Agir maintenant face aux changements climatiques

Mitigation des vagues de chaleur en milieu urbain

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ETS 28 février 2024 **CEBQ**

Agir maintenant face aux changements climatiques

Adaptation aux CC – événements extrêmes: vagues de chaleur, inondations

Mitigation des vagues de chaleur en milieu urbain
Dominique Derome

Quelles solutions d’aménagement peut-on proposer pour le mieux-être en vague de chaleur.
Nous parlerons de l’eau, de l’ombrage et des arbres.

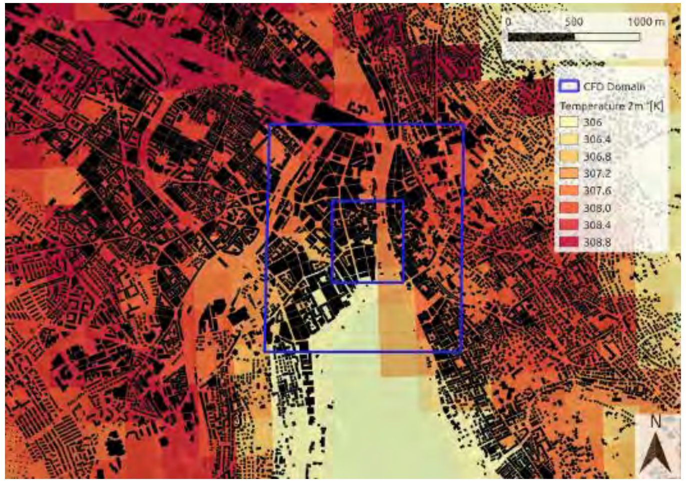
Mitigation des CC – réduction des émissions intrinsèques et en opération

Rôle de l’enveloppe dans le confort d’été 2050, décarbonation, efficacité énergétique
Marika Frenette et Célia Mailfert

Nous présenterons l'impact du réchauffement climatique sur la conception de l'enveloppe
des points de vue confort d'été et décarbonation à l’aide de deux études de cas.

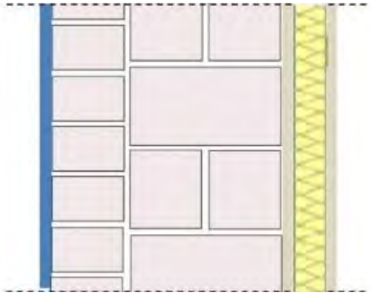
Urban climate mitigation using multiscale approach

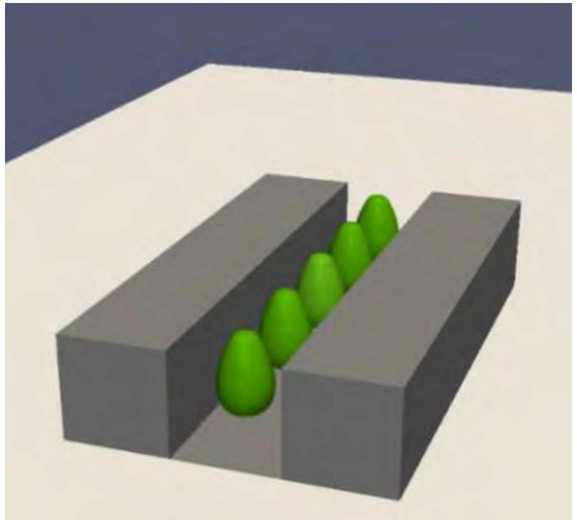
- Mesoscale
  - City and surroundings (domain size: < 200 km)
  - Meteorological models with urban parameterization



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

- Microscale
  - Local / building (domain size: < 100 m)
  - CFD models: wind, heat, moisture





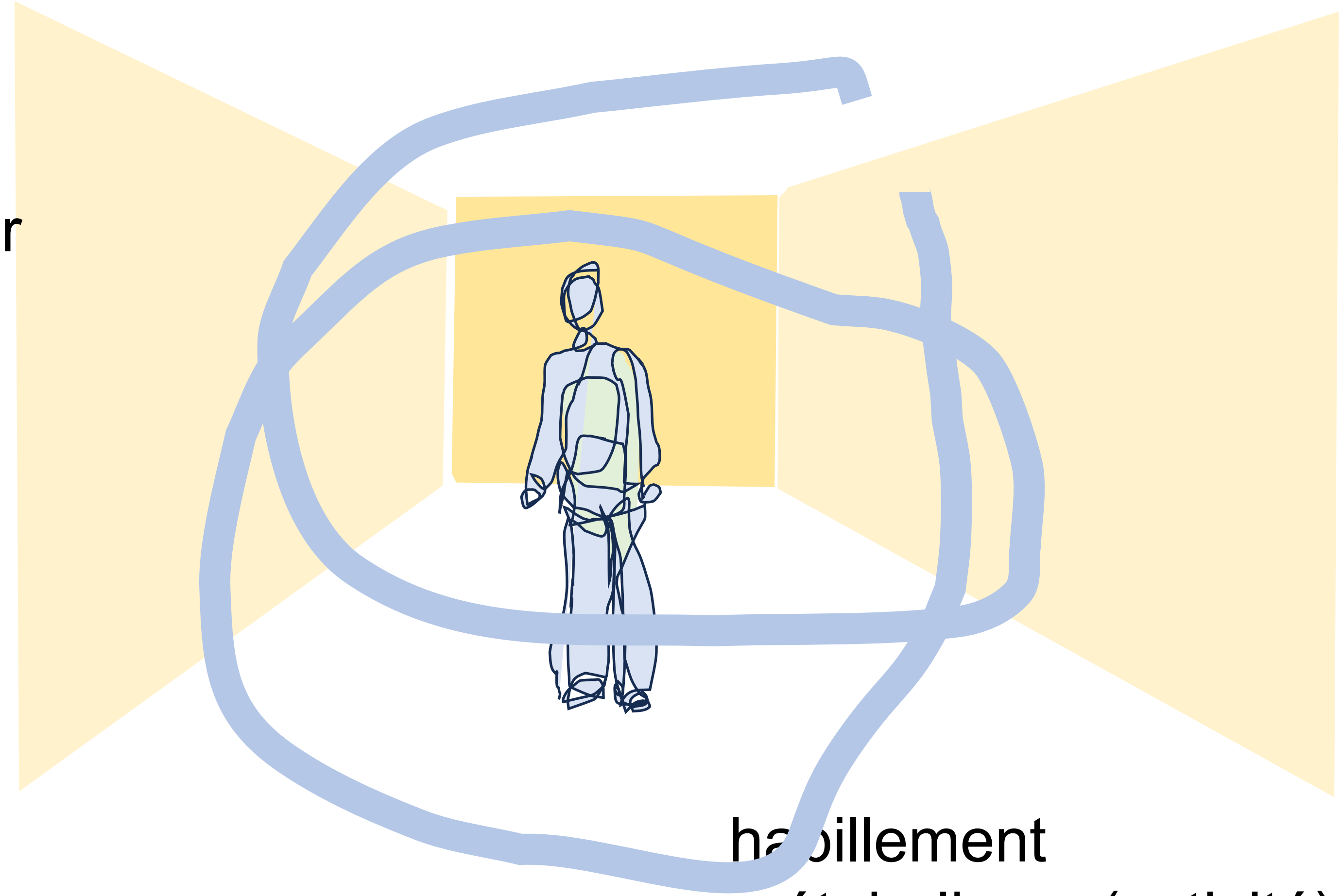
(Atmosphere **2020**, *11*(12), 1313)

Confort thermique

température de l’air

humidité relative de l’air

vitesse de l’air



habillement
métabolisme (activité)

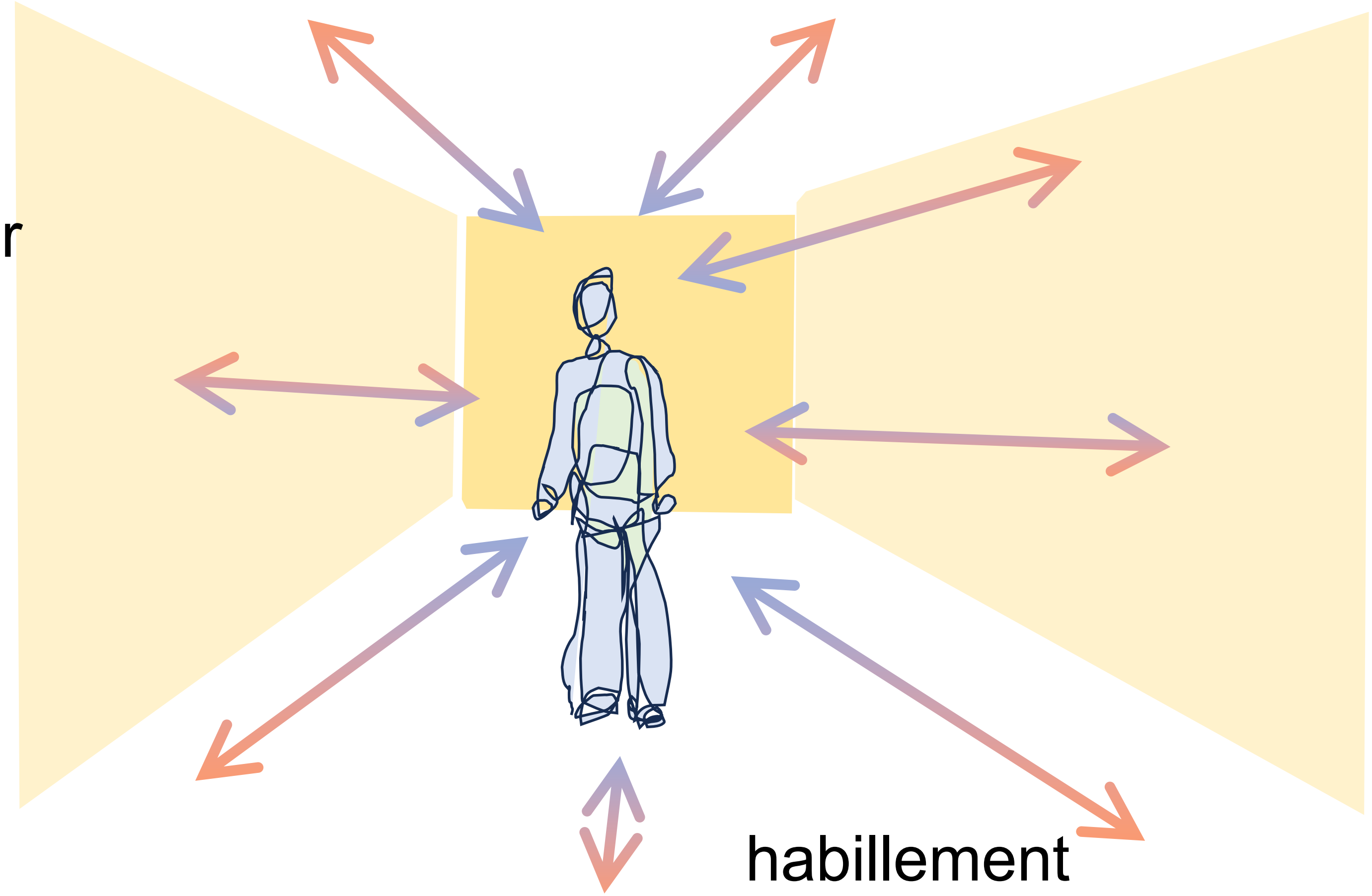
Confort thermique

température de l’air

humidité relative de l’air

vitesse de l’air

échanges radiatives
surface à surface



habillement
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Confort thermique

température de l'air

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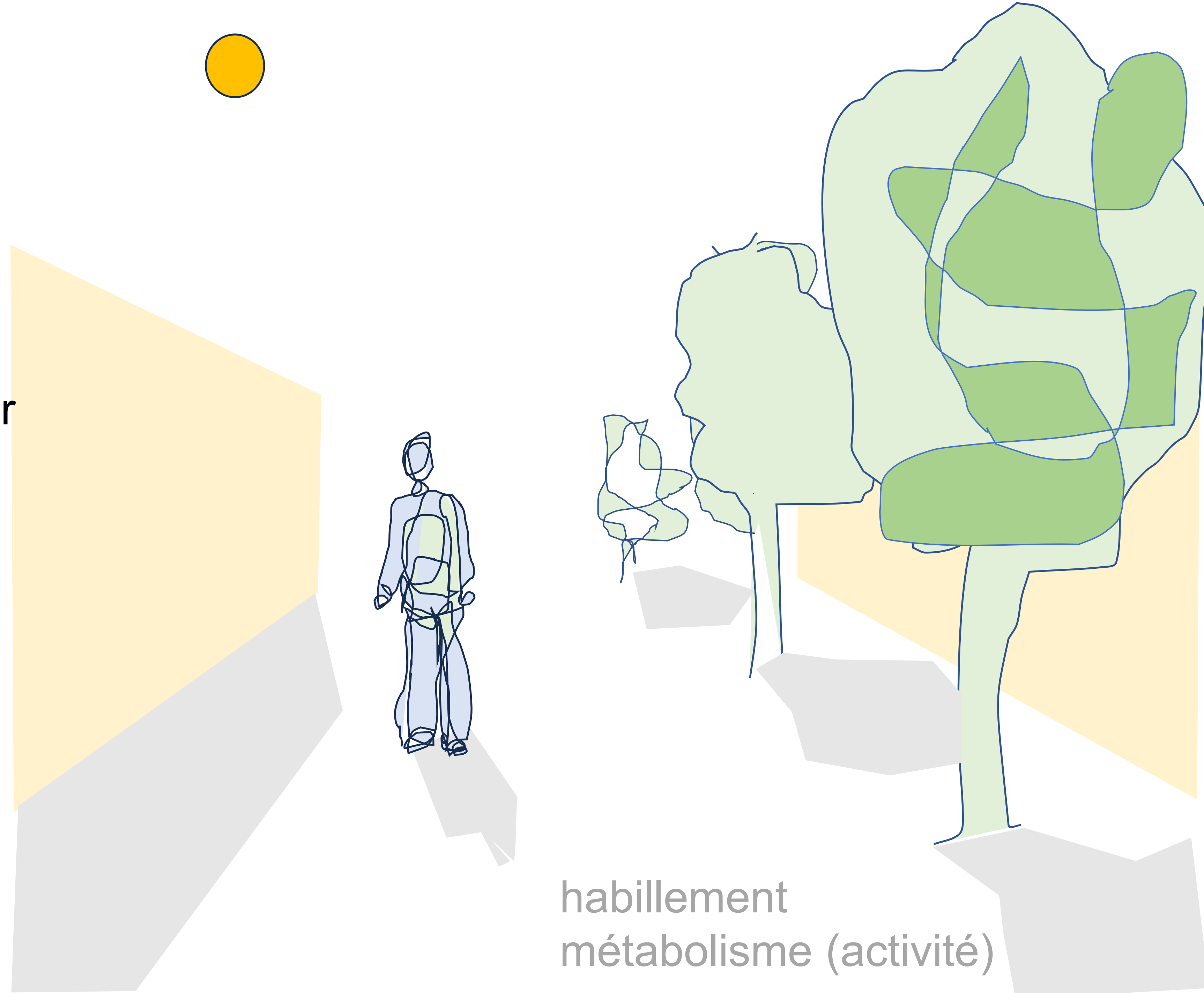


habillement
métabolisme (activité)

Indice universel de confort thermique

Evaluation du confort thermique urbain

Température ambiante équivalente
à un environnement donnant
une réponse physiologique similaire

- température de l'air
- température radiante moyenne
- humidité relative de l'air
- vitesse de l'air
- habillement
- activité

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

Effet des températures de surface irradiant la personne

Radiation solaire directe sur la personne

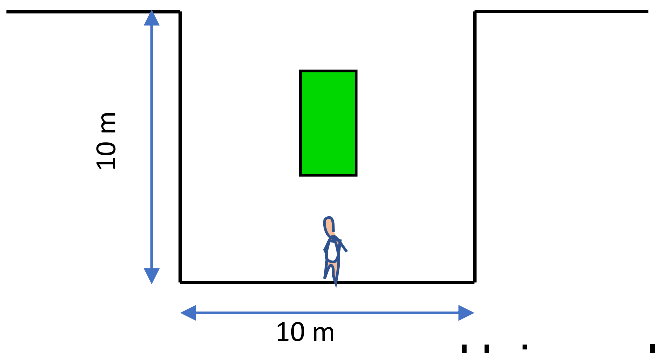
Universal Thermal Climate Index (UTCI)

UTCI range (ºC)	Stress category
> 46	Extreme heat stress (HS)
38 to 46	Very strong HS
32 to 38	Strong HS
26 to 32	Moderate HS
9 to 26	No thermal stress
0 to 9	Slight cold stress (CS)
-13 to 0	Moderate CS
-27 to -13	Strong CS
-40 to -27	Very strong CS
< -40	Extreme CS

Indice universel de confort thermique

Influence de la présence d'arbre sur le confort thermique

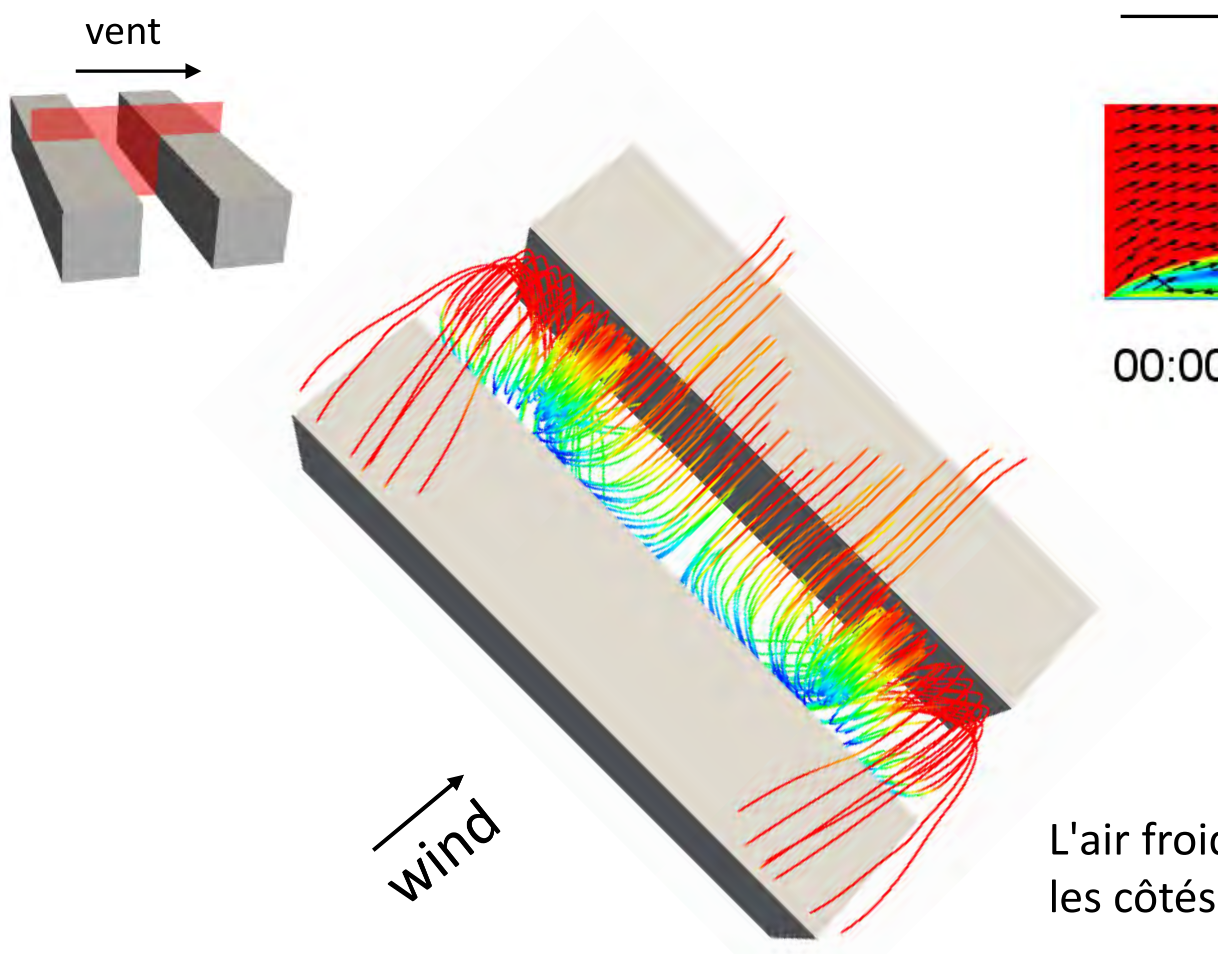
ombrage
refroidissement par évaporation



Universal Thermal Climate Index

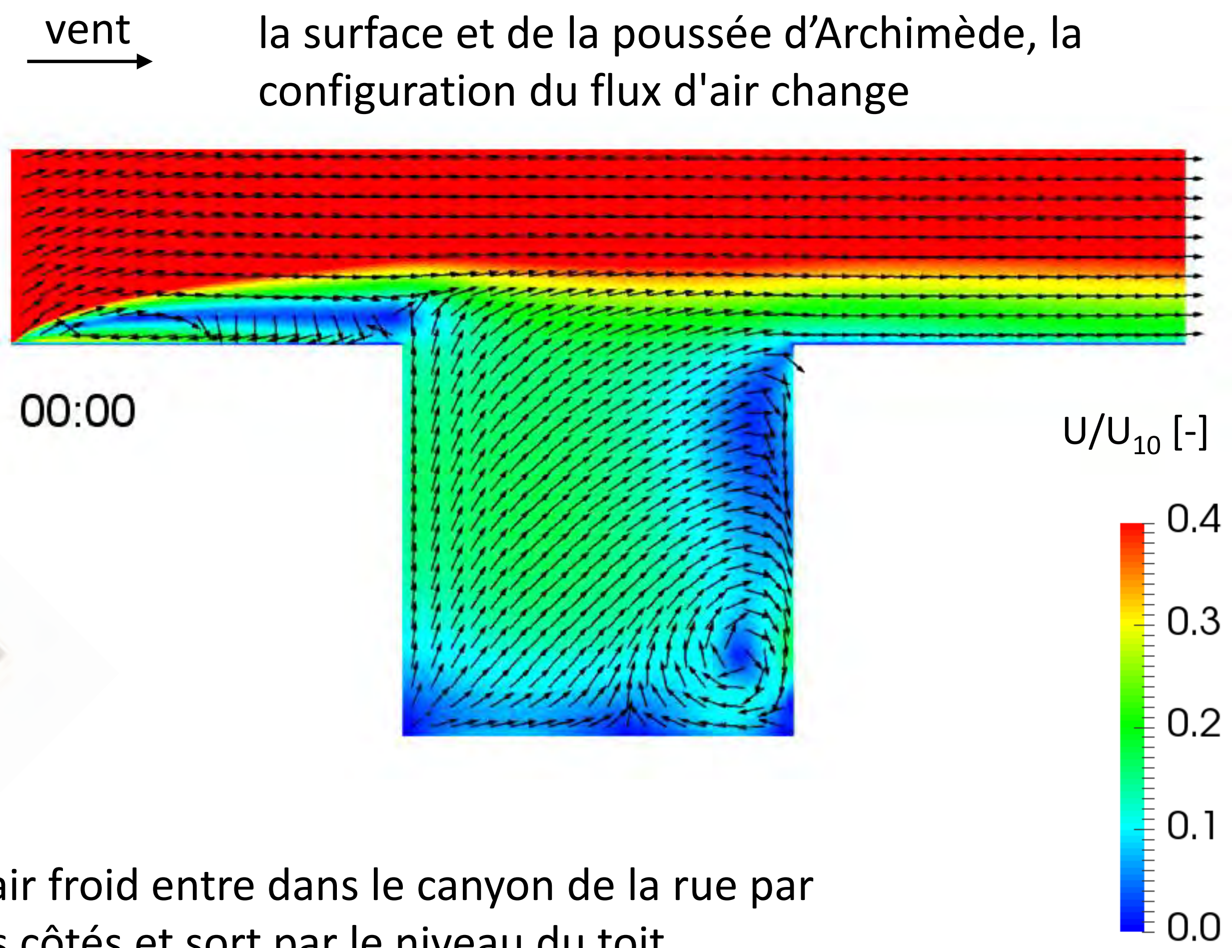
Modélisation – matériaux poreux et DFC

Champ d'écoulement du vent



lignes de vent

À 11 heures, en raison de la température élevée de la surface et de la poussée d'Archimède, la configuration du flux d'air change

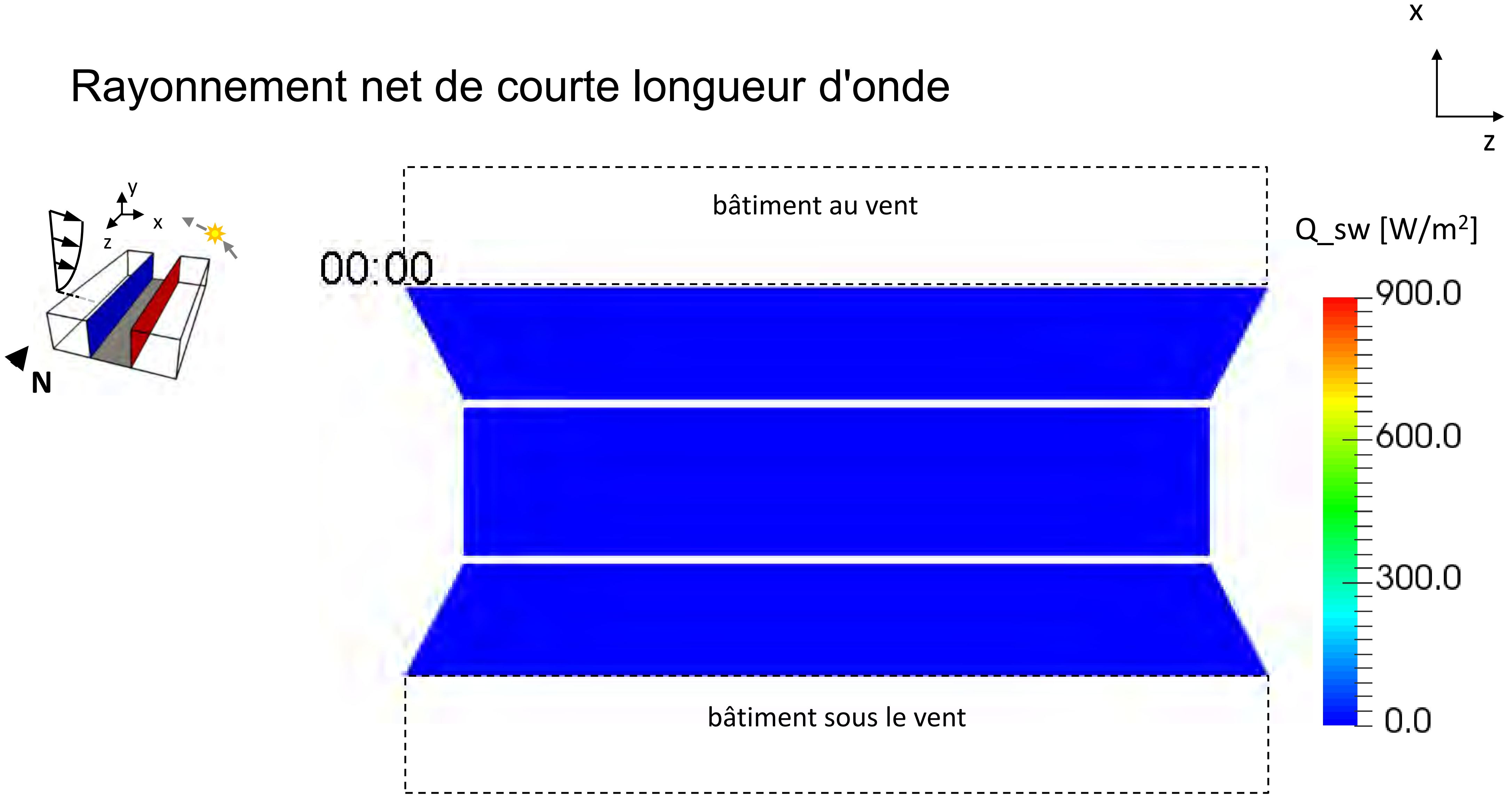


L'air froid entre dans le canyon de la rue par les côtés et sort par le niveau du toit.

A. Kubilay

Modélisation – matériaux poreux

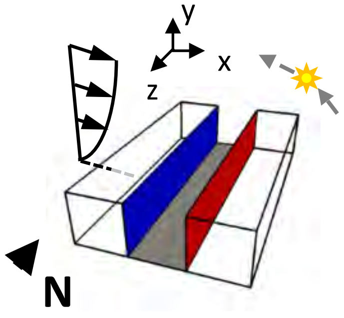
Rayonnement net de courte longueur d'onde

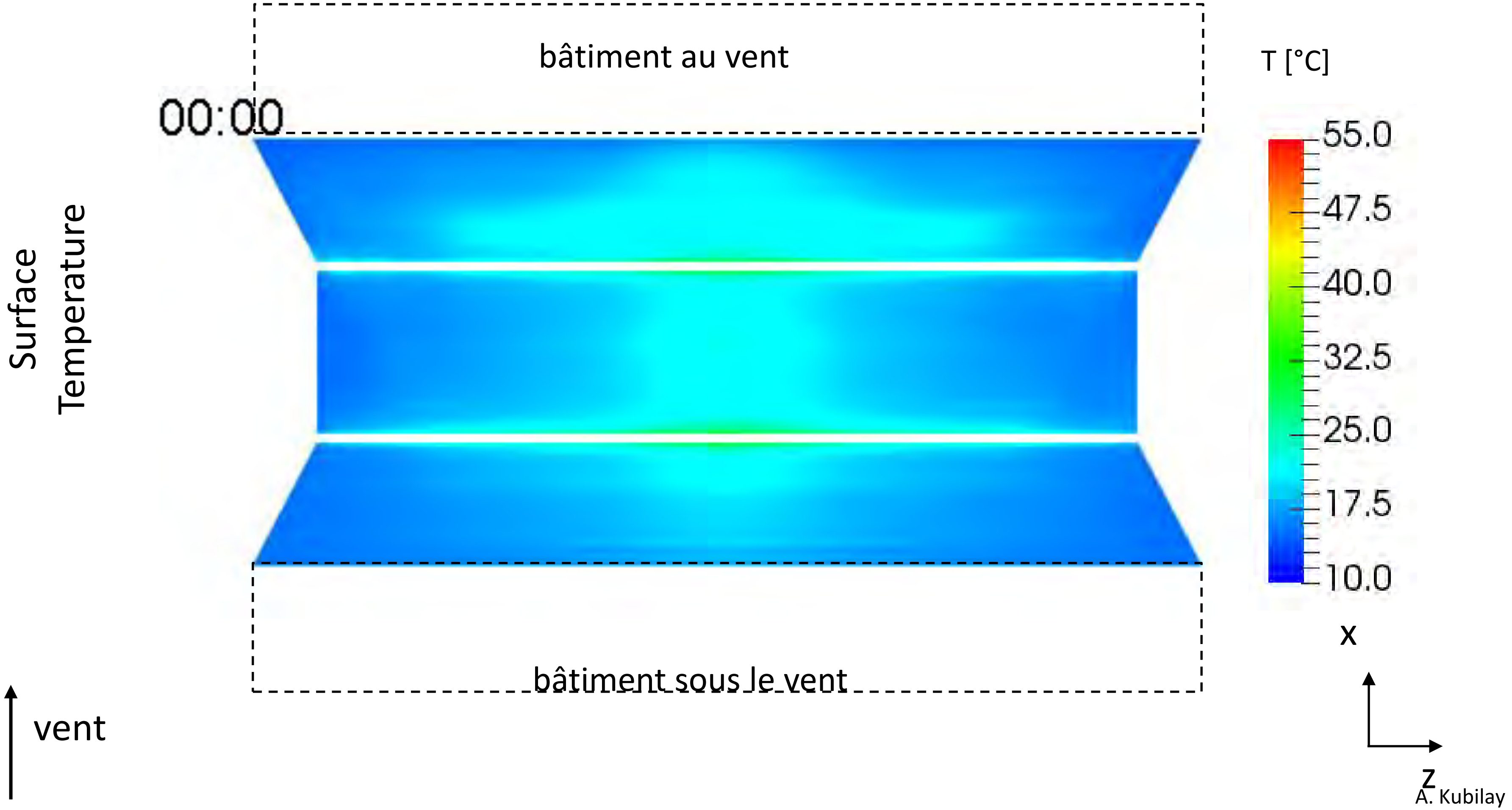


A. Kubilay

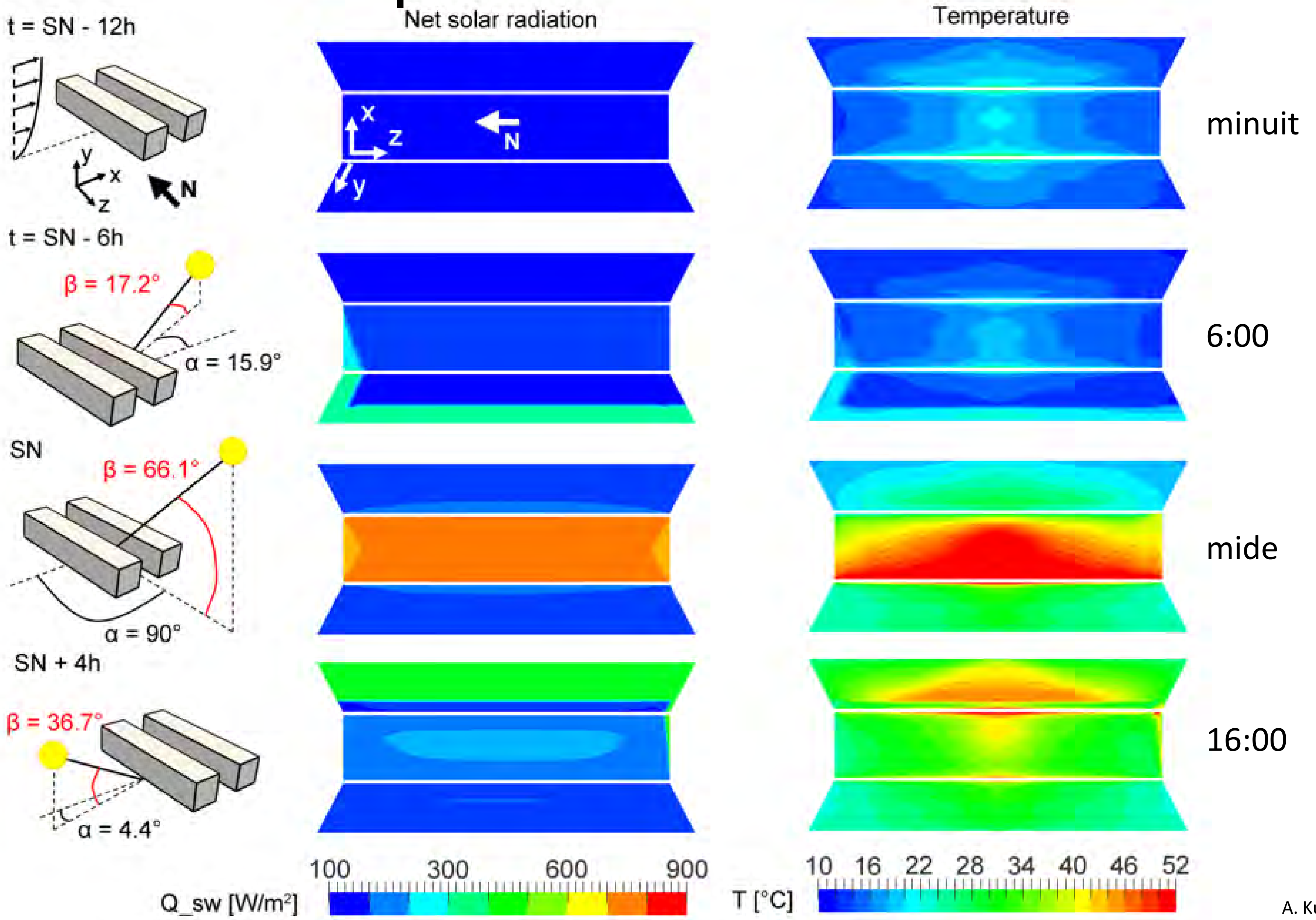
Modélisation – matériaux poreux

Température de surface





Modélisation – matériaux poreux



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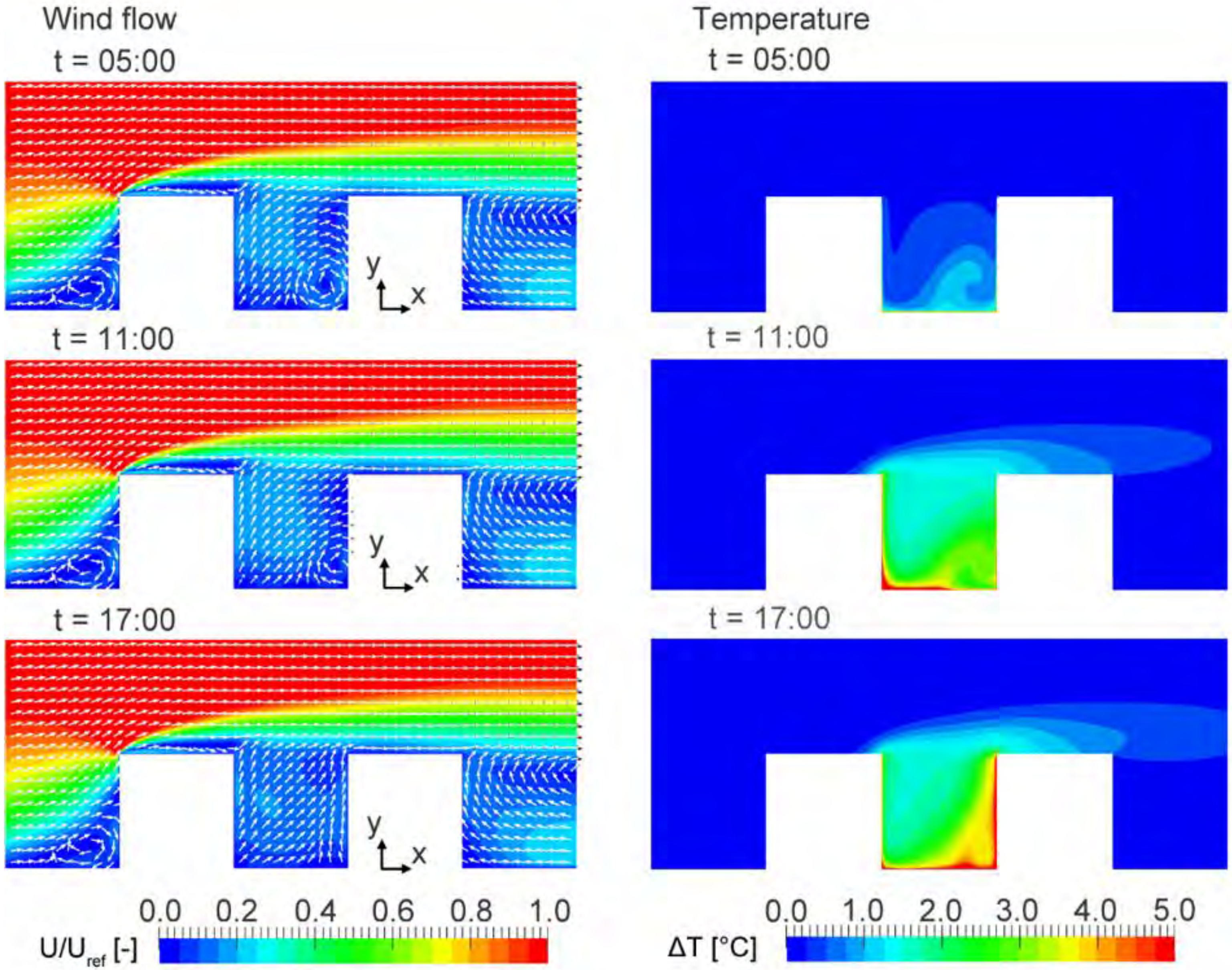
Modélisation – matériaux poreux

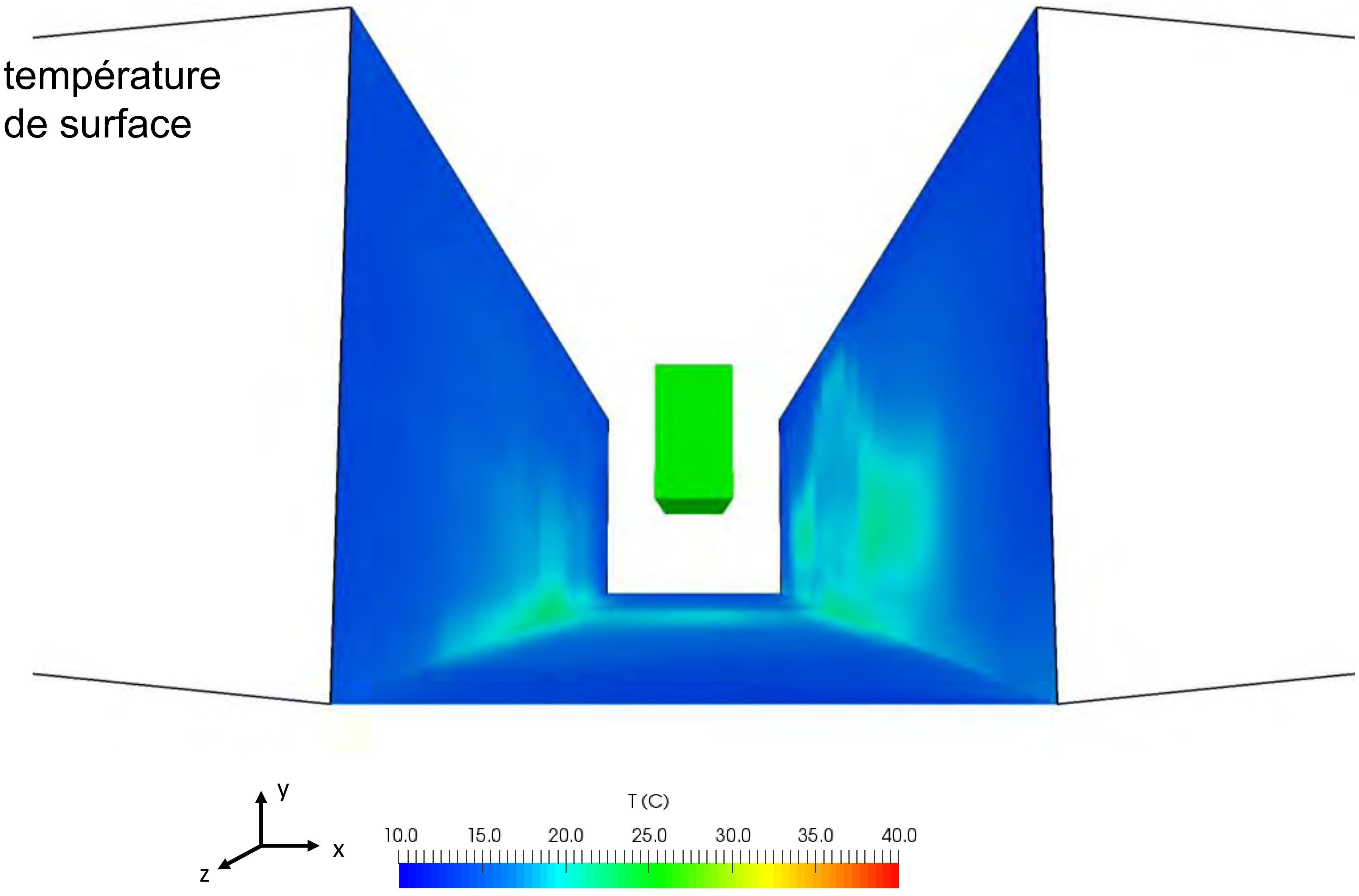


A. Kubilay

physique du milieu urbain

Modélisation

Ajout d’une rangée d’arbres dans la rue



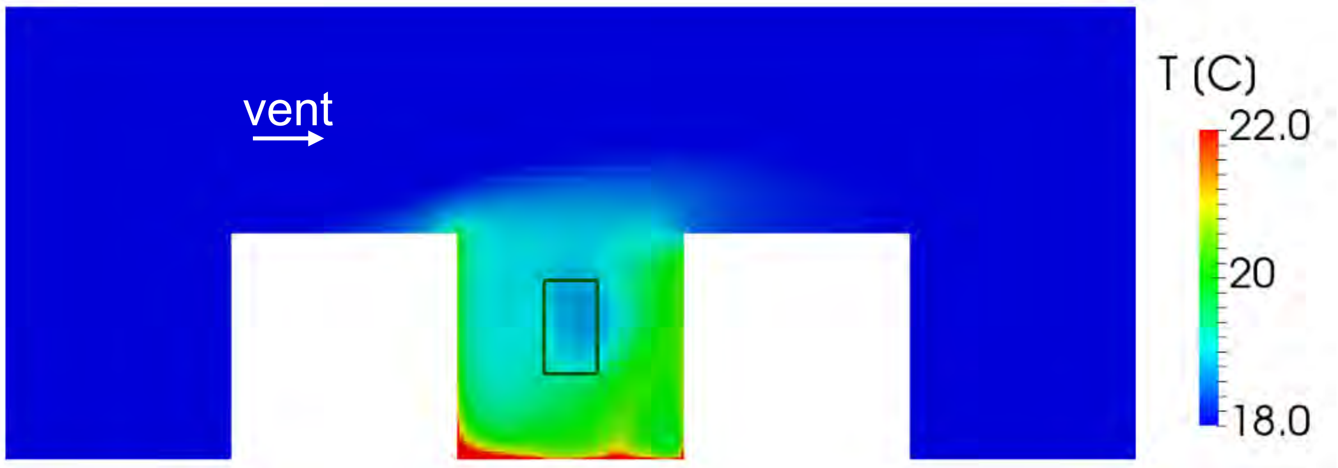
physique du milieu urbain

Modélisation

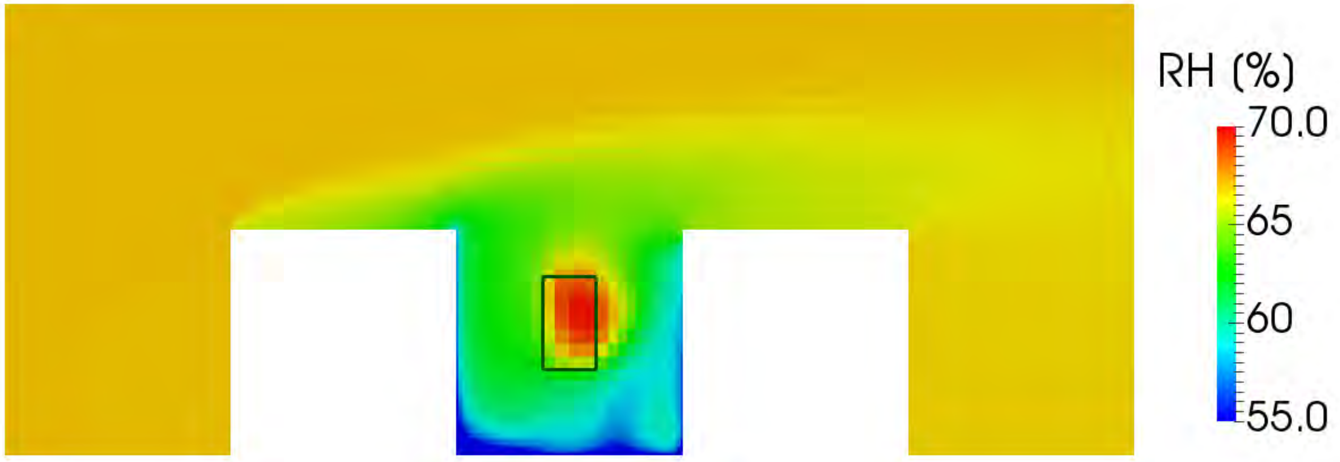
Effet de la transpiration de l'arbre

refroidissement et
humidification localement

température de l'air à midi



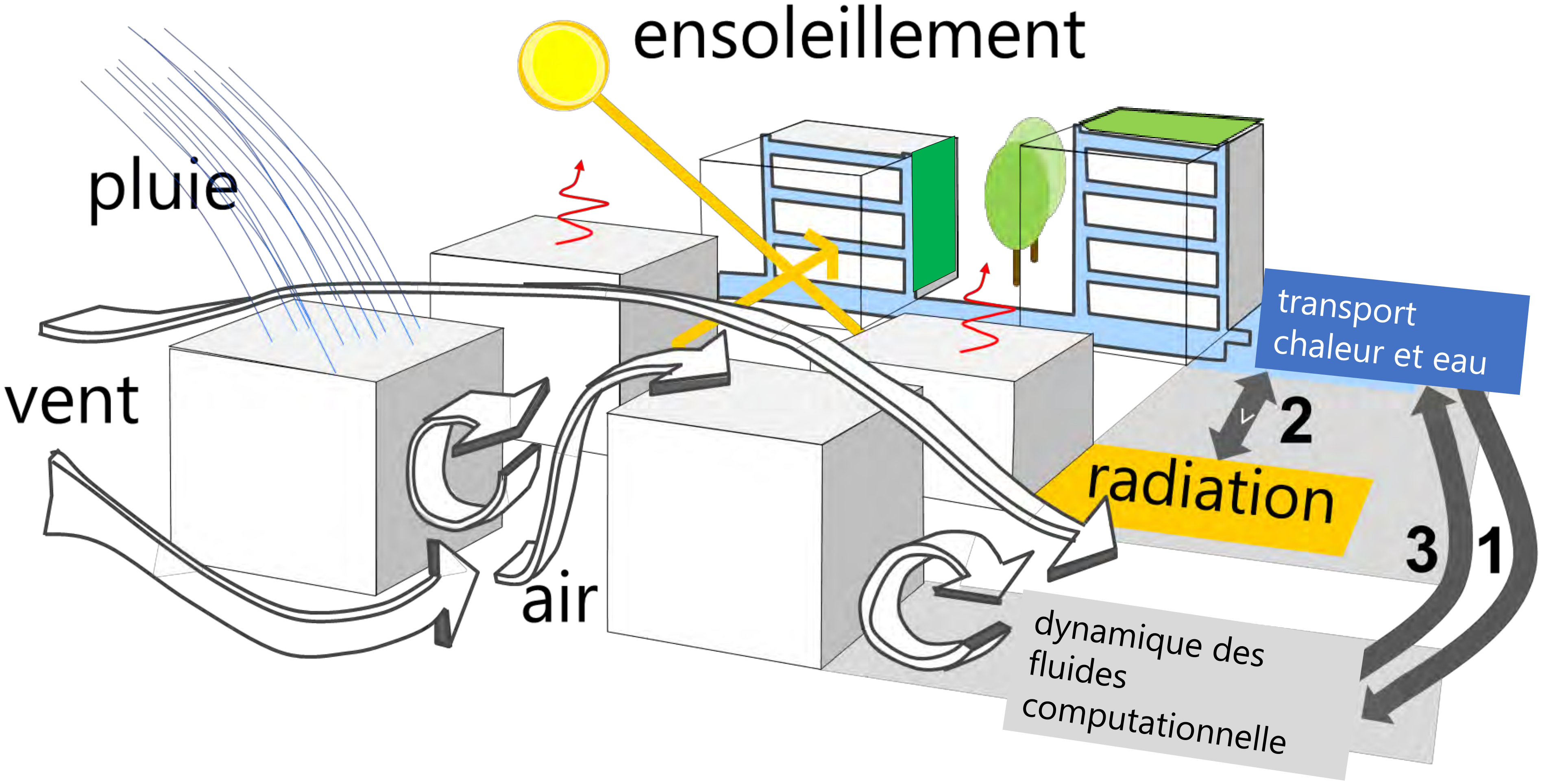
humidité relative de l'air à midi



Modélisation – DFC + rayonnement + HAM

Modèle couplé pour simuler le climat urbain

Approche: intégrer tous les aspects physiques…



Modélisation

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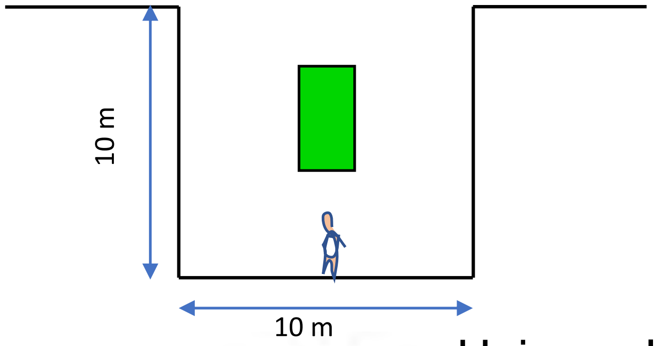
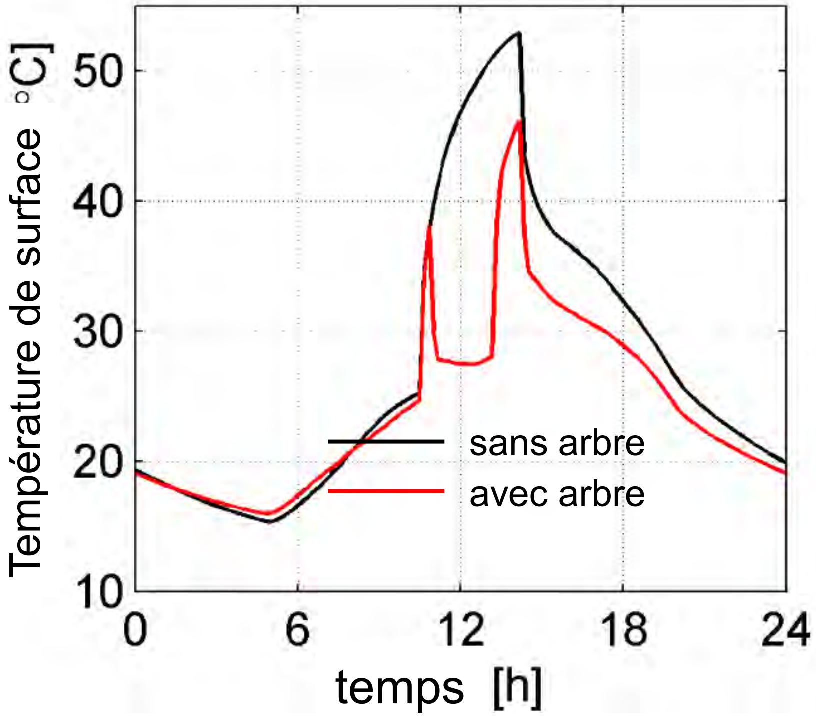
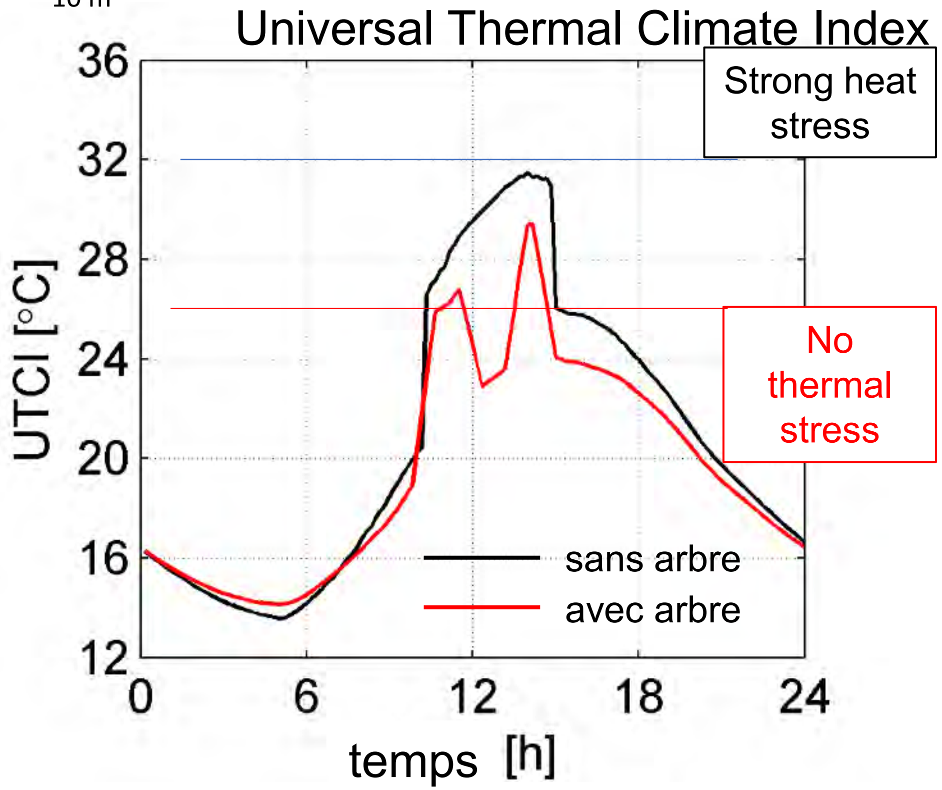
Influence de la présence d’arbre sur le confort thermique

ombrage
refroidissement par évaporation

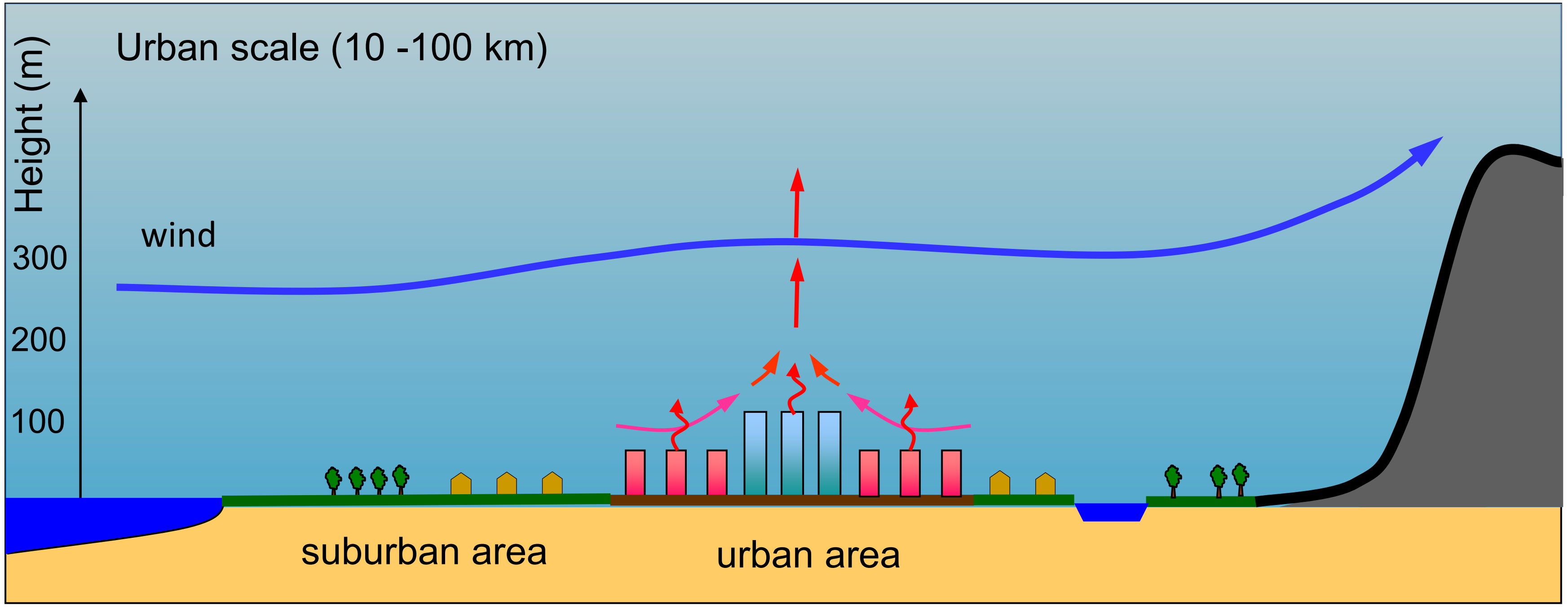


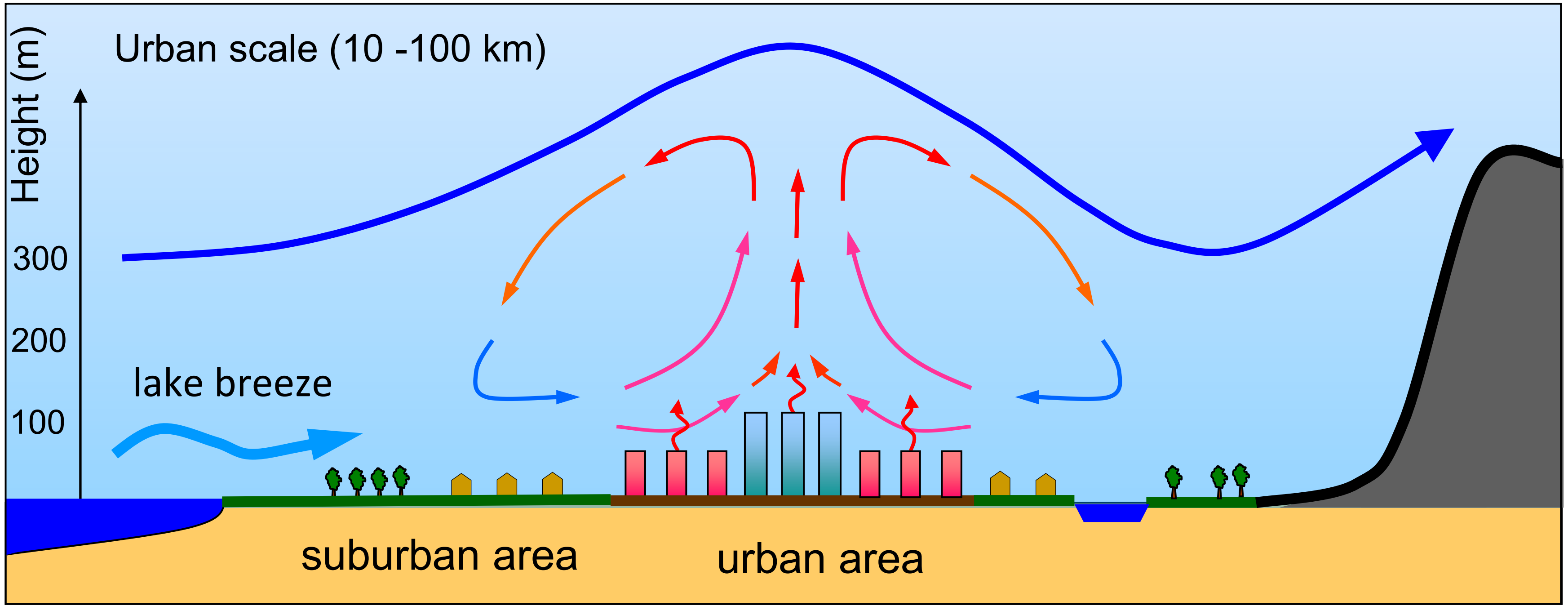




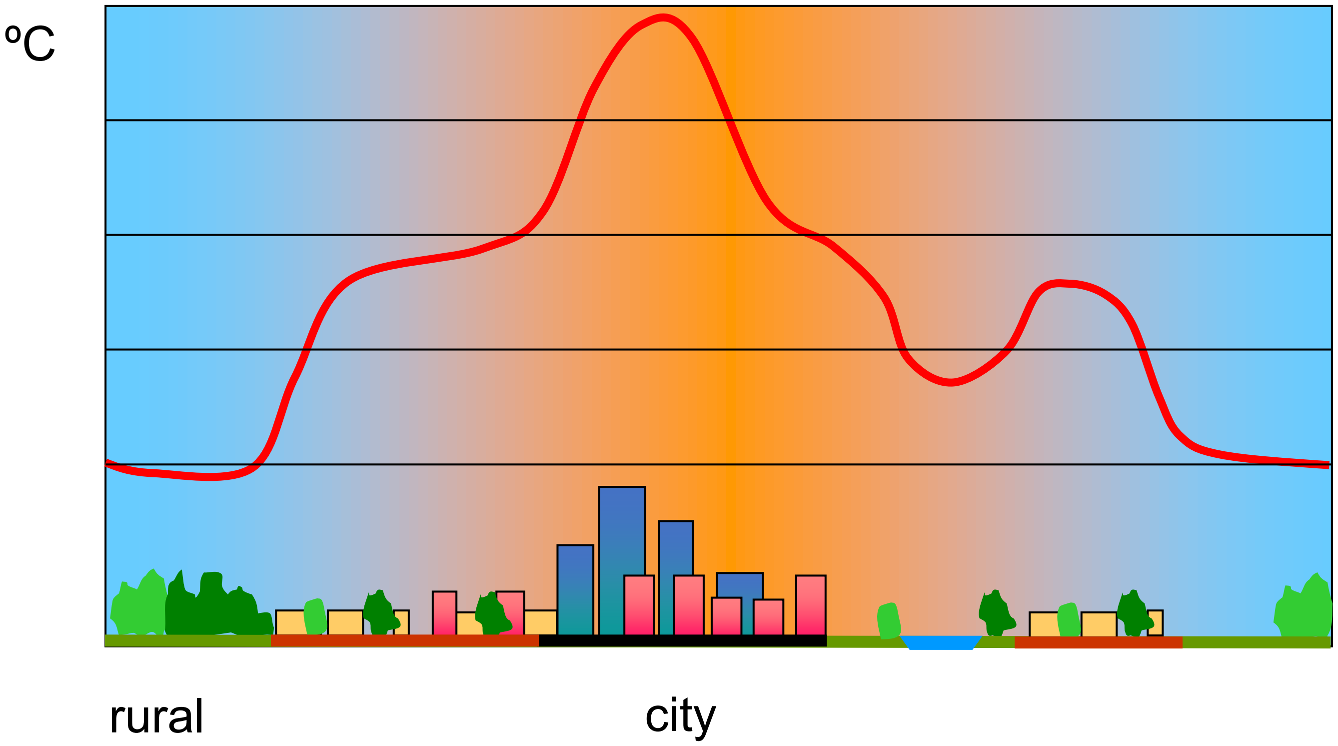
Îlots de chaleur urbain

Effets





Îlots de chaleur urbain
Effet ICU



Intensité du ICU = différence de température entre régions de ville et rural

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

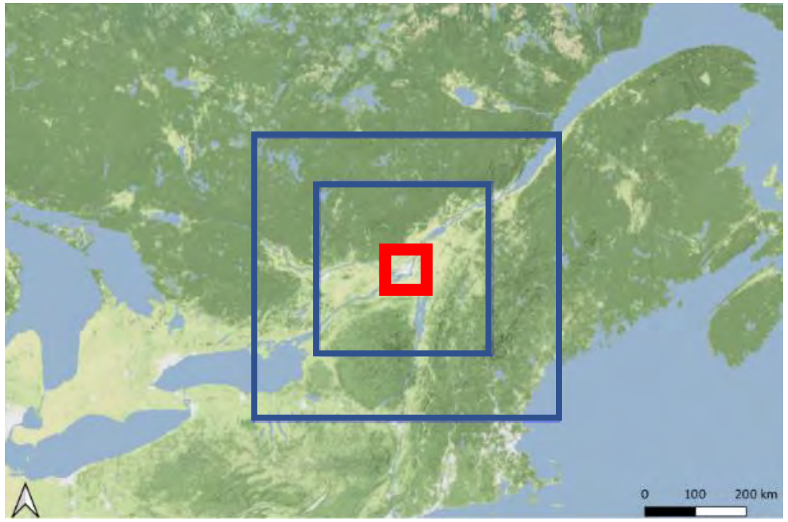
Wanner & Hertig, 1983

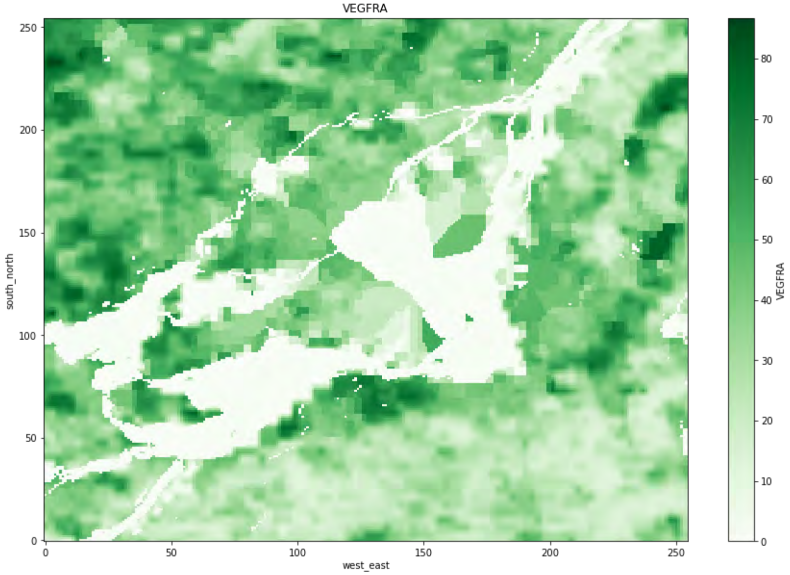
Mesoscale Meteorological Model (MMM) for HW simulation in Montreal

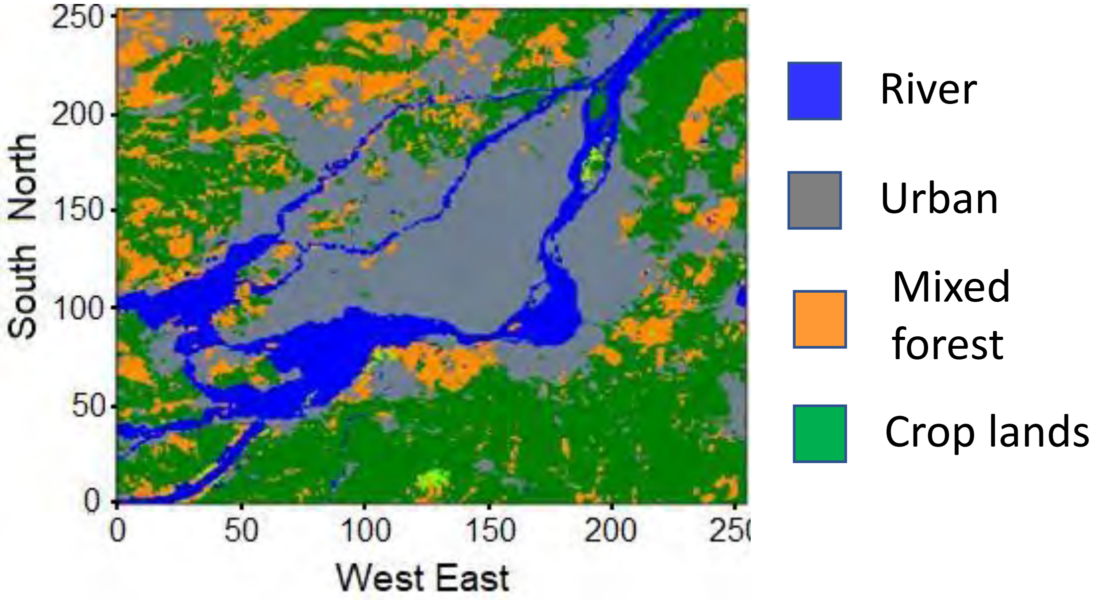
WRF simulation

- ERA-5 re-analysis model of ECMWF (European Centre for Medium-Range Weather Forecasts) on a 0.25° × 0.25° grid, three step downnesting configuration
- Resolution in smallest domain is 250 m
- Modis Land use categories based on vegetation fraction

Montreal three domain downnesting.

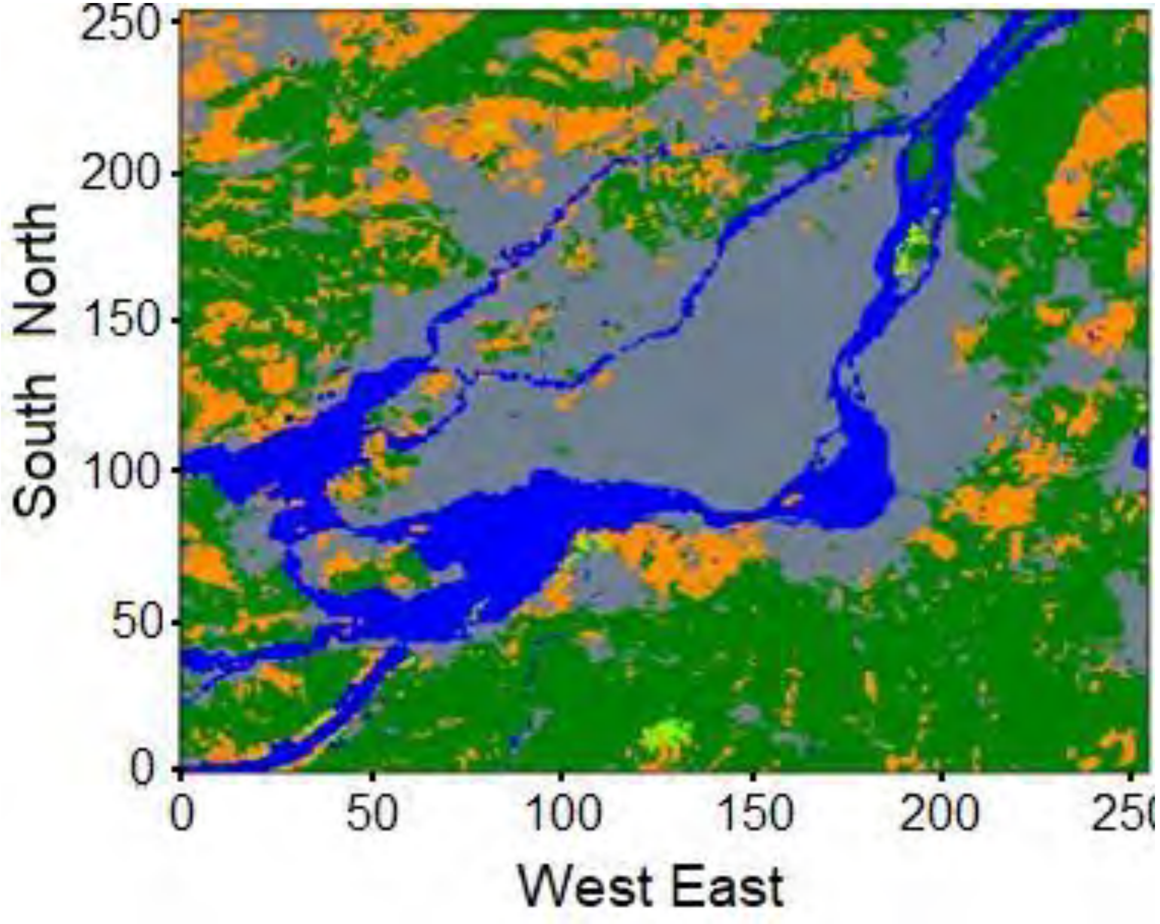




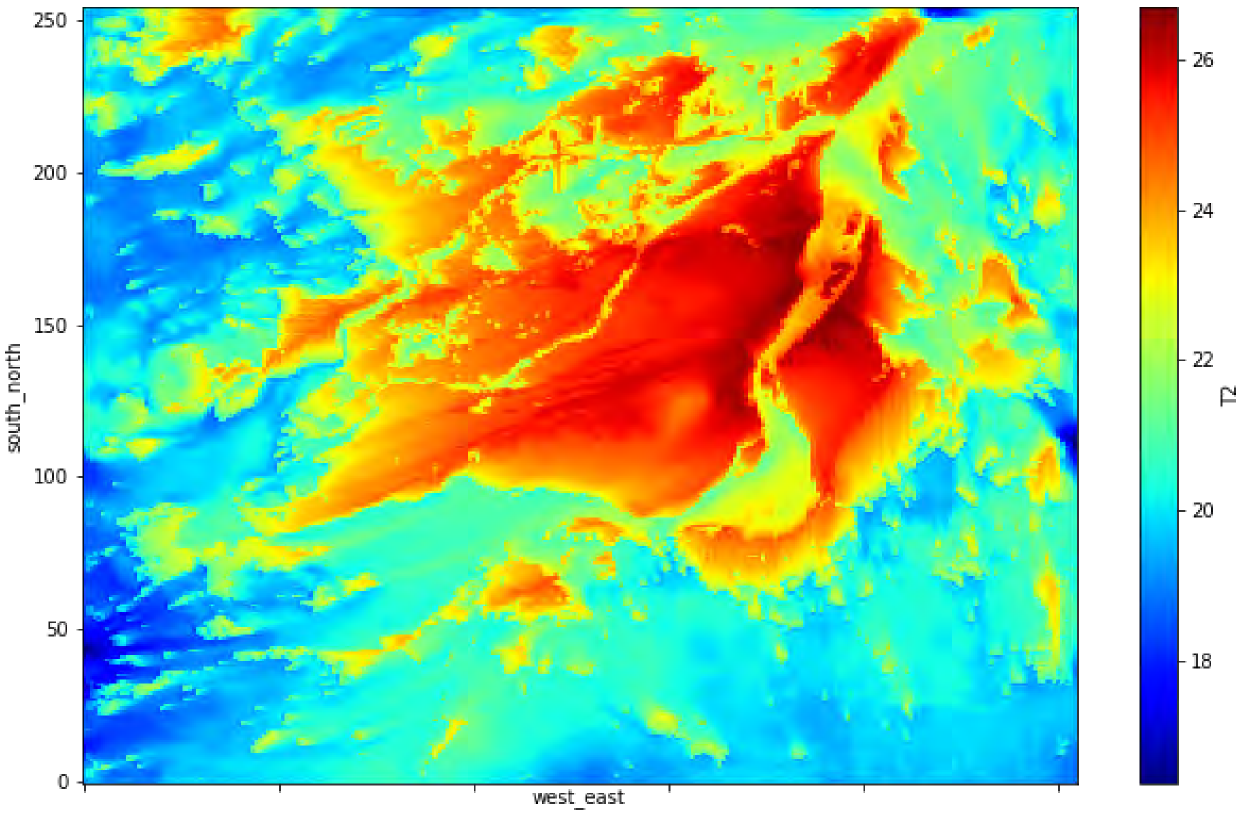


Mesoscale Meteorological Model (MMM) results for HW in Montreal

Land use in Montreal



Air temperature at 2 meter (T2) at 22 June 2020 during heat wave at 0 am.

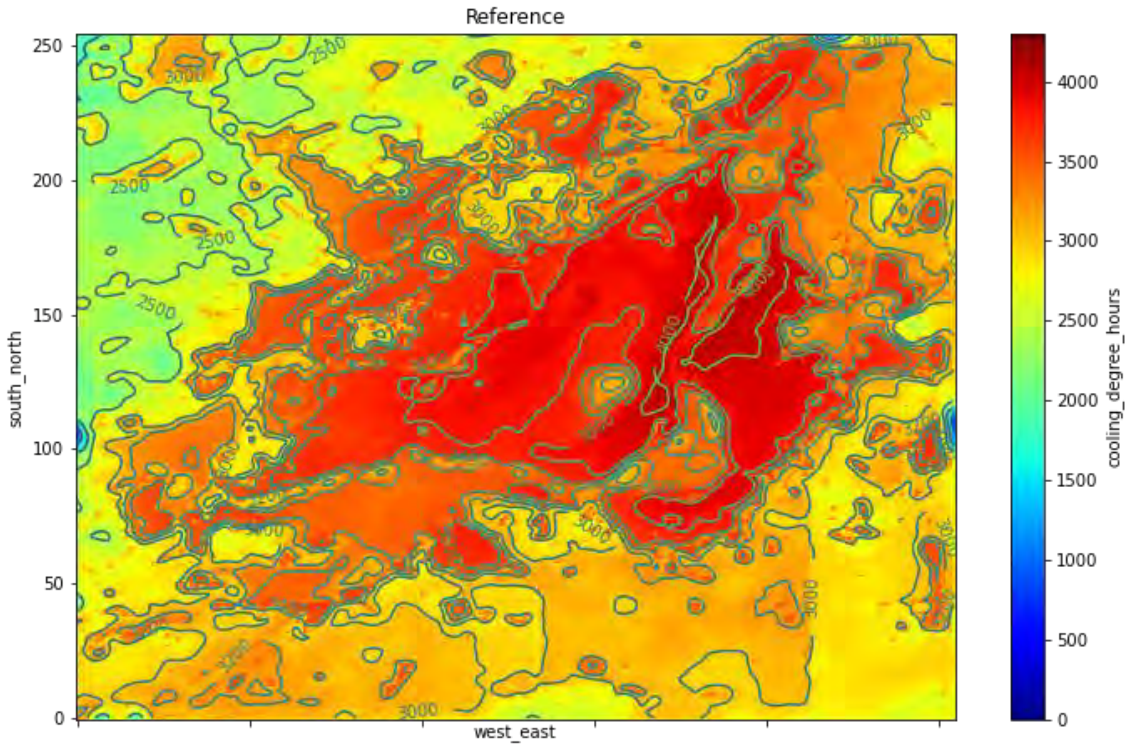


Weather Station	RMSE [°C]
Ste-Anne	2.68
Airport	2.91
McTavish	2.60

UHI characterization: CDH

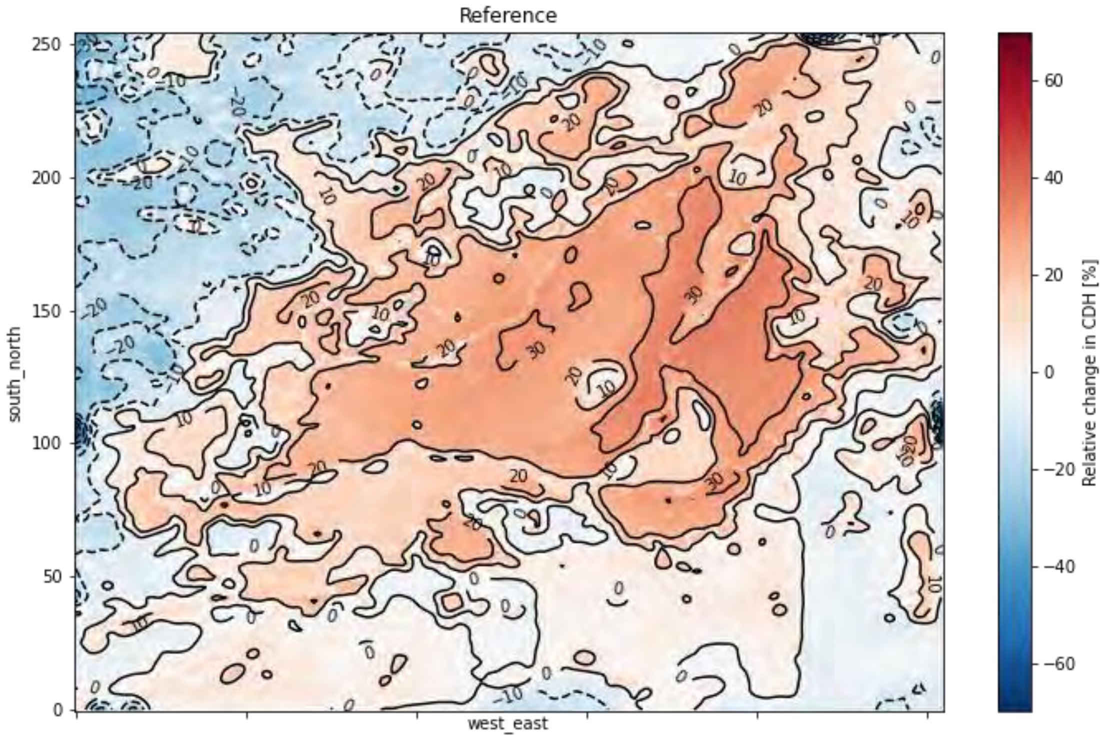
Montreal

CDH (setpoint 20°) from 15 May to 30 June 2020



CDH varies between 2400 and 4500 °C.h

Relative change CDH urban versus rural

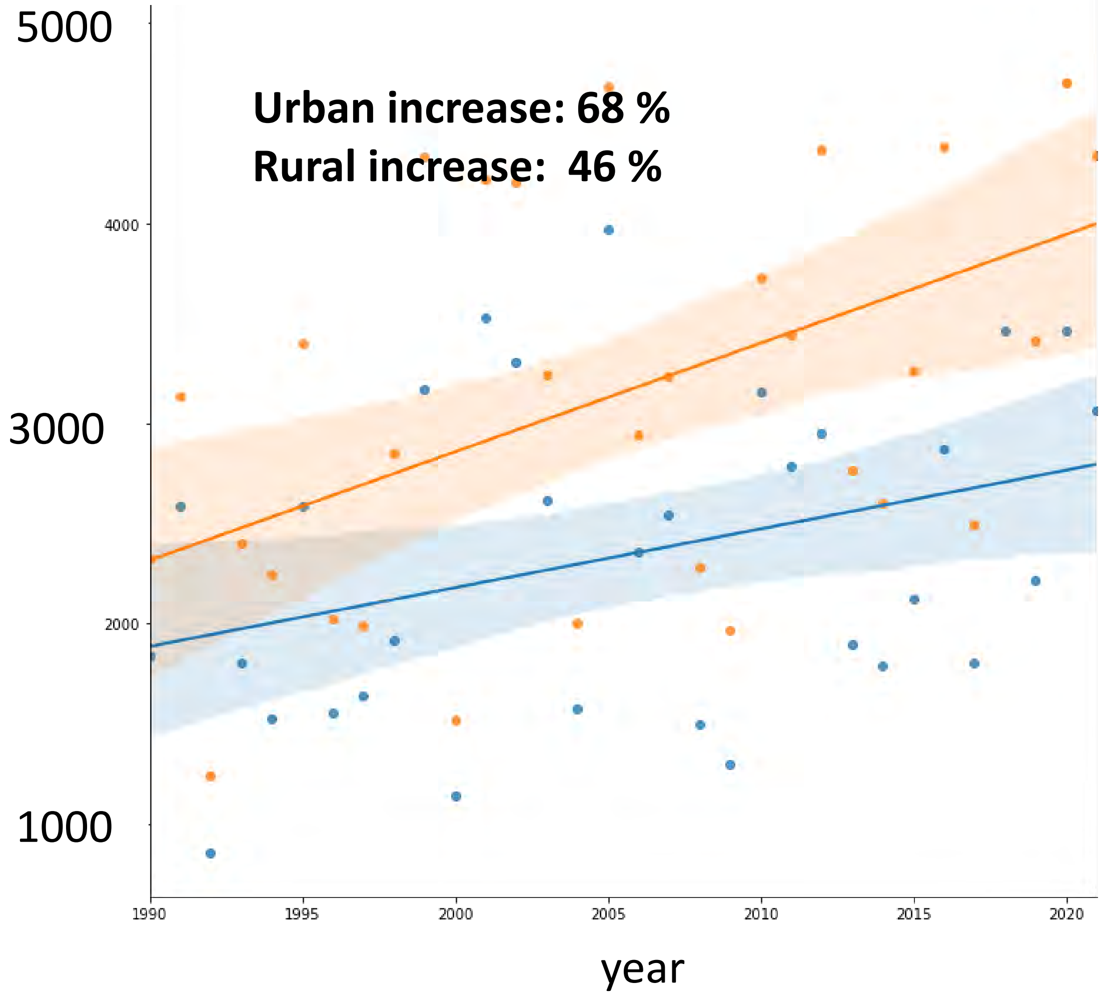


CDH varies between -25% to 40%

Yearly cooling degree hours based on historical data
1991-2020

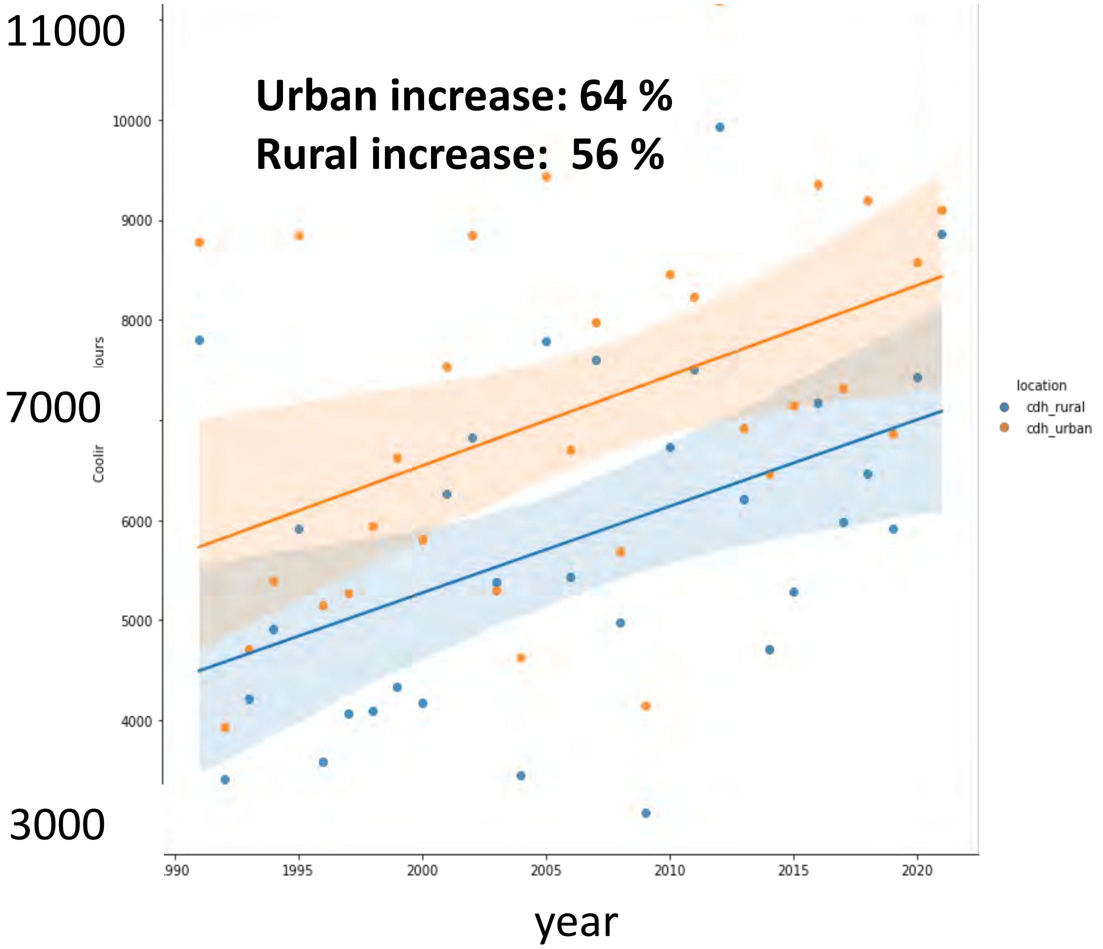
Montreal

Cooling degree hours 1991-2011



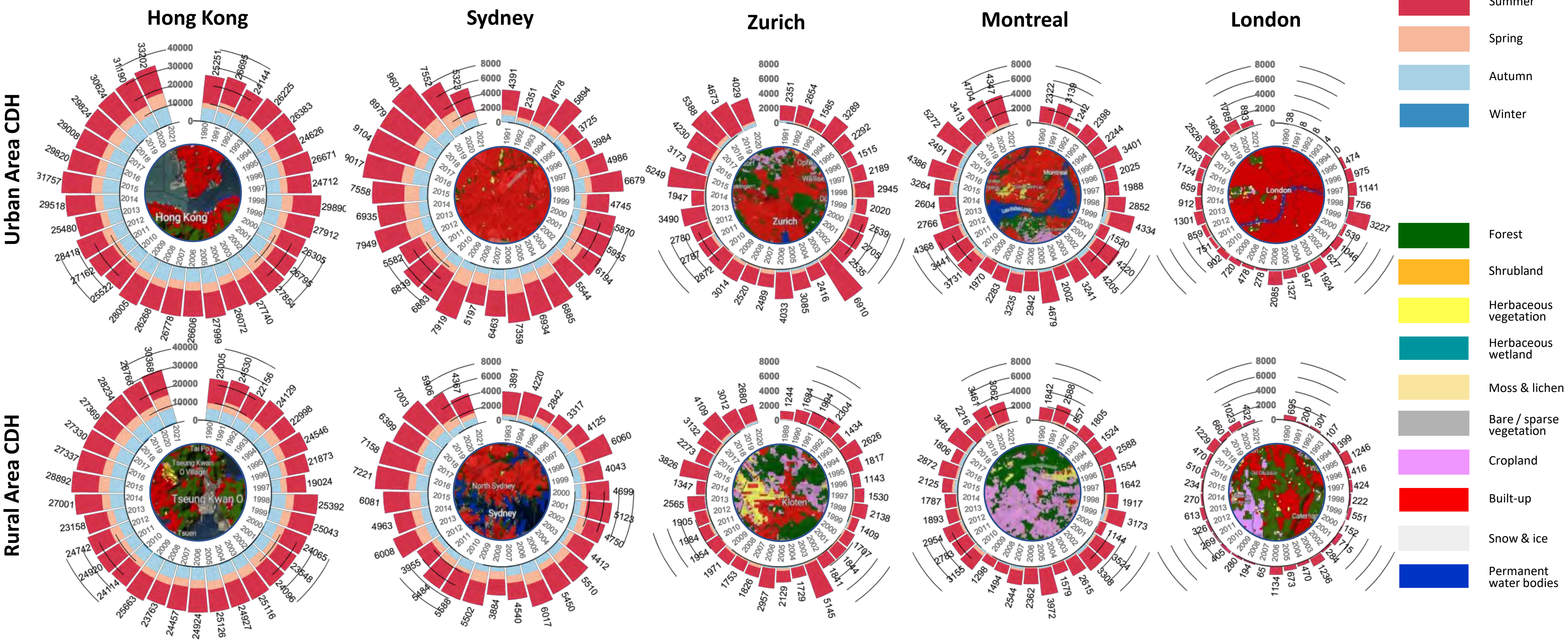
Chicago

Cooling degree hours 1991-2011

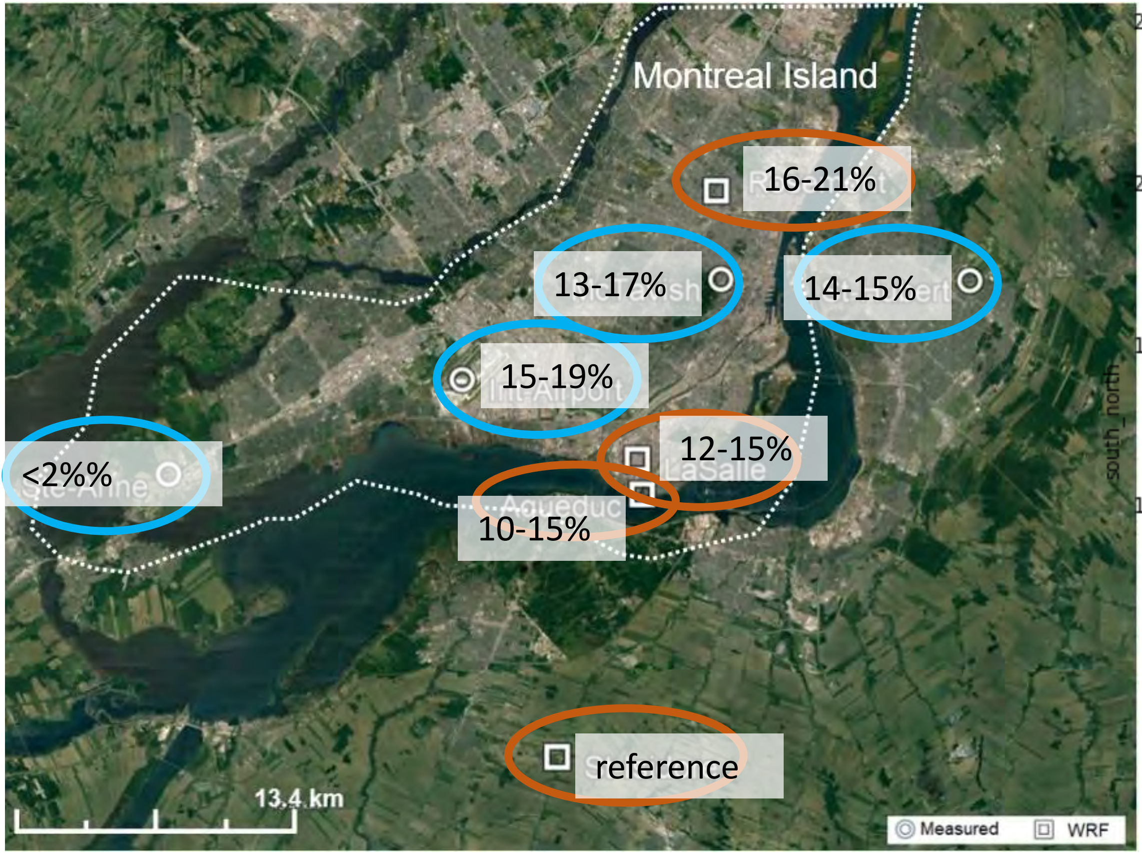


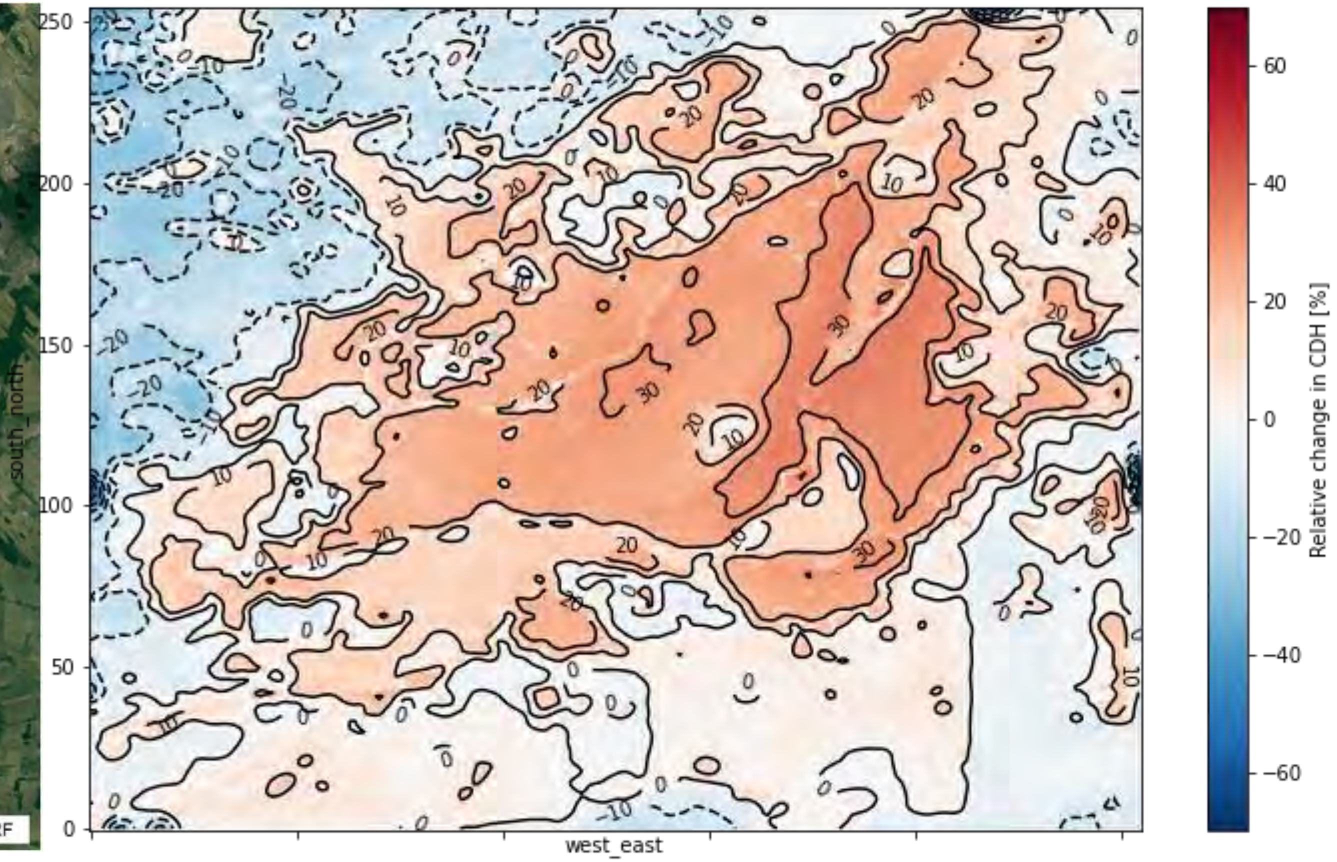
Yearly cooling degree hours based on historical data

1991-2020



Increase of cooling energy demand relative to urban location in Montreal





- The reference climate file for Montreal underpredicts CED with 30 % (rural) and 50% compared to the real CED during summer of 2019
- The CED during heatwave days is almost 50% of the total CED in 2019

Boudali Errebai F., Strebel D., Carmeliet J. and Derome D., Impact of urban heat island on cooling energy demand for residential building in Montreal using meteorological simulations and weather station observations, Energy and Buildings, vol. 273, 2022.

Definition of heatwave

Definitions vary relative to the 'normal' climate people experience

Table 4. HW definitions adopted in the reviewed literature.

Metric	Intensity	Duration (Days)	Location	Ref.
T_{max}	32 °C	10	Taiwan Region	[55]
T_{max}	32.2 °C	3	USA	[53,89,90,103,113]
T_{max}	33 °C	2	South Korea	[118]
T_{max}	33 °C	3	South Korea	[45]
T_{max}	35 °C	3	China Mainland	[29,46,115]
T_{max}	35 °C	10	Taiwan Region	[55]
T_{max}	36.5 °C	3	Spain	[59]
T_{max}	37 °C	3	Greece	[122,123]
T_{max}	90th	3	Romania	[58]
T_{max}	98th	3	Romania	[58]
T_{max}	95th	3	Romania, Australia	[58,128]
T_{max}	95th	4	Cyprus	[119]
T_{max}	97.5th	5	USA	[96]
T_{max}	97.5th and 81st	3	USA, China Mainland, Poland, UK	[28,34,104,105]
T_{max}	T_{max} + 5 °C [1]	3	UK	[129]
T_{max}	T_{max} + 5 °C [1]	5	Hungary	[117]
T_{mean}	25 °C	3	Hungary	[117]
T_{mean}	27 °C	3	Hungary	[117]
T_{mean}	90th	3	Portugal	[30]
T_{max} and T_{min}	32 °C and 16 °C	2	France	[48]
T_{max} and T_{min}	30 °C and 18 °C	3	Belgium	[112]
T_{max} and T_{min}	30 °C and 20 °C	5	Hungary	[117]
T_{max} and T_{min}	90th	3	Australia	[124]
T_{max} and T_{min}	95th	3	India	[56]
T_{max} and T_{mean}	35 °C and 29 °C	3	Singapore	[25]
HI_{max} [2]	65 °C	4	Cyprus	[119]

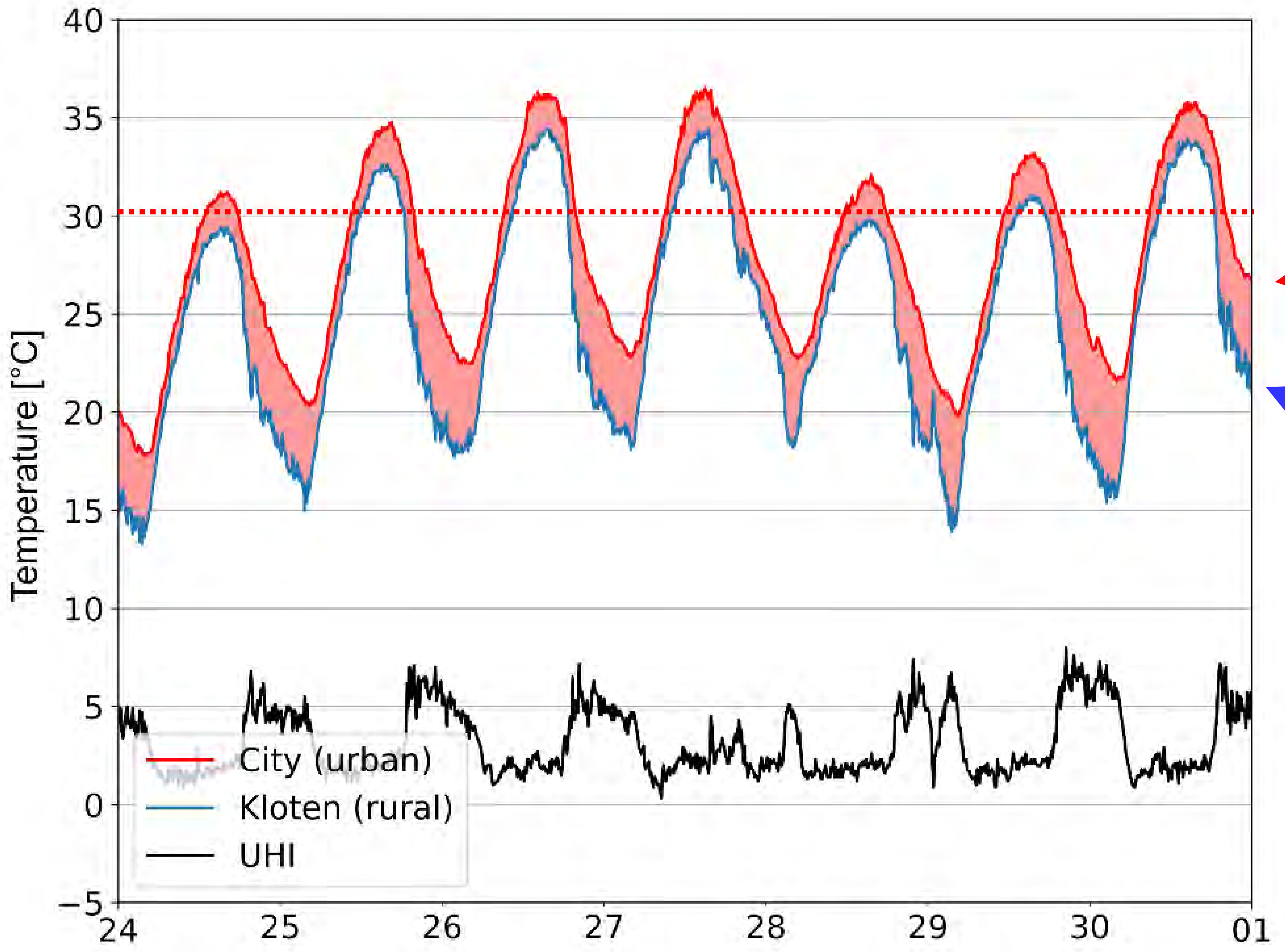
[1] T_{max} + 5 °C means the exceedance of the average daily maximum temperature by 5 °C. [2] HI= $-42.379 + 2.04901523T + 10.14333127RH - 0.22475541T \times RH - 6.83783 \times 10^{-3}T^2$ $5.481717 \times 10^{-2}RH^2 + 1.22874 \times 10^{-3}T^2RH + 8.5282 \times 10^{-4}T \times RH^2 - 0.199 \times 10^{-6}T^2RH^2$. (RH is relative humidity, T is air temperature in Fahrenheit).

Differences in

- **Metric**: T_{max}, T_{min}, HI_{max}
- **Intensity**: 30 – 37°C, percentile
- **Duration**: 3-10 days

Jing Kong, Yongling Zhao, Jan Carmeliet and Chengwang Lei, Urban Heat Island and Its Interaction with Heatwaves: A Review of Studies on Mesoscale, Sustainability, vol. 13: no. 19, pp. 10923, 2021

Example of heat wave Zurich 2019



minimum three consecutive days temperature higher than 30°C

City (urban)

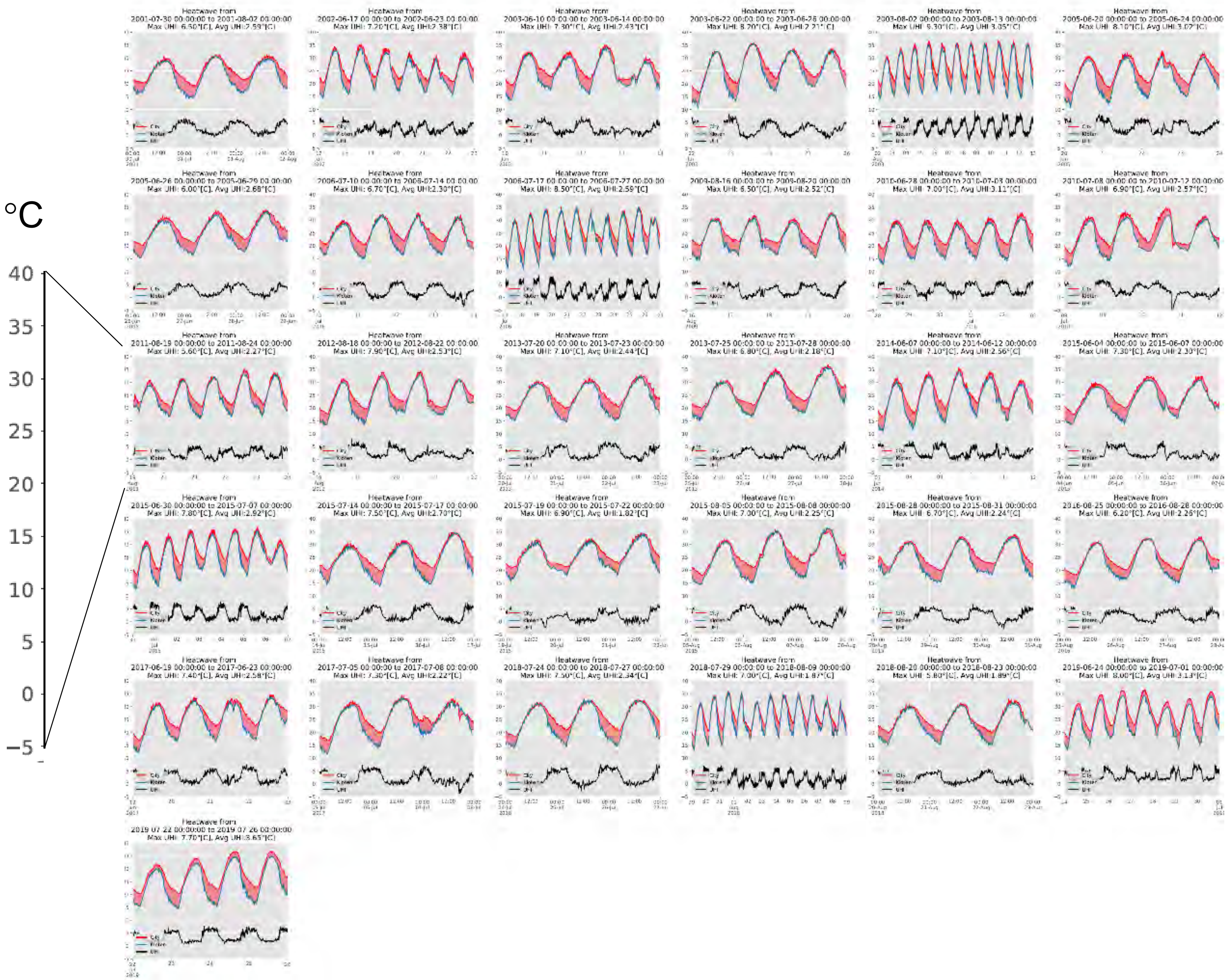
Air temperature at 2 m

Kloten (rural)

Urban heat island intensity

Urban air temperature – rural air temperature

Heatwaves in a changing climate

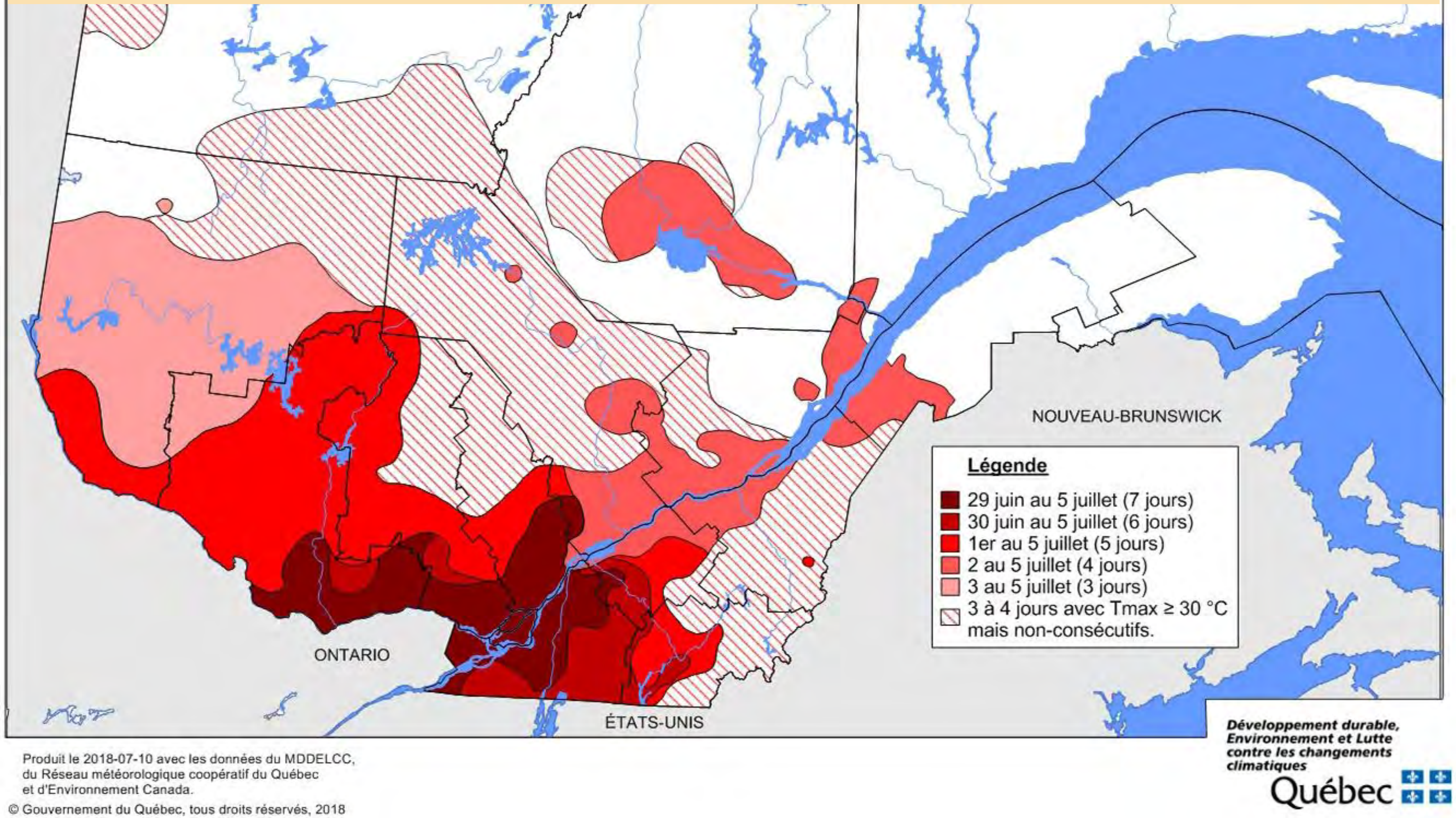


Zurich
more than 30 heat waves
in the period 2001 – 2020

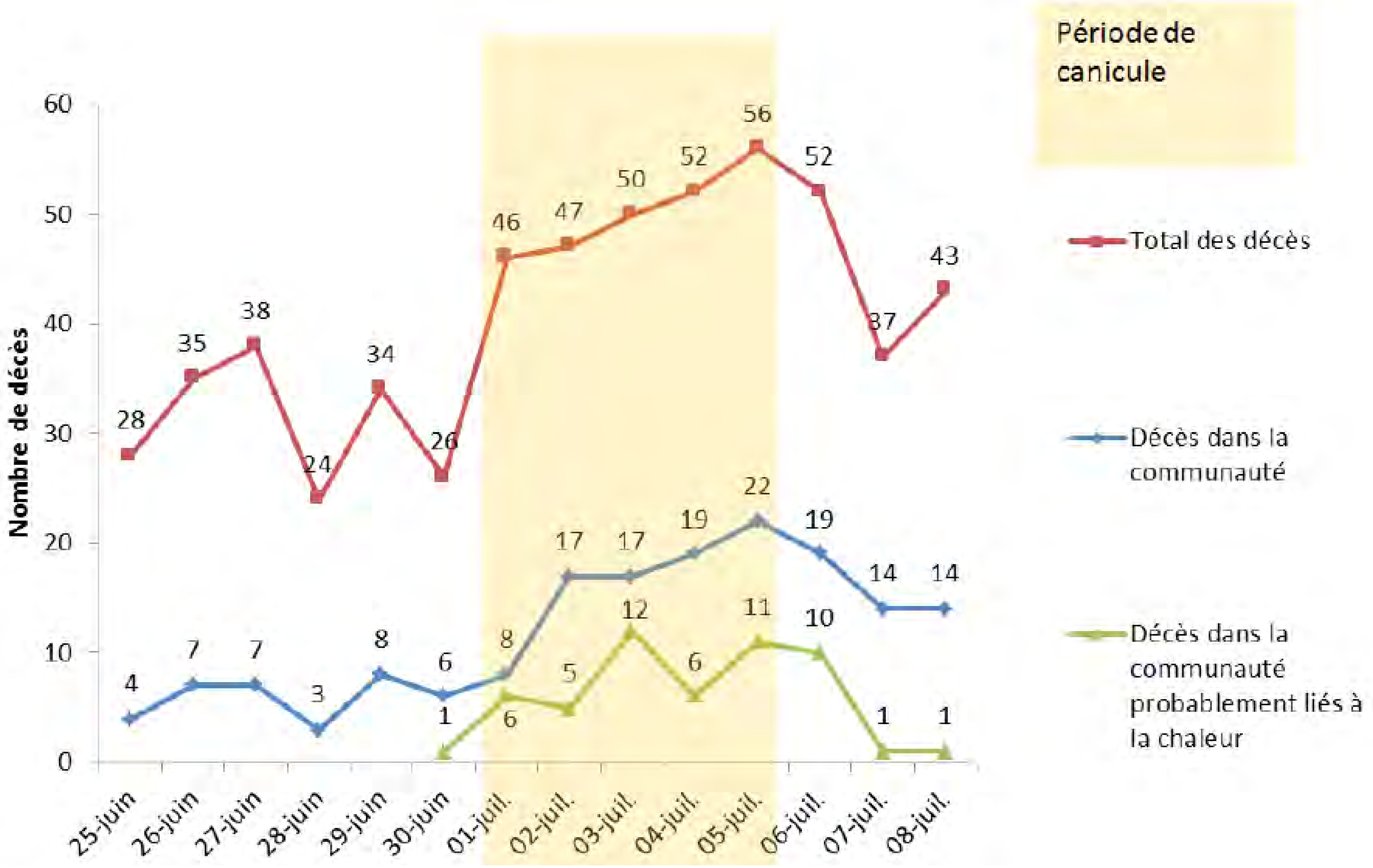
Montréal   Canicule 29 juin au 5 juillet 2018, étendue et durée

Pour la période du 30 juin au 7 juillet, la Direction régionale de santé publique de Montréal a identifié 53 décès comme étant probablement liés à la chaleur.
https://santemontreal.qc.ca/population/actualites/nouvelle/canicule-de-juillet-2018-a-montreal-publication-du-bilan-preliminaire/

La canicule a été particulièrement éprouvante à Montréal et en Montérégie, où sont survenus la grande majorité des 70 décès attribuables à la chaleur.
http://www.environnement.gouv.qc.ca/climat/Faits-saillants/2018/canicule.htm



Montréal   Canicule 29 juin au 5 juillet 2018, nombre de décès

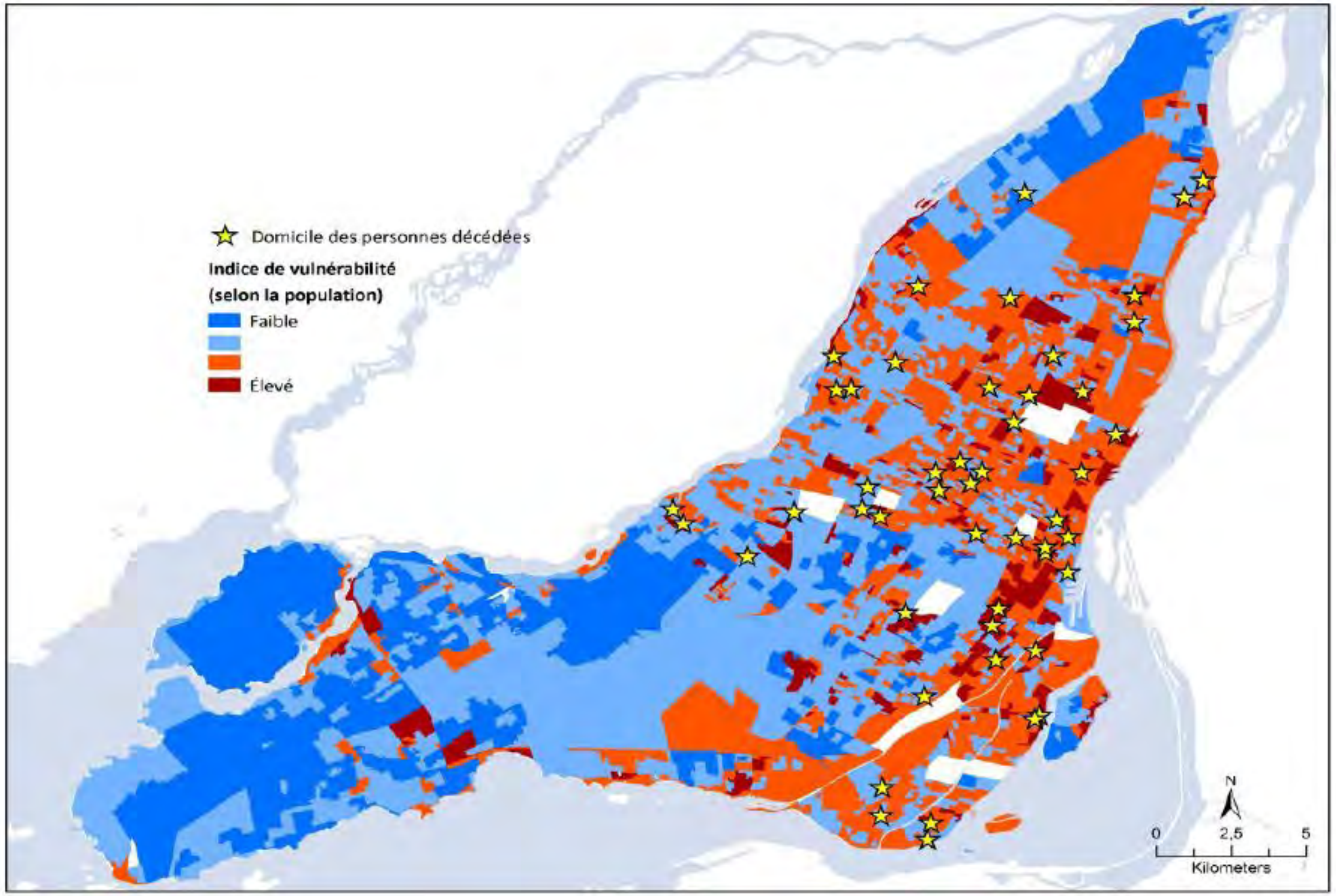


Sources : Données de la vigie sanitaire (décès totaux & décès dans la communauté), consultées le 19 juillet à 16h. Les données de décès probablement liés à la chaleur ont été répertoriées par la DRSP (2018) à la suite de signalements de médecins d'Urgences-santé.

CANICULE : JUILLET 2018 – MONTRÉAL BILAN PRÉLIMINAIRE Direction régionale de santé publique, CIUSSS du Centre-Sud-de-l'Île-de-Montréal https://santemontreal.qc.ca/fileadmin/fichiers/actualites/2018/07_juillet/BilanCaniculeV2.pdf

Montréal Canicule 29 juin au 5 juillet 2018

INDICE DE VULNÉRABILITÉ À LA CHALEUR ET LOCALISATION DES DÉCÈS LIÉS À LA CHALEUR, ÎLE DE MONTRÉAL, JUILLET 2018



Sources : La climatisation des ménages et la vulnérabilité à la chaleur extrême à Montréal (DRSP, 2017) ; signalements de décès probablement liés à la chaleur répertoriés par la DRSP

CANICULE : JUILLET 2018 – MONTRÉAL BILAN PRÉLIMINAIRE Direction régionale de santé publique, CIUSSS du Centre-Sud-de-l'Île-de-Montréal https://santemontreal.qc.ca/fileadmin/fichiers/actualites/2018/07_juillet/BilanCaniculeV2.pdf

Modeling the urban environment

- due to climate change and its effect on the urban climate
  - i.e. frequency and magnitude of heat waves
- on the urban heat island effect
  - showing higher temperatures in cities, mainly at night

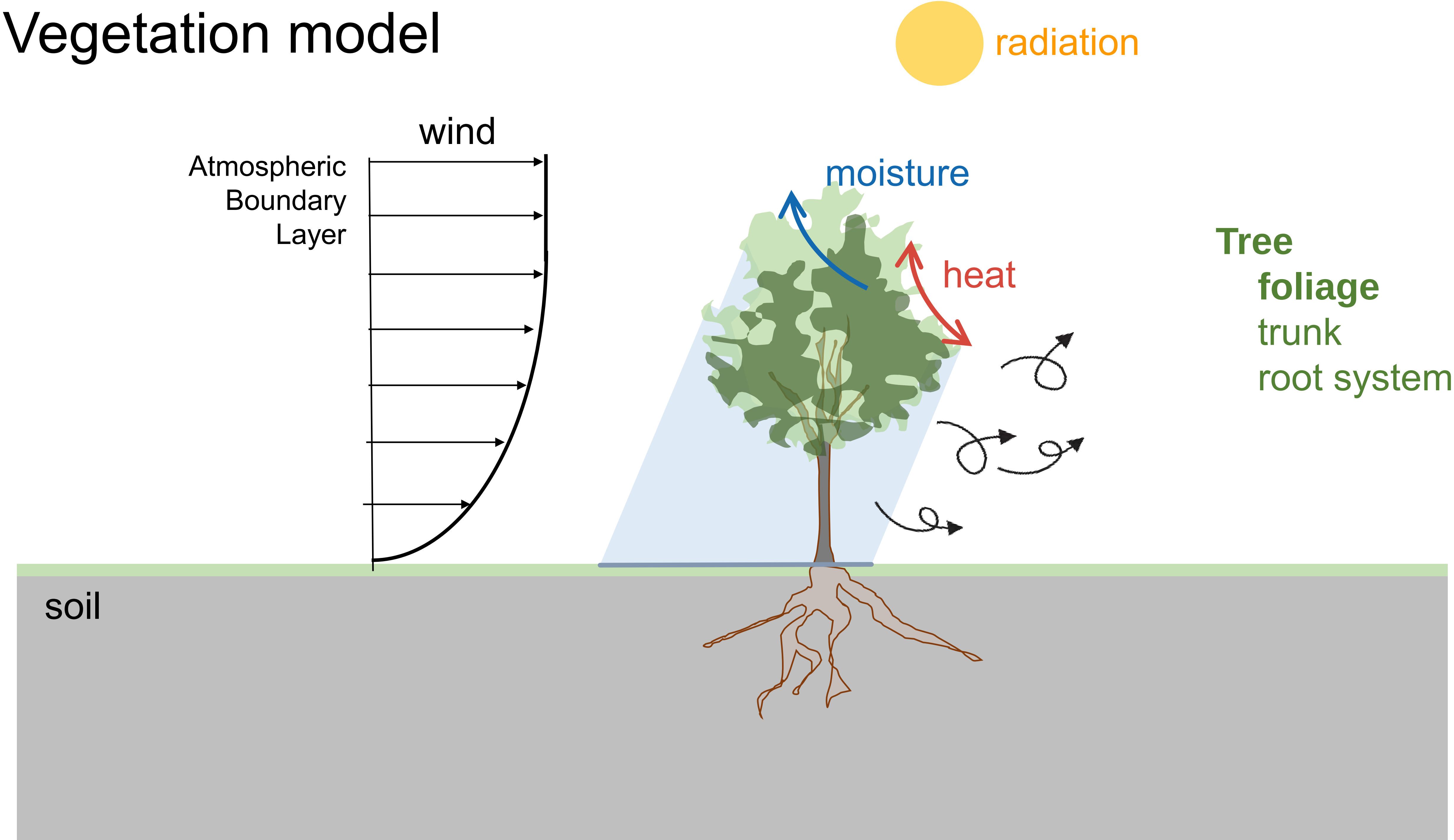
Models:

- mesoscale meteorological models
  - three-step down-nesting to get a 250 m resolution
  - use as boundary conditions for explicitly defined urban scale

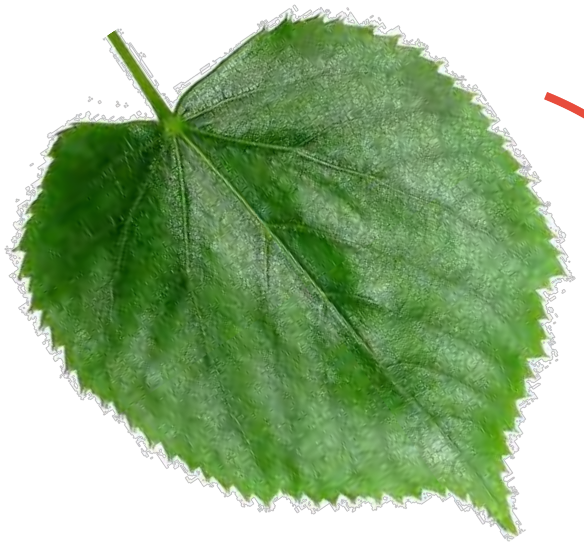
- microscale urban climate model
  - considering air, radiation, solid materials, vegetation

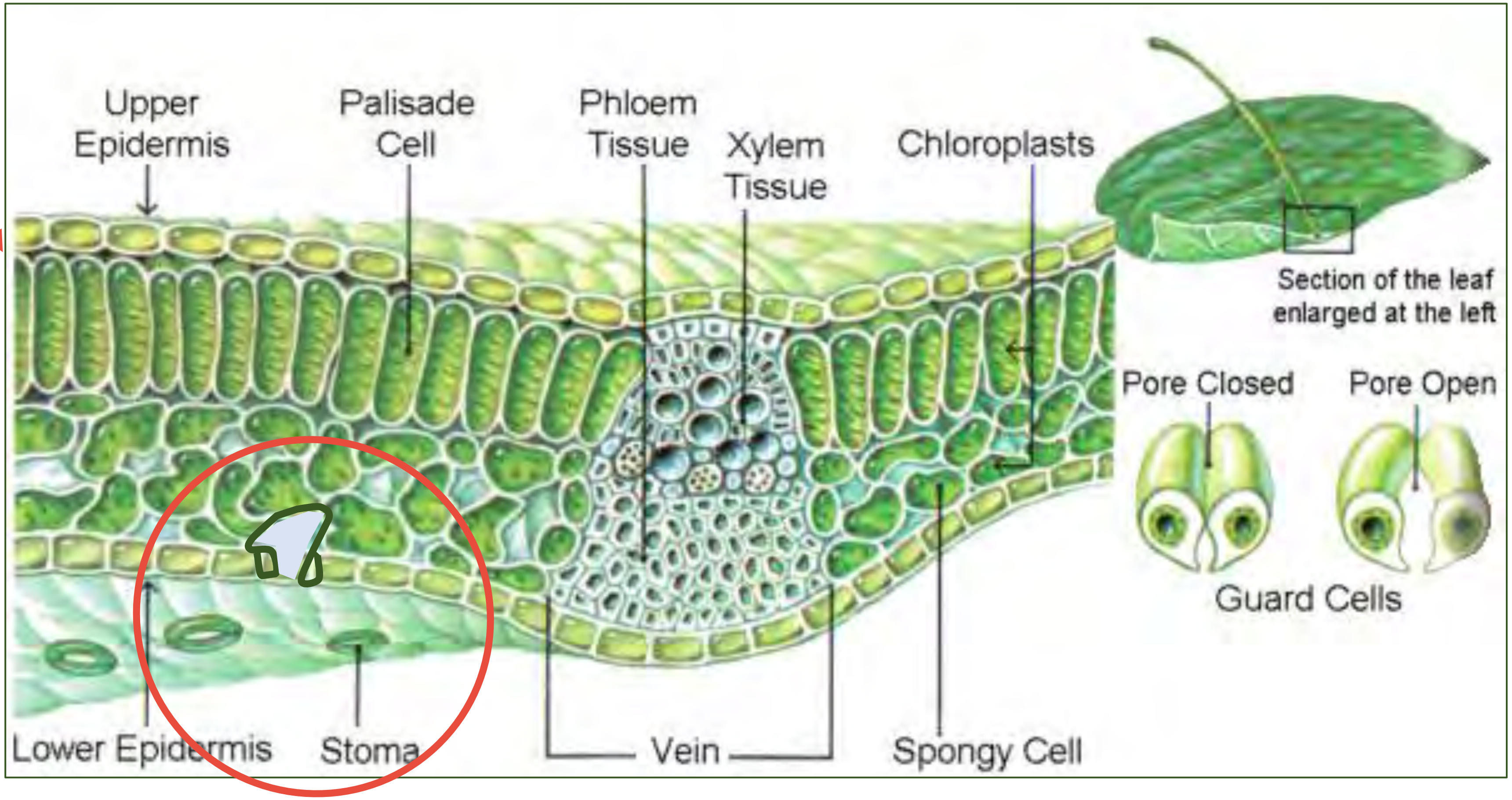
- towards local mitigation scenarios

Vegetation model

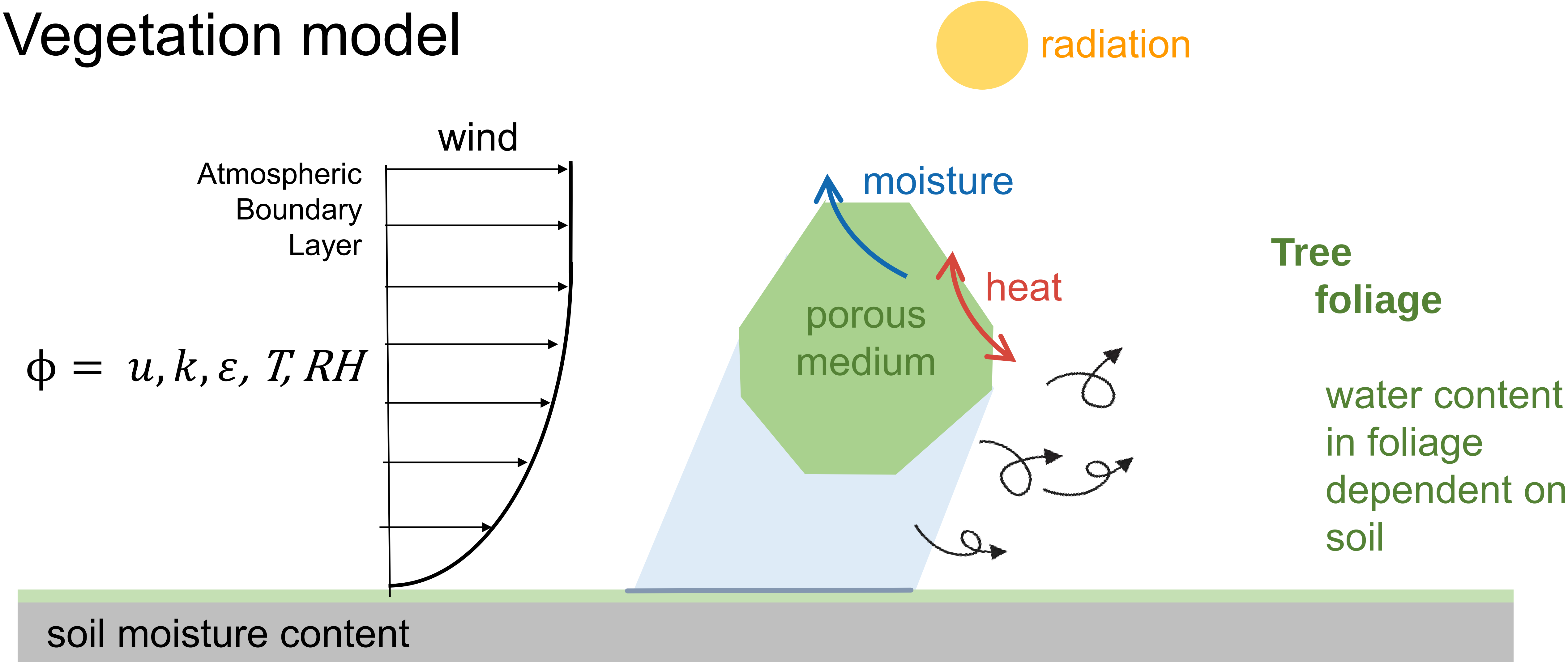


Vegetation model: **leaf model**





Vegetation model



$$\phi = u, k, \varepsilon, T, RH$$

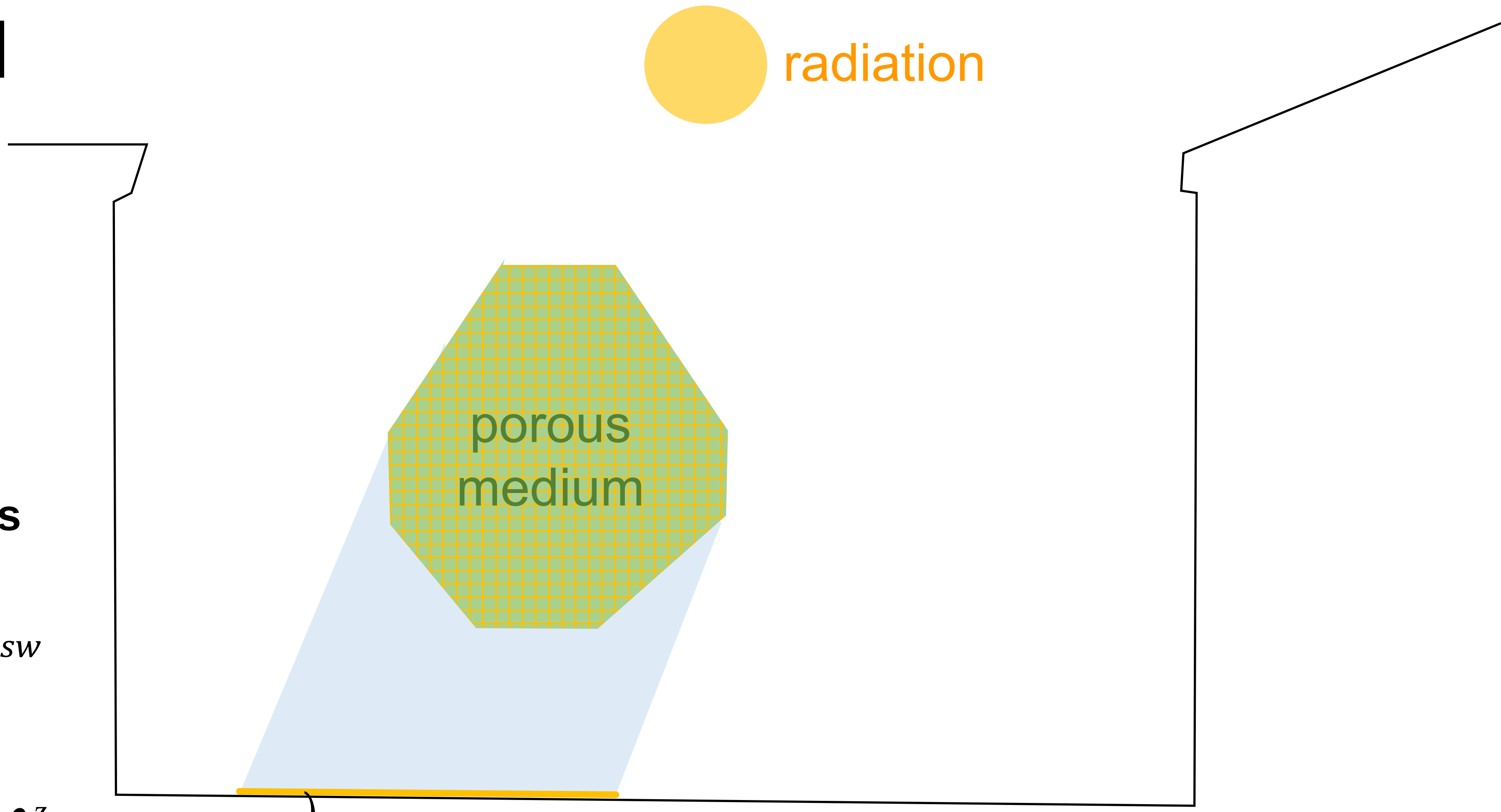
Navier Stokes equations

$$\frac{\partial \phi}{\partial t} + \overline{\boldsymbol{u}} \cdot \nabla \phi = \Gamma \nabla^2 \phi + S_\phi \quad + S_{veg}$$

source/sink

- Steady-state
- Boussinesq approx.
- Realizable $k - \varepsilon$

Vegetation model



Radiation absorbed by leafs

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

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

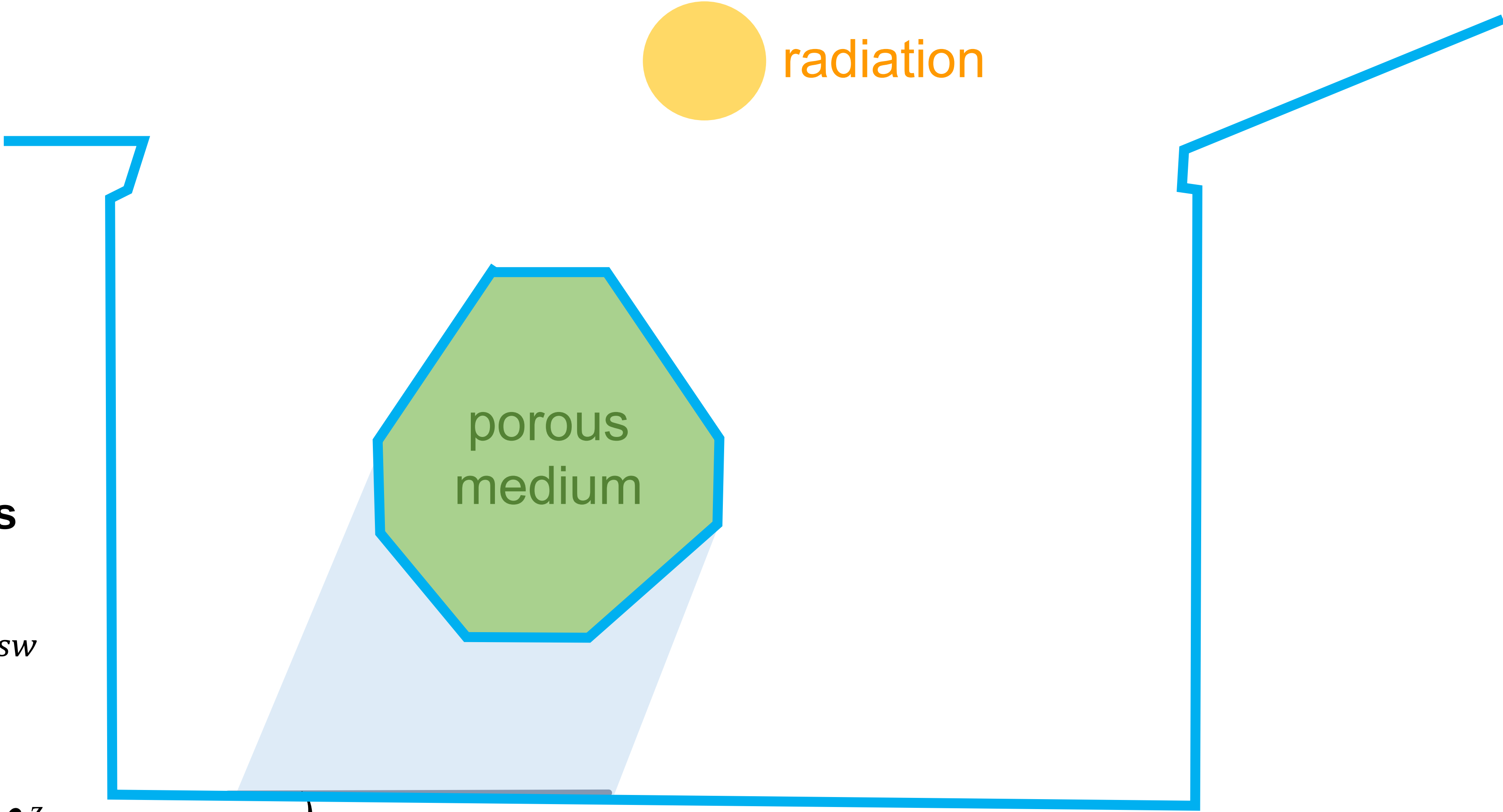
$$q_{r,sw}(z) = q_{r,sw,0}\exp\left\{-\beta\int_0^z LAI(z)\,\mathrm{dz}\right\}$$

Radiation absorbed passed the tree, if any

Tree foliage

LAI: Leaf area index

Vegetation model



Radiation absorbed by leafs

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

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

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

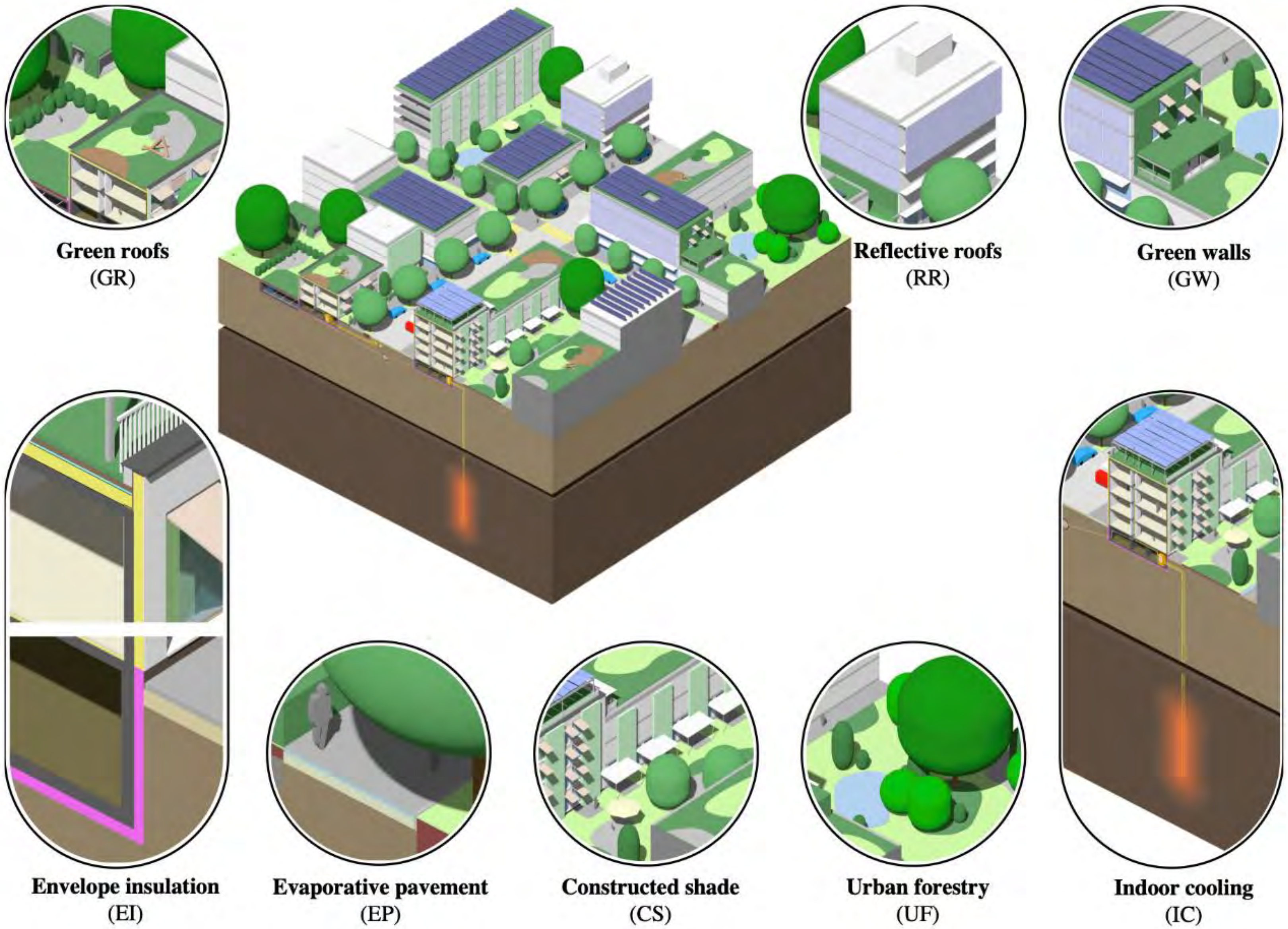
Long-wave radiative flux $q_{r,lw}$

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

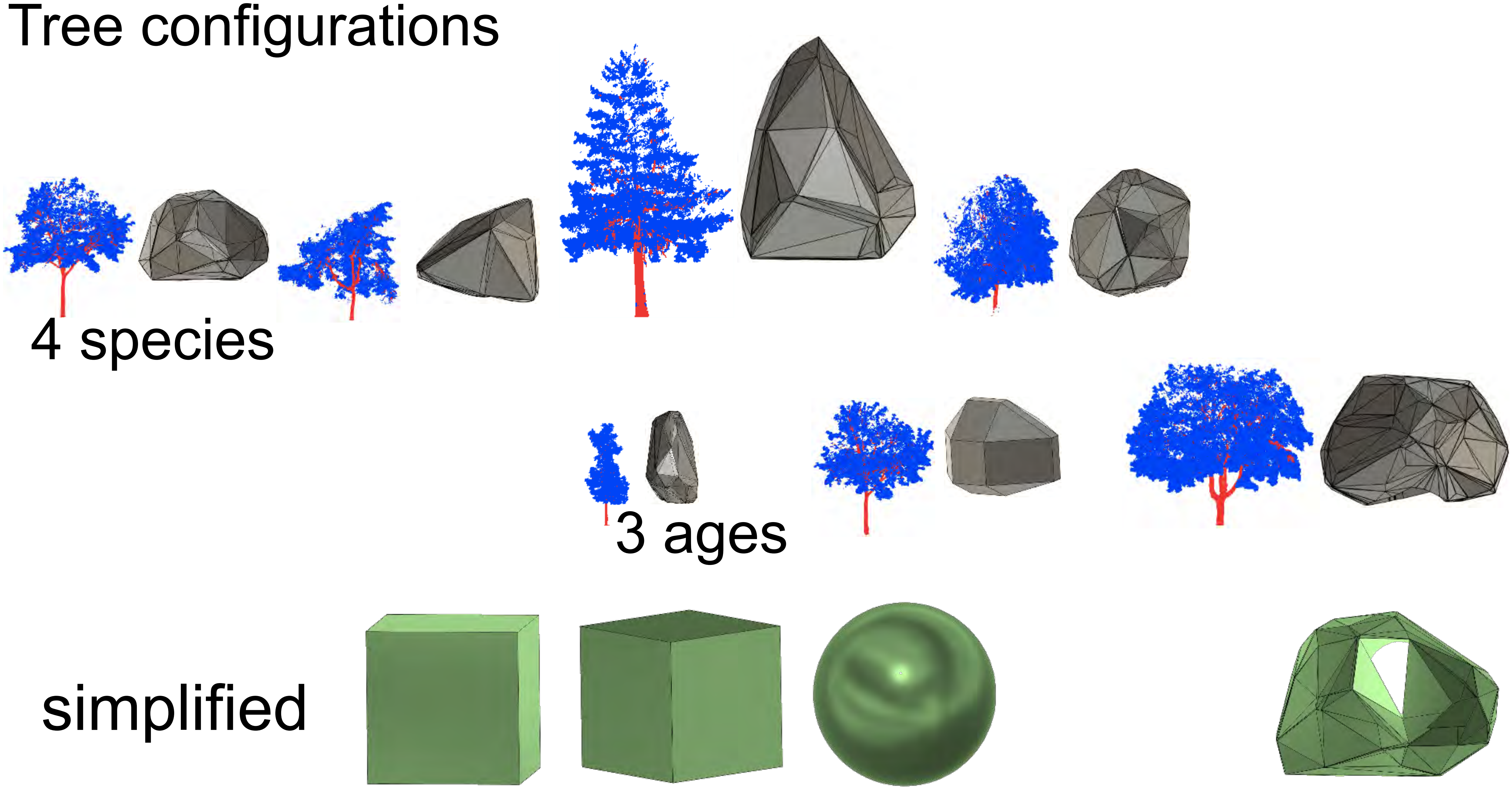
Tree foliage

LAI: Leaf area index

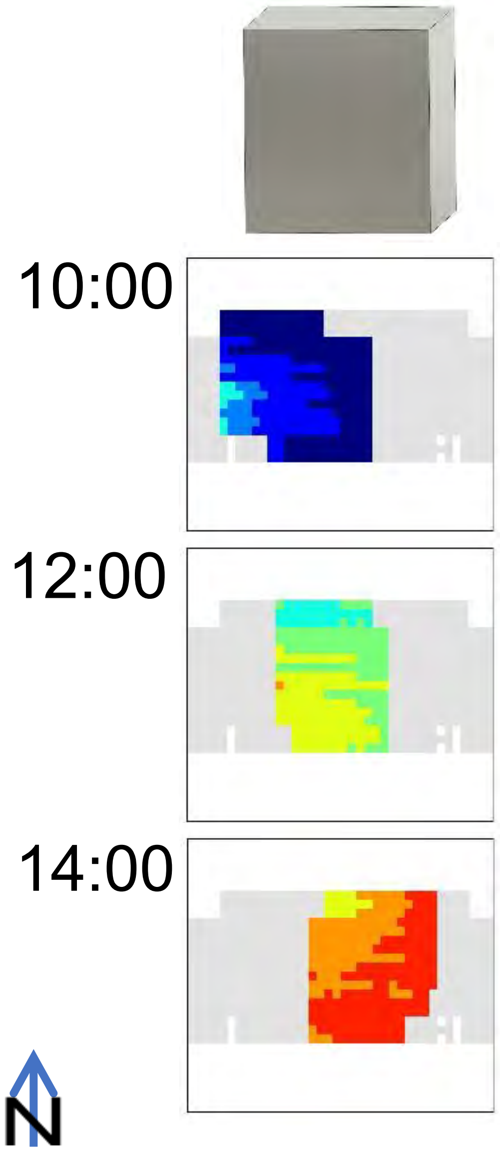
Mitigation measures for heatwaves at the microscale

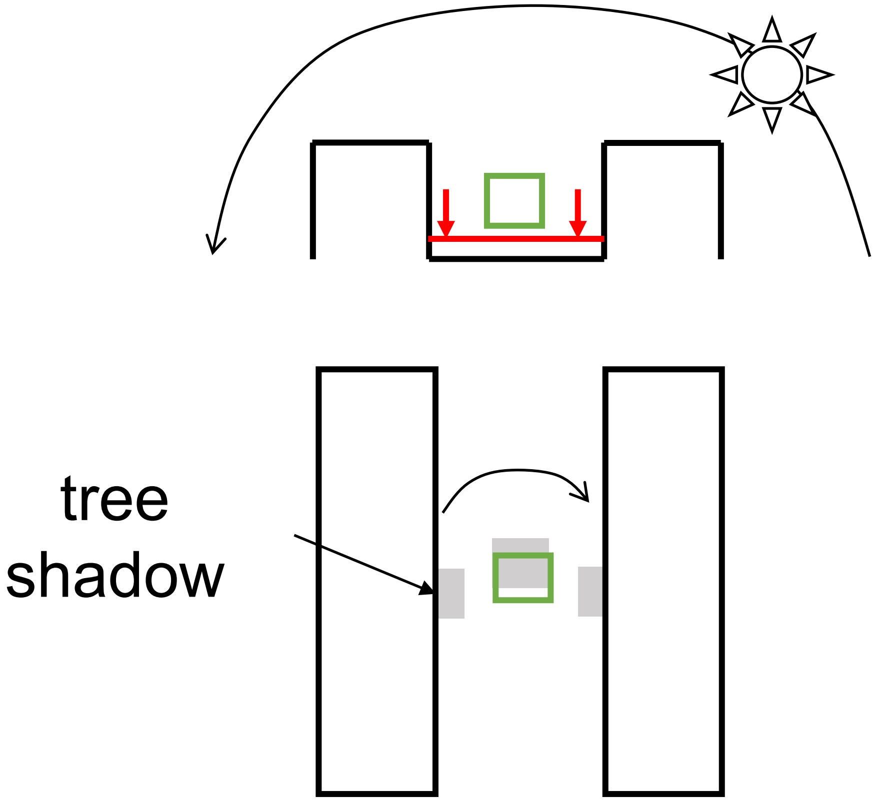


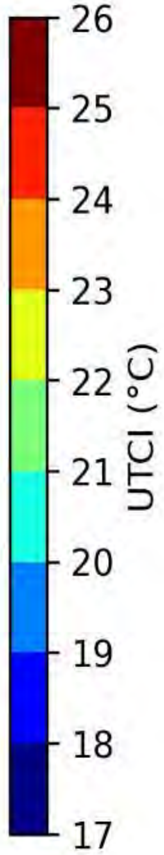
Yongling Zhao et al under review


Tree configurations
4 species
3 ages
simplified

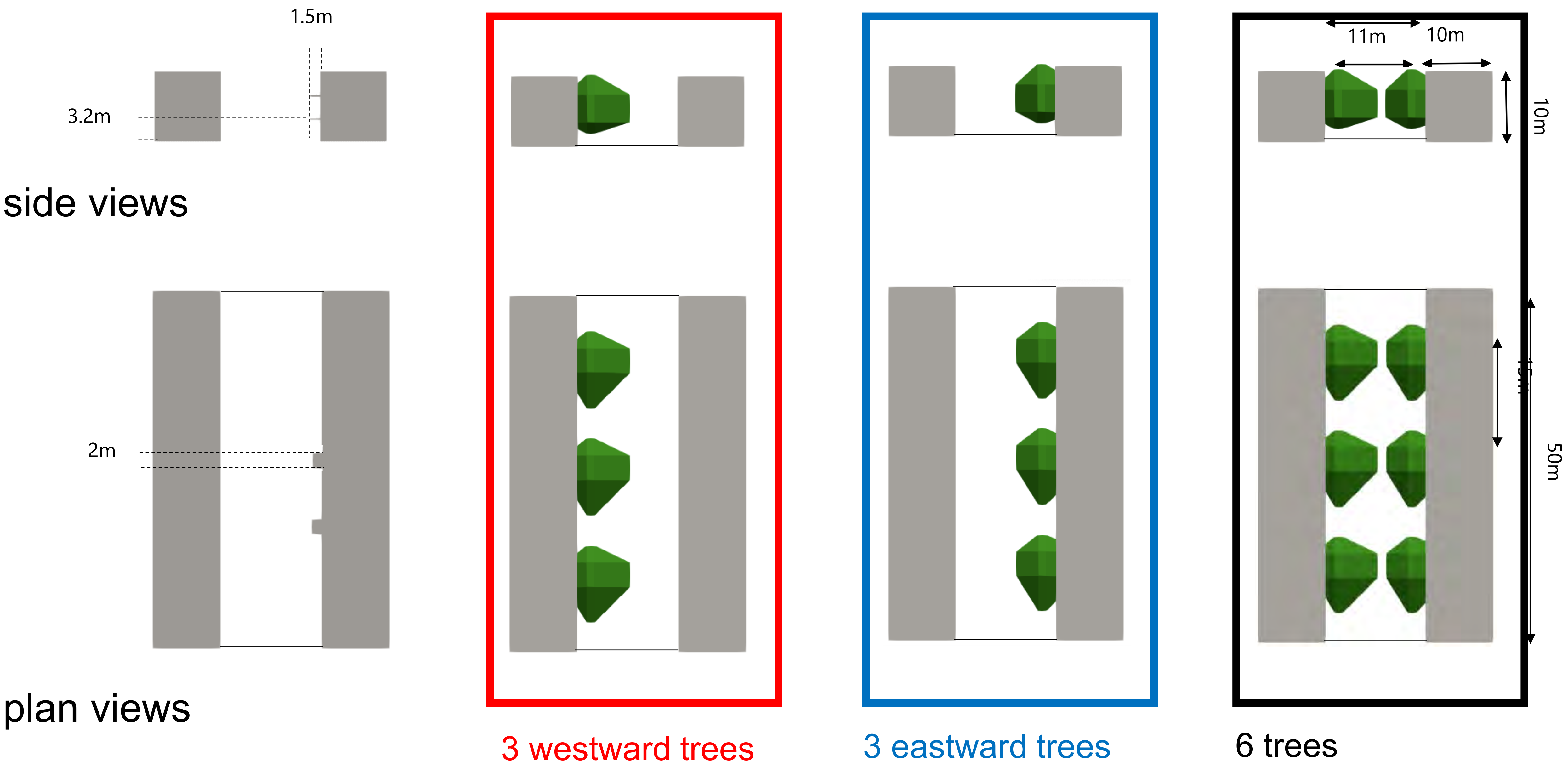
Thermal comfort in shadow of cubic foliage



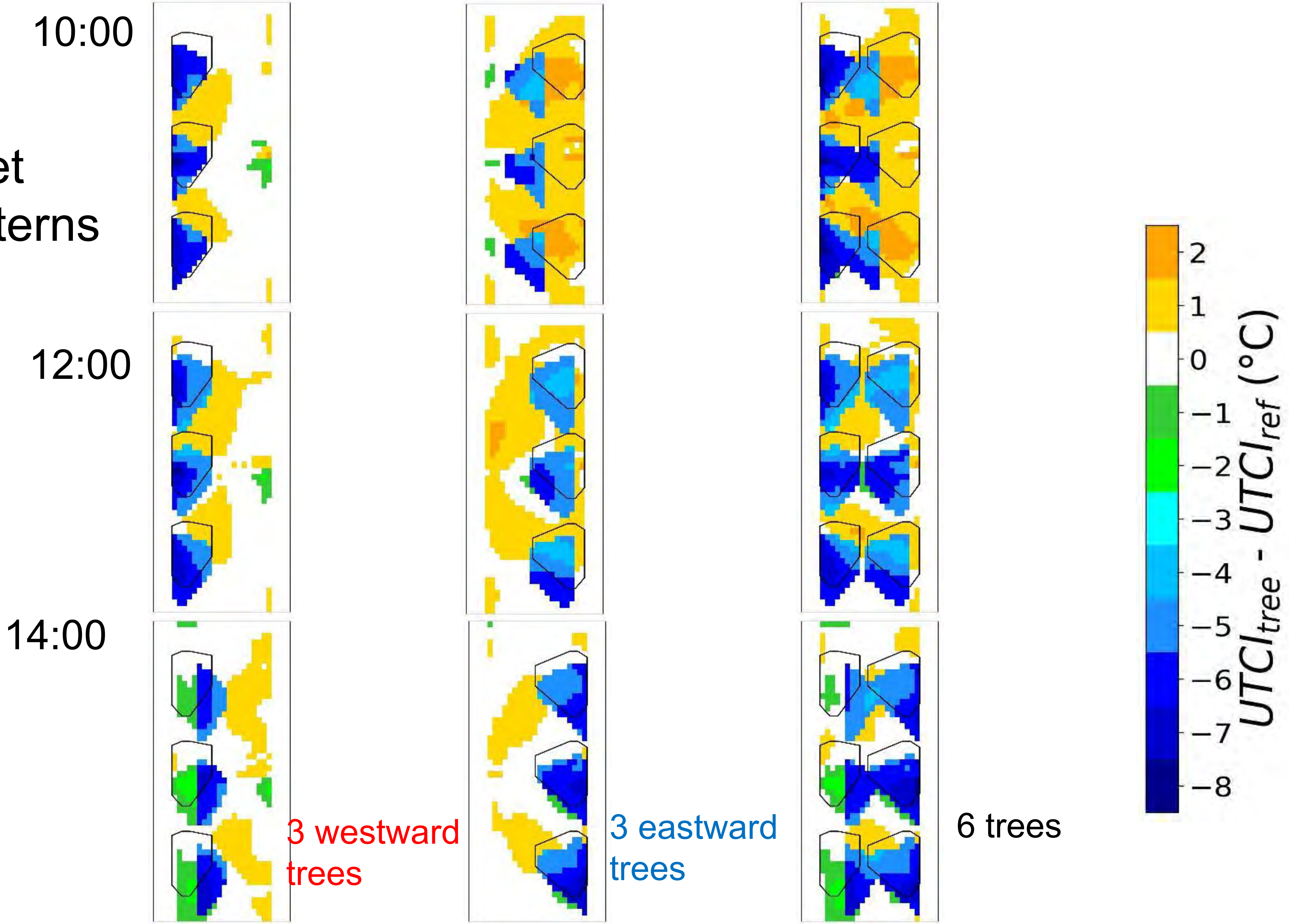




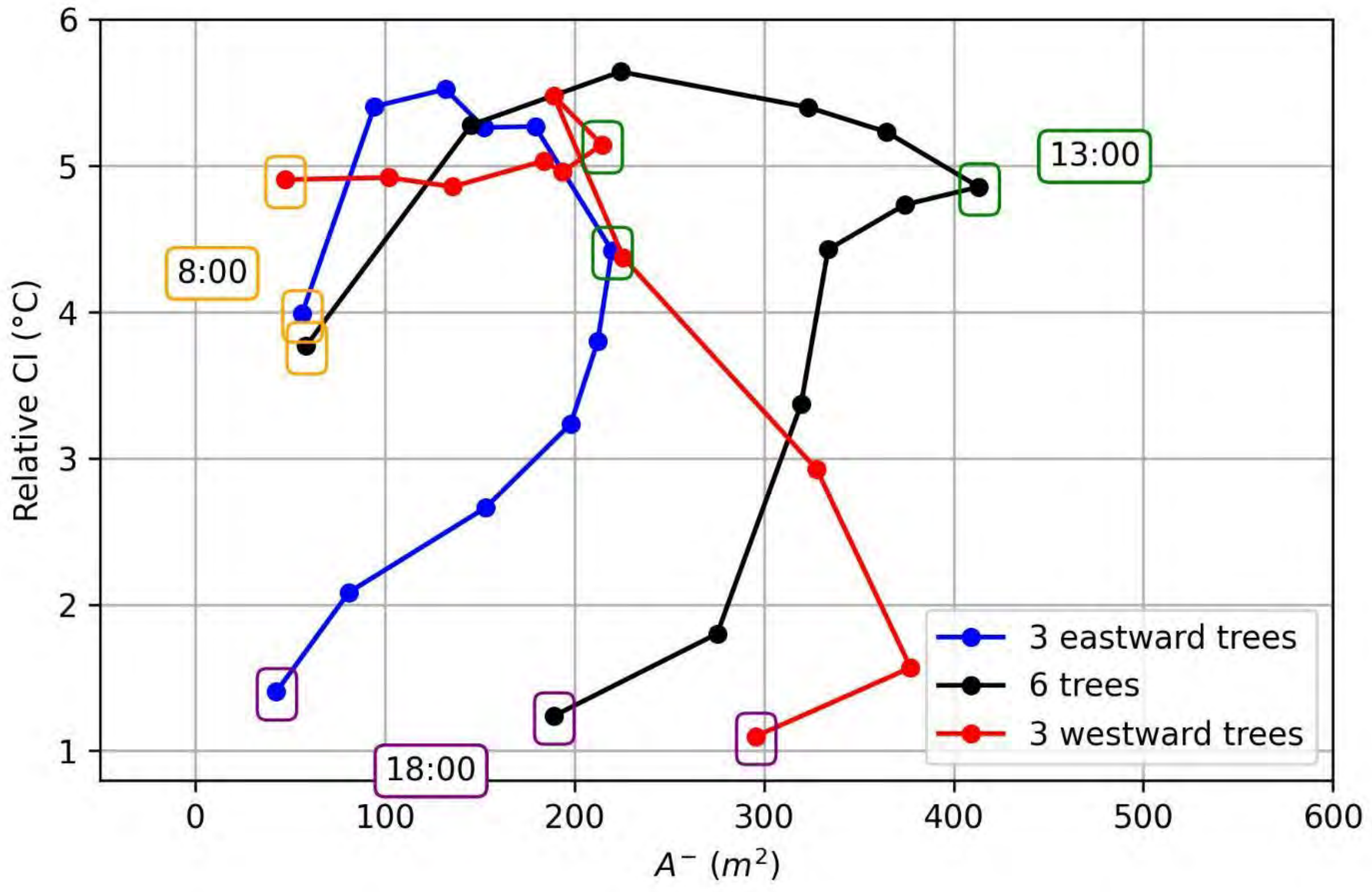
Tree planting patterns



Thermal comfort for different street tree planting patterns



Cooling impact for different tree planting patterns



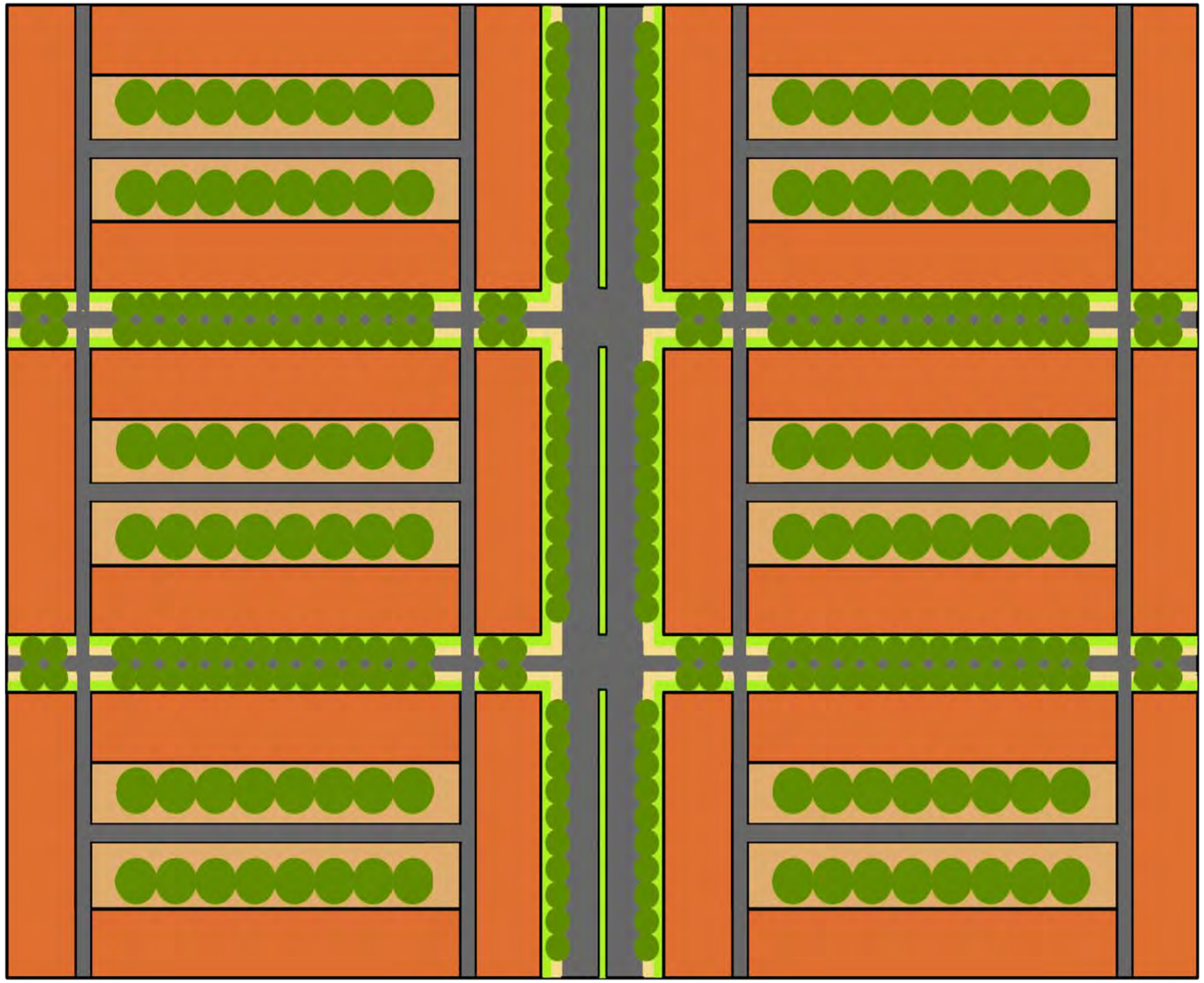
Roles of trees in a neighborhood of Montreal

Inspiration

BD Saint Joseph, Montréal QC https://www.google.com/maps/

Roles of trees in a neighborhood of Montreal

6 blocks
1 boulevard
4 cross streets
6 courtyards

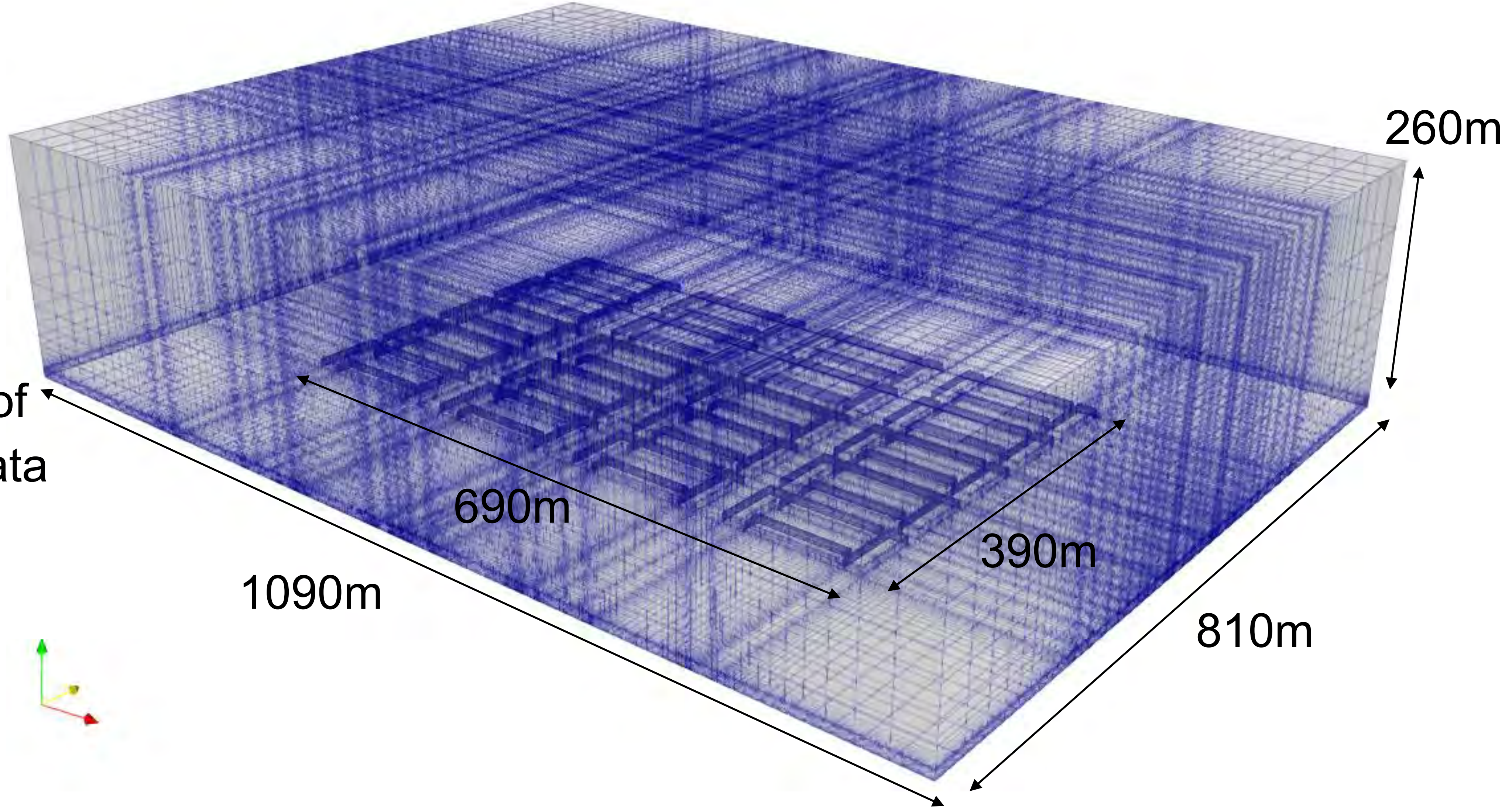


BD Saint Joseph, Montréal QC https://www.google.com/maps/

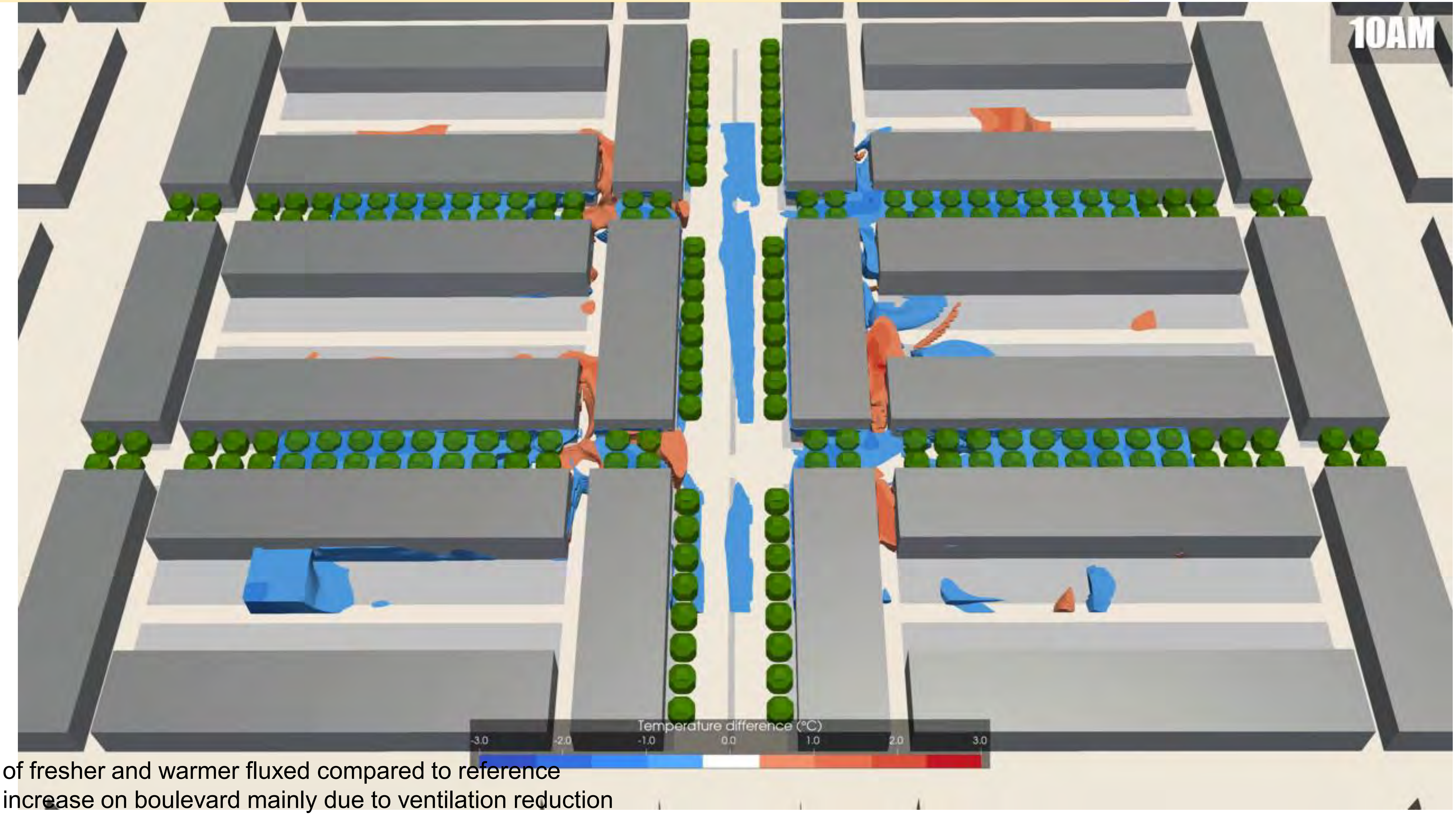
Computational domain and inputs

Boundaries :

Vertical and horizontal interpolation of mesoscale data for velocity, temperature, humidity



Trees in all streets – temperature difference



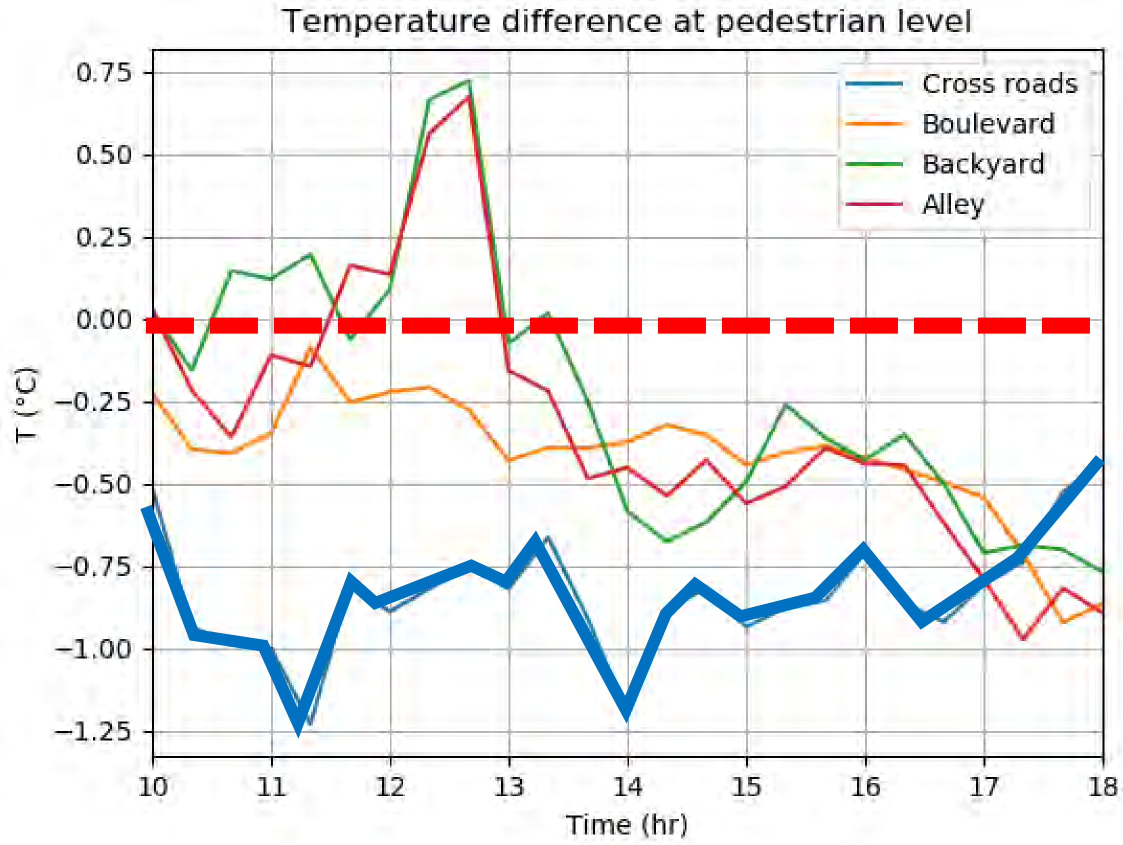
Visualization of fresher and warmer fluxed compared to reference
Temperature increase on boulevard mainly due to ventilation reduction
Pattern appears over the period
Effect of trees not only for planted zones

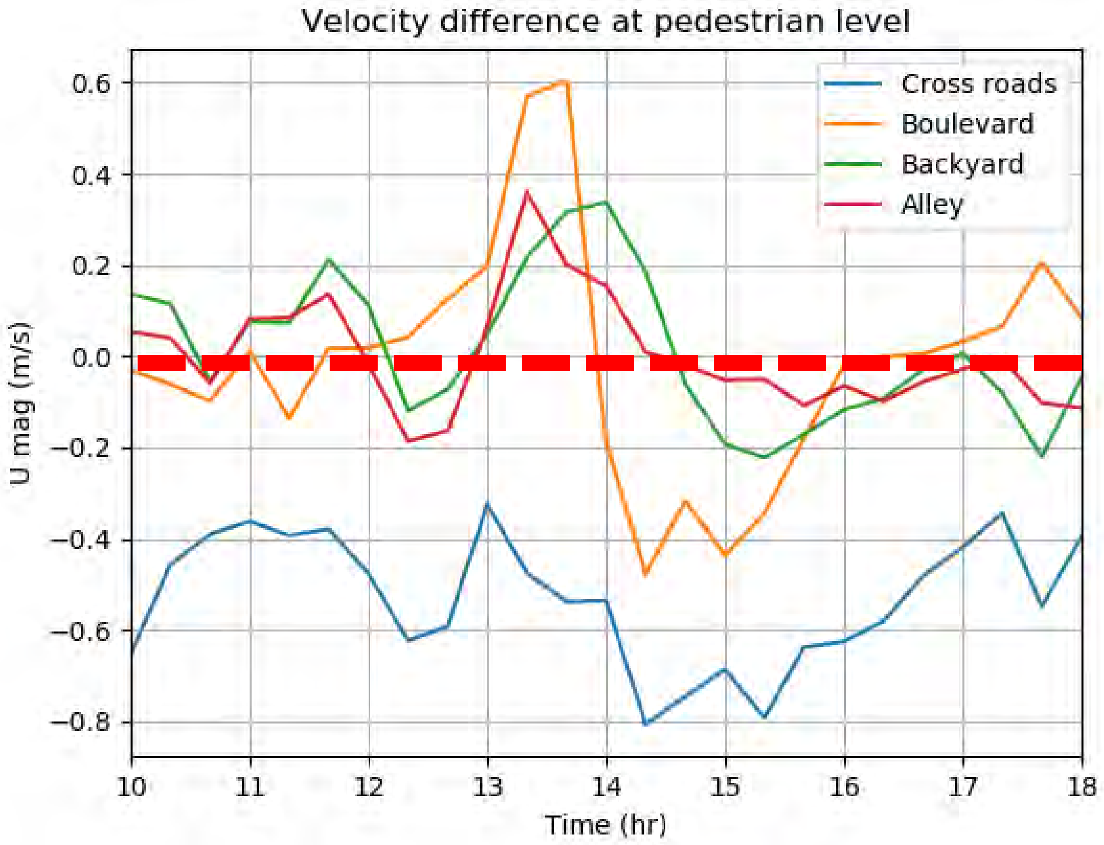
Trees in court yards – temperature difference

Enhancement is mainly by day
Court yard trees allow heat reduction in streets
No influence on the boulevard

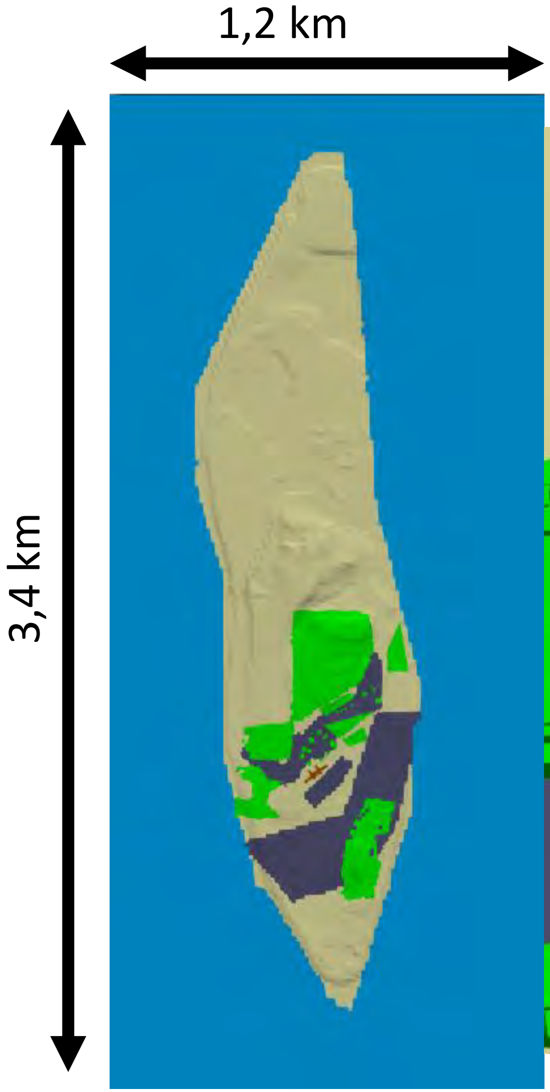
Surface temperature at 14h

small streets (128 medium trees)



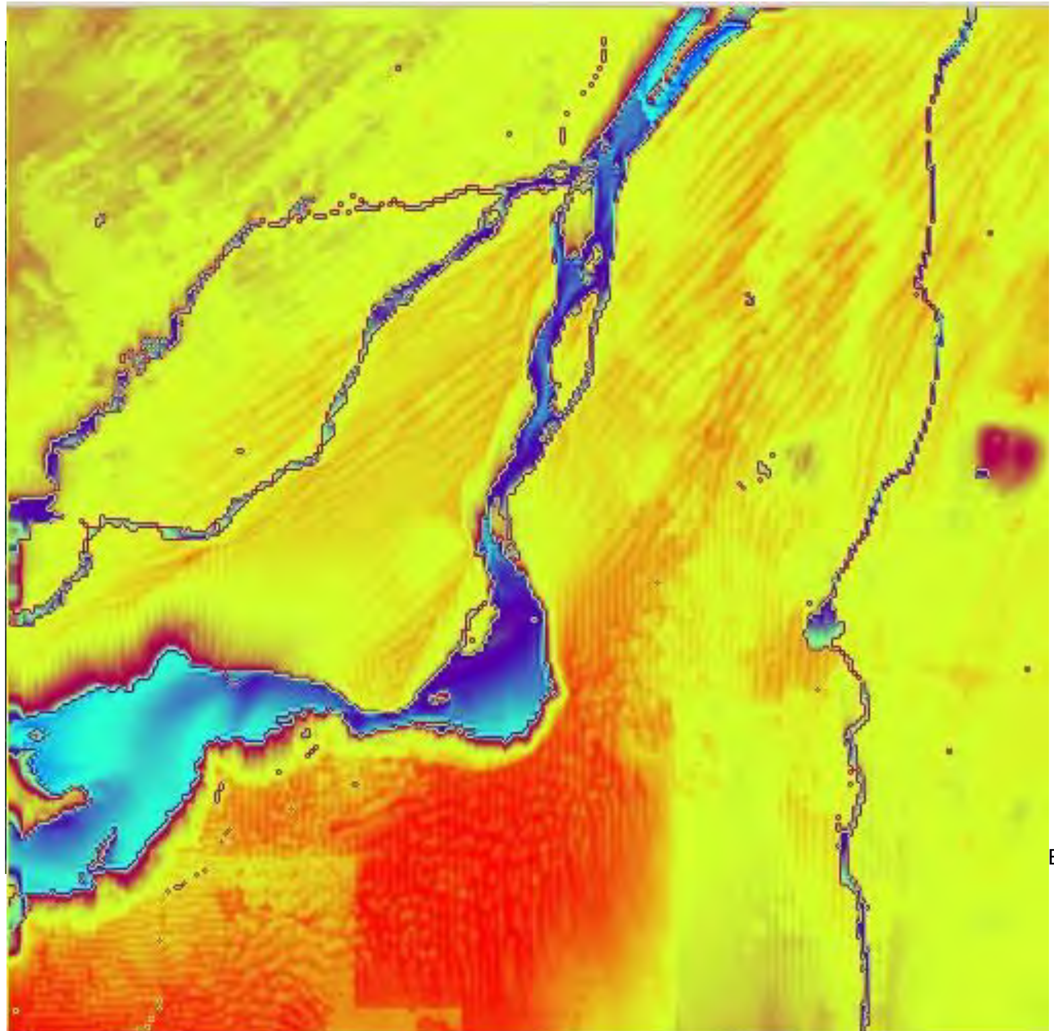


Urban park



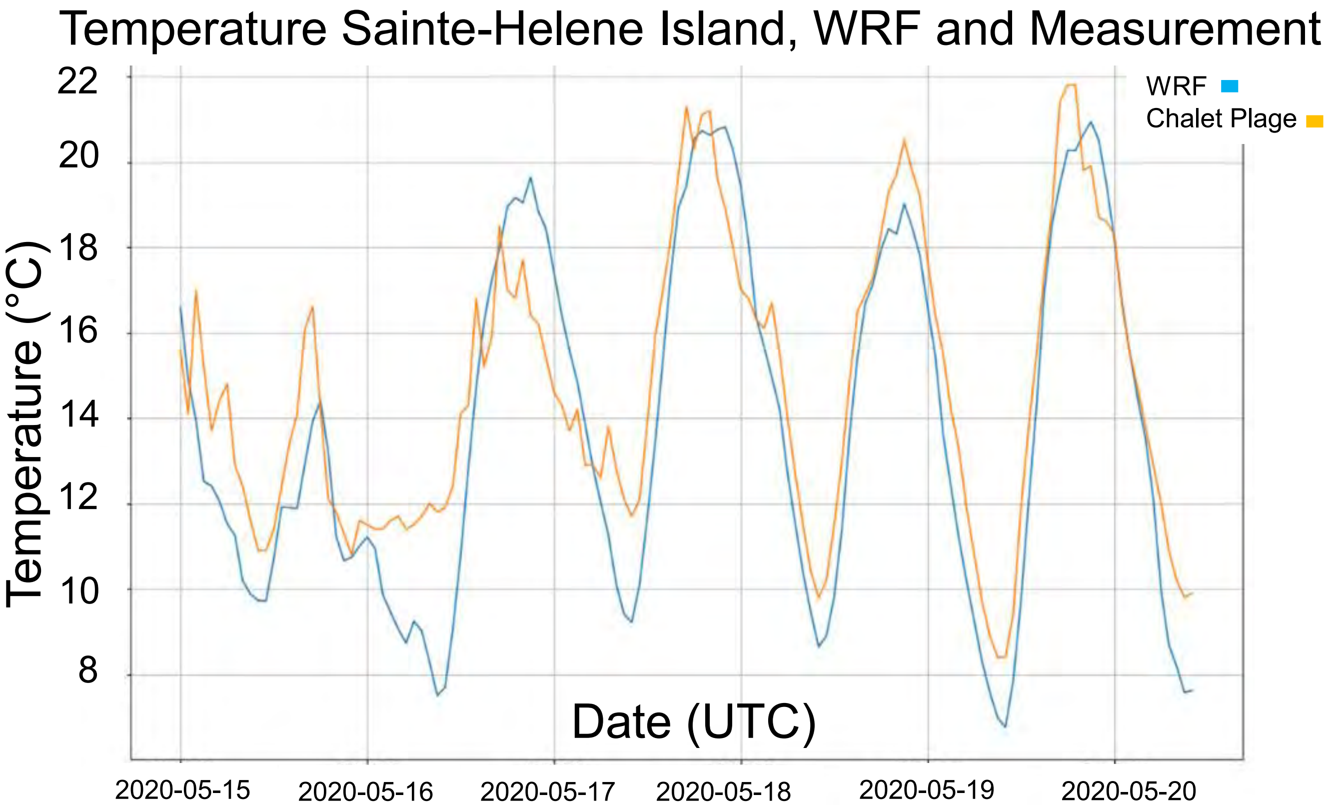
Boundary conditions from WRF

WRF for urban area



Earth

Results versus local measurements



Greening of two parking spaces

N ↑

Google Earth

Actual

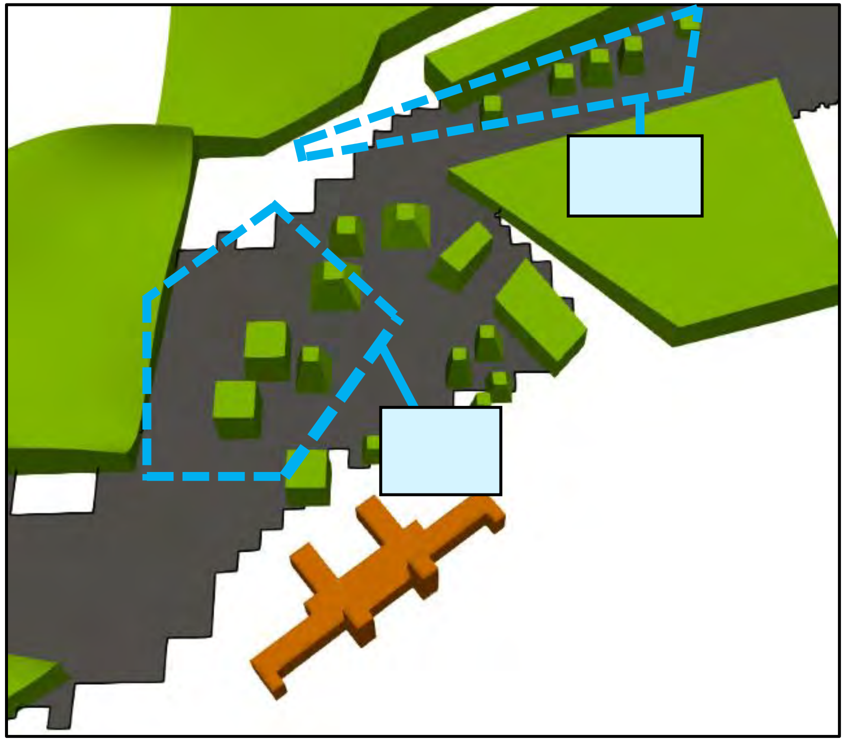
Plan directeur Parc JD 2020-2030

Planned

Plan directeur Parc JD 2020-2030

Scenarios

As-is Situation



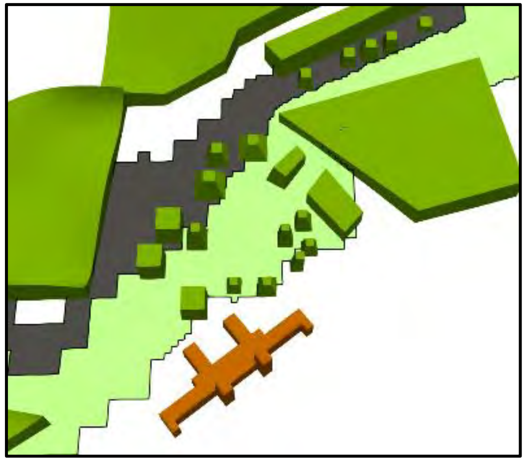
avement

rass

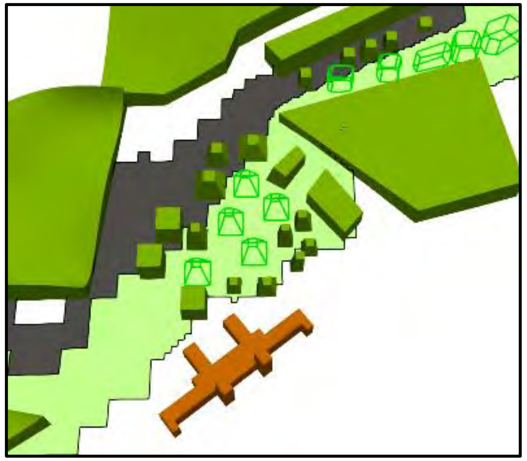
xisting trees

Ne trees

Parametric Scenarios

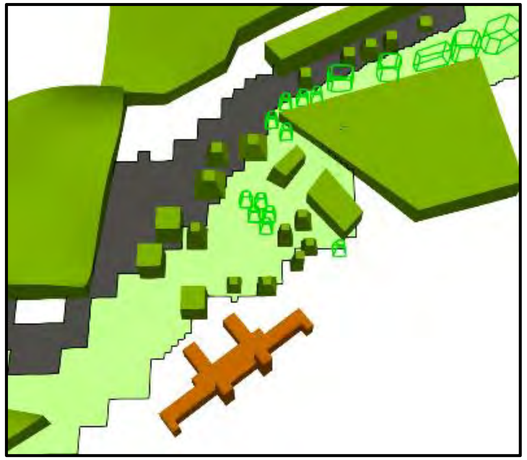


Grass

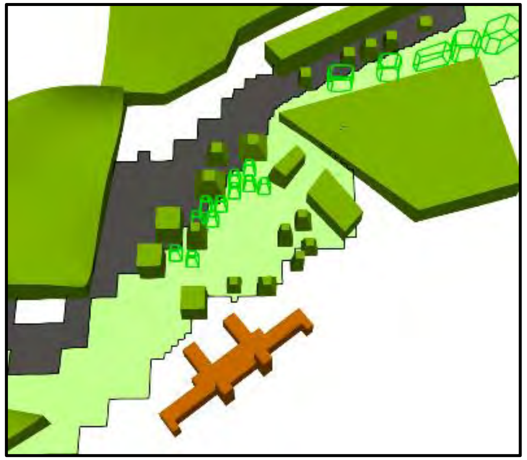


Large Trees

Retrofit Scenarios



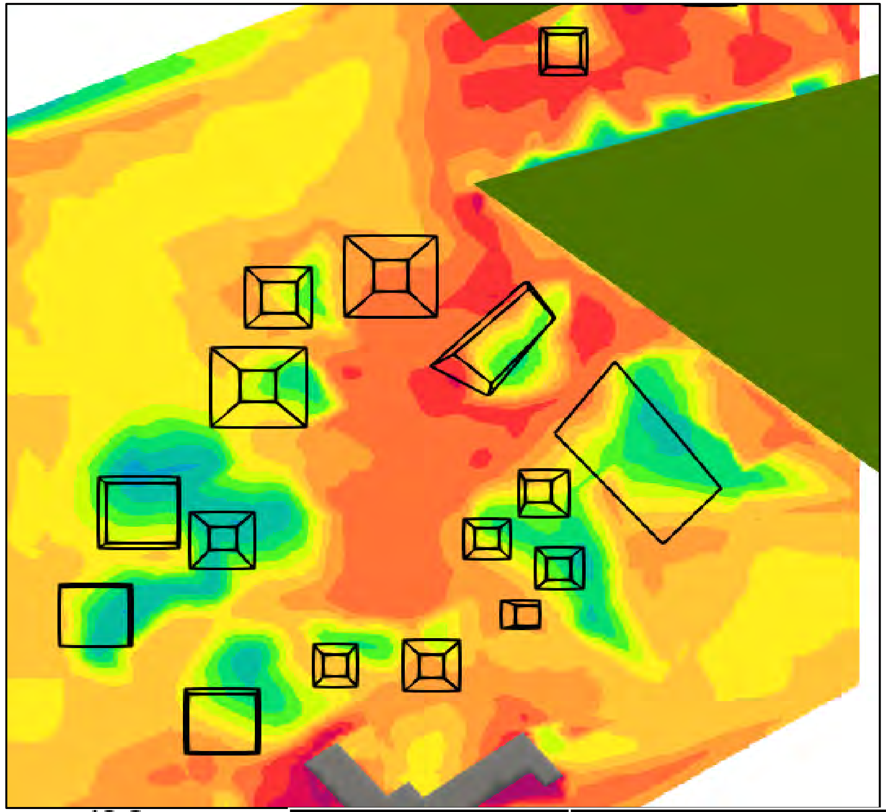
Retrofit 1

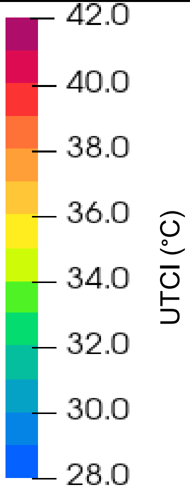


Retrofit 2

UTCI per scenarios

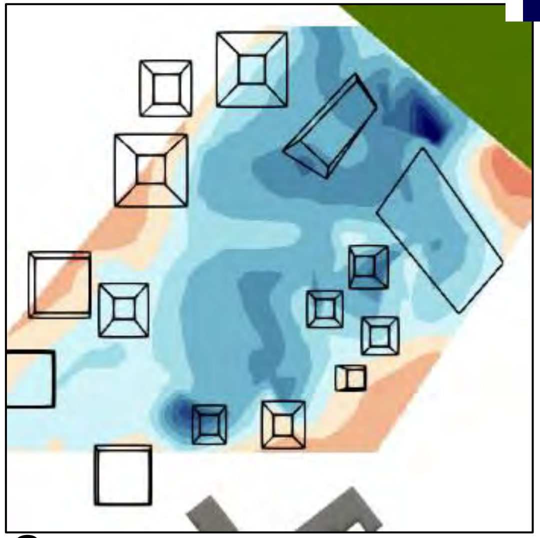
As-is Situation



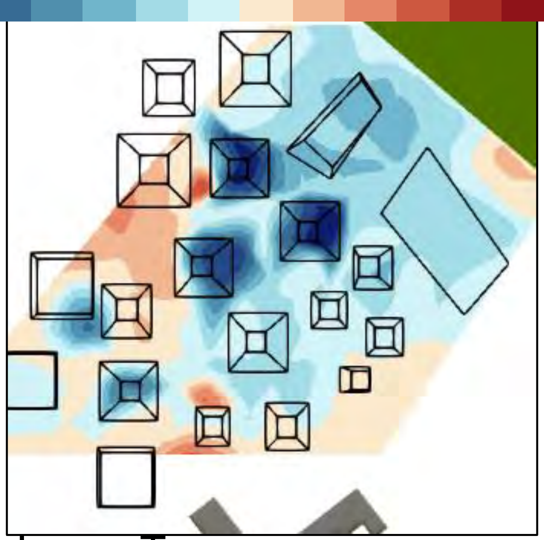


UTCI range (ºC)	Stress category
> 46	Extreme heat stress (HS)
38 to 46	Very strong HS
32 to 38	Strong HS
26 to 32	Moderate HS
9 to 26	No thermal stress
0 to 9	Slight cold stress (CS)
-13 to 0	Moderate CS
-27 to -13	Strong CS
-40 to -27	Very strong CS
< -40	Extreme CS

Parametric Scenarios

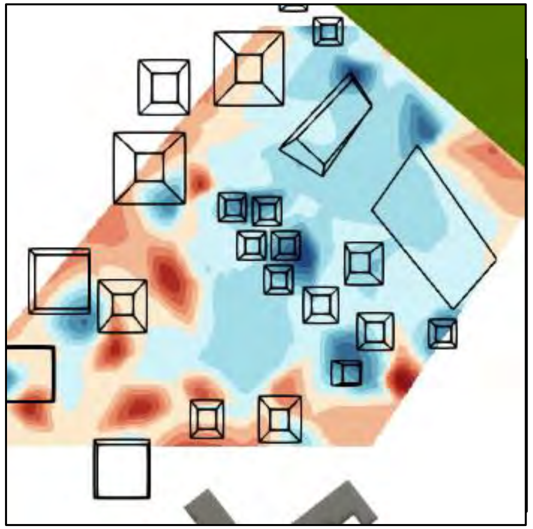


Grass

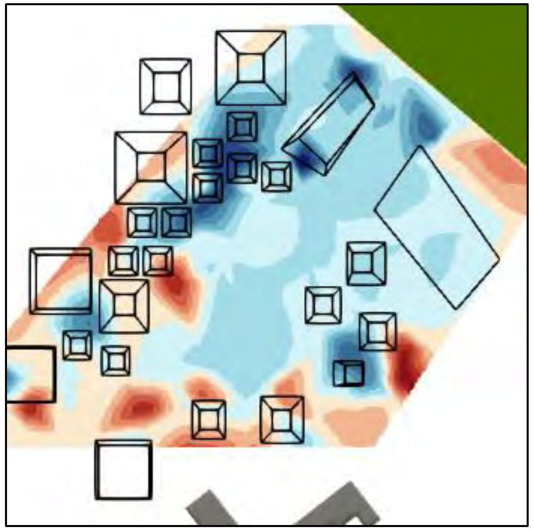


Large Trees

Retrofit Scenarios

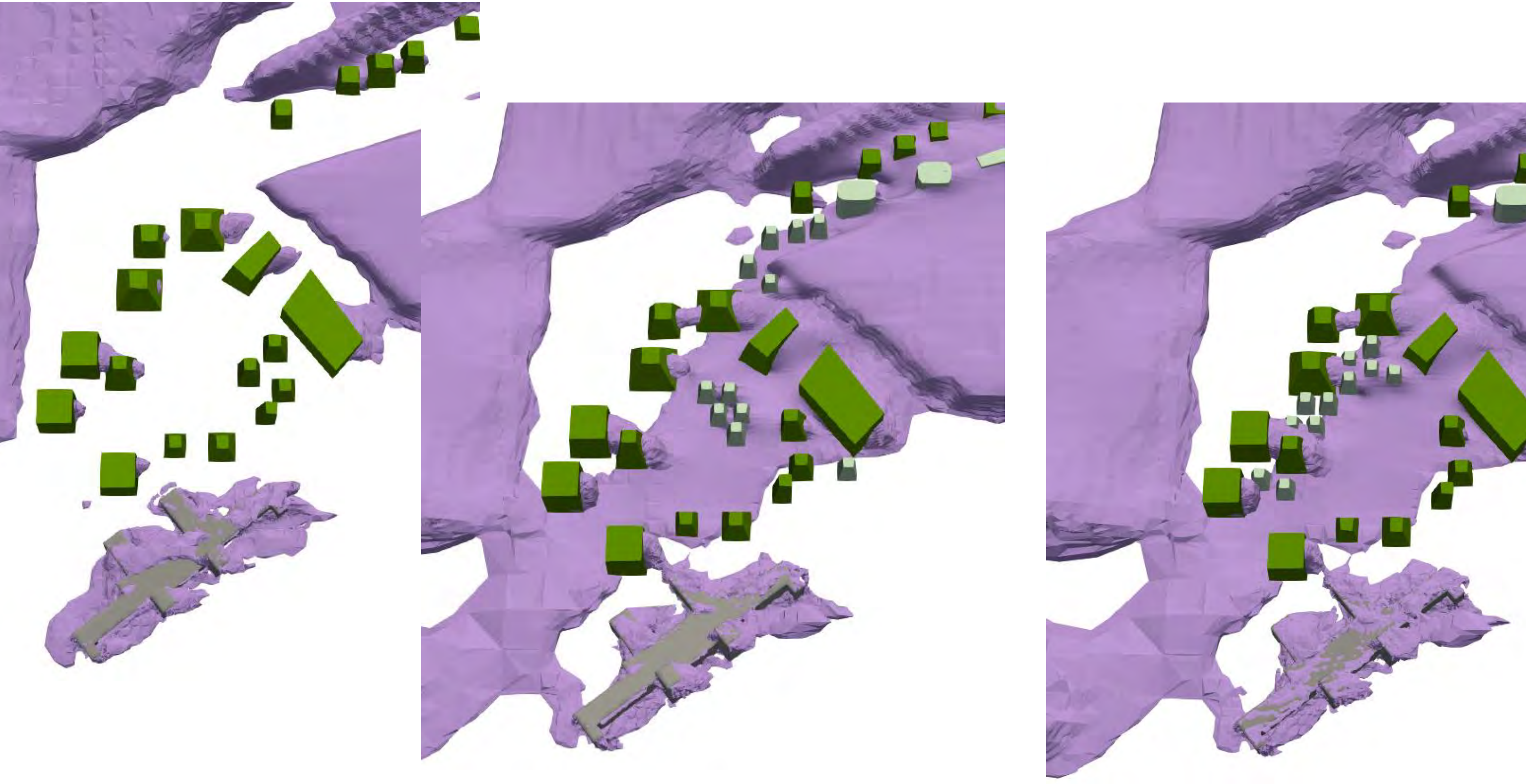


Retrofit 1



Retrofit 2

Volume of air with an air temperature of at least 2°C than inlet temperature



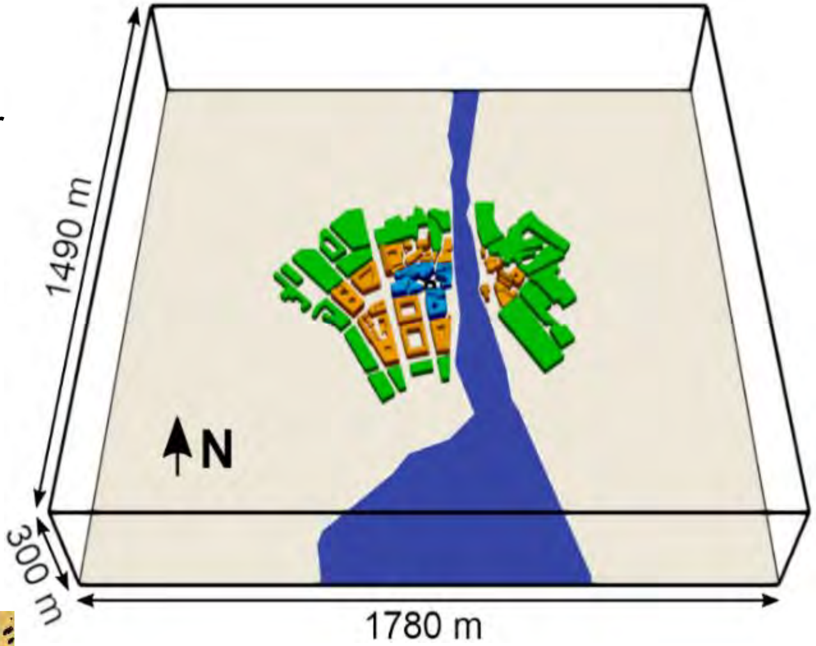
Example of heatwave mitigation
case study Münsterhof, Zürich

Andrea Ferrari, Aytaç Kubilay, Dominique Derome and Jan Carmeliet, The use of permeable and reflective pavements as a potential strategy for urban heat island mitigation, Urban Climate, vol. 31, pp. 100534, Amsterdam: Elsevier, 2019.

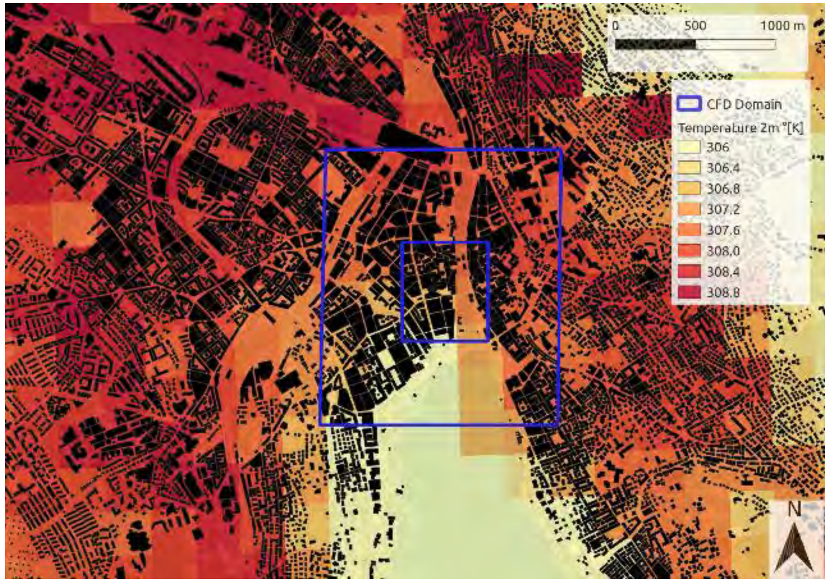
Aytaç Kubilay, Dominique Derome and Jan Carmeliet, Impact of evaporative cooling due to wetting of urban materials on local thermal comfort in a street canyon, Sustainable Cities and Society, vol. 49, pp. 101574, Amsterdam: Elsevier, 2019.

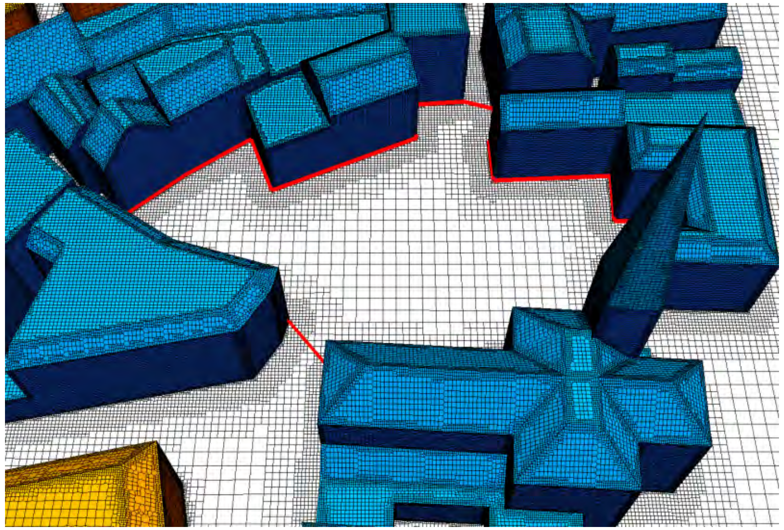
Münsterhof – coupled subdomains

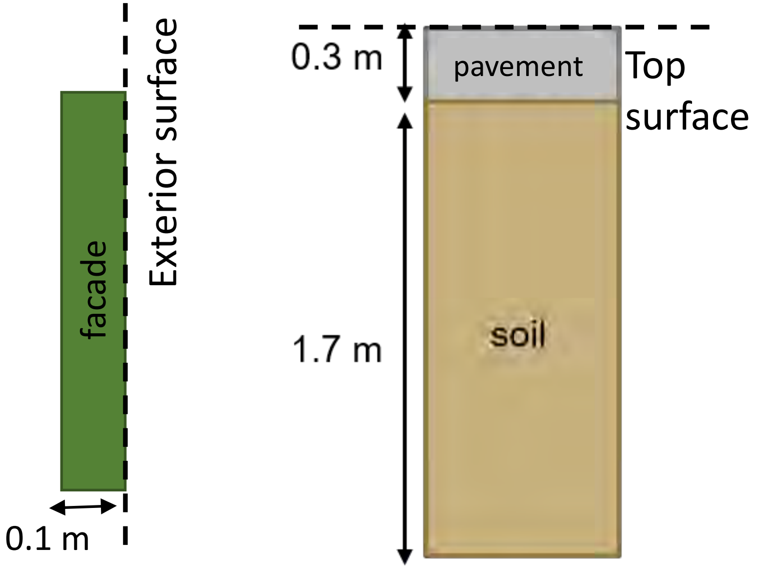
Domain for air flow
- Steady Reynolds-averaged Navier Stokes (RANS)



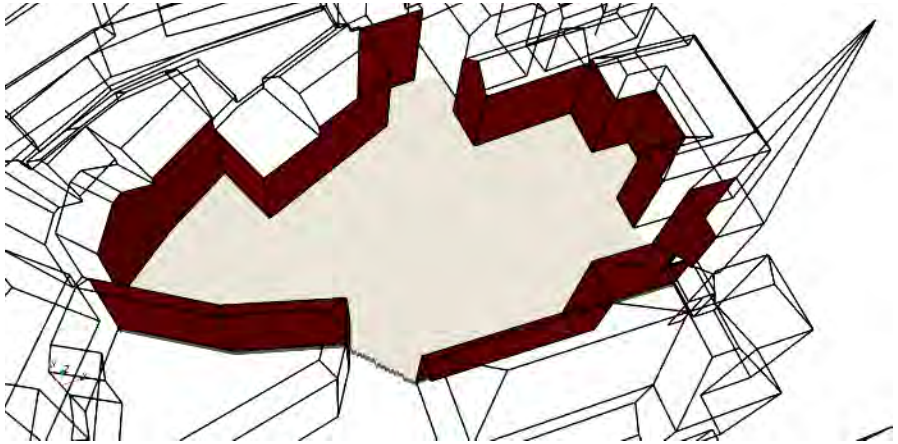
Mesoscale model
- COSMO + DCEP
- Air temperature at 2 m height





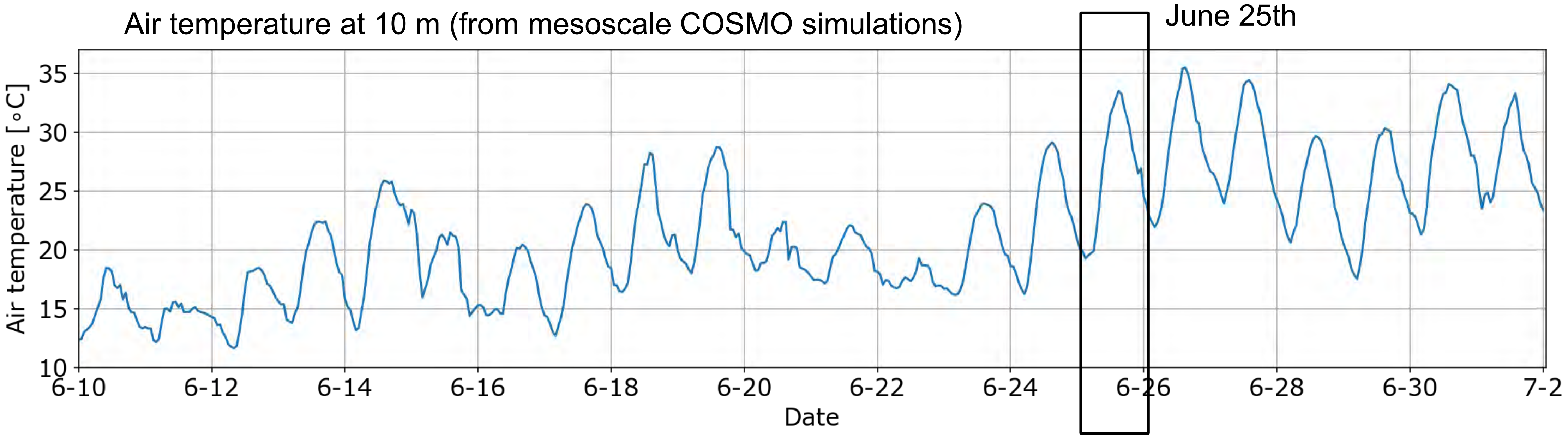


Domain for porous urban materials
- Unsteady Heat & Moisture transport

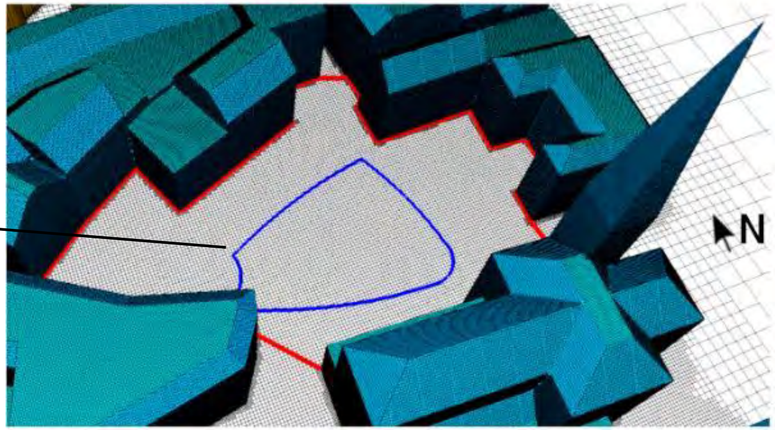


(Kubilay et al., Atmosphere **2020**, *11*(12), 1313)

Meteorological conditions – heat wave 2019 June



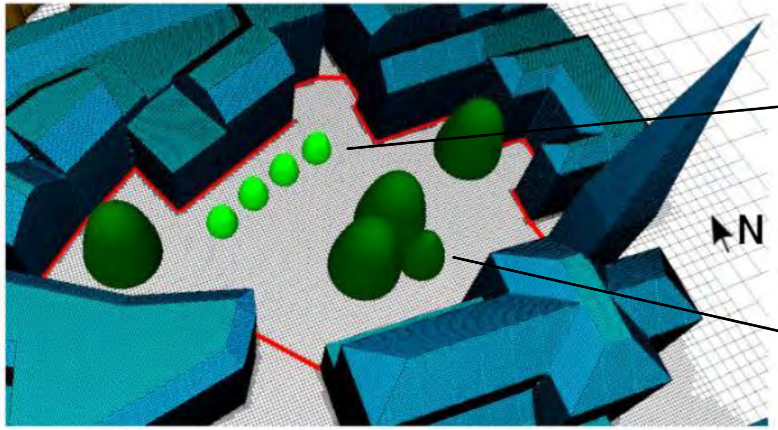
Artificial wetting



2-layer porous pavement

6 mm between 08:00-08:20

Trees



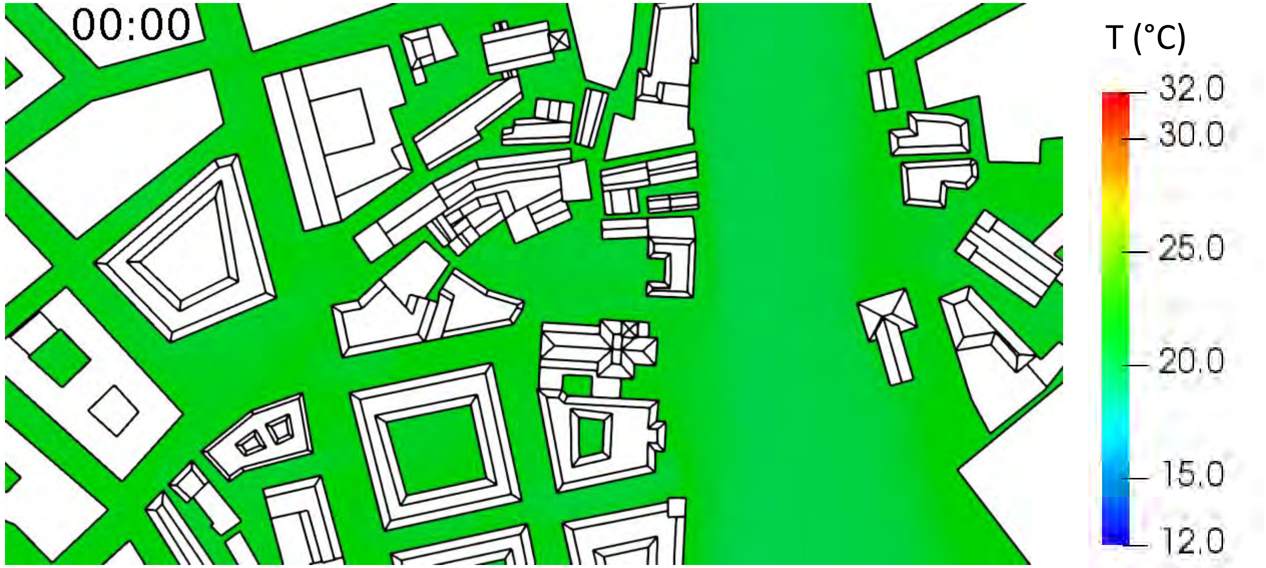
Field maple
10-12 m
LAD = 2 m^2/m^3

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

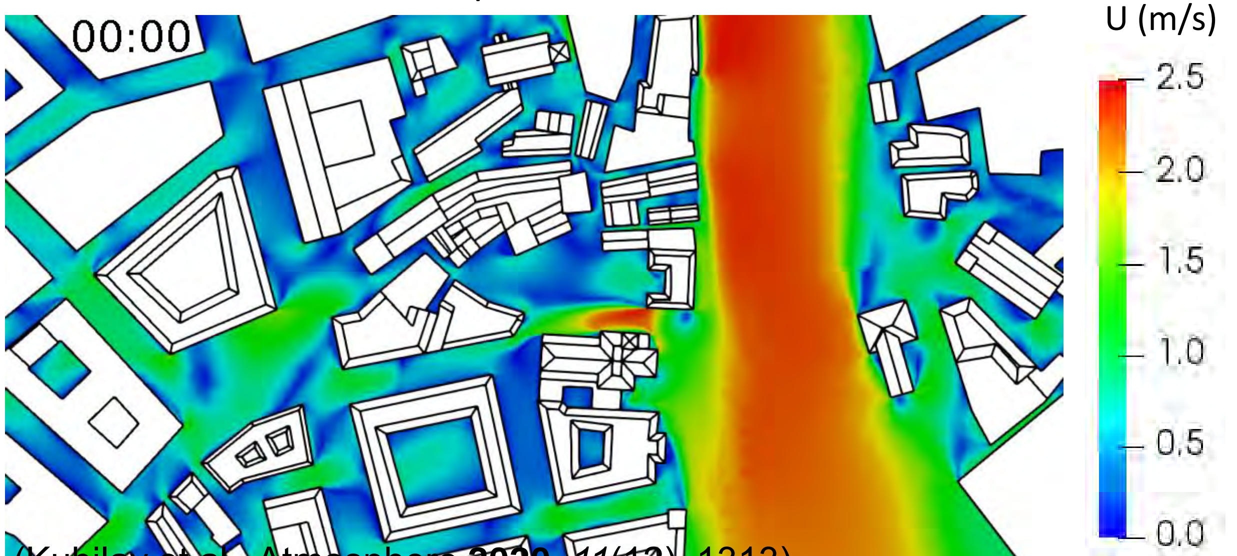
(Kubilay et al., Atmosphere **2020**, *11*(12), 1313)

Pedestrian level conditions

Air temperature at 2 m

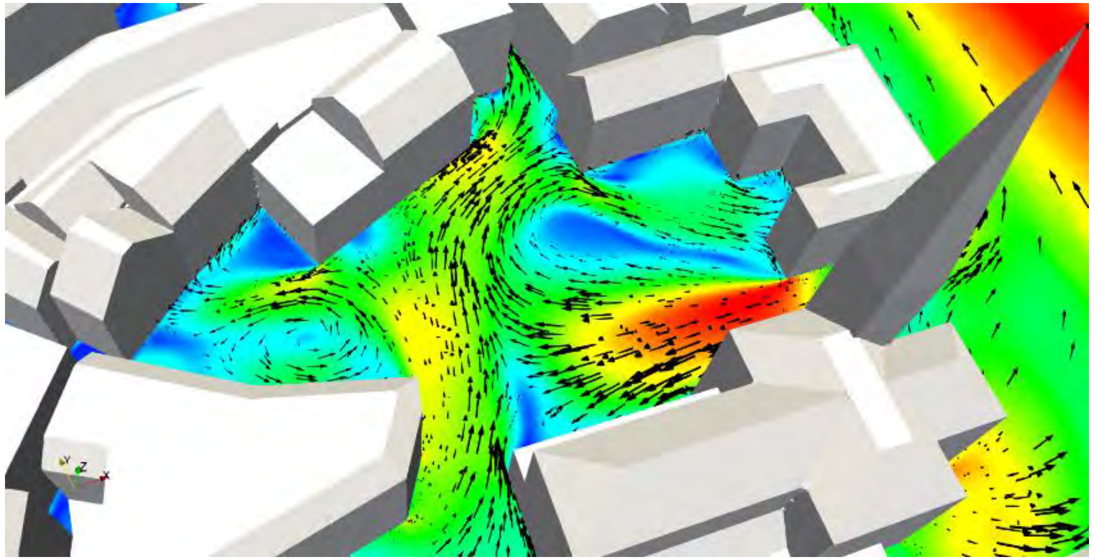


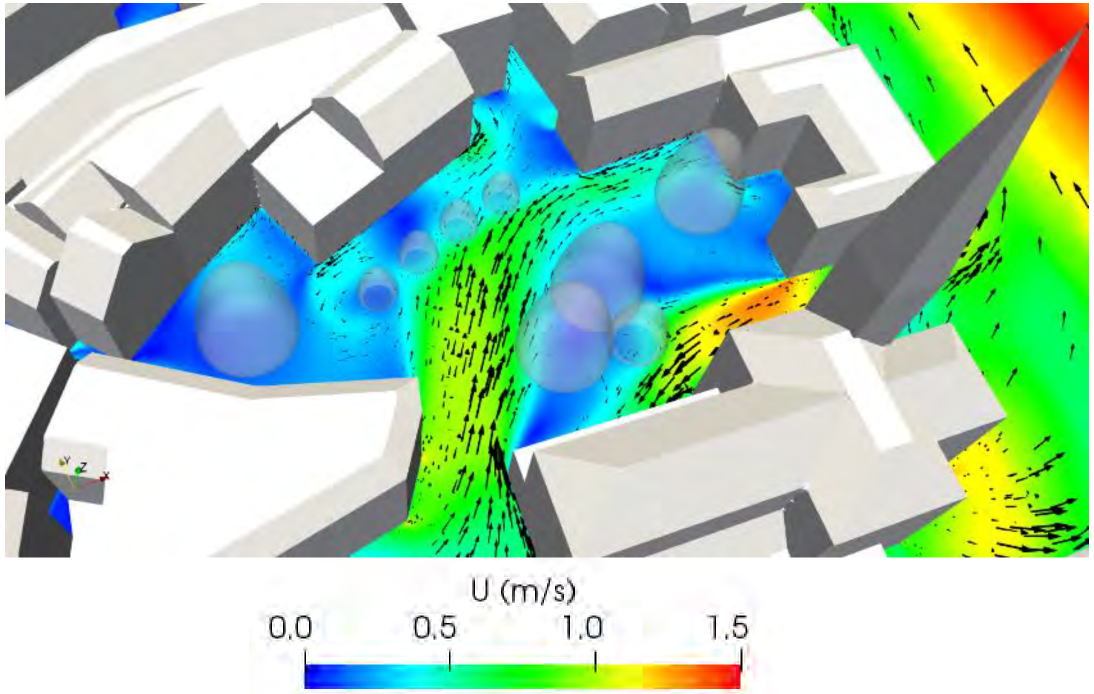
Wind speed at 2 m



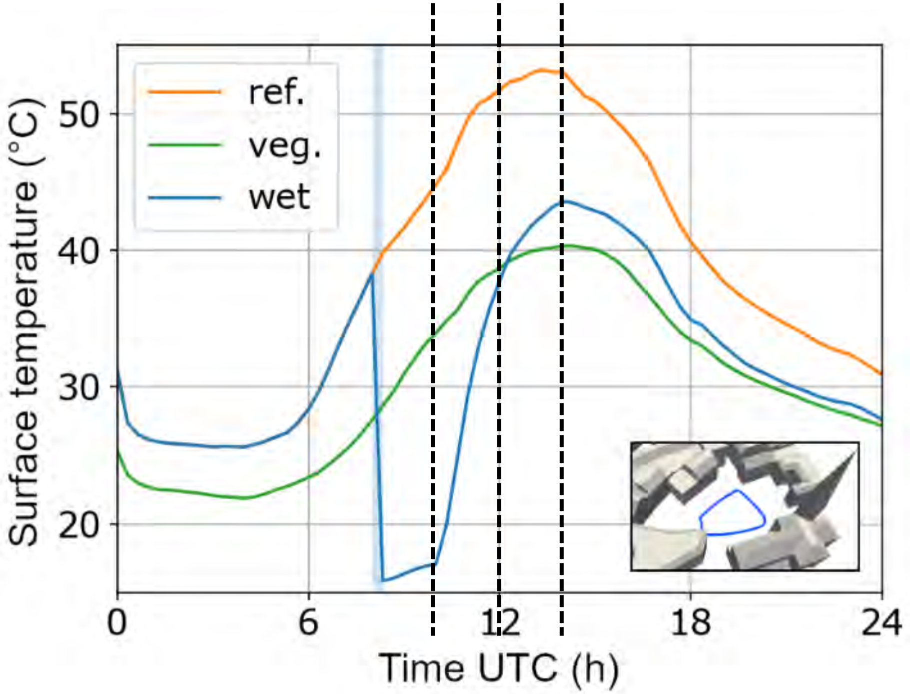
(Kubilay et al., Atmosphere **2020**, *11*(12), 1313)

wind from south

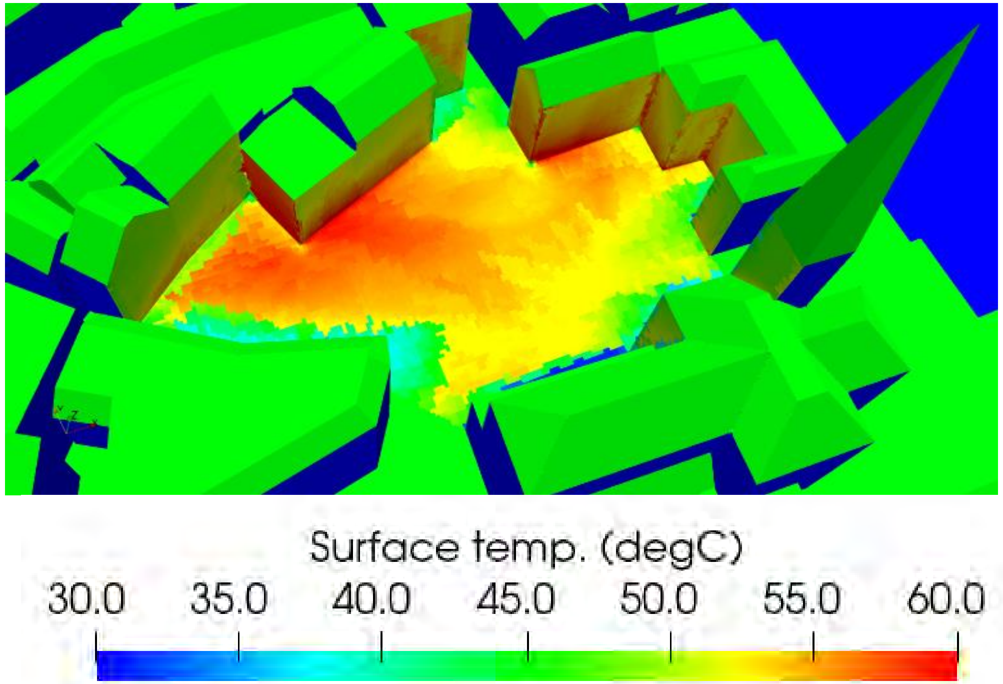




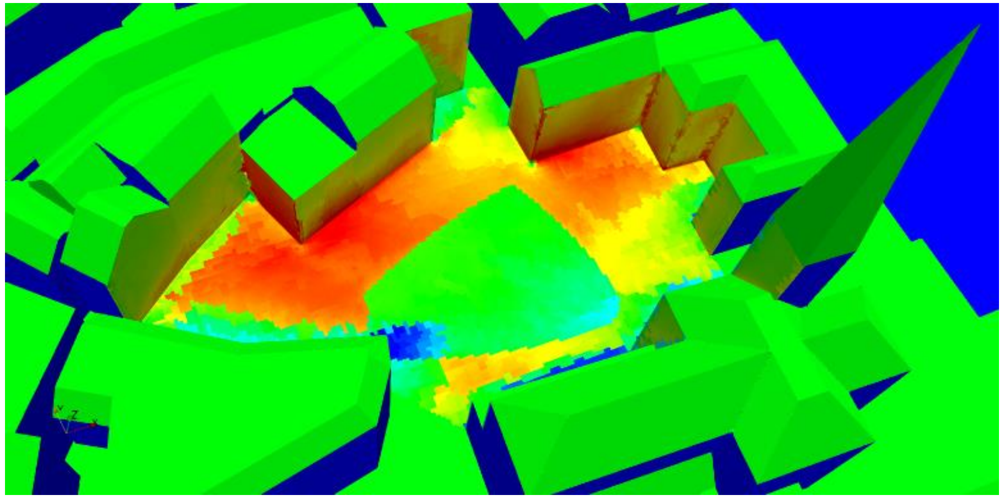
Comparison of pavement surface temperature



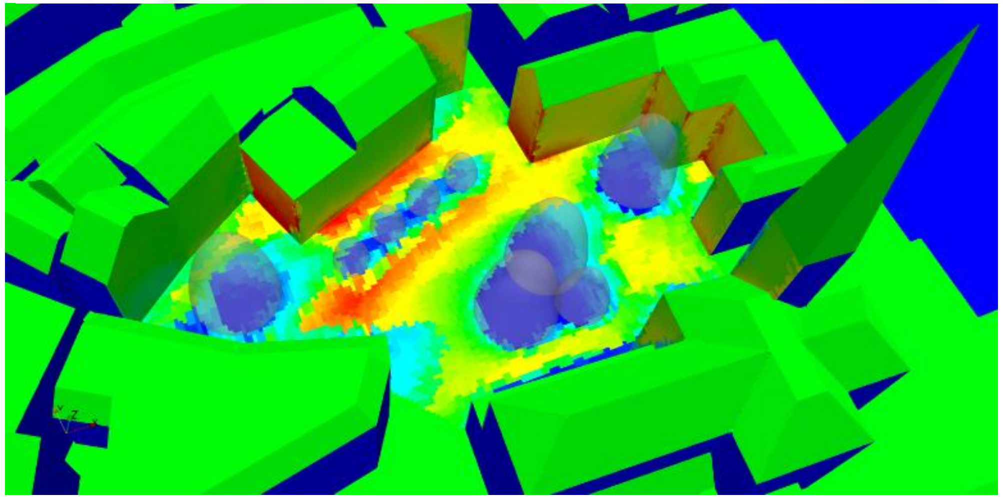
Ref.



Wet

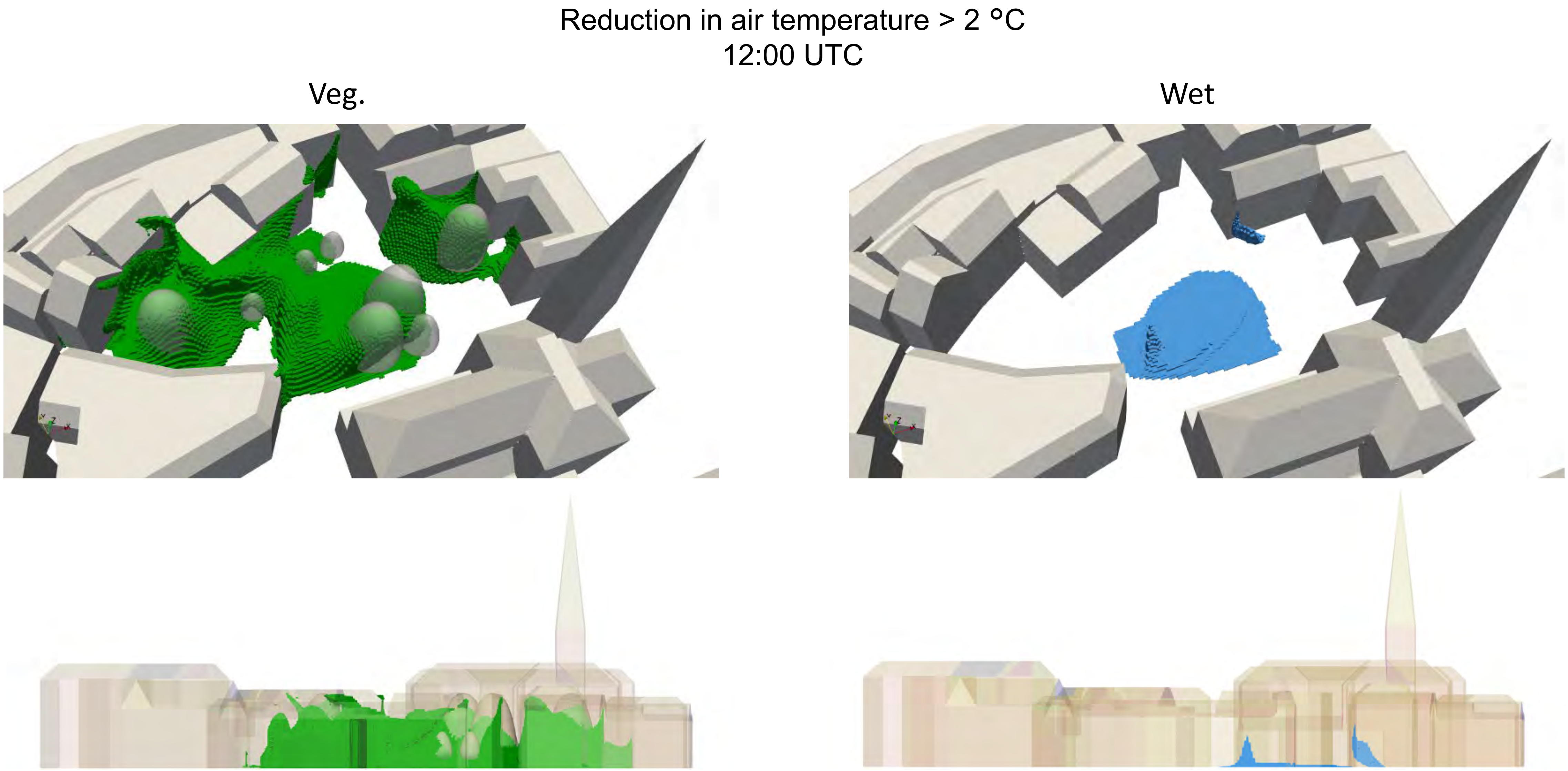


Veg.



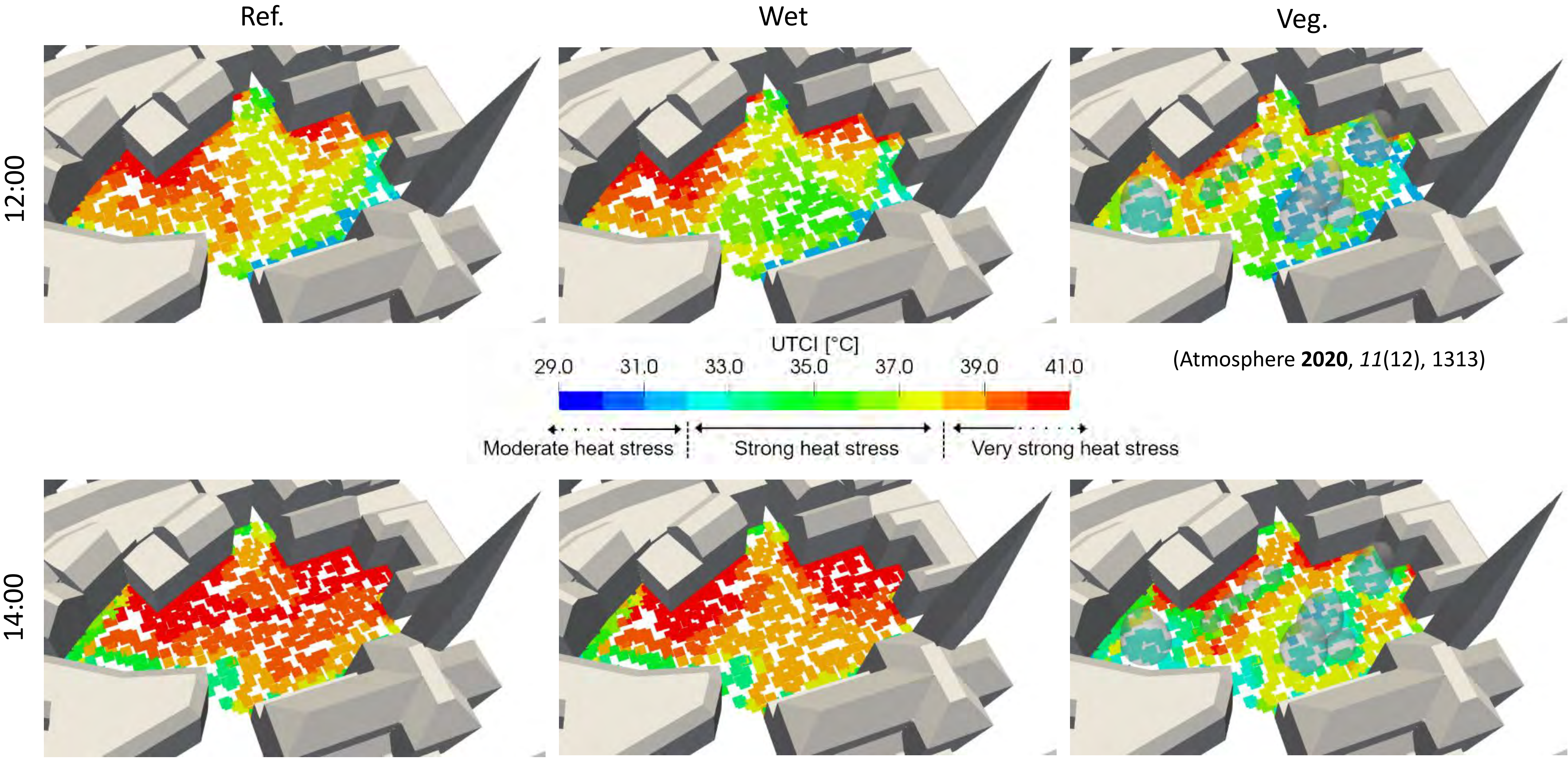
(Kubilay et al., Atmosphere **2020**, *11*(12), 1313)

Reduction in air temperature



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

Thermal comfort – Universal thermal climate index (UTCI)



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

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

Modeling trees as porous media in urban environment

microscale urban climate model

considering air, radiation, solid materials,

and porous media

vegetation: evapotranspiration of leaves

configuration of trees, from explicit (lidar) to some simplification

towards local mitigation scenarios

using different metrics of evaluation: **UCTI**, CDH, etc.

Conclusion

Urban local climate

microscale urban climate model

considering air, radiation, solid materials,

porous media

vegetation

using different metrics of evaluation: UCTI, CDH, etc.

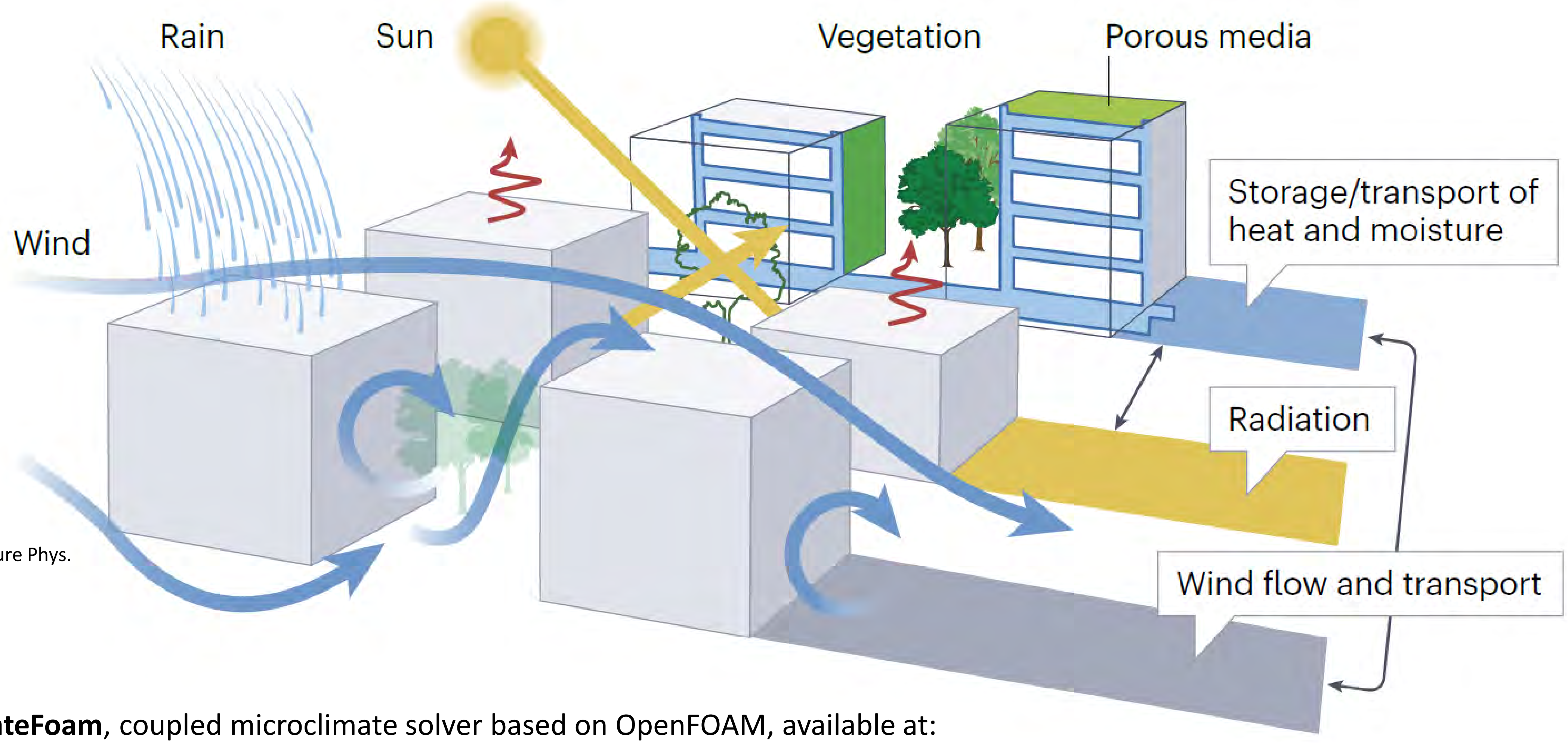
Configuration of built environment, green infrastructure,

temporary structures, etc.

Development of mitigation solutions,

towards a resilient city in the face of climate change

All physics urban climate model at the microscale



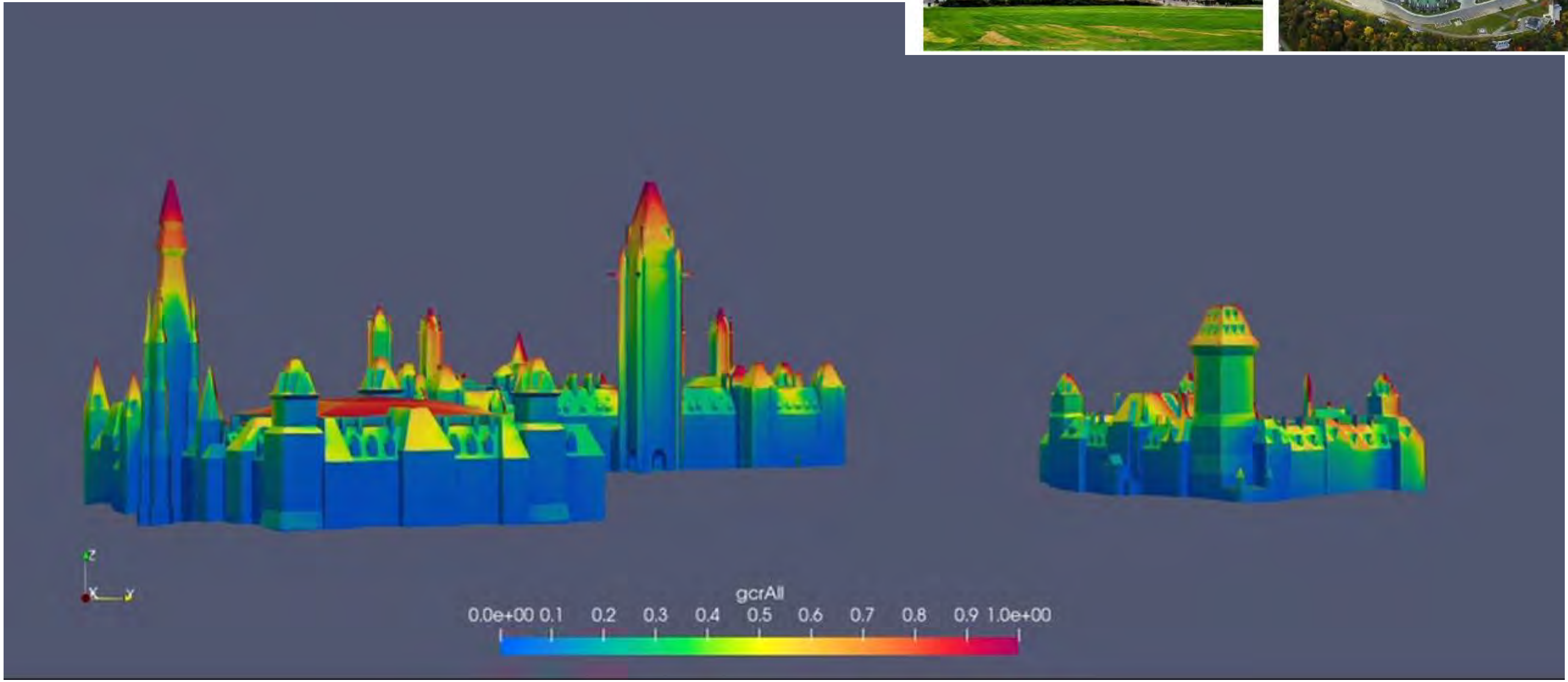
Carmeliet Derome 2023 Nature Phys.

urbanMicroclimateFoam, coupled microclimate solver based on OpenFOAM, available at:
https://gitlab.ethz.ch/openfoam-cbp/solvers/urbanmicroclimatefoam
https://carmeliet.ethz.ch/

Further read: A. Kubilay, J. Allegrini, D. Strebel, Y. Zhao, D. Derome, J. Carmeliet *(2020).* Advancement in Urban Climate Modelling at Local Scale: Urban Heat Island Mitigation and Building Cooling Demand. *Atmosphere* 11(12), 1313.

Wind-driven rain simulation

a) b)



Global catch ratio for year 2011 Ratio of yearly cumulative WDR/ horizontal rain amount

Kubilay, Bourcet et al. 2021 Buildings