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# Effectiveness of Urban Heat Island Mitigation Strategies in Cities

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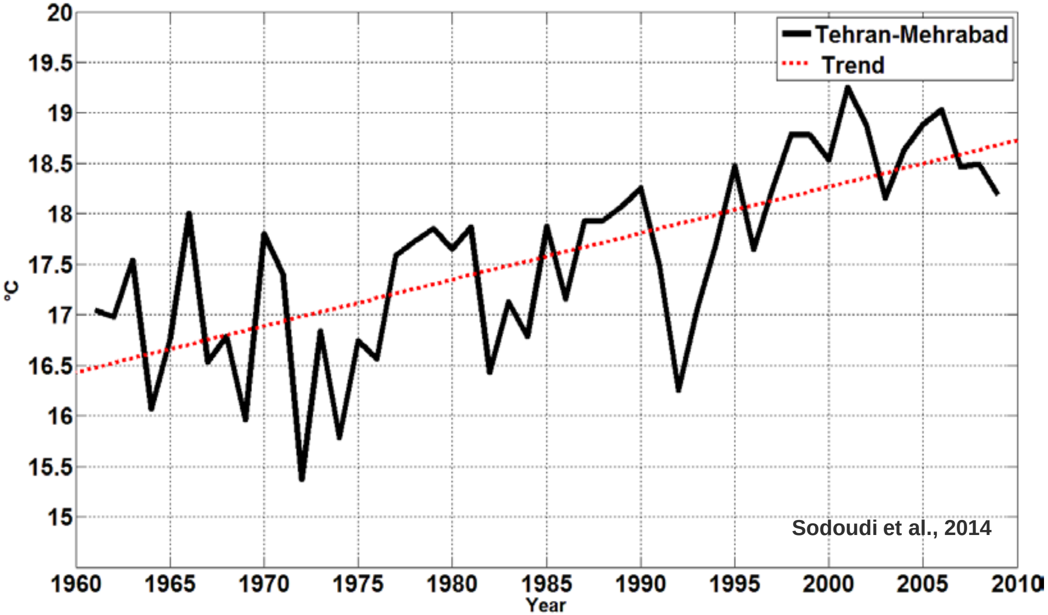
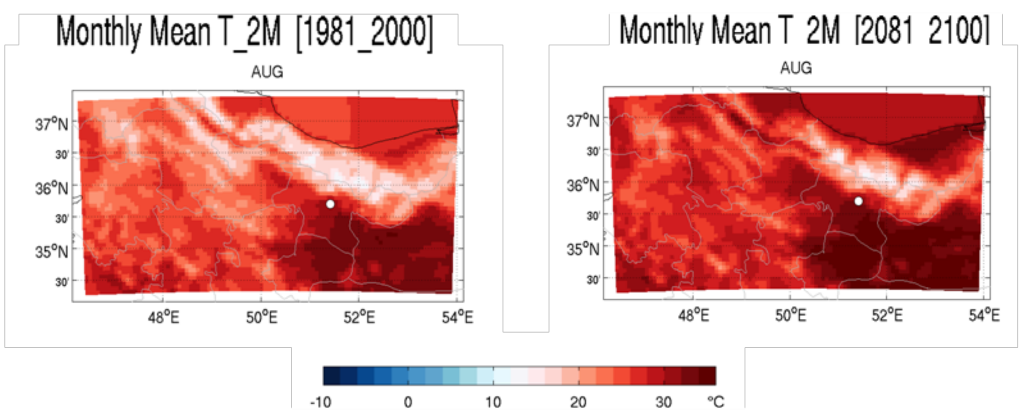
29.03.2017

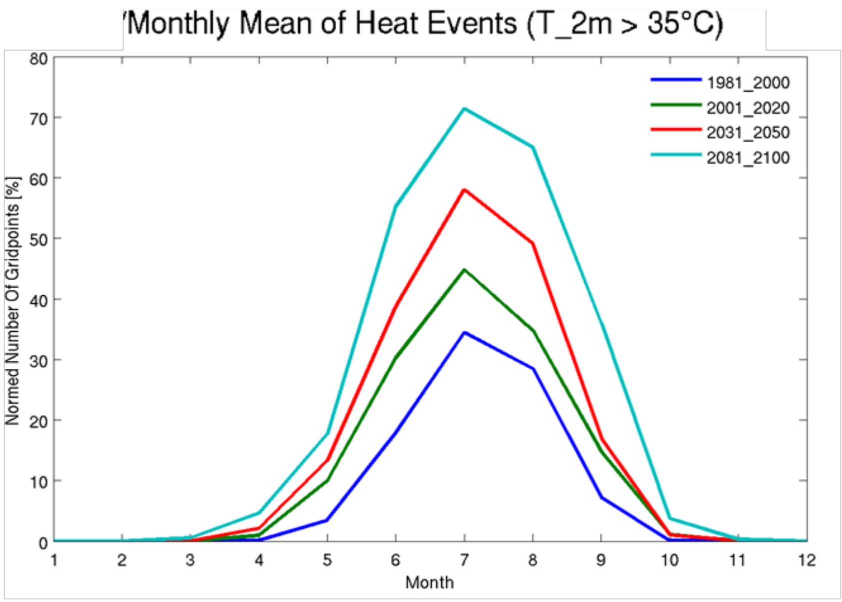
# Motivation



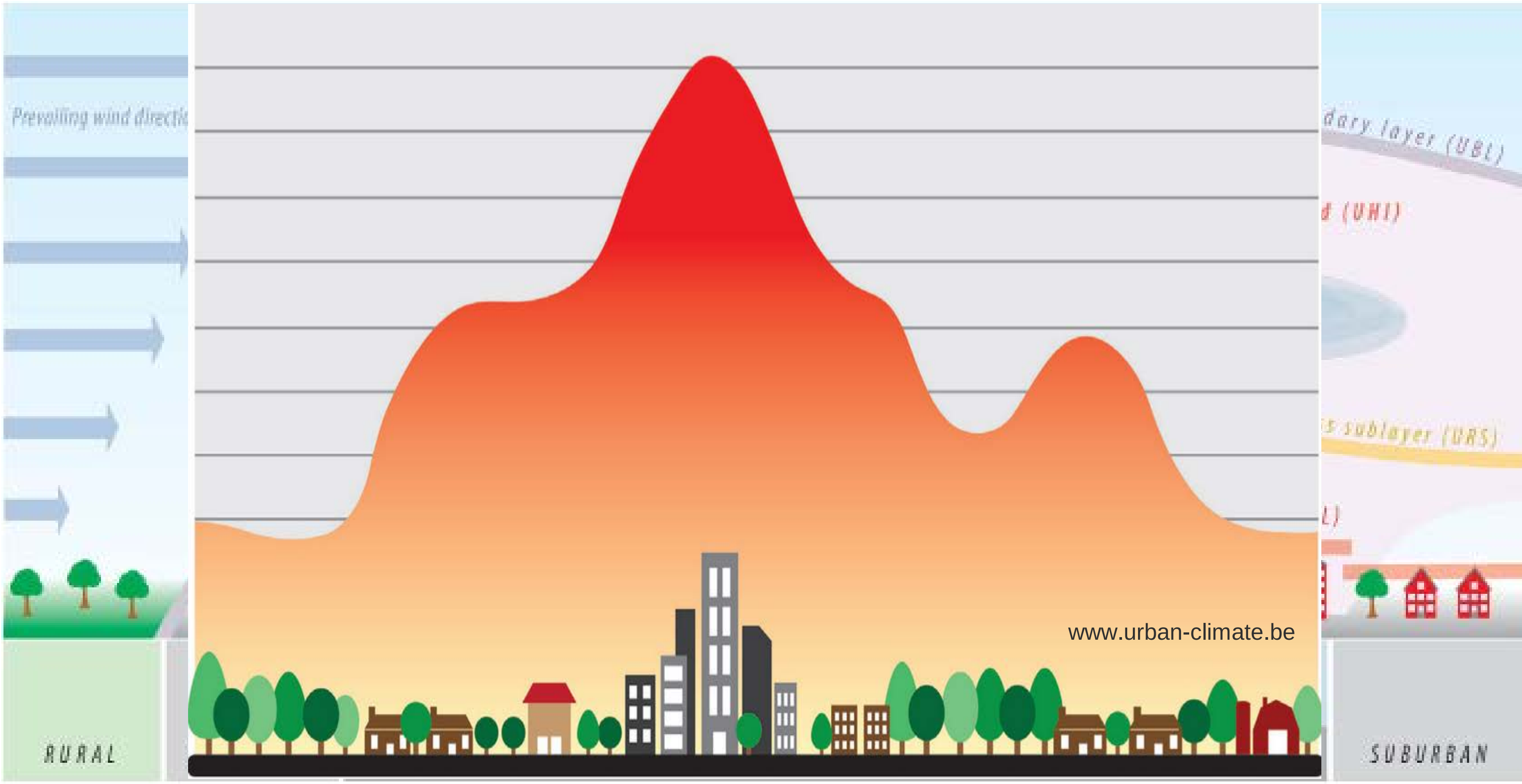

- <u>Global warming</u>
(Increase of greenhouse gases)

- <u>Urbanization</u>
(Impervious surfaces & lack of vegetation)



# Urban Climate under change




Bechtel und Schmidt (2011)

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# UHI mitigation? Why?

Reduce indoor energy demand

Improvement of outdoor microclimate

**Mitigating UHI**

- Effectiveness
- Feasability

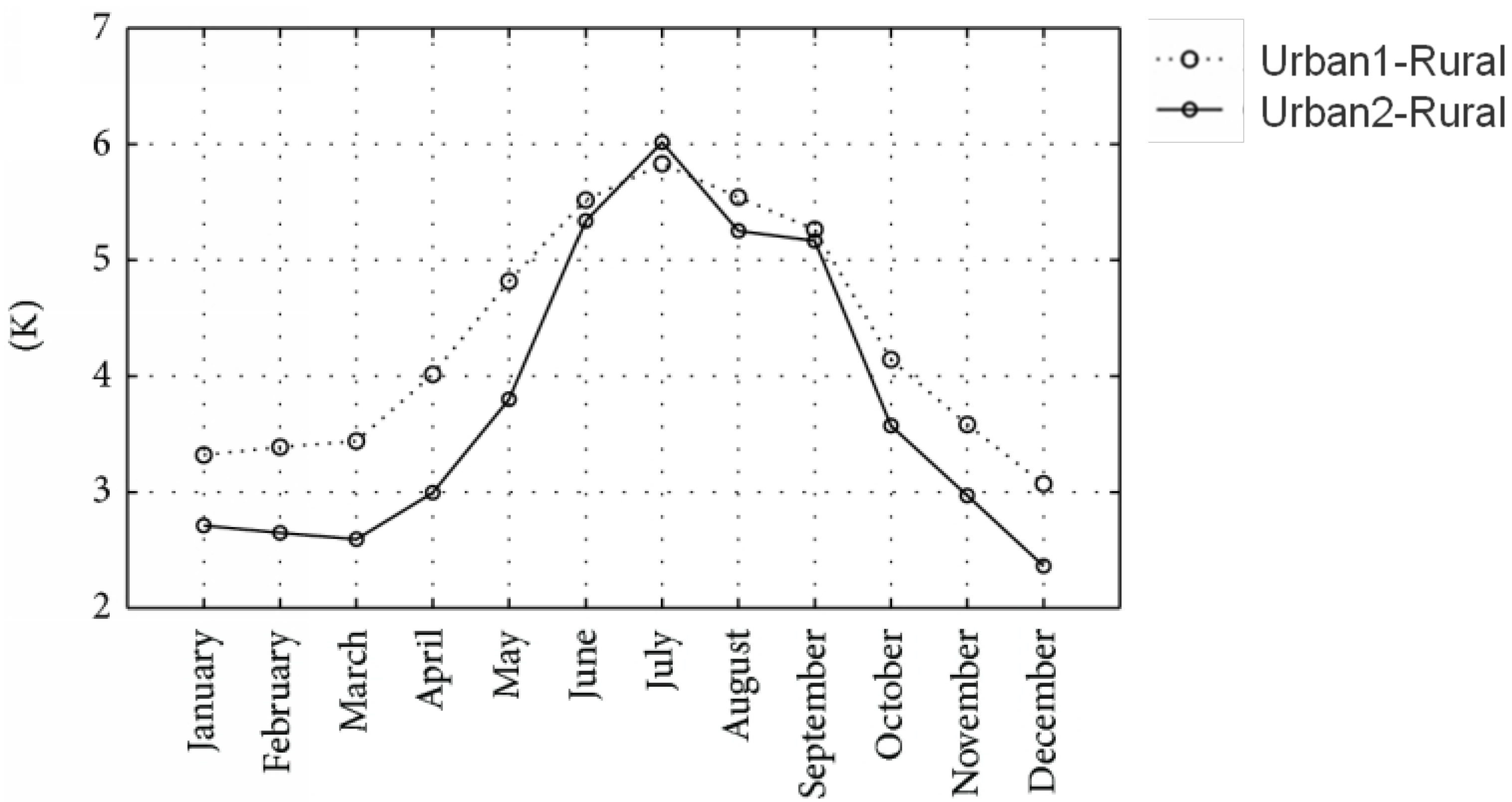
Improvement of human thermal comfort

| UTCI (°C) range | Stress Category |
|---|---|
| above +46 | extreme heat stress |
| +38 to +46 | very strong heat stress |
| +32 to +38 | strong heat stress |
| +26 to +32 | moderate heat stress |
| +9 to +26 | no thermal stress |
| +9 to 0 | slight cold stress |

Jendritzky et al. (2001)

# Urban Heat Island Intensity (UHII)

Example from Tehran




Sodoudi et al., 2014

# Examples from Research Projects

UHI mitigation /Semi-arid climate Tehran

Spatial configuration of green spaces /Berlin

Influence of Street canyon orientation on effectiveness of mitigation startegies /Berlin

Vertical and horizontal compactness/Berlin

Models

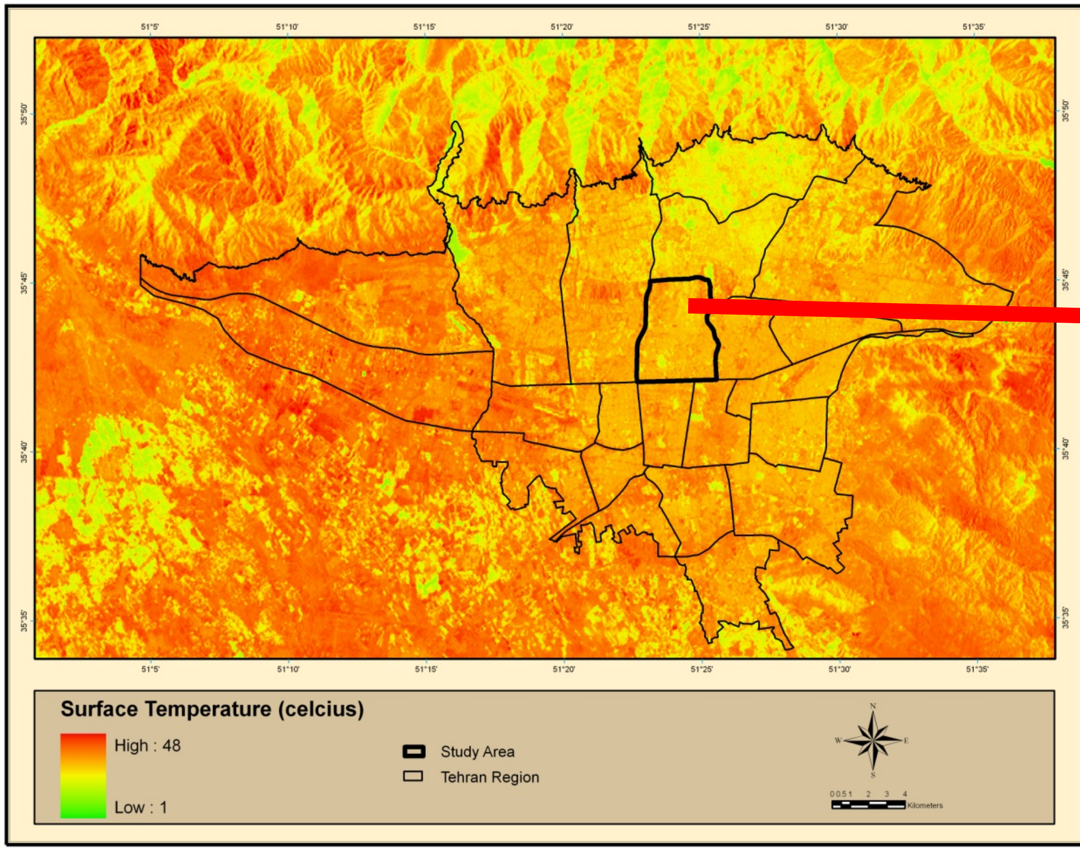
-Micro climate model ENVI-met 4 cooling

-Rayman pro/UTCI human thermal comfort

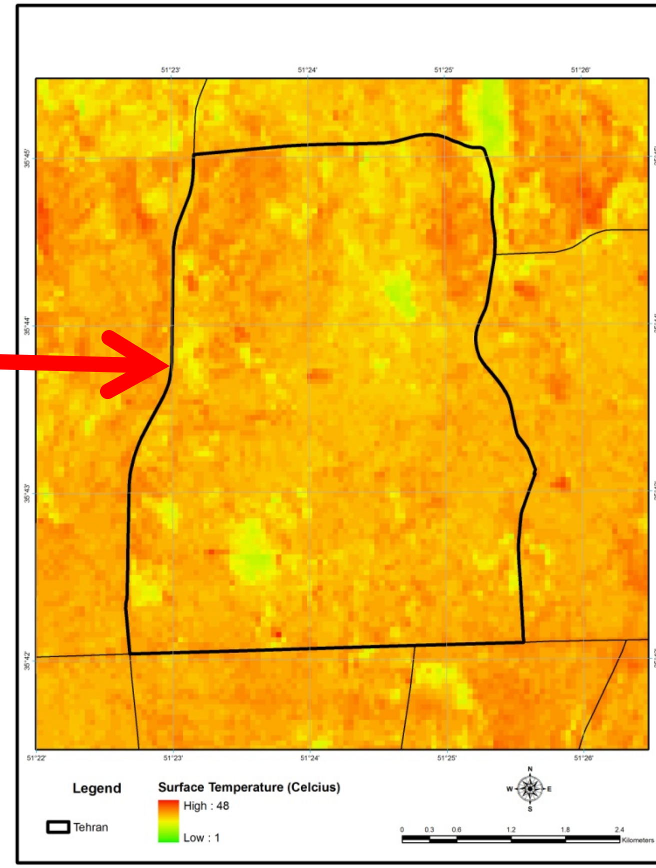
-MUKLIMO_3 Urban Climate Modeling

-Design builder Energy efficiency

# Simulation for Tehran (6th urban district)




18.07.2009 Landsat ETM7

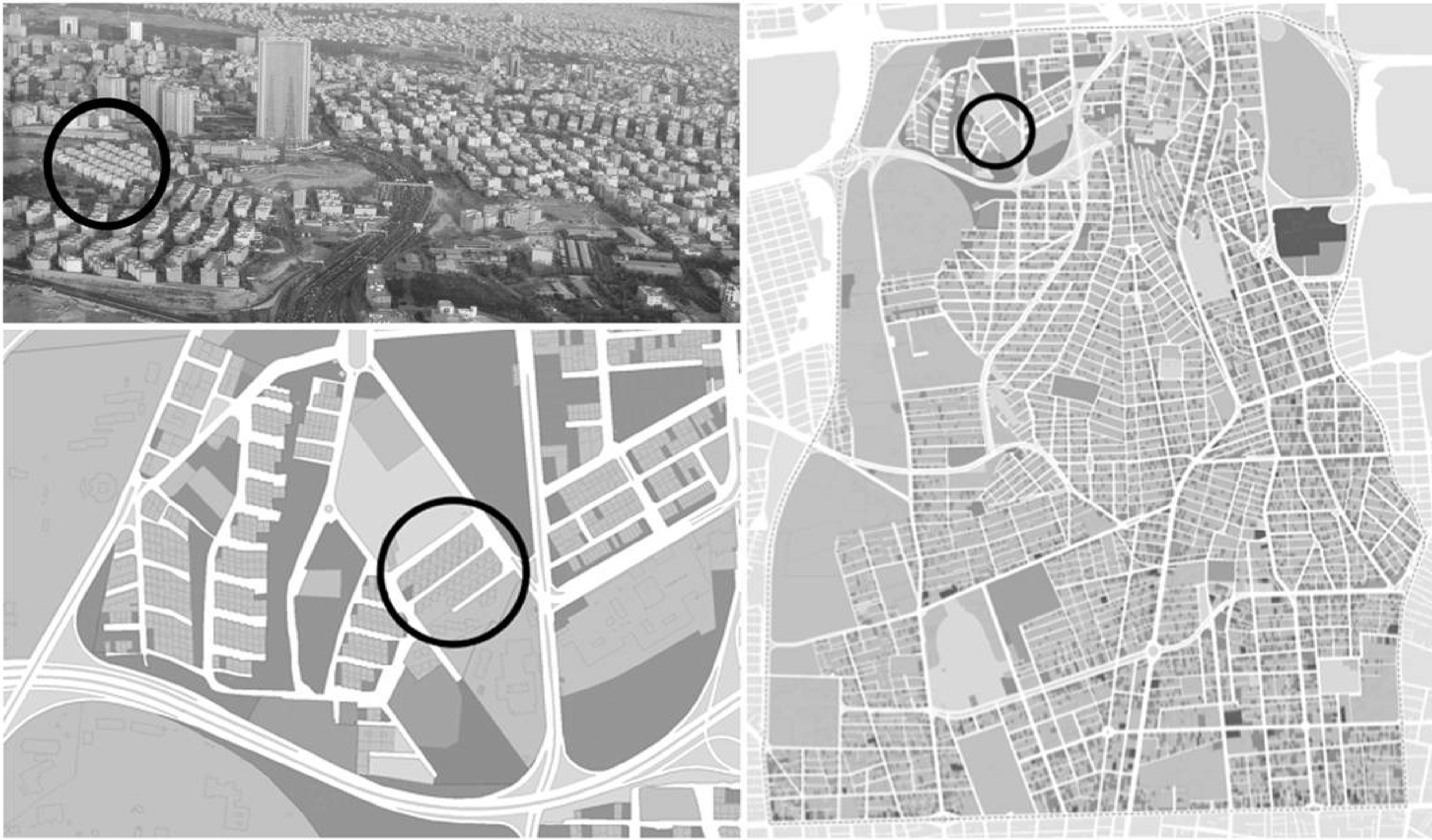



- High building density
- Low albedo

# Urban Heat Island Intensity (UHII)

| Type of land use | Percentage within 6th urban district | Area (h) |
| --- | --- | --- |
| **impervious surface area (pavement , buildings)** | 97,37% | 2087,52 |
| **vegetation (tree canopy and ground level vegetation)** | 2,4% | 51,57 |

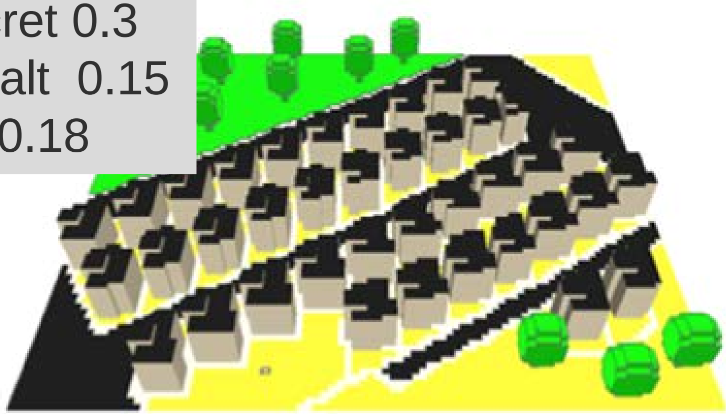
# Simulation for Tehran (6th urban district)



# Simulation for Tehran (6th urban district)

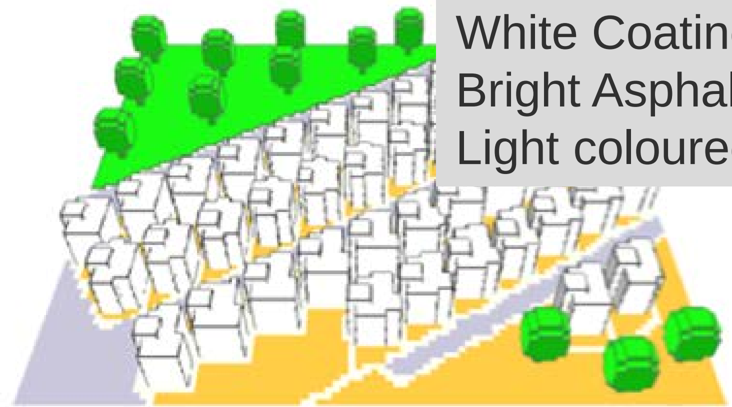
Current Situation (SC)

Concret 0.3
Asphalt 0.15
Soil 0.18

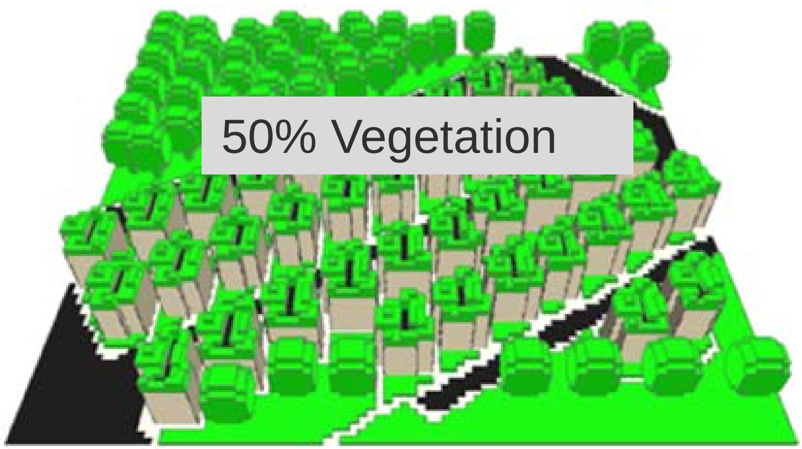


High Albedo Material (HAM)

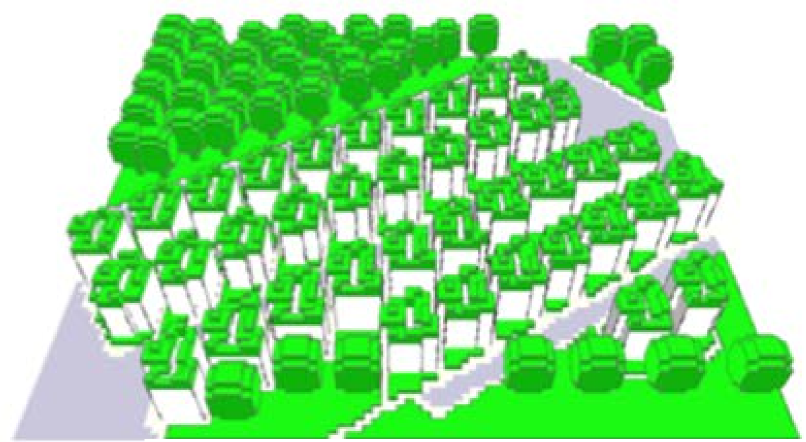
White Coating 0.85
Bright Asphalt 0.55
Light coloured Soil 0.38



50% Vegetation



Green scenario (VEG)



HYBRID: HAM+ VEG

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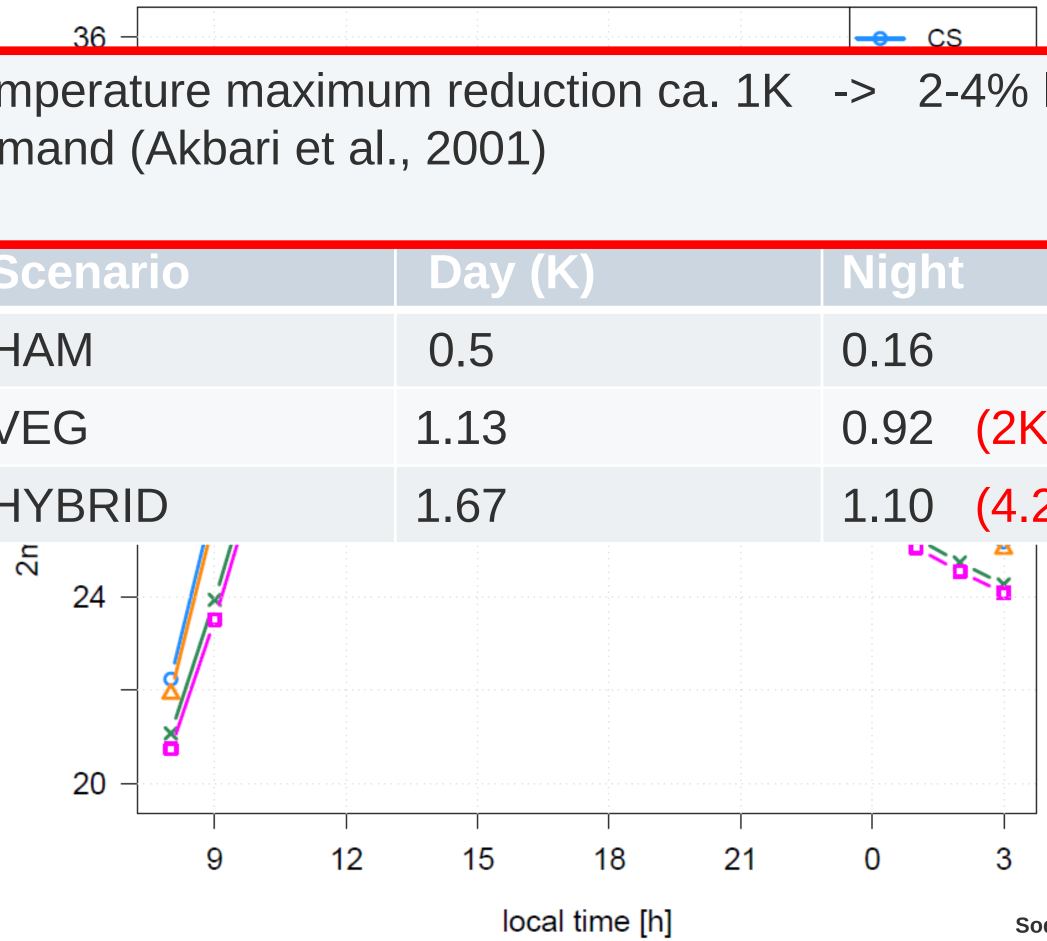
# Improving micro climate /Energy demand

Temperature maximum reduction ca. 1K -> 2-4% less energy demand (Akbari et al., 2001)

| Scenario | Day (K) | Night |
|---|---|---|
| HAM | 0.5 | 0.16 |
| VEG | 1.13 | 0.92 (2K) |
| HYBRID | 1.67 | 1.10 (4.2 K) |




Sodoudi et al., 2014

# Outcome of the project (1)

## Outcome of UHI mitigation project / Questions

Green scenario brings more cooling

Which spatial configuration of greenery?

Are the mitigation strategies applicable for the whole city?

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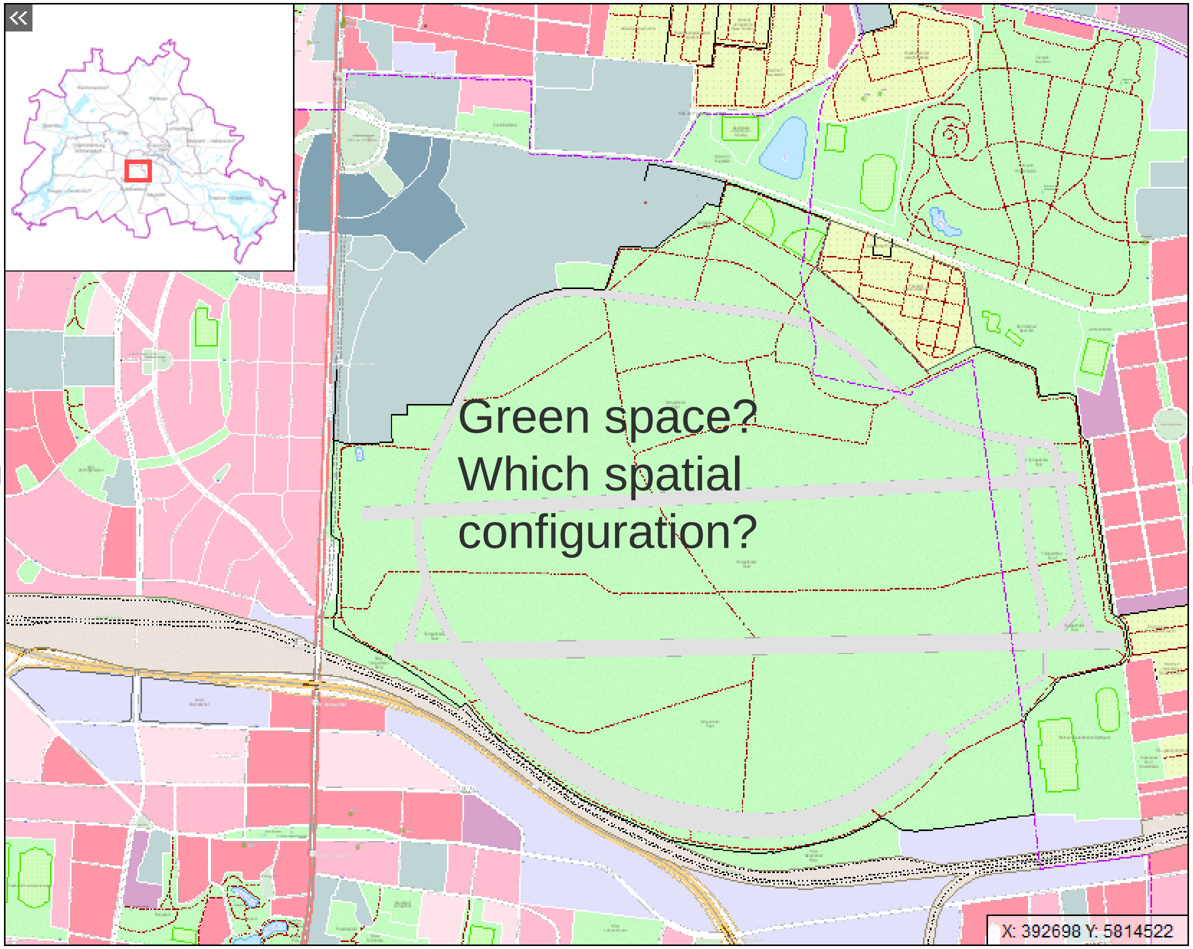
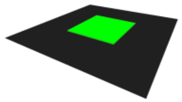
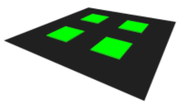
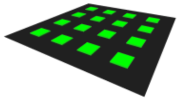
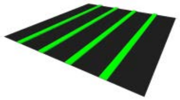
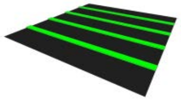
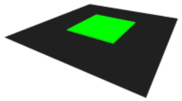
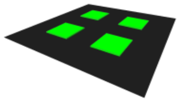
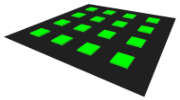
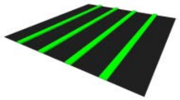
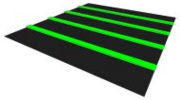
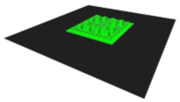
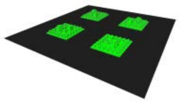
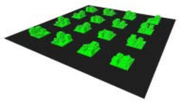
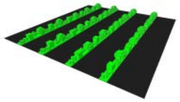
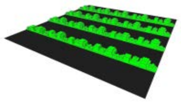
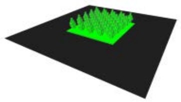
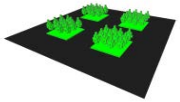
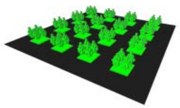
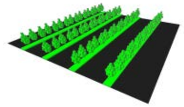
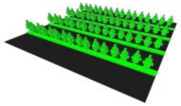
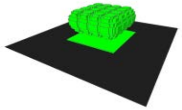
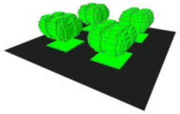
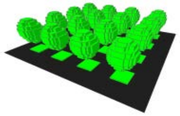
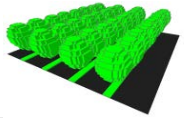
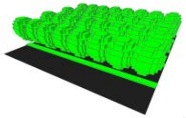
# Project Tempelhof Redevelopement

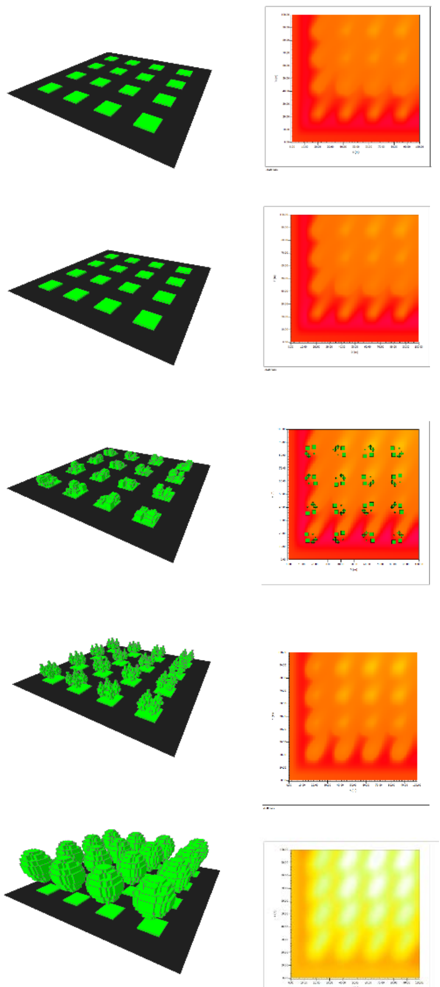



Geoportal [2015] / ATKIS® Basis-DLM-Präsentationsmodell

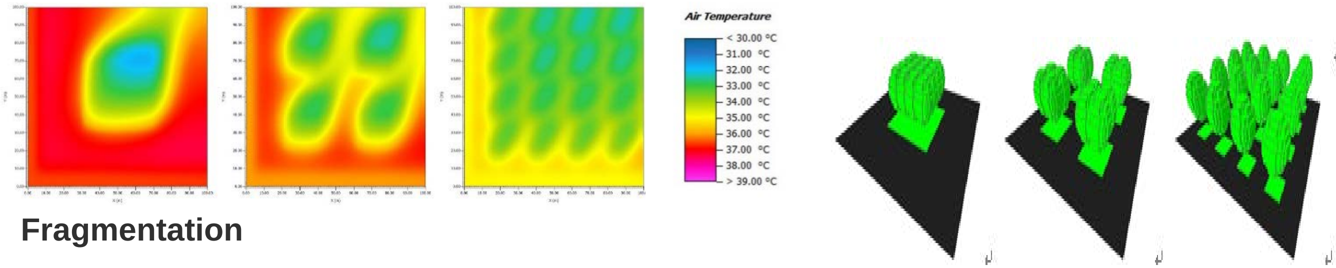
# Scenarios Table (25 types of scenarios)

| Configuration/ Type of Vegetation | 50X50m<br>Area 1 | 25X25m<br>Area 2 | 12.5X12.5m<br>Area 3 | 100X6.25m (NS)<br>Area 4 | 100X6.25m (WE)<br>Area 5 |
|---|---|---|---|---|---|
| Grass 10cm |  |  |  |  |  |
| Grass 50cm |  |  |  |  |  |
| Hedges & Shrubs |  |  |  |  |  |
| Trees-small canopies |  |  |  |  |  |
| Trees-big canopies |  |  |  |  |  |

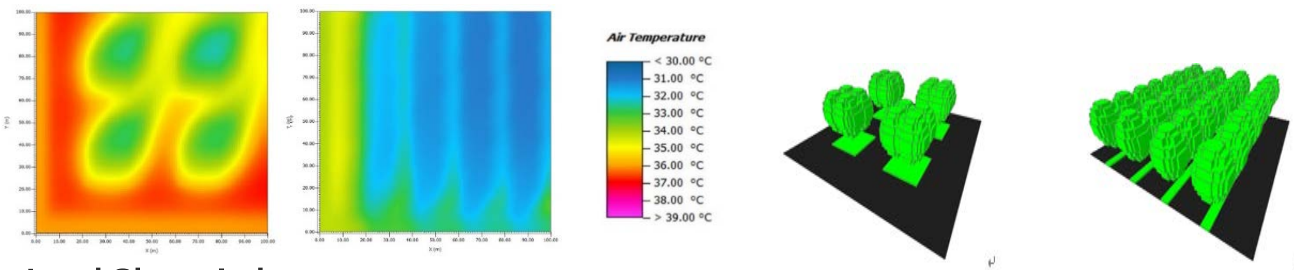
# Simulation Results



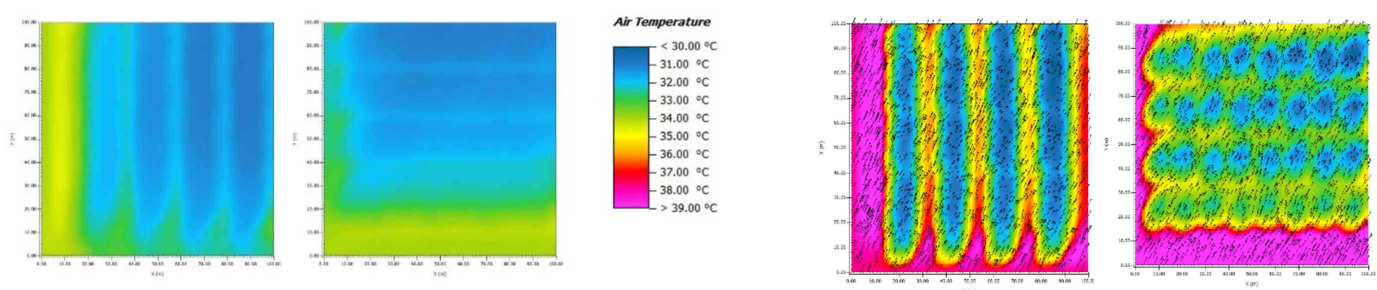
Vegetation Type




Fragmentation




Land Shape Index




Orientation

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# Outcome of the Project (2)

## Outcome of  the Project Tempelhof Redevelopment

Spatial configuration/type of green spaces is imporatnt

Wind direction plays an imporatnt role in cooling

Size of tree´s canopy/shade is the most important factor for cooling and improving thermal comfort

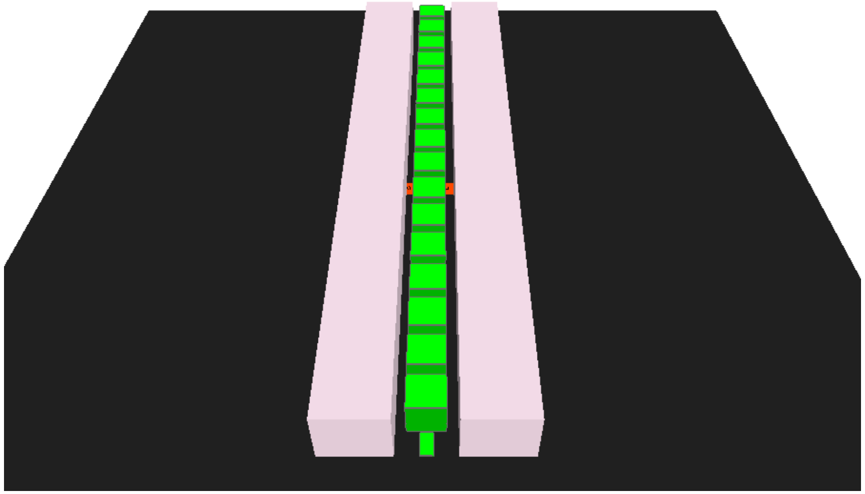
# Can we apply the same scenarios for the whole city?

Two different configurations

Street canyon orientation:

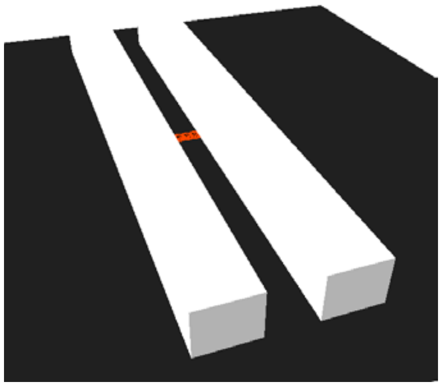
East-West with wind from the West

North-South with wind from the South

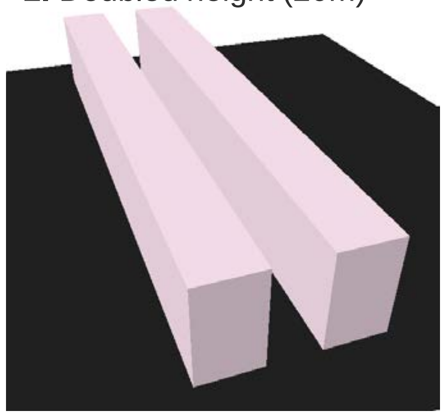


# Selected Mitigation strategies

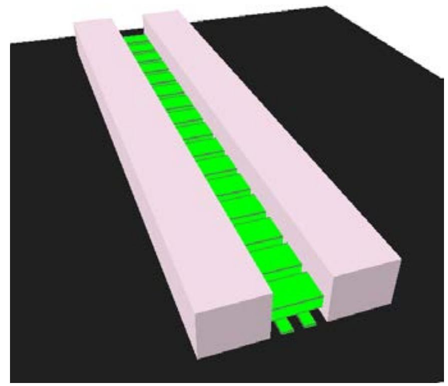
**1.** Material with high albedo



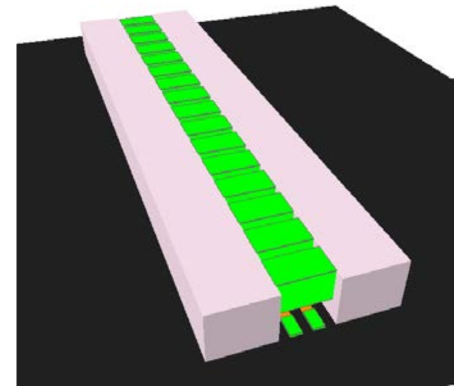
**2.** Doubled height (20m)



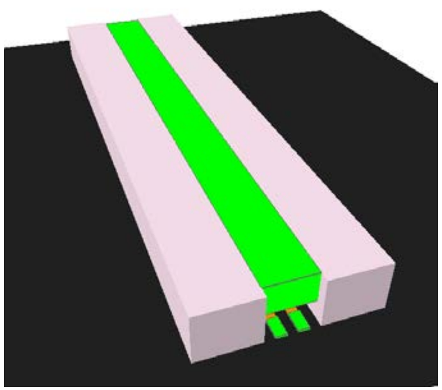
**3.** 16 young trees, on both sides



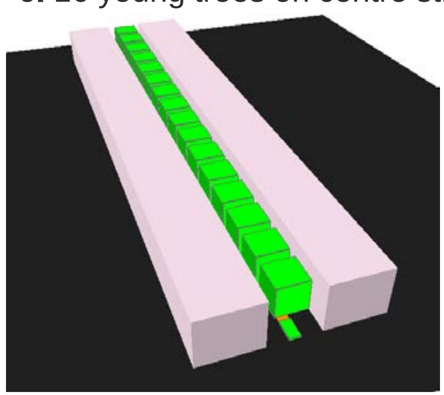
**4.** 16 big trees, on both sides



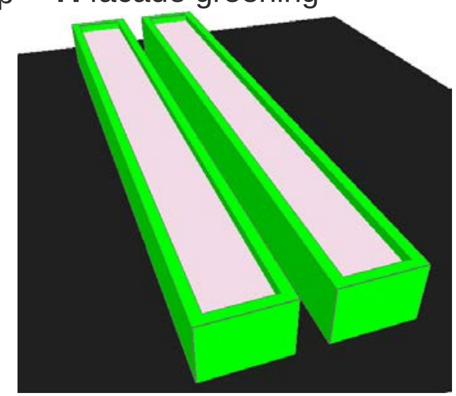
**5.** 32 big trees, on both sides



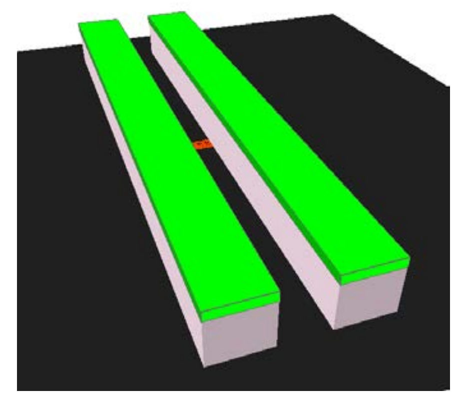
**6.** 16 young trees on centre strip



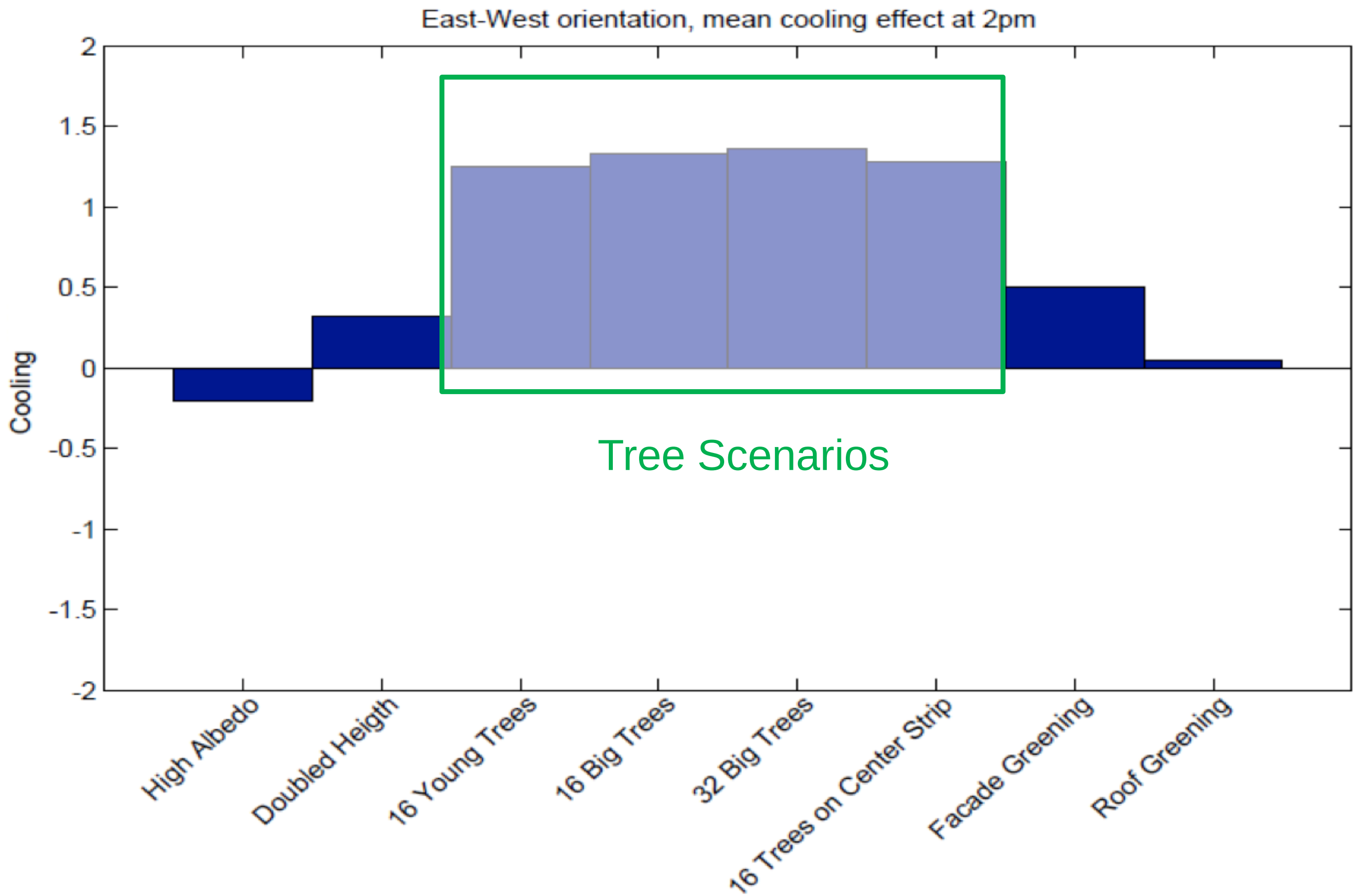
**7.** facade greening



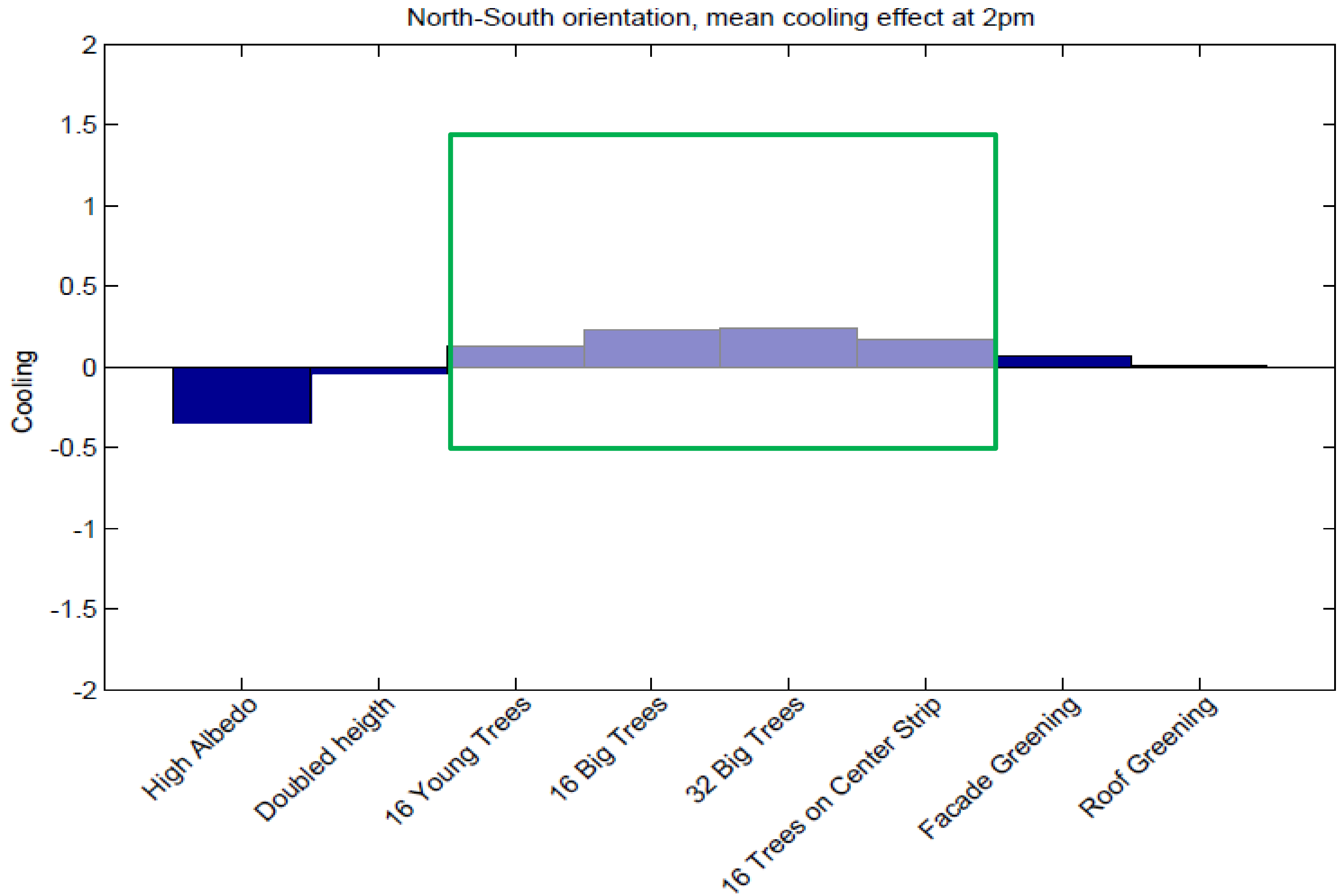
**8.** roof greening



# Effectiveness of Strategies for E-W Orientation



# Effectiveness of Strategies for N-S Orientation



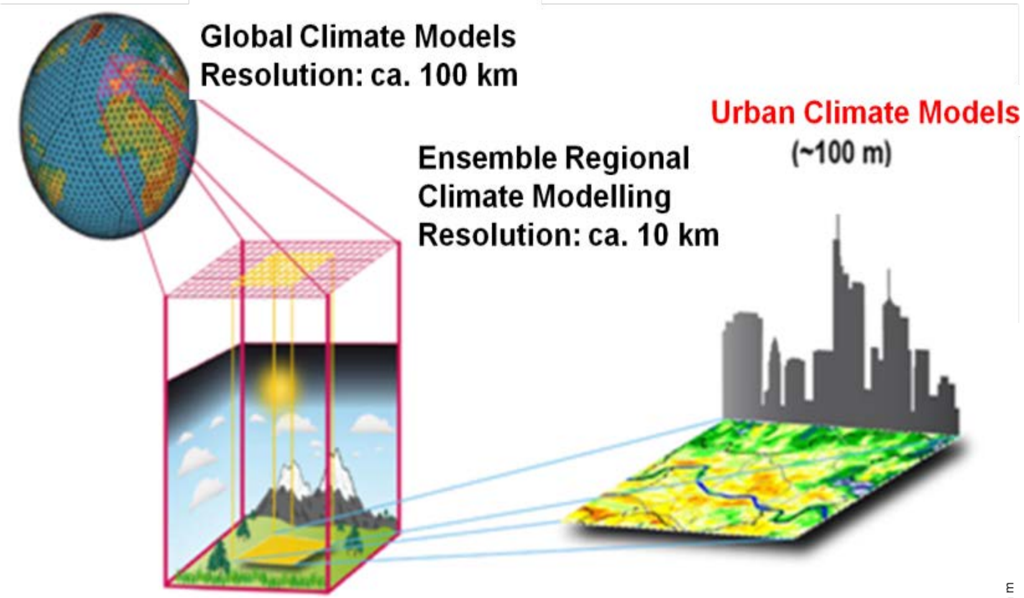
# Outcome of the Project (3)

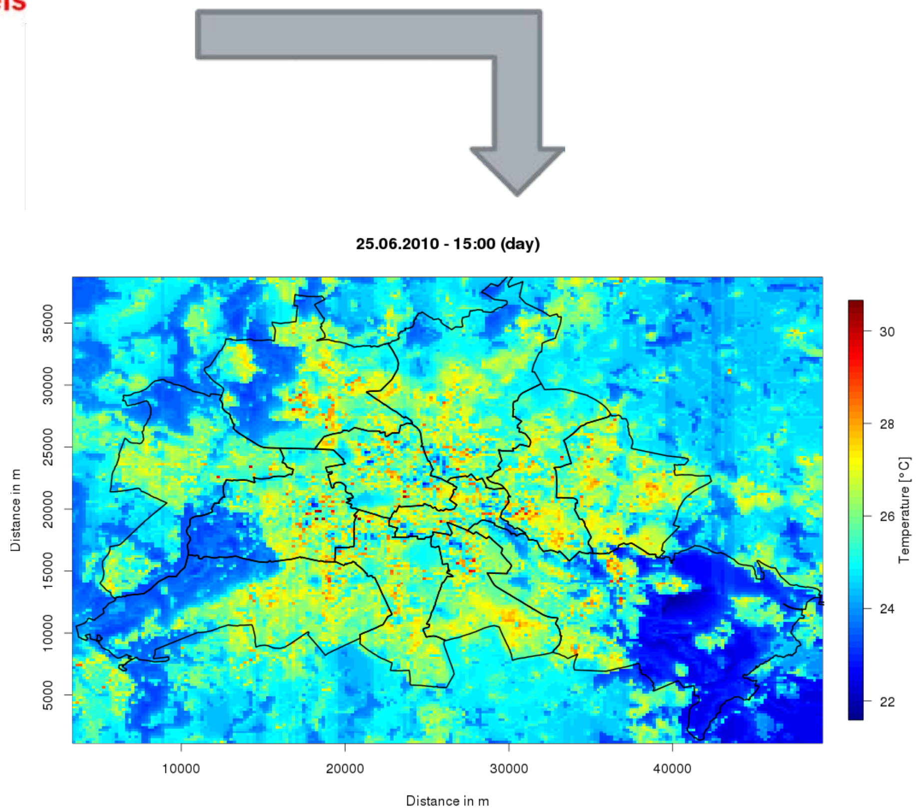
## Outcome of  the Project „Street canyon orientation“

Effective scenarios are not applicable for the whole city

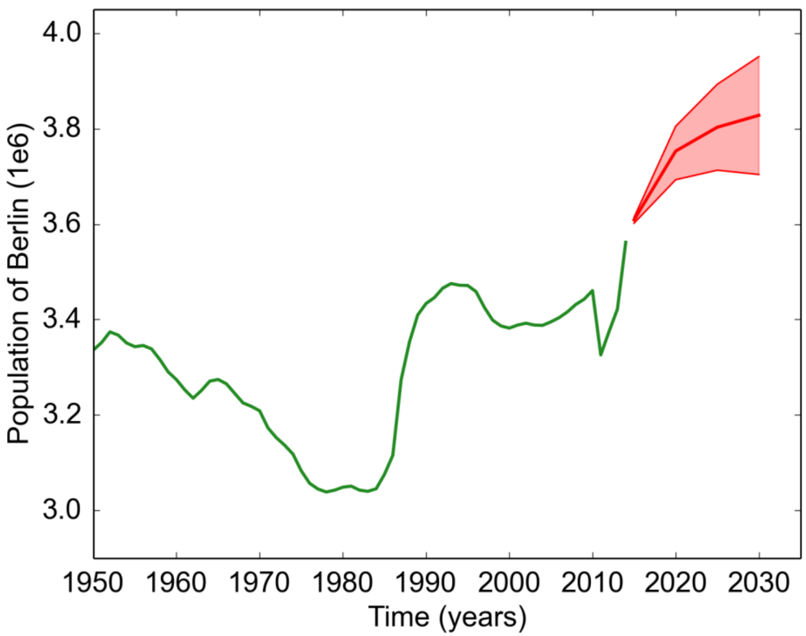
Important: urban climate model to cover the whole urban area

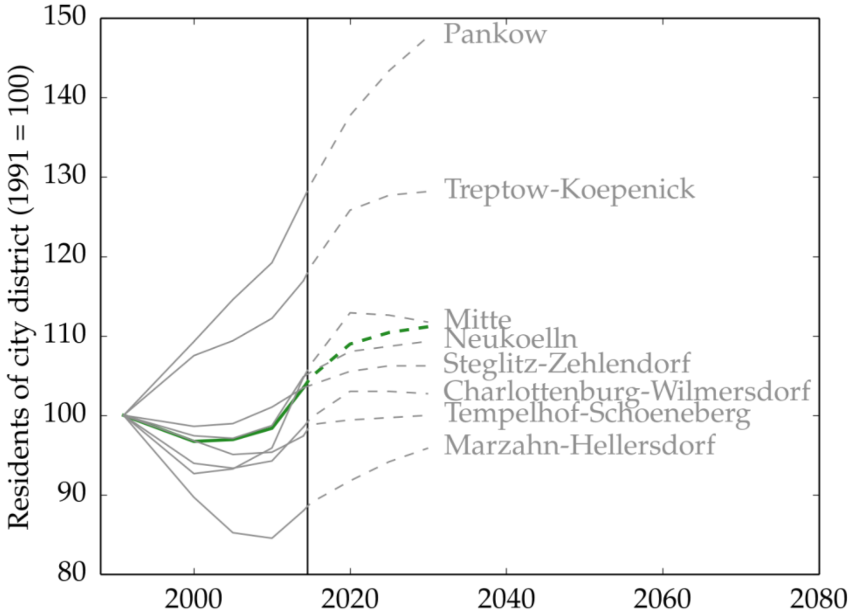
# Urban Climate Model MUKLIMO_3



# How can we generate new living spaces in Berlin?




Senatsverwaltung für Stadtentwicklung und Umwelt der Stadt Berlin (2016). Bevölkerungsprognose für Berlin und die Bezirke 2015-2030.

enhanced compactness (Nachverdichtung) as strategy to cope with population growth

How can building design support the provision of living space while maintaining/improving urban micro-climate?[1,2]

[1]M. Linsenmeier, S. Sodoudi, H. Schlünzen (in preparation)

[2]M. Straka & S. Sodoudi (in preparation)

# Solution: Compactness (horizontal and vertical)

- Horizontal compactness (buildings on wastelands)
- Vertical compactness (20m)
- Vertical compactness (30m)
- Vertical compactness (40m)

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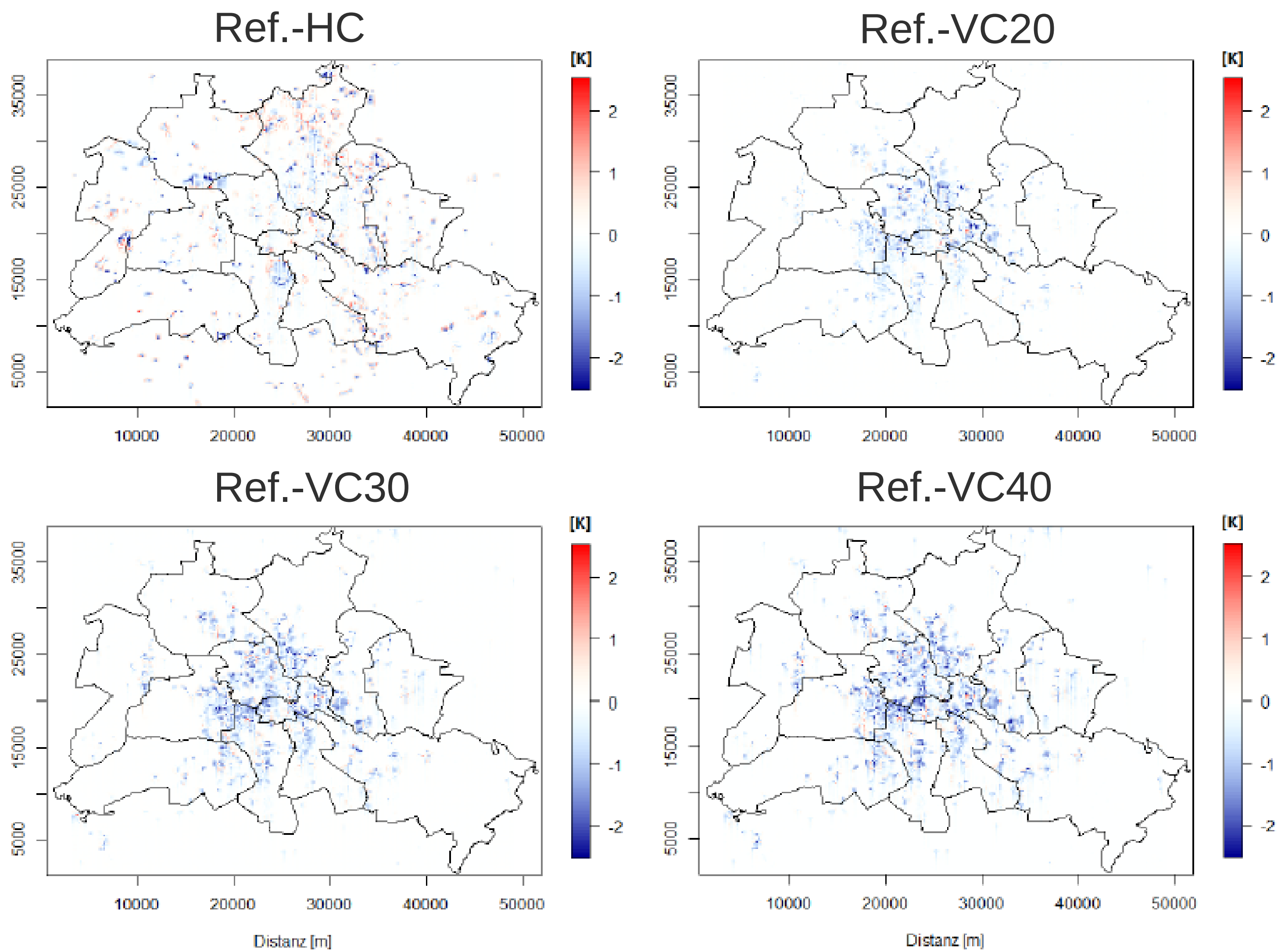
# Vertical and horizontal compactness (day time)




- Horizontal compactness (buildings on wastelands)
- Vertical compactness (20m)
- Vertical compactness (30m)
- Vertical compactness (40m)

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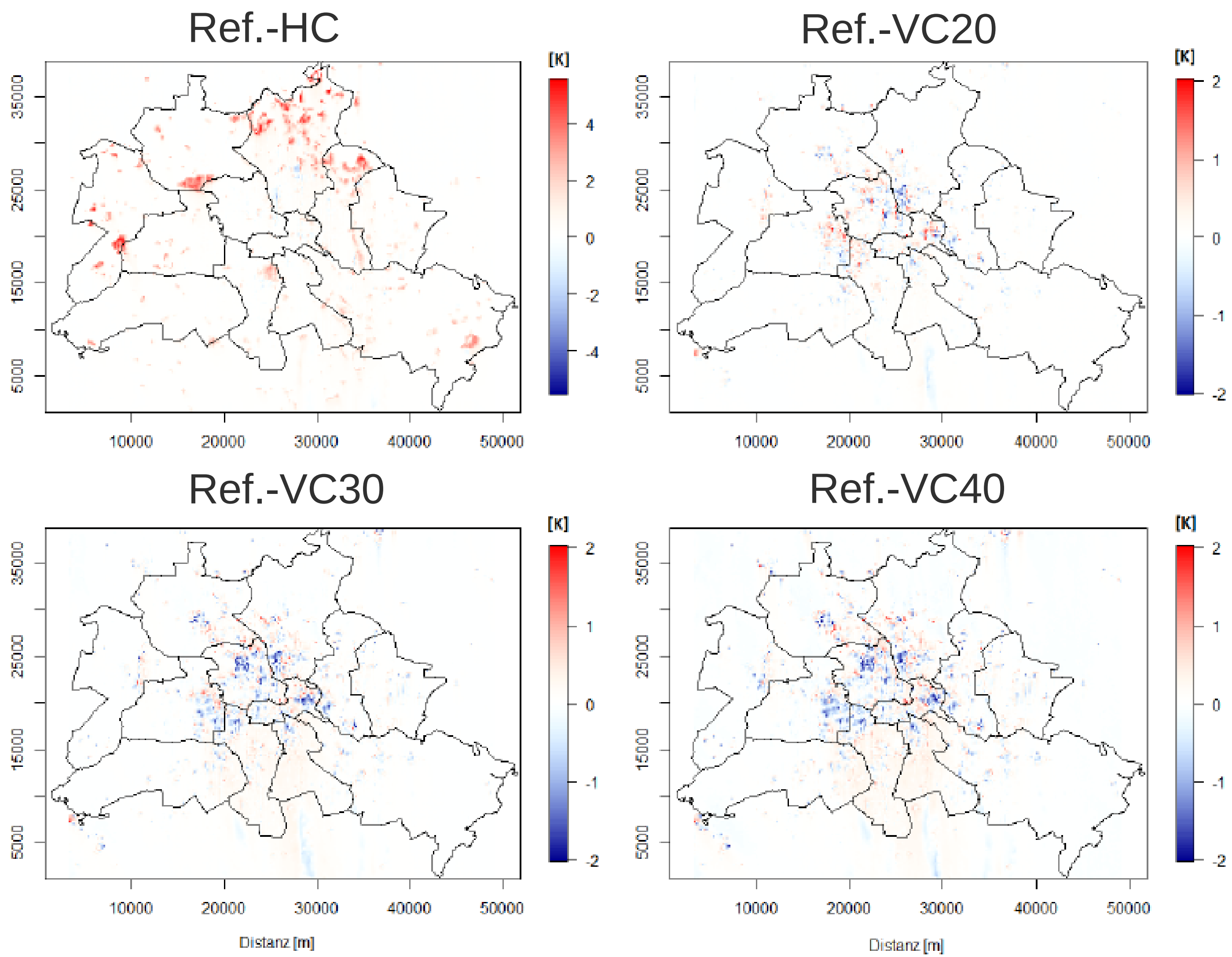
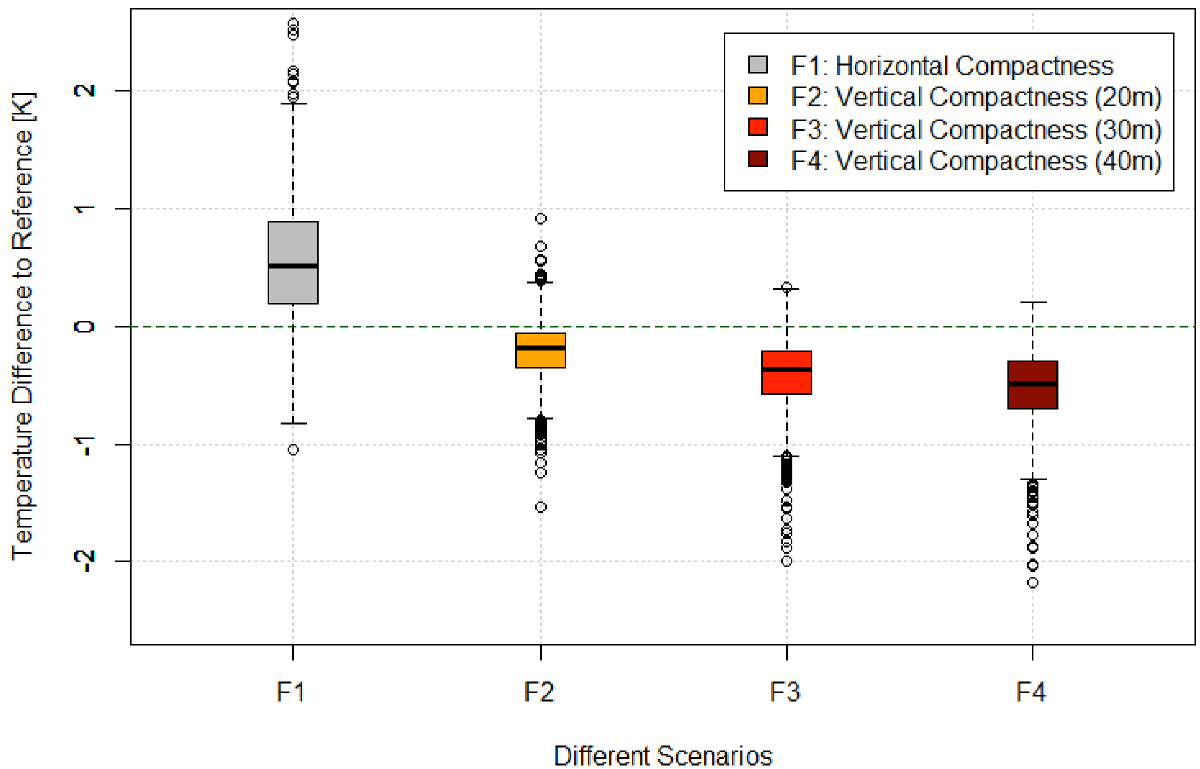
# Vertical and horizontal compactness (night time)




| |
|---|
| Horizontal compactness (buildings on wastelands) |
| Vertical compactness (20m) |
| Vertical compactness (30m) |
| Vertical compactness (40m) |

# Vertical and horizontal compactness



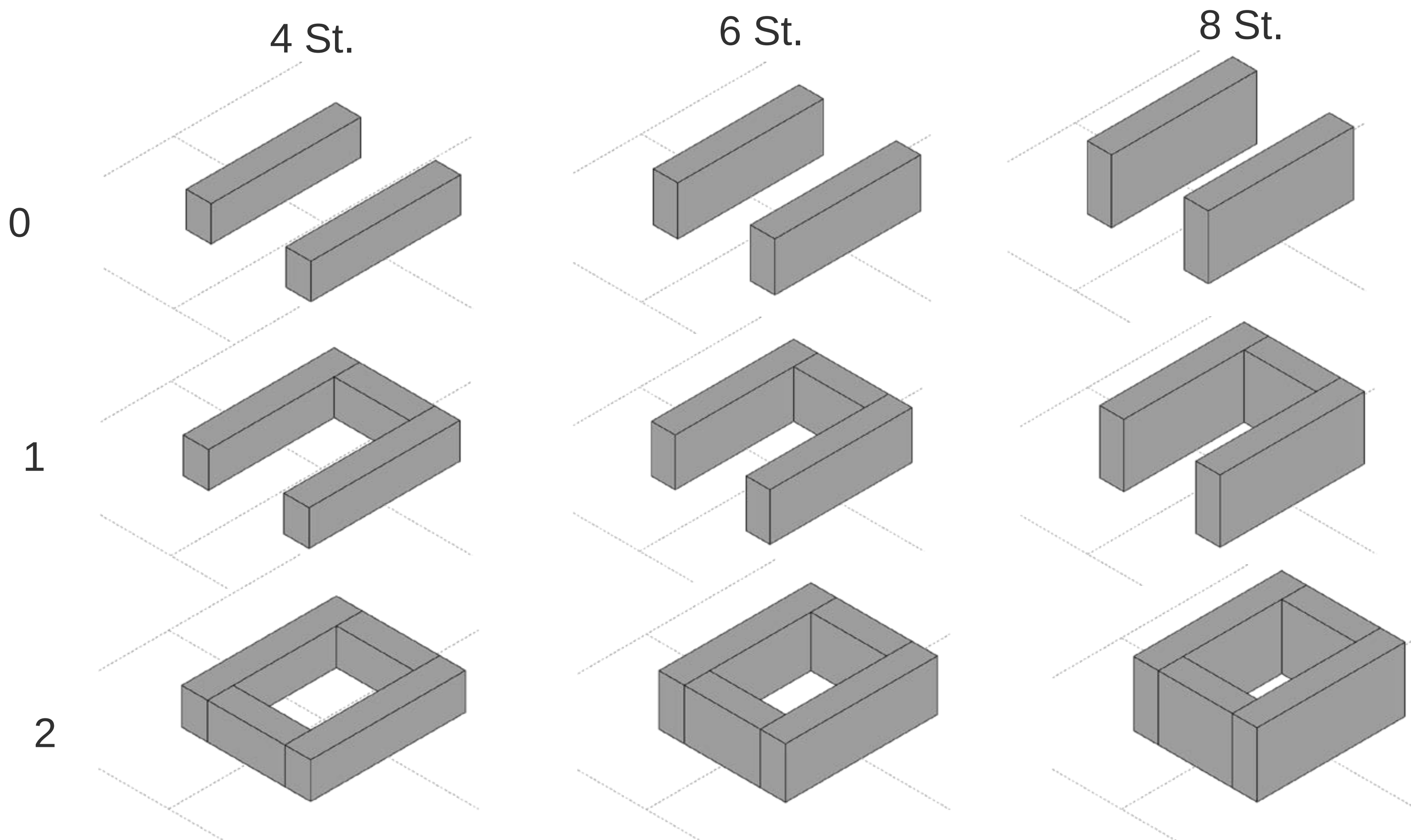

Vertical compactness shows a cooling effect for the city, horizontal compactness does not.

higher buildings bring more shade

horizontal compactness increases shade in the daytime

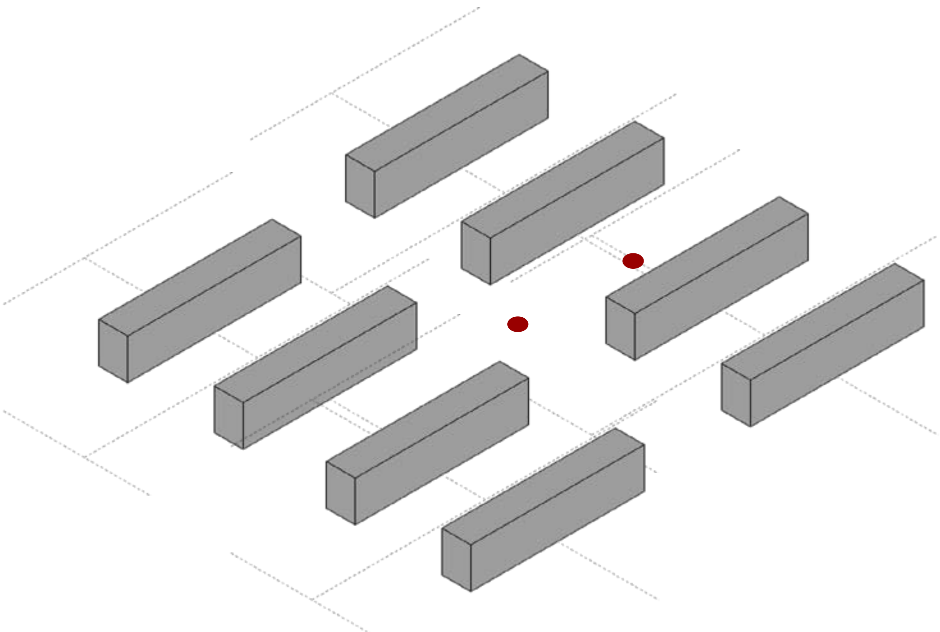
horizontal compactness decreases outgoing radiation during the night

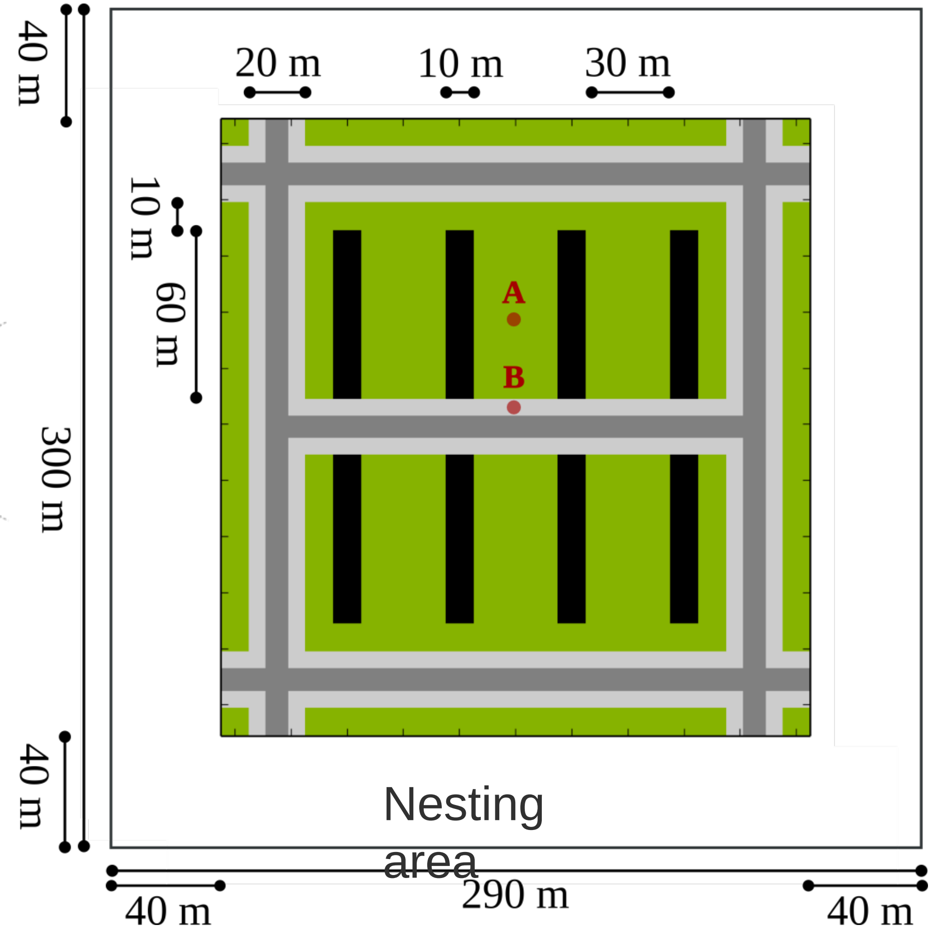
# Building scenarios




three different building heights (14 m, 20 m, 26 m)

# Building scenarios and model domain

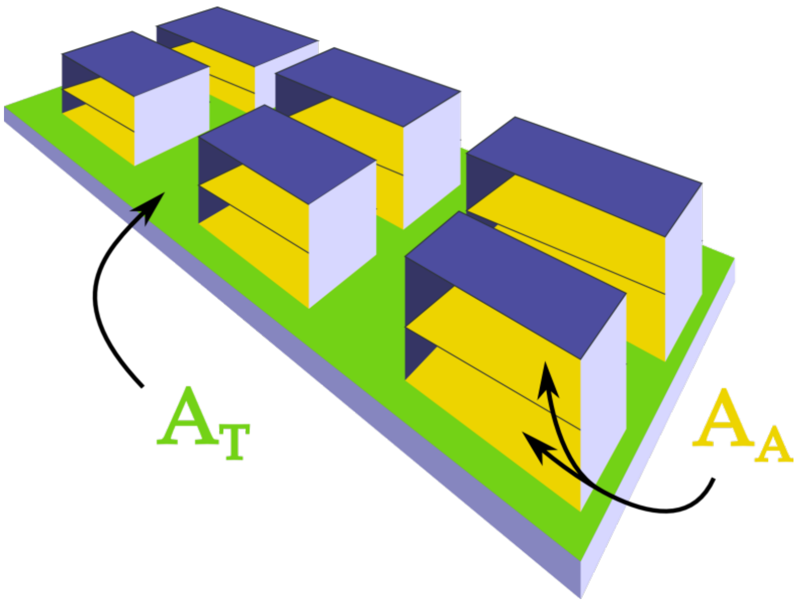




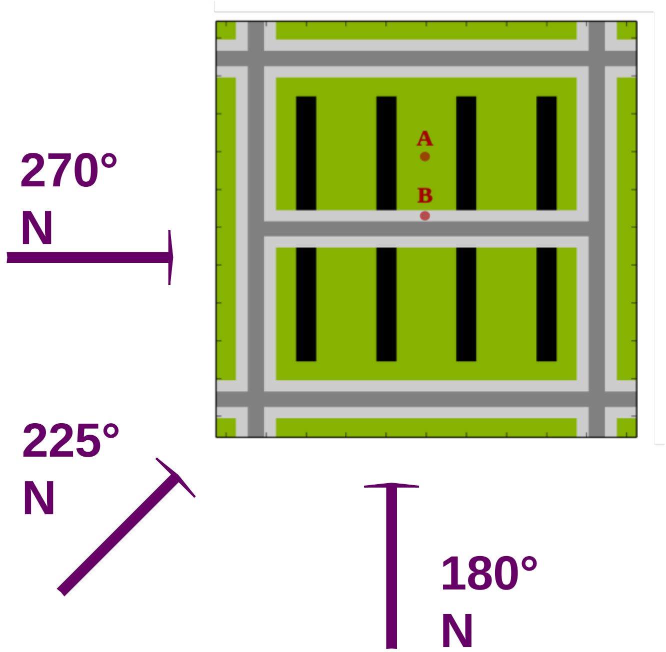

● Assessment areas/locations

## Urban compactness and wind directions

Index of **compactness** : $\dfrac{\text{Total ground floor area of buildings}}{\text{Total surface area of the model domain}}$




Three **wind directions**:



# Outdoor thermal comfort

- Expressed using the Universal Thermal Comfort Index (UTCI)

Based on four meteorological fundamentals: air temperature, relative humidity, radiation, wind speed
Distinction between day-time and night-time: hours with and hours without sun
Day-time: hours with less than strong heat stress
Night-time: mean UTCI below moderate heat stress

| UTCI (°C) range | Stress Category |
|---|---|
| above +46 | extreme heat stress |
| +38 to +46 | very strong heat stress |
| +32 to +38 | strong heat stress |
| +26 to +32 | moderate heat stress |
| +9 to +26 | no thermal stress |
| +9 to 0 | slight cold stress |

# Evaluation of thermal comfort

Day-time:

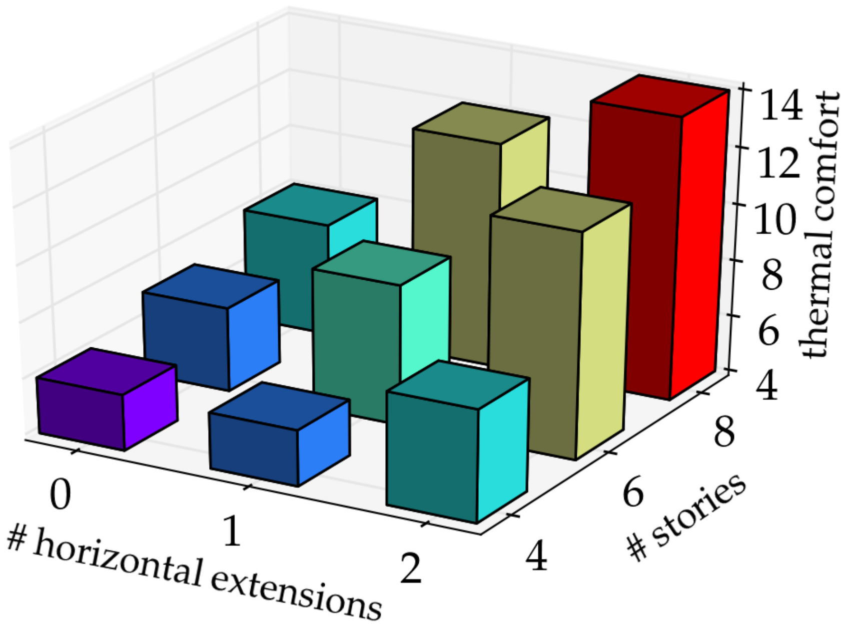
Index = 16 h (length of day) – (hours with strong heat stress)

Night-time:

Index = 26° (threshold of moderate heat stress) – (mean value of UTCI during the night)

# Results: Day-time thermal comfort

Wind direction **270°N** (assessed at B)*

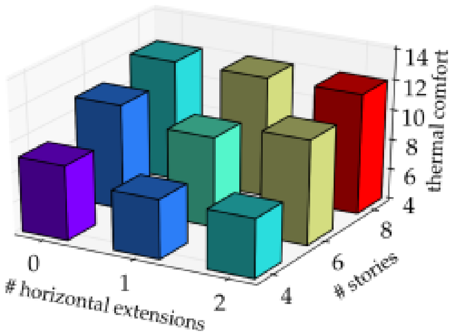



Day-time thermal comfort …

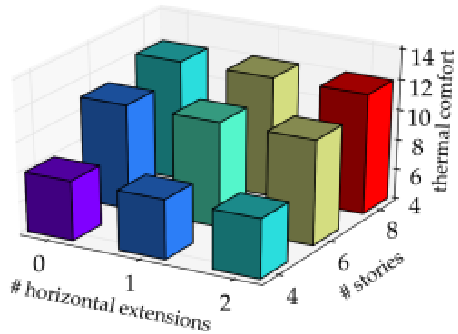
… increases with # stories,
... increases with # horizontal extensins,
=> generally increases with compactness,
... tends to be higher for vertically than for horizontally extended scenarios for equal

* Colour indicates the value of the index of compactness .

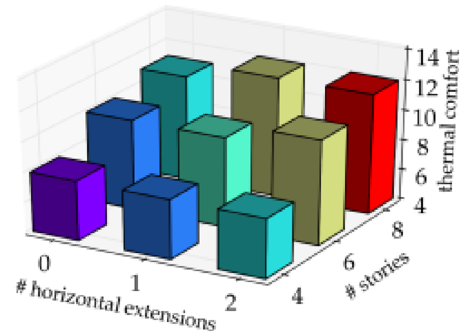
# Results: Different wind directions and assessment areas (B=SS, A=CY)



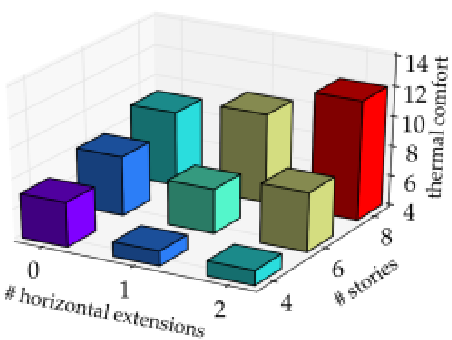

(a) CY 180



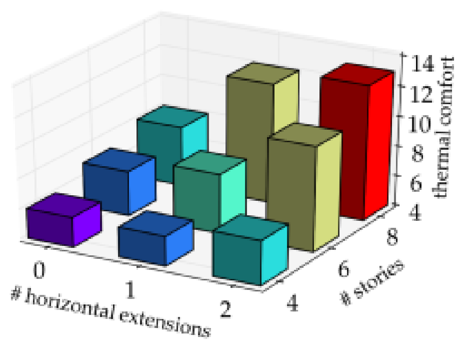

(b) CY 225



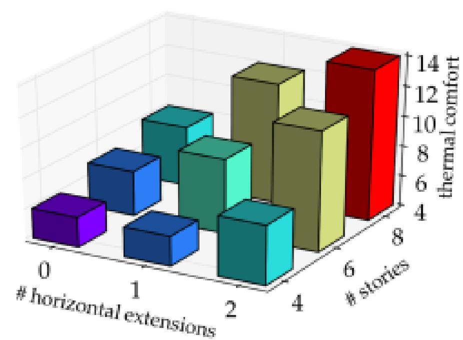

(c) CY 270




(d) SS 180




(e) SS 225




(f) SS 270

=> Pattern consistent across wind directions and assessment areas (except effect of horizontal extensions – improvements and deteriorations)

# Conclusions

- select effective mitigation strategies using numerical models or measurements
- Effective scenarios are not applicable for the whole city-> urban climate models
- Outdoor microclimate/ Human thermal comfort/ Energy efficiency
- Dialogue between urban climatologist and stake holders

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# Thank you for your attention!

# Vertical and horizontal compactness

| Sceanrio | Mean difference of 2m-temperature (3 pm) – modified LU | Mean difference of 2m-temperature (2 am) – modified LU | Mean difference of 2m-temperature – modified LU | Mean difference of 2m-temperature whole area |
|---|---|---|---|---|
| Horizontal compactness (buildings on wastelands) | 0,81 (***) | -2,30 (***) | -0,55 (***) | -0,08 (***) |
| Vertical compactness (20m) | 0,49 (***) | -0,03 (***) | 0,21 (***) | 0,00 (p = 0,16) |
| Vertical compactness (30m) | 0,61 (***) | 0,23 (***) | 0,41 (***) | 0,02 (***) |
| Vertical compactness (40m) | 0,71 (***) | 0,37 (***) | 0,52 (***) | 0,03 (***) |

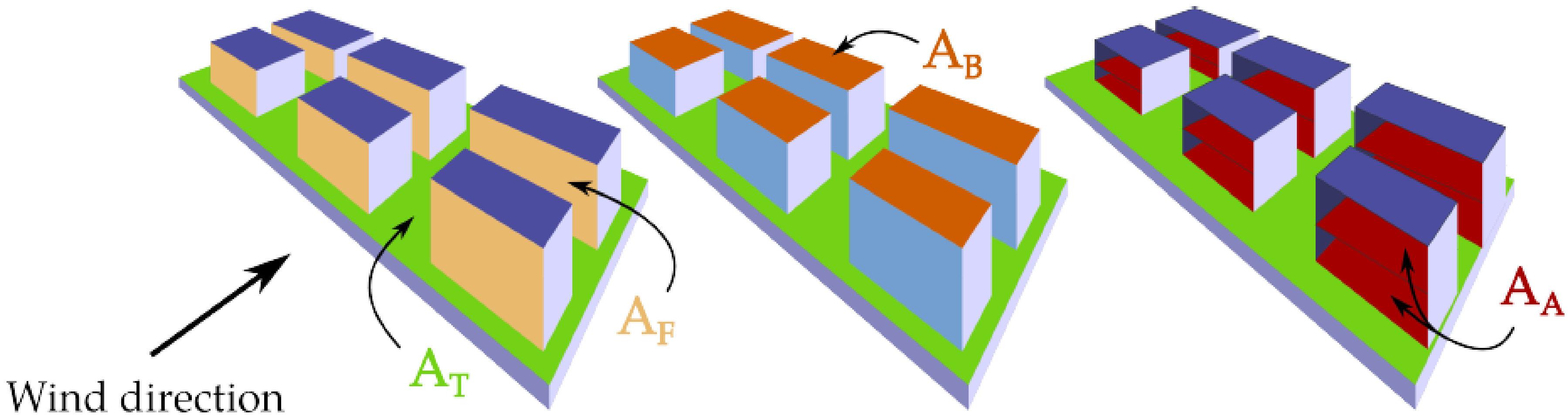
Significant differences with p > 0,05 *(*: 0,05, **: 0,01, ***: >0,01)*

Vertical compactness shows a cooling effect for the city, horizontal compactness does not.

- higher buildings bring more shade
- increase of radiative trapping can occur in dense built areas
- horizontal compactness increases shade in the daytime
- horizontal compactness decreases outgoing radiation during the night

# Compactness Indices






frontal area ratio

$$\lambda_F = \frac{A_F}{A_T}$$

building coverage ratio

$$\lambda_B = \frac{A_B}{A_T}$$

floor area ratio

$$\lambda_A = \frac{A_A}{A_T}$$

Figure 4: The location of the Michelangelostrasse in Berlin. (a) Map of Berlin and (b) zoom-in on the same map of Berlin. Source: OpenStreetMap.

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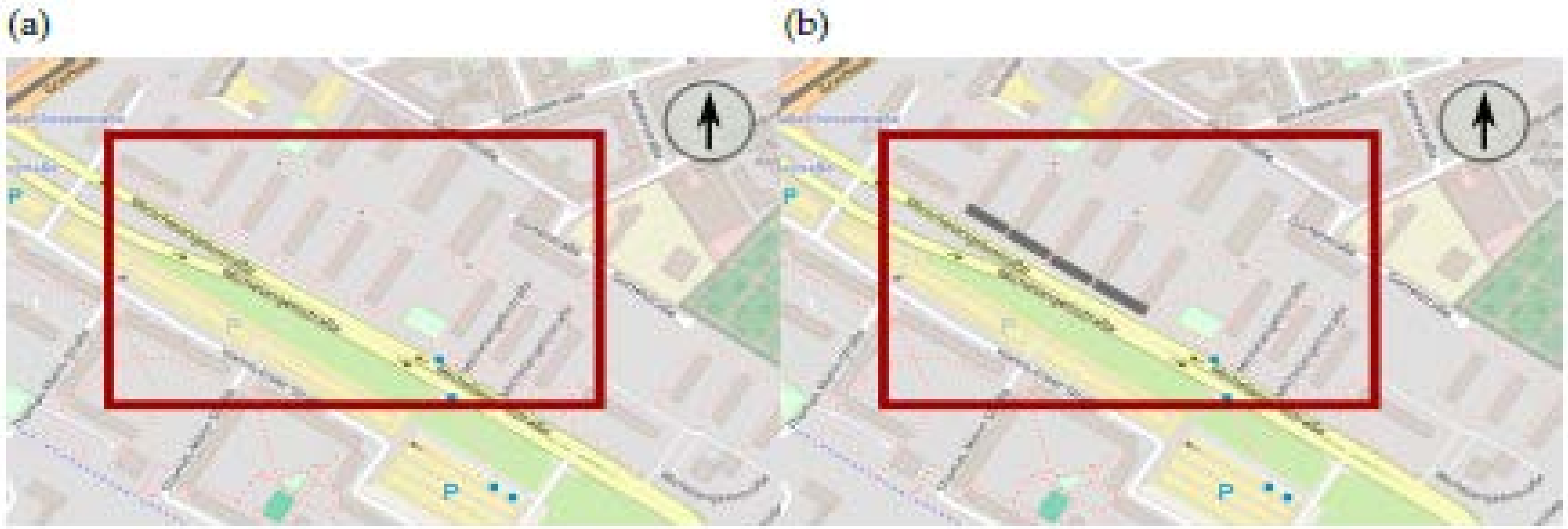


Figure 7: Map of the area around the Michelangelostraße. (a) Status quo and (b) planned modifications. Own illustration based on map from OpenStreetMap and plans provided by the Senate of Berlin.

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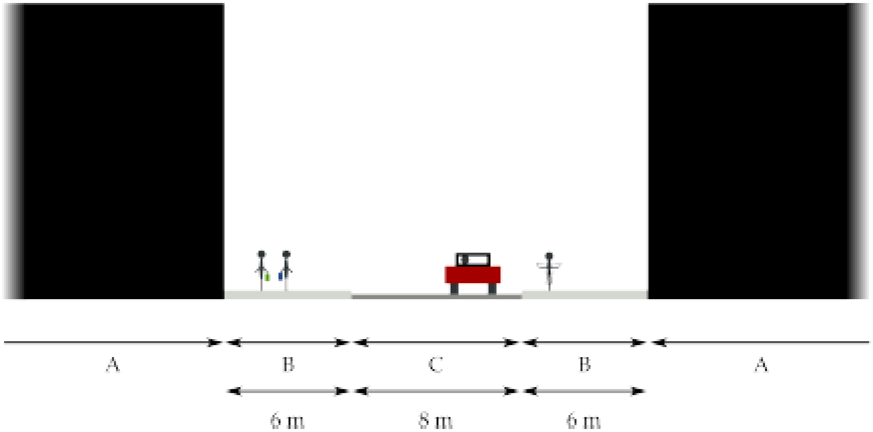
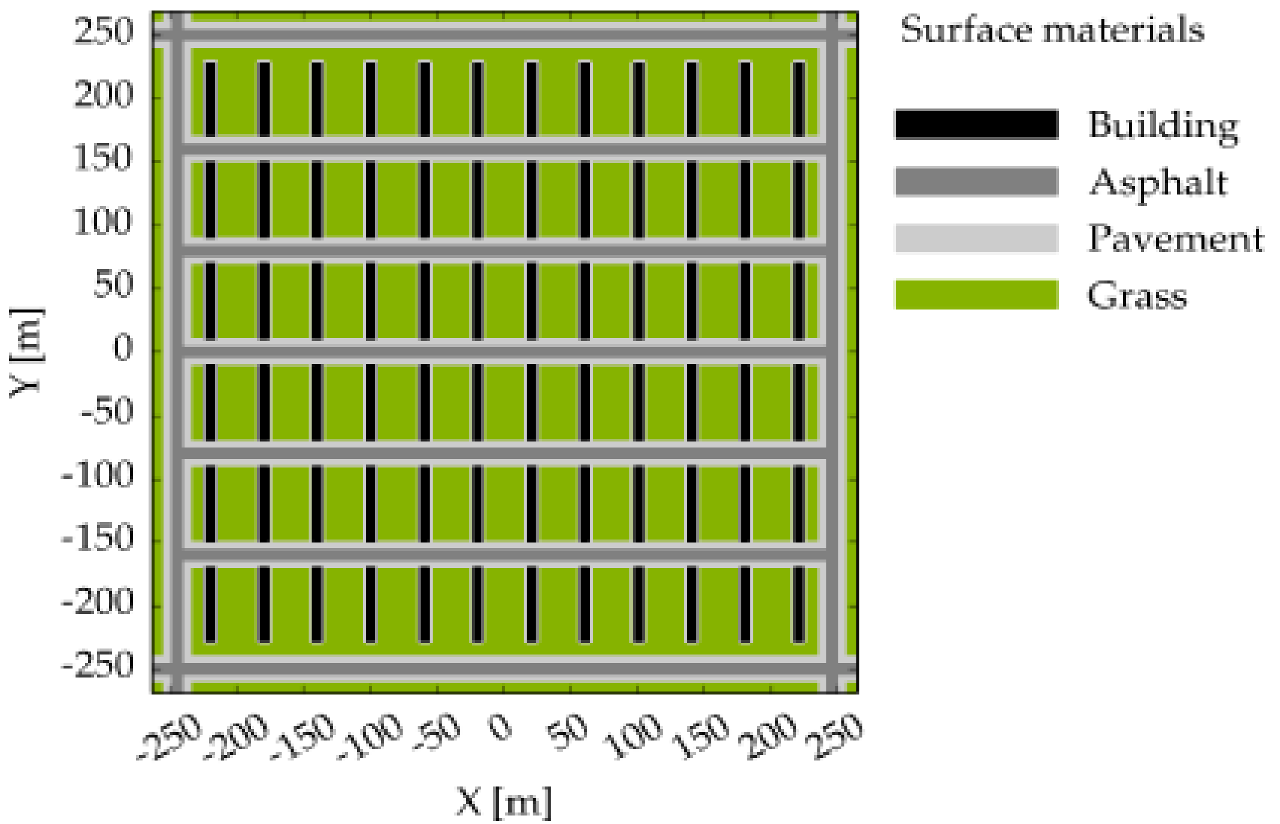



Figure 6: Cross-section through the street canyon, which is bounded by buildings (A) and consists of driving lanes (C) and side-walks including cycling lanes (B).


Surface materials
Building
Asphalt
Pavement
Grass
Y [m]
250
200
150
100
50
0
-50
-100
-150
-200
-250
X [m]
-250
-200
-150
-100
-50
0
50
100
150
200
250

29.03.2017

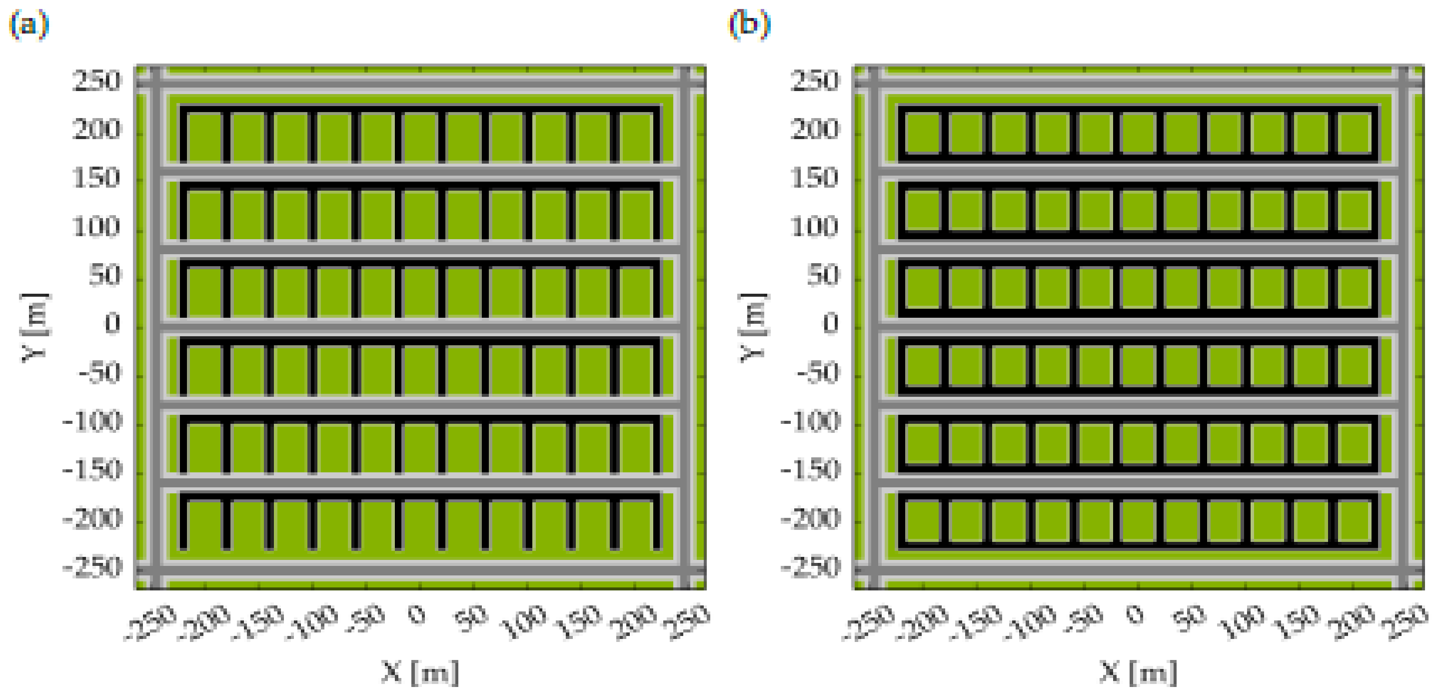



Figure 8: Model domain with (a) one and (b) two horizontal extensions. The colours indicate the same surface classes as in Figure 5.

Table 2: Attributes of the different building scenarios. Floor area of individual building block $F_A$, building height $H$ and width of the street canyon $W$. Based on core model area as in Figure 8 (530 m x 540 m) with 12 x 6 buildings. Indices of compactness of the reference scenario A4H0: $\lambda_P$ = 0.0176/0.00587/0.00415 (wind directions 270, 180, 225° N), $\lambda_B$ = 0.151, $\lambda_A$ = 0.604.

| | Attributes of building block | | | | | Indices of compactness | | |
|---|---|---|---|---|---|---|---|---|
| Building scenario | Storeys | Height [m] | Horiz. Ext. | $\hat{F}_A$ | $H/W$ | $\hat{\lambda}_P$ (270/180/225) | $\hat{\lambda}_B$ | $\hat{\lambda}_A$ |
| A4H0 | 4 | 14 | 0 | 1 | 0.7 | 1/1/1 | 1 | 1 |
| A4H1 | 4 | 14 | 1 | 1.5 | 0.7 | 1/3.75/3.75 | 1.46 | 1.46 |
| A4H2 | 4 | 14 | 2 | 2 | 0.7 | 1/3.75/3.75 | 1.92 | 1.92 |
| A6H0 | 6 | 20 | 0 | 1.5 | 1 | 1.43/1.43/1.43 | 1 | 1.5 |
| A6H1 | 6 | 20 | 1 | 2.25 | 1 | 1.43/5.36/5.36 | 1.46 | 2.19 |
| A6H2 | 6 | 20 | 2 | 3 | 1 | 1.43/5.36/5.36 | 1.92 | 2.88 |
| A8H0 | 8 | 26 | 0 | 2 | 1.3 | 1.86/1.86/1.86 | 1 | 2 |
| A8H1 | 8 | 26 | 1 | 3 | 1.3 | 1.86/6.96/6.96 | 1.46 | 2.92 |
| A8H2 | 8 | 26 | 2 | 4 | 1.3 | 1.86/6.96/6.96 | 1.92 | 3.83 |

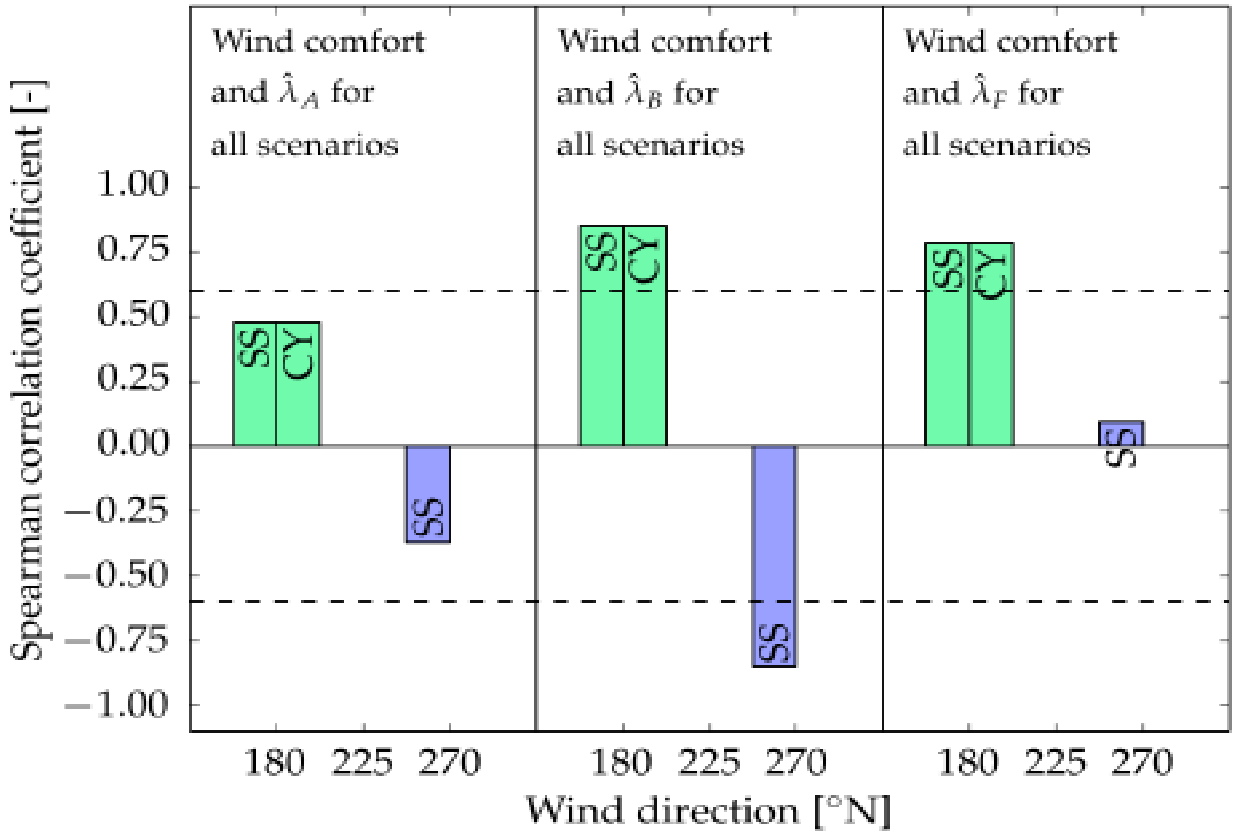



Figure 42: Correlation coefficients between indices of compactness and wind comfort for all nine building scenarios. The dashed horizontal line indicates significance of the correlation coefficient for $p = 0.05$.

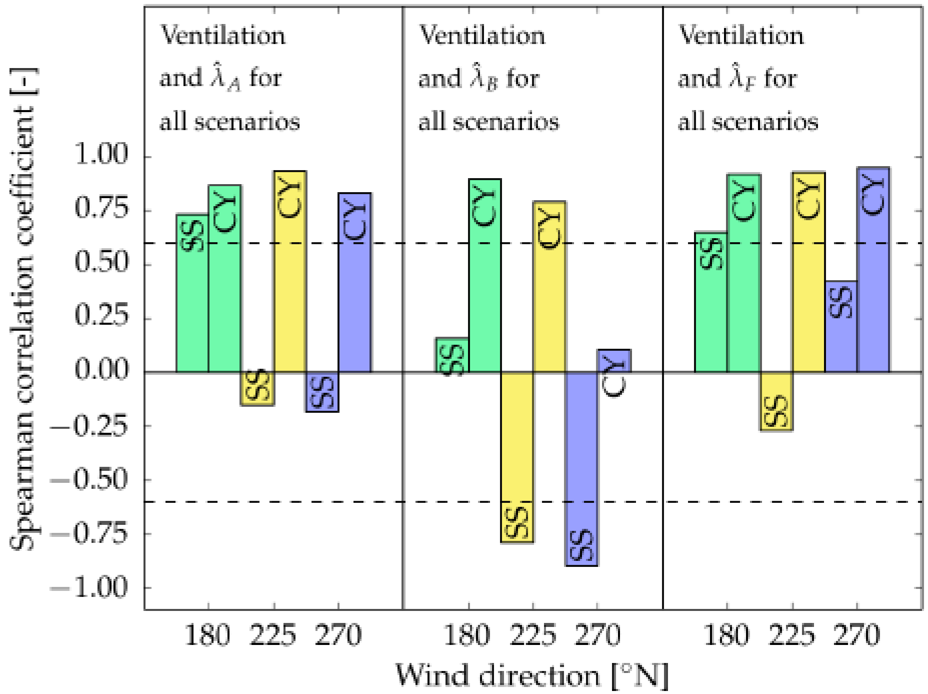



Figure 43: Correlation coefficients between indices of compactness and ventilation for all nine building scenarios. The dashed horizontal line indicates significance of the correlation coefficient for $p = 0.05$.

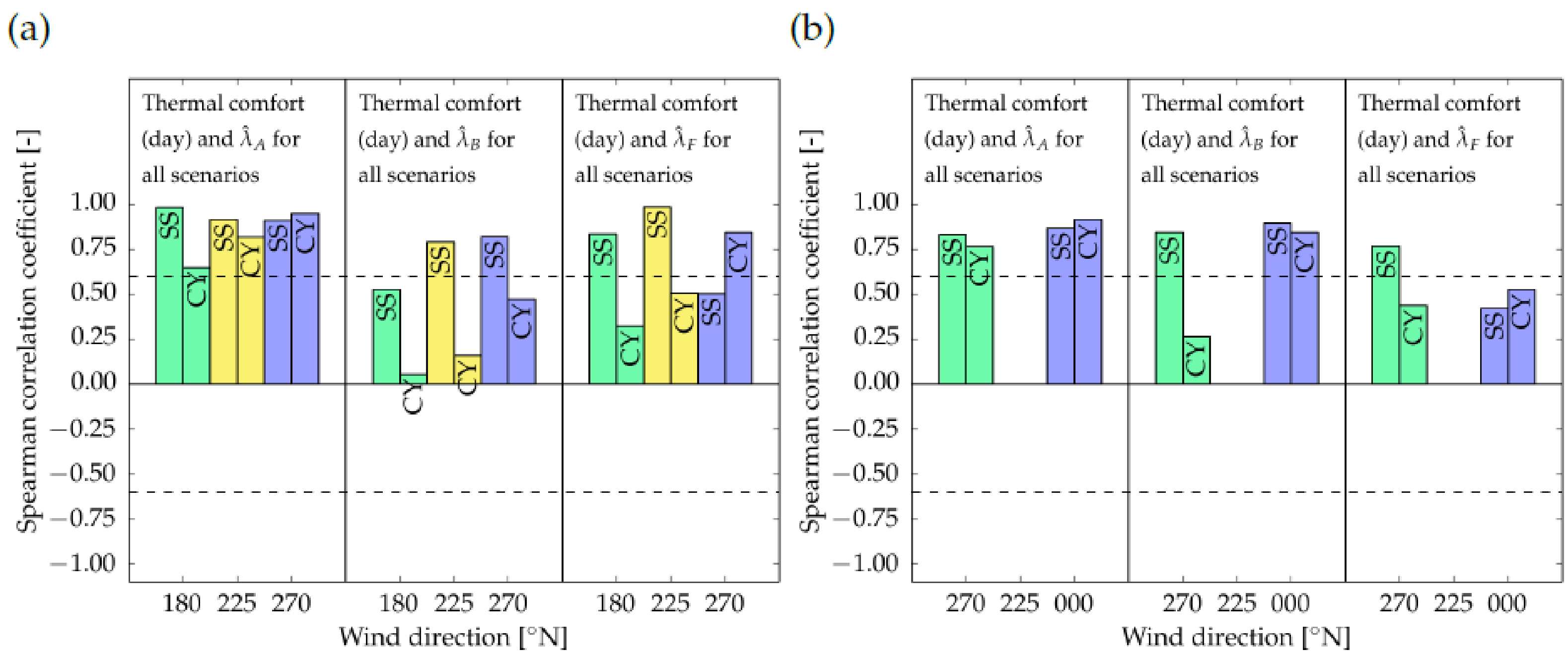



Figure 44: Correlation coefficients between indices of compactness and day-time thermal comfort for all nine building scenarios. (a) Model domain without rotation and (b) model domain with rotation by 90°. The dashed horizontal line indicates significance of the correlation coefficient for $p = 0.05$.

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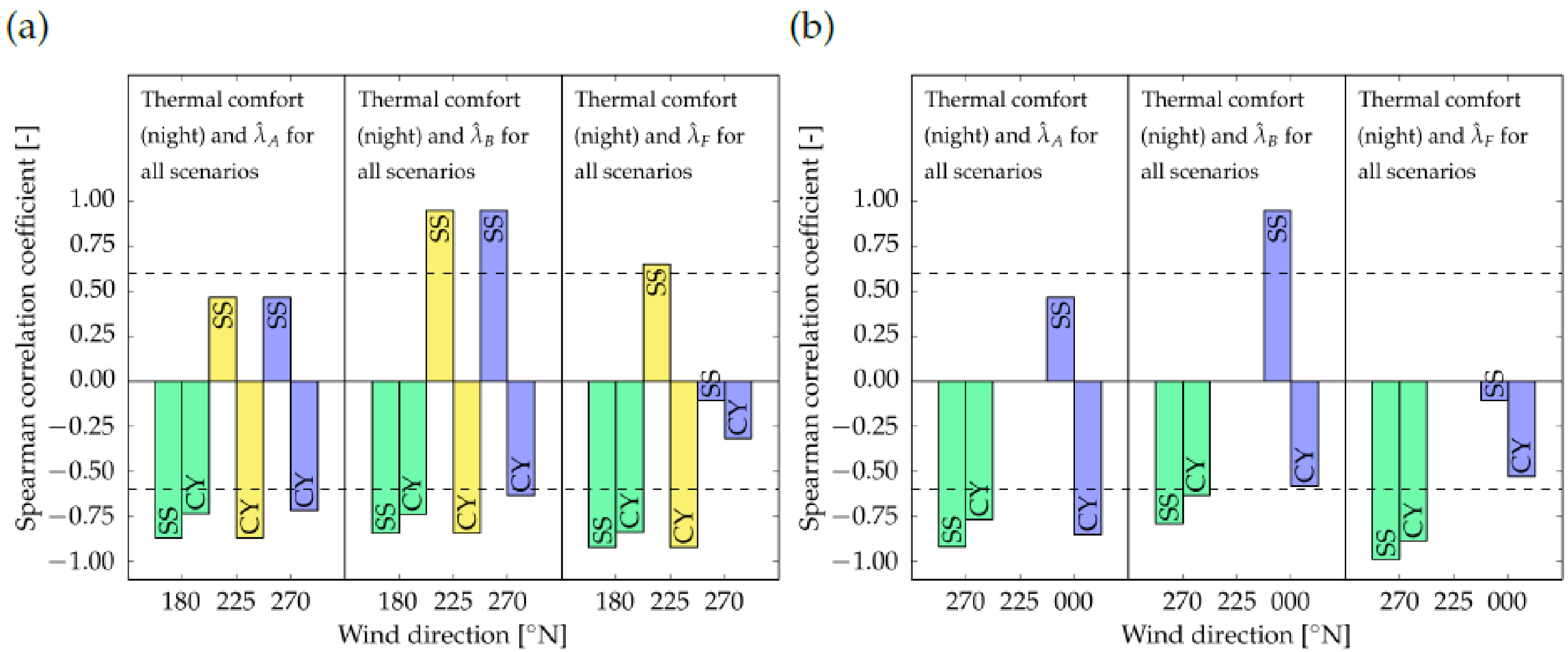


Figure 45: Correlation coefficients between indices of compactness and night-time thermal comfort for all nine building scenarios. (a) Model domain without rotation and (b) model domain with rotation by 90°. The dashed horizontal line indicates significance of the correlation coefficient for $p = 0.05$.

Wind comfort: maximum wind sped at pedestrian level using the wind comfort criteria of the Dutch wind standard

If Building are oriented perpendicular to the main wind direction, both horizontal and vertical extension tend to improve wind comfort

If parallel, both tend to reduce wind comfort

Teherfore Orientation important

# Ventilation

Entrainment of air atthe building-top level

Calculated using mean vertical wind speed and turbulent kinetic energy at top.

Impacts of compactness on ventilation are mainly determined by the building height.

Horizontal extension tend to increase ventialation if they are orineted perpendiculat to the main wind.

Tend to decrease ventilation if are parallel to wind

# Thermal comfort

Day time and night time UTCI

Number of hours with a strong heat stress

Vertical compactness (horizontal and vertical) tends to improve day-time thermal comfort appart from building orientation to the wind and rotation

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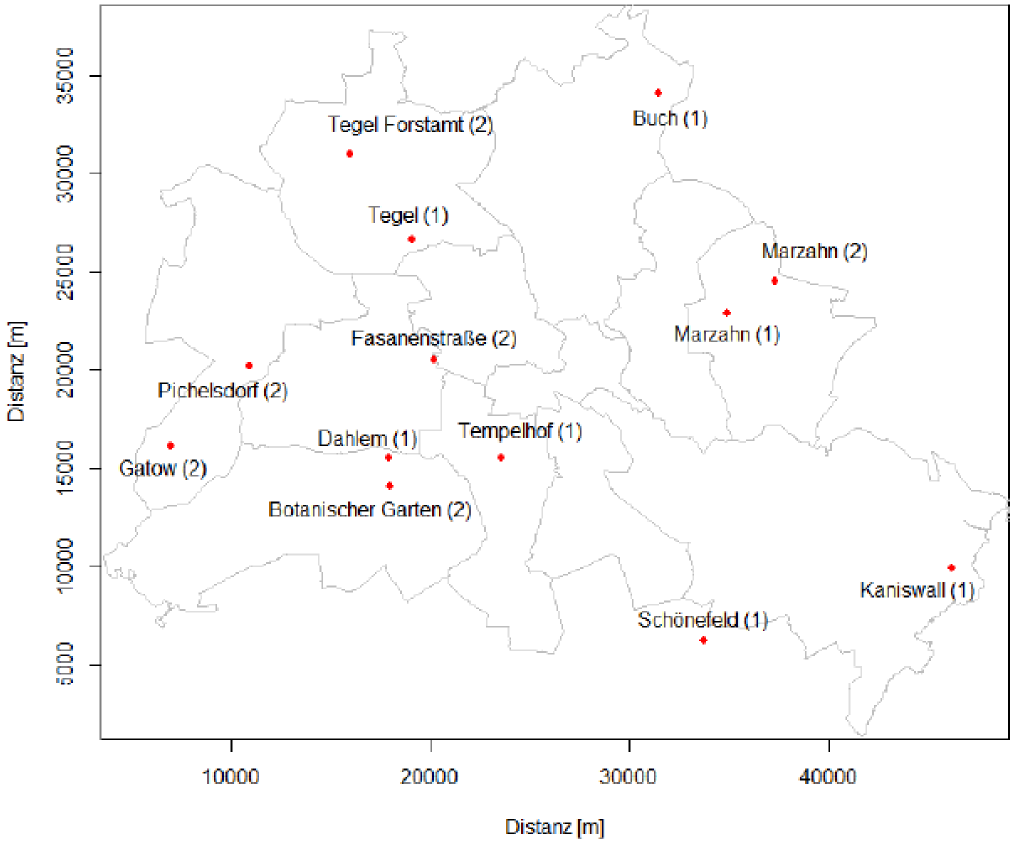
# 3. Validation of the 25.06.2010 (summer day)




Comparison with 13 measuring stations in Berlin:

- Correlation between observation and simulation at the grid point of the station (significance yes/no)

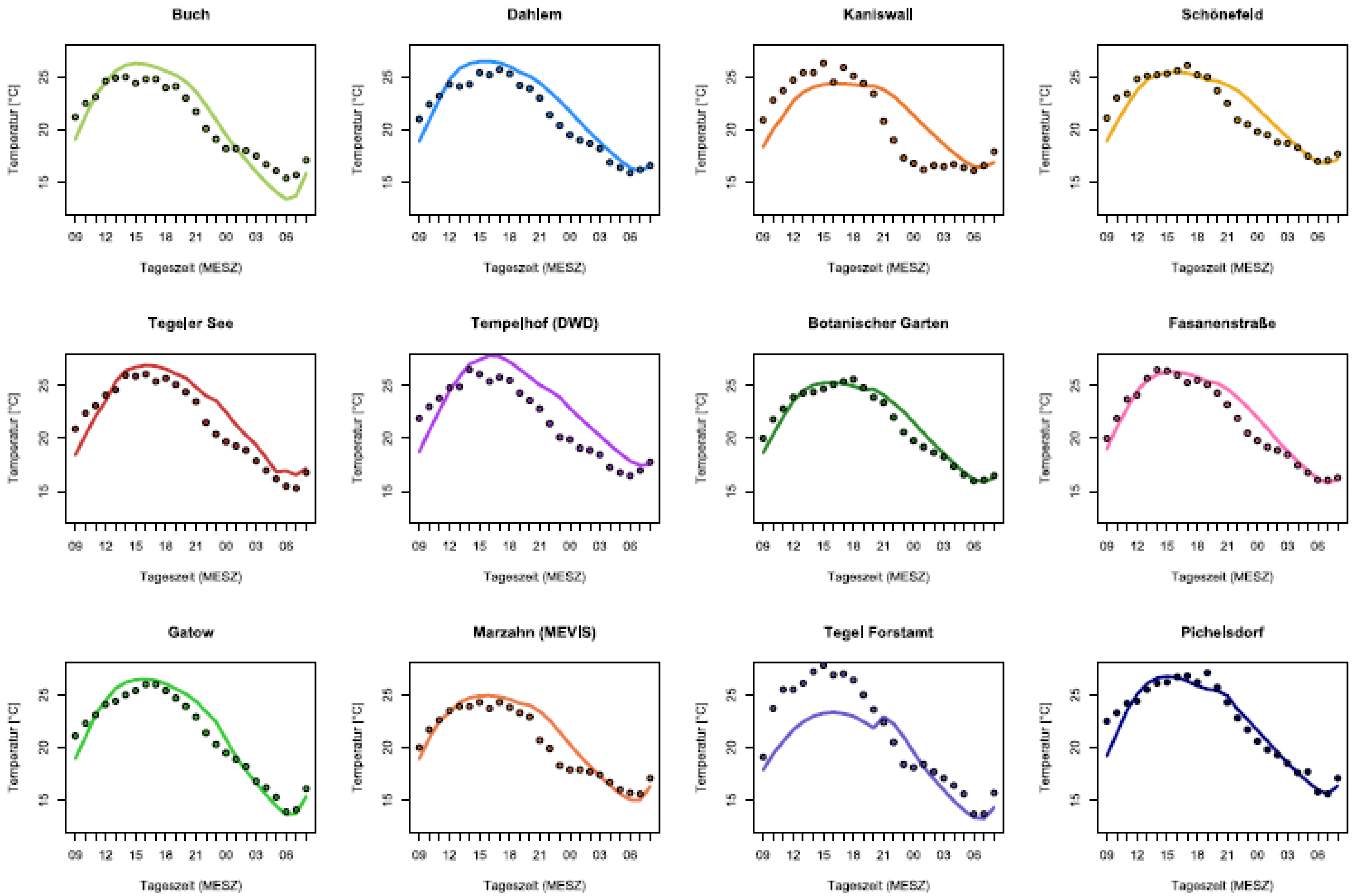
- Root Mean Square Error and Mean Error as statistical tools to quantify the quality of the simulation with MUKLIMO_3

# 3. Validation

| Changed Parameters | Changes |
| --- | --- |
| Modell version | 131024_test, 141010 (main version) |
| Surface temperature 1D | 15°C, 18°C, 21°C |
| Cloud cover | 0/8, 3/8, 6/8 |
| Soil moisture class 1D | Very dry, dry, moderate dry |
| Leaf Area Index | 1, 4 |
| Type of soil | Sandy loam, loamy sand |

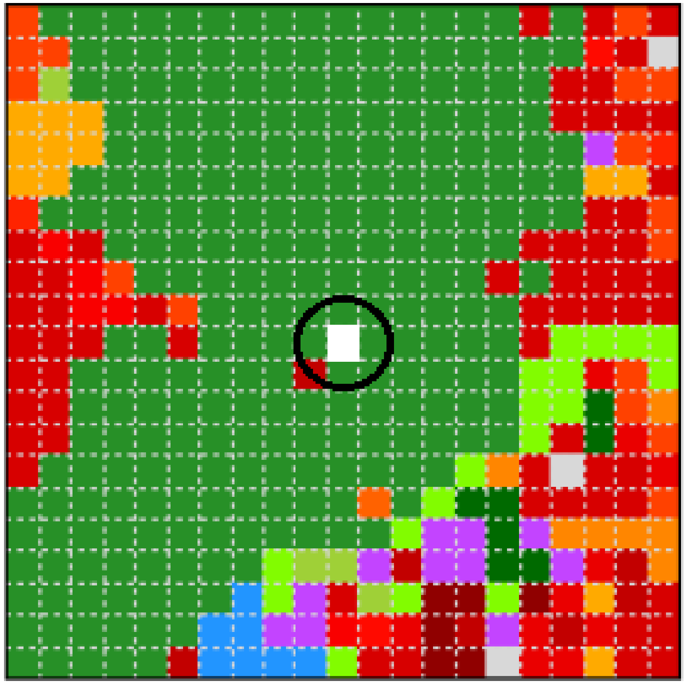
# 3. Validation

RMSE = 1,63K; ME = 0,35K; Correlation: 0,91 (significant at x level)

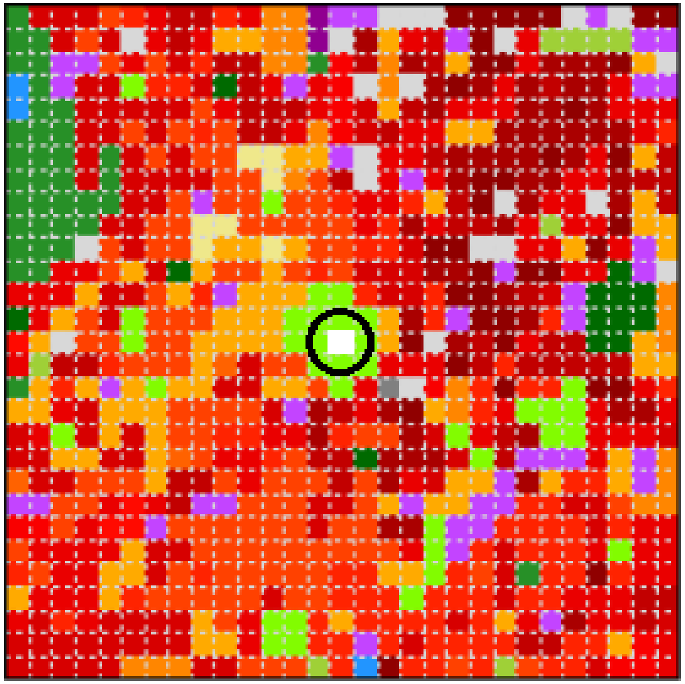


# 3. Validation

Tegel Forstamt



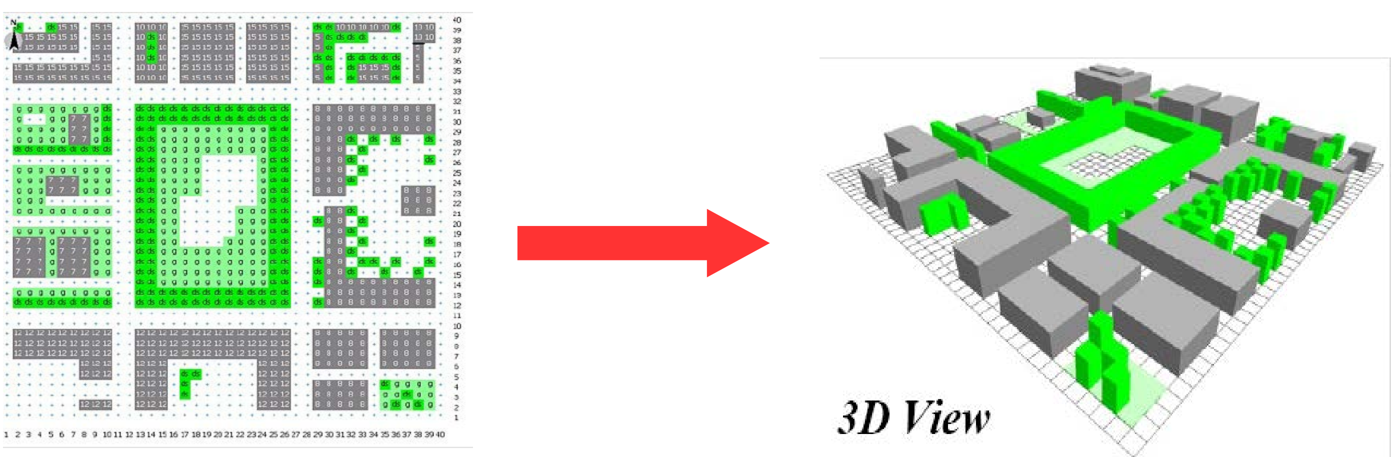
Botanischer Garten



# Micro climate simulation with ENVI-met

- 3- dimensional microclimate model designed to simulate the optimal surface-plant-air interactions in urban environment
- Temporal resolution is 24- 48 hours
- Spatial resolution 0.5 – 10 m
- Buildings, vegetation, soils/ surfaces and pollutant sources can be placed inside the model area
- combines fluid dynamics (wind flow, turbulence) with thermodynamic processes taking place at the ground surface, at walls and roofs or on plants

***2D View***

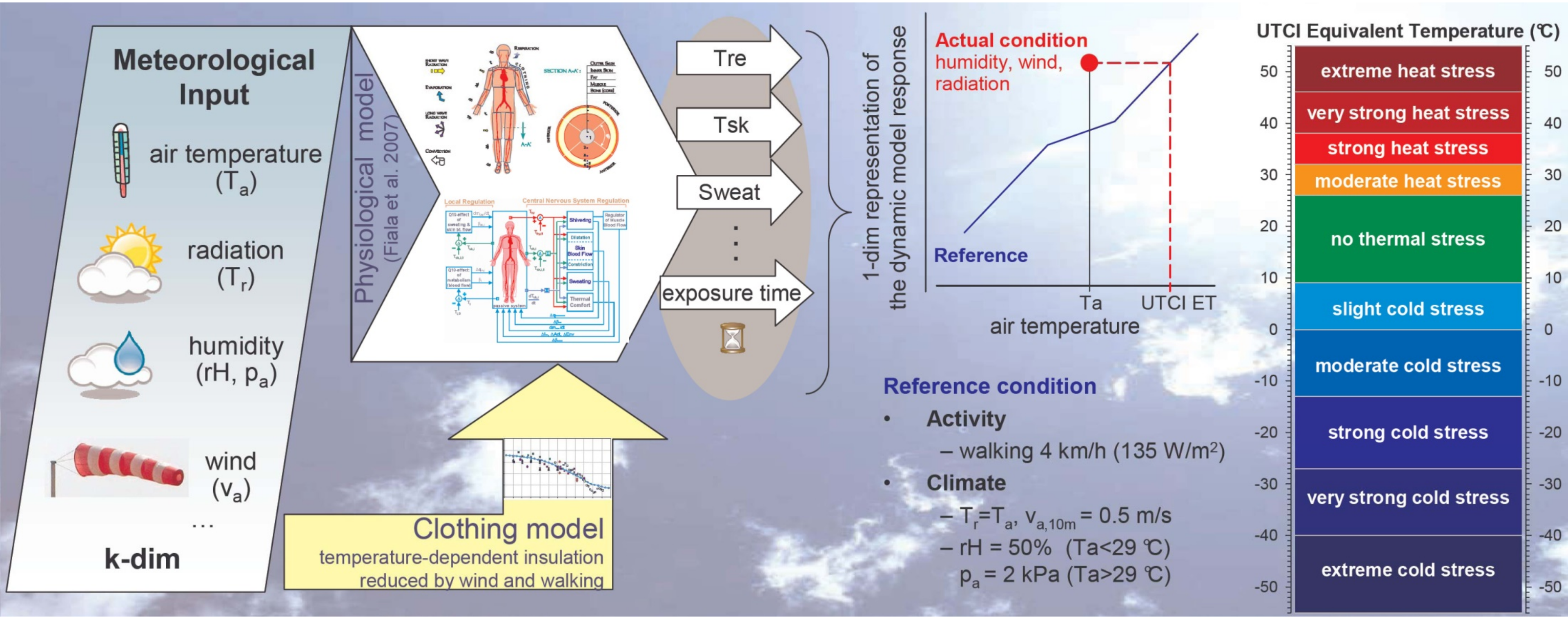


# Human Thermal Comfort--indices



## Universal Thermal Climate Index

The UTCI is based on a complex multi-node model (Fiala et al. 1999, 2001) which simulates the exchanges of energy between the body and the environment. The UTCI is defined as the air temperature (Ta) of the reference condition causing the same model response as actual conditions.




F. Pappenberger et al. 2015

29.03.2017

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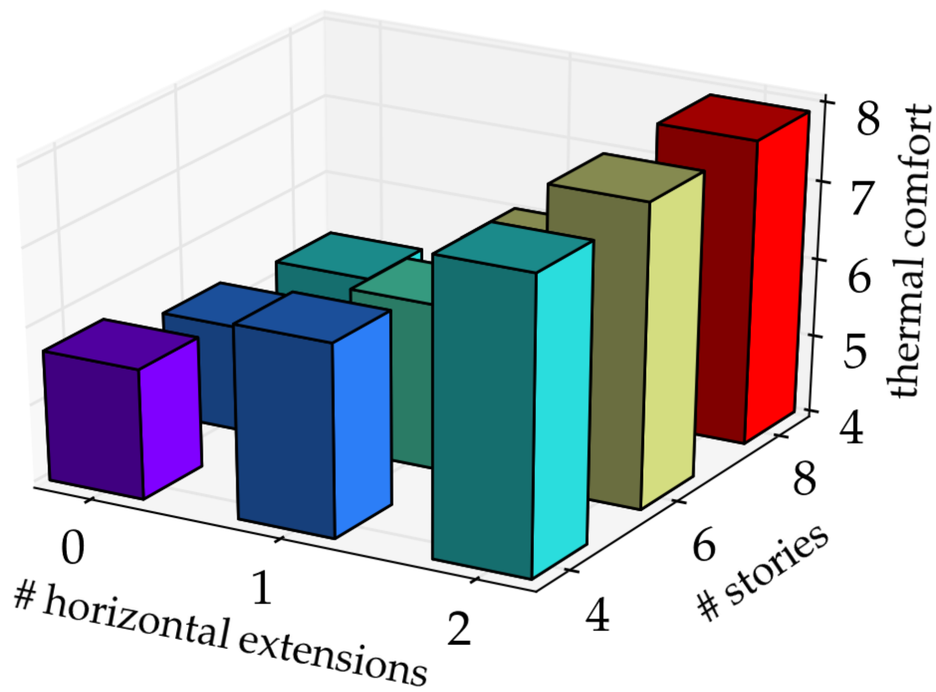
# Results: Night-time thermal comfort, wind comfort, and ventilation




During Night-time, in the Street section (point B), for Wind direction 270° N