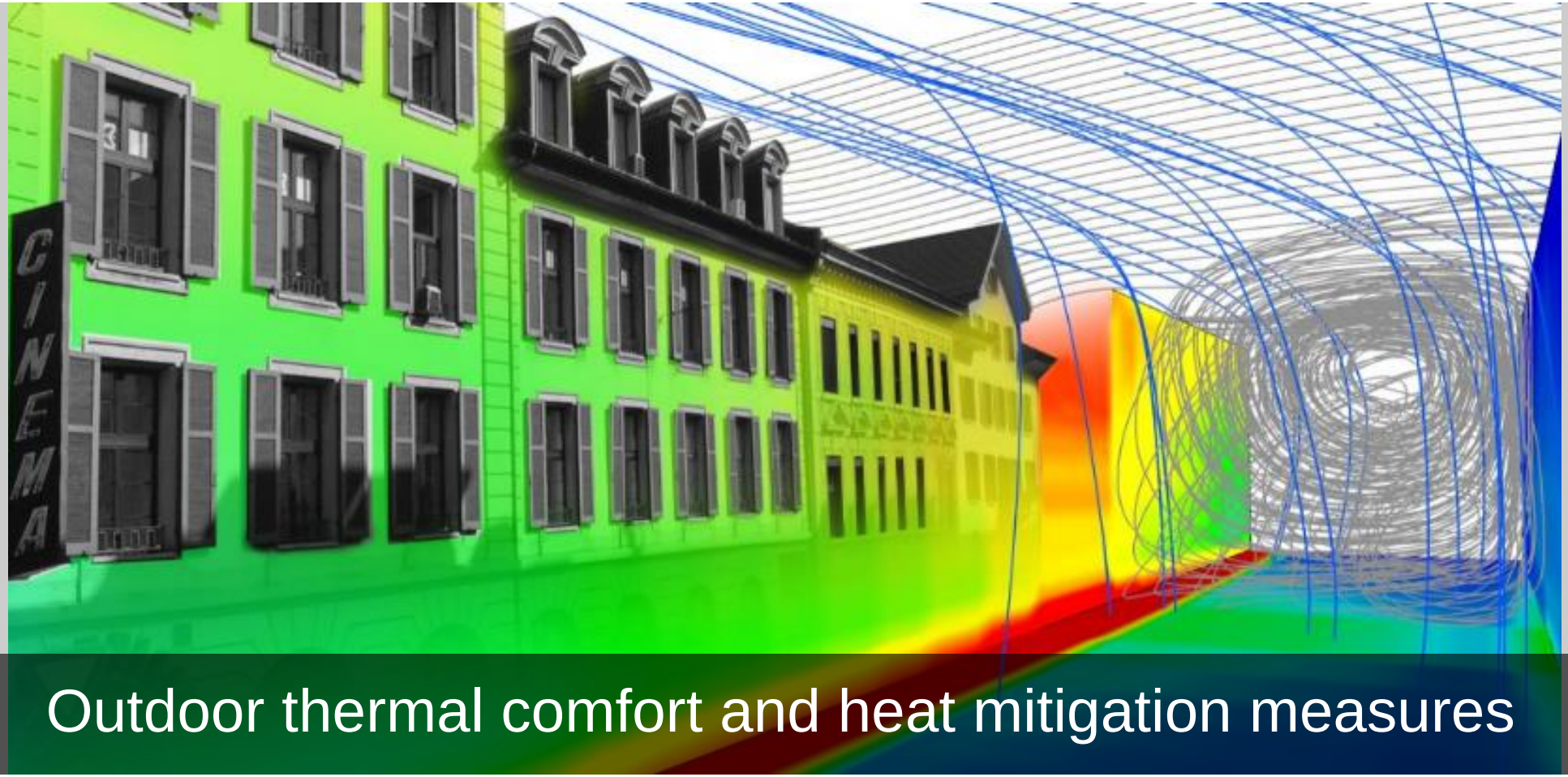
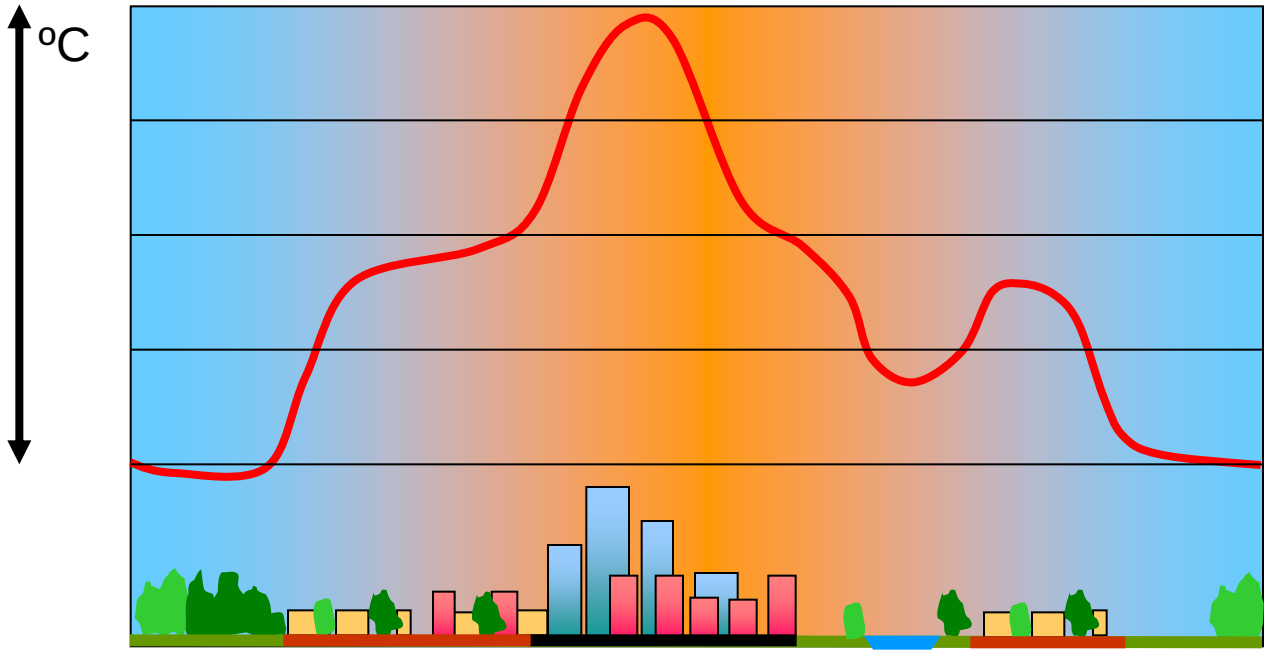


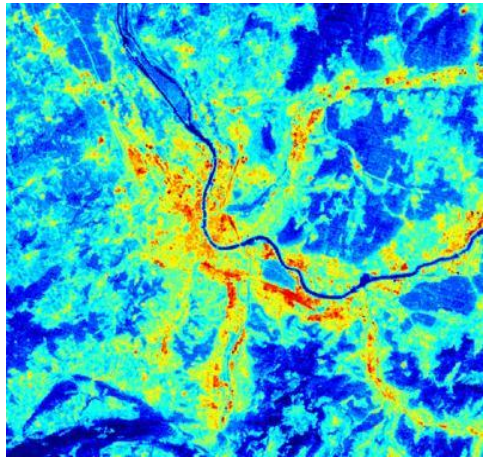
Outdoor thermal comfort and heat mitigation measures

Dr. Aytaç Kubilay
Chair of Building Physics, ETH Zurich

Urban heat island (UHI) effect



Heat island Basel



Temperature difference between city and rural temperature = urban heat island intensity

Town, City	*Heat island intensity*
Biel, Fribourg	5 K
Basel, Bern	6 K
Zürich	7 K

Wanner & Hertig, 1983

Overview

- Introduction
  - Urban heat island (UHI) effect
  - Causes of UHI
  - Outdoor thermal comfort
  - Countermeasures to UHI
  - Wind flow in urban environment
- Modeling and application examples
  - Numerical modeling of microclimate
  - Evaporative cooling
  - Impact of urban trees and high-rise buildings
  - Case study: Schönberg, Fribourg
  - Shading devices

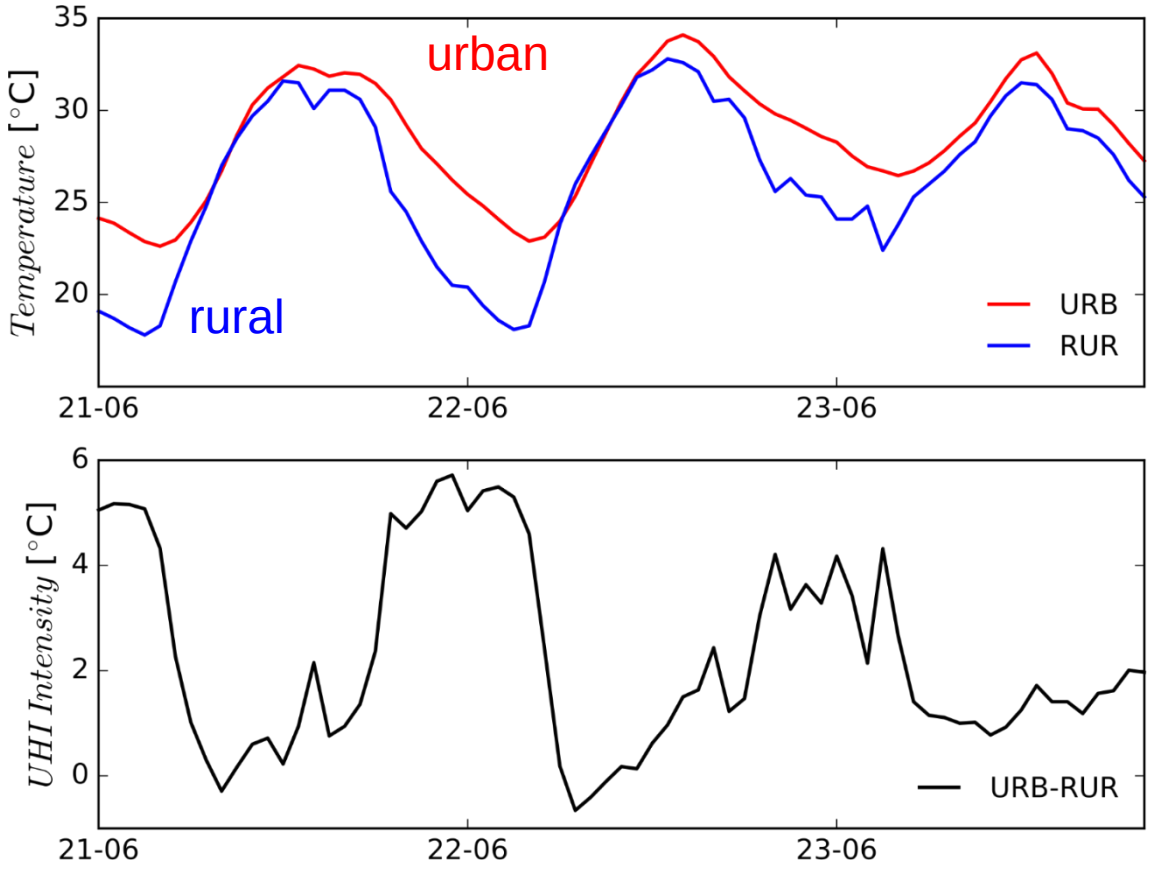
Urban climate: introduction

An urban heat island is an urban area that is significantly warmer than its surrounding rural areas.

The temperature difference usually is larger at night than during the day and is most apparent when winds are weak.

Measurement of the UHI during heat wave in Zurich, 2017

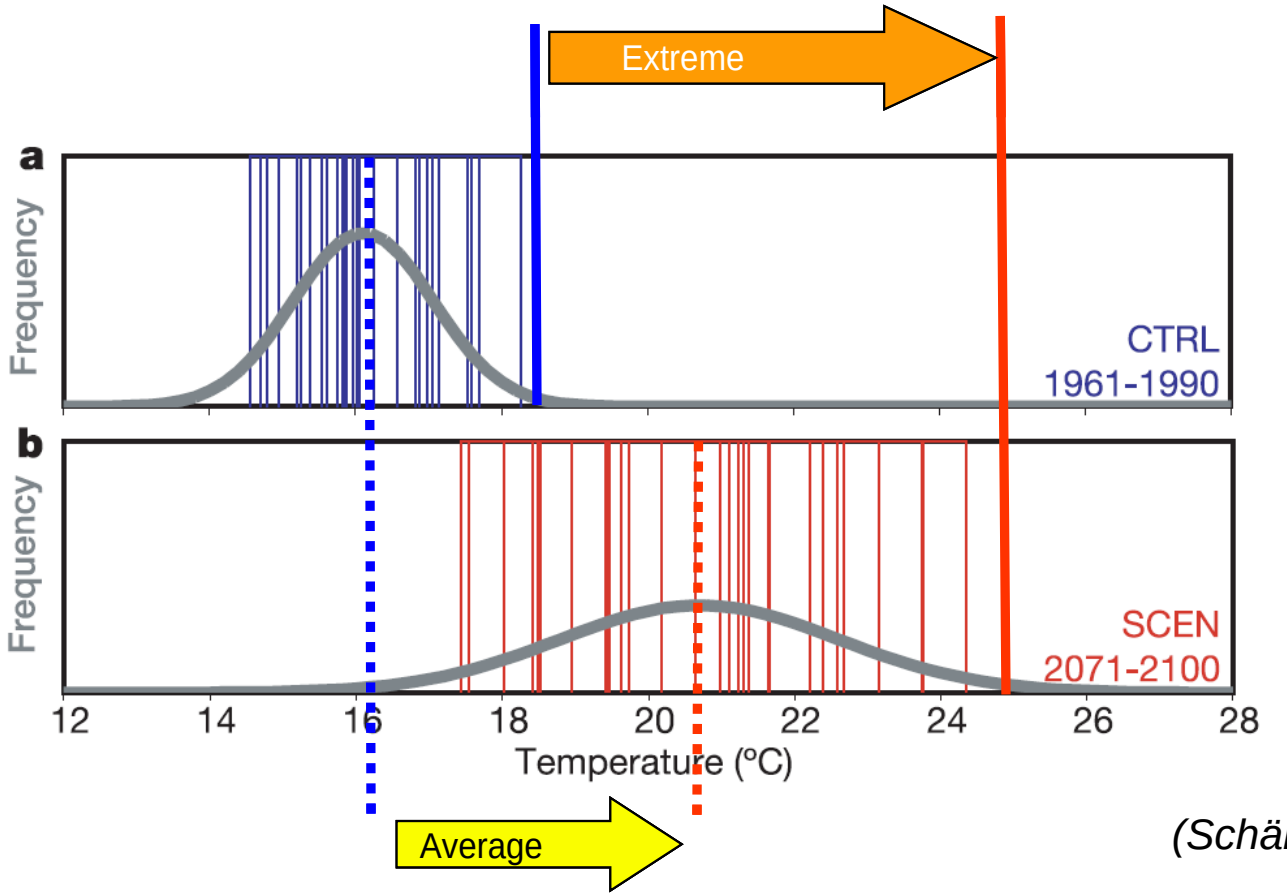
Air temperature at 2 m



Urban heat island intensity

Urban air temperature – rural air temperature

Climate change



(Schär et al. 2004, Nature)

Heat waves will be more frequent with higher amplitudes

The urban climate will change leading to higher cooling loads

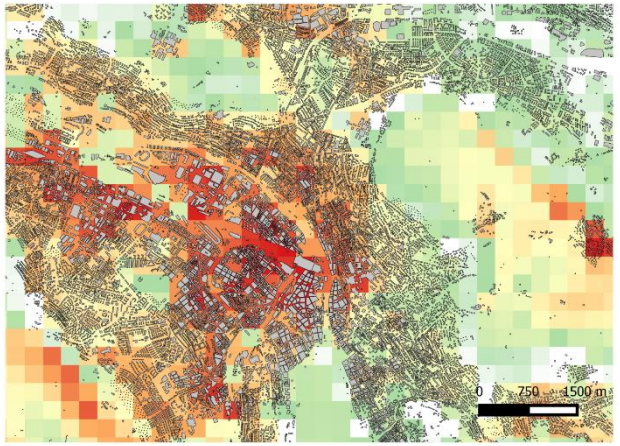
Urban climate and heat waves

- Heat waves are getting
  more **frequent**,
  with **longer duration**,
  and **higher intensity**,
  and effecting a **larger area**.

- Combined with also the urban heat island (UHI) effect

- Mitigation measures can reduce the additional heat stress during heat waves

Future Cities and Future Climates

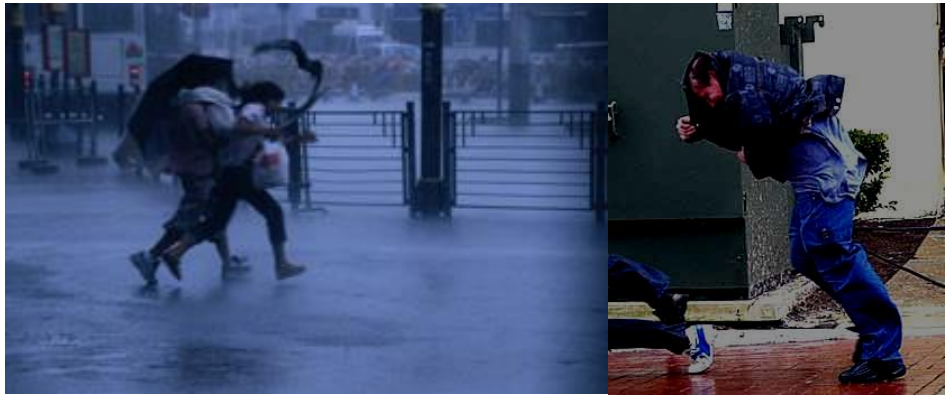


Impact

Thermal Comfort

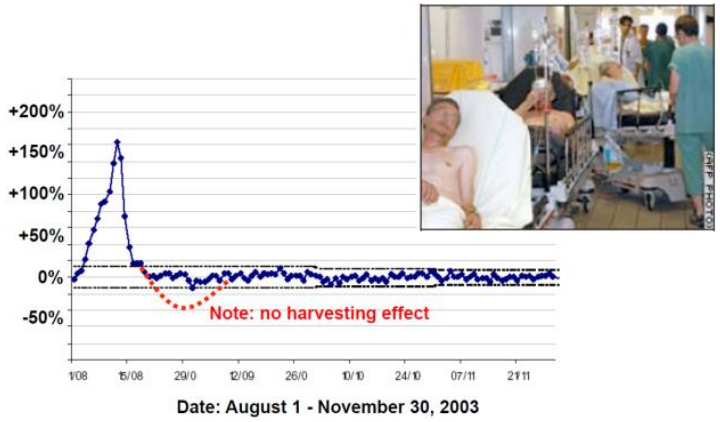
Durability

Wind Comfort



Energy use

Health



Shanghai, Pudong District, 1987

The Atlantic, August 2013

Shanghai, Pudong District, 2013

The Atlantic, August 2013

AIM: Providing an **outdoor and indoor** built environment that is:

- healthy
- comfortable

taking into account existing and/or future

- economical
- energetic
- ecological
- climatic

constraints.

Motivation

“People spend 90% of their time indoors”

→ 10% is spent outdoors

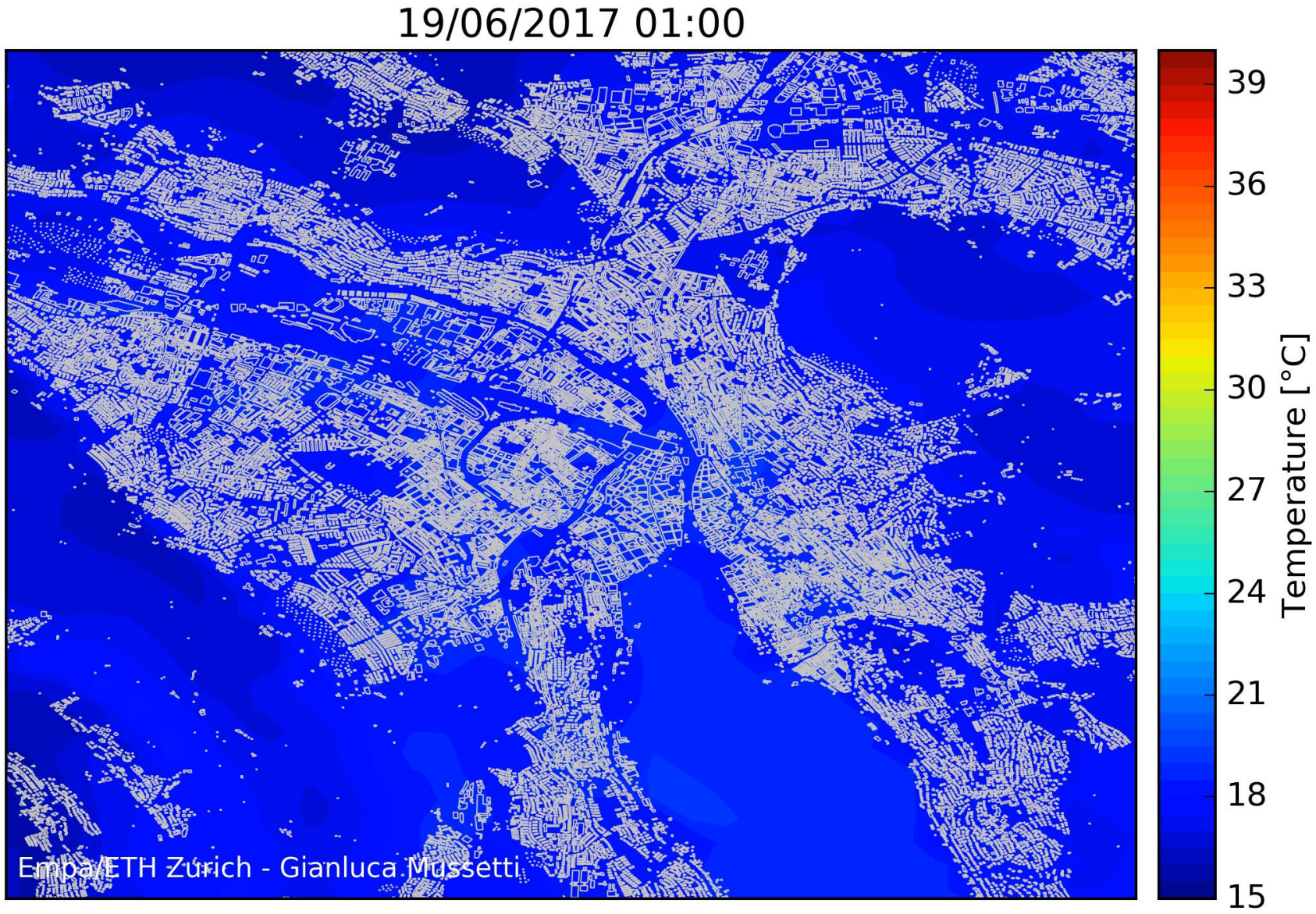
→ Outdoor environment influences the indoor environment

→ Cities are growing

→ Cities consume a lot of energy

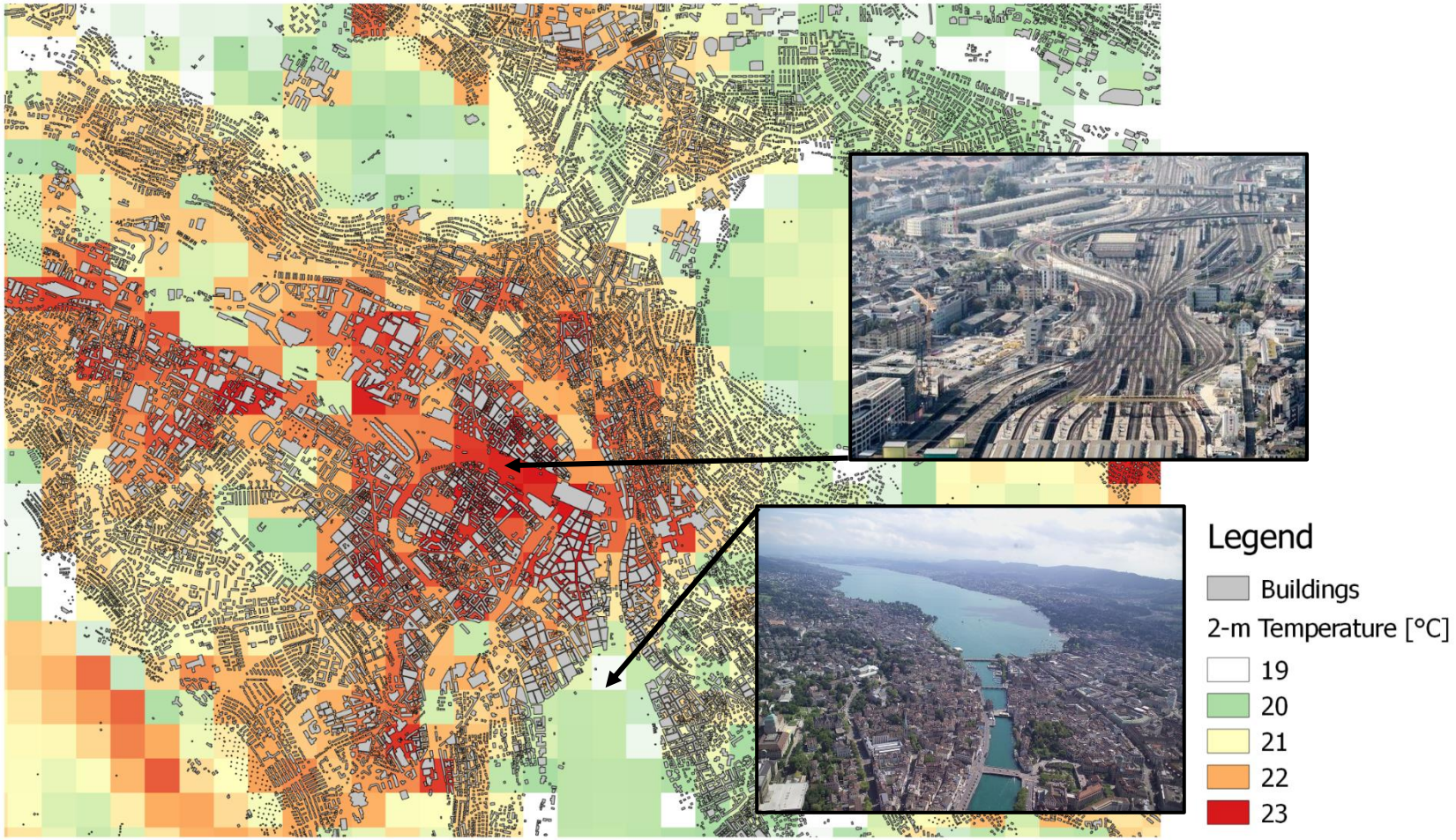
→ Climate change will impact the urban climate

Air temperature at 2 m height during heat wave in Zurich, 2017



Air temperature during heat wave in Zurich, 2017

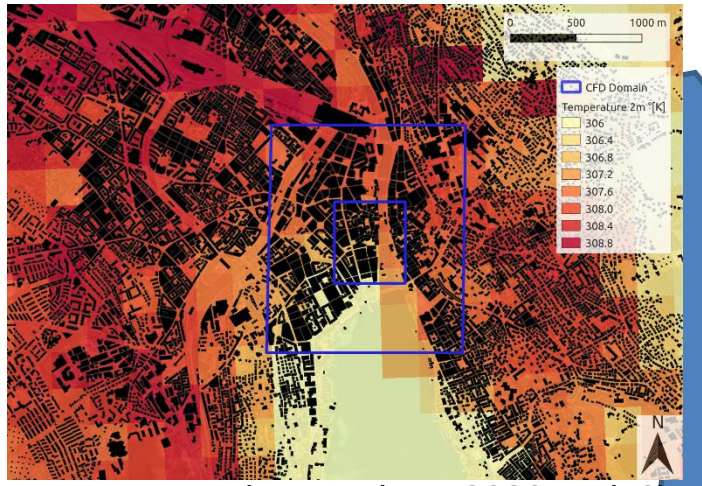
Air temperature map at 6 am 23/06/2017



(G. Mussetti, Empa/ETH)

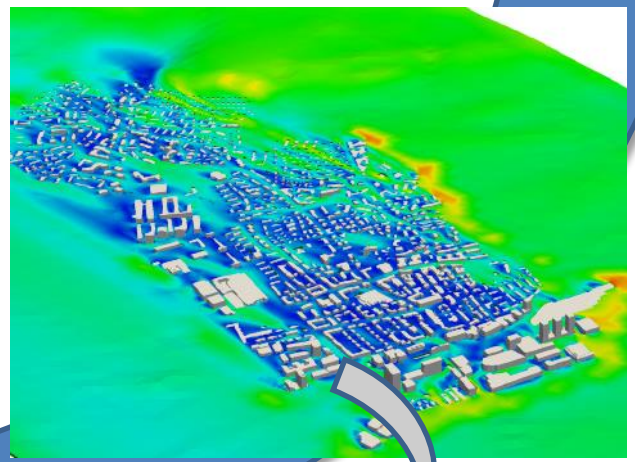
Necessity of a multi-scale approach

- Mesoscale
  - City and surroundings (domain size: < 200 km)
  - Meteorological models with urban parameterization

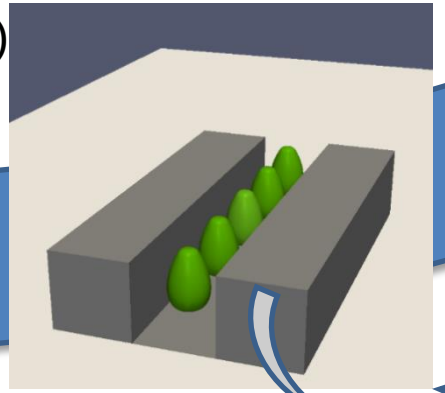


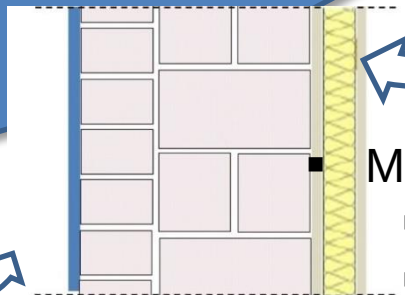
(Atmosphere **2020**, *11*(12), 1313)

- Microscale
  - Neighborhood (domain size: < 2 km)
  - CFD models



- Microscale
  - Local / building (domain size: < 100 m)
  - CFD models





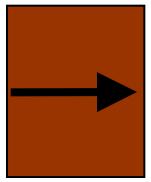
Material scale
- domain size: < 1 m)
- HAM models

Overview

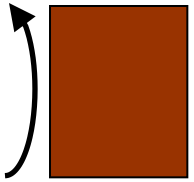
- Introduction
  - Urban heat island (UHI) effect
  - Causes of UHI

Heat transfer mechanisms

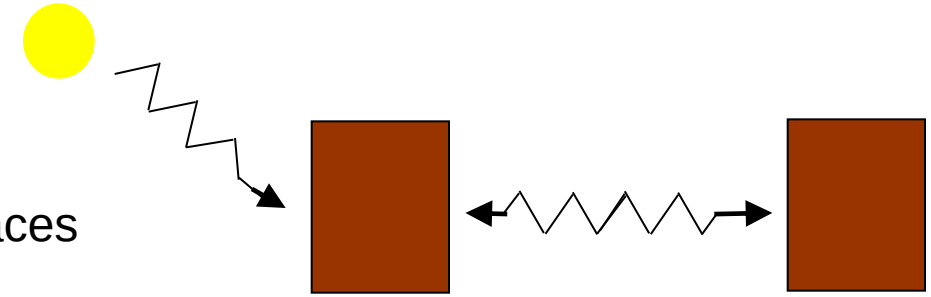
1. Conduction
   In solid materials



2. Convection
   Surface convection by wind and/or buoyancy (“stack effect”)



3. Radiation
   Short-wave radiation from the sun
   Long-wave radiation from the sky
   Long-wave radiation between surfaces

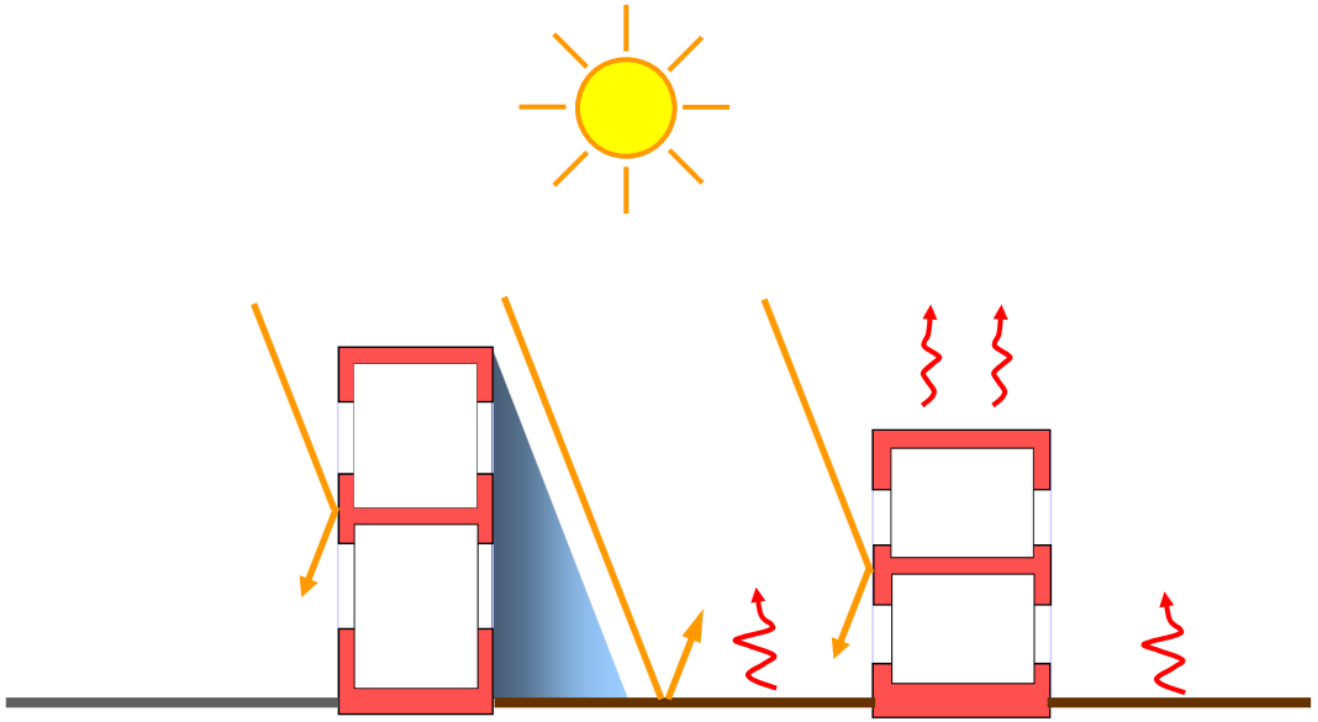


What are the causes of the UHI?

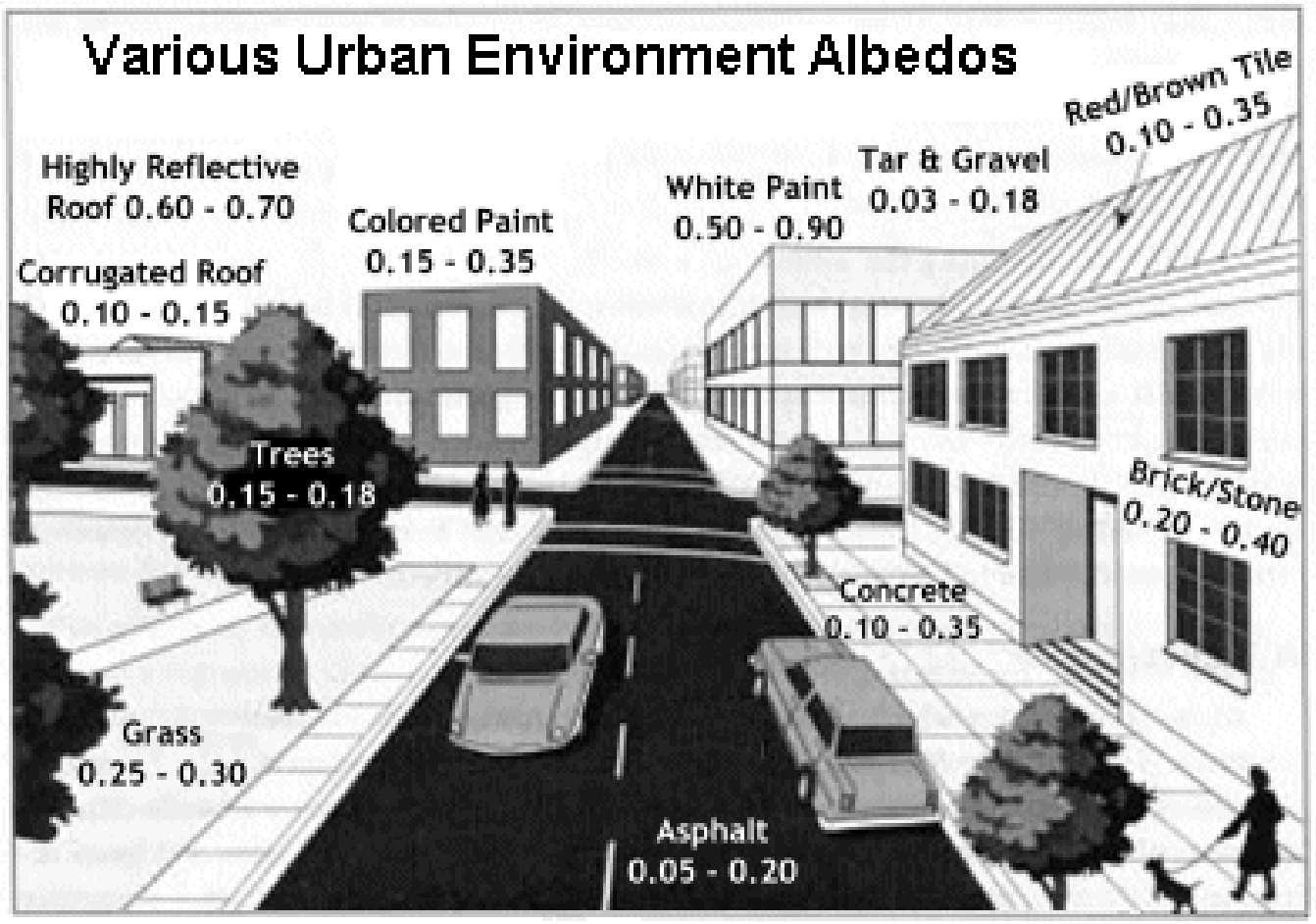
1) **increased sensible heat storage** due to the choice of materials
    - Changed thermal properties

What are the causes of the UHI?

1) **increased sensible heat storage** due to the choice of materials
2) **increased absorption of short-wave radiation**
    - reduced albedo (reflection coefficient) of urban surfaces
    - larger surface area to heat up



Changed thermal bulk and surface properties:
Albedo value

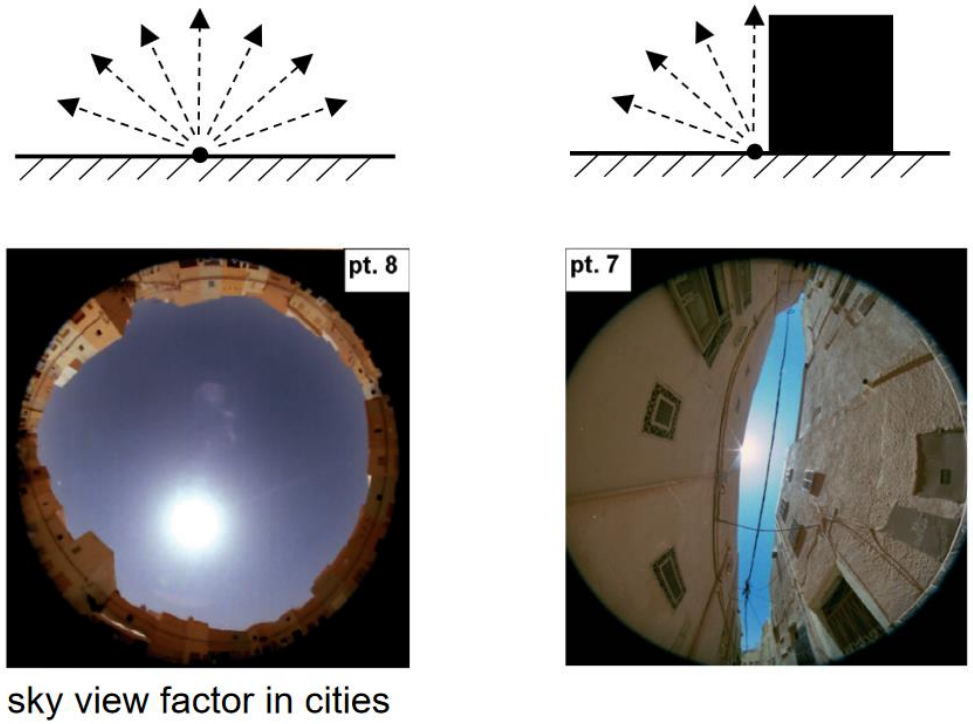


Changed thermal bulk and surface properties:
Albedo value

Pavement Type	Albedo
Asphalt	0.05 – 0.10 (new) 0.10 – 0.15 (weathered)
Gray portland cement concrete	0.35 – 0.40 (new) 0.20 – 0.30 (weathered)
White portland cement concrete	0.70 – 0.80 (new) 0.40 – 0.60 (weathered)

What are the causes of the UHI?

1) **increased sensible heat storage** due to the choice of materials
2) **increased absorption of short-wave radiation**
3) **decreased long-wave radiation** loss to the sky
   - lower sky view factor
   - reduced cooling of “warm” buildings during night time by blocking of radiation to the cold sky

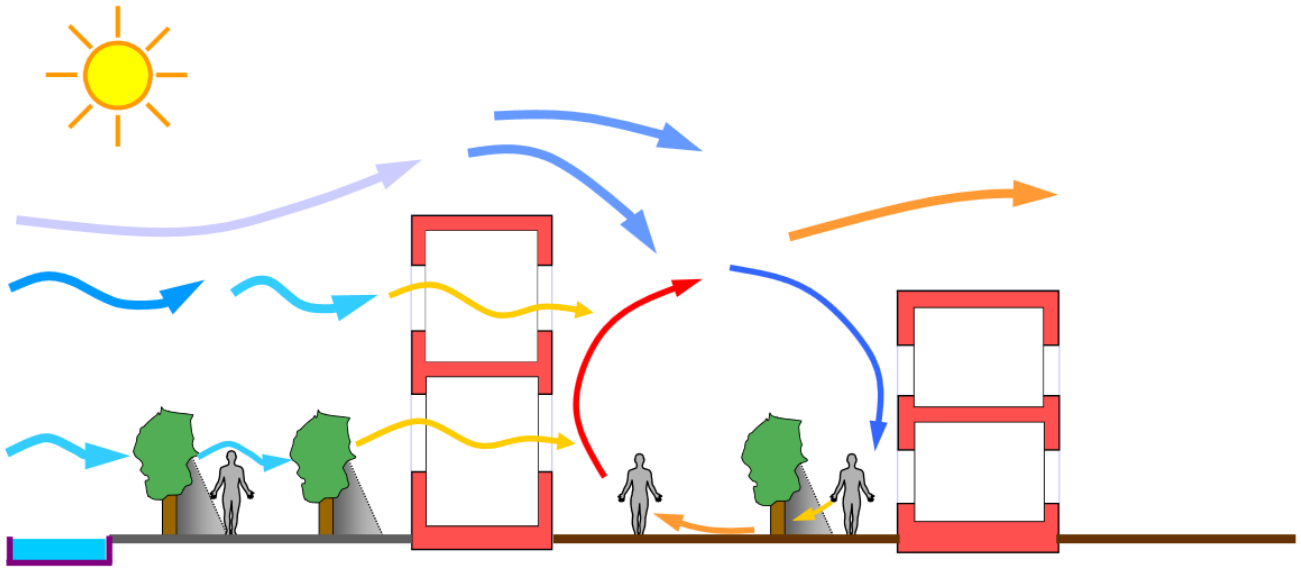


sky view factor in cities

What are the causes of the UHI?

1) **increased sensible heat storage** due to the choice of materials
2) **increased absorption of short-wave radiation**
3) **decreased long-wave radiation** loss to the sky
4) **decreased convective heat transport**

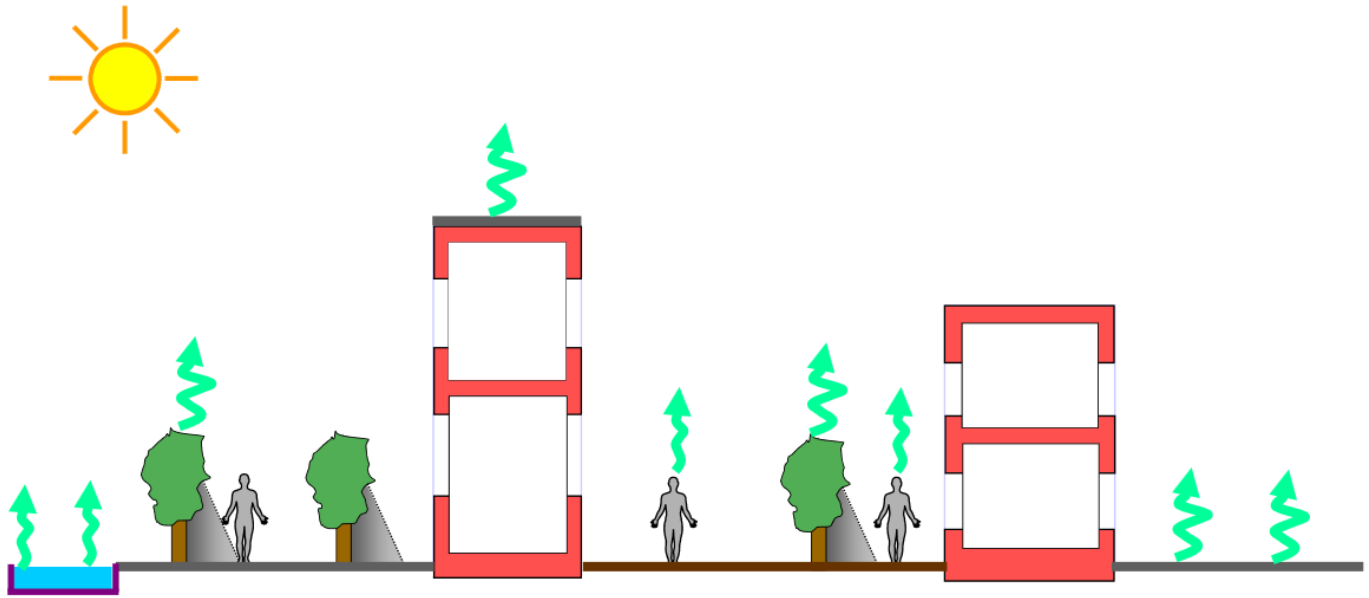
Reduced cooling of “warm” buildings due to wind shielding
reduction of convective heat and moisture transfer



reduced convective heat losses due to wind-sheltering
reduced (cross) ventilation potential

What are the causes of the UHI?

1) **increased sensible heat storage** due to the choice of materials
2) **increased absorption of short-wave radiation**
3) **decreased long-wave radiation** loss to the sky
4) **decreased convective heat transport**
5) **decreased evapotranspiration**



reduced evapotranspiration (latent heat)

What are the causes of the UHI?

1) **increased sensible heat storage** due to the choice of materials
2) **increased absorption of short-wave radiation**
3) **decreased long-wave radiation** loss to the sky
4) **decreased convective heat transport**
5) **decreased evapotranspiration**
6) **increased anthropogenic heat production**
7) **increased absorption of long-wave radiation** due to air pollution

anthropogenic heat release
transportation
industry
people

Overview

- Introduction
  - Urban heat island (UHI) effect
  - Causes of UHI
  - Outdoor thermal comfort

Evaluation of urban outdoor thermal comfort

Universal Thermal Climate Index (UTCI):
Equivalent ambient temperature of a reference environment providing the same physiological responses of a reference environment

- Air temperature
- Mean radiant temperature
- Relative humidity
- Wind speed
- Clothing
- Activity

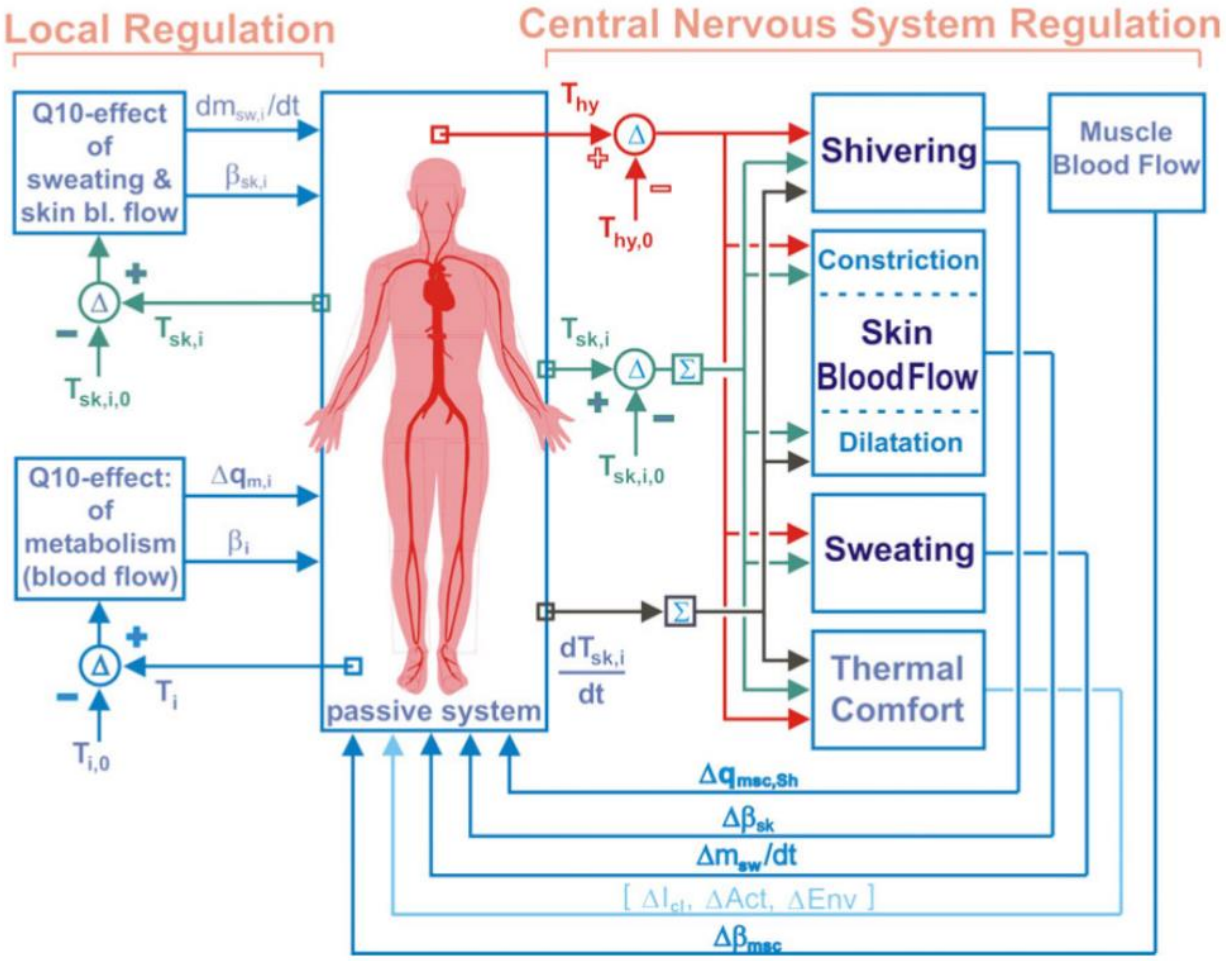
$$T_{mrt} = \left[T_{umrt}^{\ 4} + \frac{f_p \propto_p I_{dir}}{\varepsilon_p \sigma} \right]^{0.25}$$

Surface temperatures of environment radiating to the person

Direct solar radiation on person

$$UTCI = T_a + Offset(T_a, T_{MRT}, U_{wind}, p_{vapour})$$

Evaluation of urban outdoor thermal comfort



UTCI range (ºC)	Stress category
> 46	**Extreme heat stress (HS)**
38 – 46	**Very strong HS**
32 to 38	**Strong HS**
26 to 32	**Moderate HS**
9 to 26	**No thermal stress**

Thermoregulatory system model, from *Fiala et al. 2012, International Journal of Biometeorology*

Overview

- Introduction
  - Urban heat island (UHI) effect
  - Causes of UHI
  - Outdoor thermal comfort
  - Countermeasures to UHI

What are the possible counter measures for Urban Heat Island mitigation?

Purpose	Large Category	Small Category
Cool Surface	Use of Green	Maintenance of Green Land
		Garden
		Roof Greening/Garden
		Street Greening/Trees
	Use of Structural Material	Water Permeable Material
		Water Contained Material
		High Albedo Painting
		Photocatalyst
	Use of Water	Water Park/Waterfront
		Water Sprinkler
	Creation of Shading Area	Arcade
		Pergola
Promotion of Urban Ventilation	City Block Configuration	Ventilation Lane
		Arrangement of Buildings
	Building Configuration	Minimization of Aspect Area
		Pilloti
Reduction of Anthropogenic Heat	Energy-Saving	Energy-Saving Machinery
		Transport Manegement
		Energy-Saving Life Style
	Heat Release Treatment	Water Cooling Tower
		Heat Sink (River, Sea, Ground)

(Photo: Andreas Rubin – ETH)

(Photo: Christian Michel / CC BY-SA 2.0)

R. Ooka et al. 2010

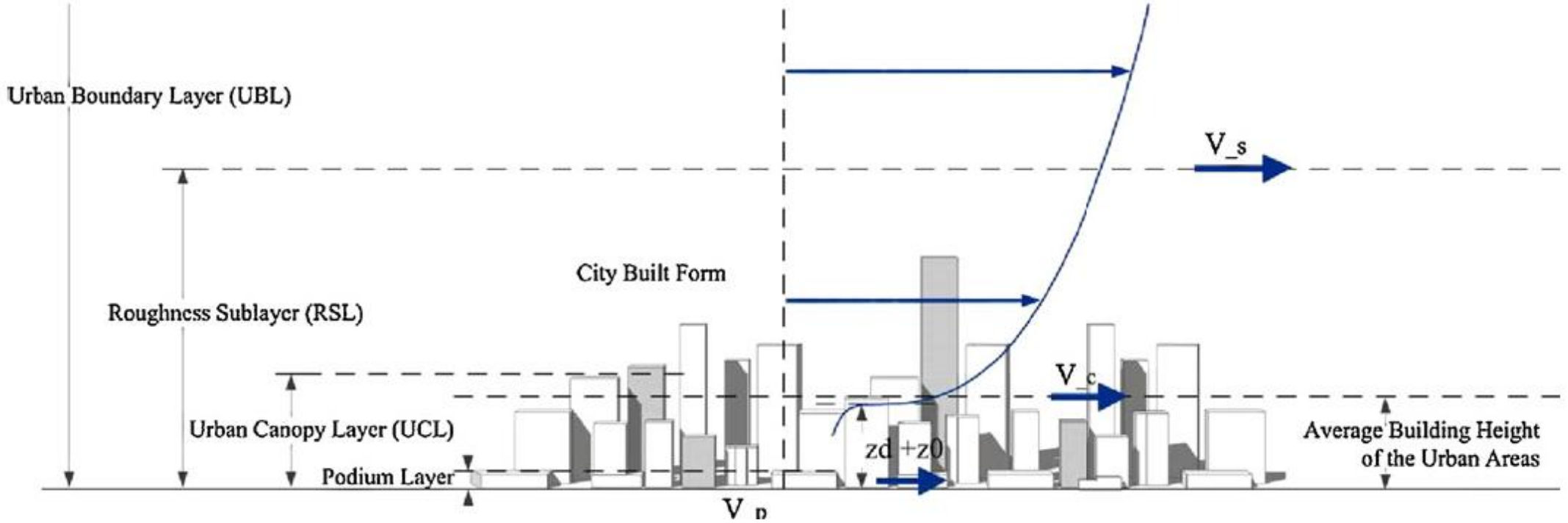
Seminar at Hong Kong Polytechnic University

Overview

- Introduction
  - Urban heat island (UHI) effect
  - Causes of UHI
  - Outdoor thermal comfort
  - Countermeasures to UHI
  - Wind flow in urban environment

Urban boundary layer

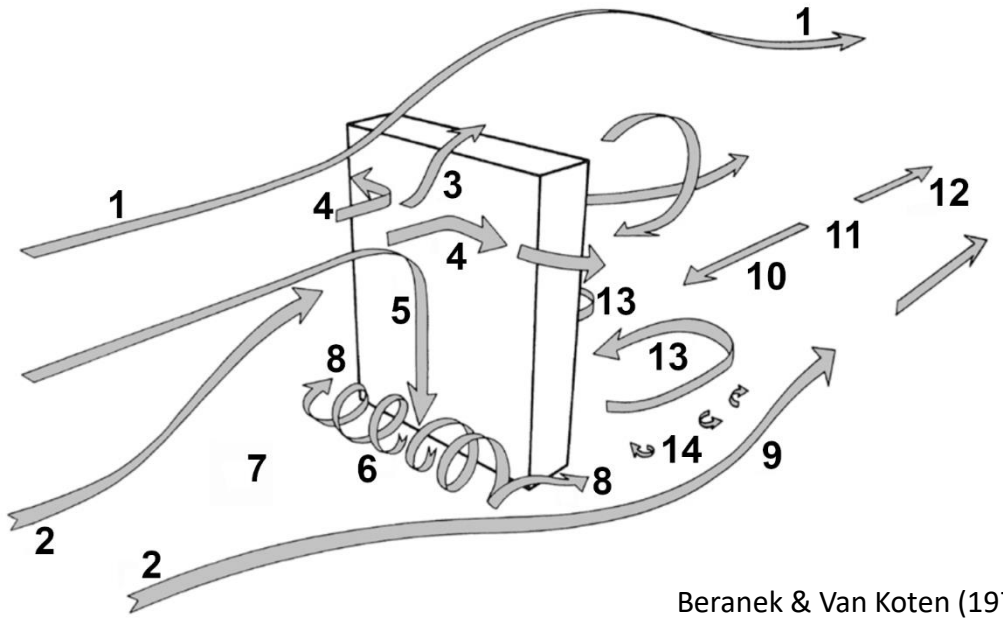
wind velocity profile



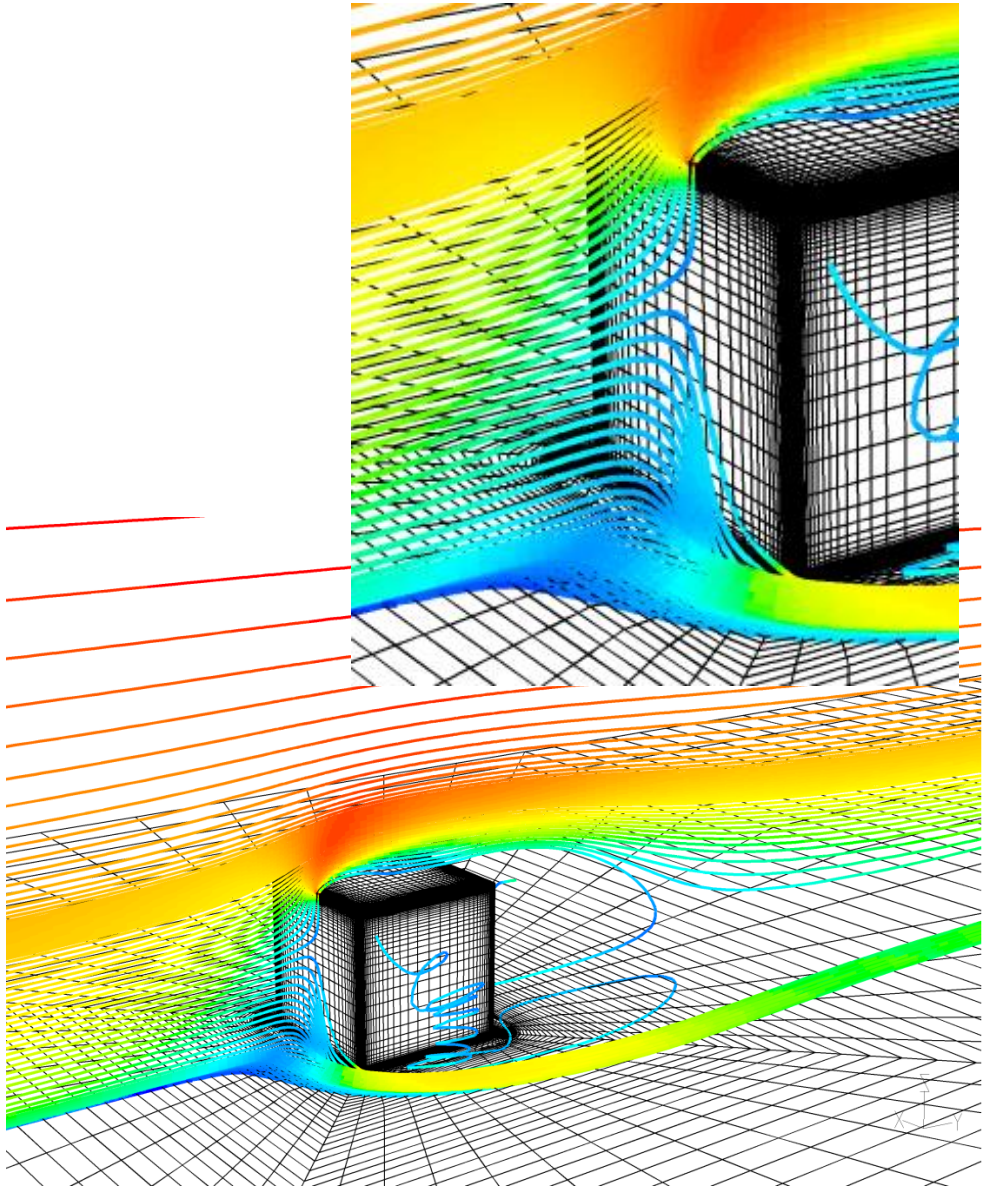
Ng E., 2011

Wind flow around a building

Stand-alone building



Beranek & Van Koten (1979)



Defraeye et al.

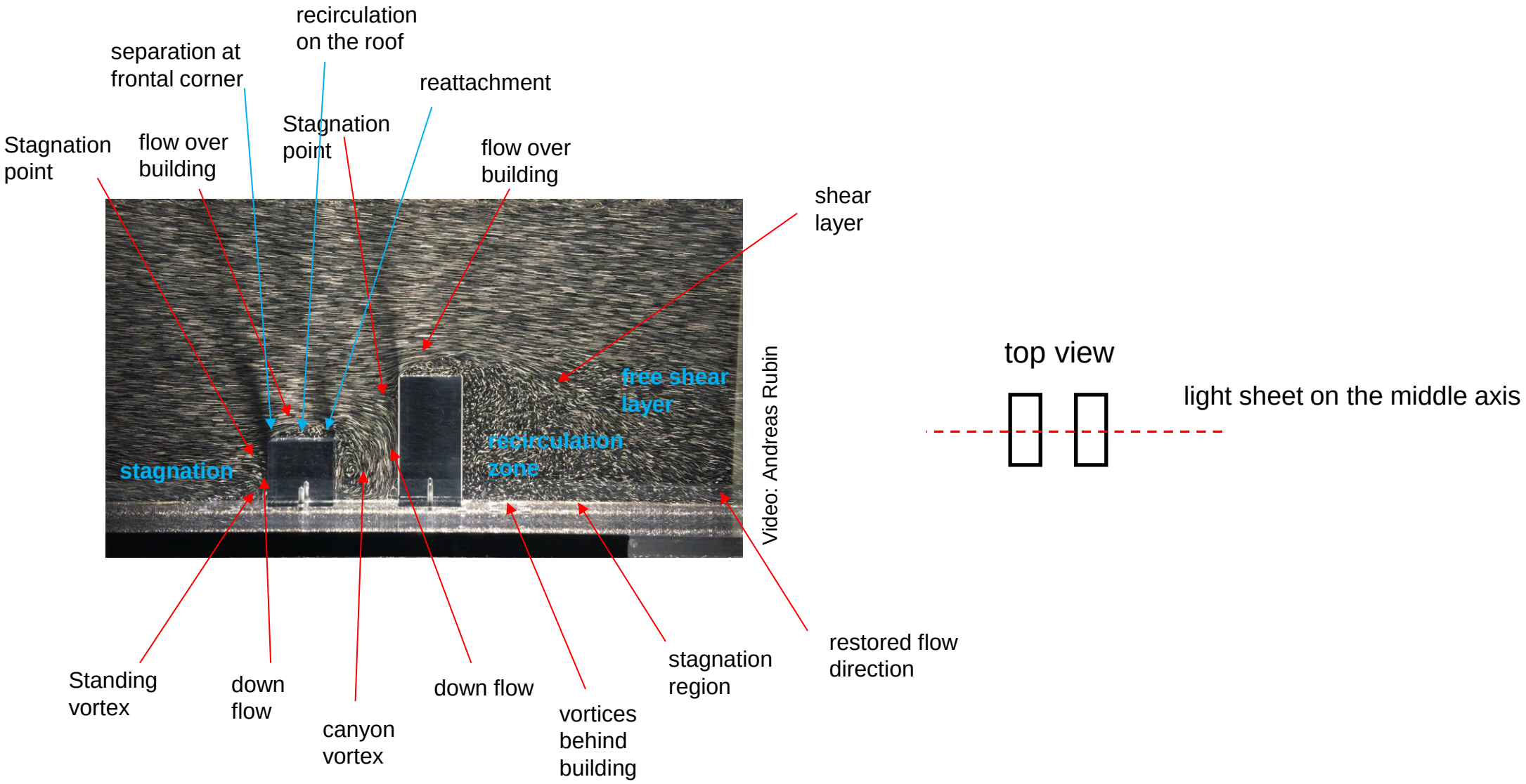
- Wind-flow patterns around buidings also influence heat removal, transport of pollutants, evaporation, moisture transport in air, etc.

Turbulent shear layer at building edges

the high buildings force the wet air to rise

Air cools down at higher height and condenses into mist

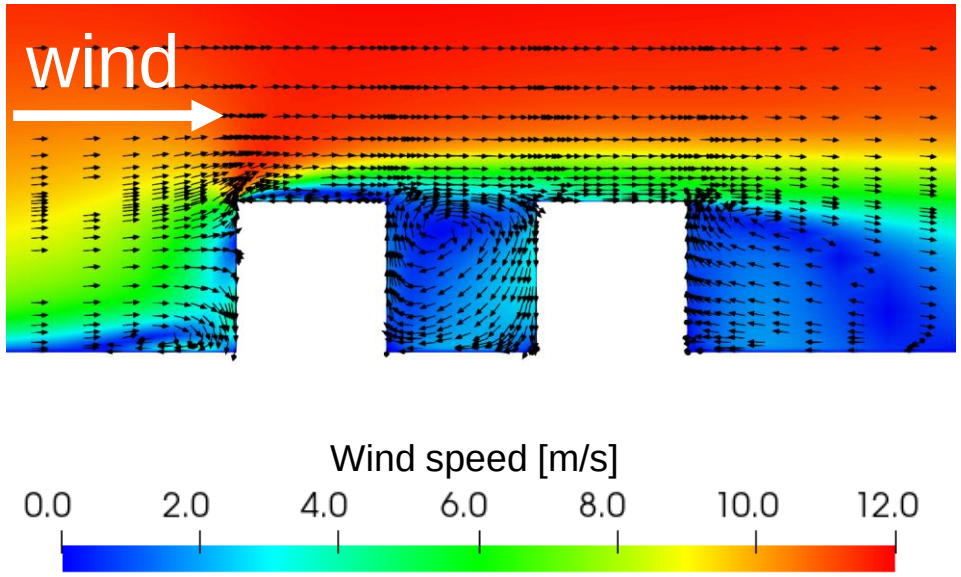
Wind-flow patterns around buildings

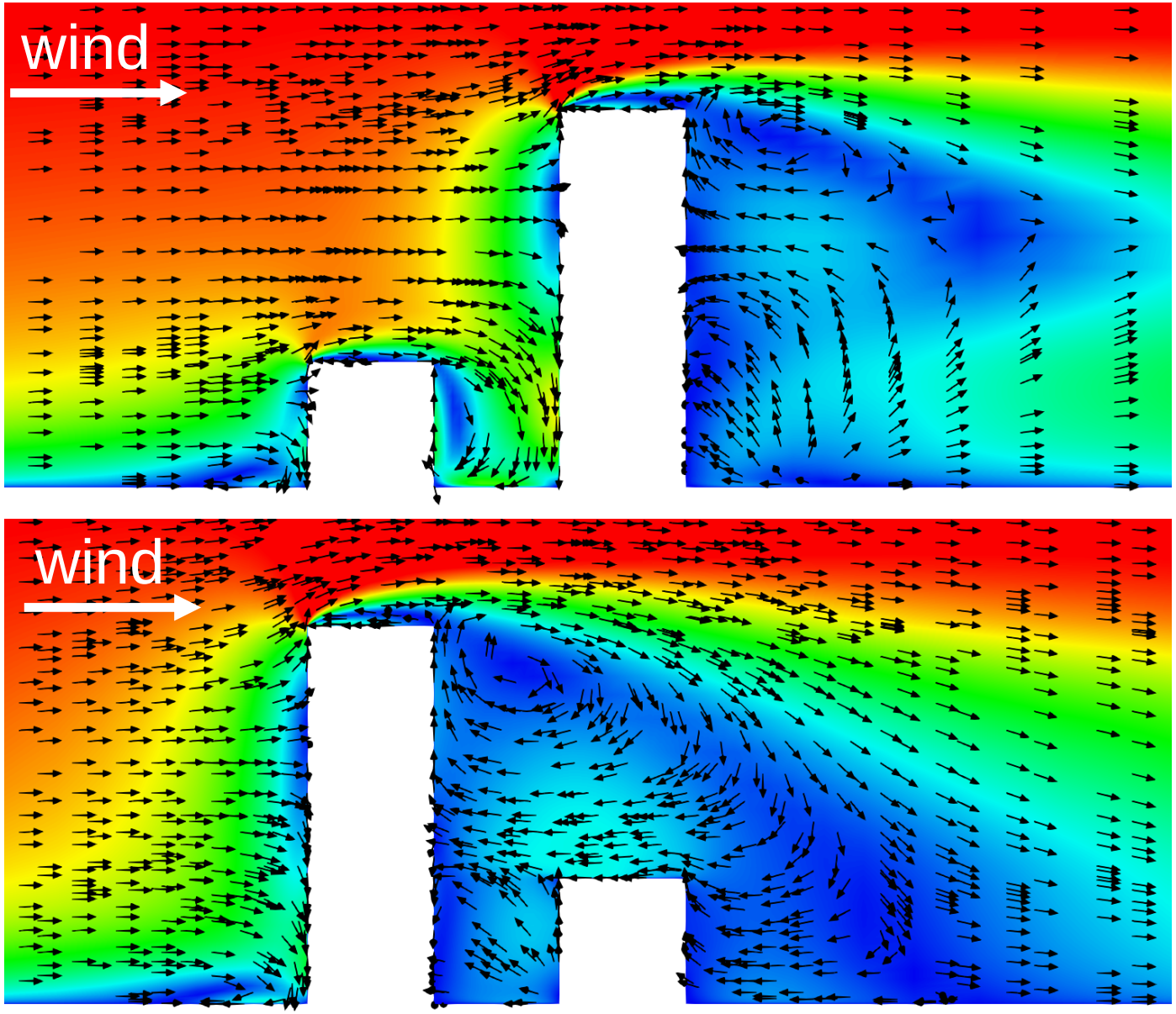


Wind flow around buildings

What happens with multiple buildings?

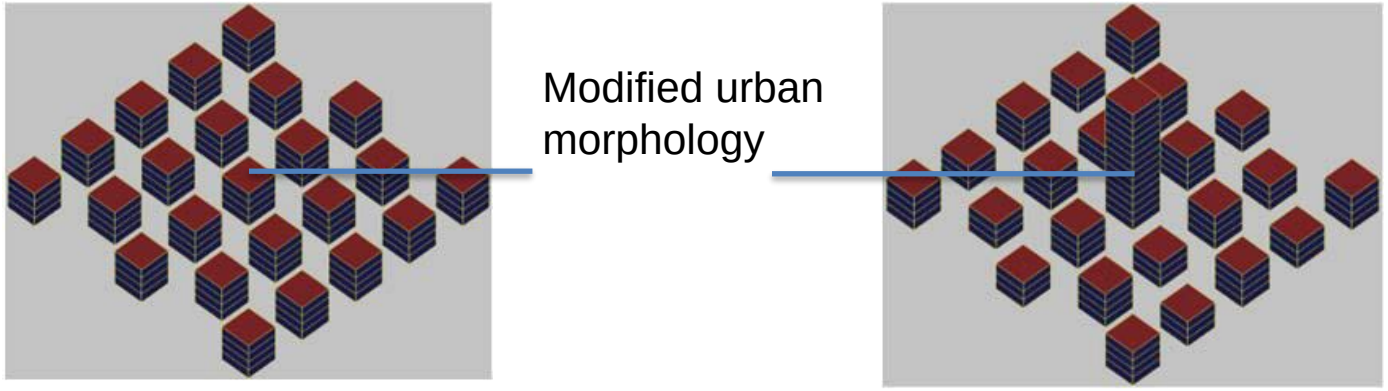
Isothermal conditions





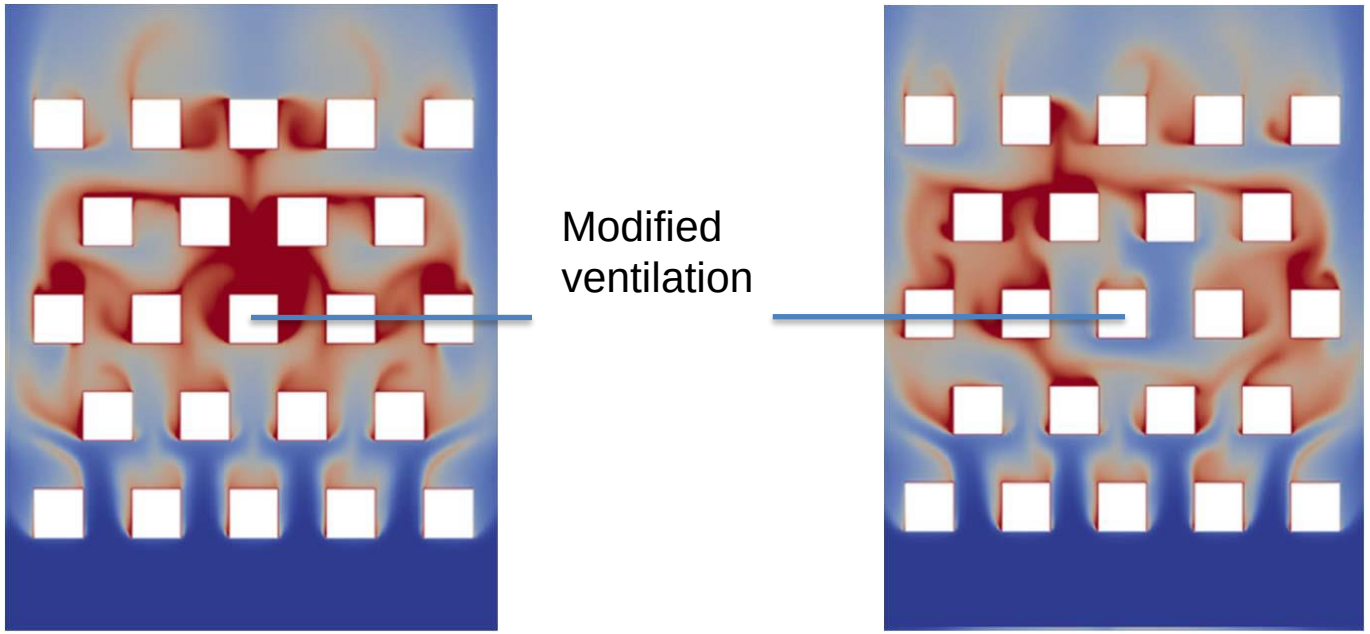
Ventilation

Cooler air directed by the high-rise building towards street level



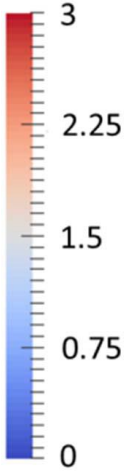
Modified urban morphology

Wind speed = 5 m/s



Modified ventilation

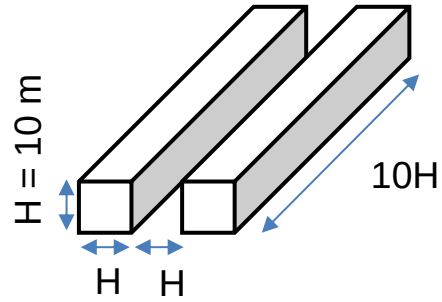
Temperature difference at 1.75 m height



Allegrini et al. **2017** Urban Climate

Local thermal hotspots

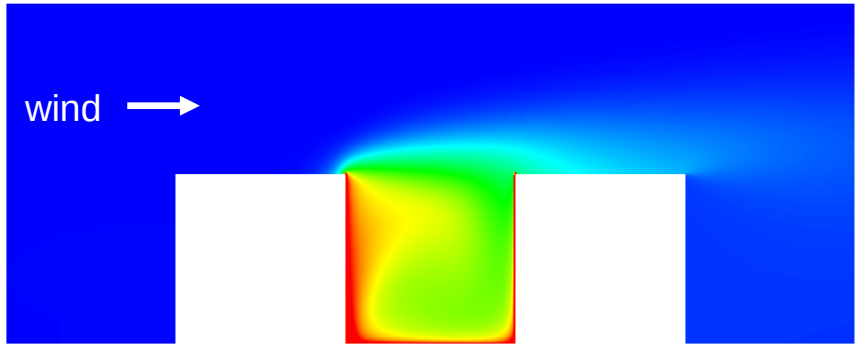
Non-isothermal conditions



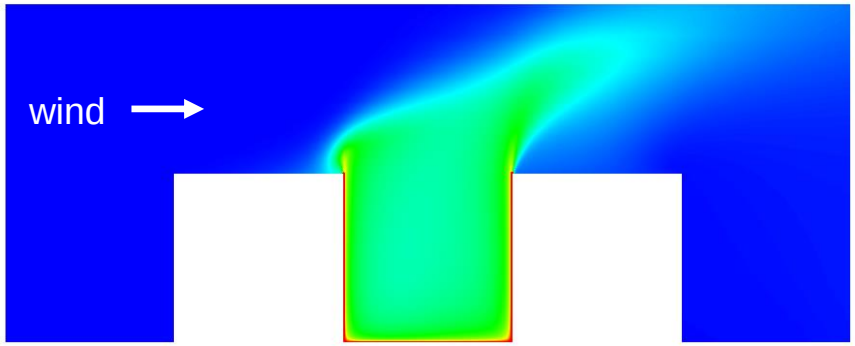
Temperature contours

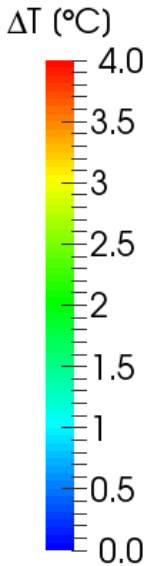
Velocity vectors

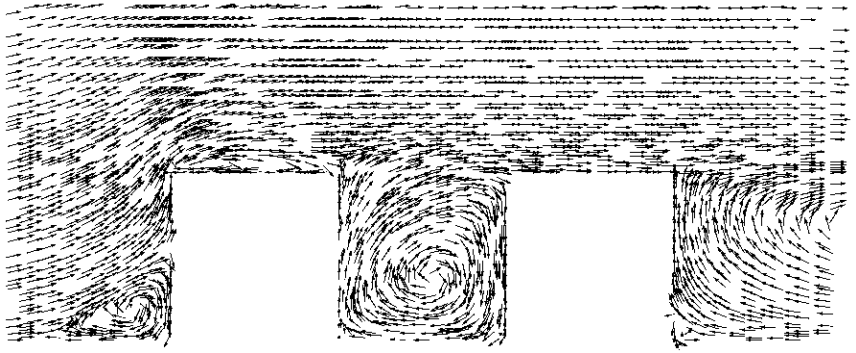
U_{ref} = 10 m/s

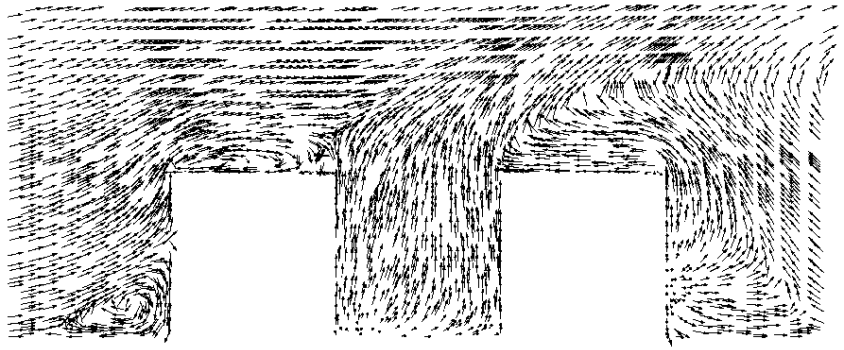


U_{ref} = 1 m/s



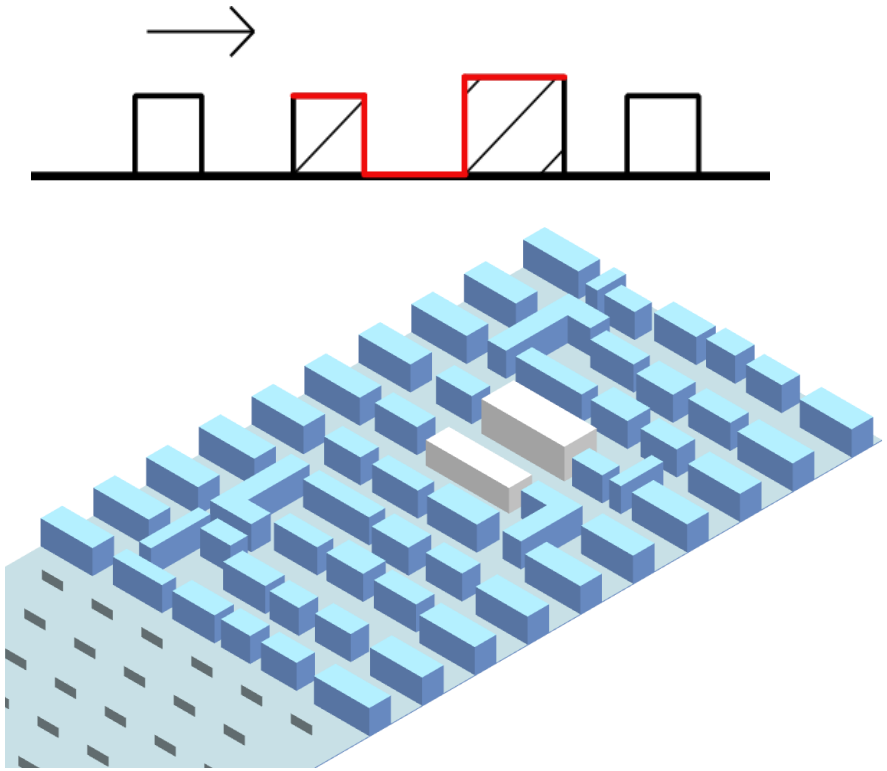




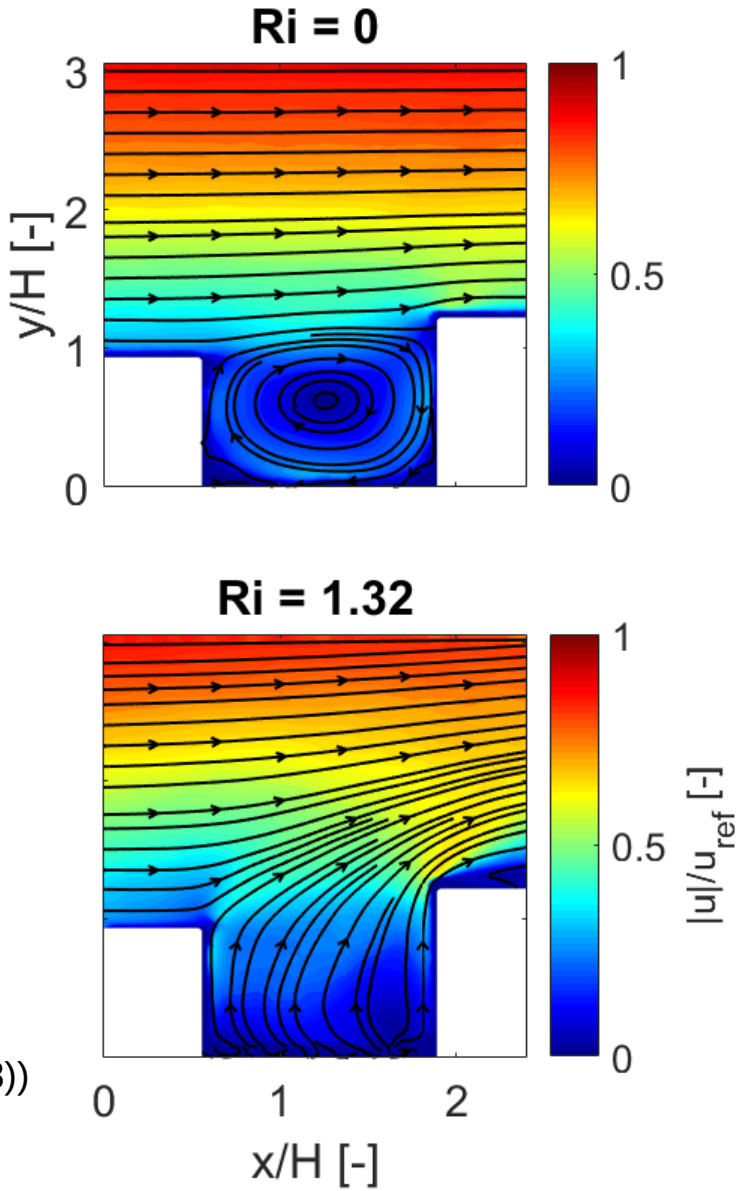


Experimental studies in wind tunnel

City quarter with heated walls



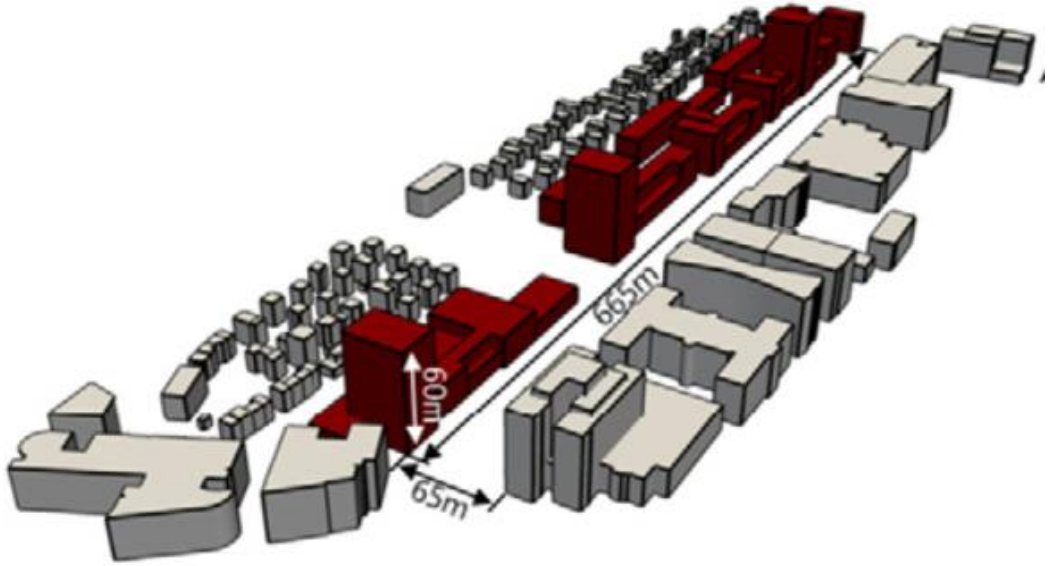
(Tsalicoglou et al, **2018**,
18th International Symposium on Flow Visualization (ISFV18))



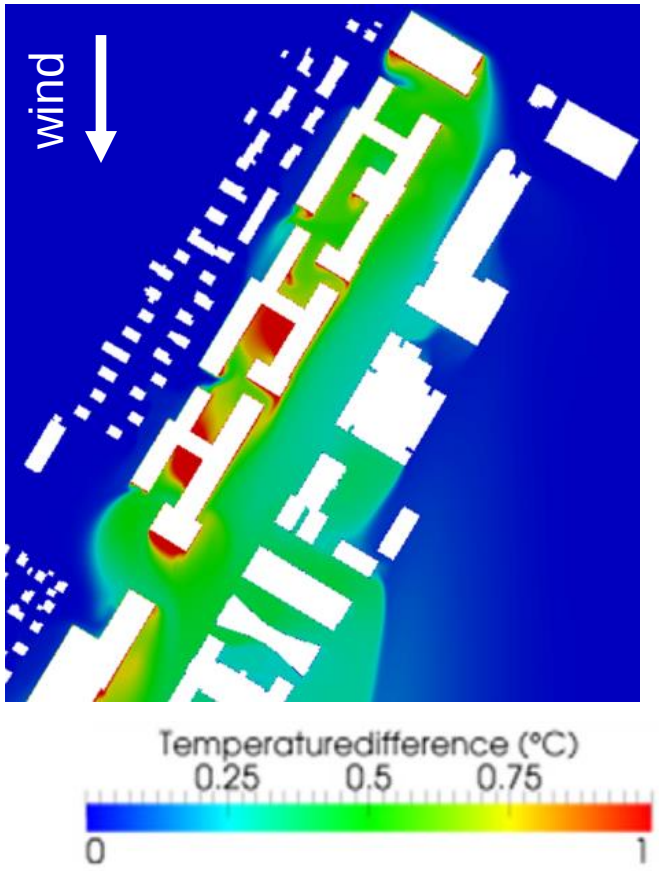
Larger Ri (Richardson number) indicates the importance of buoyancy
- Ratio of natural convection to forced convection

Local thermal hotspots

- Wind flow can affect temperature levels



Local hot spots



(Allegrini and Carmeliet, **2017**, *Urban Climate*)

Overview

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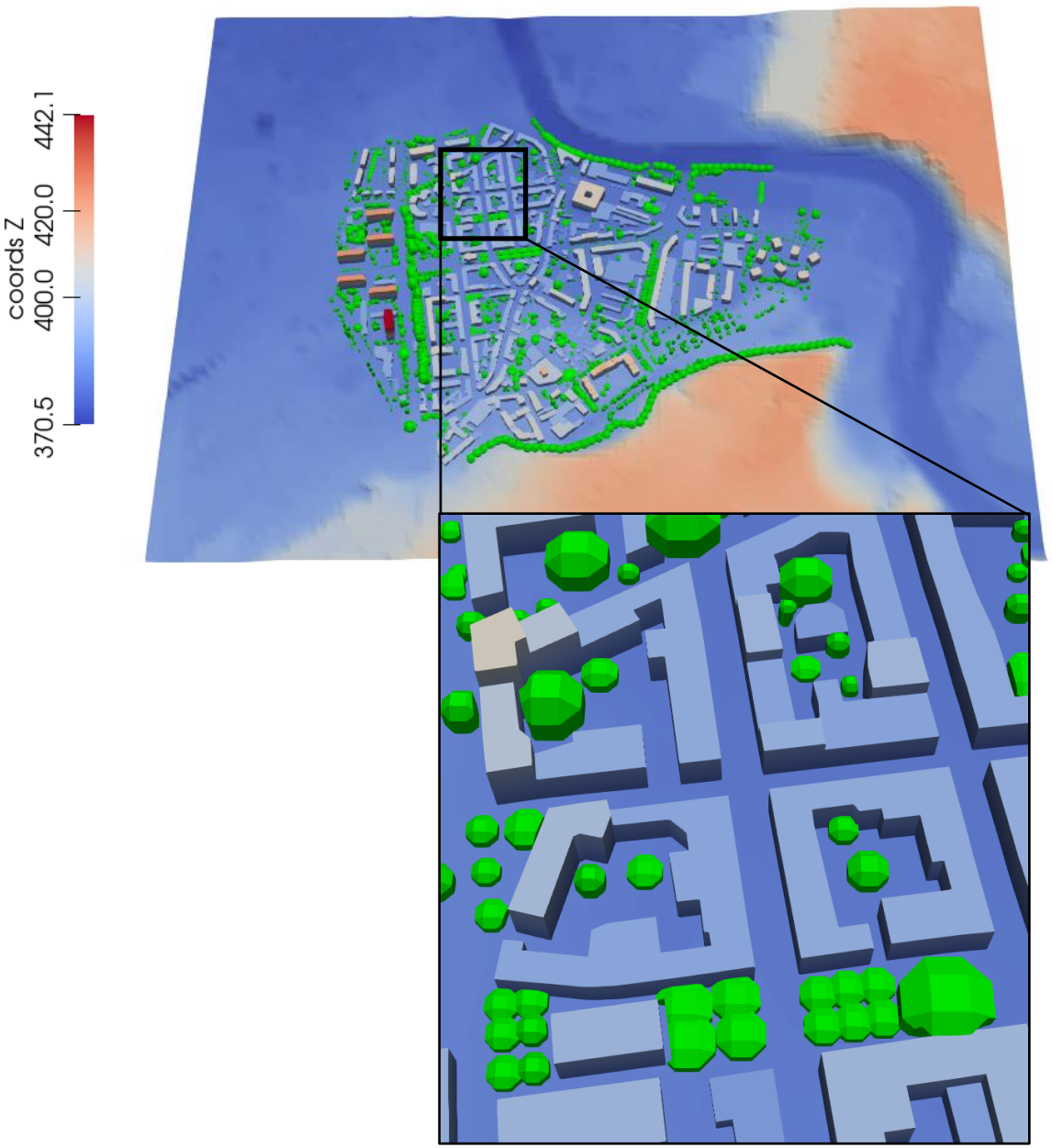
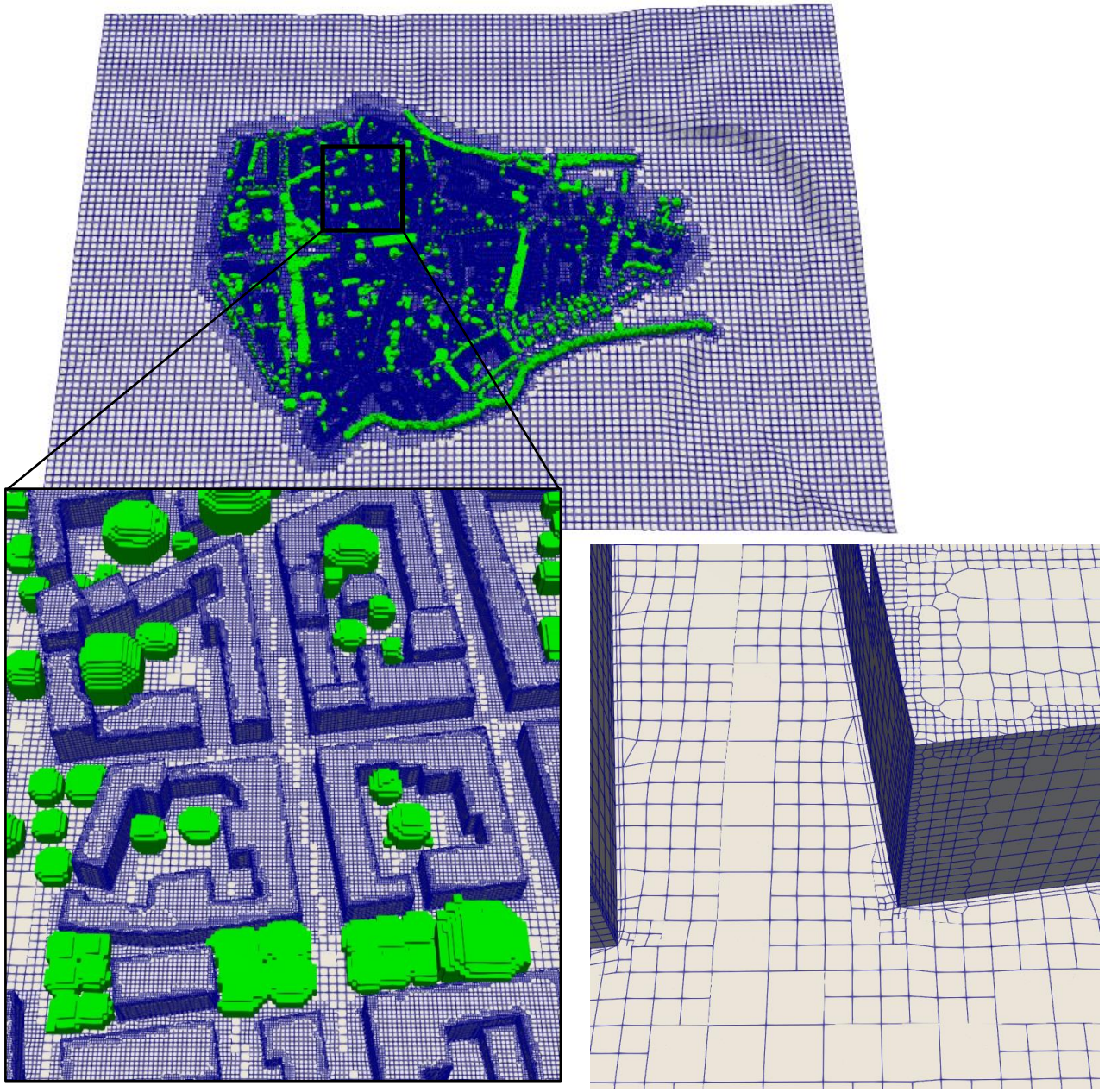
  - Numerical modeling of microclimate

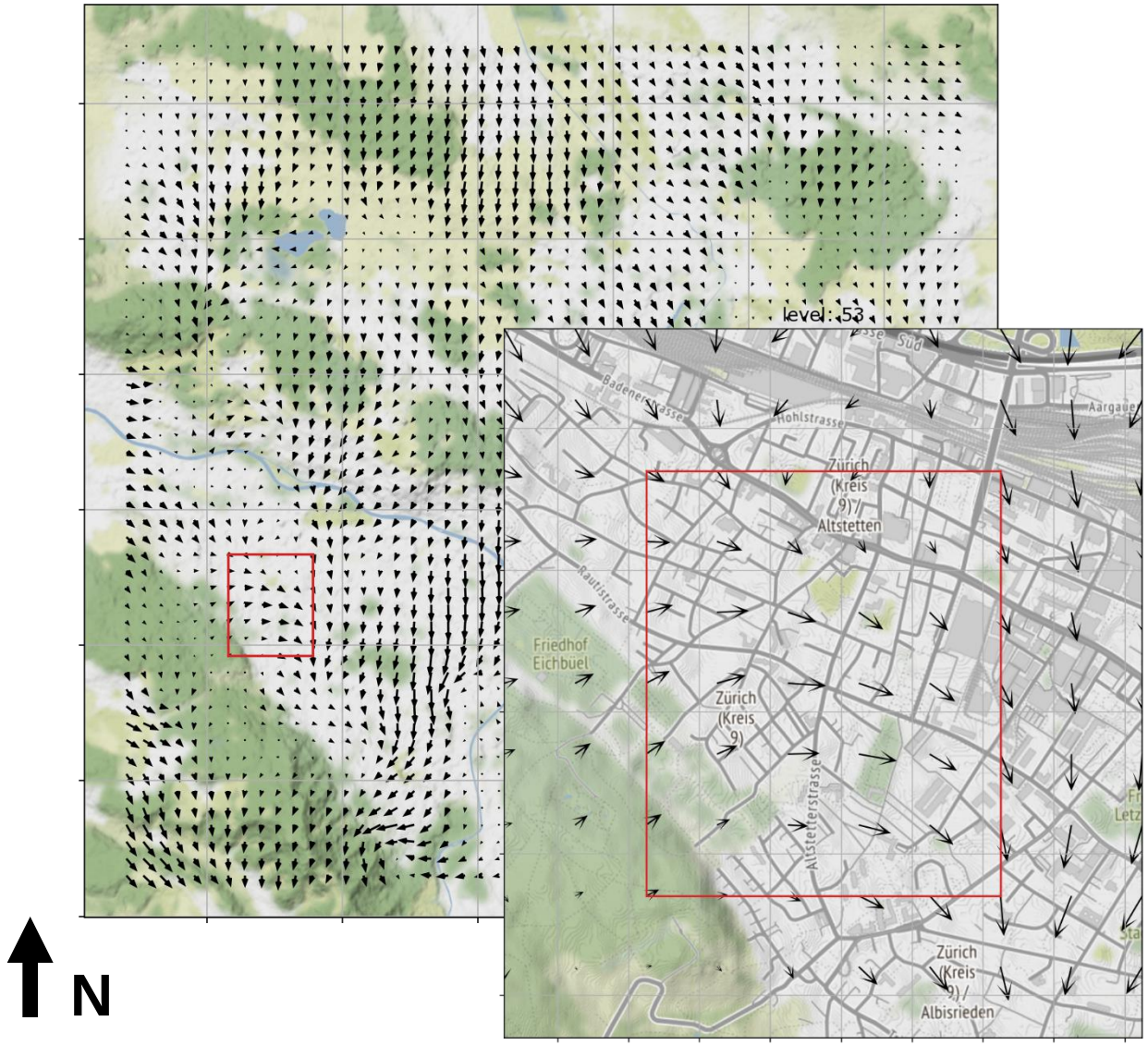
Computational models and grid generation

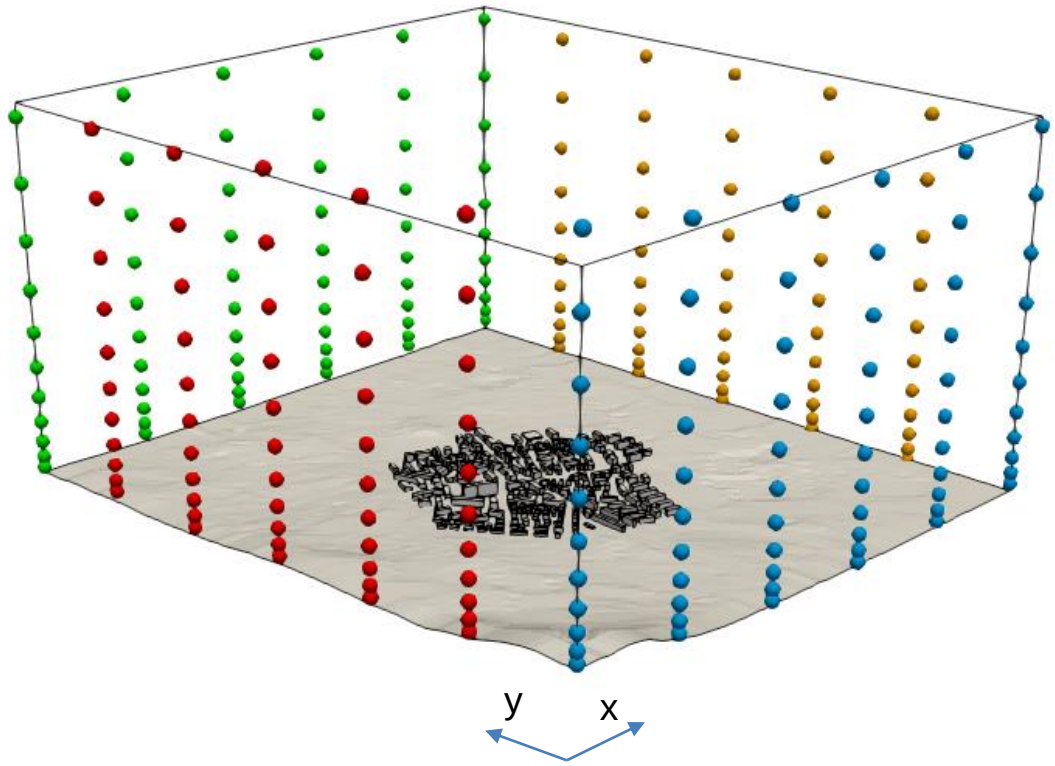




Mesoscale simulations (e.g. COSMO, WRF)

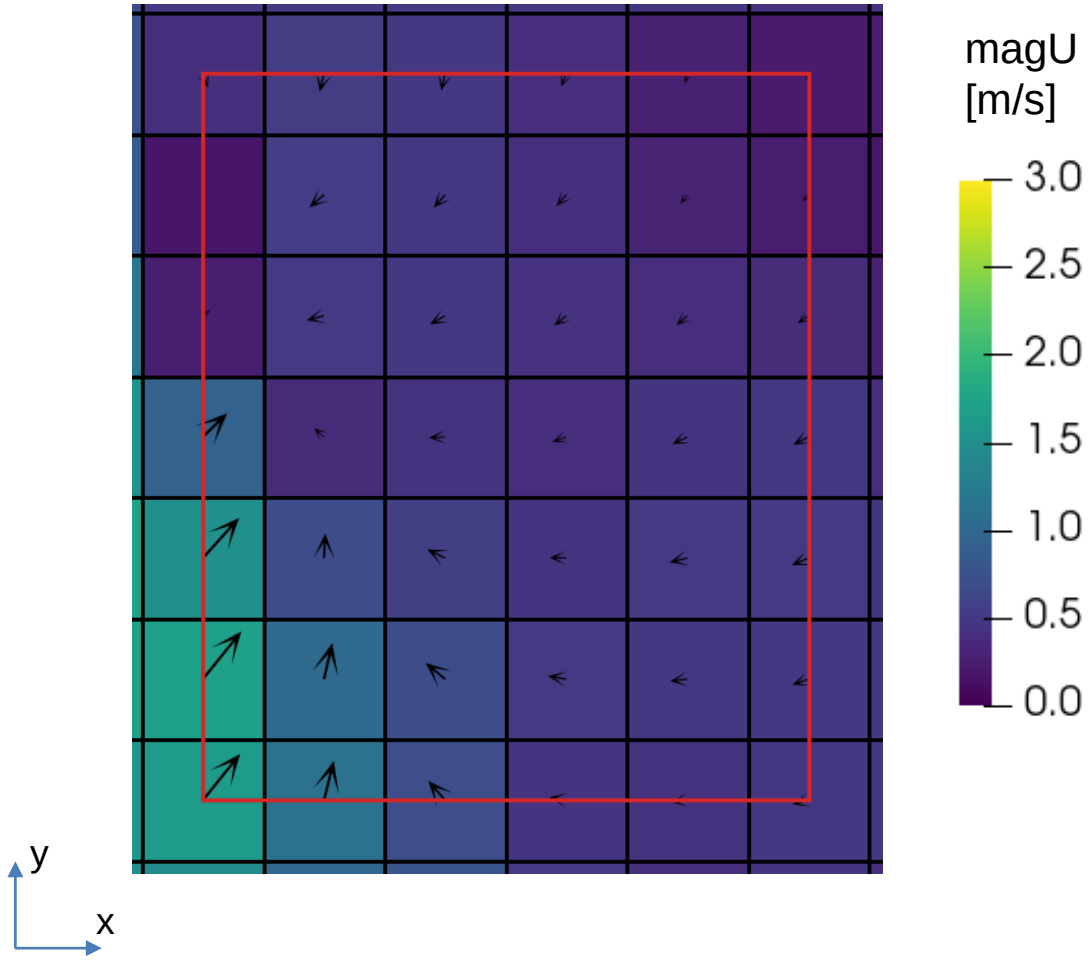
Wind-flow field on 29.07.2018 - 12:00

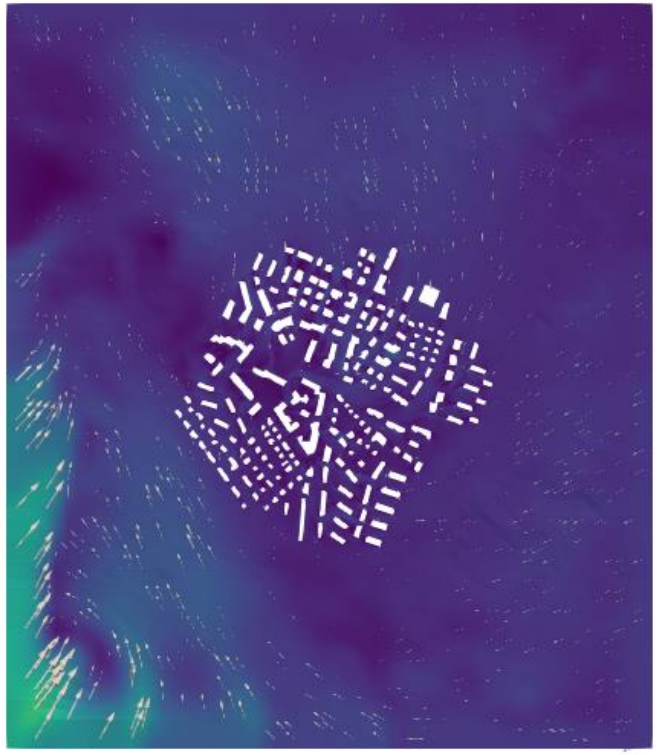




Comparison of flow fields

Magnitude of wind velocity at 10 m above ground
01:00





Typical output results / indices

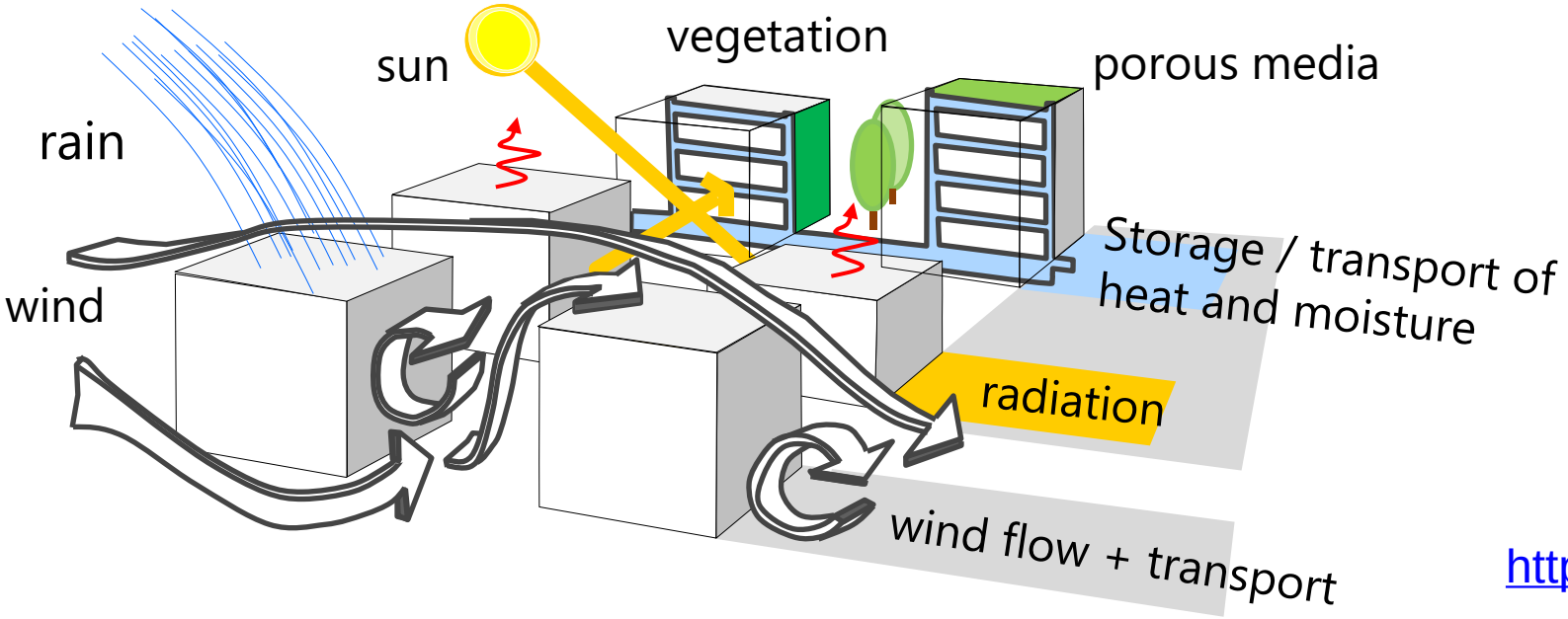
- Outdoor thermal comfort (e.g. UTCI, PET, Heat exposure index)
  - Air velocity, temperature, humidity
  - Surface temperature

- Vegetation-related
  - Transpiration rate
  - Leaf temperature

- Impacts of greenery, shading, building morphology, densification, etc.
  - Geometrical changes
  - Material changes

- Variation of temperature and humidity within urban materials
  - Evaporative cooling
  - Related durability indices (e.g. mould risk, freeze-thaw)
  - Soil moisture content

Coupled physical process in urban environment



- hamFoam
- urbanMicroclimateFoam
- windDrivenRainFoam

https://gitlab.ethz.ch/openfoam-cbp/solvers/

CFD: Building-resolved turbulent air flow due to wind and buoyancy

HAM: Heat And Moisture storage and transport in porous materials (building materials, pavements, soils, …) including phase change: evaporative cooling

RAD: Short- and long-wave radiation using view factor approach

VEG: Modeling of urban trees and green surfaces

Overview

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  - Numerical modeling of microclimate
  - Evaporative cooling

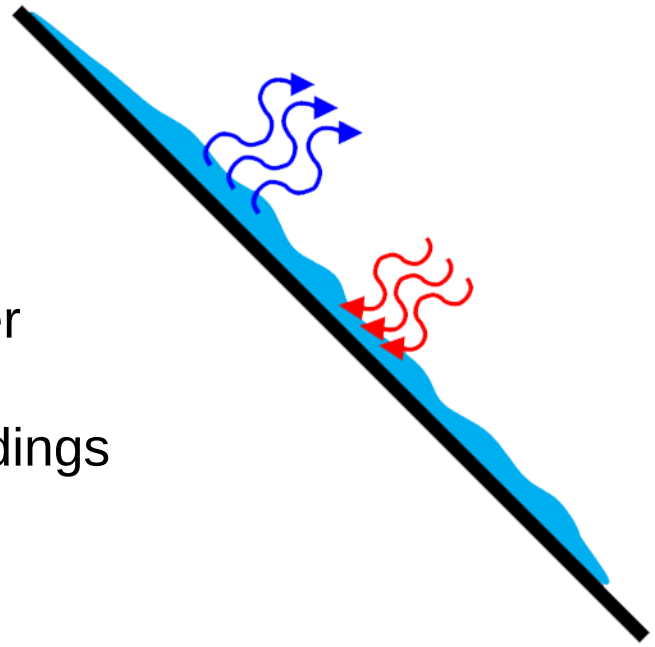
Evaporation

- Phase change of liquid water to water vapor requires energy = **latent heat L_v**

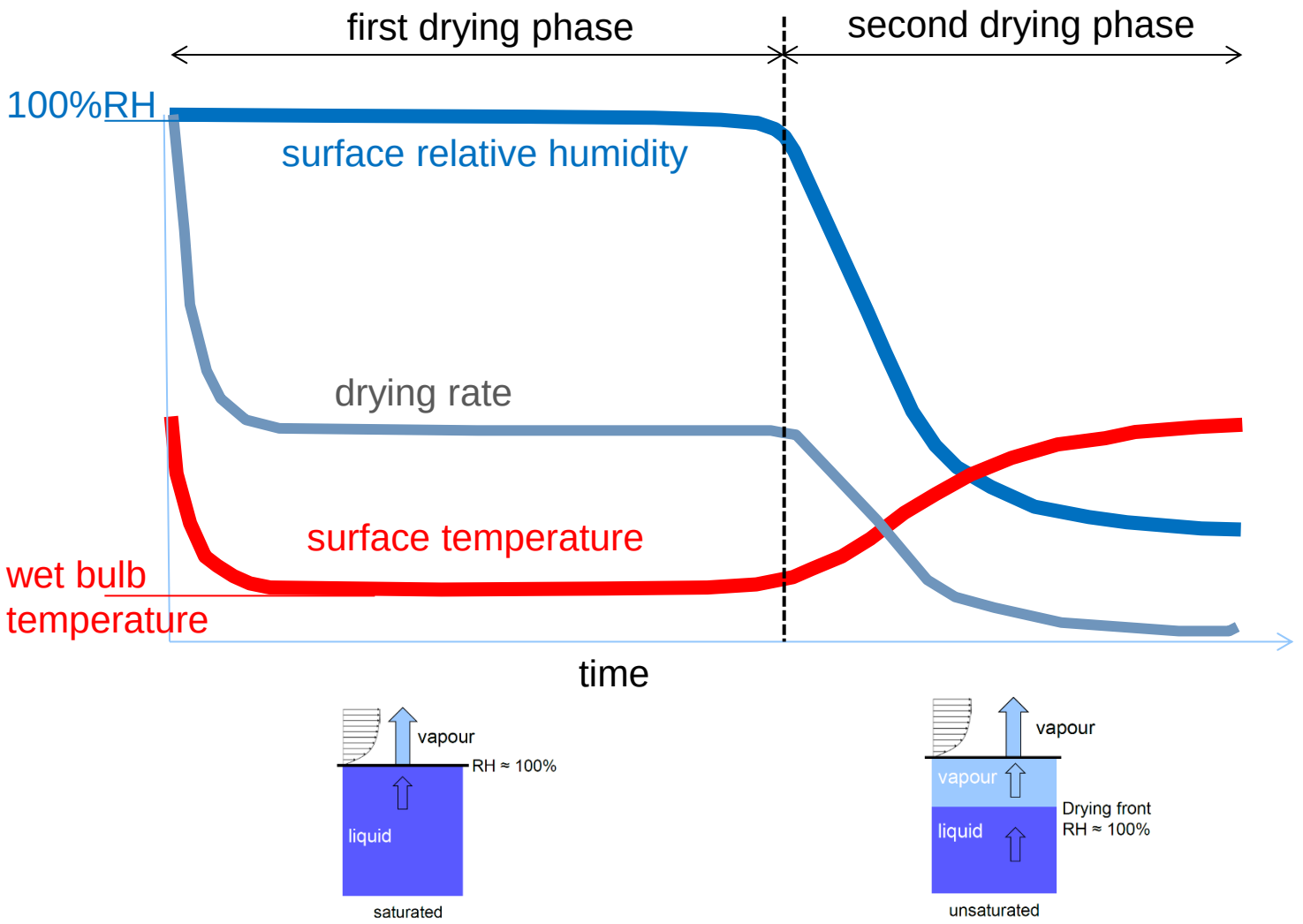
$L_v = 2.5 \times 10^6$ J/kg

- Energy required to evaporate 1 kg of water

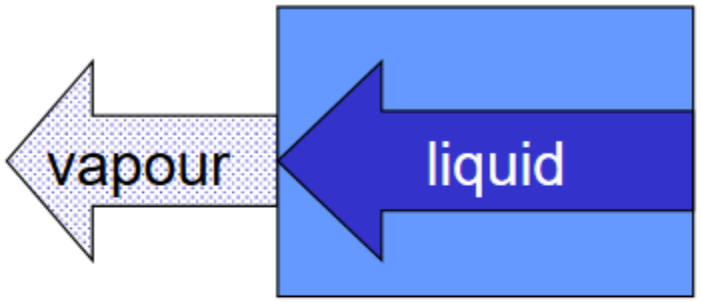
- This energy is extracted from the surroundings



Drying behavior of porous media

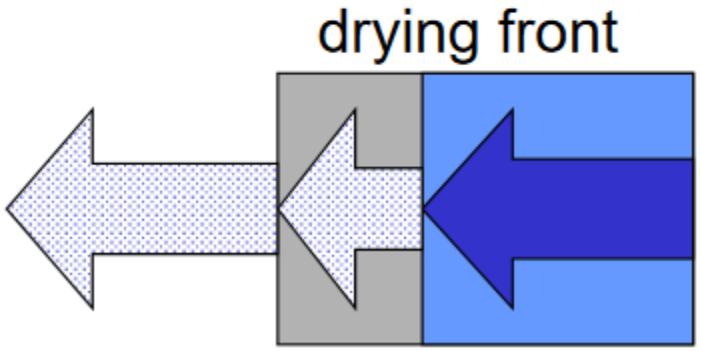


Drying behavior of porous media



First drying period

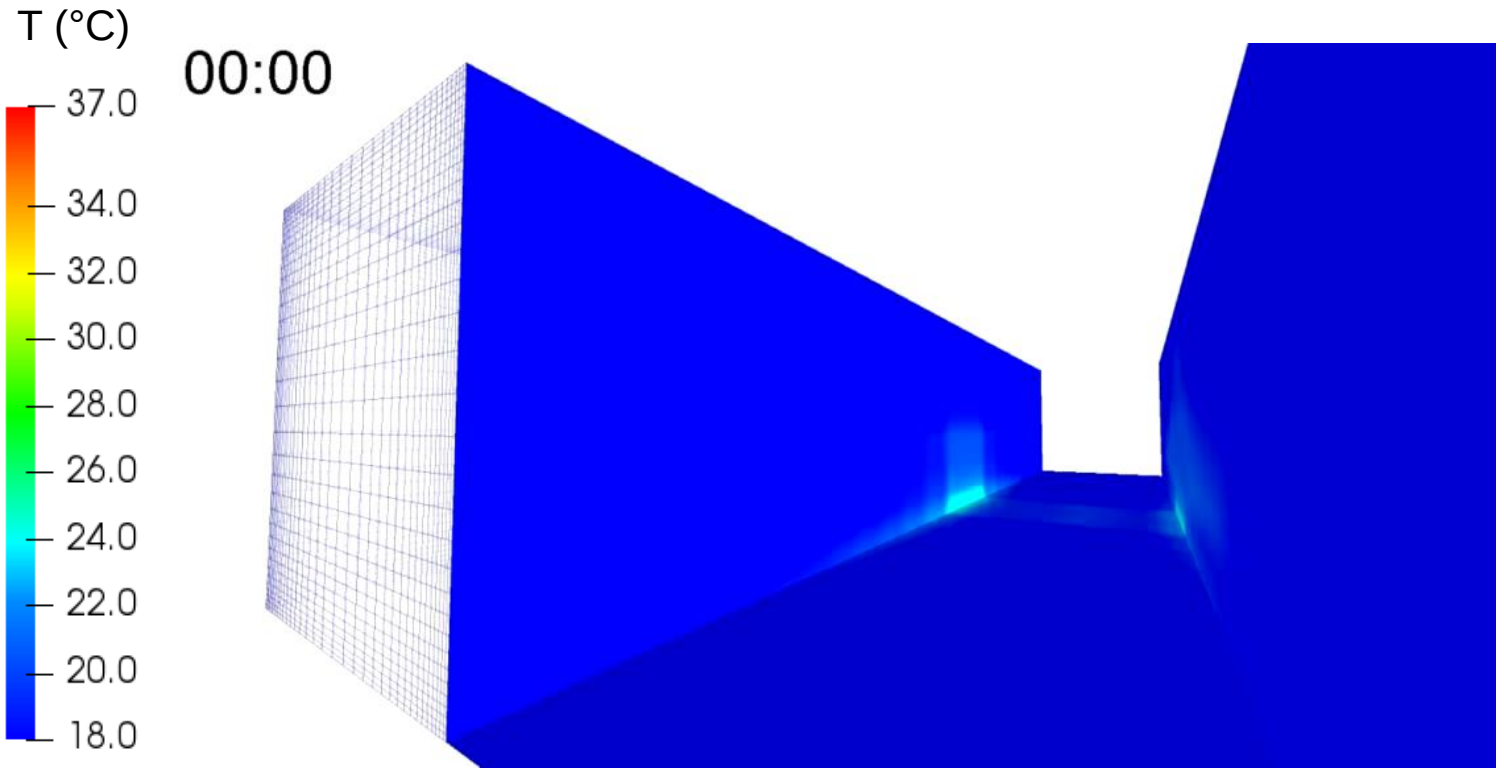
- governed by boundary conditions
- high drying rate

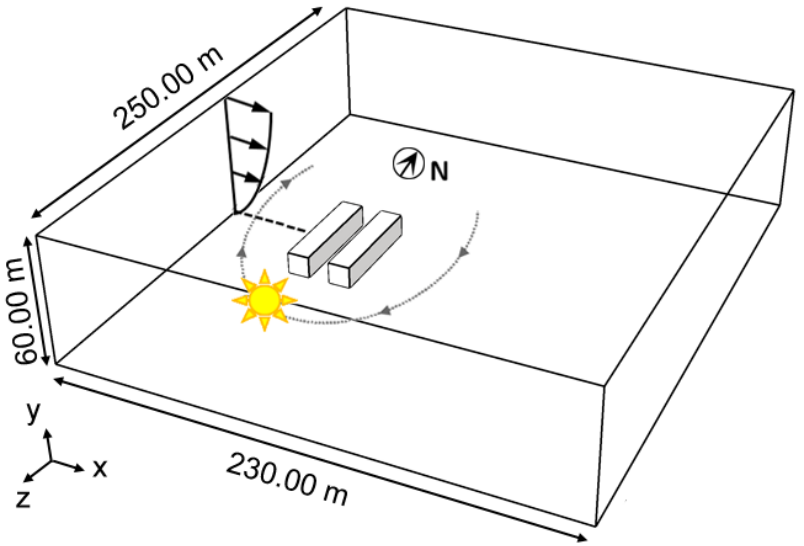


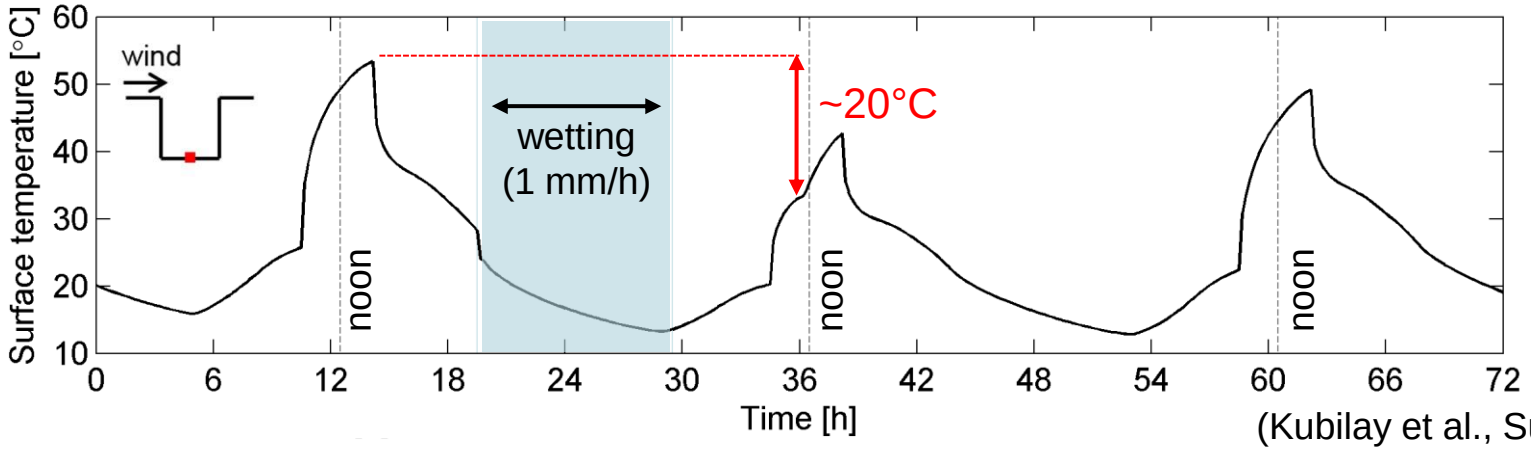
Second drying period

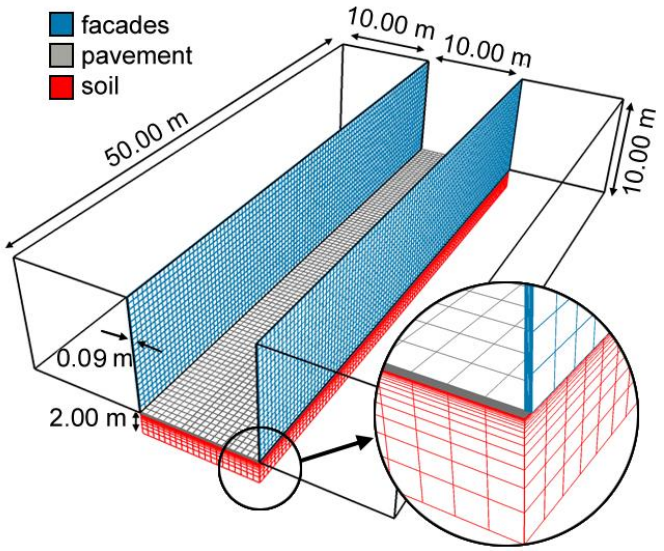
- governed by water vapour resistance factor
- low drying rate

Daily variation of surface temperature



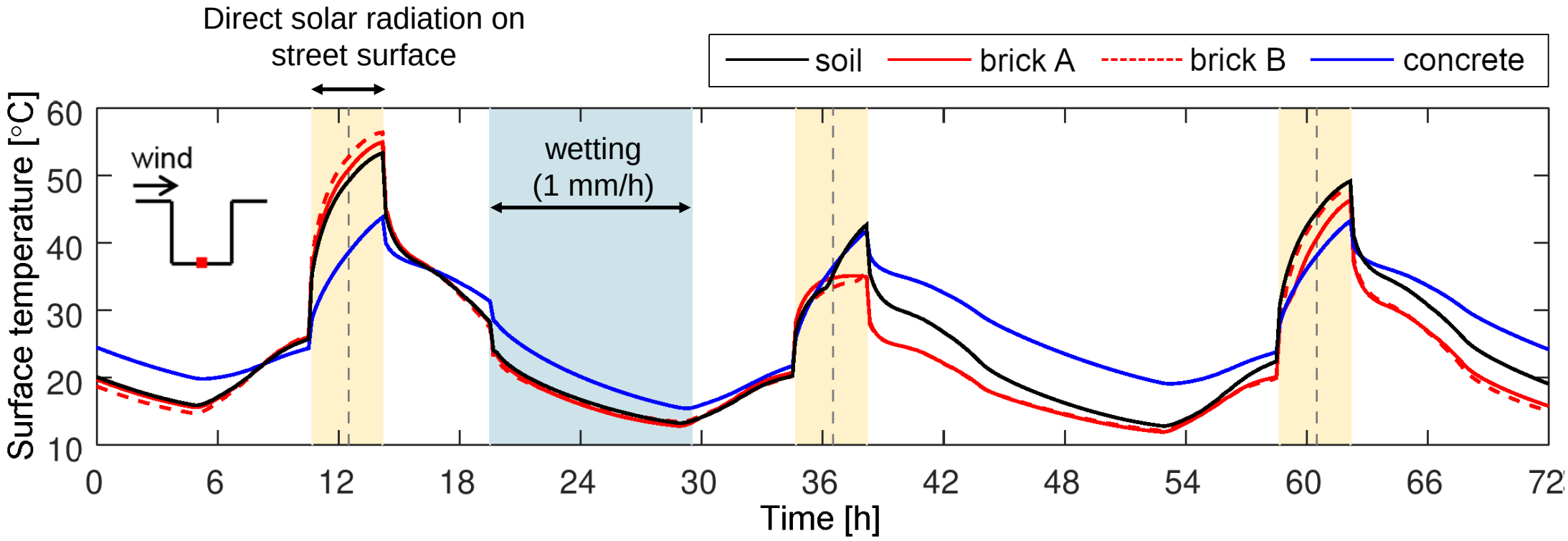






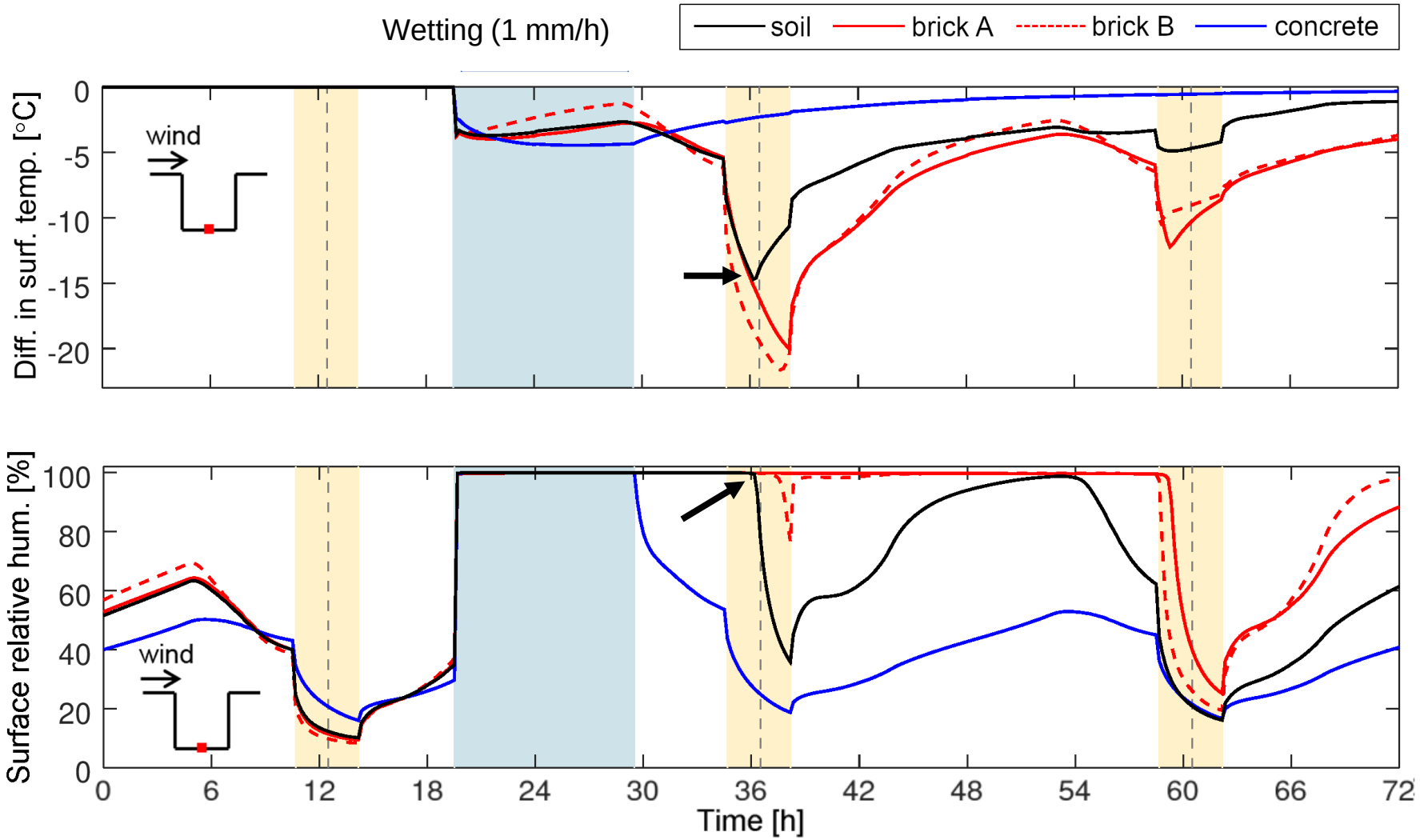
(Kubilay et al., Sustainable Cities and Soc. **2019**, 49, 101574)

Evaporative cooling at street surface with different pavement materials



(Kubilay et al., Sustainable Cities and Soc. **2019**, 49, 101574)

Street canyon evaporative cooling at pavement with different materials



Change in street surface temperature as a result of wetting

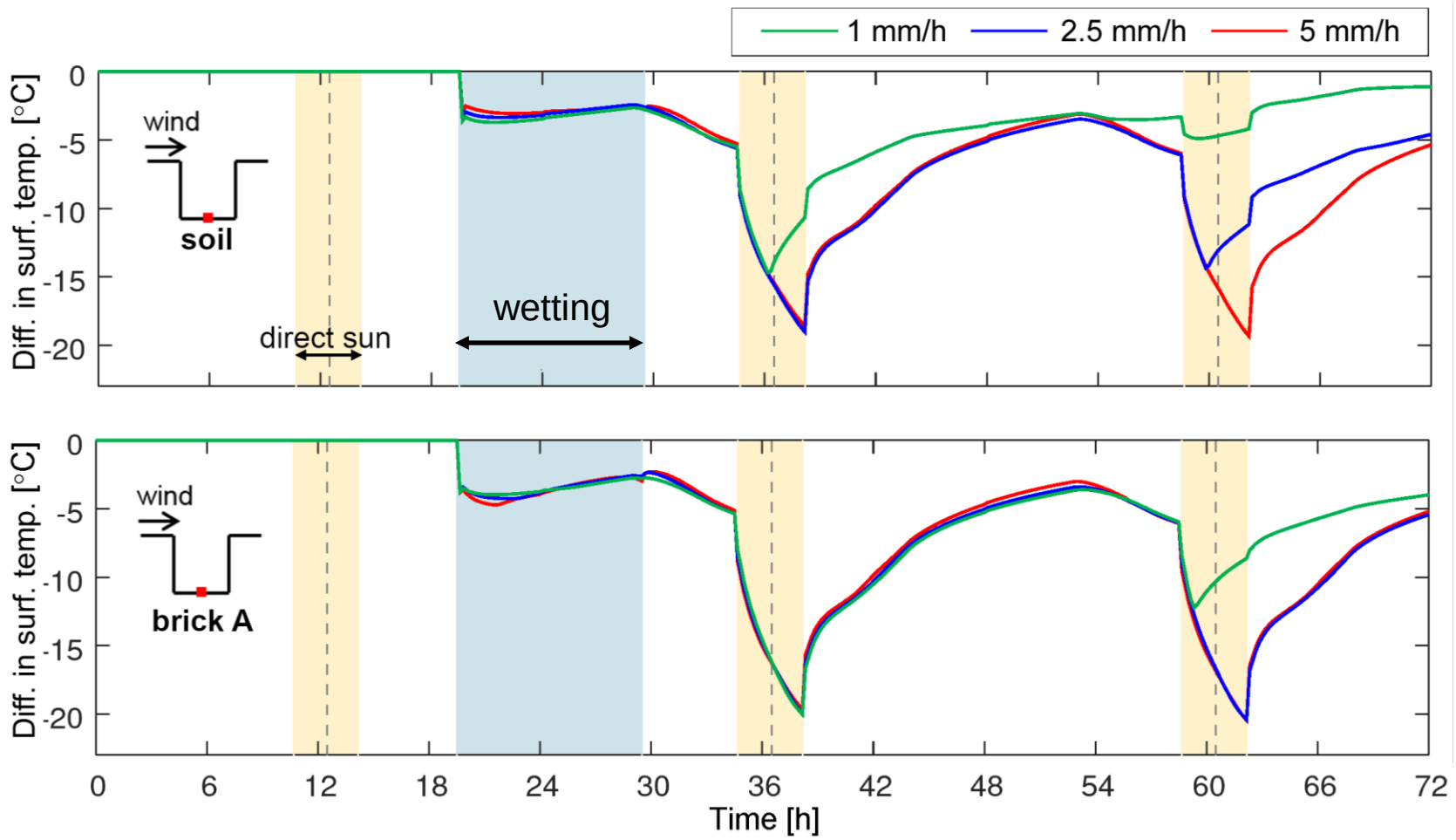
- Surface relative humidity decreases

→ Rate of evaporation decreases

→ surface temperature increases

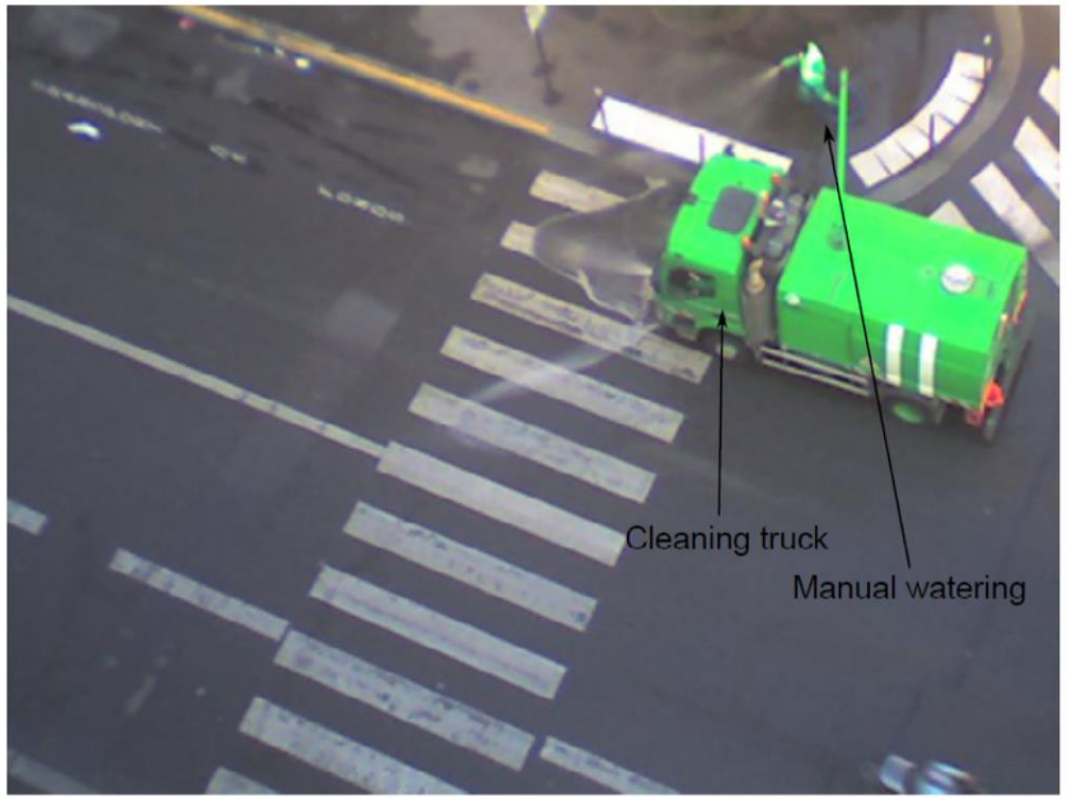
(Kubilay et al., Sustainable Cities and Soc. **2019**, 49, 101574)

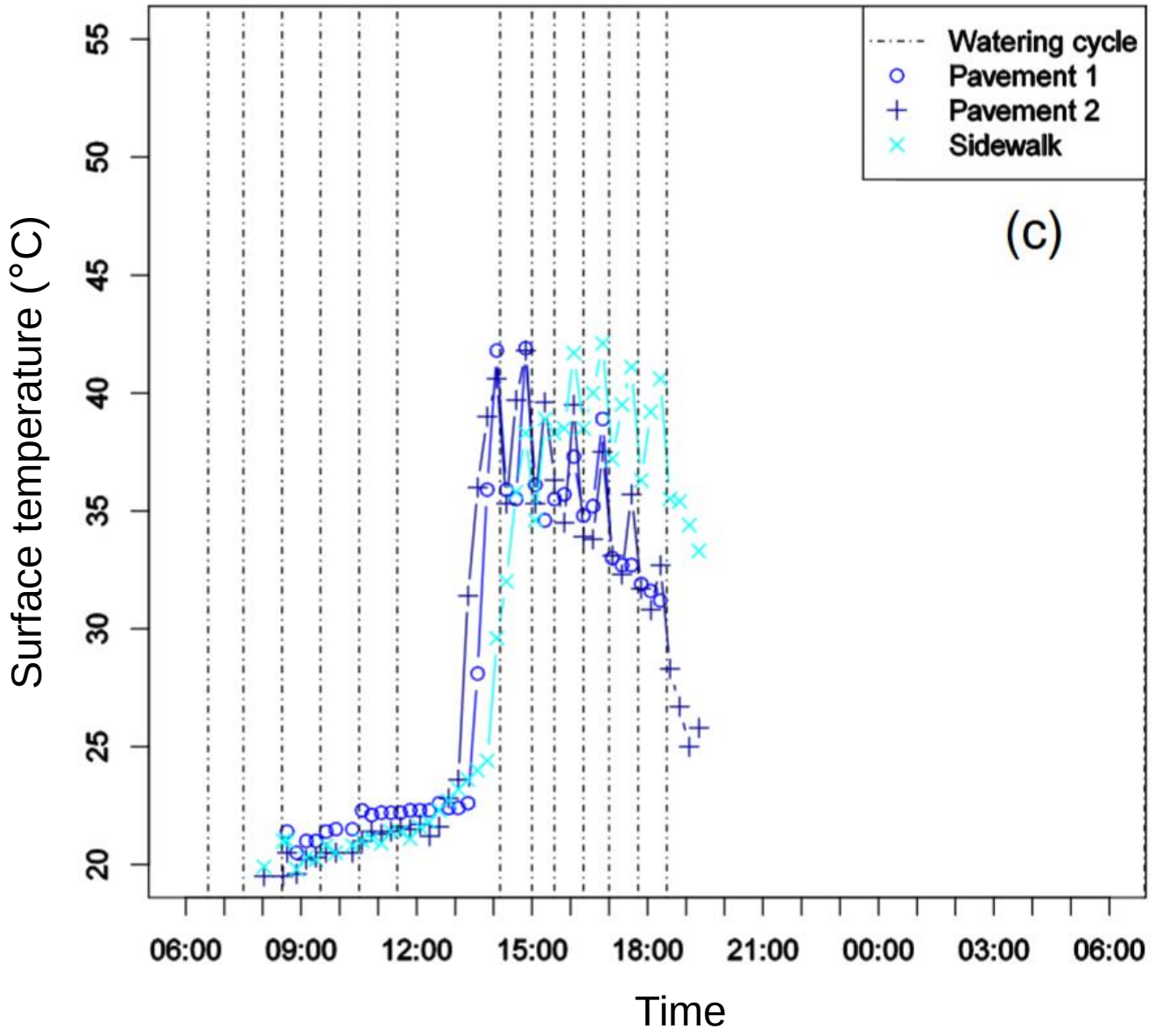
Influence of wetting intensity (duration is kept the same)



- 2nd drying phase starts earlier when wetting amount is lower
- Afterwards slower rate of evaporation → temperature increases

(Kubilay et al., Sustainable Cities and Soc. **2019**, 49, 101574)

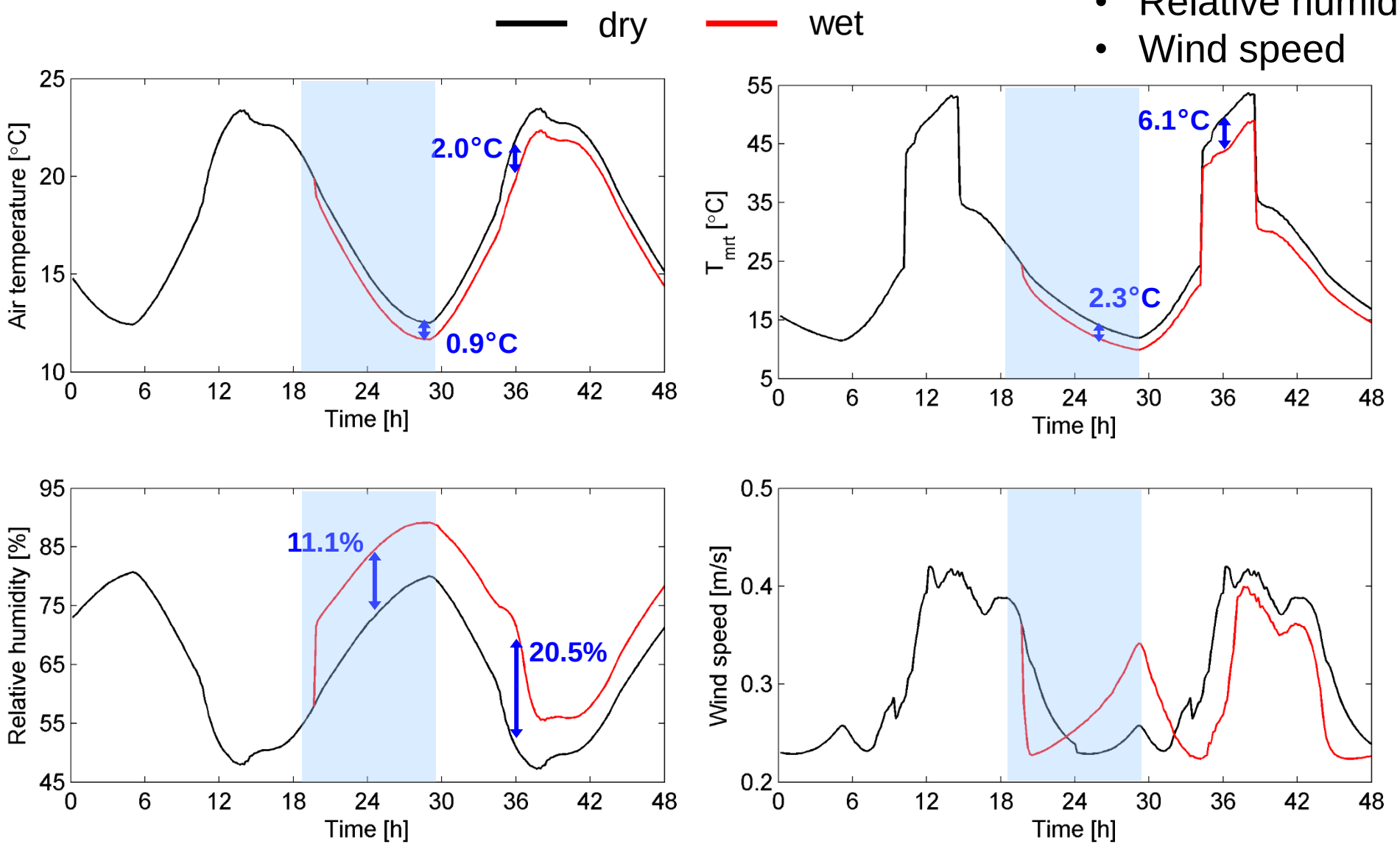




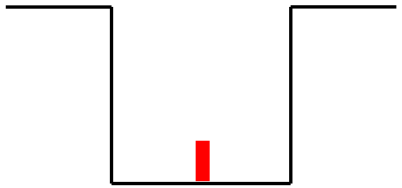
(Hendel et al., Urban Climate **2014**, 10, 189-200)

Influence of wetting on thermal comfort variables

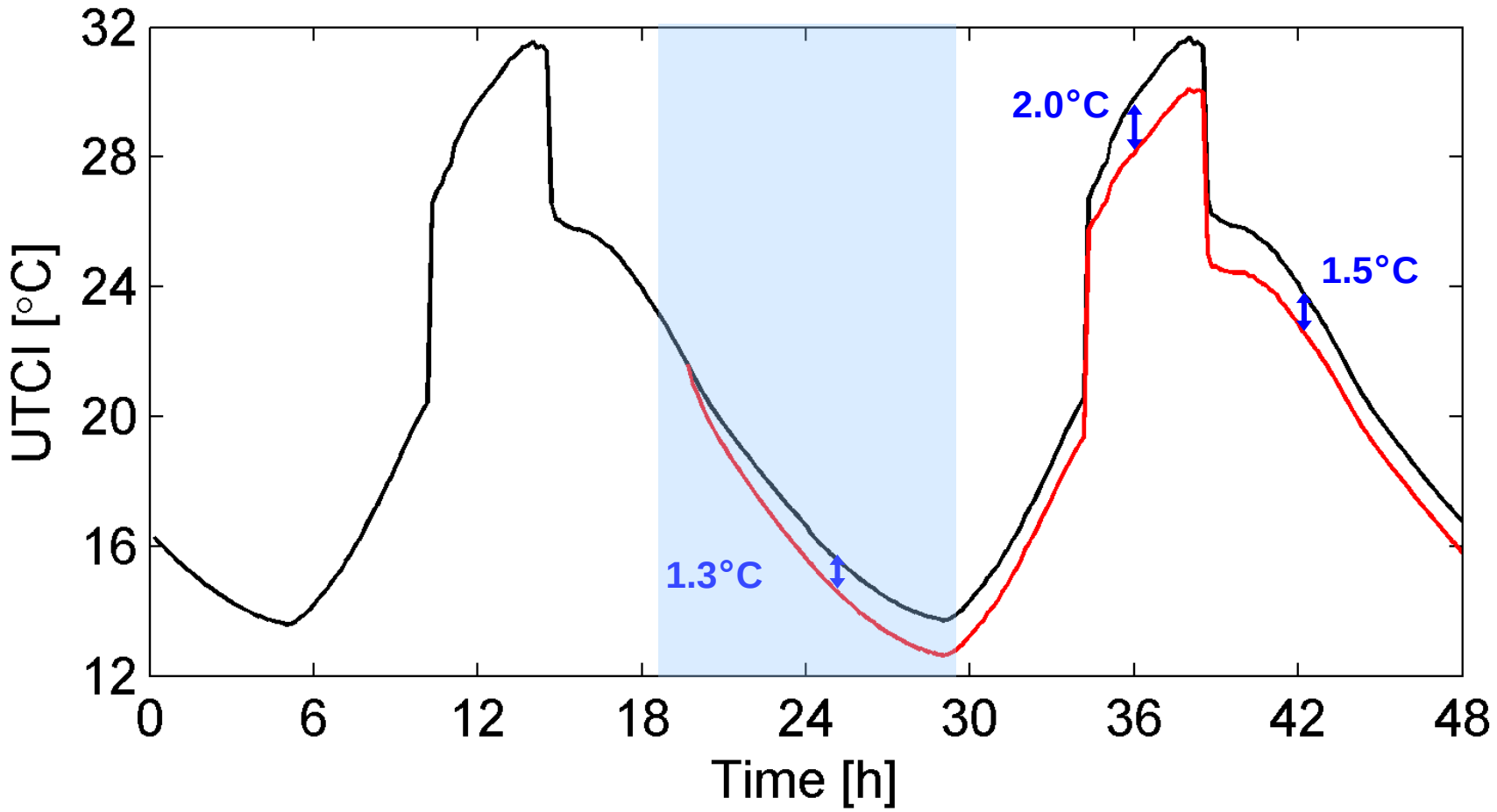
- Air temperature
- Mean radiant temperature
- Relative humidity
- Wind speed



Resulting UTCI (Universal Thermal Climate Index)



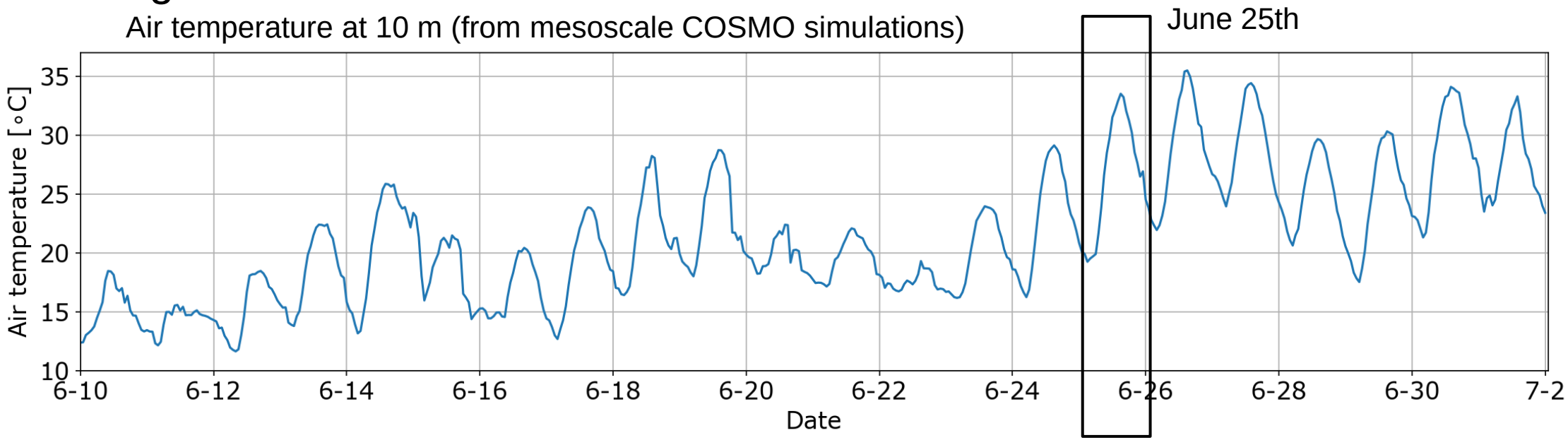
UTCI for a person standing at the center



Heat wave mitigation: case study Münsterhof, Zürich

(Photo: Adrian Michael / CC BY-SA 3.0)

Meteorological conditions – heat wave 2019 June

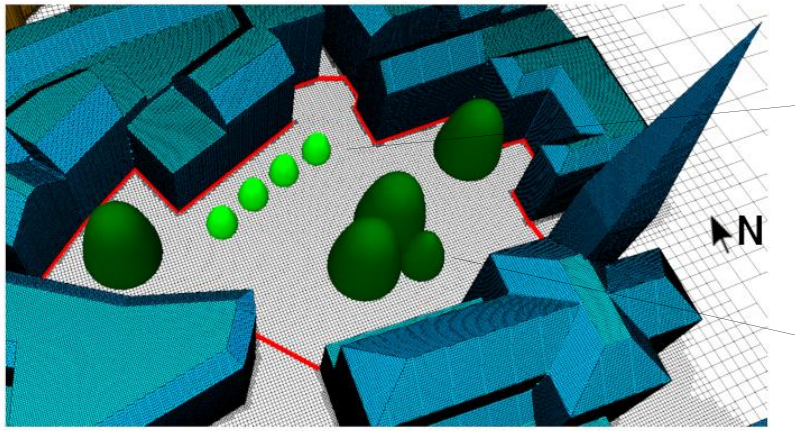


2-layer porous pavement

6 mm between 08:00-08:20

Artificial wetting

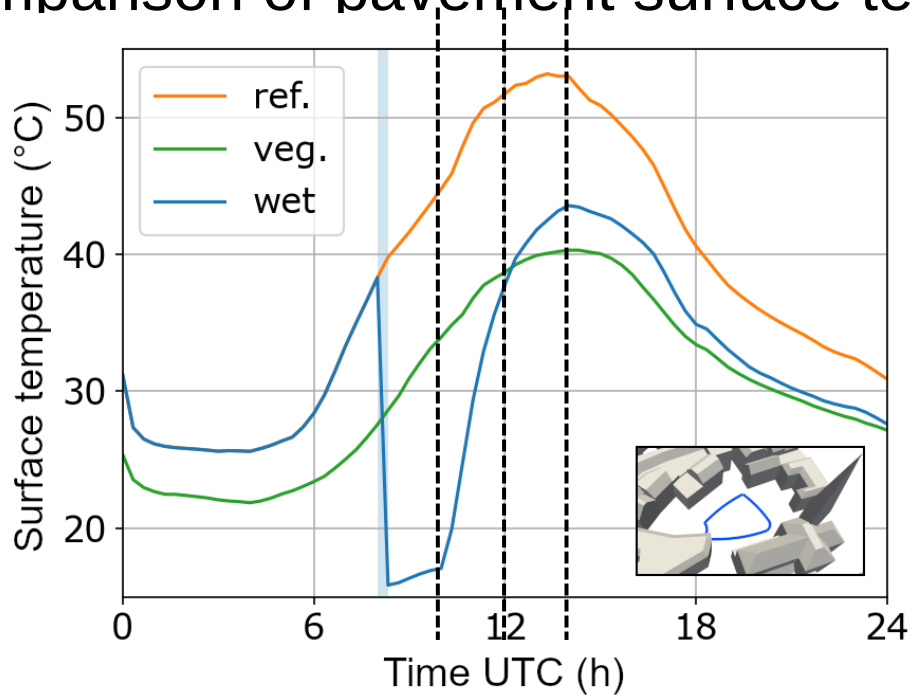
Trees



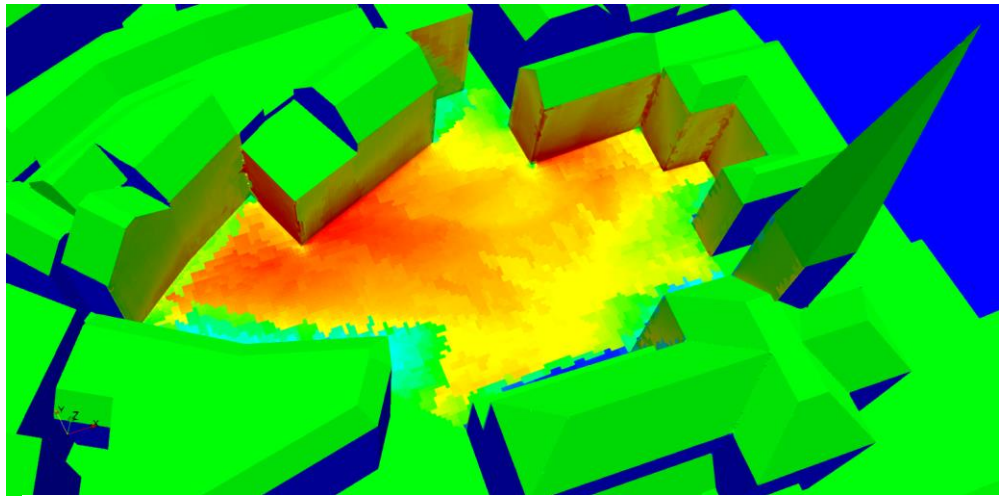
Field maple
10-12 m
LAD = 2 m^2/m^3

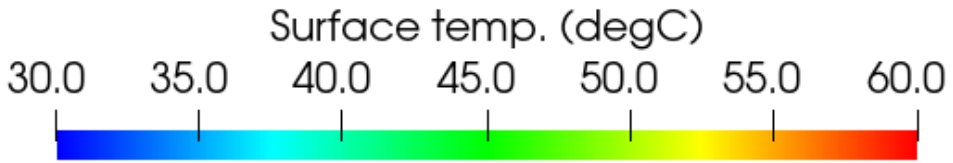
Silver linden
25-30 m
LAD = 4 m^2/m^3

Comparison of pavement surface temperature

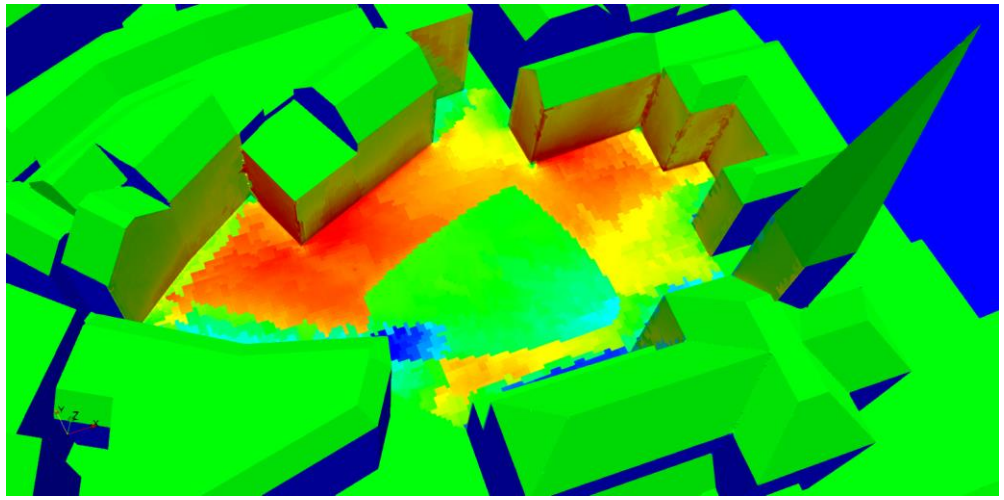


Ref.

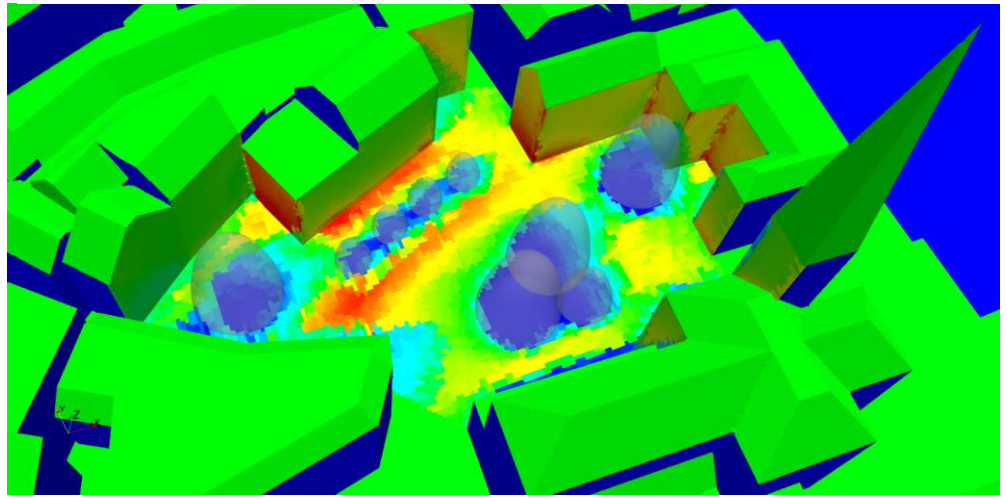




Wet



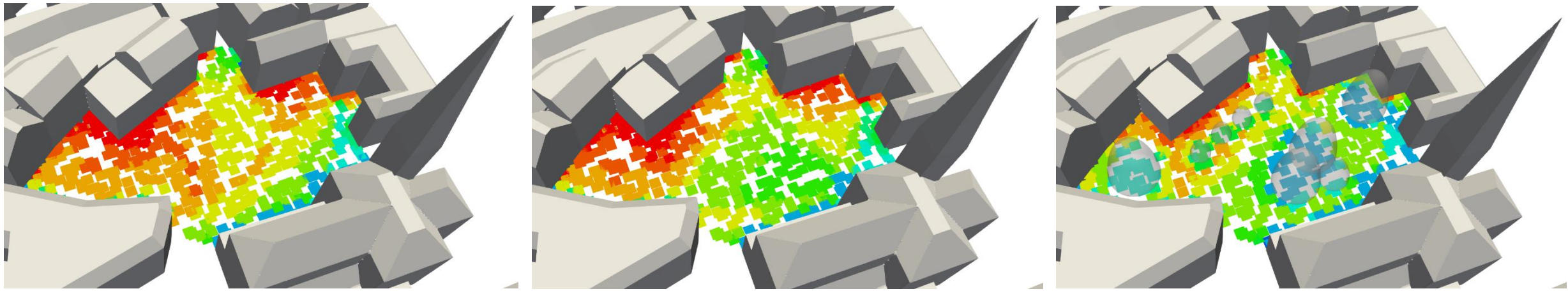
Veg.

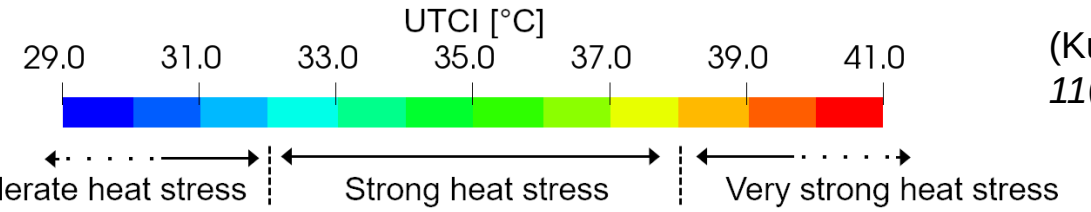


Thermal comfort – Universal thermal climate index (UTCI)

Ref. Wet Veg.

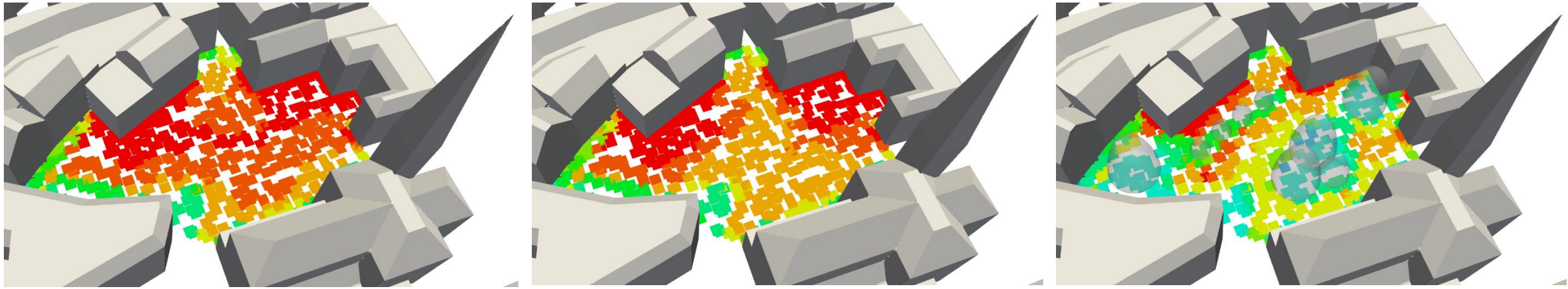
12:00





(Kubilay et al., Atmosphere **2020**, *11*(12), 1313)

14:00



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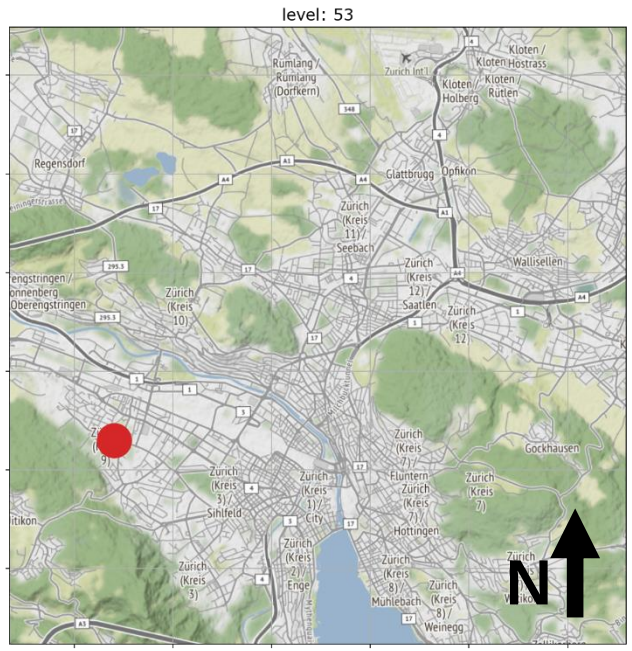
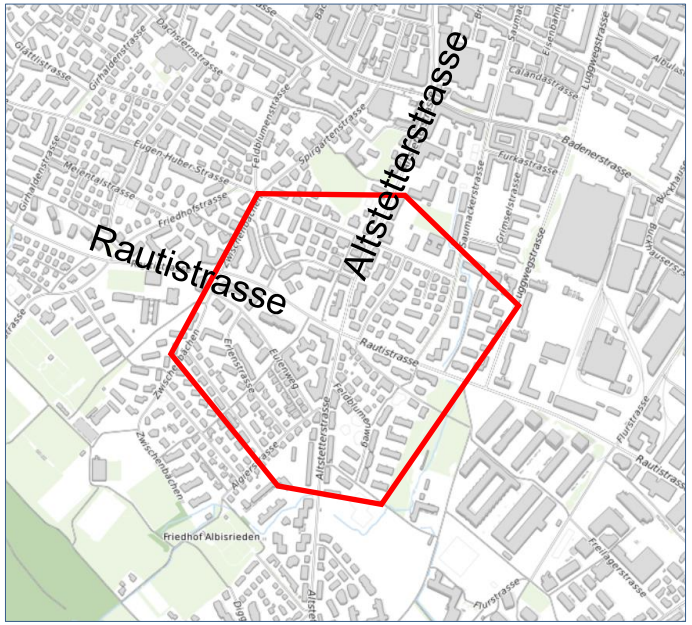
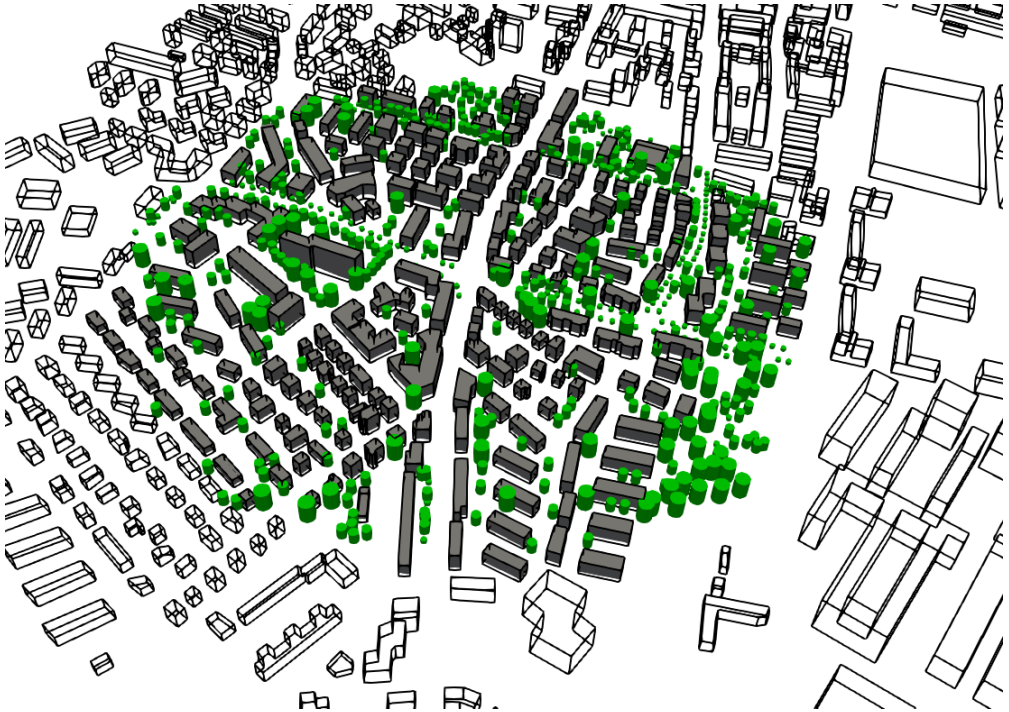
  - Impact of urban trees and high-rise buildings

- Impact of urban morphology and urban street trees
  - Densification with high-rise buildings
  - Wind sheltering & reduction in ventilation
  - Cooling by shading & transpiration

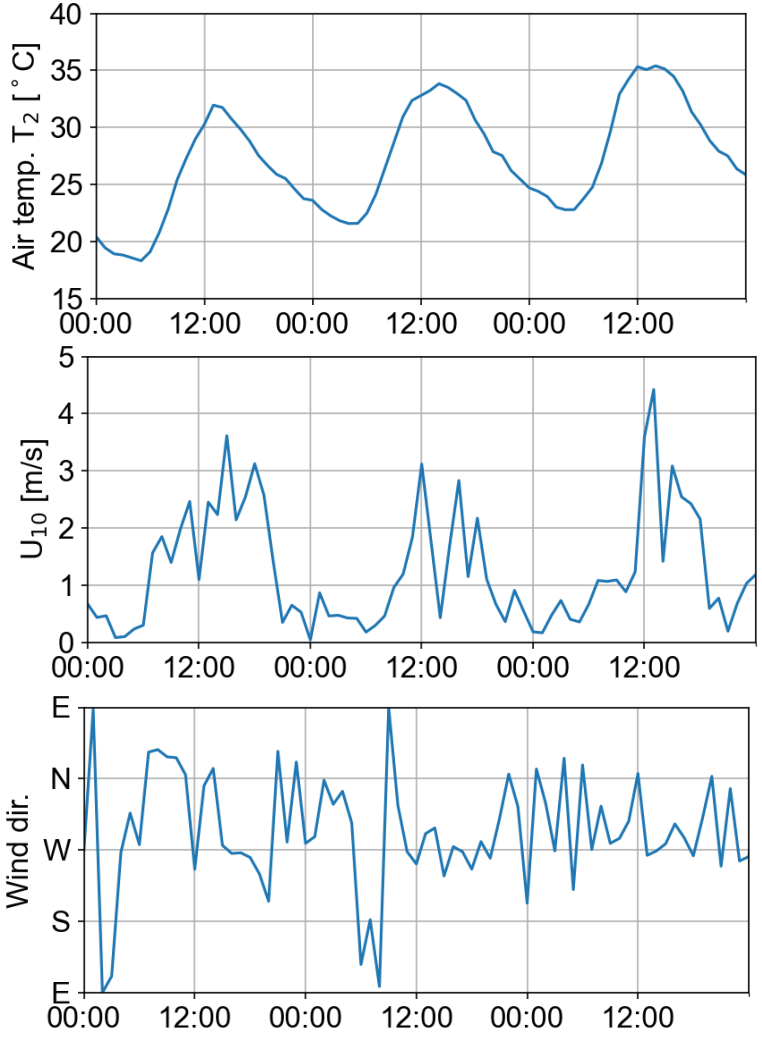






Meteorological conditions during heat wave (July 29 – 31, 2018)

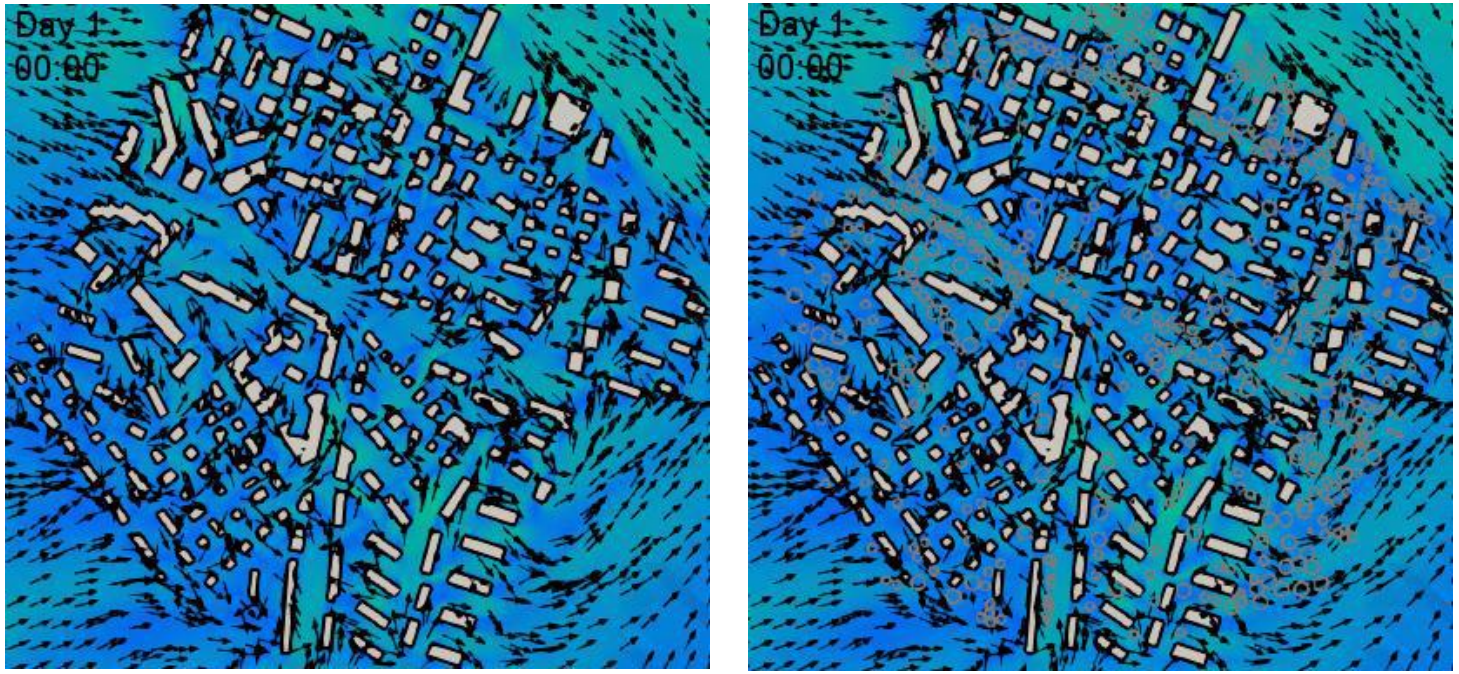
Meteorological conditions



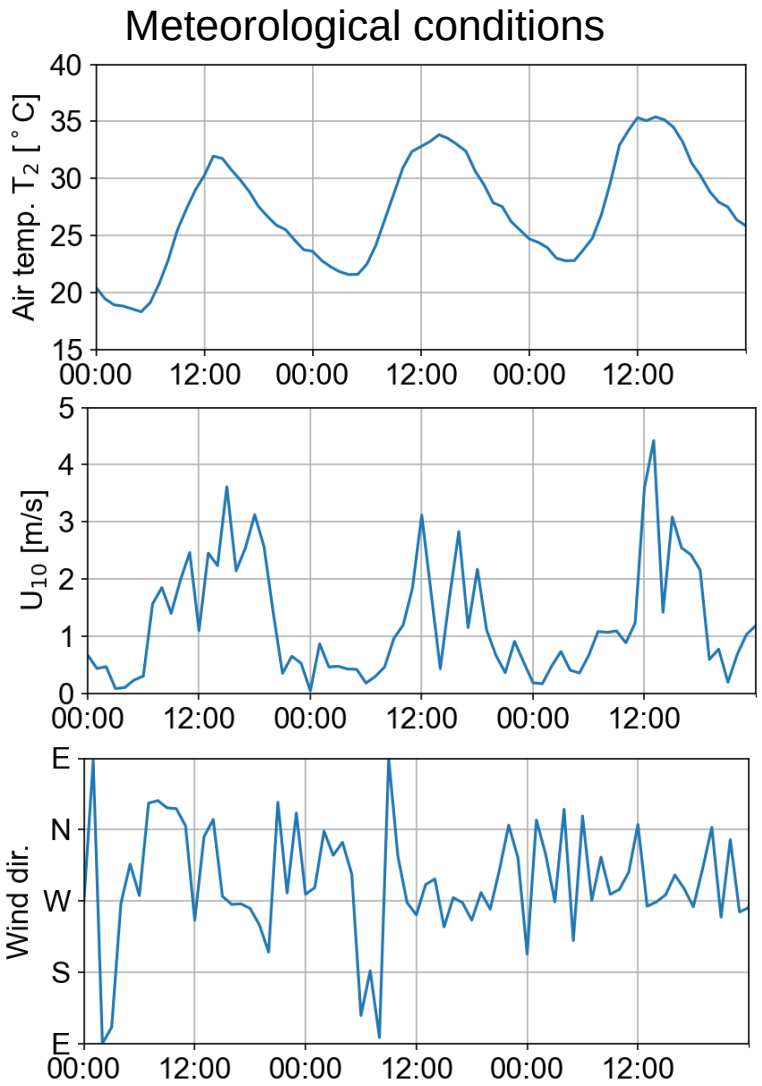
Microscale velocity magnitude at 2 m height

without trees

trees with LAD = 1 m^2/m^3



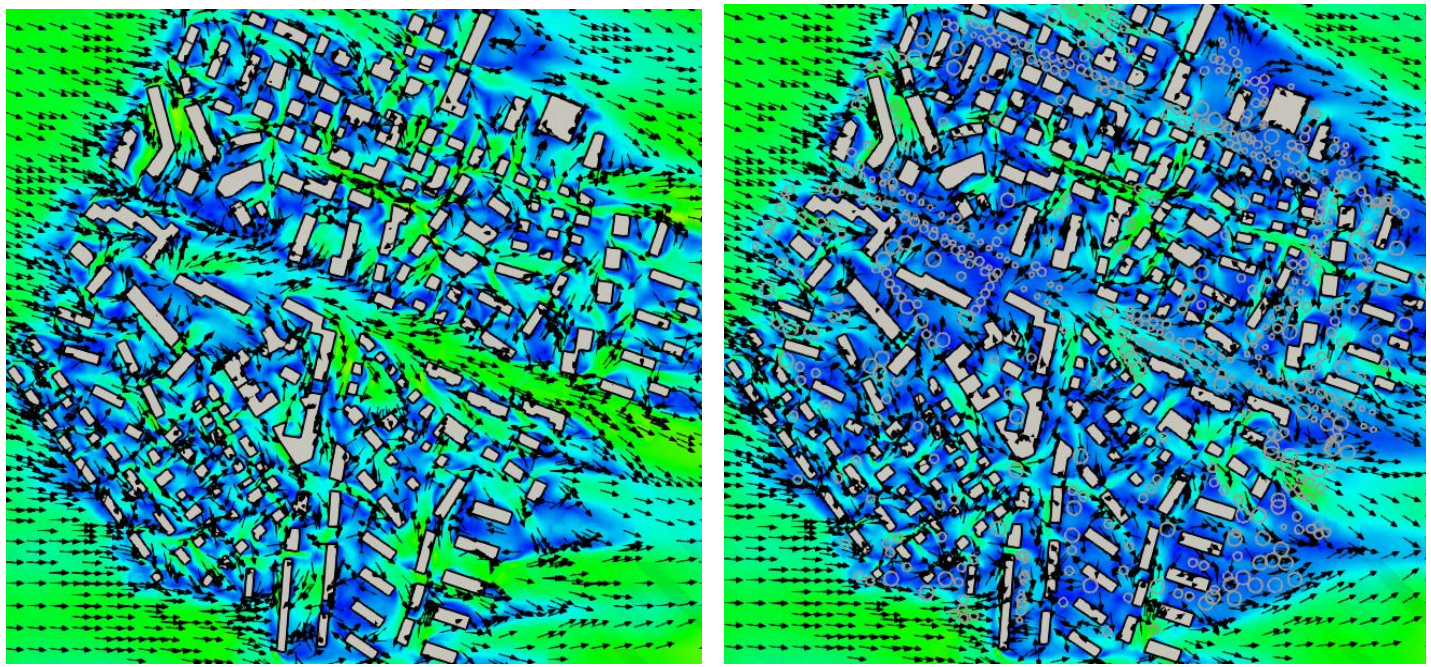
Meteorological conditions during heat wave (July 29 – 31, 2018)

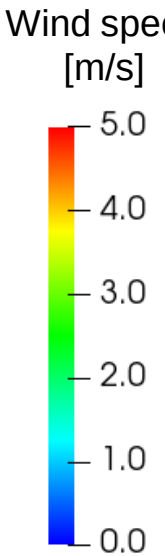


Microscale velocity magnitude at 2 m height

without trees

trees with LAD = 1 m^2/m^3

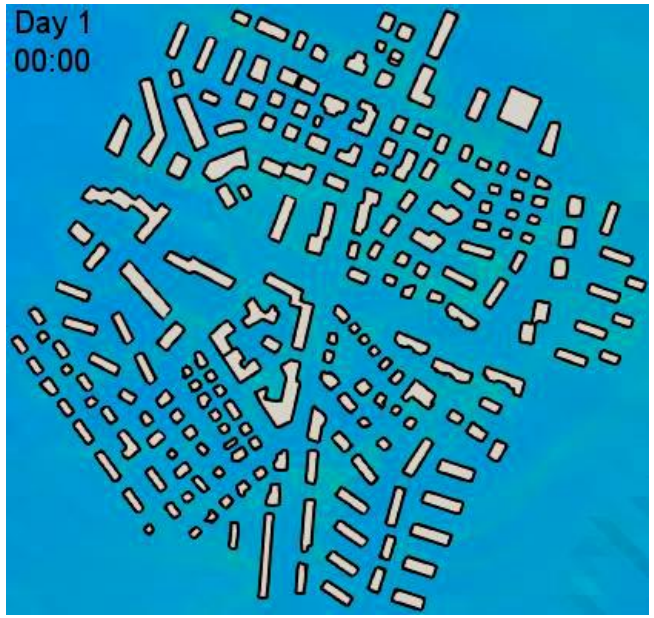




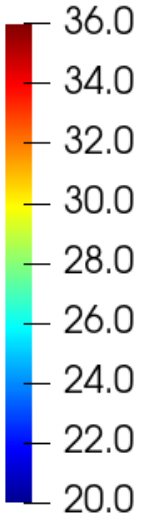
Day 3, UTC 13:40

Air temperature at street level

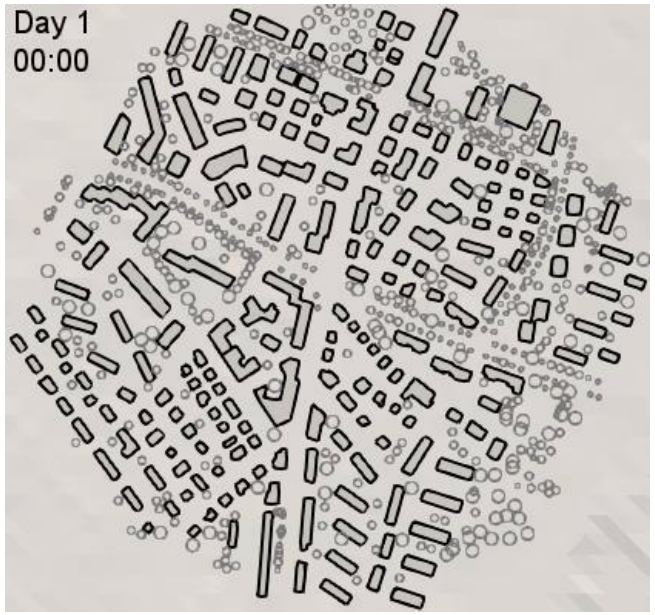
without trees



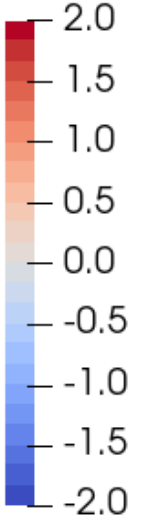
Air temperature [°C]



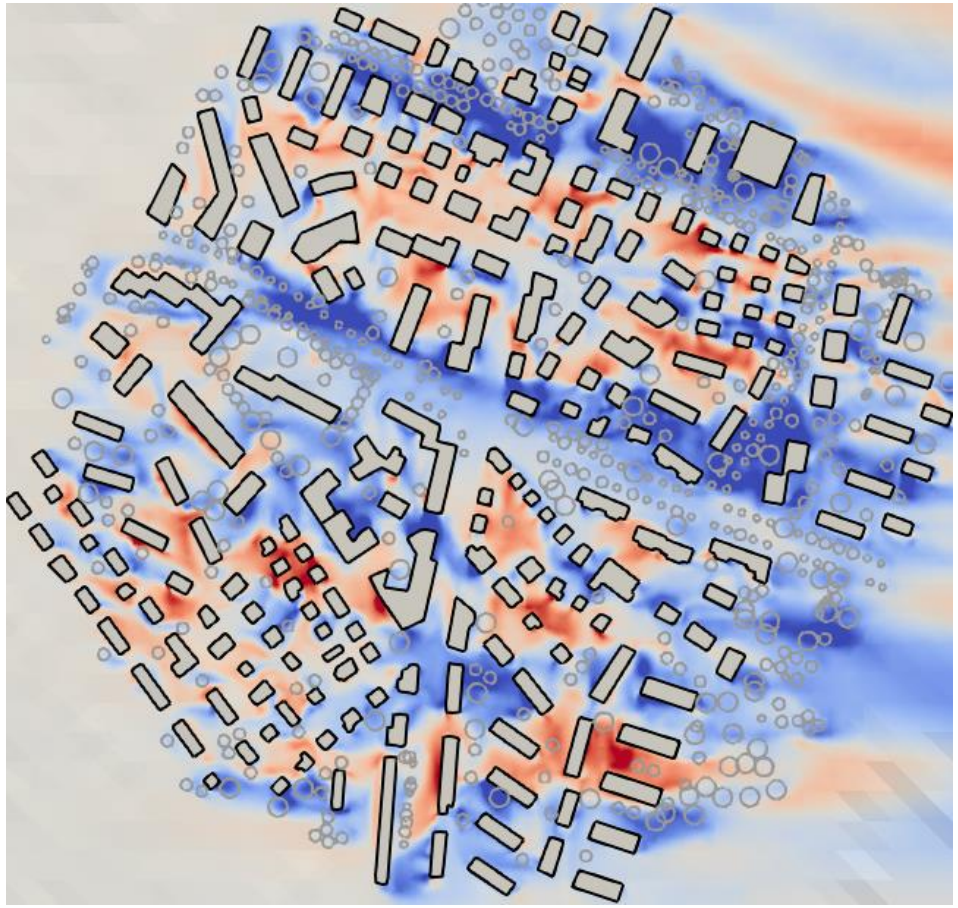
Temp. diff with trees
LAD = 1 m^2/m^3



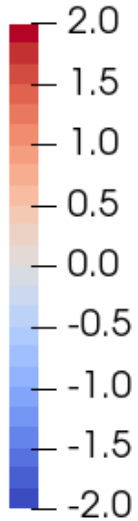
Temp diff.[°C]

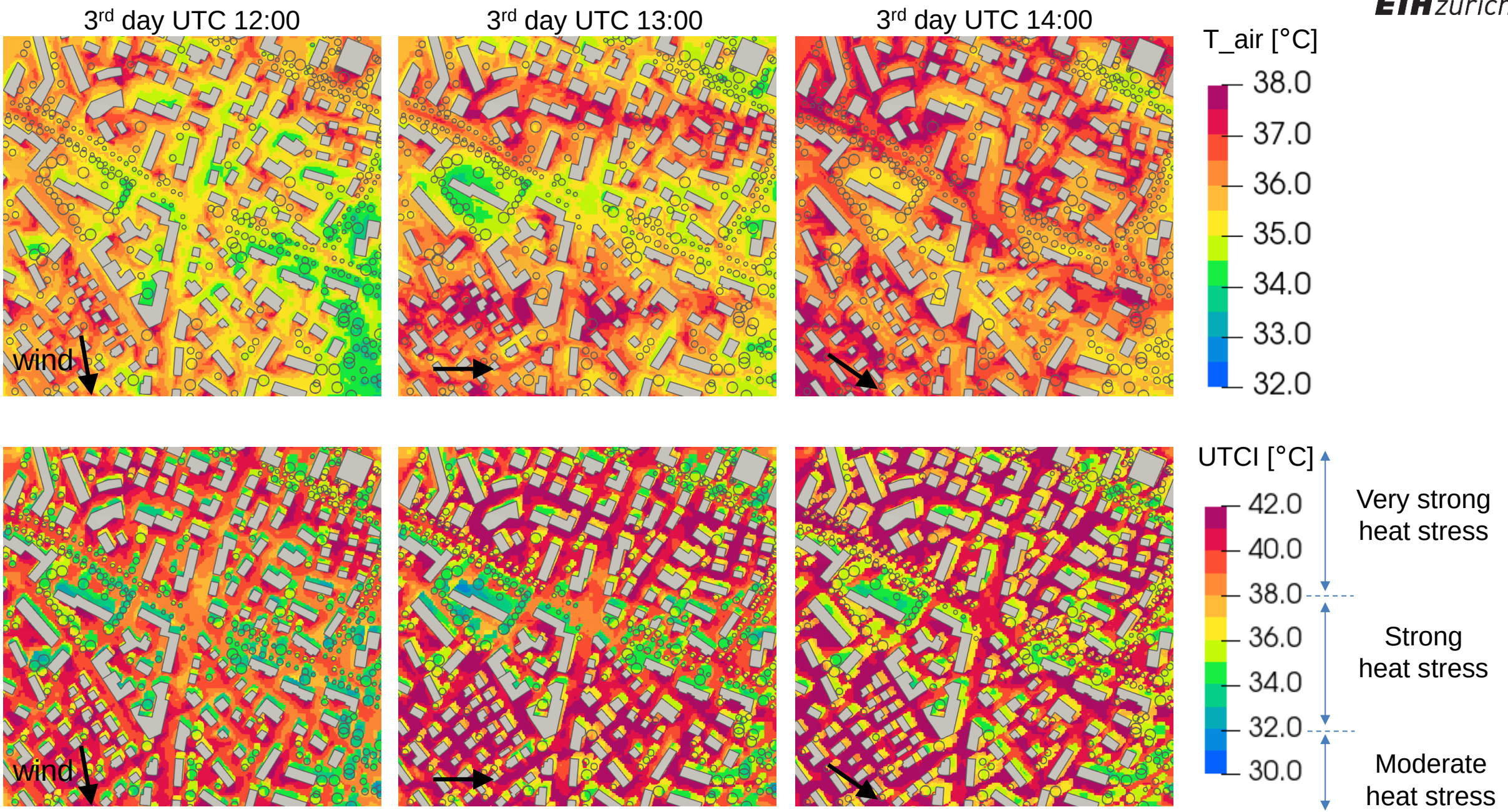


Day 3, UTC 13:40



Temp diff.[°C]




3rd day UTC 12:00
3rd day UTC 13:00
3rd day UTC 14:00
T_air [°C]
38.0
37.0
36.0
35.0
34.0
33.0
32.0
wind
wind
UTCI [°C]
42.0
40.0
38.0
36.0
34.0
32.0
30.0
Very strong heat stress
Strong heat stress
Moderate heat stress

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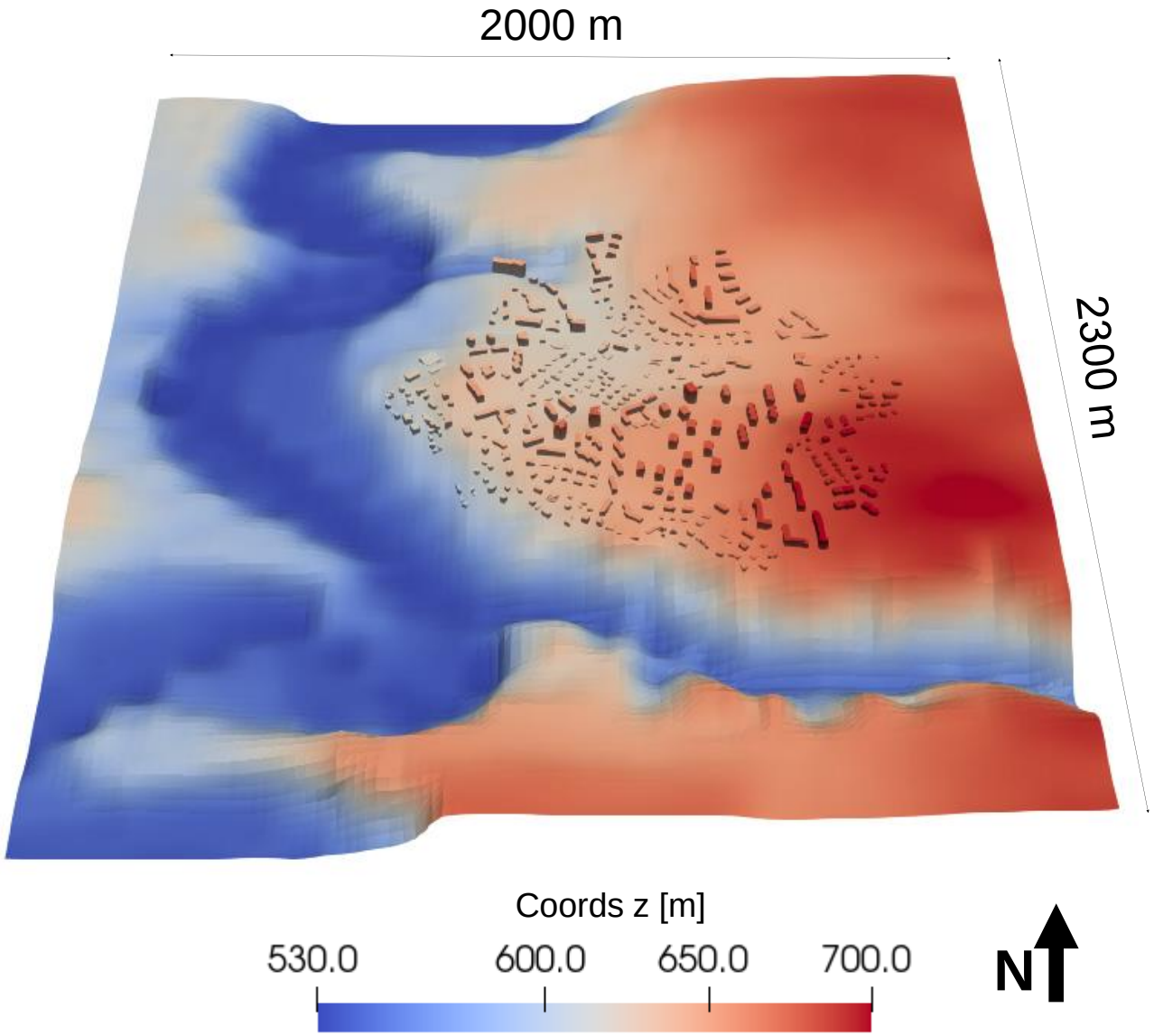
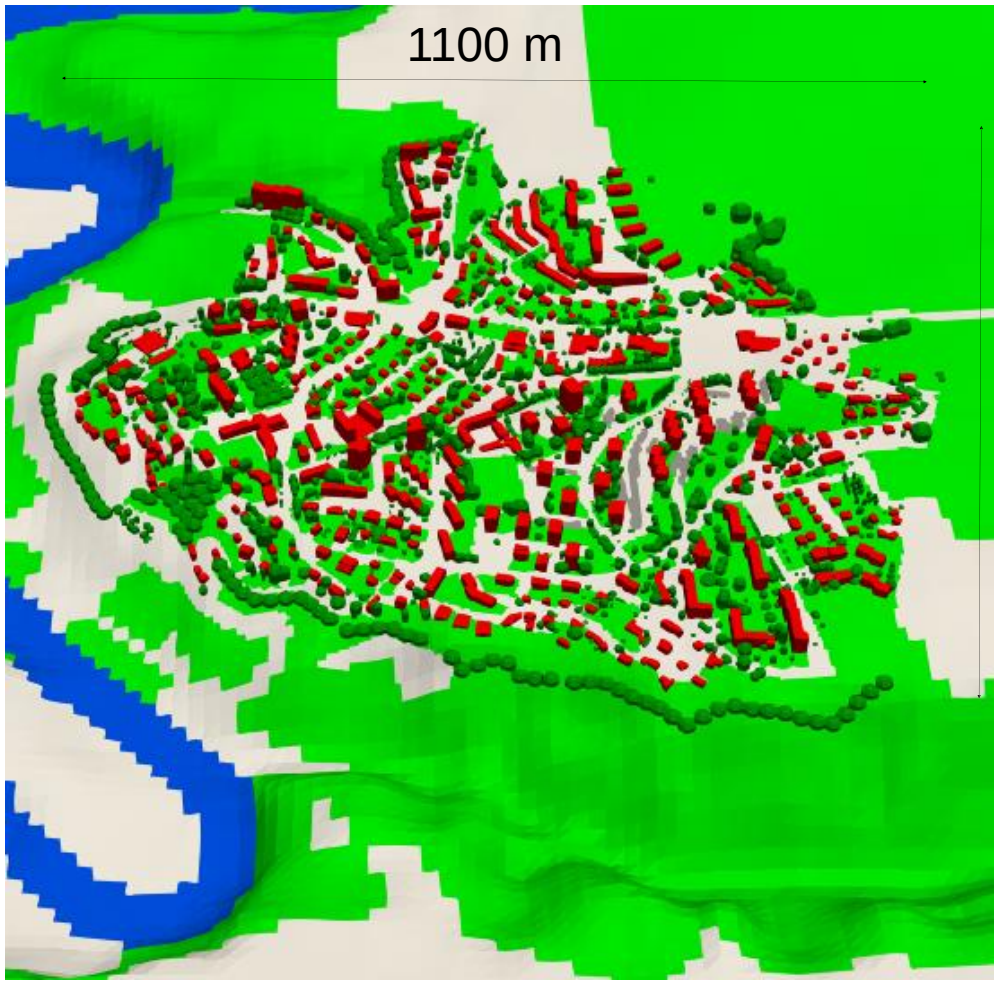
  - Case study: Schönberg, Fribourg

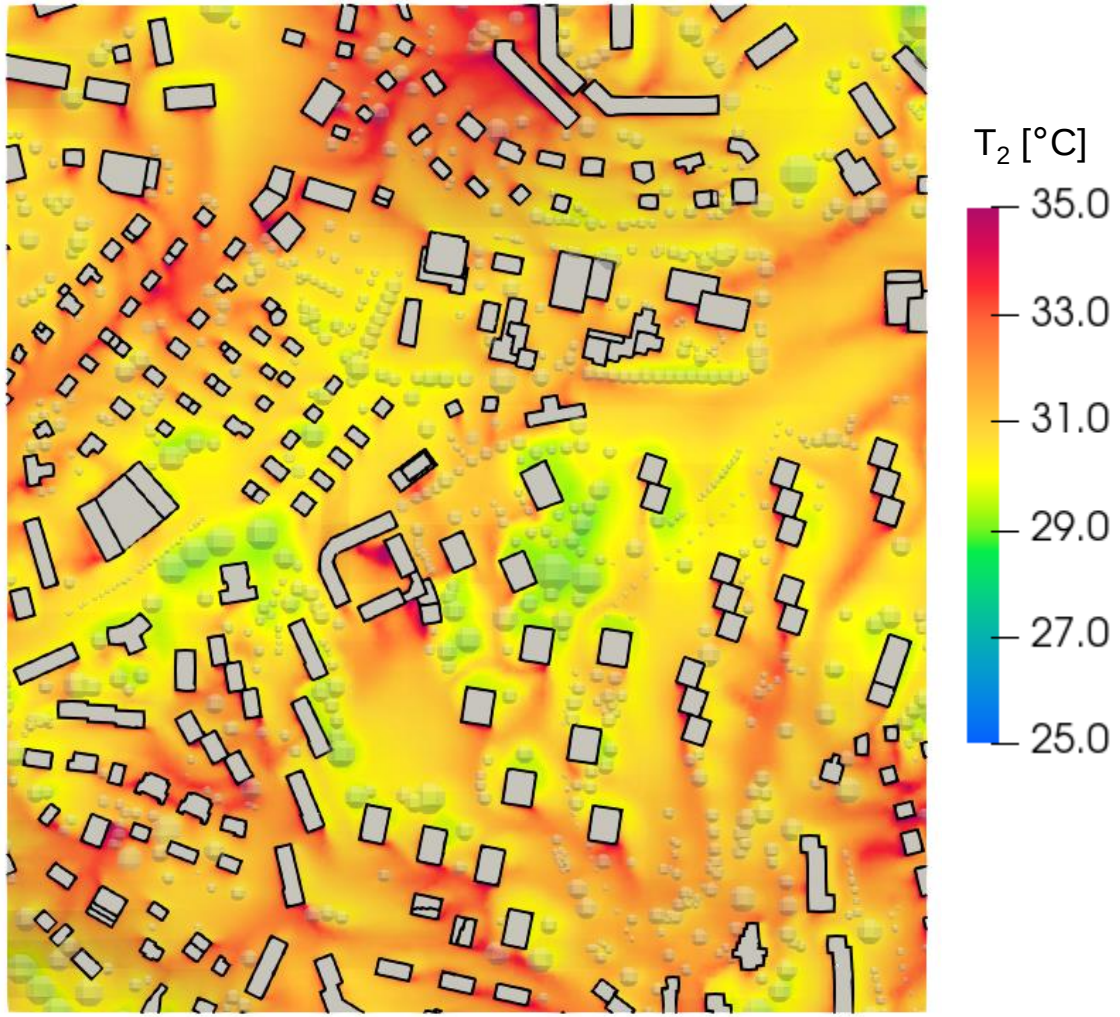
Computational domain



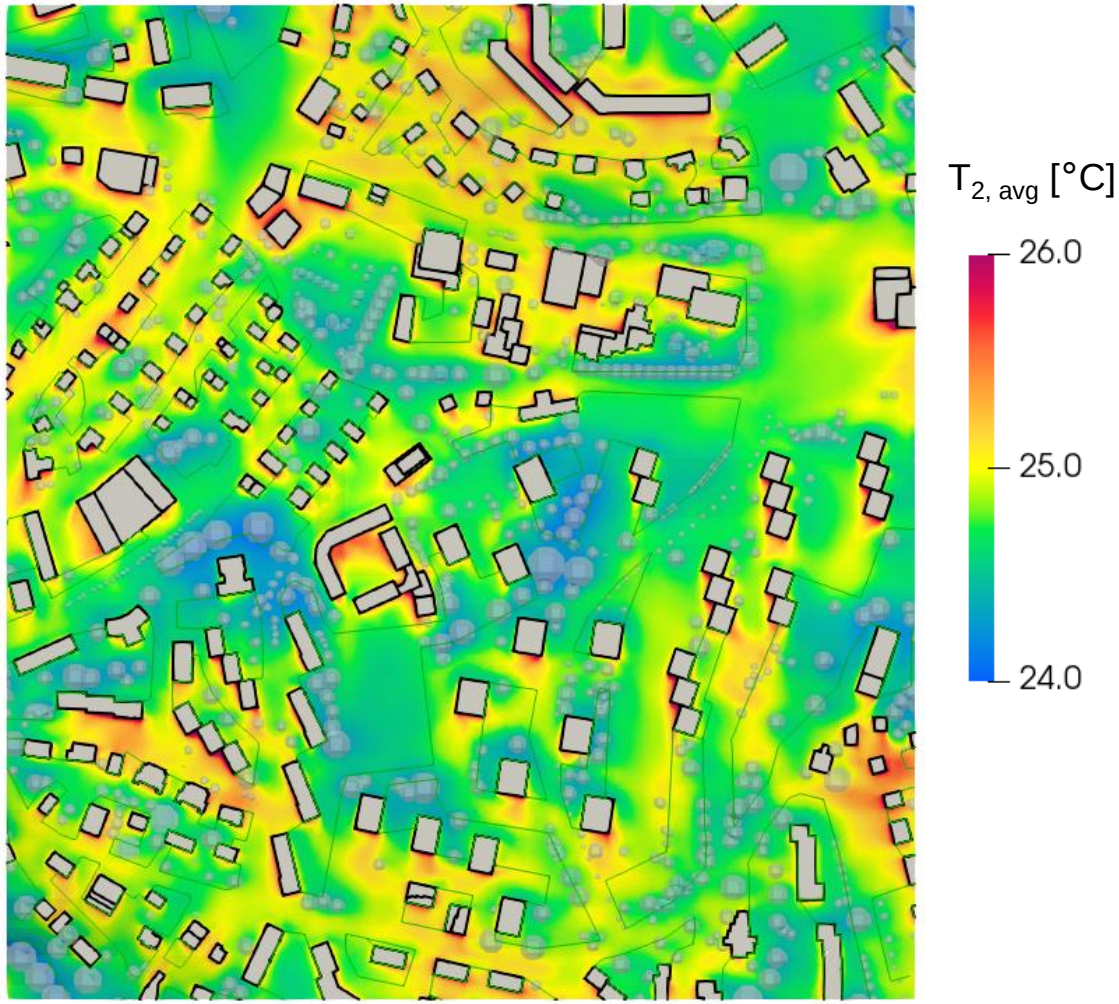


Case FR-Schönberg – Air temperature

14:00 UTC (CEST 16:00) at 2 m height

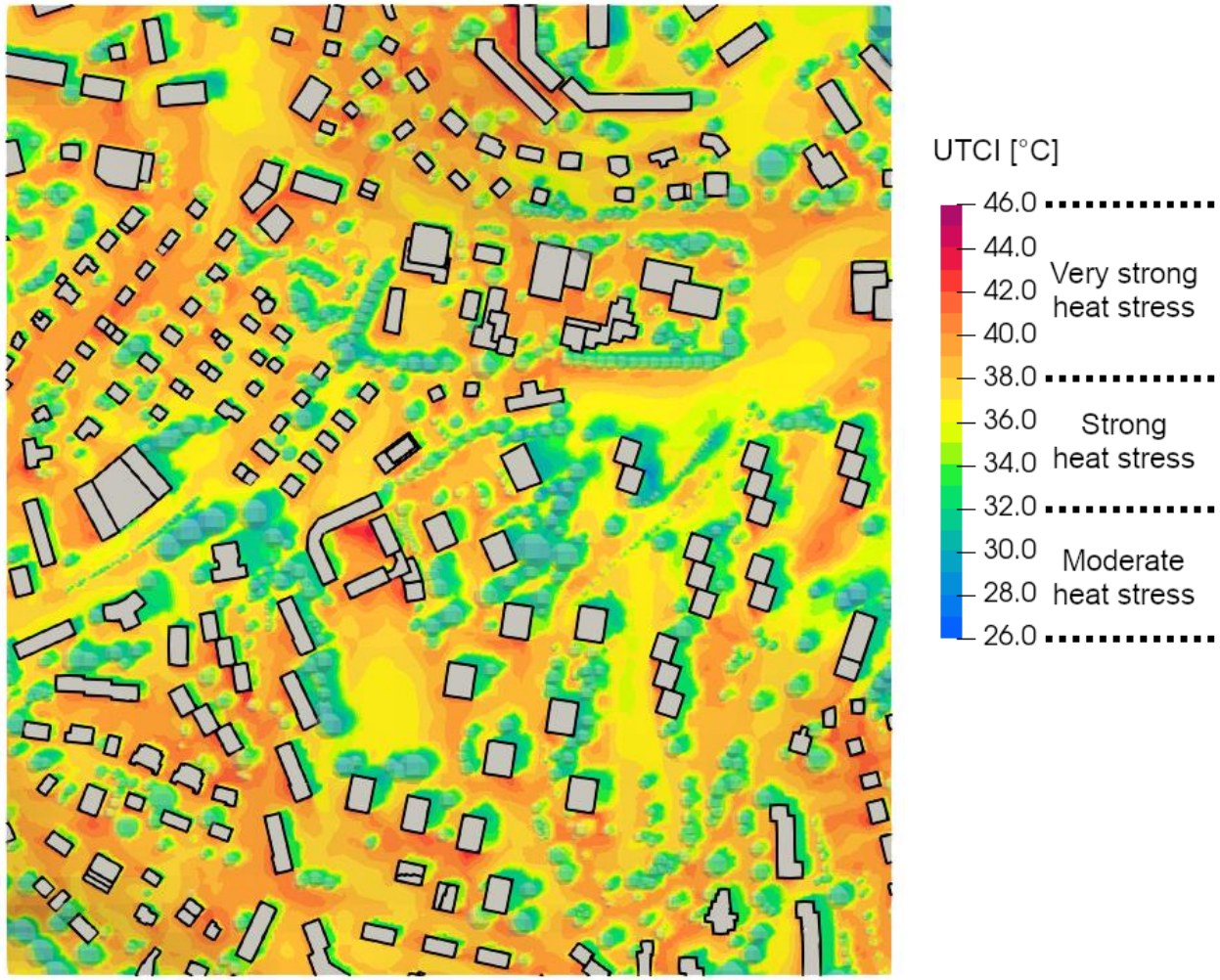


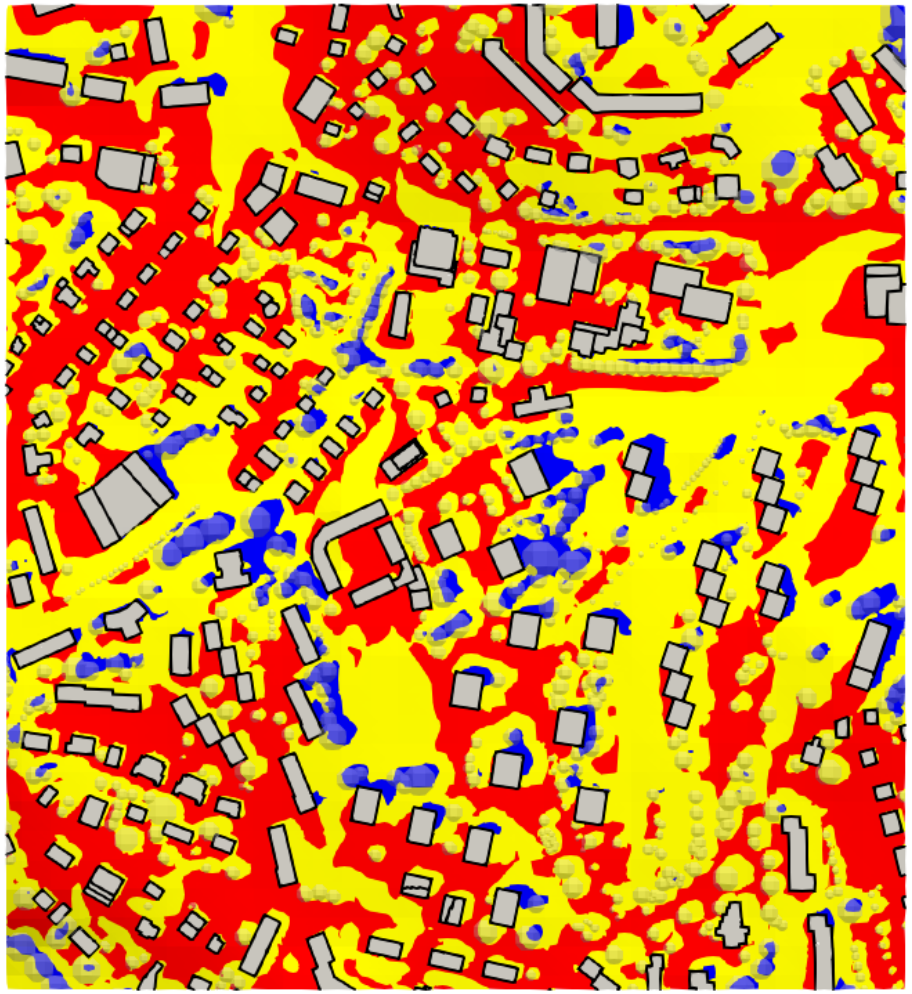
Daily average air temperature



Case FR-Schönberg – UTCI

14:00 UTC (CEST 16:00) at 2 m height





Moderate heat stress

Strong heat stress

Very strong heat stress

Overview

- Introduction
  - Urban heat island (UHI) effect
  - Causes of UHI
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  - Countermeasures to UHI
  - Wind flow in urban environment
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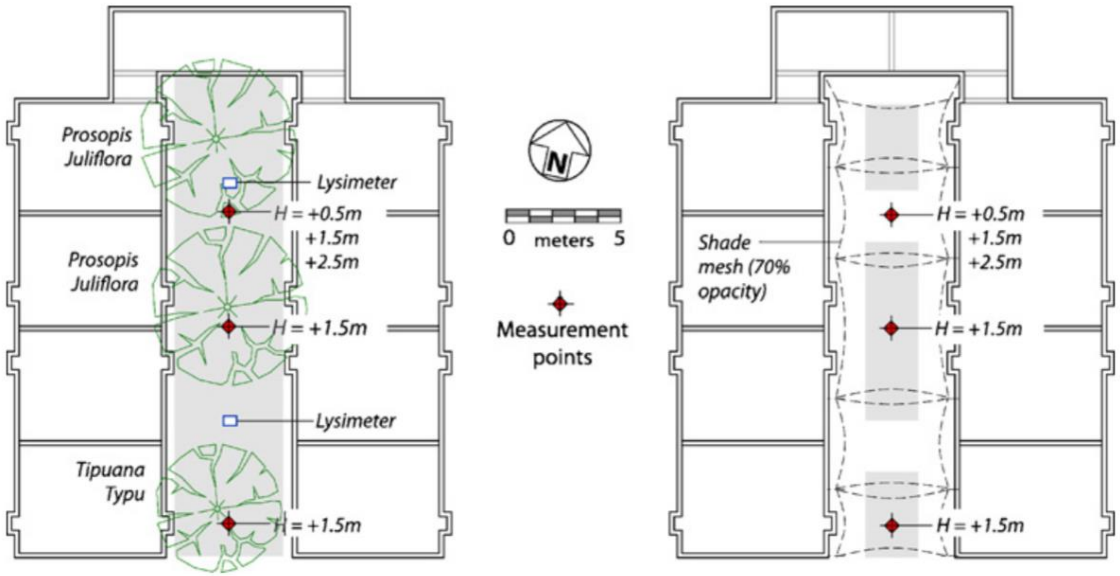
  - Numerical modeling of microclimate
  - Evaporative cooling
  - Impact of urban trees and high-rise buildings
  - Case study: Schönberg, Fribourg
  - Shading devices

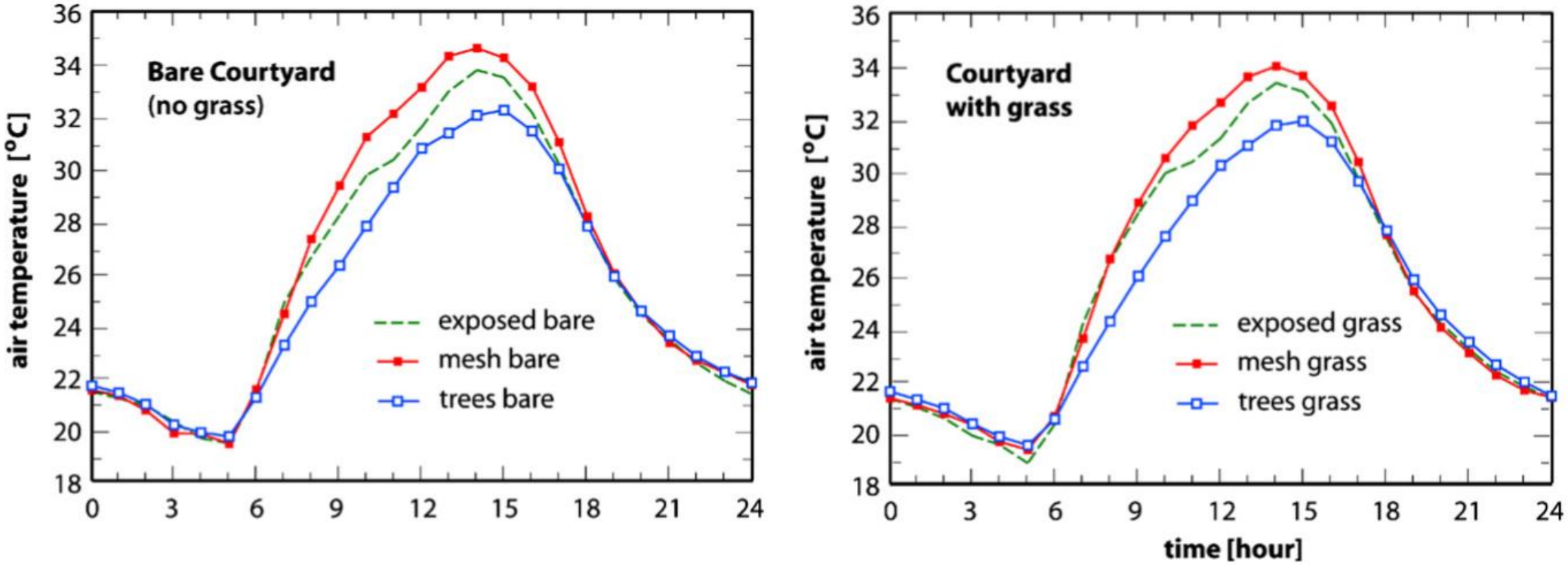
Measured air temperature in a courtyard



6 cases in two neighboring courtyards
- Exposed – bare ground and grass cover
- Trees – bare ground and grass cover
- Shading device – bare ground and grass cover

Shashua-Bar et al., 2009, Landscape and Urban Planning 92, 179–186
Shashua-Bar et al., 2011, International Journal of Climatology 31, 1498–1506

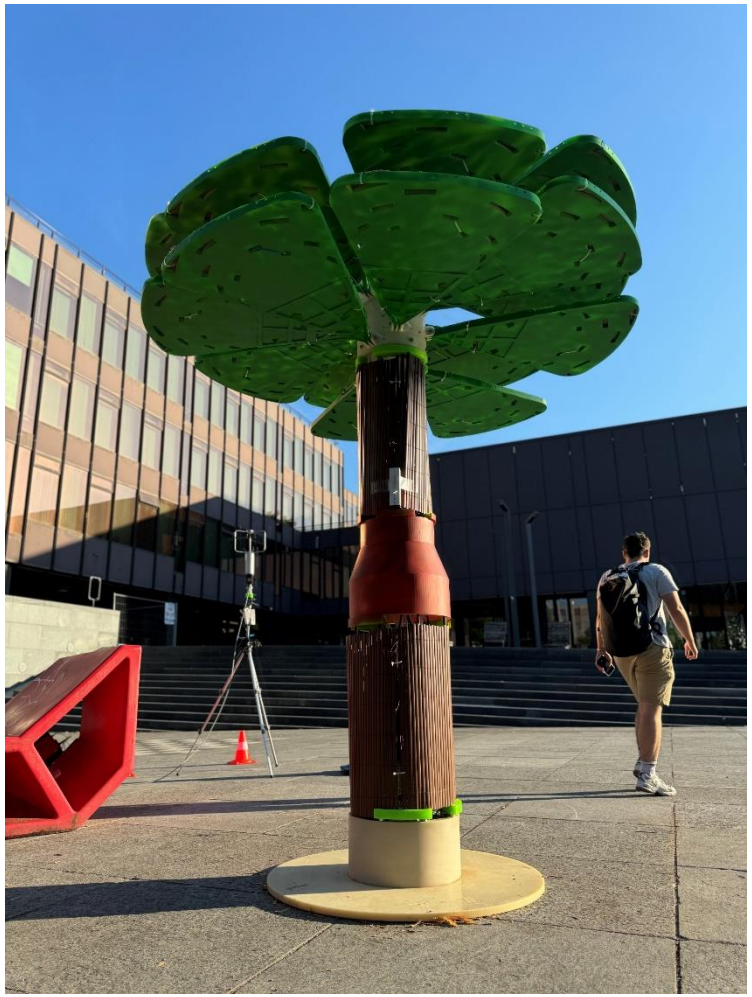
Measured air temperature in a courtyard



(Shashua-Bar et al., 2009)

Higher air temperature measured in the courtyard when the mesh shading is used!

Field Measurement and survey with shading device SAVE



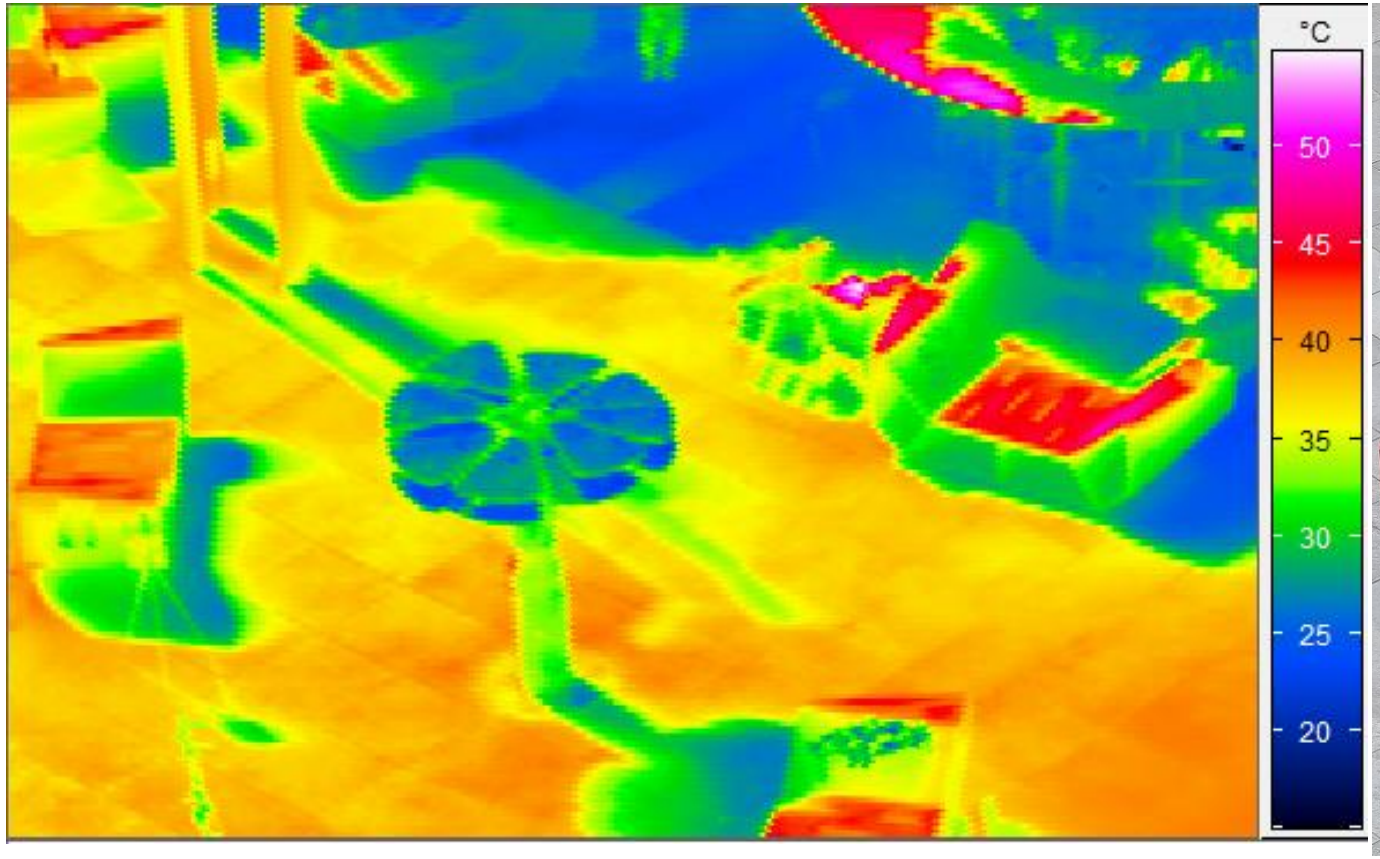
- Provides shading
- Evaporative cooling through the wetted fabric on top of the “leaves”
- “Leaves” can be rotated/closed to enhance night-time cooling

- Measurements performed in August 2024 at ETH Hönggerberg
- In collaboration with University of Cambridge

Images courtesy of Haiwei Flora Li

Field Measurement and survey with shading device SAVE

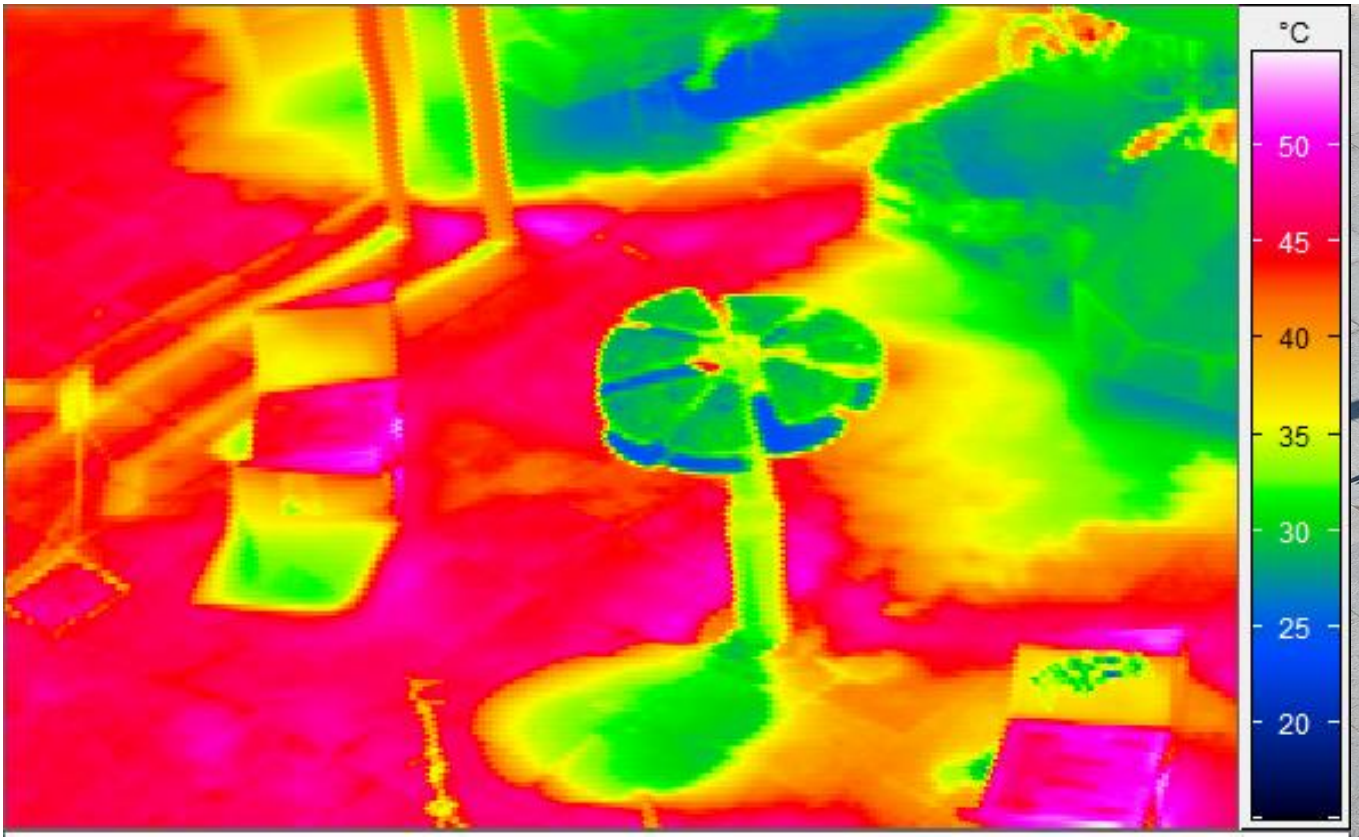
11:00 CET



Images courtesy of Haiwei Flora Li

Field Measurement and survey with shading device SAVE

15:00 CET



Images courtesy of Haiwei Flora Li

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- Final remarks

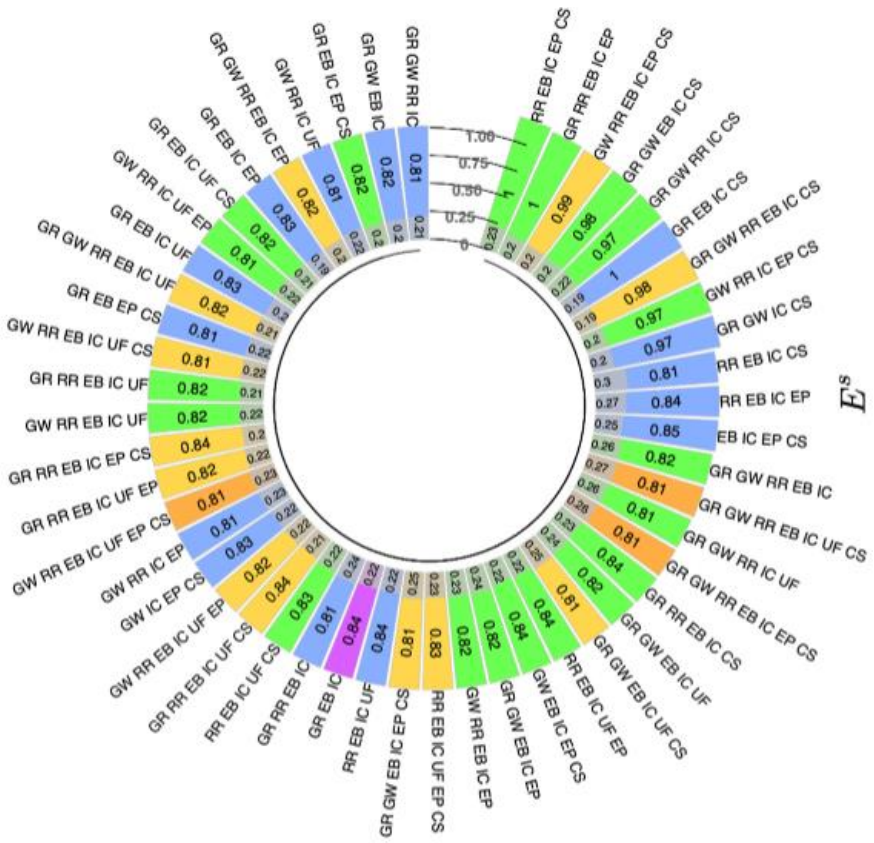
What are the possible counter measures for Urban Heat Island mitigation?

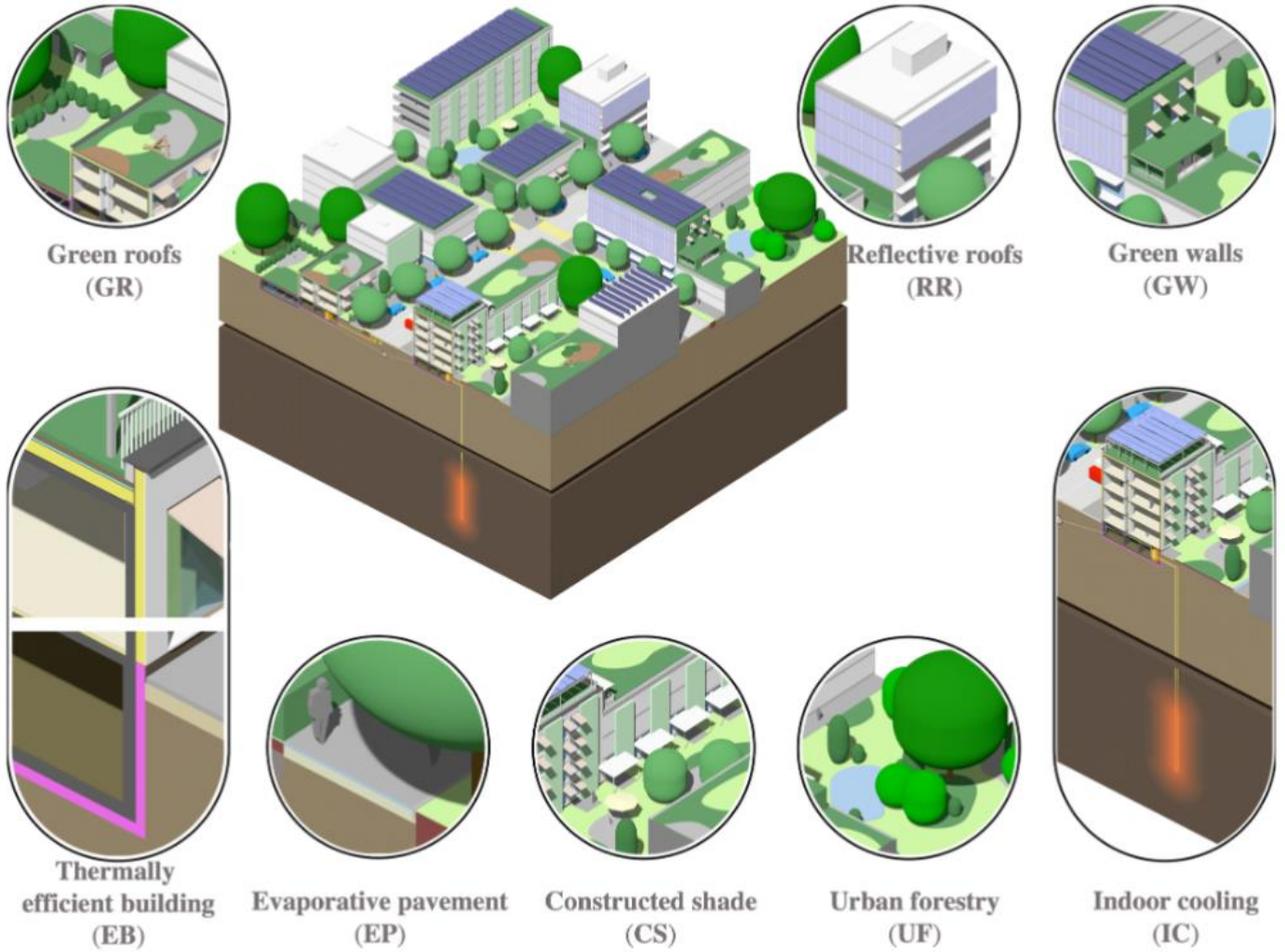
Purpose	Large Category	Small Category
Cool Surface	Use of Green	Maintenance of Green Land
		Garden
		Roof Greening/Garden
		Street Greening/Trees
	Use of Structural Material	Water Permeable Material
		Water Contained Material
		High Albedo Painting
		Photocatalyst
	Use of Water	Water Park/Waterfront
		Water Sprinkler
	Creation of Shading Area	Arcade
		Pergola
Promotion of Urban Ventilation	City Block Configuration	Ventilation Lane
		Arrangement of Buildings
	Building Configuration	Minimization of Aspect Area
		Pilloti
Reduction of Anthropogenic Heat	Energy-Saving	Energy-Saving Machinery
		Transport Manegement
		Energy-Saving Life Style
	Heat Release Treatment	Water Cooling Tower
		Heat Sink (River, Sea, Ground)

R. Ooka et al. 2010
Seminar at Hong Kong Polytechnic University

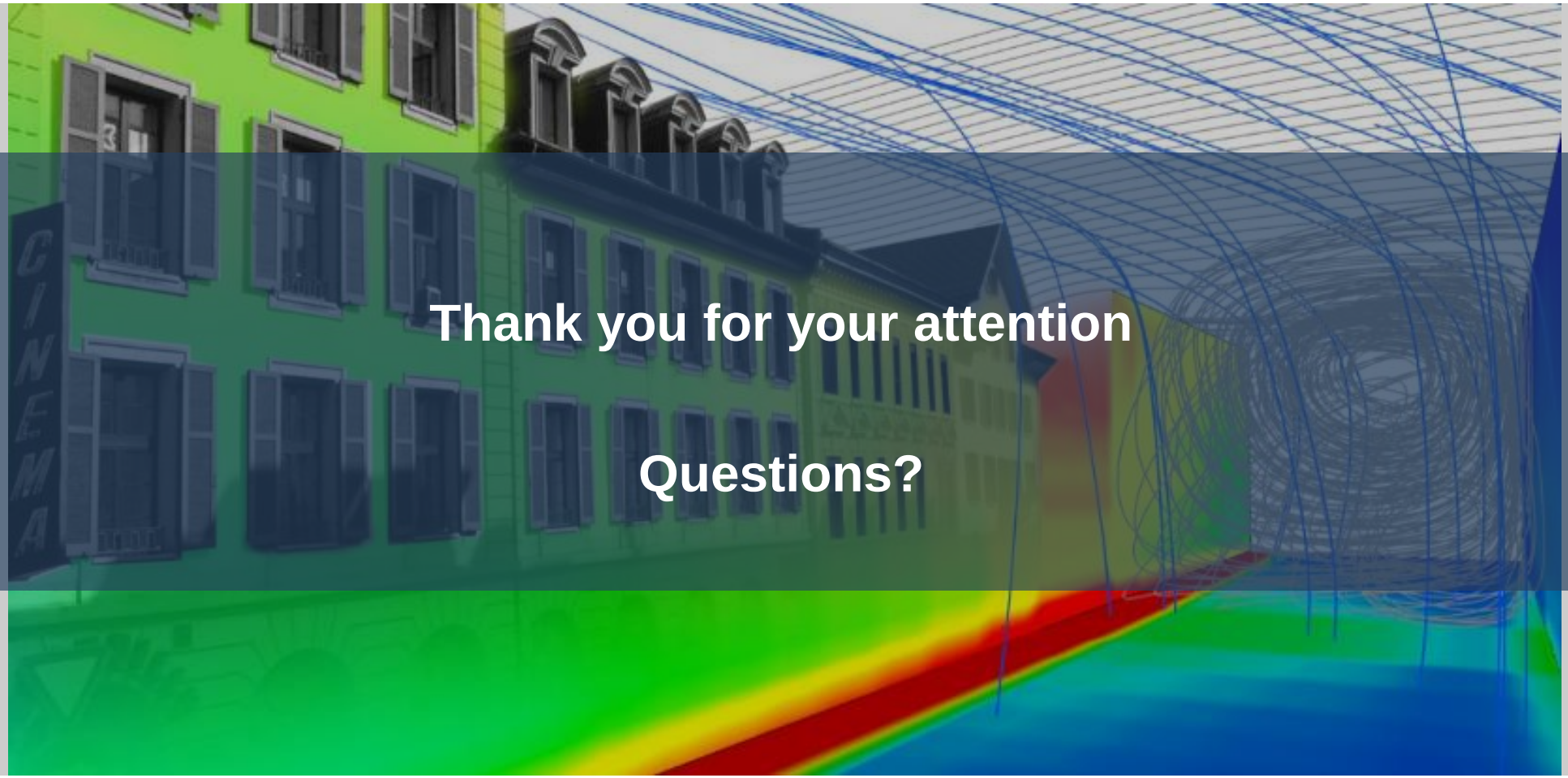
Set of mitigation measures based on:

- **Compatibility**
- **Costs**
- **Time to implement**





Zhao, Y. et al. **2023**. Beating urban heat: Multimeasure-centric solution sets and a complementary framework for decision-making. **Renewable and Sustainable Energy Reviews**



Thank you for your attention

Questions?