Urban Climate and Smart City Development

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

150 Years of Global Urbanization
This shift in demographics raises many important questions and challenges facing the future of our world, most notably how it will be fed.

<table>
<thead>
<tr>
<th>Year</th>
<th>Rural Population</th>
<th>Urban Population</th>
<th>Total Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900</td>
<td>1.6 bil</td>
<td>0.2 bil</td>
<td>1.8 bil</td>
</tr>
<tr>
<td>2008</td>
<td>6.7 bil</td>
<td>3.1 bil</td>
<td>9.8 bil</td>
</tr>
<tr>
<td>2050</td>
<td>9.7 bil</td>
<td>6.8 bil</td>
<td>16.5 bil</td>
</tr>
</tbody>
</table>

Source: http://www.museumofthecity.org/project/urban-air-pollution-in-chinese-cities/
http://environment.nationalgeographic.com/environment/photos/urban-threats/
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)
Water-Energy-Climate Feedback

- Greenhouse gas emission
- Global warming
- Increased aridity
- Precipitation pattern
- Increased energy use
- More heat release
- Increased water demand
- Less vegetation

UHI

Climate
Urban Heat Mitigation

**Urban heat island**

- Large heat storage in engineering materials
- Reduced evaporative cooling due to small vegetative cover
- Built-up landscape traps radiation and inhibits advective cooling
- Waste heat released from anthropogenic activities

**Smart cities**

- Novel engineering material
- Urban green landscape
- Resilient urban form design
- 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
CONTENTS

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

Sensing the Campus

Wireless Sensor Network
Sensing the City

Mobile Urban Sensing Technologies (MUST)

Led by Maider Llaguno-Munitxa
Heterogeneous Urban Environment

Spatiotemporal temperature variability

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

Spatial

42880 grids (500 m x 500 m)

Temporal

1440 time (30-min interval)

61,747,200
Monthly Mean Temperature

(a) New York City

(b) Chicago

(c) Pittsburgh

(d) Phoenix
Sensor Network Design

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

Sensor Network Design

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

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

How about extreme temperatures?

Optimal sensing strategy by combing mobile and fixed stations

Urban Canopy Model

Urban surface energy balance: \[ R_n + Q = H + \text{LE} + G \]

\( R_n \) 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.

- 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:

- **Outdoor irrigation**
- **Anthropogenic latent heat**
- **Oasis effect**
- **Evaporation over engineering materials**

*Yang et al. Boundary-layer Meteorol. 2015*
In-situ Data Collection

Urban canopy parameters for each site is estimated based on field measurements and remote sensing technique.
Model Evaluation at 4 Cities

Beijing

Phoenix

Vancouver

Montreal

Yang et al. *Boundary-layer. Meteorol. 2015*
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- Smart City Development
- Neighborhood Scale
- Future Work
Paved surfaces, including roads, parking areas and sidewalks, covers about 36-45% of urban surfaces for a variety of metropolitan areas (Gray & Finster, 2009)

Reflective Materials

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

Building height = street width

Impact of Material Thermal Property

<table>
<thead>
<tr>
<th></th>
<th>Reflective material</th>
<th>Material of low thermal conductivity</th>
<th>Material of large heat capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building energy efficiency enhancement</td>
<td>24.07%</td>
<td>40.30%</td>
<td>25.20%</td>
</tr>
</tbody>
</table>
Novel Engineering Materials

Urban Green Landscape

Wang, Zhao, Yang and Song Appl. Energy 2016
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 °C, but maintaining residual soil moisture of 0.10
“Smart” Irrigation Schemes

Energy-Water Tradeoff

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

<table>
<thead>
<tr>
<th>Activating top-soil temperature (°C)</th>
<th>Saving ($ m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>-8</td>
</tr>
<tr>
<td>20</td>
<td>-4</td>
</tr>
<tr>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>22</td>
<td>4</td>
</tr>
<tr>
<td>23</td>
<td>8</td>
</tr>
<tr>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>25</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
</tr>
</tbody>
</table>

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

*Yang* and Wang, 2015 Energy Build.
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Coupled Atmosphere-Urban Modeling

Upscaling the neighbourhood-scale results brings uncertainty:

- Spatial heterogeneity of land surfaces
- Lack of land-atmosphere interactions
Planning for a Growing Desert City

Low Water-use Xeric neighbor

Water stress

Thermal comfort

High Water-use Mesic neighbor

(Golden, 2004)
Urban Policy Dilemma

Source: https://www.glendaleaz.com/waterconservation/landscaperebates.cfm
http://www.mesaaz.gov/residents/water-conservation/residential-grass-to-xeriscape-rebate
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

A fully–greening city consumes $1.61 \times 10^8 \text{ m}^3$ more water during the summer.

Mean annual water consumption about 75 $\text{ m}^3$ per person (Gober and Kirkwood 2010)

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

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

Yang and Wang Landscape Urban Plan. 2017
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

25% green roof coverage over buildings

City-scale plan

Regional plan

Chicago

Los Angeles

Miami

New York City

Phoenix

Pittsburgh
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

_Yang_ and Bou-Zeid _Landscape Urban Plan_. 2019
Cooling benefit of green roofs increases non-linearly with the intervention area.

The shape of metropolitan areas and its geoclimatic setting control the scaling.

Yang and Bou-Zeid Landscape Urban Plan. 2019
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?

https://www.dnainfo.com/chicago/20150109/downtown/history-of-winter-chicago-it-could-be-worse-definitely-was
Early 2014 North American cold wave

Urban heat islands intensified during daytime \((0.65 \pm 0.34 \degree C, \text{ mean } \pm \text{ standard deviation among cities})\), and even more noticeably during night-time \((1.32 \pm 0.78 \degree C)\)
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.

Mechanism of intensified night-time UHI

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 $11.5 \pm 3.1 \, ^\circ C$
- Anomaly under heat waves ($3.7 \pm 1.5 \, ^\circ C$) 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).
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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.

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!