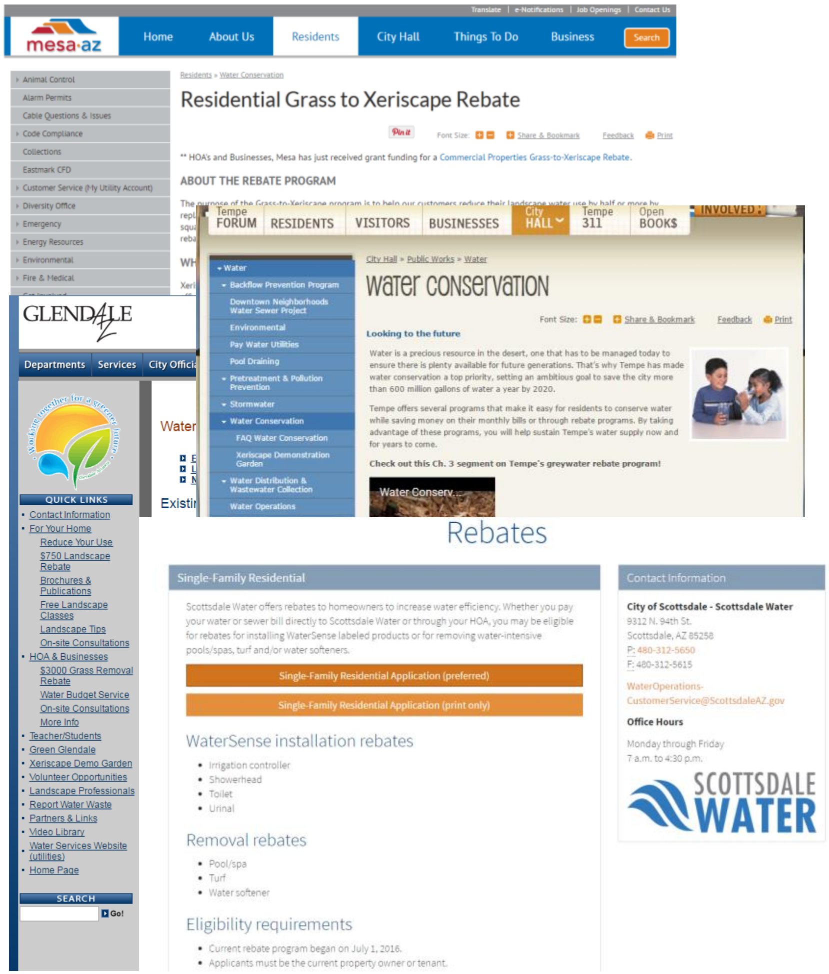
Water stress

Thermal comfort

Low Water-use Xeric neighbor

High Water-use Mesic neighbor

Urban Policy Dilemma



Sustainable Horticulture and Arboriculture for a Designed Environment

Shade Phoenix 2030

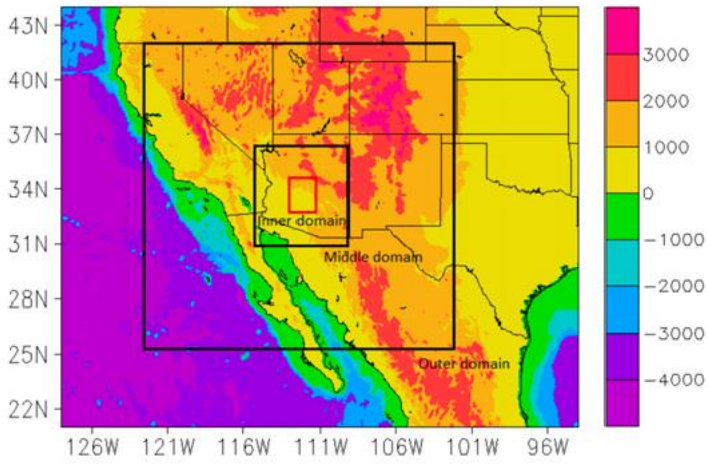
PARKS & OPEN SPACES

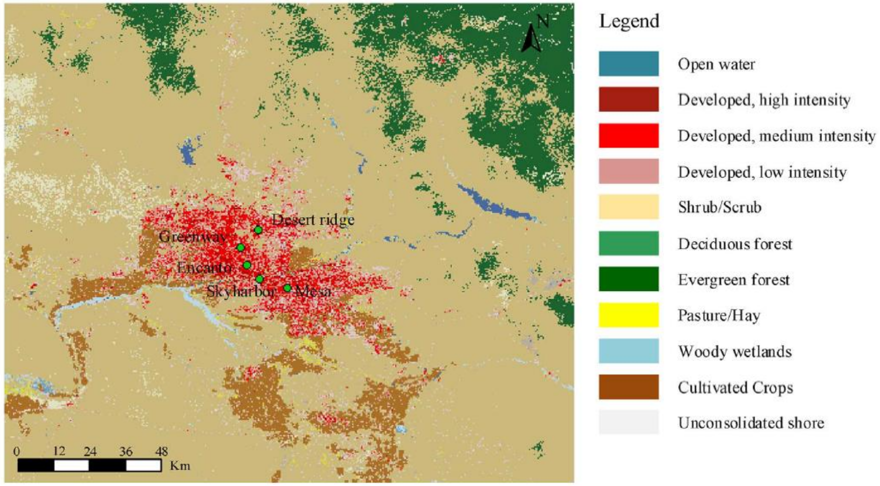
2050 GOAL: Having all residents within a **five-minute walk** of a park or open space by:

1. Adding **new parks or open space** in underserved areas.
2. Adding **150 miles of paths, greenways, and bikeways** throughout the City, and transforming an additional 150 miles of canals into vibrant public space.
3. **Reducing the urban heat island effect** through green infrastructure as well as doubling the current tree and shade canopy to 25%.

Source: https://www.glendaleaz.com/waterconservation/landscaperebates.cfm
http://www.mesaaz.gov/residents/water-conservation/residential-grass-to-xeriscape-rebate
http://www.chandleraz.gov/default.aspx?pageid=746
http://www.tempe.gov/city-hall/public-works/water/water-conservation
http://www.scottsdaleaz.gov/water/rebates

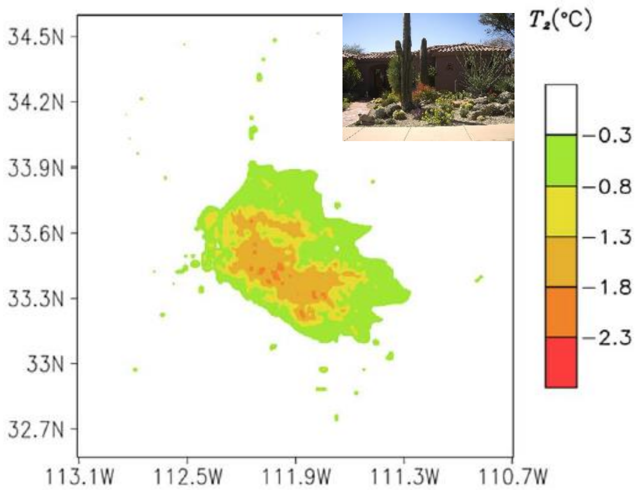
High-resolution Weather Simulation



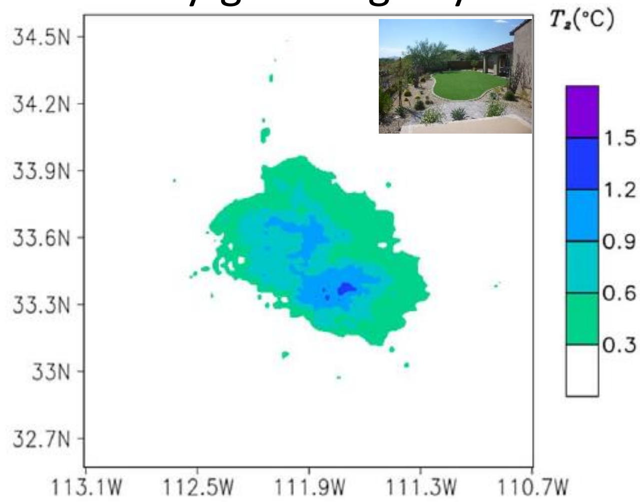


Yang and Wang *Landscape Urban Plan.* 2017

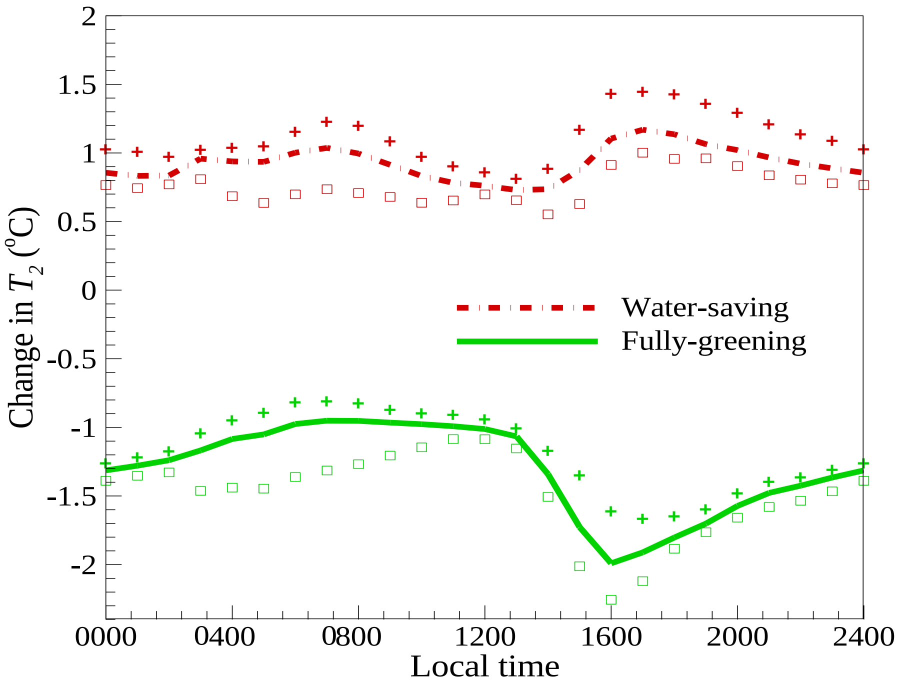
Water-saving city



Fully-greening city



Social-Environmental Tradeoff



Yang and Wang *Landscape Urban Plan.* 2017

A fully−greening city consumes 1.61×10^8 m^3 more water during the summer

Mean annual water consumption about 75 m^3 per person (Gober and Kirkwood 2010)

$$1.61 \times 10^8 (m^3) / 75 (m^3/person) = 2.15 \times 10^6 \text{ person}$$

Projected population growth 2.62 million by 2050 in the medium series (ADOA 2015)

Green Roofs in Sustainability Blueprint

Tokyo, Japan: Private buildings larger than 1000 m^2 and public buildings larger than 250 m^2 required to have 20% of rooftop greened

Basel, Switzerland: green roofs mandated on all new buildings with flat roofs and for roofs over 500 m^2

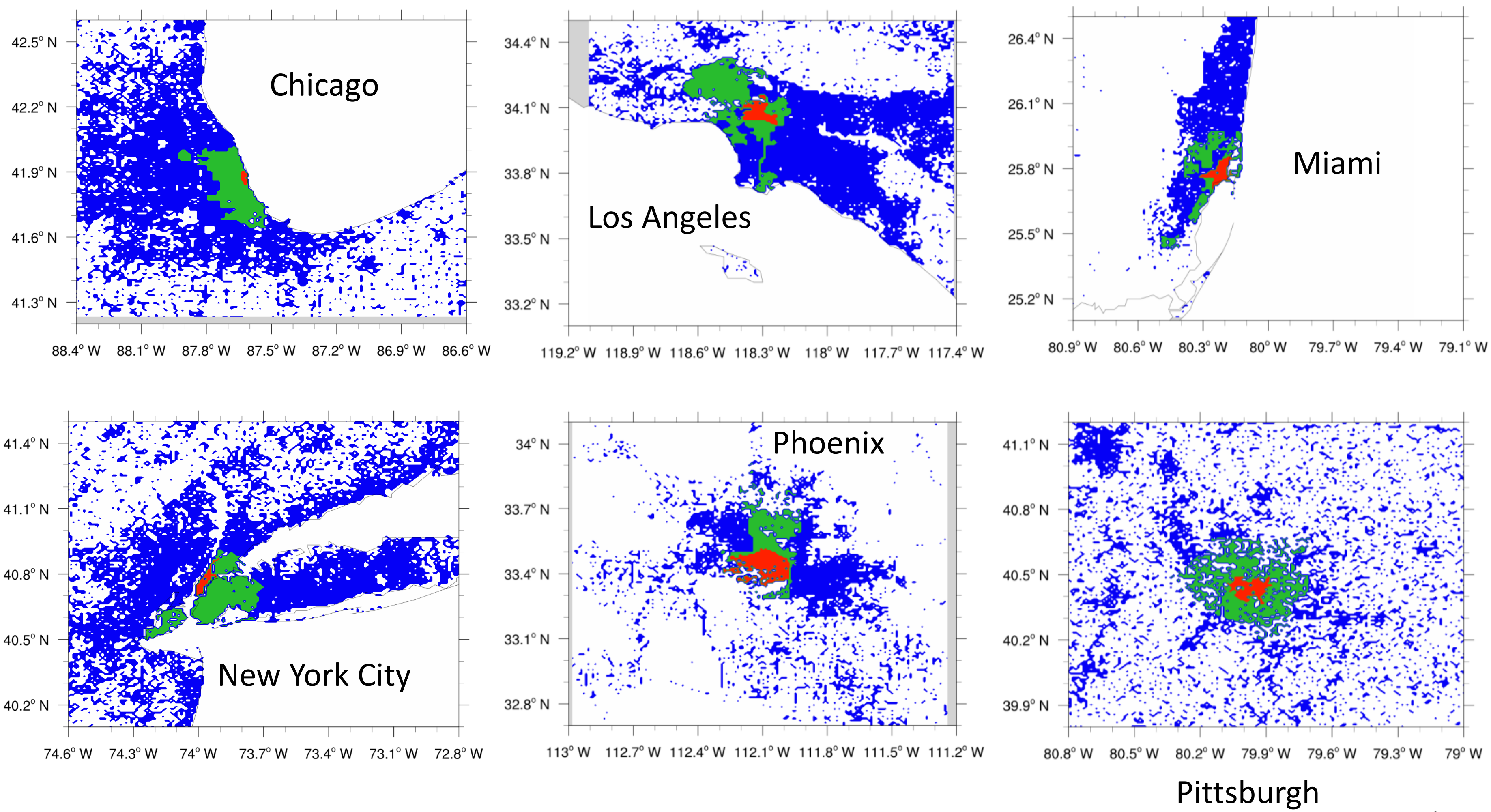
Portland, Oregon: all new city-owned facilities include a green roof with 70% coverage

Can cities mitigate heat islands by their local plans and efforts?

Multi-level Mitigation Plans

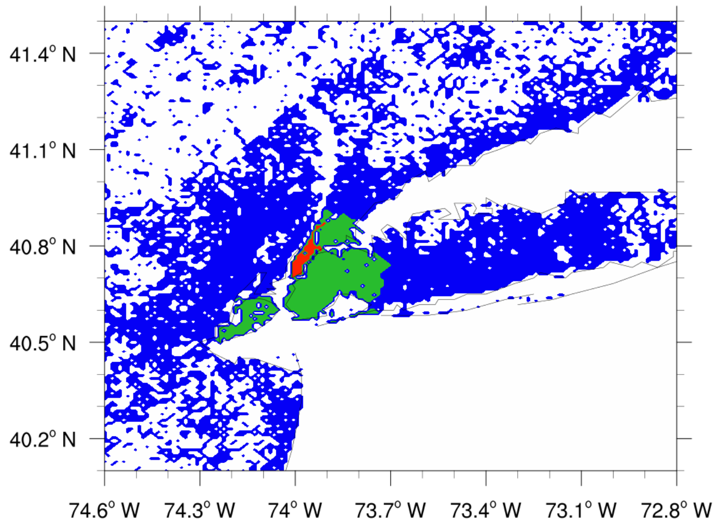
Local plan | City-scale plan | Regional plan

25% green roof coverage over buildings

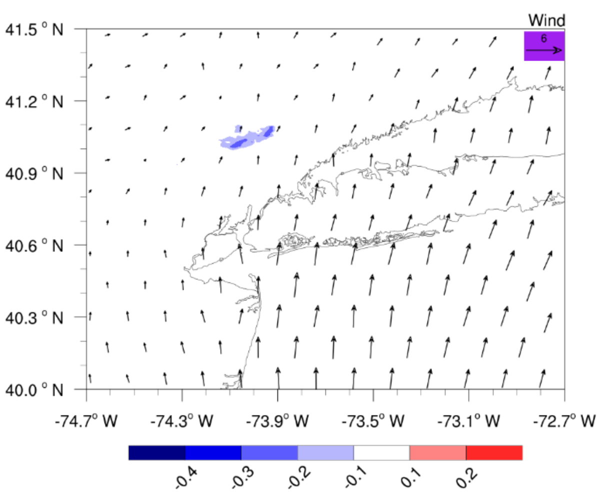


Regional Cooling by Green Roofs

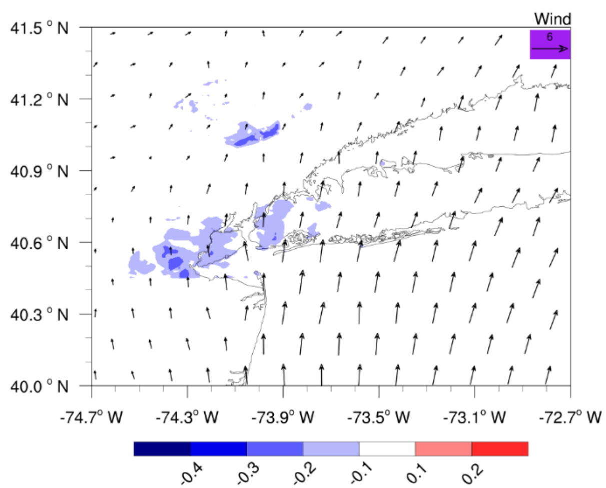
New York City



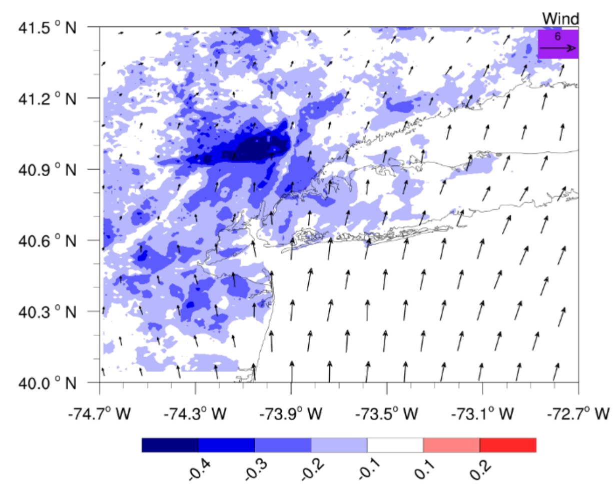
Local plan



City-scale plan



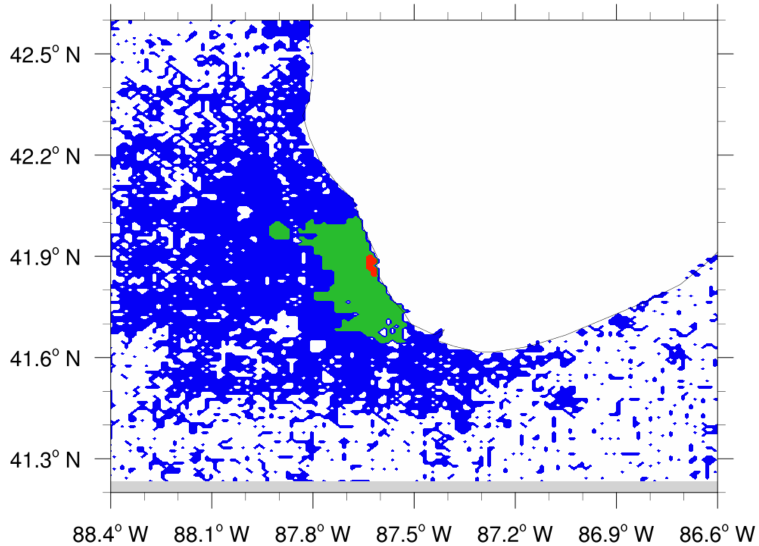
Regional plan



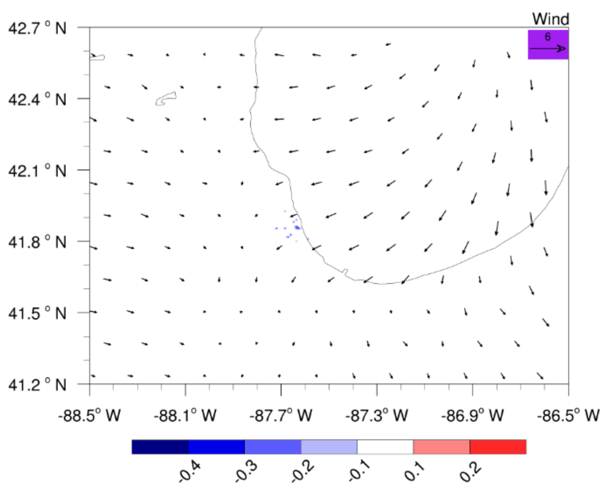
Yang and Bou-Zeid *Landscape Urban Plan.* 2019

Regional Cooling by Green Roofs

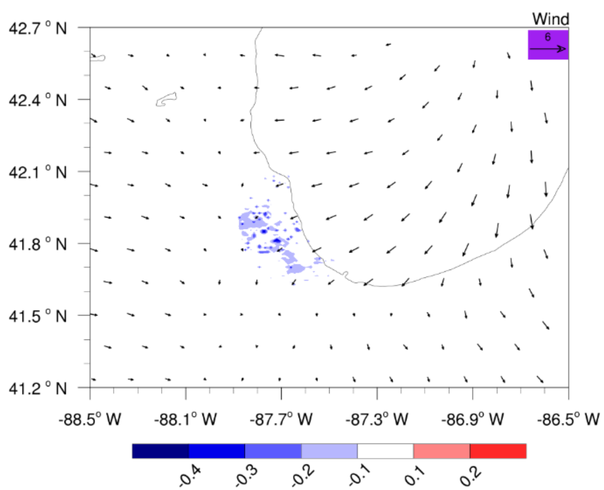
Chicago



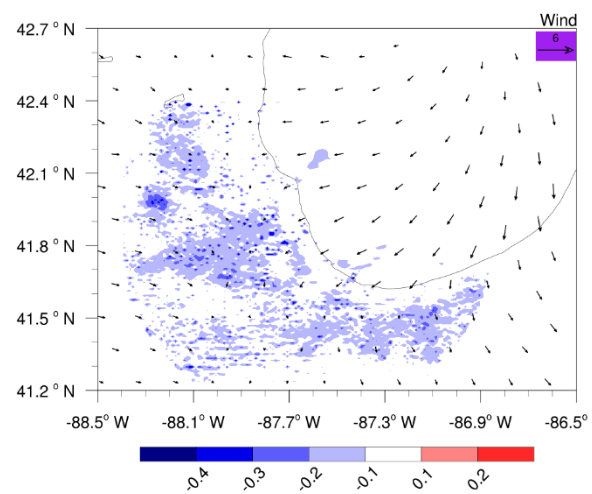
Local plan



City-scale plan



Regional plan



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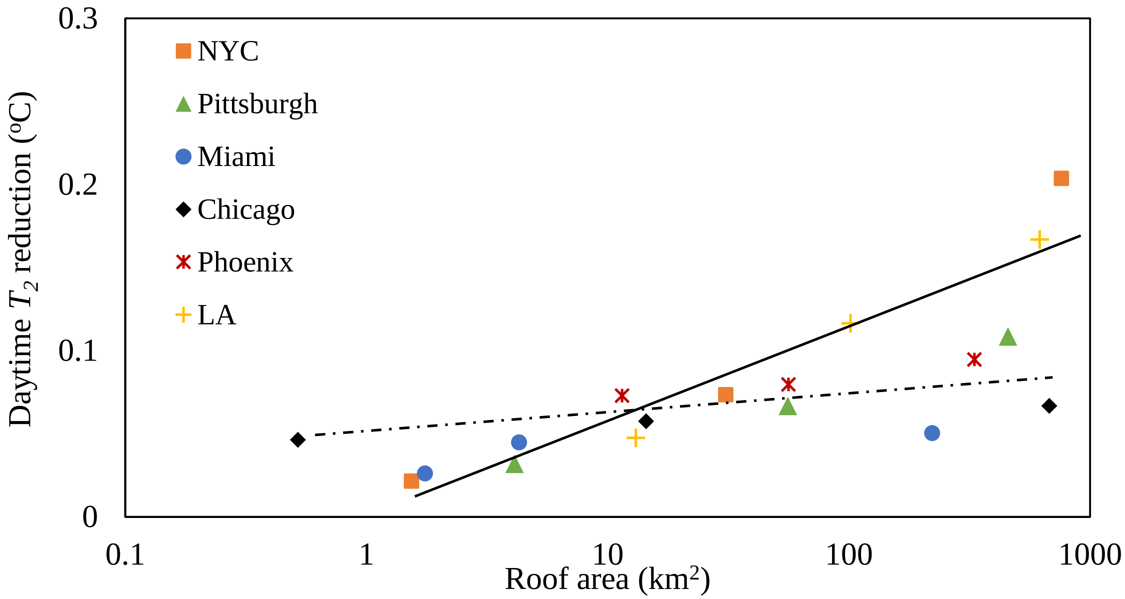
Scale Dependence of Cooling Benefit



- Cooling benefit of green roofs increases non-linearly with the intervention area
- The shape of metropolitan areas and its geoclimatic setting control the scaling

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UHI under cold waves

2019 United States cold wave: Temperatures below −30.0 °C in the midwest of the United States during late January

2017 European cold wave: The lowest temperature was −45.4 °C in Central and East Europe on January 5, 93 people across Europe died

2016 East Asia cold wave: Caused over 100 known deaths across East Asia, South Asia and Southeast Asia.



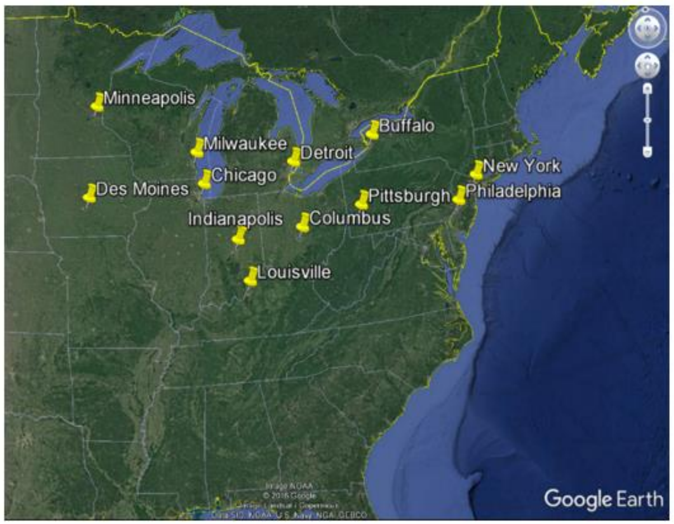
To what extent will the UHI intensify or weaken under anomalously low regional temperatures?

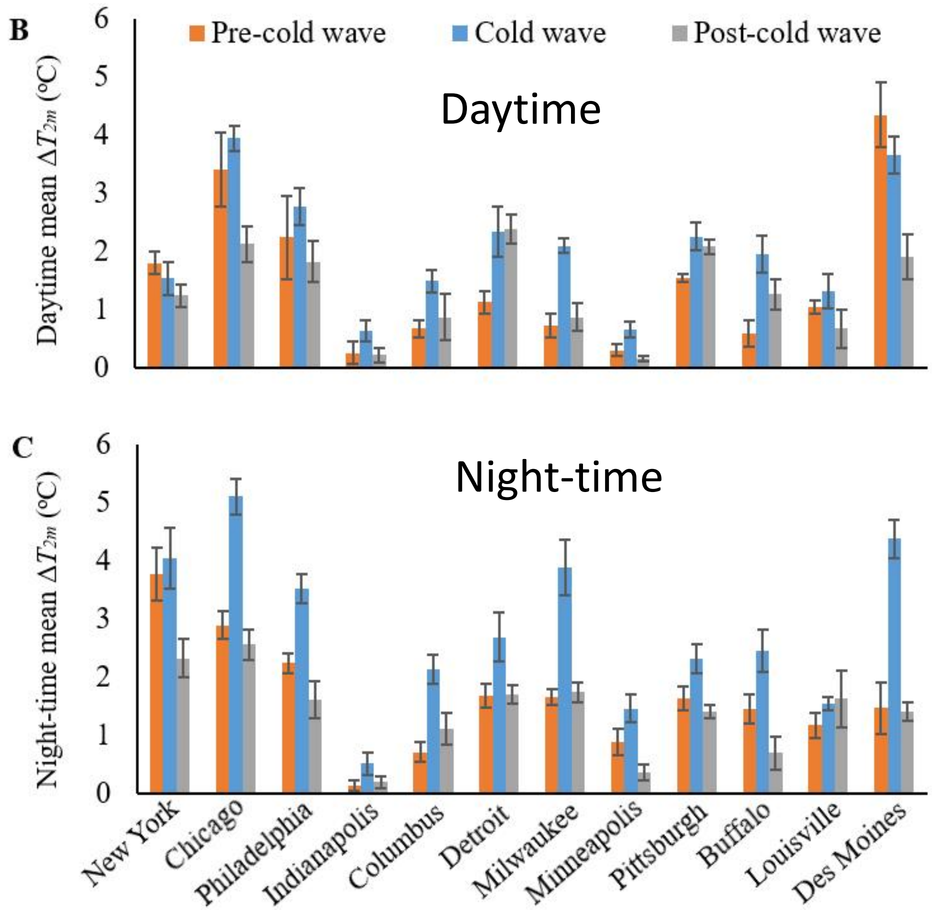
Source: http://www.c3headlines.com/global-warming-urban-heat-island-bias/
https://www.dnainfo.com/chicago/20150109/downtown/history-of-winter-chicago-it-could-be-worse-definitely-was

Early 2014 North American cold wave

Yang and Bou-Zeid 2018, *J. Appl. Meteorol. Clim.*

A

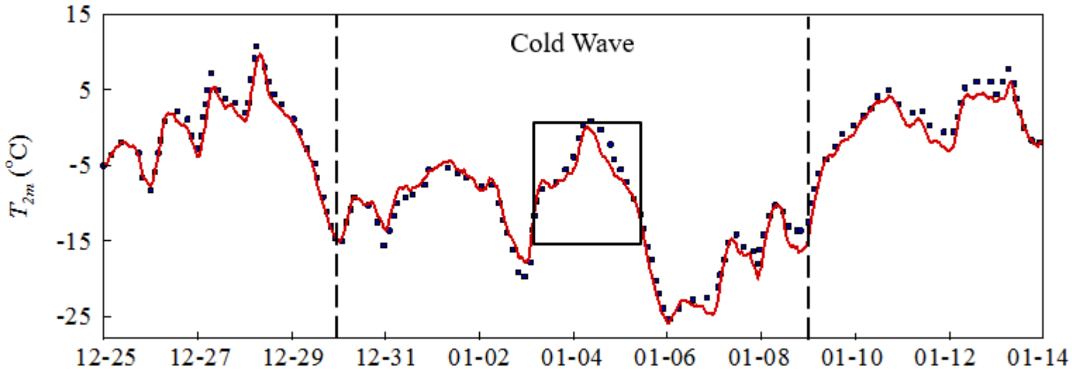




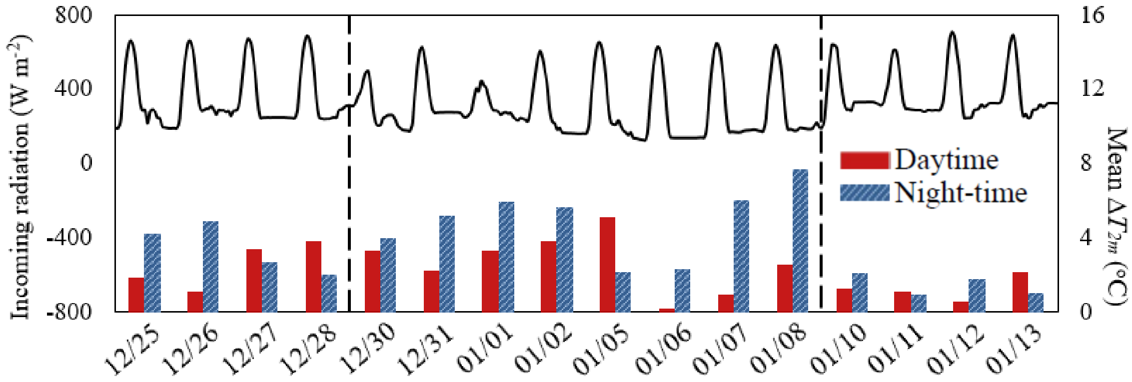
$$\mathrm{UHI} = T_{urb} - T_{rul}$$

Urban heat islands intensified during daytime (0.65 ± 0.34 ^{o}C, mean ± standard deviation among cities), and even more noticeably during night-time (1.32 ± 0.78 ^{o}C)

Temporal evolution of UHI



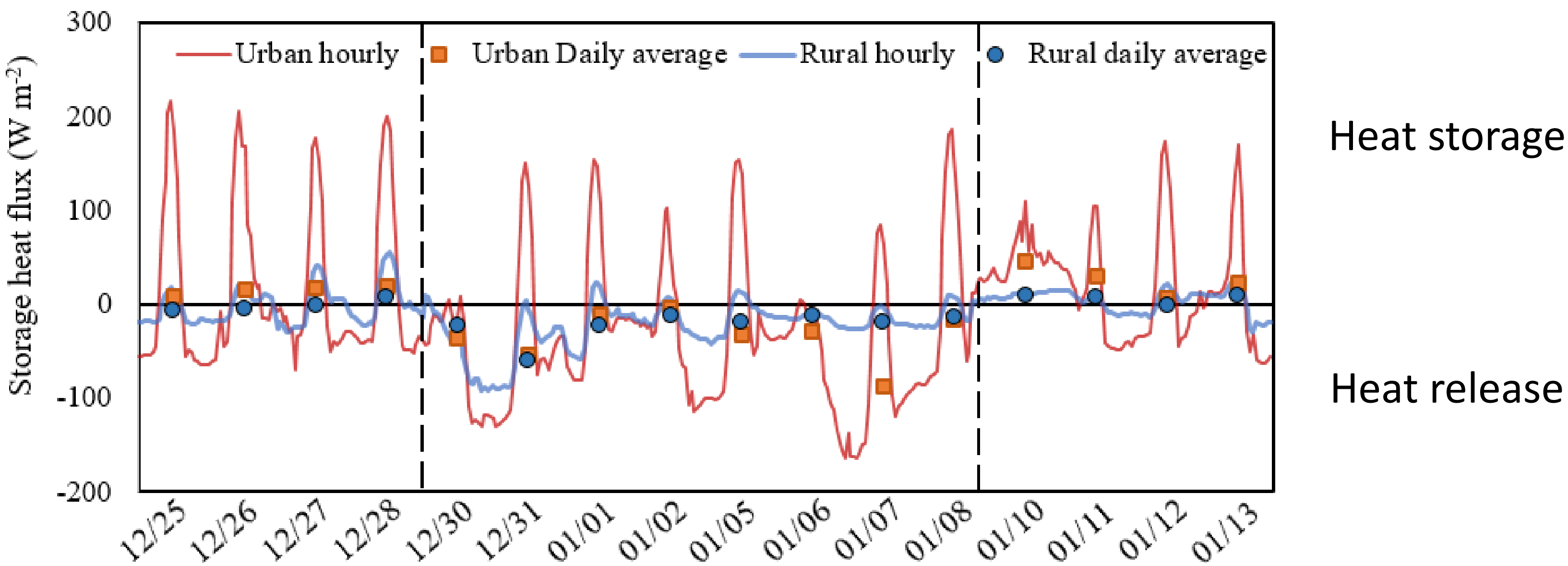
❖ WRF simulation is able to reproduce the temperature variation across the cold wave event



❖ Intensification of UHI during the cold wave correlates weakly with incoming solar radiation

Yang and Bou-Zeid 2018, *J. Appl. Meteorol. Clim.*

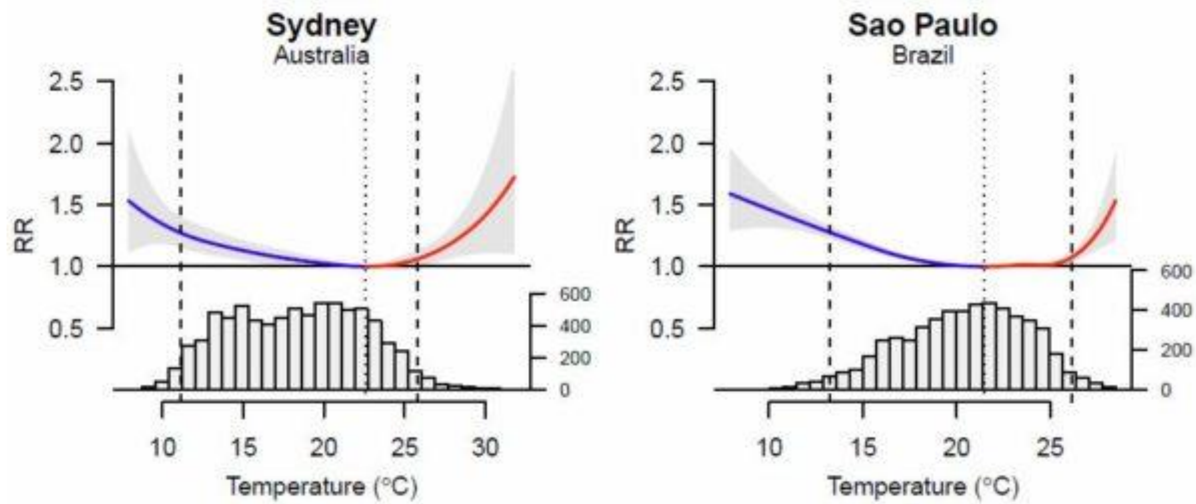
Mechanism of intensified night-time UHI



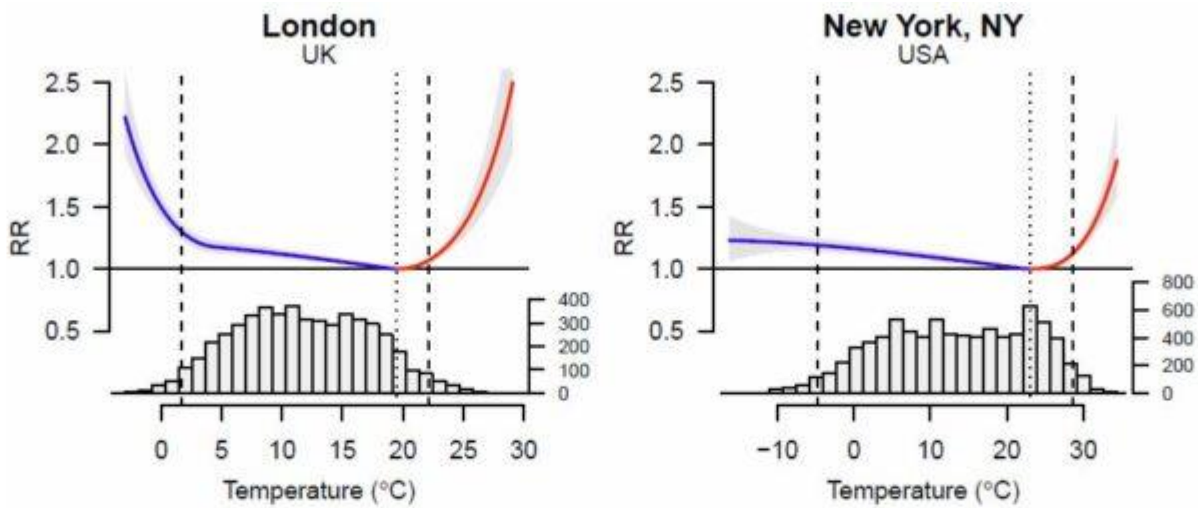
Yang and Bou-Zeid 2018, *J. Appl. Meteorol. Clim.*

Night-time surge in UHI is controlled by the heat release from urban fabric (engineering materials as "thermal battery")

Climate change and human health

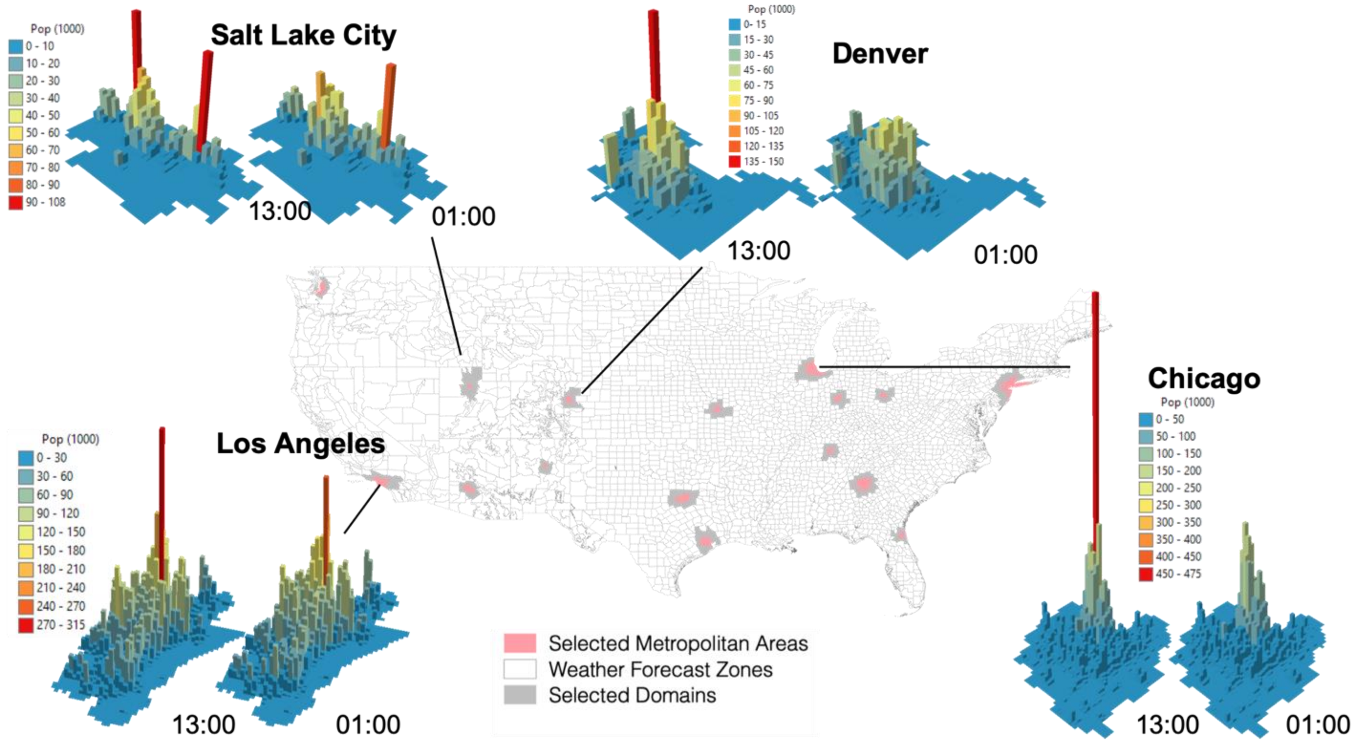


Implicit assumption: temporal variation of spatially aggregated temperature can pick up the risk signal



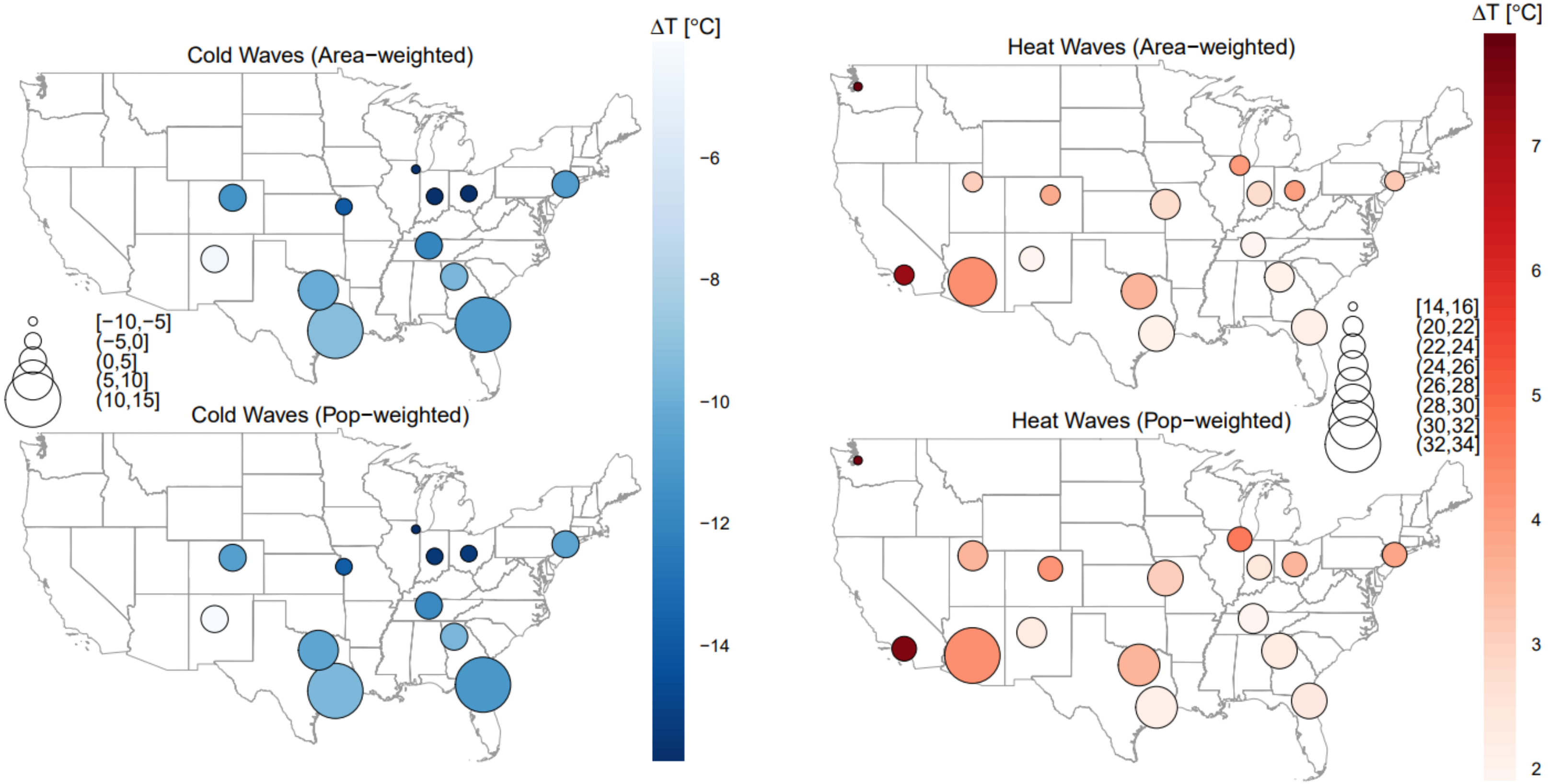
Gasparrini et al. 2015, *The Lancet*

US residents' exposure to extreme heat and cold



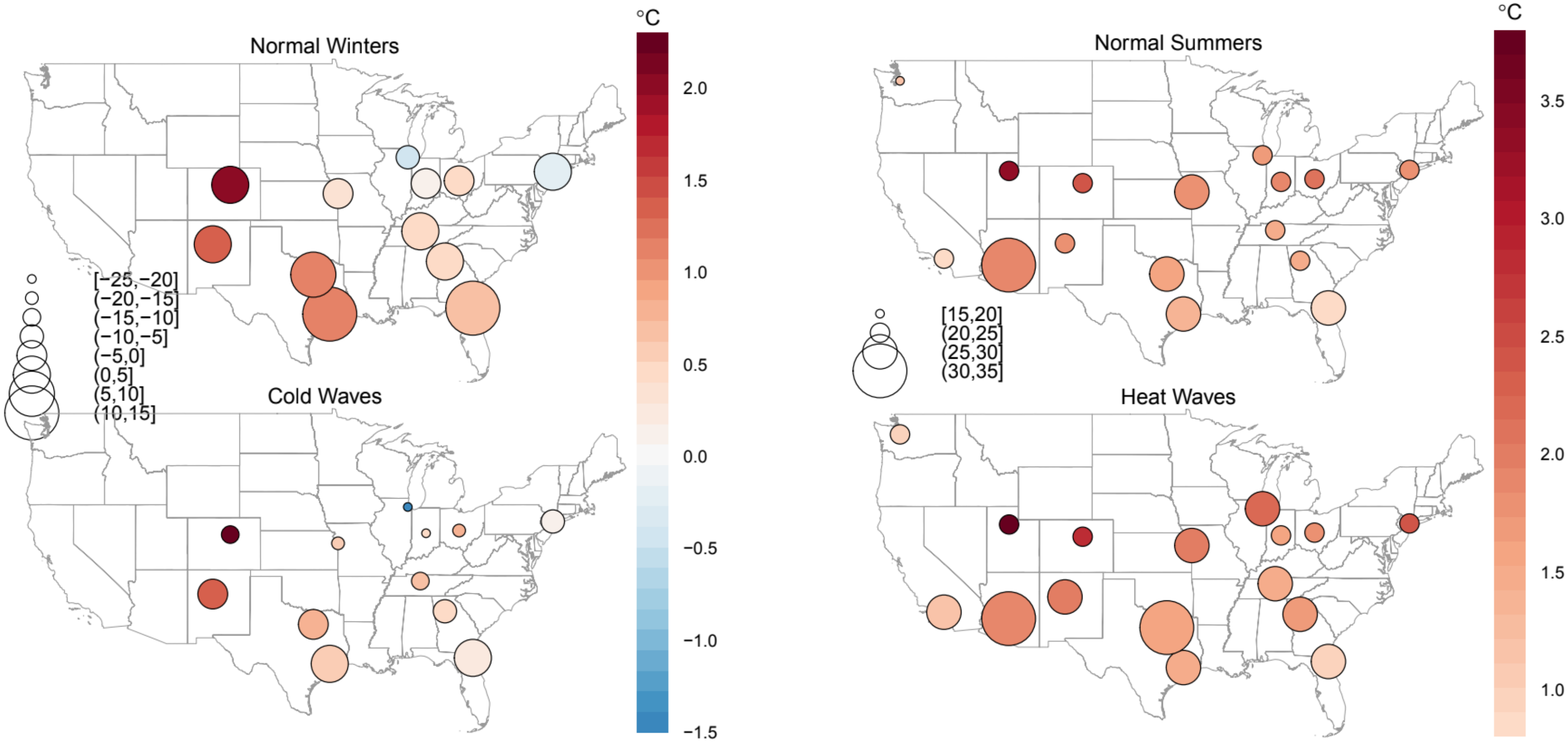
- Worker commute data from the 2006-2010 Census Transportation Planning Products (CTPP) (https://ctpp.transportation.org/)
- 16 major United States metropolitan areas
- Three major heat waves (Jul 13 – Aug 29 in 2006, Jul 11 – Aug 10 in 2011, and Jun 18 – Jul 20 in 2012) and one cold wave (Jan 1 – Feb 1 in 2014)

Temperature anomaly under extreme weather



- ➢ Cold wave lowers the area-weighted mean 2-m air temperature by 11.5 ± 3.1 °C
- ➢ Anomaly under heat waves (3.7 ± 1.5 °C) is much smaller than the cold anomaly

Impact of population dynamics



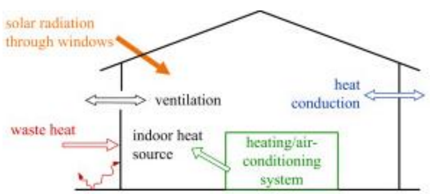
- Population dynamics lessen the exposure of urban residents to extreme cold by 0.4 ± 0.8 °C, but substantially increased the exposure to heat waves 2.0 ± 0.8 °C (more than half of the heat wave hazard 3.7 ± 1.5 °C)

CONTENTS

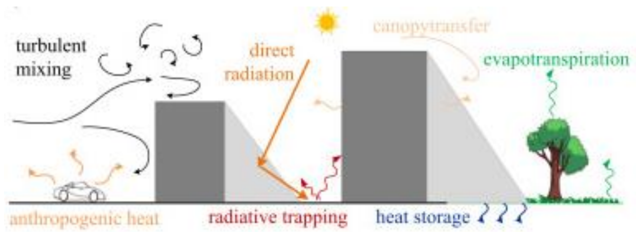
- Background and Motivation
- Experimental Investigation
- Urban Canopy Model
- Smart City Development
- Future Work

Conclusions

- ❖ Challenges posed to the Water-Energy-Climate nexus in the urban environment could be managed through strategic urban planning and policy
- ❖ The environmental benefits of mitigation strategies exhibit strong variations with geographic and climatic conditions, and are subject to change with the scale



Building scale
(~10 – 100 m)



Neighborhood scale
(~100 – 1000 m)

City and Regional scale
(~1000 – 10000 m)

Experimentation should be prompted at a case-by-case basis to test the overall value of individual measures for developing smart cities in different regions


Thank you!