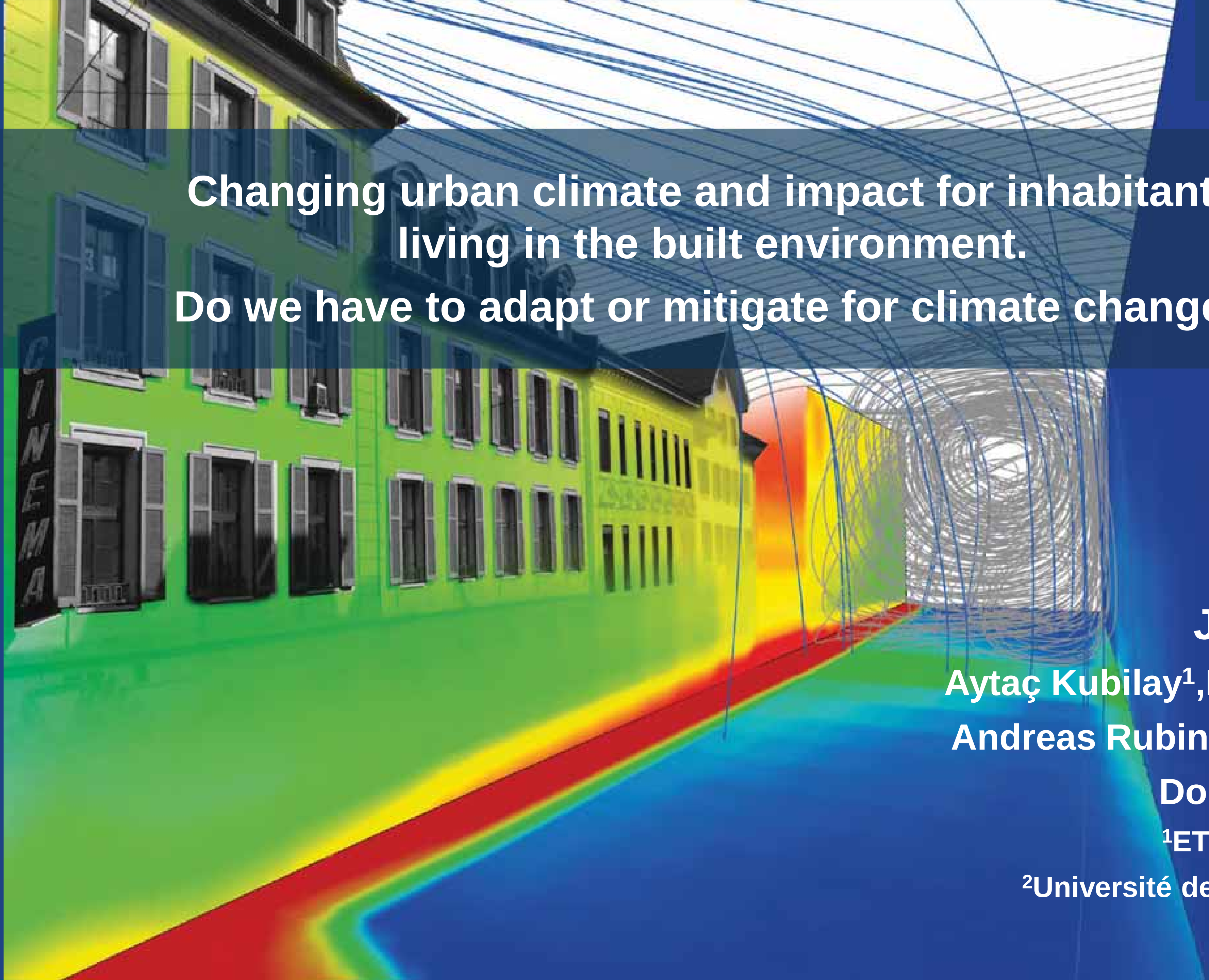


Changing urban climate and impact for inhabitants living in the built environment.

Do we have to adapt or mitigate for climate change?

Jan Carmeliet[1],

Aytaç Kubilay[1],Dominik Strebel[1],

Andreas Rubin[1],Yongling Zhao[1],

Dominique Derome[2]

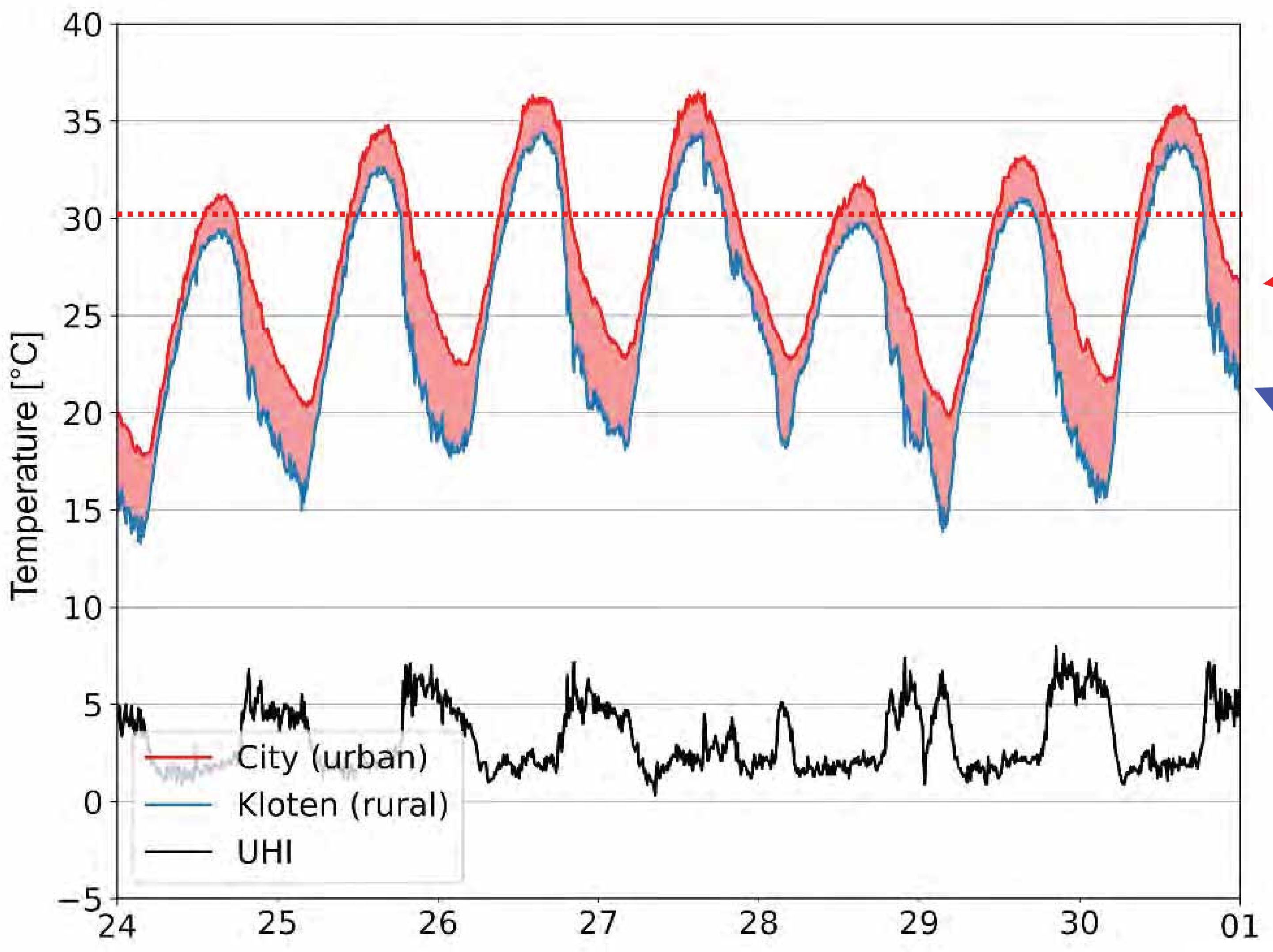
[1]ETH Zurich, Switzerland

[2]Université de Sherbrooke, Canada

Urban climate in Zürich, Switzerland

Touristic info: Climate with no excessive heat, cold nor humidity

Example of heatwave Zurich 2019



minimum three consecutive days temperature higher than 30°C

City (urban)

Air temperature at 2 m

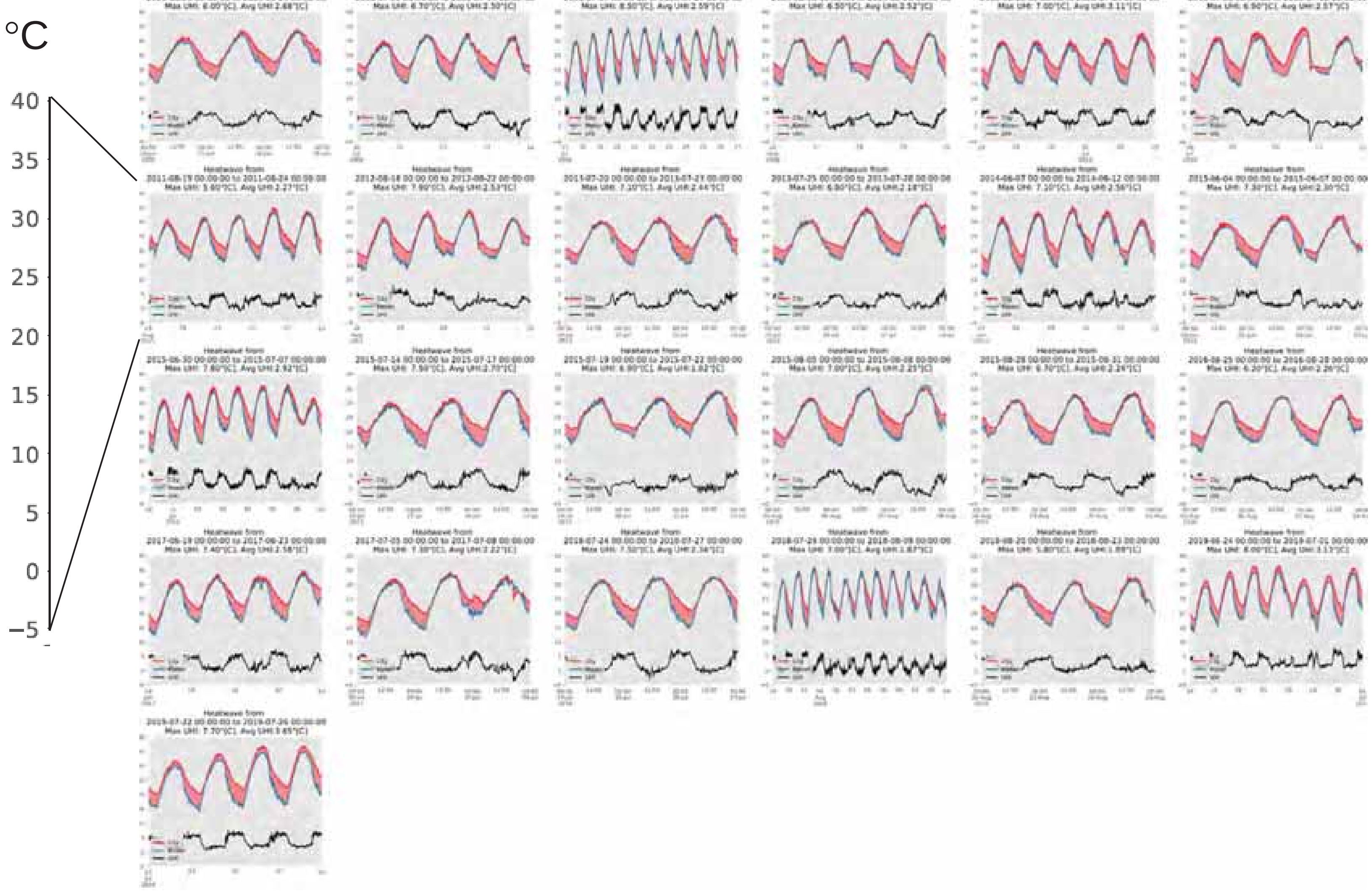
Kloten (rural)

Urban heat island intensity

Urban air temperature – rural air temperature

A. Kubilay. 2021

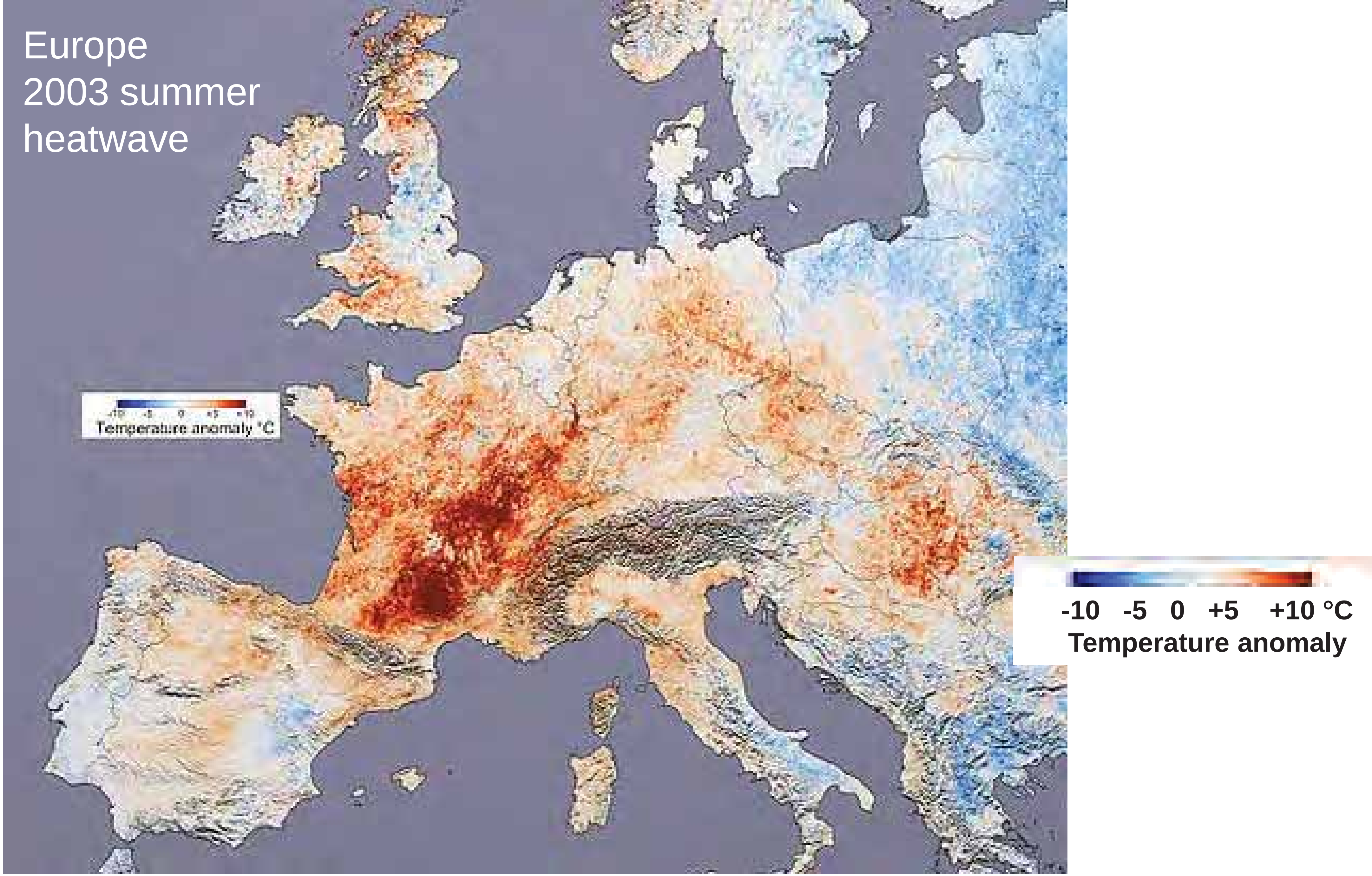
Heatwaves in a changing climate



Zurich
more than 30 heat waves
in the period 2001 – 2020

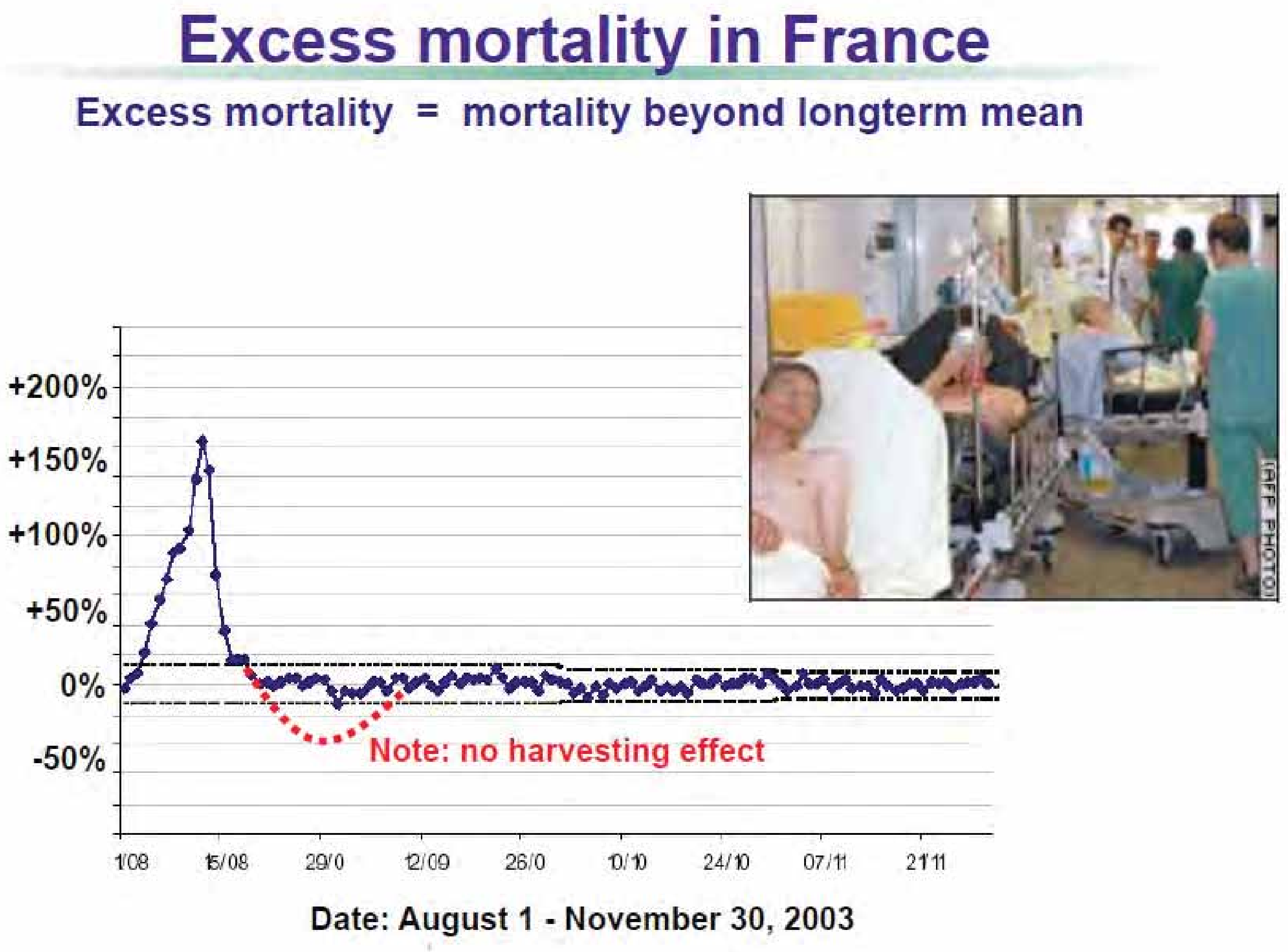
D. Strebel. 2021

Europe 2003 summer heatwave



J.F. Barlow, U. Reading

Heatwaves have a dramatic impact on health and wellbeing



(INSERM 2004)

Final estimate
70’000 excess deaths

Greatest impact on **elderly, chronically ill and young children**

In France, traditionally there is **no active cooling** in residential building (air conditioning)

Heat waves have an dramatic impact on health and wellbeing

53'000 more **heat-related deaths** **in July 2022** in Europe compared to 2016-2019 monthly average

Gerry Broome / AP Photo

= **16%** **more deaths** in July 2022 than usual

As comparison

3 % excess mortality in July 2020 due to **COVID-19 pandemic**
6 % excess mortality in July 2021

www.sciencealert.com

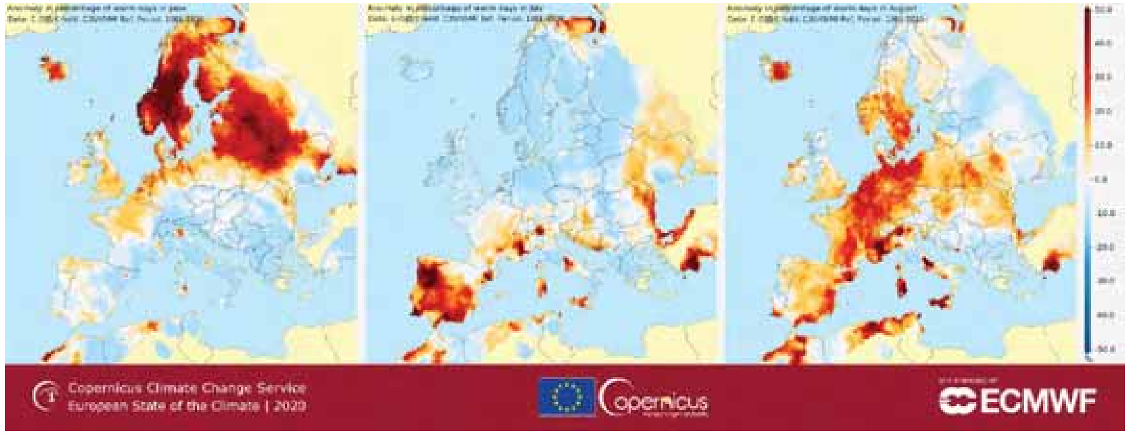
Spain

= **37% heat-related excess mortality**

Heatwaves in Europe: Finland the summer of 2021.

In Europe this summer hot extremes affected several countries. Researchers in Finland have looked at the excess number of deaths during the summer of 2021 in Finland.

GUNNELL E. SANDANGER
PUBLISHED 14.12.2021



Percentage of hot days in 2020: June, July, August

In Finland, heatwaves normally not perceived as major health threat (cool summers)

400 heat-related excess deaths in summer 2021

Due to **acclimatisation**, heat-related excess mortality in Finland at thermal conditions which are still considered comfortable in Spain, Greece

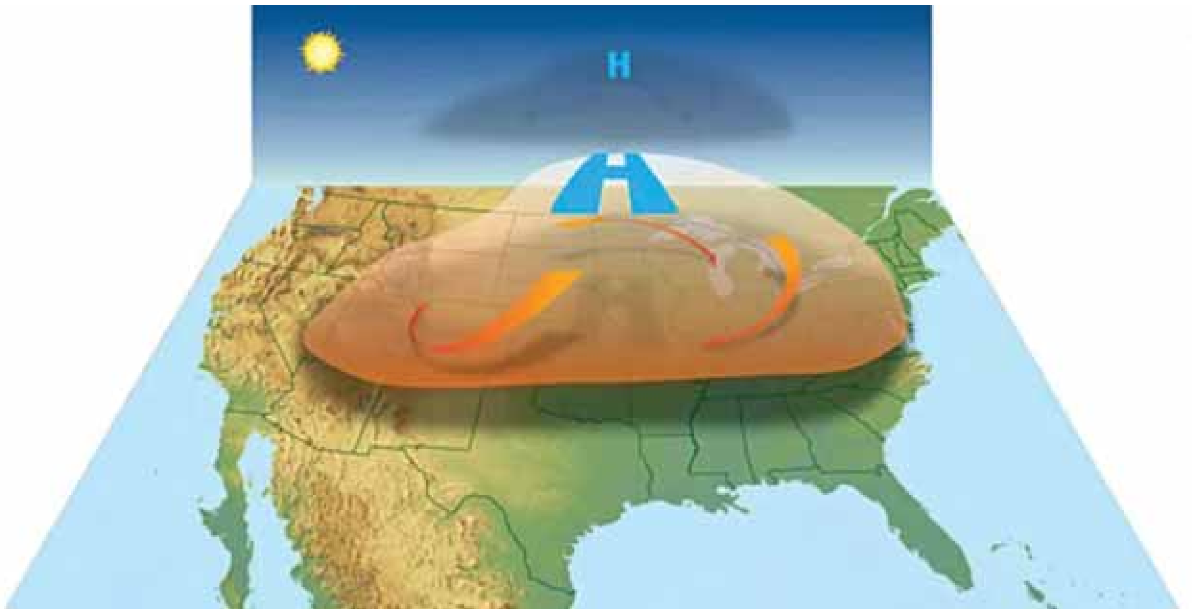
Awareness for heatwaves related problems is increasing

V. Kollanus et al. Environmental research, 2021

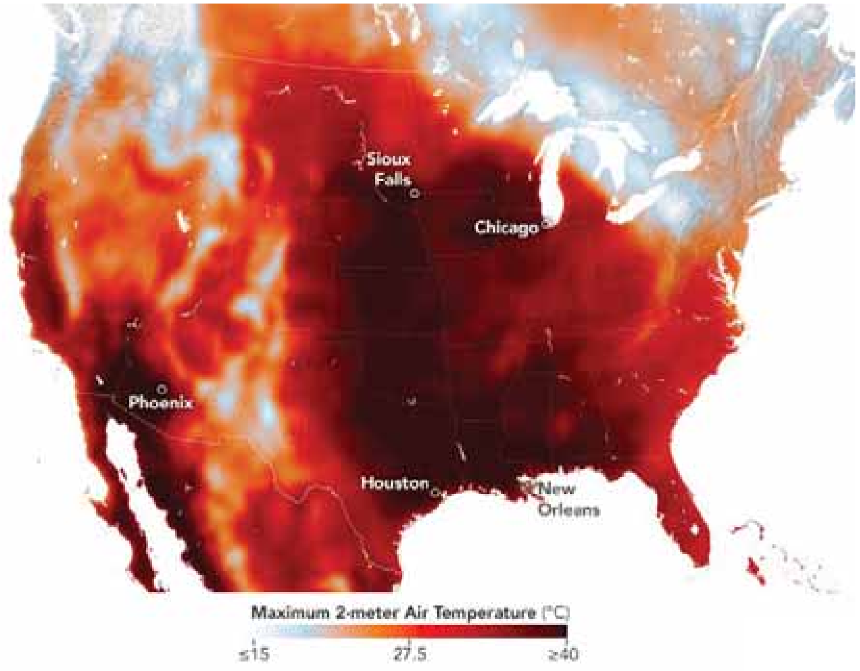
Origin of heatwave

Key ingredients

- Higher air temperatures
- Stable high-pressure system providing sinking of air forming **a cap that traps heat** that would otherwise rise into the air and cool before circulating back to the surface
- **buoyancy-driven heat dome**



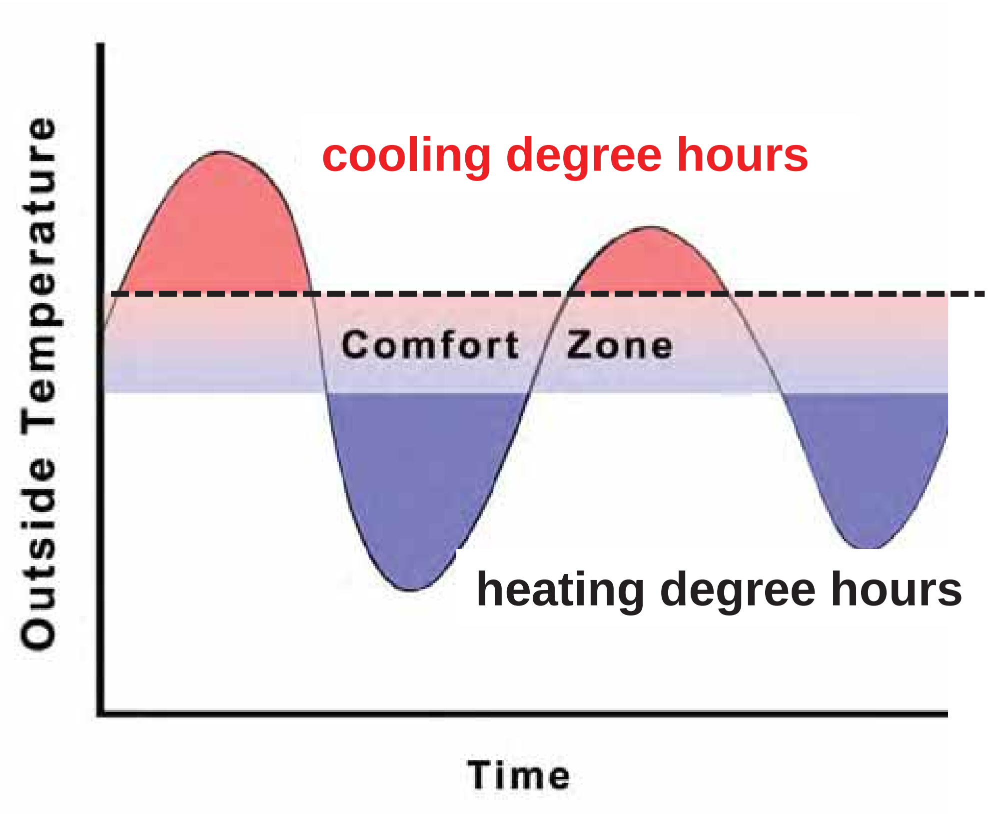
U. S. National Weather Service/Wikimedia Commons



earthobservatory.nasa.gov, August 2023

Cooling Degree Hours (CDH) as Heatwave metric

- Cumulative value over total period of interest
- Indicative for thermal discomfort and building cooling demand for buildings

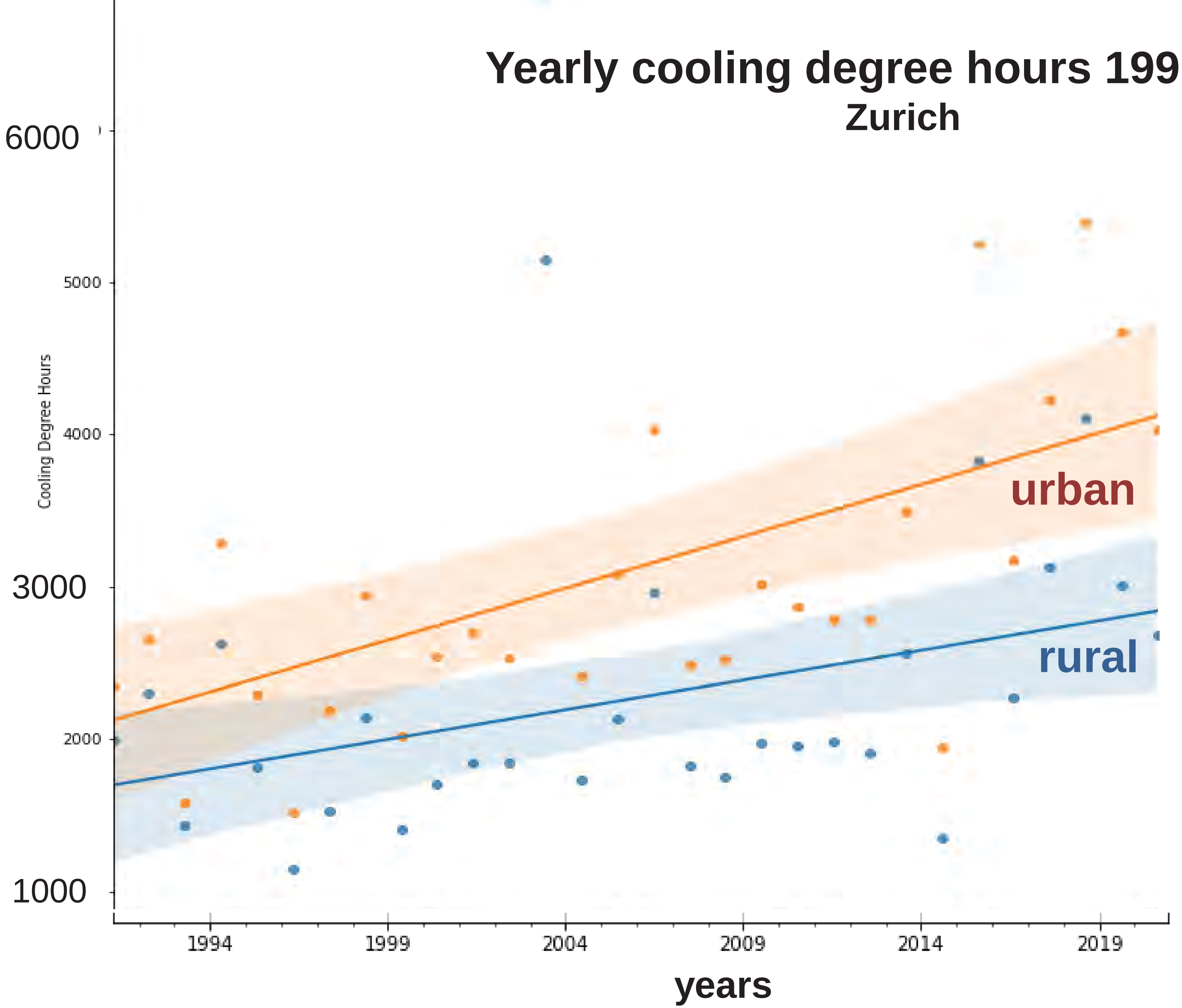


Base temperature 22 °C

https://www.weatherbit.io/blog/tag/cooling

Yearly cooling degree hours 1991-2020

Zurich

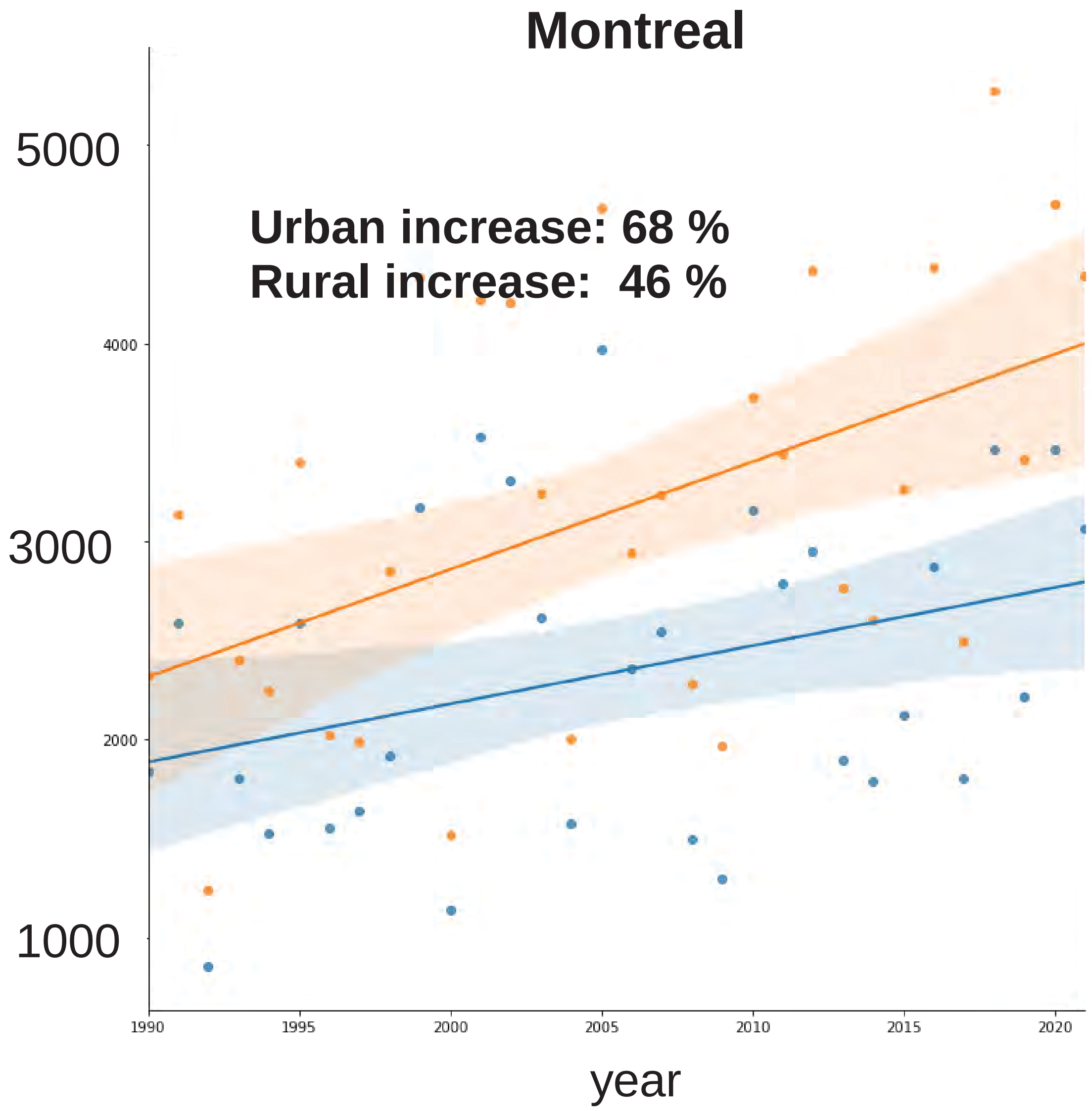


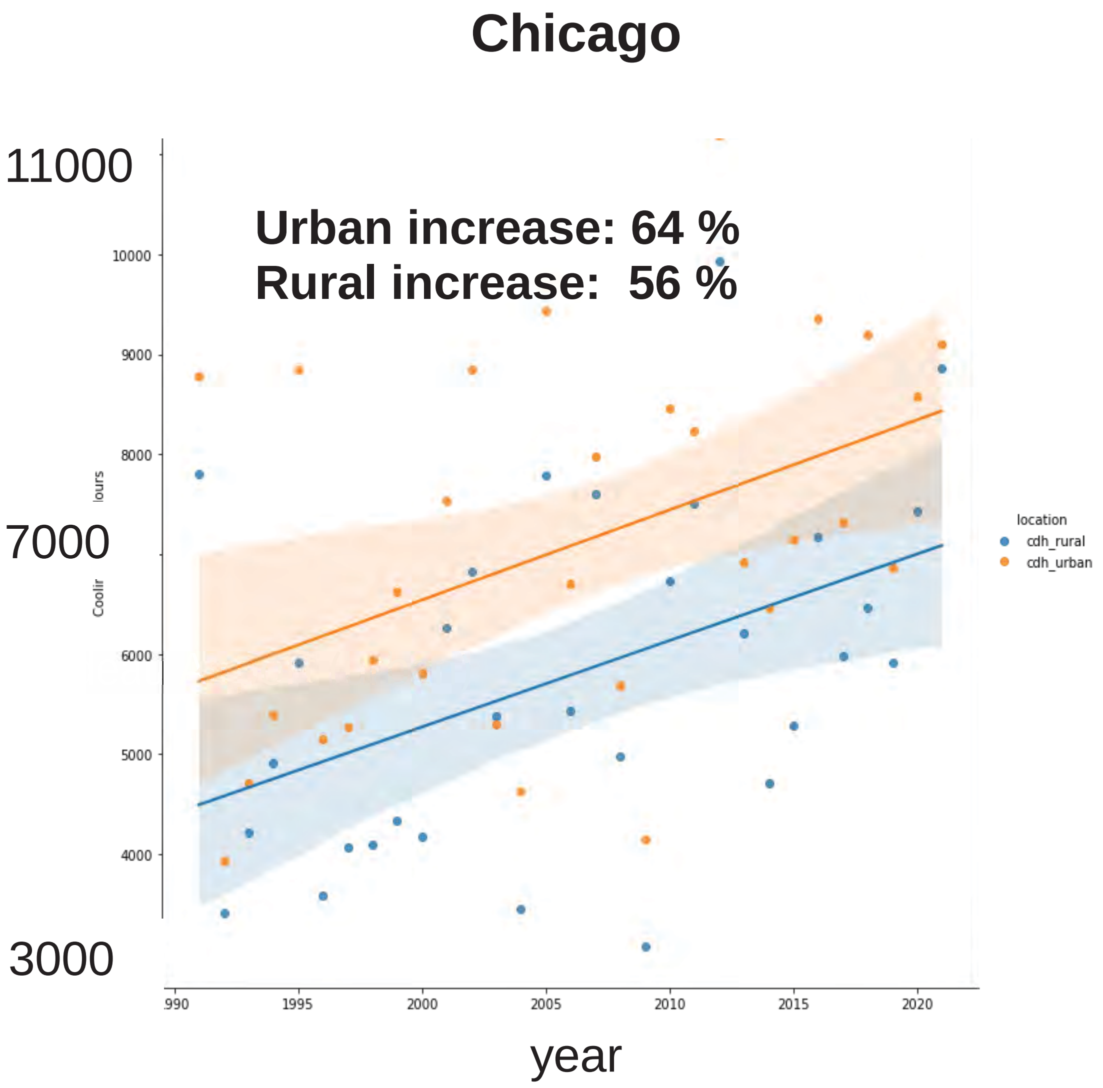
Urban increase: 95 %

Rural increase: 65 %

D. Strebel. 2021

Yearly cooling degree hours 1991-2020



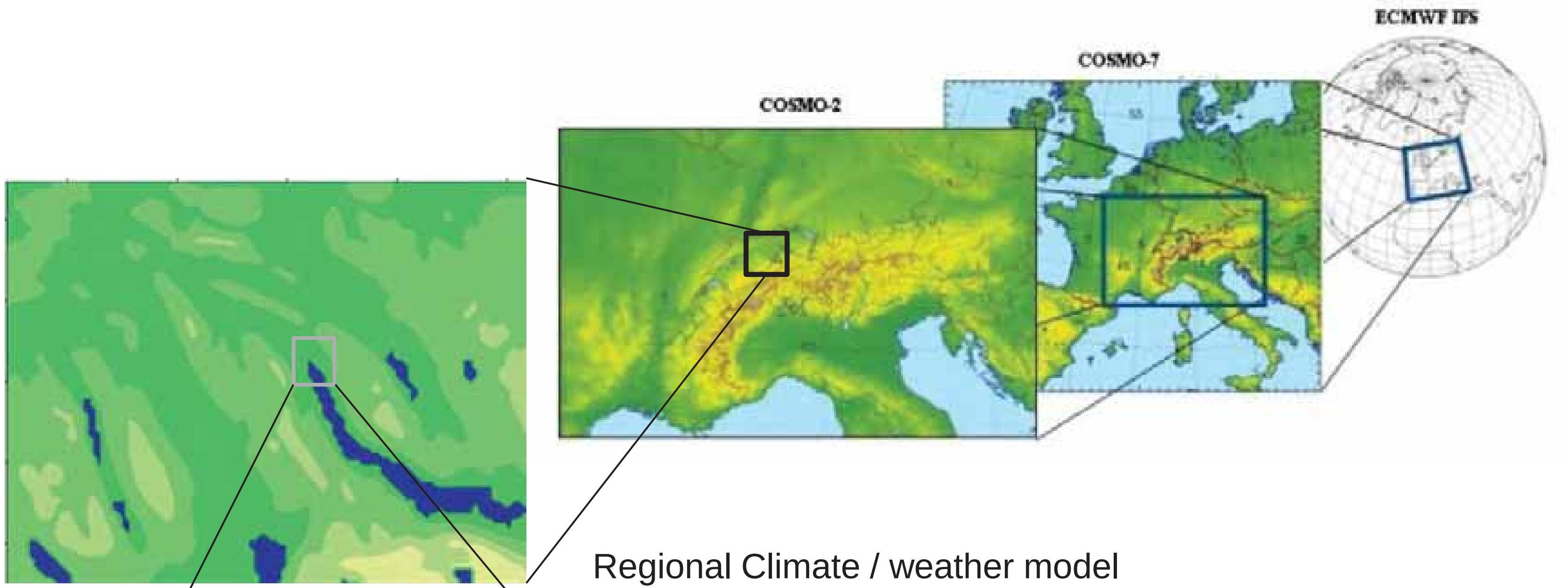


D. Strebel. 2021

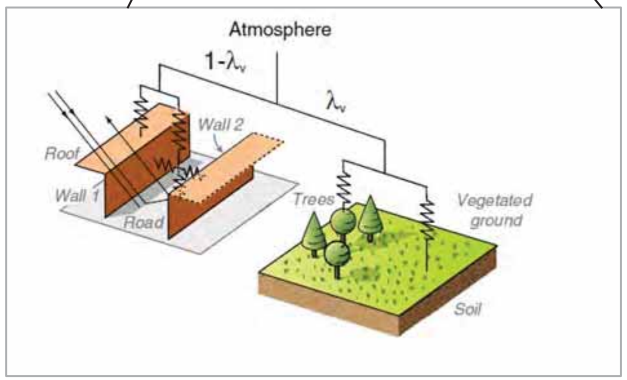
Case study Zurich

Mesoscopic Meteorological Model & Urban Parametrization

General circulation model



Regional Climate / weather model

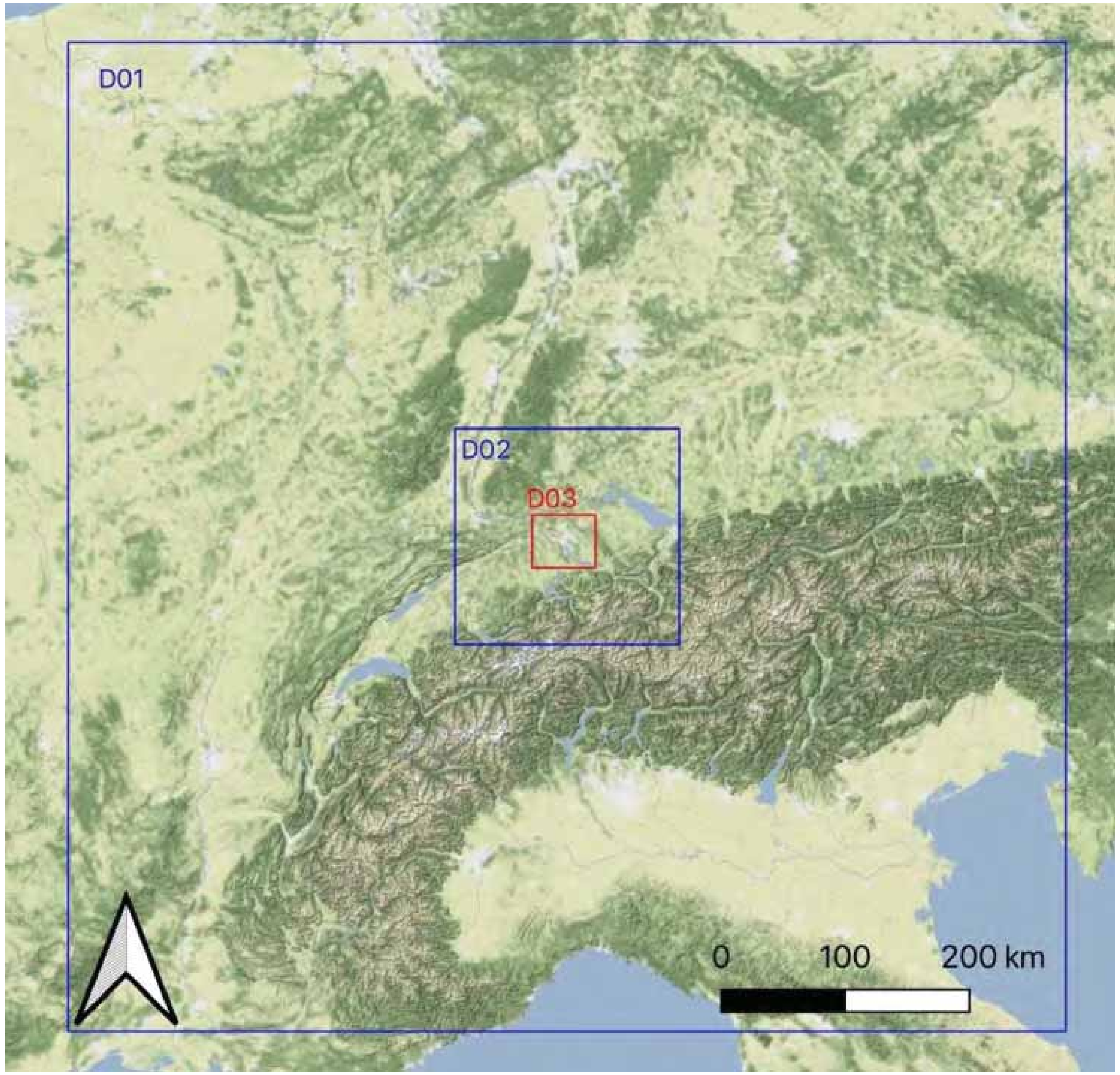


Mesoscale weather and climate model (COSMO) in climate mode (CCLM) **coupled with Building Effect Parametrization (BEP)**

Double Canyon Effect Parametrization (DCEP)
Urban Canopy model (UCM)
Martilli et al. 2002; Schubert et al. 2012; Schubert & Grossman-Clarke 2014

Mussetti et al, 2018

Mesoscale Meteorological Model (MMM) of Zurich



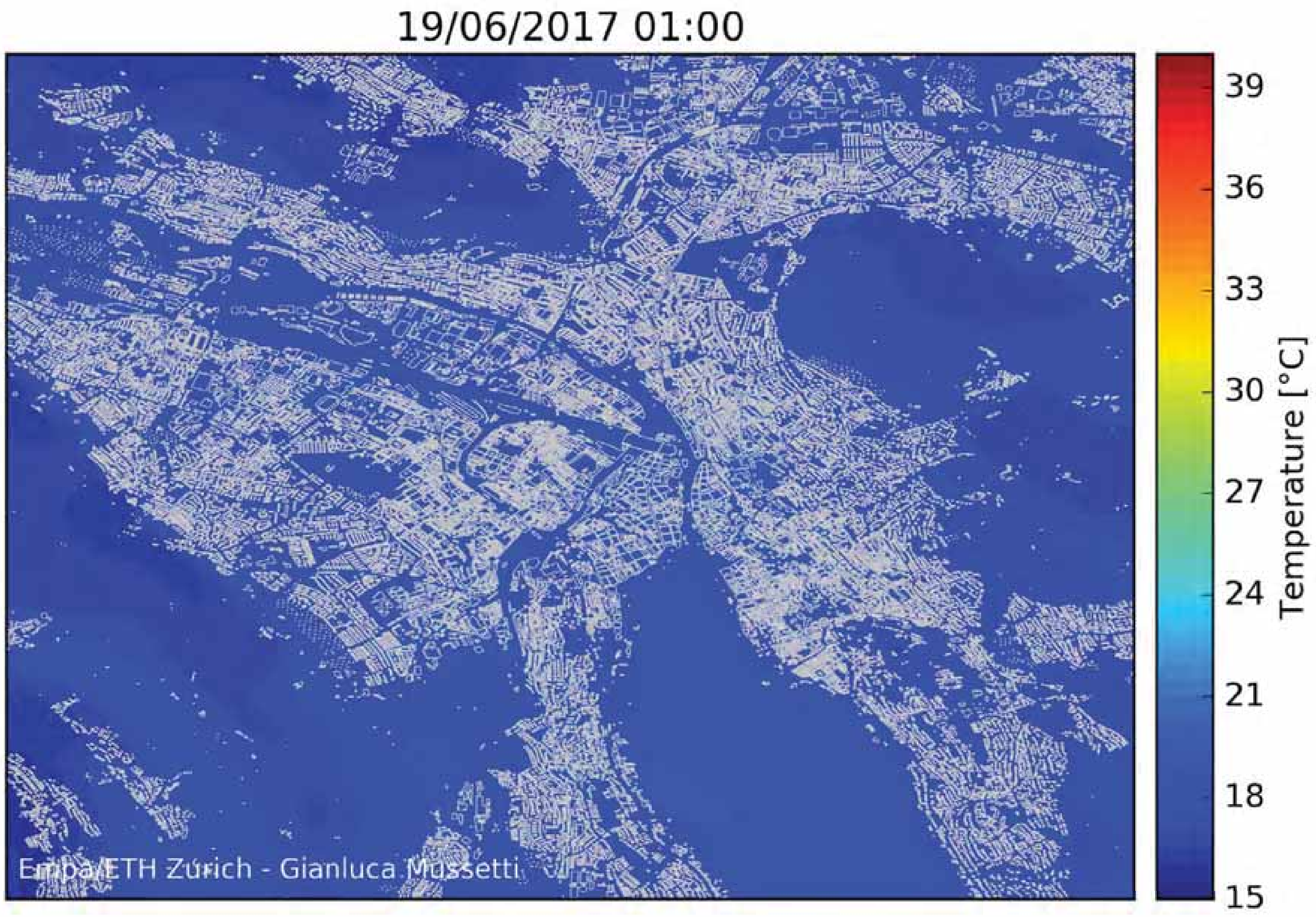
Three domains

- largest domain D01: grid size 6.25km
- smallest domain D03: grid size 250m

Strebel et al. 2023

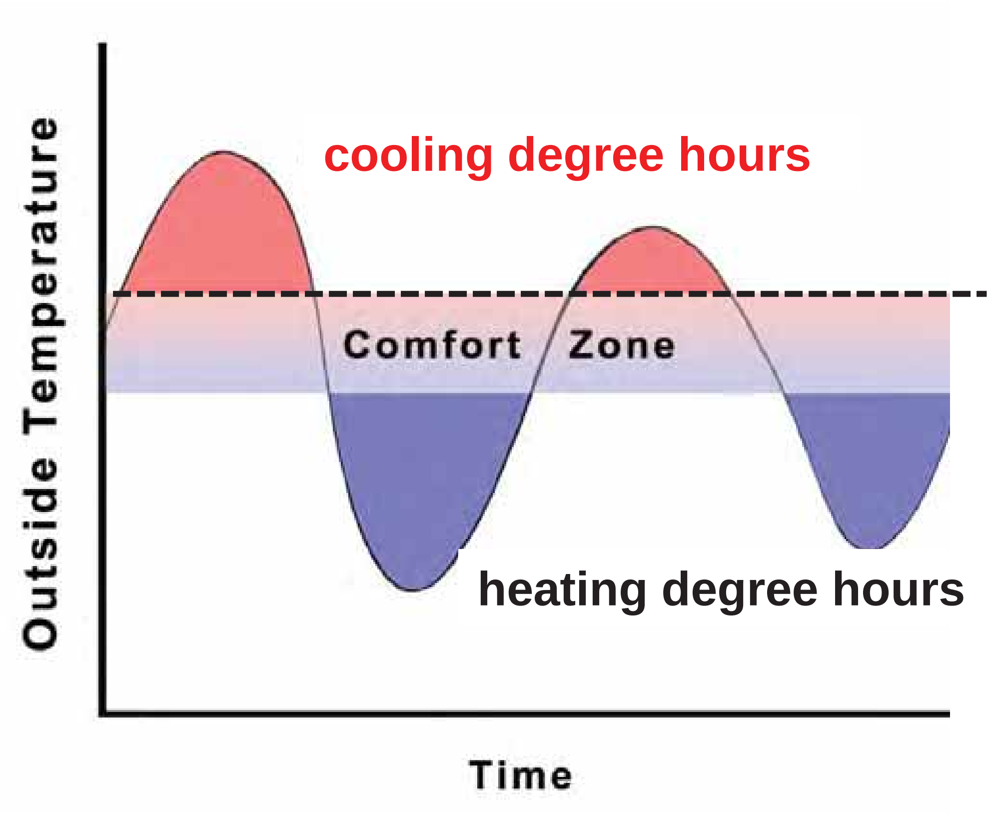
D. Strebel. 2022

Heatwave June 2017 in Zurich



Cooling Degree Hours (CDH) as Urban Heat Island metric

- Cumulative value over total period of interest
- Indicative for thermal discomfort and building cooling demand for buildings

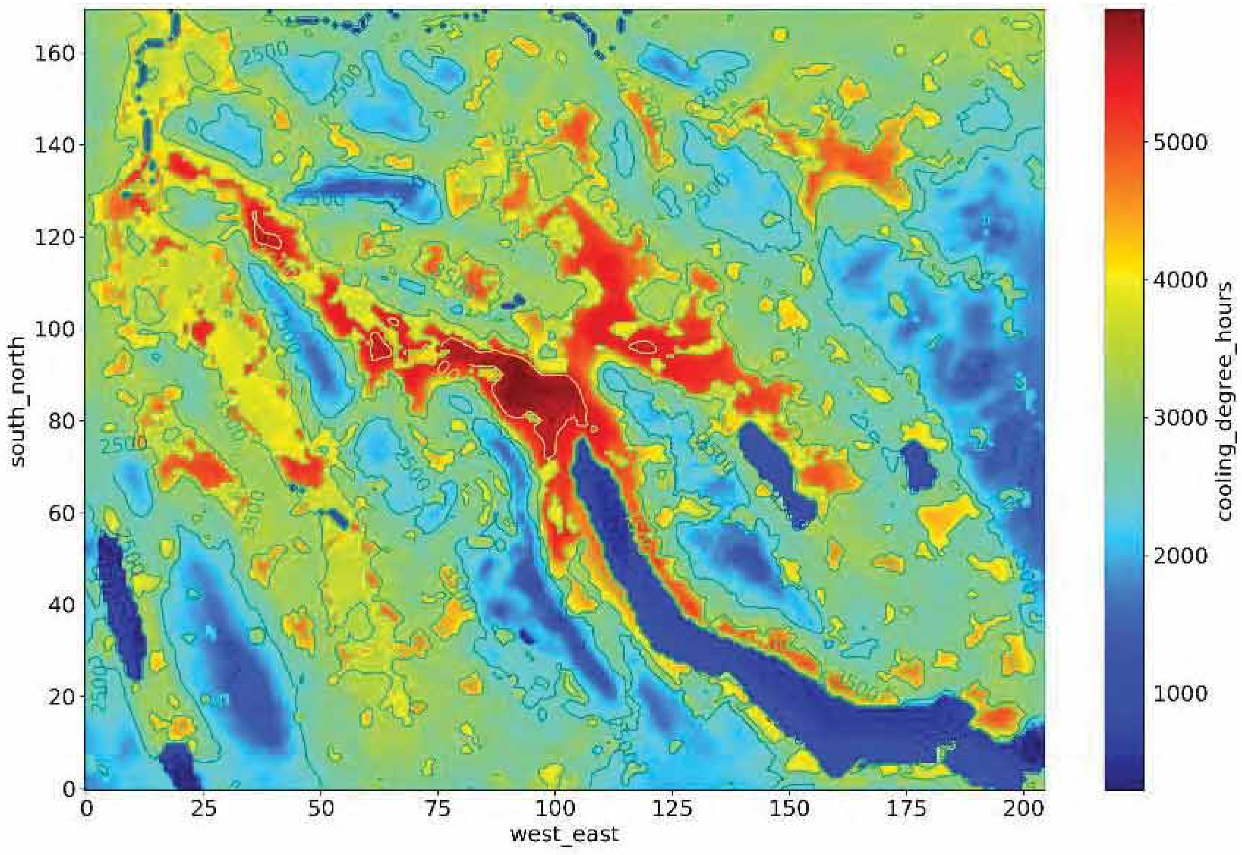


Base temperature 22 °C

https://www.weatherbit.io/blog/tag/cooling

Cooling degree hours map June-July 2019

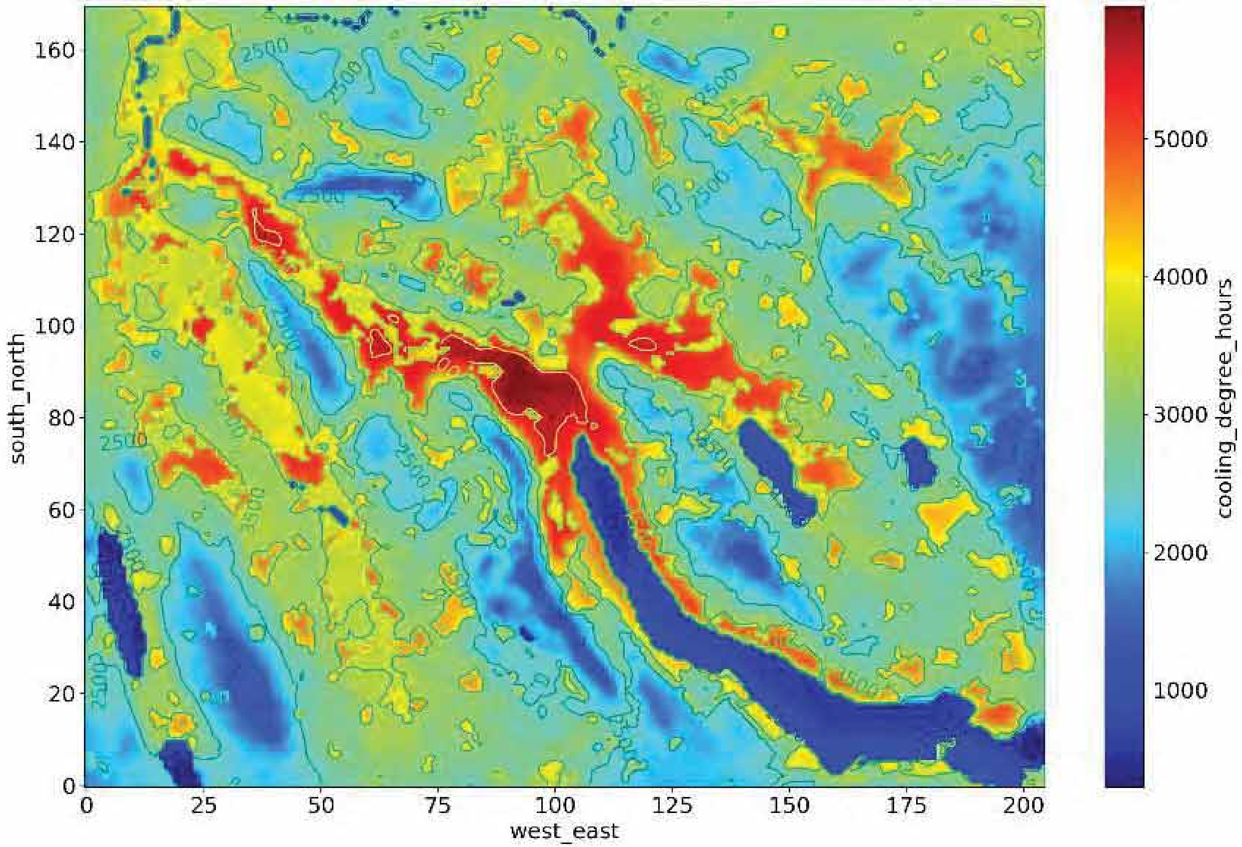
CDHs (h°C)



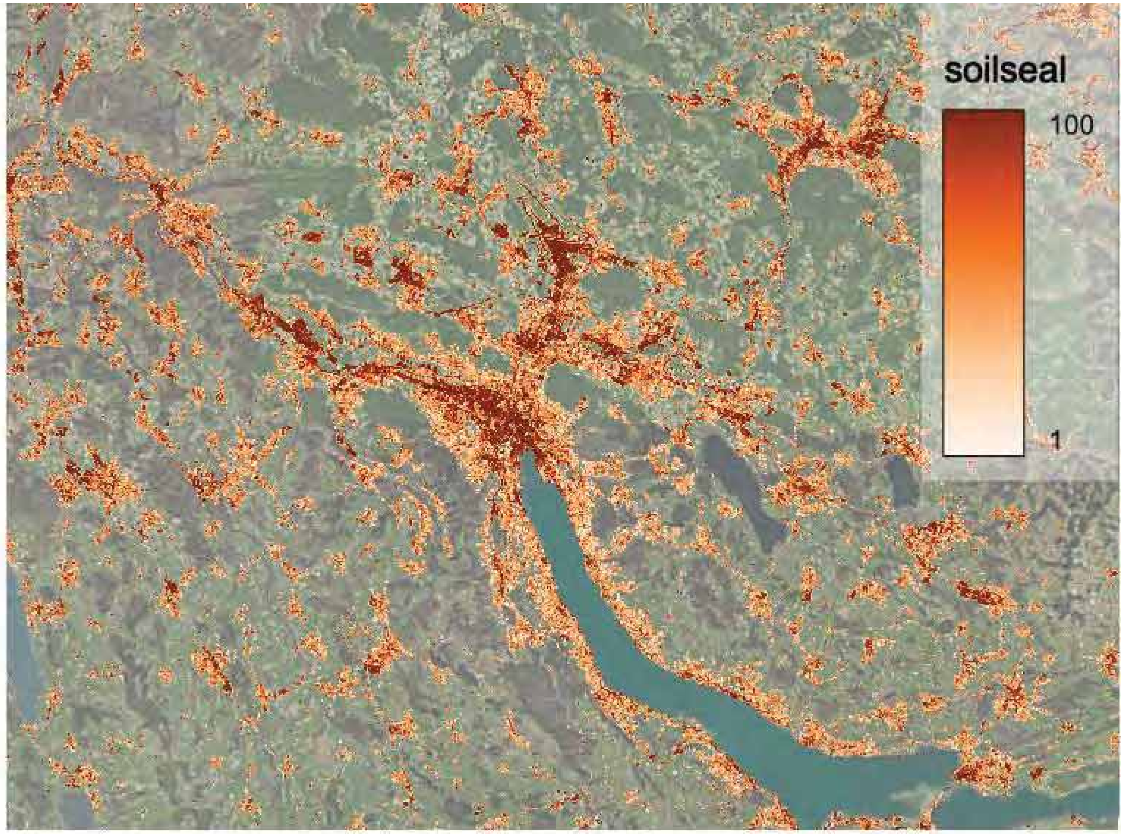
Strebel et al. 2023

Cooling degree hours map June-July 2019

CDHs (h°C)



soil sealing (%)

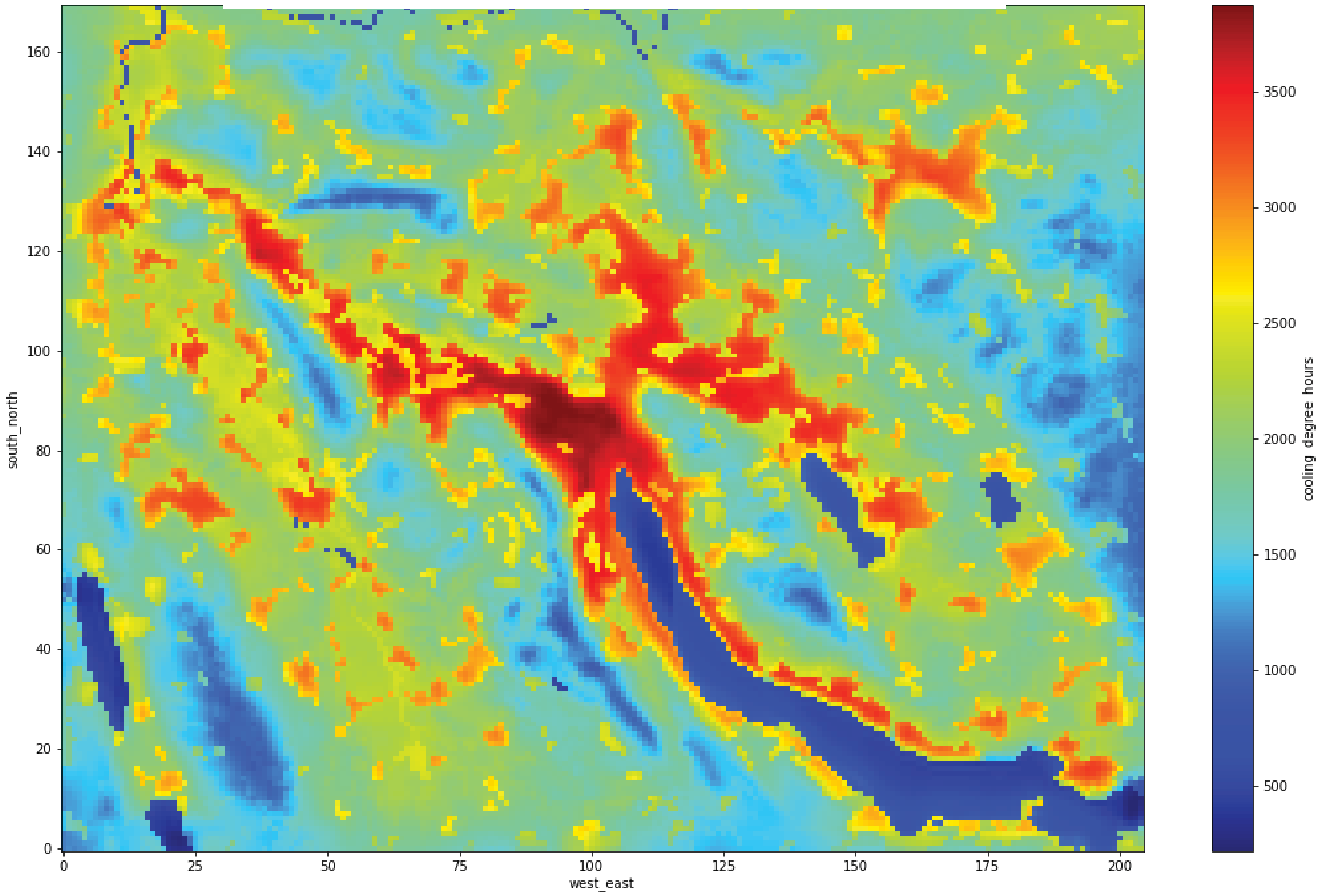


Strong correlation between **soil sealing** and **cooling degree hours**

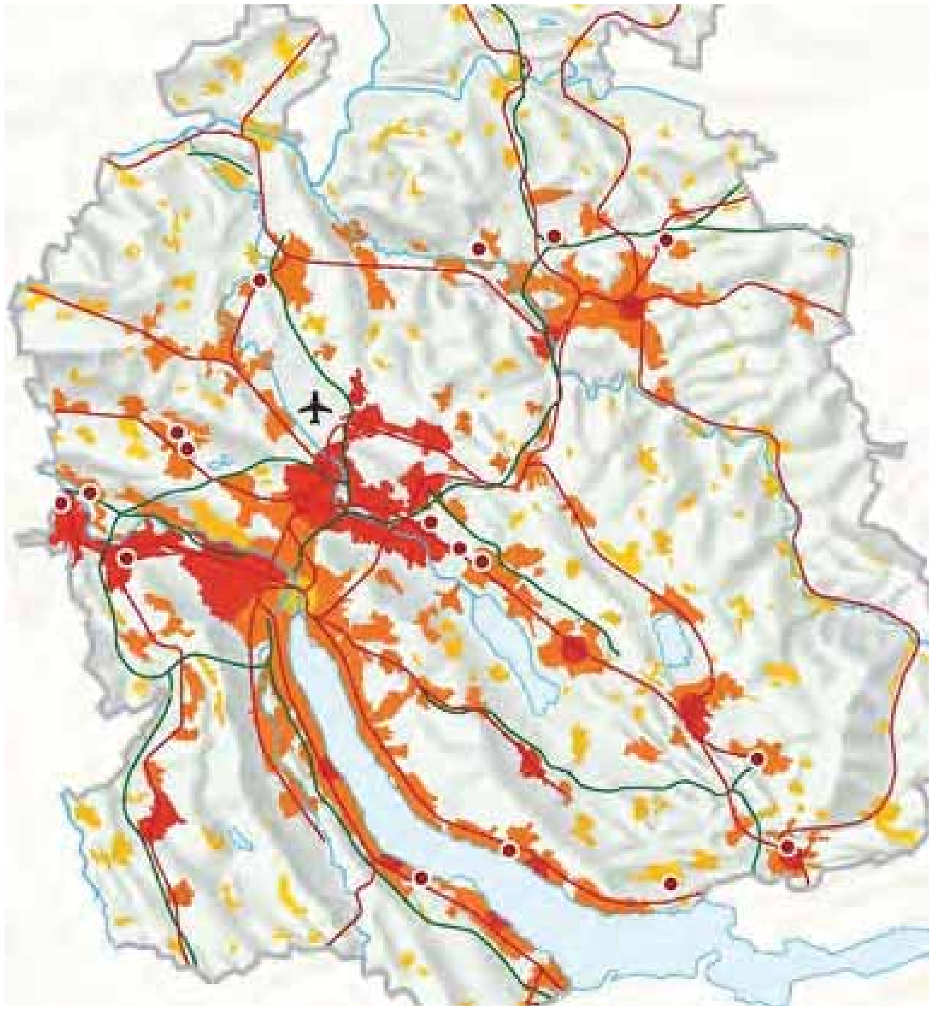
Strebel et al. 2023

UHI characterization using CDHs, June-July 2019

CDHs (h°C)



Strong correlation between **densification** and **cooling degree hours**

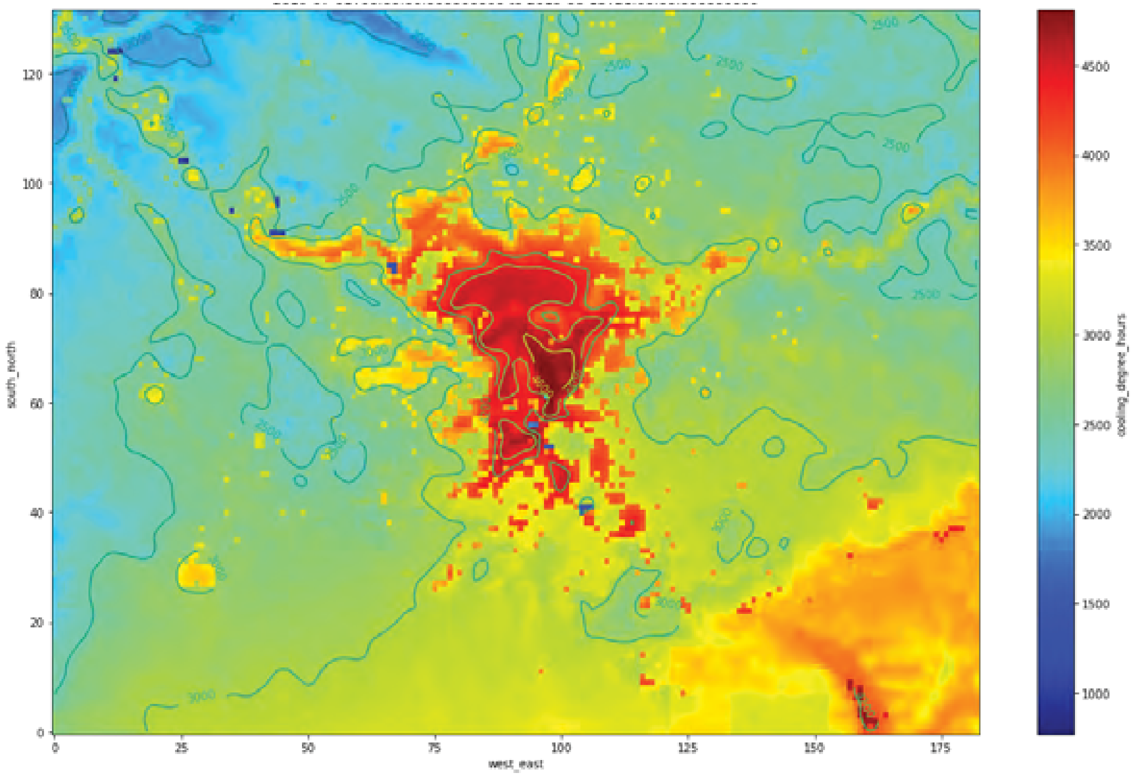


Strebel et al. 2023

UHI with CDH, 01 July to 15 August 2019

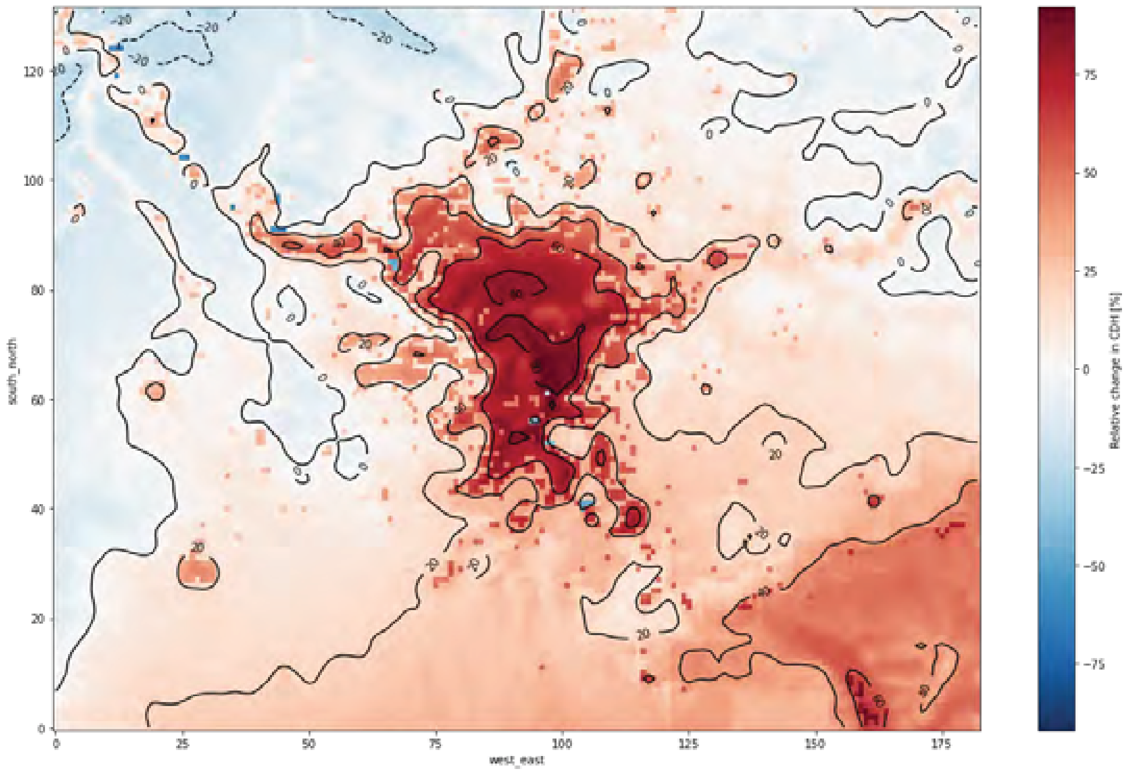
Paris

CDHs (h°C)



CDH varies between 1500 and 4500 °C.h

Relative change CDH urban versus rural



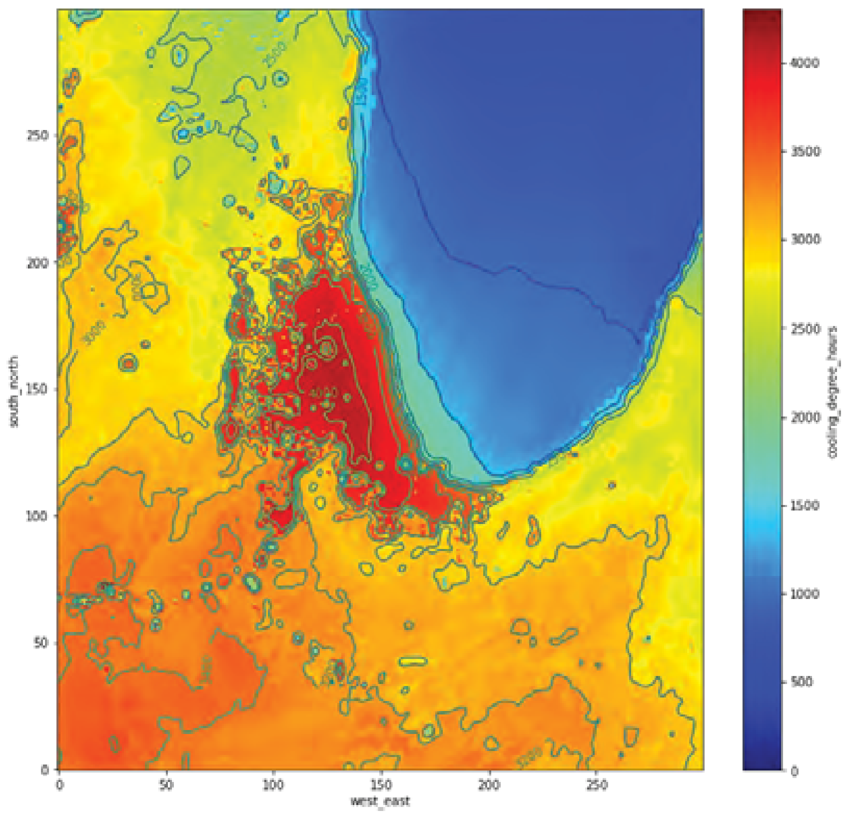
up to 80% change in CDH

Strebel et al. 2023

UHI with CDH, from 1 June to 30 June 2012

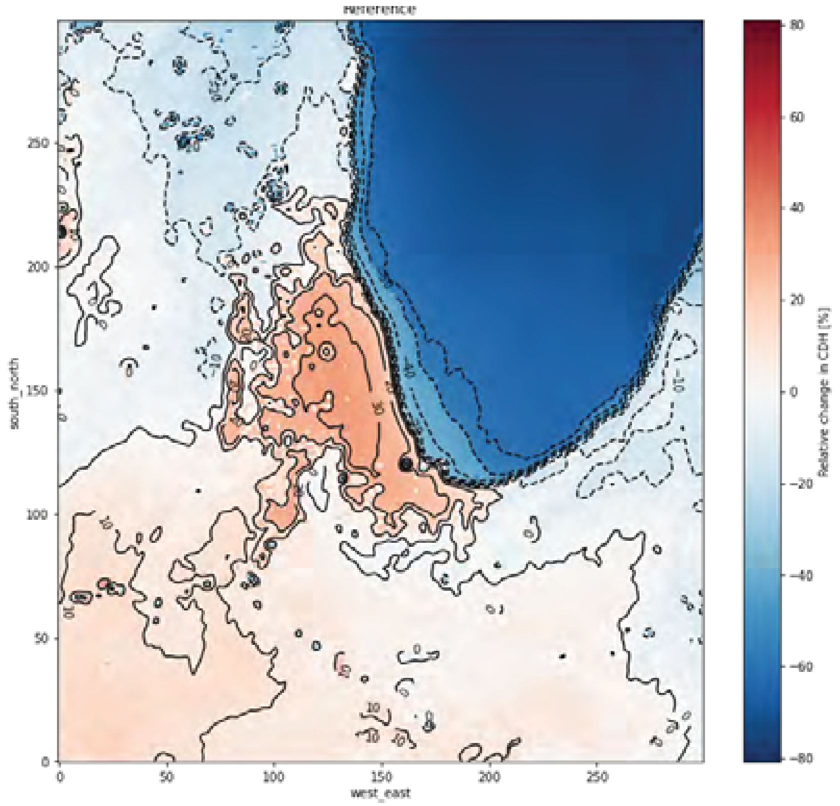
Chicago

CDHs (h°C)



CDH varies between 2500 and 4500 °C.h

Relative change CDH urban versus rural



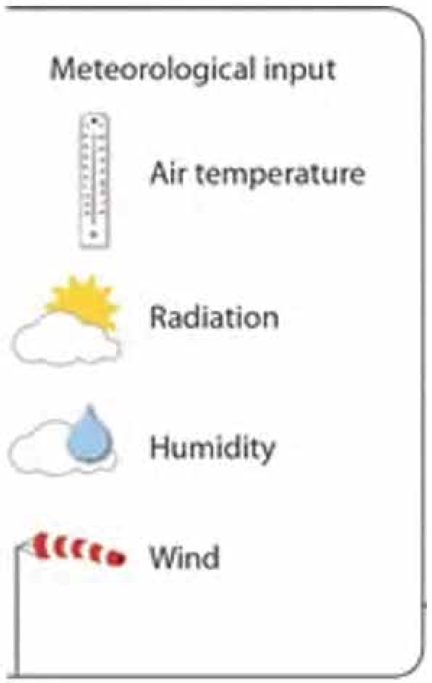
up to 40% change in CDH

Strebel et al. 2023

Thermal comfort analysis

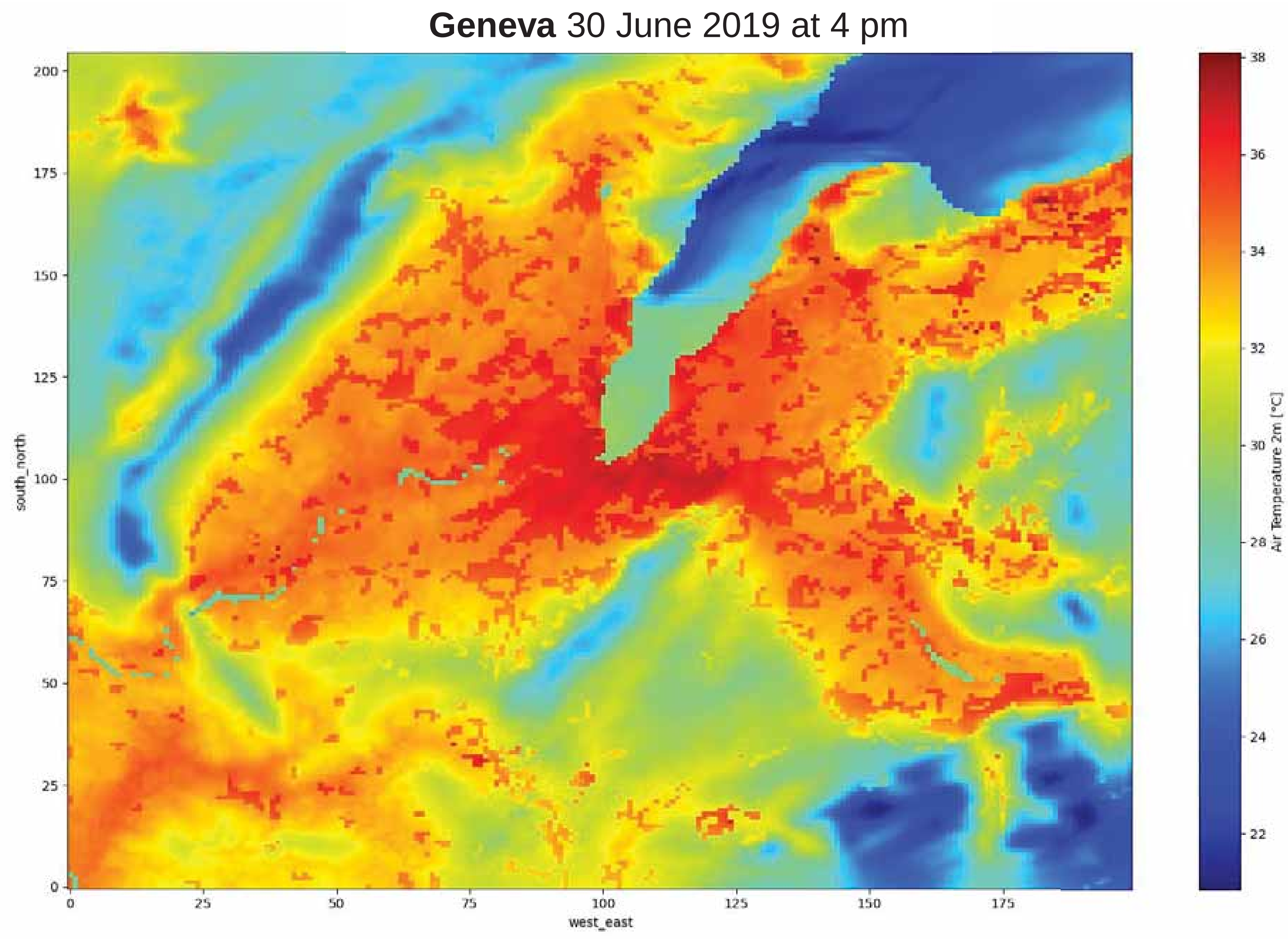
Case study: Geneva

Universal Thermal Comfort Index (UTCI)



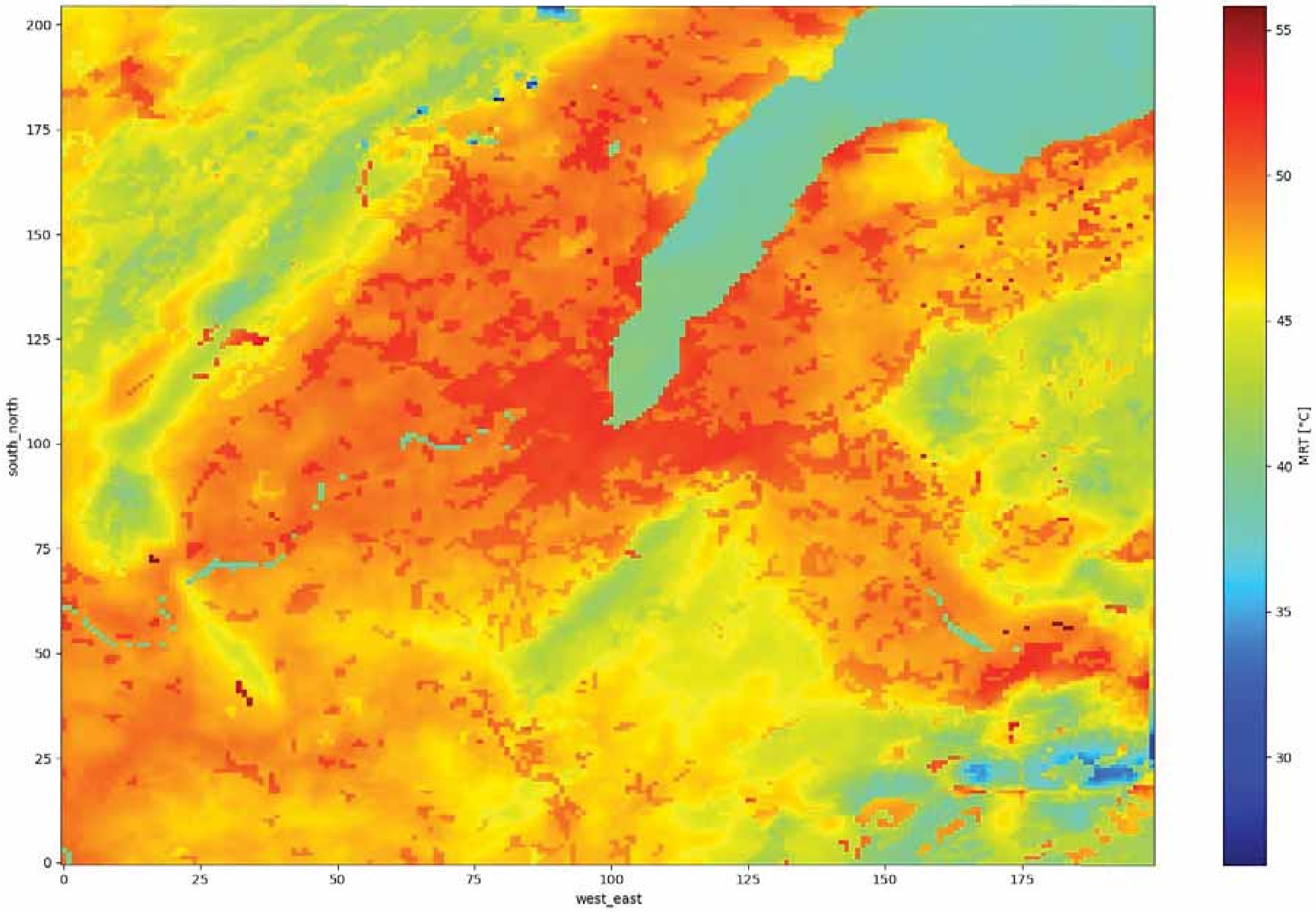
Strebel et al. 2023

Air temperature at 2m map

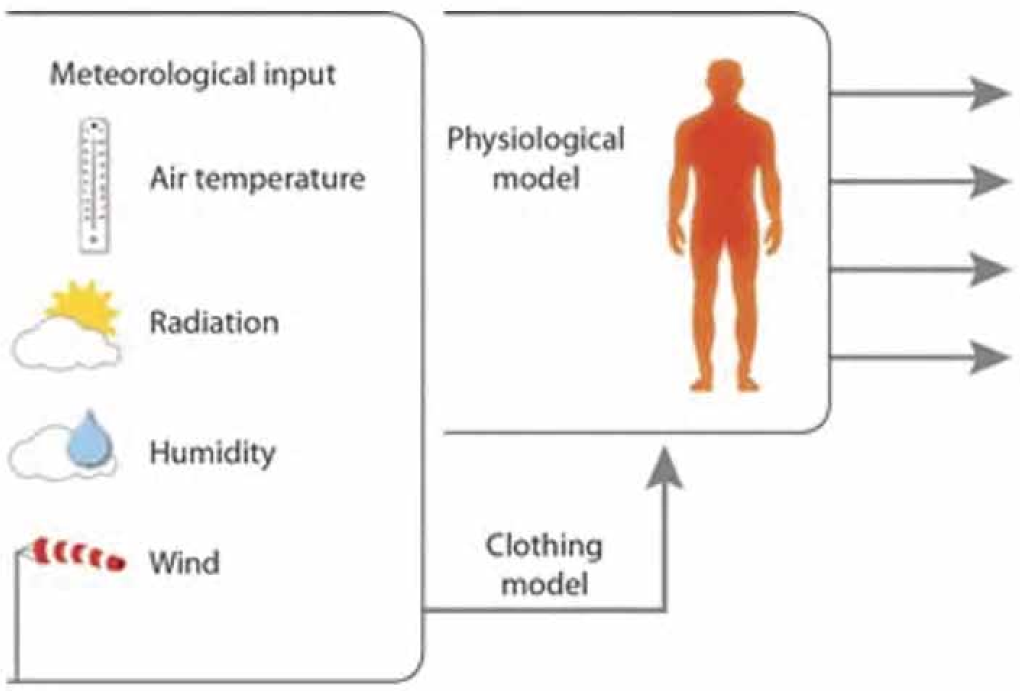


Mean radiant temperature map

Geneva 30 June 2019 at 4 pm



Universal Thermal Comfort Index (UTCI)



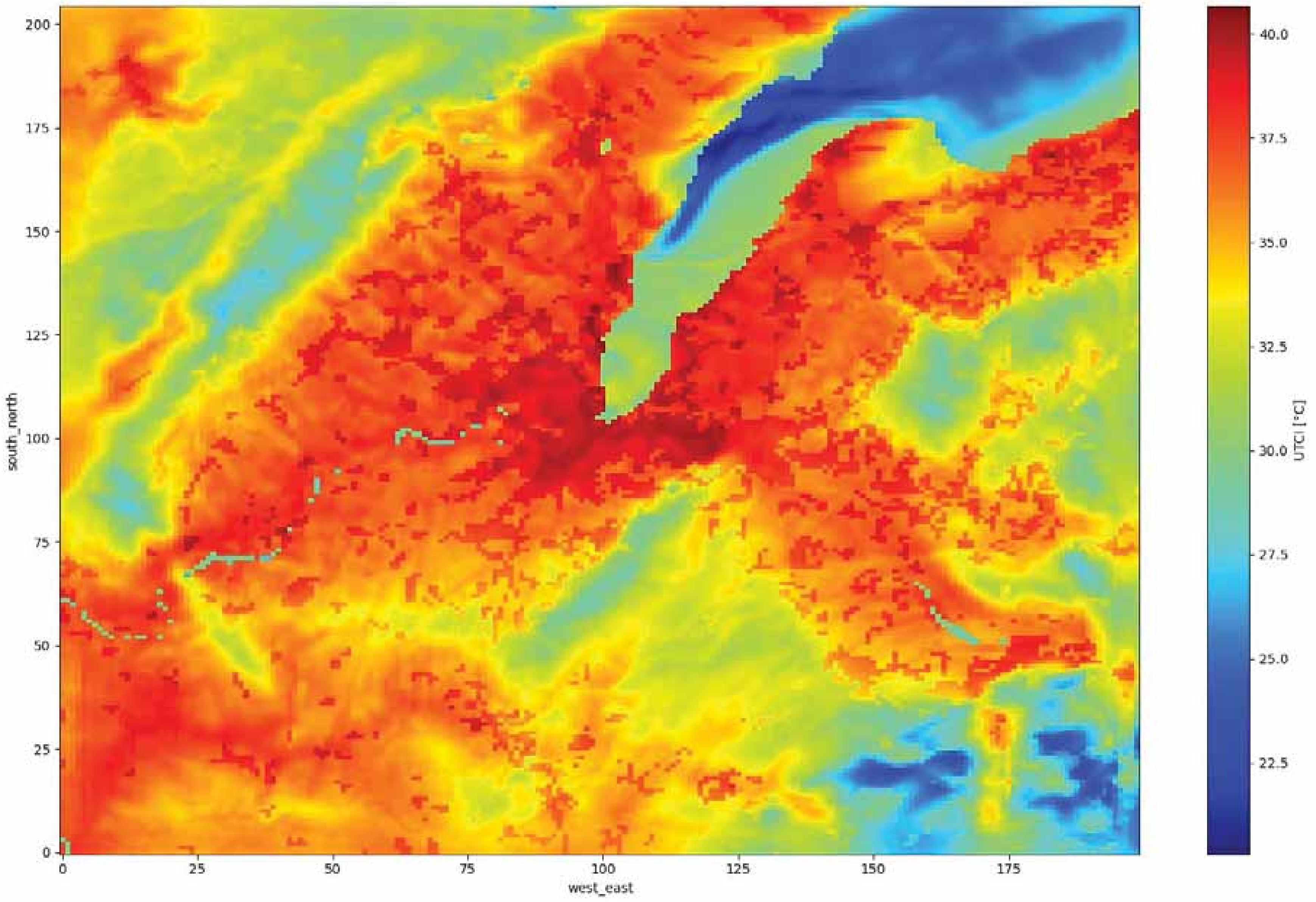
UTCI (°C)	Stress category
UTCI > 46	extreme heat stress
38 < UTCI < 46	very strong heat stress
32 < UTCI < 38	strong heat stress
26 < UTCI < 32	moderate heat stress
9 < UTCI < 26	no thermal stress
0 < UTCI < 9	slight cold stress
-13 < UTCI < 0	moderate cold stress
-27 < UTCI < -13	strong cold stress
-40 < UTCI < -27	very strong cold stress
UTCI < -40	extreme cold stress

Source: Blazejczyk et. al 2014

Strebel et al. 2023

Universal Thermal Comfort Index map

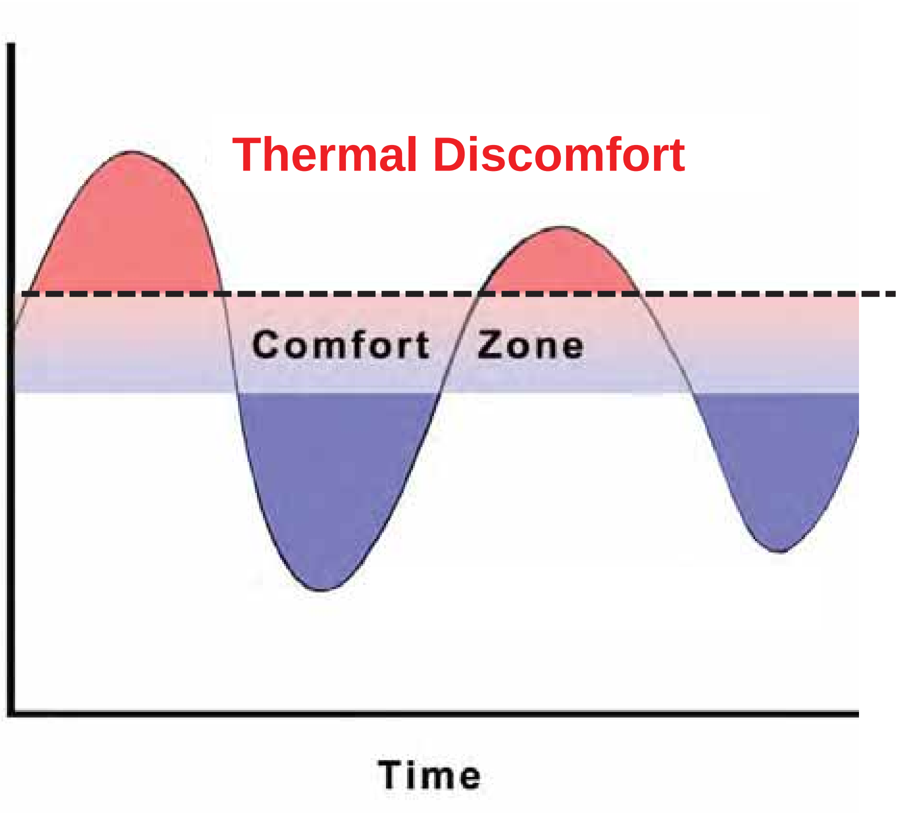
Geneva 30 June 2019 at 4 pm



Thermal Discomfort Hours (TDH) as Urban Heat Island metric

Cumulative value over total period of interest

Universal Thermal Comfort Temperature

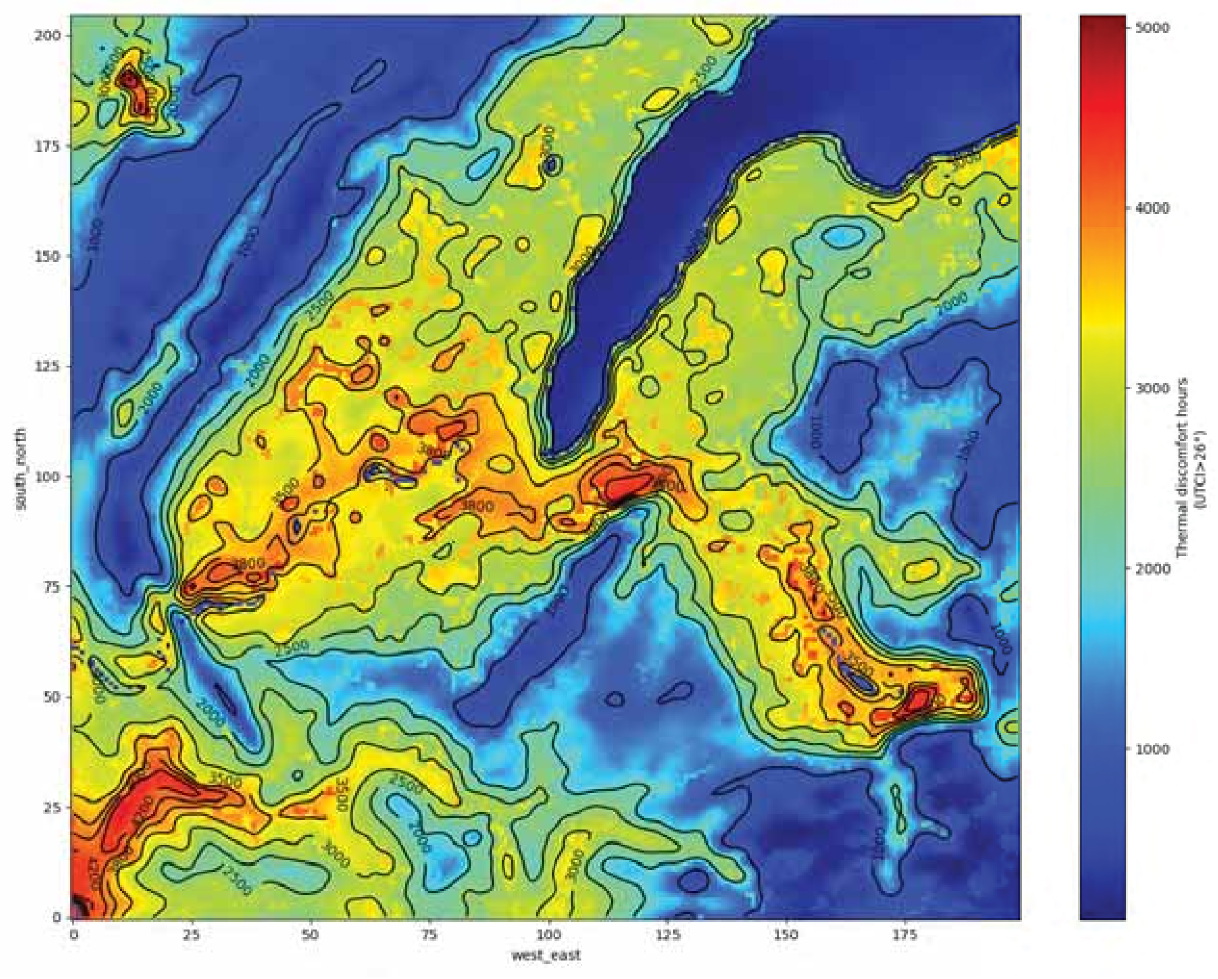


Limit UTCI 26 °C

https://www.weatherbit.io/blog/tag/cooling

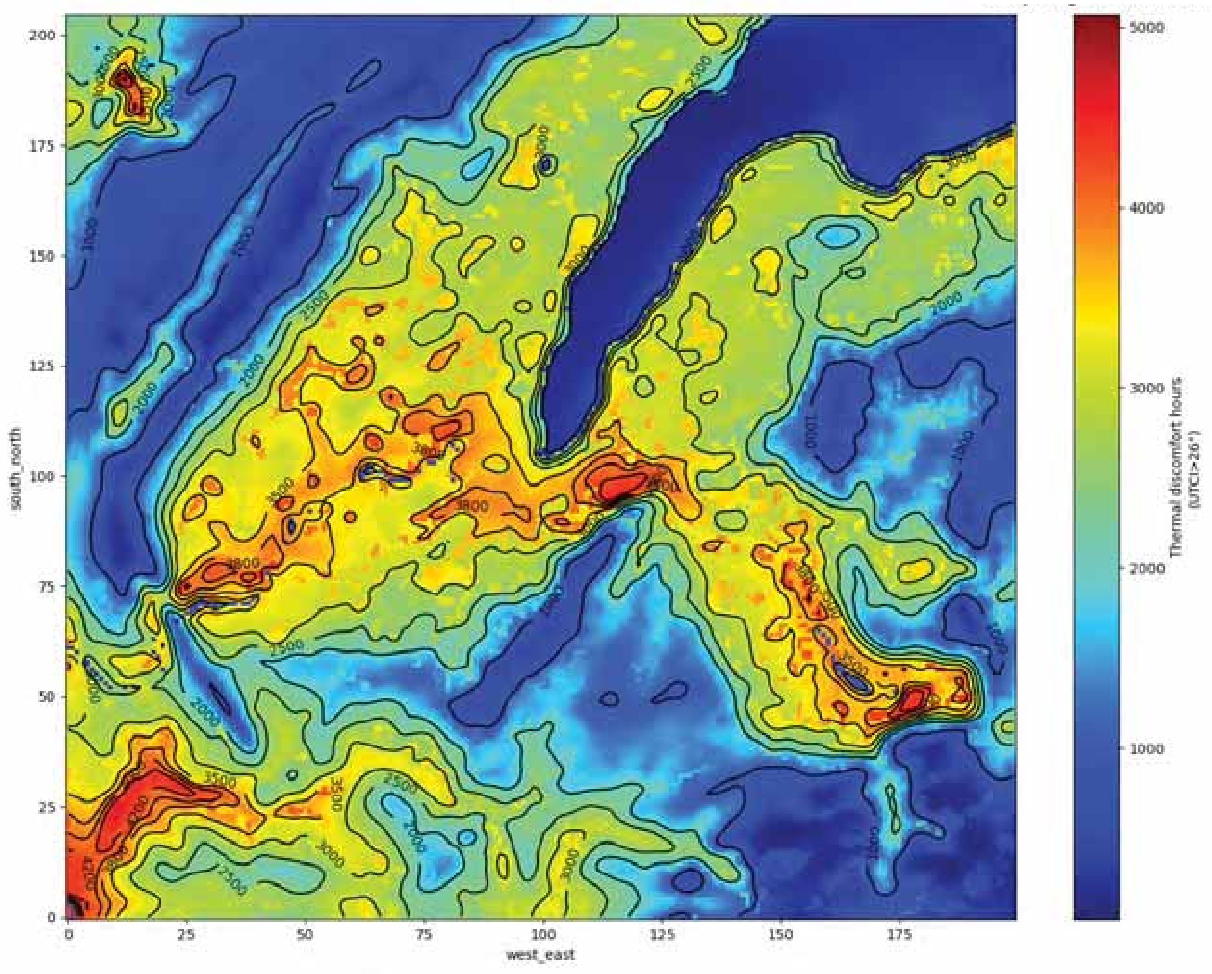
Thermal Discomfort Hours (TDH) map for Geneva

Thermal Discomfort Hours

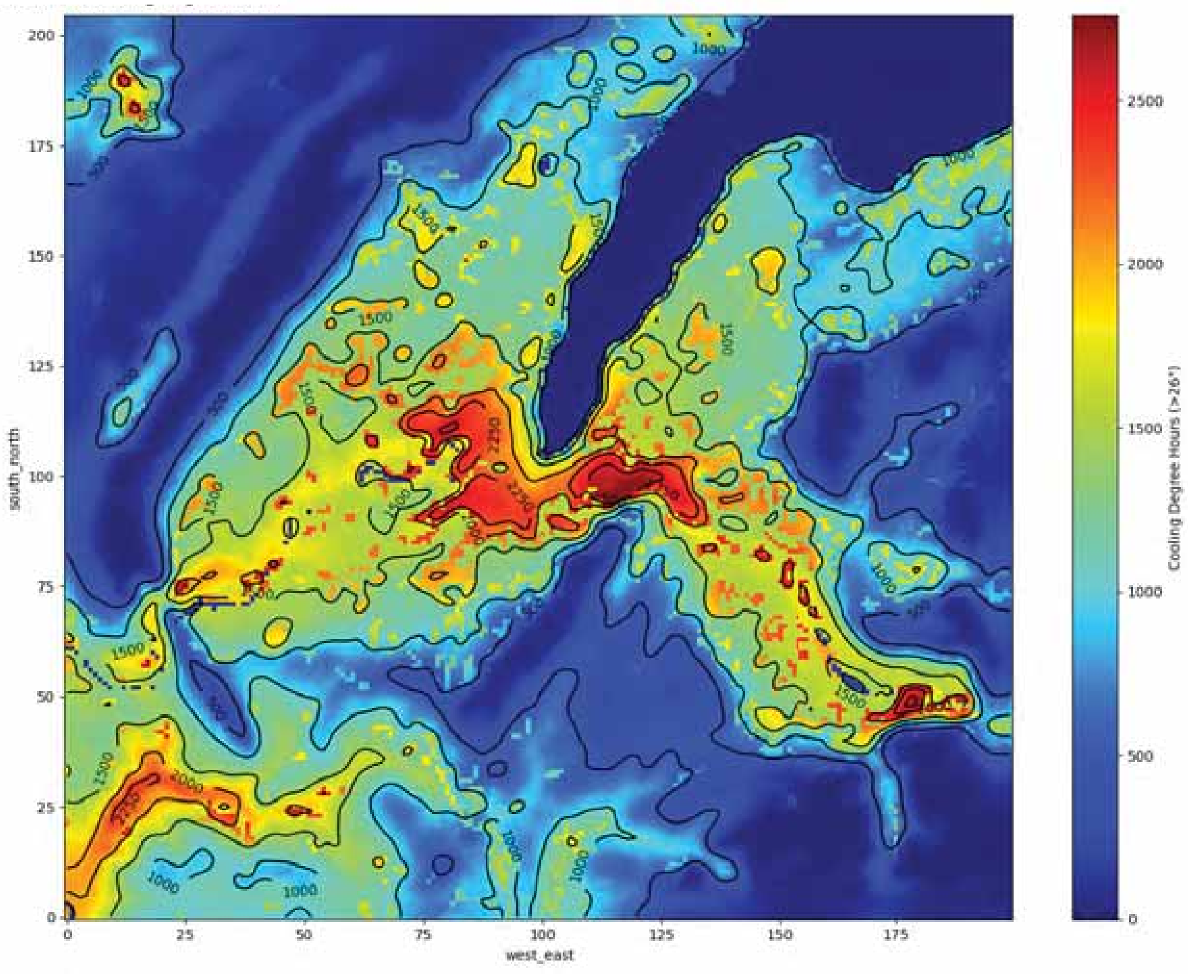


Thermal Discomfort Hours (TDH) map for Geneva

Thermal Discomfort Hours

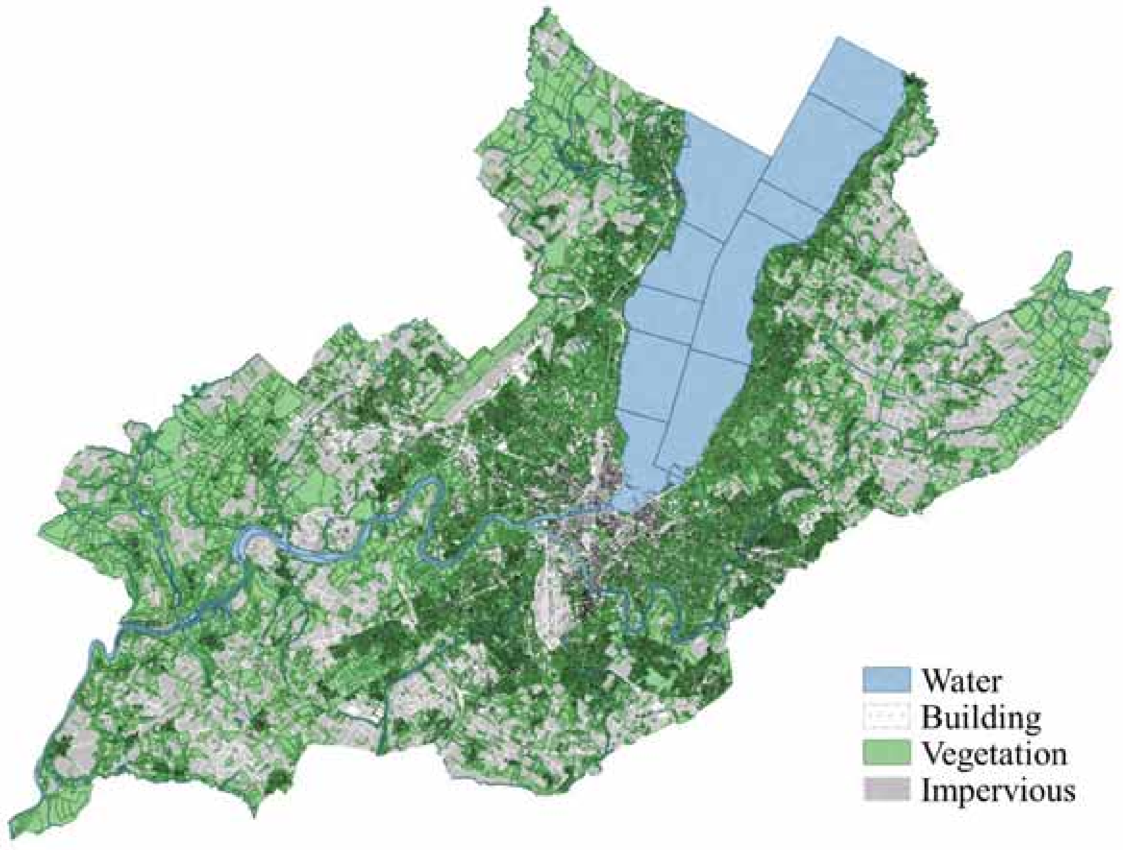


Cooling Degree Hours



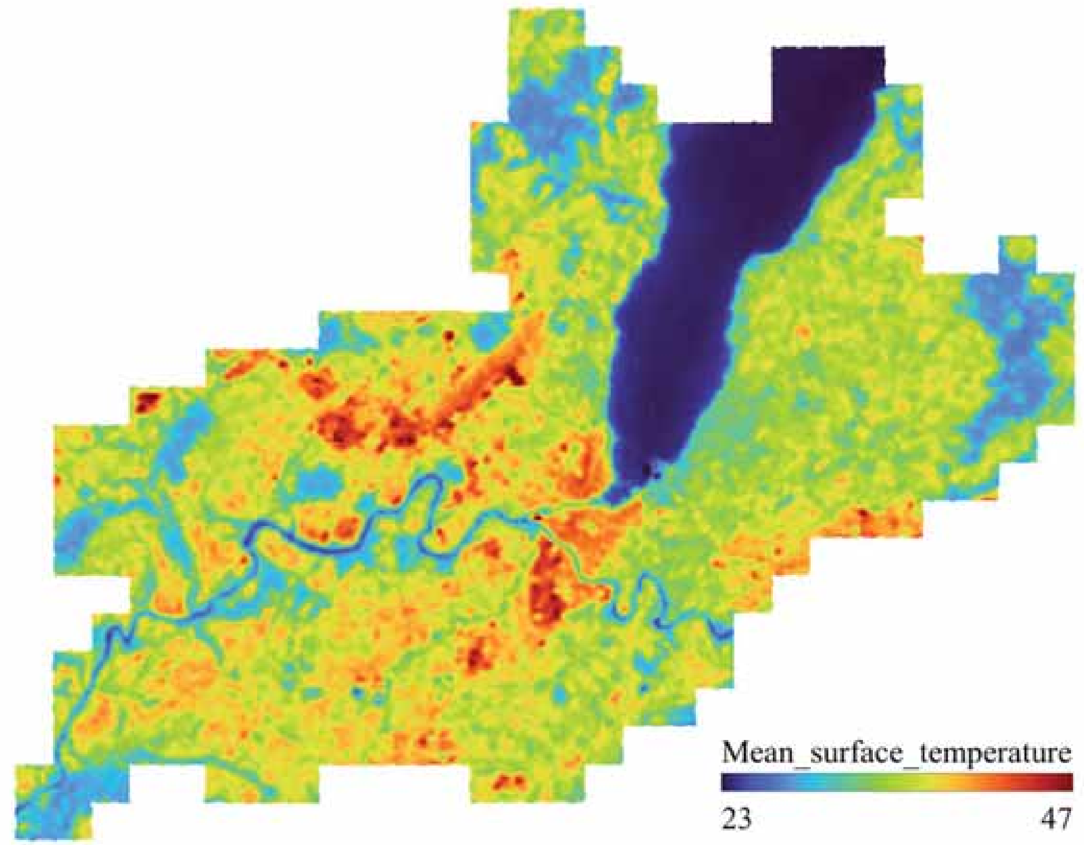
Intra-urban diversity during heatwaves: a clustering approach

Land use data



Measured mean surface temperature

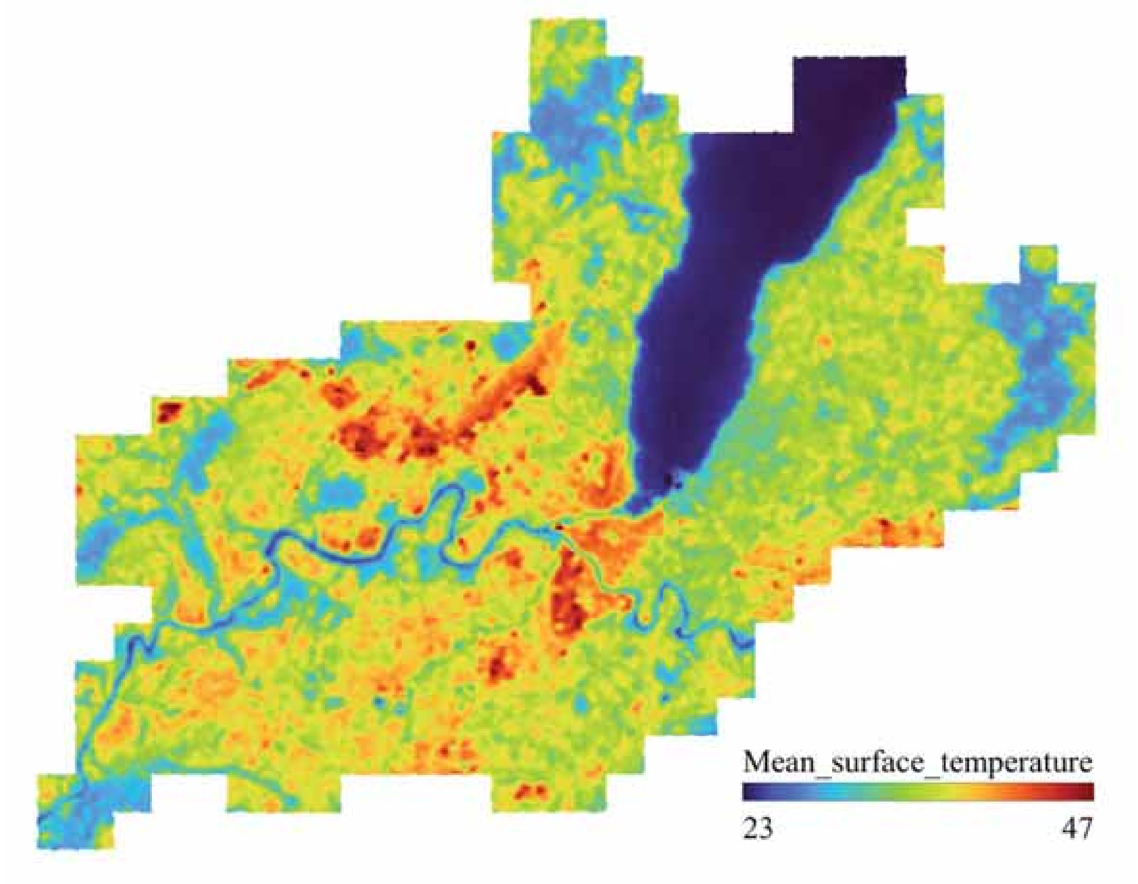
June, July, August 2019-2022



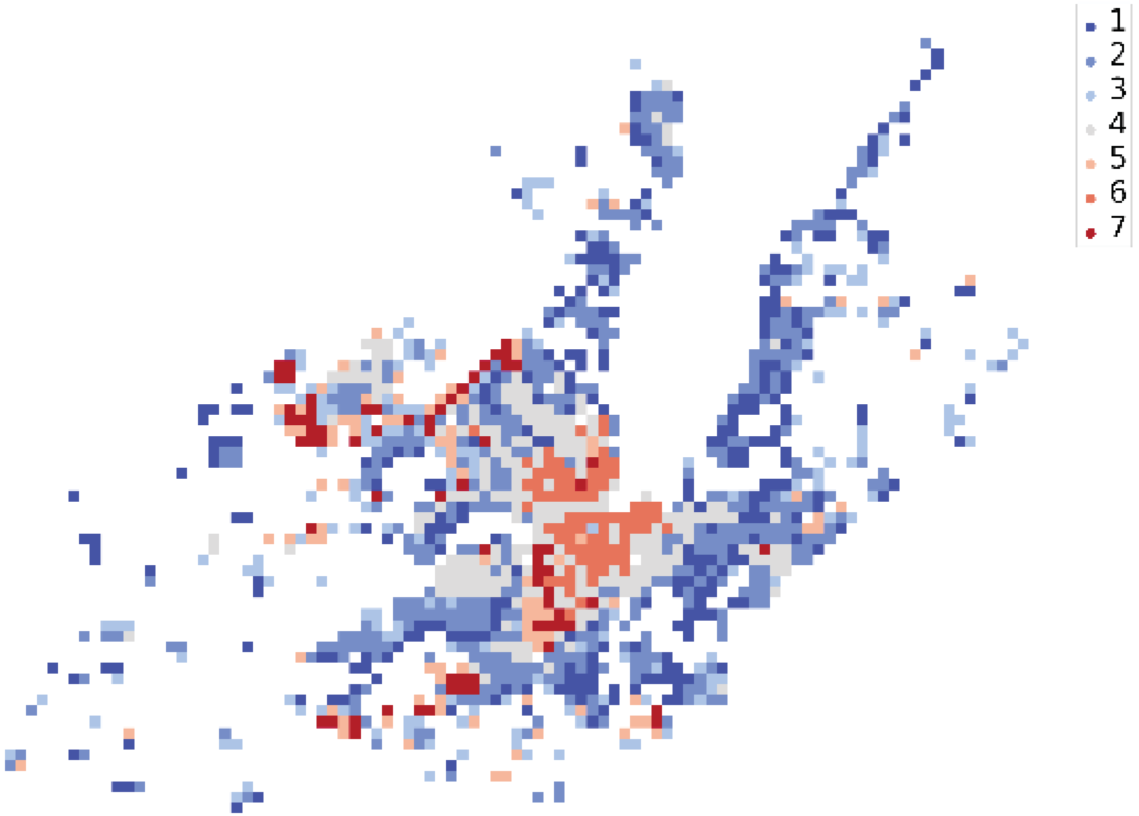
Jianxiu Wen et al. 2023

Intra-urban diversity during heatwaves: a clustering approach

Measured mean surface temperature
June, July, August 2019-2022

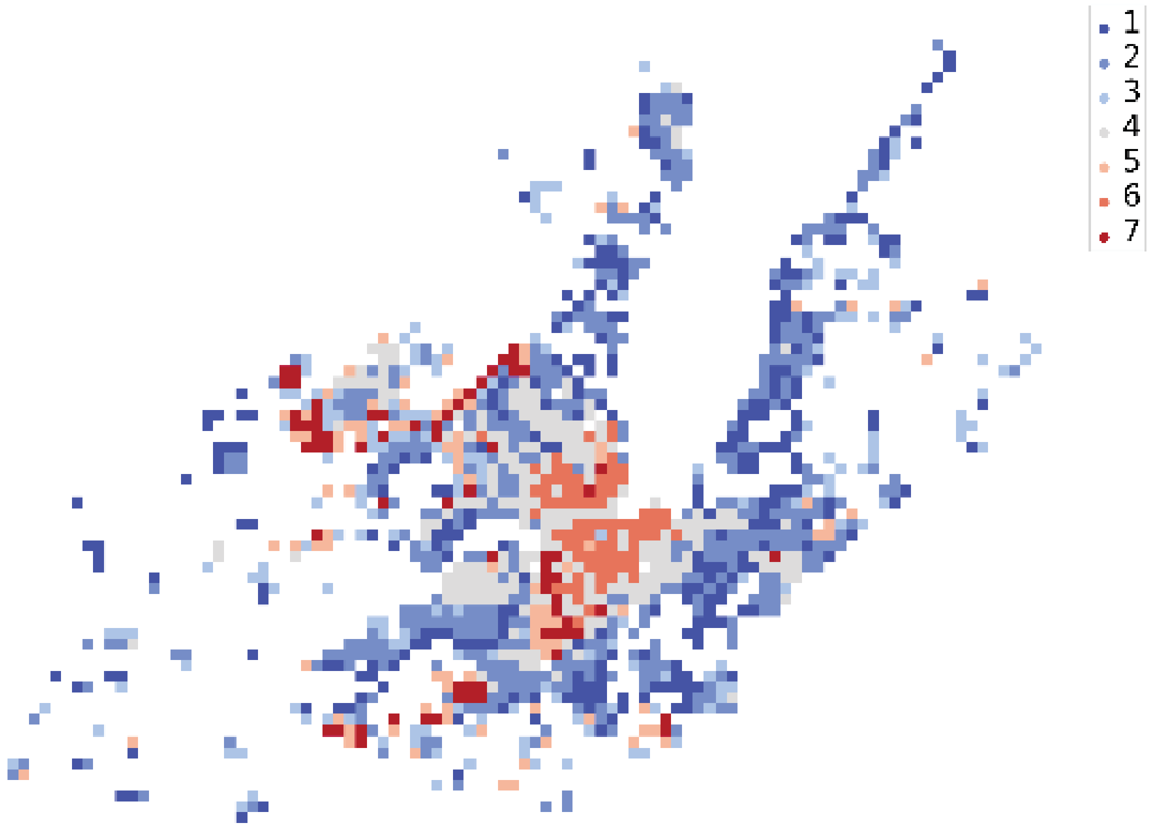


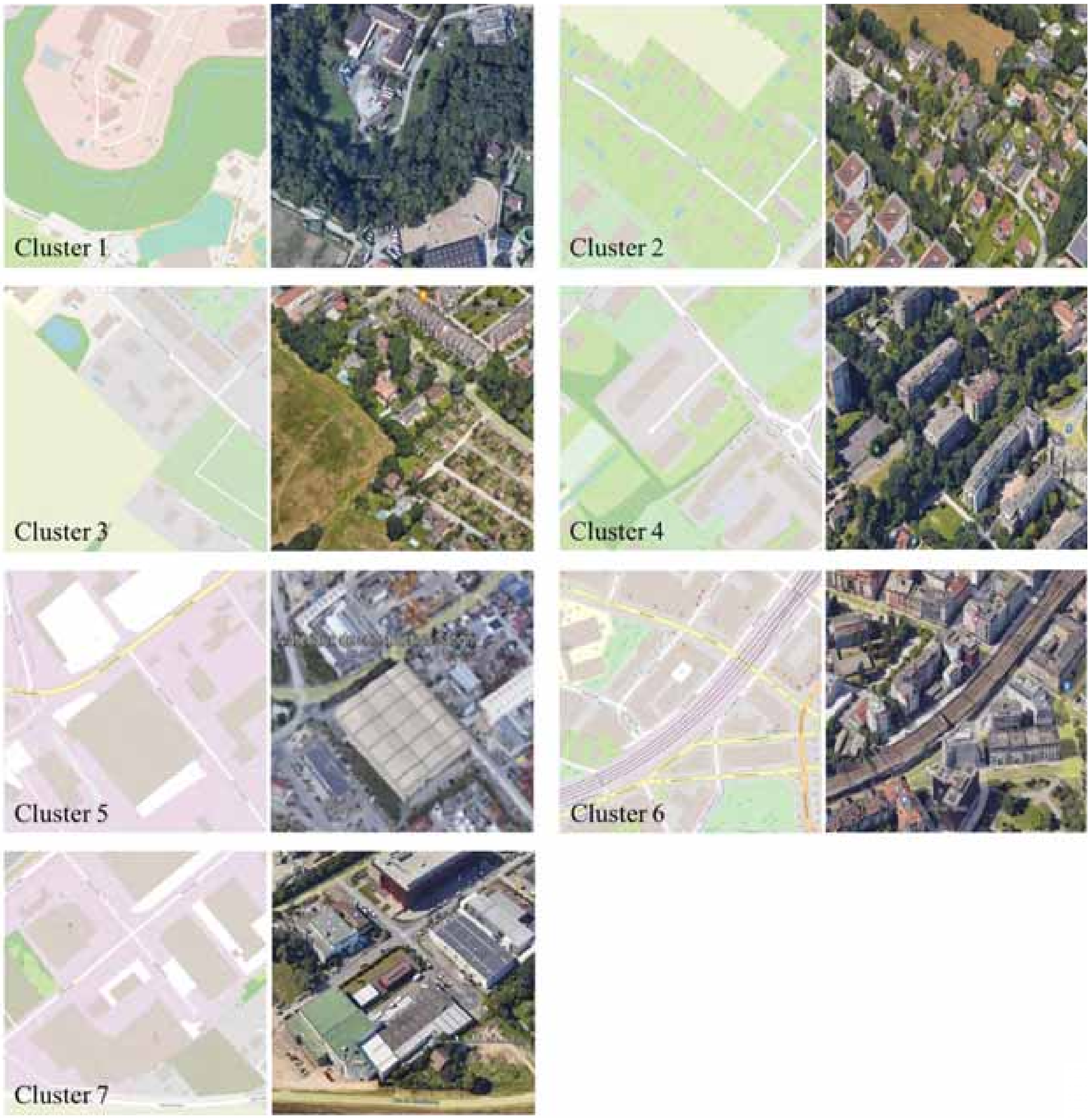
Seven clusters based on land use and building morphology



Jianxiu Wen et al. 2023

Intra-urban diversity during heatwaves: a clustering approach

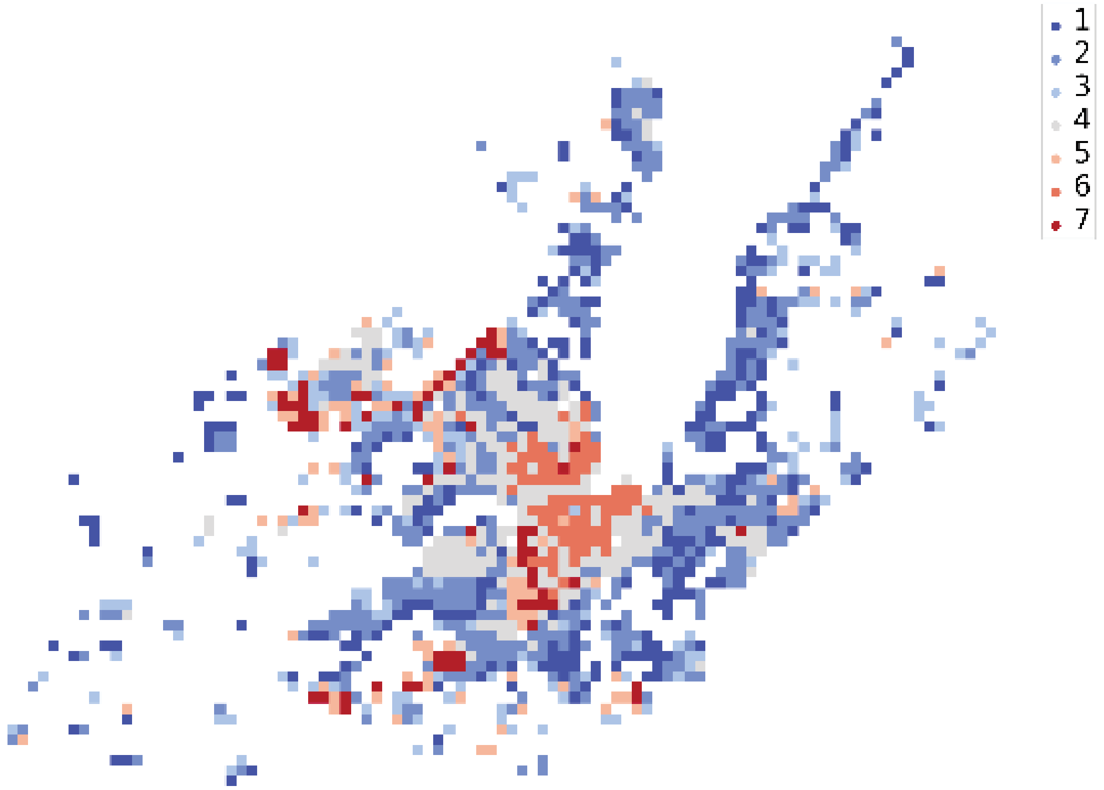




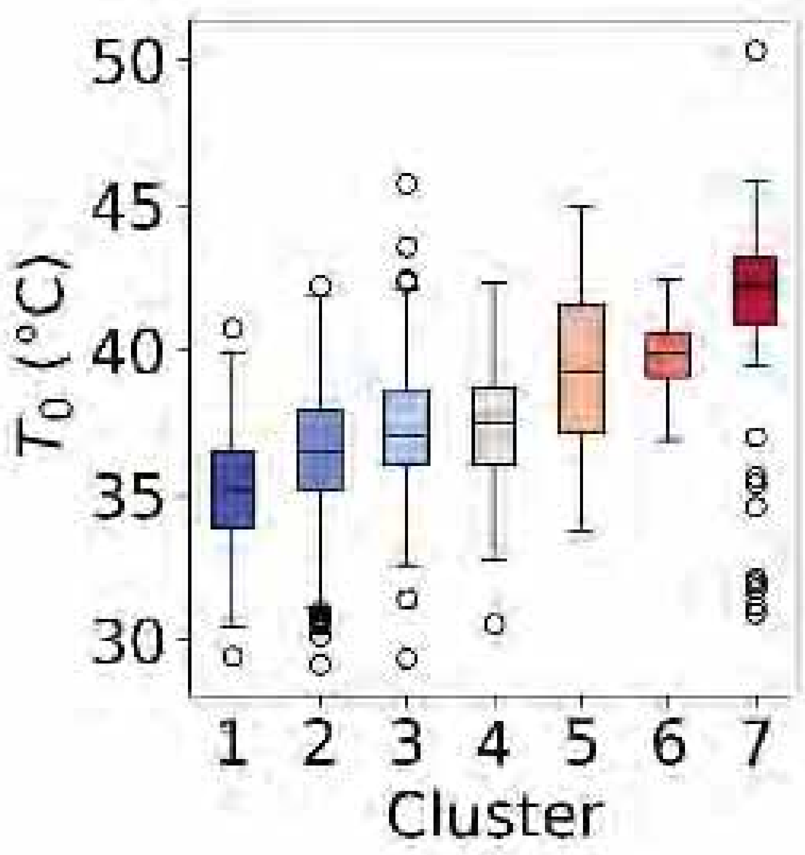
Jianxiu Wen et al. 2023

Intra-urban diversity during heatwaves: a clustering approach

Cluster map



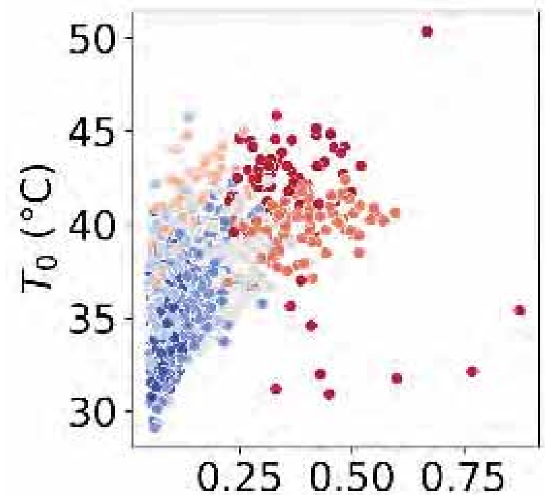
surface temperature



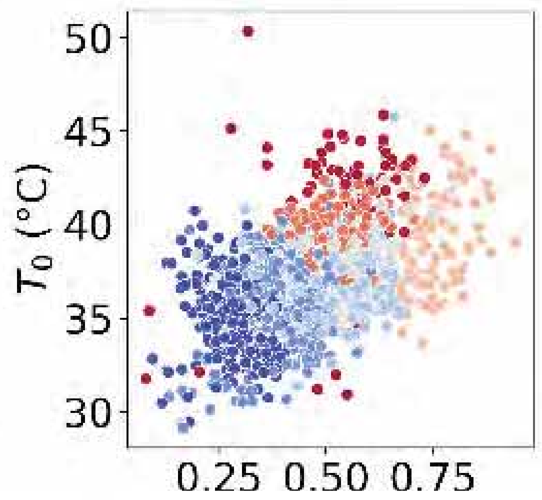
Jianxiu Wen et al. 2023

Most important influencing factors

Increase in
heat storage



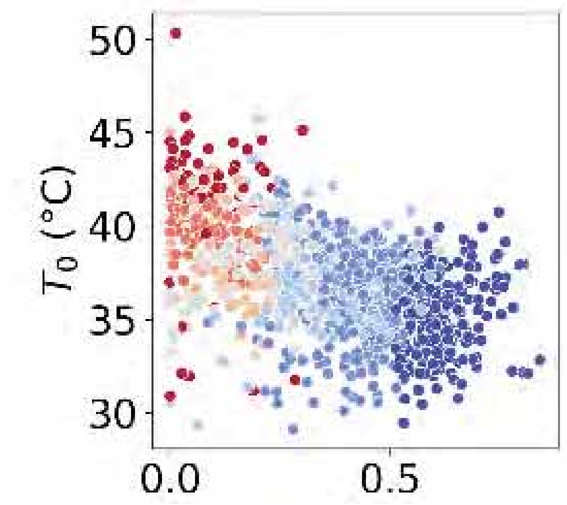
Buildings land cover area



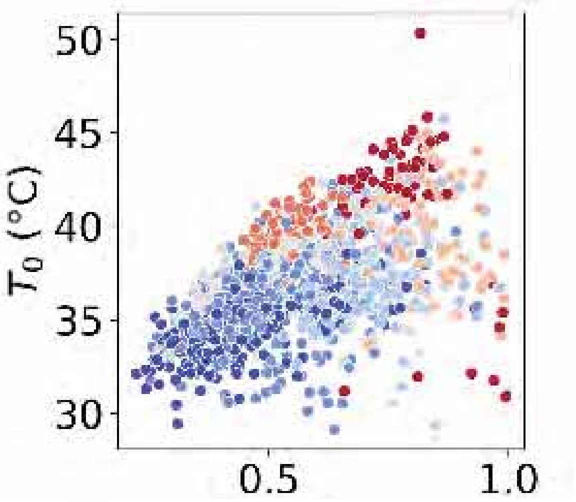
Impervious surface land cover area

Lack of
evaporative cooling

Increase in
Shadowing
Transpirative cooling



Vegetation land cover area



Integrated sky view factor

Decrease in
shadowing

Jianxiu Wen et al. 2023

Intra-urban diversity during heatwaves: a clustering approach

What can we learn?

Cluster 1 $\leftrightarrow$ 3: 24% of land cover from vegetation to impervious surfaces $\Rightarrow \Delta T =$ **+ 2.2 °C**

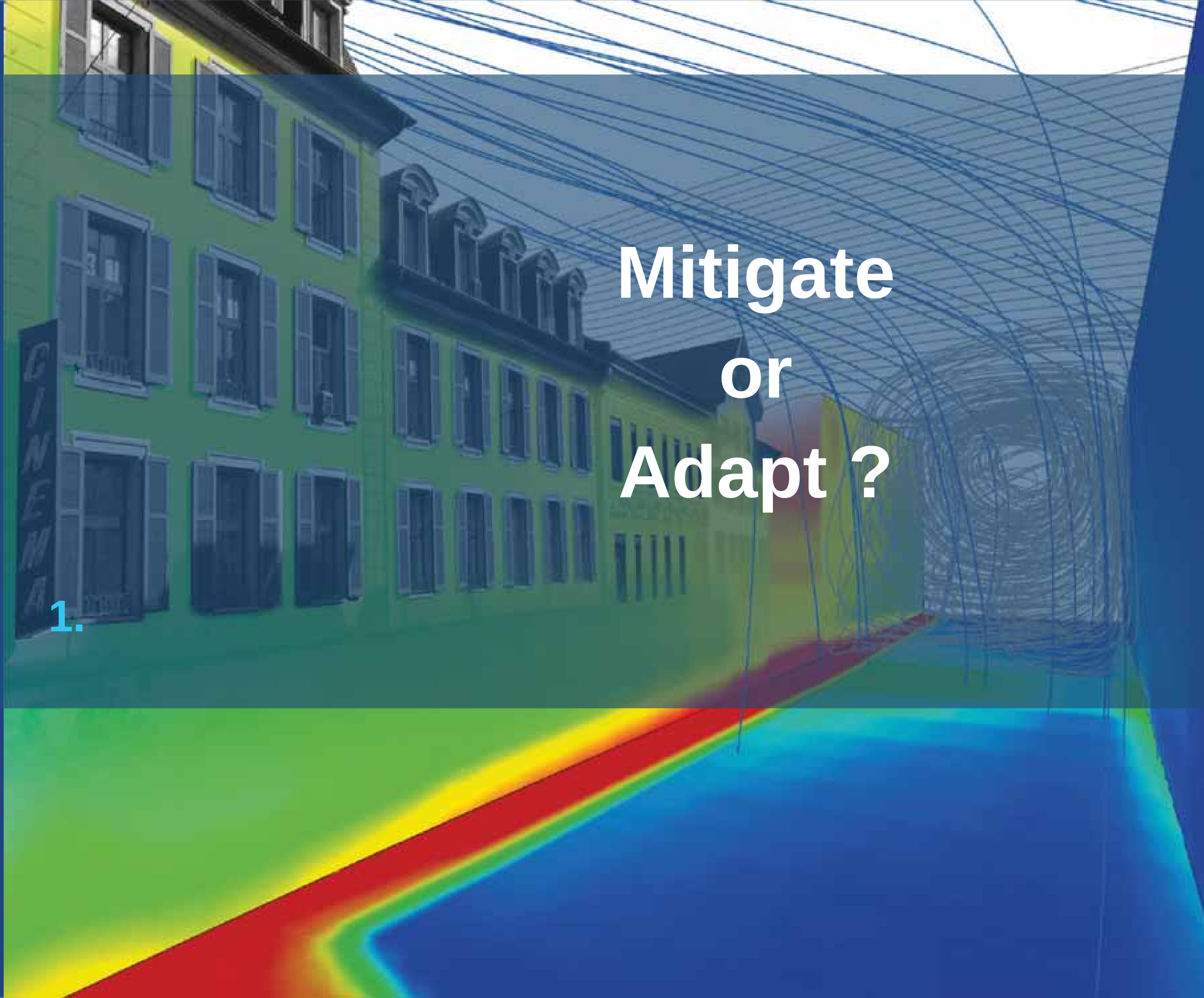
Cluster 2 $\leftrightarrow$ 5: 32% of land cover from vegetation to impervious surfaces $\Rightarrow \Delta T =$ **+ 3 °C**

Cluster 4 $\leftrightarrow$ 6: 19% of land cover from vegetation to buildings $\Rightarrow \Delta T =$ **+ 2.4 °C**

Cluster 3 $\leftrightarrow$ 7: 28% of land cover from vegetation to higher buildings $\Rightarrow \Delta T =$ **+ 4 °C**

At least 20% of vegetation land cover area is needed to prevent high surface temperatures

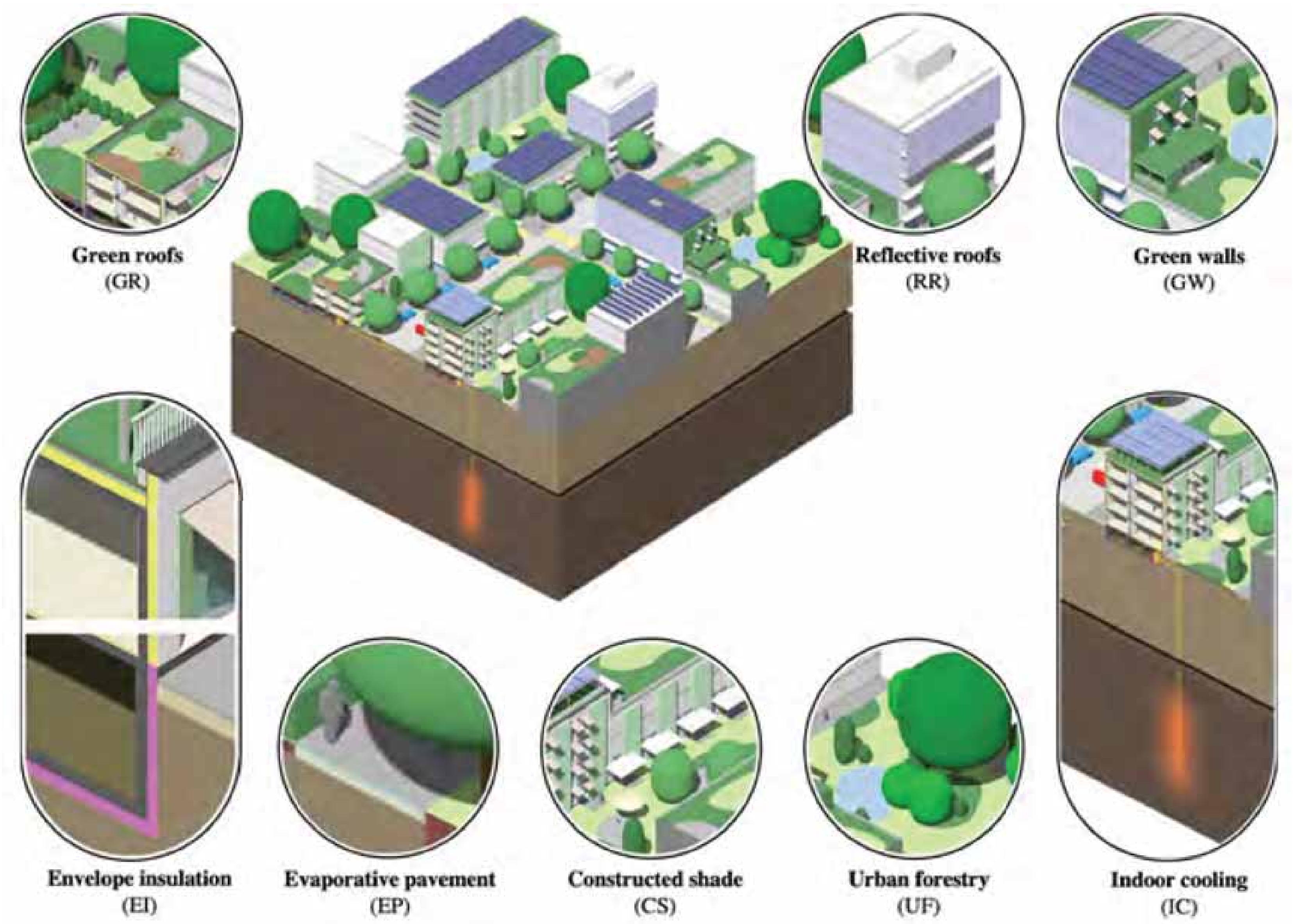
Jianxiu Wen et al. 2023



Mitigate
or
Adapt ?

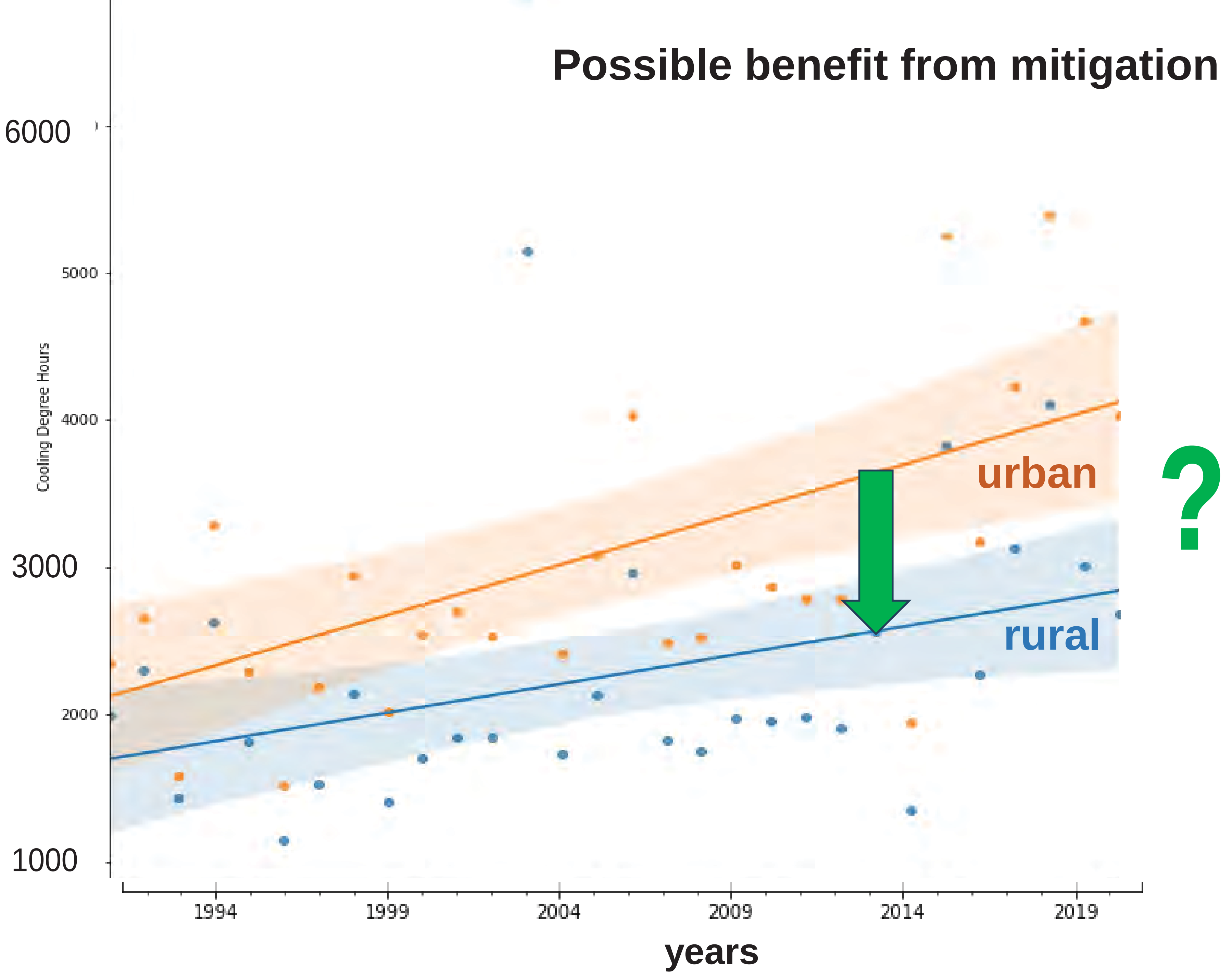
1.

Mitigation measures for heatwaves at the microscale



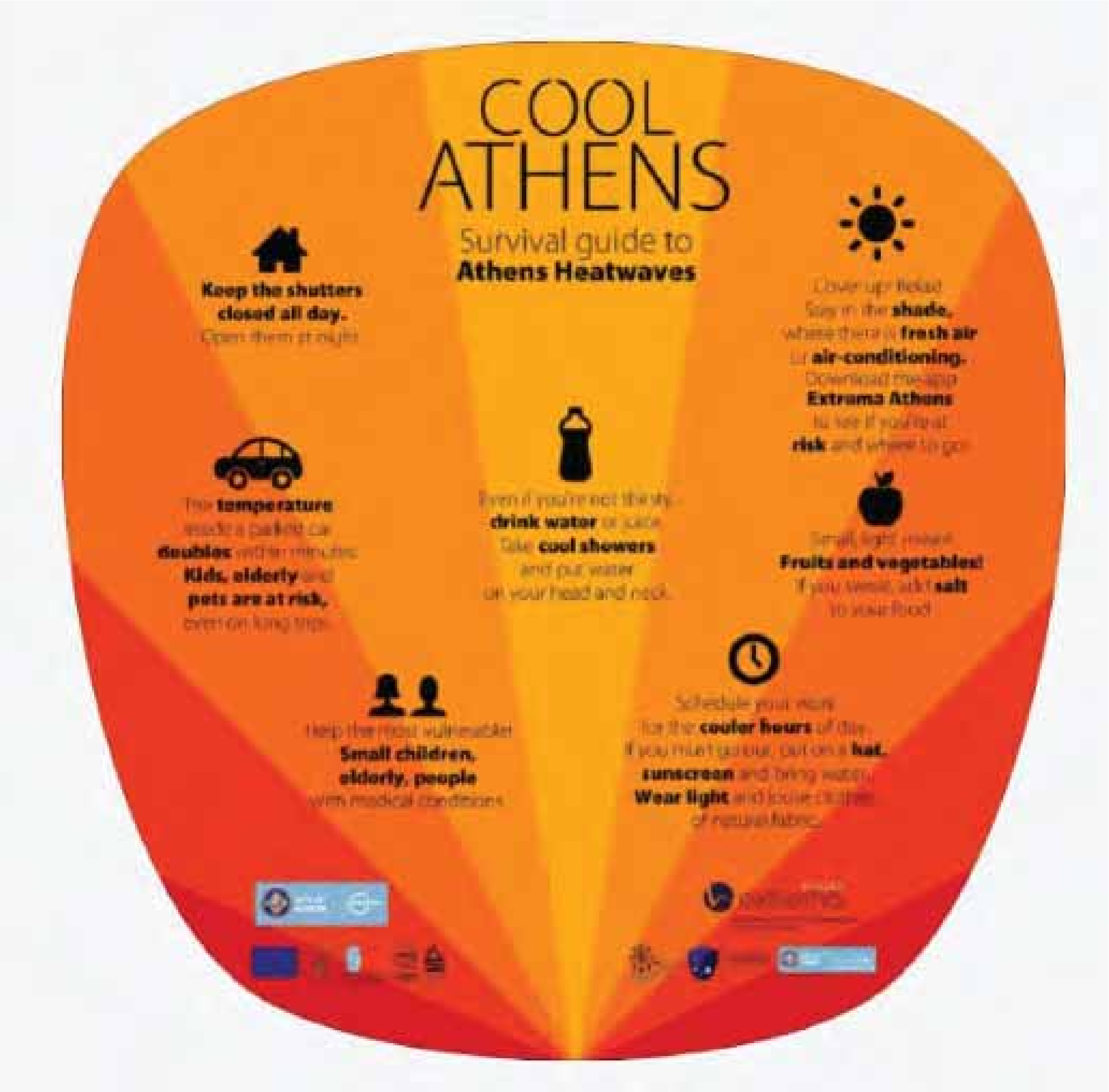
Y. Zhao et al. 2023

Possible benefit from mitigation



D. Strebel. 2021

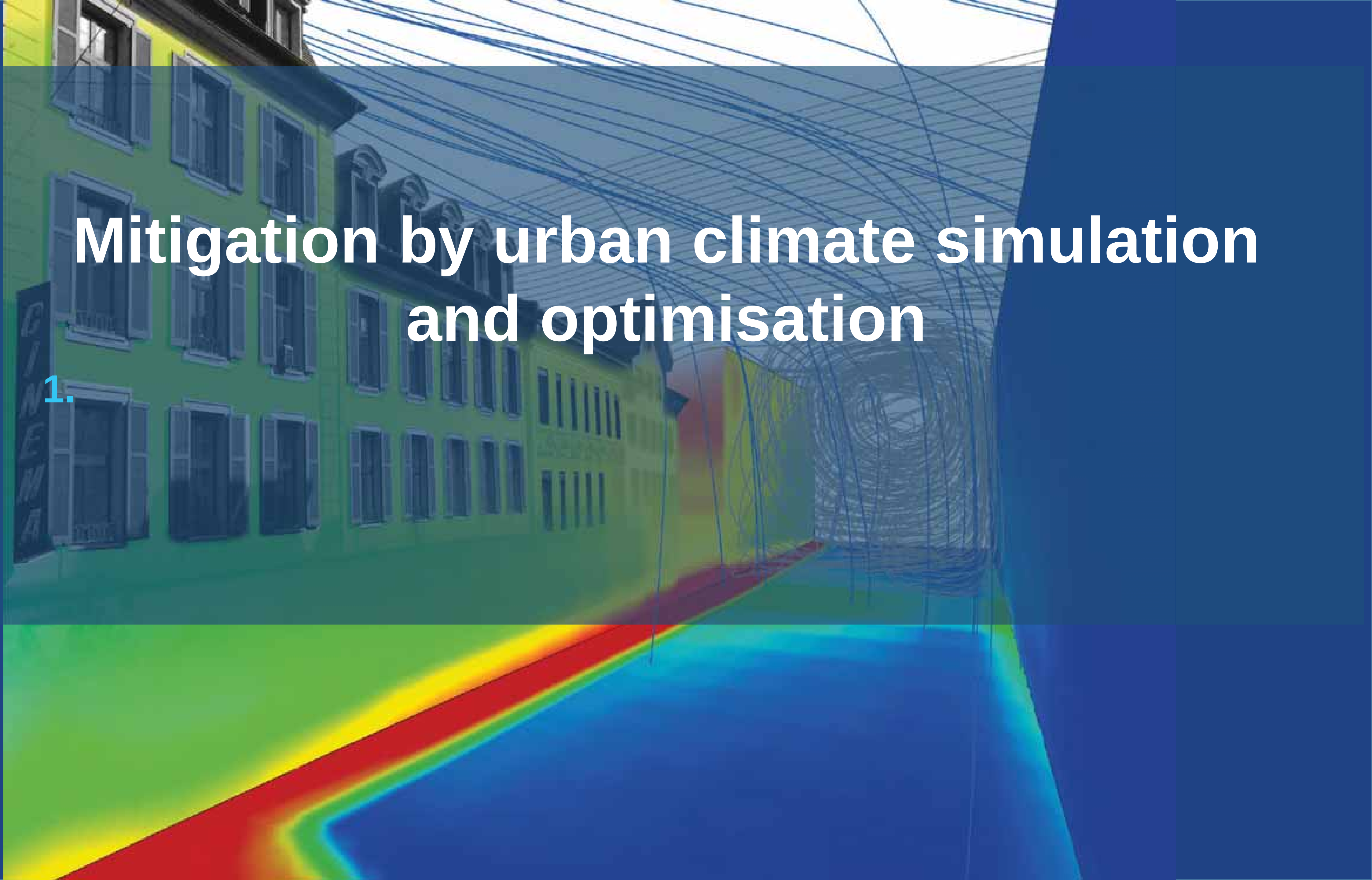
Heatwave adaptation



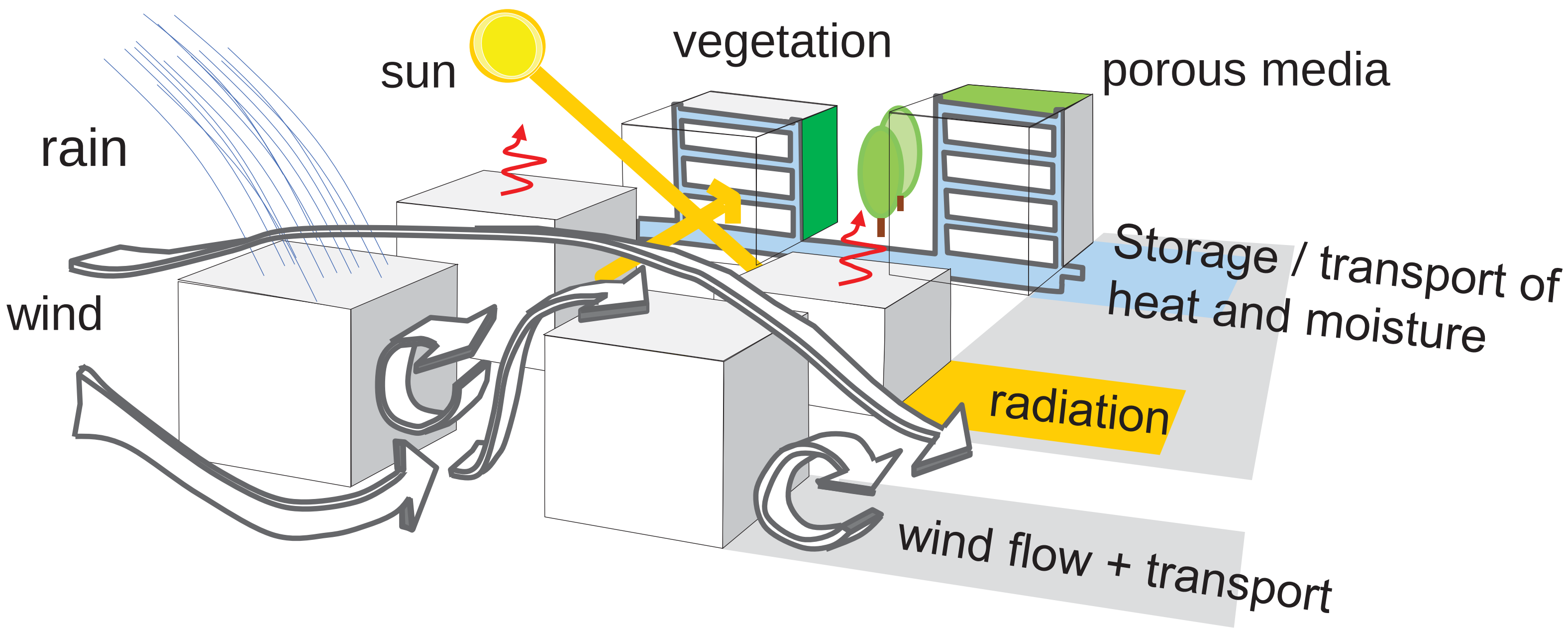
Heatwave adaptation

Mitigation by urban climate simulation and optimisation

1.

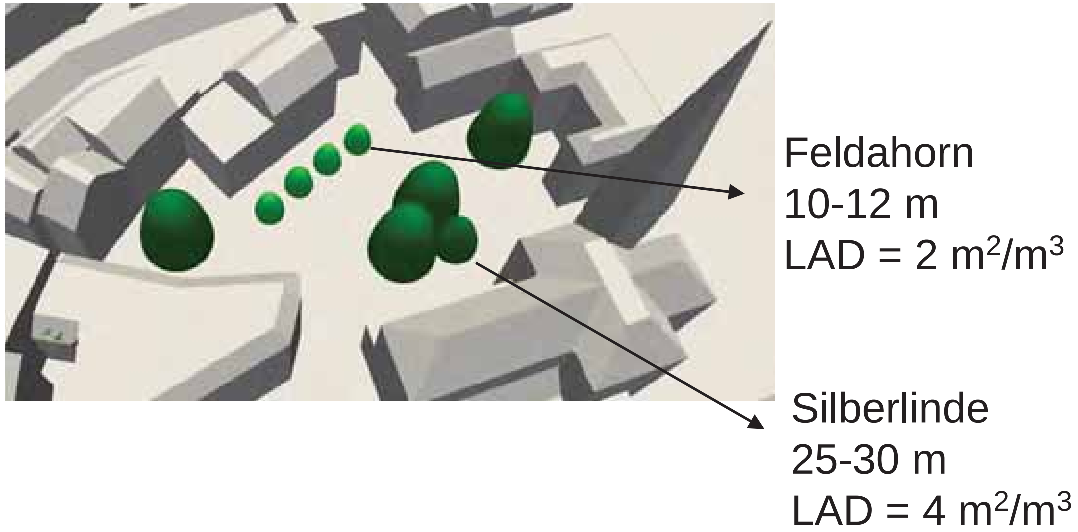


Modelling of coupled physical processes in the urban environment



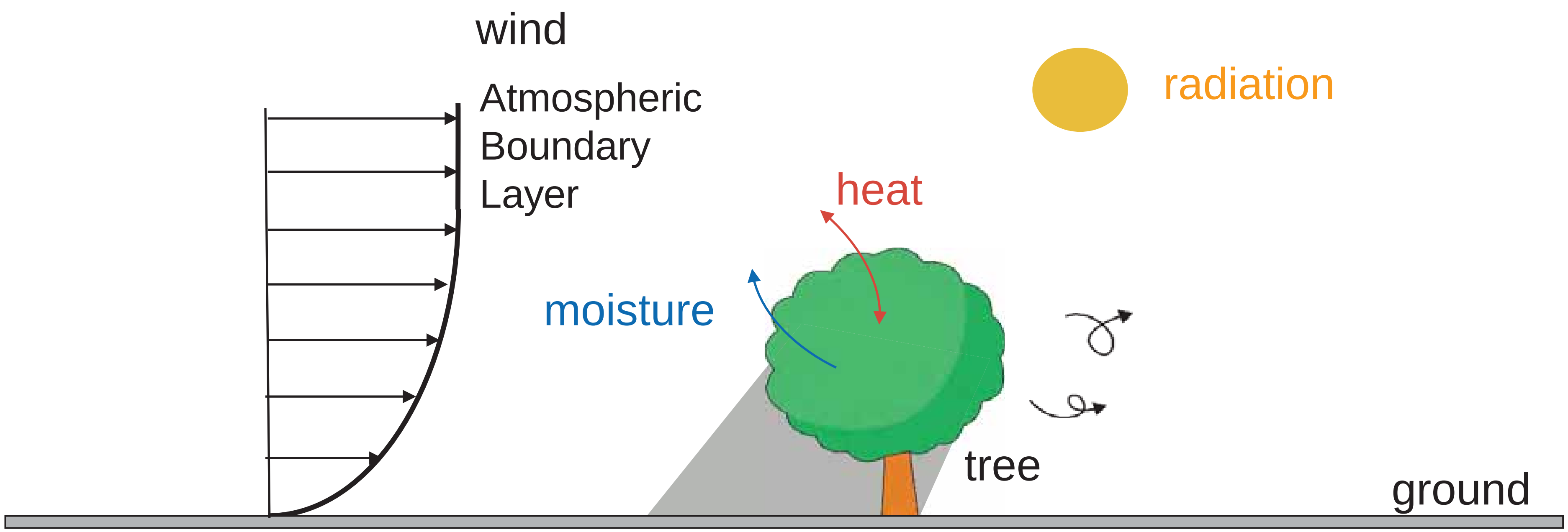
- **CFD-RANS**: Building-resolved turbulent air flow due to wind and buoyancy
- **Radiation**: short- and long-wave radiation using view factor approach
- **HAM**: Heat And Moisture storage and transport in porous materials (building materials, pavements, soils, …) including phase change: evaporative cooling
- **Vegetation models**: trees, grass, ….
- **Wind driven rain**: Eulerian multiphase mode

Multiscale modeling of vegetation including transpiration



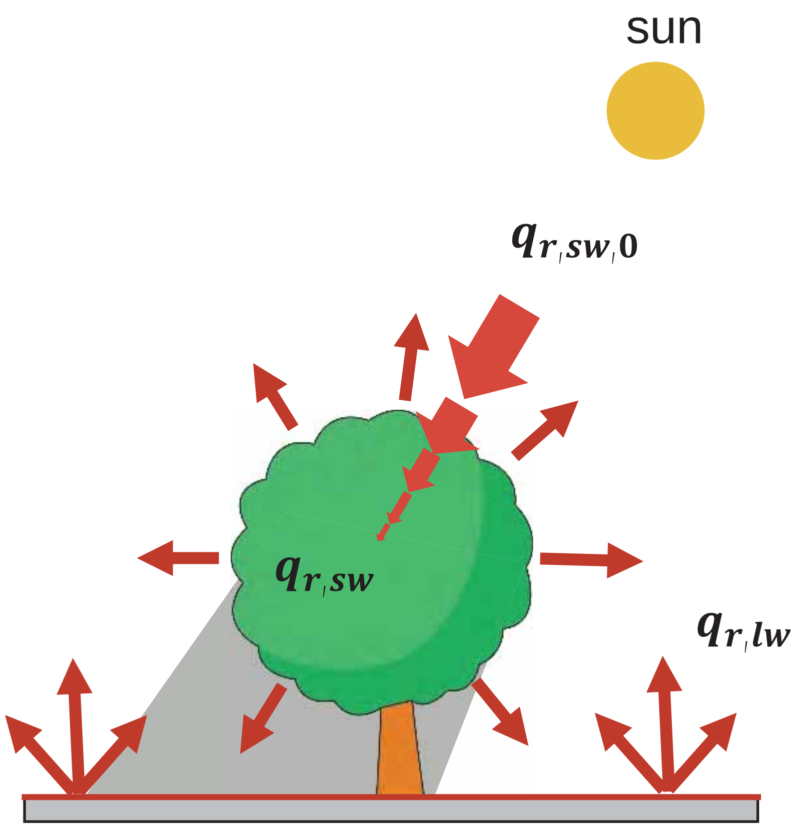
Kubilay et al., 2020

Multiscale modeling of vegetation including transpiration



Vegetation modelled as **multiscale porous medium** with **sink and source** terms for **momentum**, **heat** and **moisture**

Multiscale modeling of vegetation: radiation exchange by leafs



Radiation absorbed by leafs

Short-wave radiative flux $q_{r,sw}$

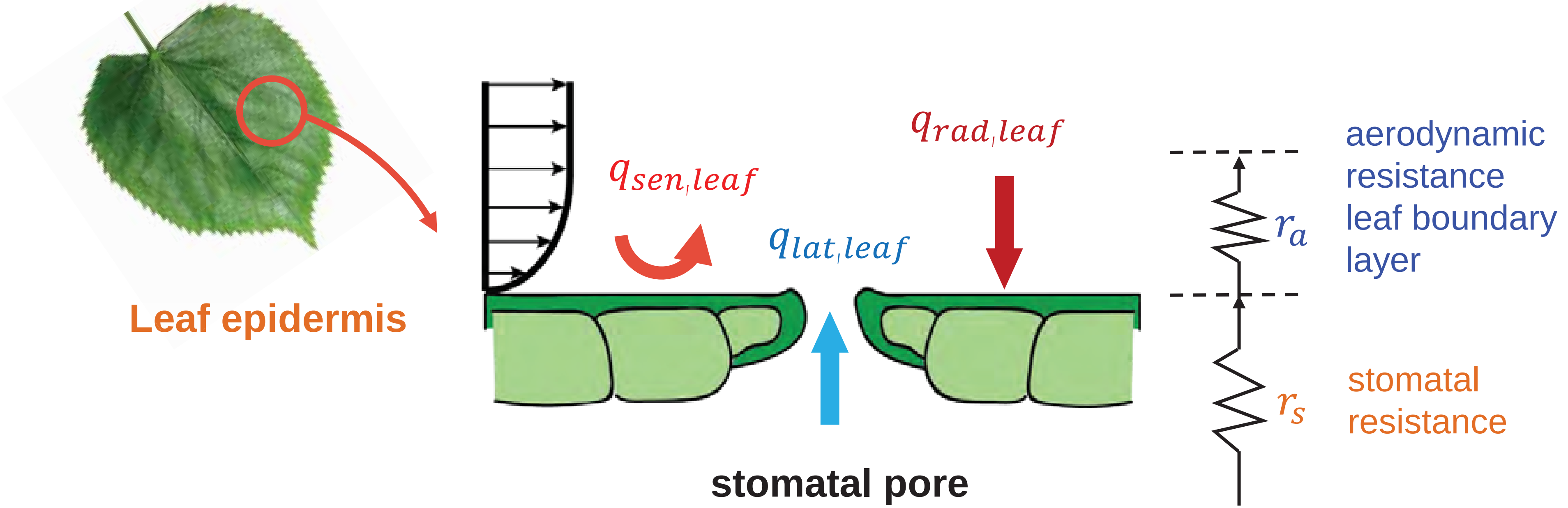
- Ray-tracing
- **Beer-Lambert law**

$$q_{r,sw}(z) = q_{r,sw,0} \exp\left\{-\beta \int_0^z LAI(z)\, dz\right\}$$

Long-wave radiative flux $q_{r,lw}$

- Ray-tracing
- **View-factor model**

Multiscale modeling of vegetation: leaf model



$$q_{sen,leaf} = h_{c,h}(r_a)\cdot\left(T_{leaf} - T_e\right)$$

convective heat transfer coefficient

$$q_{lat,leaf} = L_v h_{c,m}(r_a, r_s)\left(p_{v,leaf} - p_{v,e}\right)$$

latent heat of vaporization

convective moisture transfer coefficient

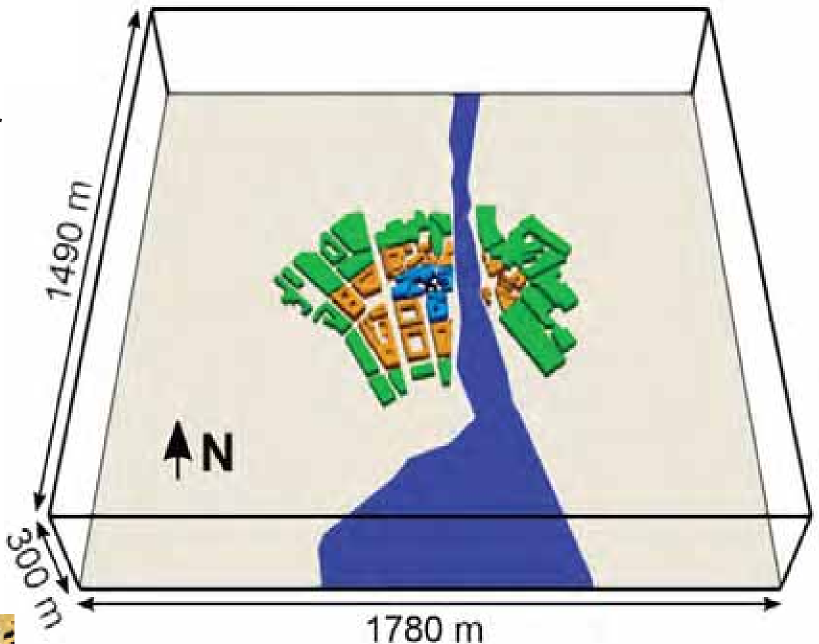
Vapour Pressure difference

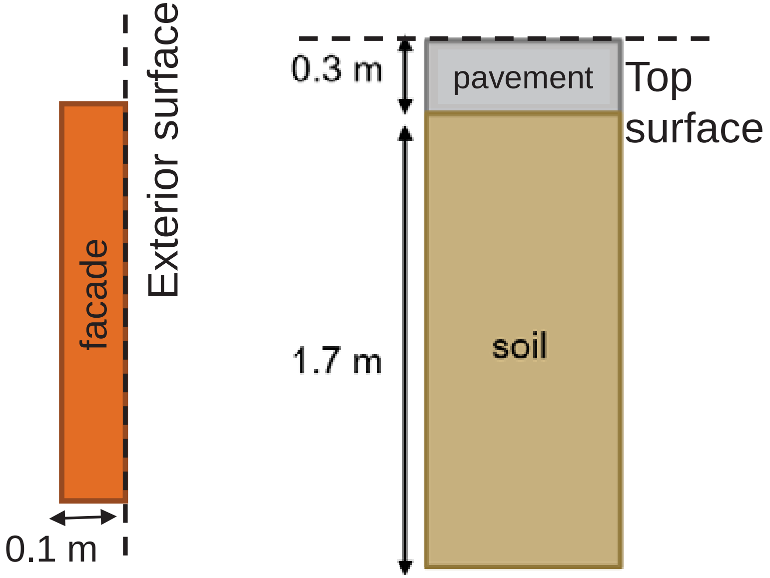
Heatwave mitigation: case study Münsterhof, Zürich

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

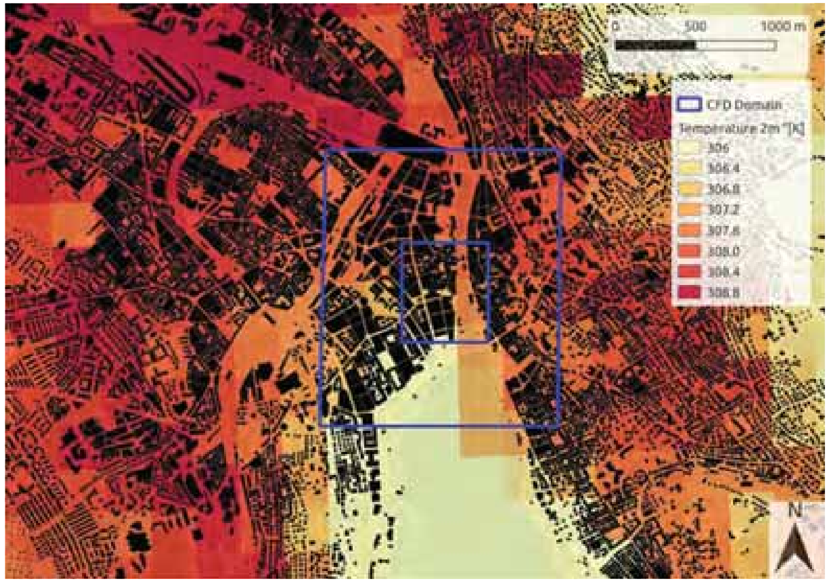
Münsterhof – coupled subdomains

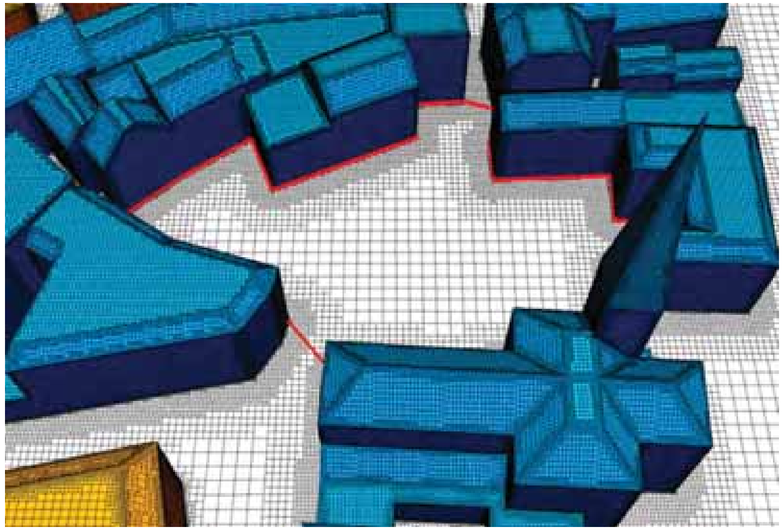
Domain for air flow
- Steady Reynolds-averaged Navier Stokes (RANS)



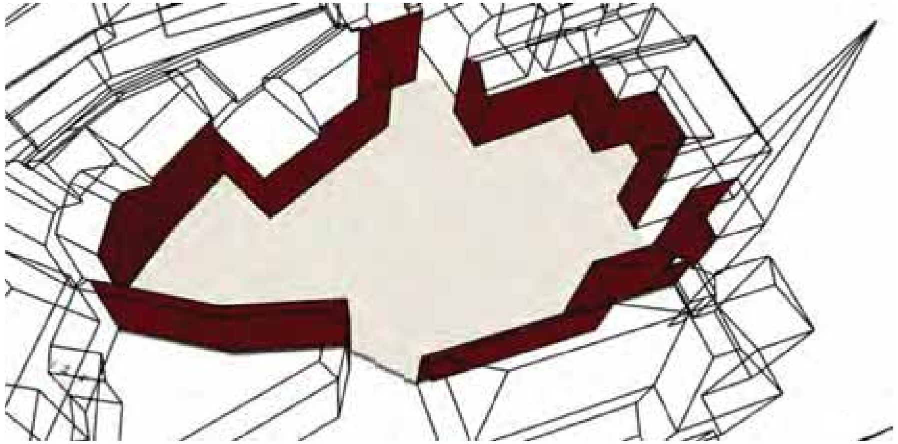


Mesoscale model
- COSMO + DCEP
- Air temperature at 2 m height





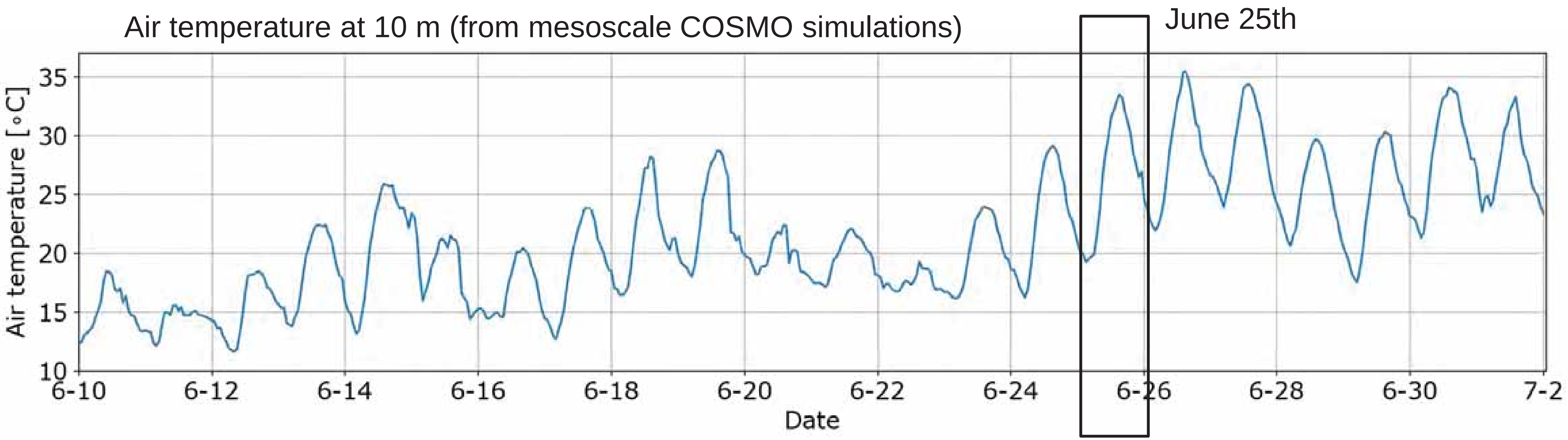
Domain for porous urban materials
- Unsteady Heat & Moisture transport



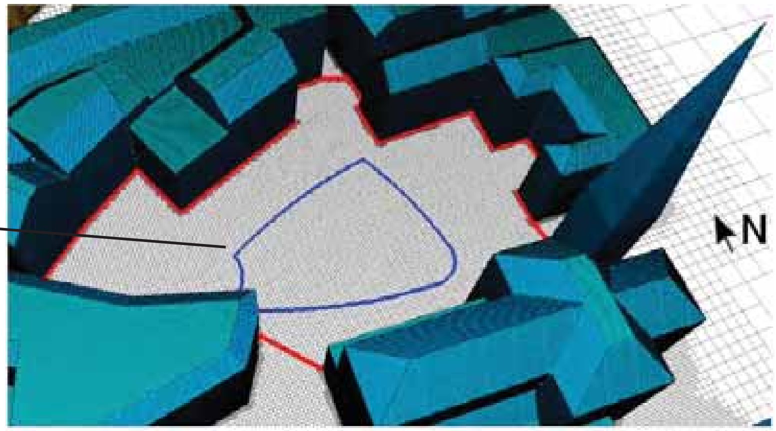
Kubilay et al., 2020

Meteorological conditions – heat wave 2019 June

Air temperature at 10 m (from mesoscale COSMO simulations)



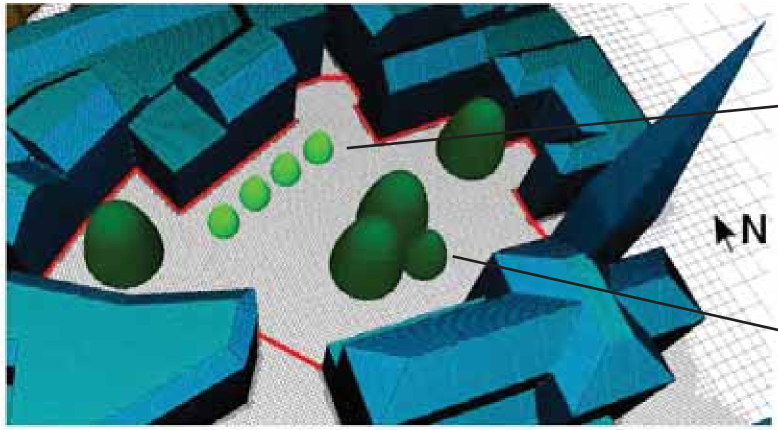
Artificial wetting



2-layer porous pavement

6 mm between 08:00-08:20

Trees



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

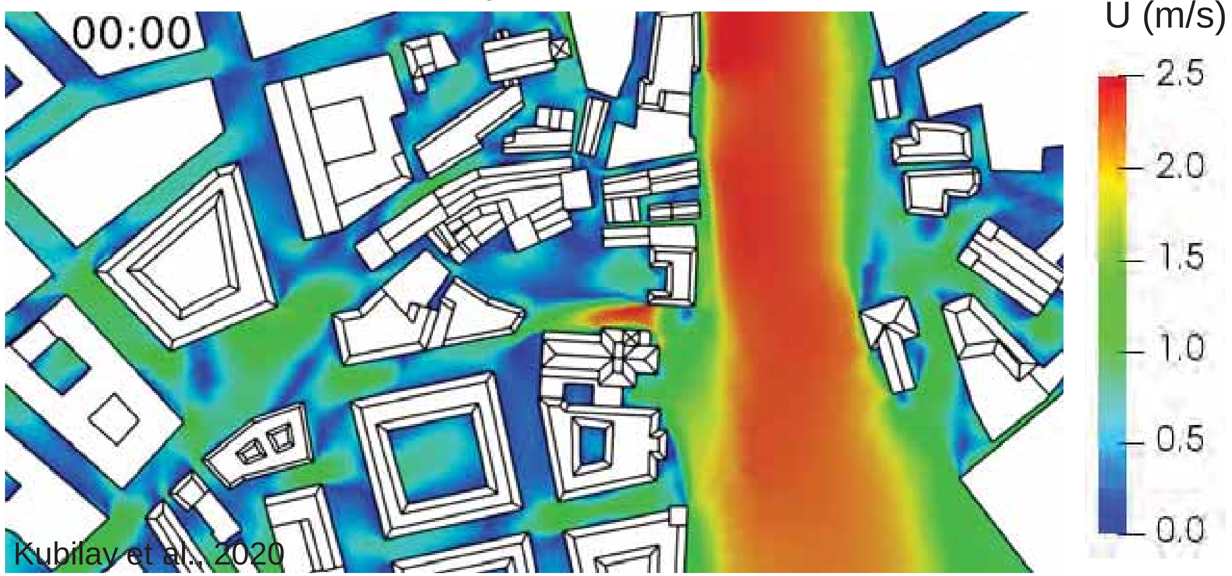
Silver linden
25-30 m
LAD = 4 m^2/m^3

Kubilay et al., 2020

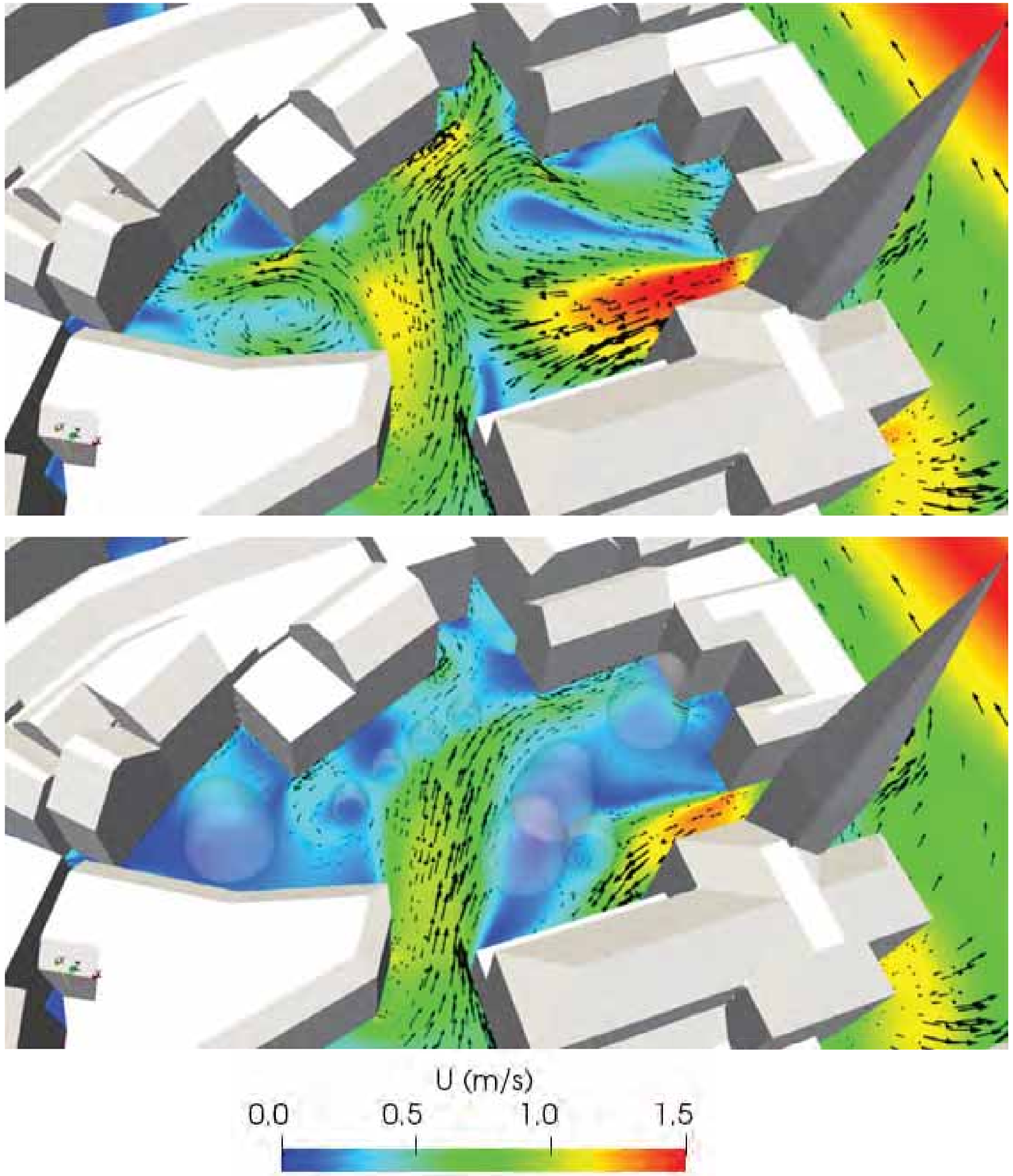
Pedestrian level conditions

Air temperature at 2 m

Wind speed at 2 m



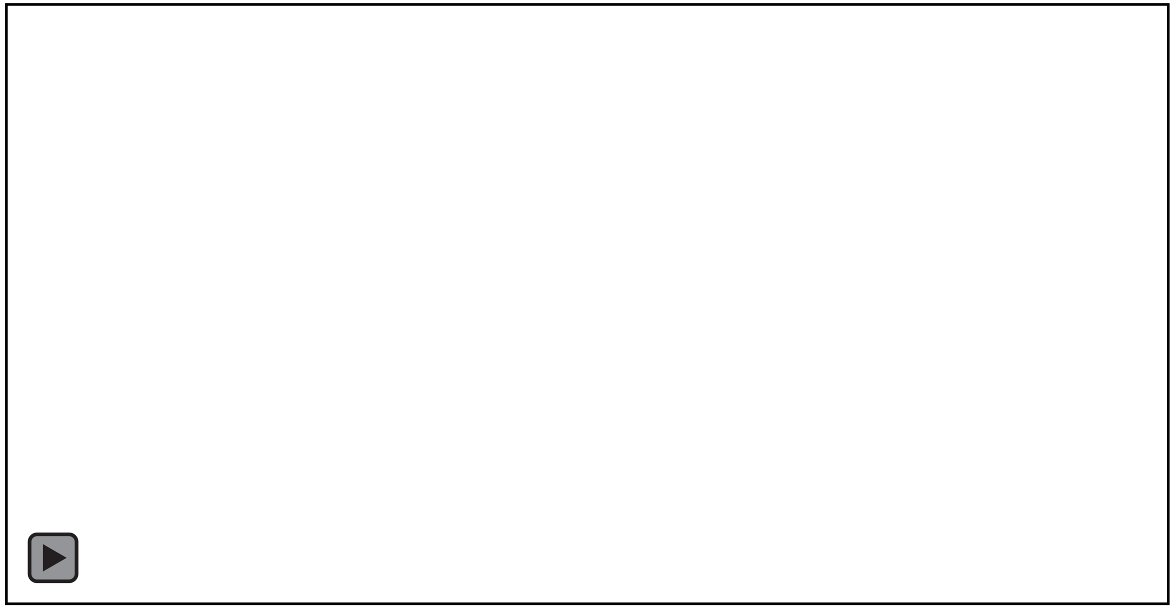
wind from south



Surface temperatures

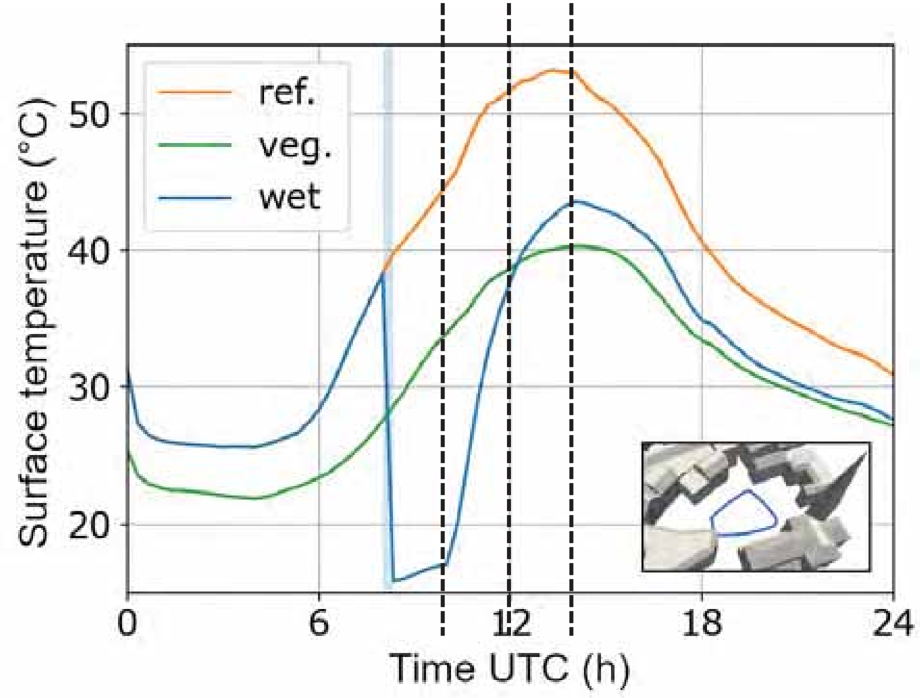
Surface temperature – ref.

Surface temperature – veg.

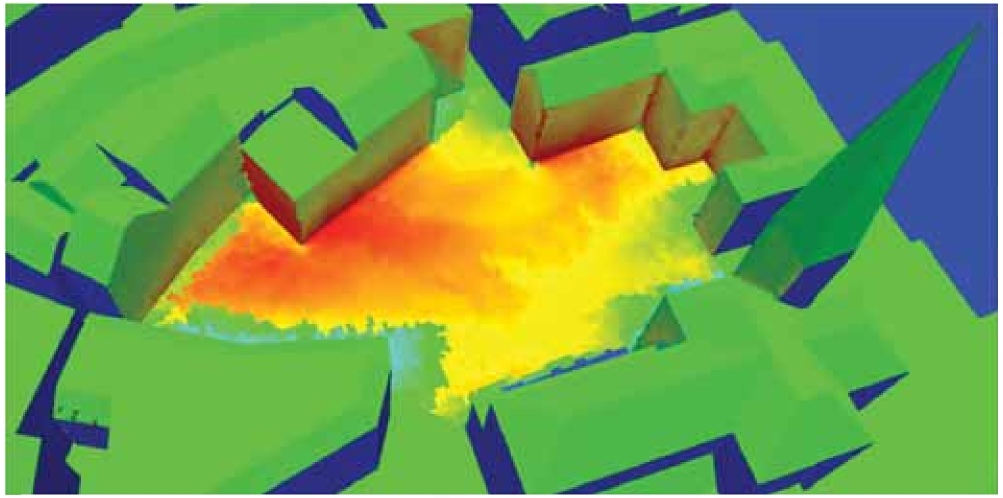


Kubilay et al., 2020

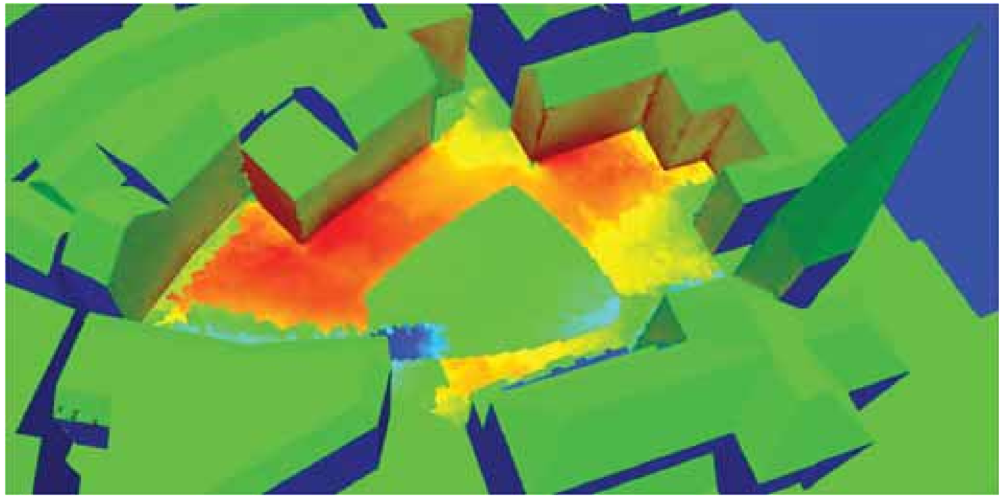
Comparison of pavement surface temperature



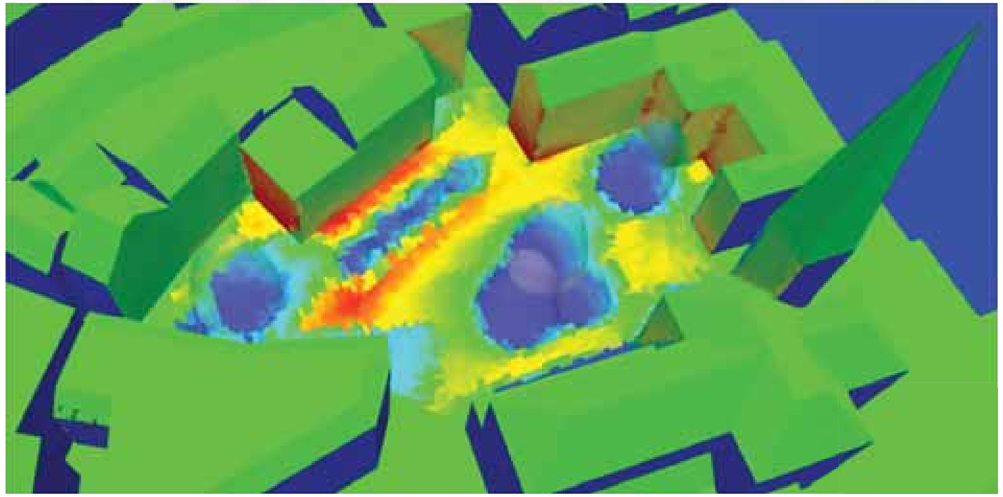
Ref.



Wet



Veg.



Kubilay et al., 2020

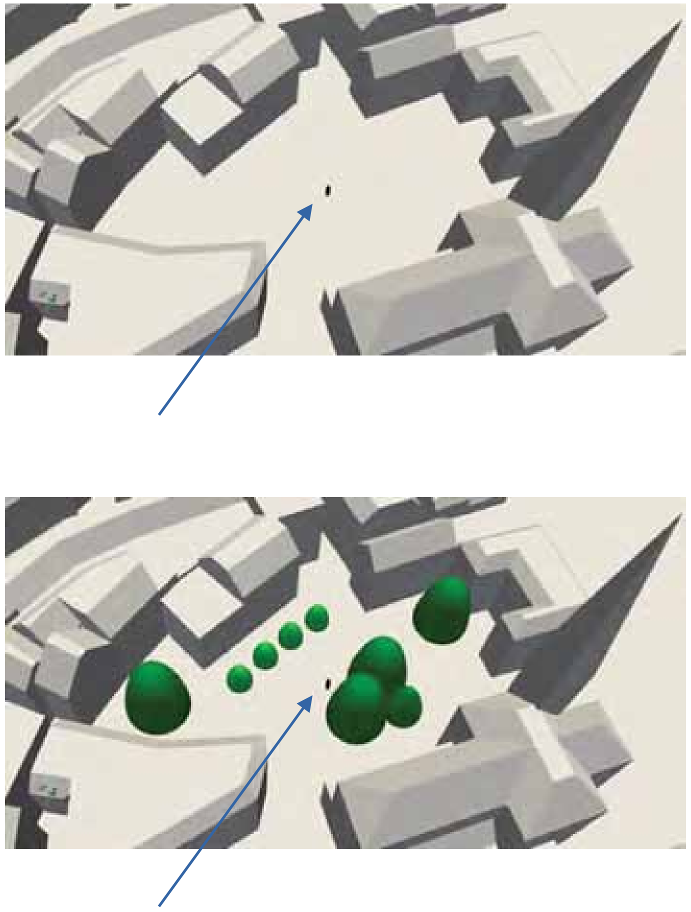
Reduction in air temperature

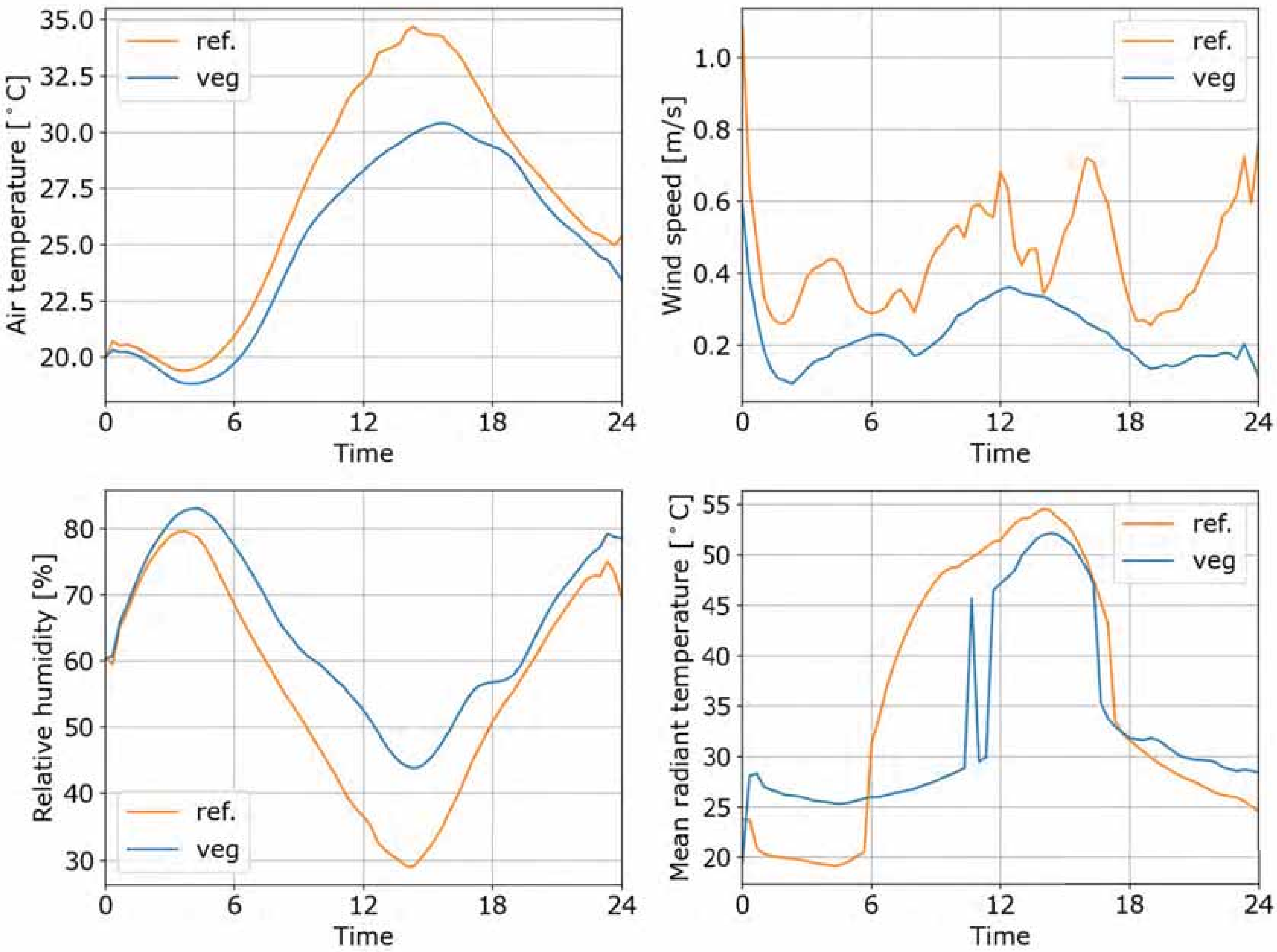
Reduction in air temperature > 2 °C
12:00 UTC

Veg. Wet

Kubilay et al., 2020

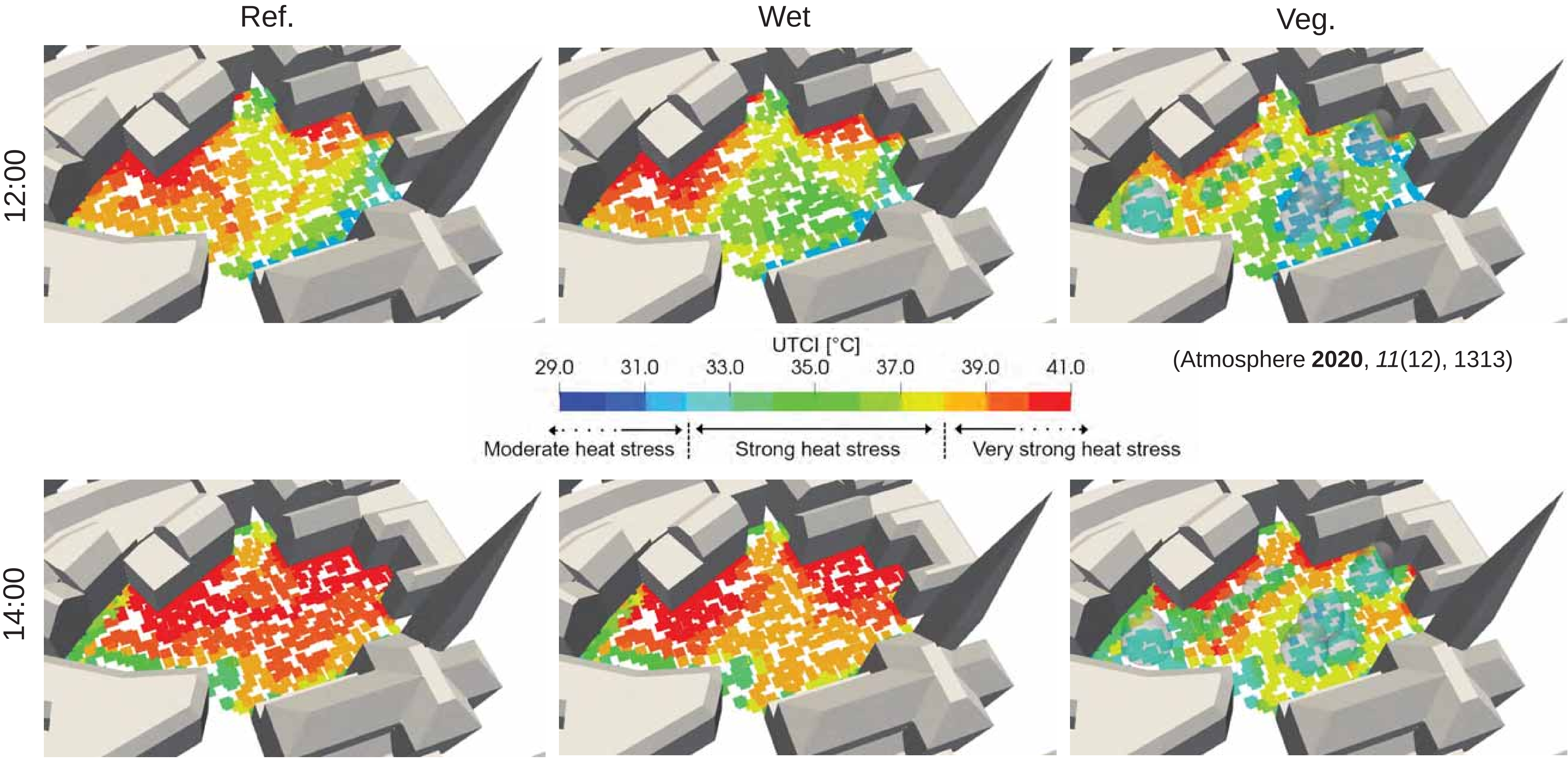
Thermal comfort influencing factors – local temporal





Kubilay et al., 2020

Thermal comfort – Universal thermal climate index (UTCI)

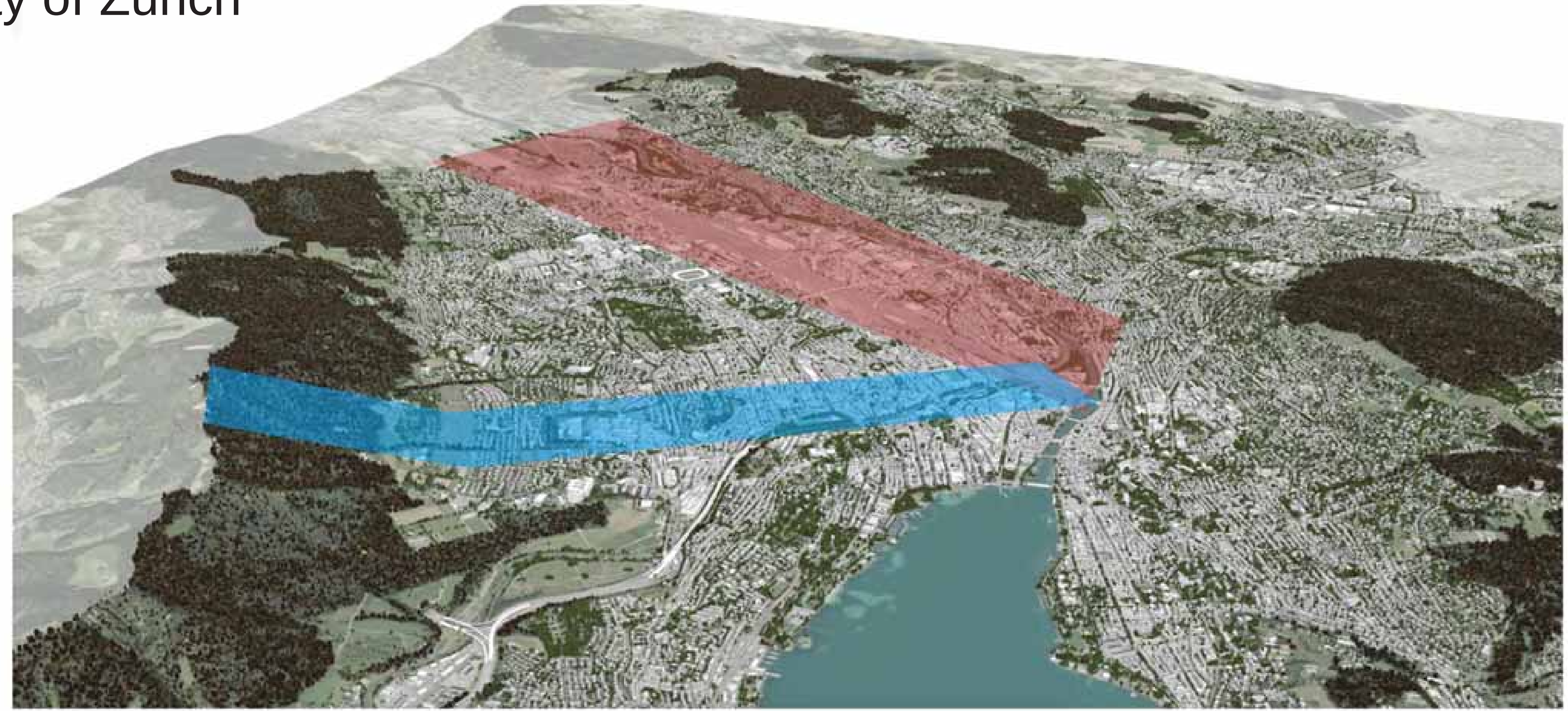


(Atmosphere **2020**, *11*(12), 1313)

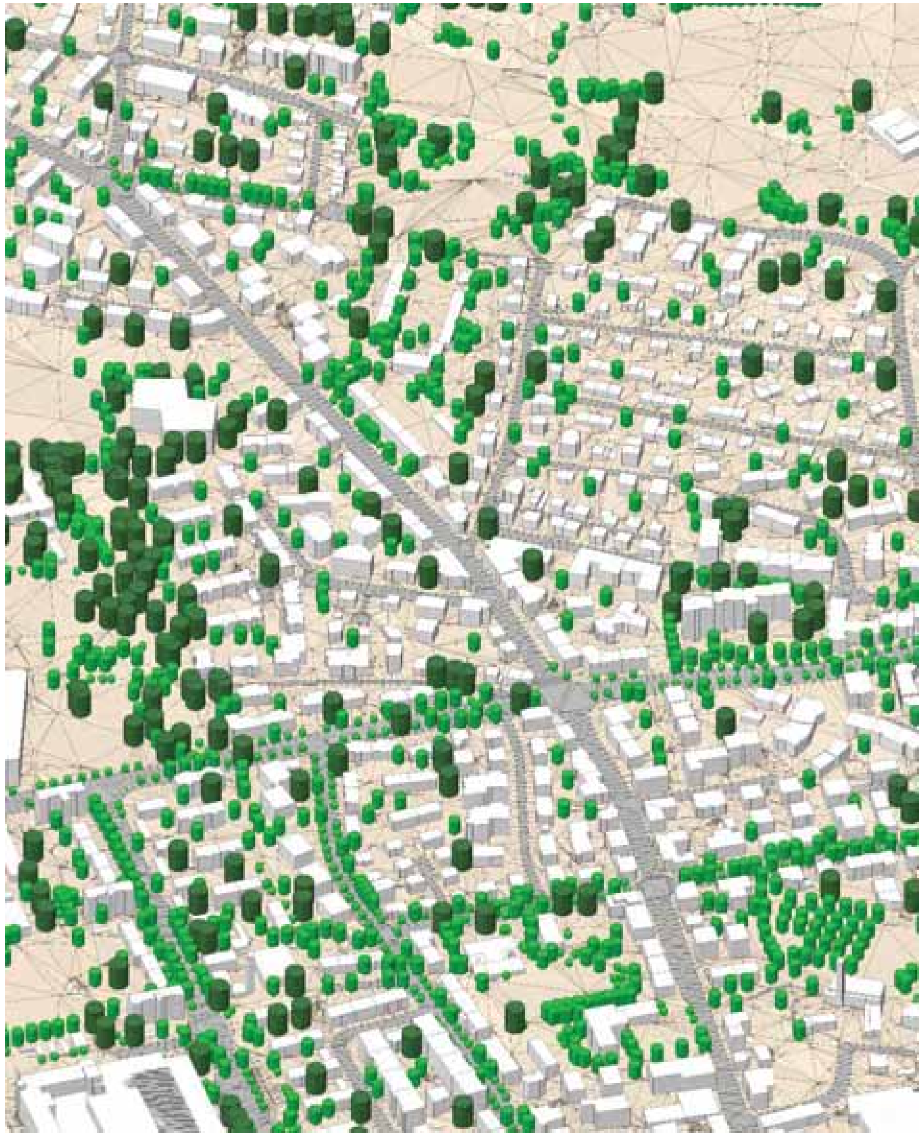
Kubilay et al., 2020

Green mitigation measures, densification, night cooling potential by cold winds from vegetated hills

City of Zurich



Different scenarios for densification, greening and ventilation



current situation

Different scenarios for densification, greening and ventilation

Densified

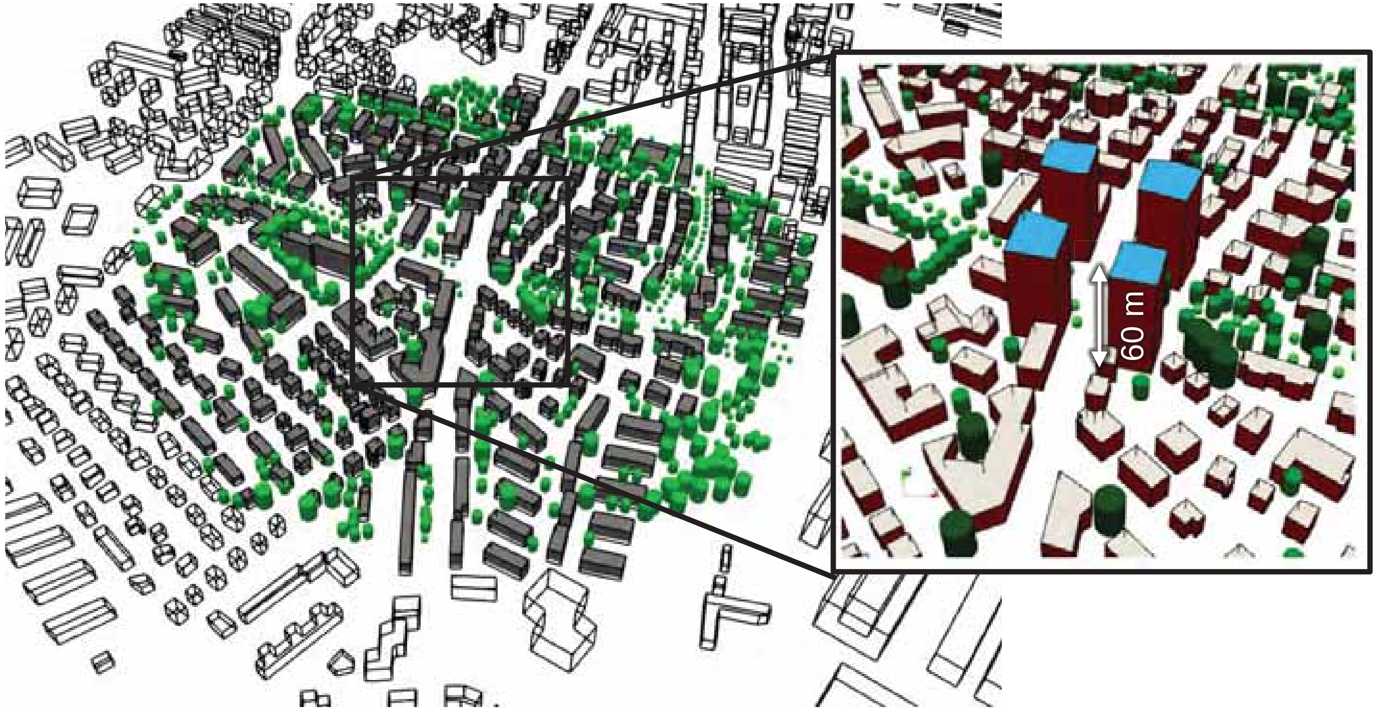
Densified with gaps between buildings

Different scenarios for densification, greening and ventilation

Densified + trees

Densified with gaps + trees

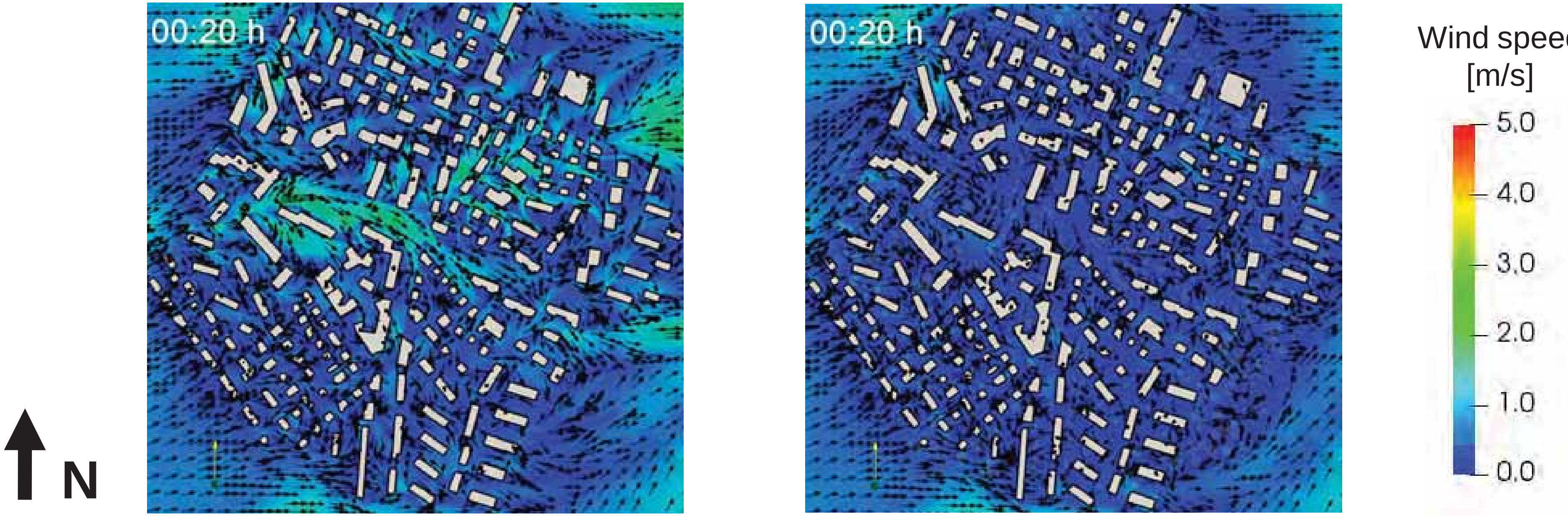
Study of thermal comfort around Rauti-square, Zurich



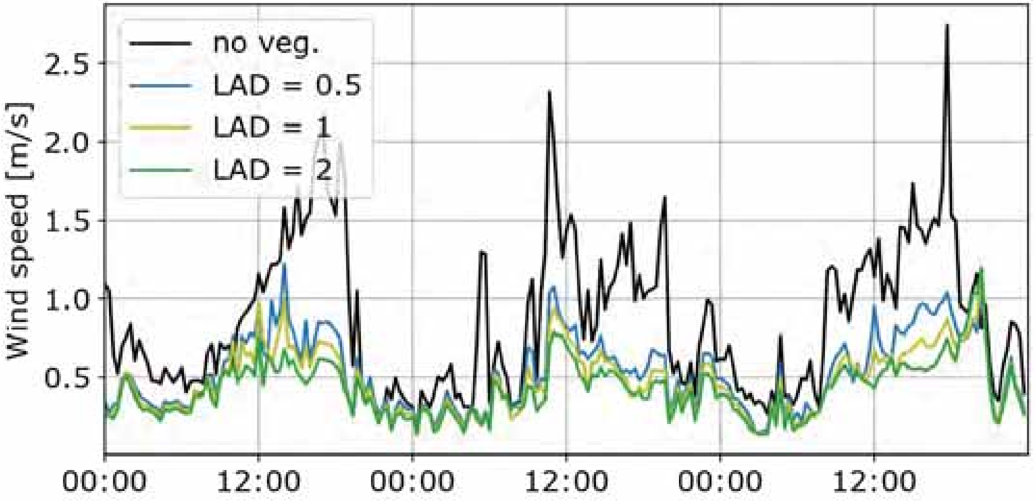
Street level conditions – wind speed

Velocity magnitude at 2 m height

without vegetation | trees LAD = 2 m^2/m^3

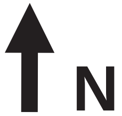


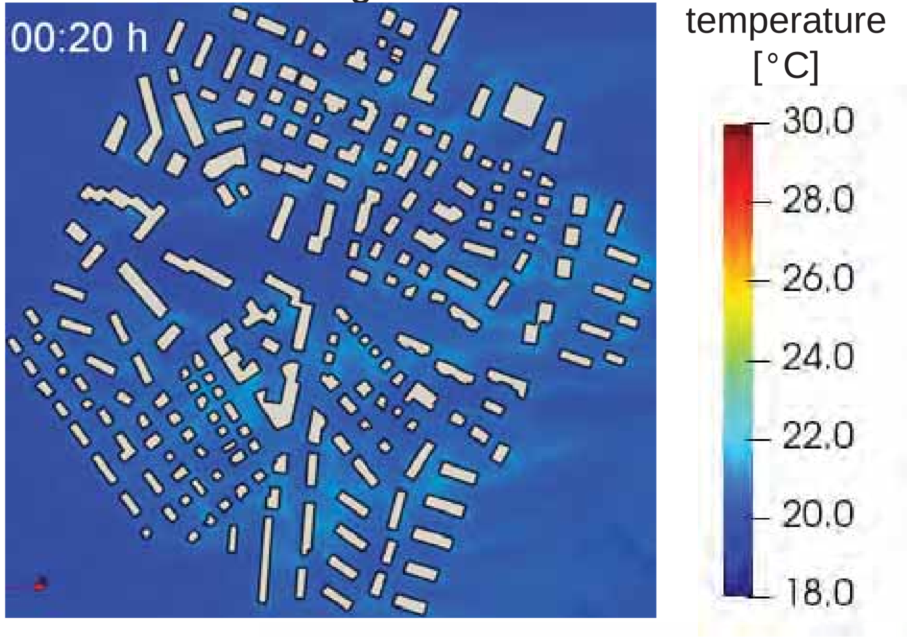
Average conditions at Rautiplatz (street level)



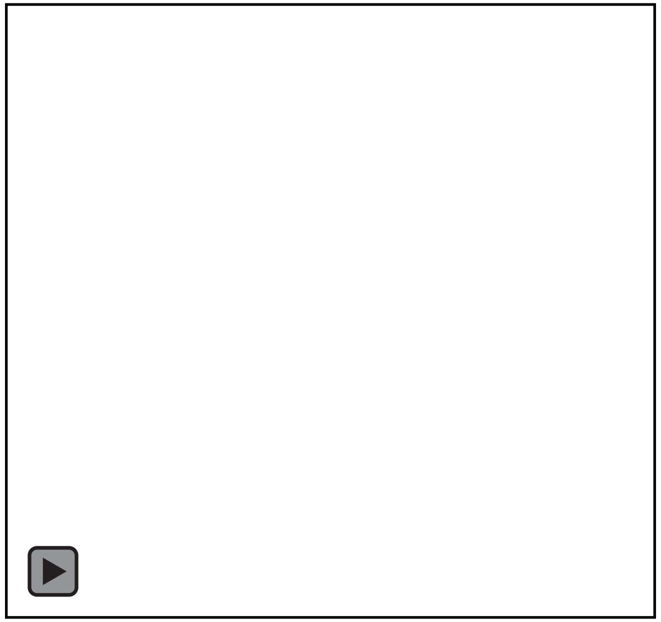
Street level conditions – air temperature

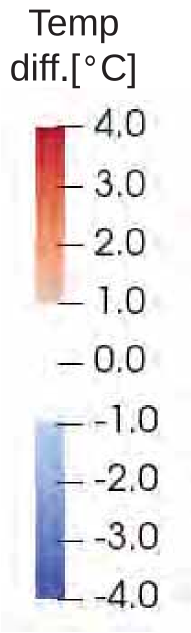
Air temperature at 2 m height without vegetation



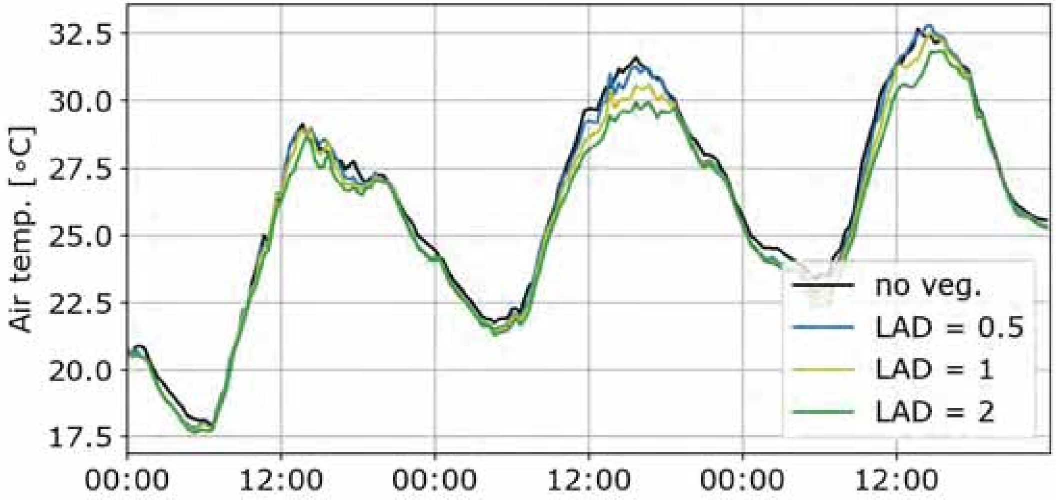


trees LAD = 2 m²/m³

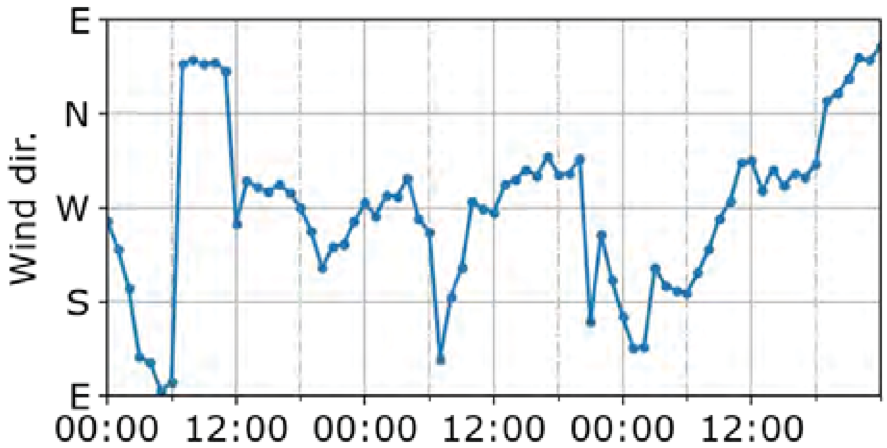


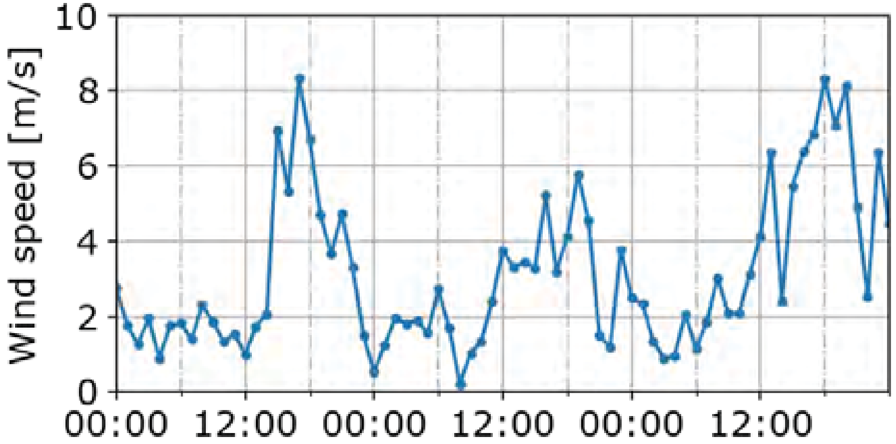


Average conditions at Rautiplatz (street level)

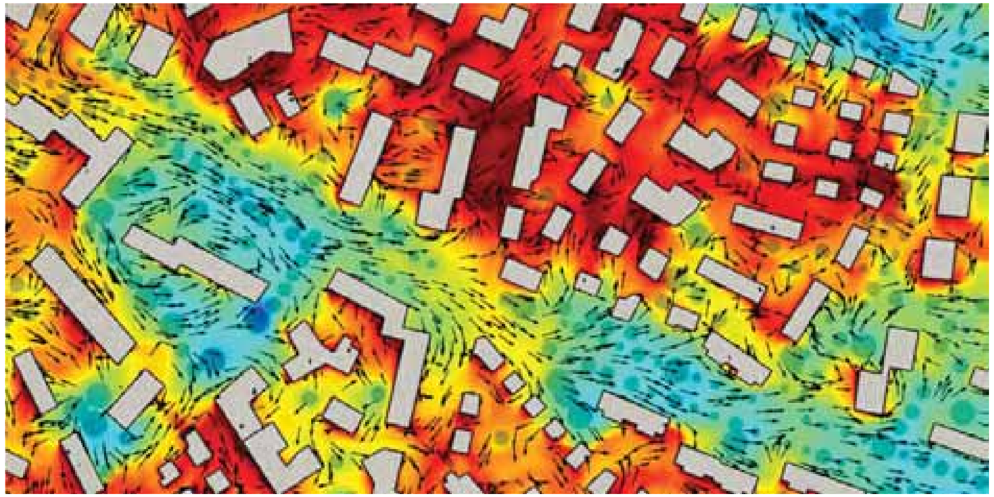


Conditions can change locally with wind direction





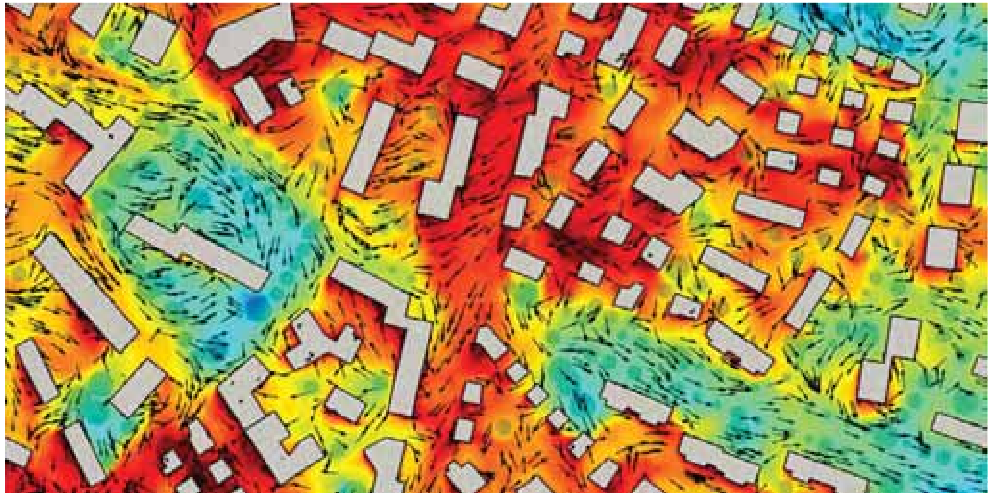
Wind



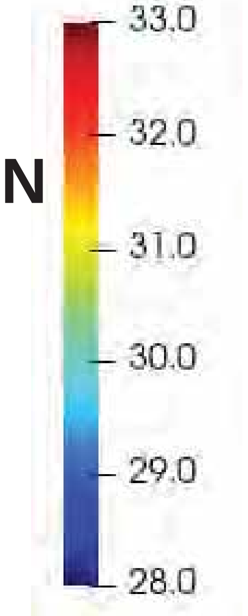
N

Main flow direction changes

Wind



Air temp. [°C]

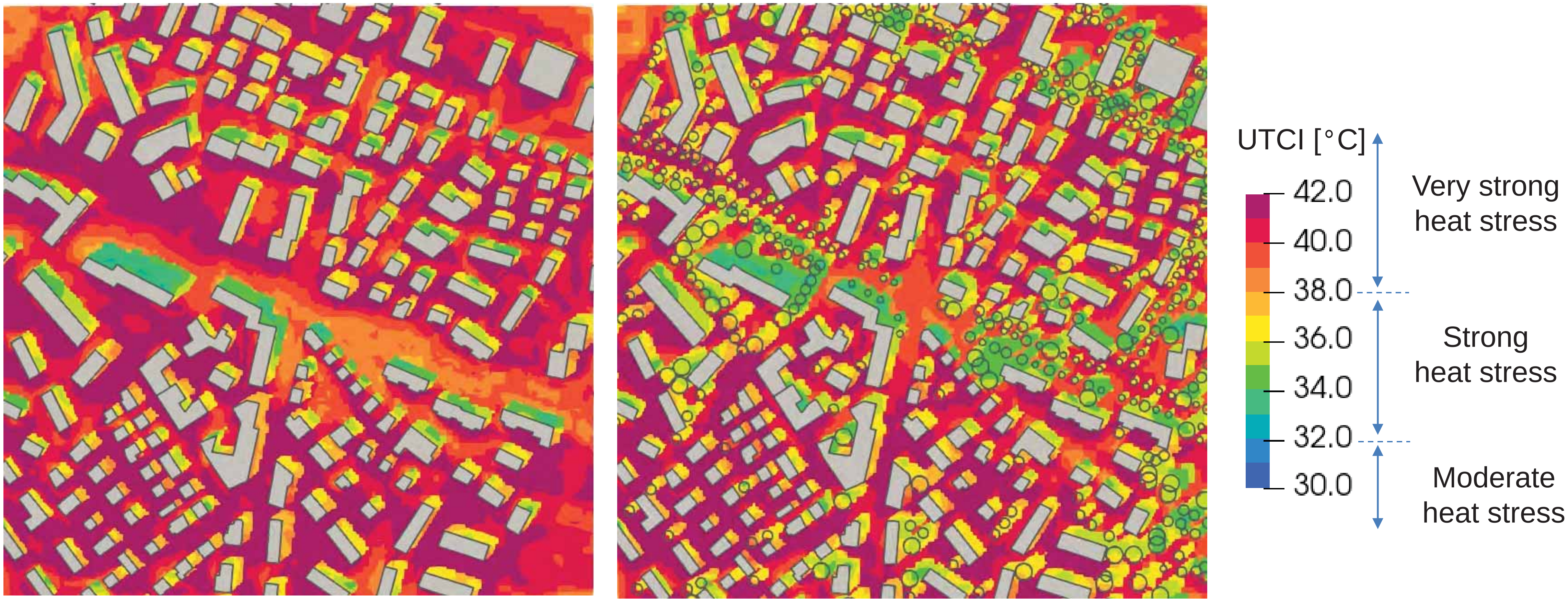


Impact on pedestrian thermal comfort

without trees

with trees LAD = 1 m²/m³

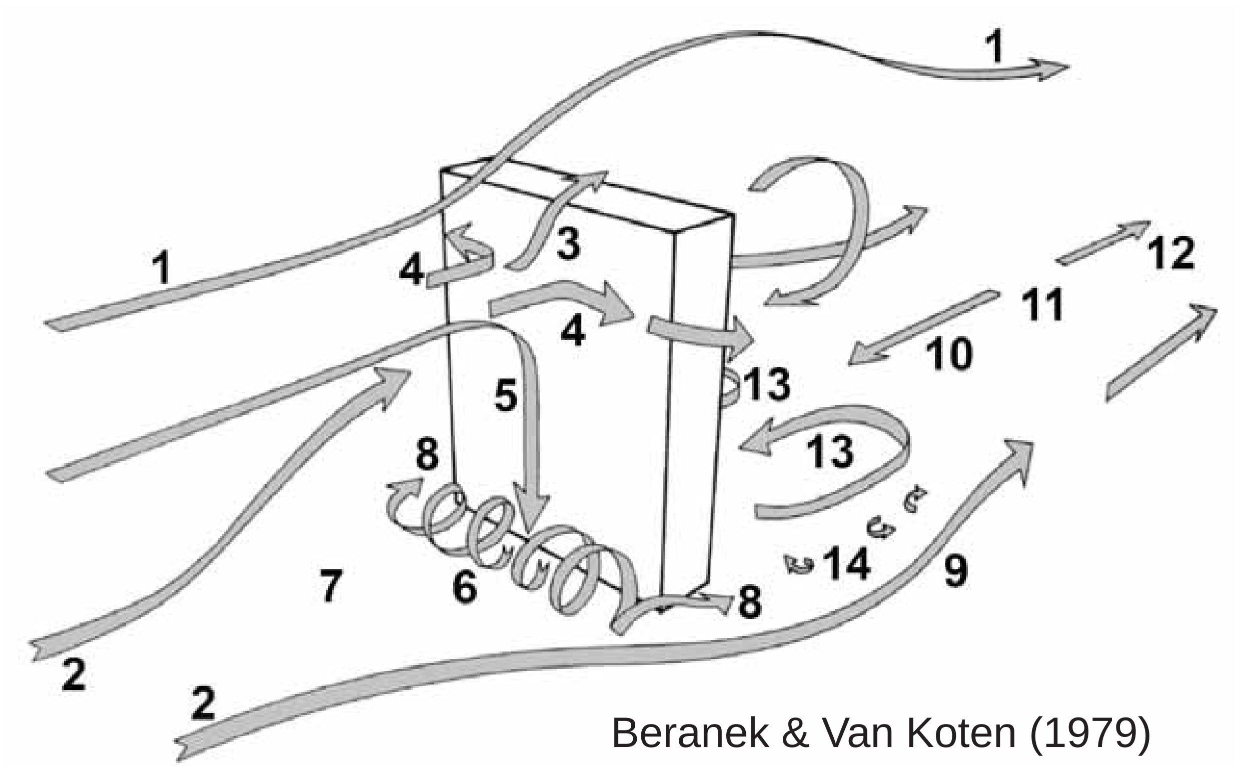
Day 3
UTC 13:40



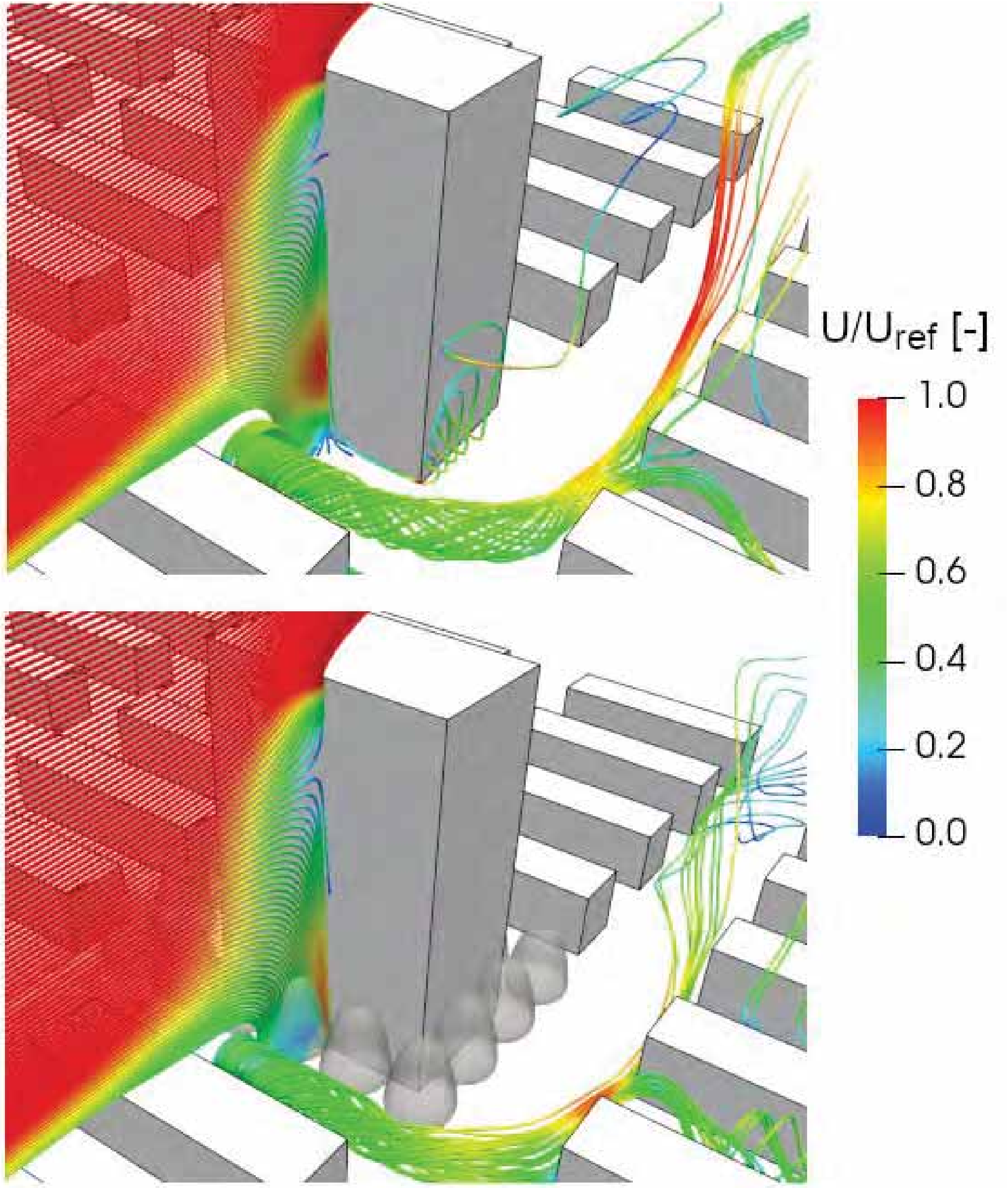
Avg. air temp.: 36.8 °C

Avg. air temp.: 36.3 °C

Wind flow around high-rise buildings

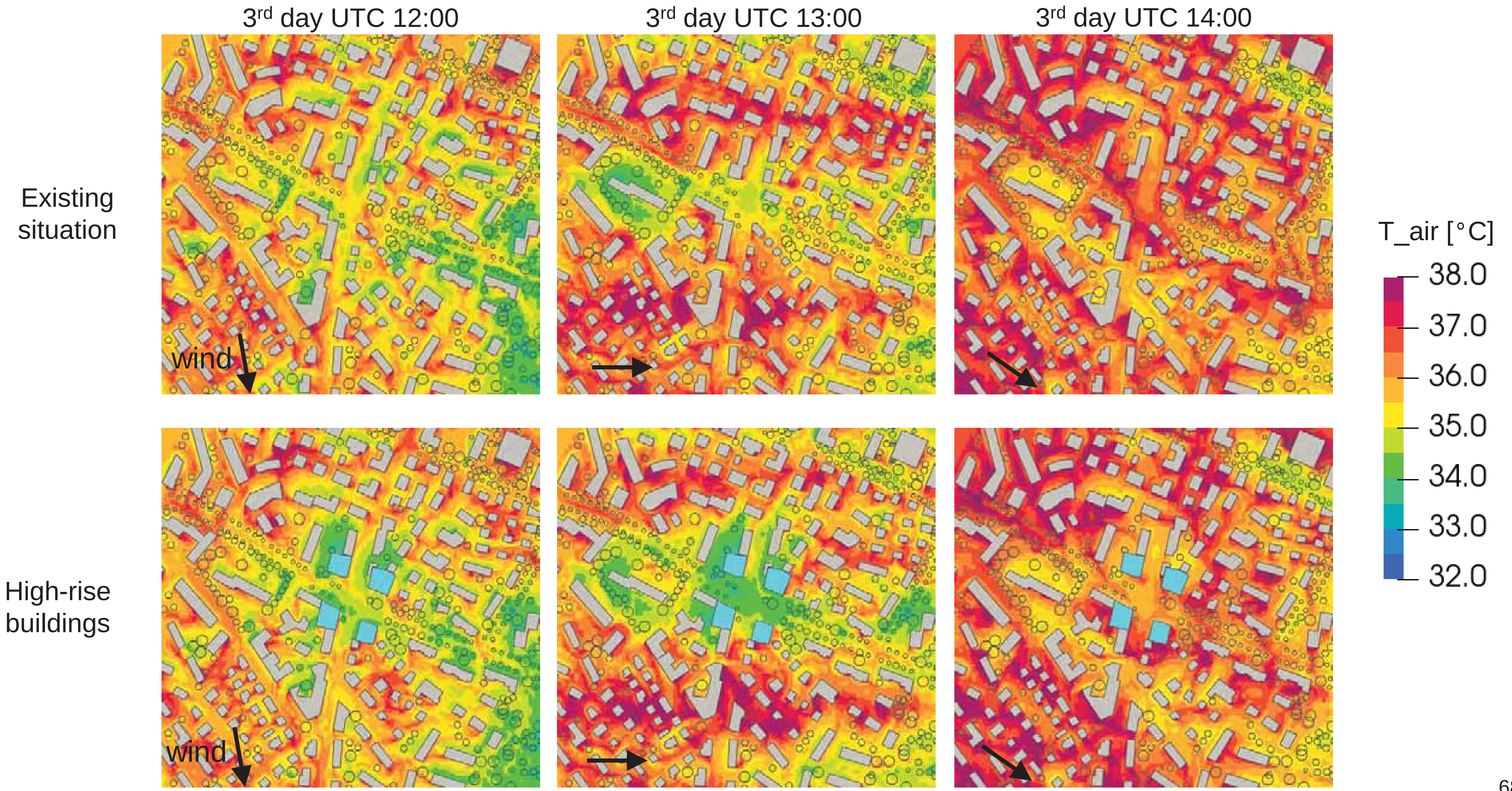


Beranek & Van Koten (1979)



Kubilay et al. (*submitted for publication*, JWEIA)

Comparison of air temperature (with trees)

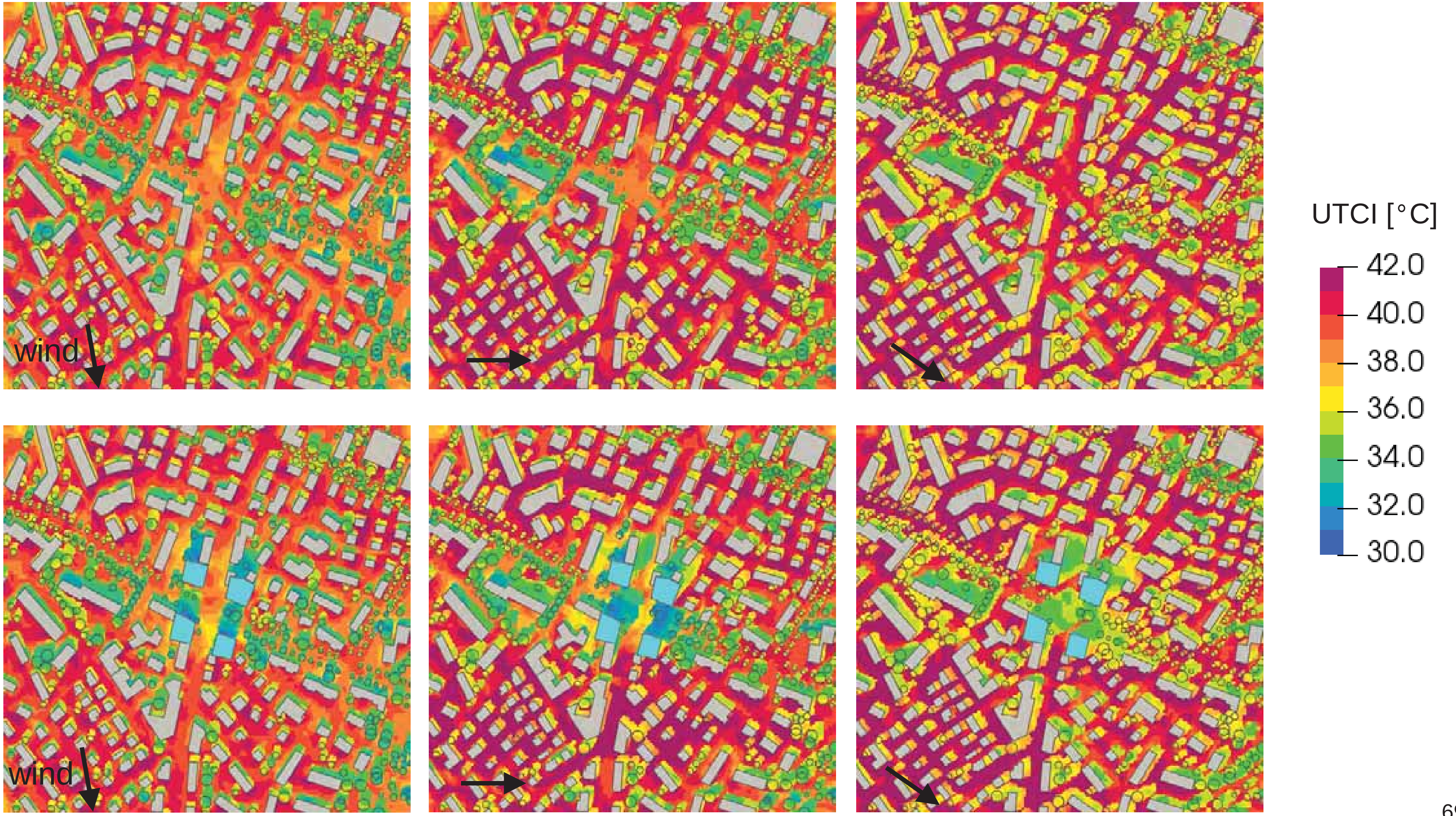


Comparison of UTCI (with trees)

3rd day UTC 12:00 | 3rd day UTC 13:00 | 3rd day UTC 14:00

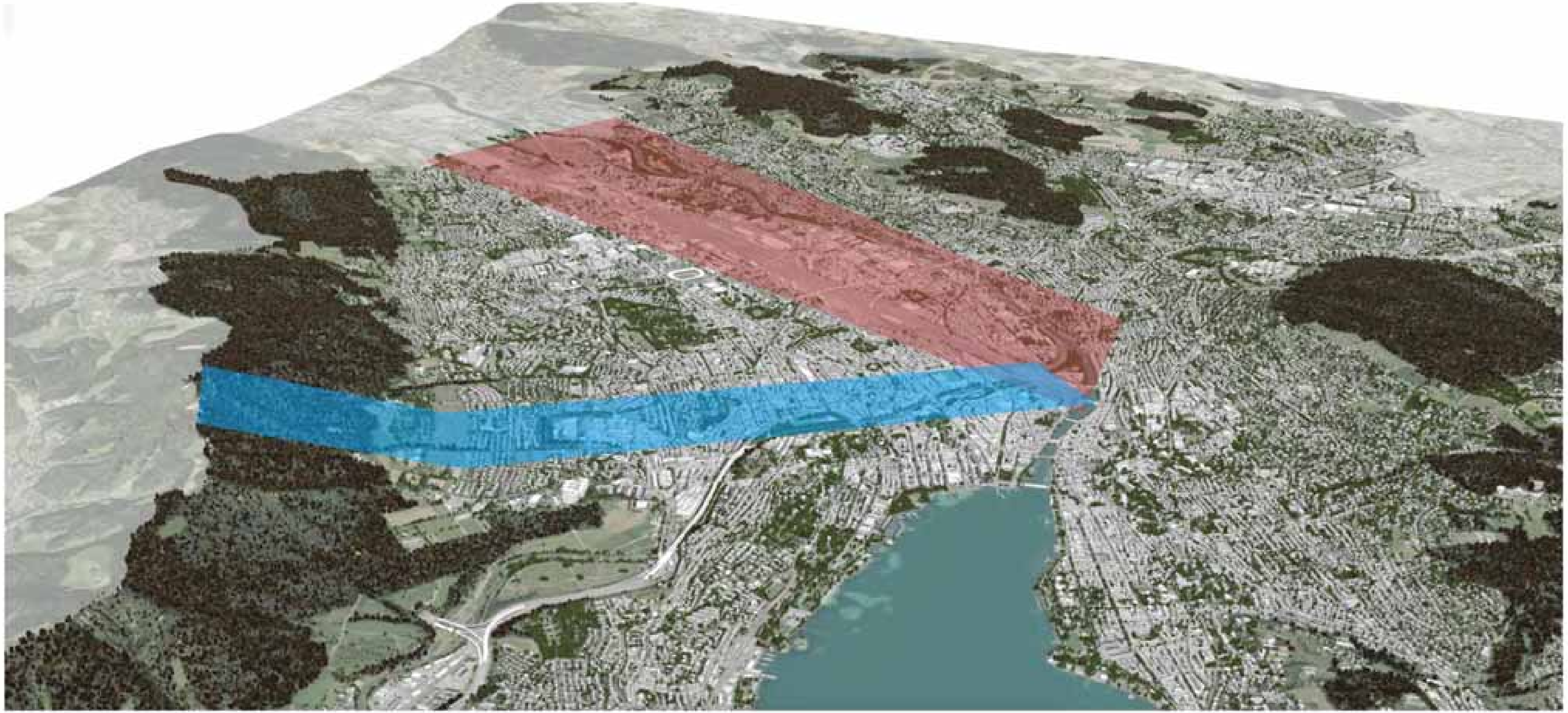
Existing situation

High-rise buildings



Night cooling potential by cold winds from vegetated hills

City of Zurich

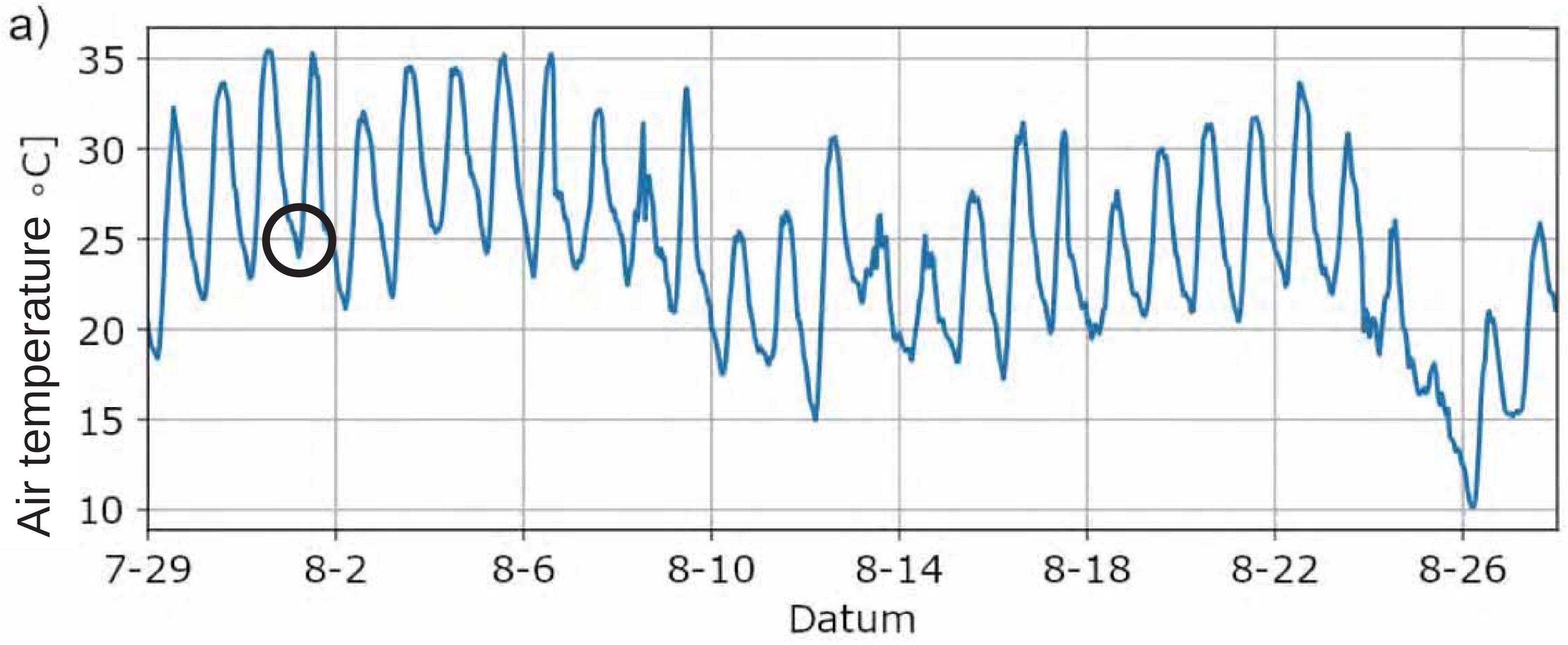


Study of night cooling potential

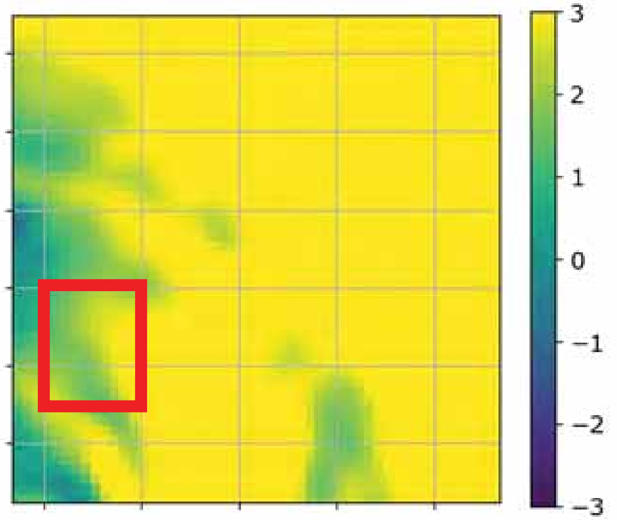
Heatwave summer 2018

Highest night temperatures during heat wave

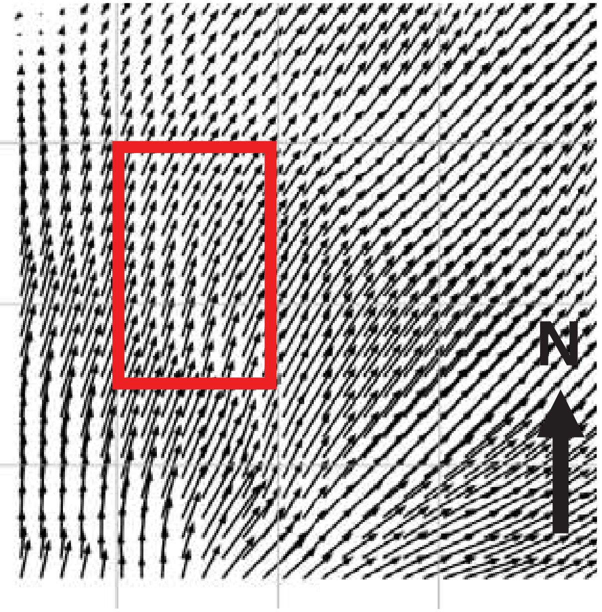
Wind south-southwest, hill wind speed 3m/s



Ux [m/s]



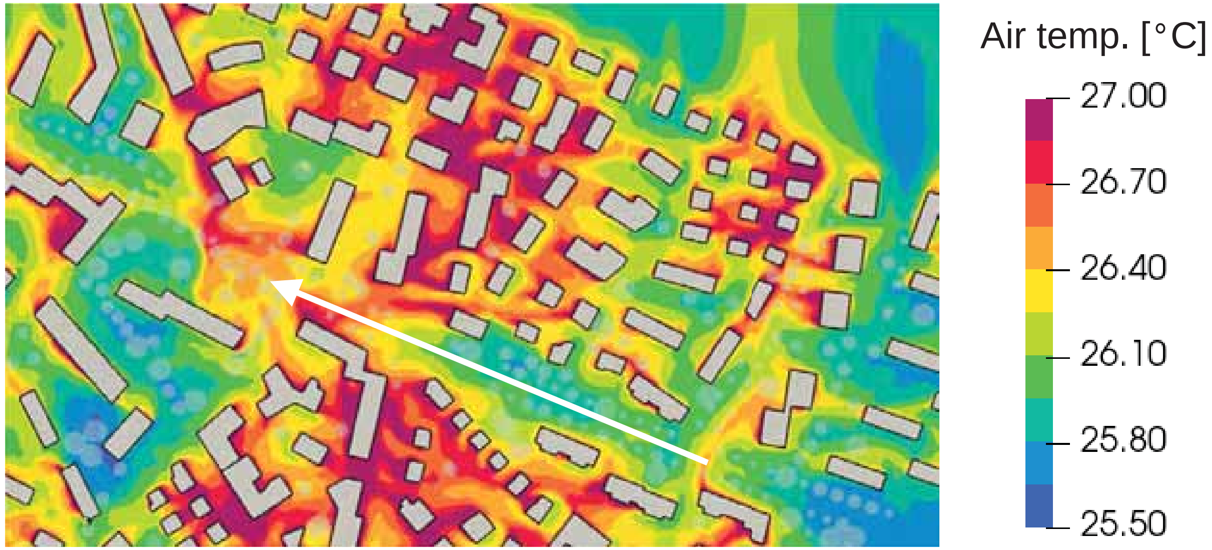
Wind direction

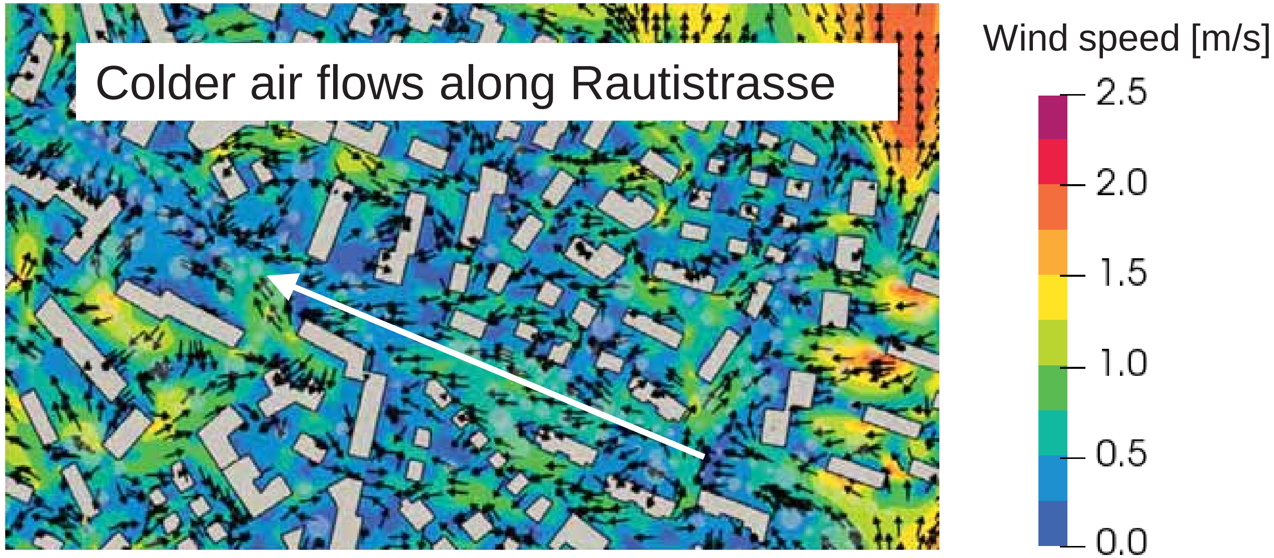


Nighttime conditions with wind from south

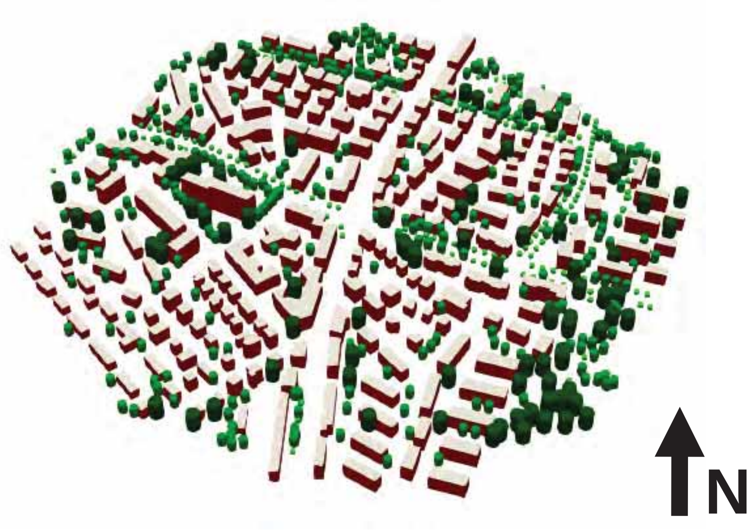
Current situation

Wind

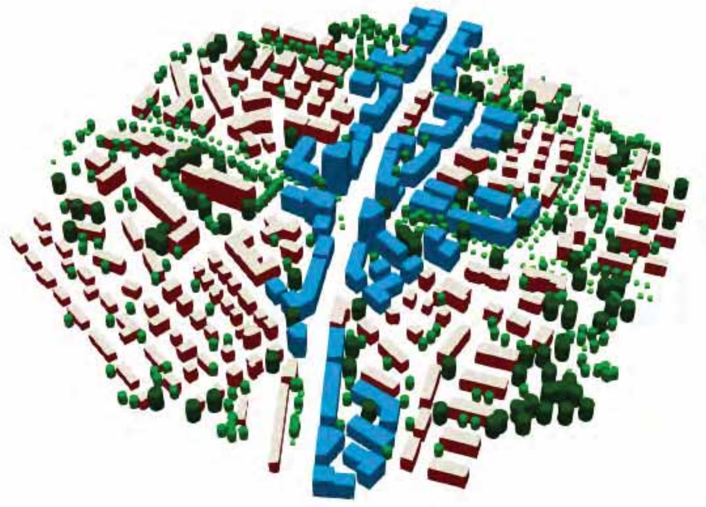




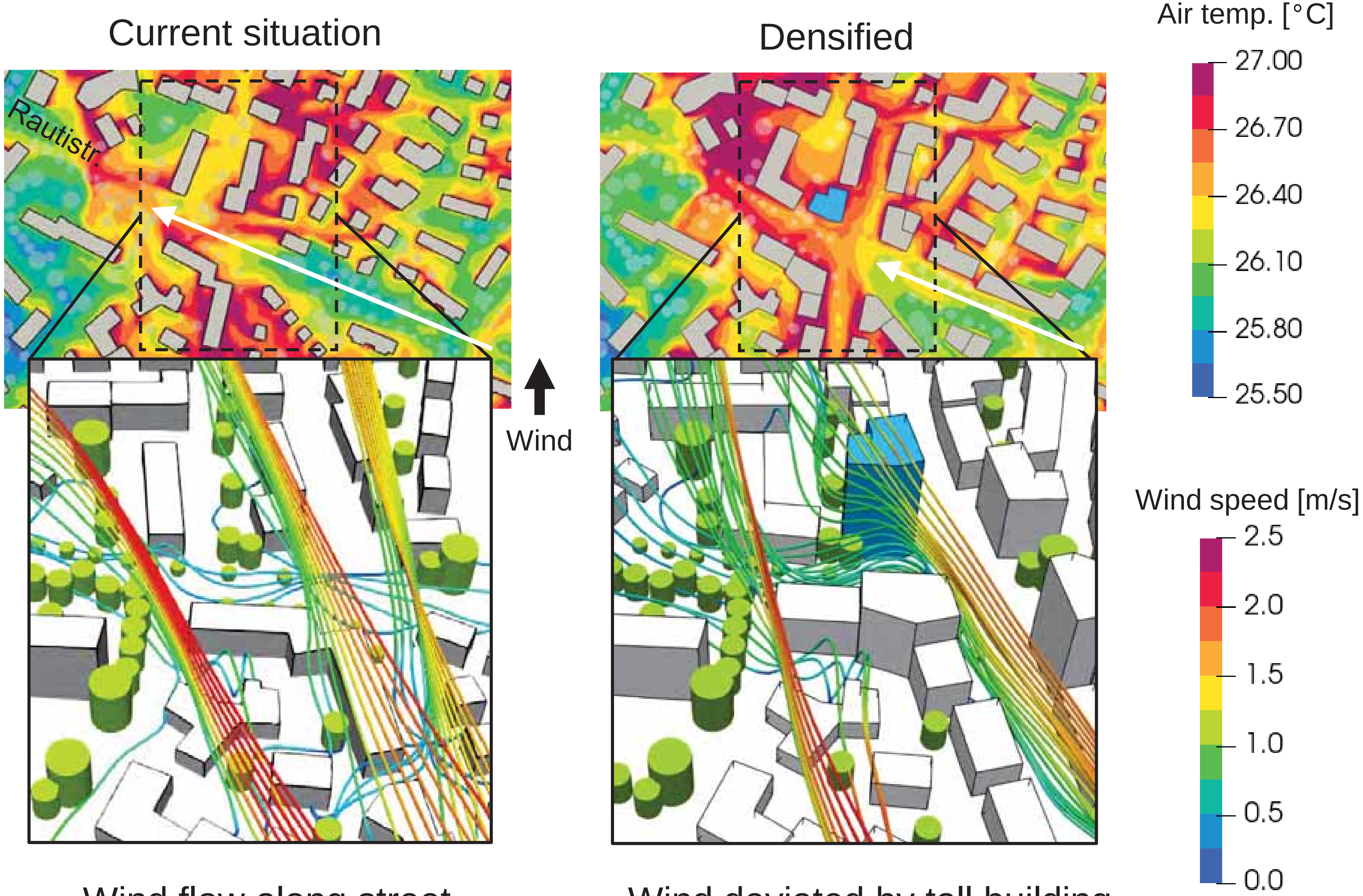
Current situation



Densified case



Nighttime conditions with wind from south



Wind flow along street

Wind deviated by tall building

Influence of gaps between the buildings

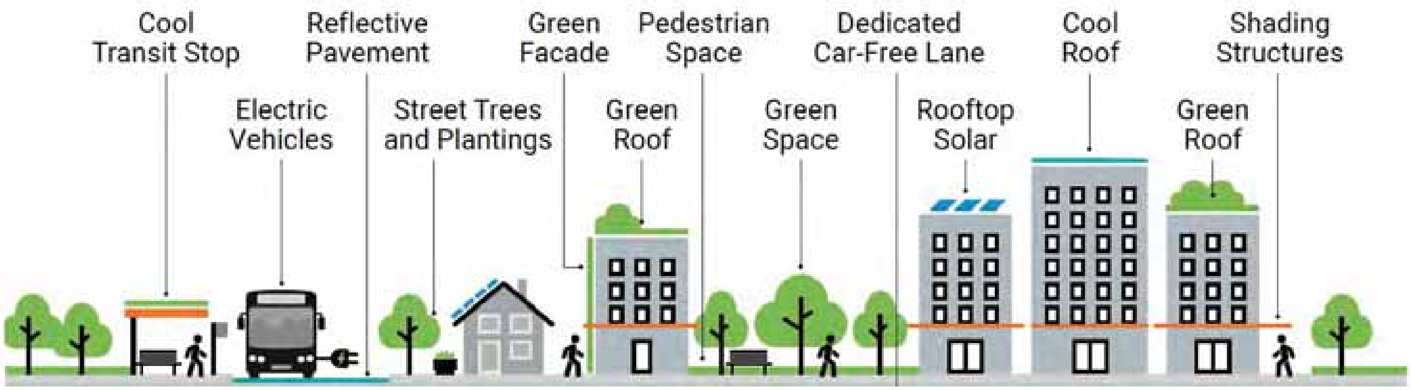
Better local climate in large open courtyards

More open in terms of building orientation and wind-blocking.

Design of optimal urban vegetation solutions

Impact of

- Street trees and planting
  - Amount: tree cover, LAD, …
  - Structure: size, distance, …
  - ….
- Green facades, green roofs
- Green space (parks)
- Green shading



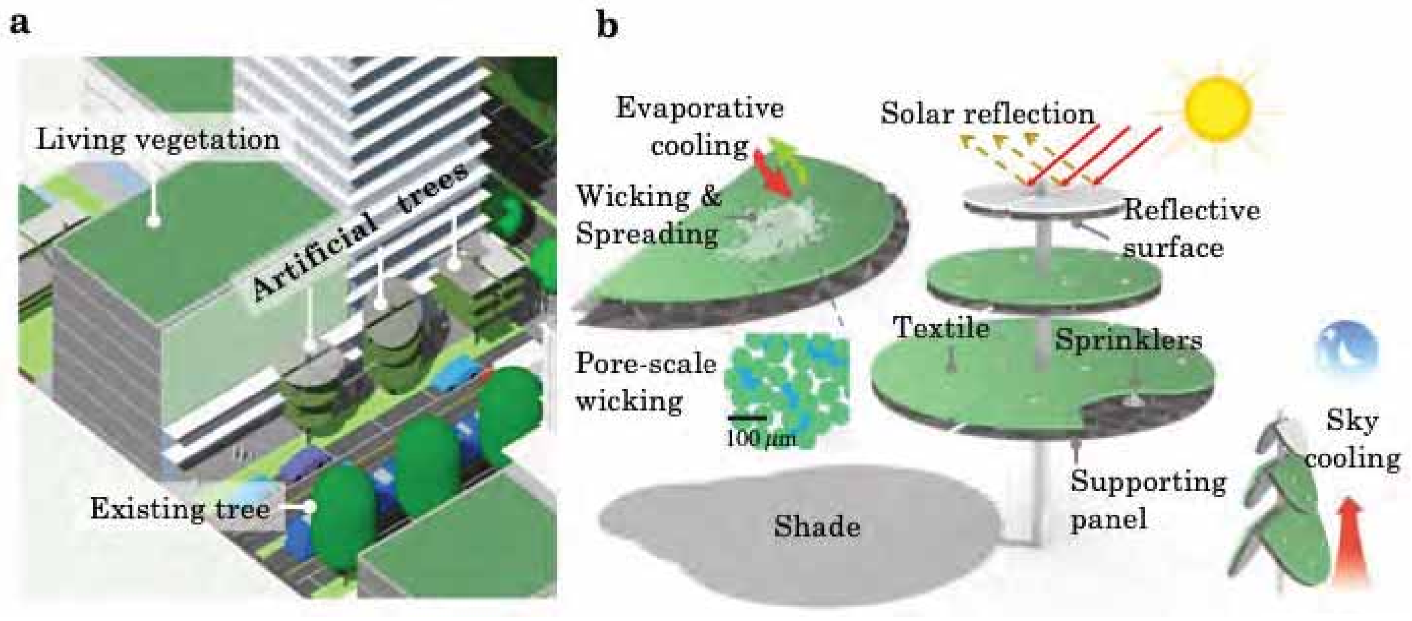
Campbell et al. 2021

Taking into account

- Growth of trees
- Urban water cycle
- Building morphology
- Background climate

Innovation

- Bio-inspired artificial solutions
- Green balconies as heat exchanger
- Urban farming

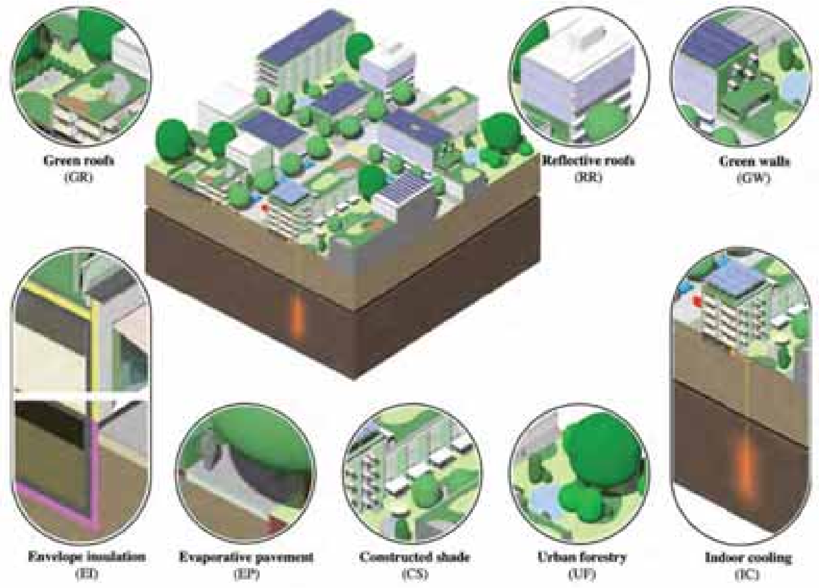


Y. Zhao et al., 2023

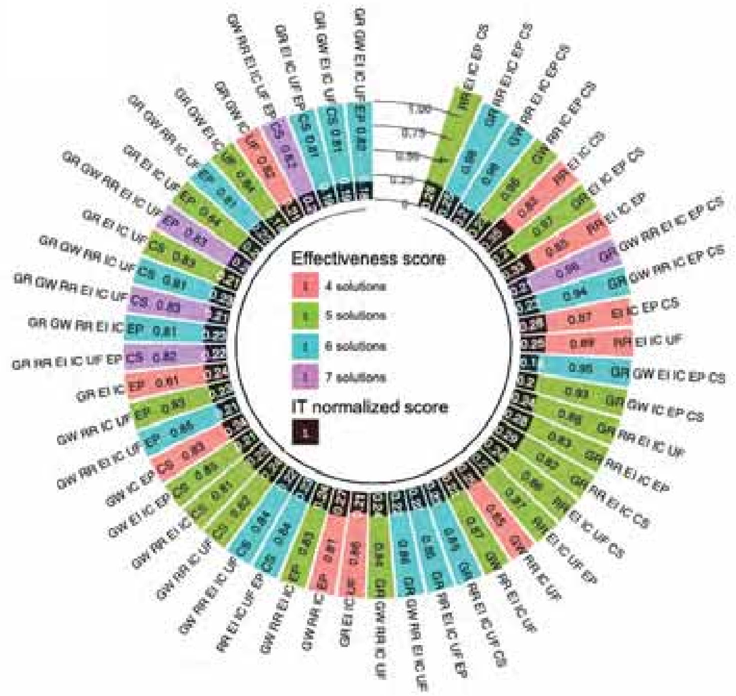
Selection of optimal set of heat wave mitigation measures

Selection criteria

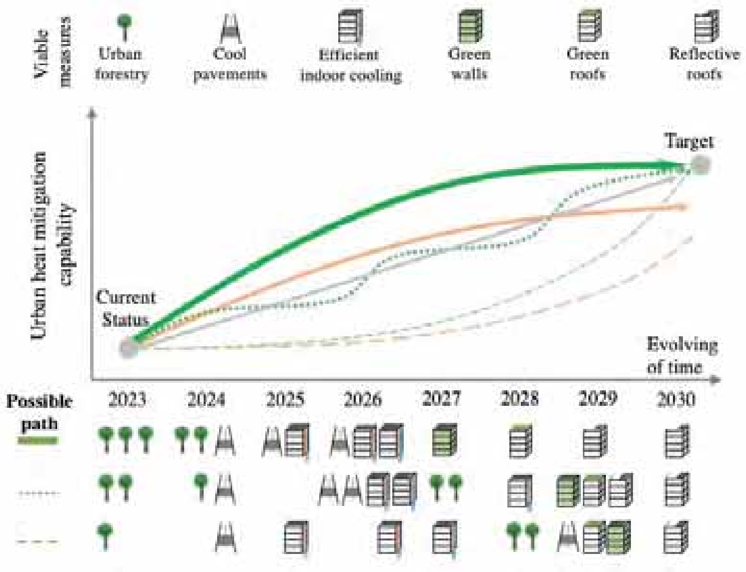
- Impact on comfort, health
- Time for implementation
- Compatibility
- Costs and inequity
- Acceptability



Reflective roofs, insulated envelopes, evaporative pavements, constructed shade



Road map for implementation



Co-benefits of heat mitigation on

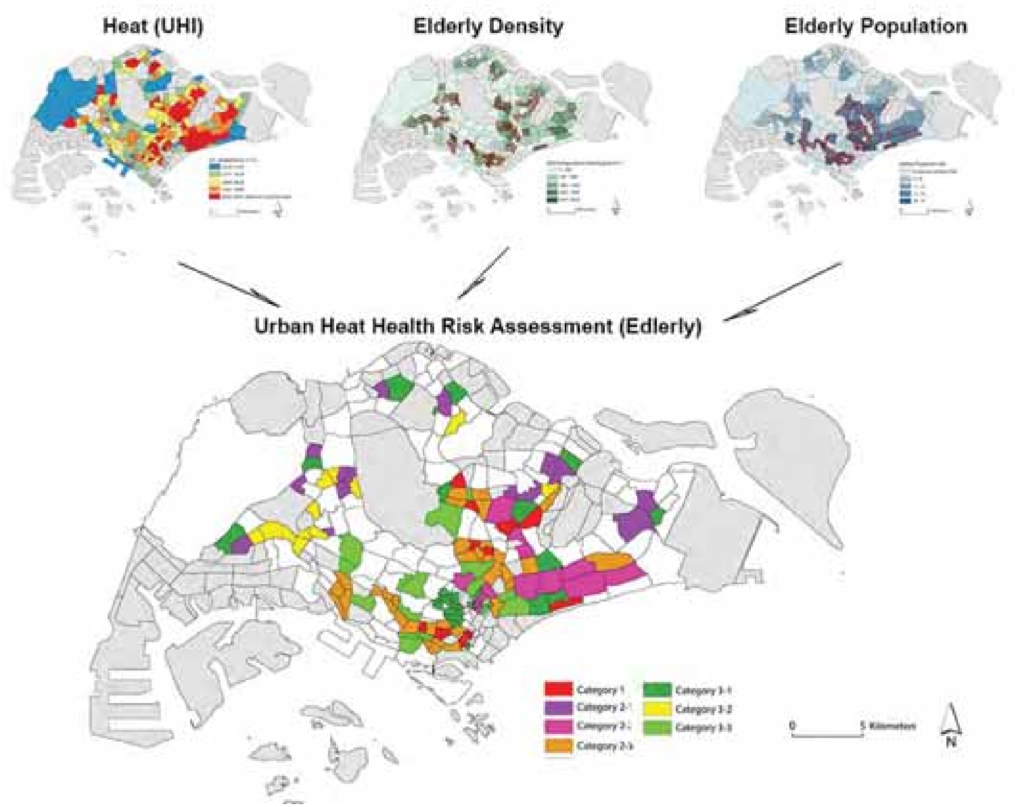
- Microclimate and bio-diversity
- Wellbeing
- Energy (cooling)
- De-carbonation
- Resilience

Y. Zhao et al., 2023

Socioeconomics Impacts

Sound scientific and technical basis + Focus on people exposed to the risks

Exposure and Vulnerability (Risk Evaluation)



Urban heat risk assessment for the elderly population in Singaporee, as preliminary research

Public Acceptability (Political Feasibility)

August 10, 2018 by politicalscience

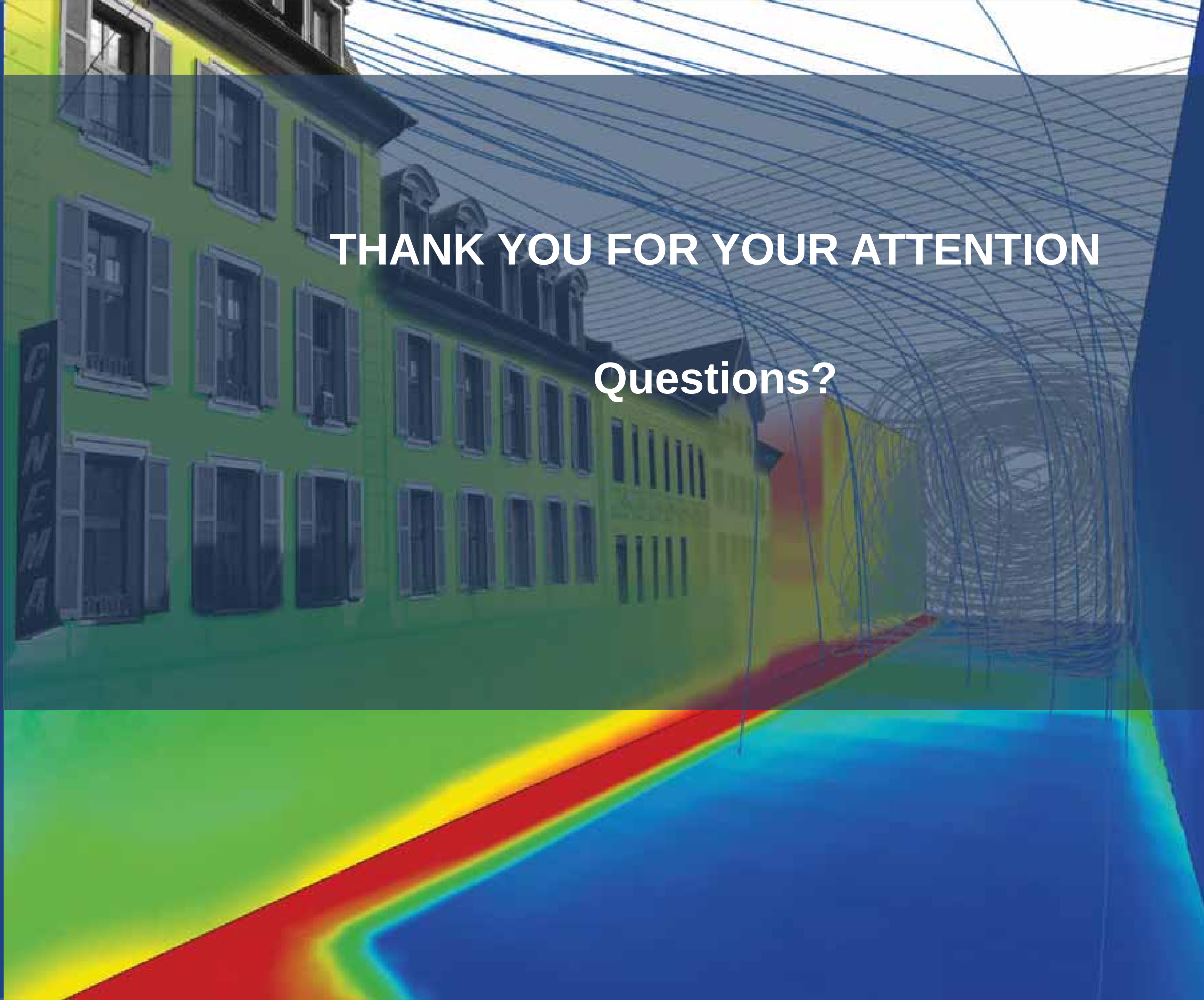
Vote on various mitigation measures

☐Yes; ☐No; ☐I do not know

CONCLUSIONS

- We are responsible for climate change and increase in heatwaves
- We (will) have to adapt
- We (will) have to mitigate

- We need to plan mitigation/adaptation on short and long term
- We need urban microclimate physical models to design sets of mitigation measures and plan when to implement
- We need building physics to take into account the urban microclimate and design adequate passive and free cooling sytems



THANK YOU FOR YOUR ATTENTION

Questions?