Developing Climate Resilient Cities: From Heat Islands to Urban Digital Twins

Dev Niyogi

The University of Texas Extreme weather, climate and Urban Sustainability (TExUS) Lab

William Stamps Farish Chair Professor

Jackson School of Geosciences

And Professor, Department of Civil, Architectural, and Environmental Engineering. University of Texas at Austin

Email: happy1@utexas.edu

https://www.linkedin.com/in/texus/

(Affiliated faculty – Oden Institute for Computational Engineering and Sciences; UT Center for Space Research; UT Environmental Science Institute; Planet Texas2050; Good Systems/ Smart Cities)

[Former Indiana State Climatologist and Professor Purdue University/ Department of Agronomy and Department of Earth, Atmospheric Planetary Sciences/ Division of Environmental and Ecological Engineering/ West Lafayette, IN]

Cities are important

drivers of economy, culture, creativity, branding,…

Cities while epitomizing technological advances and opportunities can also represent what can potentially go wrong if technology is not effectively utilized

Urban problems: sprawl

Urban problems: pollution

Urban problems: weather, flooding

Growing Cities and Urbanization is a dominant global change underway.

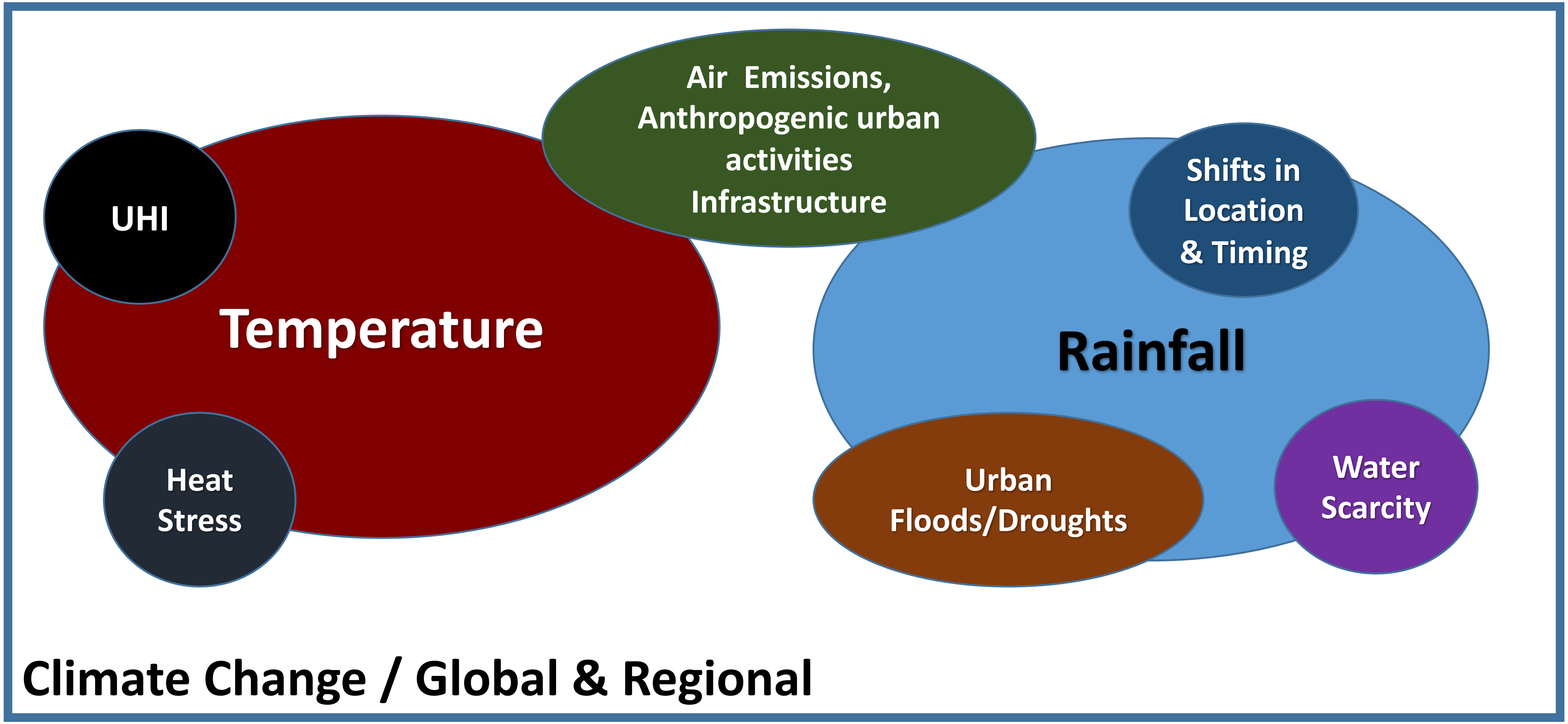
Urbanization is causing significant, and detectable, changes in regional climate through temperature and rainfall modification

http://webpages.scu.edu/ftp/jready/family_urbanizationandmodernization.html

Research Premise

- Improved Scientific Knowledge , Computational Tools and Models if blended with community needs can help develop tools that can help with predicting and managing climate extremes; help develop climate-ready cities through design and infrastructure planning.

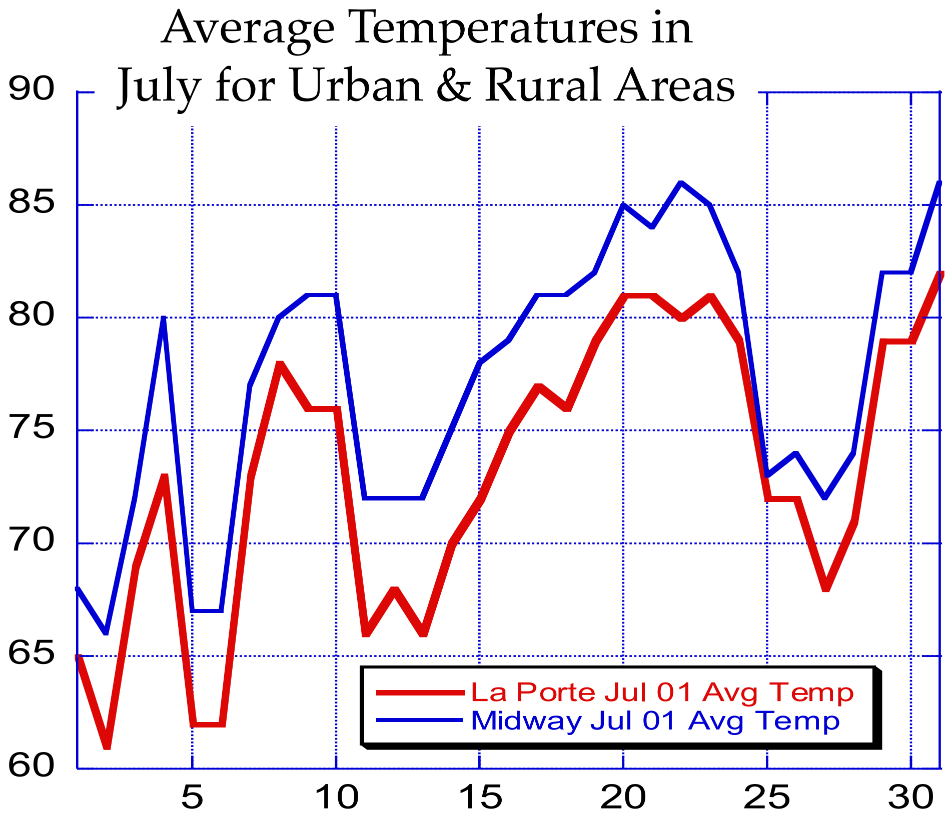
Conceptual diagram of major Urban Climate Issues

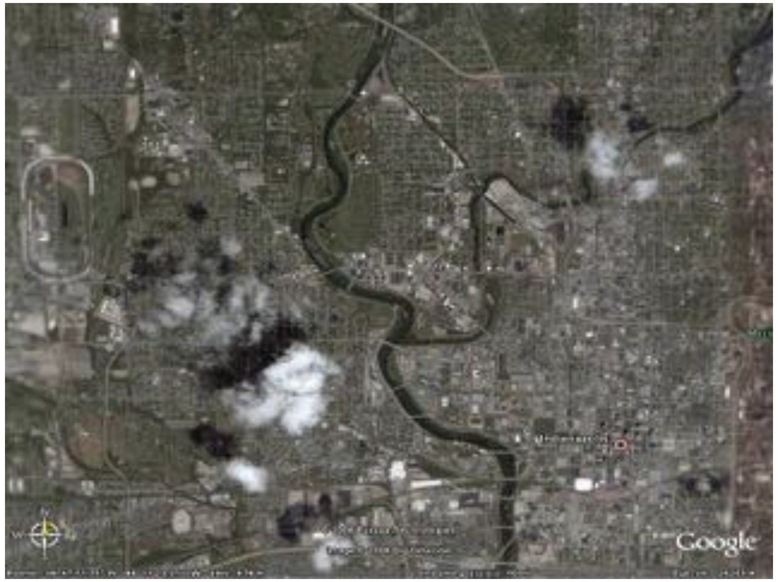


Slide from Dr. Akshara, CDAC

How do cities affect weather/ climate?

Urbanization and land use change leads to regional temperature changes (warming= Urban Heat Island)





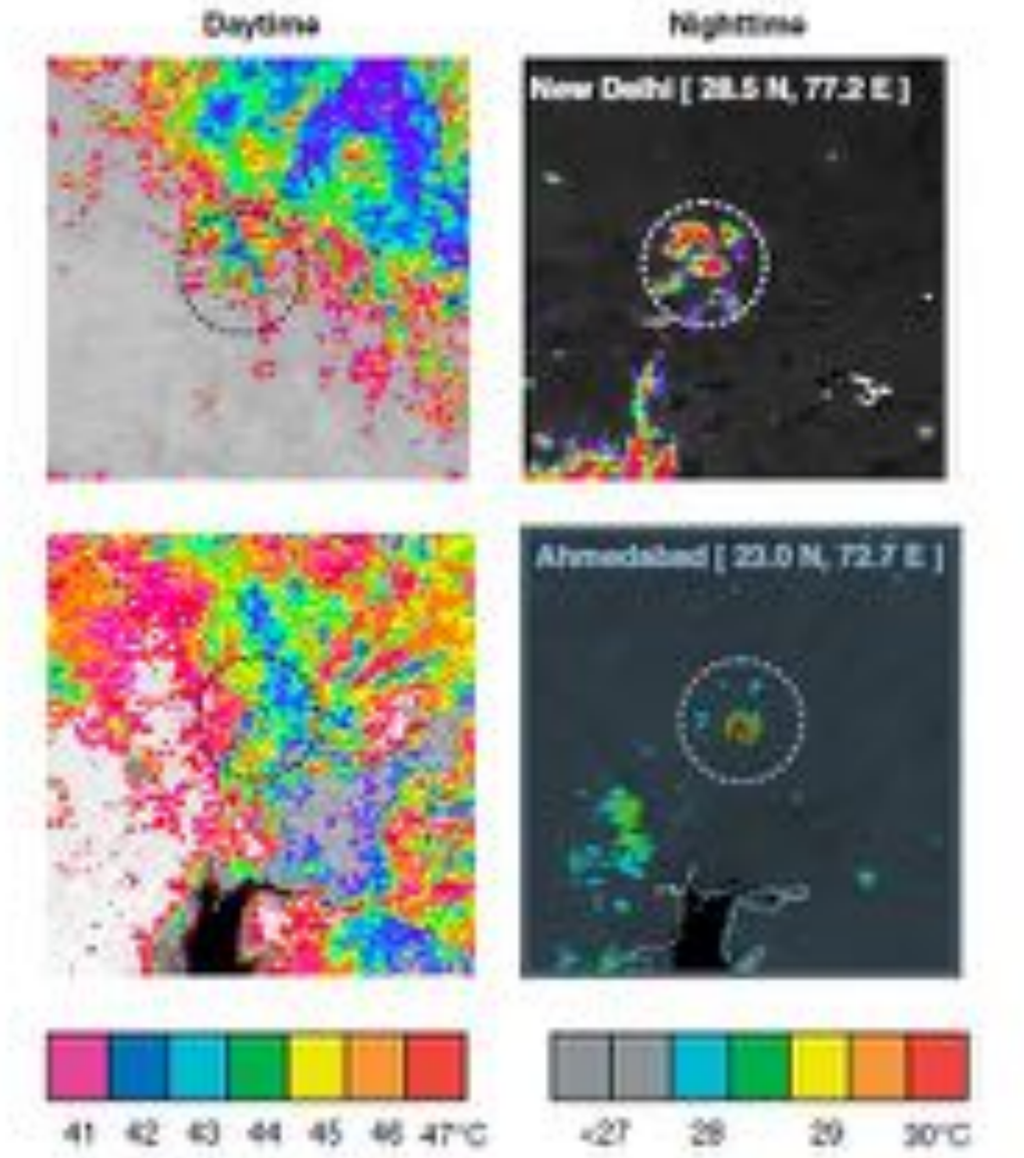
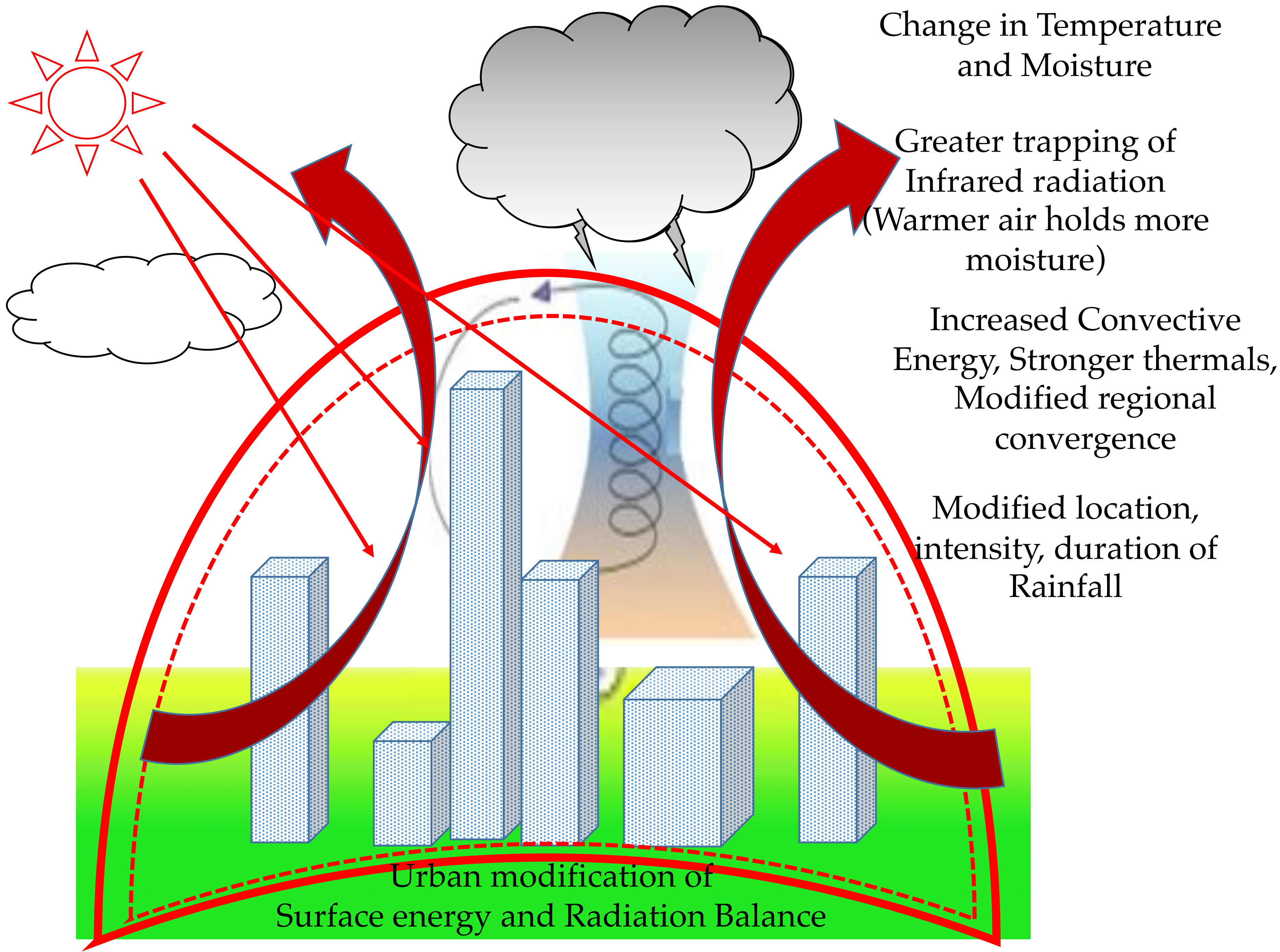


Figure 9. MODIS-retrieved land-surface temperature for two major cities of India during summer. Center of the circles denote approximate location of the city. This figure is available in colour online at

Examples of Urban Heat Islands

Kishtawal et al. 2010, IJOC



Change in Temperature and Moisture
Greater trapping of Infrared radiation (Warmer air holds more moisture)
Increased Convective Energy, Stronger thermals, Modified regional convergence
Modified location, intensity, duration of Rainfall
Urban modification of Surface energy and Radiation Balance

Urbanization Impacts Scale Beyond the Surface (temperature)

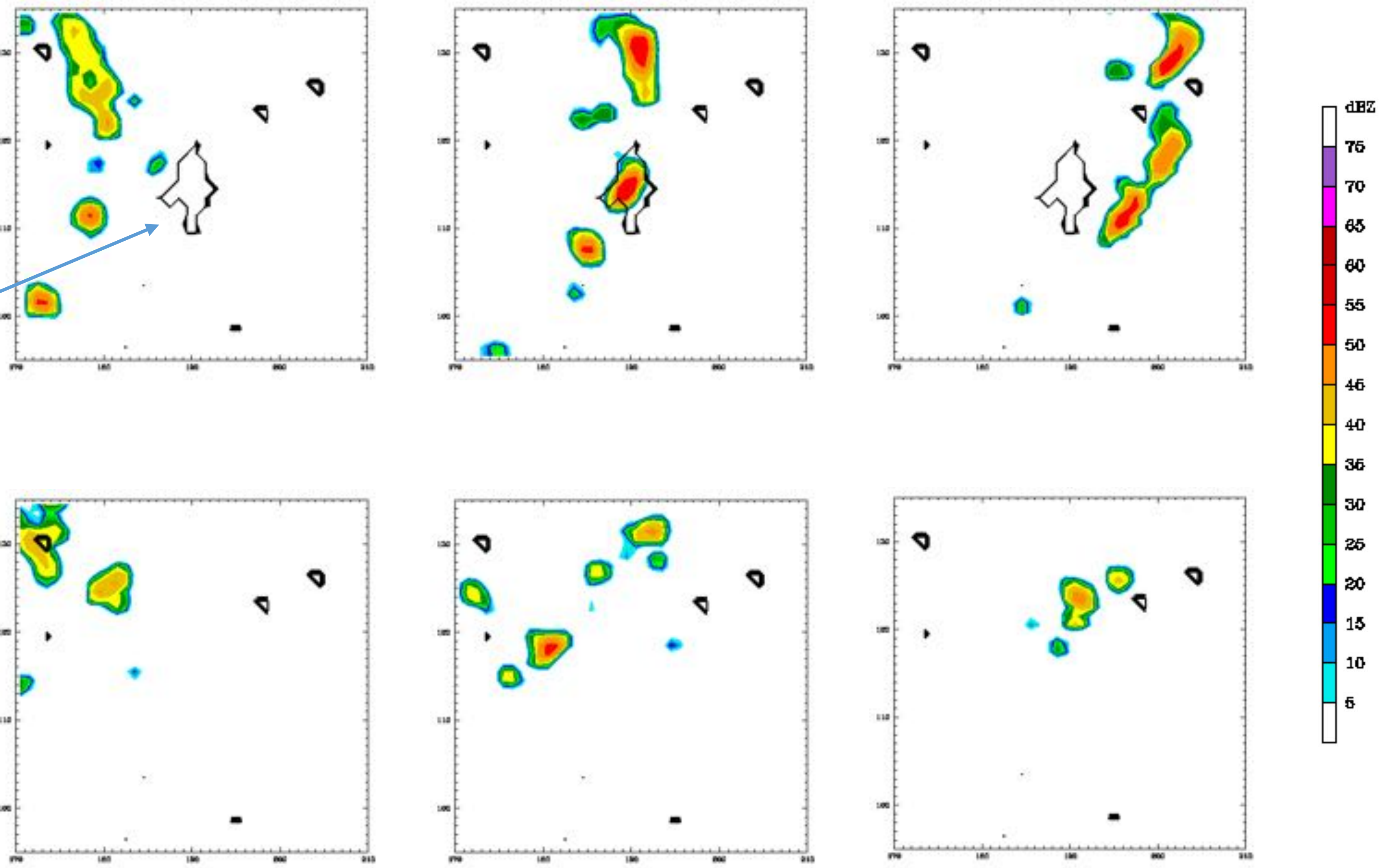
The enhanced weather model predicted radar reflectivity convection and rainfall is simulated only when urban – rural gradients boundary exists

0100 UTC 0200 UTC 0300 UTC

With Indianapolis Urban Area

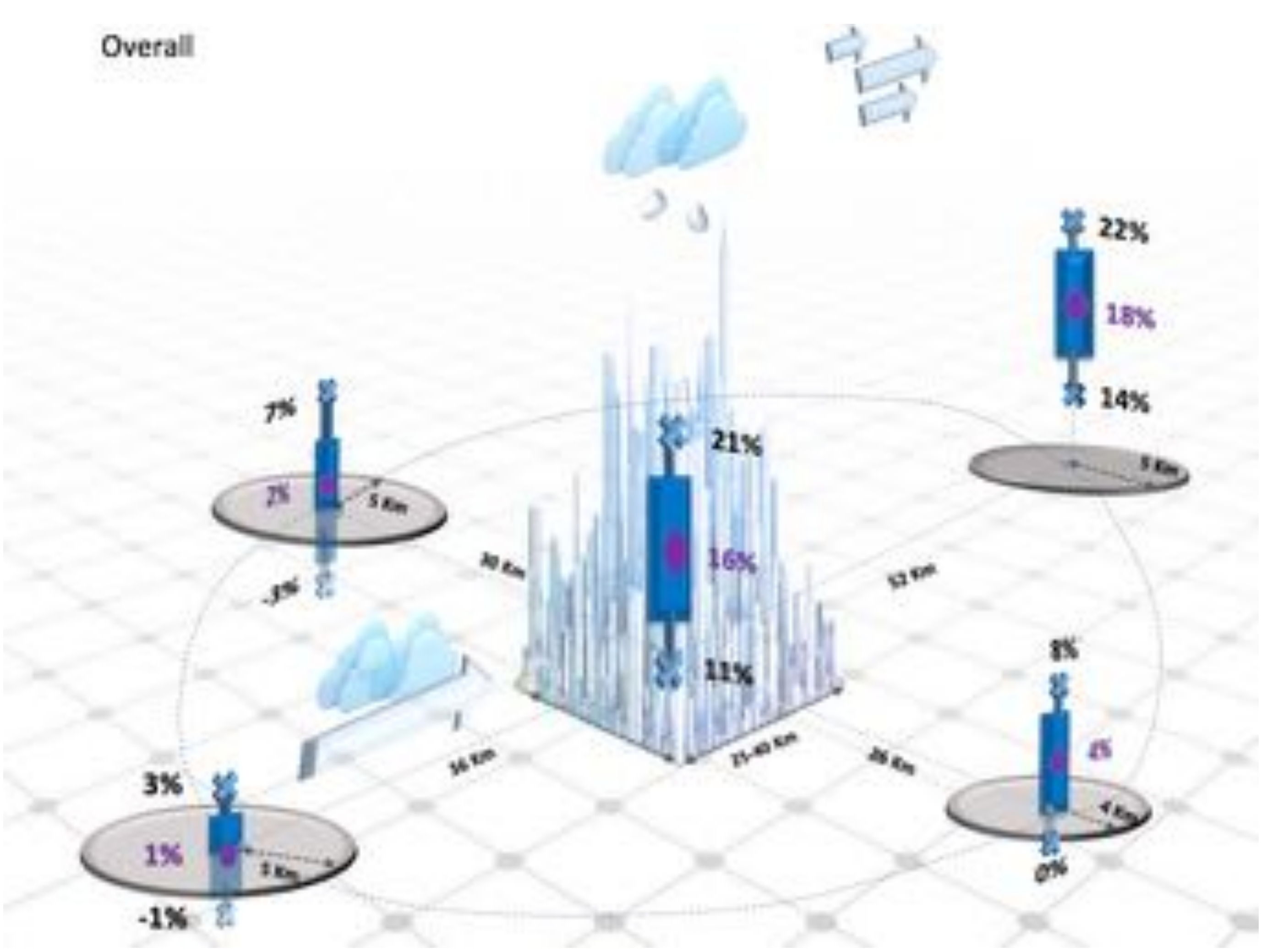
Indianapolis

Without Indianapolis Urban Feedback



Meta-analysis of urbanization impact on rainfall modification

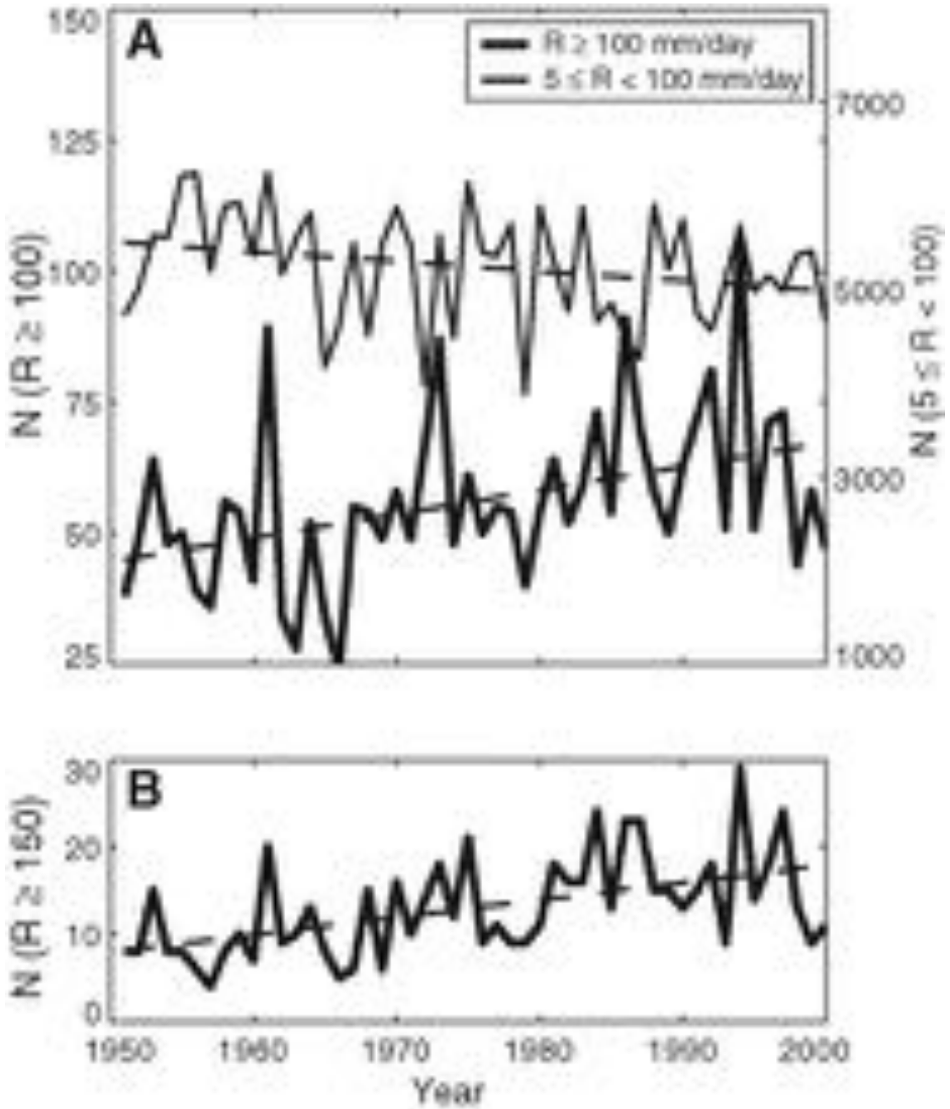
Jie Liu & Dev Niyogi ; *Scientific Reports*, 9,
Article number: 7301 (2019) https://www.nature.com/articles/s41598-019-42494-2



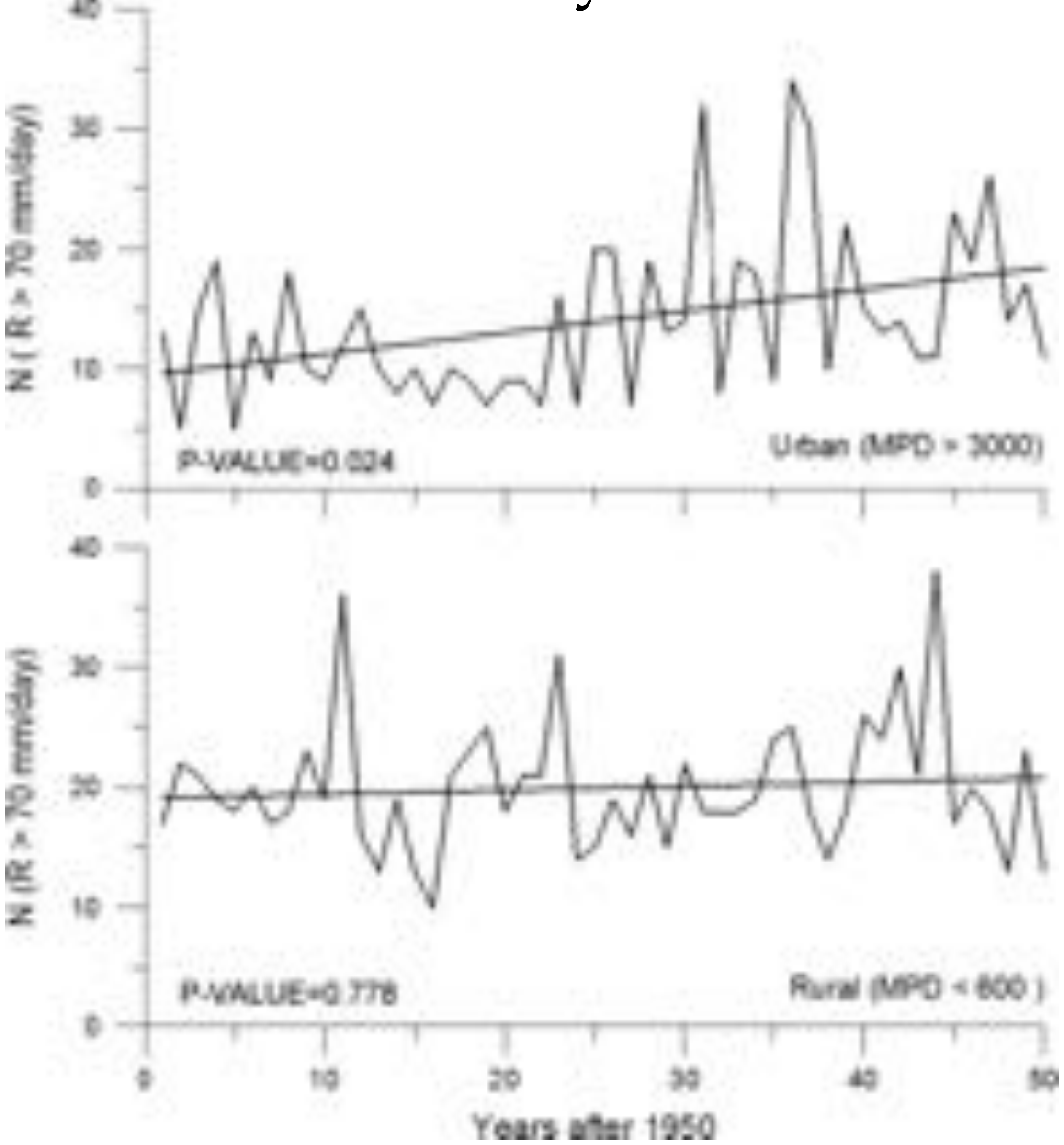
- Urbanization modifies rainfall, such that mean precipitation is enhanced by
- 18% downwind of the city,
- 16% over the city,
- 2% on the left and 4% on the right with respect to the storm direction.
- The rainfall enhancement occurred approximately 20–50 km from the city center.
- Rainfall increases not only downwind of the city but also over the city.

Can the urban impact scale up to affect regional climate?

Indian monsoon rainfall is becoming more extreme (Science, 2006)



Reassessment…
Heavy rainfall trend only noted for urban grids



Kishtawal et al. 2010, IJOC

Cities affect climate..

Can we design cities to get the “desired” climate?

(e.g. cooling…Where should it rain)

Or use City Knowledge to improve prediction of urban extremes?

How can we make smart cities to be resilient cities? (How to use technology effectively in making cities more liveable?)

How can we get information on cities and blend them into weather models to improve city-level forecasts?

Argonne NATIONAL LABORATORY

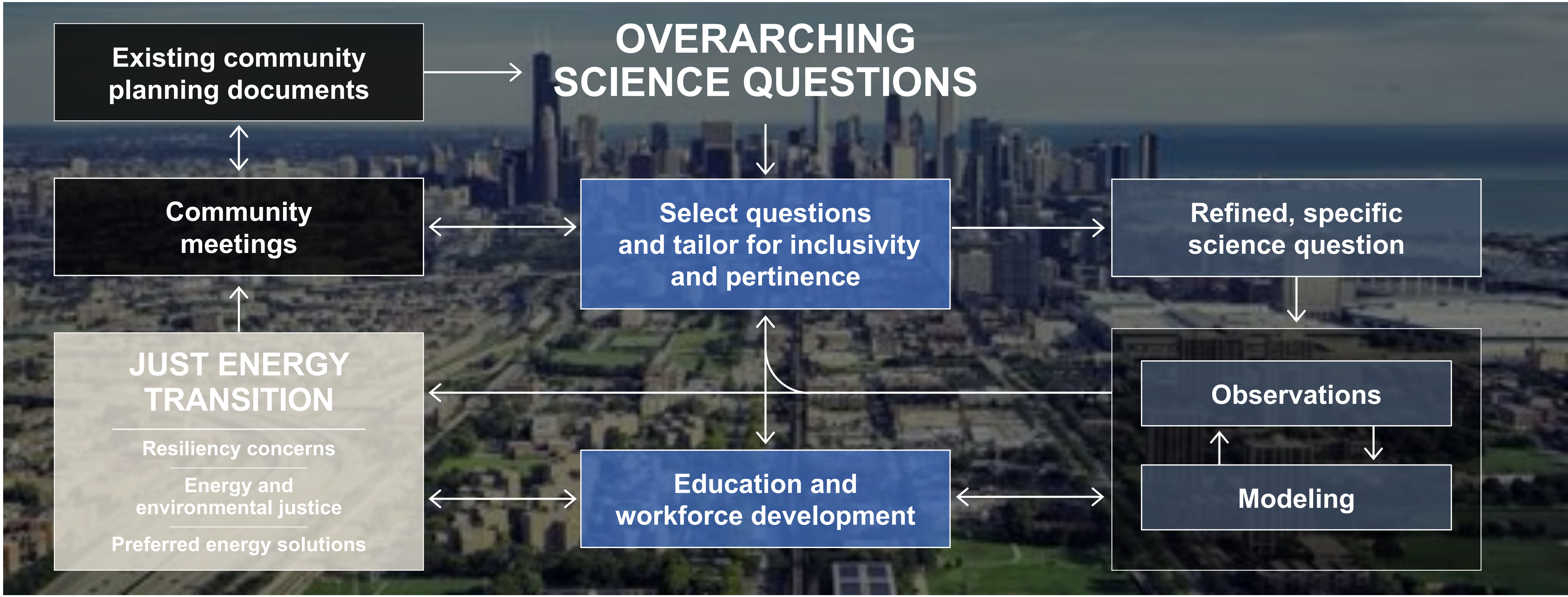
CHICAGO'S

URBAN INTEGRATED FIELD LABORATORY

CROCUS
Community Research on Climate & Urban Science

Slides courtesy Dr. Cristina Negri, Chicago IFL PI

Community Driven Science

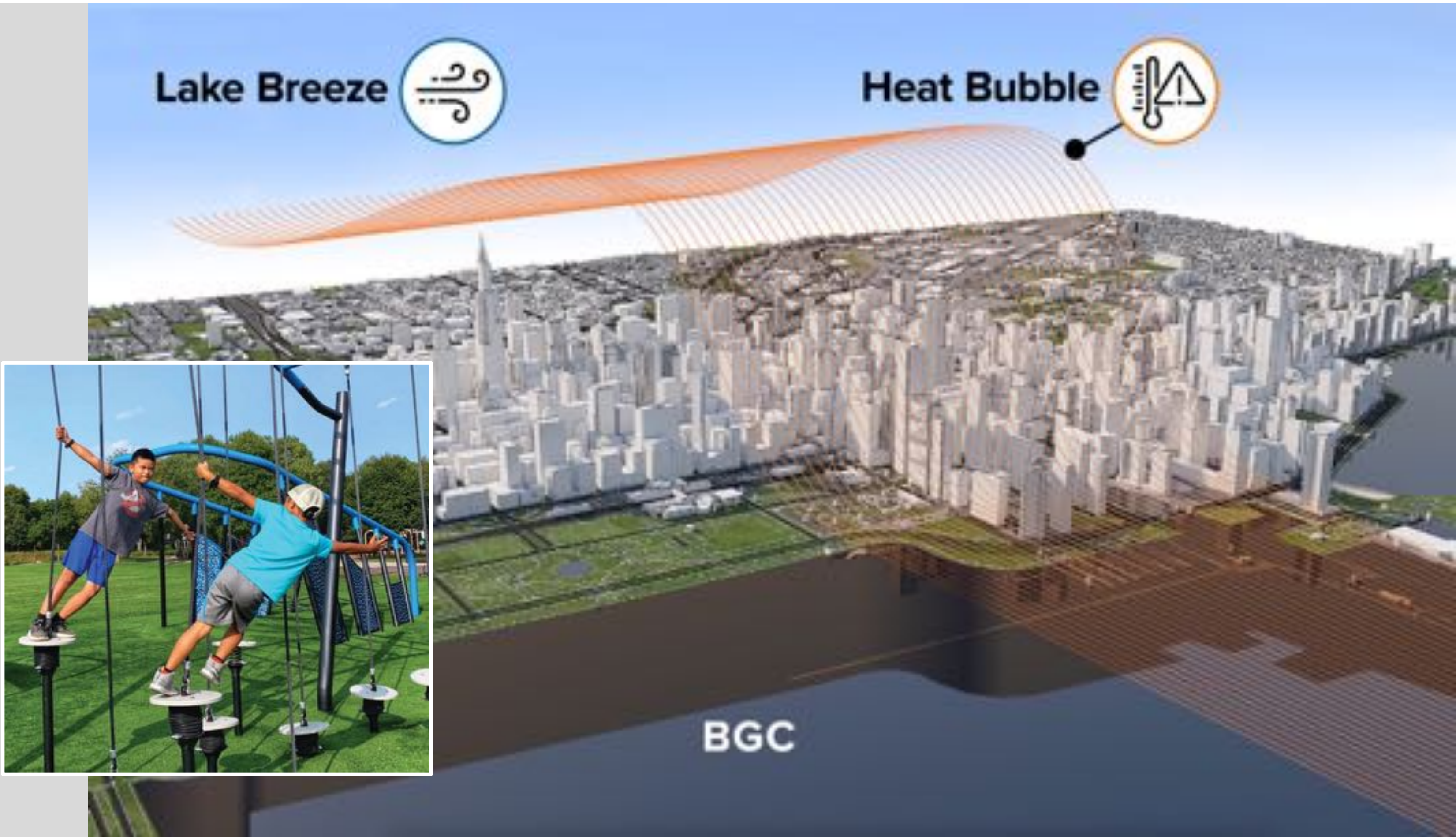


Vision

The next five years

We will deliver a reliable representation of the complex urban Chicago Metro environment and its feedbacks with climate.

- A systems-based approach for integrating, physical, biological and human dimensions
- A framework to simulate, evaluate and project the impacts and feedbacks between climate and urban systems



MISSION

Community Research on Climate and Urban Science

Work with communities to develop, deploy and use a diverse **measurement and observational infrastructure** to reveal microclimates in urban areas and their dynamics in the heterogeneous urban fabric.

Model these microclimates in the urban environment and the interaction of physical climate factors with human and economic factors and decisions.

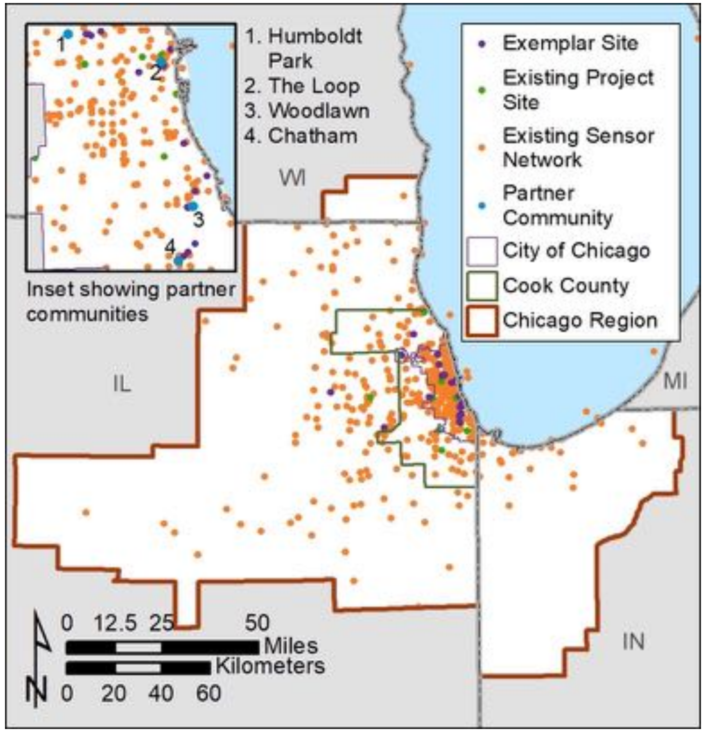
Use this integrated canvas to **reveal the environmental drivers that exacerbate environmental injustice** and social polarization in urban communities and **enable the co-design, with impacted communities,** of resilience and adaptation strategies.

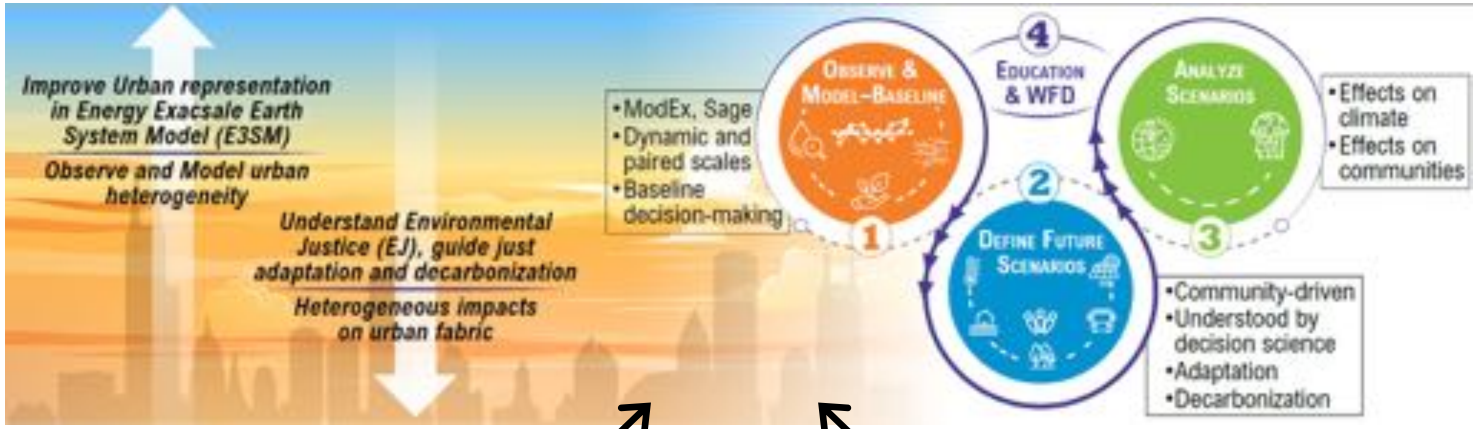
Apply this approach to **focus on specific neighborhoods by testing** various climate change mitigation actions and develop decision support tools based on individual and community-scale decision making.

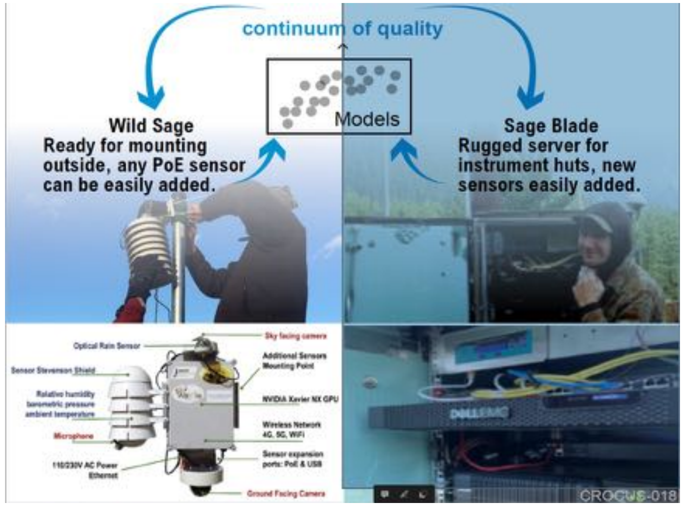
Use the science program in its mission to **train and educate** the next generation of climate work force in the region with hands on experiences and innovative curricula.

Sensing and modeling to understand urban climate challenges

The Chicago region provides an excellent focal point for understanding urban to regional climate science and how to implement solutions that are equitable to communities.







Team Crocus

CROCUS
Community Research on Climate & Urban Science

RESEARCH AND EDUCATION

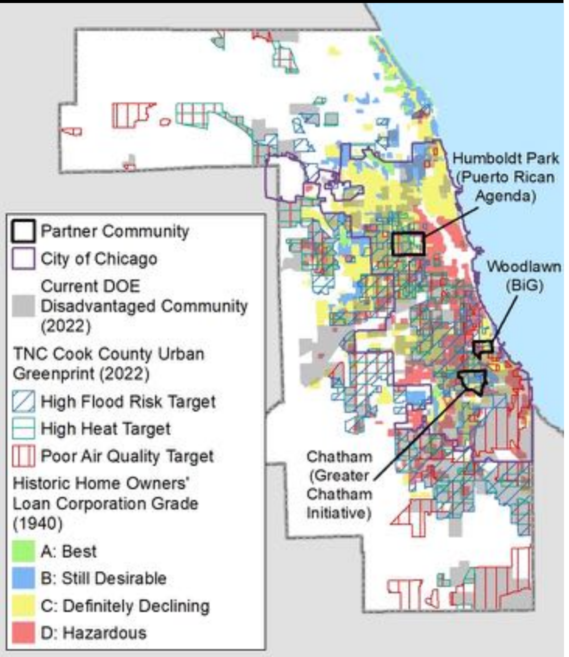
- Argonne National Laboratory
- University of Illinois at Chicago
- Chicago State University
- Northeastern Illinois University
- Community Colleges of Chicago
- North Carolina A&T
- Notre Dame University
- University of Chicago
- Northwestern University
- Wash U St. Louis
- University of Illinois at Urbana Champaign
- University of Texas Austin
- U. Wisconsin Madison

COMMUNITIES

- Blacks in Green
- Greater Chatham Initiative
- Puerto Rican Agenda
- Metropolitan Mayors Caucus
- *Center for Neighborhood Technology**
- *Elevate**
- *Environmental Law and Policy Center**

INDUSTRY AND LOCAL GOVERNMENT

- Local Government
- World Business Chicago
- CMAP – Chicago Metropolitan Agency for Planning
- Museum of Science and Industry
- Shedd Aquarium
- ComEd
- JC Decaux



Inequities that exist today have old roots in Chicago and Cook County, which have pushed communities into the most physically challenging areas.

The Baltimore SoCial-Environmental Collaborative IFL

Slide from Ben Zaitchik, JHU, BSEC PI

The BSEC Approach

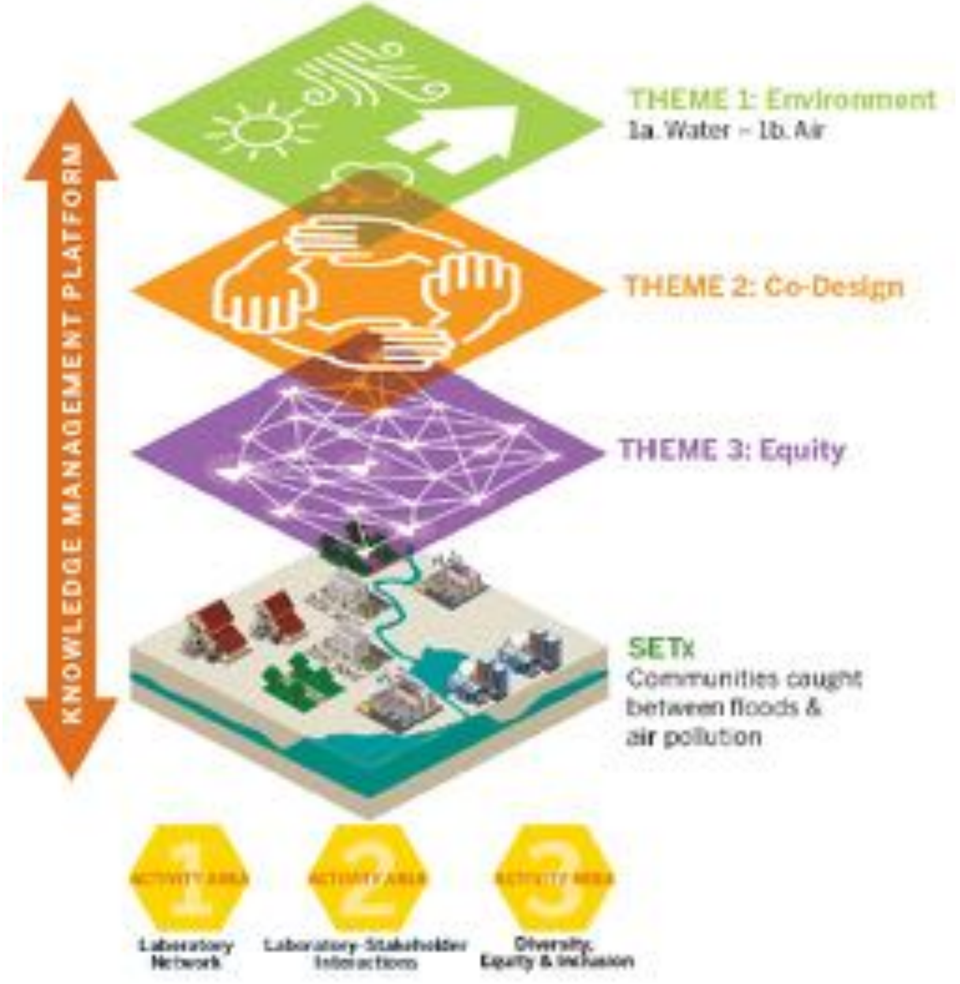
Project Goal: produce the urban climate science needed to inform community-guided *potential equitable pathways* for climate action.

Guiding premise: equitable adaptation is a product of place-based co-creation of knowledge. The IFL, then, has to be designed collaboratively, with measurement objectives guided by community priorities.

Implication: the IFL is iterative, with observation and modeling components designed to be both robust and flexible to collaborative learning throughout the life of the project.

Indicators of success (example): integration of IFL analyses and participatory design methods to Baltimore City's forthcoming *Climate Action Plan* and *Disaster Preparedness and Planning Project (DP3)* and subsequent implementation activities.

Overarching questions



Department of Energy Urban Field Labs

UT Austin SETx: Southeast Texas

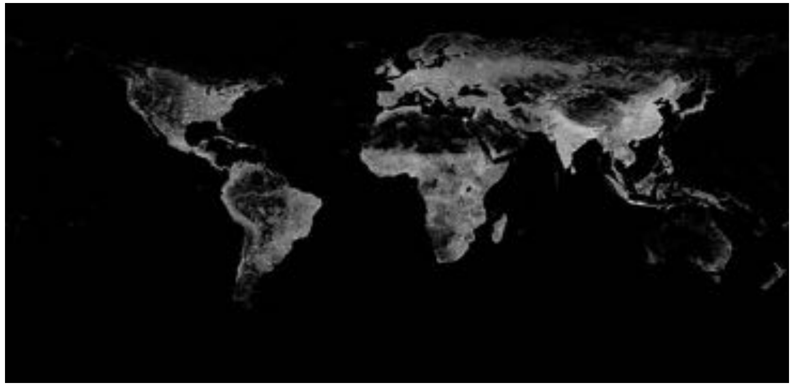
- Which processes and variables need to be captured in regional scale hydrological and atmospheric models so that they are representative of the conditions experienced by local communities and help inform adaptation strategies?

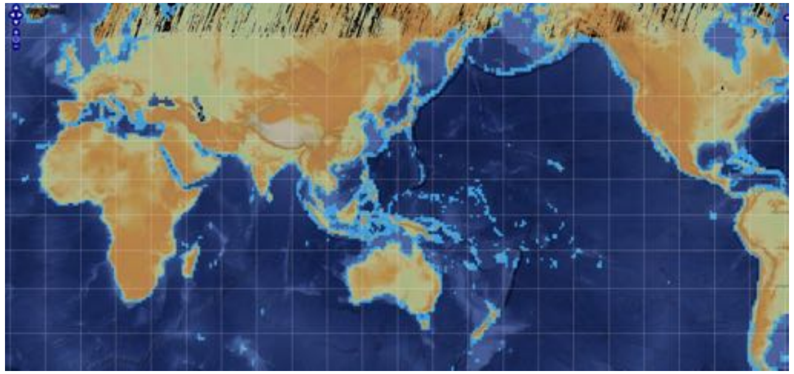
- How can we understand the linkages between and within natural, built, and social systems in urbanized regions to better support natural and human resilience?

Slide from Prof. Paola Passalacqua, SETx IFL PI

Input: Heterogeneous Data

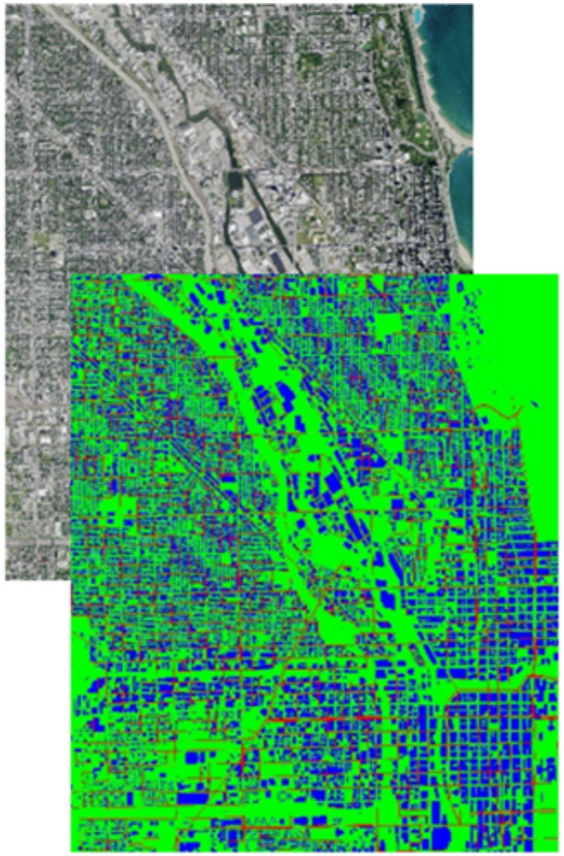
LandScan Data (Population)

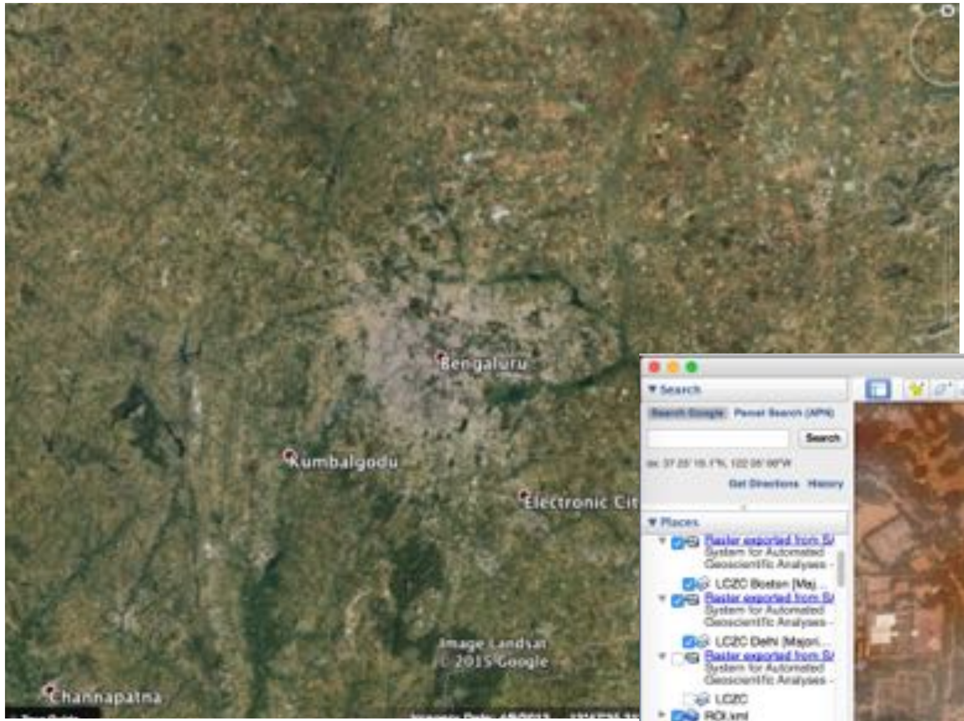


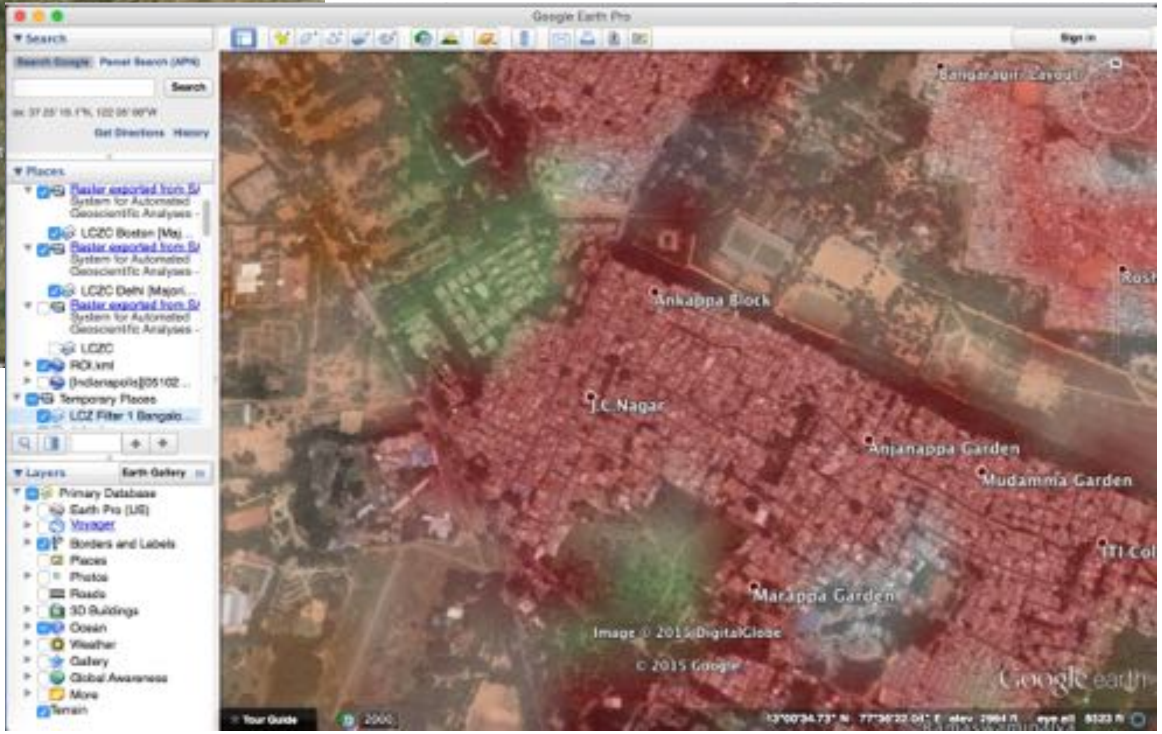


JAXA SRTM Data (Elevation)

Segmented Satellite of Target Area



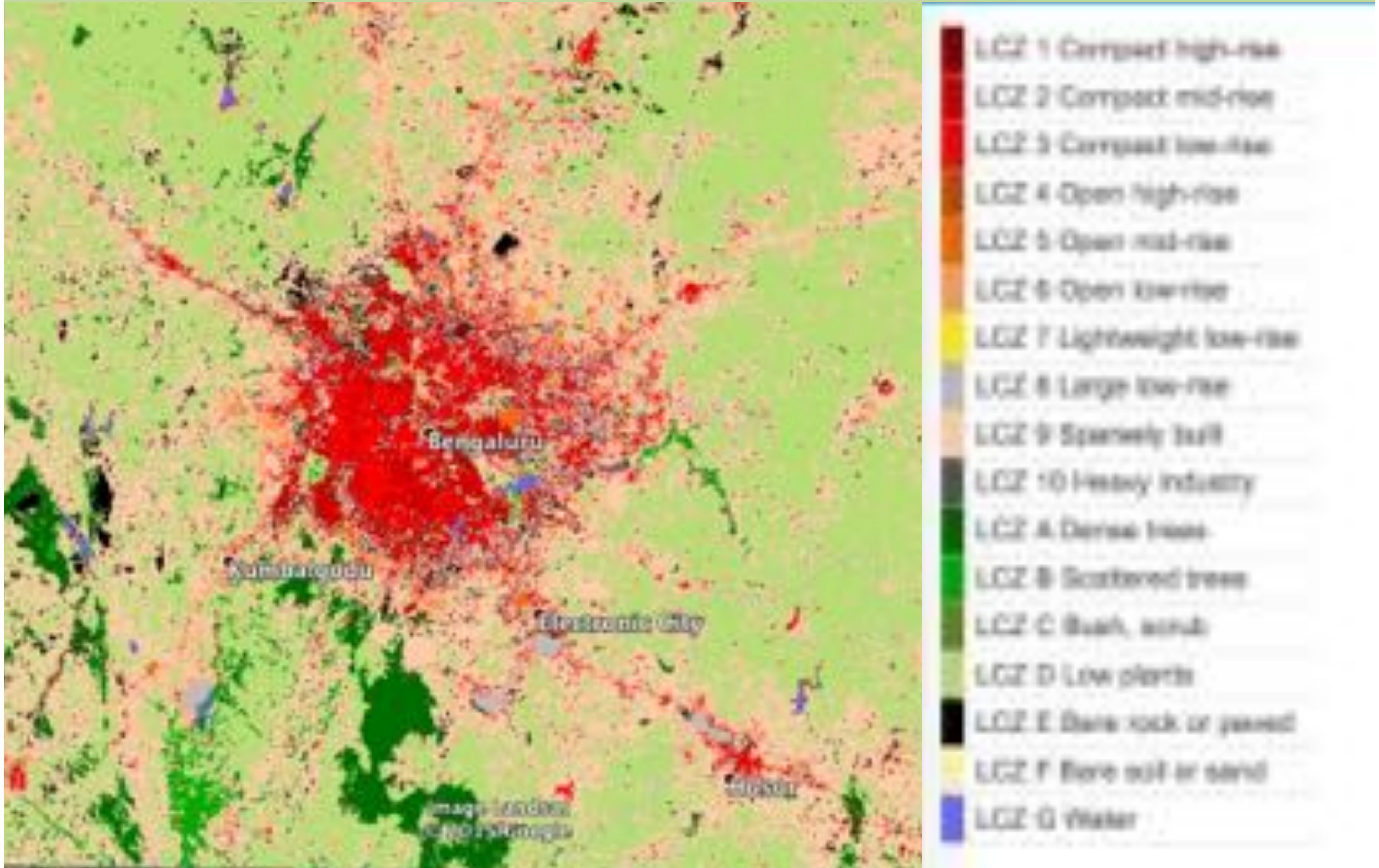




WUDAPT for weather models

Google Earth, Open Street Maps and Landsat Imagery based reclassification of Cities, with Local Survey and Verification, and Rendering. Map released to broader community.

Example of New Urban Climate Zone map



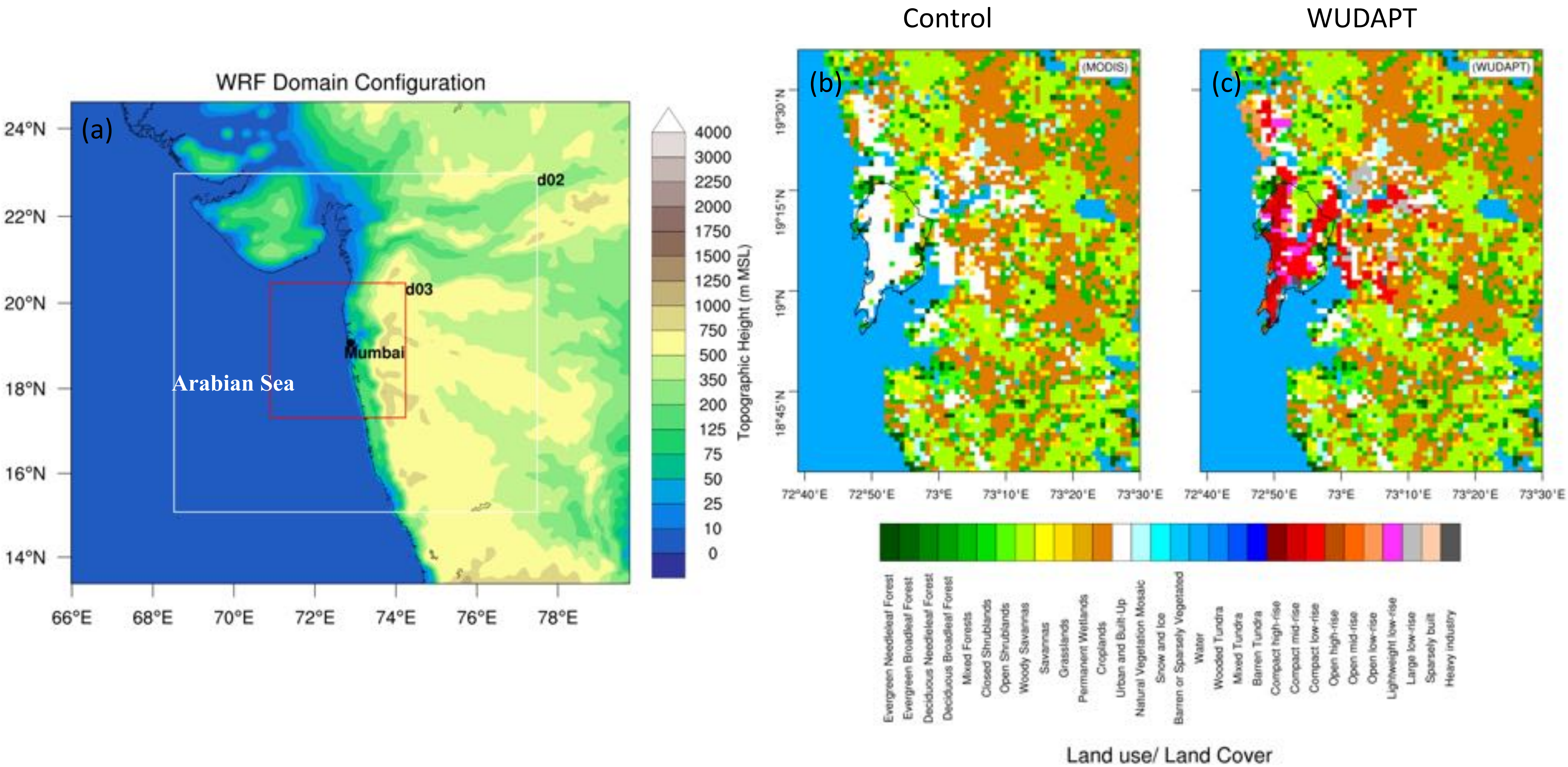
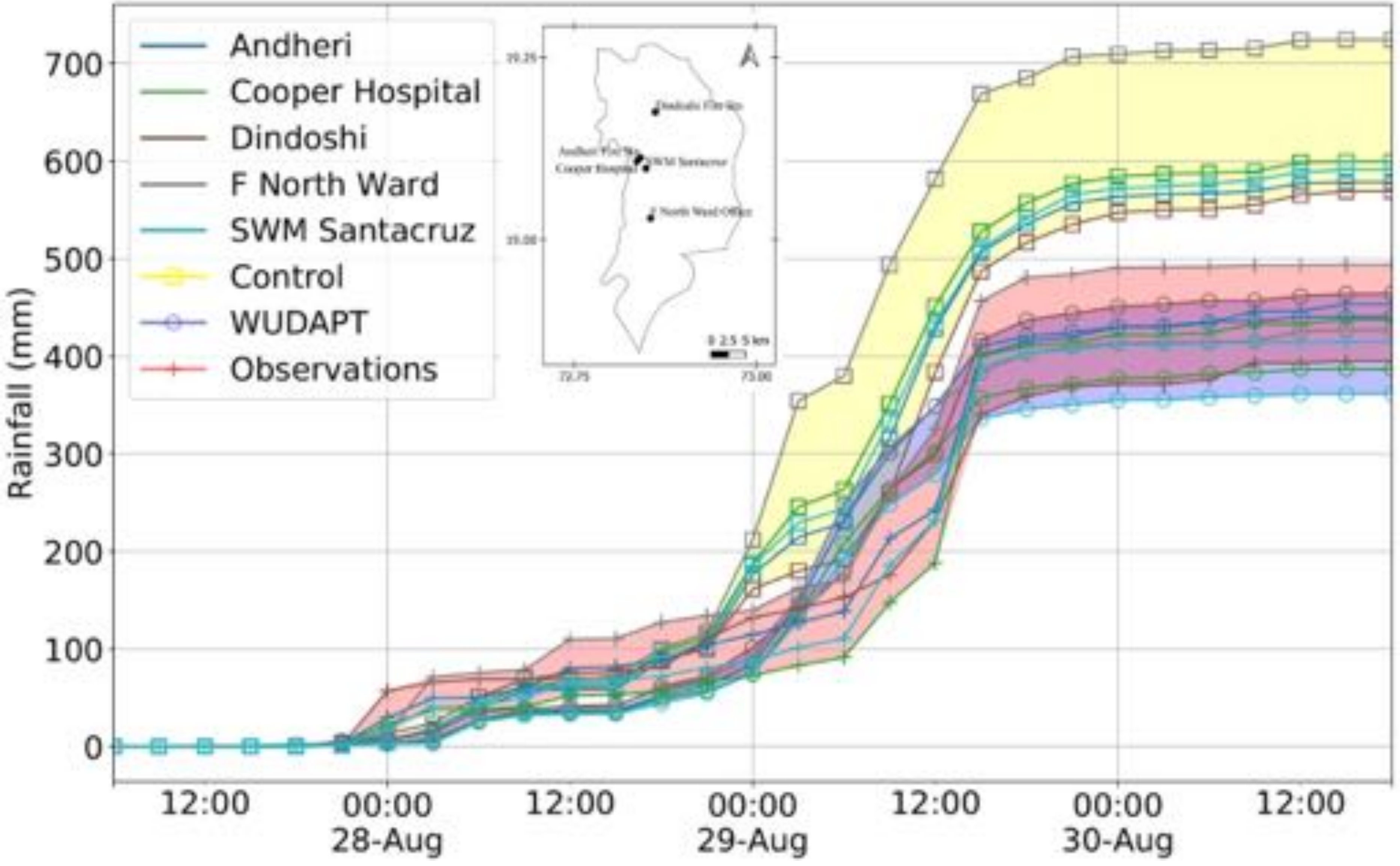
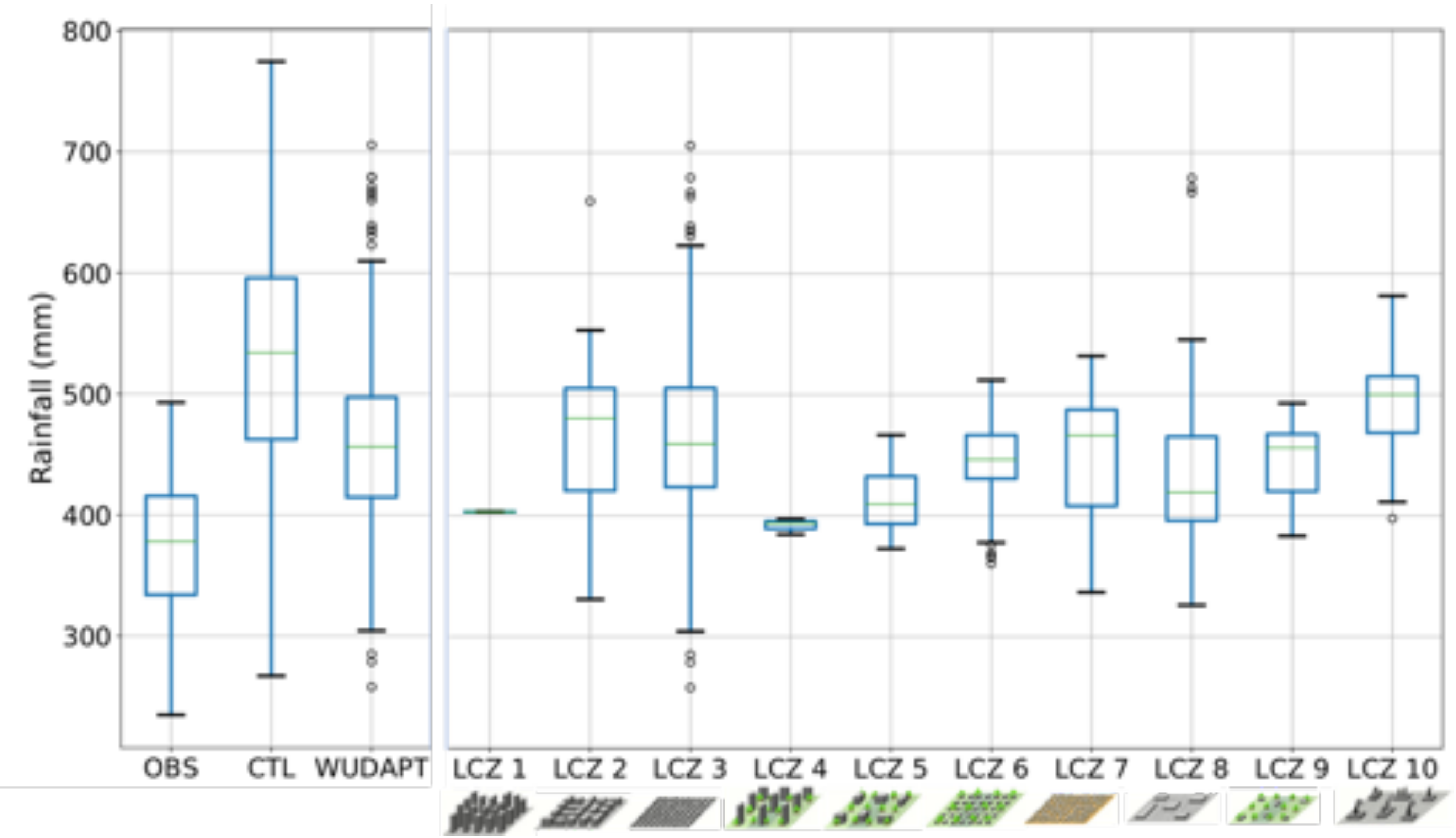


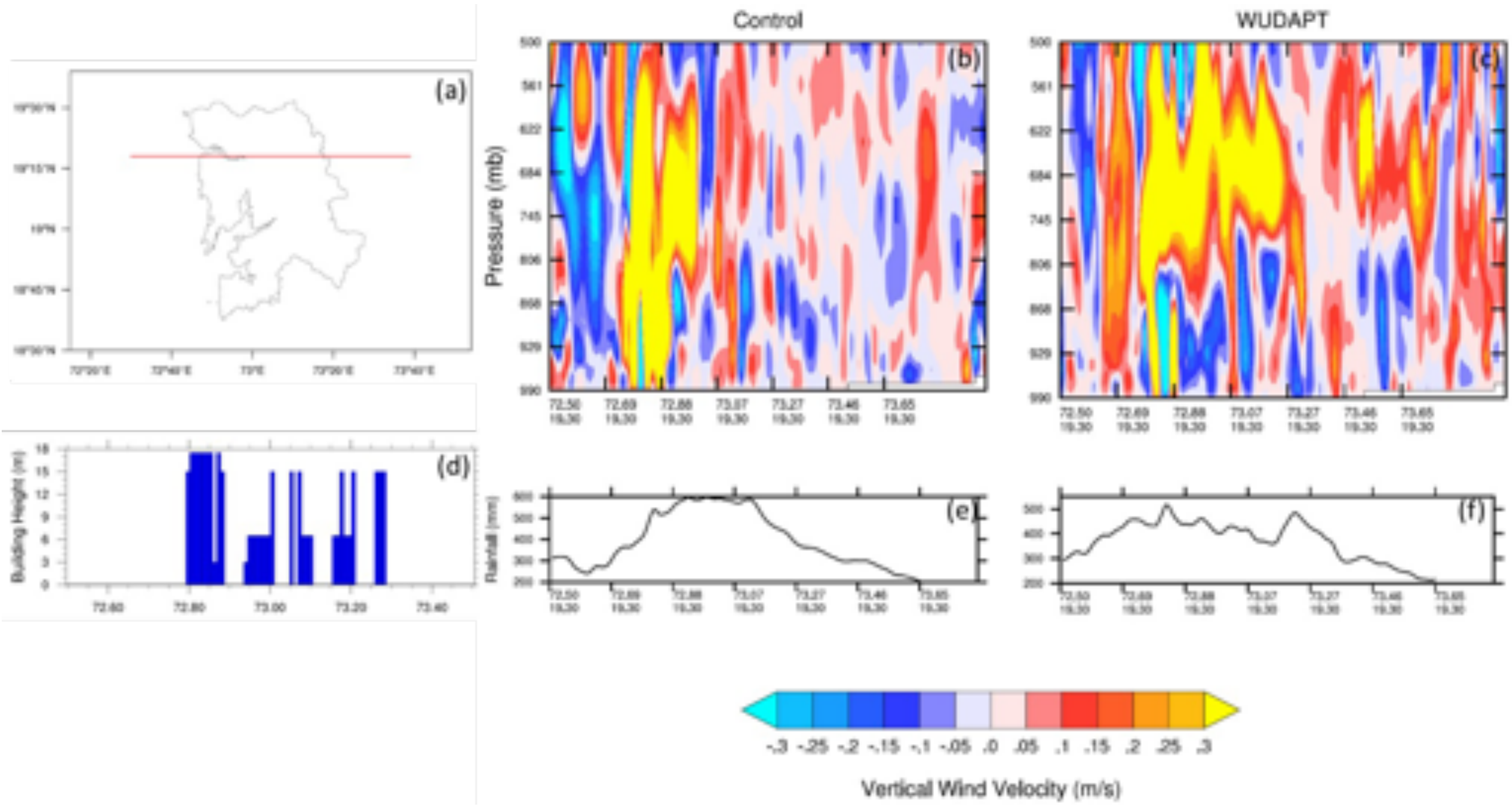
Figure 1: (a) Domain configuration of WRF (b) Land use/ land cover for control (MODIS) and including LCZ classes (WUDAPT) Black line represents the study area.



Andheri
Cooper Hospital
Dindoshi
F North Ward
SWM Santacruz
Control
WUDAPT
Observations
Rainfall (mm)
0
100
200
300
400
500
600
700
12:00
00:00
28-Aug
12:00
00:00
29-Aug
12:00
00:00
30-Aug
12:00
0 2.5 5 km
72.75
73.00



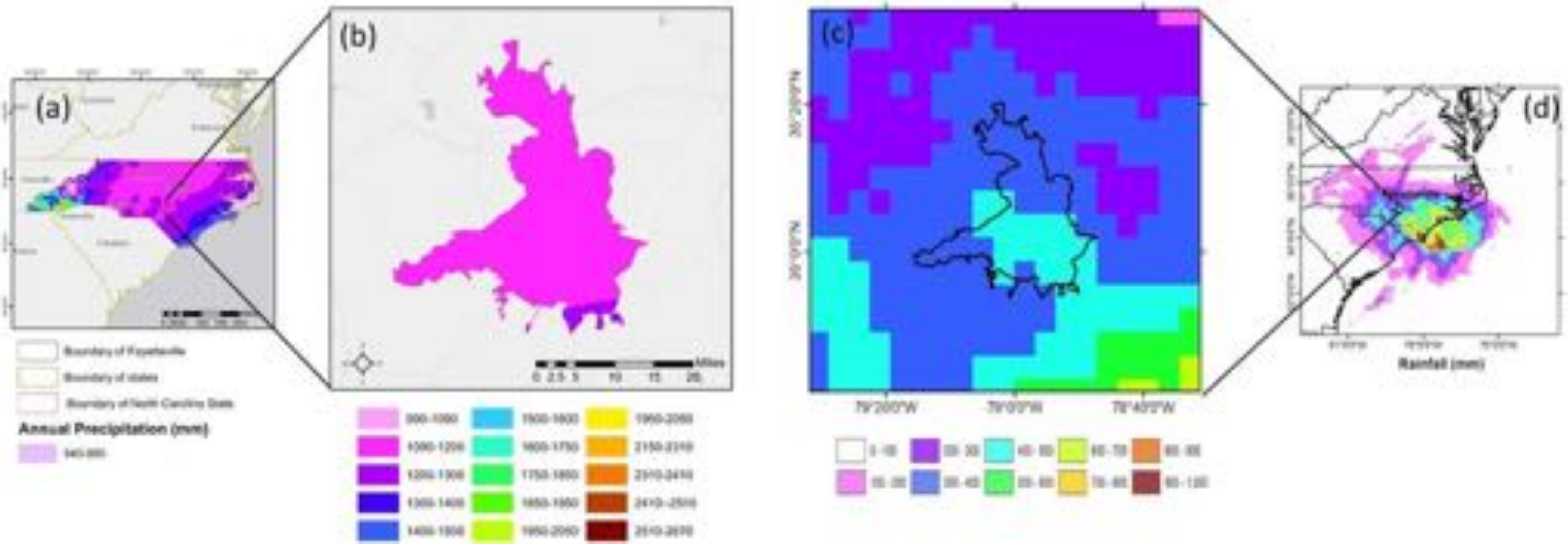
Rainfall (mm)
800
700
600
500
400
300
OBS
CTL
WUDAPT
LCZ 1
LCZ 2
LCZ 3
LCZ 4
LCZ 5
LCZ 6
LCZ 7
LCZ 8
LCZ 9
LCZ 10



Control
WUDAPT
(a)
(b)
(c)
(d)
(e)
(f)
Pressure (mb)
Building Height (m)
Rainfall (mm)
72.60
72.80
73.00
73.20
73.40
-.3 -.25 -.2 -.15 -.1 -.05 .0 .05 .1 .15 .2 .25 .3
Vertical Wind Velocity (m/s)

Impact of Urban Parameterization on Simulation of Hurricane Rainfall

- **Key Points:**
- The WRF model quantitative precipitation forecast over the urban domain was sensitive to urban physics for an intense, large-scale event such as a hurricane.
- The consideration of detailed urban physics in the WRF model simulation reduced the simulated rainfall error over the urban region by 16.5%.
- The improved model rainfall appears to be in response to accurate simulation of mesoscale surface gradients.



(a)
Boundary of Fayetteville
Boundary of states
Boundary of North Carolina State
Annual Precipitation (mm)
(b)
Miles
(c)
(d)
Rainfall (mm)

Struggle between Simplicity and Complexity

Complexity

More Processes

Often Process Understanding and **DATA** is a missing feature

Simplicity

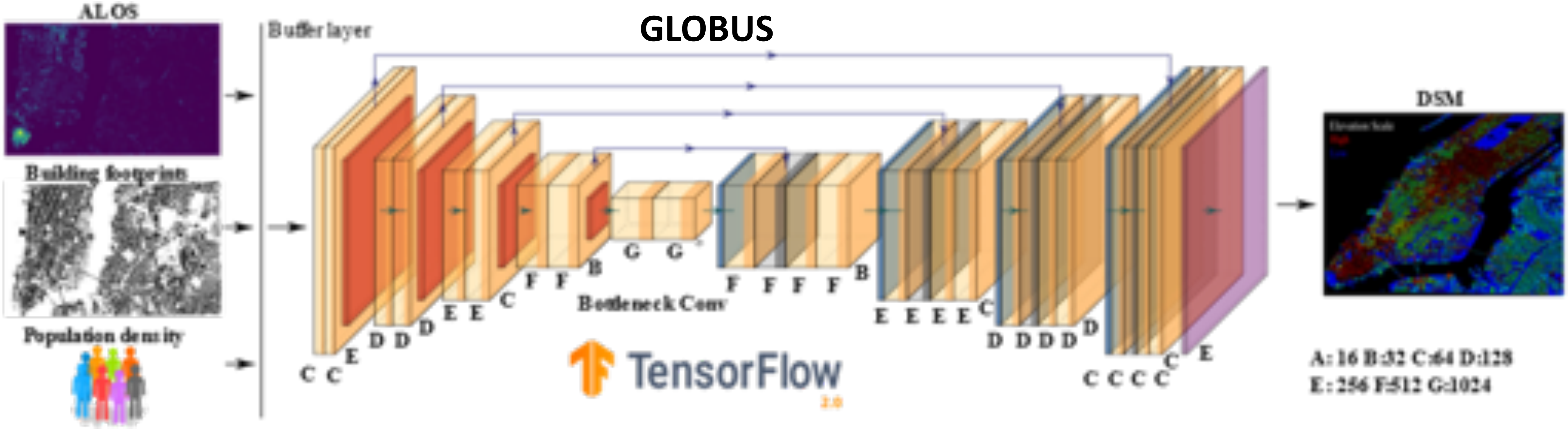
More Applications

Examples of data that you don't have in complex models: Building height

First challenge or opportunity for Digital Twins

- Creating synthetic data from DT/ simple models for use in process/ complex models

GLOBUS

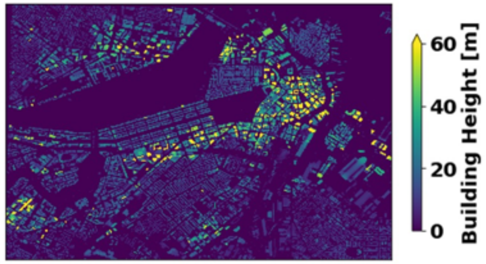


Presented at IAUC 2022

Harsh Kamath, Manmeet Singh, Lori Magruder, Zong-Liang Yang and Dev Niyogi

https://arxiv.org/ftp/arxiv/papers/2205/2205.12224.pdf

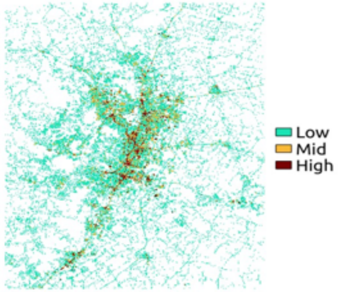
GLOBUS to WRF (G2W) Framework



GLOBUS normalized Digital Surface Model

GLOBUS derived urban parameters	Used by Urban Canopy Model (UCM)
Plan area fraction	Single-layer (Kusaka et al., 2001) and Multi-layer (Martilli et al., 2002)
Area averaged building height	
Building surface to plan area ratio	
Histogram of building heights	Multi-layer
Mean building heights	Single-layer
Standard deviation of building heights	
Frontal area index	

+



Land cover derived from ESA worldcover or Local climate zones (LCZs)

GEOGRID

Presented at IAUC 2022

Harsh Kamath, Manmeet Singh, Lori Magruder, Zong-Liang Yang and Dev Niyogi

https://arxiv.org/ftp/arxiv/papers/2205/2205.12224.pdf

NOAA NIHHIS Austin Heat Island Study with G2W (Globus to WRF)

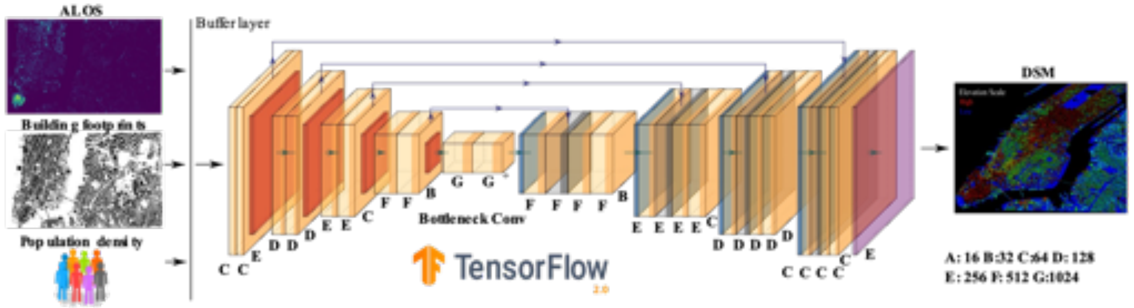


Fig. 1 GLOBUS architecture (U-Net based)

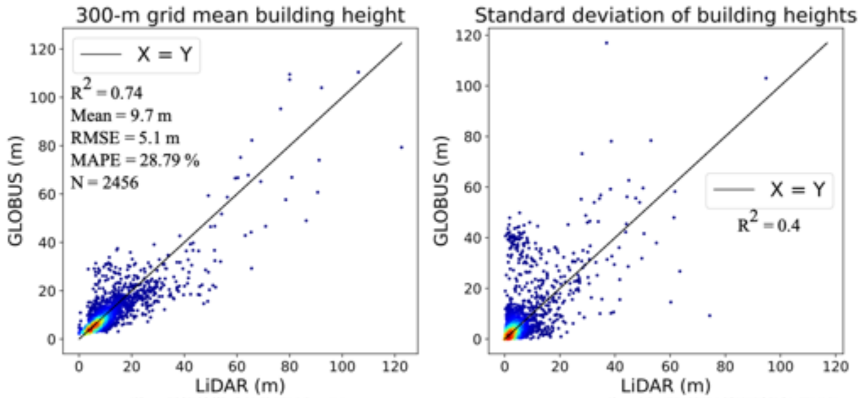


Fig. 2 Scatter plots showing the validation of GLOBUS using LiDAR as the ground truth at 300-m spatial resolution.

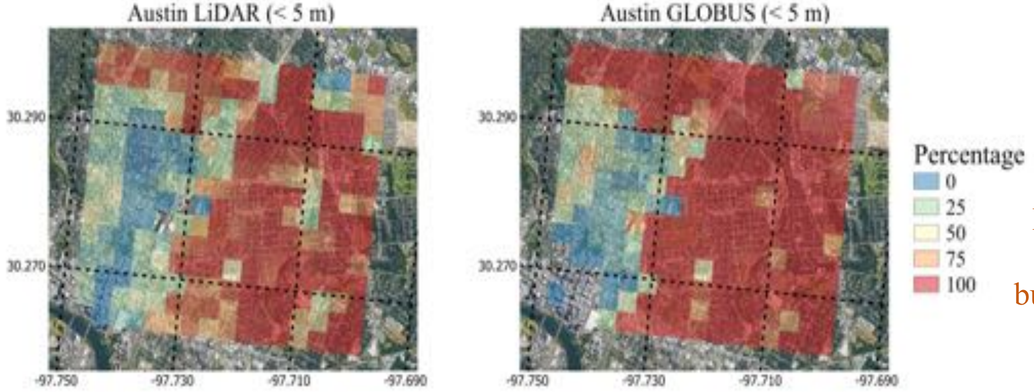


Fig. 3 Histogram of building heights: percentage of buildings with heights less than 5-m in Austin downtown .

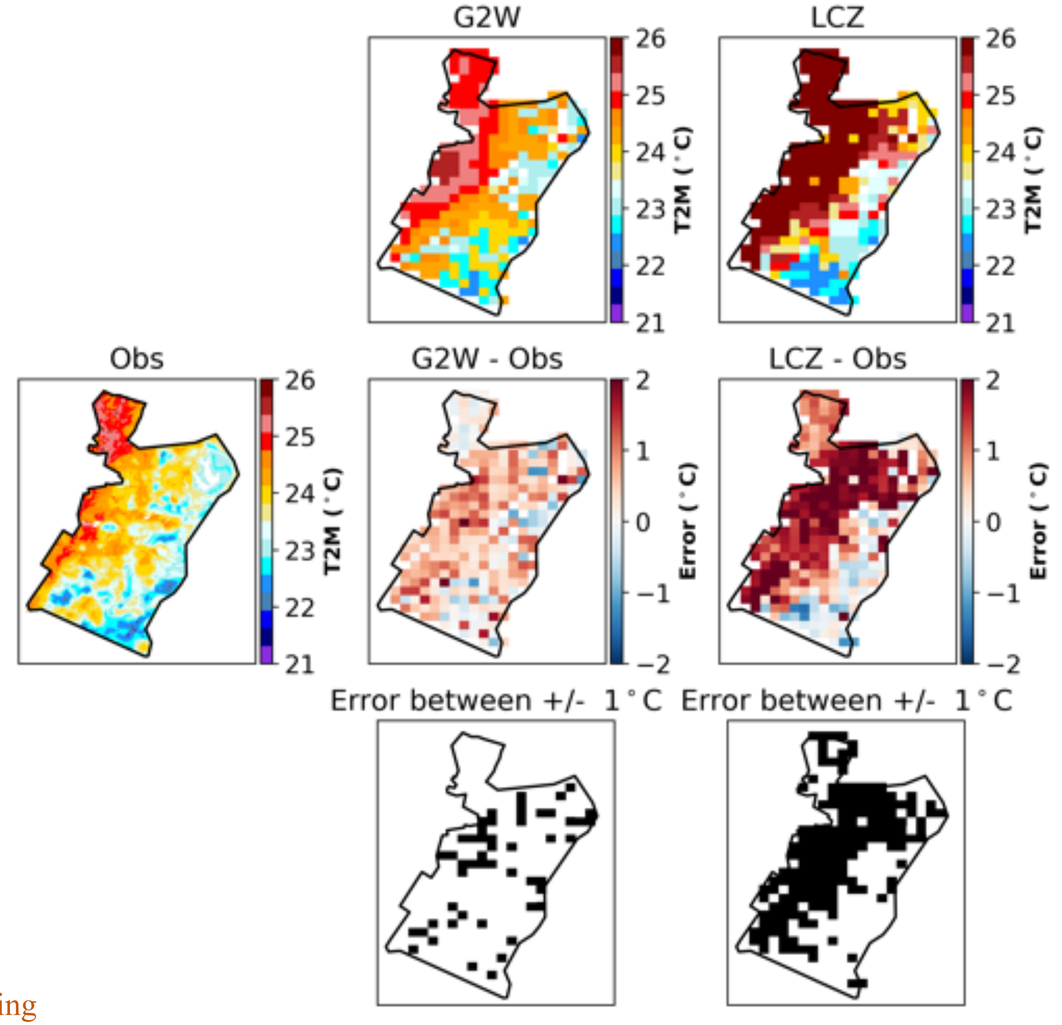
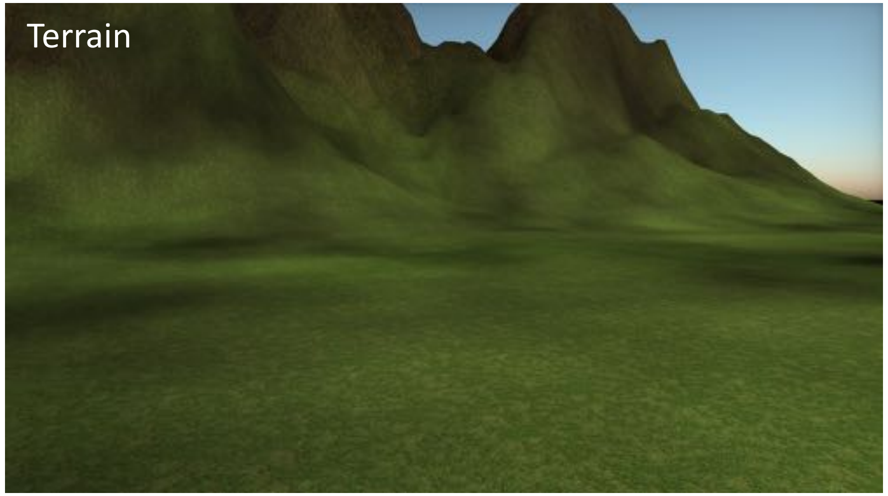


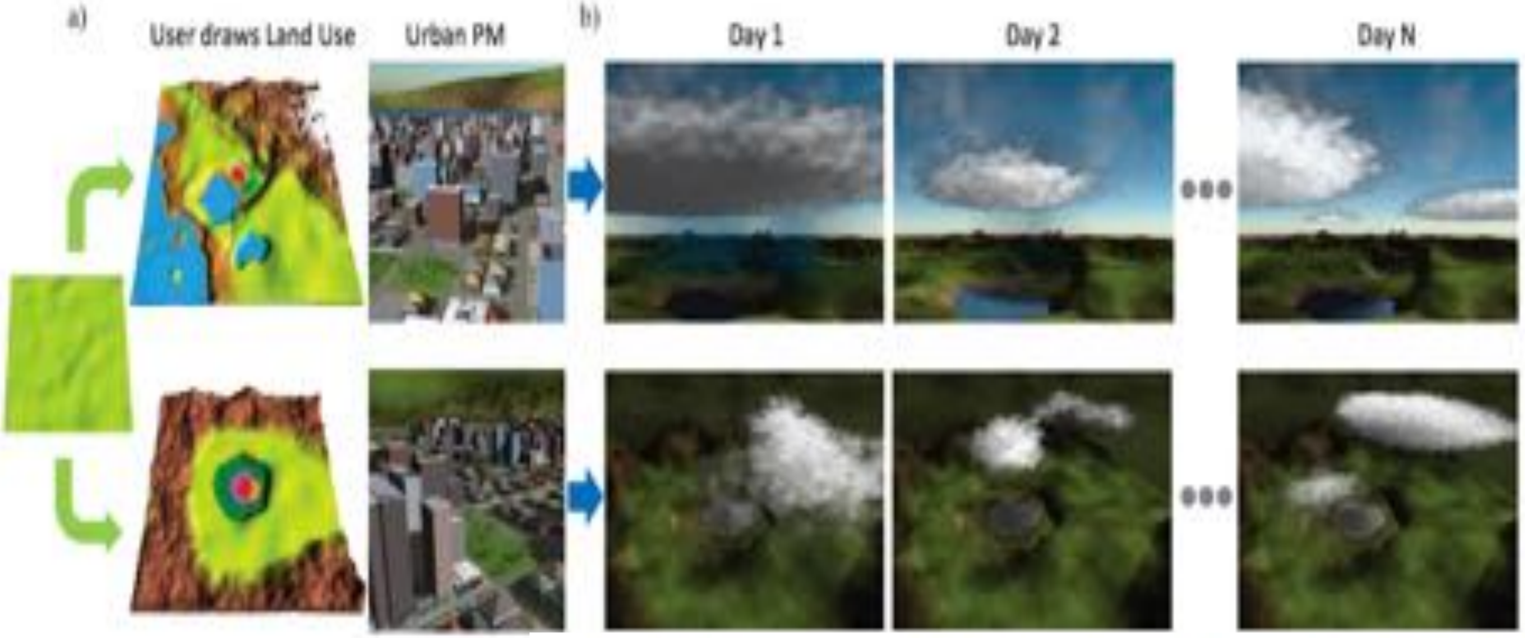
Fig. 4 WRF simulations of 2-meter temperature over Austin

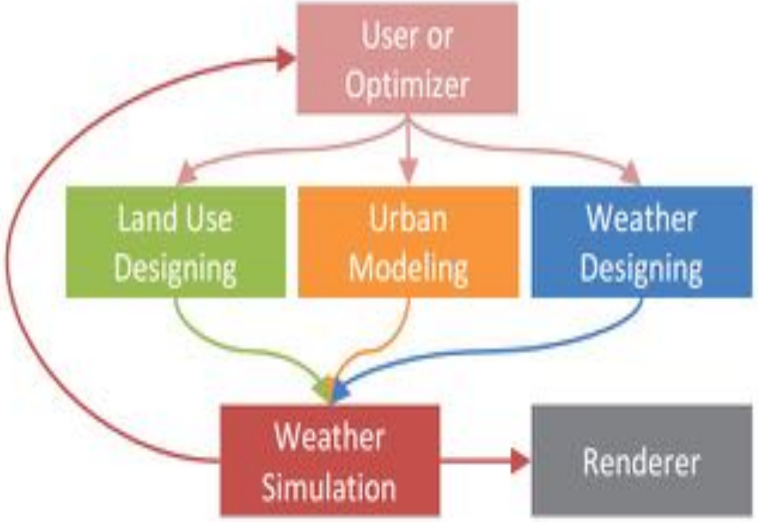
https://arxiv.org/ftp/arxiv/papers/2205/2205.12224.pdf

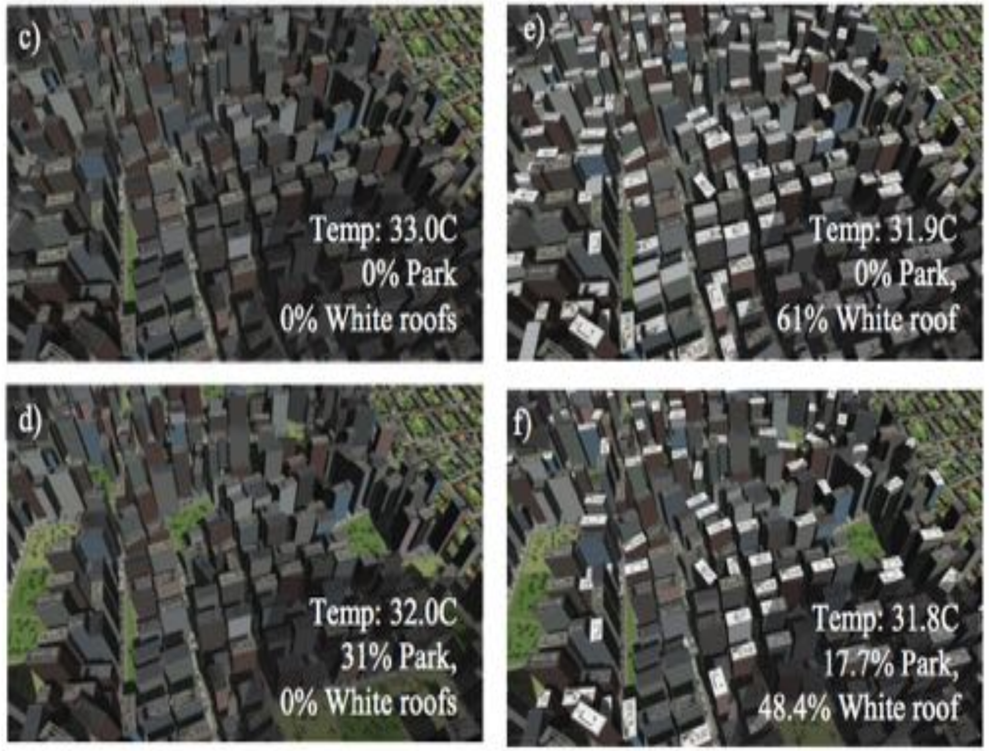
Interfacing Video Gaming Visualization with Urban Weather Models



Procedural modeling of coupled urban land atmospheric interaction

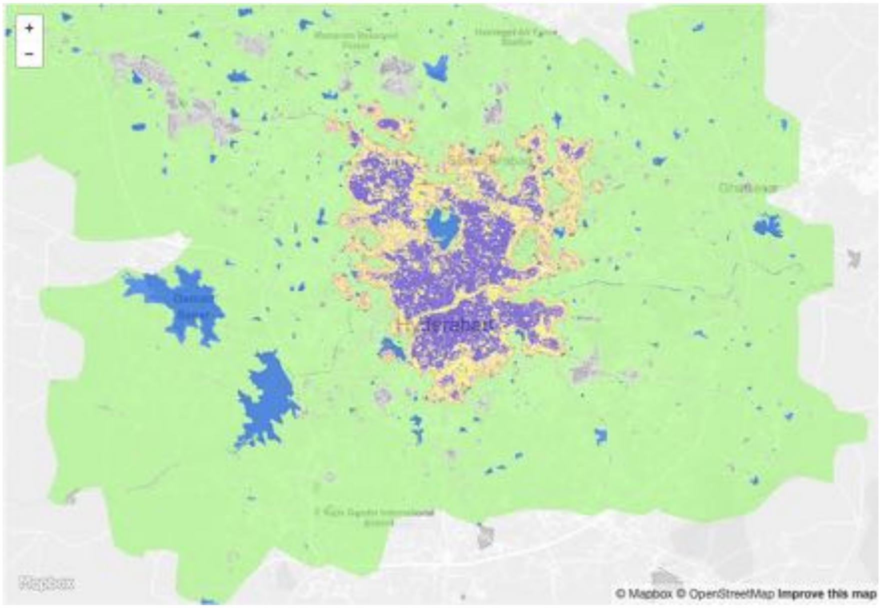




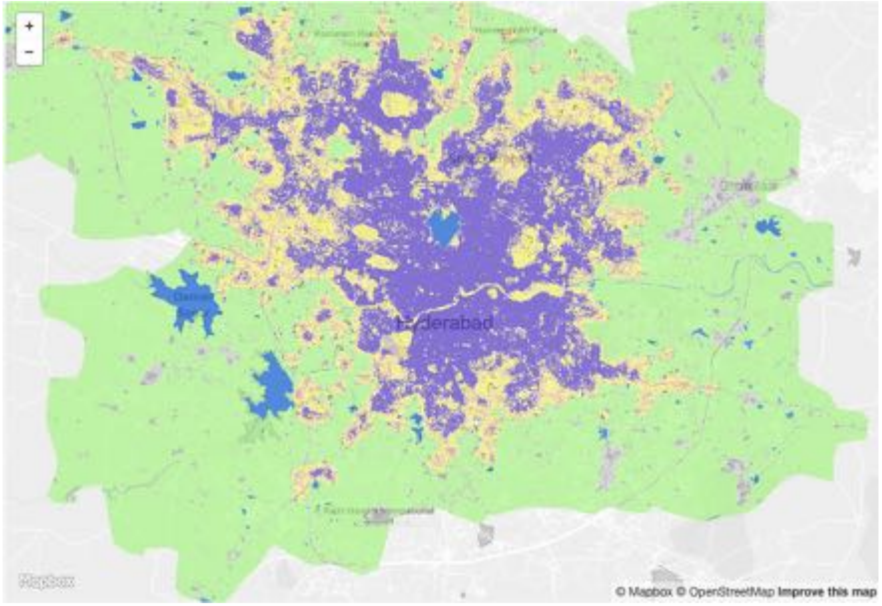


Source: Garcia-Dorado, I. *et al* (2016)

Hyderabad, India



1990



2014

http://www.atlasofurbanexpansion.org/

Hyderabad, India

Gathering Information on Typical Dwellings USA

© realtor.com

Second opportunity for DT*

Speed of computation

Urban science to Urban planning

Greenscapes, urban Greening

Changes in temperature and city's climate

urban WRF

Computer visualization

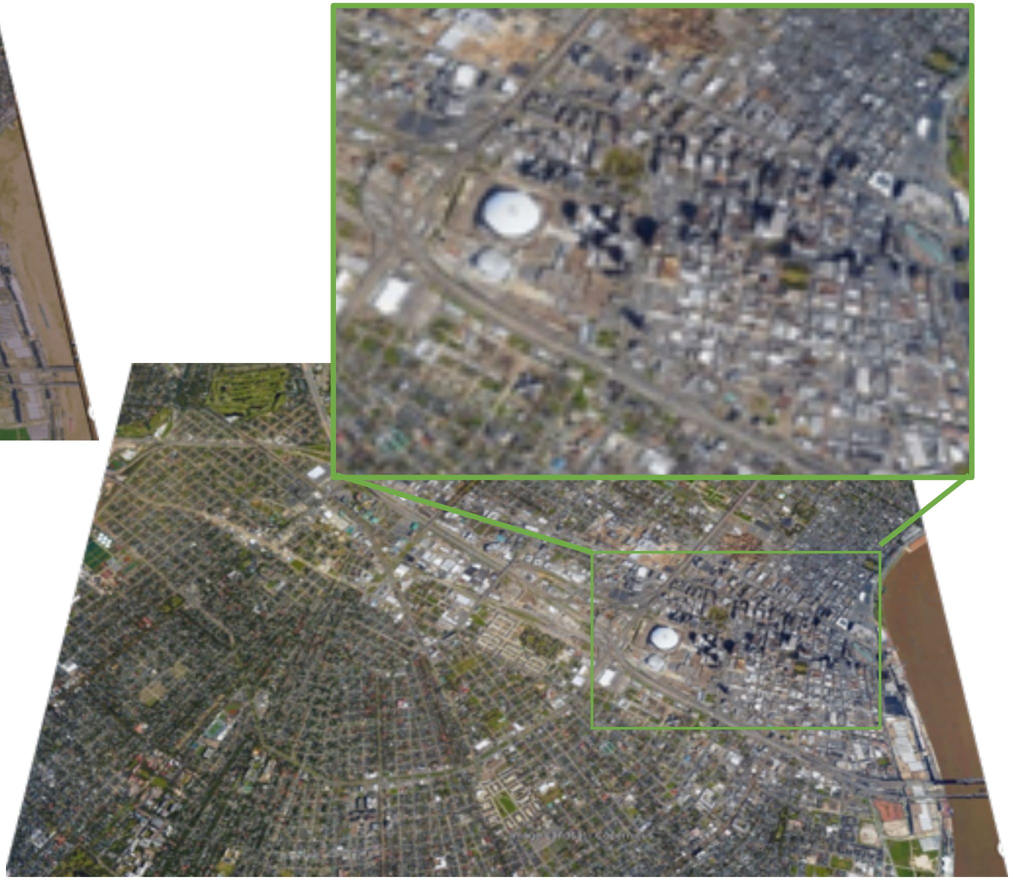
Model initial conditions to WRF: hours to days

Seconds to minutes

https://www.linkedin.com/feed/update/urn:li:activity:68990156

Output: Procedural 3D Model

New Orleans: Procedural Model



New Orleans: Aerial Image

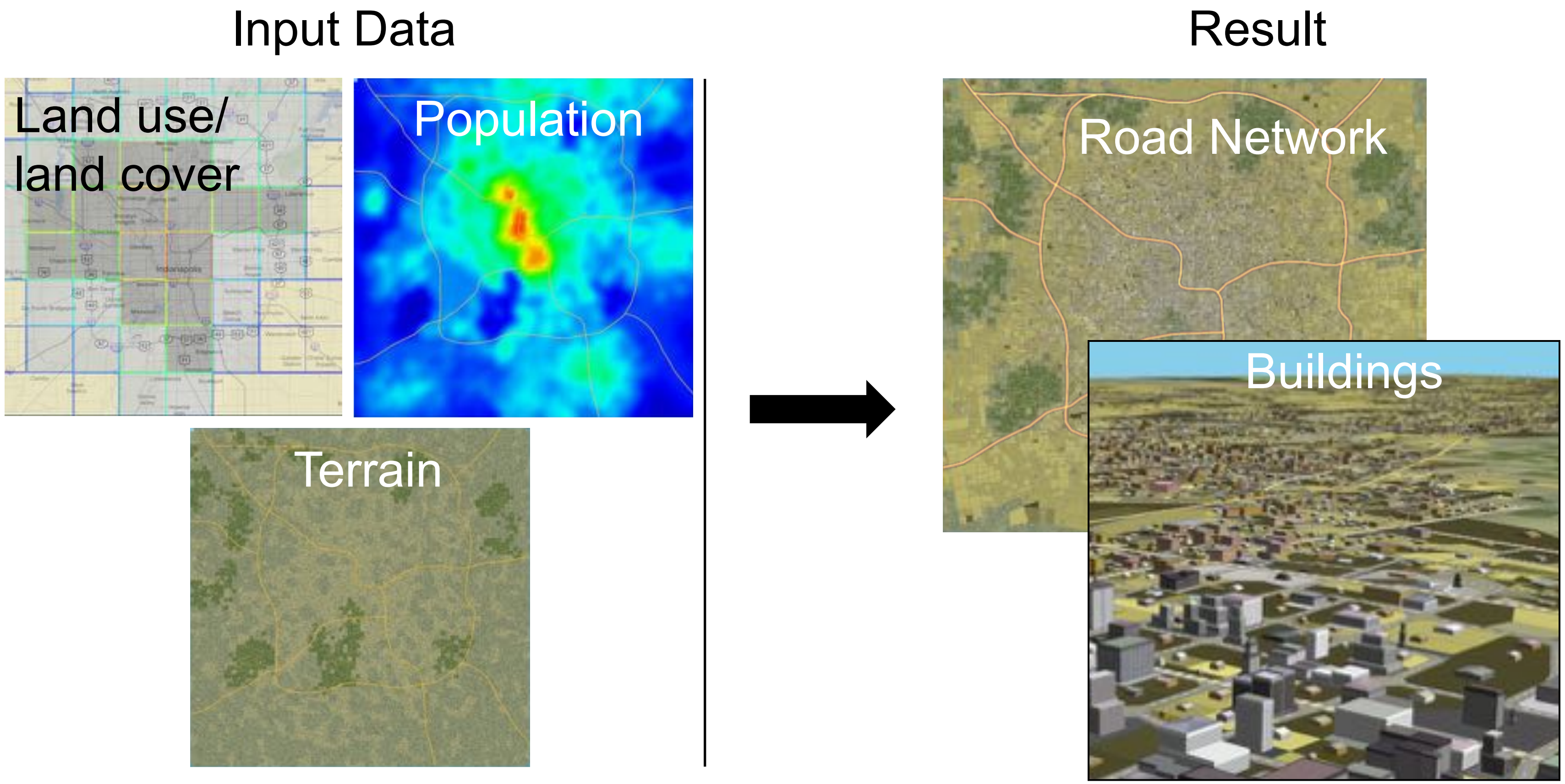
Output: Procedural 3D Model

Dublin – 3D Urban Procedural Model

Dublin – 3D Google Earth

Content Design Example

Inverse Urban Weather

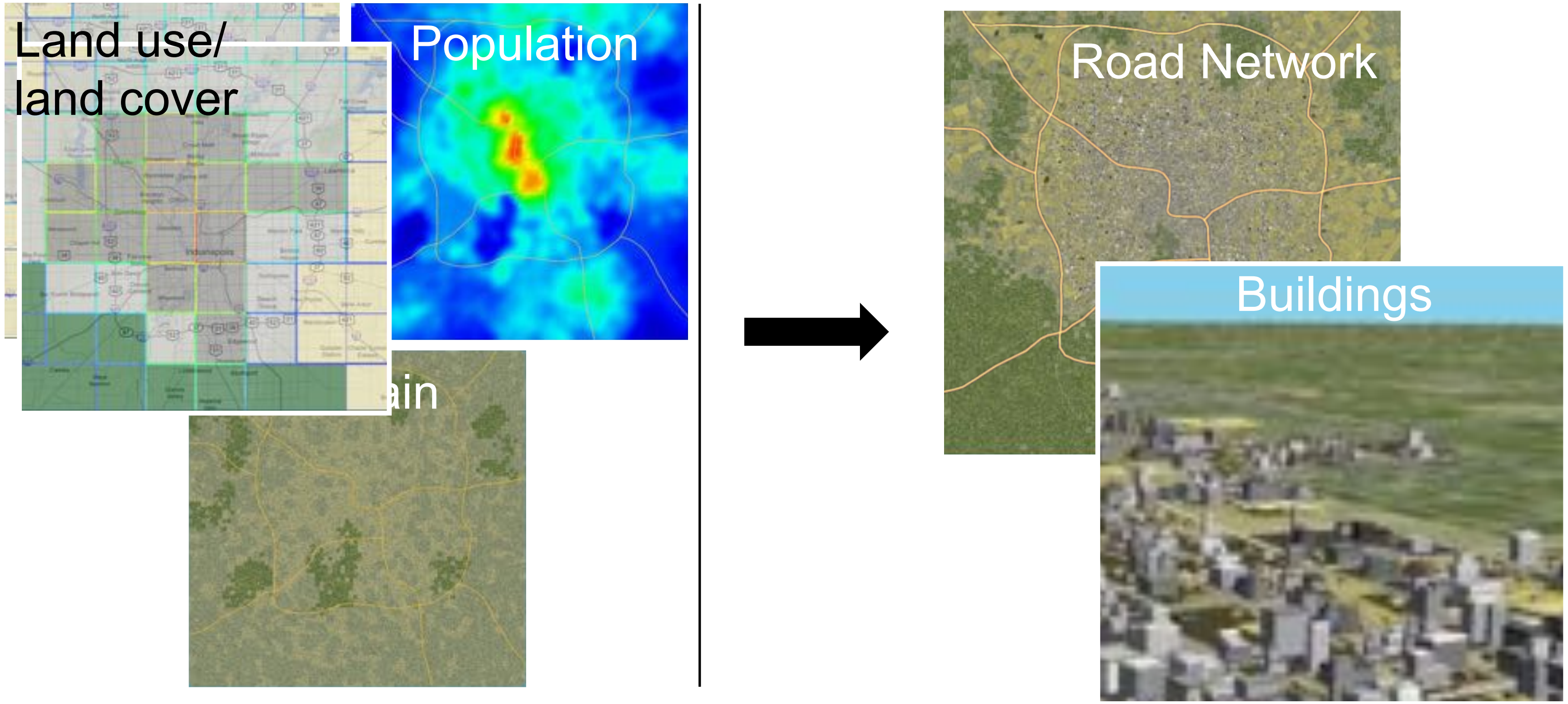


[Aliaga et al. 2013]

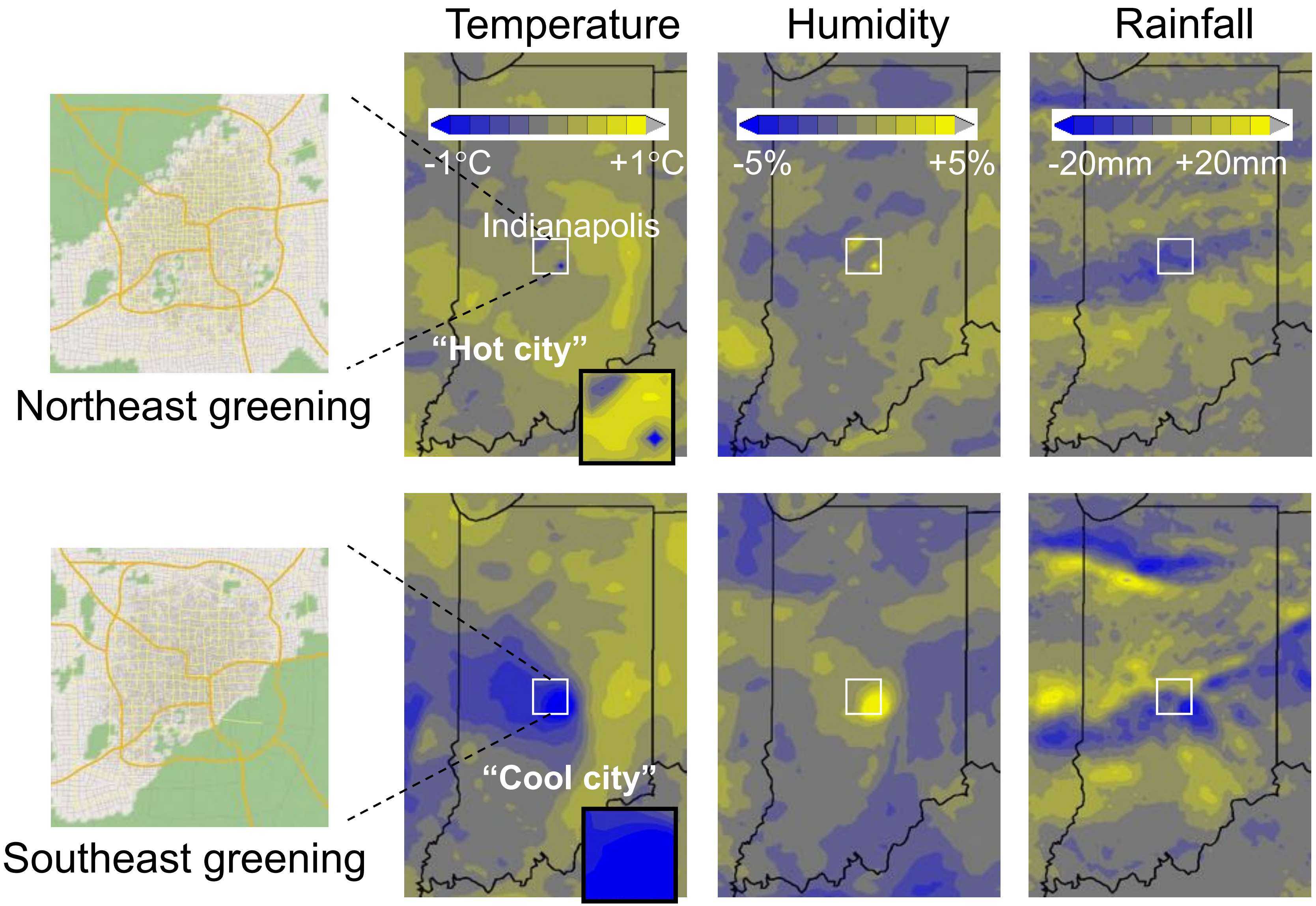
Inverse Urban Weather

Modified LULC (else same)

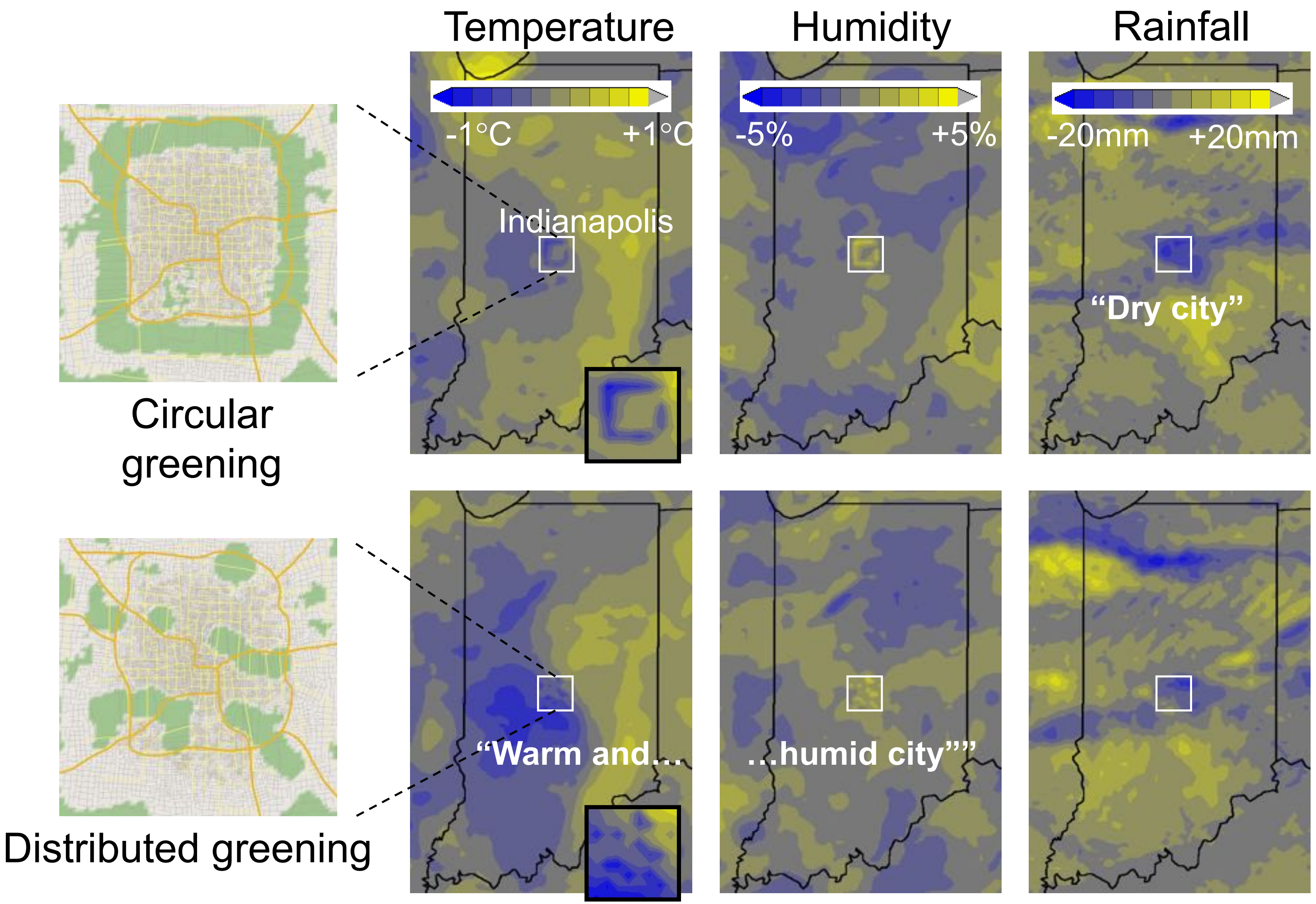
Modified Result



Inverse Urban Weather: Trees



Inverse Urban Weather: Trees



How would you design the traffic of a city?

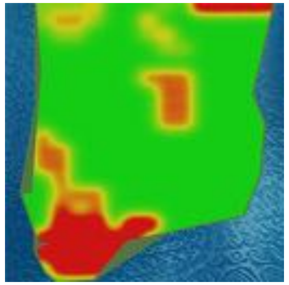
Results: Traffic Improvement

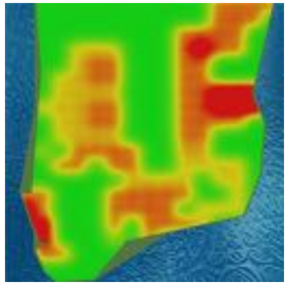
Initial Simulation

Travel Time: 60min

CO: 1012 gr

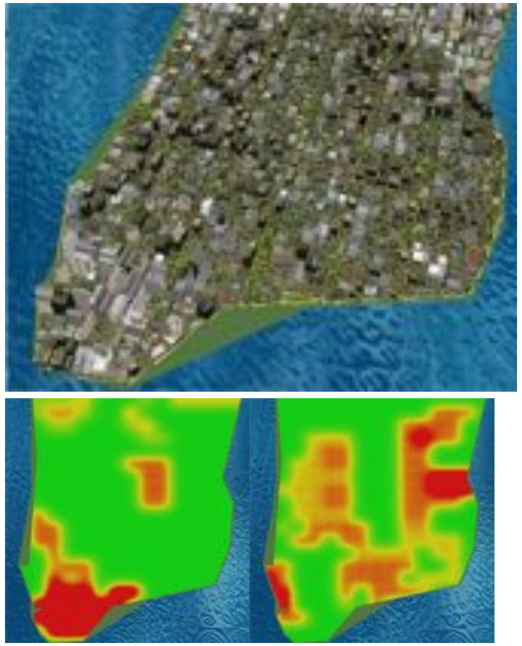
The user wants to optimize the city to 50, 40, and 30 min as maximum Travel Time



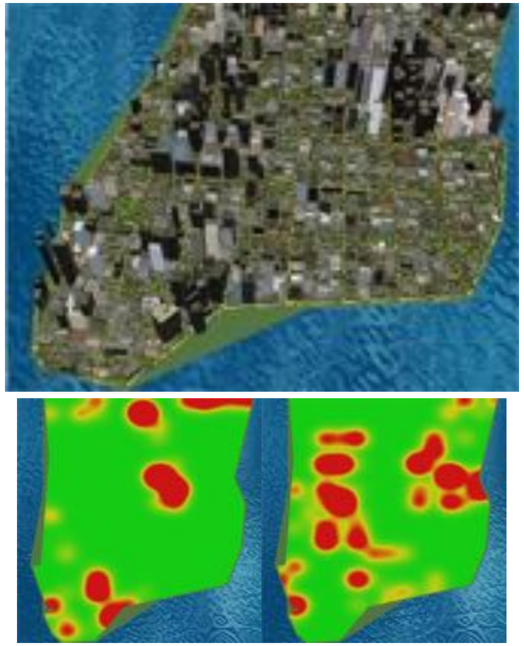


Results: Traffic Improvement

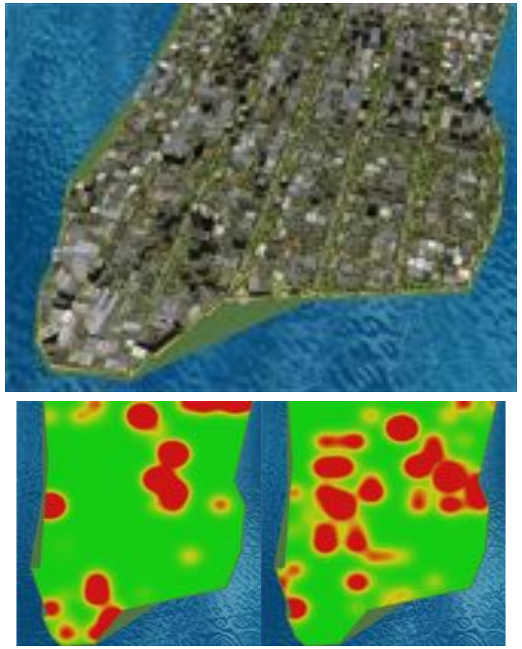
Solutions:



Travel Time: 50 min
CO: 980gr
52 Lanes



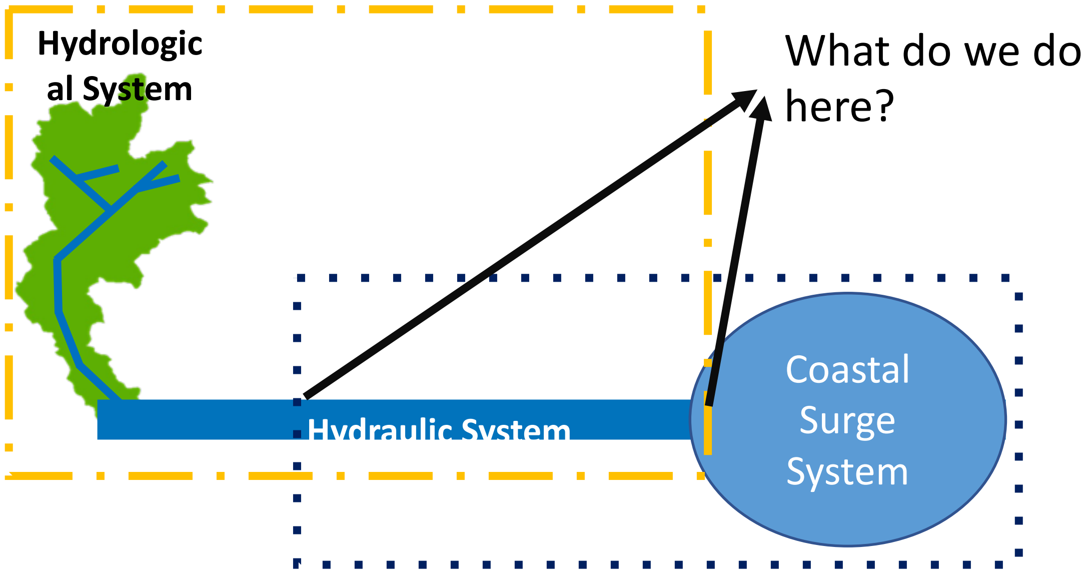
Travel Time: 40 min
CO: 622gr
16% Jobs
31% People
34 Lanes



Travel Time: 30 min
CO: 484gr
29% Jobs
44% People
61 Lanes

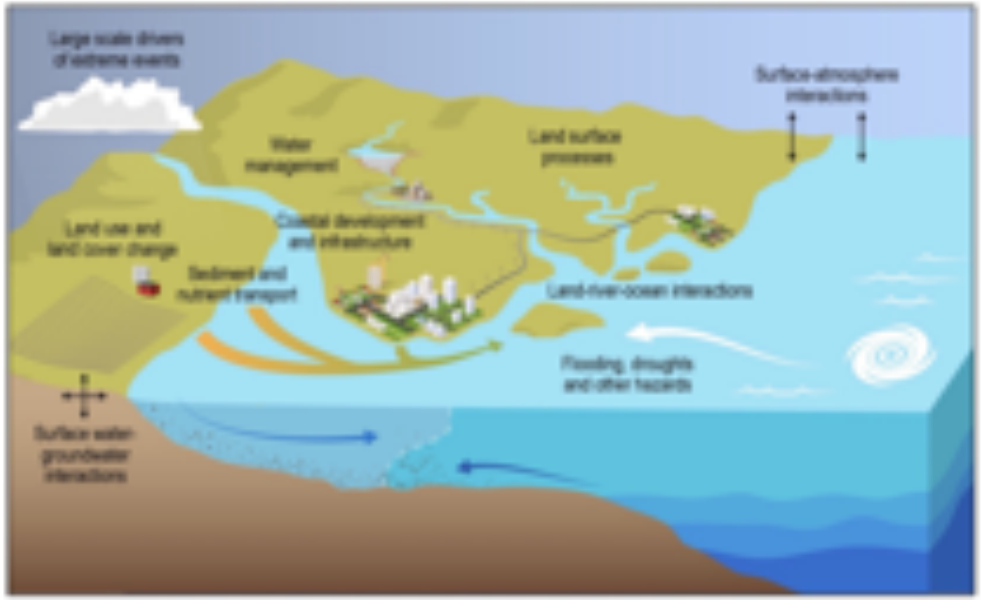
Third opportunity for Urban Digital Twins
Scalability

Application: Model coupling



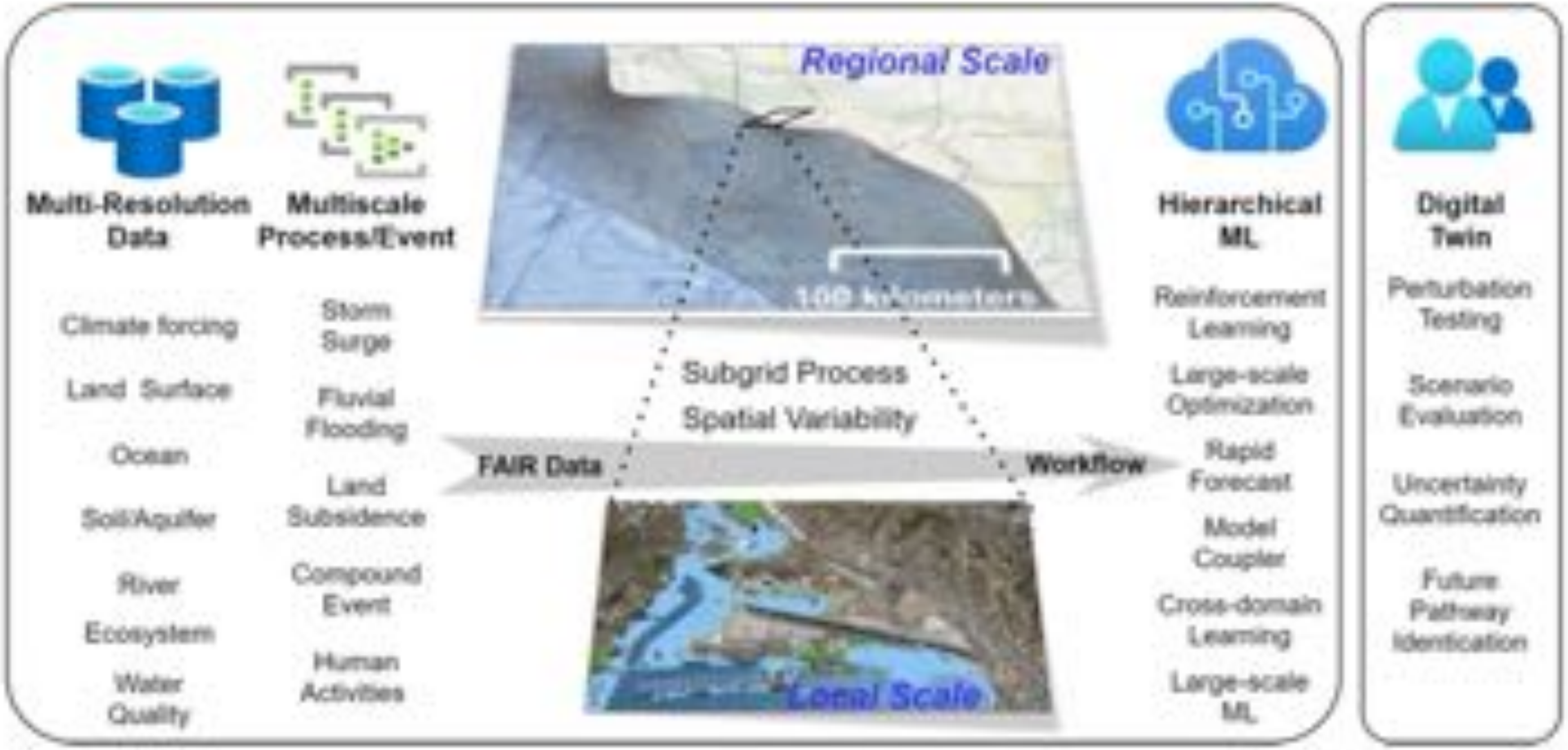
The University of Texas at Austin
Oden Institute for Computational Engineering and Sciences

Goal: Development of Digital Twin capabilities to understand the complex interplay between data and models. We will explore new multiphysics model couplings, scientific Machine Learning, data assimilation, data interoperability, etc, building from the E3SM modeling framework. The DT framework will be tested on applications in the Gulf Coast land/coastal interface.



The University of Texas at Austin
Oden Institute for Computational Engineering and Sciences

Proposed Research: MuSiKAL Framework=>Digital Twin



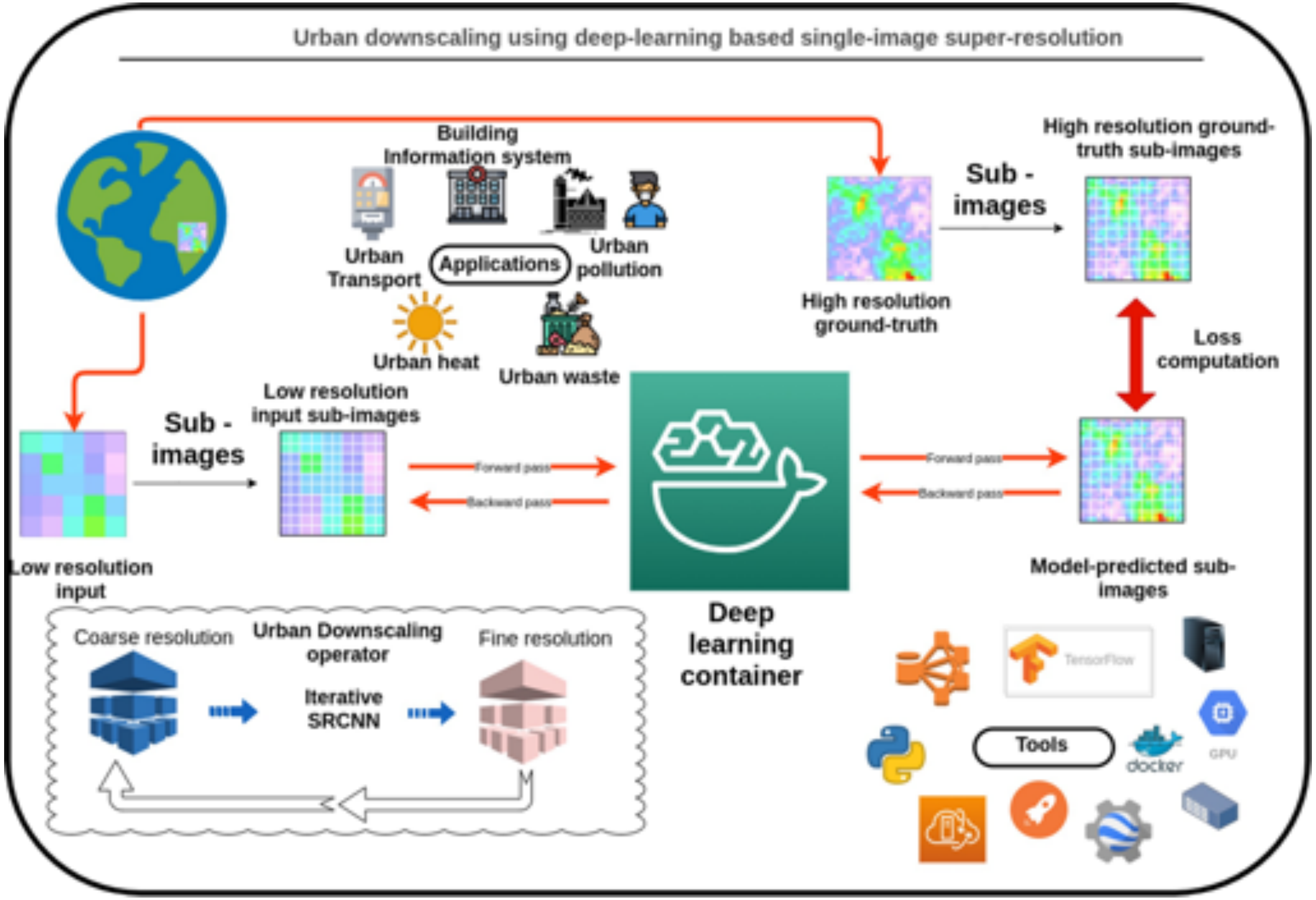
Super resolution downscaling for urban precipitation

Development of 300-m precipitation product over City of Austin from JAXA GsMAP satellite+Merged product at 10 km, hourly resolution

3 x3 deg box over Austin

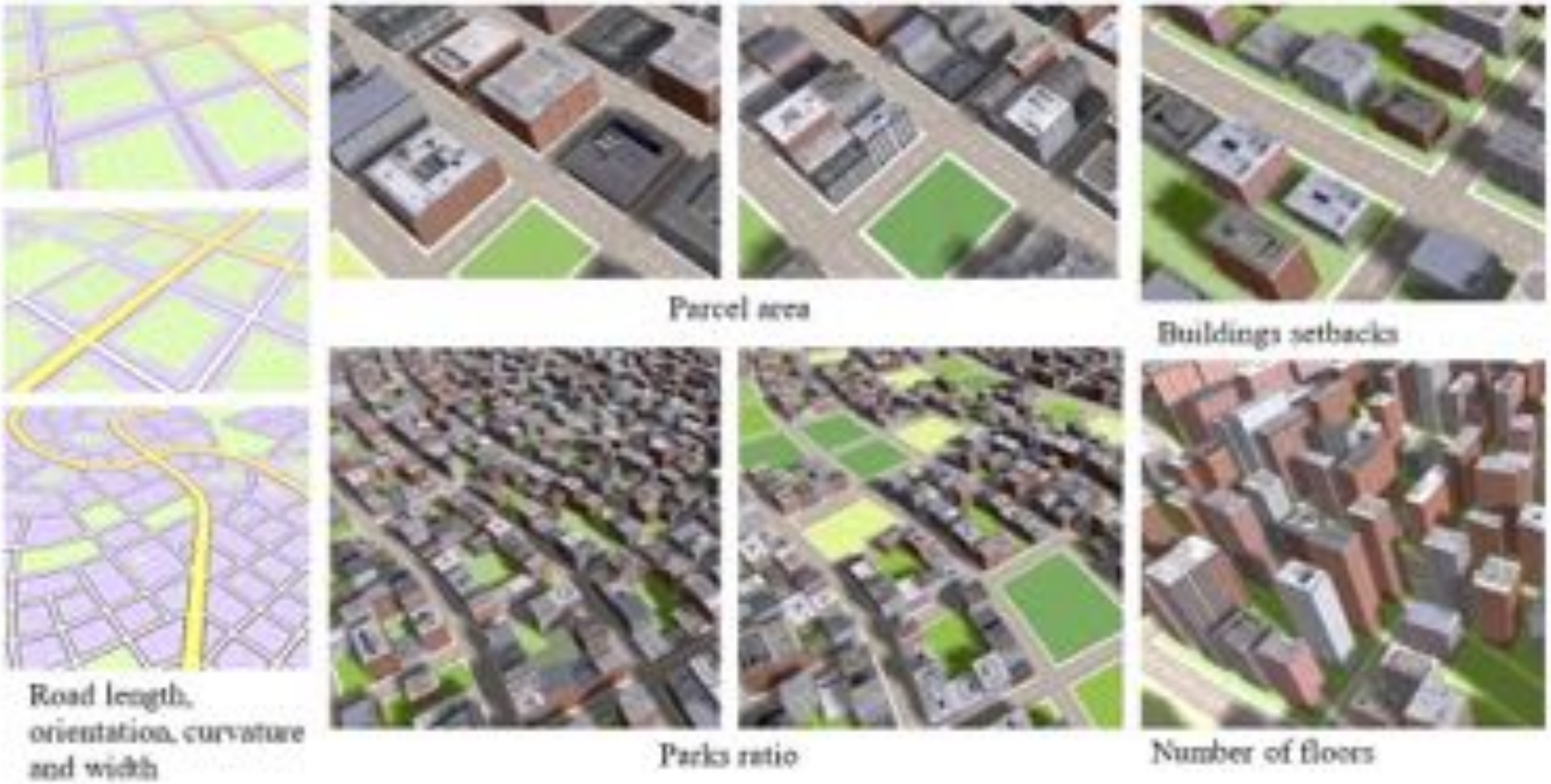
Iterative SR-CNN – 300 m grid out

Duration: 2001-2020



Manmeet Singh, Nachiketa Acharya, Sajad Jamshidi, Junfeng Jiao, Zong-Liang Yang, Marc Coudert, Zach Baumer, Dev Niyogi, submitted to Computational Urban Sciences

Inverse Urban Flooding



Looking forward

- Continued opportunity for simpler input conditions, development of ensembles, decision specific output
- Challenges and precautions
  - Framing (what is DT, what it is not)
  - Important to support physics based models not replace them
  - Recognize meteorological science is exceptionally challenging
  - Cities can be the solution for climate change – not the problem!
  -

Happy to discuss more

(and have an email to prove it!)

Email: happy1@utexas.edu

dev.niyogi@jsg.utexas.edu