Urban Meteorology: Bridging Observations, Crowdsourcing and Modelling

Gert-Jan Steeneveld

The

CLIMATE OF LONDON

DEDUCED FROM

Meteorological Observations,

MADE IN THE METROPOLIS,
AND AT
VARIOUS PLACES AROUND IT.

BY LUKE HOWARD, GENT.

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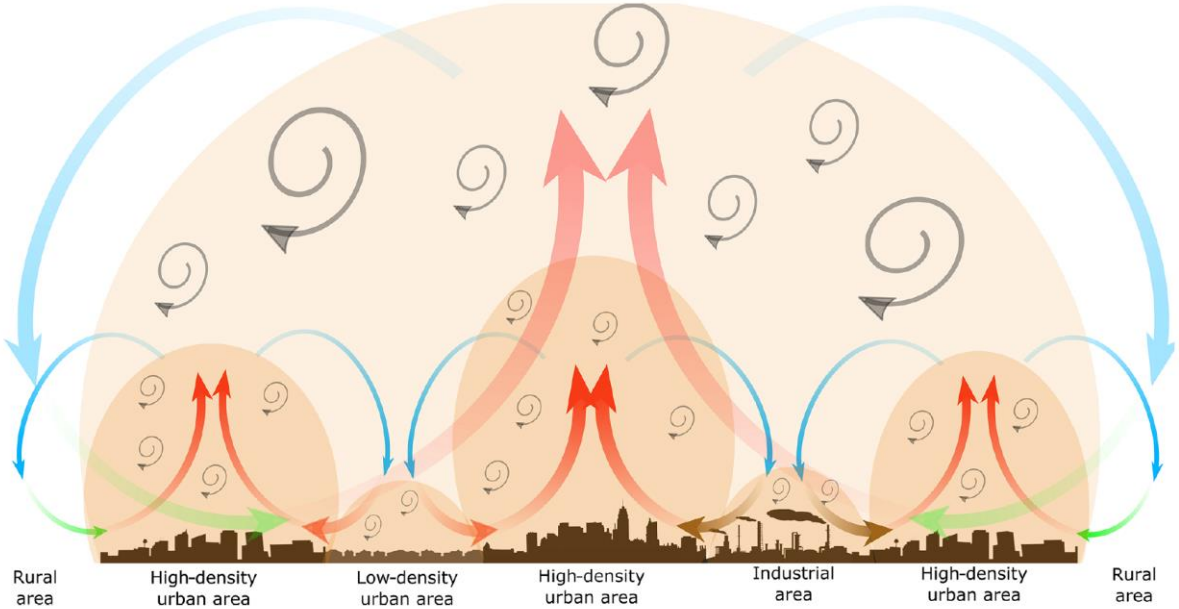
FESSTVaL
Field Experiment on Submesoscale Spatio-Temporal Variability in Lindenberg

Motivation to study urban meteorology

From Megacities (10M inhabitants, 33 right now) -> Gigacities



Questions concerning

Heat
Health
Air Quality
Energy
Urban Planning
Biodiversity
Effect on weather?
Effect on climate?
Non-linear interactions

Kulmula et al., 2021

Motivation to study urban meteorology

June 16, 2021
2:29 PM CEST
Last Updated 12 days ago

Energy

Texas power demand to keep breaking June records in heatwave

2 minute read

Reuters

Energy

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Science

This article is more than 2 years old

Upsurge in sleeping problems due to UK's longest heatwave in 40 years

People left tired, irritable and less productive at work after nights of poor shuteye

Denis Campbell *and* Sarah Marsh

Fri 13 Jul 2018 12.30 BST

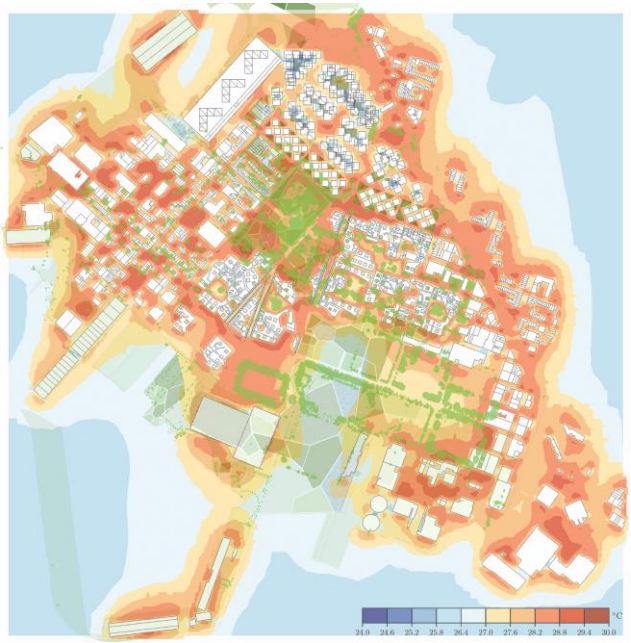
Couple struggle to sleep. Photograph: PhotoAlto/Frederic Cirou/Getty Images/PhotoAlto

Britain's longest heatwave since 1976 has led to a upsurge in sleeping problems, with people left tired, irritable and less productive at work after sweaty nights of poor-quality shuteye.

Record temperatures of up to 32.4C (90.3F) have been stopping many people getting a proper rest as they struggle to get to sleep in rooms that are uncomfortably warm, experts say.

"I'm very aware of people reporting more difficulties sleeping as the temperature increases, both personally and professionally," said Dr Michael

Health



Urban planning

Raven et al. 2018

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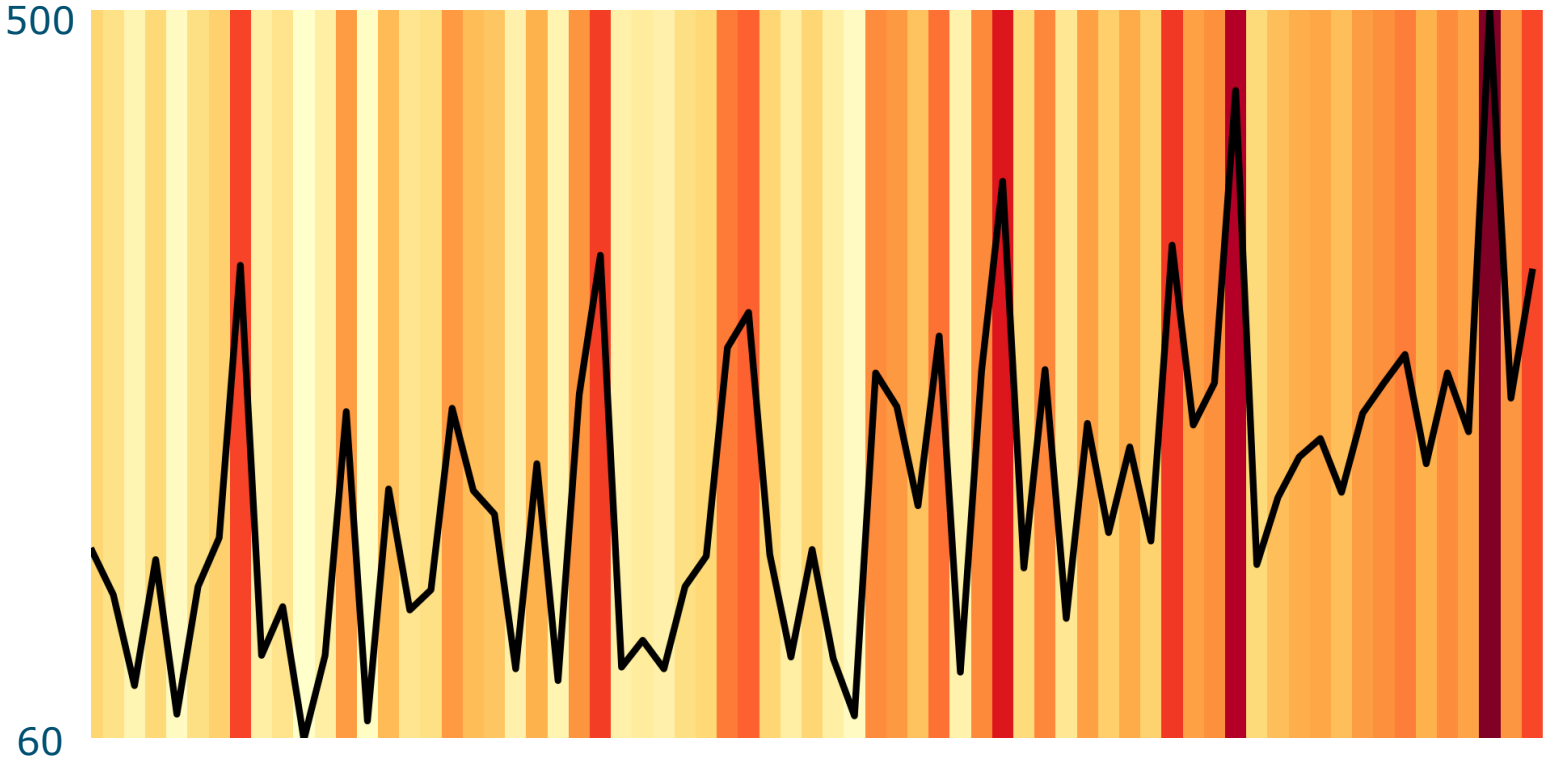
#showyourstripes Amsterdam. Climate change



Yearly hours of Physiologically Equivalent Temperature > 23 degrees (1951-2020).

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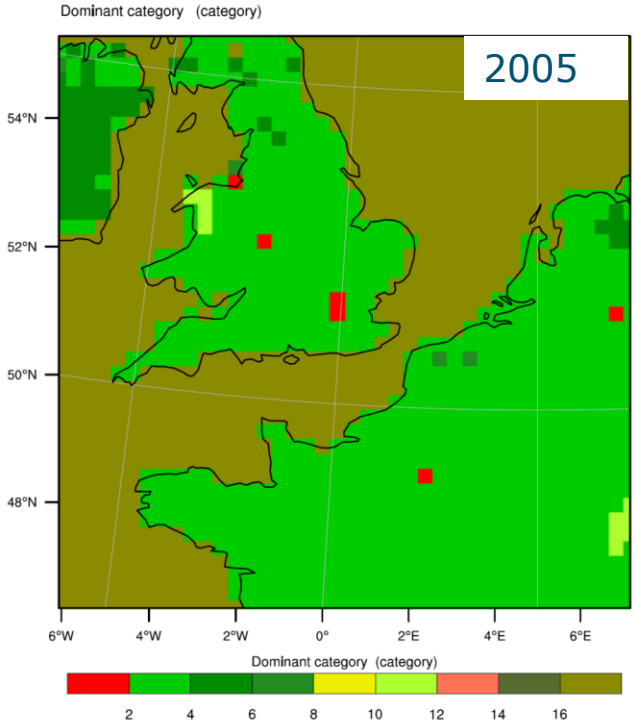
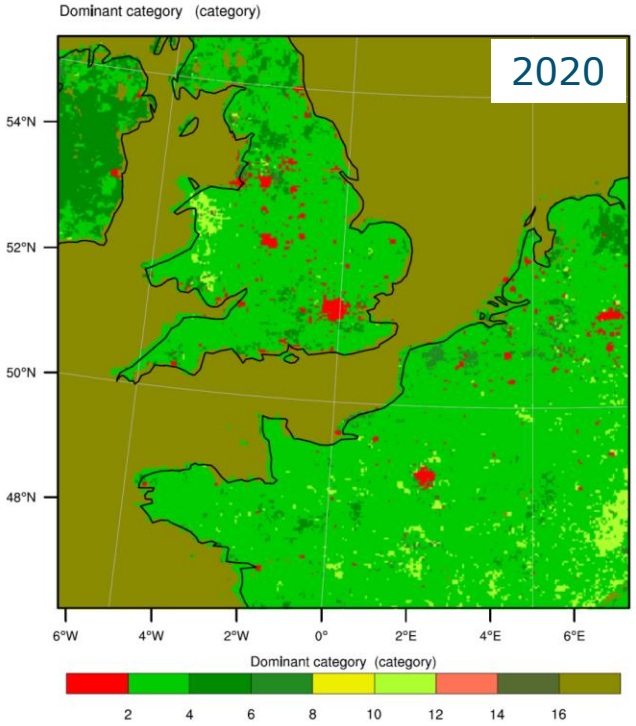
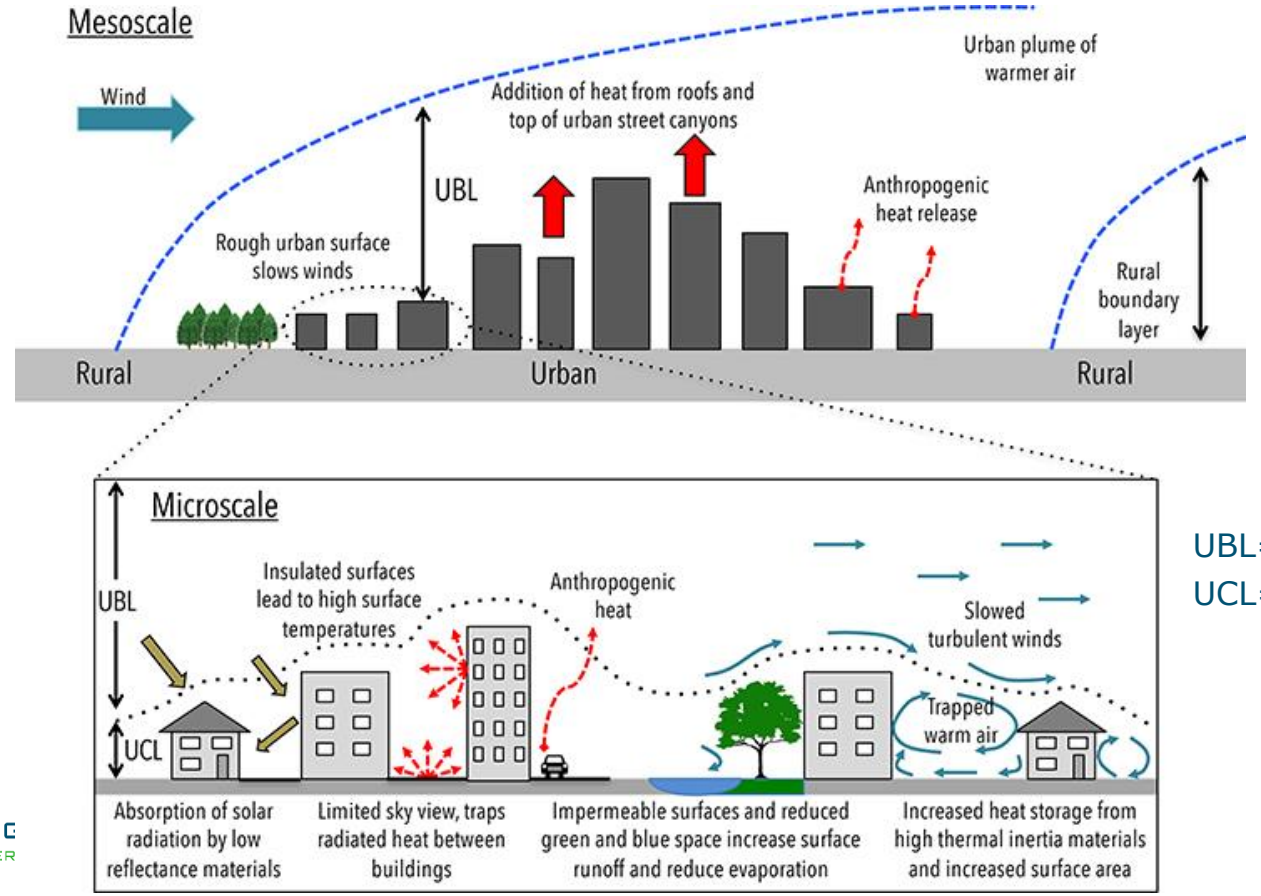
Motivation to study urban meteorology

Cities start to appear in our model grids!





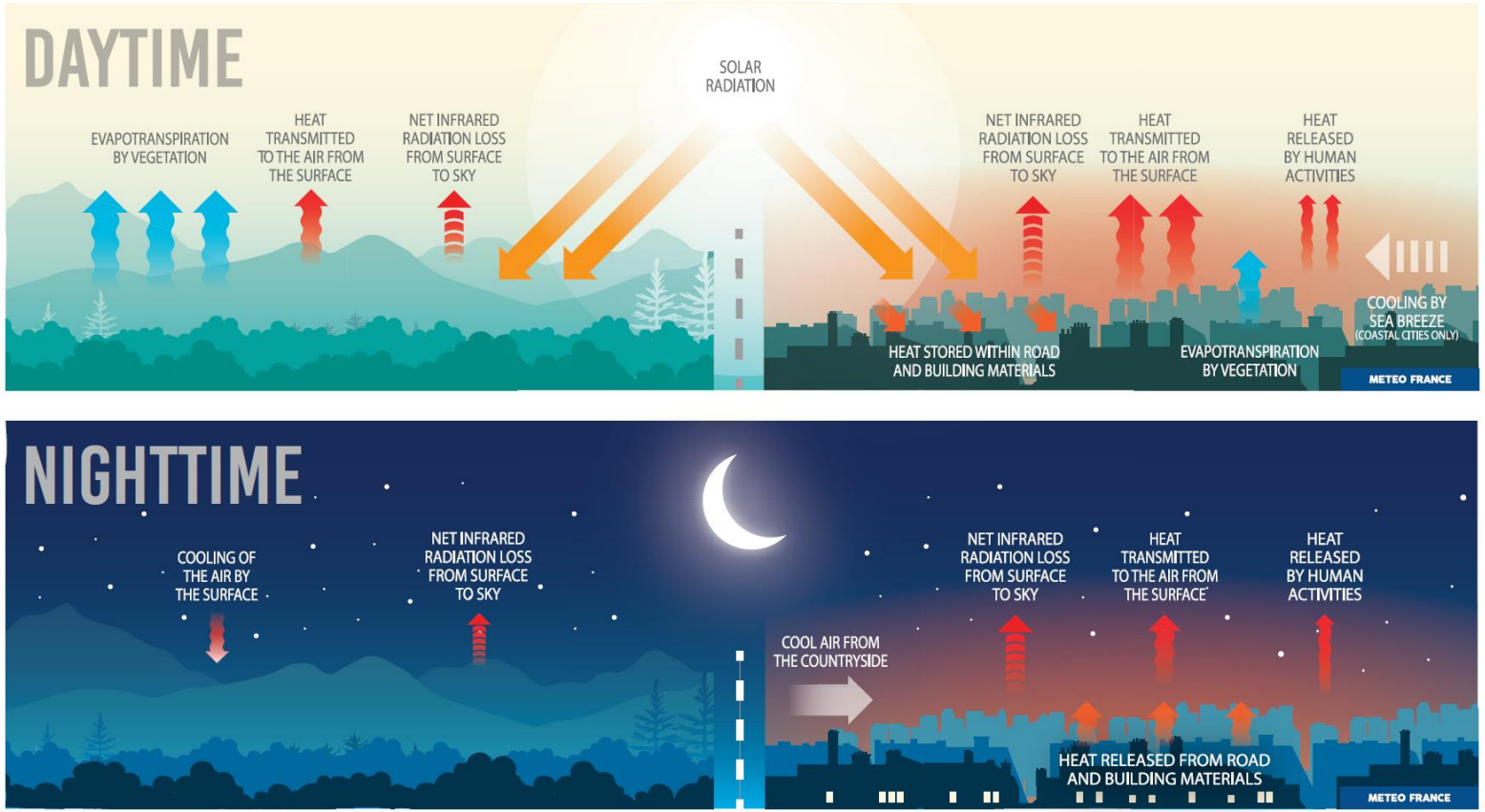
Scales studied in urban meteorology



UBL= Urban boundary layer

UCL= Urban canopy layer

Urban radiation and energy balance

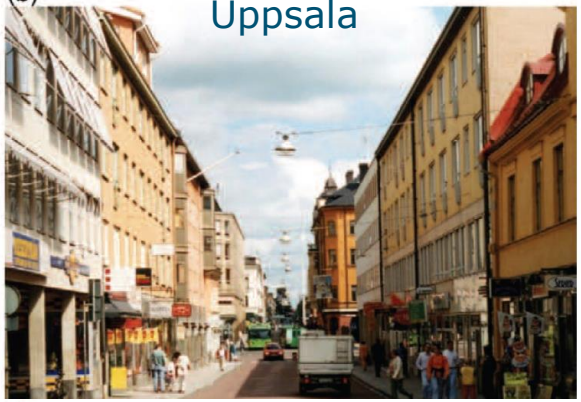


Masson et al., 2020

How to define “urban” (for obs and modelling)?

(a)

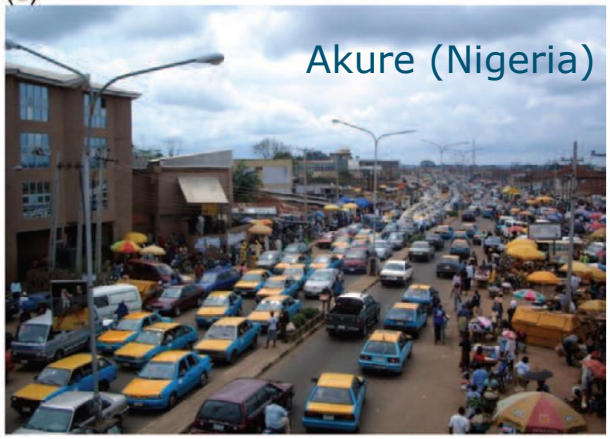
(b)



All urban.
But all look different!!!

(c)

(d)



Stewart and Oke 2012

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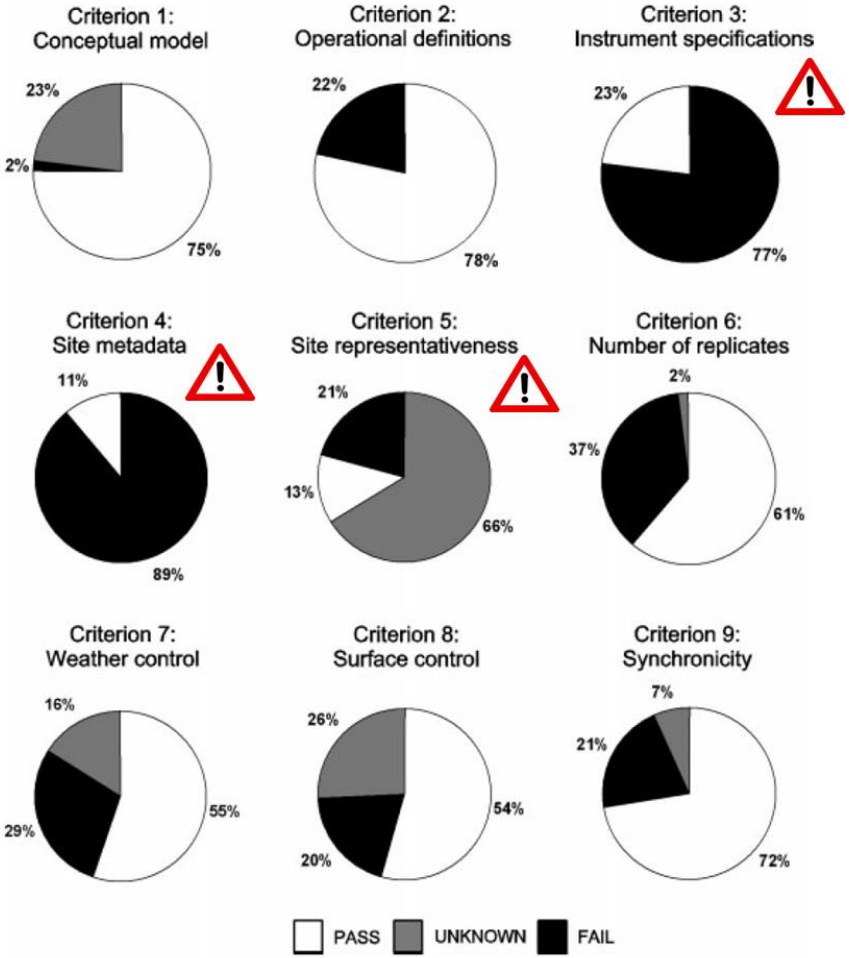
How to define “urban”?

- “Rural” site in Tokyo!

Stewart and Oke 2012

How to define “urban”?

- Understanding observations
- 9 criteria for documentation

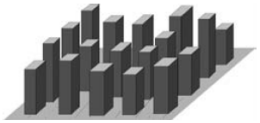
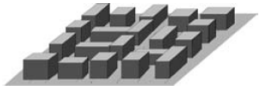
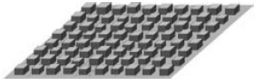
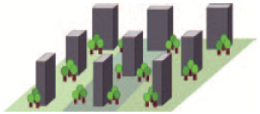
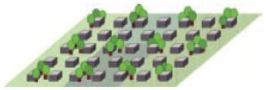
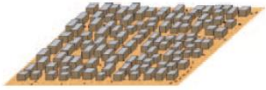


Stewart 2011

How to define “urban”?: Local Climate Zones

- **Simple and logical nomenclature** by which objects/areas can be named and described
- Facilitate information transfer by associating objects/areas **in the real world** with an organized system of **generic classes**.
- **inductive generalization** (sample is a good estimate for population)
- inclusive of all regions
- independent of all cultures,
- quantifiable according to class properties that are relevant to surface **thermal climate** at the local **scale (250 m – 1 km)**

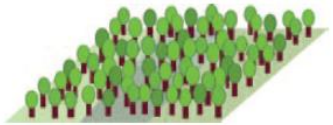
How to define “urban”?

Built types	Definition
1. Compact high-rise 	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.
2. Compact midrise 	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.
3. Compact low-rise 	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.
4. Open high-rise 	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.
5. Open midrise 	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.
6. Open low-rise 	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.
7. Lightweight low-rise 	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard-packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).
8. Large low-rise 	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.
9. Sparsely built 	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).
10. Heavy industry 	Low-rise and midrise industrial structures (towers, tanks, stacks). Few or no trees. Land cover mostly paved or hard-packed. Metal, steel, and concrete construction materials.

Stewart and Oke 2012

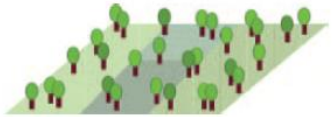
How to define “rural”?

A. Dense trees



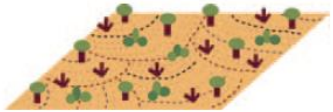
Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.

B. Scattered trees



Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.

C. Bush, scrub



Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.

D. Low plants

Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.

E. Bare rock or paved

Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.

F. Bare soil or sand

Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture.

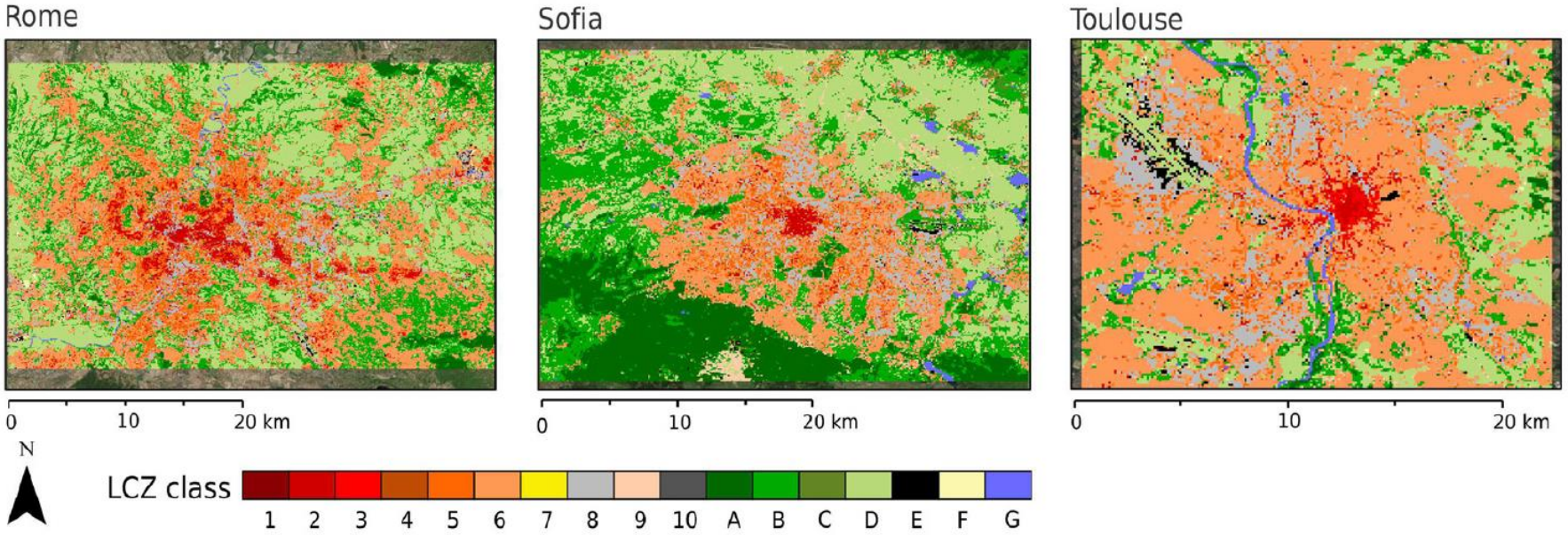
G. Water

Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.

Stewart and Oke 2012

How to define “urban”?

WUDAPT: World Urban Database and Portal Tool



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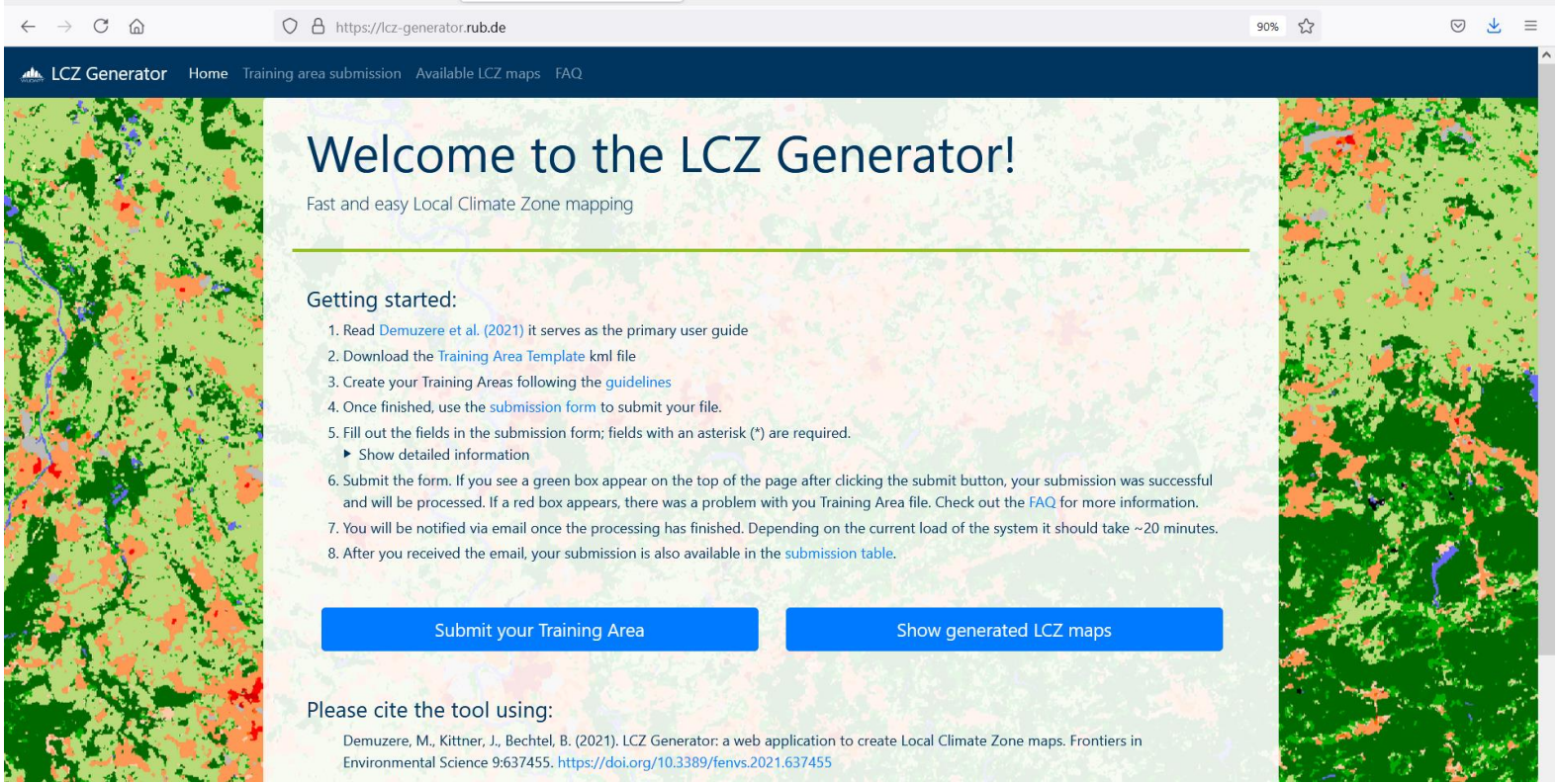
Demuzere M, Bechtel B, Middel A, Mills G (2019) Mapping Europe into local climate zones. PLoS ONE 14(4): e0214474.

Web-based LCZ generator.



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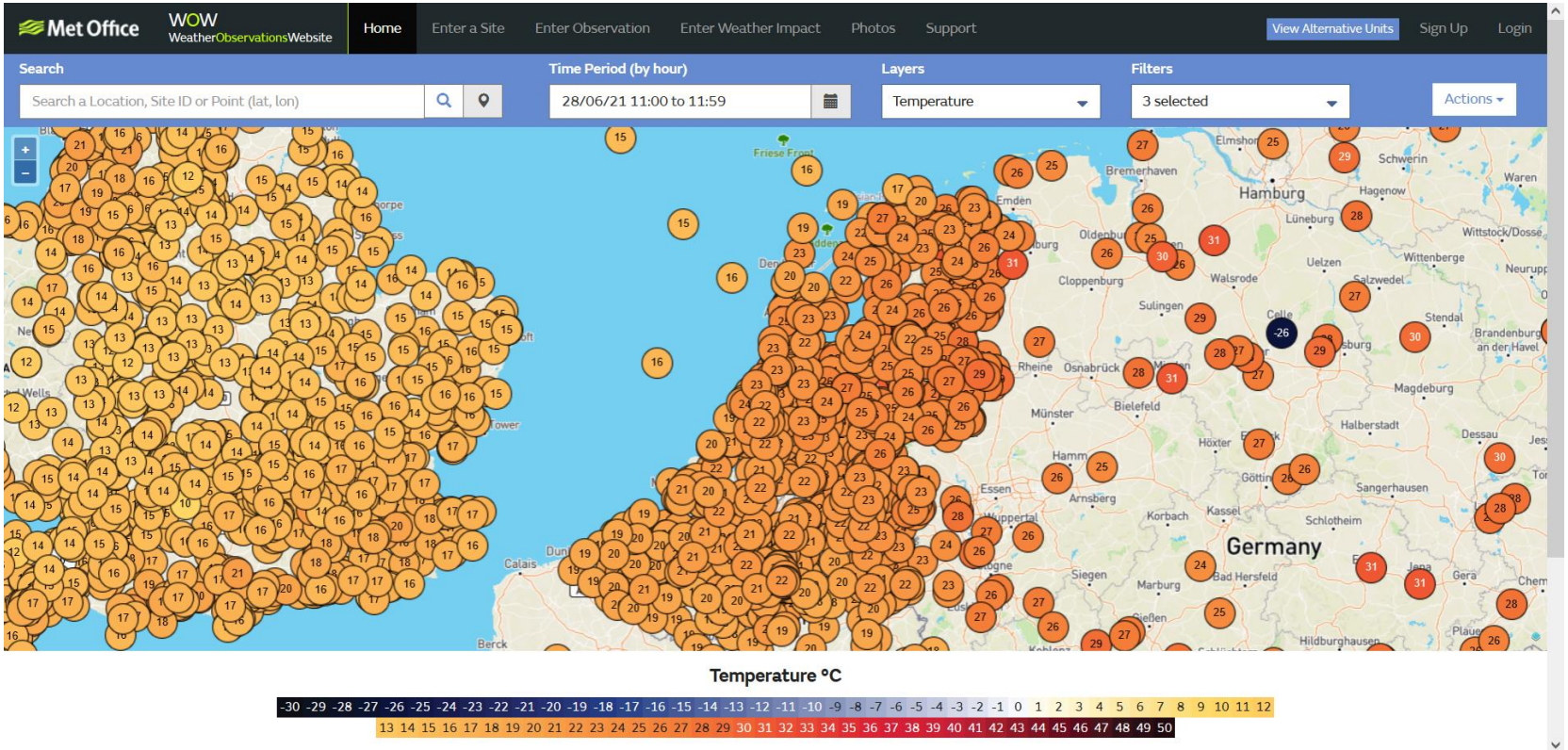
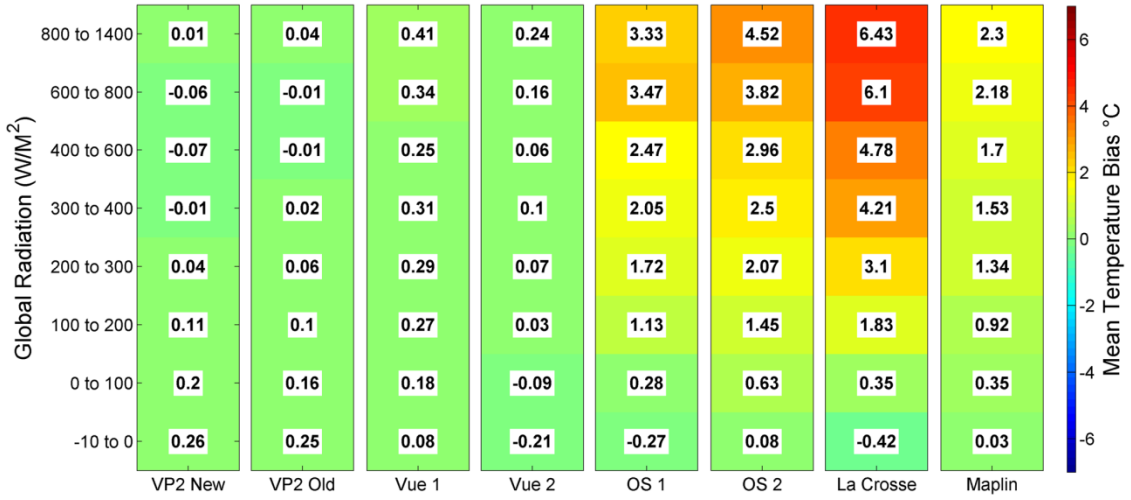
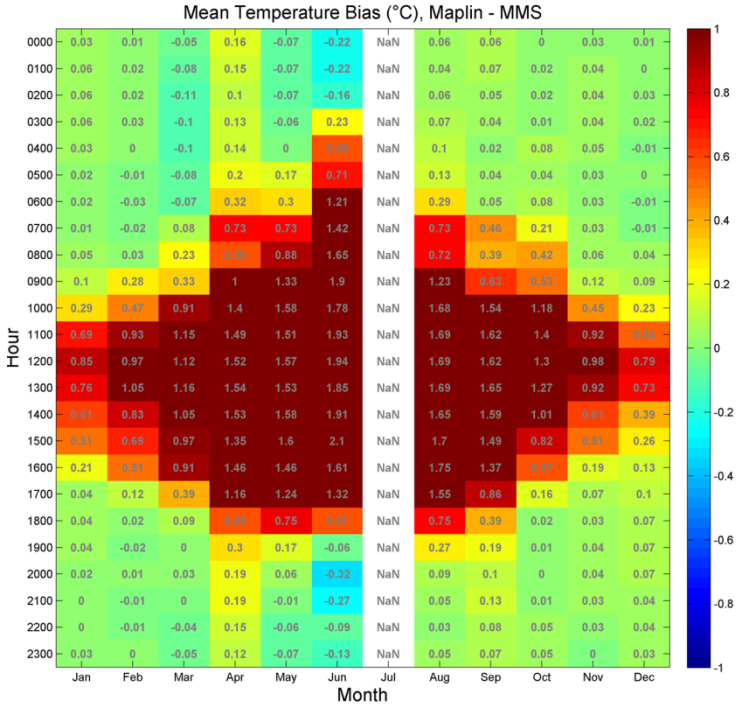
Crowdsourcing: main platforms

- www.netatmo.com, www.wundergrond.com, wow.metoffice.gov.uk/



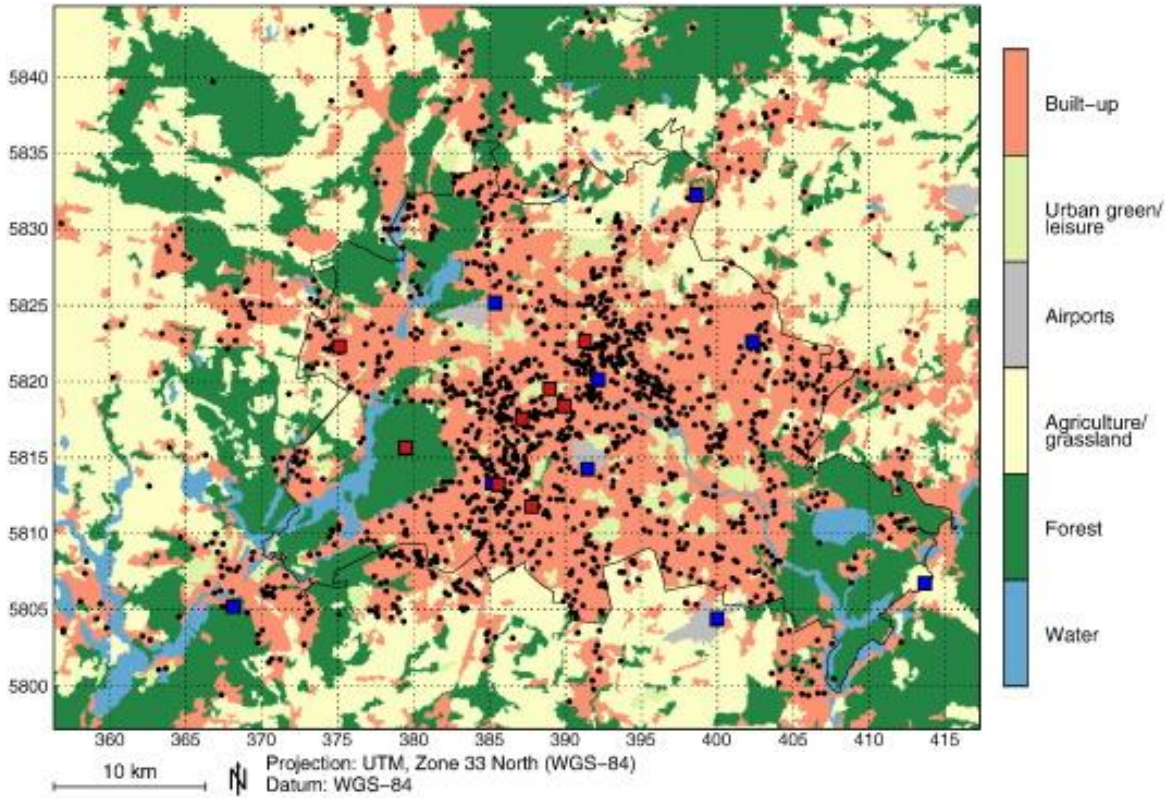
Crowdsourcing: data challenges





Bell et al 2013

Crowdsourcing: data challenges



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Meier et al, 2017

Crowdsourcing: Protocol for data selection

Quality level	Description criteria for data filtering	Potential error sources	Percent of raw data
A0	Crowdsourced air temperature (T_{crowd}) raw data with correct timestamp	Netatmo API and server limits	100.0
A1	Netatmo stations with valid metadata (latitude, longitude)	User-specific operating error	97.9
A2	80% hourly data per day	Intermittent failure of wireless network, loss of battery power, server failure	91.7
A3	80% daily data per month	Intermittent failure of wireless network, loss of battery power, server failure	70.1
B	Indoor station filter, monthly average and standard deviation of daily minimum air temperature (TN)	User-specific installation error (misuse), netatmo outdoor module set up indoors	59.7
C1	Systematic radiative error filter, positive and significant correlation between global radiation and air temperature difference ($T_{crowd\_ID} - T_{ref}$)	Netatmo outdoor module set up in a sunlit location (no radiation shield)	52.0
C2	Single value radiative error filter, flagging day-time values when air temperature difference ($T_{crowd\_ID} - T_{ref}$) > $3 * SD$ in T_{ref}	At times the netatmo outdoor module received direct short wave radiation	47.3
D	Outlier filter based on spatial average of $T_{crowd} \pm 3 * SD$ in T_{crowd}	netatmo outdoor module temporarily moved, other measurement errors	47.1

1500 stations for Berlin, **47%** useful for analysis UHI intensity etc.

Analog for wind in Droste et al (2020) and rain in De Vos et al (2020)

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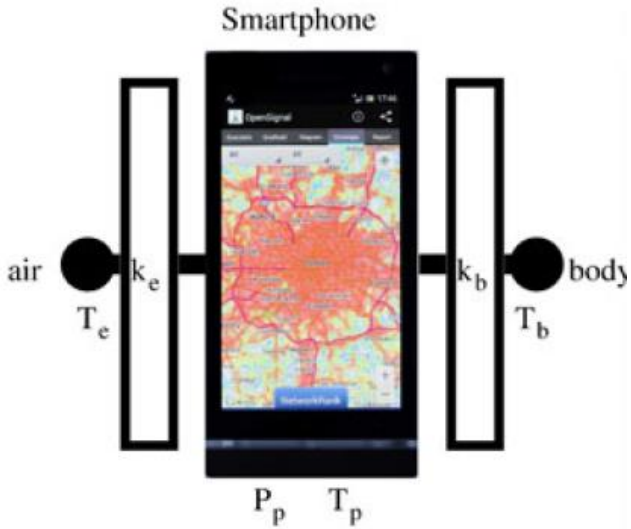
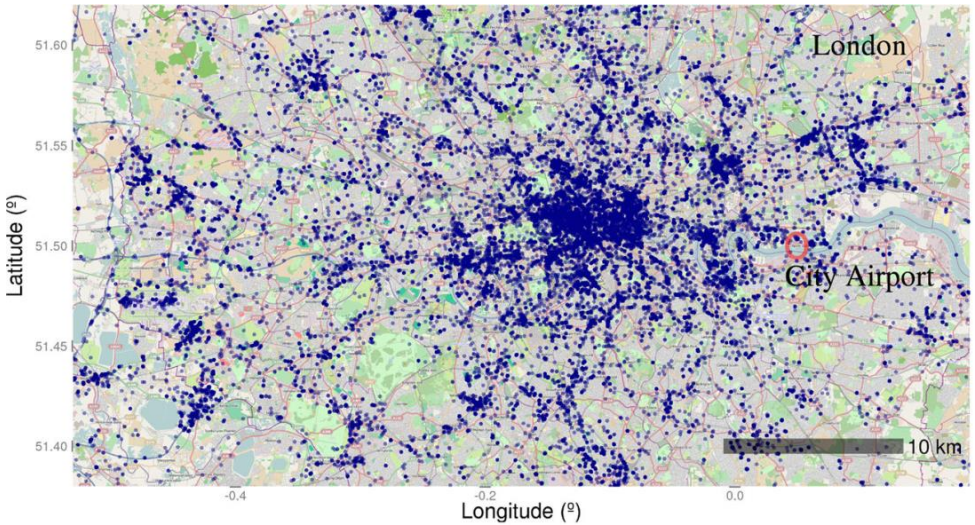
Crowdsourcing: Smartphone data





$$\bar{T}^{\mathrm{A,day}}_{\mathrm{e},j,d} = m_j \bar{T}^{\mathrm{A,day}}_{\mathrm{p},j,d} + c_j + \epsilon_{j,d},$$

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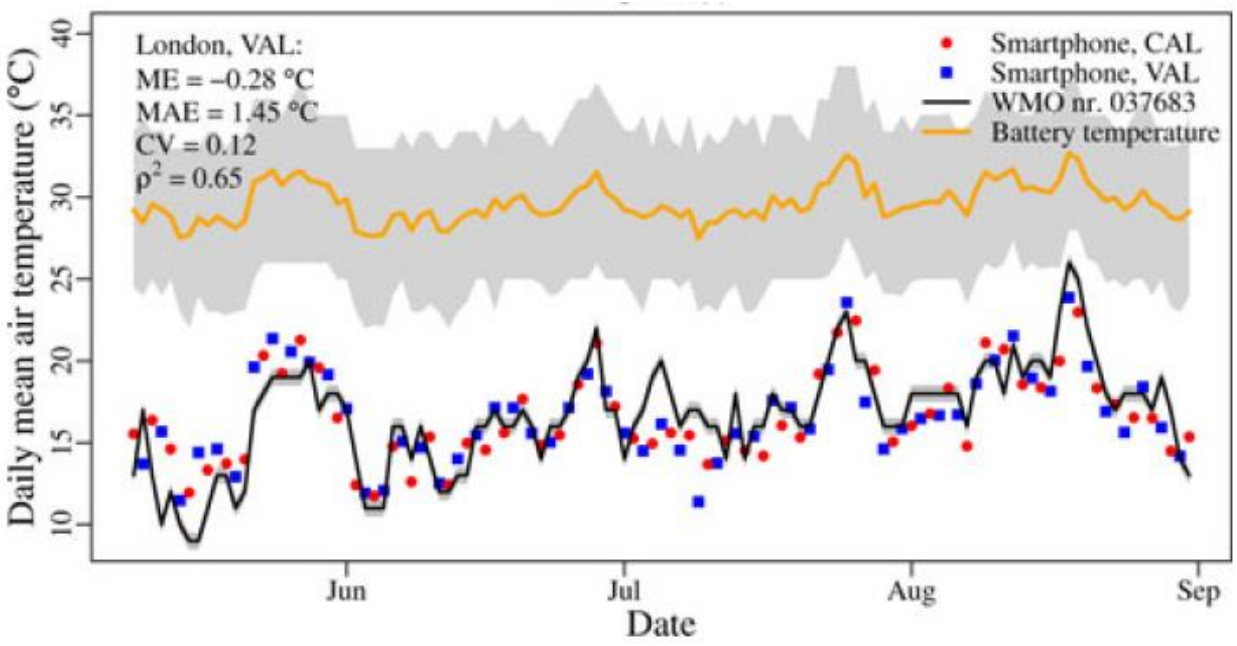
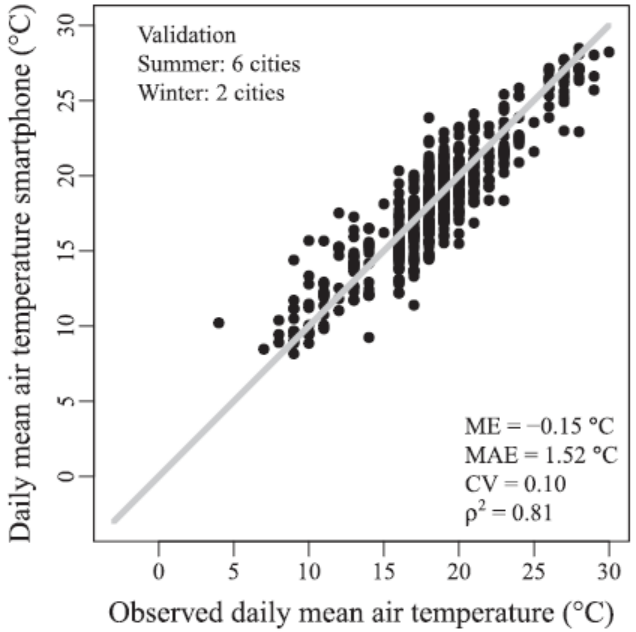
Overeem et al, 2013, Droste et al, 2017

Crowdsourcing: Smartphone data





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Later on refined to neighbourhood and LCZ scales in Droste et al (2017)

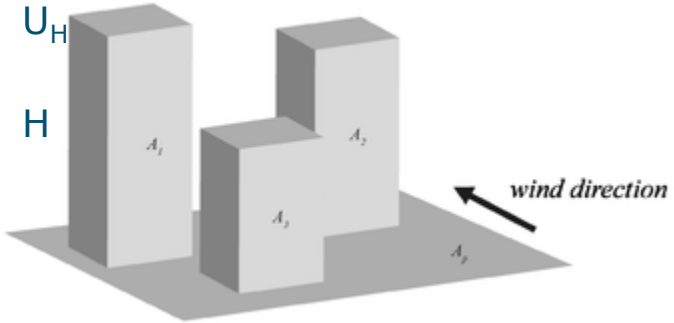
Modelling Hierarchies

- GIS based models
- Large-Eddy Simulations
- NWP/mesoscale modelling
- Climate models

Depends on your task/question!

Modelling Hierarchies: GIS based models

- Use physiological equivalent temperature (thresholds are known from physiological studies)
- Force with rural AWS data, Digital Elevation model, tree database
- Need 1 m2 spatial resolution
- Shadow, wind, temperature



$$u(1.2) = u_H e^{\left(9.6\frac{A_f}{A_d}\left(\frac{1.2}{H}-1\right)\right)}$$

$$UHI_{\max} = \left(2 - SVF - f_{\text{veg}}\right)\sqrt[4]{\frac{S{\downarrow}DTR^3}{U}}$$

McDonald (2000)

Af/Ad: frontal area index

UHI: urban heat island effect
SVF: sky view factor
fveg: green fraction
U: wind speed
S: downwelling solar radiation
DTR: Tmax-Tmin

Theeuwes et al (2017)

Modelling Hierarchies: GIS based models

Koopmans et al., 2020

Modelling Hierarchies: GIS based models

Koopmans et al., 2020

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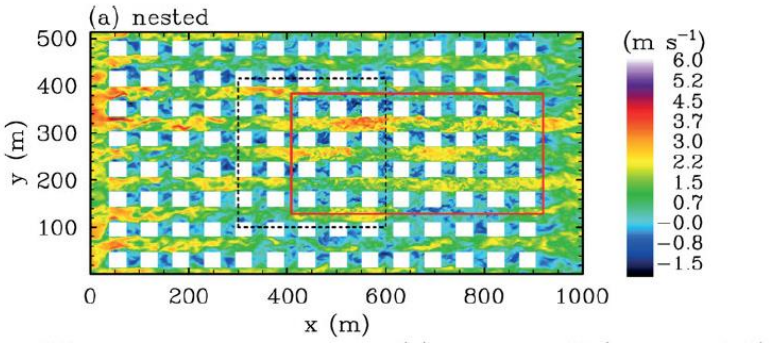
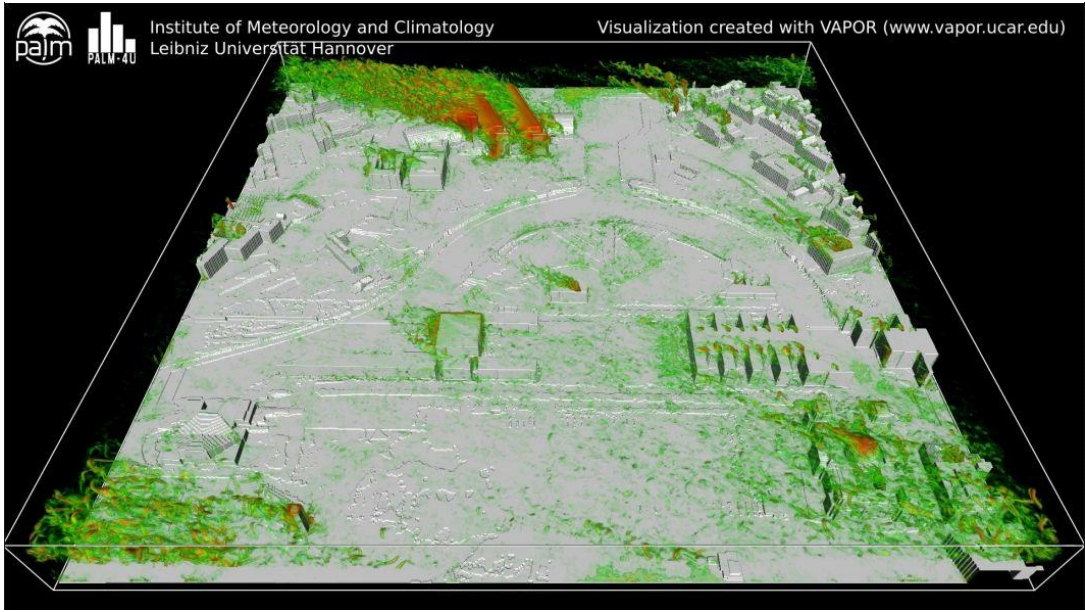
Modelling Hierarchies: Large-Eddy Simulations



- Filtered Navier Stokes equation
- Sub grid contribution
- High resolution building data required
- Computationally expensive



Example Berlin

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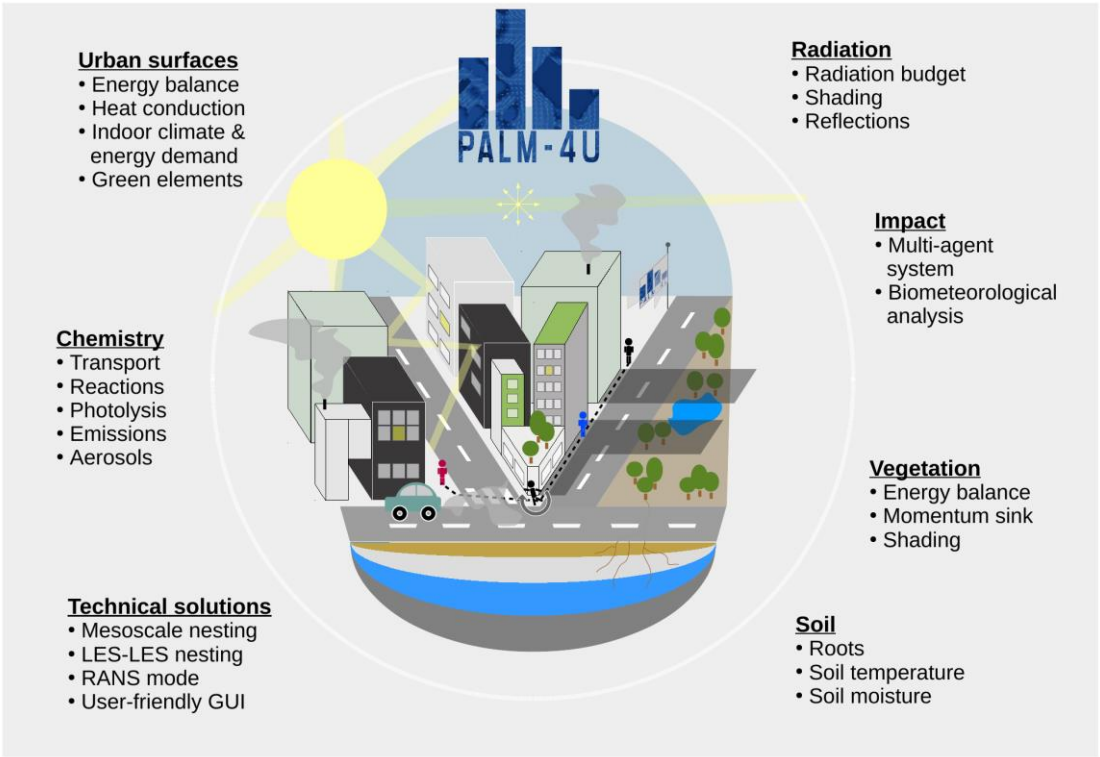
Maronga et al., 2019, Meteorol Z

Modelling Hierarchies: Large Eddy Simulations



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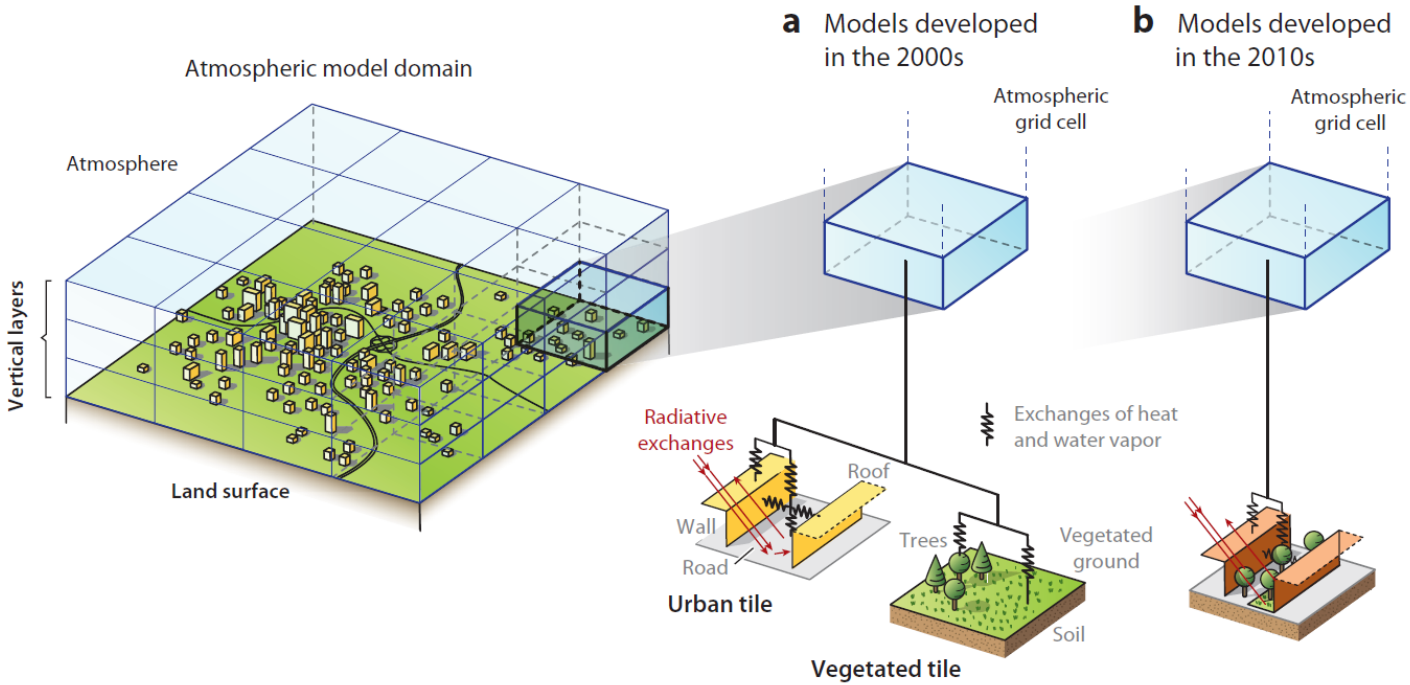
https://palm.muk.uni-hannover.de/trac/wiki/palm4u

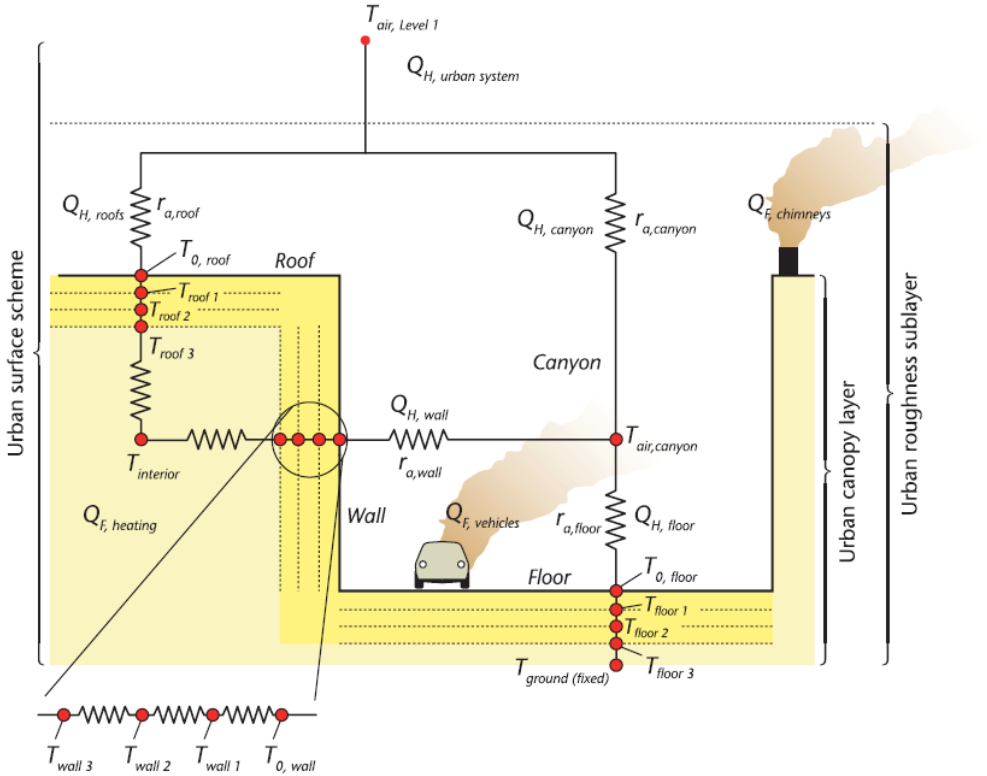
Modelling Hierarchies: NWP models



Resistance approaches at different levels of complexity

Masson et al. 2020

Modelling Hierarchies: NWP models



Monin Obukhov

Engineer approaches for resistances

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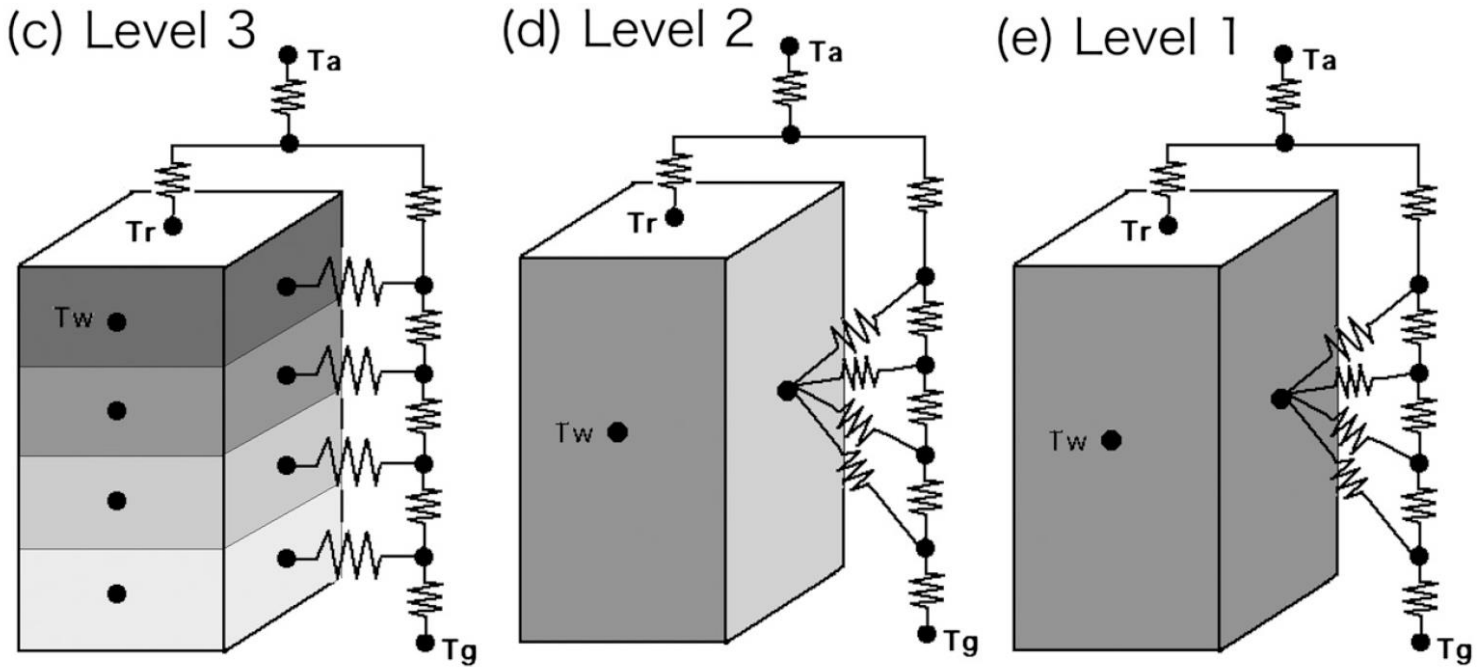
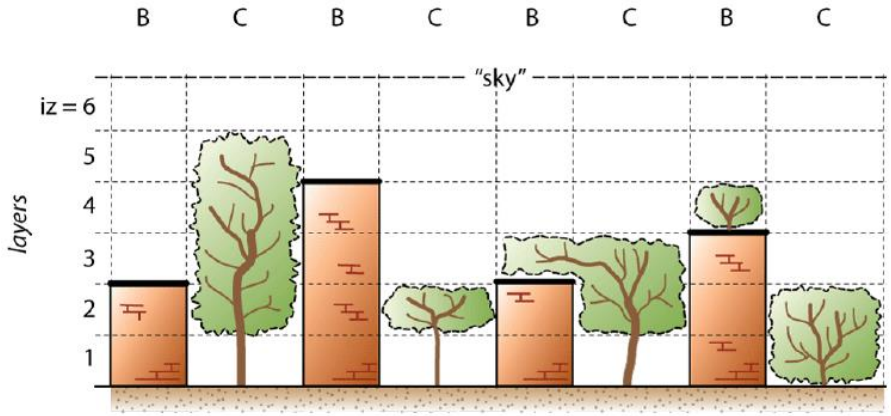
Lots of (uncertain) geographical information needed!

Modelling Hierarchies: NWP models



Ikedi et al 2009

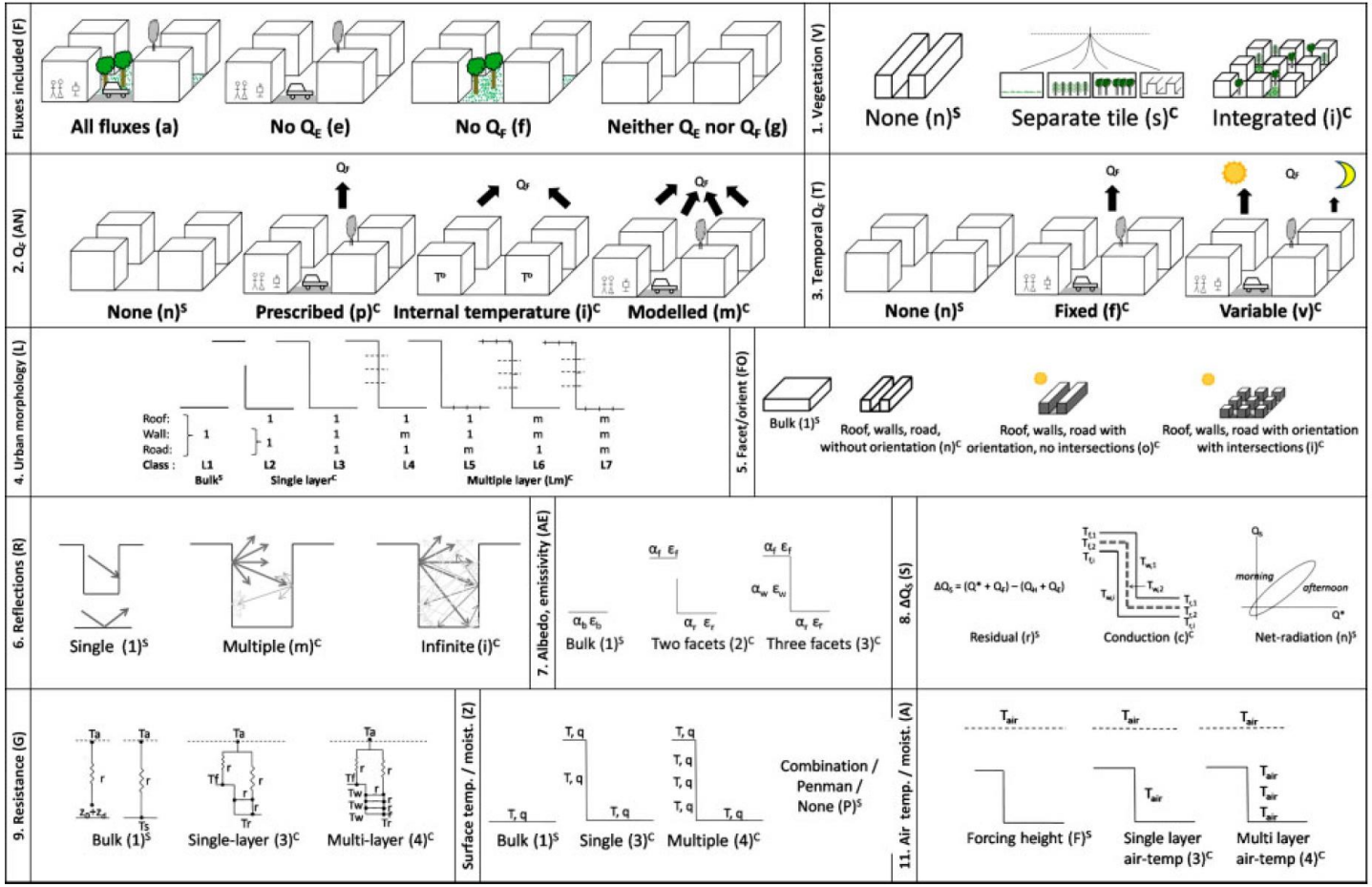
Modelling Hierarchies: NWP models



- Tree foliage is evenly distributed across the 'canyon' or 'building' spaces
- Beer's law for attenuation by vegetation; spherical leaf angle distribution with *clumping*
- Ray tracing, view factors, and matrix inversion

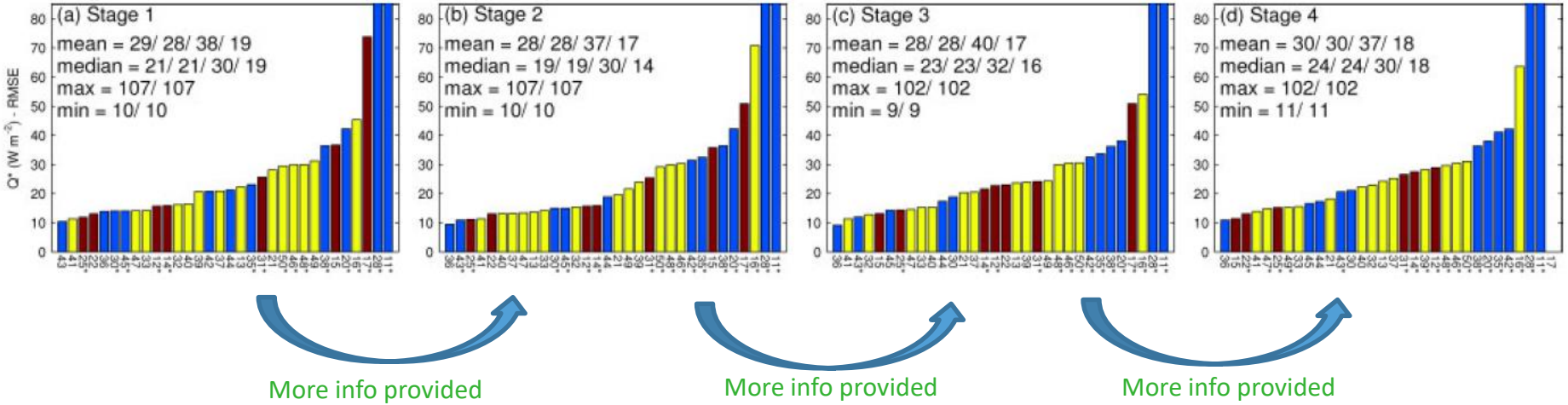
Kraaijenhof et al 2015

Modelling Hierarchies: Does complexity pay off?



Modelling Hierarchies: Does complexity pay off?

Blue: simple model; yellow: intermediate complexity; red: complex model



No preference for simple or complex model

Essential: vegetation, anthropogenic heat included

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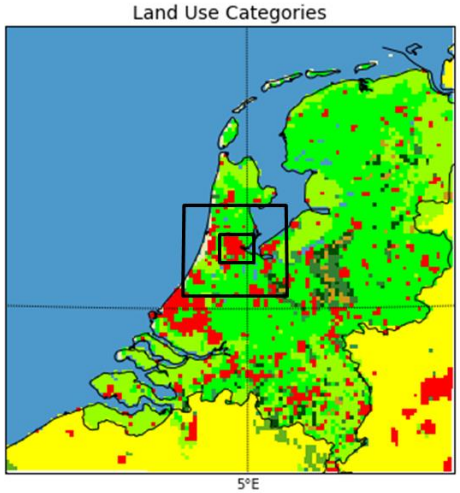
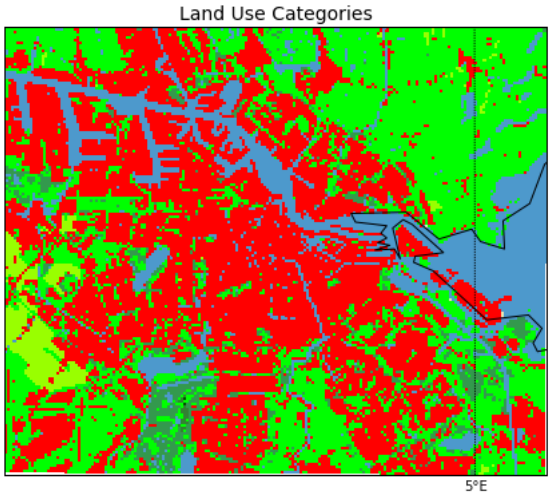
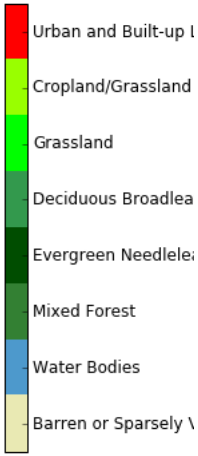
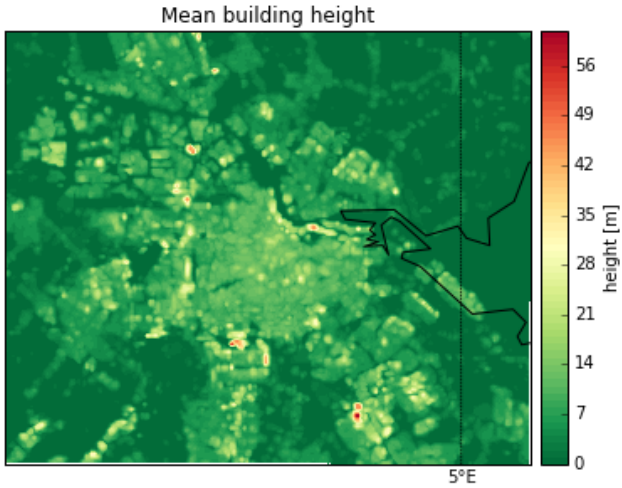
Grimmond et al., 2011

How to forecast ? WRF at 100 m grid spacing









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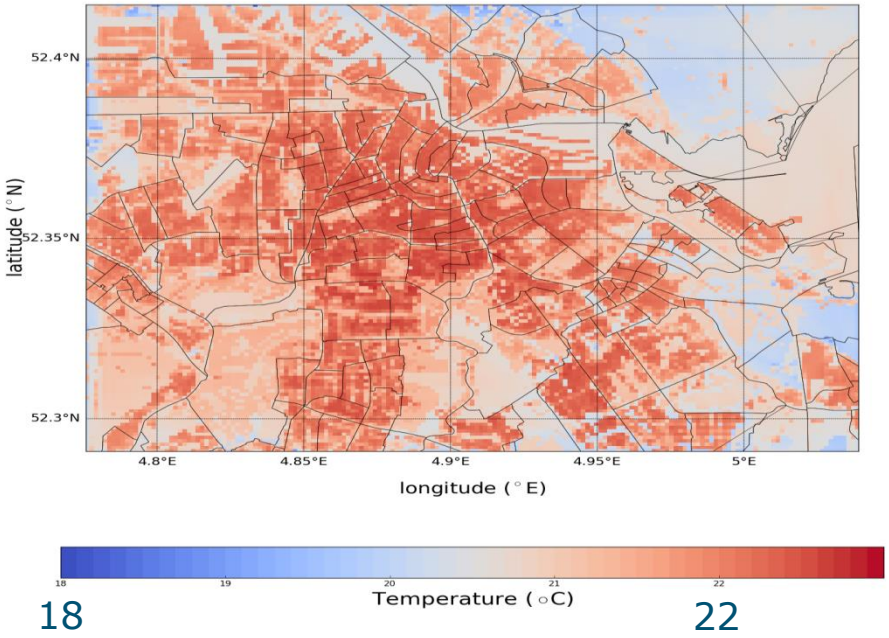
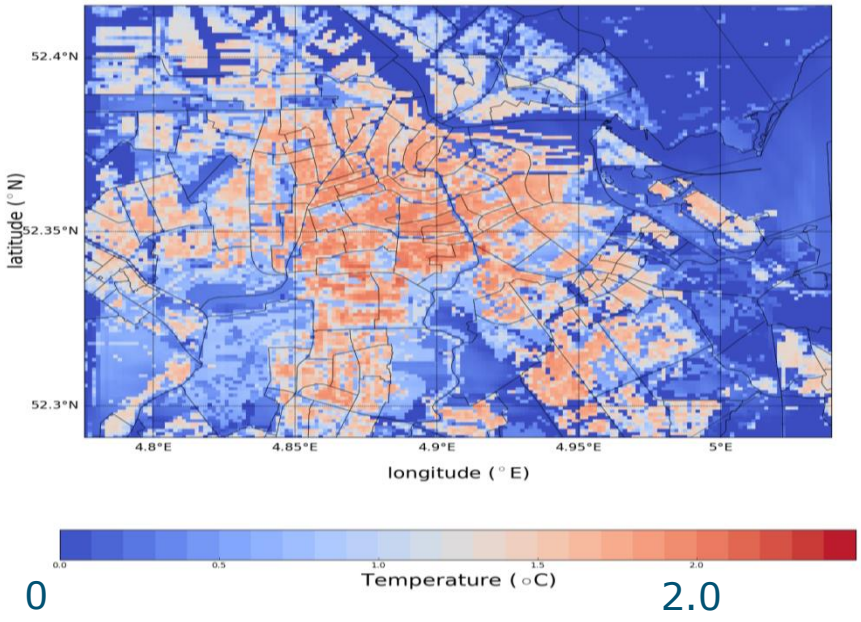
Weather Research and Forecasting model at 100 m resolution for a complete summer

Temperature



18 22

UHI



0 2.0

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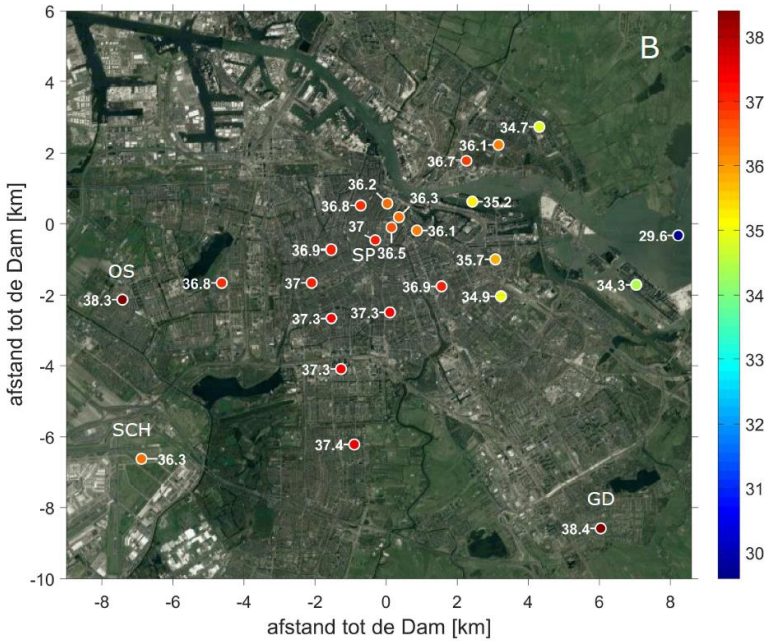
However, model cold bias ~1.5 K

Data assimilation in crowdsourced data in WRF

Weather Underground

About 300 stations in NL

Direct transfer to wunderground website



Validation: Amsterdam Atmospheric Monitoring Supersite

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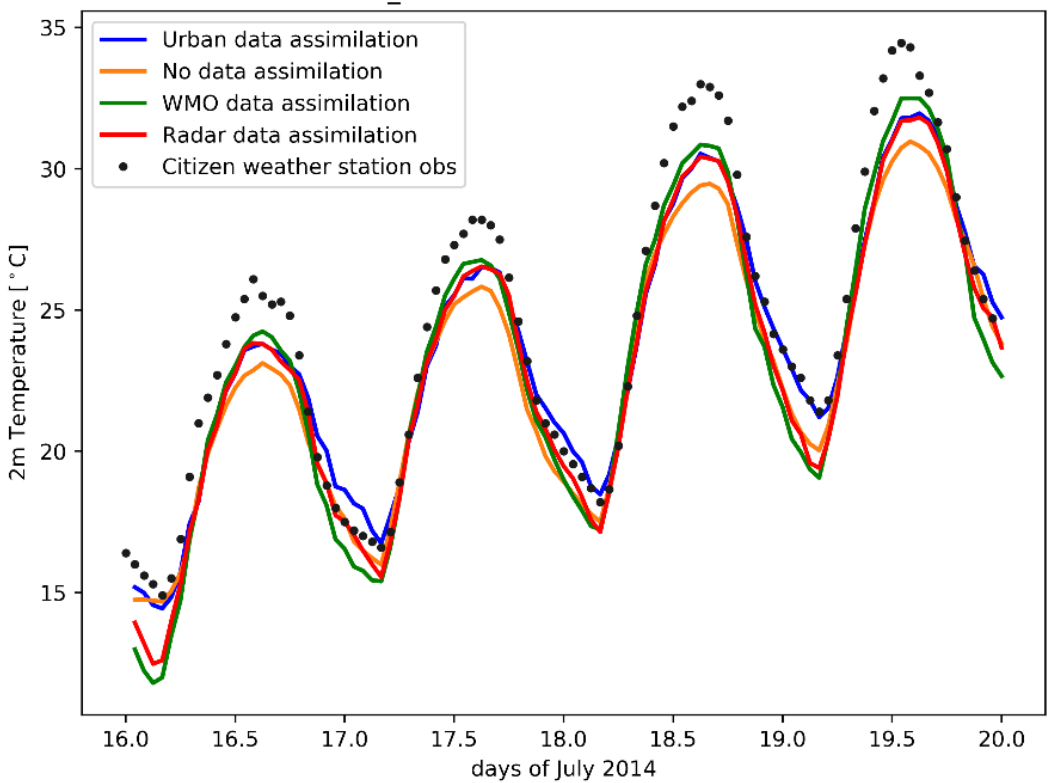
Data assimilation in crowdsourced data in WRF



No DA:
RMSE = 2.30 ^{o}C
Bias = -1.46 ^{o}C
WMO
RMSE = 2.31 ^{o}C
Bias = -1.52 ^{o}C
WMO+radar
RMSE = 2.07 ^{o}C
Bias = -1.36 ^{o}C
WMO+radar+urban:
RMSE= 1.69 ^{o}C
Bias= -0.71 ^{o}C

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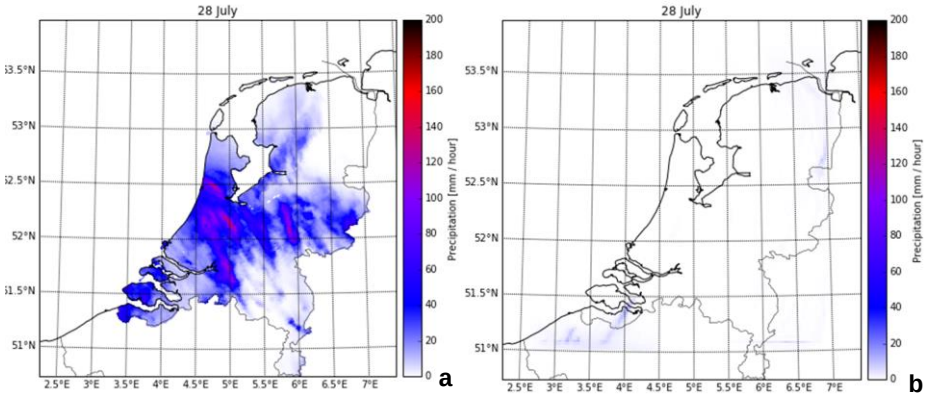
Koopmans et al., 2021, to be submitted

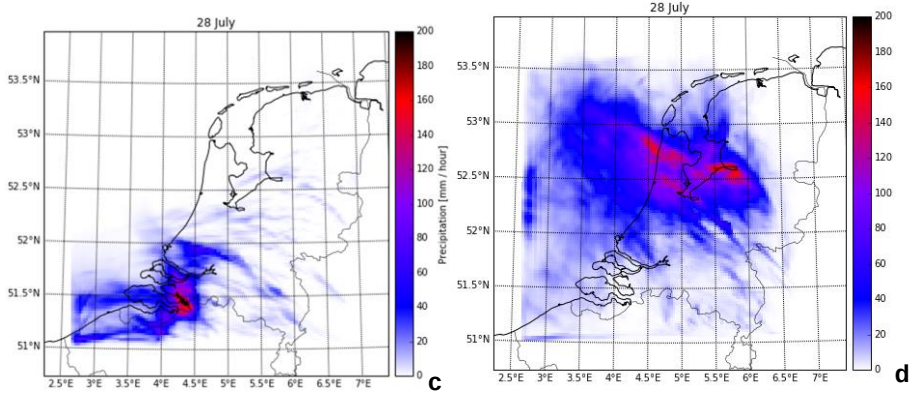
Data assimilation in crowdsourced data in WRF

OBS



NO-DA

DA-WMO

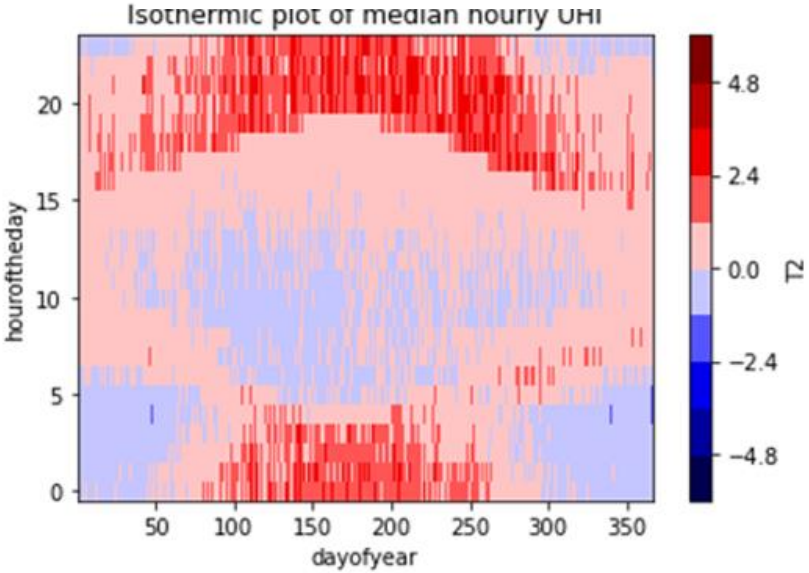


DA-ALL

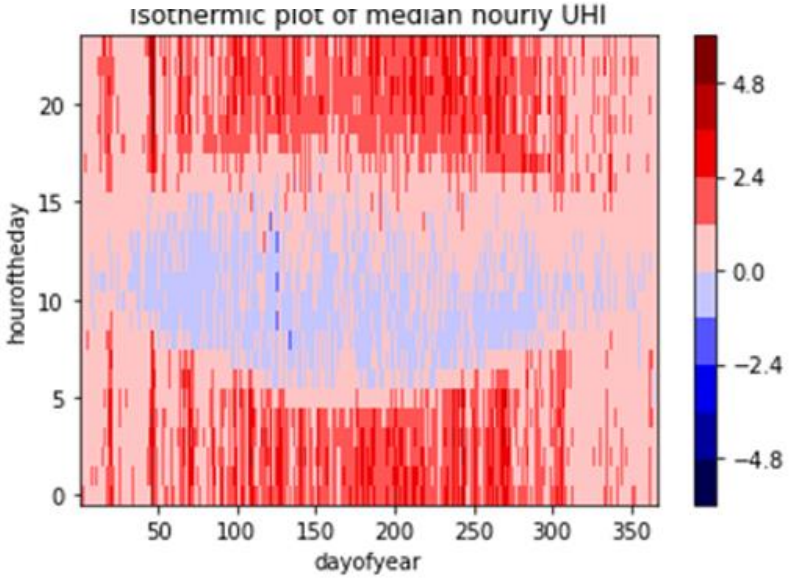
Koopmans et al., 2021,

ERA-urban: 15 y of modelled weather in Adam @167 m

Isopleths



model

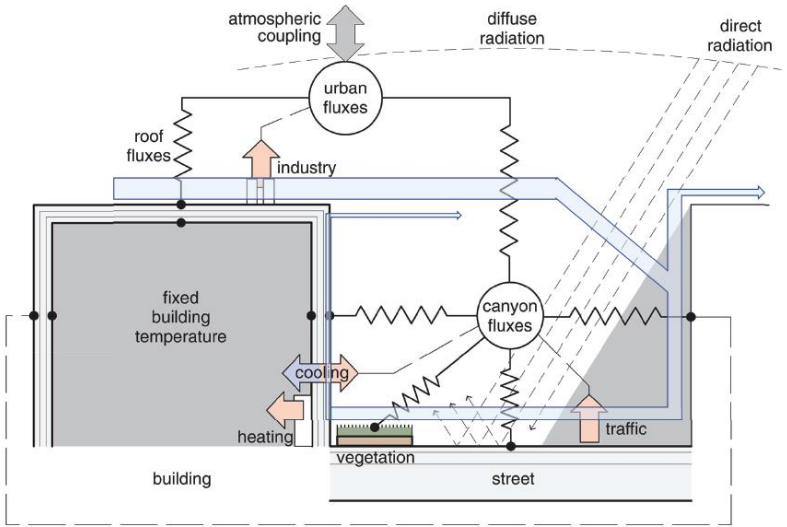


obs

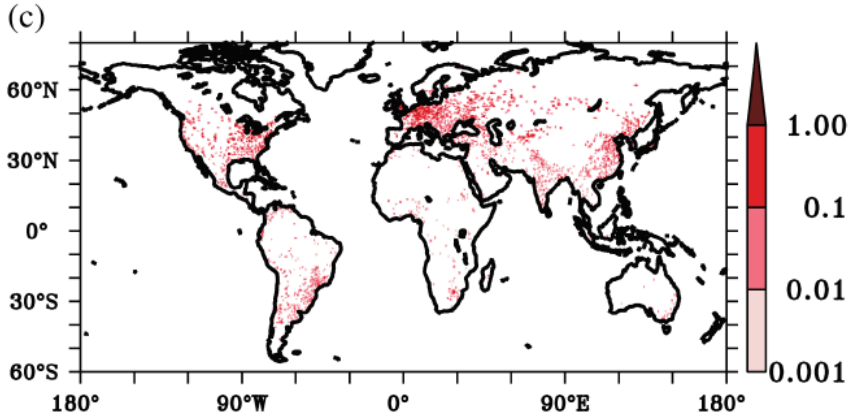
Courtesy Arthur Maas

Modelling Hierarchies: Climate models

Conformal Cubic Atmospheric Model (CCAM) at 50 km resolution.



Rel simple scheme



Anthropogenic heat map (W/m2 uncertain).

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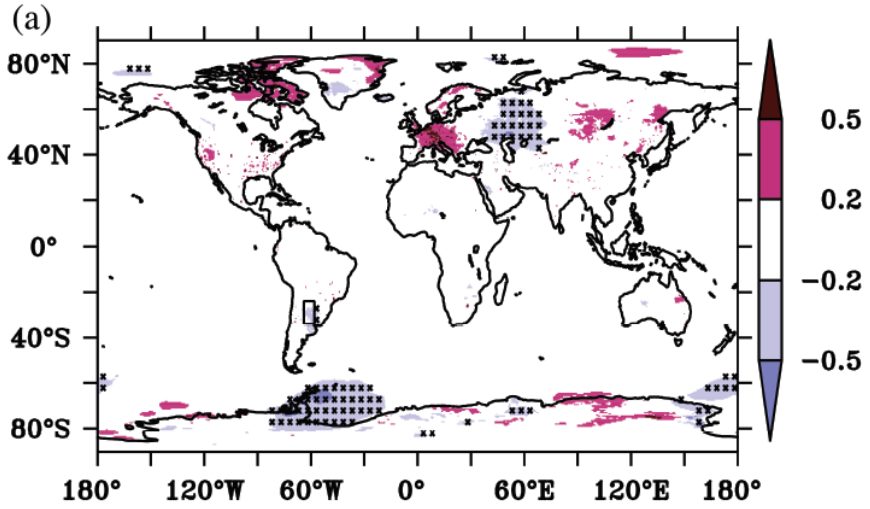
Katzfey et al., 2020

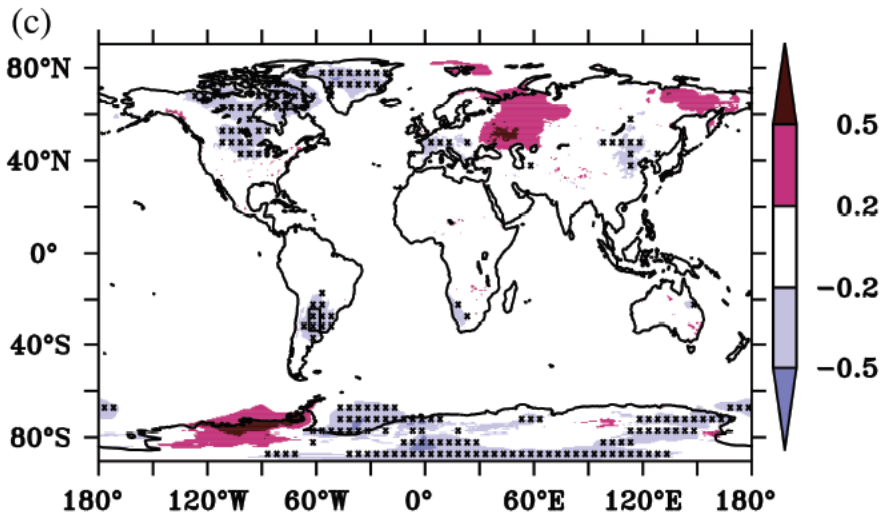
Modelling Hierarchies: Climate models

Urban – no urban. Veg map 1.



Temperature difference

Urban – no urban, Veg map 2.



Temperature difference

Large regional impacts, but sensitive to forcing, and boundary conditions.

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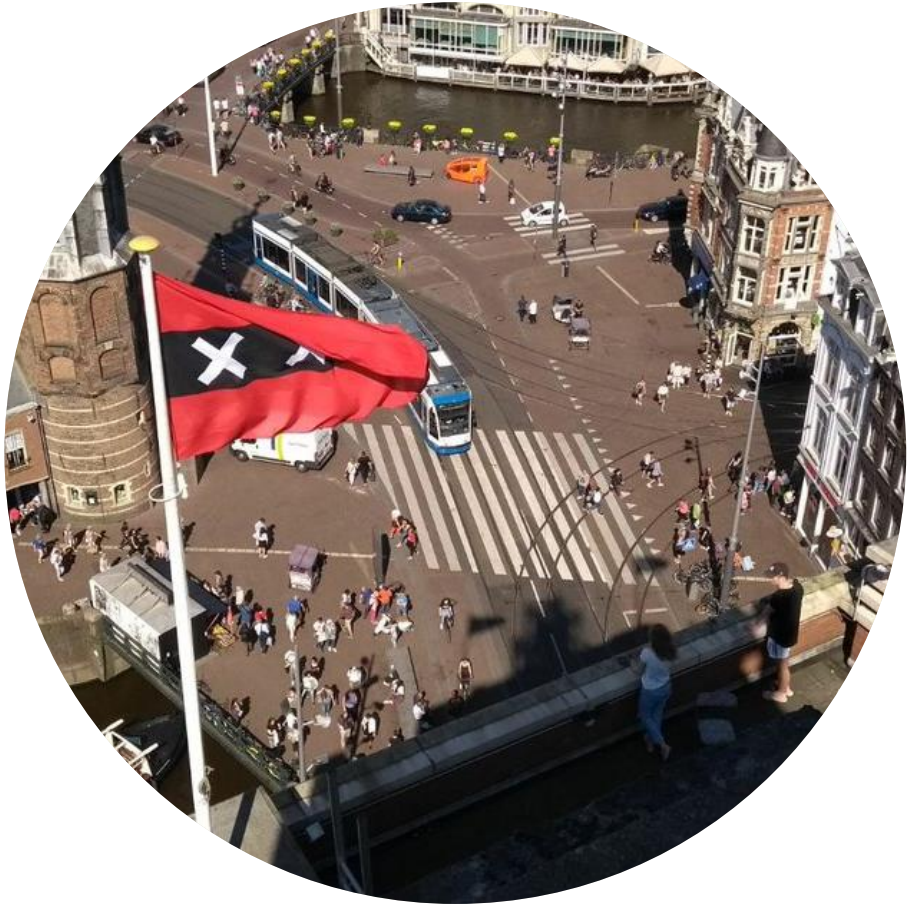
Katzfey et al., 2020

Concluding remarks

- Urban meteorology is relatively new playing field, but relevant for health, energy demand planning, urban planning, air quality, ...
- Crowdsourcing useful for temperature, wind speed, rainfall provided good selection protocol.
- Different model approaches for different goals and scales.
- Description of urban morphology critical but uncertain.
- Future surfaces: solar panels, green roofs, green walls, cool roofs ..

Thanks for your attention

Any questions?



Special flows