The Metrosphere

How Humans, Infrastructure and Nature Shape the Emerging Environment of Cities

PRINCETON UNIVERSITY

Elie Bou-Zeid

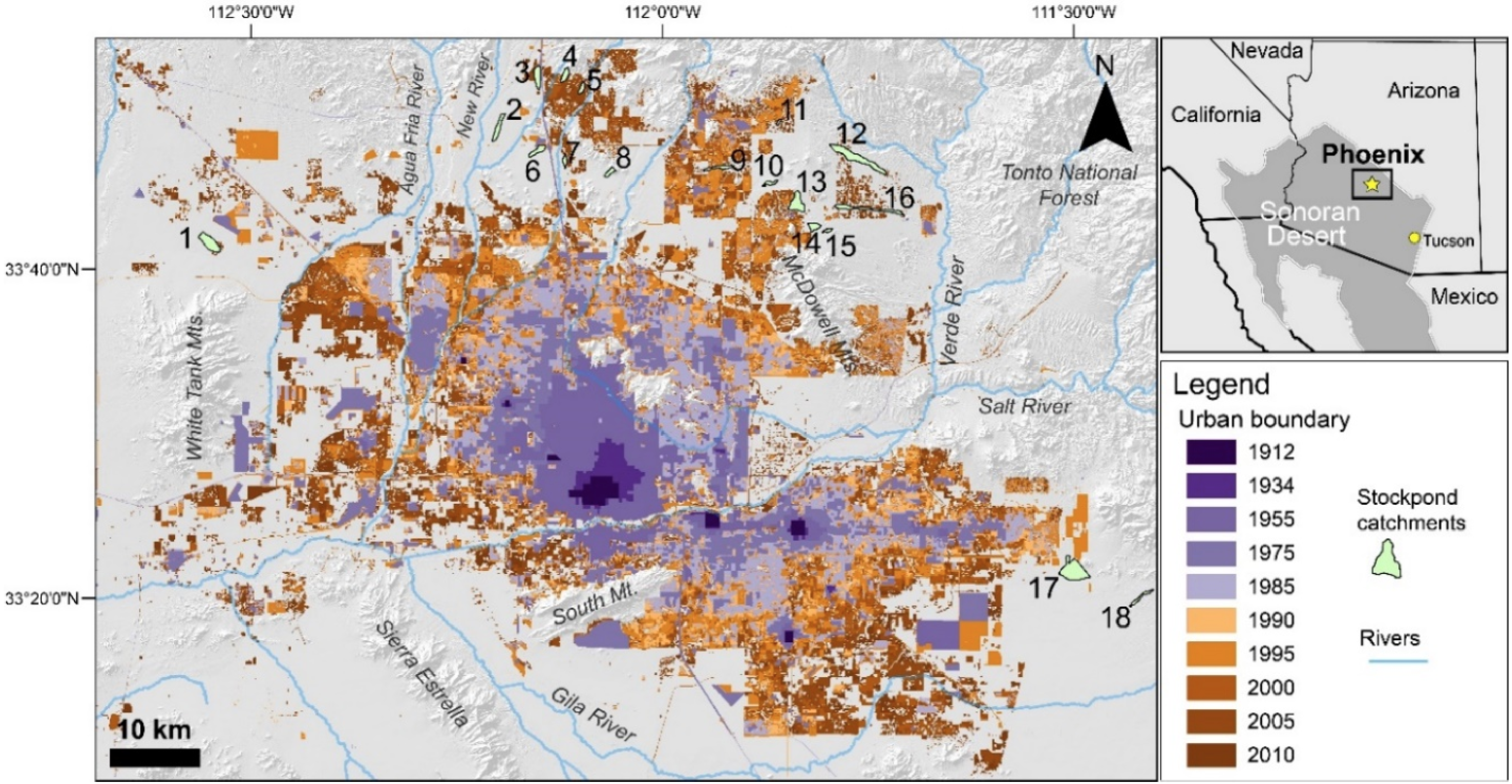
What is the Metrosphere?

Shanghai

A new environment (surfaces, air layers, water bodies, snow cover) the dynamics of which are largely controlled by human design and activities

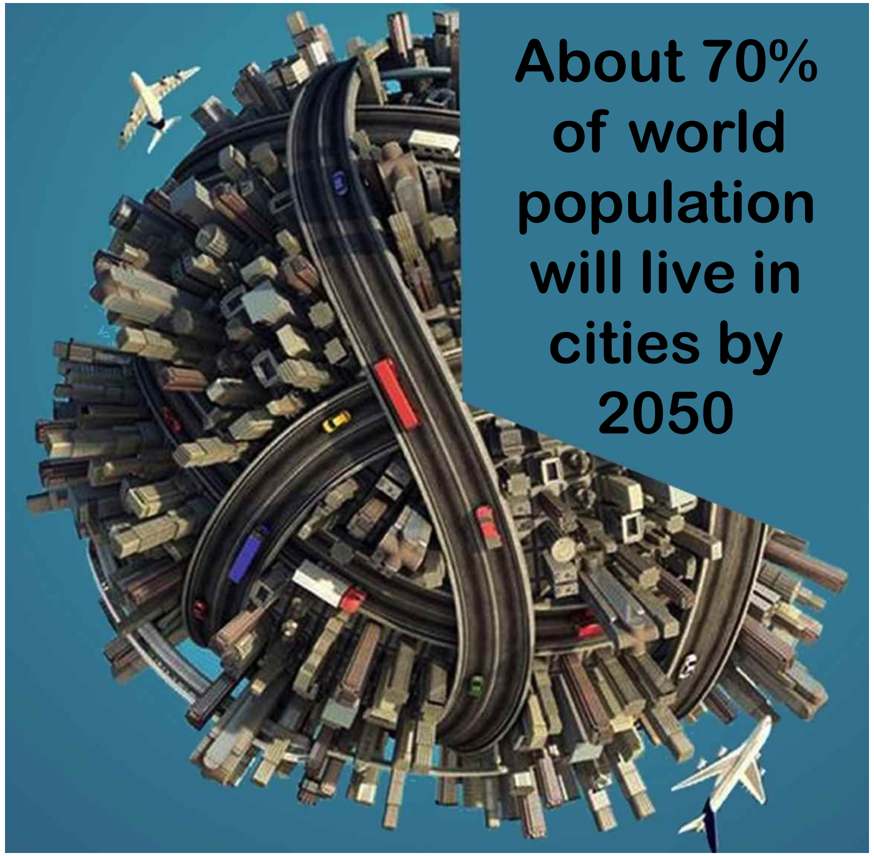
Expansion of the Metrosphere

Phoenix



The future of cities

Cities today
consume ~ 75% of energy,
emit ~ 80% of GHGs

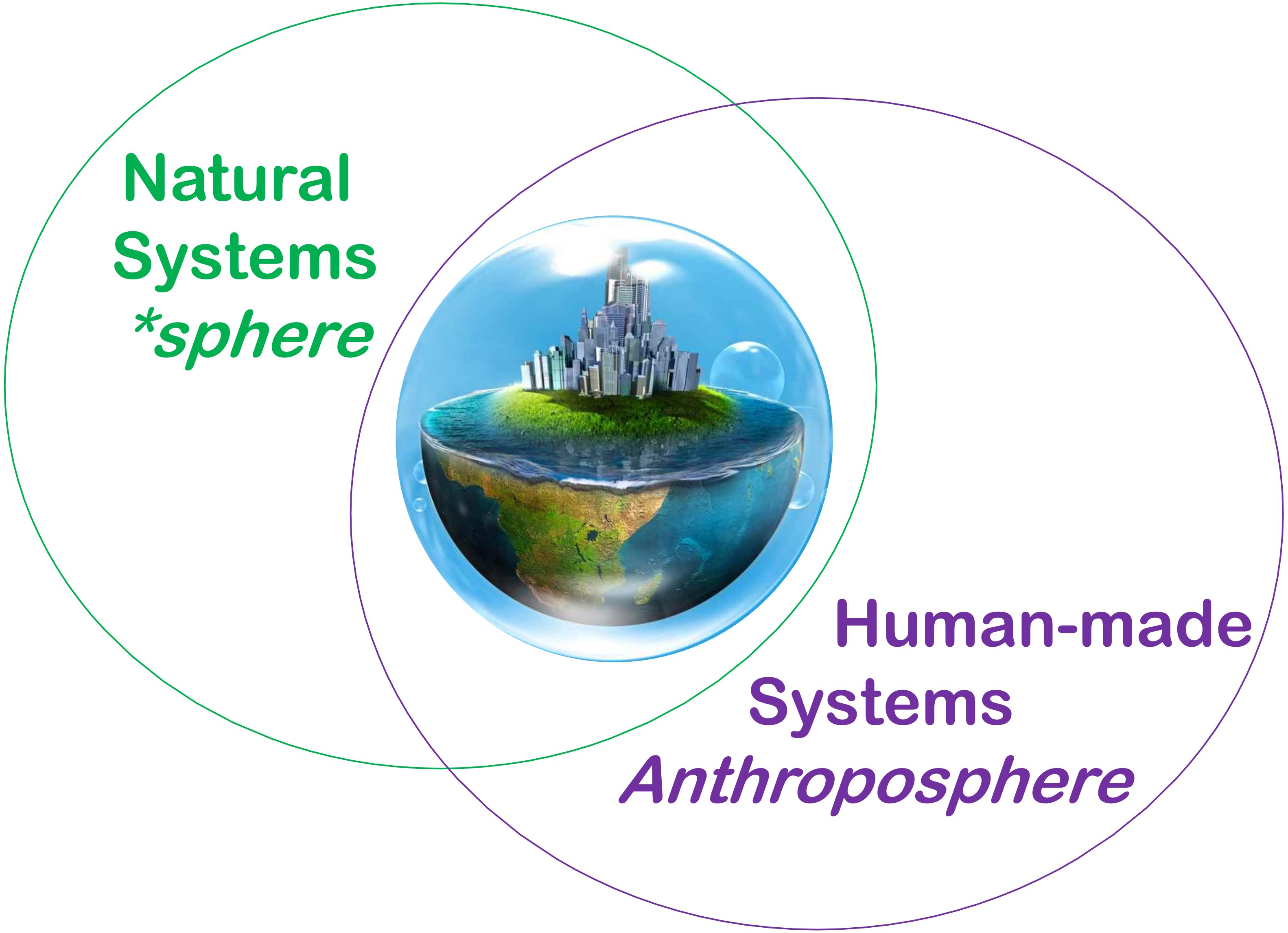


About 70% of world population will live in cities by 2050

Cities are where the Grand Challenges will be overcome

Or not

Cities are where we interact with the planet

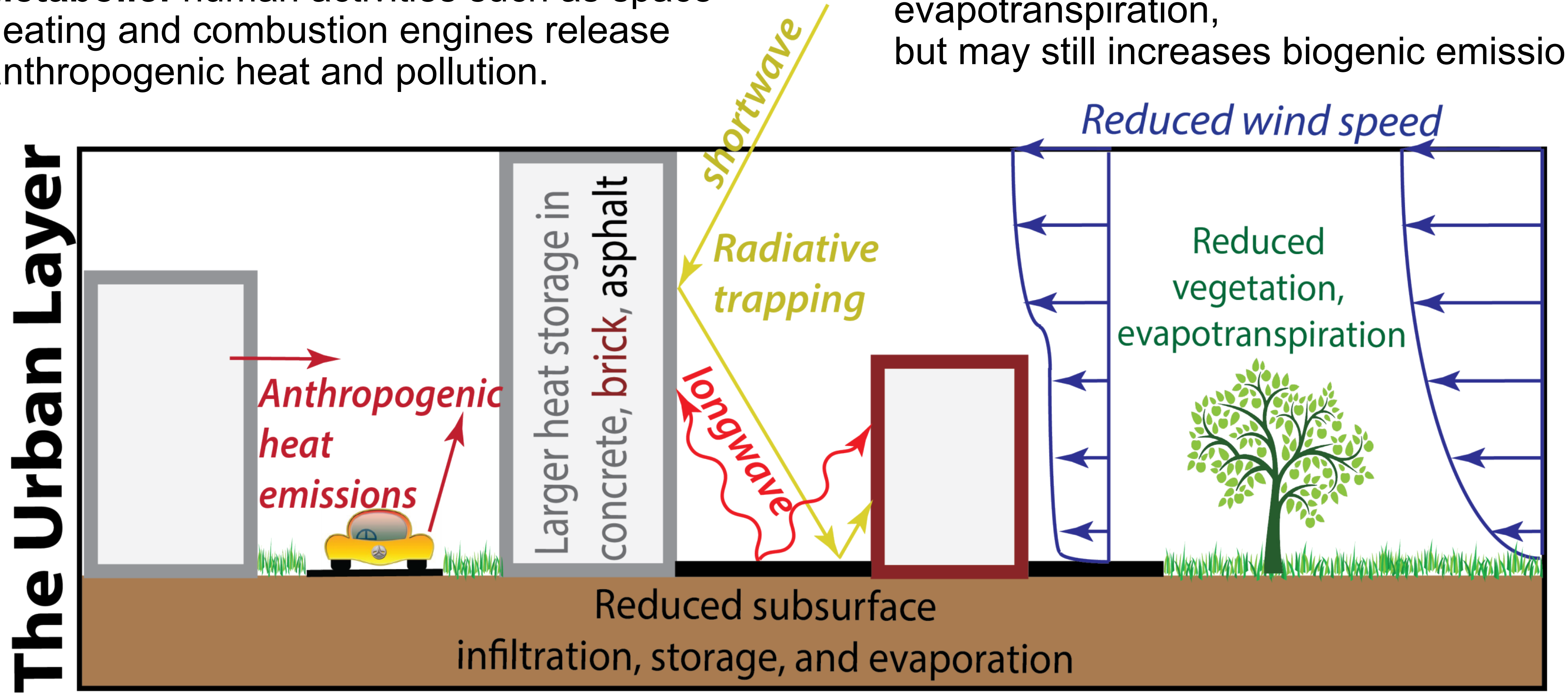


Urban infrastructure will double by 2055

Urban Grand Challenge:
How to design and plan these new buildings and infrastructure, while advancing resilience, environmental quality, sustainability, equity, and livability

Drivers of urban-rural climatic differences

- **Radiative:** darker surfaces, geometric trapping.
- **Material:** (e.g. concrete) that can store a lot of heat for a long time.
- **Metabolic:** human activities such as space heating and combustion engines release anthropogenic heat and pollution.
- **Geometric:** complex surface are better at trapping radiation and slowing wind.
- **Eco-hydrologic:** lack of pervious soils and vegetation reduces surface water and evapotranspiration,
  but may still increases biogenic emissions



Drivers of urban-rural environmental differences

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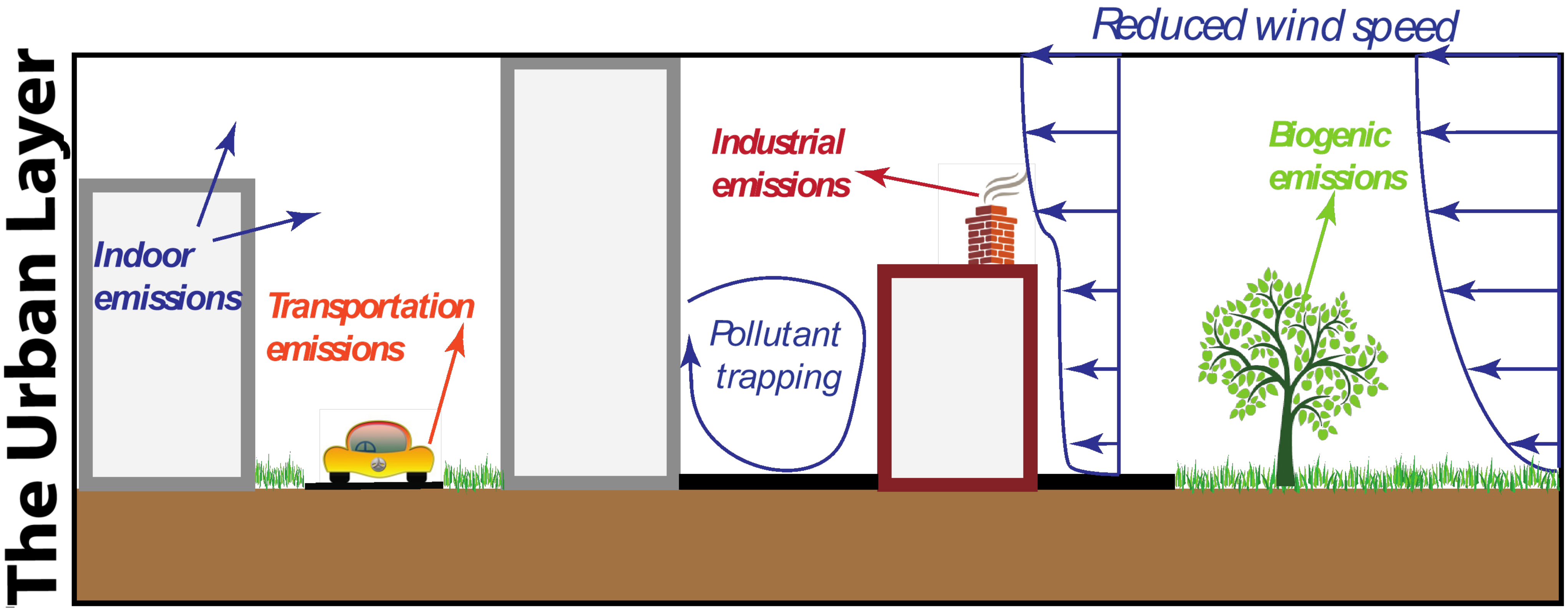


Urbanization vs. Global Warming

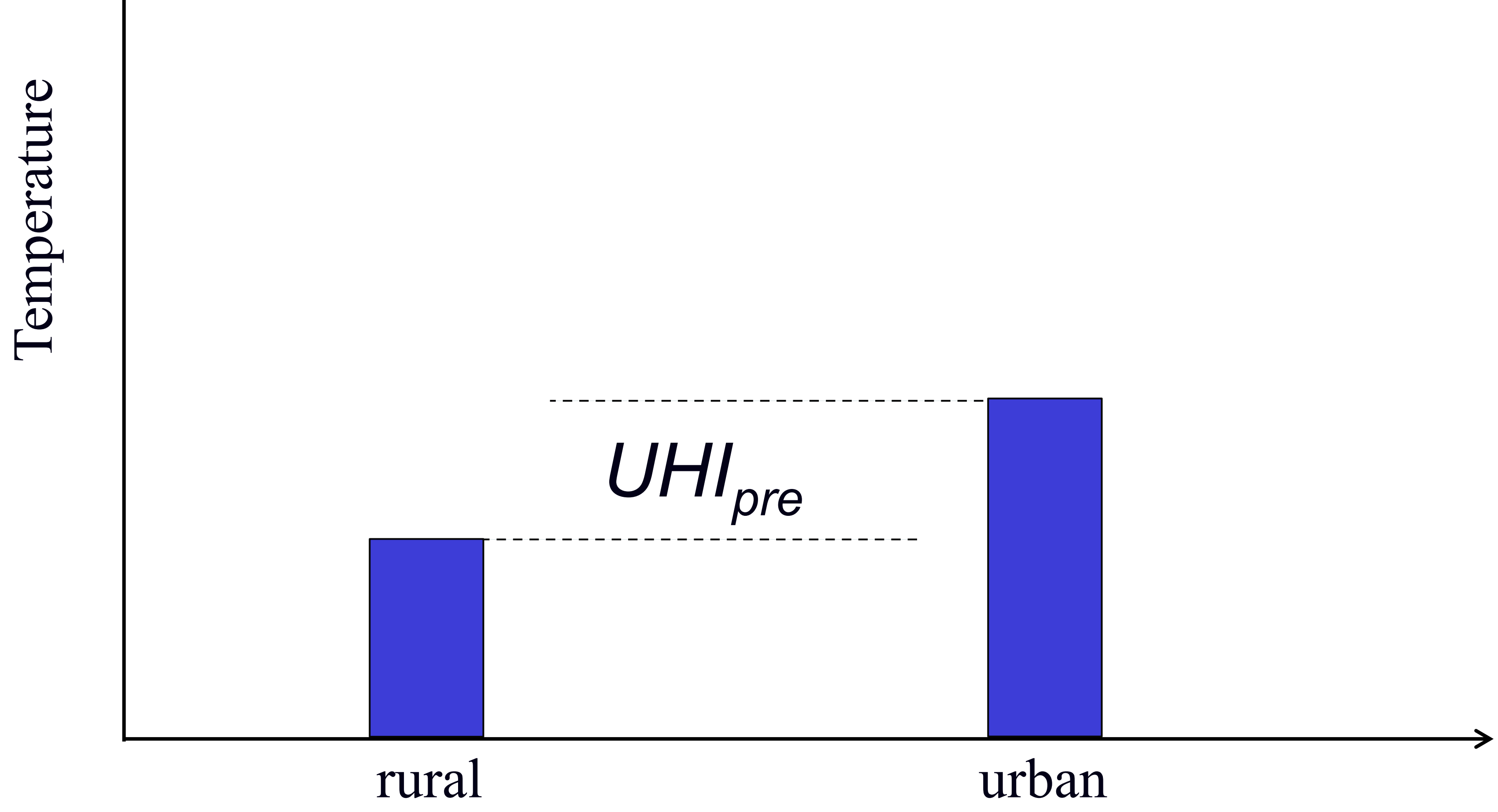
- Urban heat Island
- Modified precipitation & urban water cycle
- Modified ecology and biogeochemical cycles

- Increased intensity and duration of heat waves
- Changing precipitation and evaporation patterns
- Impacts on ecology and biogeochemical cycles

- How will these impacts (and mostly their extremes) interact?
- Will there be positive or negative or no feedbacks?
- How should we deal with the risk and try to mitigate it?

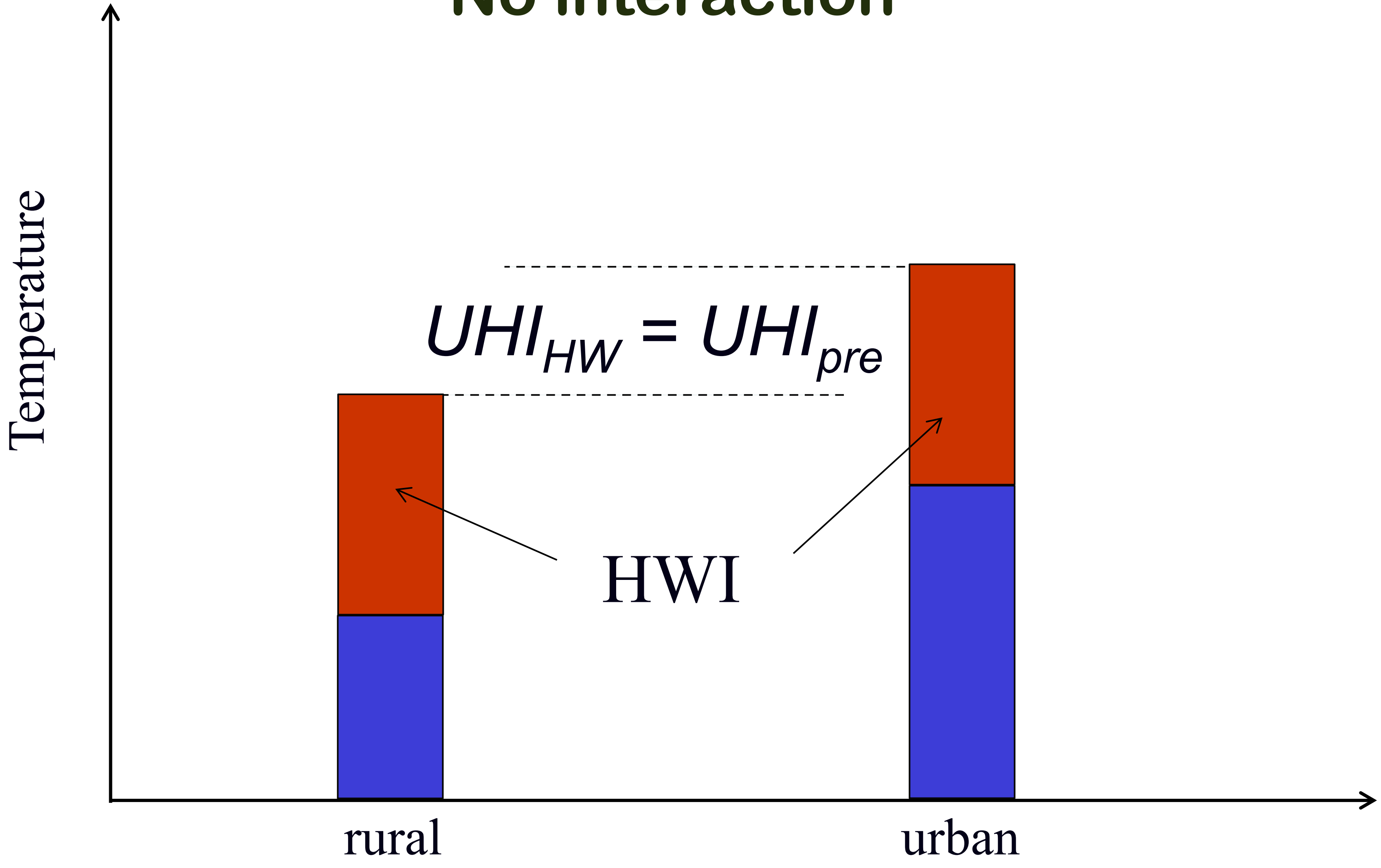
How do UHIs and HWs interact?

Heat waves are the
largest cause of weather related fatalities in US



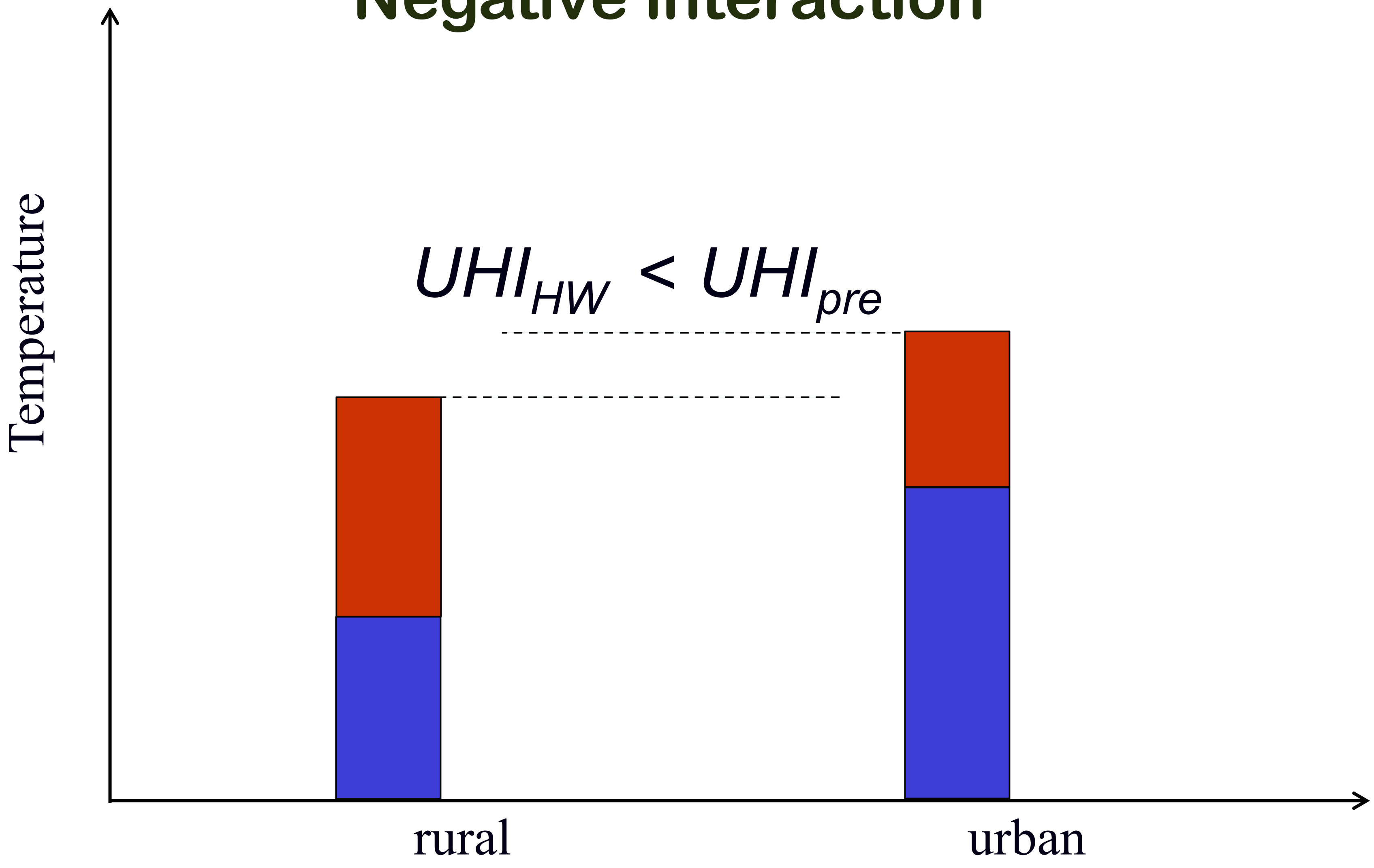
How do UHIs and HWs interact?

No interaction



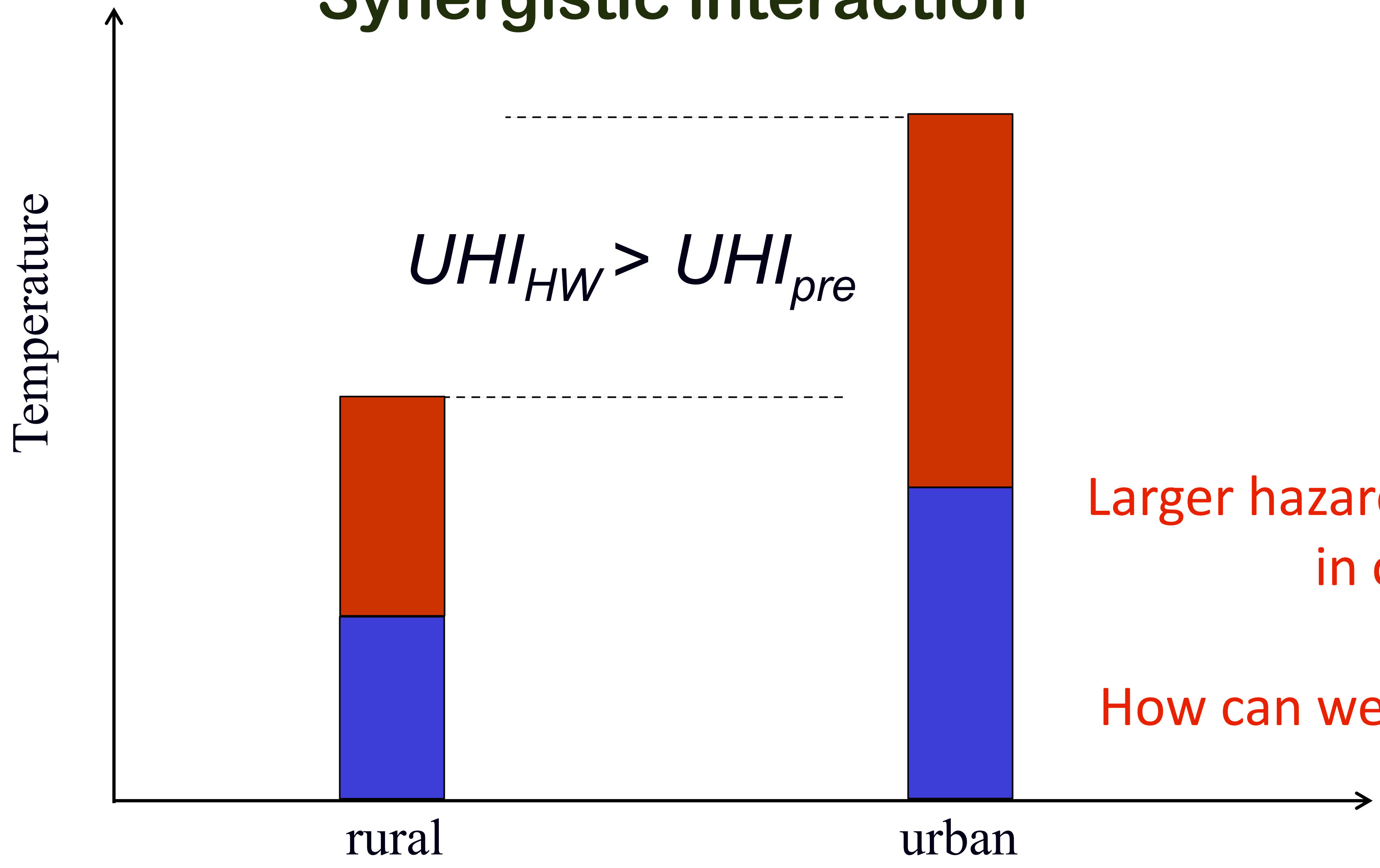
How do UHIs and HWs interact?

Negative interaction



How do UHIs and HWs interact?

Synergistic interaction



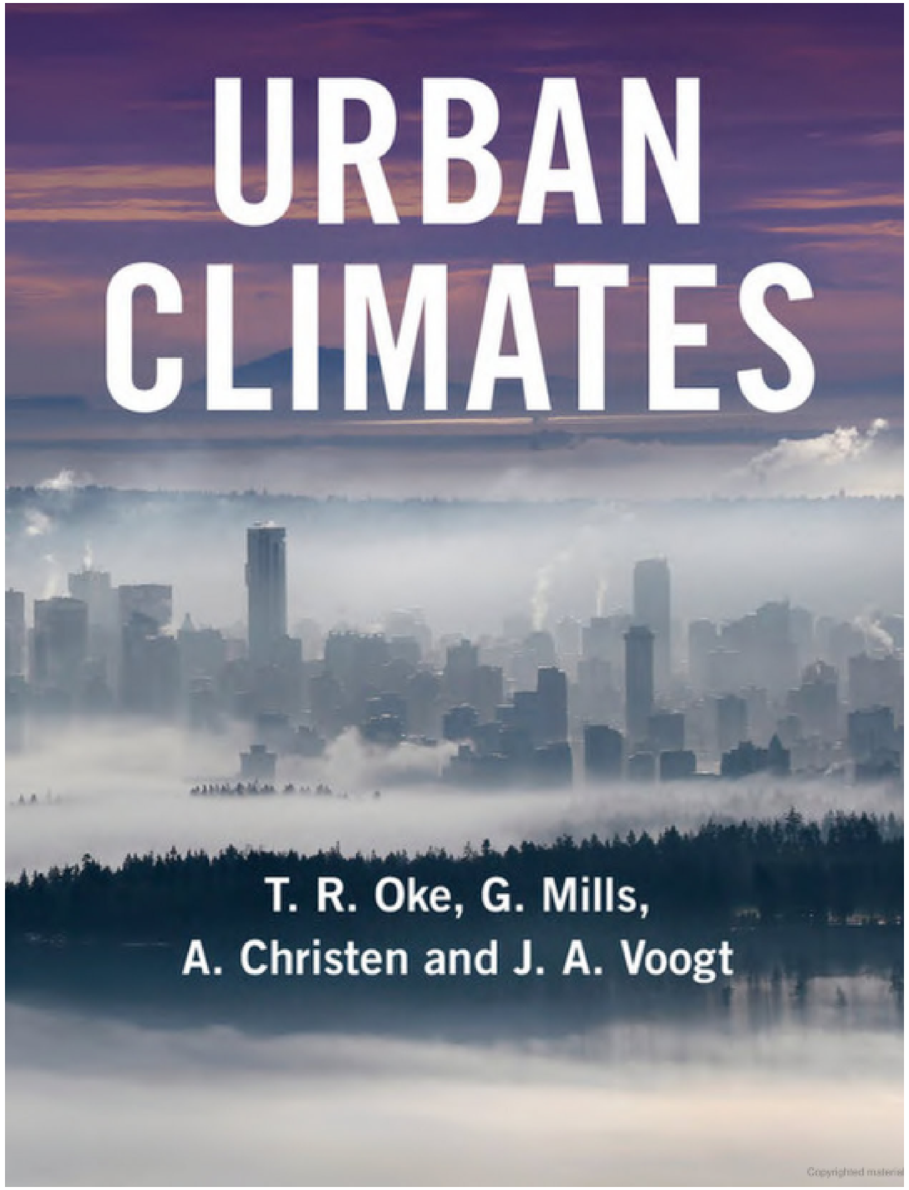
Larger hazard and exposure in cities?

How can we protect them?

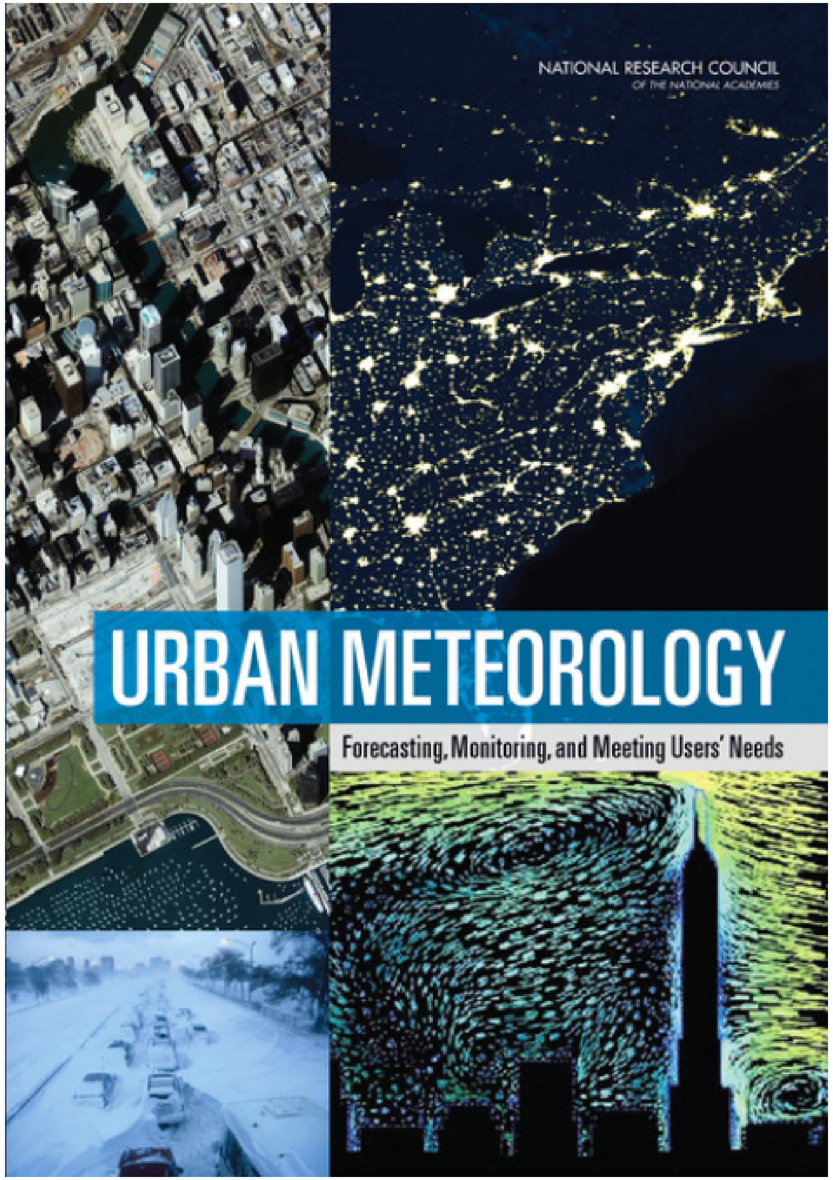
Needed transitions for resilience

- Transitions in the spatial and temporal scales
- Transitions in sensing strategies and devices
- Transitions in mobility and space use
- Transitions in heat mitigation technologies
- Transitions in equity of technology and action

Transitions in the spatial and temporal scales



The design criteria for resilience need to account for the tails of the hazard distribution, not only the mean

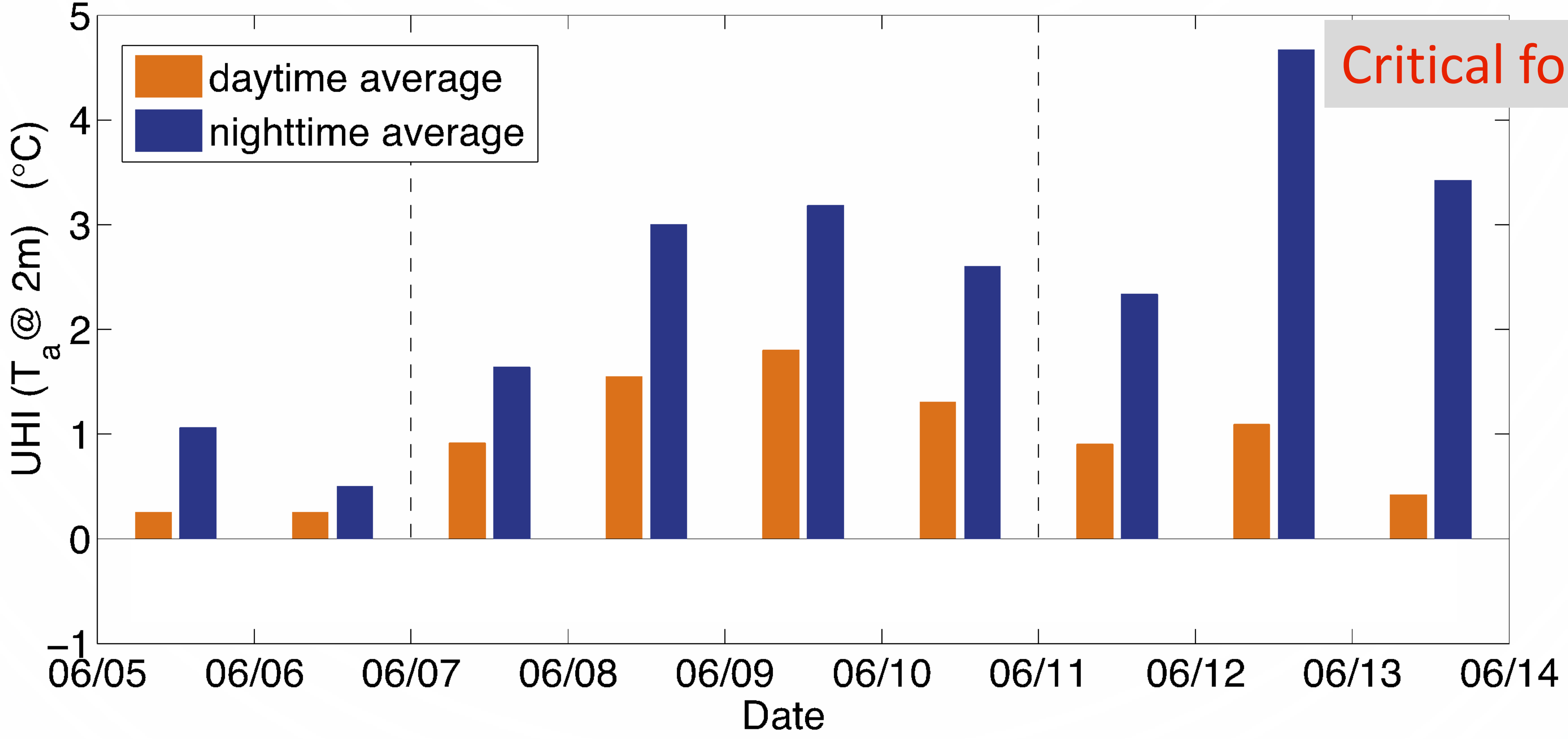


Needed transitions: temporal scales

Daily variations of the UHI in Baltimore

ASOS Observations : DMH – BWI

$$UHI = T_{urban}(x_i,t) - T_{rural}(r_i,t)$$



Critical for resilience

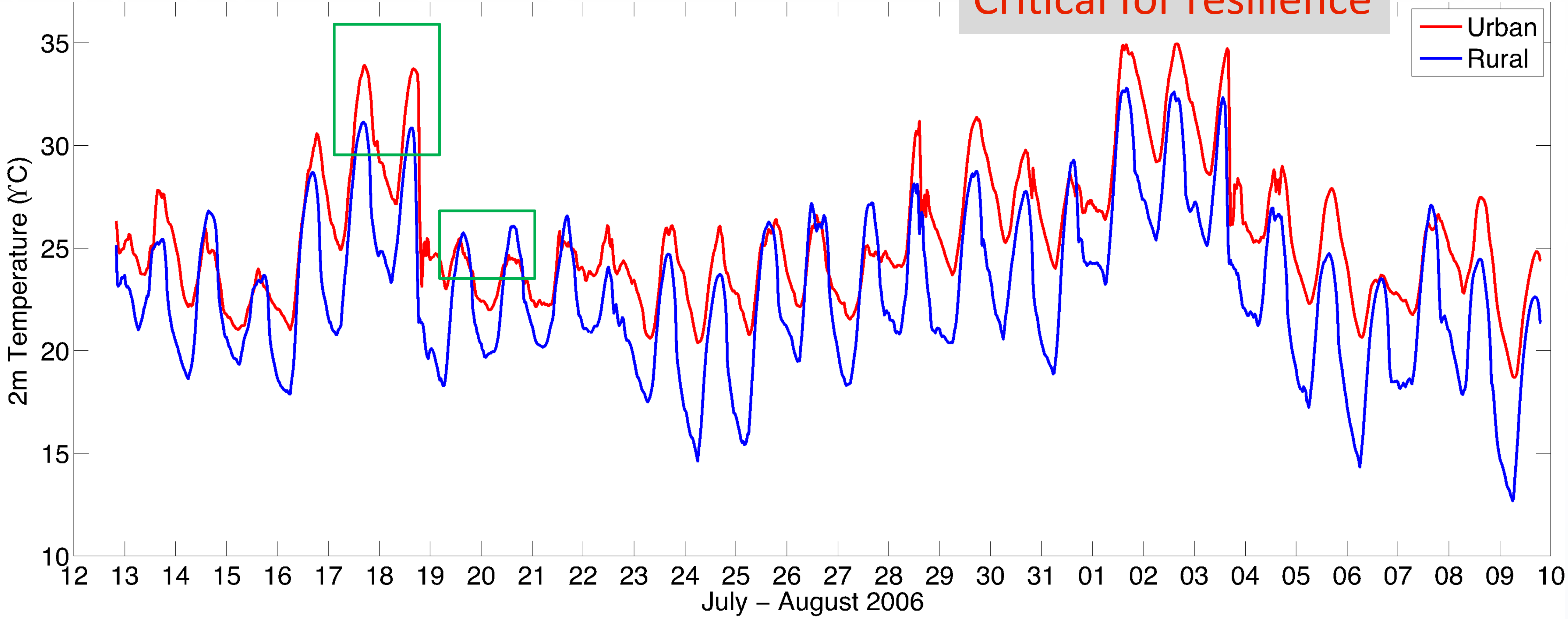
Needed transitions: temporal scales

Daily variations of the UHI in Baltimore

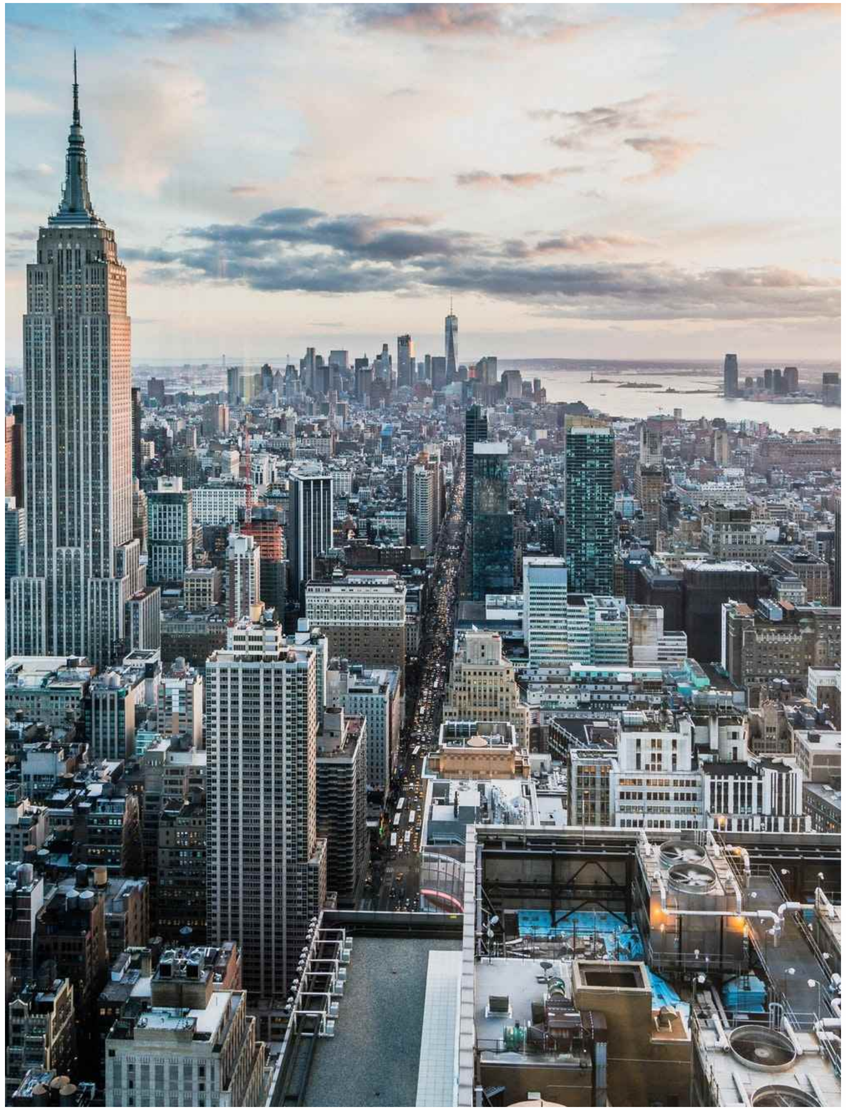
WRF simulations

$$UHI = T_{urban}(x_i, t) - T_{rural}(r_i, t)$$

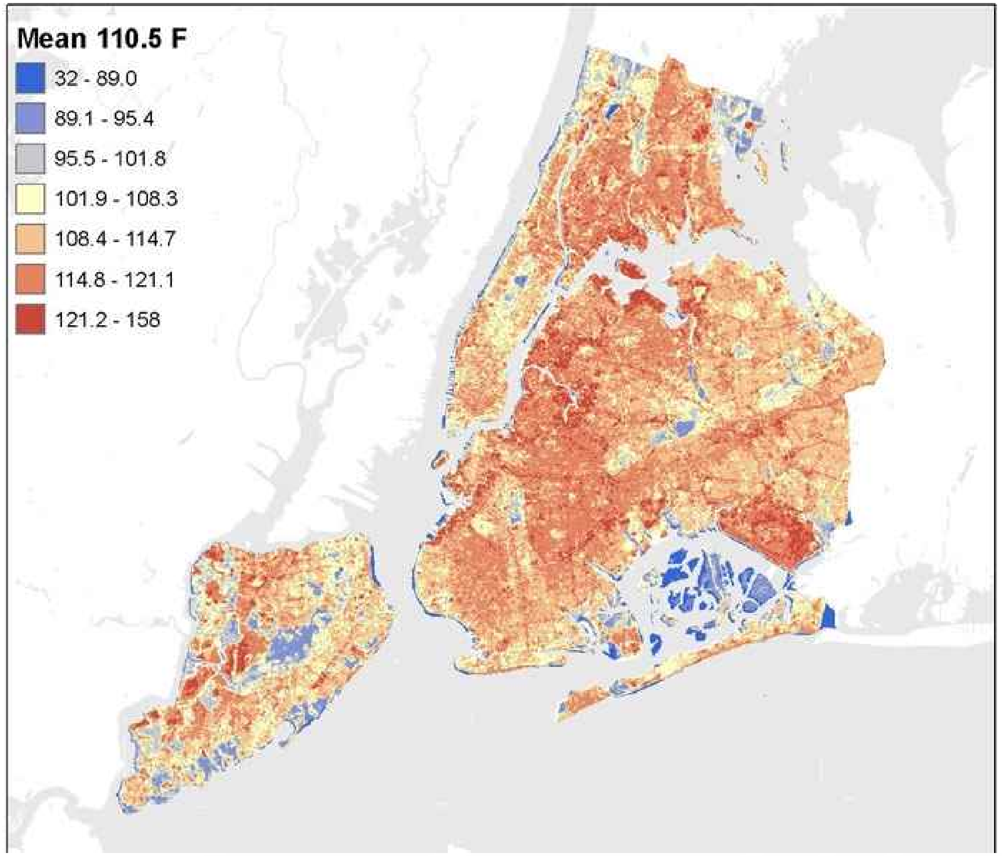
Critical for resilience



Needed transitions: spatial scales



Landsat Surface Temperature August 14 2002 10:30am



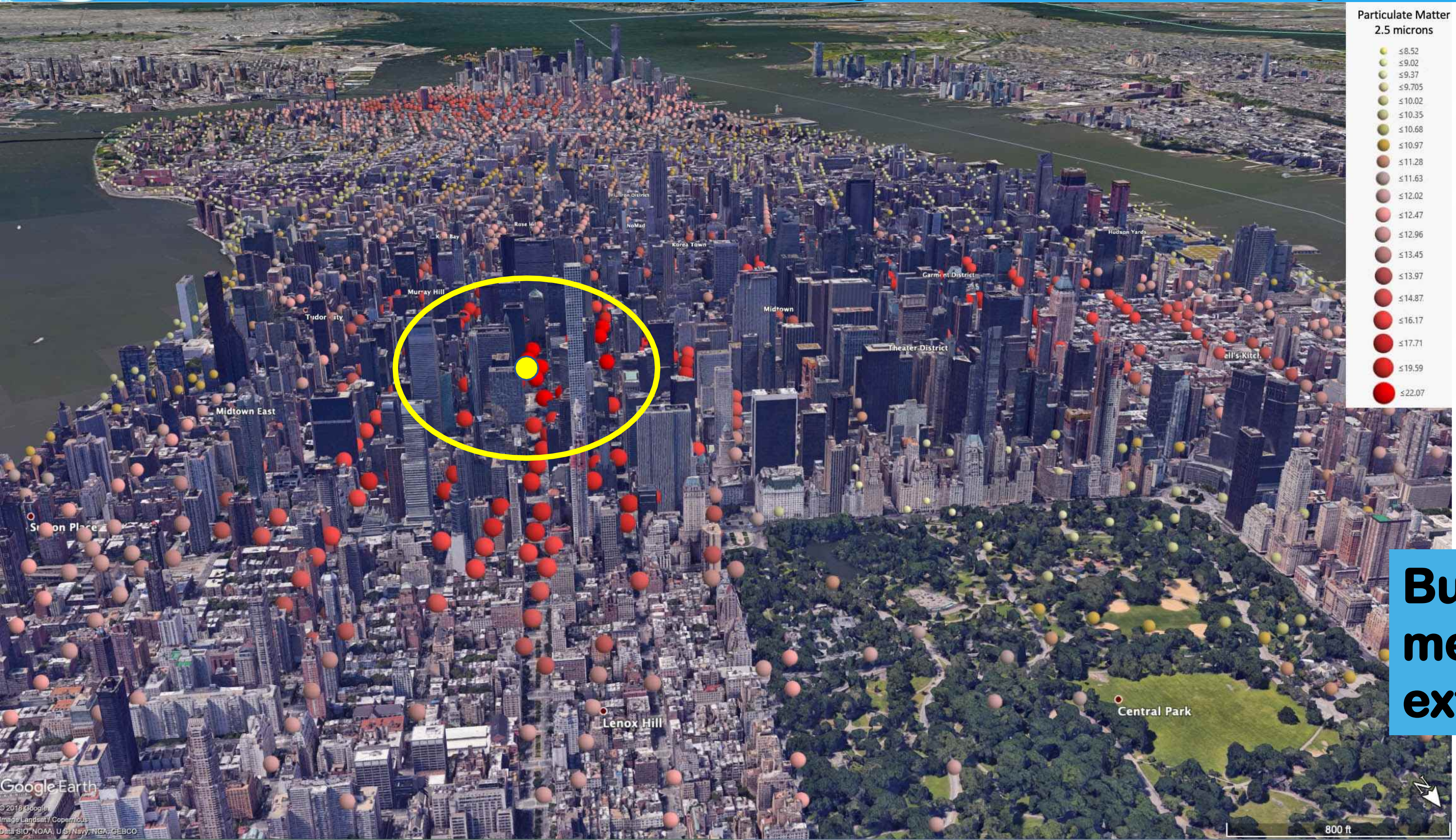
Spatiotemporal temperature variability

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

The environmental neighborhood is the area influencing the environmental quality at a given point in a city.

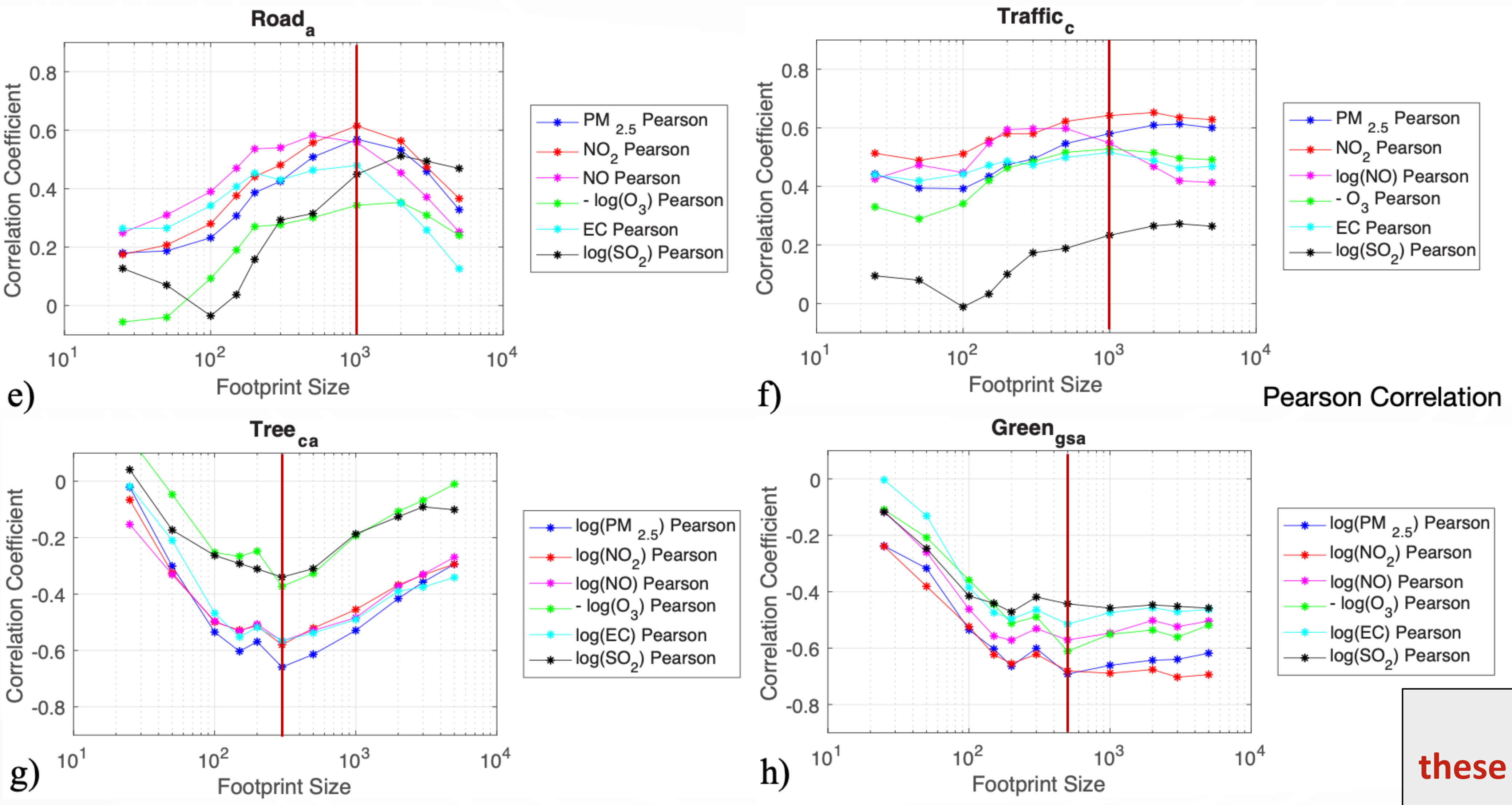
The environmental stressors vary strongly in time and in space (horizontally and vertically).

The environmental neighborhood is the area influencing the environmental quality at a given point in a city.



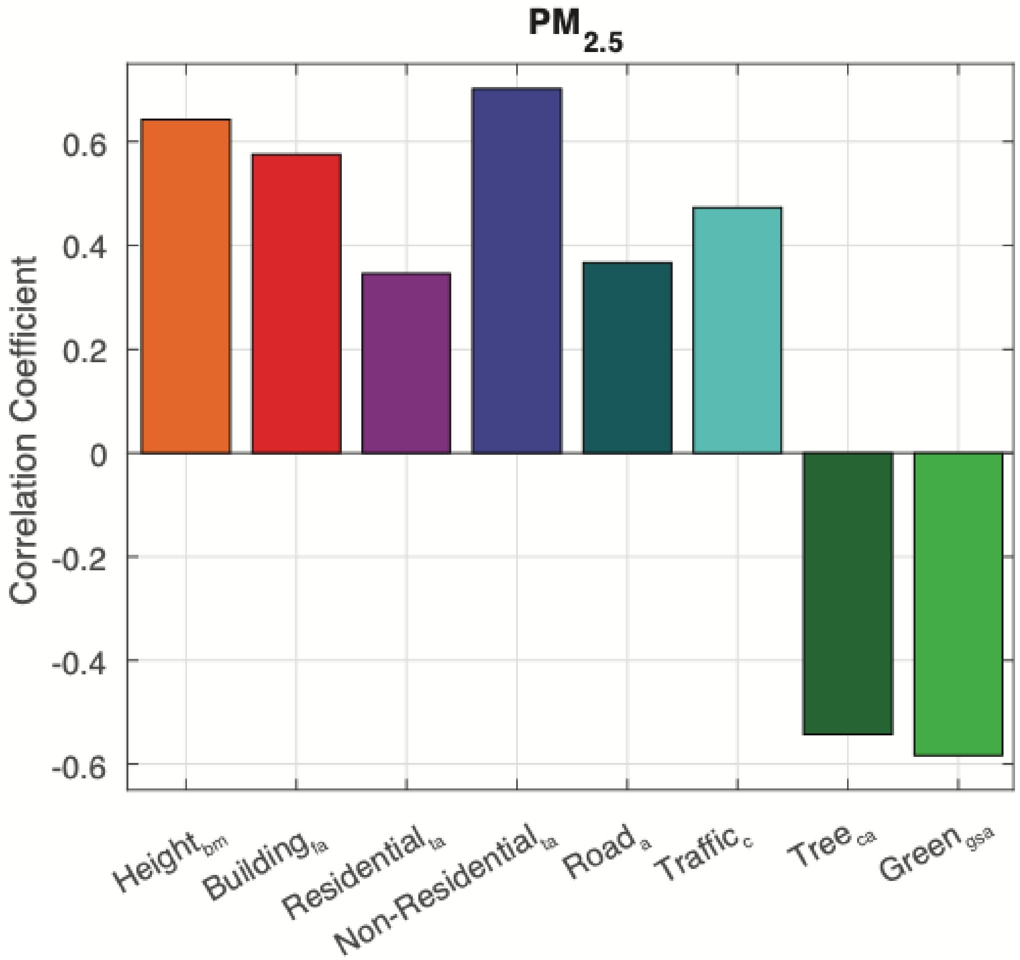
But how to measure its extent?

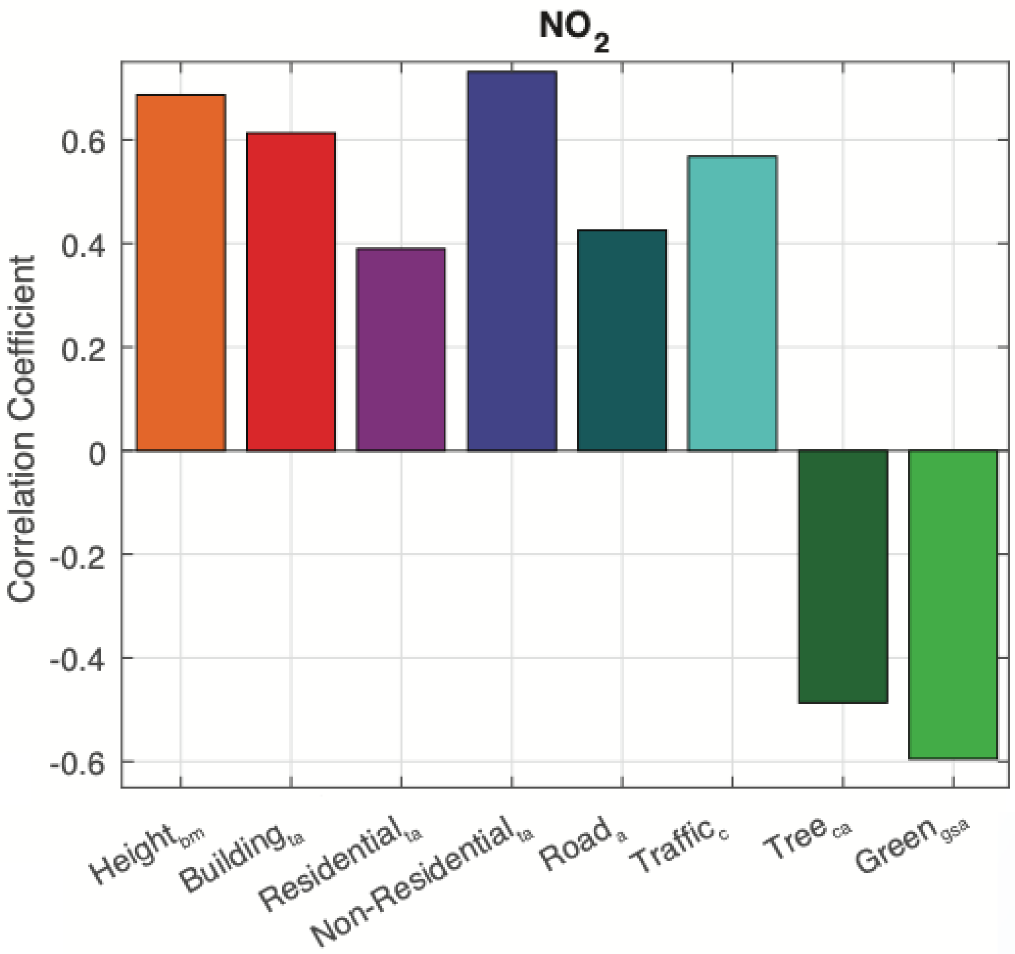
What scale maximizes correlation?



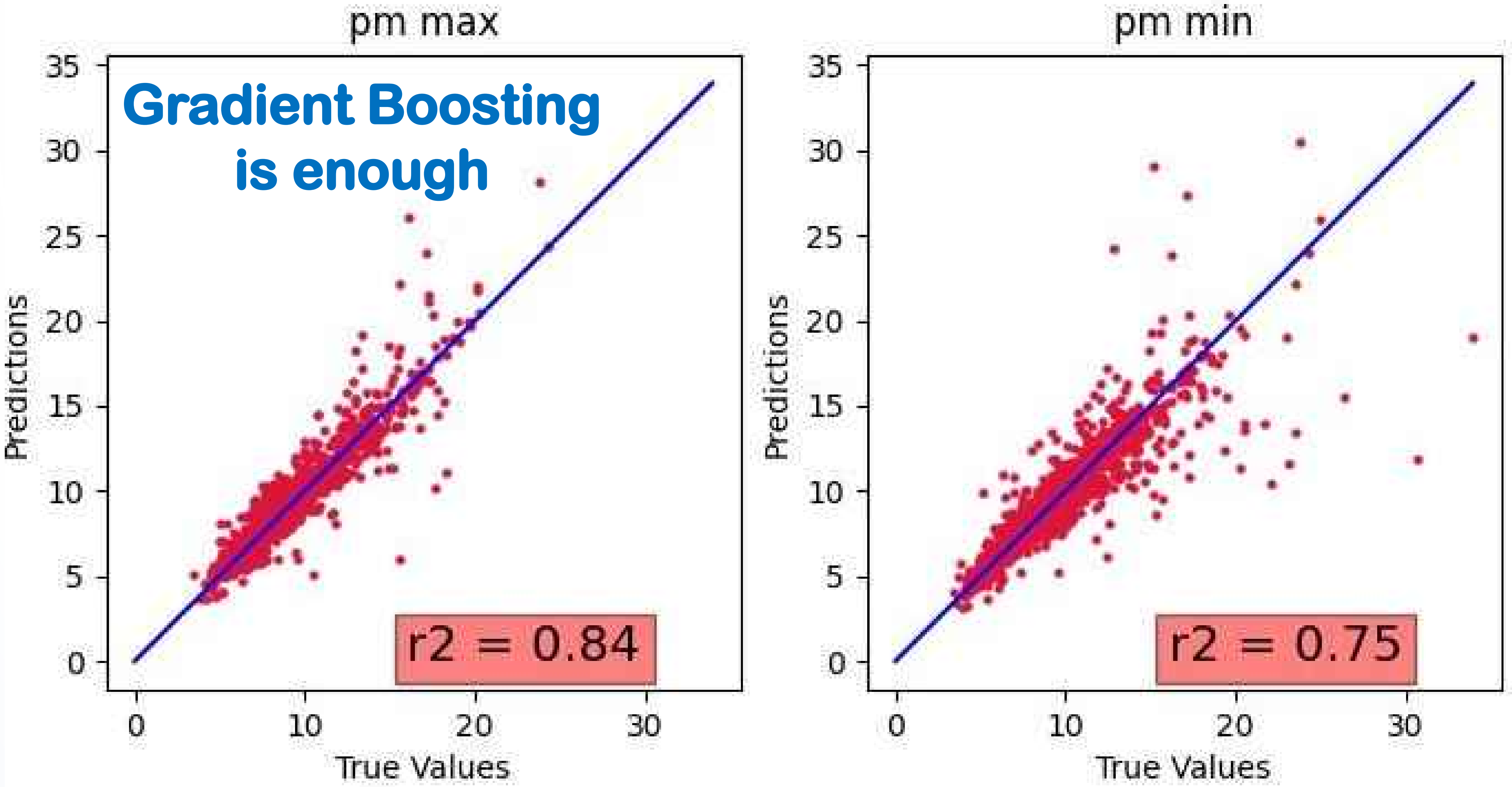
For AQ, these neighborhoods are ~ 0.2-1 km

Main determinants in NYC

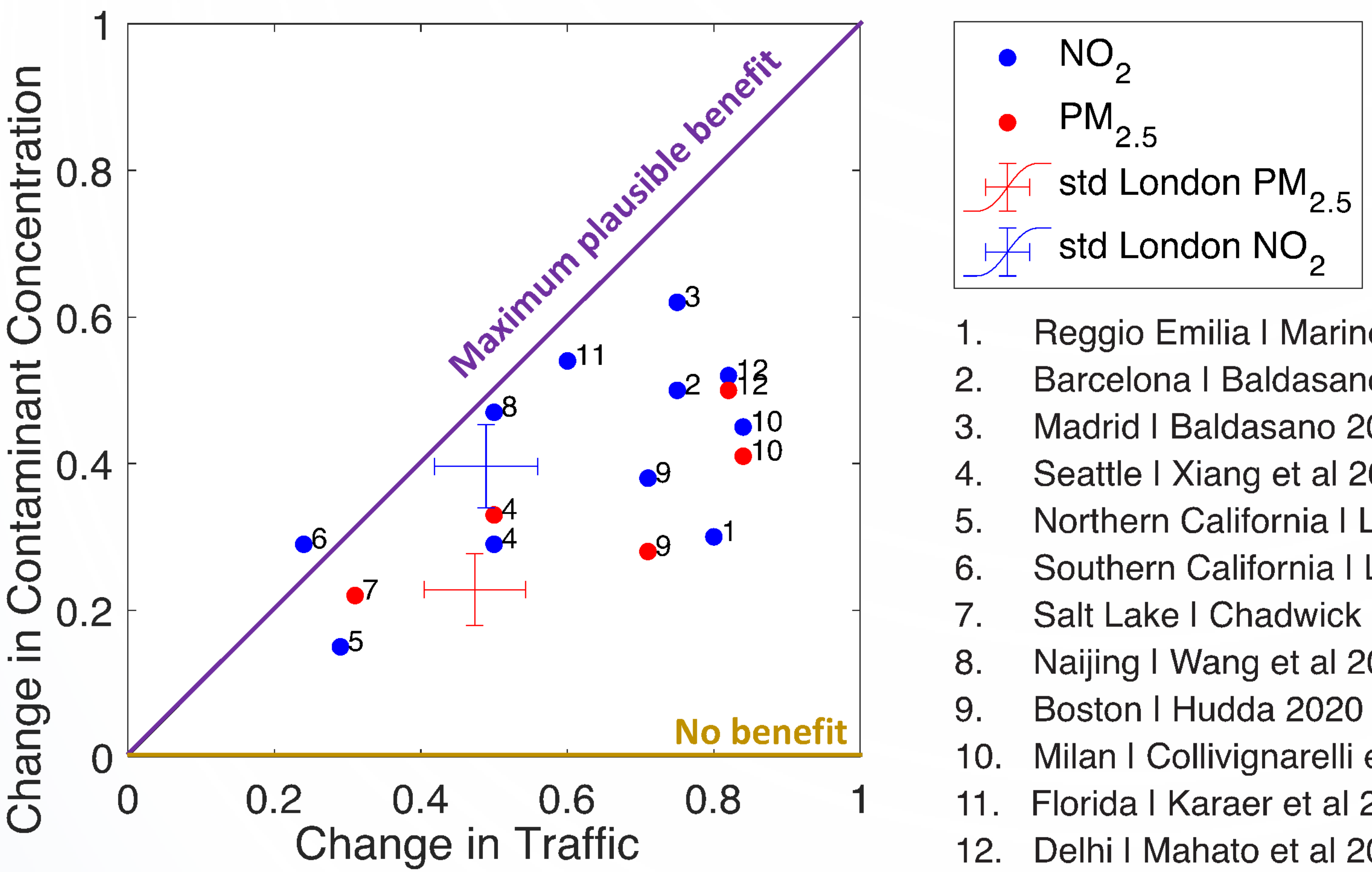




Machine learning models for AQ



Role of Traffic, the Covid lockdown experiment



1. Reggio Emilia I Marinello 2021
2. Barcelona I Baldasano 2020
3. Madrid I Baldasano 2020
4. Seattle I Xiang et al 2020
5. Northern California I Liu et al 2021
6. Southern California I Liu et al 2021
7. Salt Lake I Chadwick et al 2021
8. Naijing I Wang et al 2020
9. Boston I Hudda 2020
10. Milan I Collivignarelli et al 2020
11. Florida I Karaer et al 2020
12. Delhi I Mahato et al 2020

$$\text{Elasticity} = \frac{\text{Concentration \% reduction}}{\text{Traffic \% reduction}}$$

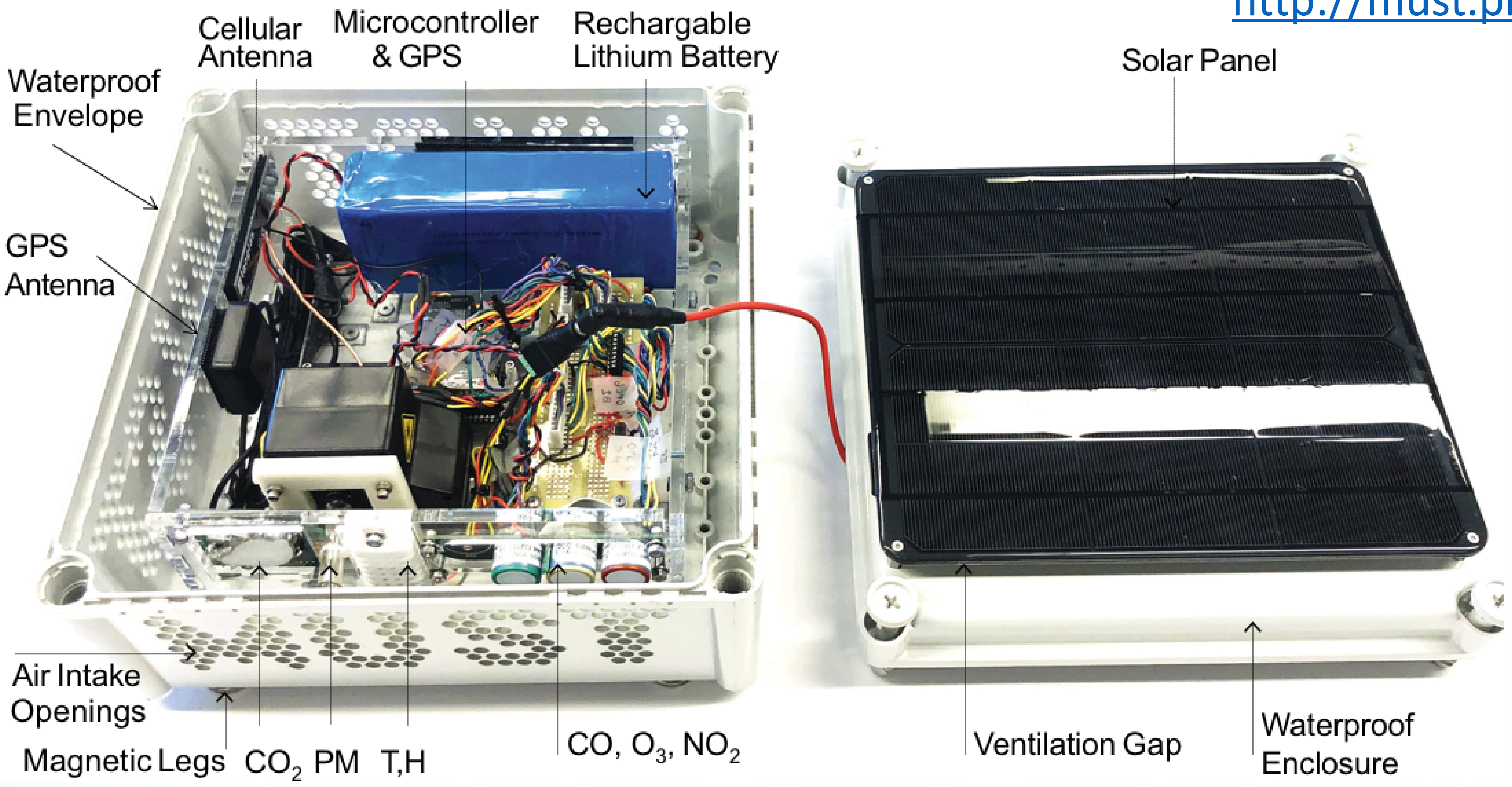
Across ours + 12 studies

Elasticity for $NO_2 = 0.71$
Elasticity for PM $= 0.56$

Transitions in sensing strategies and devices

Mobile Urban Sensing Technologies

http://site.princeton.edu
http://must.princeton.edu



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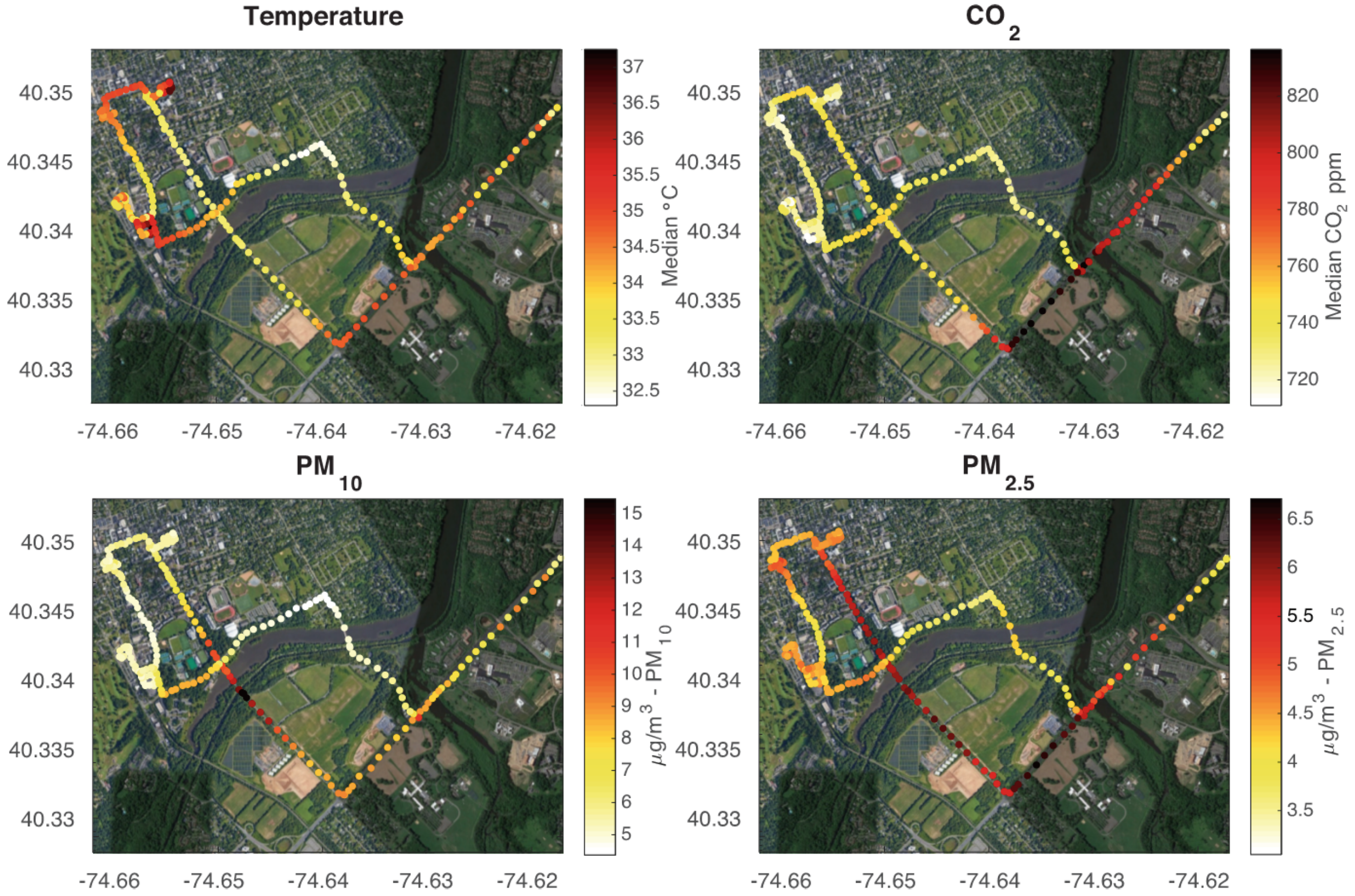
Transitions in sensing strategies and devices
Mobile Urban Sensing Technologies



Multi-trip averages

of Temperature, CO_2, $PM_{2.5}$ and PM_{10} concentrations

On the afternoon of July 17th 2019

Simulations for experimental design: Fixed + mobile sensors

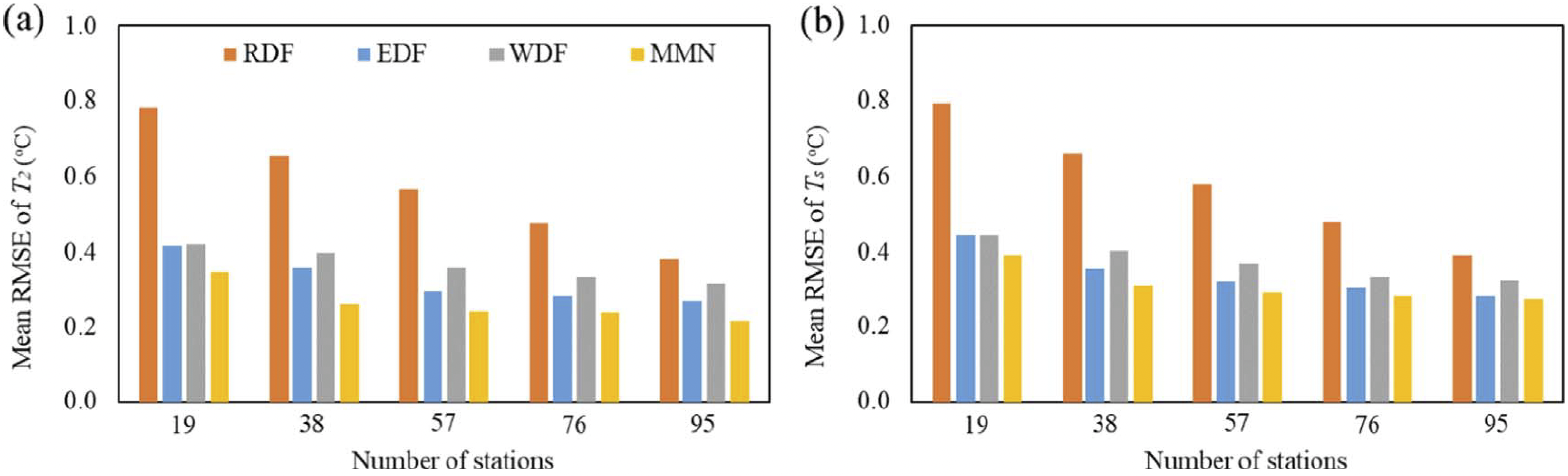


Figure 5. Mean RMSEs of monthly mean (a) T_2 and (b) T_s by different measurement networks over the entire studied area of four cities.

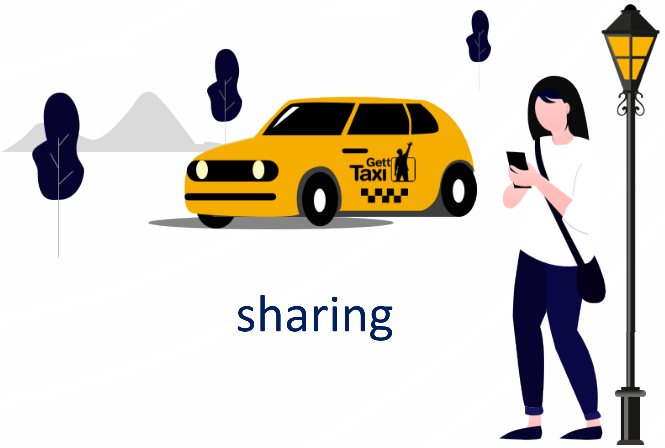
RDF: Randomly Distributed Fixed
EDF: Evenly Distributed Fixed (to cover all percentages of imperviousness)
WDF: Weighted Distributed Fixed (to skew to more common types of surfaces)
MMN: Mobile Measurement Network

For extremes, you need hybrid networks

Transitions in Mobility

Harnessing the urban livability and environmental opportunities of emerging mobility solutions

Autonomy + connectivity



sharing

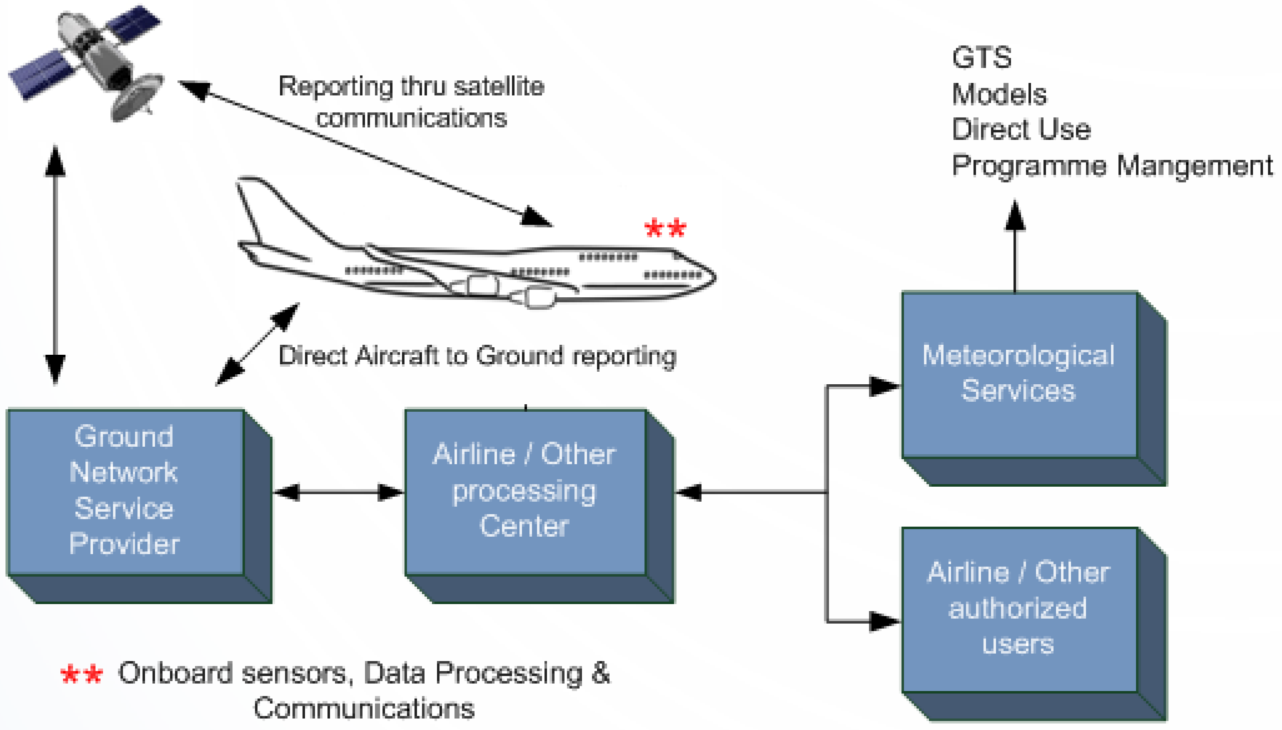
Micro-mobility

electrification

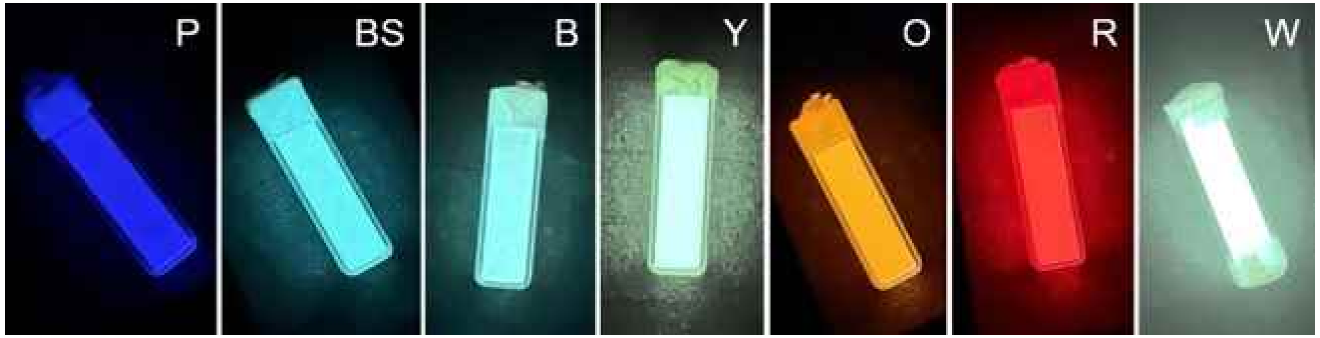
Monitor the benefits for AQ and thermal comfort

Data collection by autonomous shared fleets

A ground-based ACARS/AMDAR program?

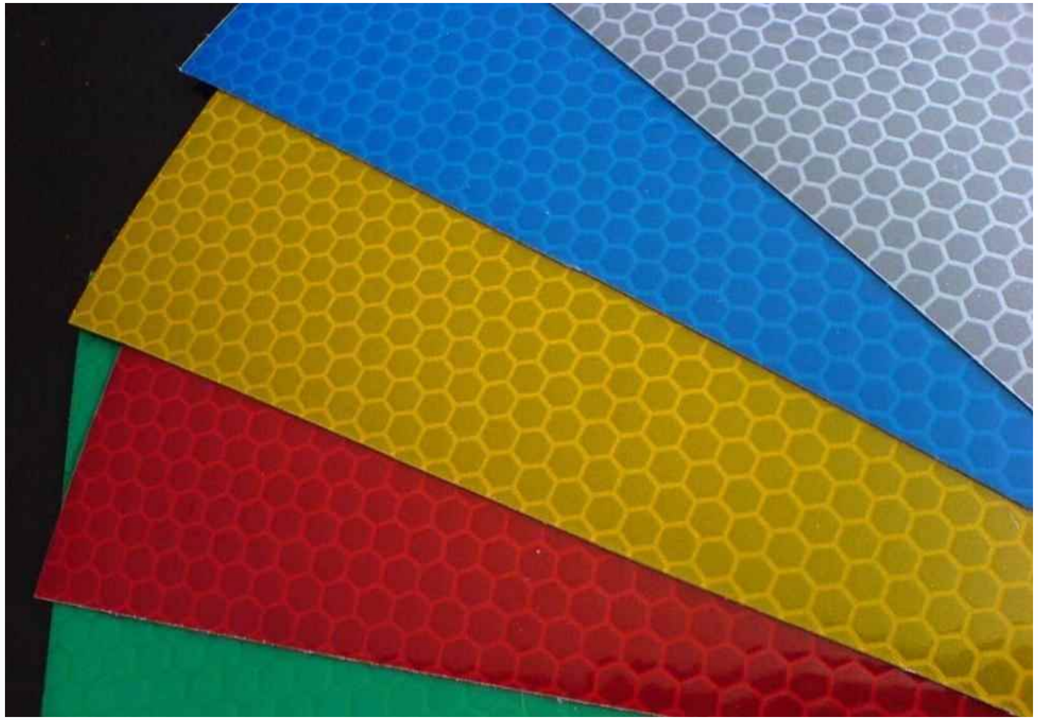


Transitions in urban cooling technologies



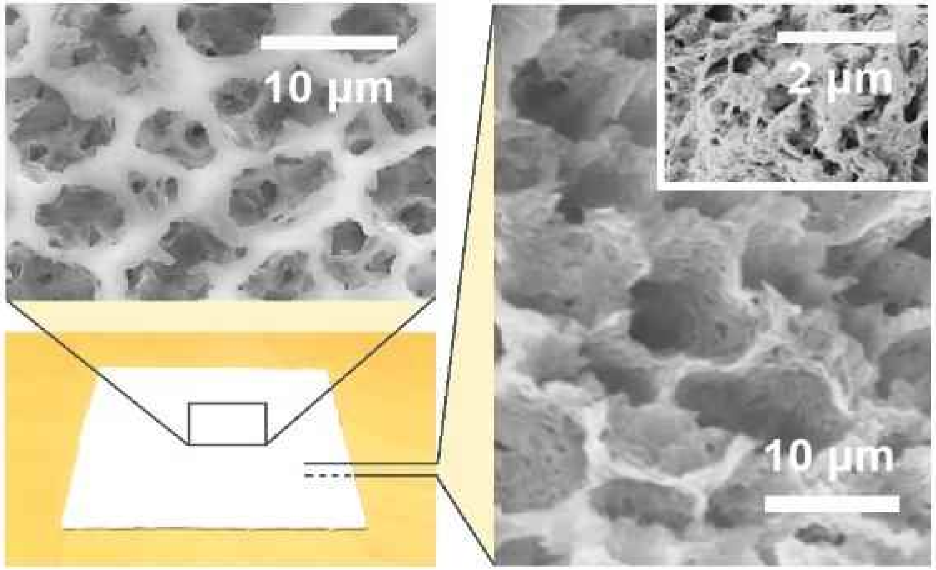
Photoluminescence

Retroreflectors



Thermochromic

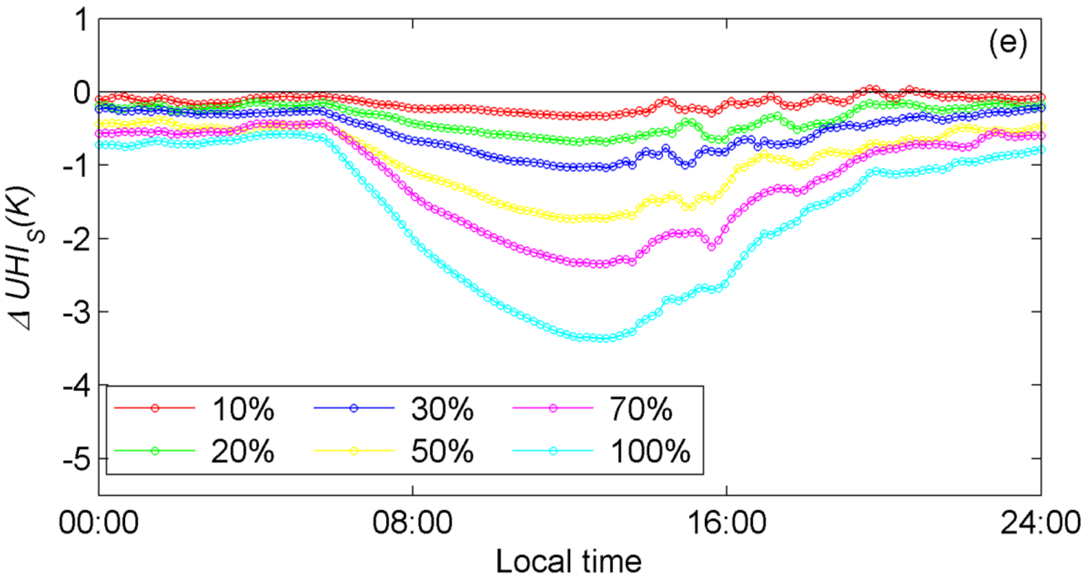
Band & directional emitters



Cool roofs

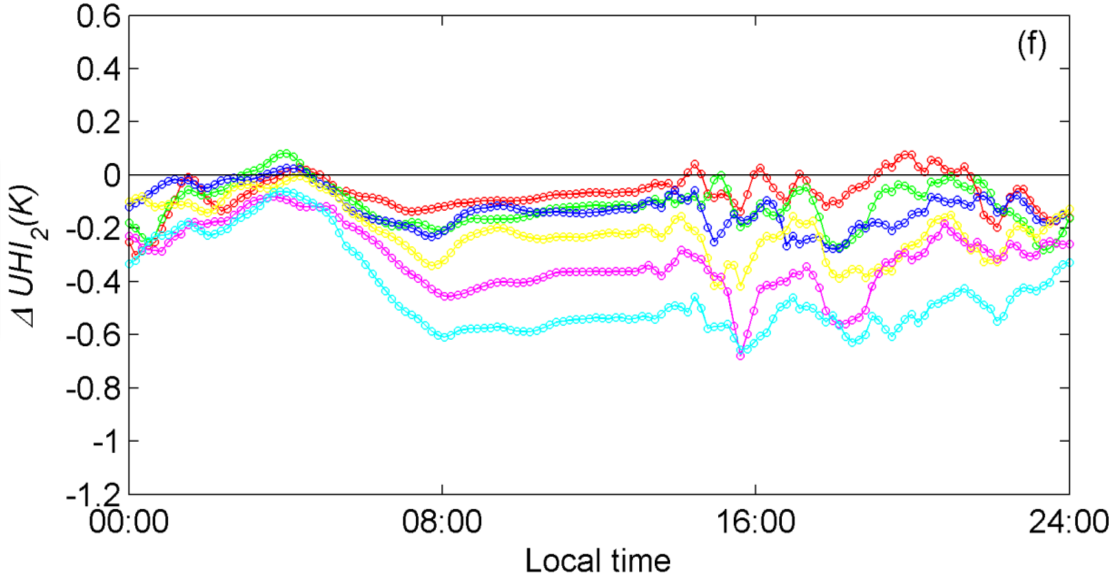
00:00 (UTC) June 7
to 00:00 (UTC) June 10
Averaged diurnal cycles

Surface temperature



Roofs' albedo increased to 0.7 (computed dynamically by the UCM)

2m air temperature



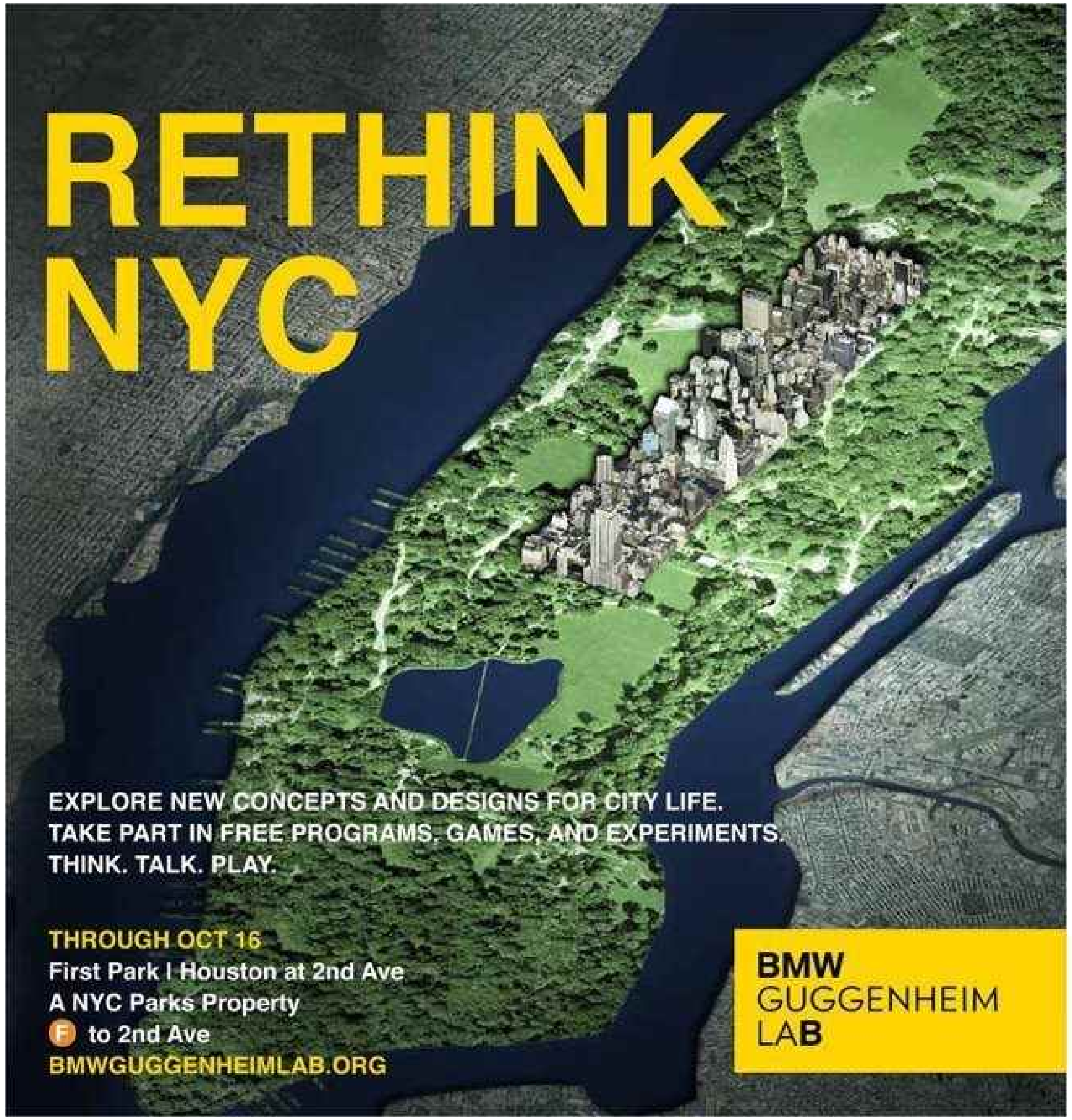
Green roofs

00:00 (UTC) June 7
to 00:00 (UTC) June 10
Averaged diurnal cycles

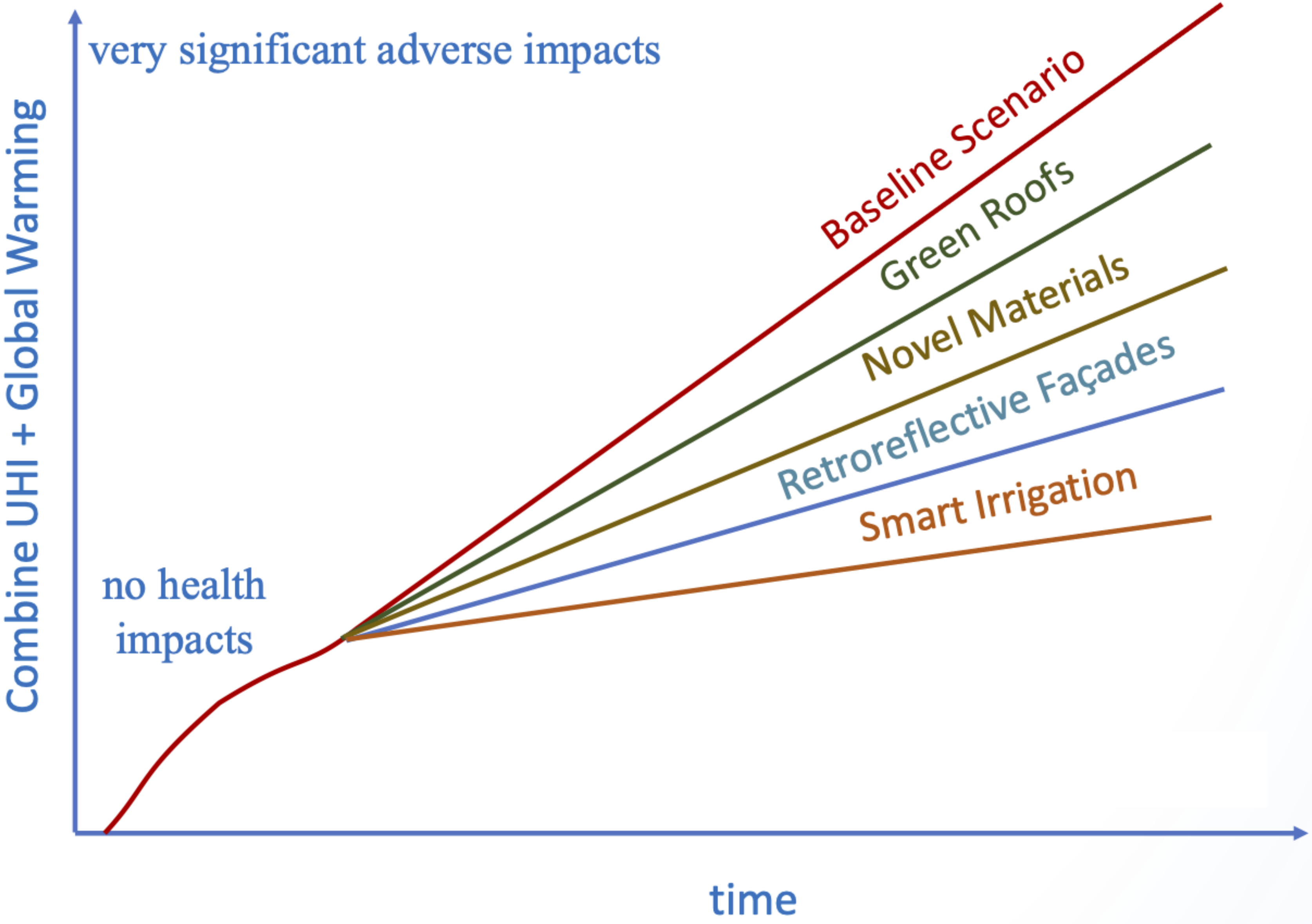
Surface temperature

UCM in WRF
roofs evaporating
at ~ 50% of E_p
(computed dynamically
by the UCM)

2m air temperature

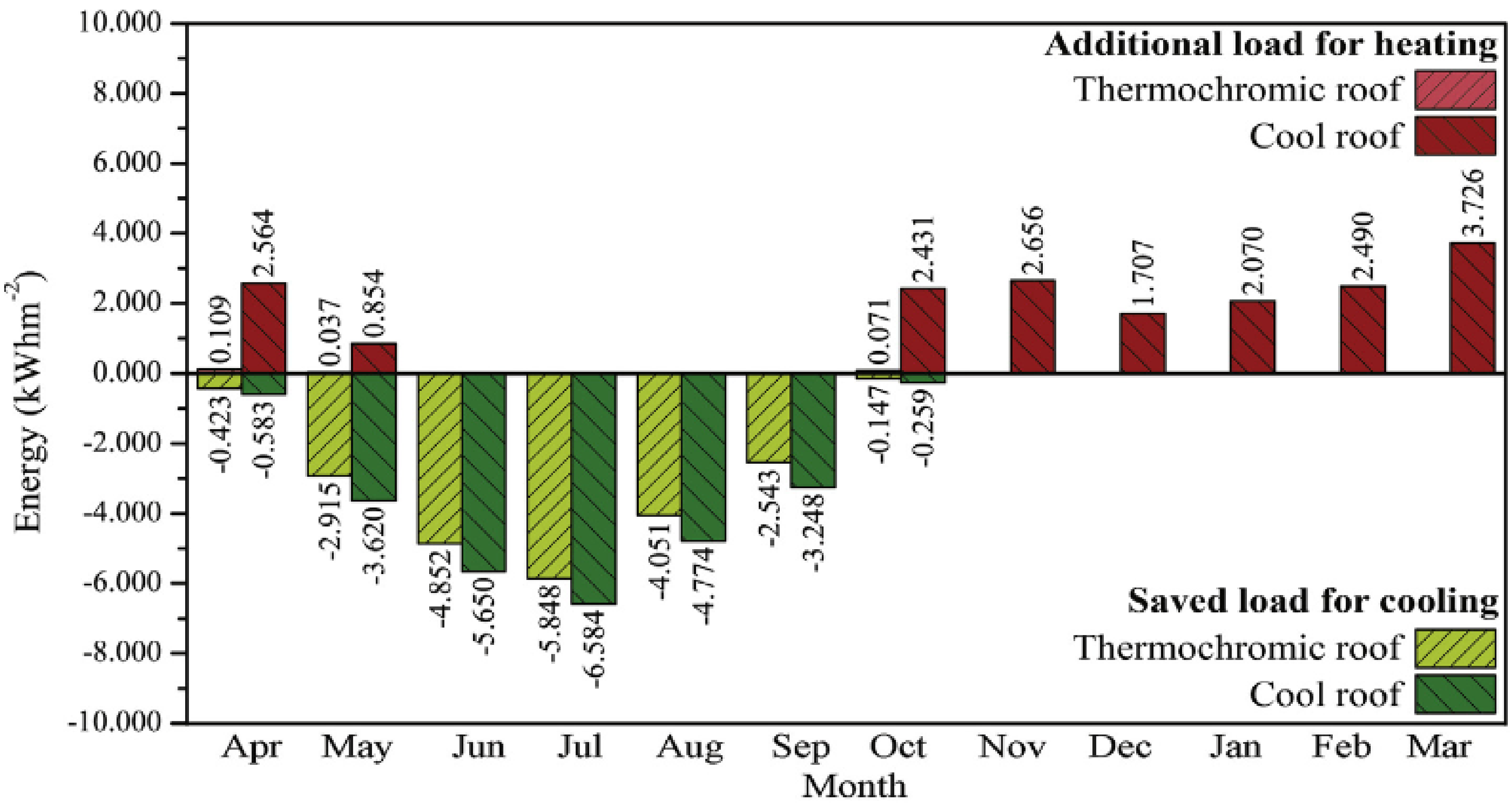


Wedges of urban cooling … Portfolio of solutions



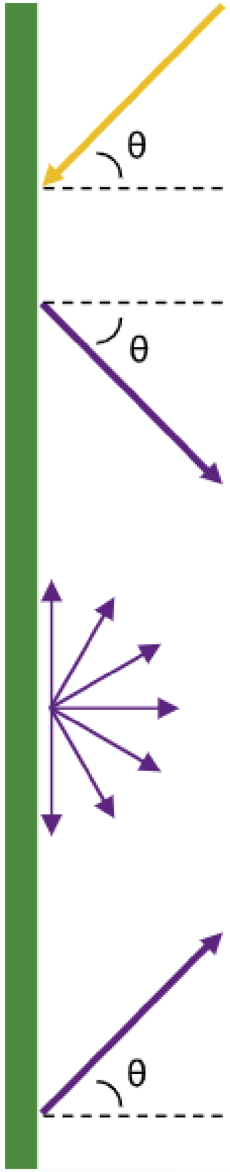
Thermochromic energy savings

Almost same summertime benefits as a cool roof, but no wintertime penalty



Difference between cumulative energy load per m^2 of roof relative to a black roof

Retroreflective walls and ground cooling

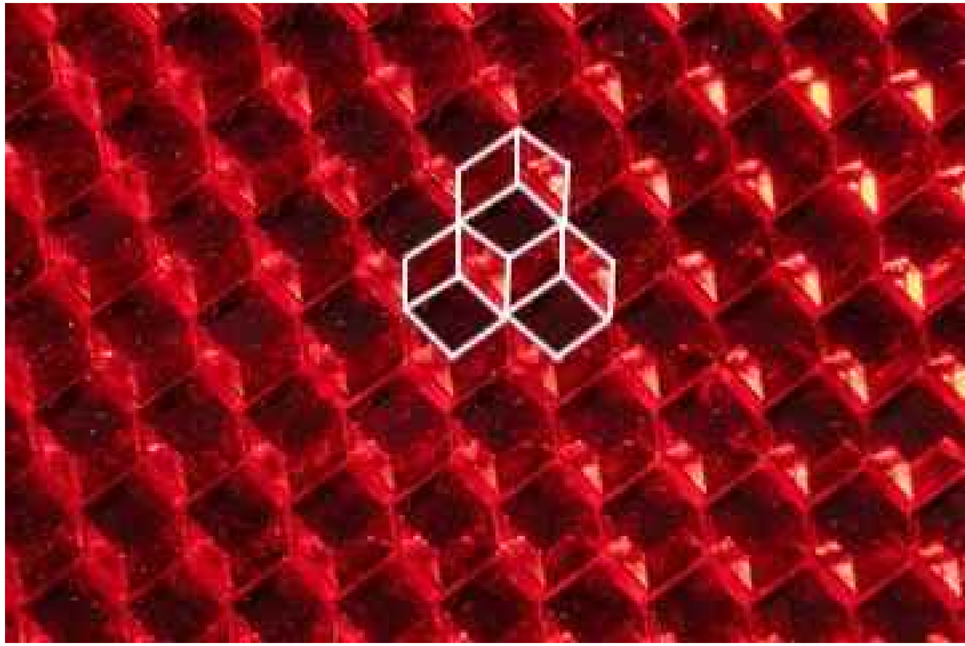


Incident light

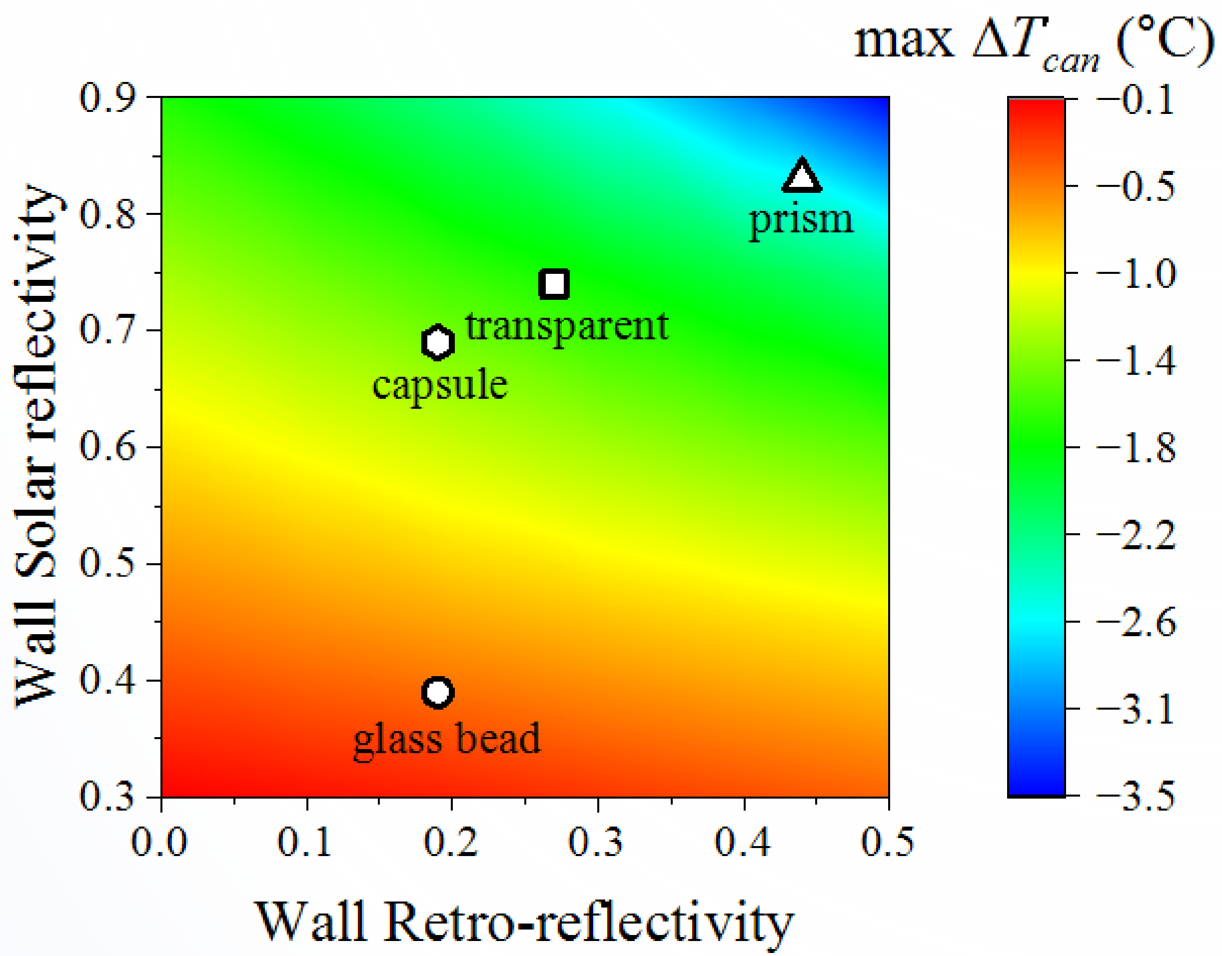
Specular reflection
(perfectly mirrorlike)

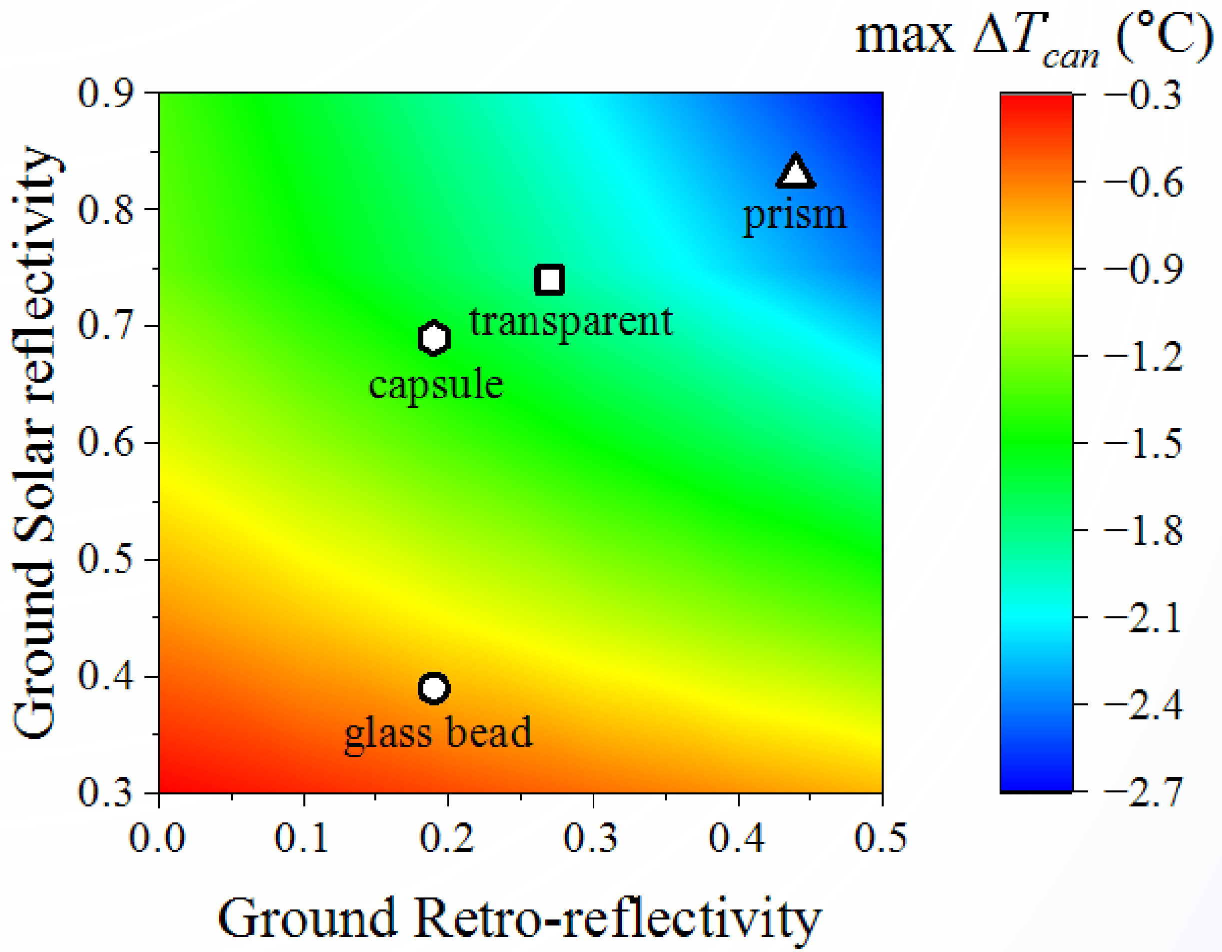
Lambertian reflection
(perfectly diffuse)

Retroreflection
(back to source)

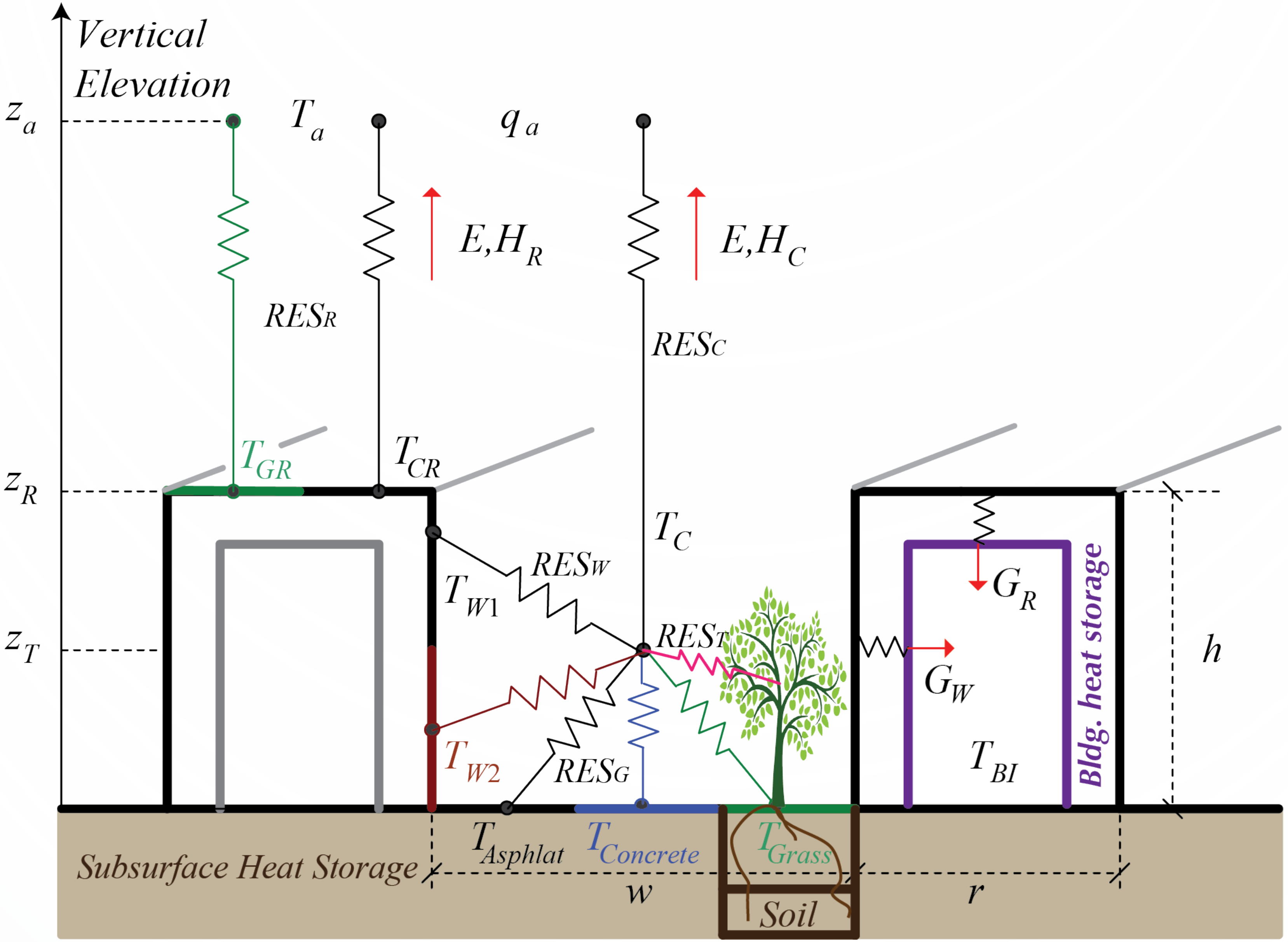


Retroreflective walls and ground cooling

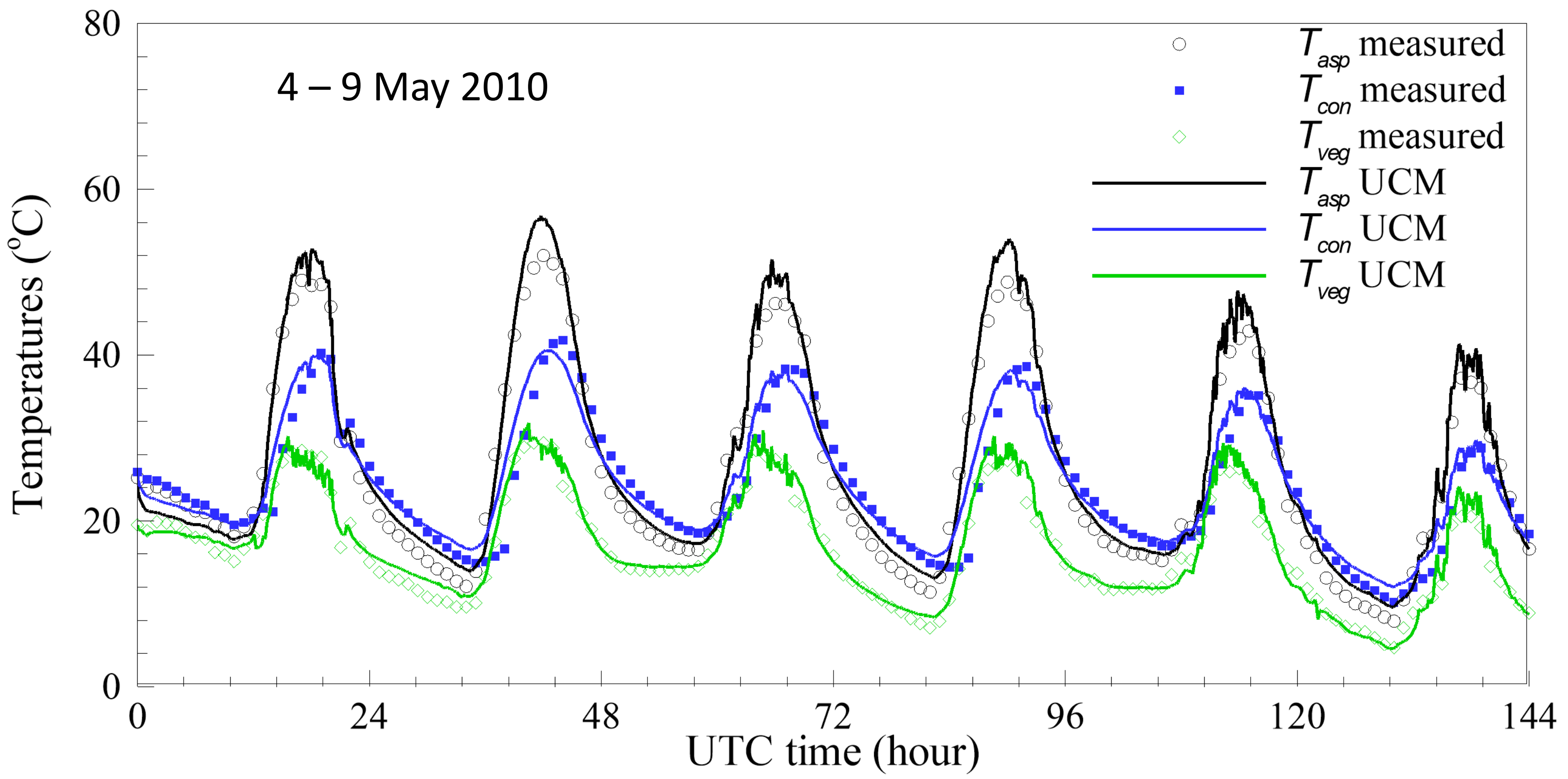




How do we examine these physics?



Model validation



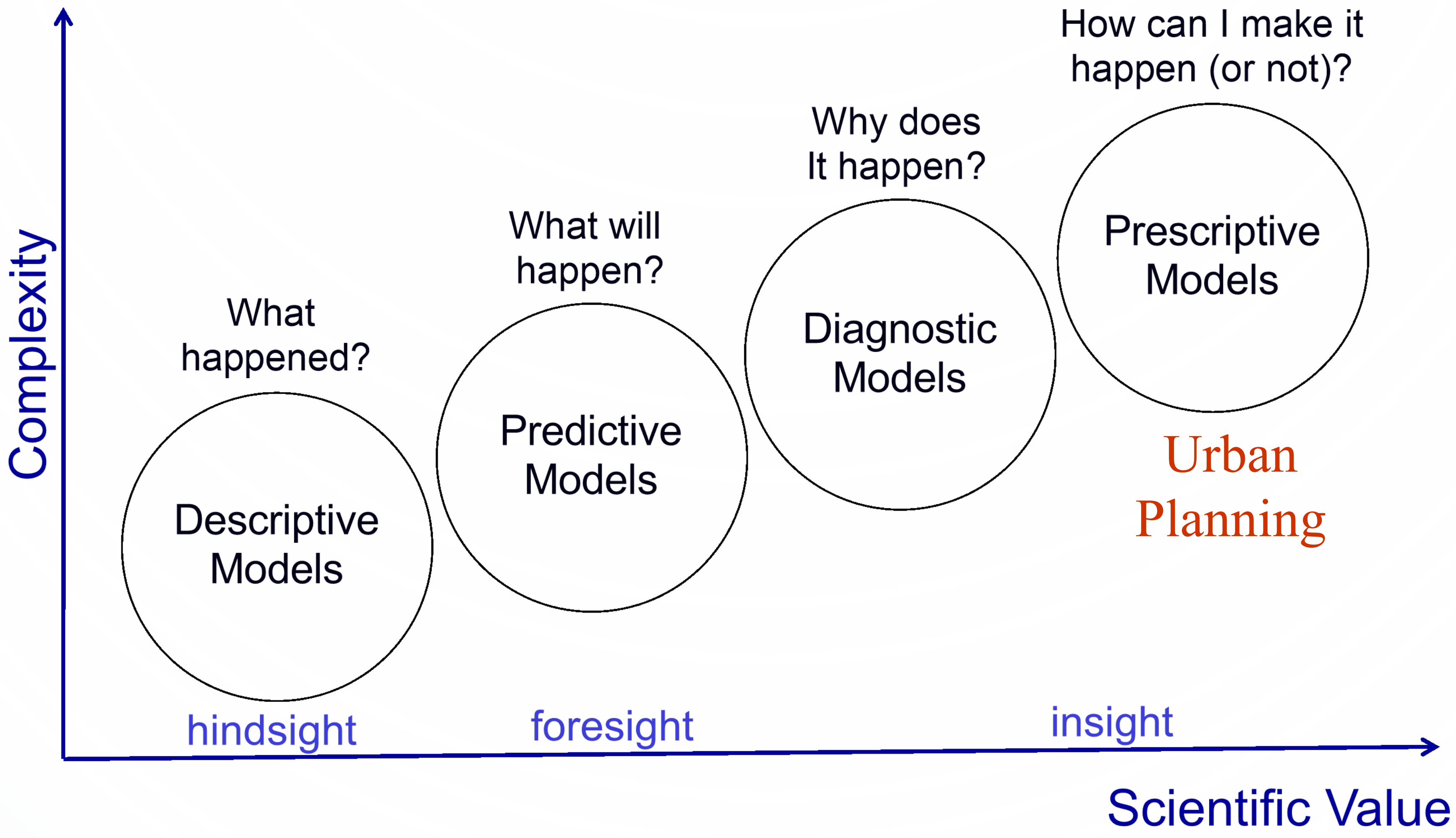
Models errors << differences between subfacets

Princeton campus

Offline Runs

What models are needed for urban planning?

- What are the data analytics or modeling frameworks I have access to, what can they do?



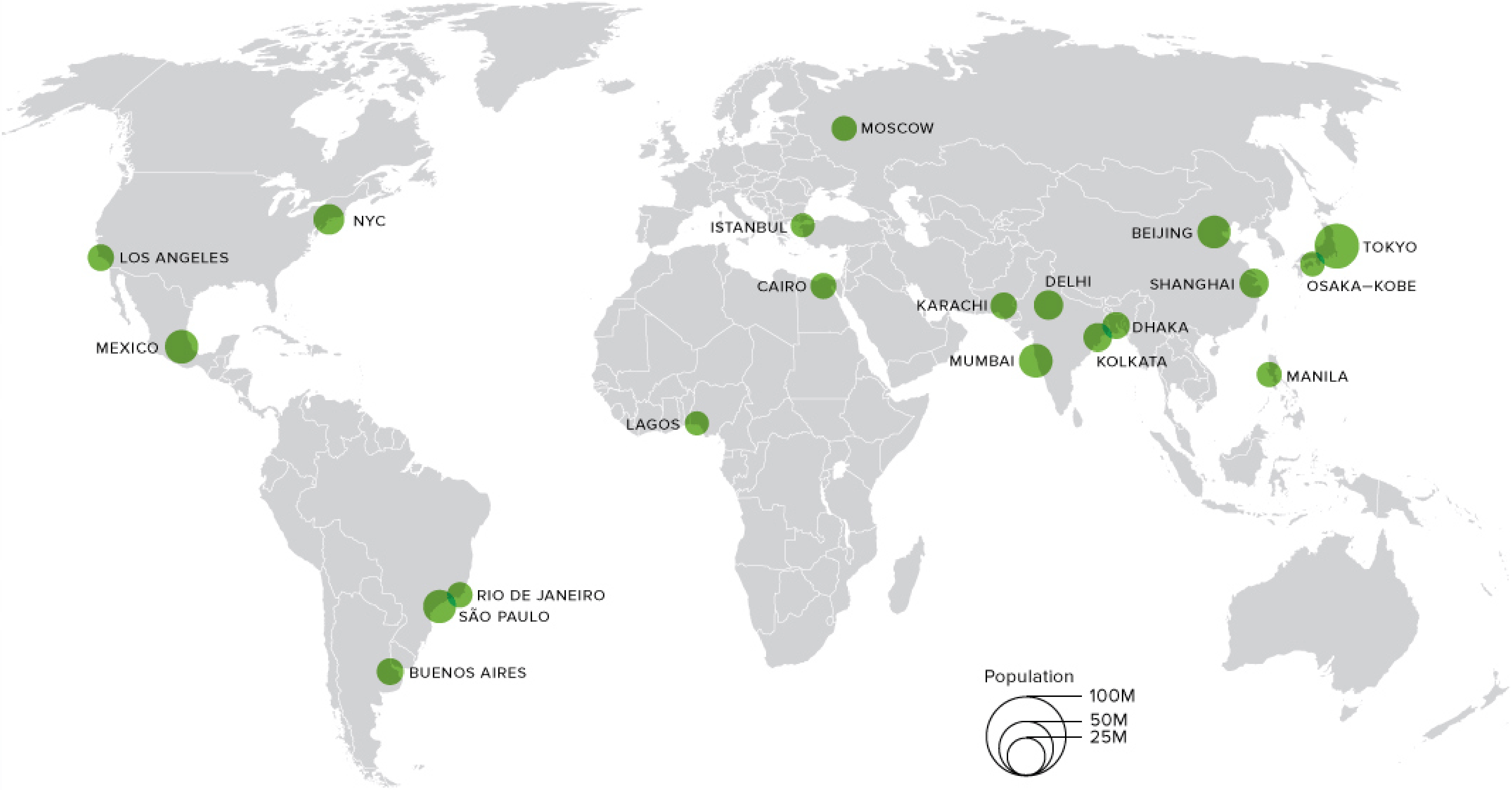
Transitions in equity of technology and action

THE WORLD'S 20 MOST POPULOUS MEGACITIES (2010 - 2100)

A total of 13 African cities will surpass New York in size over the next 80 years

2010 TOP 20 CITIES BY POPULATION

Equity at the Global Scale

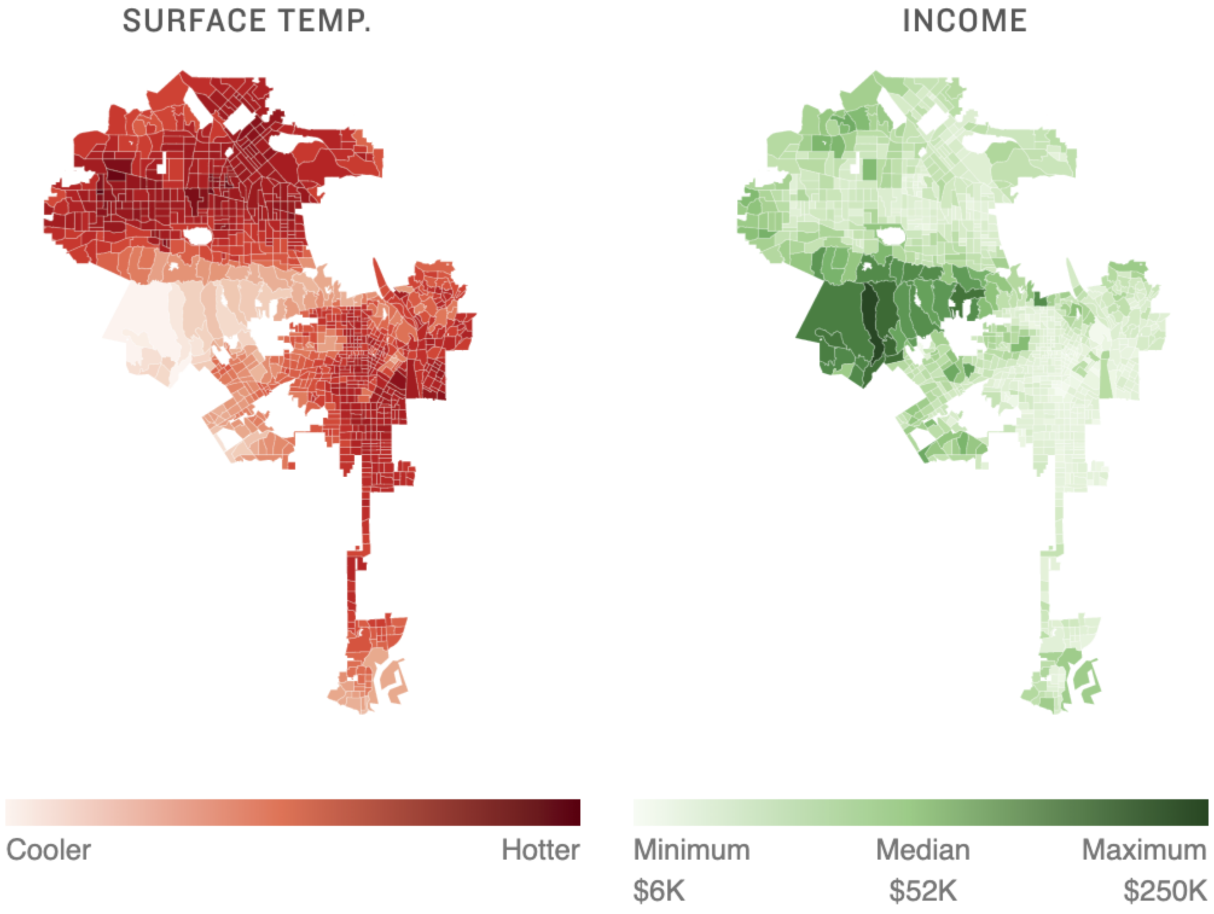


SOURCE: Global Cities Institute

visualcapitalist.com

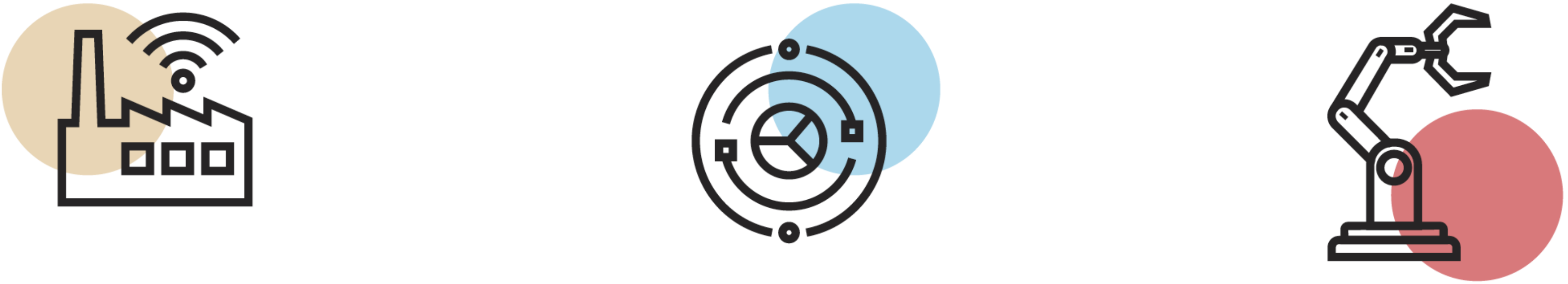
Equity at the city scale

- Technological portfolios should aim to redress existing inequalities, not only to avoid aggravating them



https://www.npr.org/2019/09/03/754044732/as-rising-heat-bakes-u-s-cities-the-poor-often-feel-it-most?t=1643409435490

Examples of uncertain outcomes



An Equitable Technological Future for Cities

By Elie Bou-Zeid

TheSciTechLawyer WINTER 2022

https://t.co/Itdkh58F2q

The most basic of questions

- Is the technology equally accessible and beneficial to all citizens? And if not, will people without access be significantly disadvantaged?
  - cell phones
- Could the technology discriminate in its interaction with humans based on race, color, sex and gender identity, sexual orientation, age, national origin, religion, or physical or mental disability?
  - machine vision and the trolley problem
- Is the plan for the deployment of this technology designed to, or does it inadvertently, favor access for certain groups or income levels?
  - heat mitigation equity

Thanks

NSF

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SAMSUNG RESEARCH AMERICA

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- Zhihua Wang
- Dan Li
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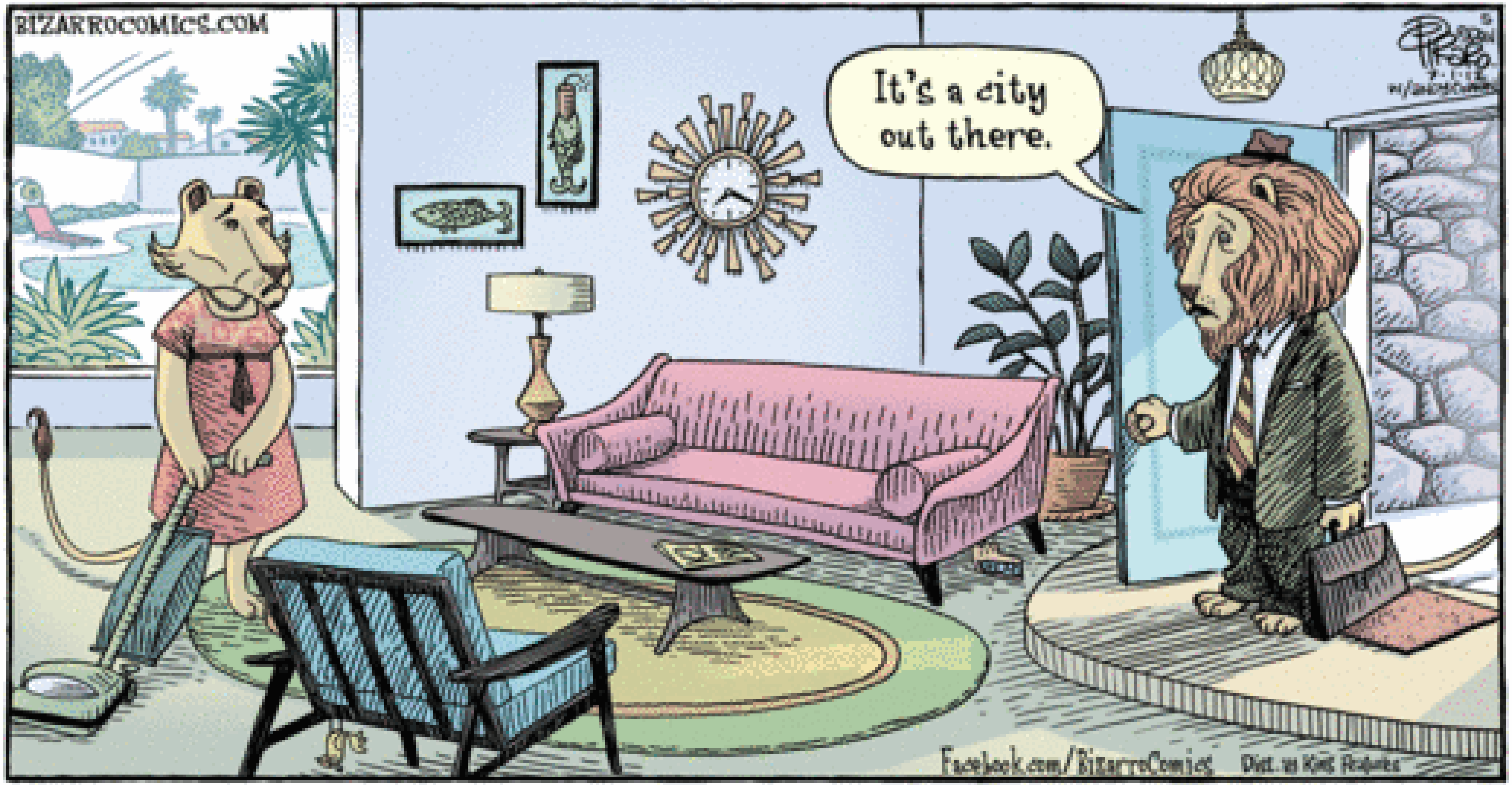
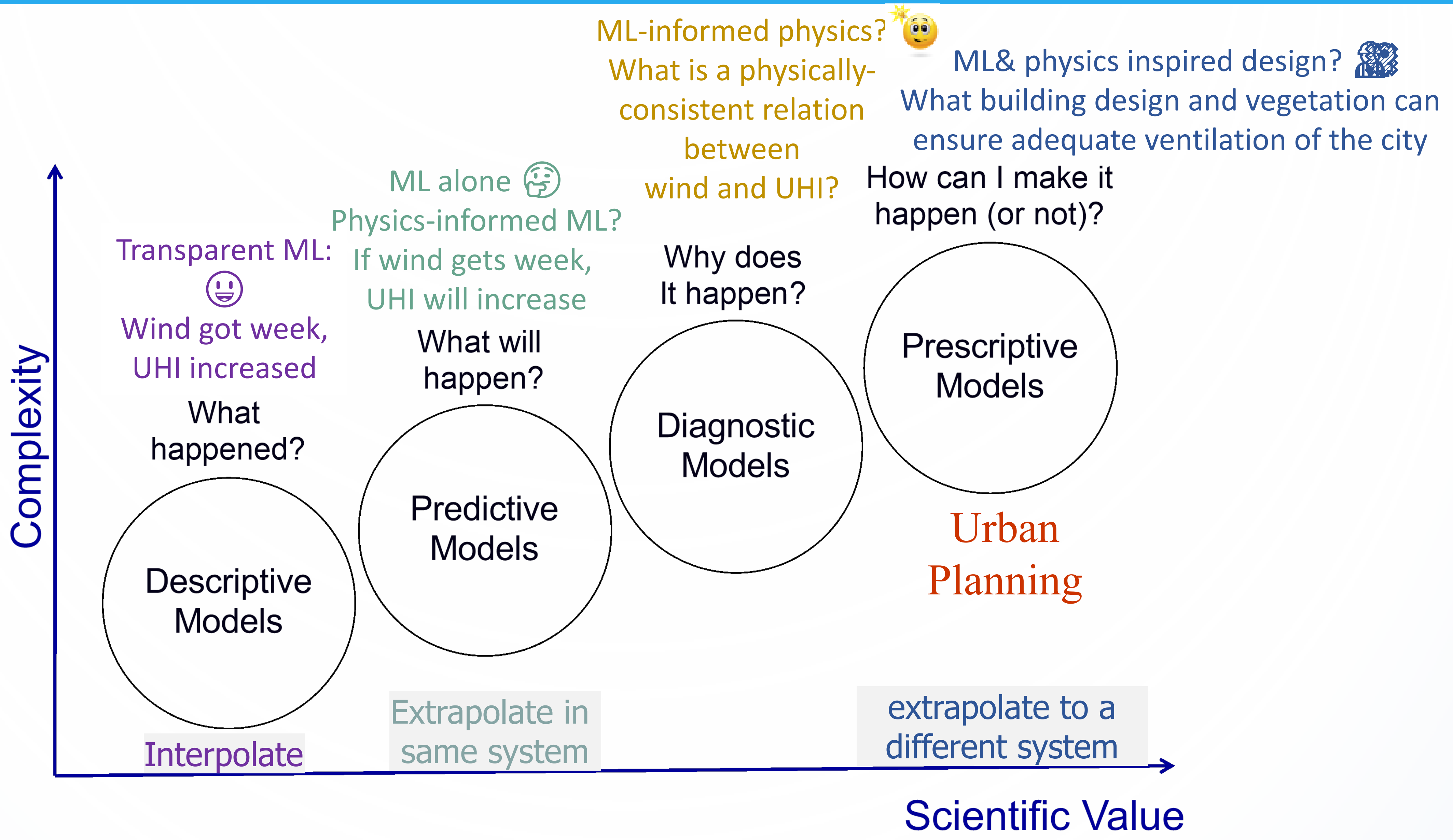

BIZARROCOMICS.COM
It's a city out there.
Facebook.com/BizarroComics

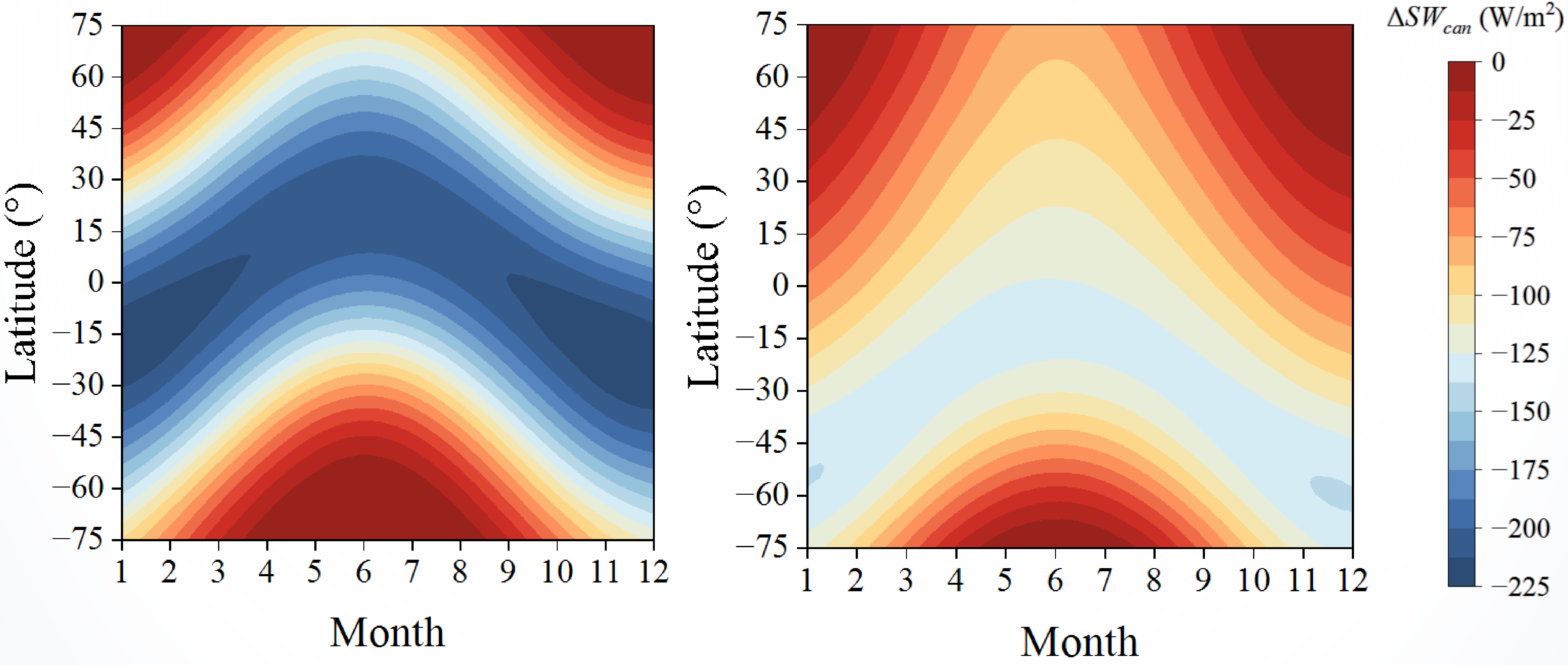
What is the role of machine learning?



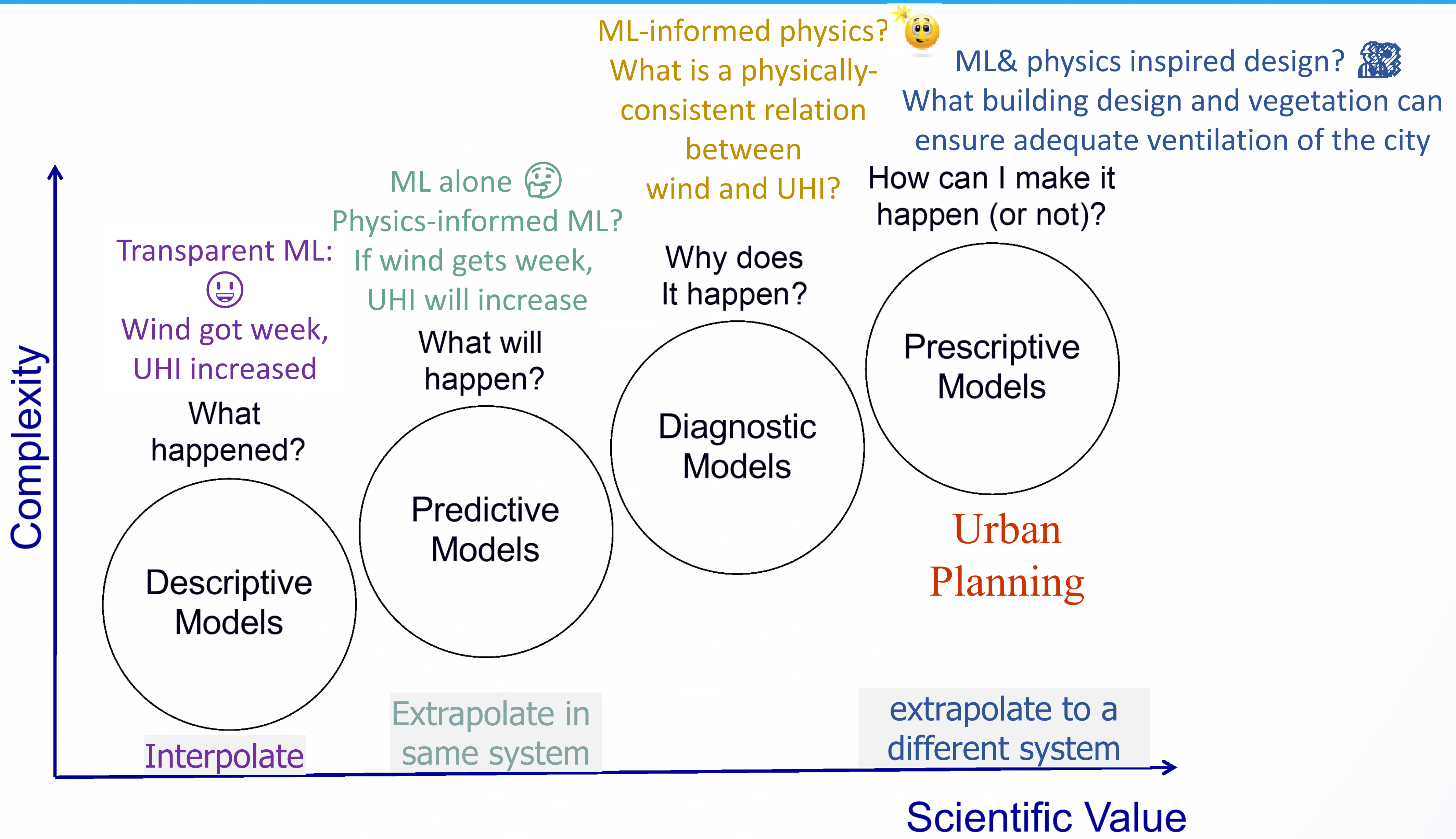
Too many questions, too little time

1. What are the environmental signatures of emerging mobility technologies in current cities, and can you teach ML to detect vehicle type with simple data?
2. How should cities leverage the new vehicles and smart infrastructure as sensing platforms for continuous and dense monitoring of their future impacts, and how can the data be more broadly utilized to advance urban livability, sustainability, and resilience?
3. How can we model the different penetration rates, and use these models to design scenarios with desirable VMTs and modal mix?
4. How can we project the individual and synergistic impacts of these technologies on urban environmental and livability conditions?
5. How can cities reimagine urban space to design human-centered infrastructure, and enable mobility portfolios, that can support their desired outcomes?

Retroreflective walls and ground cooling



What is the role of machine learning?



The big picture

- The efficient movement of people, goods and services is a critical component of modern economies, particularly in large towns and cities.
- But transport is also a major emitter of pollutants, GHGs, noise, and heat in the urban environment, and most of these emissions are associated with combustion processes.
- **Opportunity or threat?** A major shift is occurring right now in urban transportation technology and markets that will have deep impacts on the environmental footprint of urban mobility.
- NJ is one of the leading states in adoption of electrification and other new mobility tech: a perfect lab for such a project.

The technological shift – positive forces

- **Electrification**: The switch from internal combustion engines to electric ones will be rapid (especially for the short urban commutes) and will occur simultaneously with a shift in electric generation to cleaner sources (even the remaining dirtier ones will be outside of cities). Electric cars will emit less pollutants, GHGs, noise and heat, enabling a healthier urban environment.
- **Micromobility:** Scooters, e-bikes, and more novel concepts like the PUMA are rapidly expanding, and mostly in cities. They transport 1 or 2 people in much lighter vehicles, emitting less (noise, heat, pollutants and GHGs, since they are almost exclusively electric), and occupying less street and parking space.

The technological shift – negative forces

- **Automation:** Fully autonomy (level 5) is not around the corner, but the earliest roll-out of autonomous technology will be in cities where all street details and images can be mapped accurately. Autonomy reduces the cost of trips and makes them more convenient, increasing traveled miles and potentially exacerbating environmental disbenefits in cities. They are expected to significantly reduce traffic accidents, a positive impact on citizens, but they may also lead to increased sprawl.
- **Sharing:** Change of ownership models from individually-owned to a shared fleet is already underway. This shift can also reduce the cost and increase ease of car transport, potentially increasing miles traveled, environmental disbenefits, and sprawl. But it is expected to significantly reduce the need for parking space, which can then be used for other purposes.

The technological shift – the unknowns

- **Connectivity:** If autonomy and shared mobility also come with "**connectivity**" (cars being able to communicate with each other), the city-scale flow might become more efficient leading to less traffic jams.

- If autonomy and sharing technologies also accelerate electrification and promote micro-vehicles, they can have a significantly positive impact on urban environments.
- Even the technological shifts that may on their own worsen environmental outcomes could have positive socio-economic benefits, providing transport access to lower income communities.

Grand Challenge

- How emerging mobility can be harnessed to ameliorate the environment quality and livability in our cities.
  - reducing urban carbon and air pollution, as well as water, noise and heat hazards
  - reimagining space in cities to shift it from conventional transportation infrastructure to a use suited for emerging mobility and smart infrastructure, serving broader health and livability goals.