A Planetary-Scale Data–Model Integration Framework to Resolve Urban Impacts Across Scales

TC (Tirthankar Chakraborty)
Earth Scientist,
Earth System Modeling Group,
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Pacific Northwest NATIONAL LABORATORY

E3SM Energy Exascale Earth System Model

U.S. DEPARTMENT OF ENERGY

A Planetary-Scale Data–Model Integration Framework to Resolve Urban Impacts Across Scales and Examine Weather Extremes over Coastal U.S. Cities

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Presentation Overview

BACKGROUND

MOTIVATION

RESEARCH PLANS

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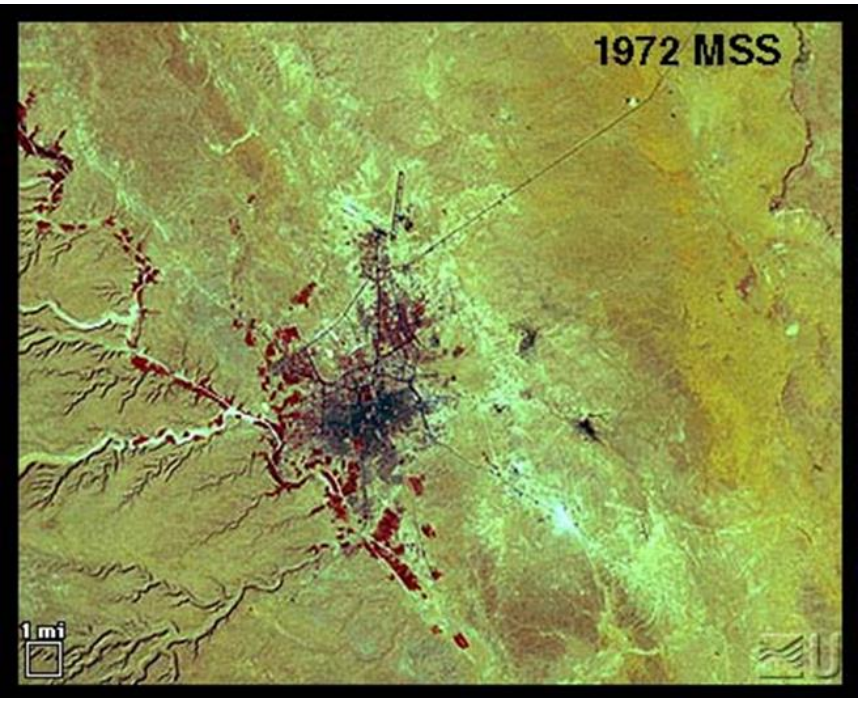
RESEARCH PLANS

The physical process of urbanization

- Replacement of natural land surfaces with built-up structures



Source: NASA and USGS

The physical process of urbanization

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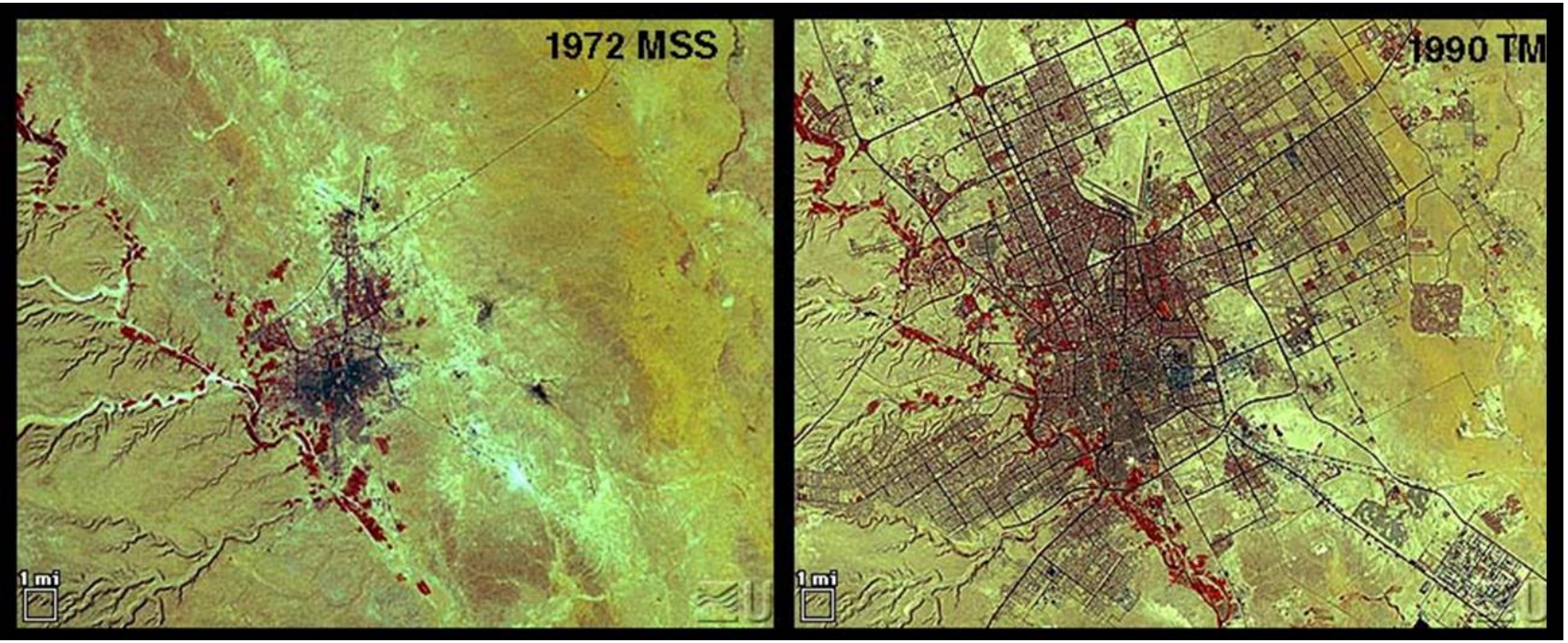

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The physical process of urbanization

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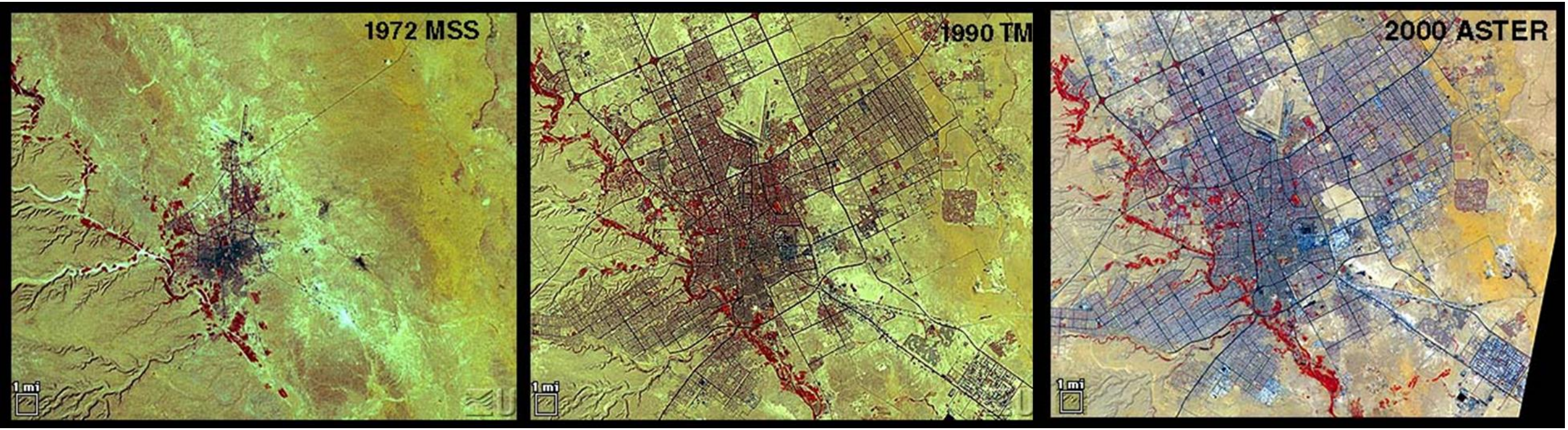

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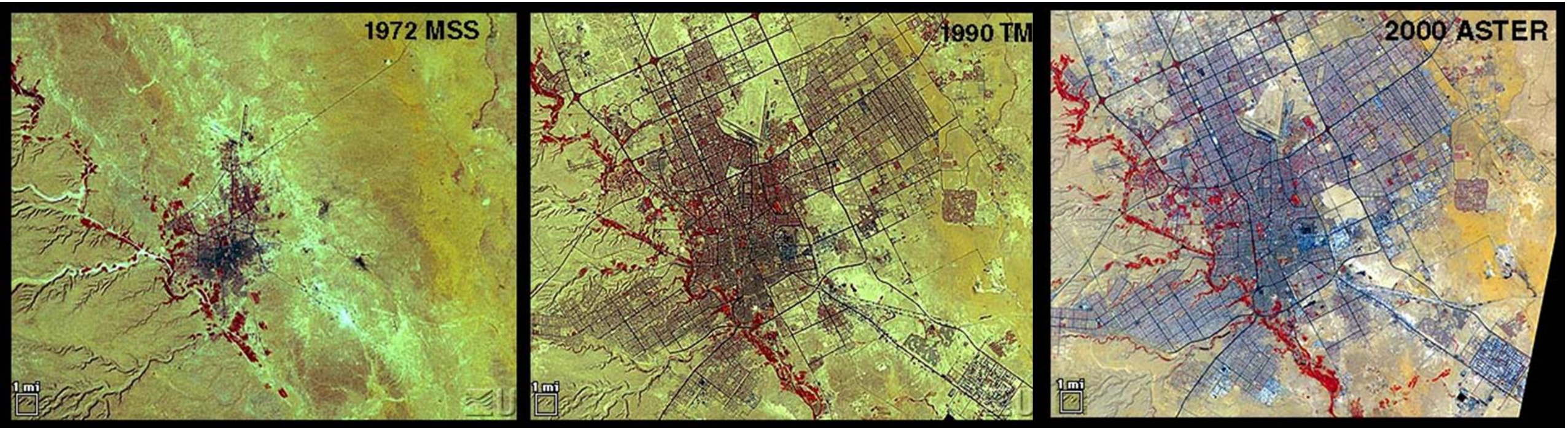
The physical process of urbanization

- Replacement of natural land surfaces with built-up structures
- Broadly, any change in natural land cover due to urban planning (e.g. addition of urban green spaces and transition from native to non-native vegetation), constitutes urbanization



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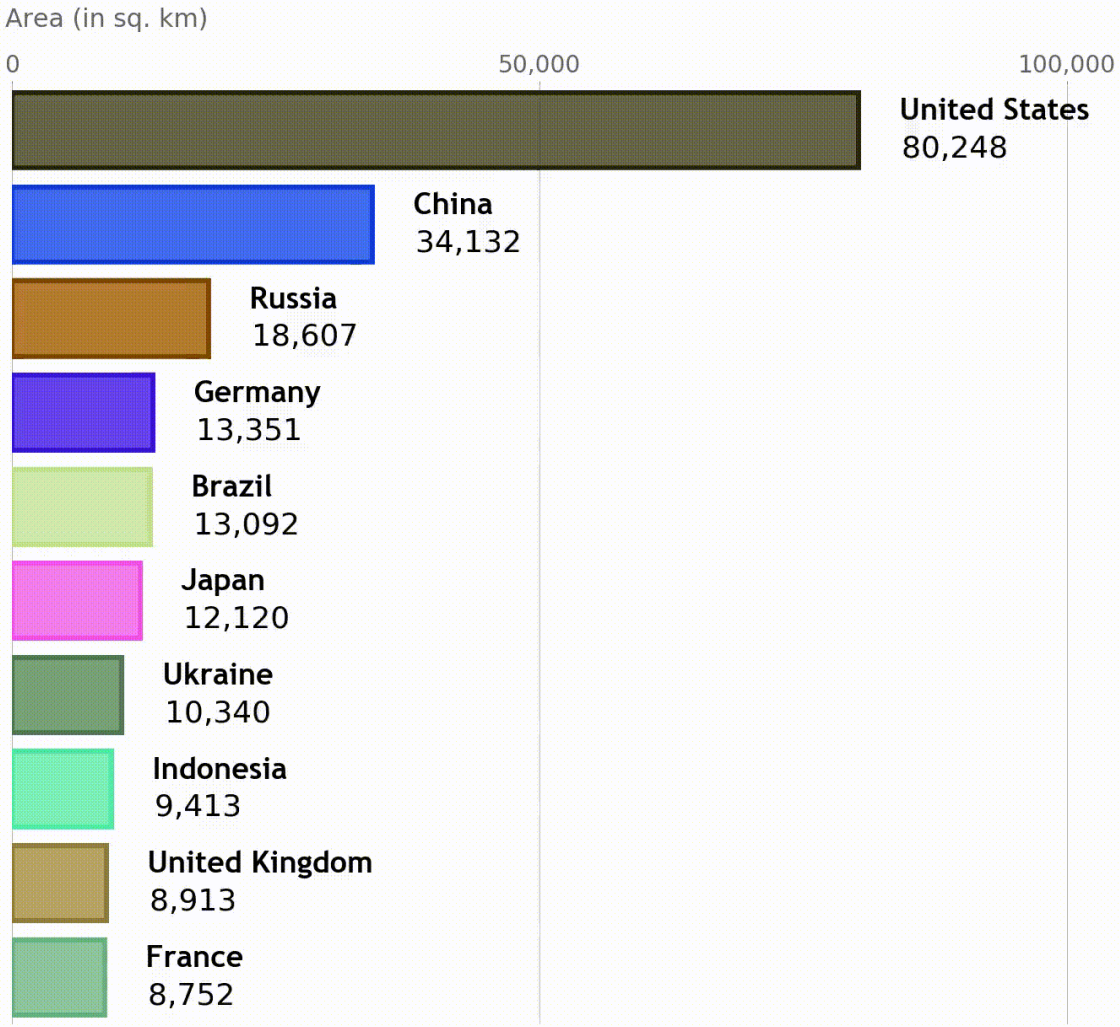
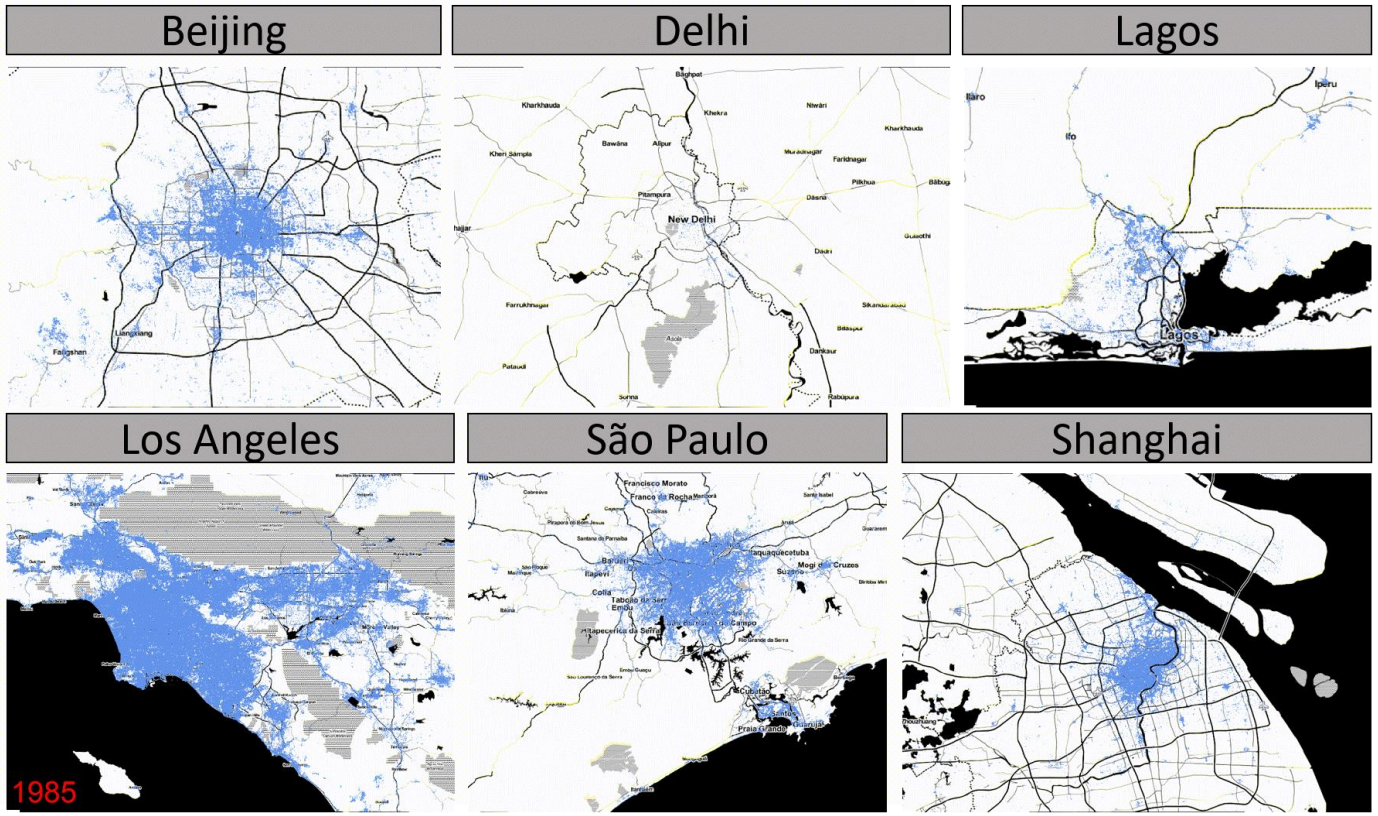
Rapid historical urban expansion

Countries with the highest built-up area

1992



Urban areas have grown tremendously in the last few decades



Urban impacts on weather and climate

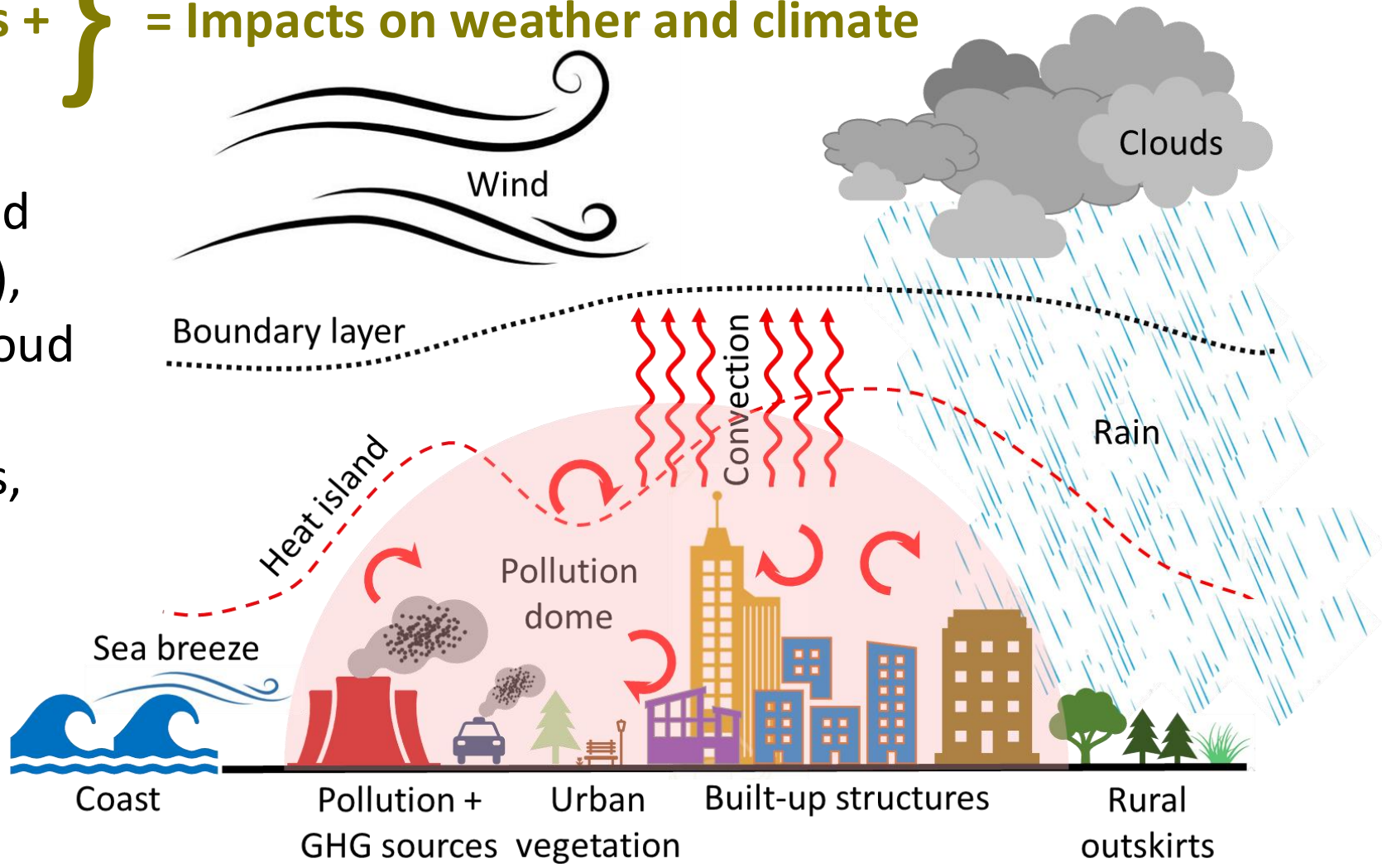
Increase in urban extent +
changes in surface properties +
anthropogenic activities } **= Impacts on weather and climate**

Modified from Qian, Chakraborty *et al.*, 2022

Urban impacts on weather and climate

Increase in urban extent + changes in surface properties + anthropogenic activities } **= Impacts on weather and climate**

- Urbanization causes localized warming (urban heat island), drying (urban dry island), cloud formation and precipitation over and downwind of cities, enhanced air pollution, etc.
- Urban growth and densification may lead to further feedbacks to the atmosphere



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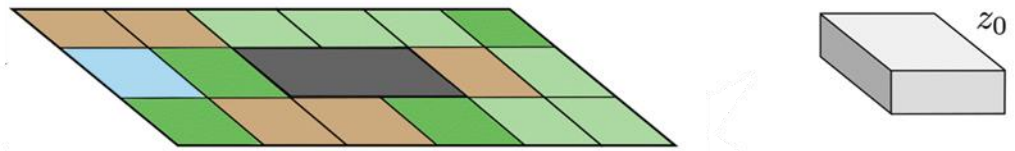
Urban representation in Earth system models

Mostly slabs or no urban

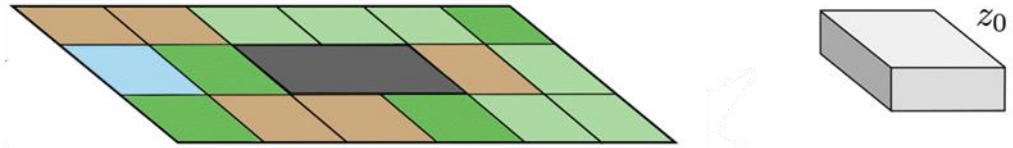


- Urban areas are rarely represented in global models
- We assume that urban land fraction is small and won't impact broader climate
- The few global models with urban representation are too simple

Hertwig *et al.*, 2020

Urban representation in E3SM

Mostly slabs or no urban



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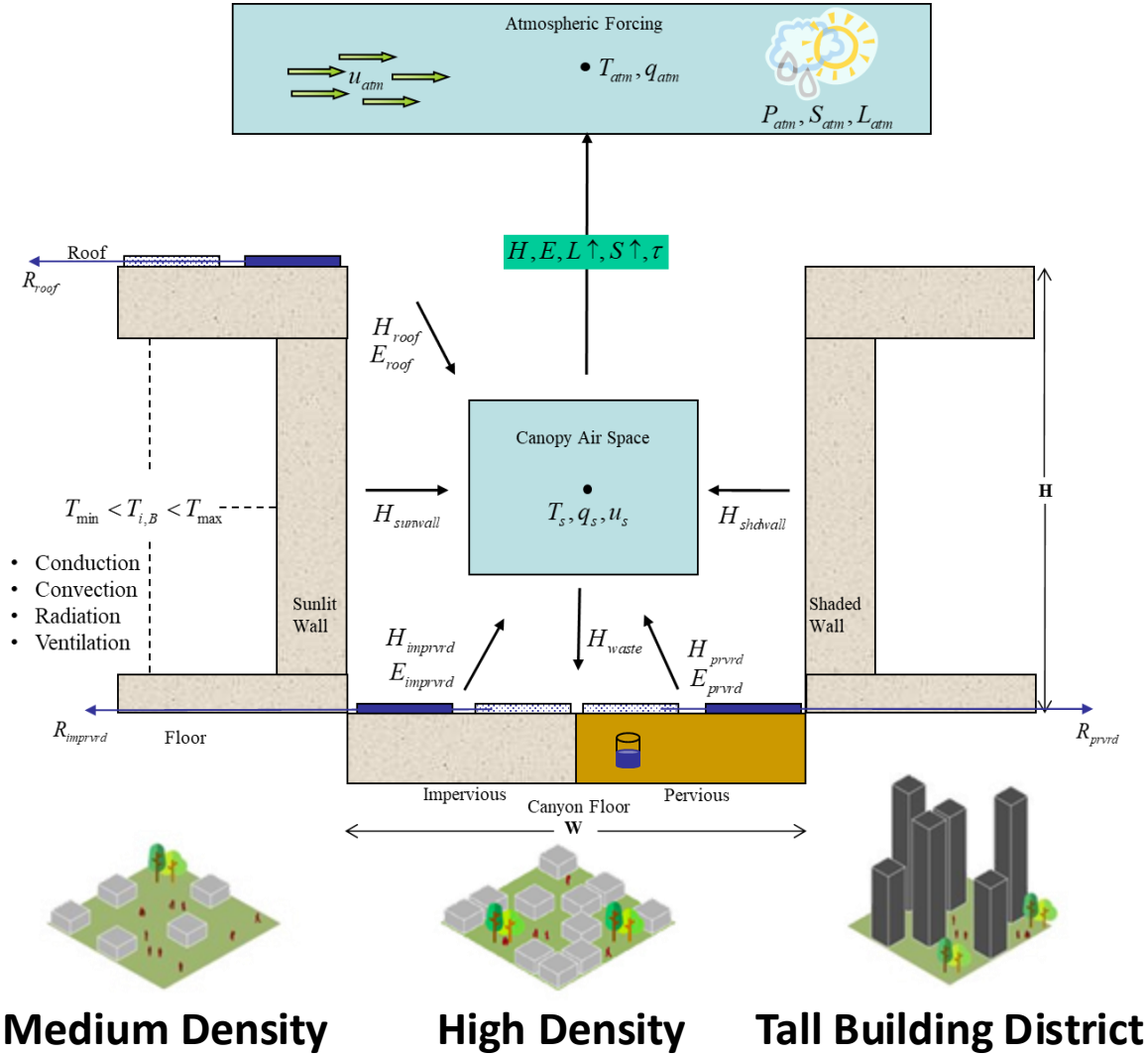
E3SM: DOE's Energy Exascale Earth System Model

Urban canopy structure in E3SM

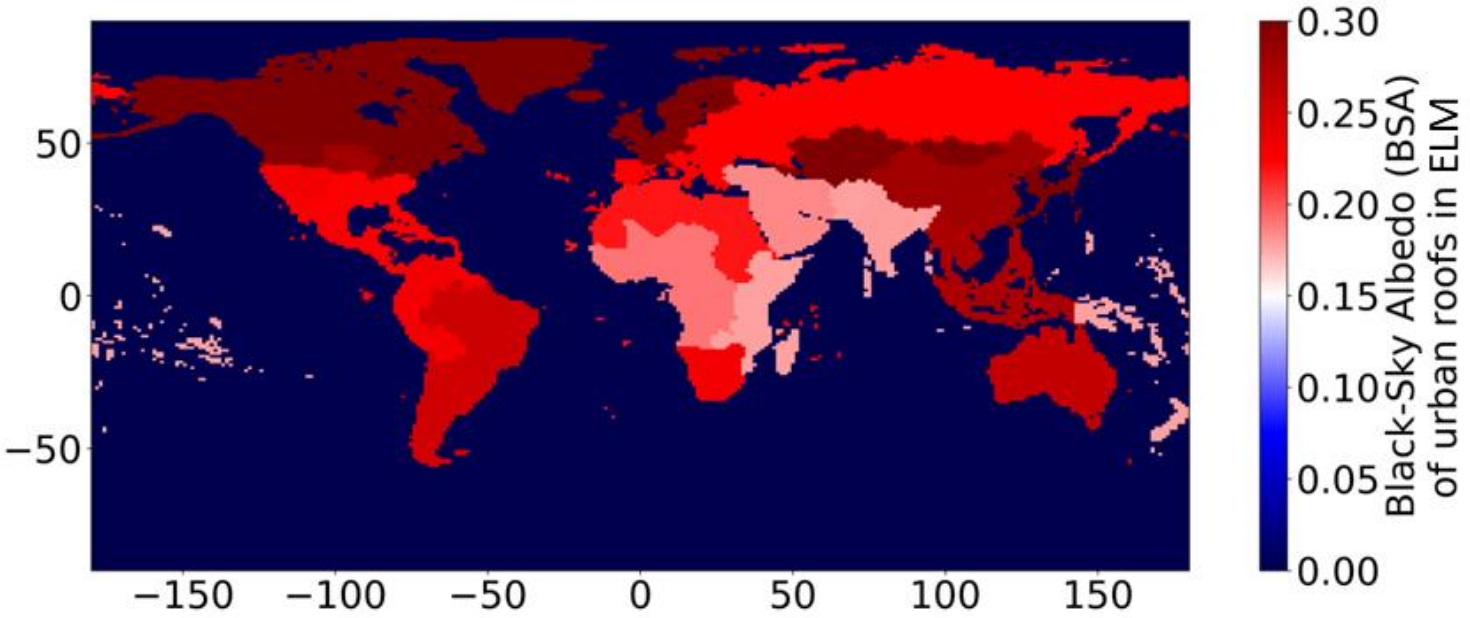


Medium Density **High Density** **Tall Building District**

Hertwig *et al.*, 2020

Modified from Ching *et al.*, 2014

Poor surface constraints for urban areas



- In E3SM, the world is divided into 33 regions, each with unique values for urban radiative, thermal, and morphological parameters

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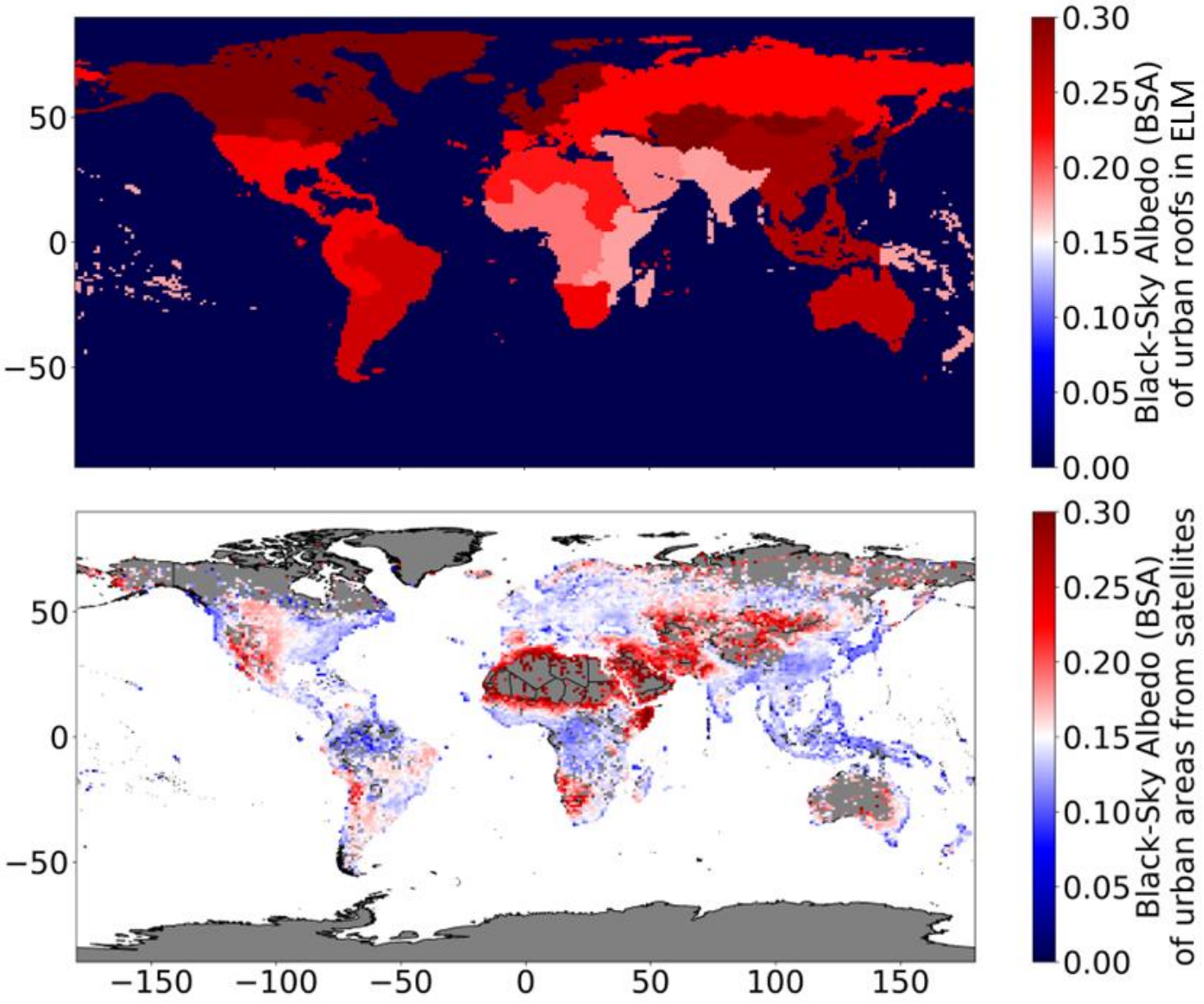
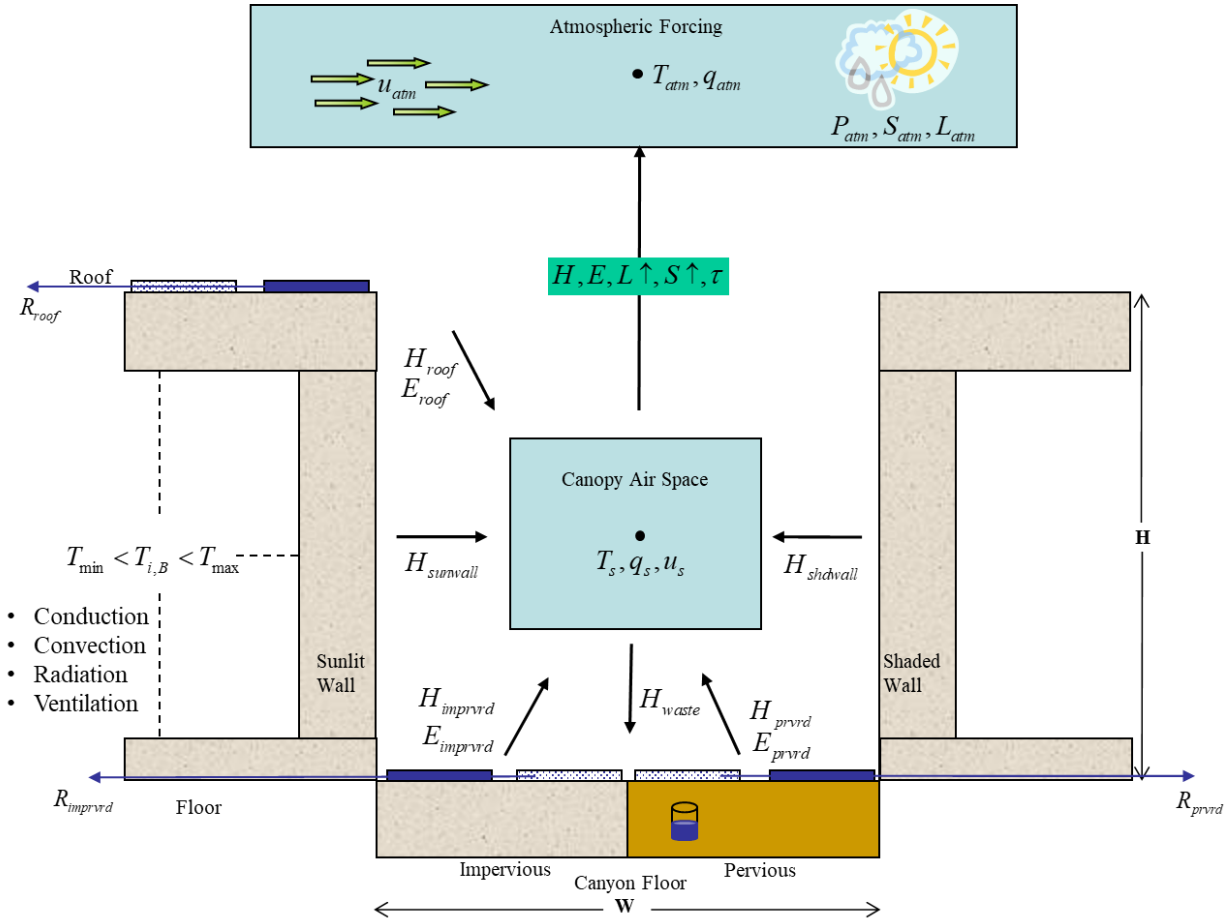


- In E3SM, the world is divided into 33 regions, each with unique values for urban radiative, thermal, and morphological parameters
- Actual variability, as seen from satellites, is much higher than what is represented in the model.
- Would strongly impact simulations of cross-sample variability in urban climate

No vegetation within urban areas

Urban canopy structure in E3SM



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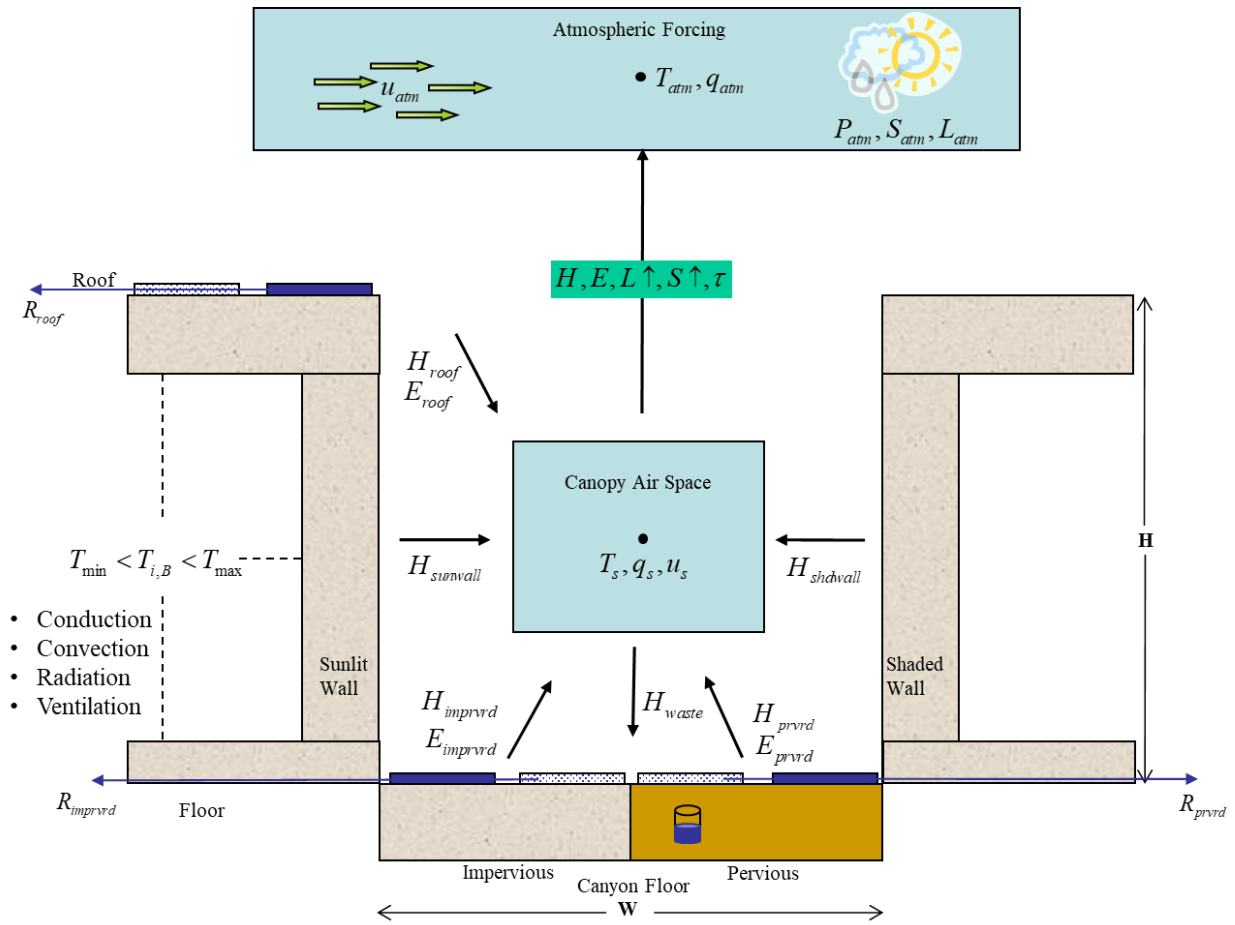
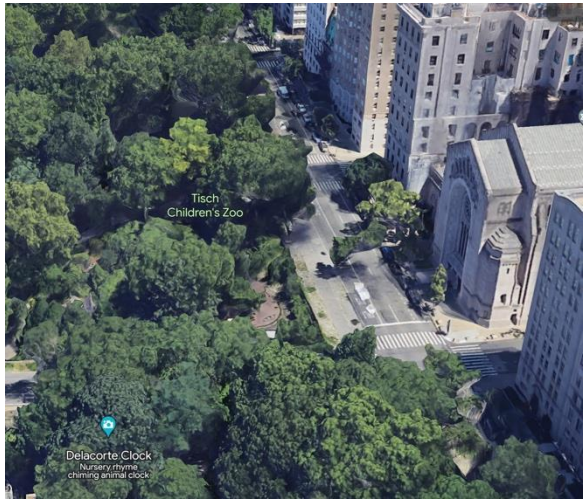
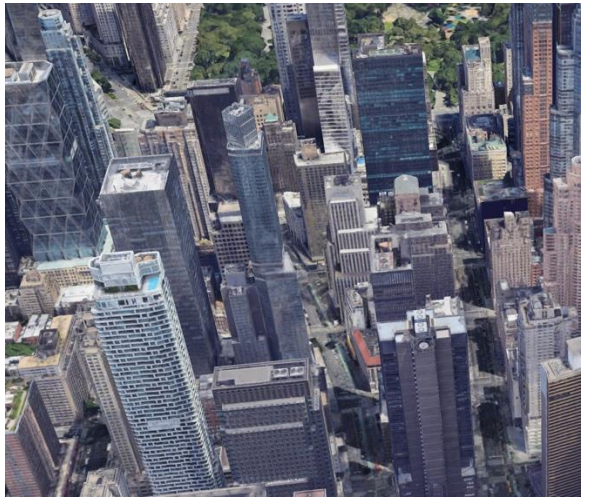
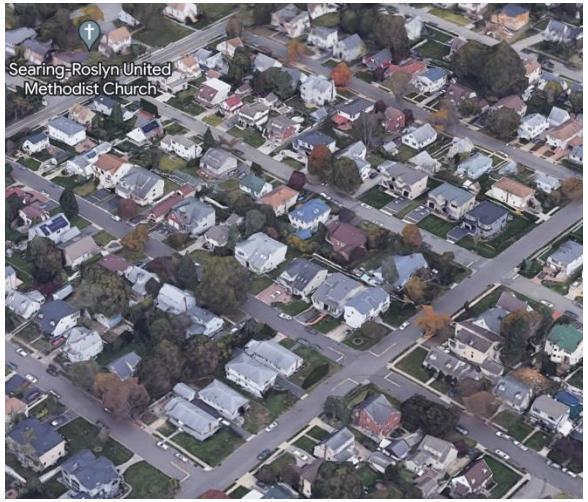


Real cities?







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Source: Google

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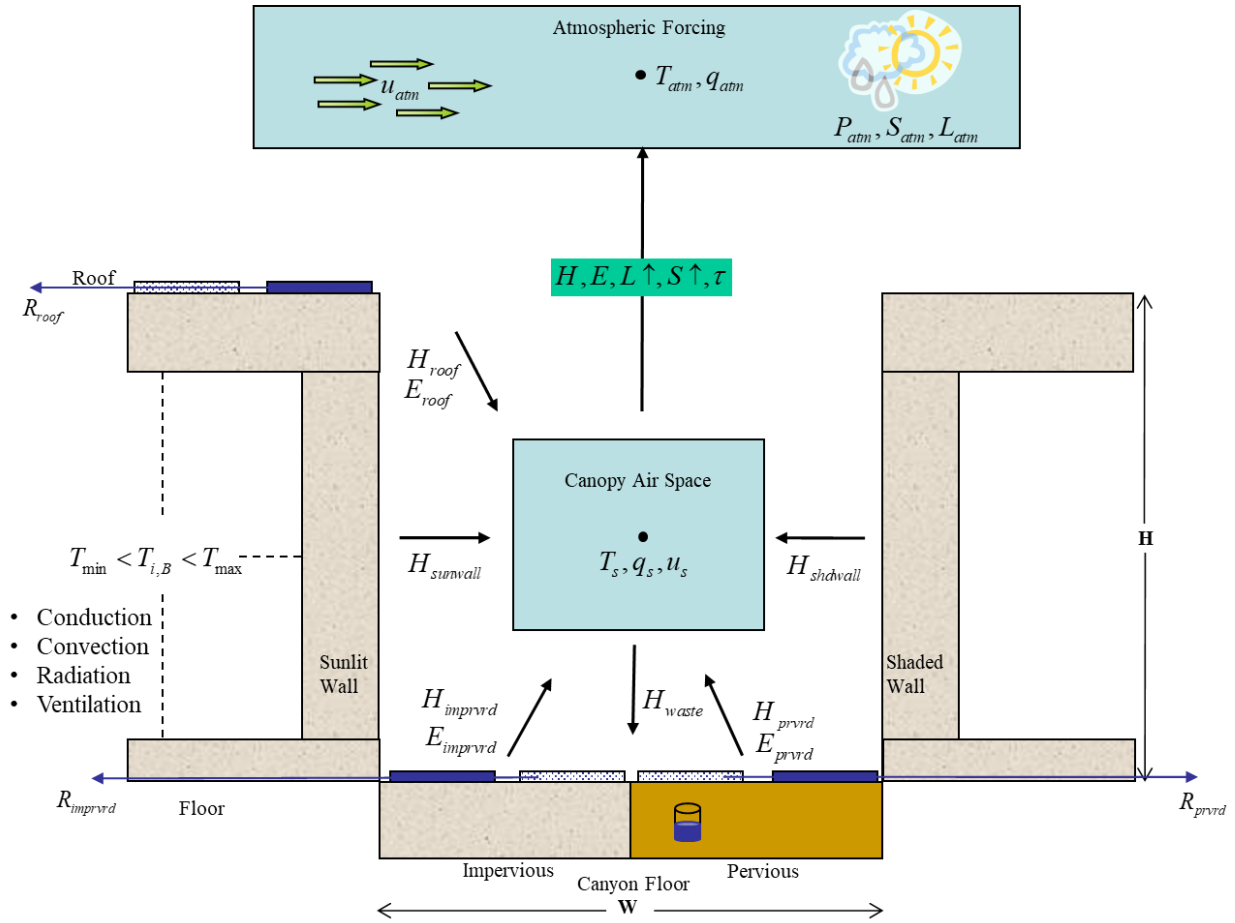


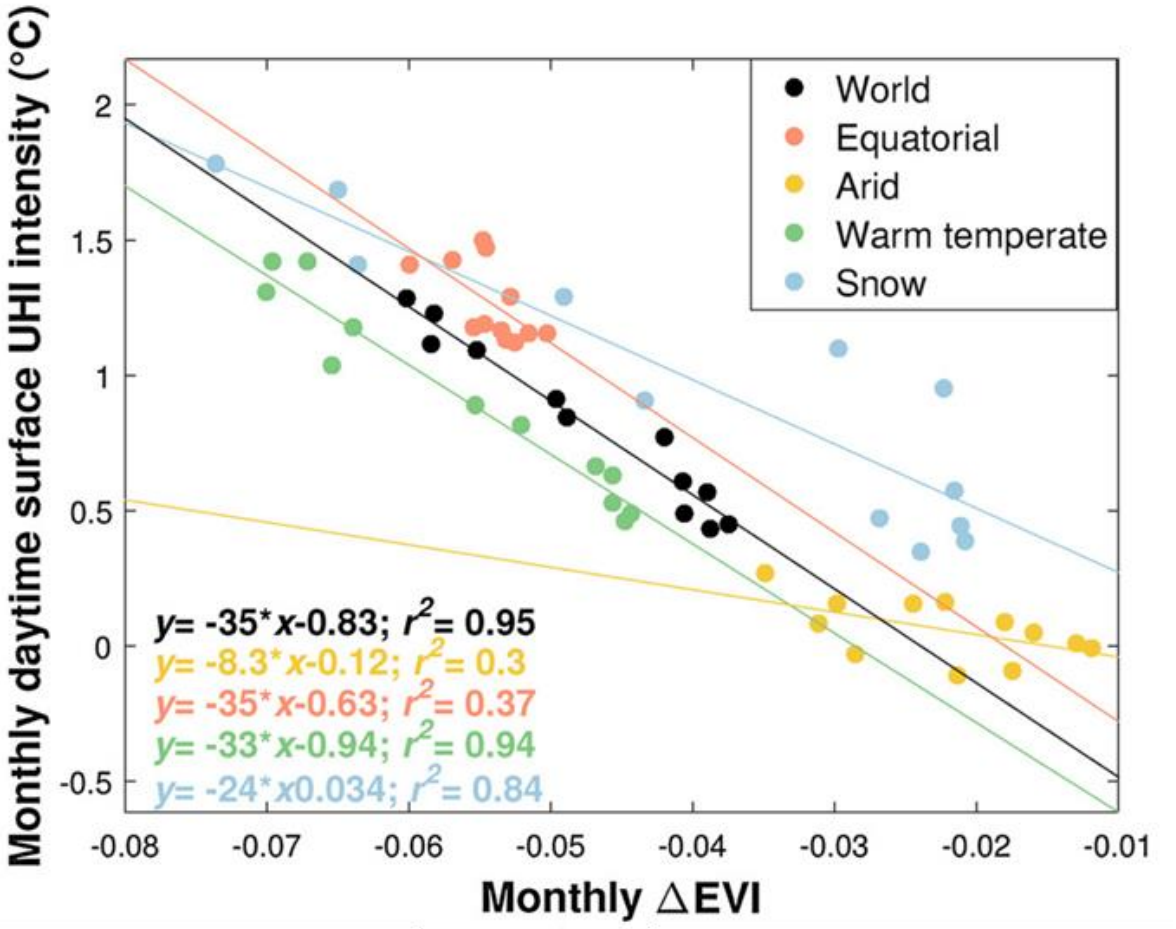
Real cities?

Modified from *Ching et al.*, 2014

Source: My Instagram

Importance of urban vegetation

- Urban vegetation modifies weather and climate
- Urban and rural vegetation are not identical, both in amount and properties



Chakraborty and Lee, 2019

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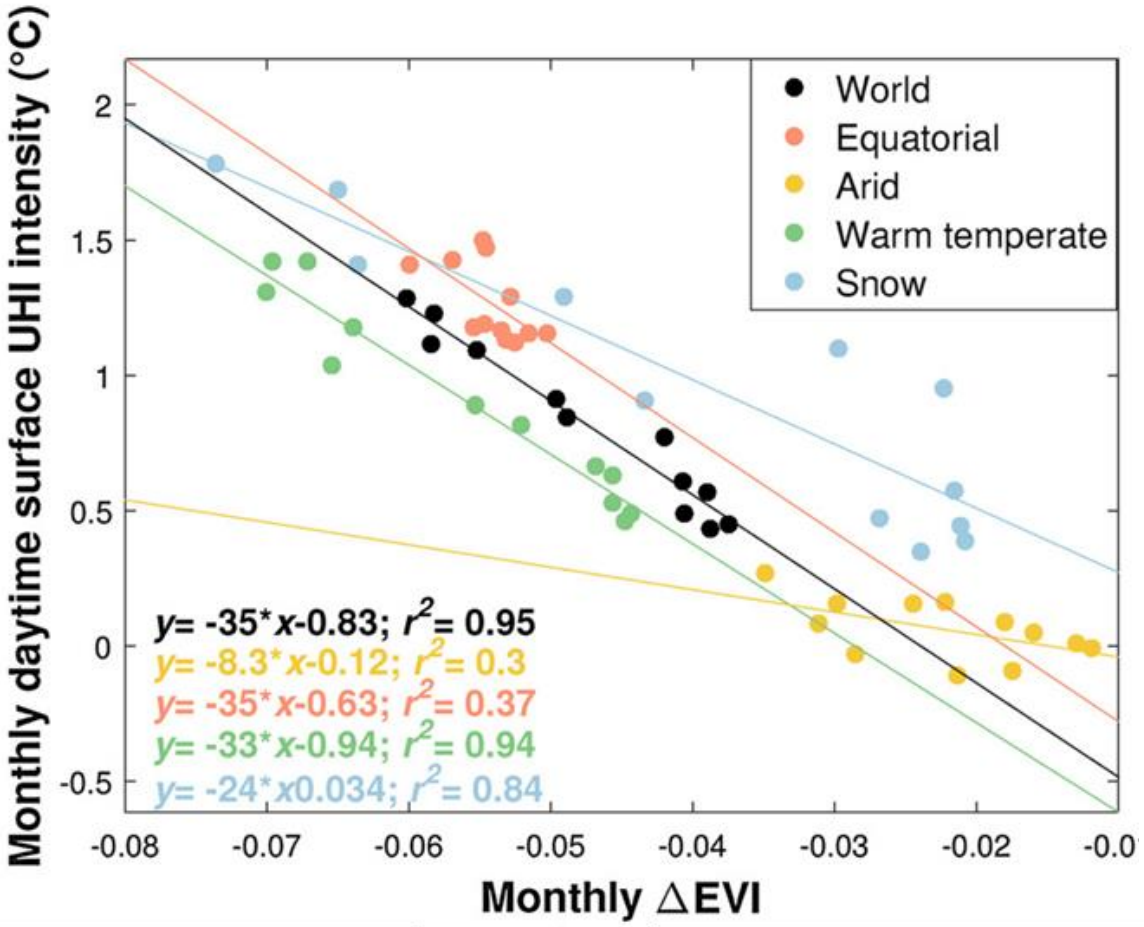
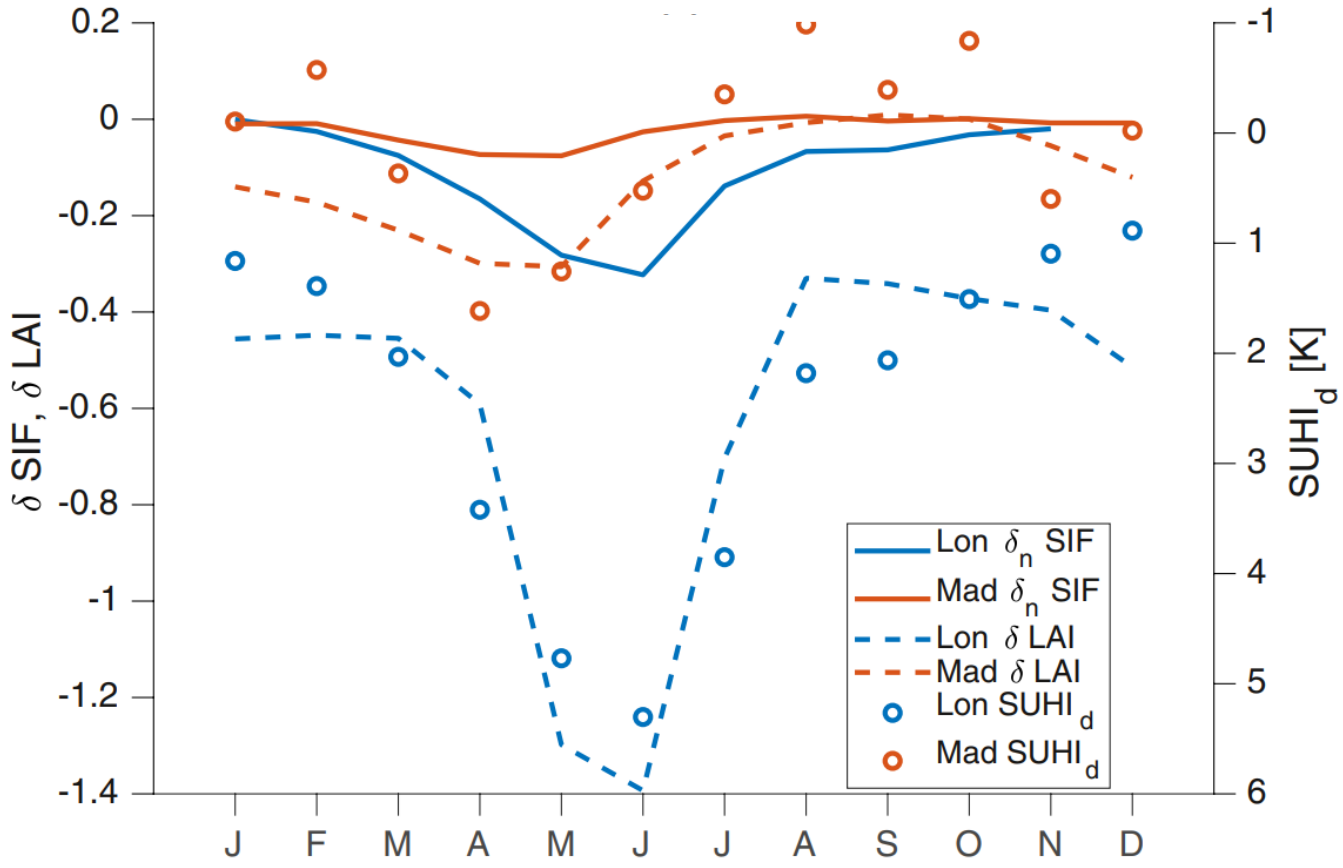
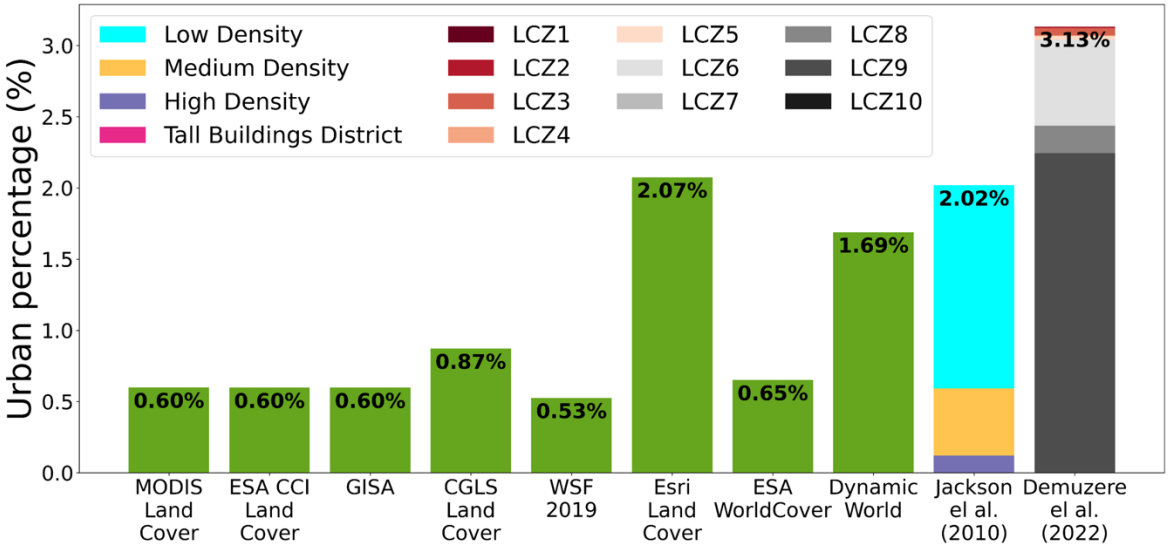




Chakraborty and Lee, 2019

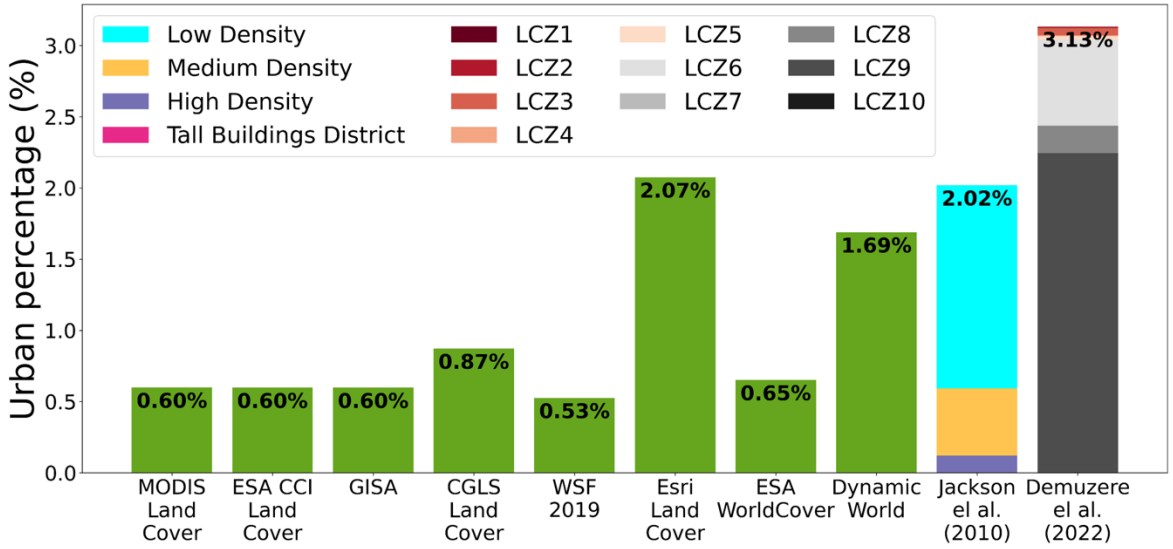
Paschalis *et al.*, 2021

Static urban representation in E3SM



- Current urban extent in E3SM Land Model (ELM) is based on a circa 2001 dataset
- Uses population-based urban definitions
- Low density class data are not used
- Static for historical and future simulations

Static urban representation in E3SM



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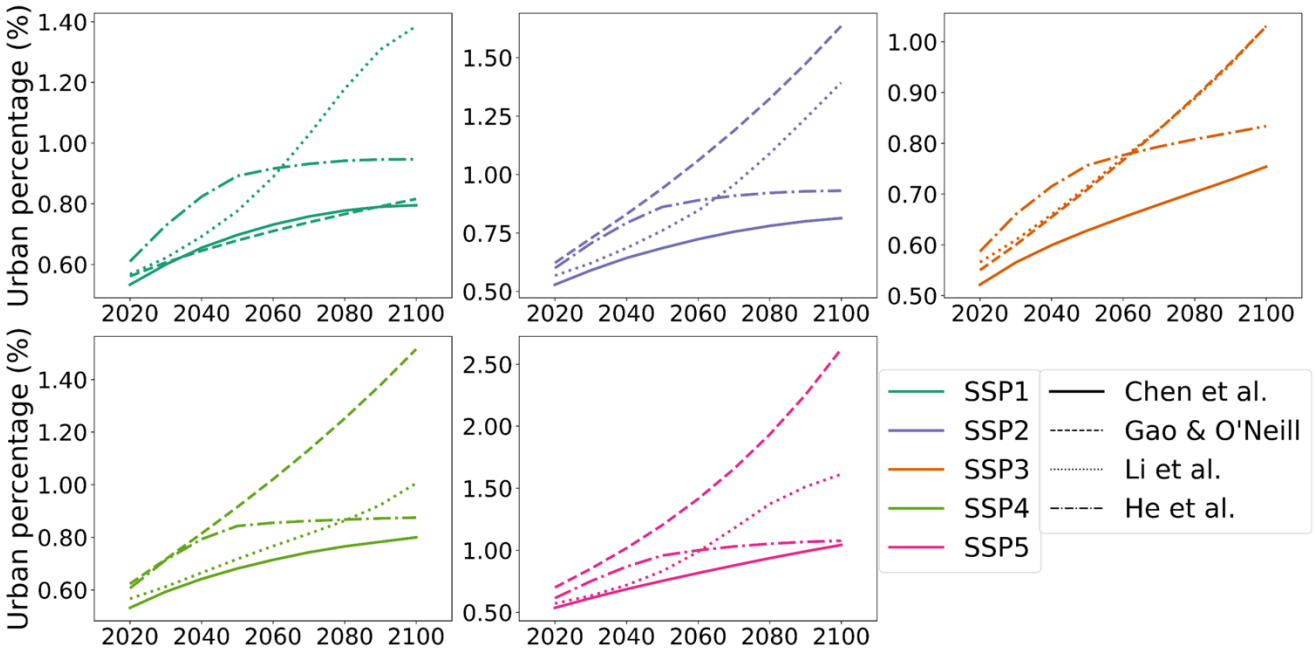
- Significant future urban expansion
- Large uncertainties across datasets



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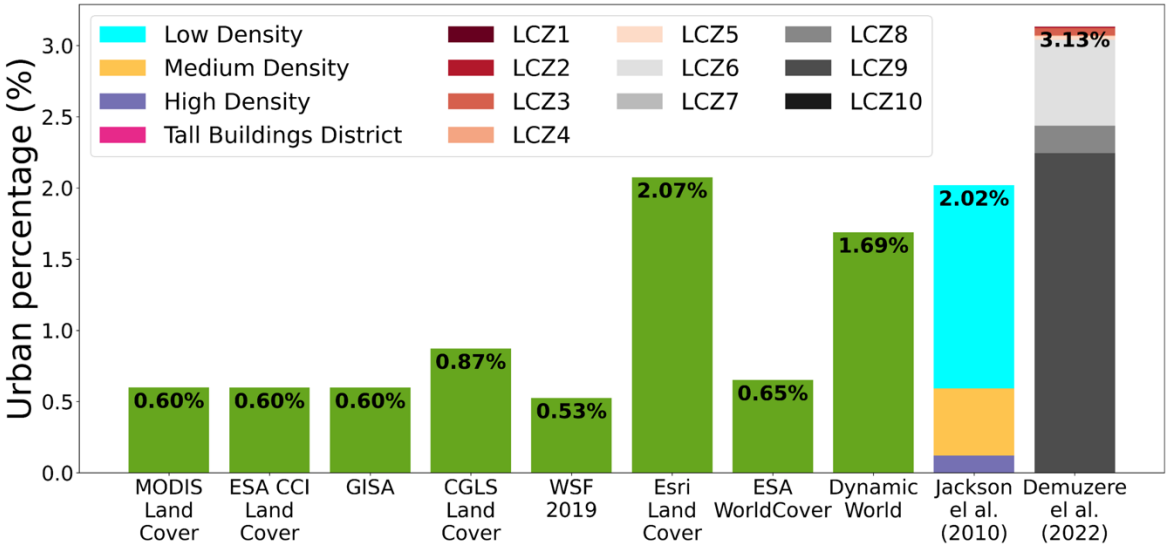

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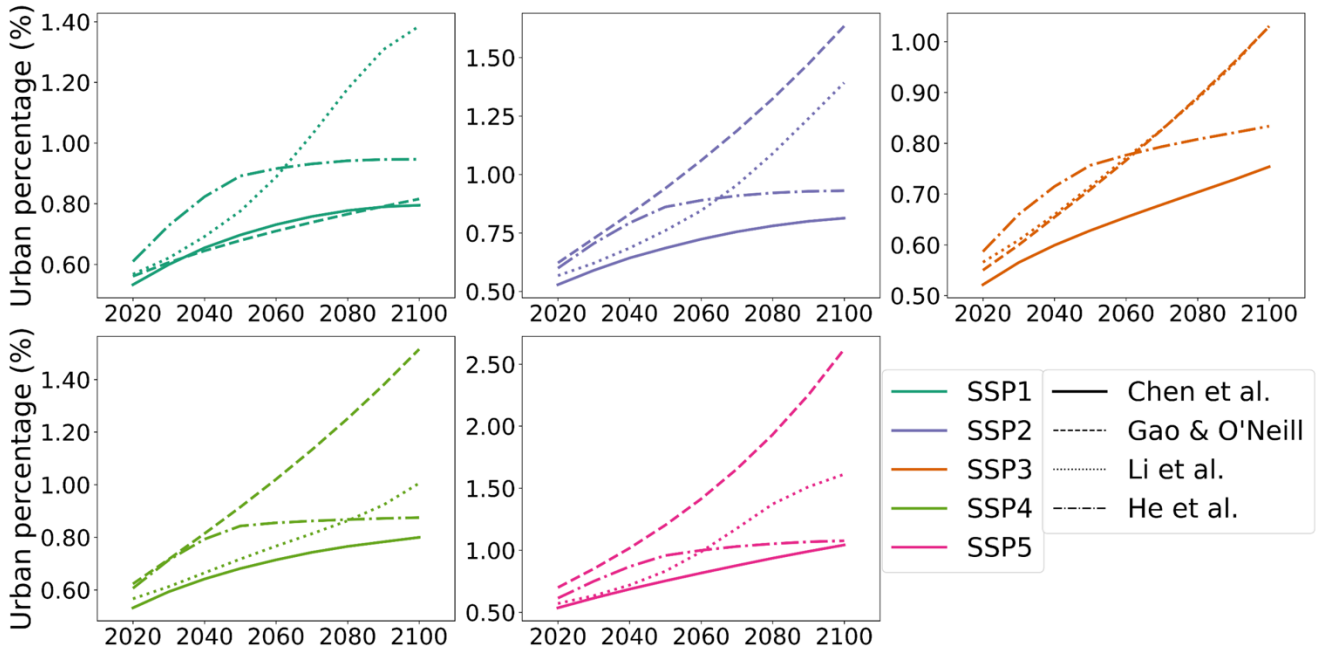
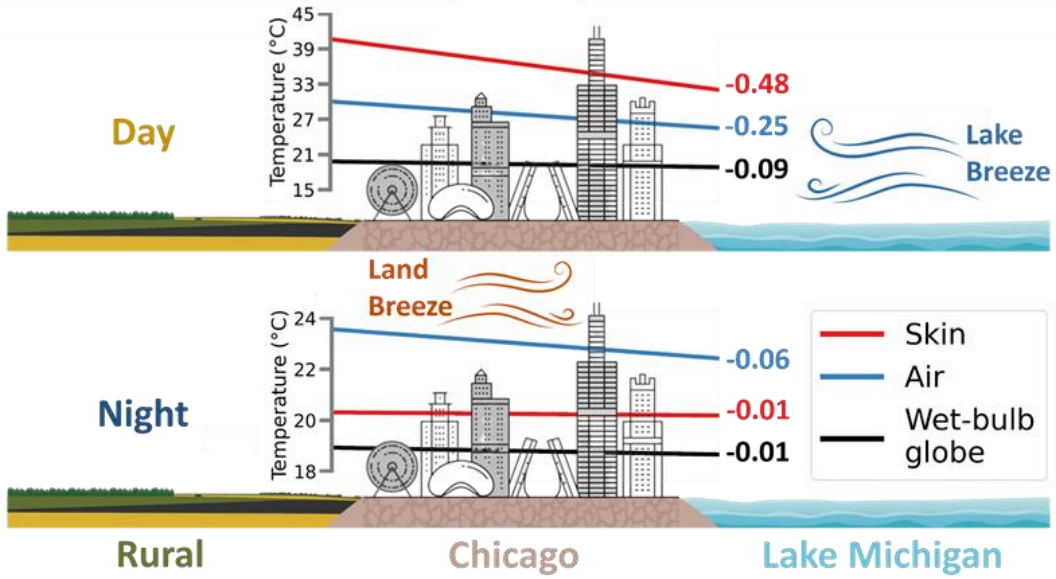
- Significant future urban expansion
- Large uncertainties across datasets
- Urban properties will also change

Urban Evolution = Urban expansion + change in urban properties over time



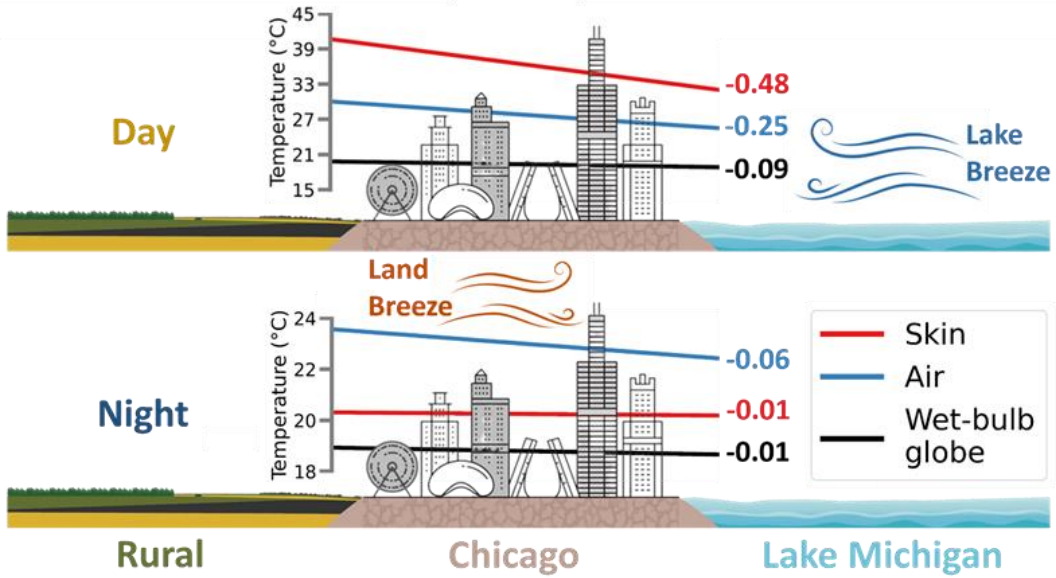
Resolving coastal processes?



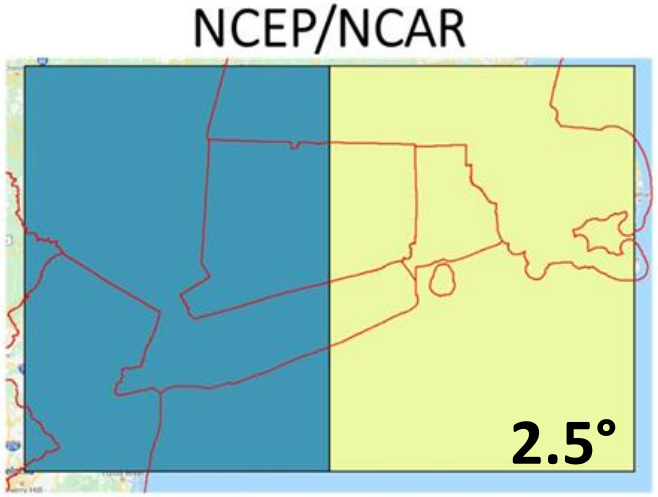
- Majority of global urban population lives in coastal cities
- Urban-coastal interactions are complex
- Large spatial gradients expected along coastlines, as well as hard-to-simulate extreme weather phenomena

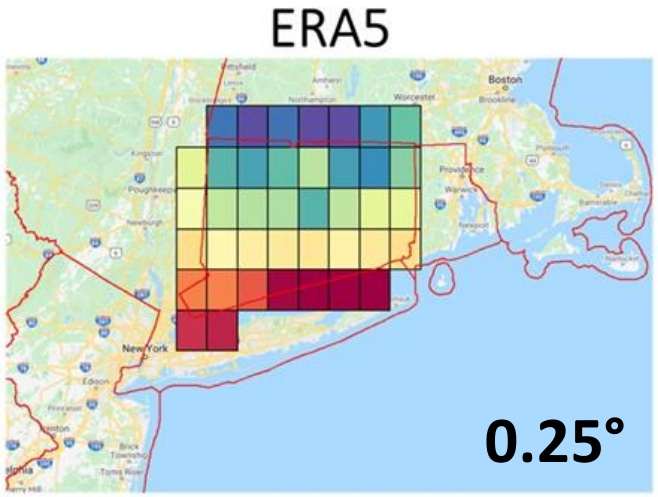
Chakraborty *et al.*, 2023

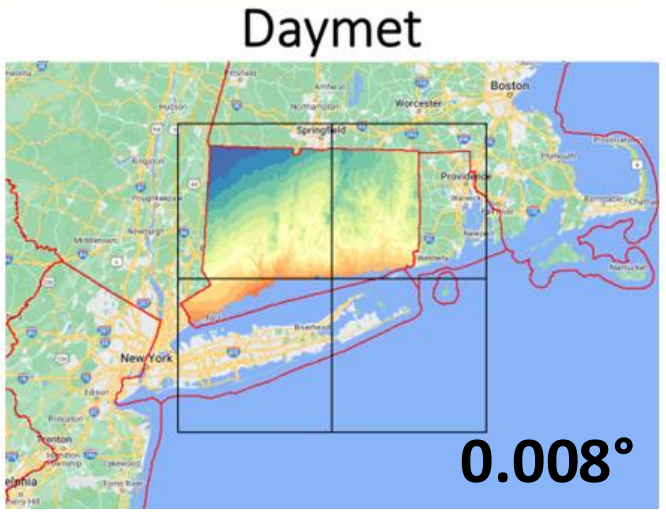
Resolving coastal processes?

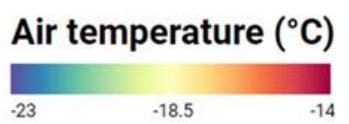


- E3SM is regularly run at too coarse a resolution to adequately resolve land-to-water gradients
- For coastal cities, spatial variability of surface properties not represented
- Model does not care where urban area is within grid









Notes:
Minimum 2m air temperature on January 1st, 2018

Mean air temperature for Connecticut:
NCEP/NCAR = -21.1 °C
ERA5 = -19.1 °C
Daymet = -19.5 °C

Chakraborty *et al.*, 2023

BACKGROUND

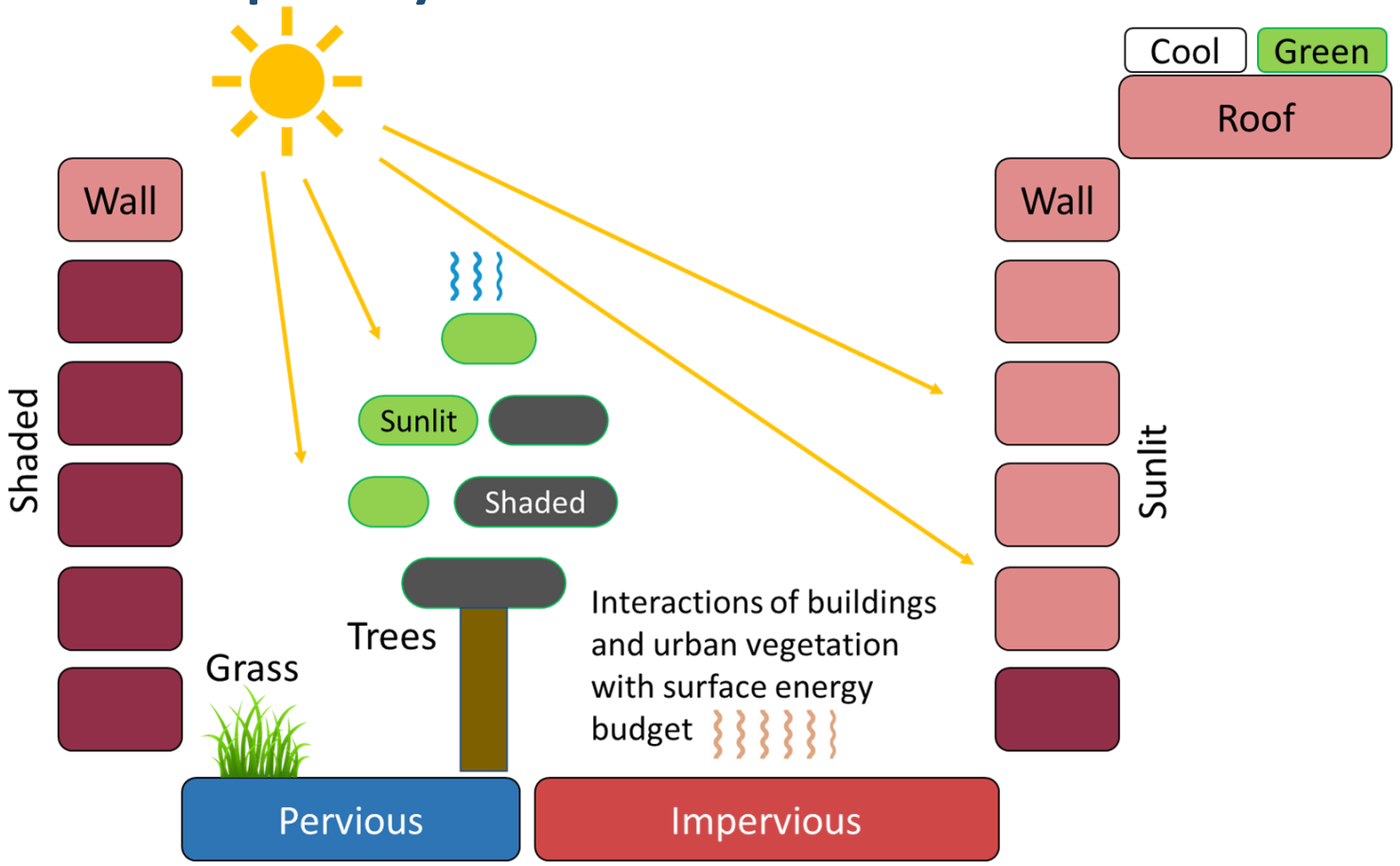
MOTIVATION

RESEARCH PLANS

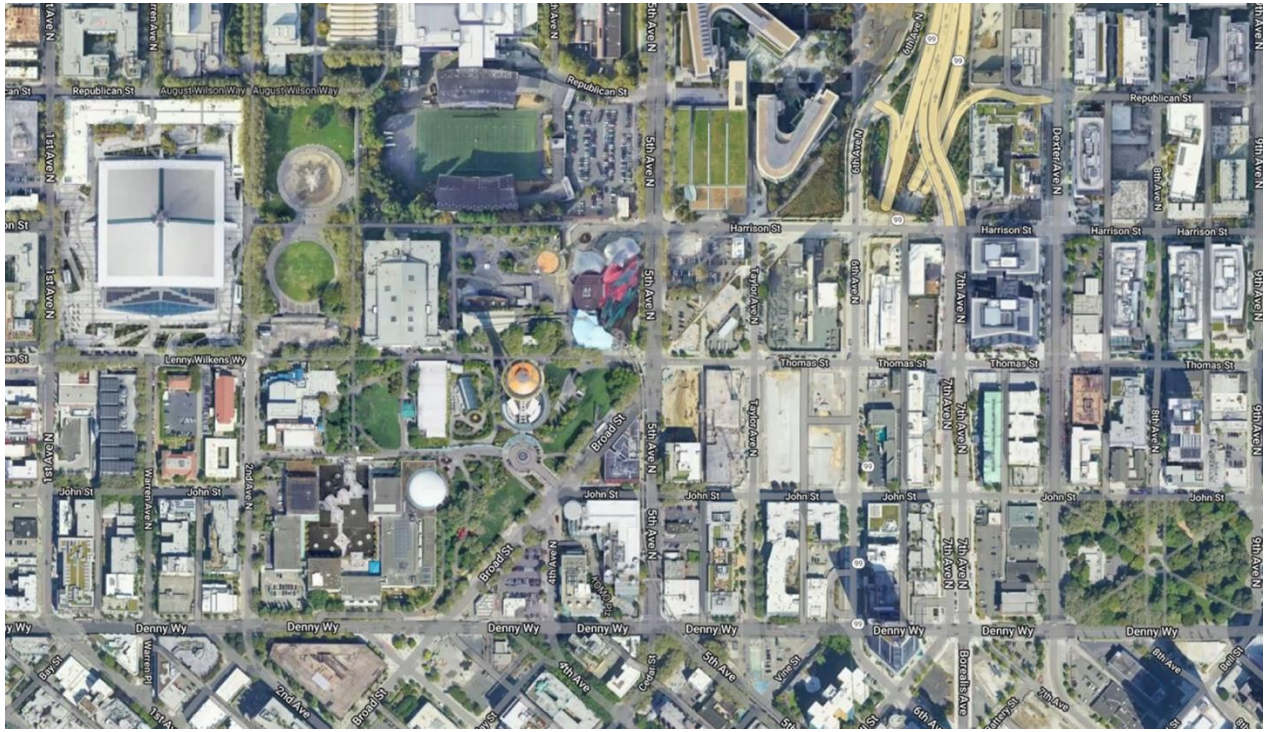
New urban parameterization for E3SM

Objective 1: Develop a new urban parameterization for E3SM

- **Explicitly representing urban vegetation and its interactions with climate**
- **Global spatially continuous urban surface dataset**

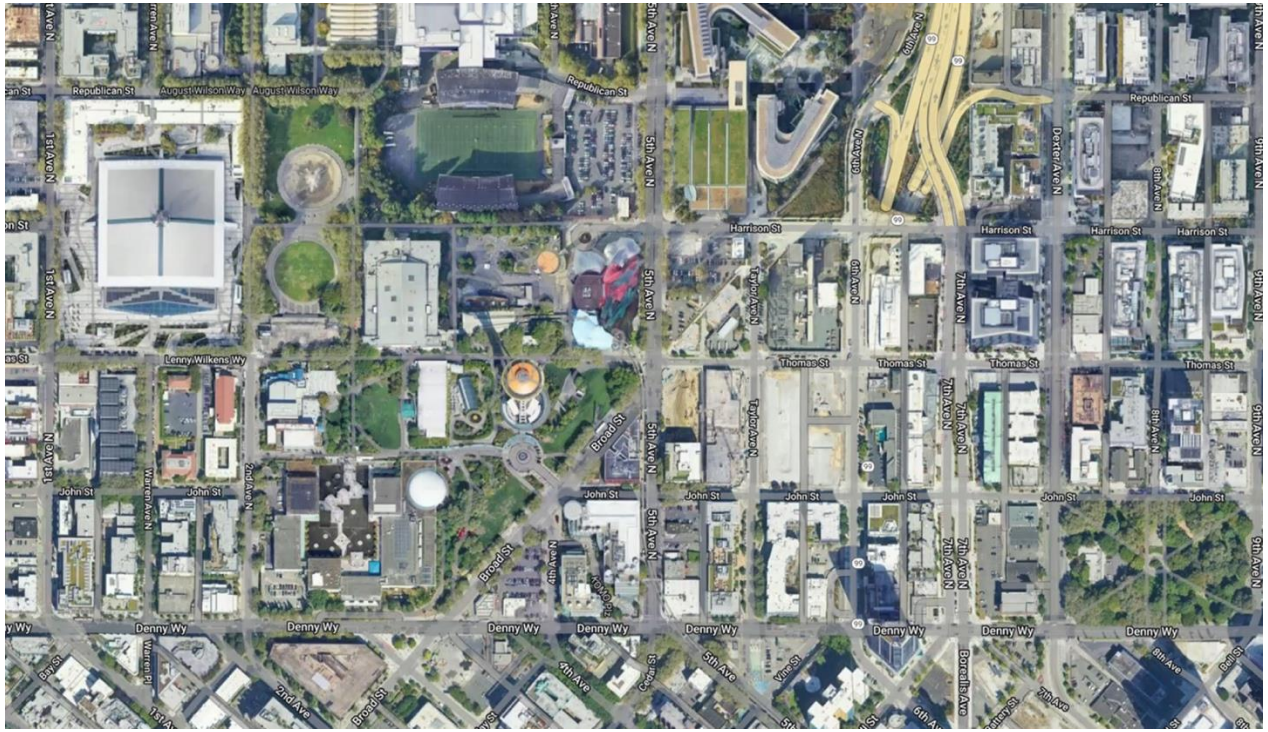


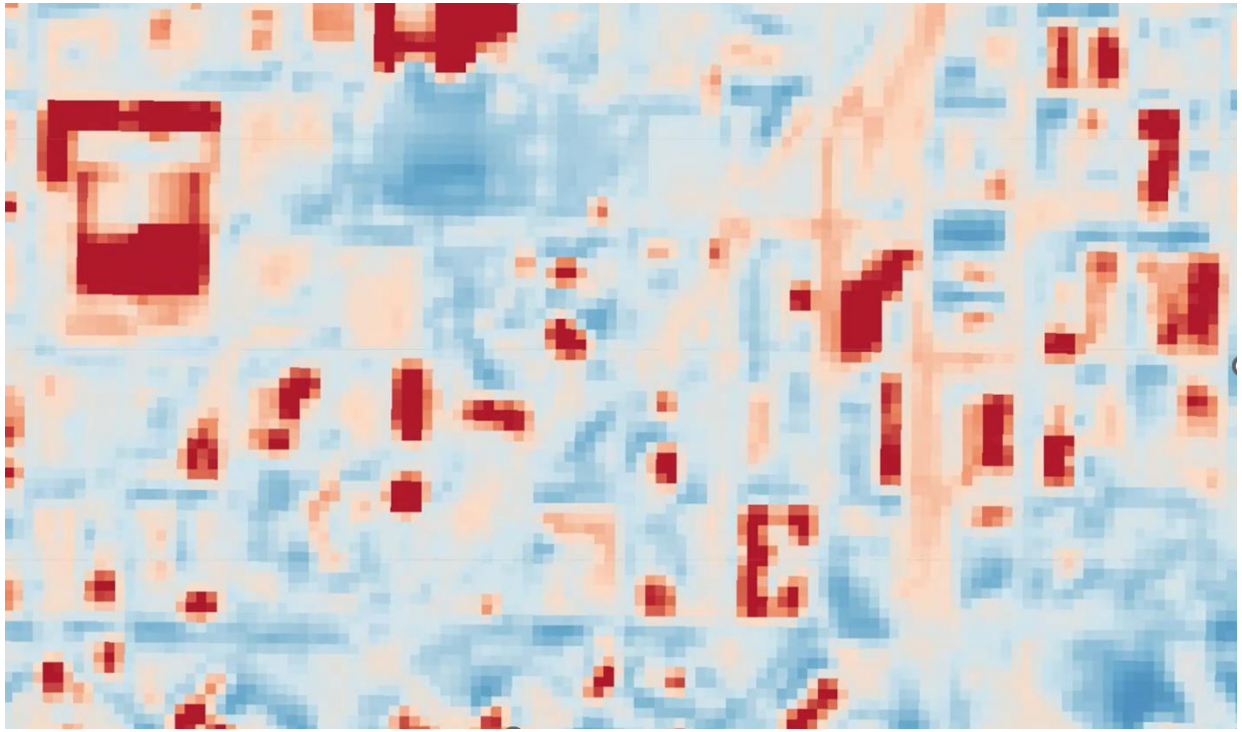
Generating a global 1 km urban dataset



- Leverage and develop high resolution satellite-derived global products

Generating a global 1 km urban dataset





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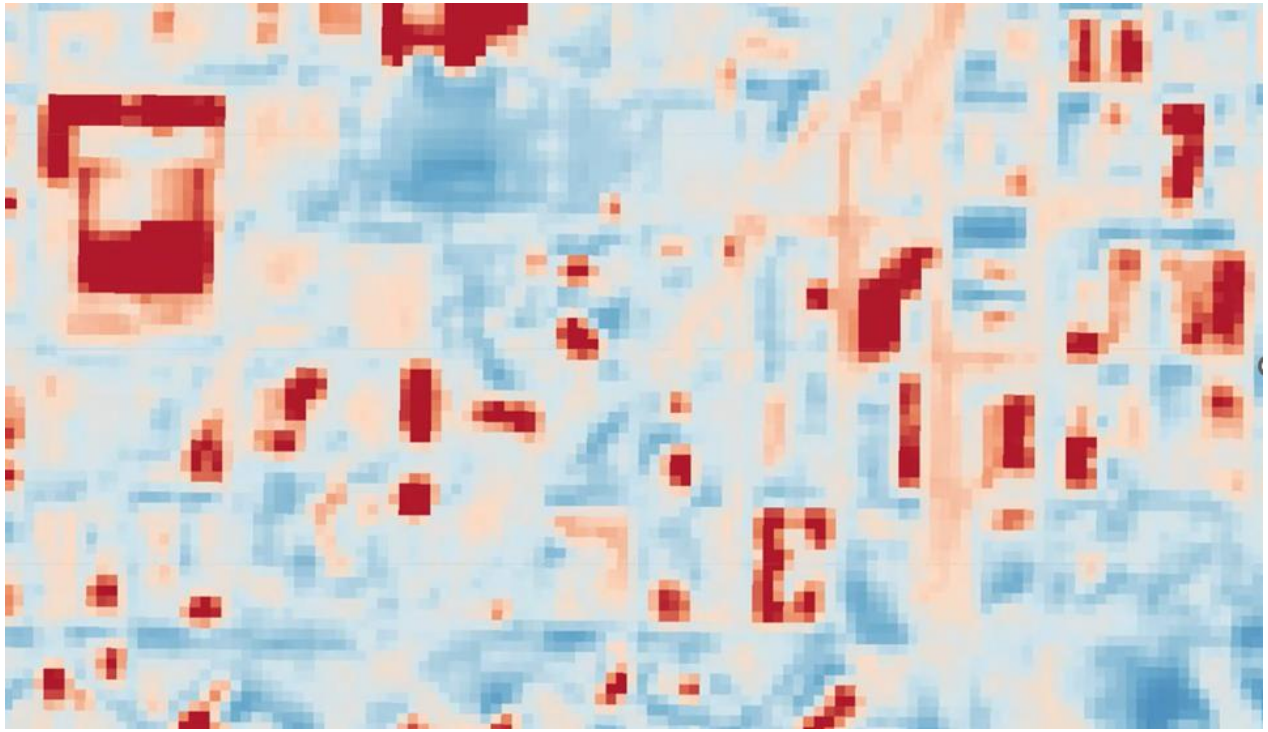

- Leverage and develop high resolution satellite-derived global products
- Combine products with building and road datasets
- Extract roof, wall, and road parameters for all 1 km urban pixel in the world

Wu *et al.*, *In Prep*

Source: Microsoft

Some initial results

E3SM urban surface constraints

Radiative	Roof | Impervious Road | Pervious Road | Wall Emissivity
	Roof | Impervious Road | Pervious Road | Wall Albedo
Morphological	Roof Height
	Canyon Height-to-width Ratio
	Roof Fraction | Pervious Road Fraction
	Urban Percentage
Thermal	Numbers of impervious road layers
	Roof | Wall Thickness
	Minimum | Maximum Interior Building Temperature
	Roof | Impervious Road | Wall Thermal Conductivity
	Roof | Impervious Road | Wall Volumetric Heat Capacity

Cheng *et al., In Prep*

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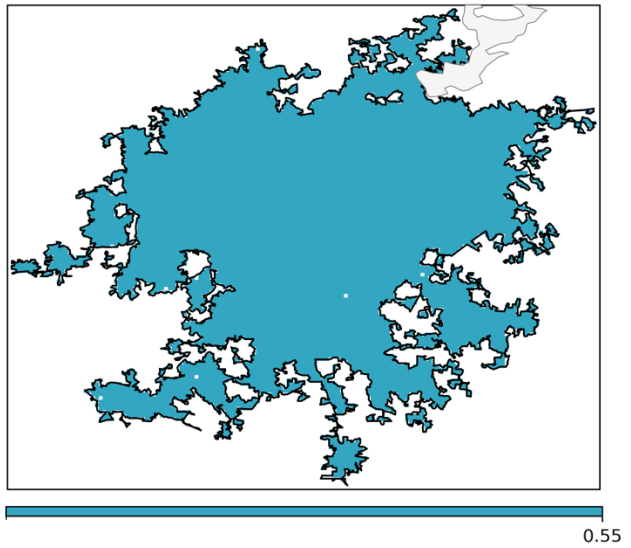
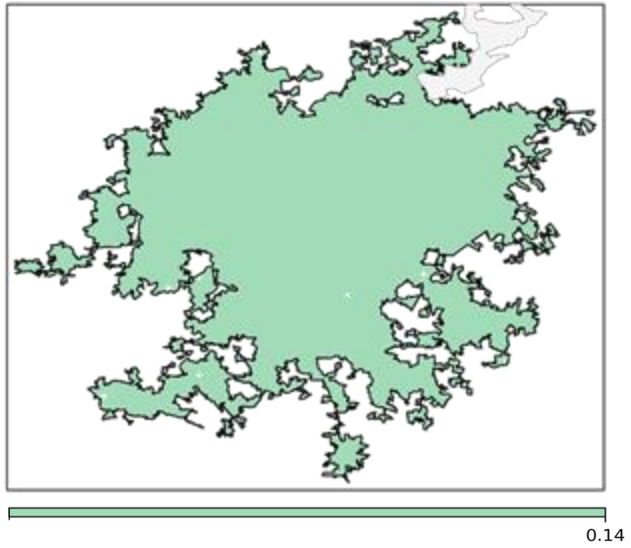
Default roof fraction



Default roof albedo



Cheng *et al., In Prep*

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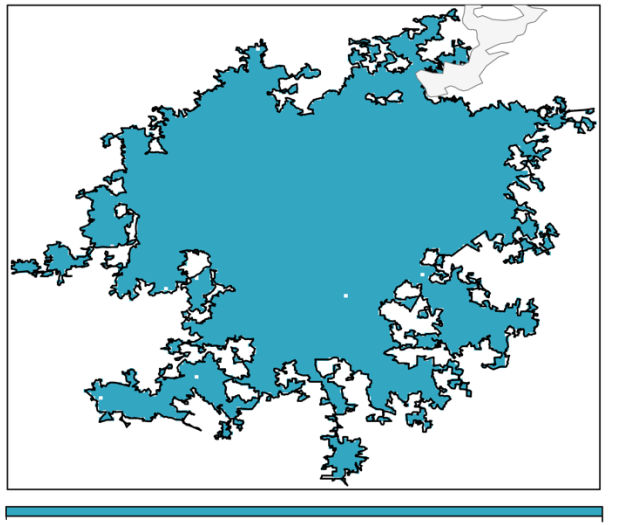

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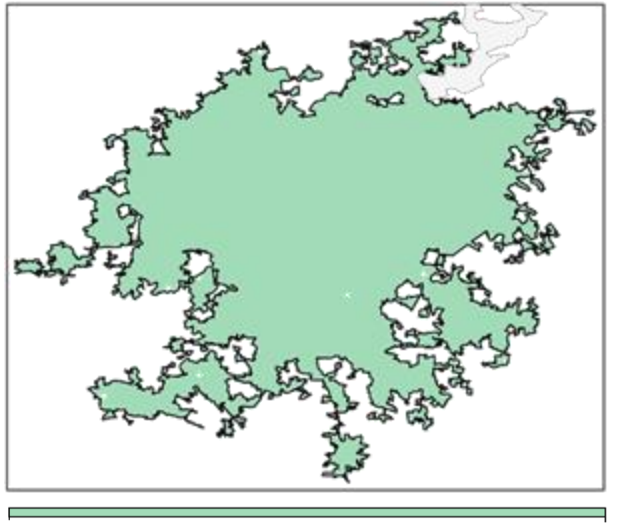
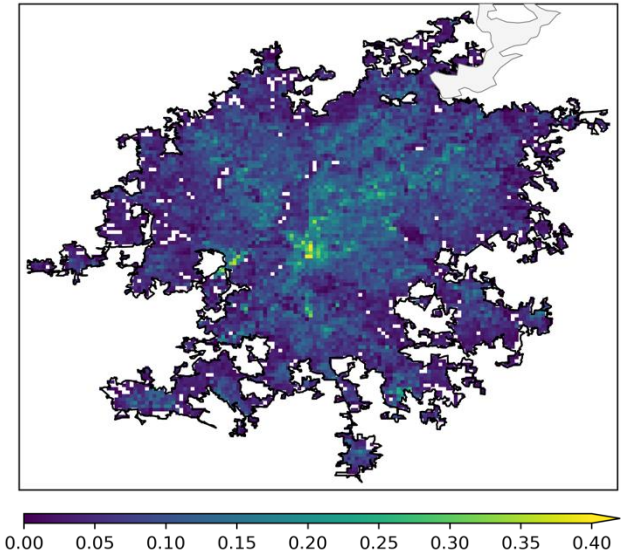
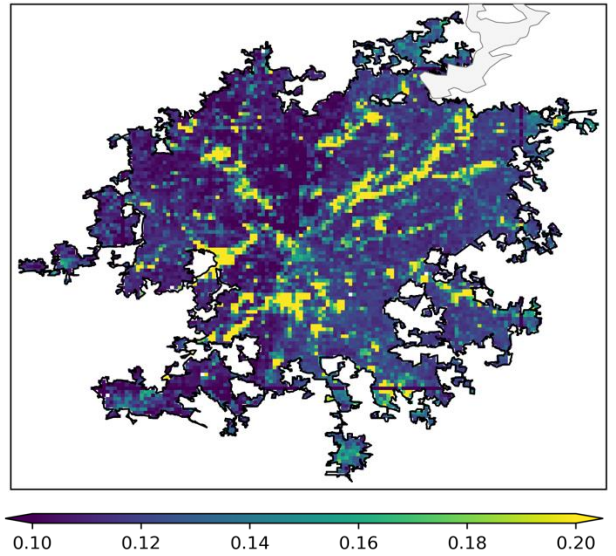


Updated roof fraction



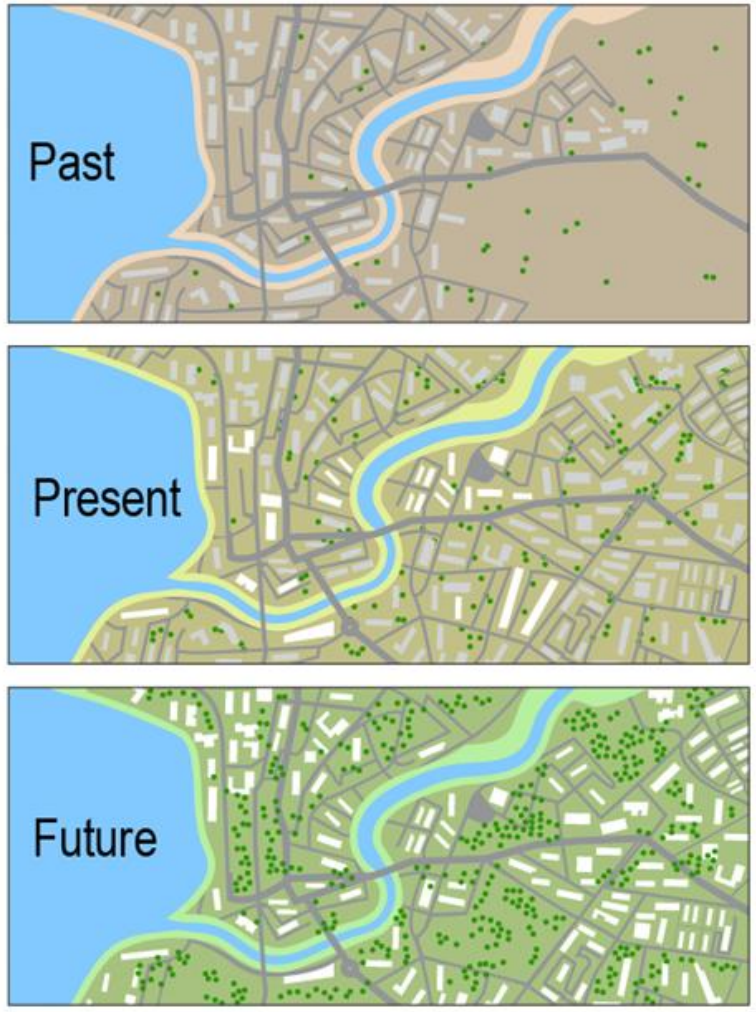
Updated roof albedo



Cheng *et al., In Prep*

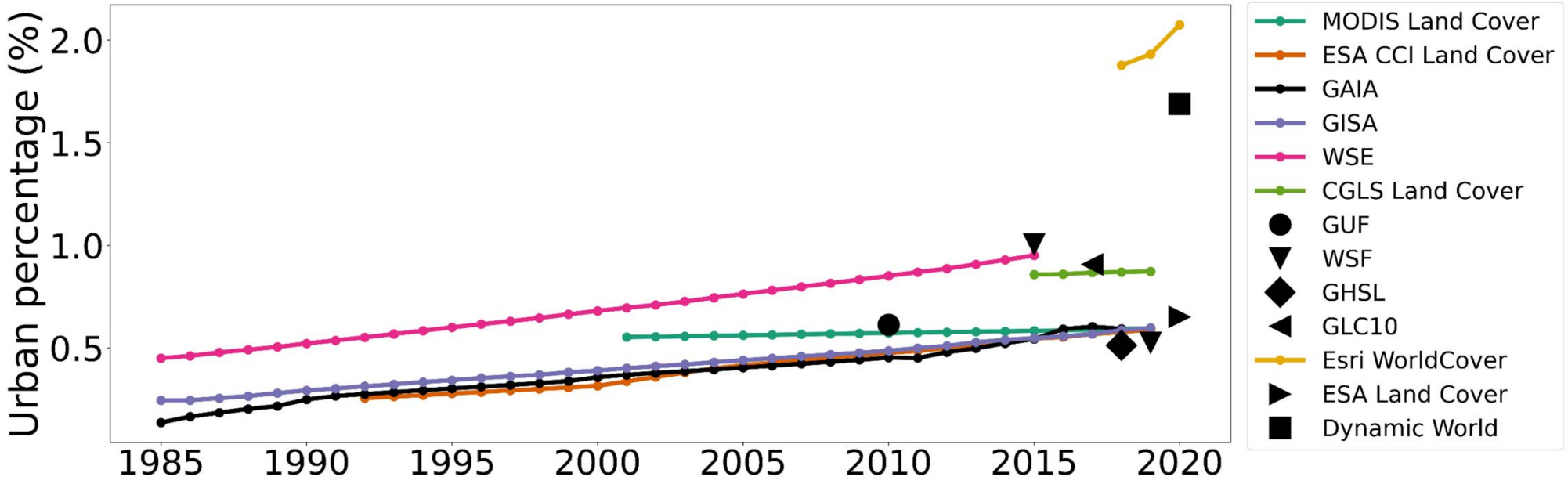
Examining urban evolution and its impacts

Objective 2: Isolate the role of urban evolution on surface climate from continental to coastal scales



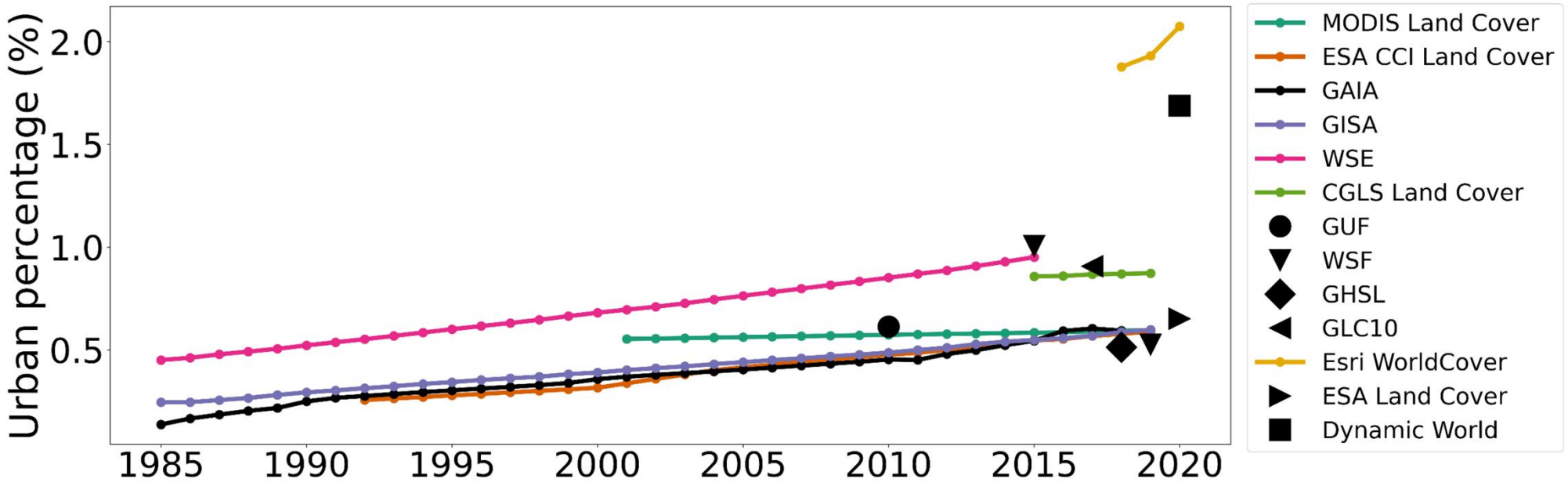
- Generate spatiotemporally varying estimates of urban evolution
- Develop high resolution forcing over coastal areas across scenarios (historical to future climate projections)
- Land only simulations to examine urban impacts on surface climate across scales

Developing temporally varying urban parameters

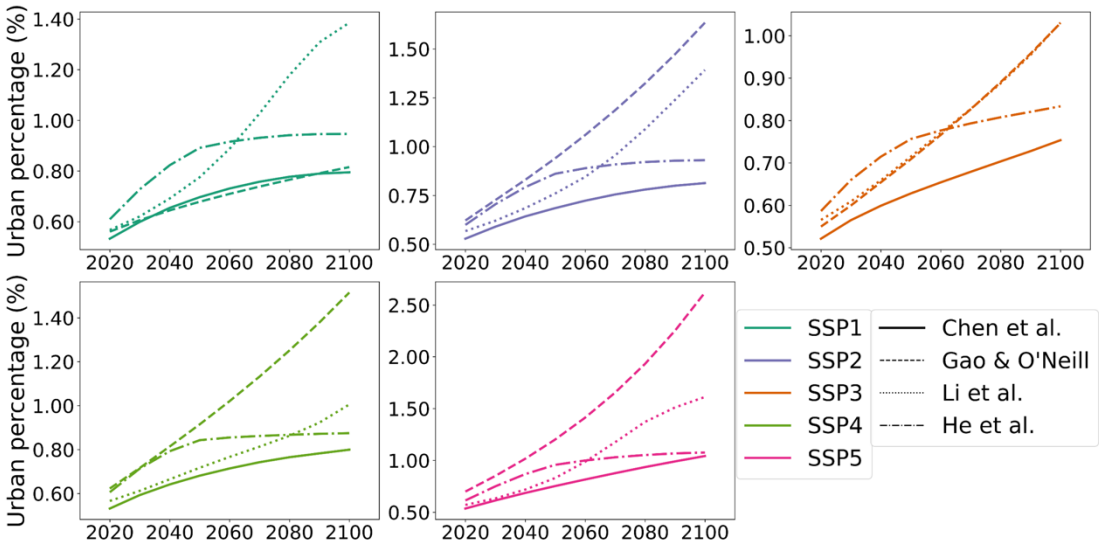


- Time series forecasting models as a function of historical properties

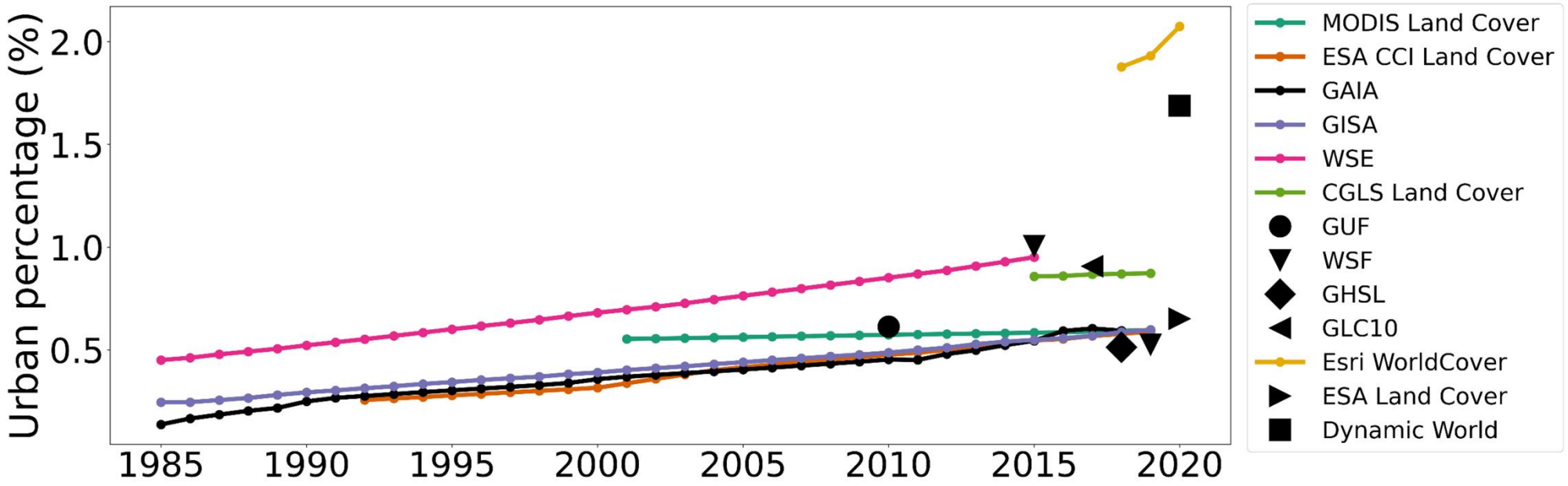
Developing temporally varying urban parameters



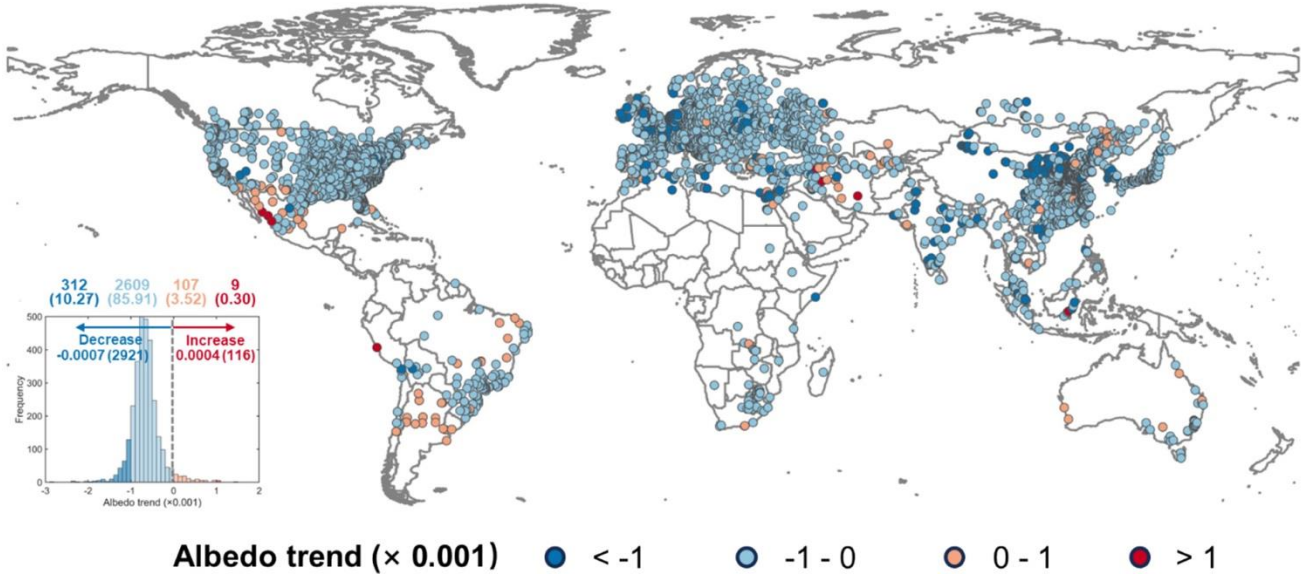
- Time series forecasting models as a function of historical properties
- Constrained by future projections by scenarios



Developing temporally varying urban parameters



- Time series forecasting models as a function of historical properties
- Constrained by future projections by scenarios
- Change in urban properties and extent over space and time



Chakraborty *et al.*, *Under Review*

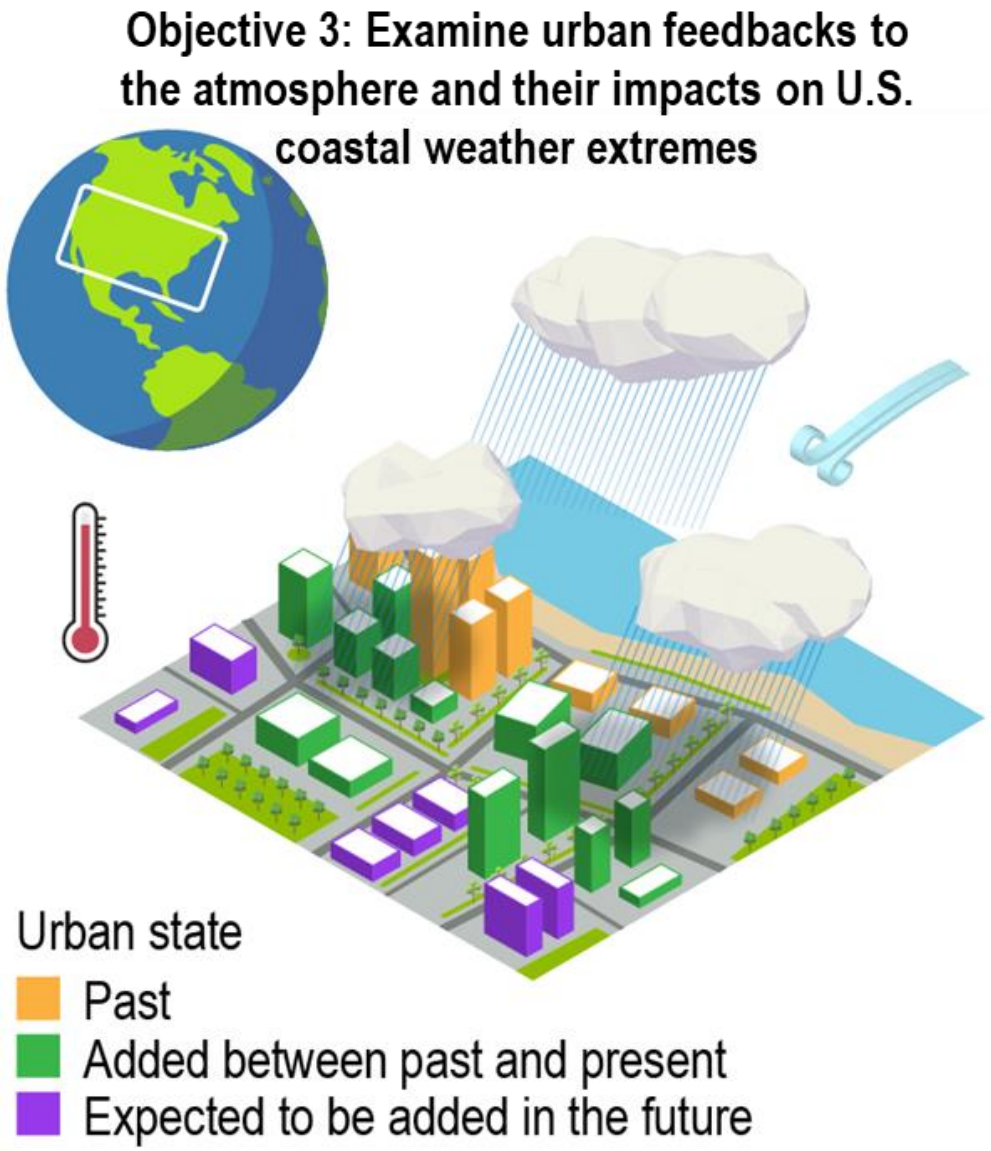
Wu *et al.*, 2024

Downscaled forcing datasets along U.S. coastline

- Physics-constrained convolutional neural networks to capture coastal gradients
- Constrained by mass and energy budget of the entire grid (based on coarser future climate projections)

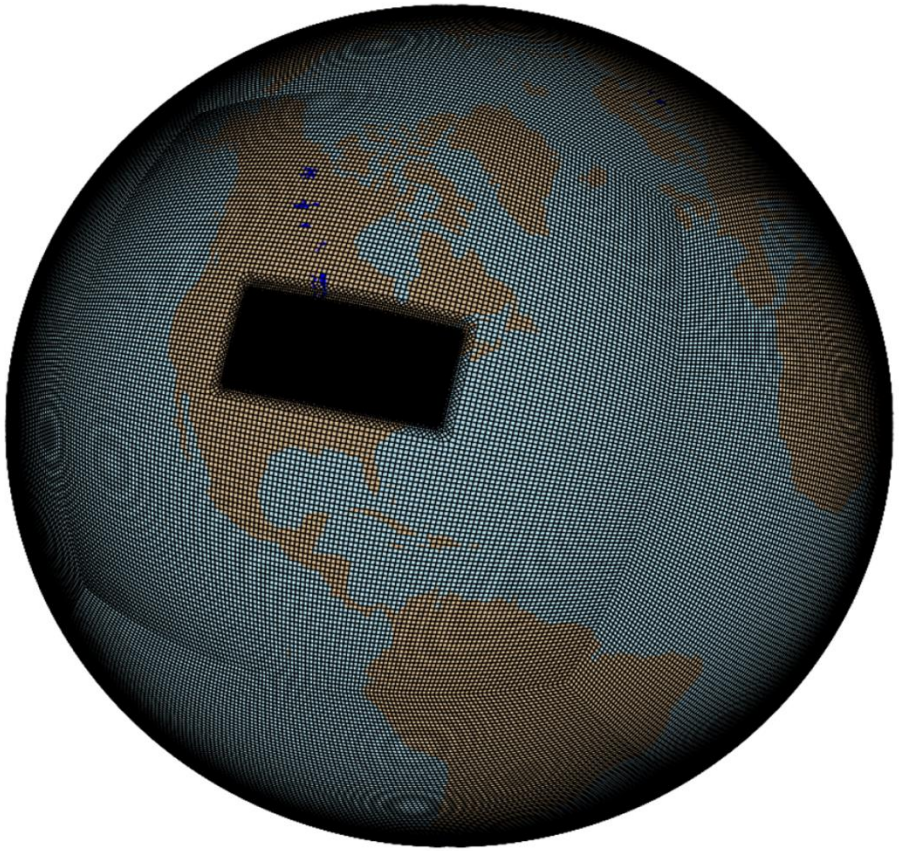
Harder *et al.*, *Under Review*

Examining feedbacks and studying extreme events



- Examining feedback from CONUS to coastal scales
- Urban impacts on coastal weather extremes

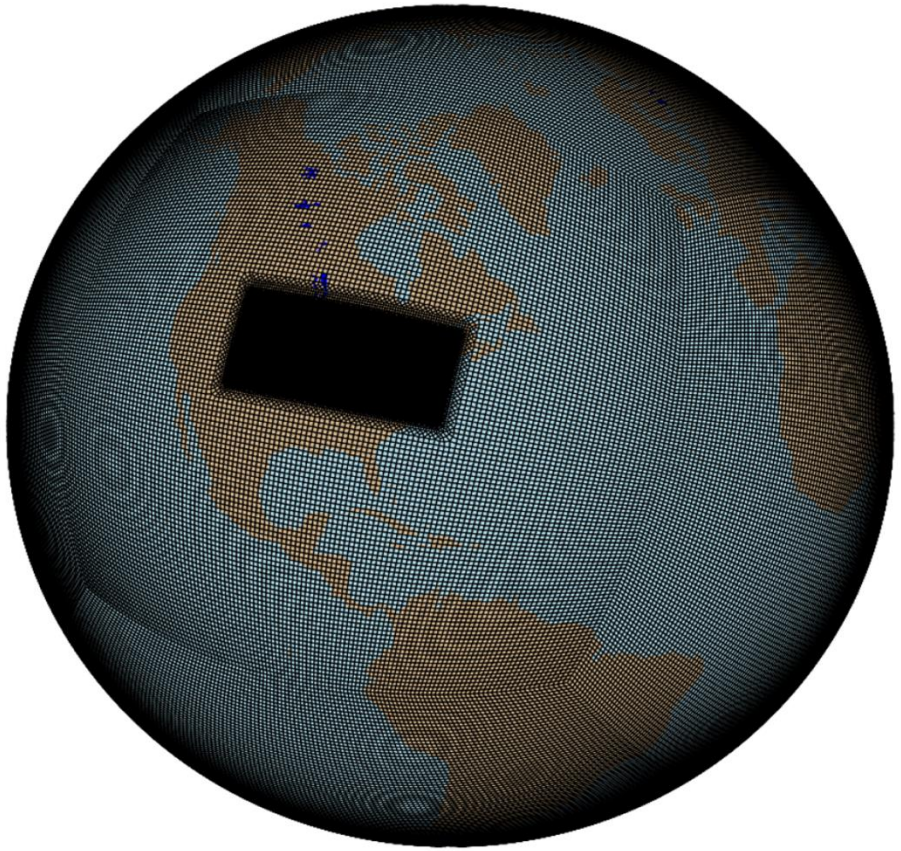
Running E3SM with regionally refined grids at 1 km



Regionally refined Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM) at ~3.25 km resolution

Liu *et al.*, 2023

Running E3SM with regionally refined grids at 1 km



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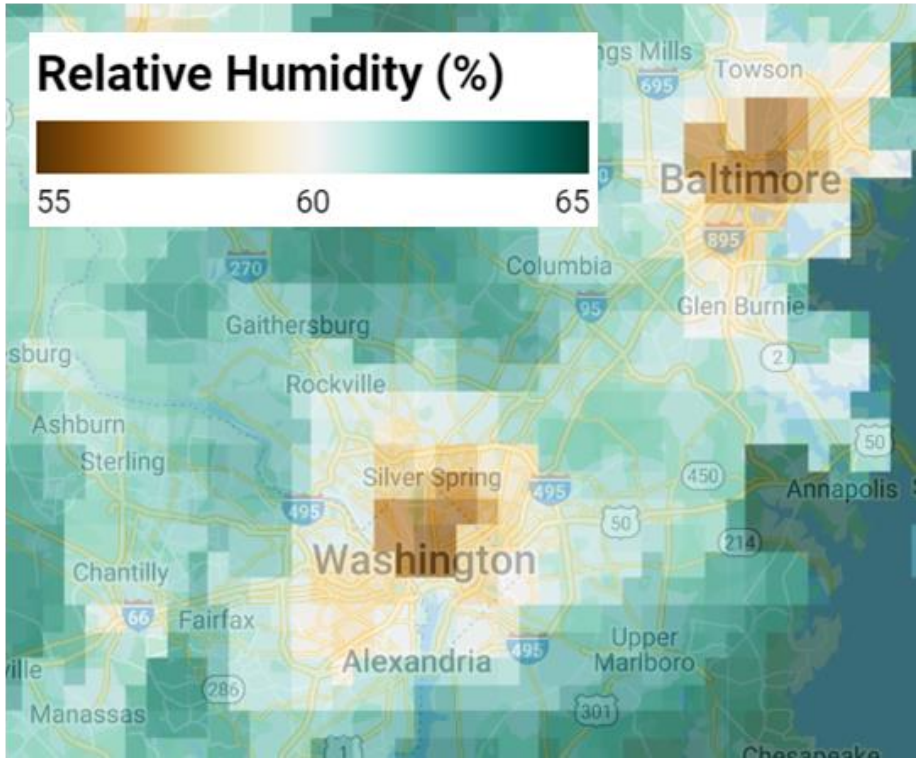


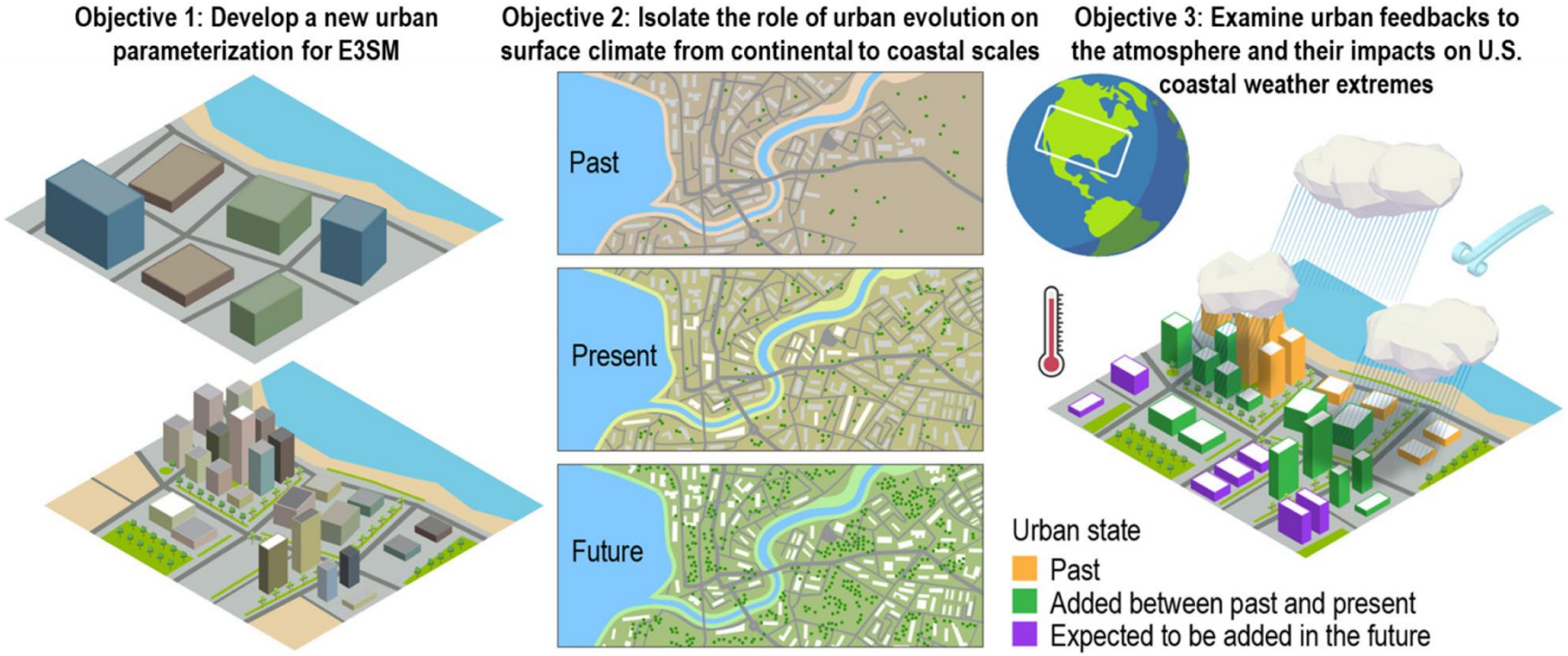
- Isolate specific extreme events from coarser coupled simulations (drought, heatwave, storms)
- Run perturbation simulations with different urban scenarios

Liu *et al.*, 2023

Chakraborty *et al.*, *In Prep*

Multiple critical collaborations across labs, other institutions, and countries

Overall schematic of proposed research



Integration with other DOE-funded projects

Data sharing & model benchmarking

CROCUS
Community Research on Climate & Urban Science

BSEC

Co-developing future urban evolution scenarios

IM3

Calibrating model improvements to isolate coastal-urban interactions

COMPASS
Coastal Observations, Mechanisms, and Predictions Across Systems and Scales

GREAT LAKES MODELING

ICOM

Thank you!