Urban climate modelling

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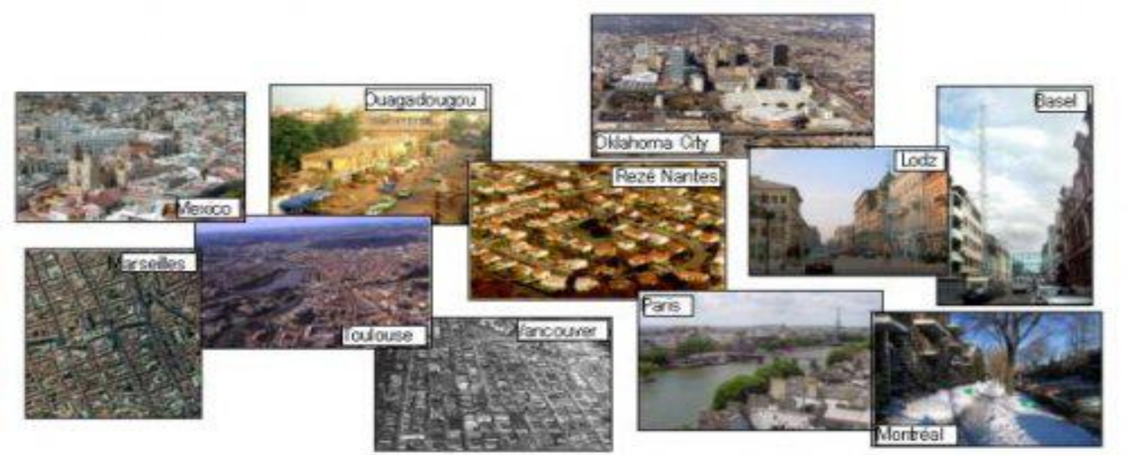
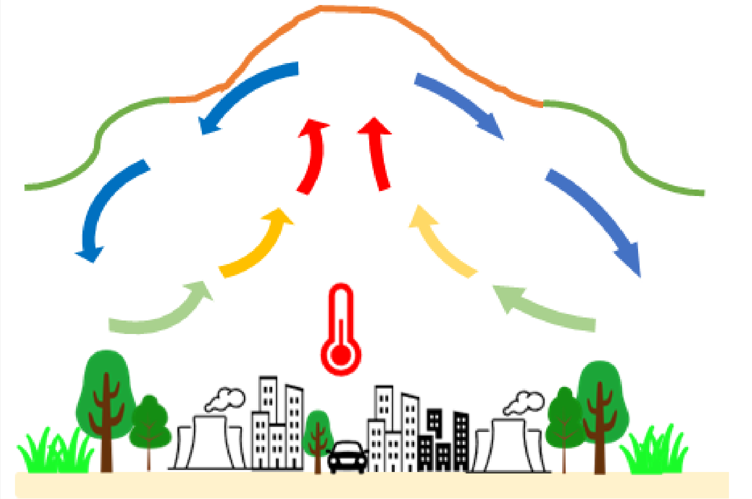
UGent | 6th July 2023





[Credit: NASA]

FAQ 1.1: Do we understand climate change better than when the IPCC started?

Yes. Between 1990 and 2021, observations, models and climate understanding improved, while the dominant role of human influence in global warming was confirmed.

	1990 IPCC First Assessment	2021 IPCC Sixth Assessment
Understanding		
Human influence on climate	Suspected	Established fact
Energy budget	Open (inconsistent estimates)	Closed (inputs = outputs + retained energy)
Sea level budget	Open (inconsistent estimates)	Closed (sum of contributions = observed sea level rise)
Observations		
Global warming since late 1800s	0.3–0.6°C	0.95–1.20°C
Land surface temperature	1887 stations (1861–1990)	Up to 40,000 stations (1750–2020)
Geological records	5 million years (temperature) 5 million years (sea level) 160,000 years (CO_2)	65 million years (temperature) 50 million years (sea level) 450 milion years (CO_2)
Global ocean heat content	1955–1981 (two regions)	1871–2018 (global)
Satellite remote sensing	Temperature, snow cover, Earth radiation budget	Temperature, cryosphere, Earth radiation budget, CO_2, sea level, clouds, aerosols, land cover, many others

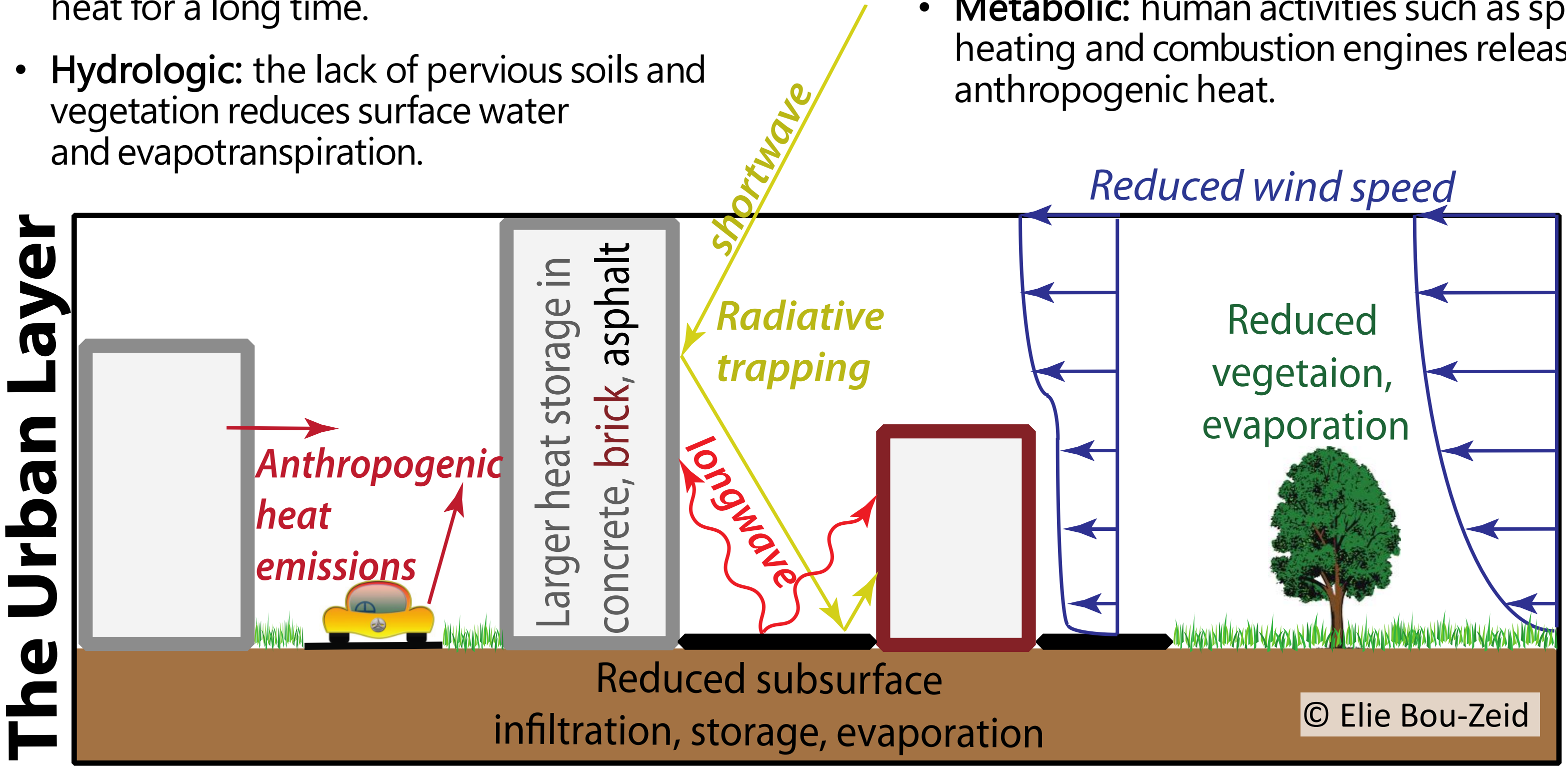
Climate models

	Global (1990)	Global (2021)	Regional (2021)
State of the art	General circulation models	Earth system models	High-resolution models
Typical model resolution	500 km	100 km	25–50 km
Major elements	Circulating atmosphere and ocean Radiative transfer Land physics Sea ice	Circulating atmosphere and ocean Radiative transfer Land physics Sea ice Atmospheric chemistry Land use/cover Land and ocean biogeochemistry Aerosol and cloud interations	

WMO UNEP

Drivers of urban-rural climatic differences

- **Radiative:** darker surfaces, geometric trapping.
- **Material:** (e.g. concrete) that can store a lot of heat for a long time.
- **Hydrologic:** the lack of pervious soils and vegetation reduces surface water and evapotranspiration.
- **Geometric:** complex surface are better at trapping radiation and slowing wind.
- **Metabolic:** human activities such as space heating and combustion engines release anthropogenic heat.



Computing resources

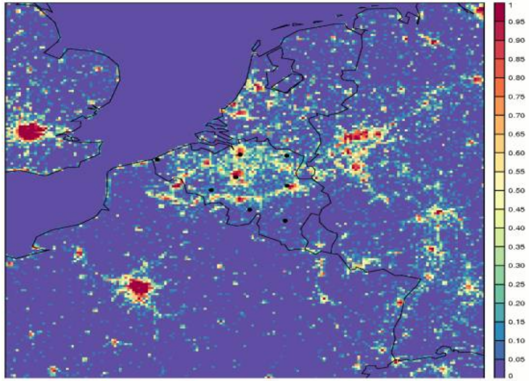
<u>Example: Operational domain size</u>

Δ X=Δ Y=4 km   Nx=Ny=181

Nz=46 ; Δt=180 s

For **1 day** (Nx*Ny*Nz)*86400/Δt

=> **7.23 10^8** calculations are needed.



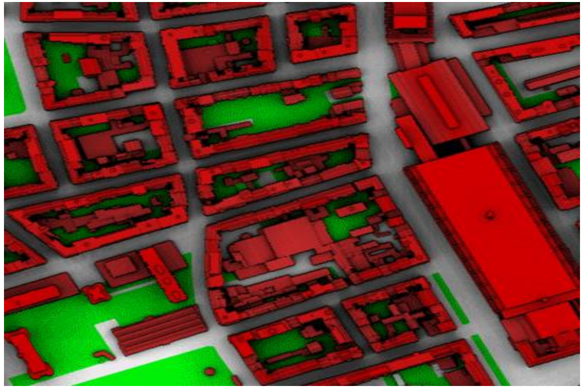
<u>To resolve buildings</u>

ΔX=ΔY=10 m

Nz=46 ; Δt=0.003 s

For **1 day 6.94 10^18** calculations

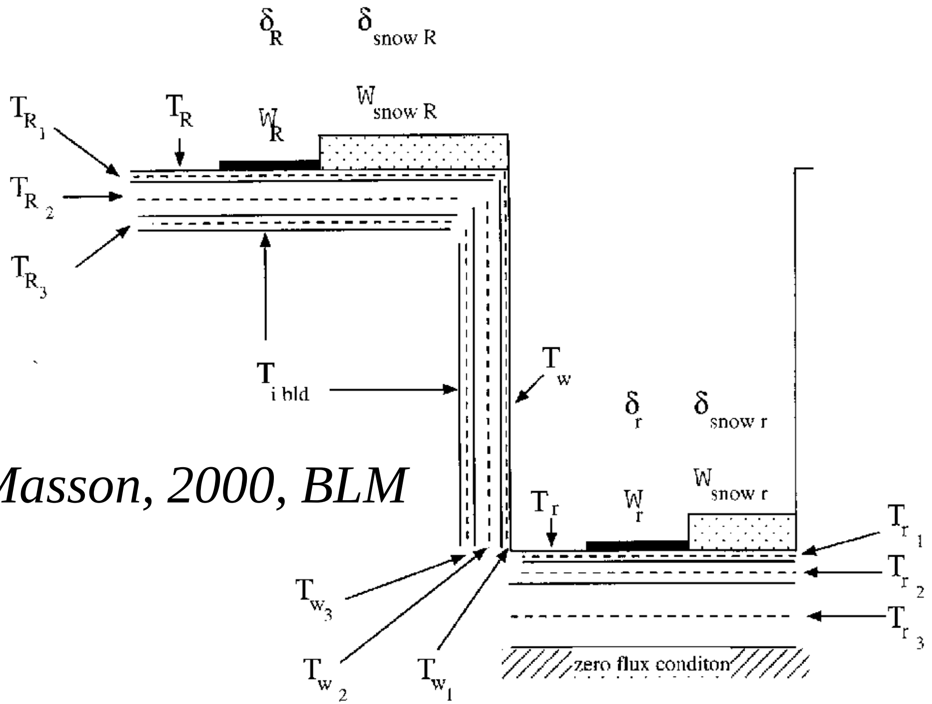
Computer **10^10** faster than today.



Cities and urban areas Versus rocks

Town Energy Balance

TEB is based on the “canyon” concept which considers a single road, bordered by facing buildings.



Masson, 2000, BLM

Input parameters

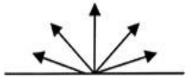
Symbol	Designation of symbol	Unit
Geometric parameters		
a_{town}	Fractional area occupied by artificial material	–
a_{bld}	Fractional artificial area occupied by buildings	–
$1 - a_{\text{bld}}$	Fractional artificial area occupied by roads	–
h	Building height	m
h/l	Building aspect ratio	–
h/w	Canyon aspect ratio	–
$z_{0_{\text{town}}}$	Dynamic roughness length for the building/canyon system	m
Radiative parameters		
$\alpha_R, \alpha_r, \alpha_w$	Roof, road and wall albedos	–
$\epsilon_R, \epsilon_r, \epsilon_w$	Roof, road and wall emissivities	–
Thermal parameters		
$d_{R_k}, d_{r_k}, d_{w_k}$	Thickness of the kth roof, road or wall layer	m
$\lambda_{R_k}, \lambda_{r_k}, \lambda_{w_k}$	Thermal conductivity of the kth roof, road or wall layer	$\text{W m}^{-1}\ \text{K}^{-1}$
$C_{R_k}, C_{r_k}, C_{w_k}$	Heat capacity of the kth roof, road or wall layer	$\text{J m}^{-3}\ \text{K}^{-1}$

Trapping of radiation

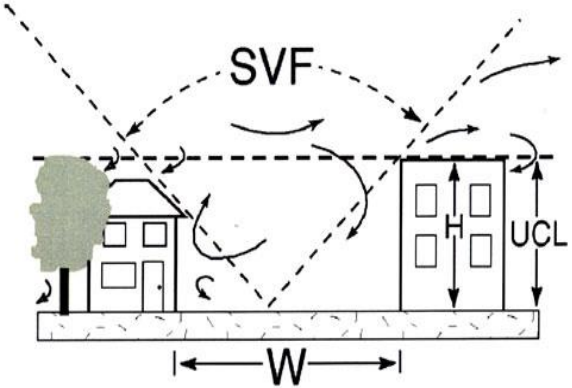
Figure 1: Examples of sky view factor (SVF)

a) An example of a SVF of one, for an open site such as a wide field or the top of a large building.

SVF=1



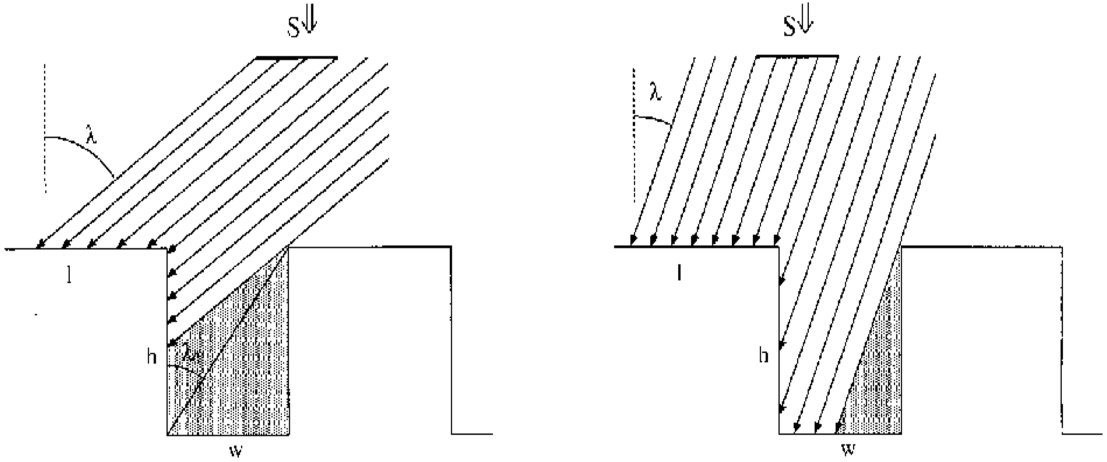
b) In urban areas, the fraction of sky visible from the ground (the SVF) is decreased (less than one) by buildings and vegetation (adapted from Oke 1997; H is the building height; W is the canyon width; UCL is the urban canopy layer)



$$\Psi_r = [(h/w)^2 + 1]^{1/2} - h/w,$$

$$\Psi_w = \frac{1}{2}\{h/w + 1 - [(h/w)^2 + 1]^{1/2}\}/(h/w).$$

Solar radiation



road perpendicular to sun direction

road perpendicular to sun direction

$$S_r^{\Downarrow} = S^{\Downarrow}\left[\frac{2\theta_0}{\pi} - \frac{2}{\pi}\frac{h}{w}\tan(\lambda)(1-\cos(\theta_0))\right],$$

$$S_w^{\Downarrow} = S^{\Downarrow}\left[\frac{w}{h}\left(\frac{1}{2} - \frac{\theta_0}{\pi}\right) + \frac{1}{\pi}\tan(\lambda)(1-\cos(\theta_0))\right],$$

$$S_R^{\Downarrow} = S^{\Downarrow}.$$

Anthropogenic fluxes

1. Domestic heating : Constant internal temperature 19°C.

2. Combustion sources: Traffic + industry. Heat and moisture fluxes averaged over the town are specified by user:

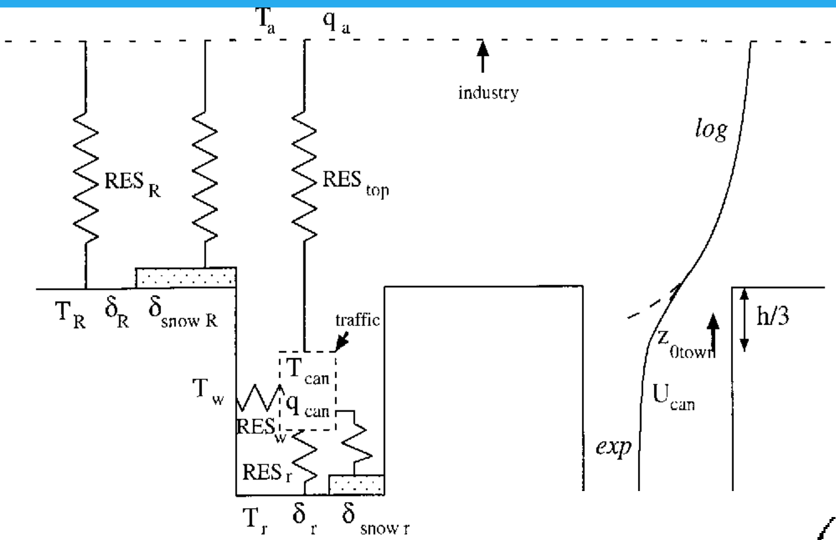
H_traffic

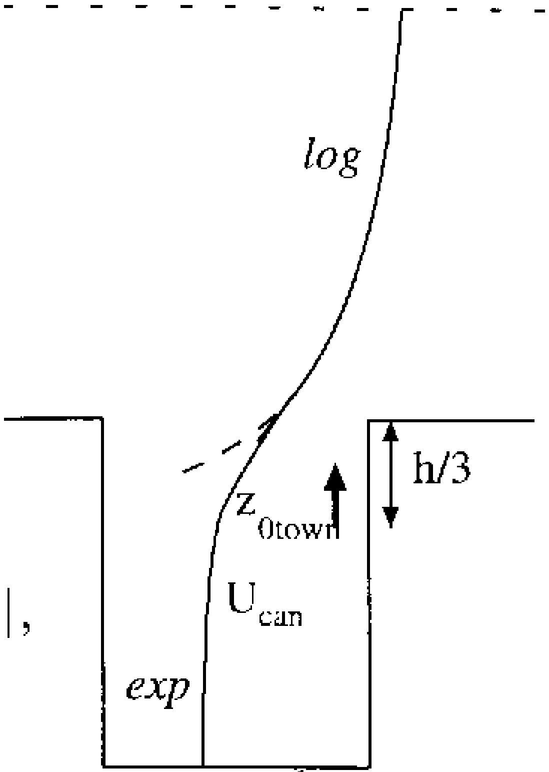
LE_traffic

H_industry

LE_industry

The anthropogenic flux do not influence the surface energy balance, it influence the canyon budget.





$$W_{\rm can} = u_* = \sqrt{C_d}\,|\mathbf{U}_a|, \qquad U_{\rm top} = \frac{2}{\pi}\,\frac{\ln\left(\frac{h/3}{z_{0_{\rm town}}}\right)}{\ln\left(\frac{\Delta z + h/3}{z_{0_{\rm town}}}\right)}\,|\mathbf{U}_a|,$$

$$U_{\rm can} = \frac{2}{\pi}\exp\left(-\frac{1}{4}\frac{h}{w}\right)\frac{\ln\left(\frac{h/3}{z_{0_{\rm town}}}\right)}{\ln\left(\frac{\Delta z + h/3}{z_{0_{\rm town}}}\right)}\,|\mathbf{U}_a|.$$

$$\mathrm{RES}_r = \mathrm{RES}_w = \left(11.8 + 4.2\sqrt{U_{\rm can}^2 + W_{\rm can}^2}\right)^{-1}.$$

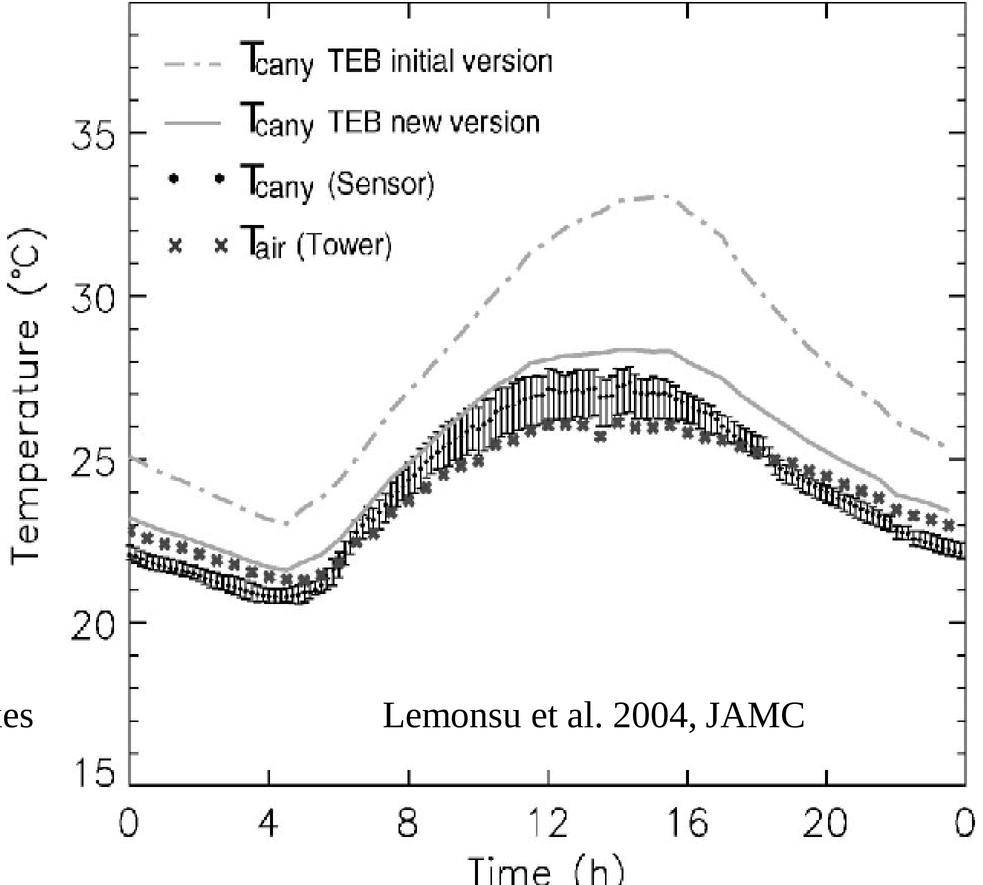
Evaluation of TEB

Marseilles

$$W_{\text{can}} = u_* = \sqrt{C_d}|\mathbf{U}_a|,$$

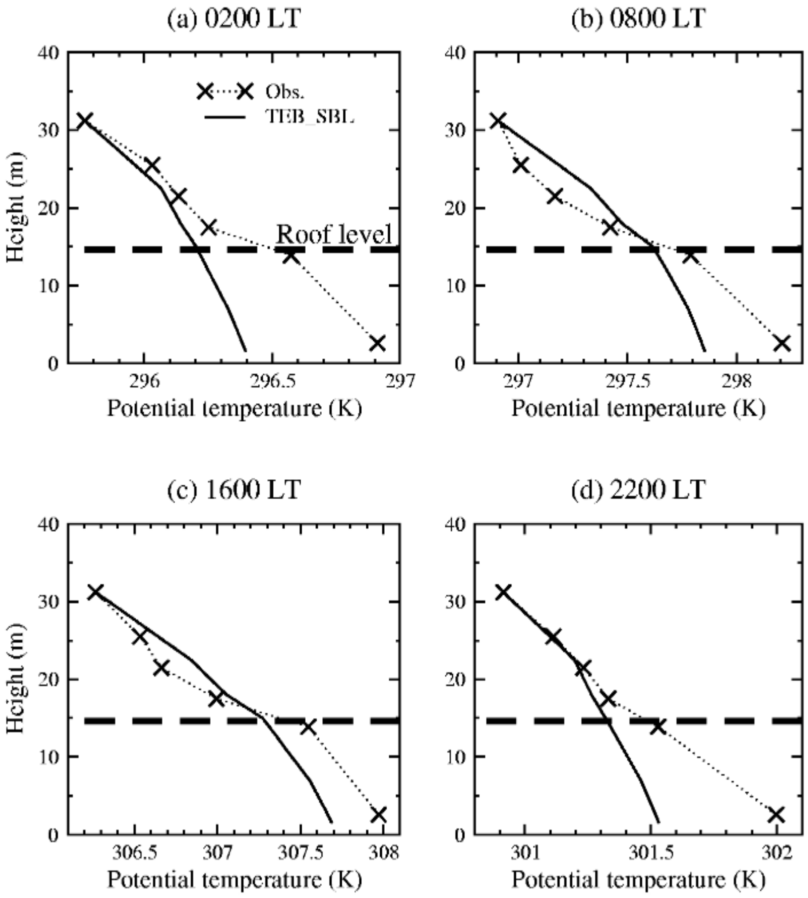
$$W_{can} = u_{\vee} + \left(\frac{g}{T_{can}} Q_0 z_{bld}\right)^{1/3}$$

Qo encompass both the road and wall turbulent heat fluxes

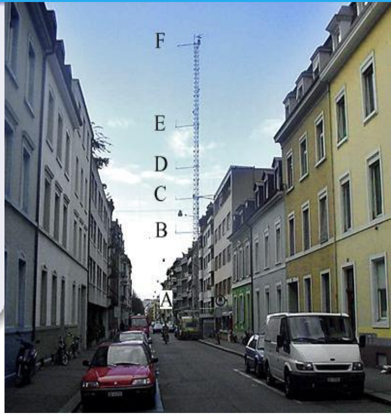


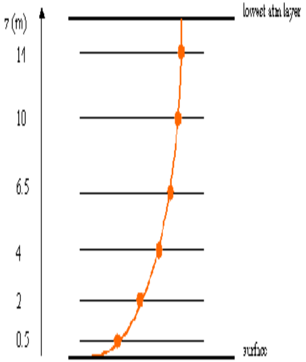
Lemonsu et al. 2004, JAMC

Basel

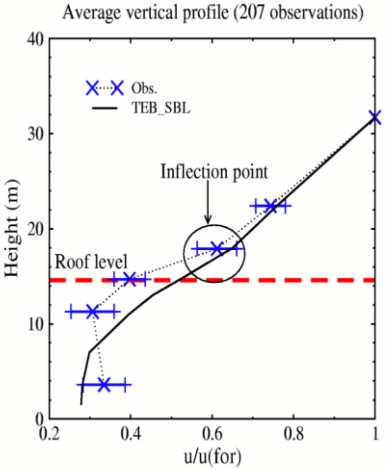


- 1d vertical prognostic scheme
- extra layers between lowest atmospheric level and surface
- takes into account large scale forcing, turbulence and drag due to canopy



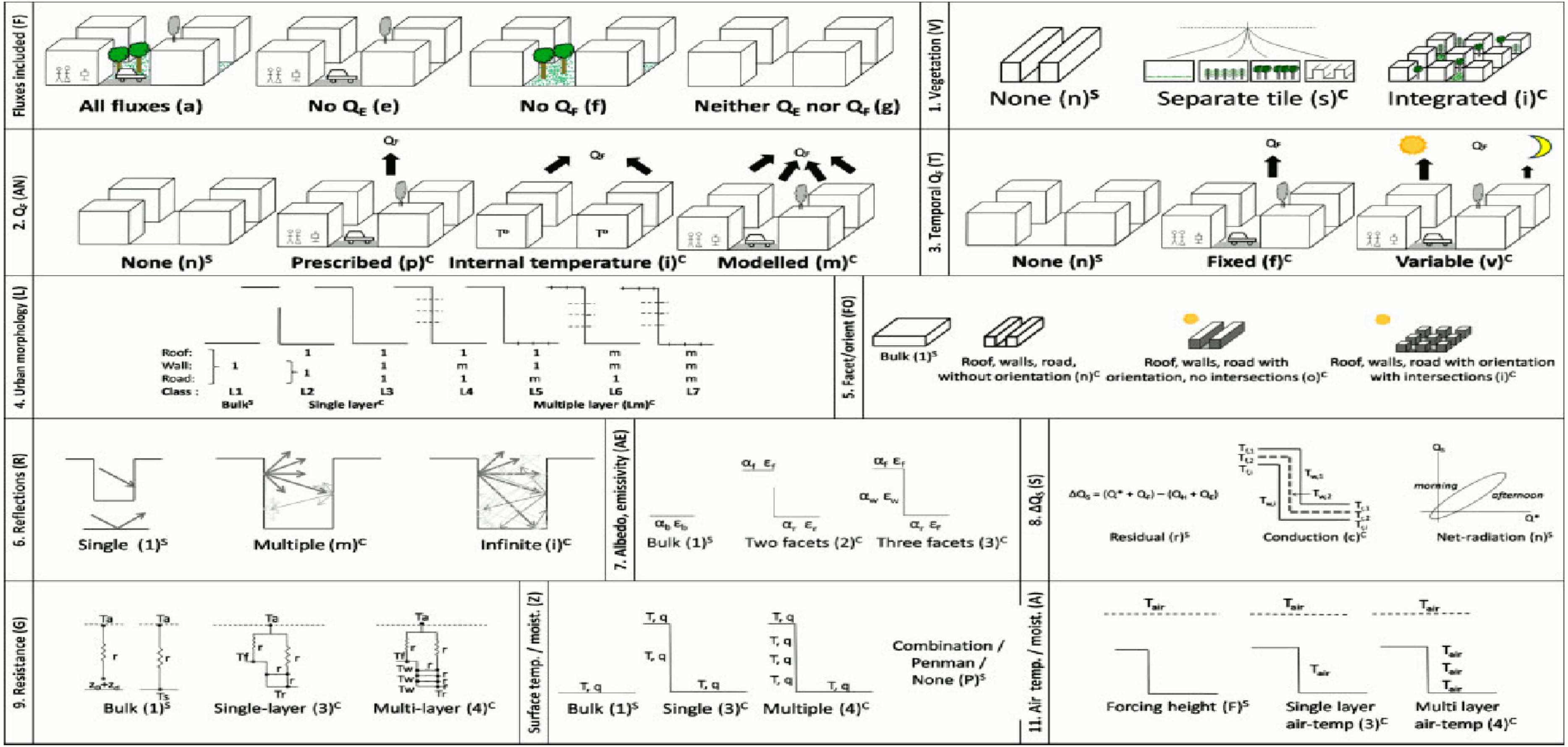


Hamdi and Masson 2008, JAMC



2 meters variables are computed in a prognostic way

Melbourne



Fluxes included (F)
All fluxes (a)
No Q_E (e)
No Q_F (f)
Neither Q_E nor Q_F (g)
1. Vegetation (V)
None (n)^S
Separate tile (s)^C
Integrated (i)^C
2. Q_F (AN)
None (n)^S
Prescribed (p)^C
Internal temperature (i)^C
Modelled (m)^C
3. Temporal Q_F (T)
None (n)^S
Fixed (f)^C
Variable (v)^C
4. Urban morphology (L)
Roof:
Wall:
Road:
Class :
Bulk^S
Single layer^C
Multiple layer (Lm)^C
5. Facet/orient (FO)
Bulk (1)^S
Roof, walls, road, without orientation (n)^C
Roof, walls, road with orientation, no intersections (o)^C
Roof, walls, road with orientation with intersections (i)^C
6. Reflections (R)
Single (1)^S
Multiple (m)^C
Infinite (i)^C
7. Albedo, emissivity (AE)
Bulk (1)^S
Two facets (2)^C
Three facets (3)^C
8. ΔQ_S (S)
$\Delta Q_S = (Q^* + Q_F) - (Q_H + Q_E)$
Residual (r)^S
Conduction (c)^C
morning
afternoon
Net-radiation (n)^S
9. Resistance (G)
Bulk (1)^S
Single-layer (3)^C
Multi-layer (4)^C
Surface temp. / moist. (Z)
Bulk (1)^S
Single (3)^C
Multiple (4)^C
Combination / Penman / None (P)^S
11. Air temp. / moist. (A)
Forcing height (F)^S
Single layer air-temp (3)^C
Multi layer air-temp (4)^C

Stages

Table I. The number of versions of each model used in the comparison and number of groups using it.

Code	Model name	References	Versions	Groups
BEP02	Building effect parameterization	Martilli *et al.* (2002)	1	1
BEP_BEM08	BEP coupled with building energy model	Martilli *et al.* (2002); Salamanca *et al.* (2009, 2010); Salamanca and Martilli (2010)	1	1
CLMU	Community land model – urban	Oleson *et al.* (2008a, 2008b)	1	1
IISUCM	Institute of industrial science urban canopy model	Kawamoto and Ooka (2006, 2009a, 2009b)	1	1
JULES	Joint UK land environment simulator	Essery *et al.* (2003); Best (2005); Best *et al.* (2006)	4	2
LUMPS	Local-scale urban meteorological parameterization scheme	Grimmond and Oke (2002); Offerle *et al.* (2003); Loridan *et al.* (2010b)	2	1
NKUA	University of Athens model	Dandou *et al.* (2005)	1	1
MORUSES	Met Office reading urban surface exchange scheme	Harman *et al.* (2004a, 2004b); Porson *et al.* (2010)	2	1
MUCM	Multi-layer urban canopy model	Kondo and Liu (1998); Kondo *et al.* (2005)	1	1
NJU-UCM-S	Nanjing University urban canopy model-single layer	Masson (2000); Kusaka *et al.* (2001)	1	1
NJUC-UM-M	Nanjing University urban canopy model-multiple layer	Kondo *et al.* (2005), Kanda (2005a, 2005b)	1	1
NSLUCM/ NSLUCMK/ NSLUCM-WRF	Noah land surface model/single-layer urban canopy model	Kusaka *et al.* (2001); Chen *et al.* (2004); Loridan *et al.* (2010a)	3	3
SM2U	Soil Model for submesoscales (urbanized)	Dupont and Mestayer (2006); Dupont *et al.* (2006)	1	1
SNUUCM	Seoul National University urban canopy model	Ryu *et al.* (2009)	1	1
SRUM2/ SRUM4	Single column reading urban model tile version	Harman and Belcher (2006)	4	1
SUEB	Slab urban energy balance model	Fortuniak (2003); Fortuniak *et al.* (2004, 2005)	1	1
SUMM	Simple urban energy balance model for mesoscale simulation	Kanda *et al.* (2005a, 2005b); Kawai *et al.* (2007, 2009)	1	1
TEB	Town energy balance	Masson (2000); Masson *et al.* (2002); Lemonsu *et al.* (2004); Pigeon *et al.* (2008)	1	1
TEB-ml	Town energy balance with multi-layer option	Hamdi and Masson (2008); Masson and Seity (2009)	1	1
TUF2D	Temperatures of urban facets 2D	Krayenhoff and Voogt (2007)	1	1
TUF3D	Temperatures of urban facets 3D	Krayenhoff and Voogt (2007)	1	1
VUCM	Vegetated urban canopy model	Lee and Park (2008)	1	1

Note these are assigned anonymous numerical identifiers in the analysis.

	Category	Data provided
Stage 1	Forcing data	K↓, L↓, air temperature, station pressure, specific humidity, wind components, rainfall
Stage 1	Site	Latitude*, Longitude* Measurement height: 6.25 mean roughness height

Stage 2	Plan area fraction	Pervious = 0.38 Impervious = 0.62

Stage 3	Heights	Instrument height	40 m	
		Roughness length for momentum	0.4 m	
		Maximum height of roughness elements	12 m	
		Mean building height	6.4 m	
		Height to width ratio	0.42	
		Mean wall to plan area ratio	0.4	
	Plan area fraction	Surface cover	Fraction	Total
		Building	0.445	Impervious 0.62
		Concrete	0.045	
		Road	0.130	
		Vegetation (excl. grass)	0.225	Pervious 0.38
		Grass	0.150	
		Other (bare or pools)	0.005	
	Other	Urban climate zone = 5 Population density = 415.78 km^{-2}		

Stages

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Stage 4: Material characteristics

Wall	d	C_p	c	λ
1	40.40	1008.5	1.25	0.61
2	54.00	1456.3	1.40	0.43
3	42.00	1010.0	0.0013^{c}	0.024^{d}
4	12.50	837.0	0.67^{a}	0.16^{a}
Roof				
1	11.6	865.2	2.07	6.53
2	50.00	965.3	0.0071	0.025
3	40.00	1880.0	1.50^{a}	0.23^{a}
4	12.50	837.0	0.67^{a}	0.16^{a}
Road				
1	28.75	912.79	1.14	1.17
2	158.3^{a}	840	1.05^{a}	0.30^{a}
3	112.5^{a}	840	1.29^{a}	0.42^{a}
4	650.45^{a}	801	1.43^{b}	3.72^{b}

ρ^{a} brick = 1500; softwood = 560.5; hardwood = 800; concrete = 1822; asphalt = 2100; glass = 2535.7; asbestos cement building board = 1920; asbestos cement tiles = 1900; terracotta = 1700; metal = 7900; fibreglass = 60; air = 1.29; gypsum/plaster board = 800; coarse crushed rock = 1250; fine crushed rock = 1540; sandy loam = 1780

Site albedo = 0.15 | Site emissivity = 0.973

Stages

Stage 4: details of layers components for each facet

Layer	Wall					
	Material	%	C_p	c^a	λ^a	d
1	Brick	27.94	840.0	1.26	0.71	110
	Softwood	59.43	1975.5	1.11	0.14	20
	Concrete	5.37	837.0	1.52	0.87	100
	Asbestos cement	5.37	1005.0	1.93	0.58	8
	Concrete/wood	1.13	1406.2	1.31	0.79	60
	Metal	0.76	1105.0	8.73	72.00	3
2	Hardwood	80	1880	1.50	0.23	40
	Brick	20	840.0	1.26	0.71	110
3	Insulation (air)					
4	Gypsum/plaster board					

Layer	Roof						
		Material	%	C_p	c^a	λ^a	d
1		Metal	30	1105	8.73	72.00	3.0
	Tile	Concrete	40	837	1.52	1.10	16.5
	Tile	Terracotta	20	837	1.42	0.99	16.5
	Tile	Asbestos cement	10	945	1.79	0.55	8.0
2		Air	85	1010	0.0013	0.024	50
		Fibreglass	15	712	0.04	0.03	50
3		Wood					
4		Gypsum/ plaster board					

Layer	Road					
	Material	%	C_p	c^a	λ^a	d
1	Asphalt	75	920	1.10	1.2	35
	Concrete	25	837.0	1.5	0.87	10
2	Coarse crushed rock					
3	Fine crushed rock					
4	Soil (sandy loam)					

Conclusions

The dominant physical processes in the urban environment that models need to be able to simulate in order:

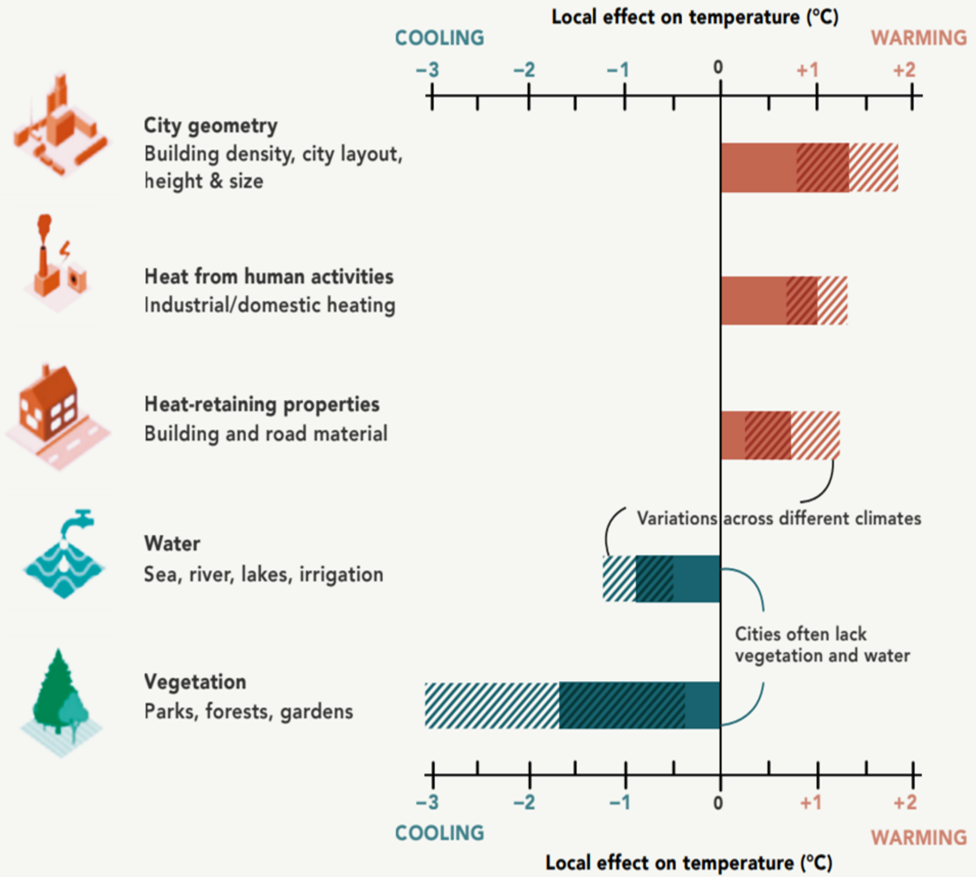
1. Changes to the bulk albedo of the surface that result from building materials

2. Shortwave trapping from the canyon geometry

3. The reduction in outgoing long-wave radiation from the street canyon due to reduced sky view factor

4. The contrast between this and the roofs that see a full sky view

5. The evaporation from the vegetation



Conclusions

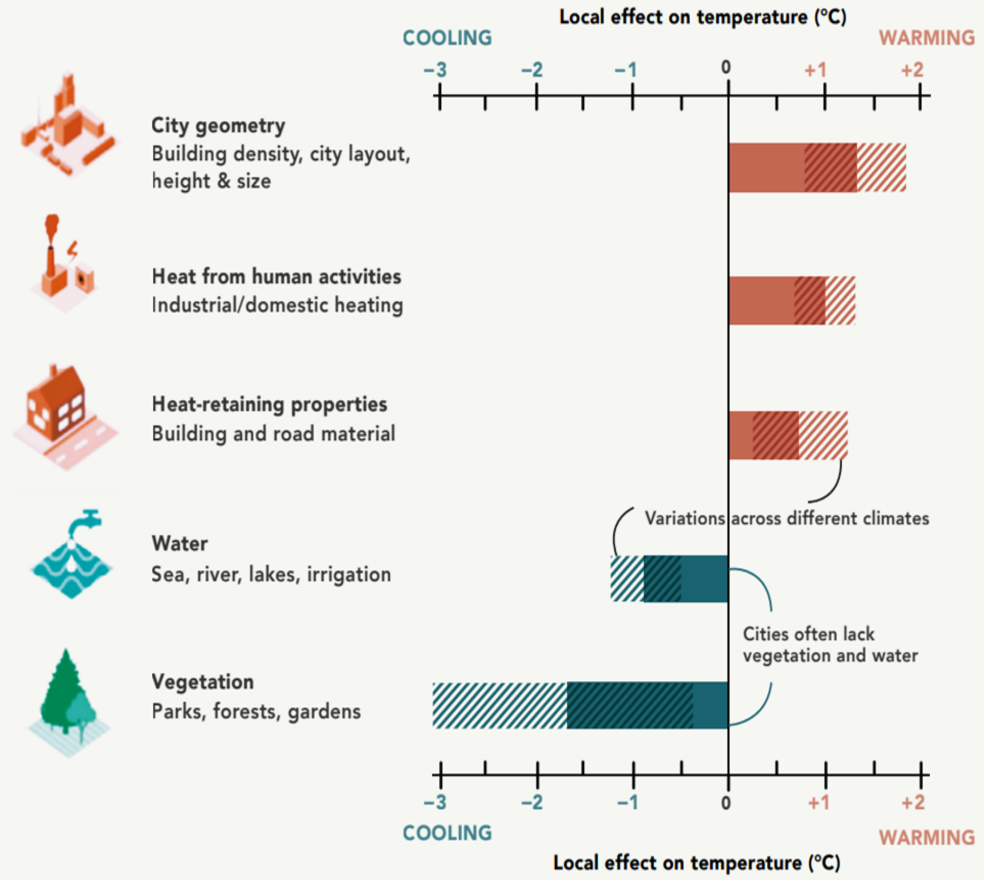
The key urban parameters are:

1. The bulk surface albedo

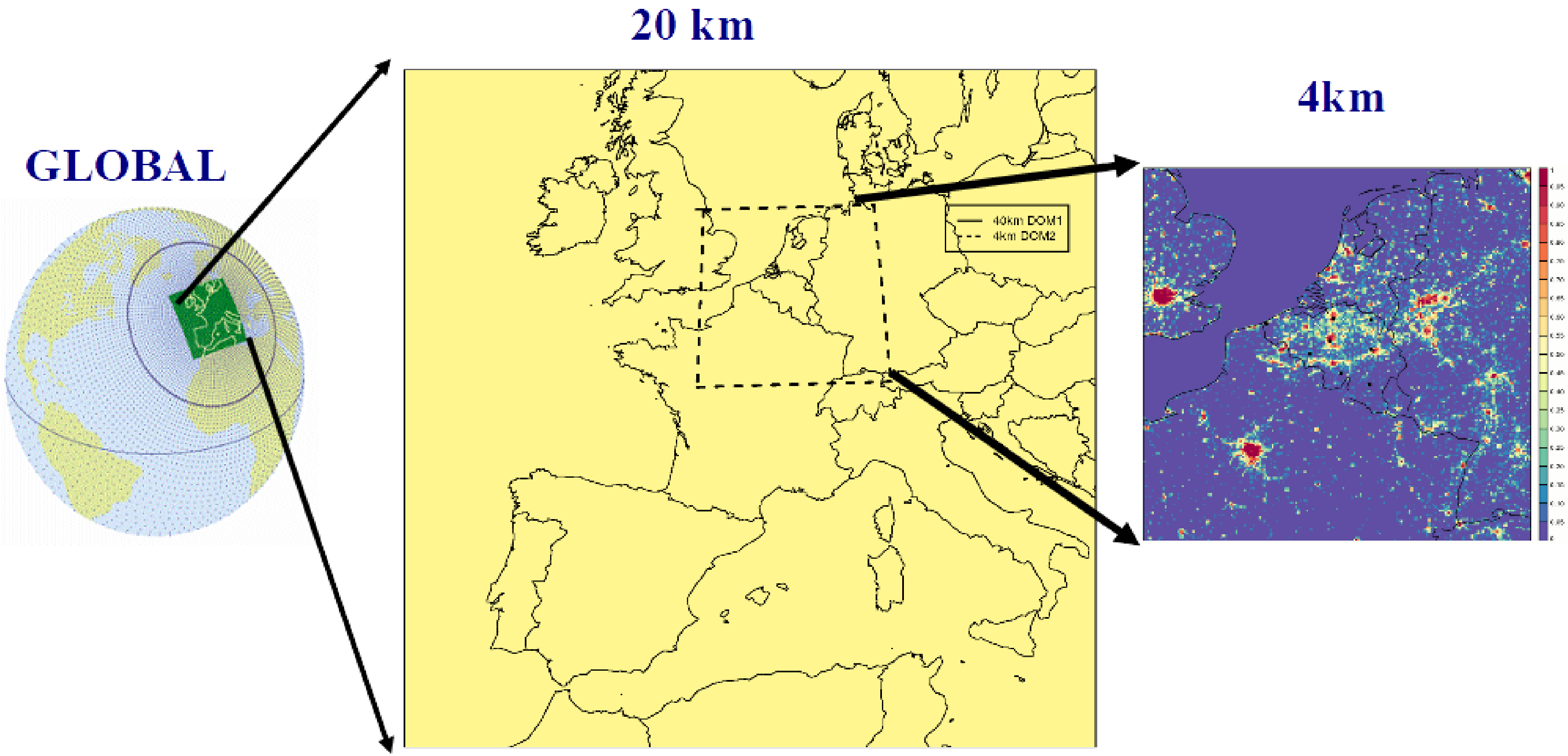
2. The height to width ratio of the urban canyon

3. The fraction of buildings roofs to the urban canyons

4. The vegetation fraction

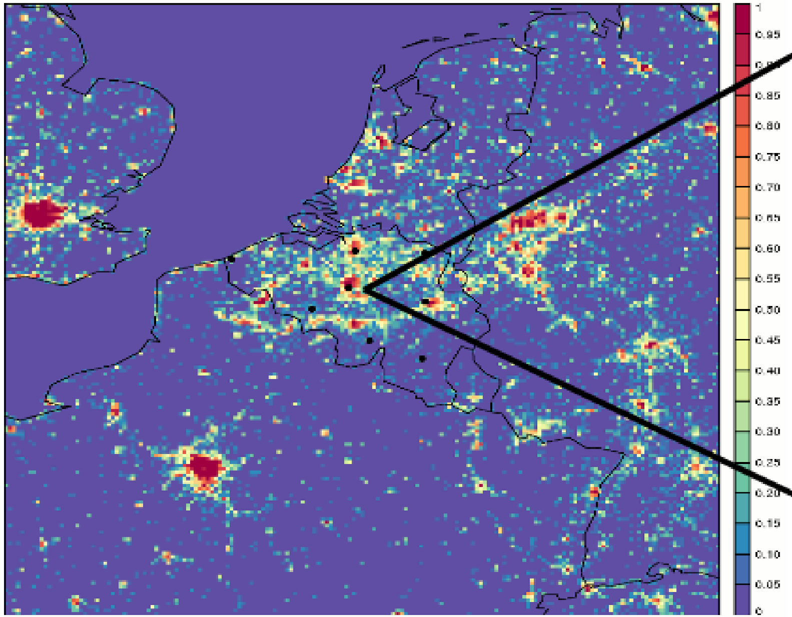


Urban climate: ALARO-SURFEX/TEB

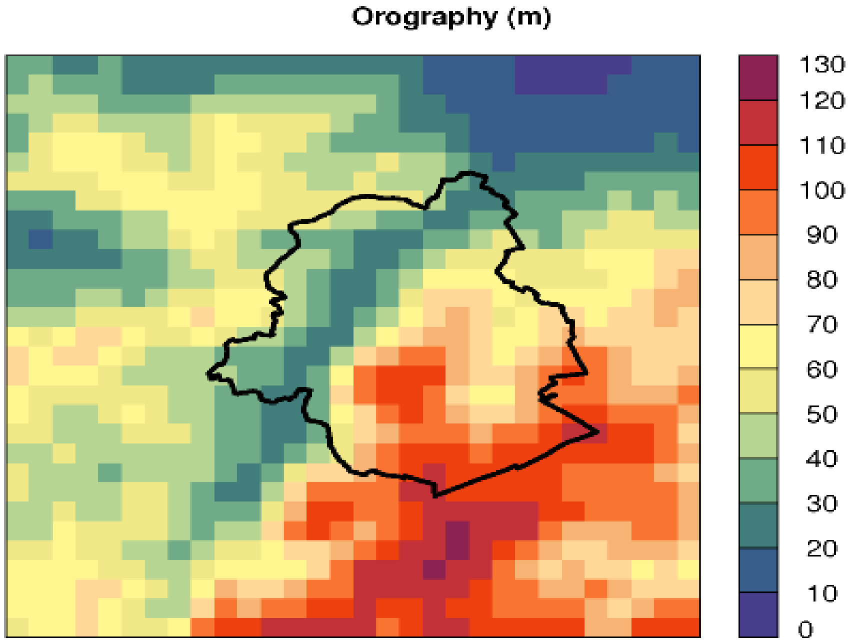


SURFEX offline

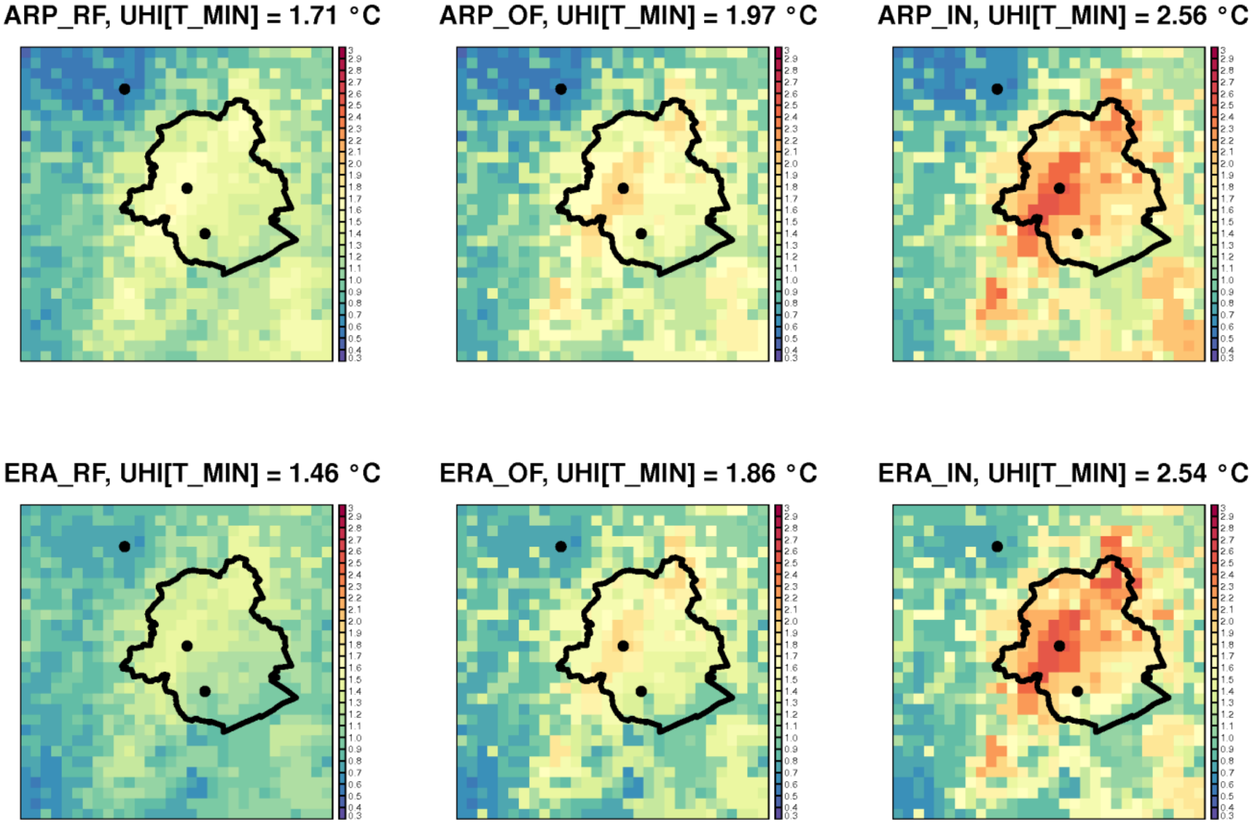
ALARO+SURFEX INLINE 4km

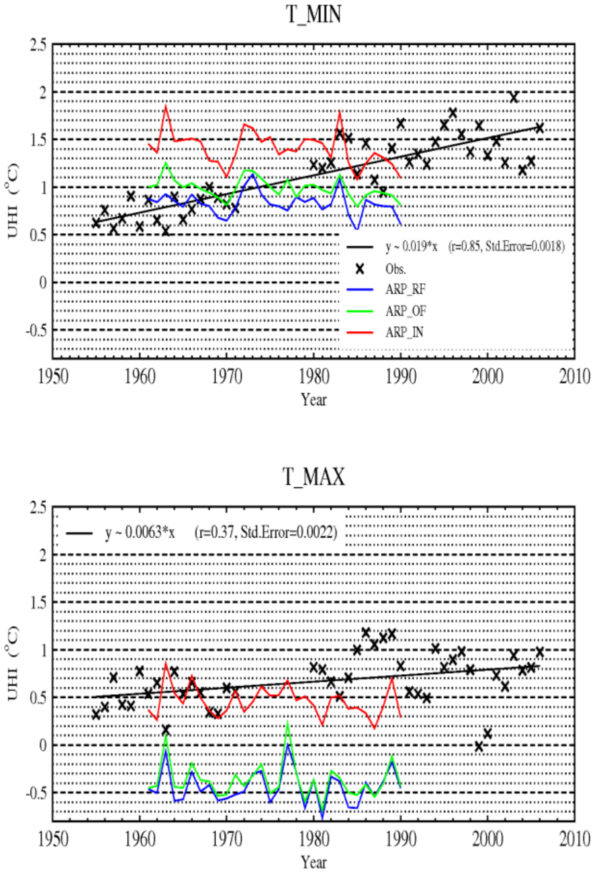


SURFEX OFFLINE 1 km, Brussels, 30x30



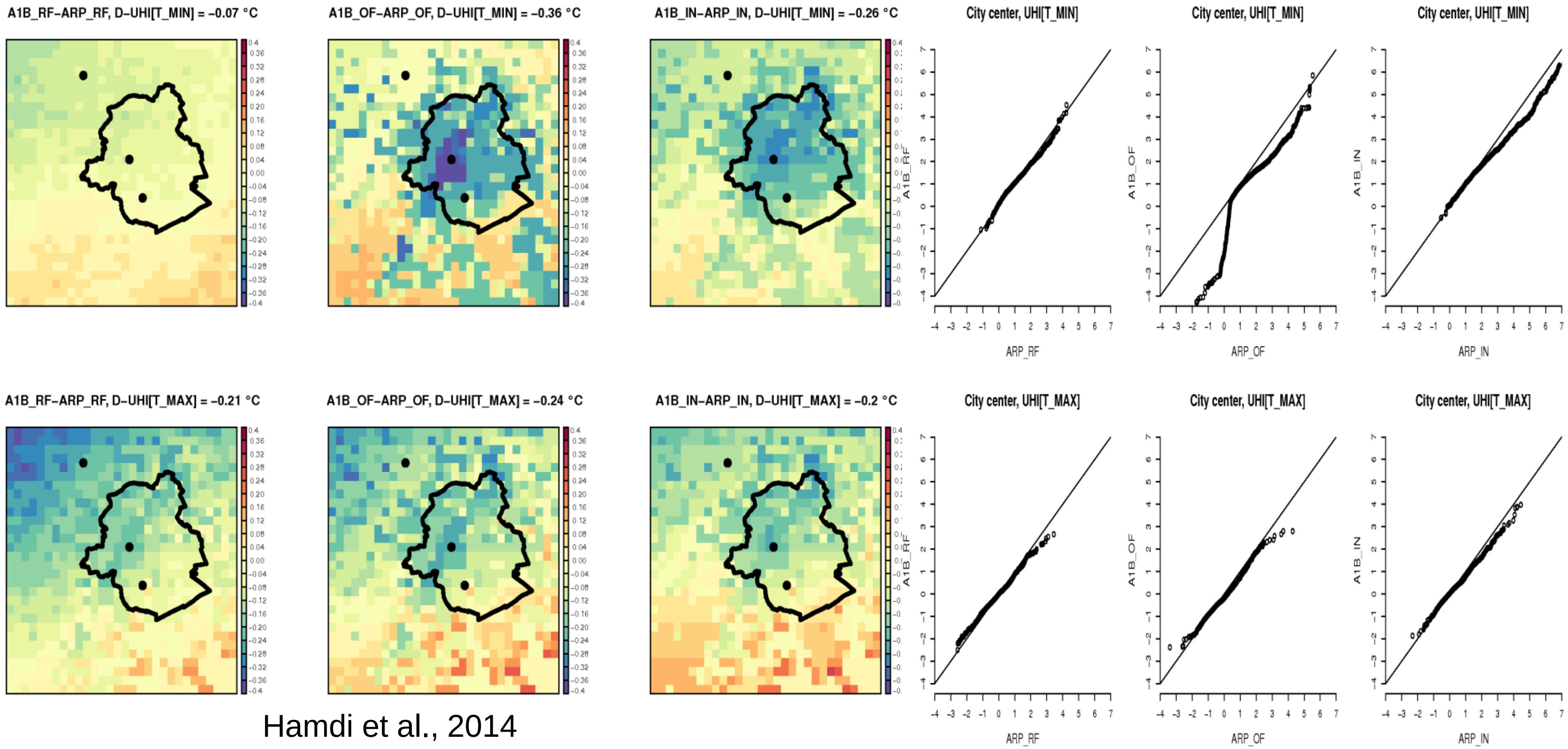
Is slab/offline approach enough for climate runs?





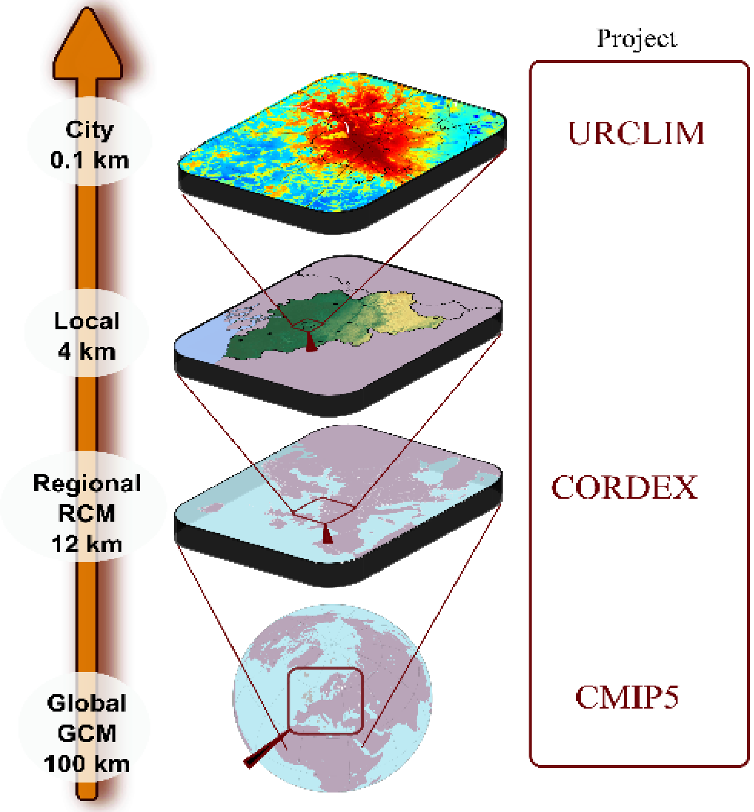
Hamdi et al., 2014

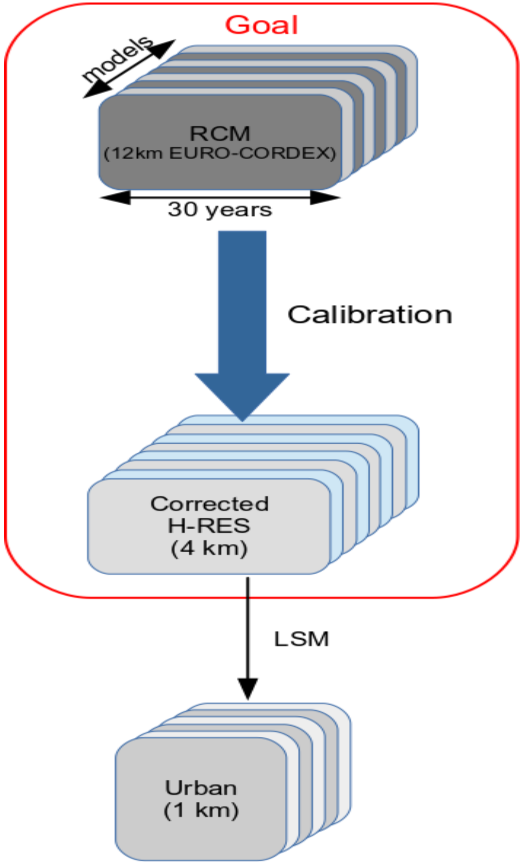
What about future climate



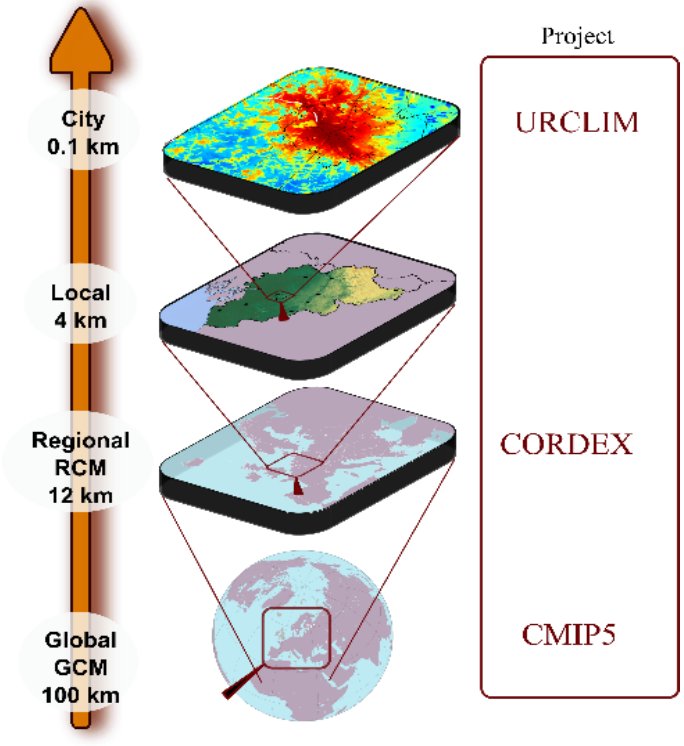
Hamdi et al., 2014

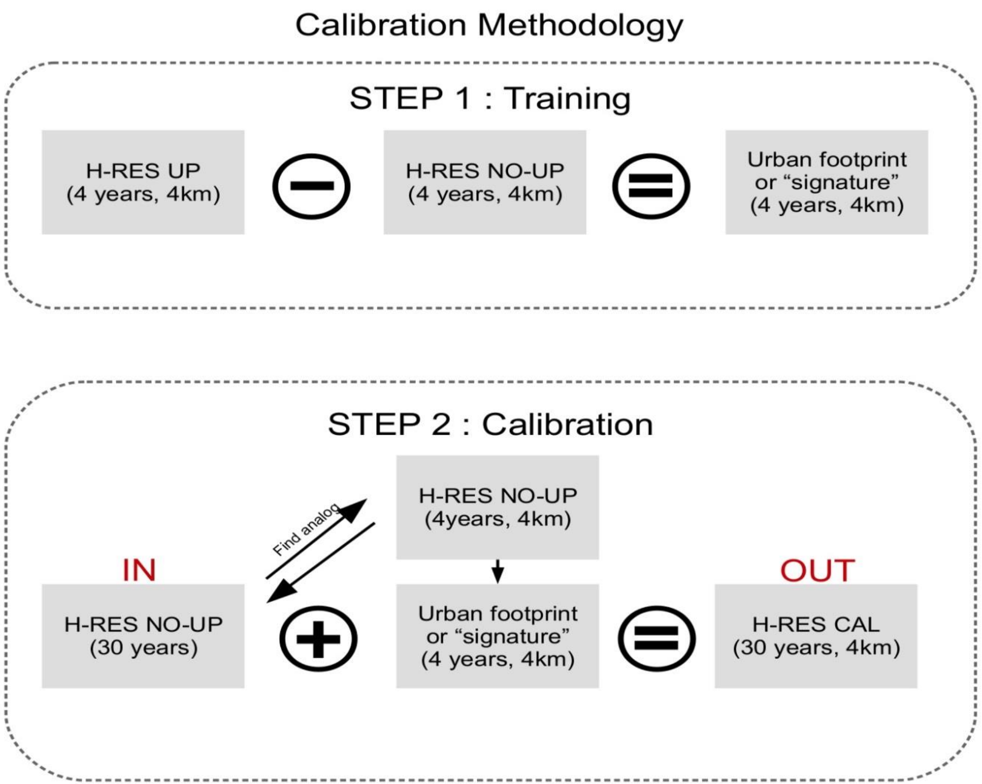
What about ensemble runs?



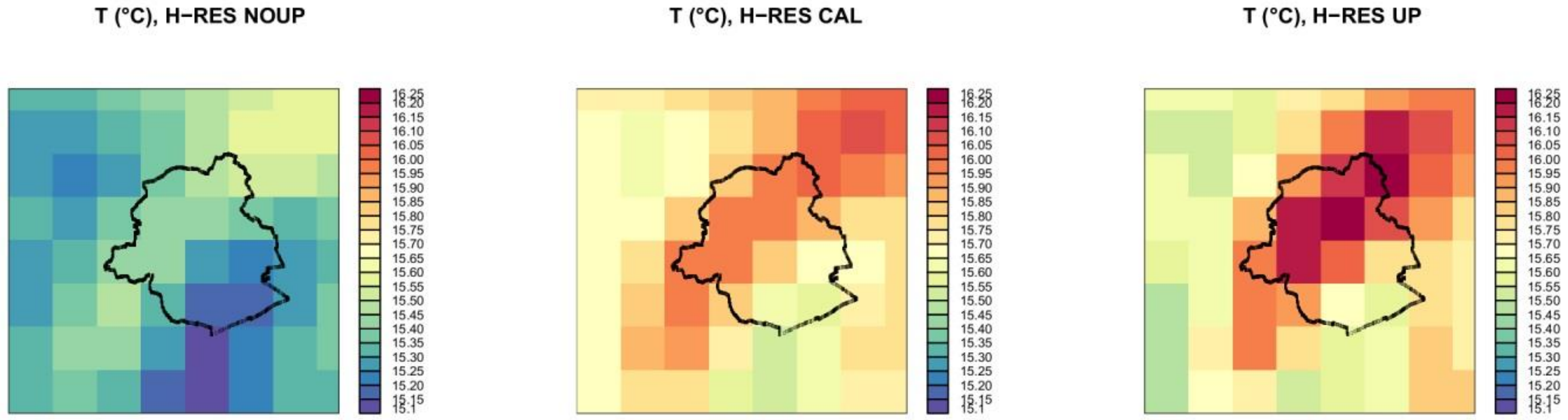


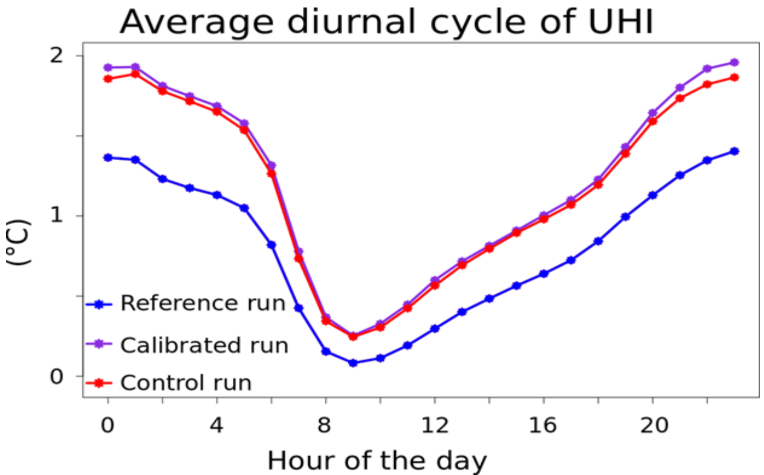
Urban signature





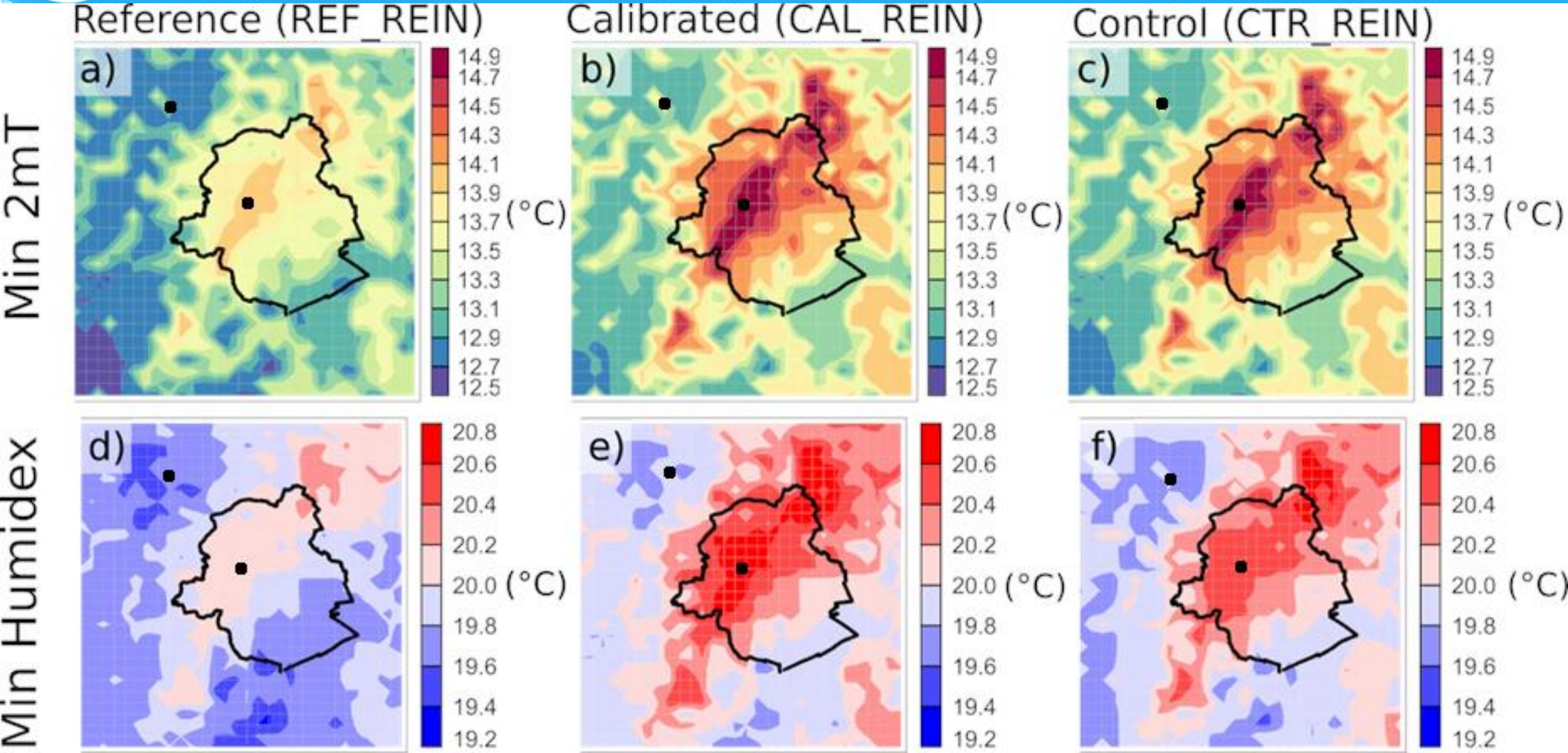
Proof of concept



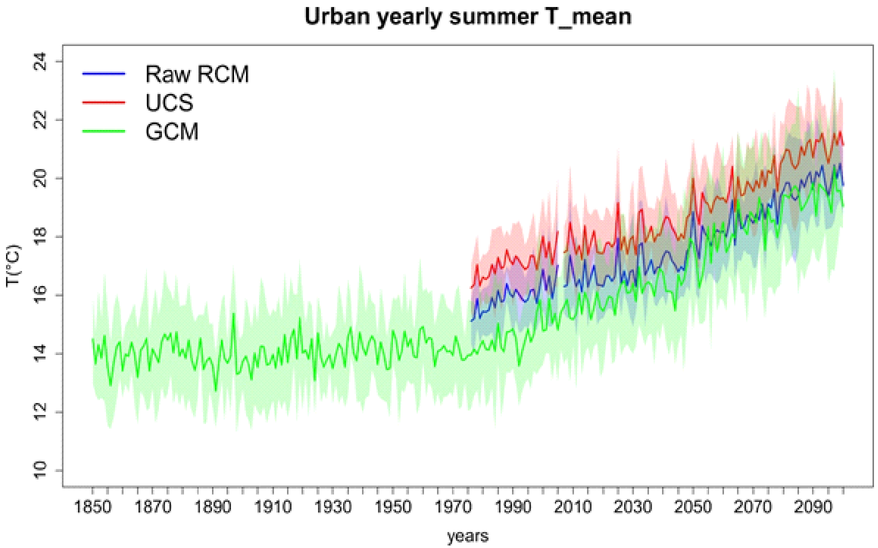


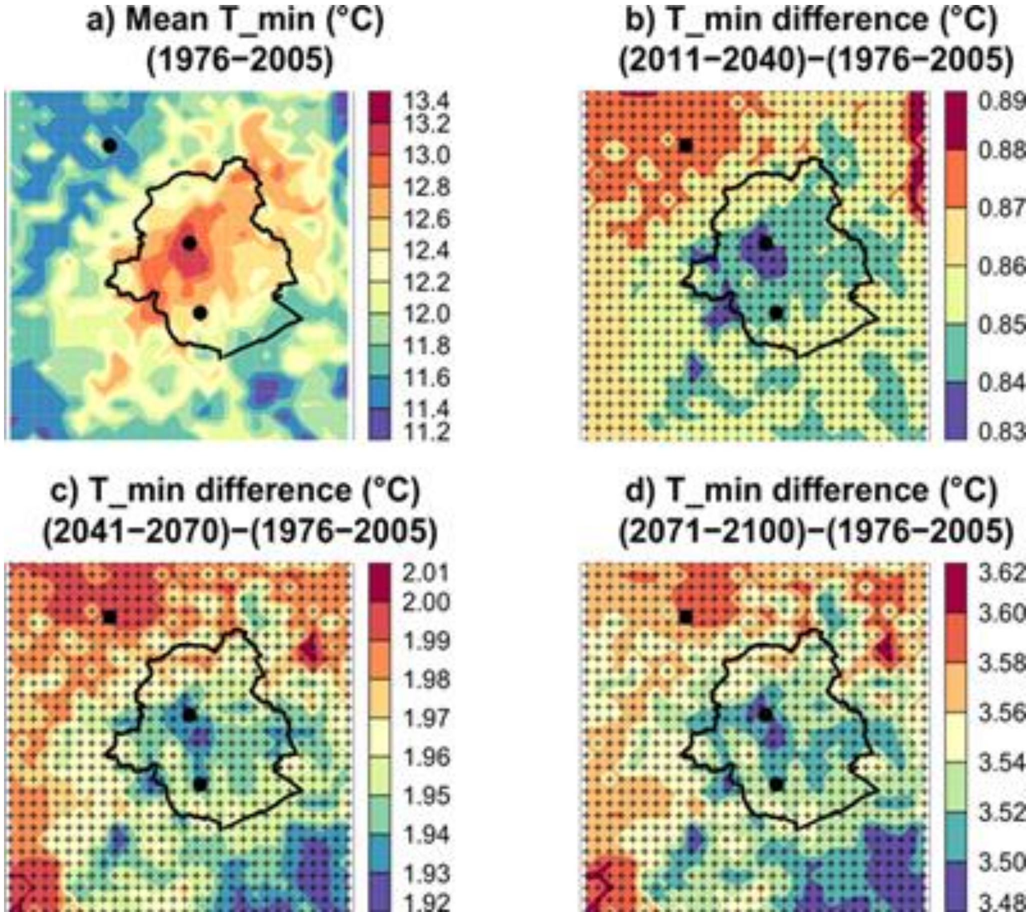
Duchêne et al. 2020

Proof of concept



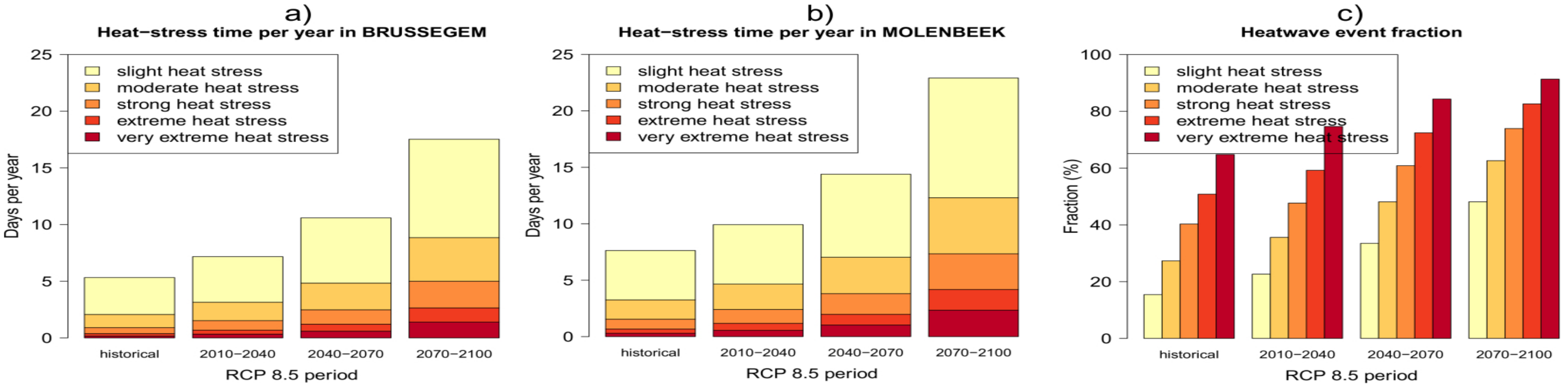
Application: EURO-CORDEX Ensemble downscaled

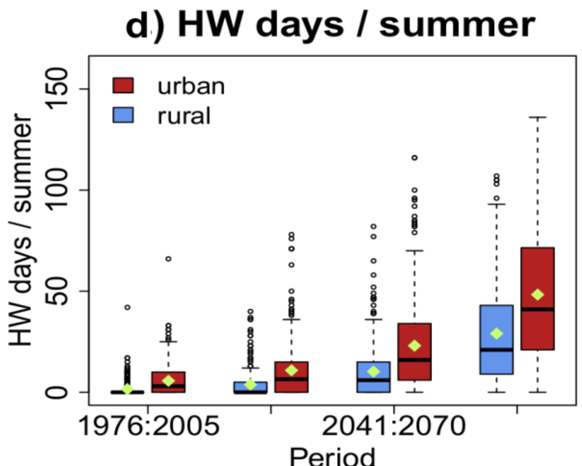




Duchêne et al. 2022

Application: EURO-CORDEX Ensemble downscaled

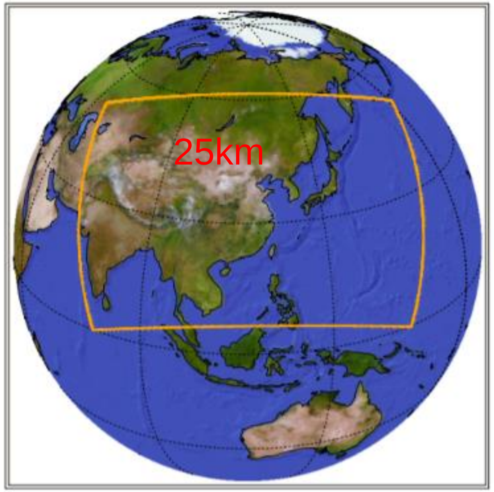




Duchêne et al. 2022

Beijing, China: CORDEX: EA

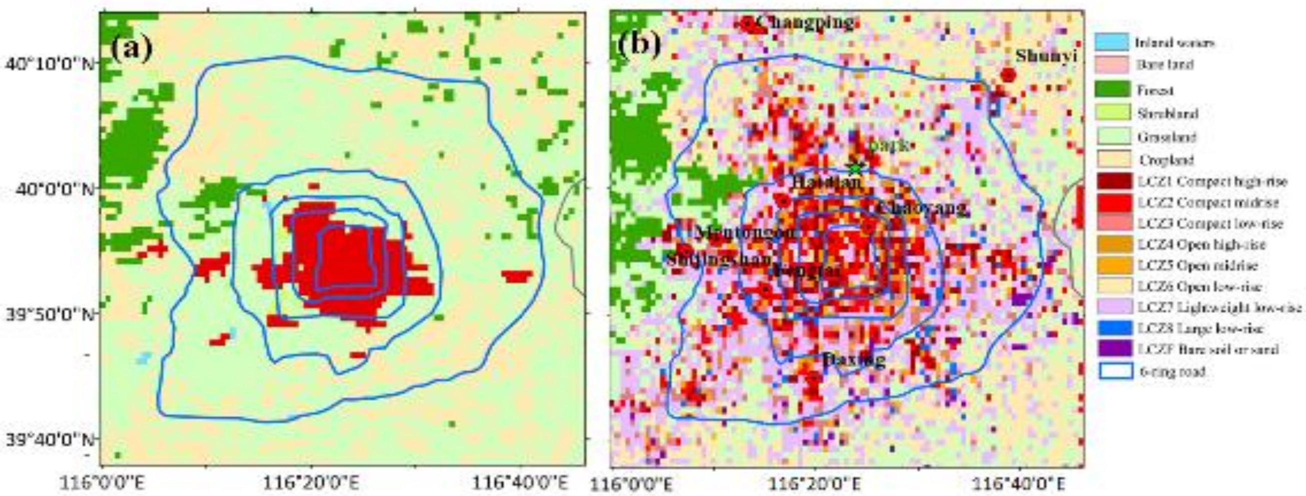
Experimental Design



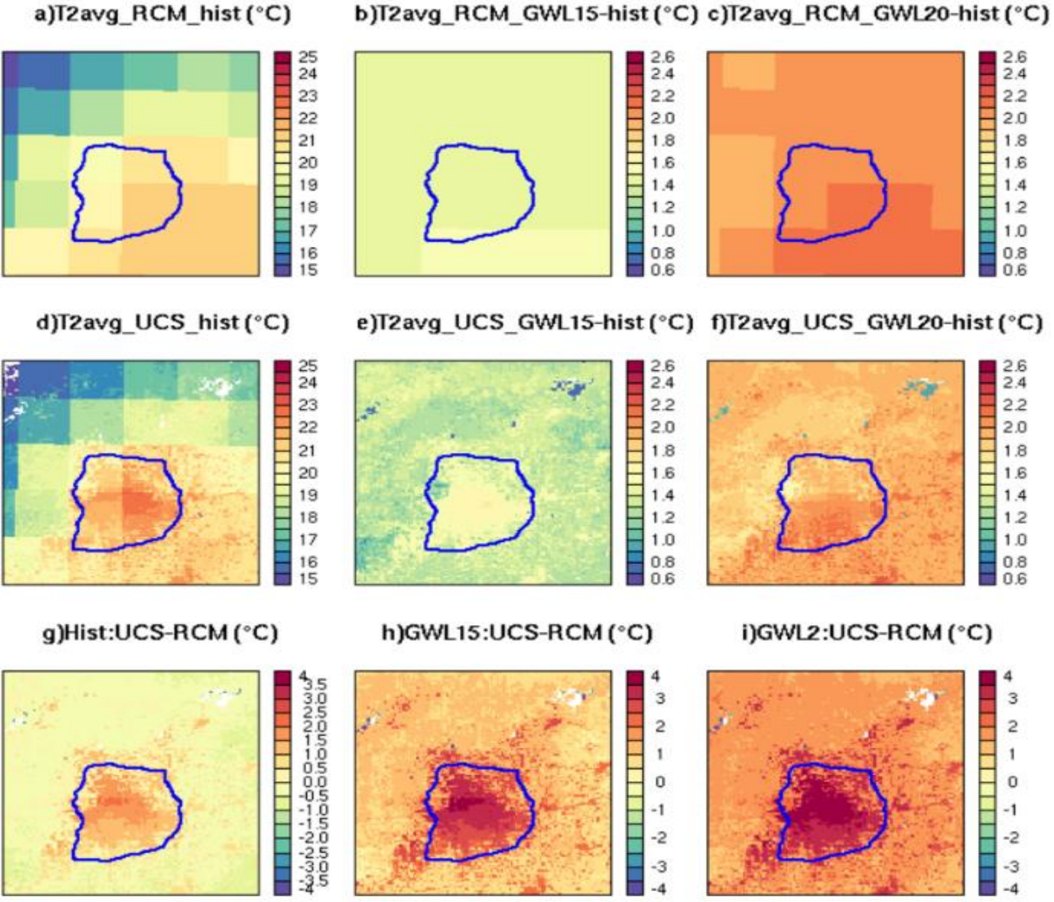
The EAS22-CORDEX ensemble members

GCM_run	RCM	Scenario	Member
HadGEM2-ES	RegCM	Historical, RCP85	r1i1p1
MPI-ESM-MR	RegCM	Historical, RCP85	r1i1p1
NorESM1-M	RegCM	Historical, RCP85	r1i1p1

GCMs	SWL1.5	SWL2
HadGEM2-ES_RCP85	2025 (1.27)	2037 (2.07)
MPI-ESM-MR_RCP85	2020 (2.26)	2038 (2.70)
NorESM1-M_RCP85	2032 (2.26)	2047 (3.09)



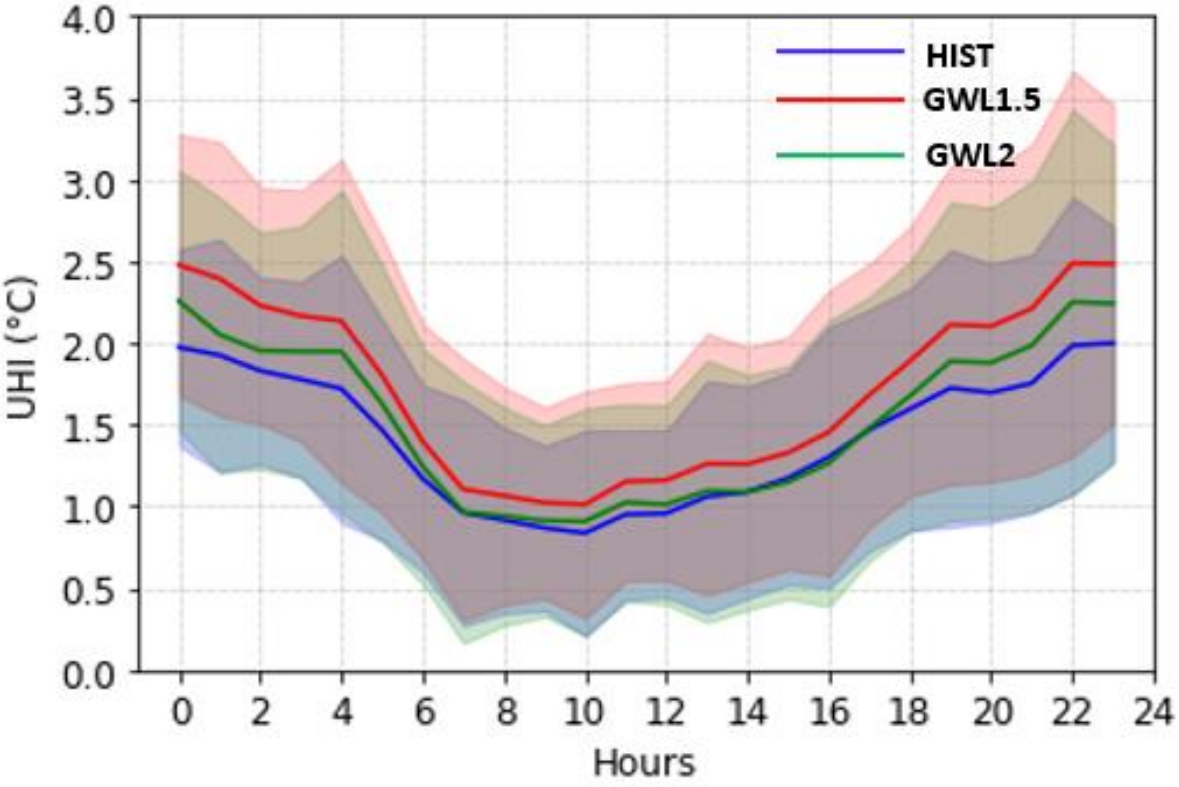
Beijing, China: CORDEX: EA



- The mean ensemble temperatures bias of T2max of rural and urban areas computed by UCS (urban corrected simulations) are -0.47 °C, -0.29 °C respectively, which were improved compared to raw RCMs (-1.30 °C,-2.09 °C).

- An average summer warming reaching up to 3.5 °C and 4 °C at GWL1.5 and GWL2.0, respectively, in central urban area of Beijing。

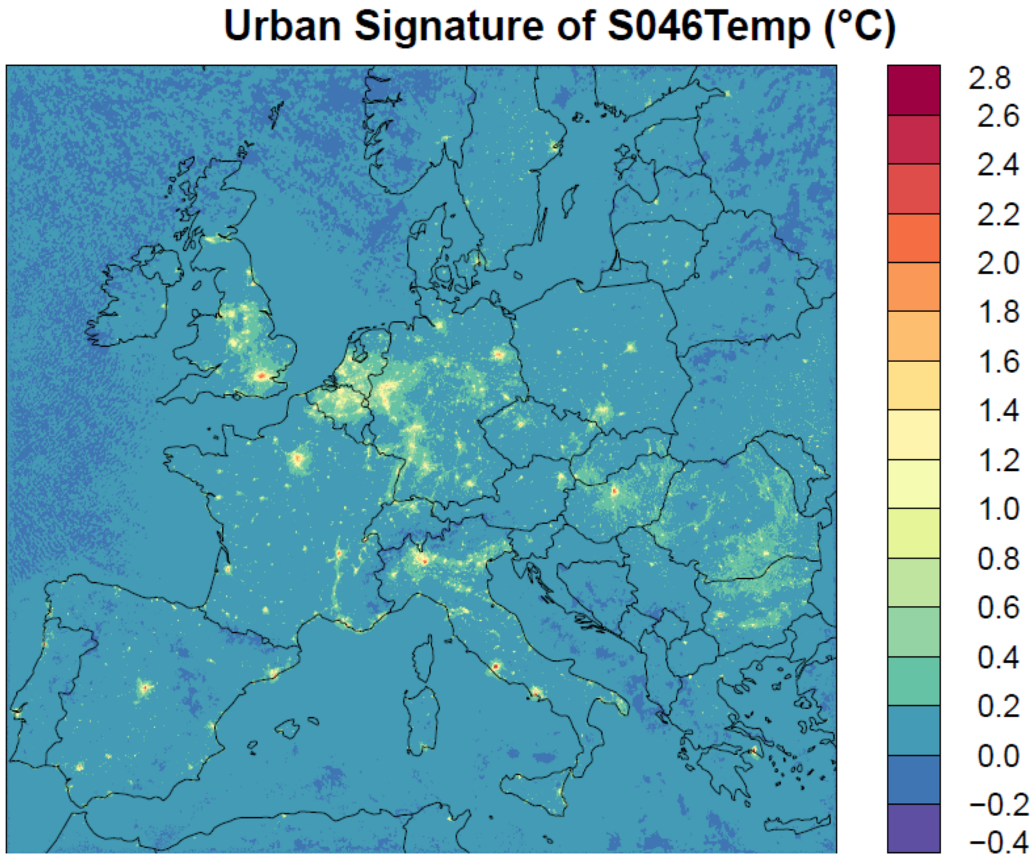
Beijing, China: CORDEX: EA



- The Urban heat island (UHI) intensity firstly increase under GWL1.5 and then decrease under GWL2.0, which can be related to increased downward longwave radiation by ~10 W/m^2.

- During the historical period, the UHI reaches a maximum value of 1.98 ± 0.90 °C at 2200 local time, but lowest in the period 0800-1100 local time.

Europe



Future work of Sara top