POTSDAM INSTITUTE FOR CLIMATE IMPACT RESEARCH

Urban form and urban heat island effect

Yunfei Li

yunfei.li@pik-potsdam.de

29. Oct. 2020

Leibniz Association

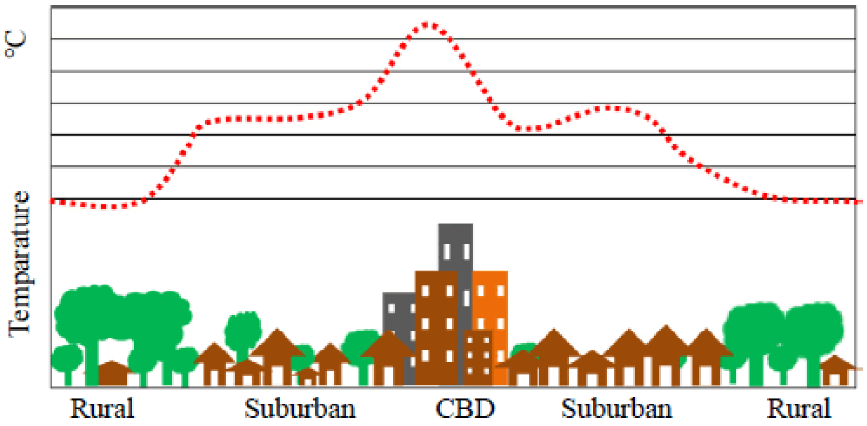
Publilshed work:
Li Y, Schubert S, Rybski D, Kropp, J.P. (2020): On the influence of density and morphology on the Urban Heat Island intensity. Nature communications.

Outline

Background

Urban heat island (UHI) effect

Causes



sketch of an urban heat island profile*

- more heat storage:
  - evaporation, albedo ↓
  - Thermal conductivity, capacity ↑
- more trapping:
  - wind ventilation ↓
  - in-canyon reflection ↑
- anthropogenic heat release:
  - traffic ↑
  - cooling, heating ↑

$$T_{urban} > T_{rural}$$

Costs

- impacts human health, air quality, aquatic systems, and energy consumption.
- amplifies heat stress costs by interacting with heat waves and climate change.
- Urbanization results in UHI effect and is expected to continue.

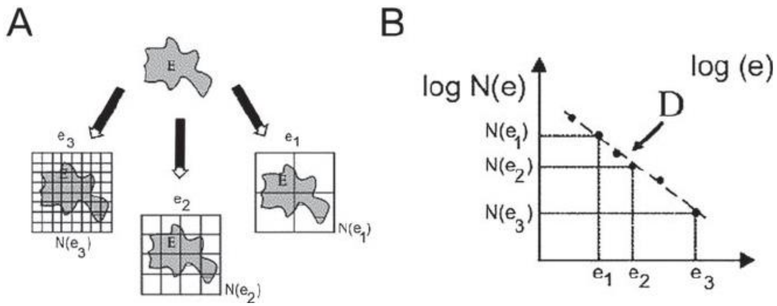
P I K

* Bhargava, A., Lakmini, S., & Bhargava, S. (2017). J. Biodivers. Endanger. Species

Preceding work on surface UHI*

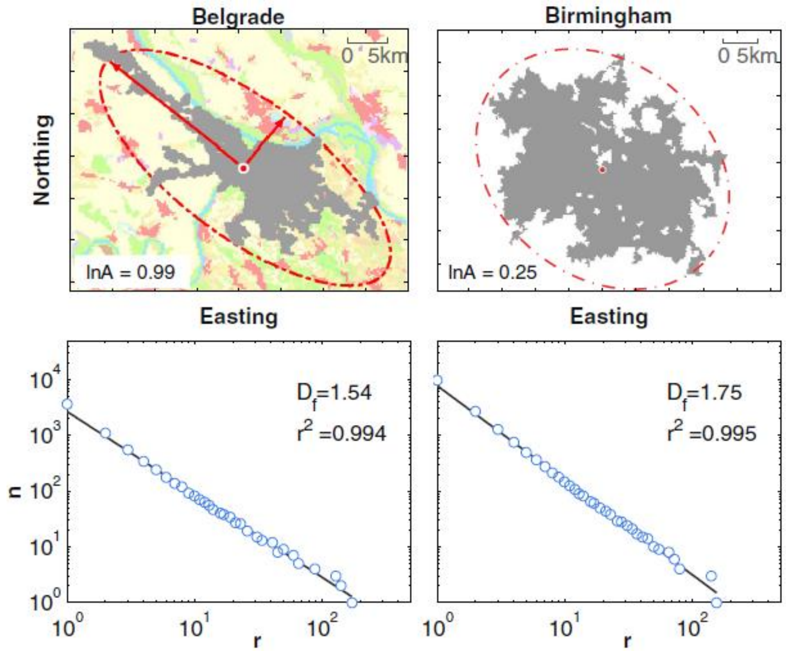
Factors influence land surface UHI

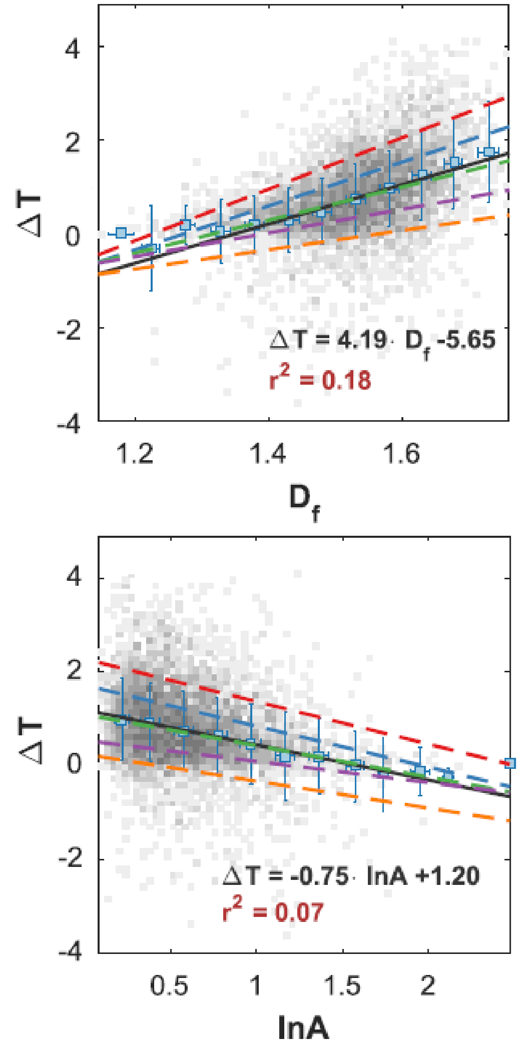
- Fractal dimension
- anisometry



Anisometry
A

fractal
Dimension
D_f





- Zhou, B., Rybski, D. & Kropp, J.P. *Scientific Reports* (2017).
- Boxcounting ref: Azua-Bustos, A., C. Vega, T. Peres-Acle, and R. Vicuña. *LPICo* (2010).

Questions

- **Questions:**
  - ? How does urban morphology influence the canopy layer UHI effect
  - ? Can this influence be quantitated for a better understanding

- **Current knowledges:**
  - Denser cities tend to have stronger UHI intensity.
  - Factors influencing UHI effect interact nonlinearly with each other.
  - Many factors at micro/block scale influence small scale thermal environment.

Methodology

Conceptual framework

- **Necessaries**
  - ❑ high spatial resolution and coverage temperature data
  - ❑ Urban structures vaying in morphology
  - ❑ Factor seperating analysis

- **Tools:**
  - **Numerical climate model**

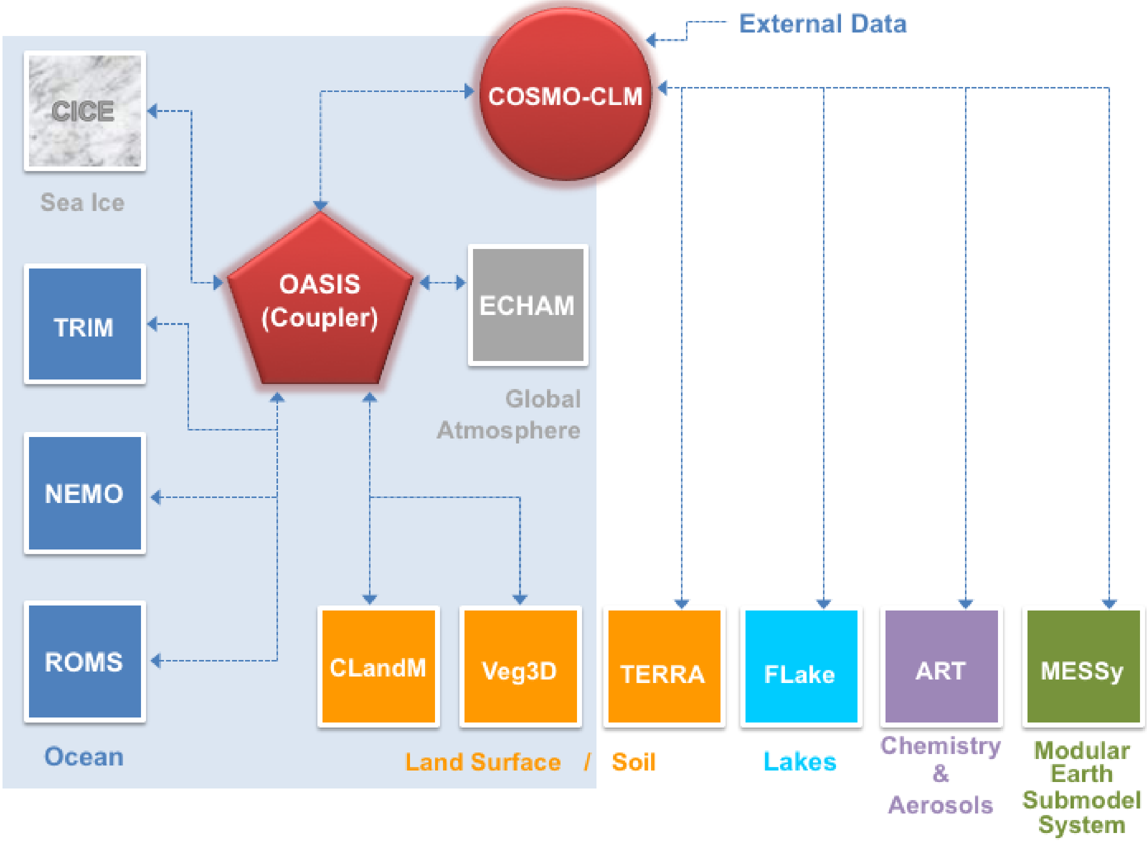
    Run Controlled urban climate simulations
  - **Gravitational urban growth model**

    Create different urban structures

P I K

Climate model

- **COSMO model in CLimate Mode (COSMO-CLM)**
  - nonhydrostatic regional climate model based on the Local Model (LM) and COSMO (COnsortium for Small-scale MOdelling) model.



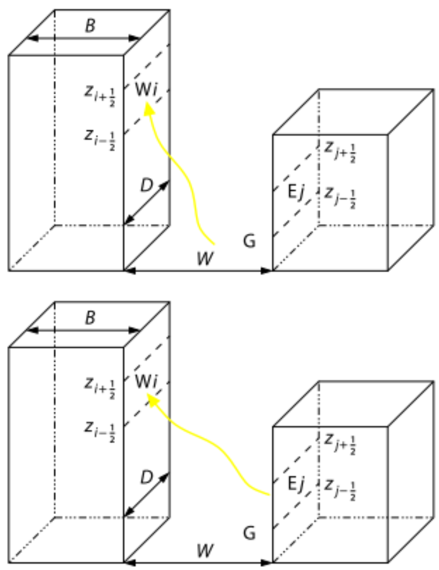
Overview COSMO-CLM*

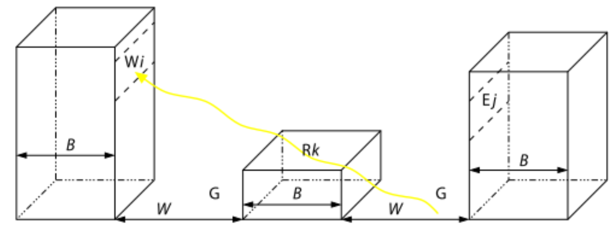
* https://www.clm-community.eu/

Urban canopy model

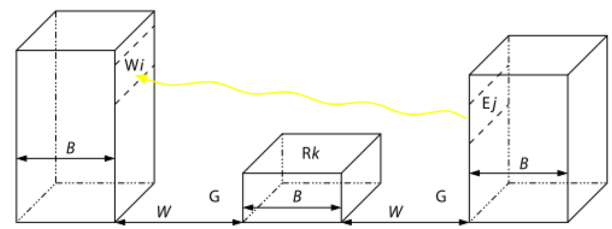
- **double-canyon effect parametrization (DCEP)* based on Building Effect Parameterization (BEP)**

  UCP (urban canopy parameters) input:
  - Urban fraction
  - Urban canyon direction
  - Building height distribution
  - Building width
  - Street width

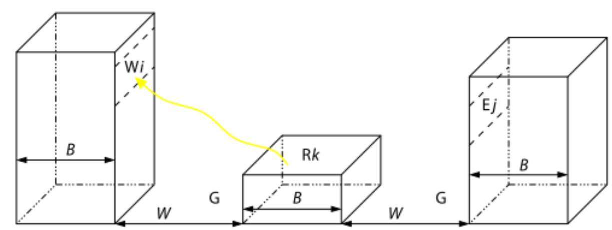




a) Radiation received from the ground surface G of a neighbouring canyon



b) Radiation received from the *j*th east wall element E*j* of a neighbouring canyon



c) Radiation received from the *k*th roof surface

* Schubert, S., Grossman-Clarke, S., & Martilli, A. Boundary-layer meteorology (2012).

Gravitational model*

- **Conception: growth is more likely to take place close to urban space.**

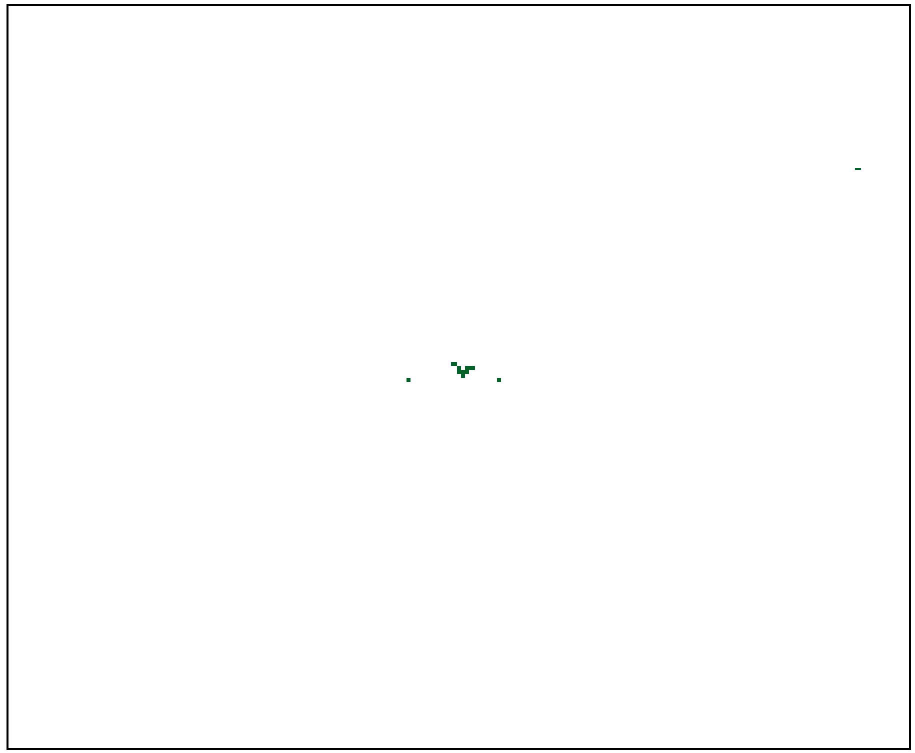
- **In a $N \times N$square lattice, set centeral cell value $w = 1$, 0 for all other cells:**
  - For any cell $\boldsymbol{i}$, influenced by another cell $\boldsymbol{j}$, in a gravitation like form: $\frac{G\mathrm{w_j}}{d_{\mathrm{ij}}^{\gamma}}$;
  - Overall influences from the system on cell $\boldsymbol{i}$: $\mathrm{G}\sum_{j\neq i} w_j * d_{ij}^{-\gamma}$;
  - Normalize by $\sum_{j\neq i} d_{ij}^{-\gamma}$, the growth probability of cell $\boldsymbol{i}$: $q_i = G\frac{\sum_{k\neq j} w_k * d_{j,k}^{-\gamma}}{\sum_{k\neq j} d_{j,k}^{-\gamma}}$;
  - Roll a number $\mathrm{z}_i \in [0,1]$ for each cell $\boldsymbol{i}$, compare with q_i:
    - $z_i \geq q_i$: do nothing
    - $z_i < q_i$: $w_i = w_i + 1$
  - Reclaculate q_i and do another interation.

- **control the growth pattern using different γ.**

P I K

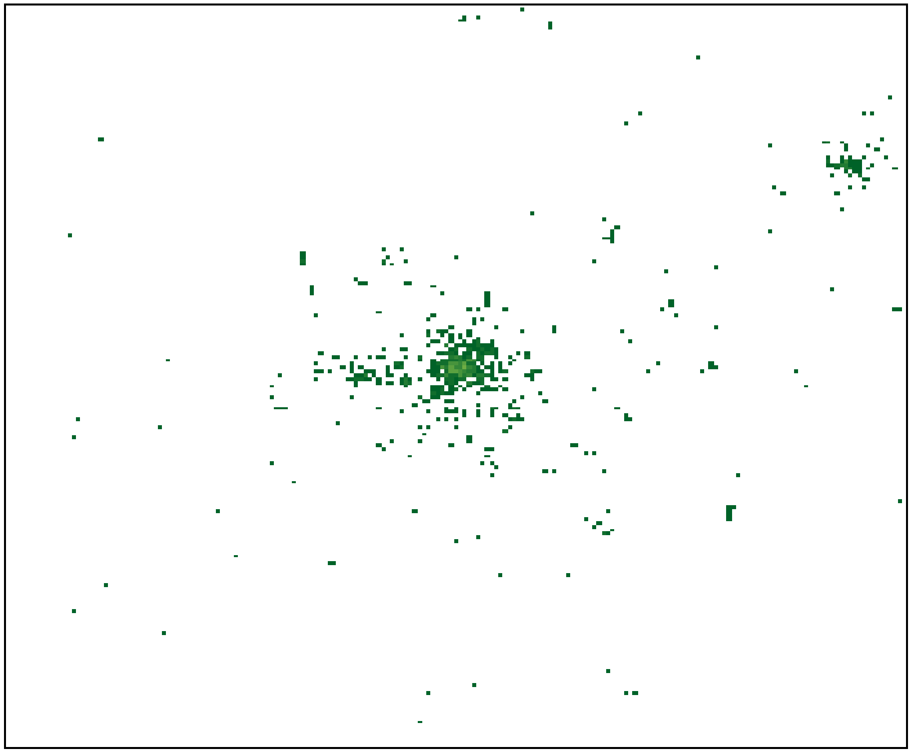
* Li Y, Rybski D, Kropp JP. Singularity cities. *Environment and Planning B.* (2019)

Gravitational model output



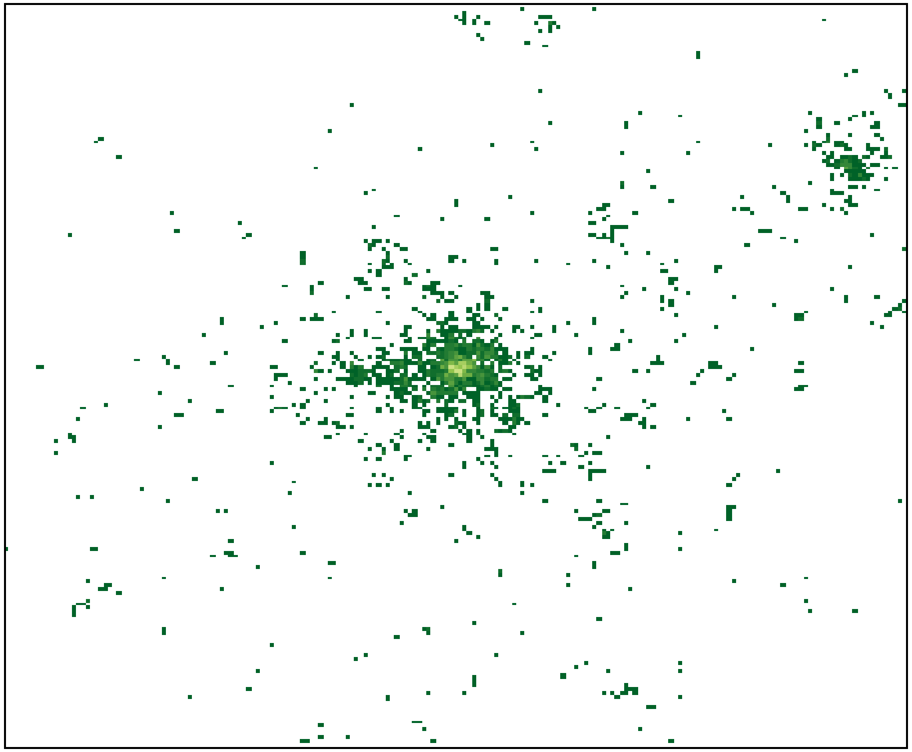
γ =2.5, Step = 1

Gravitational model output



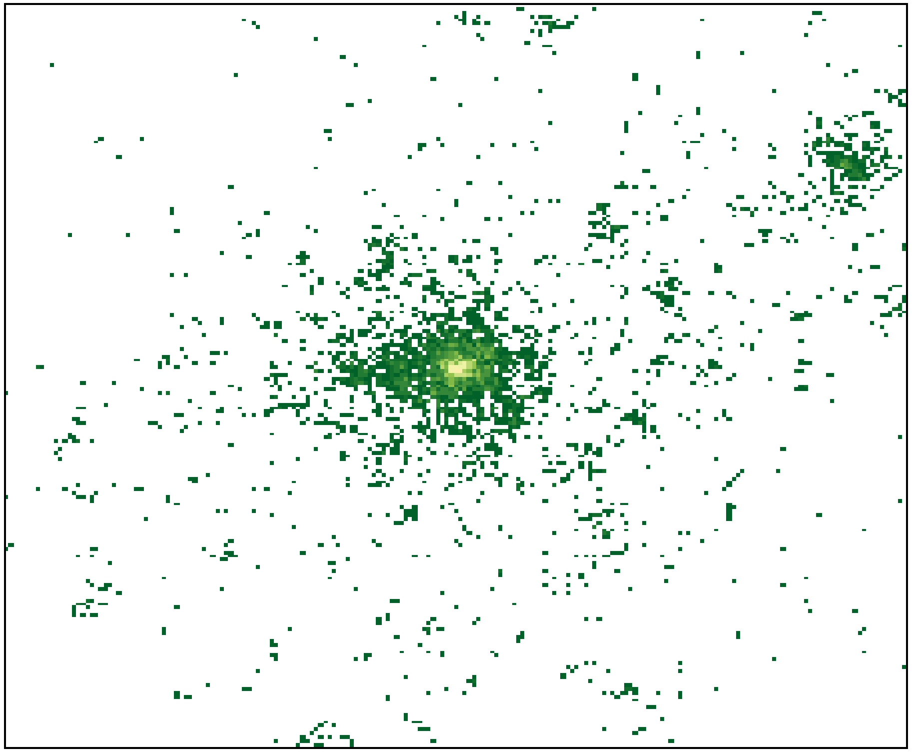
γ =2.5, Step = 5

Gravitational model output



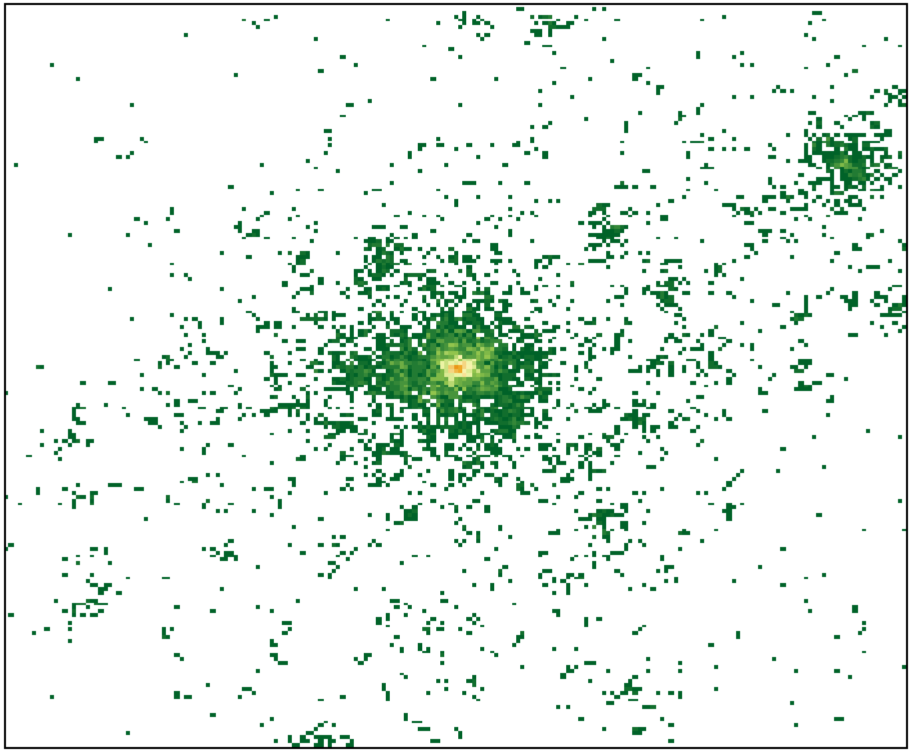
γ =2.5, Step = 10

Gravitational model output



γ =2.5, Step = 15

Gravitational model output

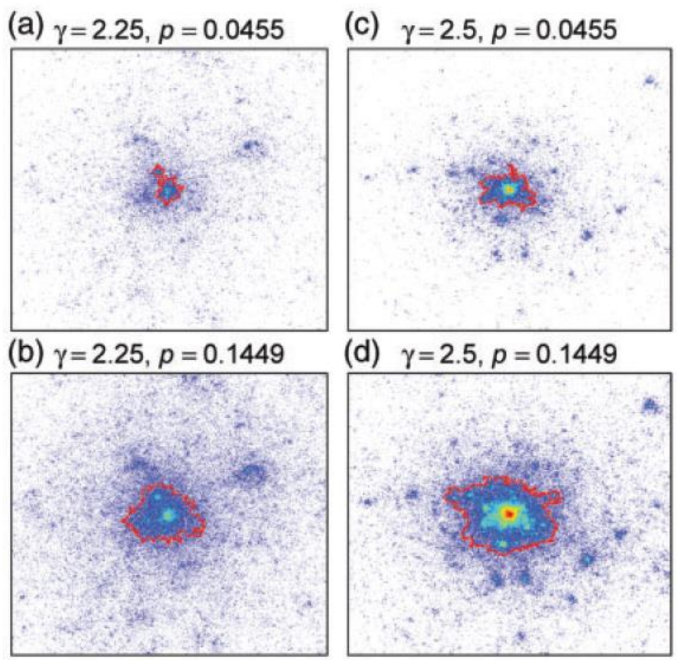


γ =2.5, Step = 20

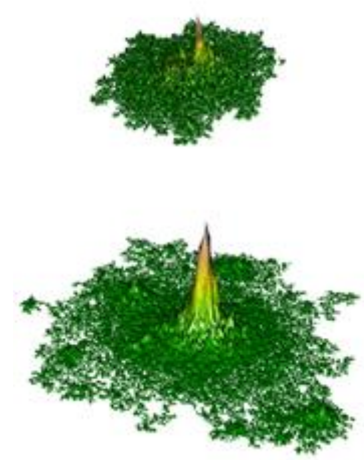
Artifitial 3D urban structures

- **Gravitational model urban growth model**
  - reproducing various attributes of real world cities:
    - radial gradients population of density and impervious surface fraction
    - various fractal dimension
    - power-law between the population and city size
    - urbanisation probabilty profile along the distance to urban sites

$$q_i = G \frac{\sum_{j \neq i} w_j * d_{i,j}^{-\gamma}}{\sum_{j \neq i} d_{i,j}^{-\gamma}}$$

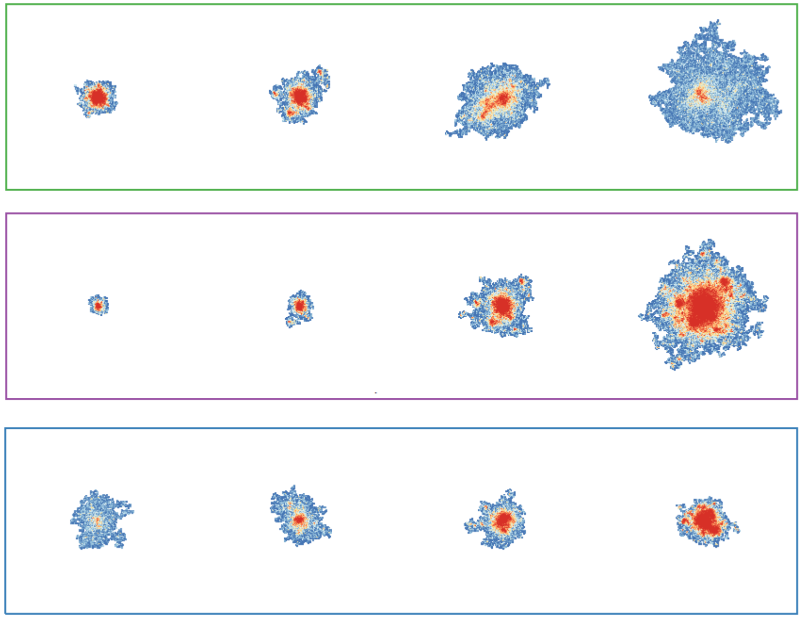


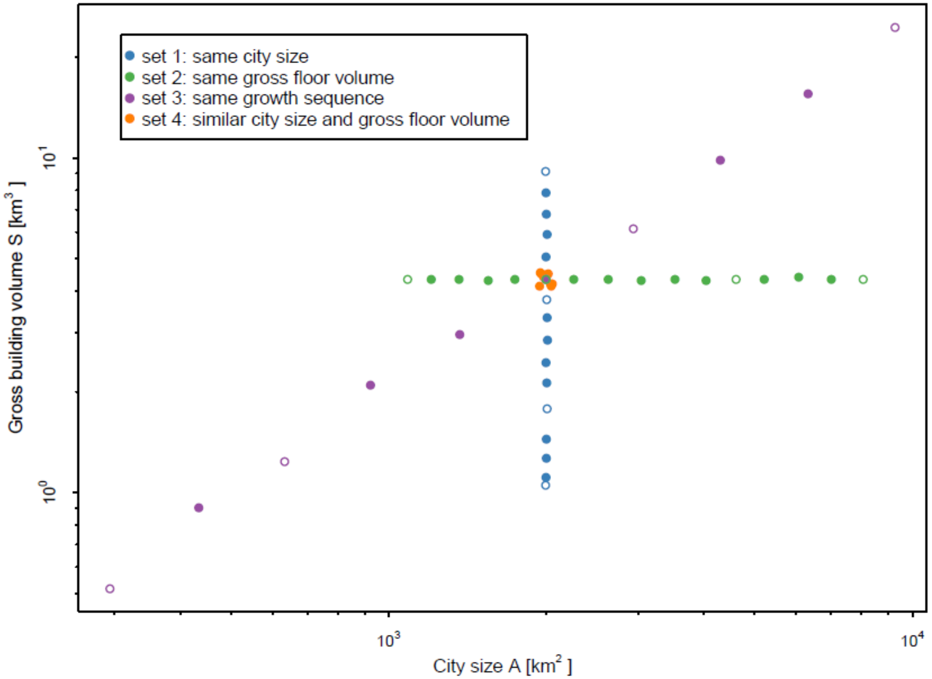
CCA



3D urban structures

- **4 series from gravitational model*:**
  - Same gross building volume, different sizes
  - Same size, different gross building volume
  - same growth series
  - Same size and gross building volume, different shapes

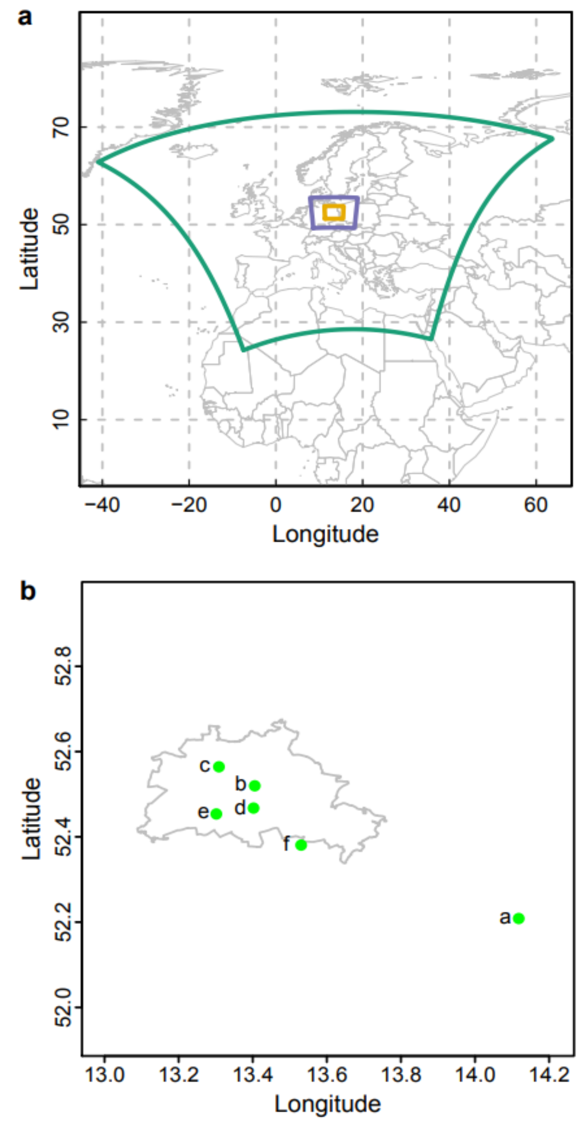




PIK

Numerical model setup

- **Urban climate simulation**
  - COSMO-CLM downscaling :
    ERA-Interim -> 16km-> 2.8km
  - COSMO-CLM/DCEP:
    2.8km -> 1km (300km centered at Berlin area)
  - Peroid: Heat weave event, 1st -7th, August 2003
  - Output: hourly 2m Temperature



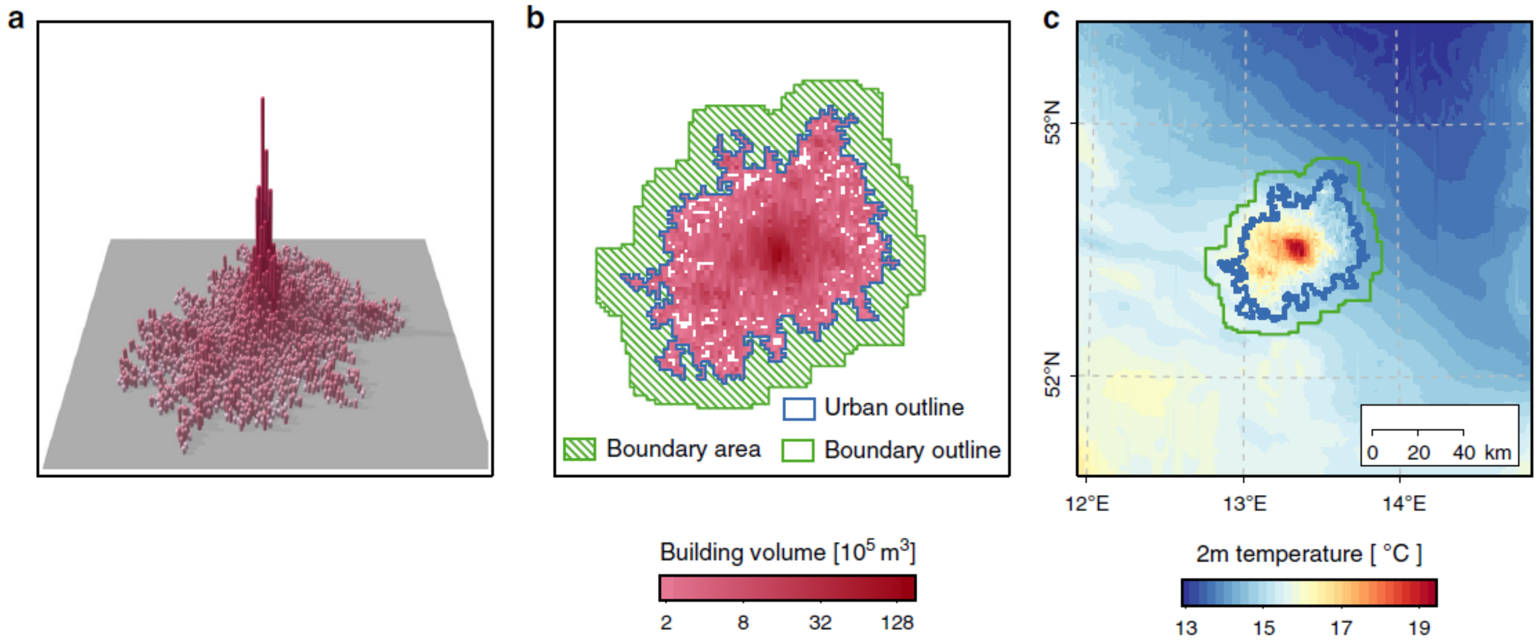
- **Validation of reference run**

	Lindenberg	Alex	Dahlem	Schön	Tegel	Tempel
ME	-0.252	-0.305	1.179	0.684	-0.264	0.693
MAE	0.785	0.703	1.604	0.871	0.823	1.146
RMSE	0.998	0.879	2.088	1.147	1.055	1.427

P I K

UHI calculation

- Boundary creation:
  - $A_{bd} \approx A_{urb}$
- UHI intensity calc:
  - $\Delta T \approx \overline{T}_{urb} - \overline{T}_{bd}$



PIK

Results

$\Delta T \sim$ urban size and building density

- **Nonlinear fitting of the average daily max UHI intensity :**

$$\Delta \boldsymbol{T} = a \log S + b \log A + c \quad (1)$$

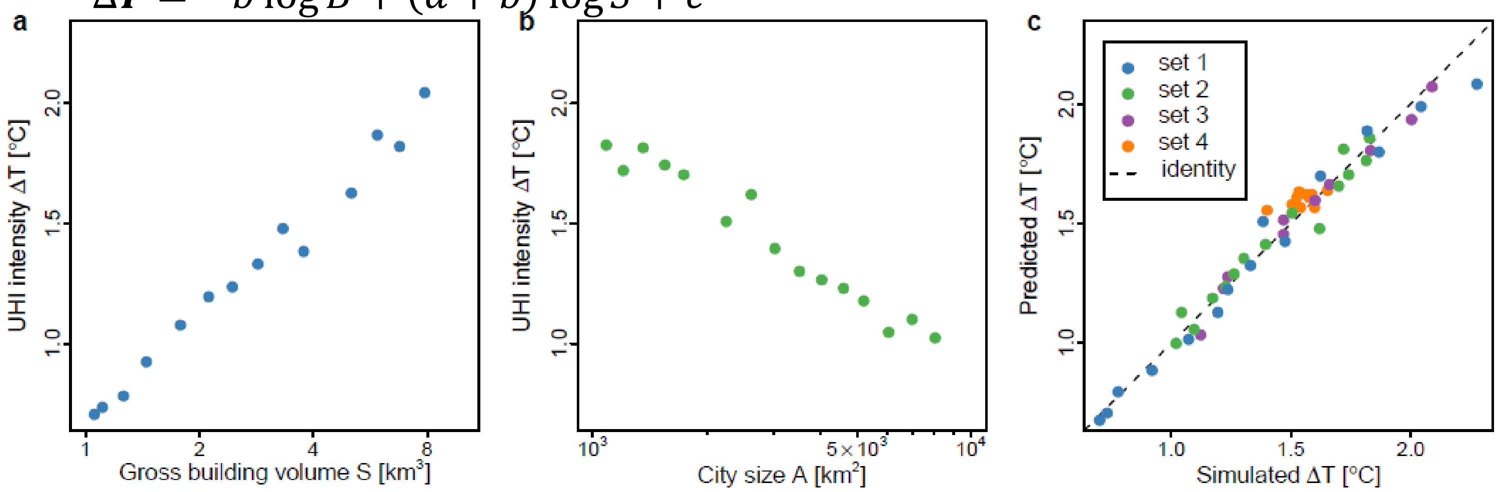
$$r^2 = 0.95 \text{ ,(S gross building volume, A urban area)}$$

- **Introduce building density B:**
  - Replace S with A*B:

$$\Delta \boldsymbol{T} = a \log B + (a + b) \log A + c$$

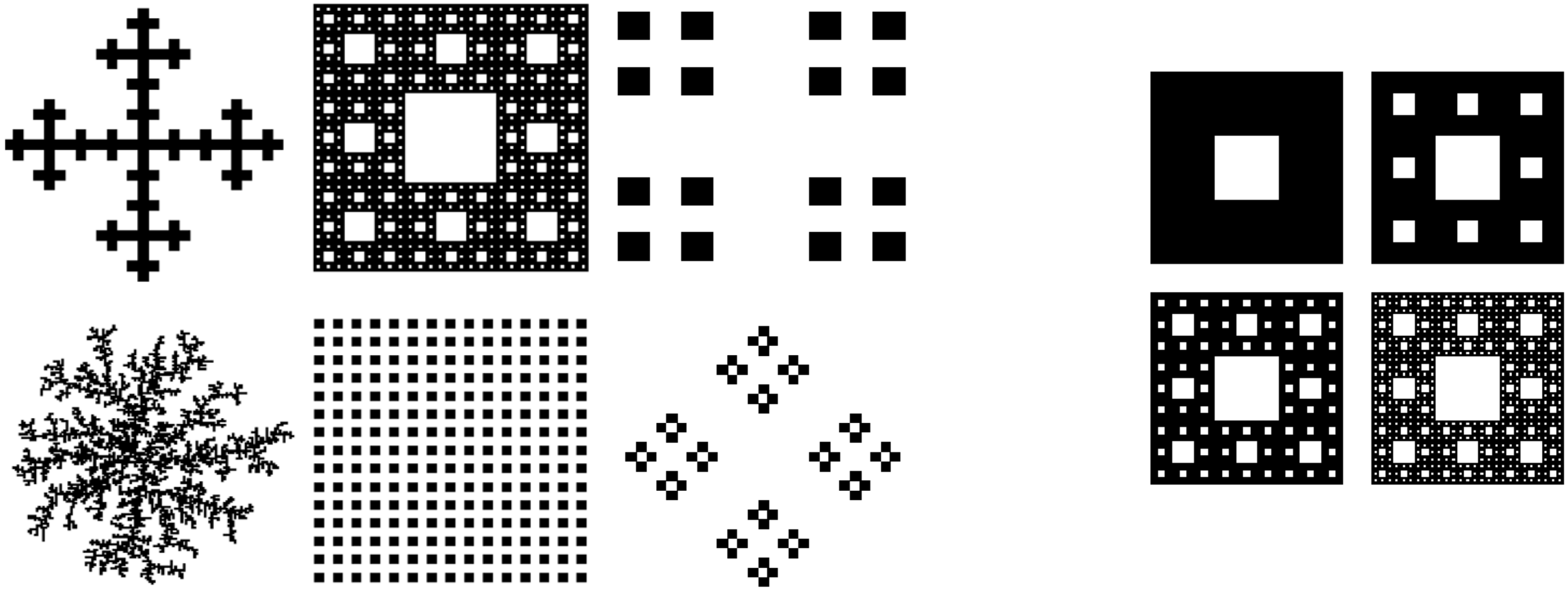
  - Replace A with S/B:

$$\Delta \boldsymbol{T} = -b \log B + (a + b) \log S + c$$



Special fractal patterns

- **10 types of special fractal patterns**
  - each type with varying sizes
  - 41 clusters in total

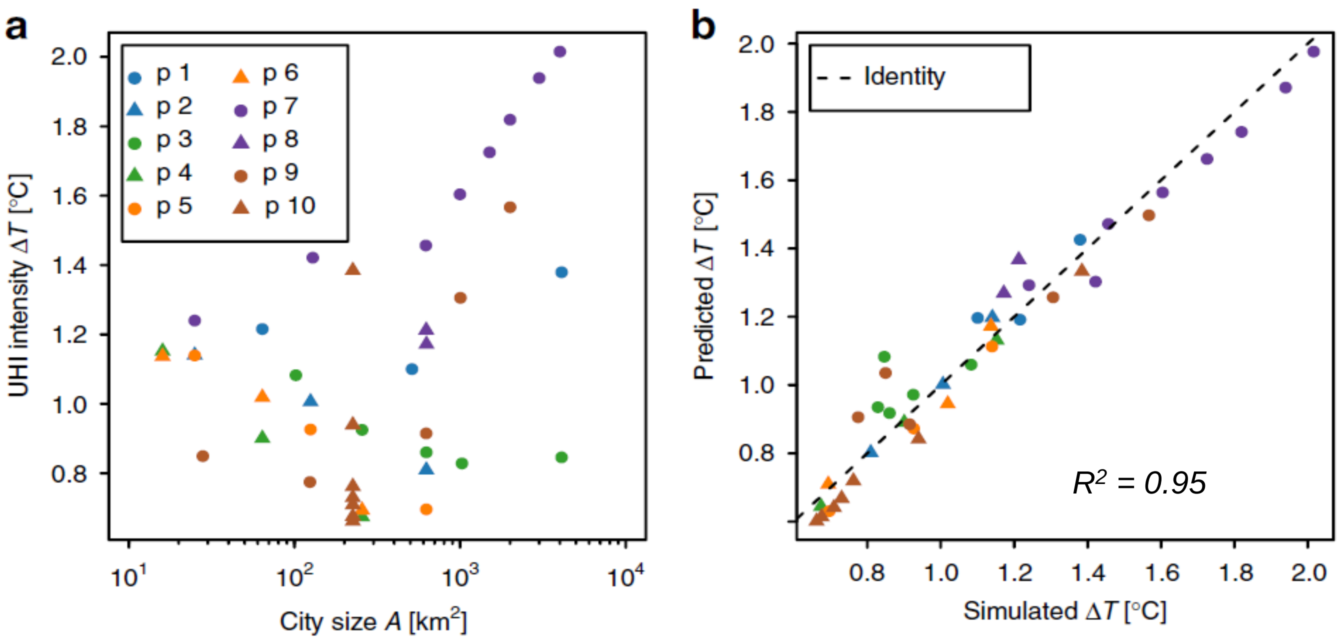


Special fractal patterns

- **special fractal patterns**
  - homegenous building volume for each grid cell, $S = \alpha A$

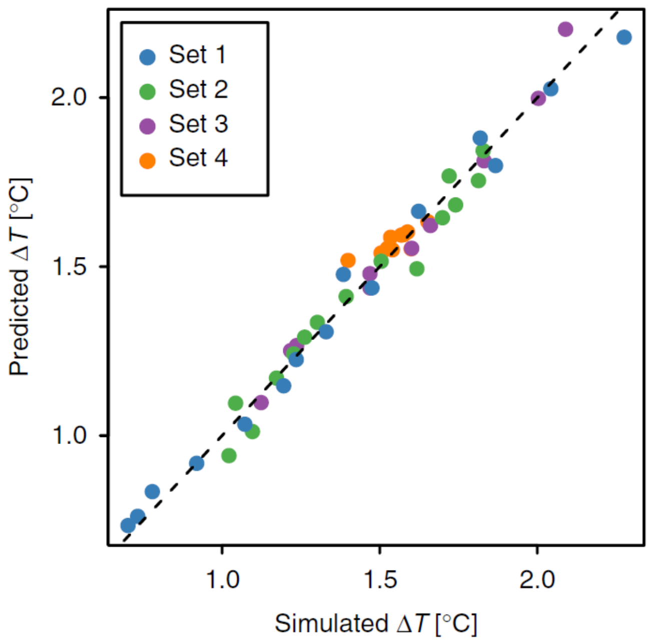
$$\Delta \boldsymbol{T} = a \log S + b \log A + c \Rightarrow \Delta \boldsymbol{T} = a \log A + c \quad \text{-(2)}$$

- $\boldsymbol{\Delta T} = a \log S + b \log A + c \frac{1}{N} \sum_j^N \sum_{i \neq j}^N d_{ij}^{-\frac{3}{2}} + d \quad \text{-(3)}$
  - d_{ij}: distance between urban grid i and j,



General regression

- $\Delta T = a \log S + b \log A + cD + d$, where: $D = \frac{1}{N}\sum_{j}^{N}\sum_{i\neq j}^{N}(\frac{f_{ui}w_i}{Y_i})^{\frac{1}{2}}d_{ij}^{-\frac{3}{2}}$ -(4)
  - d_{ij}: distance between urban grid i and j,
  - w_i, Y_i, f_{ui} : gross building volume, street canyon width, urban surface fraction for urban grid i
- Fitting results:
  - $a = 0.28, b = -0.26, \ c = 0.07, d = 2.43$
  - $R^2 = 0.99$

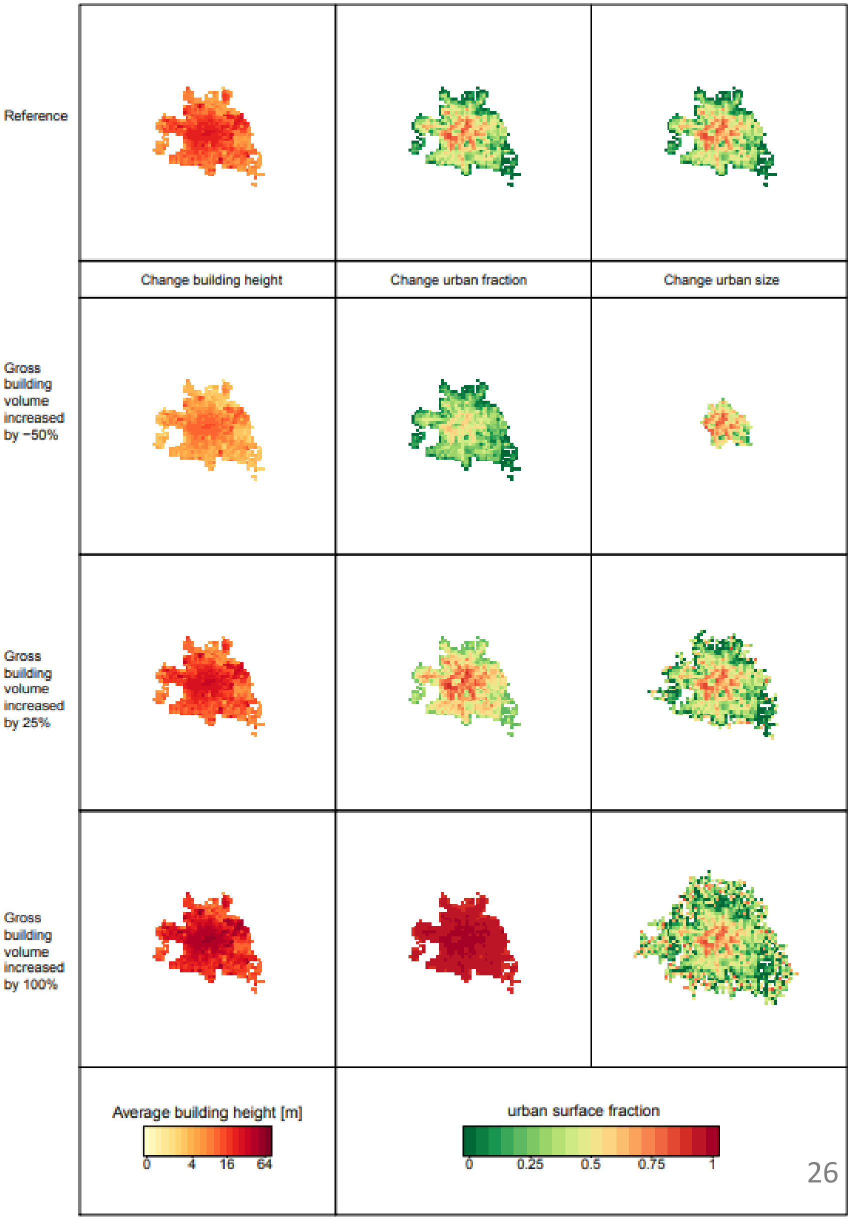


Application to a real-world example

- **Scenarios based on real urban structure data of Berlin**

- **Increase gross building volume by -50%, -25%, 25%, 50%, 100% through changing:**
  - Building height
  - Urban fraction
  - Urban area

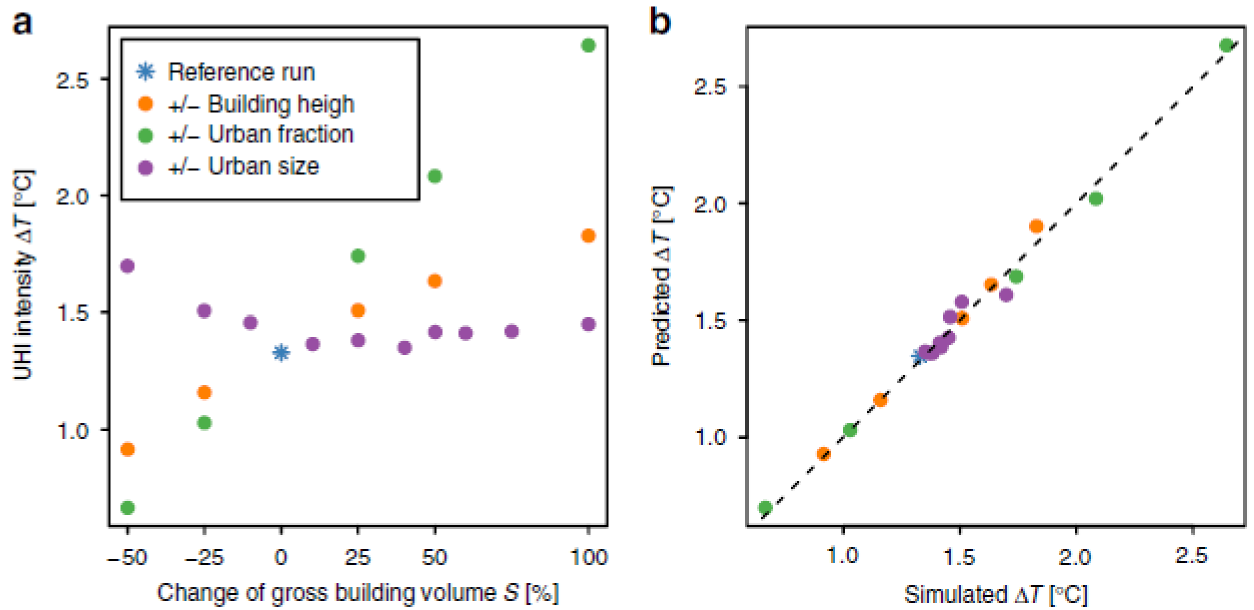
Relative to the current real data



P I K

Application to a real-world example

- Taller buildings are better than larger building footprints



Summary

Conclusion:

- **Our results shows that:**
  - Building density is the dominant factor contributing urban heat island
  - Cities larger in area do not necessarily mean stronger urban heat island intensity
  - If the city is constrained from outward extending for future development to accommodate growing population, taller buildings are better than the share of land surface covered by building
  - Given the same size and gross building volume, urban development scenarios with more compact morphology have stronger urban heat island intensity.

Further discussions

- With the parameters known, our approach can serve as an UHI rule of thumb for the comparison of urban development scenarios.
- Future work exploring the influence of background climate on the regression model would be helpful for a more generalized undertsanding.
- Theoretical explanation on the regression model would also promote general understanding.
- Anthropogenic heat all matters in some cities.

Thanks!

Potsdam Institute for Climate Impact Research (PIK)
Research department Climate Resilience
Urban transformation group:
https://www.pik-potsdam.de/en/institute/departments/climate-resilience/research/urban-transformations

Personal homepage at PIK:
https://www.pik-potsdam.de/members/yunfeili

PIK