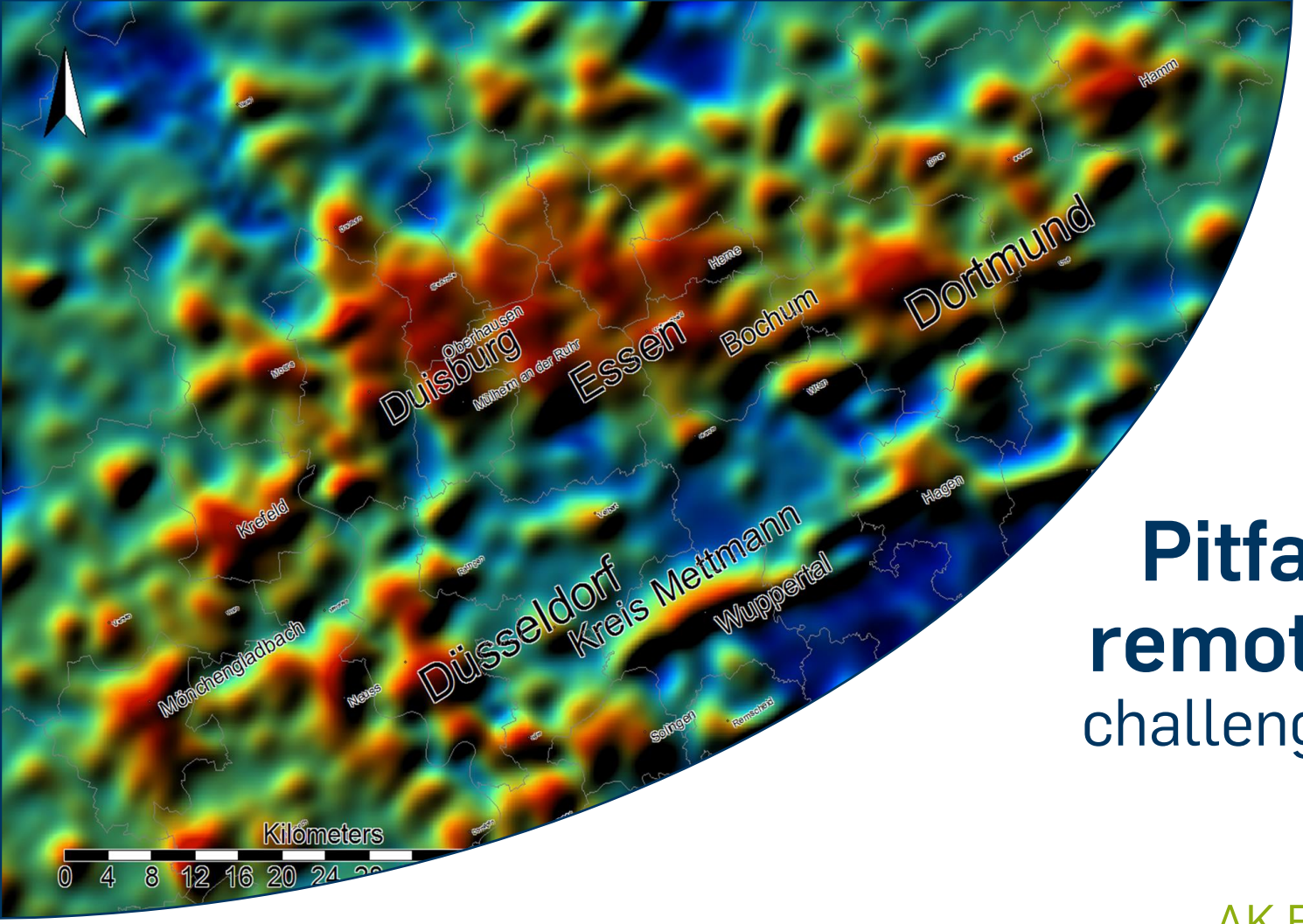


BUCL
BOCHUM URBAN CLIMATE LAB

RUB

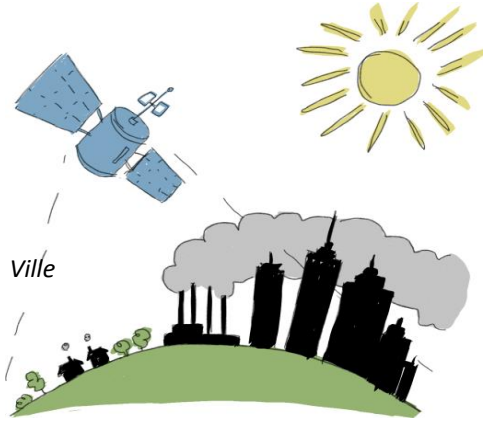
Pitfalls in urban thermal remote sensing – chances and challenges for management of urban systems

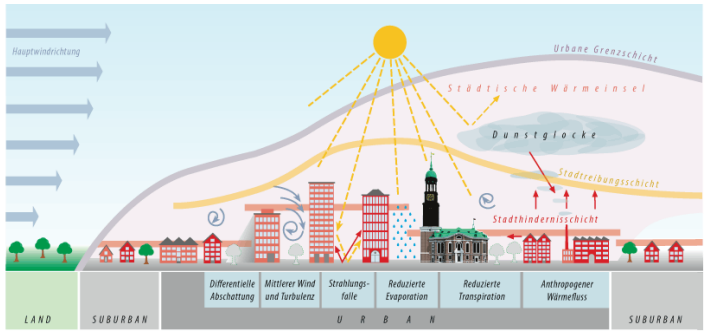
AK Fernerkundung | 30.9.25 | Bochum

Benjamin Bechtel, Wenfeng Zhan, Huilin Du, TC Chakraborty, **Simone Kotthaus**, E. **Scott Krayenhoff**, Alberto Martilli, Marzie Naserikia, Negin Nazarian, **Matthias Roth**, Panagiotis Sismanidis, **Iain D. Stewart**, **James Voogt**

RUBclim

About me





Prof. Dr. Benjamin Bechtel
climate.rub.de

New IAUC executive elected for 2022-2026

2022-01-14 *in* *IAUC Admin, IAUC Statements*

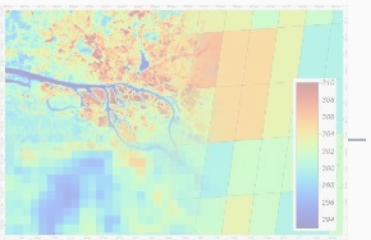
The IAUC board has elected and approved a new executive for the period August 2022 – August 2026:

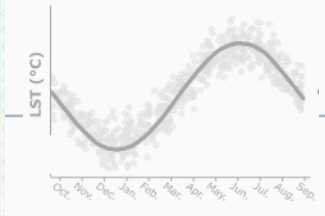
Ariane Middel
President 2022-26

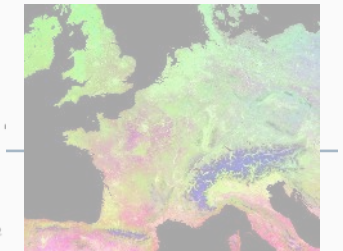
Benjamin Bechtel
Secretary 2022-26

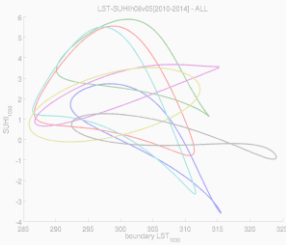
Dev Niyogi
Treasurer 2022-26

PLOS CLIMATE

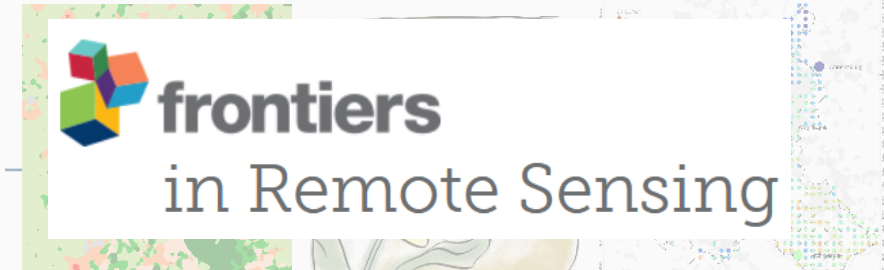






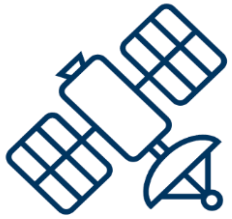


WUDAPT
WORLD URBAN DATABASE & ACCESS PORTAL TOOLS



frontiers
in Remote Sensing

About us – RUB urban climatology



Smart Resilient

Green

Remote sensing of urban climates

Modelling, Urban climate informatics

Crowd sourcing and smart city

Applied urban climatology and climate adaption

Relevant Projects

land surface temperature cci

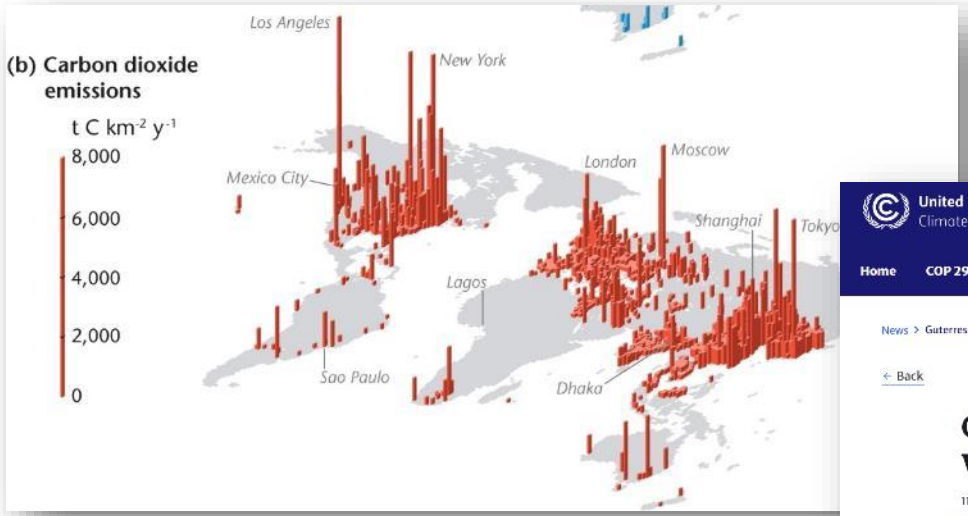
Data2Resilience

DFG – ENLIGHT

CARMINE
Co-create Climate Resilience

Data2Resilience

Why? | Cities and climate change



Oke et al. 2017

United Nations Climate Change

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Guterres: "Cities Are Where the Climate Battle Will Largely Be Won or Lost"

11 October 2019

Article

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Climate Change A Factor In Unprecedented LA Fires

January 13, 2025

By Gavin Madakumbura[1], Chad Thackeray[2], Alex Hall[3], Park Williams[1], Jesse Norris[2], and Ray Sukhdeo[2]

Cities and Climate Change (IPCC SR AR6)

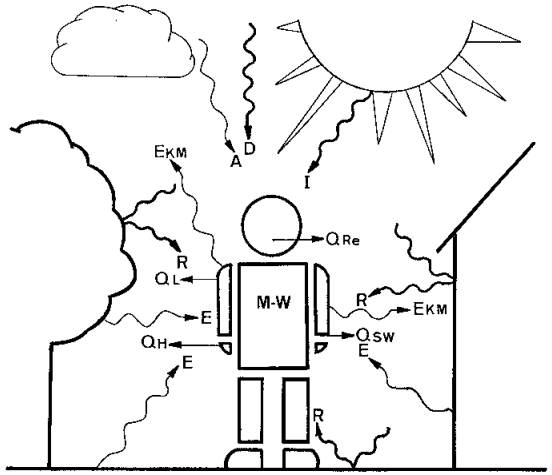
1. Causer and amplifier

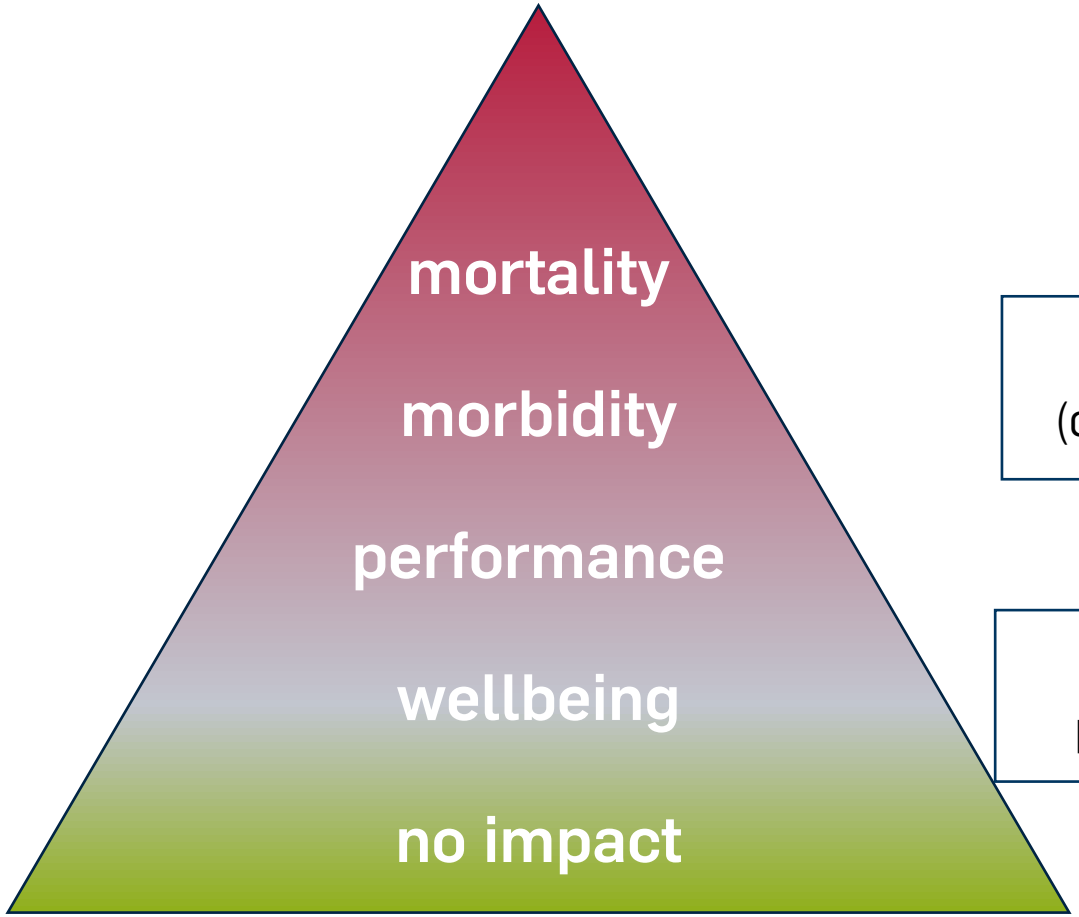
Strategy: Mitigation
(=Klimaschutz)

2. particularly **vulnerable for impacts**

Strategy: Adaptation
(=Anpassung)

Heat stress – possible impacts

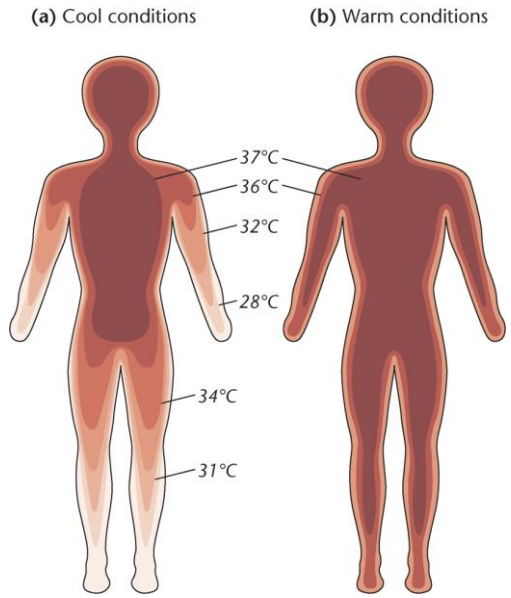




Disease (quantifiable)

subjective perception

„Risk-Pyramid“

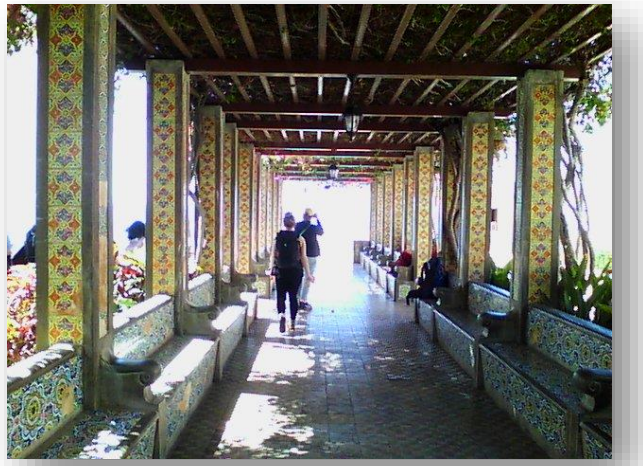


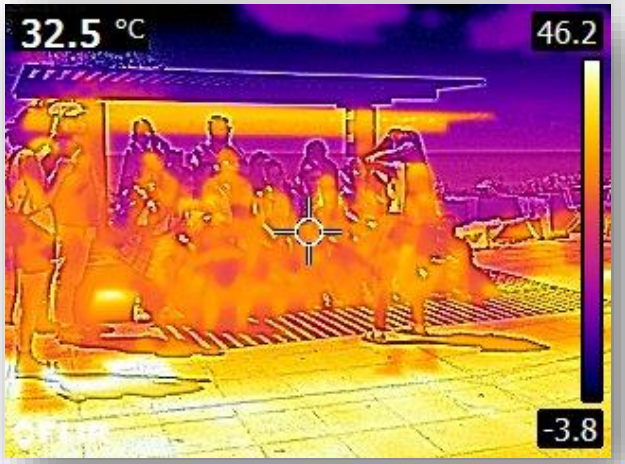
After Jendritzki, 2014 AK Klim

Oke et al. (2017)

What we need to know and why

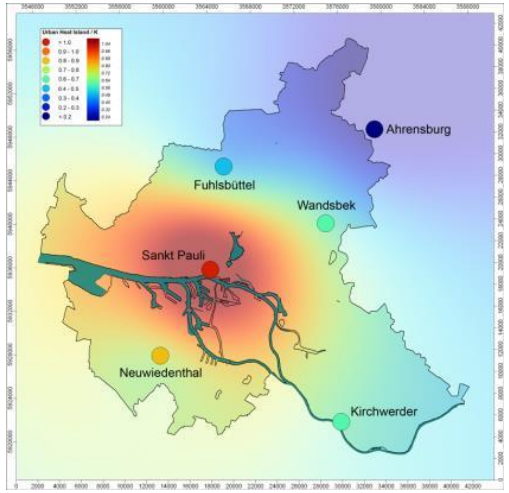
- Decision-makers need to know:
  - Which neighbourhoods are most exposed?
  - Who is most vulnerable at what times and during which season?
  - Do interventions deliver measurable benefits?
- Assessment and monitoring are utterly important to direct resources effectively.
- The choice of urban heat metrics is crucial
- Using the wrong variables to characterize urban overheating risk can lead to:
  - Ineffective adaptation strategies
  - Inequitable outcomes
  - Counter-productive results

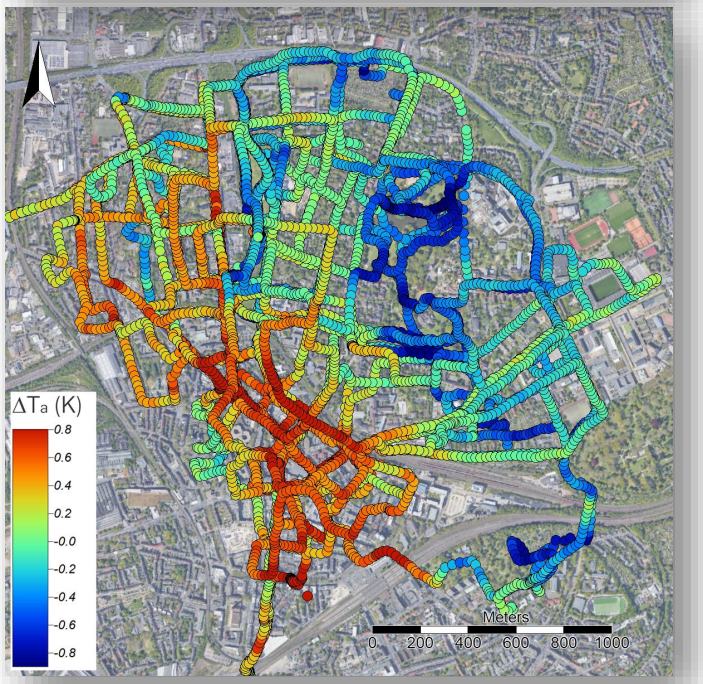


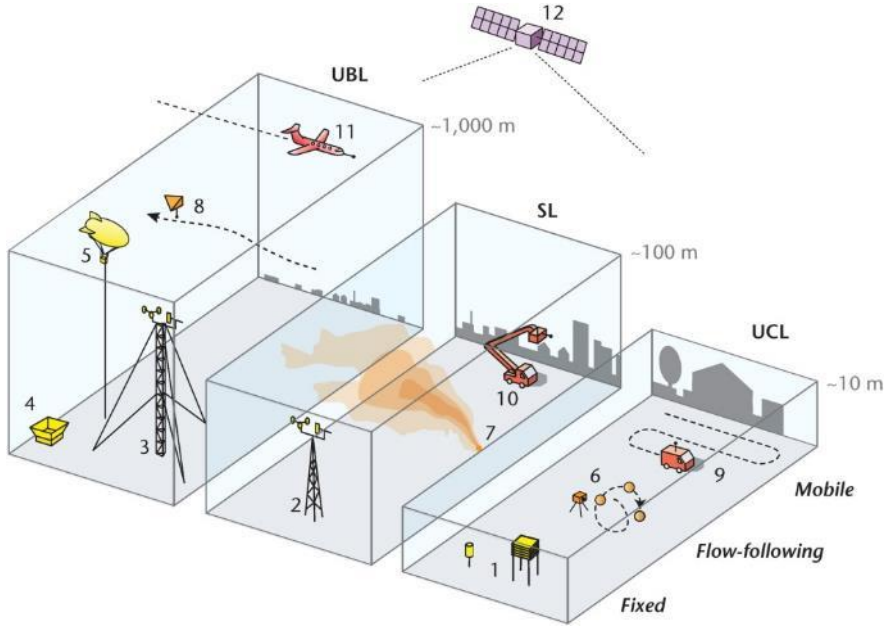


Effective adaptation requires reliable metrics.

Urban Heat Monitoring







- Various approaches
- Most common: Ta from stations & transects
- Tradeoffs in resolution (spatial, temporal) and completeness
- Costs vs accuracy
- Sparse coverage, especially in Global South

Oke et al. 2017

Solution: Satellite LST?

- Attractive: global availability, detailed, intuitive maps
- Widely adopted – rapidely growing literature
- Increasingly used in policy & (adapatation) funding decisions

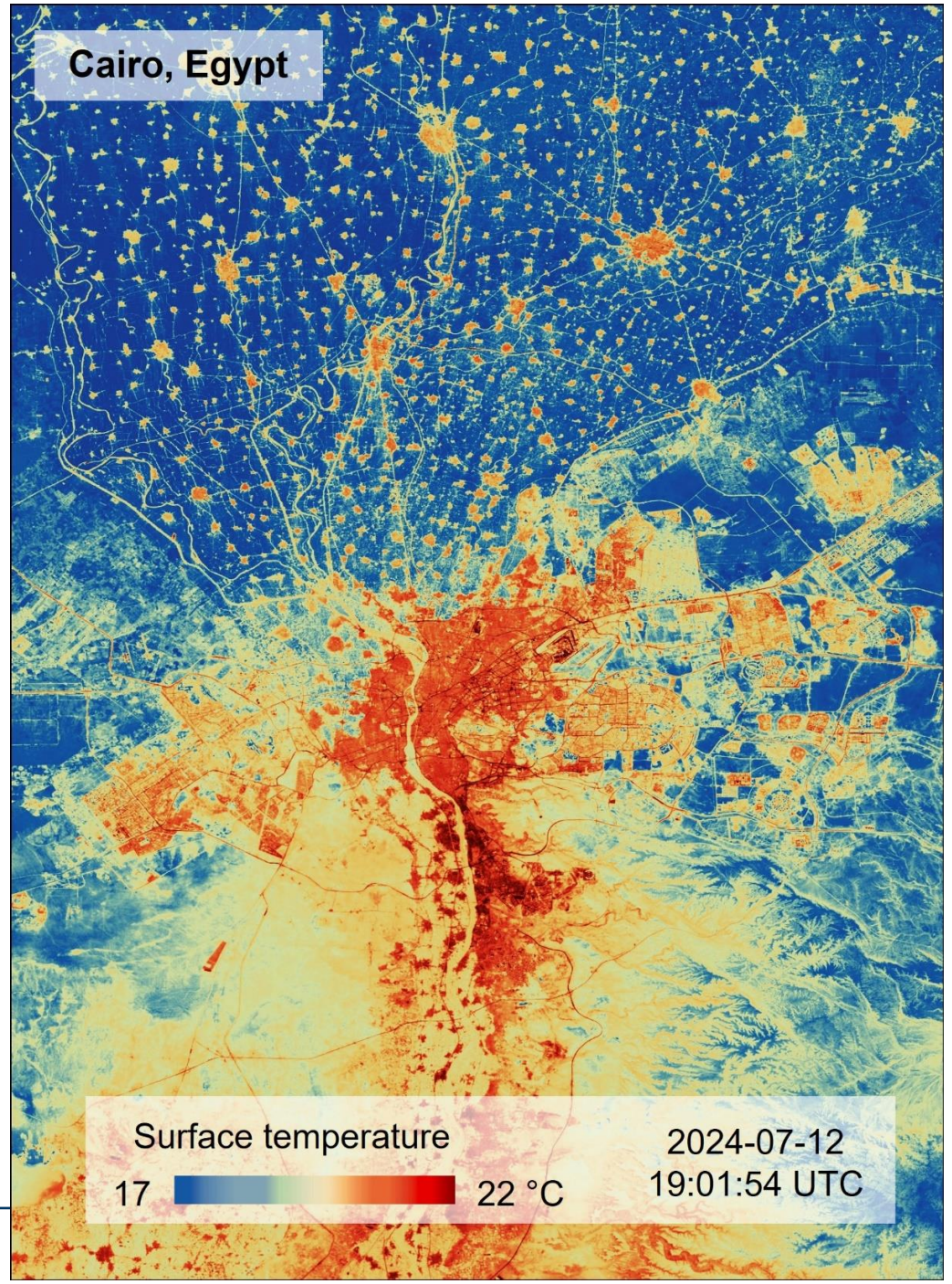
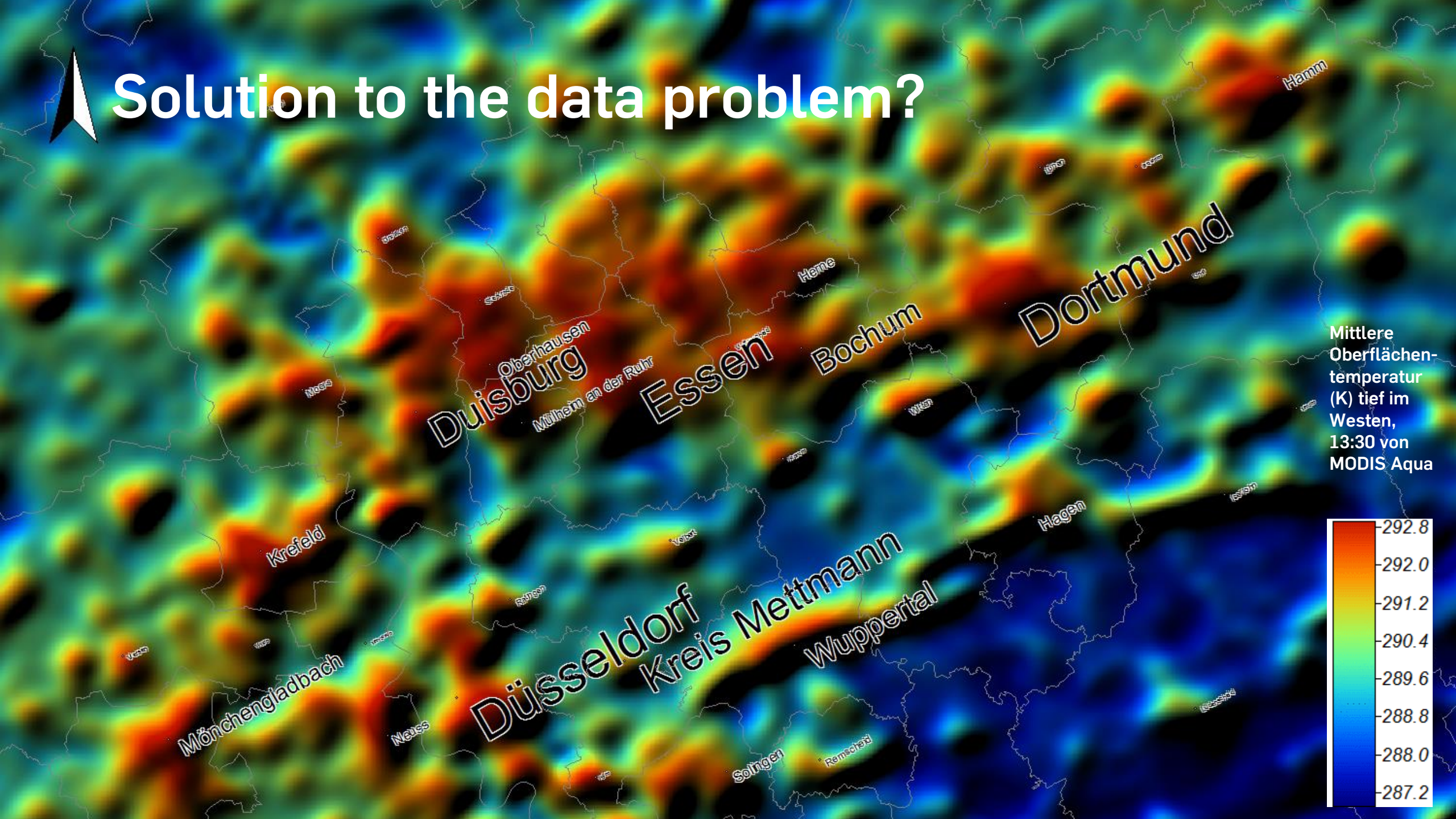
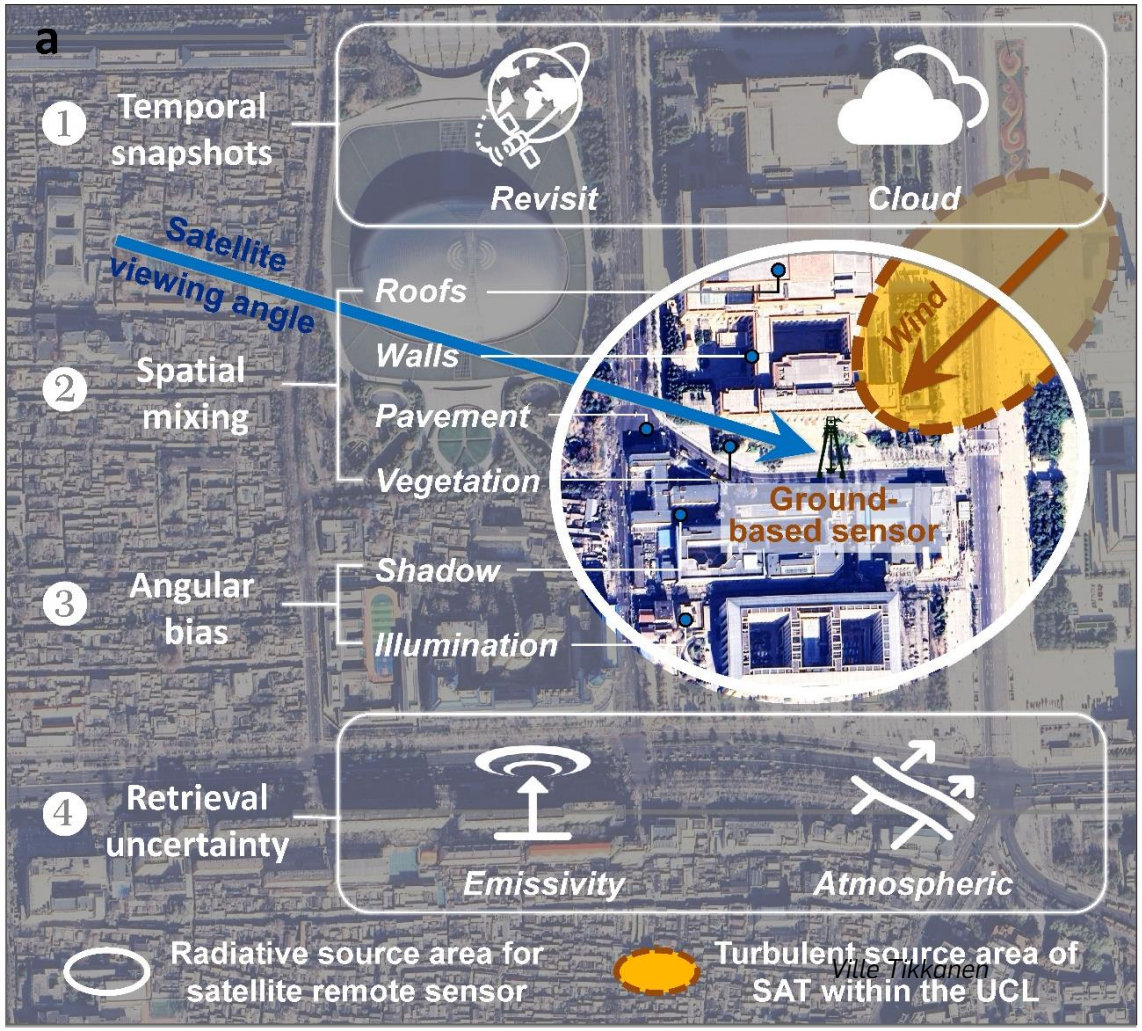


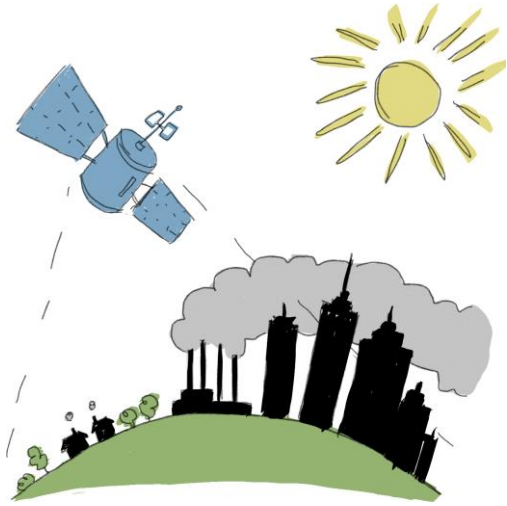
Fig: Hulin Du

Solution to the data problem?



Limitations of LST



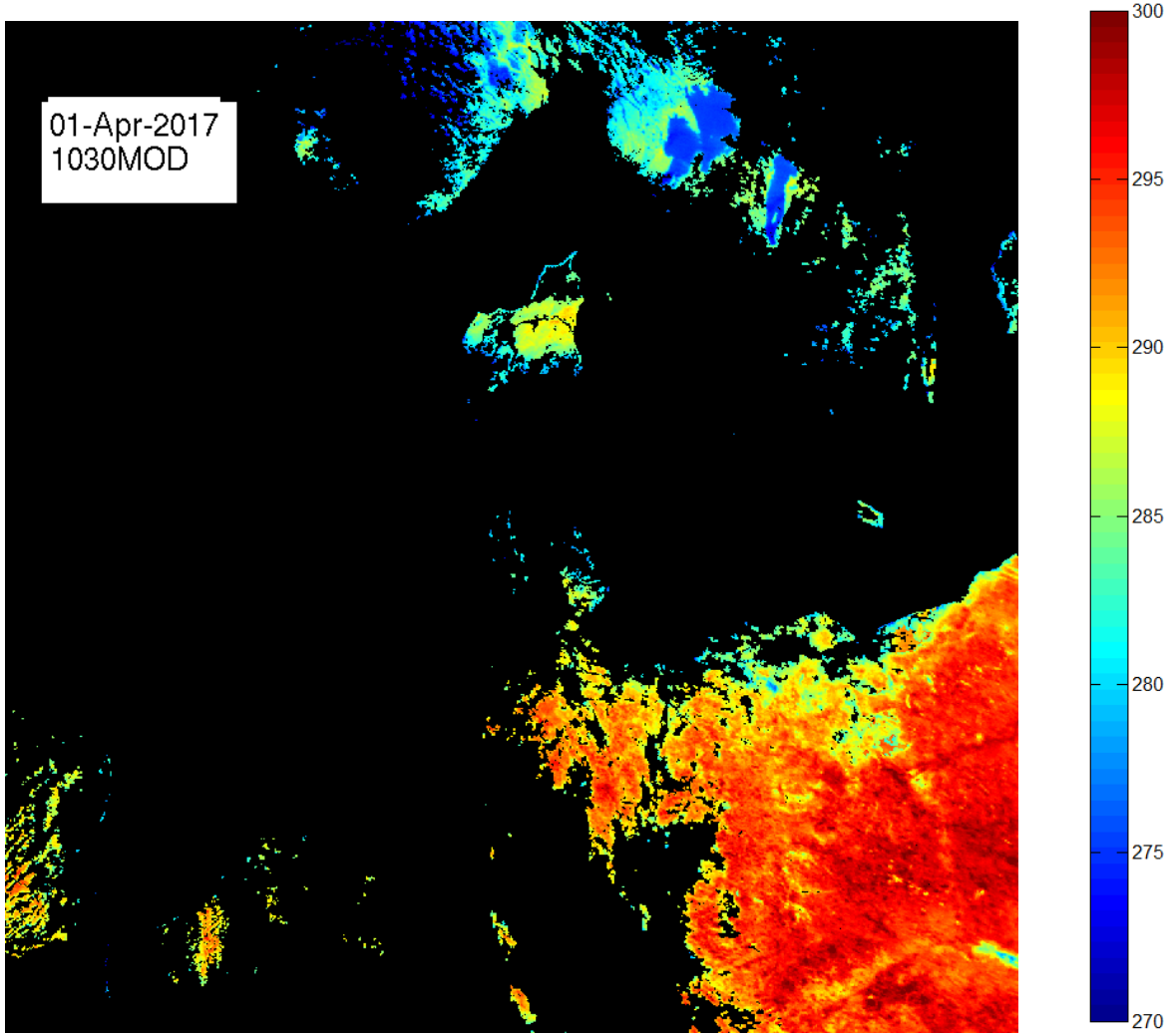


Need to understand the key limitations

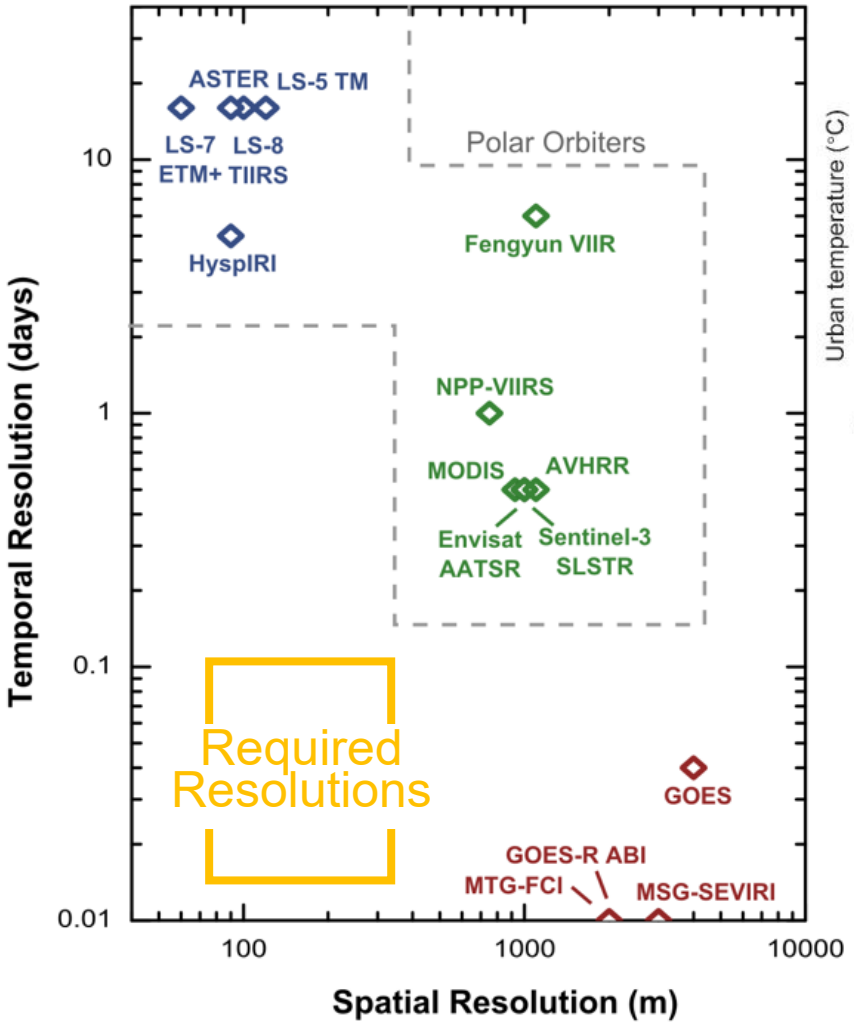
- Temporal dynamics
- Spatial Mixing
- Angular bias
- Retrieval uncertainty

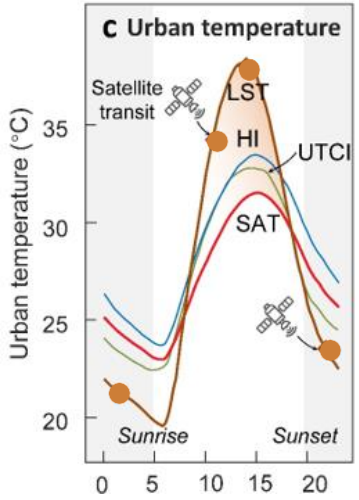
Limitation I: Temporal Snapshots

- Fixed overpass times
- Misses diurnal cycle, esp. nocturnal heat retention
- High spatial variability
- Temporal variability on different time-scales, day-to-day, weather patterns, seasonal
- Only clear sky, no data under cloud cover
- Hardly any cloud free situations for larger ROIs

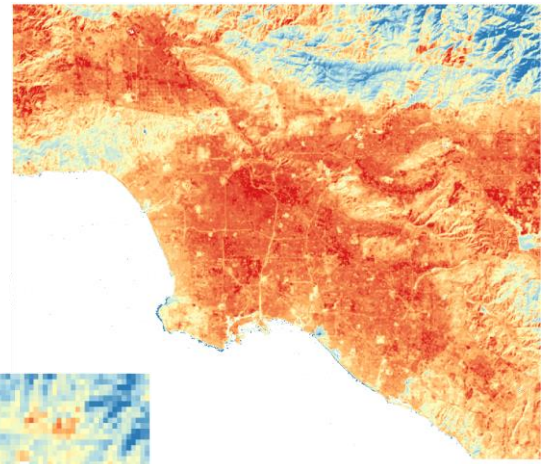


Limitation I: Temporal Snapshots

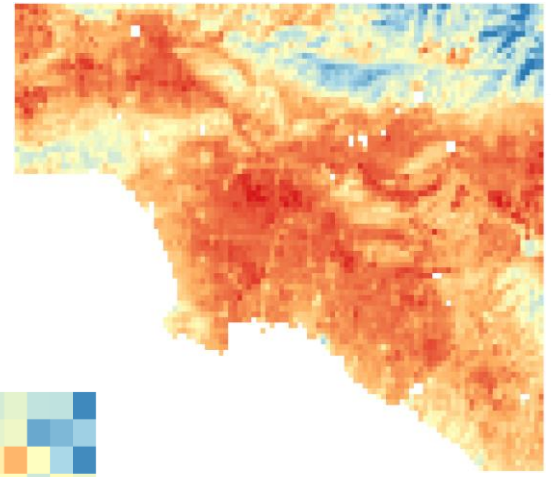




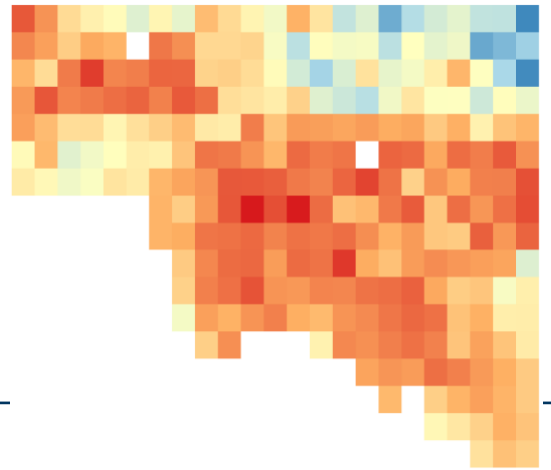
100 m | 16 days



1 km | 12 h



4-5 km | 15 min

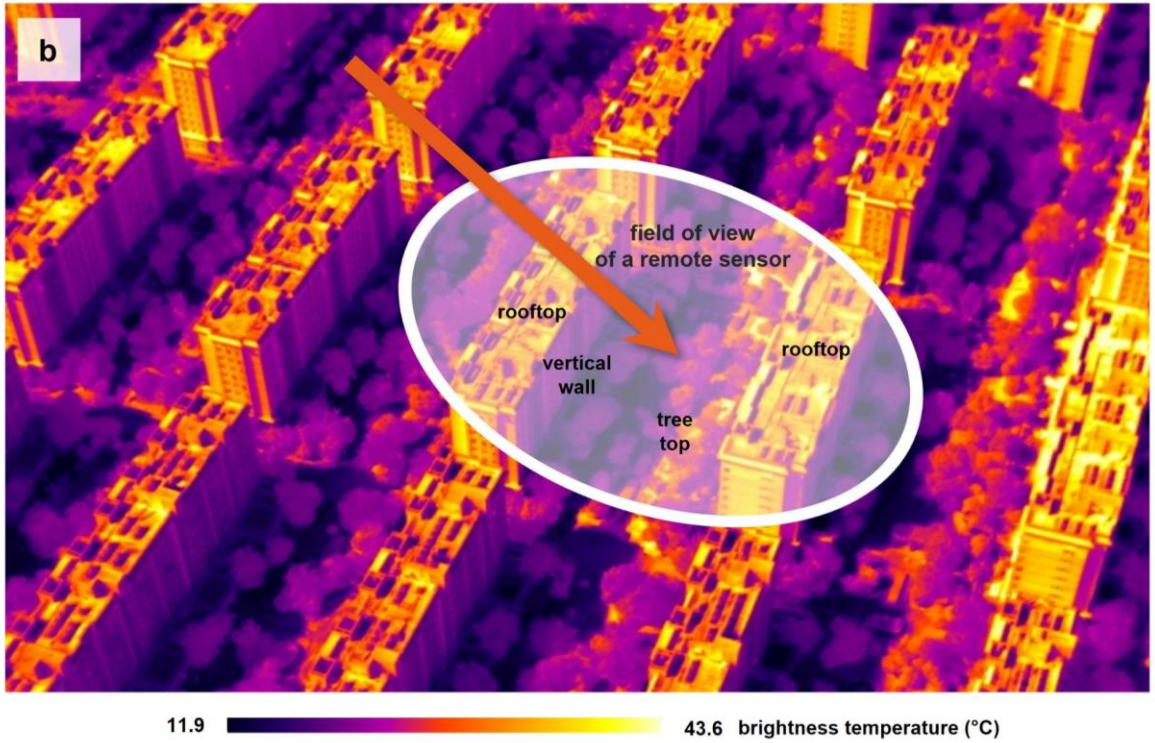


So we need just better sensors, right?

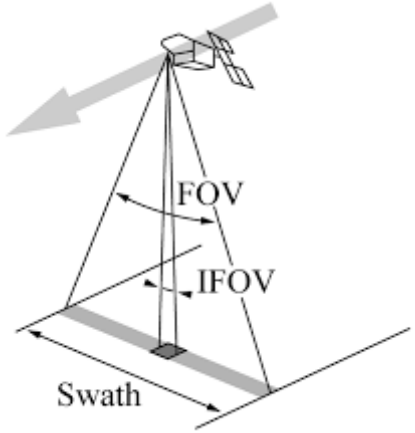
Limit. II: Spatial Mixing

What do we actually see?

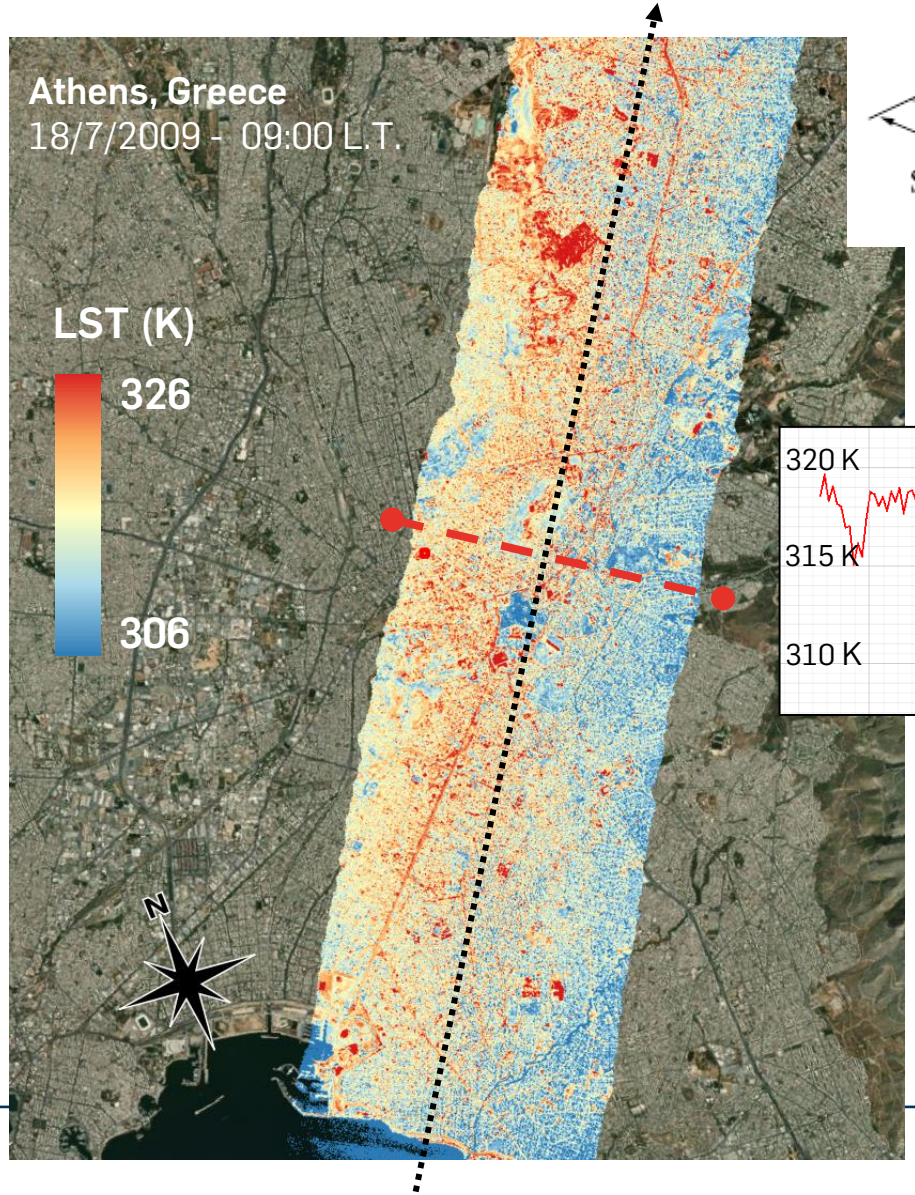
- Pixels combine roofs, trees, pavements
- Over-represents roofs, under-represents shaded spaces
- Blurs microclimate heterogeneity



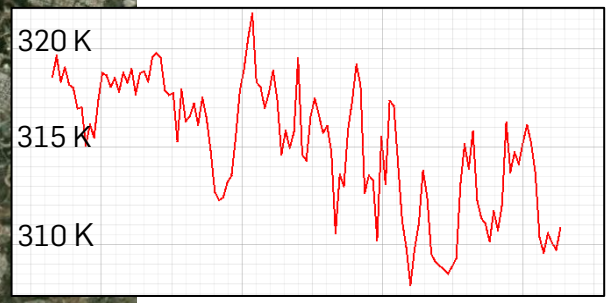
Limitation III: Angular Bias



On the left, the sensor samples the sunlit facets and, on the right, the shaded.

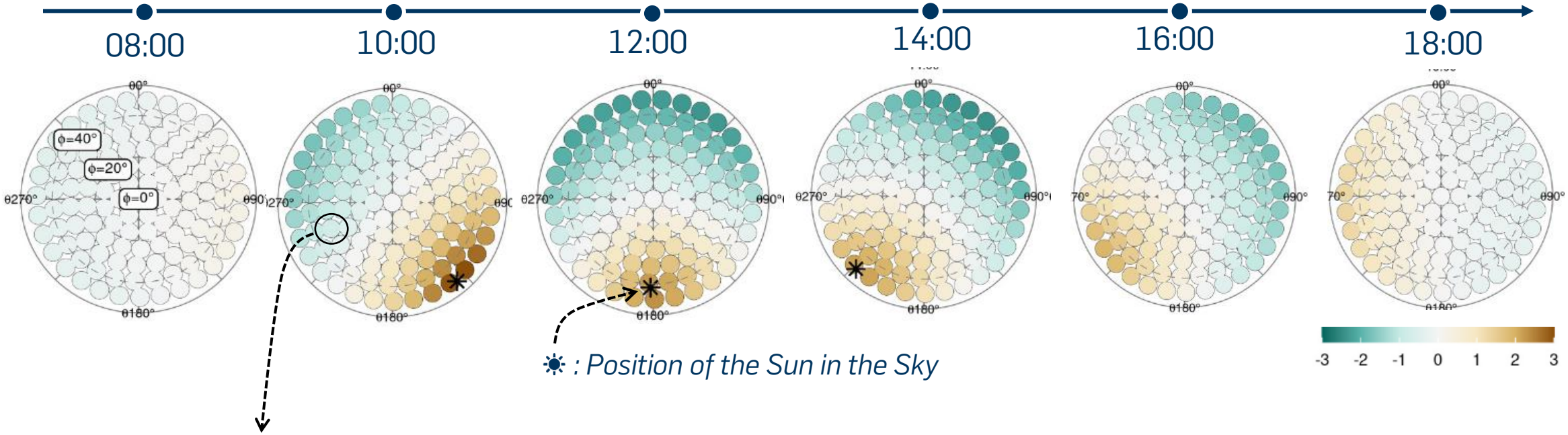


Horizontal Profile



Limitation III: Angular Bias

Simulated thermal Anisotropy [in K] as a function of local solar time.

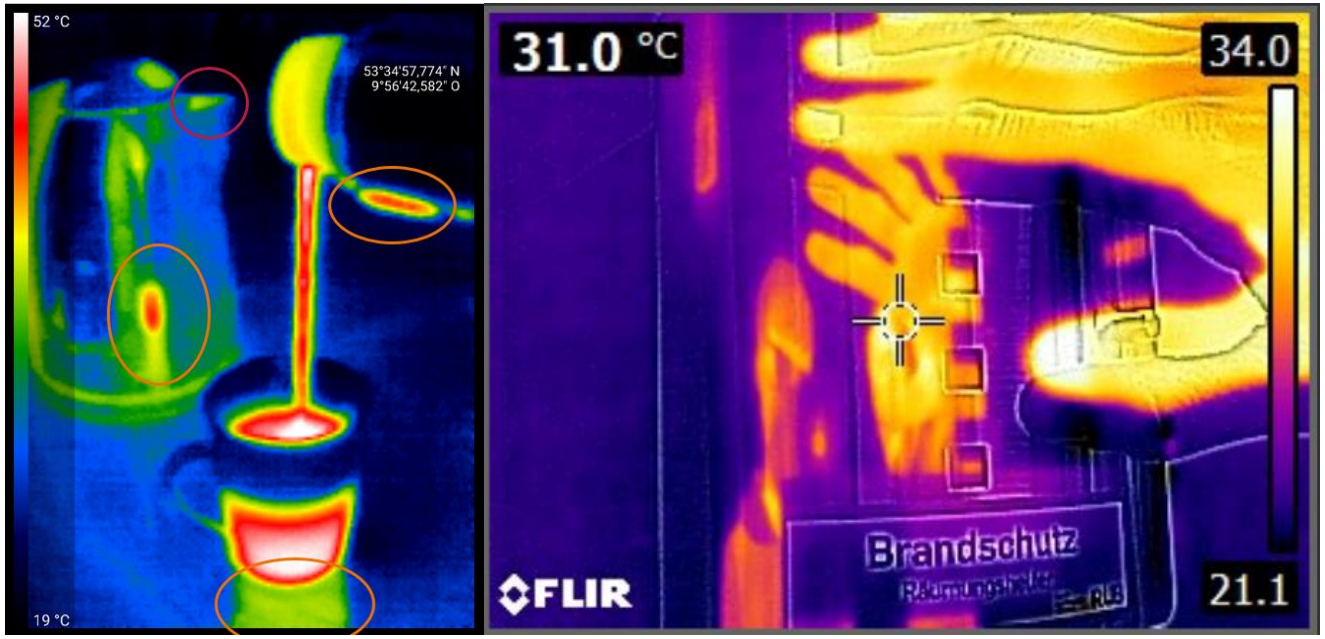


What does it show: If a sensor was viewing the surface from that position, then the measured LST would be lower by 0-1 K than that measured from the nadir (center of each plot).

Source: **Morrison et al. 2023**

Limitation IV: Retrieval Uncertainty

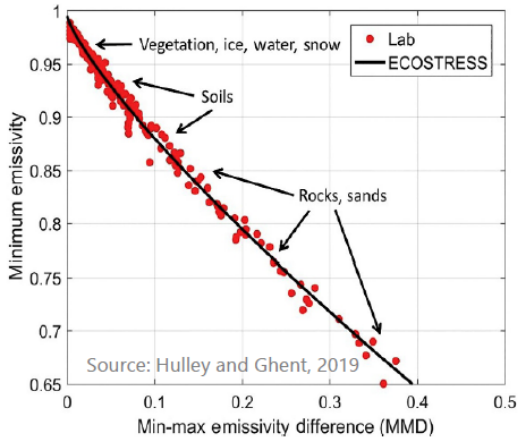
- Depends on emissivity assumptions (none of standard algorithms suited for urban areas, not even TES)
- Atmospheric corrections uncertain
- Errors often 3–5 °C, can easily ecxeed warming signal

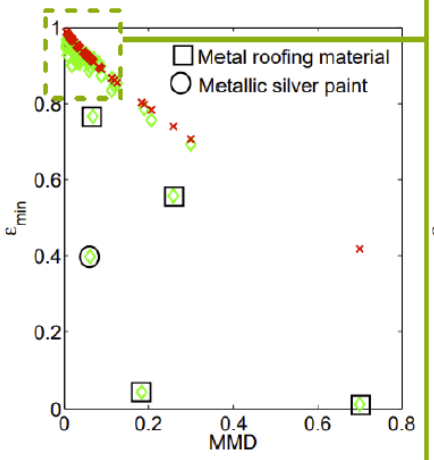


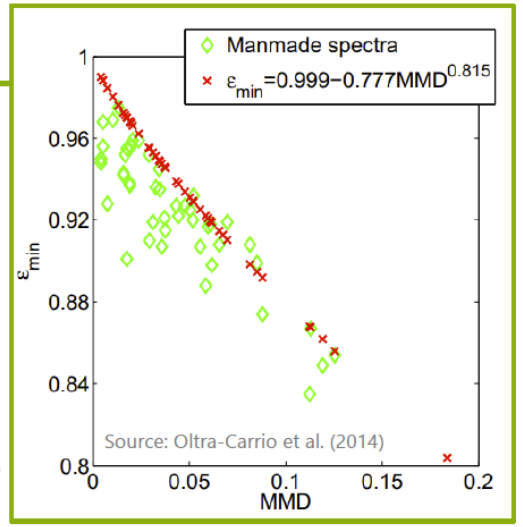
The ECOSTRESS MMD calibration curve consisting of a broad range of terrestrial materials (rocks, sand, soil, water, vegetation, and ice).

vs.

The MMD relationship used in the DESIREX campaign which was based on 54 artificial materials from the ASTER library

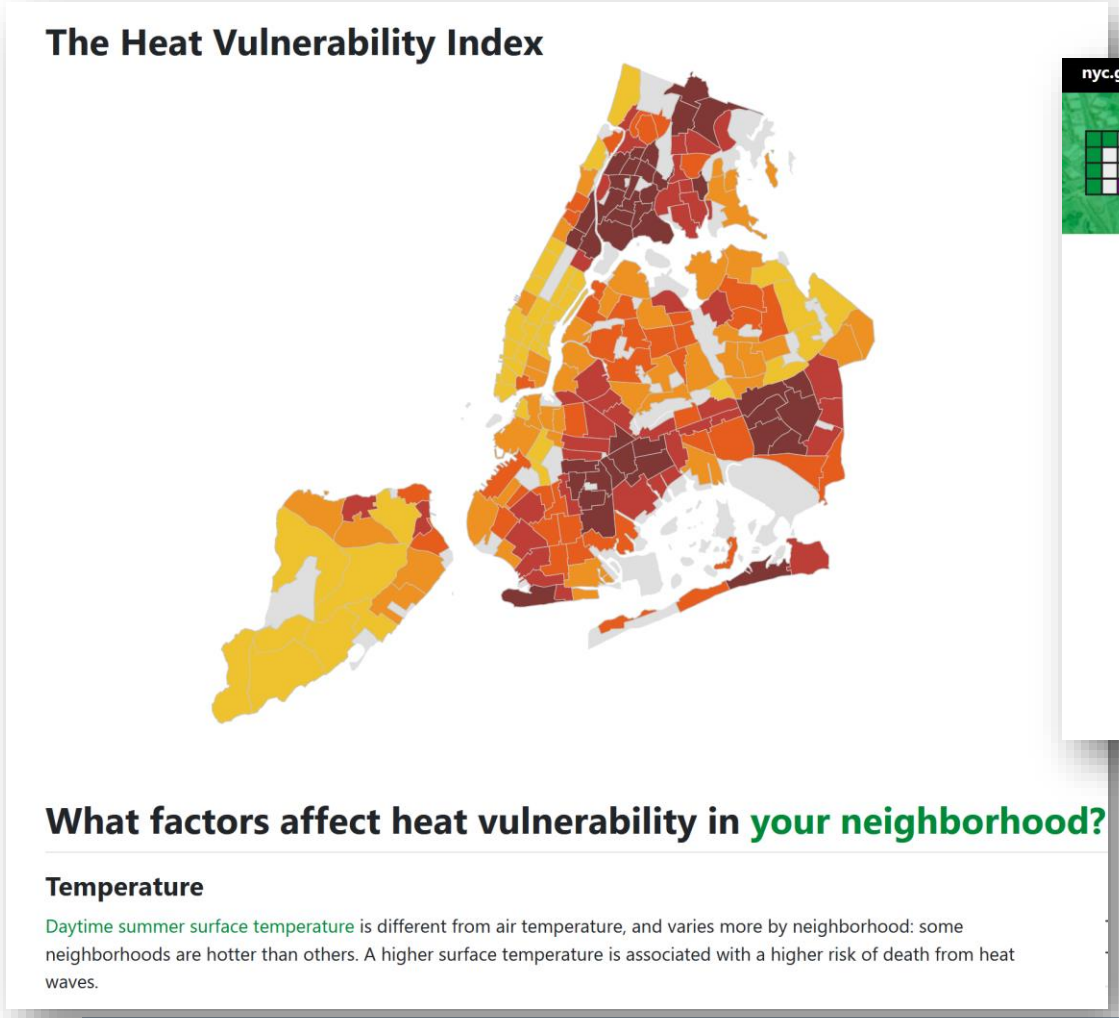


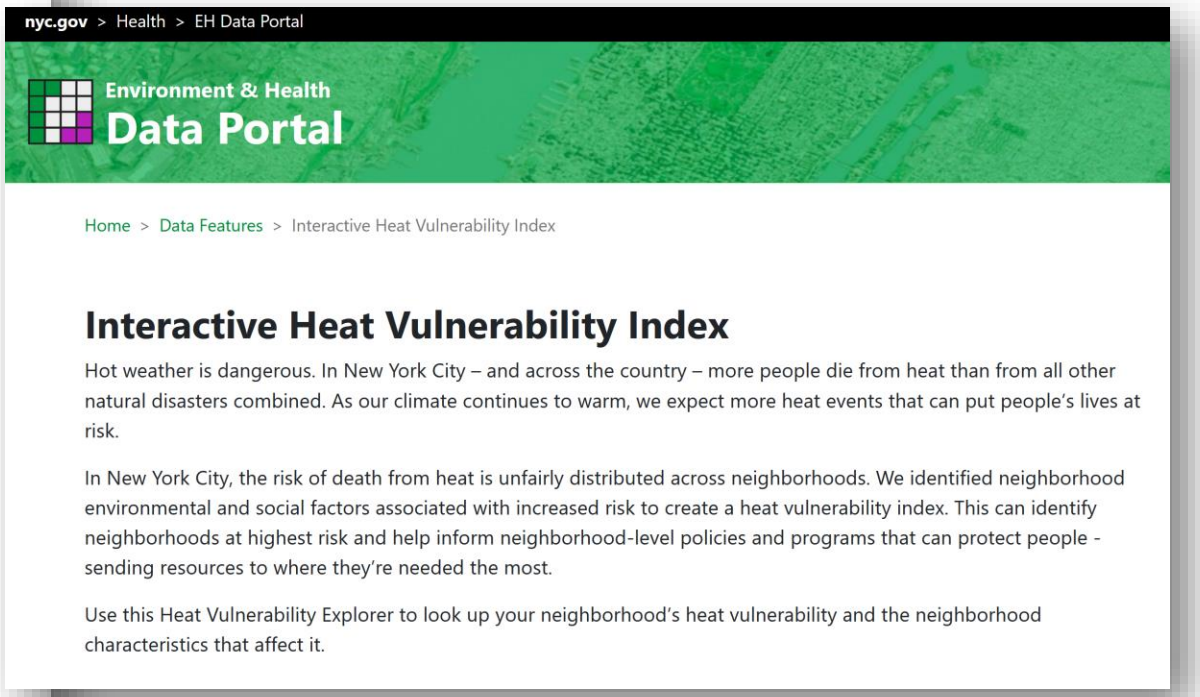




Hulley, G. & Ghent, D. Taking the Temperature of the Earth: Steps Towards Integrated Understanding of Variability and Change. (Elsevier, Amsterdam, Netherlands, 2019).
Oltra-Carrió, Rosa, et al. "Analysis of the performance of the TES algorithm over urban areas." IEEE Transactions on Geoscience and Remote Sensing 52.11 (2014): 6989-6998.

LST is rather unrelated to heat stress

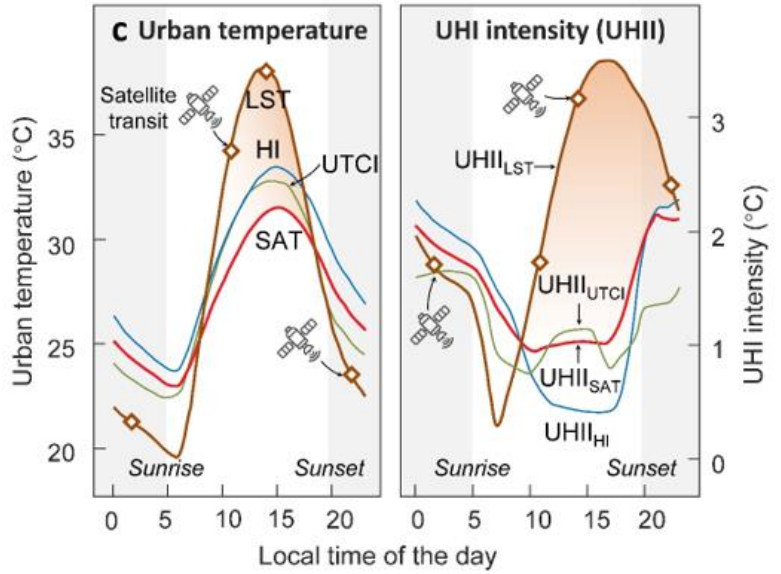


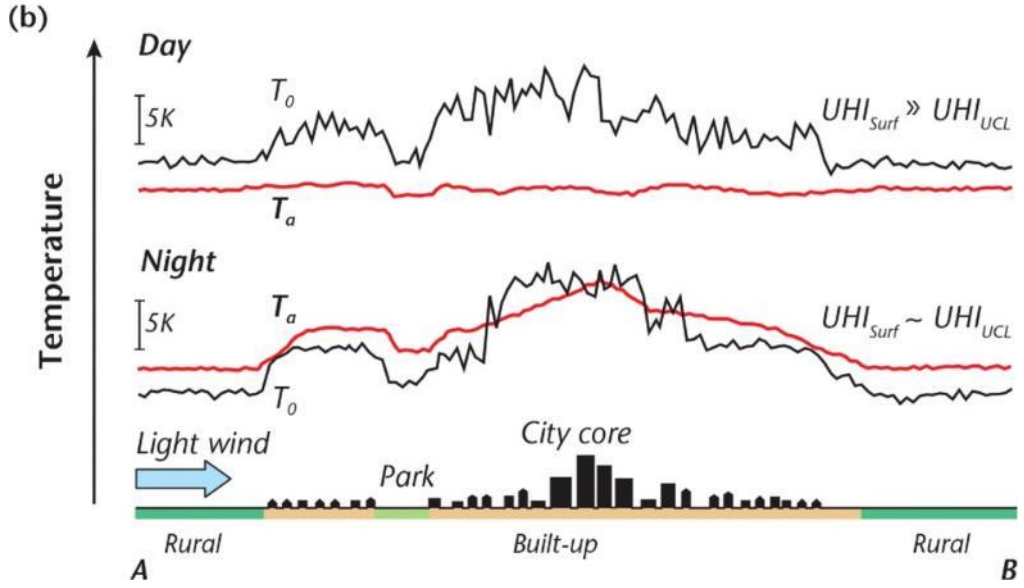


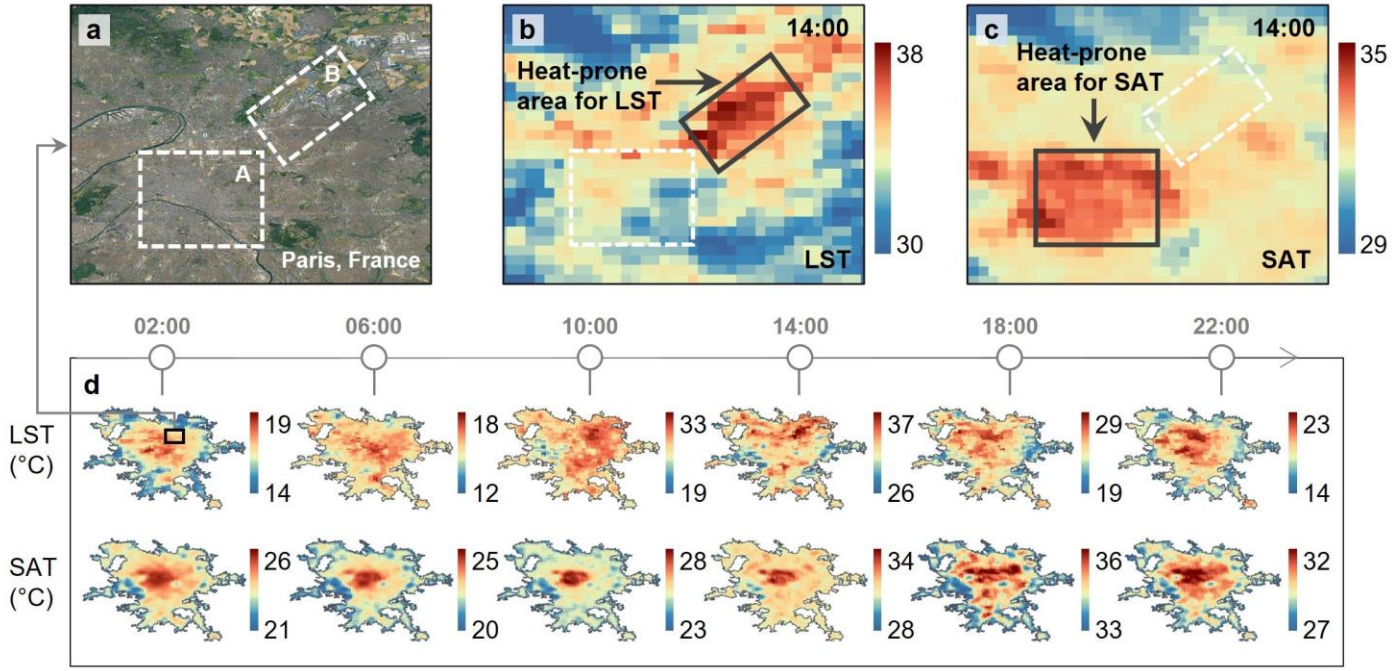
https://a816-dohbesp.nyc.gov/IndicatorPublic/data-features/hvi/

LST vs. Ta: Divergent Signals

- SUHI at day, CLUHI at night
- Weak daytime correlations
- Different spatial patterns



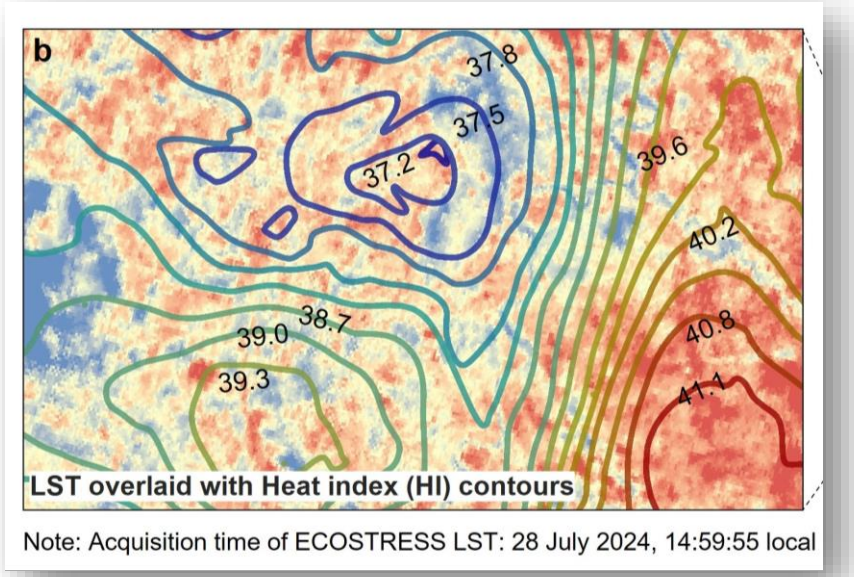


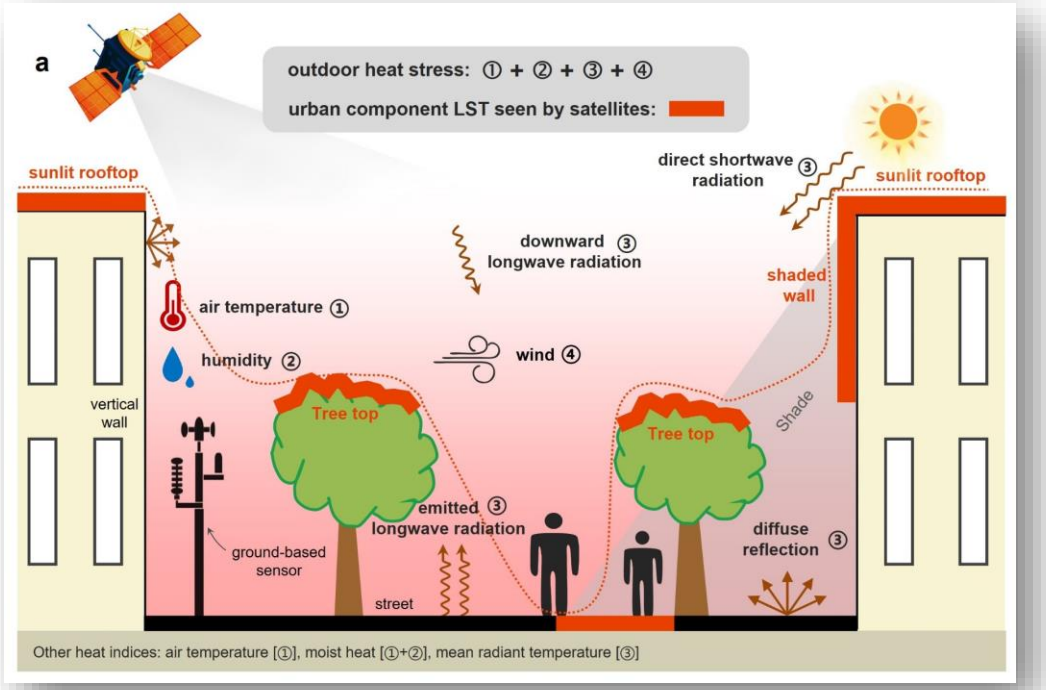


Oke et al. 2017, Zhan et al. 2025

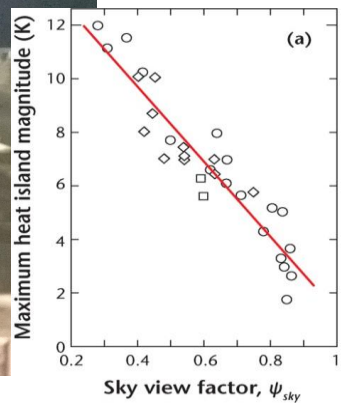
LST vs. Human-Relevant Heat Metrics

- LST is poor proxy for HI, UTCI, Tmrt
- RH, wind & radiation within canyon missing
- Dense canopies → decoupling



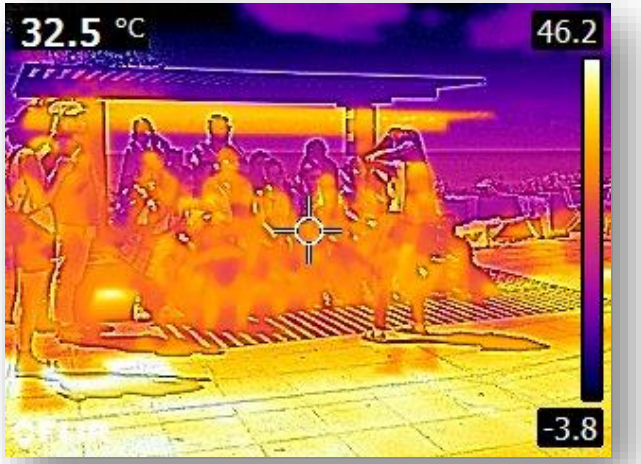


Zhan et al. 2025



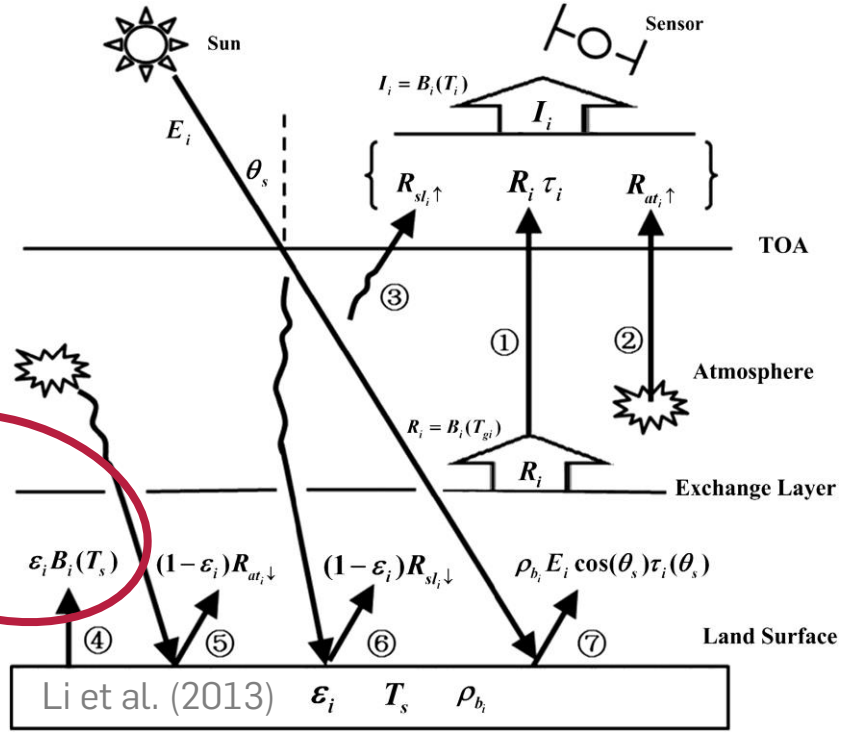
Oke et al. 2017

Urban energy balance

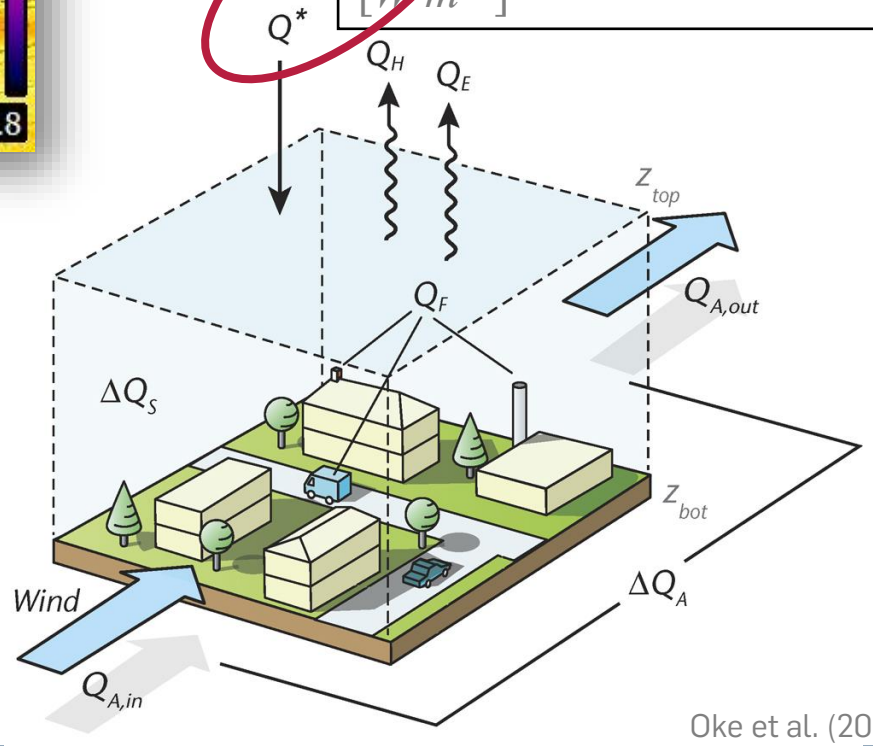


Oh my god they killed λ!

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow \quad [W\,m^{-2}]$$



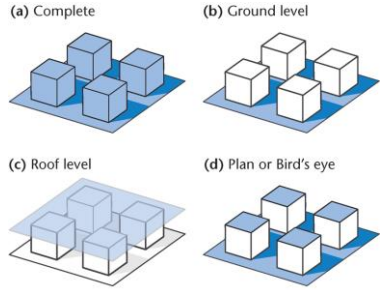
(b)



Oke et al. (2017)

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

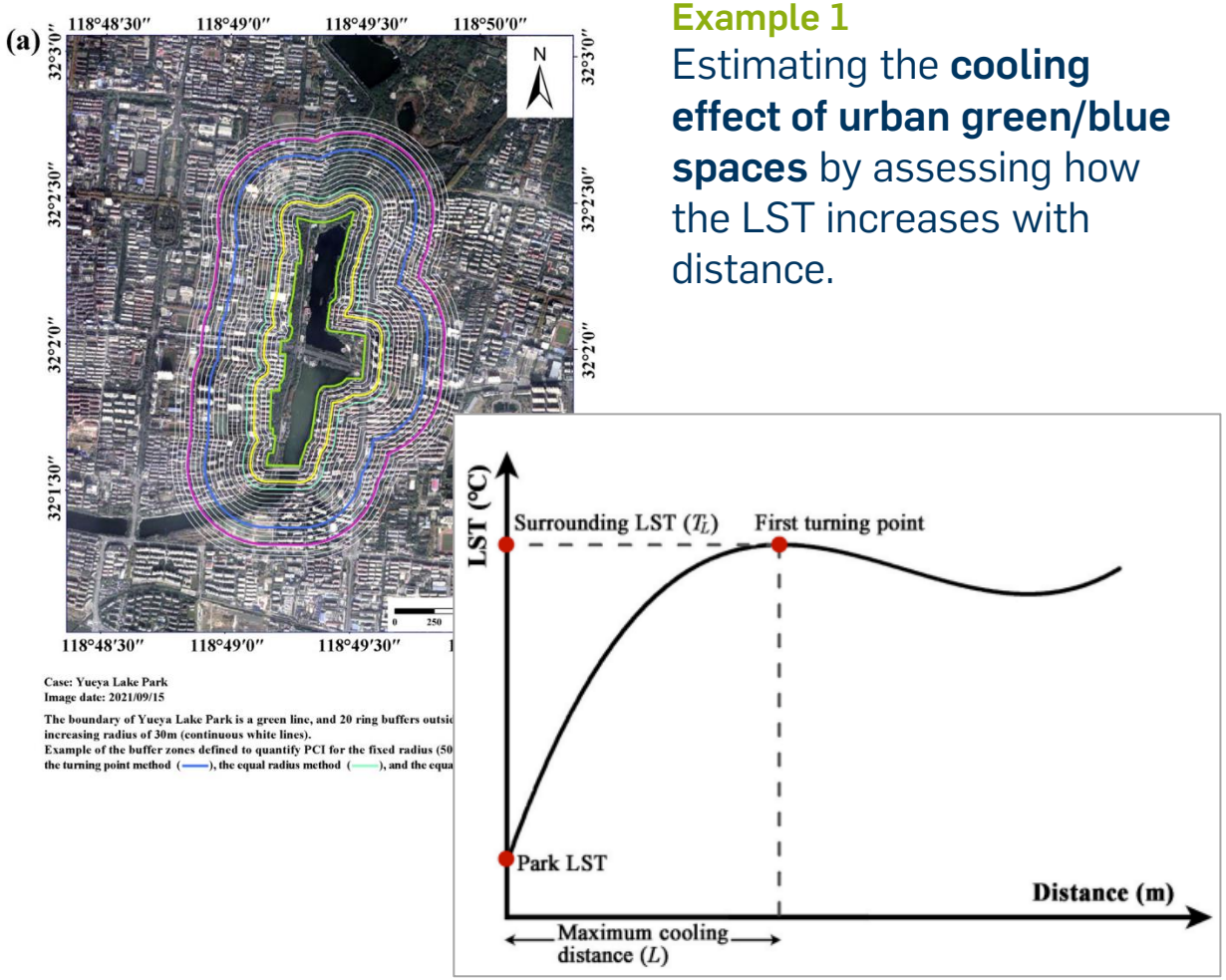
There is no such thing as THE urban surface.



Oke et al. (2017)

Li et al. (2013) Satellite-derived land surface temperature: Current status and perspectives. RSE 131:14–37

Examples of Misuse of LST



Example 1

Estimating the **cooling effect of urban green/blue spaces** by assessing how the LST increases with distance.

Heat conduction? 🤔 🙄

Example 2

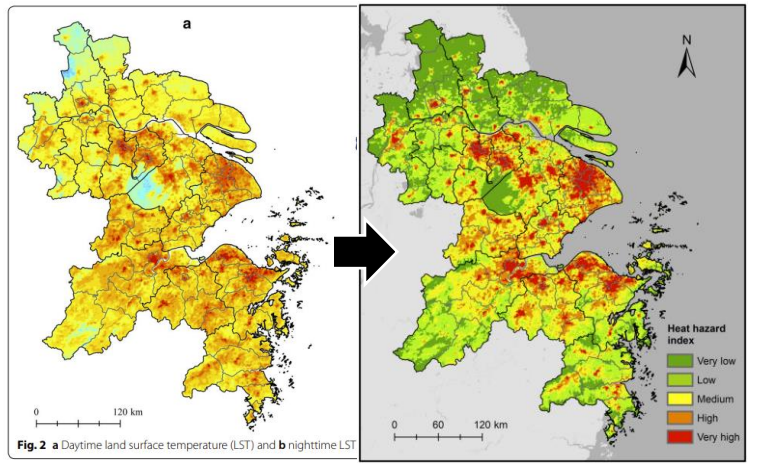
LST is used as a proxy to Heat Hazard.

Excerpt from a peer-reviewed paper: "Two clear sky [MODIS] LST images for daytime and nighttime during an exceptional heat wave were utilized for heat hazard analysis, considering the quality of LST image and cloud contamination in the study area.

…

Then, two LST images were simply added and normalized to obtain the heat hazard index in the study area ranging from 0 to 1 using the ArcGIS software."

LST



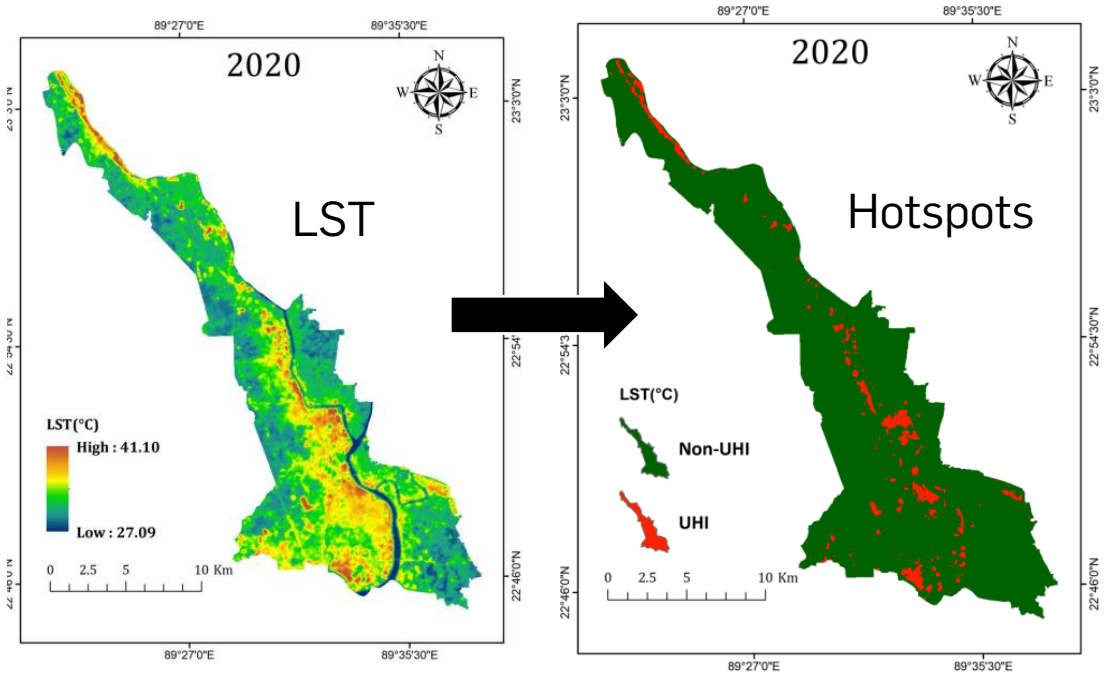
Heat Hazard

Examples of Misuse of LST

Example 3

LST for detecting thermally discomfortable areas.

Excerpt from a peer-reviewed paper: "LST values were used to delineate the hot spots within the study area. The hotspots are areas within the urban heat island with higher temperatures [LST] and uncomfortable for humans."



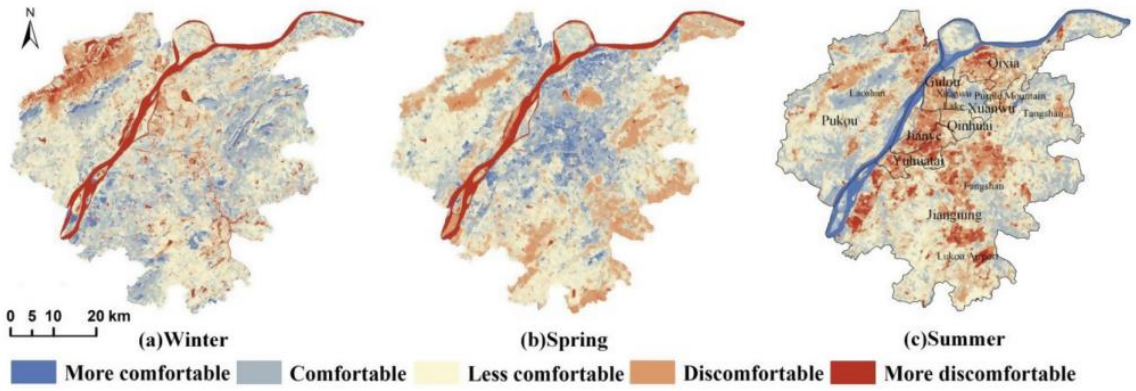
Example 4

Replacing Tair with LST in Heat Indices:

Excerpt from a peer-reviewed paper: "A new index, the modified temperature-humidity index (MTHI), is proposed by replacing the T [air temperature] and RH with the LST and the Normalized Difference Moisture Index (NDMI)."

$$THI = 1.8T + 32 - 0.55 \times (1 - 0.01RH) \times (1.8T - 26)$$

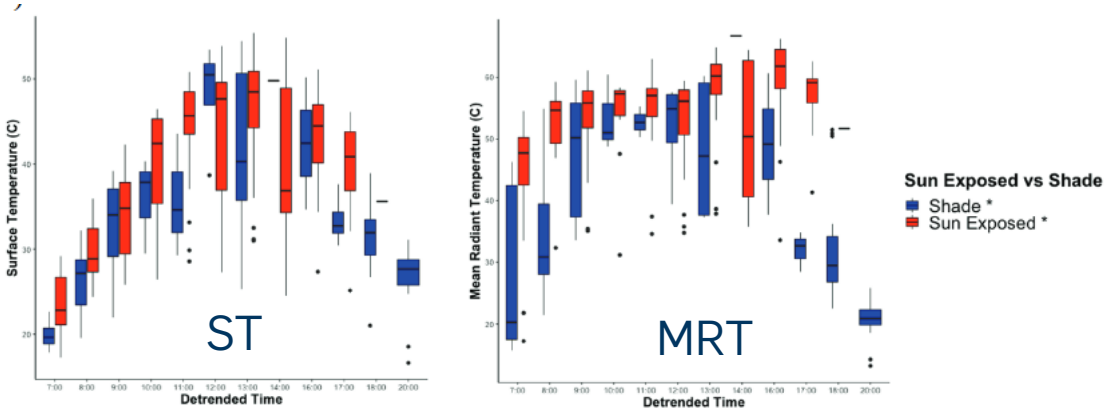
$$MTHI = 1.8 \times LST + 32 - 0.55 \times (1 - NDMI) \times (1.8 \times LST - 26)$$



Misuse in Heat Stress & Public Health

The Issue:

Relying on LST alone to infer or quantify outdoor heat stress is deeply misleading and potentially dangerous when performing downstream cost-benefit analyses for informing the allocation of critical public health resources.



Why is this the case?

A. The disparity between LST and Ta is systematic and consequential.

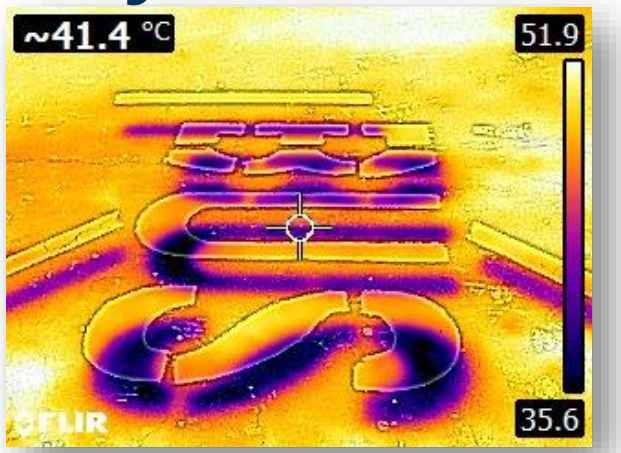
B. Outdoor thermal comfort depends not only on Ta but also on humidity, radiation, and wind – factors mostly unrepresented by LST.

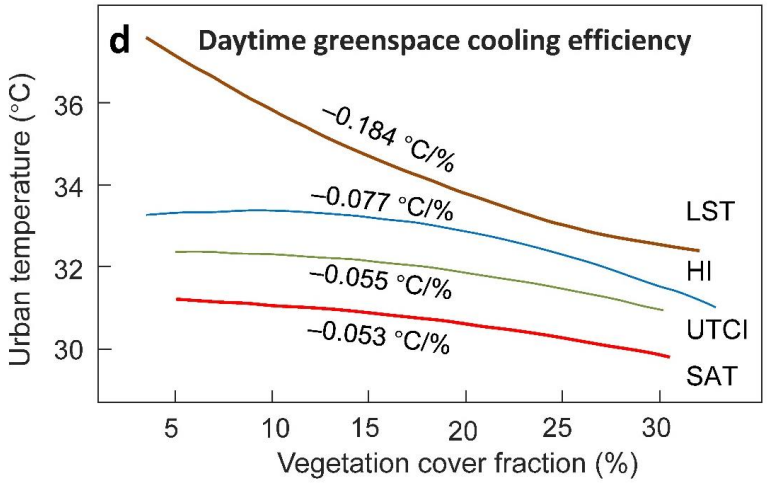
C. Critical contributions emitted by streets, building walls, and trees are often missing or poorly represented in satellite LST.

Kelly Turner, V., Rogers, M. L., Zhang, Y., Middel, A., Schneider, F. A., Ocón, J. P., et al. (2022). More than surface temperature: mitigating thermal exposure in hyper-local land system. *Journal of Land Use Science*, *17*(1), 79–99. https://doi.org/10.1080/1747423X.2021.2015003

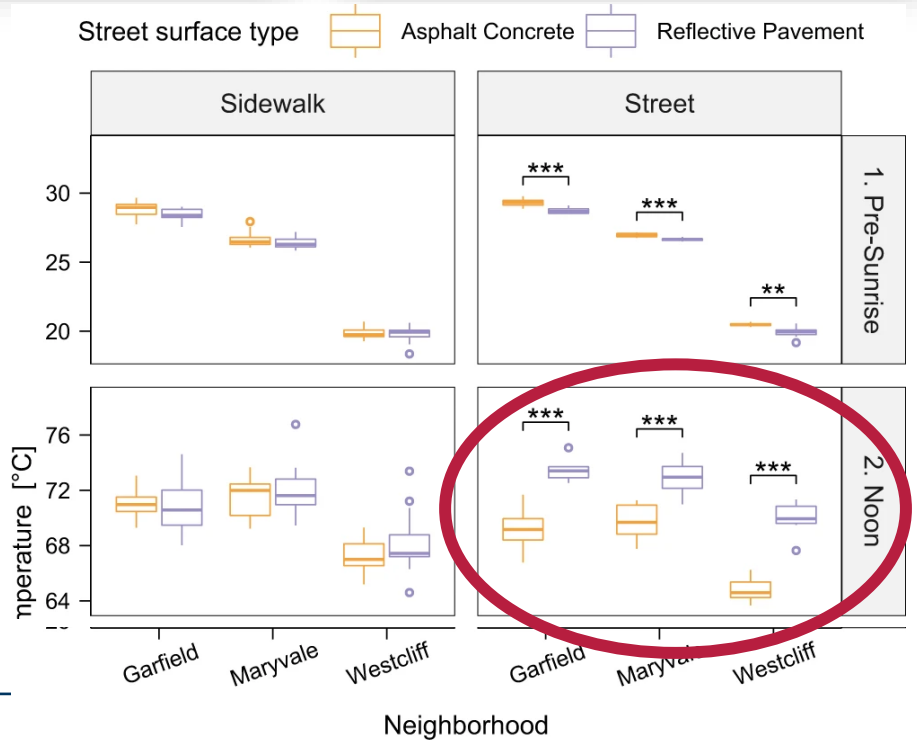
Misuse in Cooling Efficiency Assessments

- Vegetation cooling overstated in LST
- Spillover often artefacts of land cover
- **Reflective pavements paradox**





Tmrt



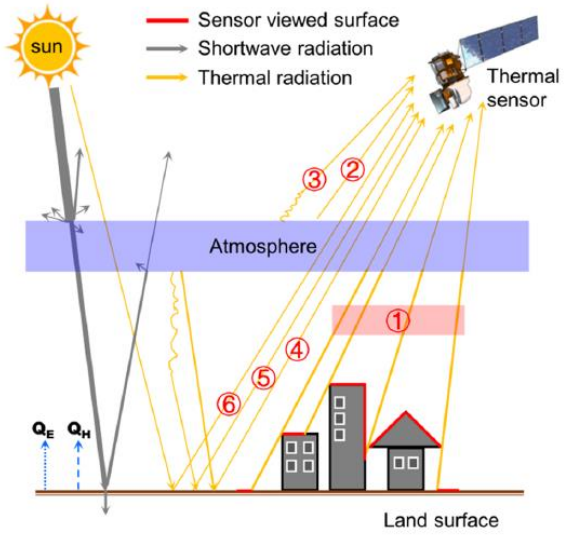
Zhan et al 2025 preprint

Schneider et al. 2023

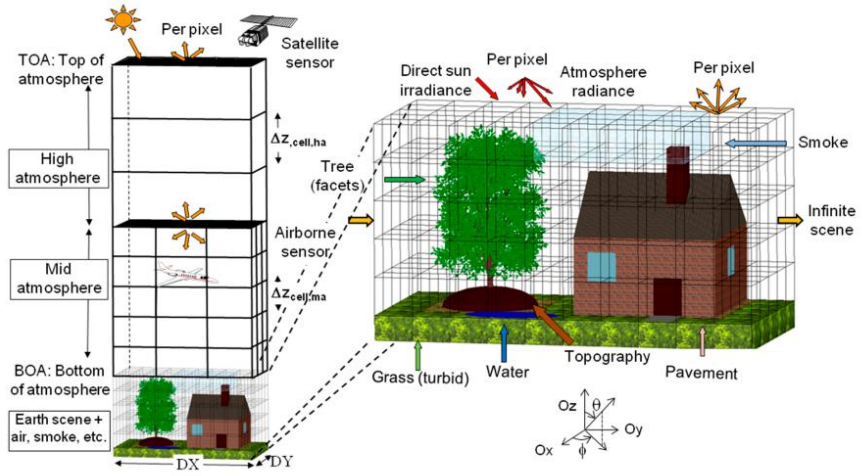
Need to understand the signal

To understand the measured signal we need **obstacle-resolving numerical models of urban form and radiation exchanges that can model the relation between:**

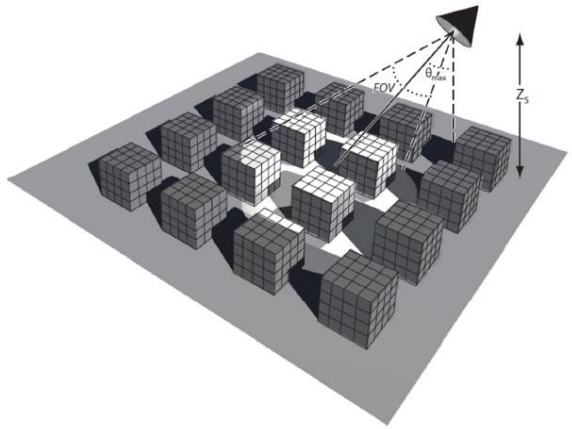
- the satellite viewing geometry
- the 3D urban form
- and the urban facet properties (albedo, emissivity, etc.)



DART 3D RT model



SUM & TUF-3D

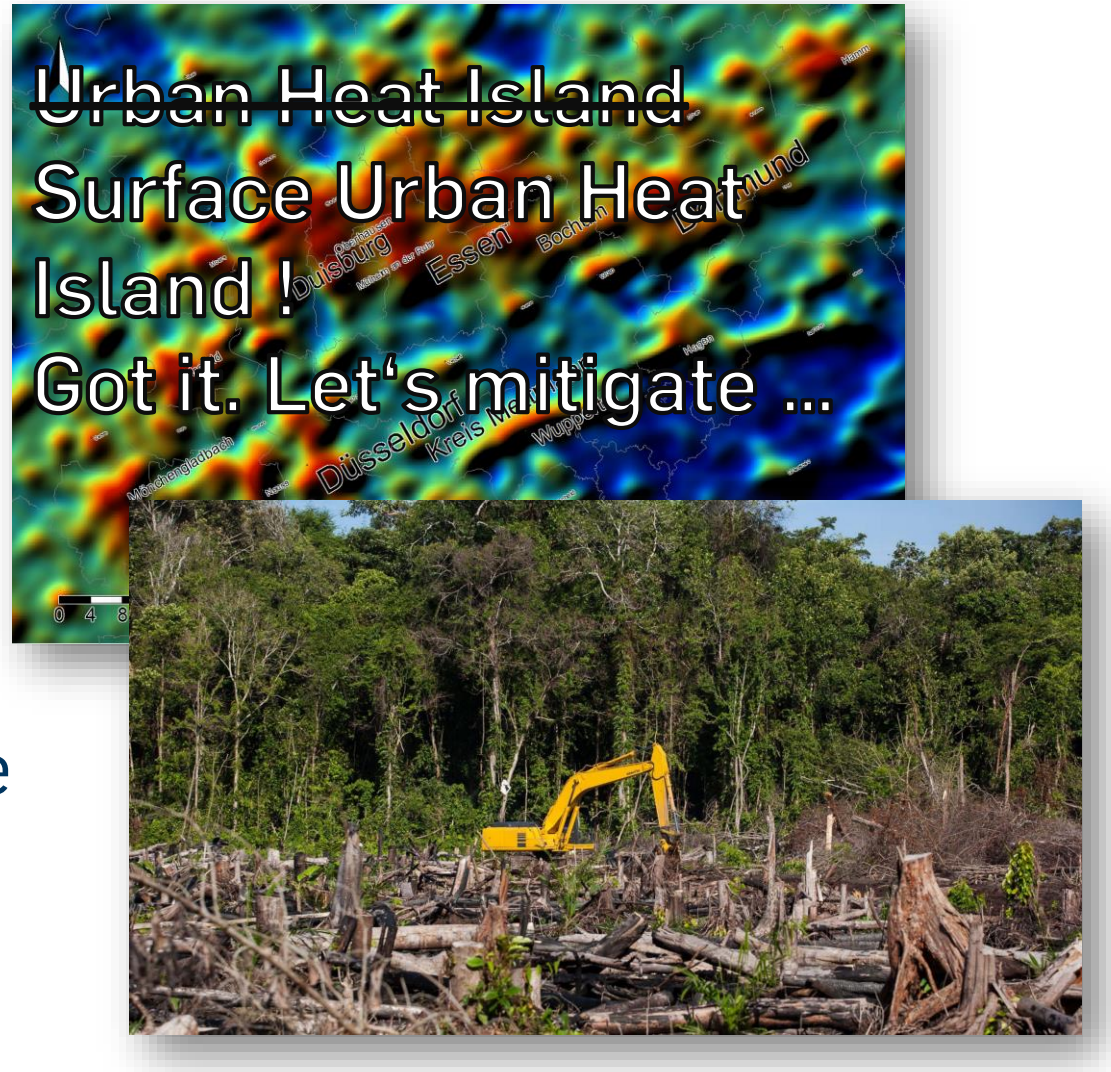


- D. Zhou et al., Remote Sensing. 11 (2019), doi:10.3390/rs11010048.

E. Krayenhoff, J. Voogt, Remote Sensing. 8, 108 (2016).

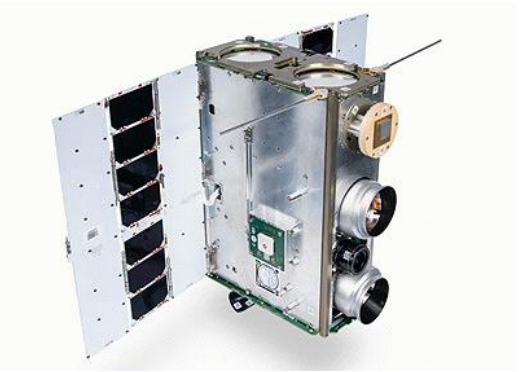
Pathways Forward I: Better Practices

- Always label results as LST-based
- Avoid ambiguous 'temperature' wording
- Don't conflate with exposure or comfort
- Carefully watch policy relevance
- Look at absolute values, not relative (UHI)
- Best practice review ???



Pathways Forward II: Technical Improvements

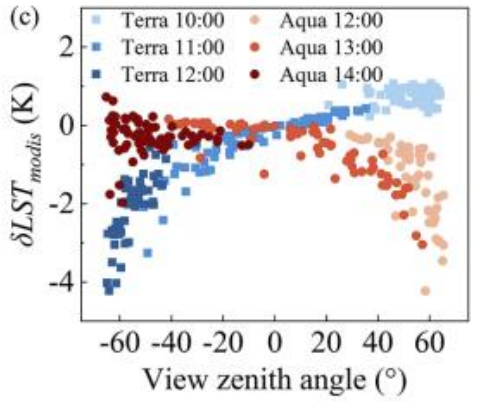
- **New and upcoming missions:**
  - SDGSAT-1 (China),
  - TRISHNA (France and India),
  - LSTM (EU)
  - Private micro-satellites (constellr, satVu, orora, etc.)
- **What advantages they bring:**
  - Higher spatial resolution (≤50 m)
  - Nighttime observations 🎉
  - Multi-spectral TIR observations that allow the simultaneous retrieval of LST and LSE.



Pathways Forward II: Technical Improvements

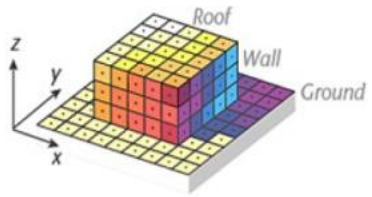
Anisotropy Correction

- Anisotropy can be a source of noise but also of information.
  - ***Noise***: When merging multi-sensor or multi-temporal observations.
  - ***Beneficial***: thermal unmixing

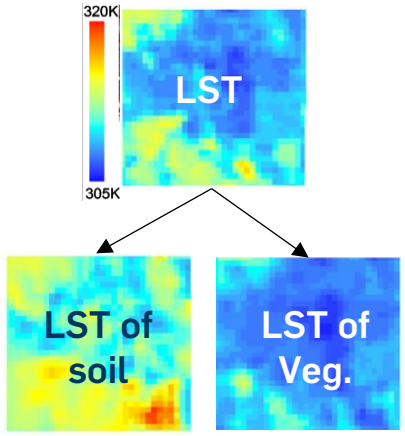


Application Specific Metrics

- Complete Surface Temperatures

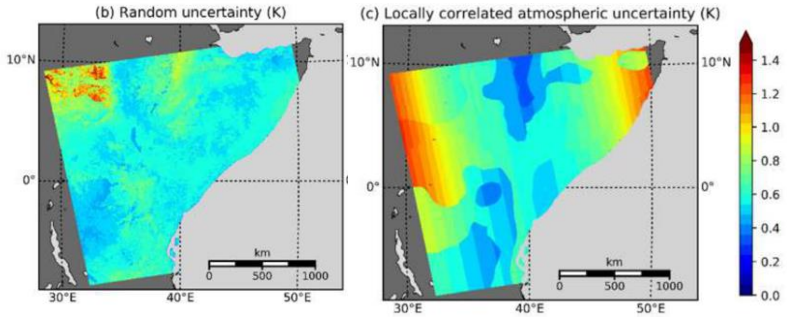


- Component surface temperatures



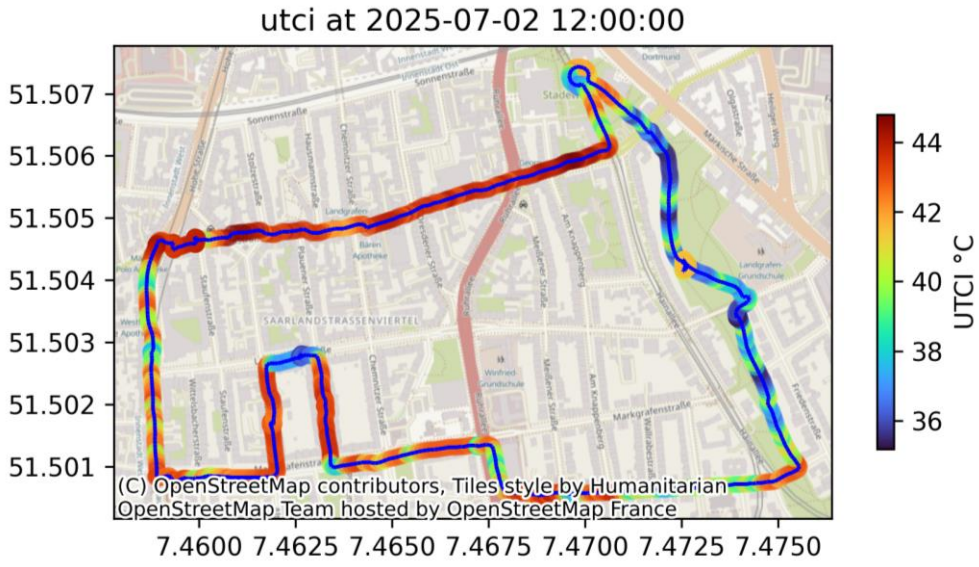
LST Uncertainty

- New LST products---especially those designed for climate analysis---provide a complete quantification of the LST uncertainty budget.
- This information should not be ignored but it should be properly propagated and incorporated into our models.



Pathways Forward III: Integration & Outlook

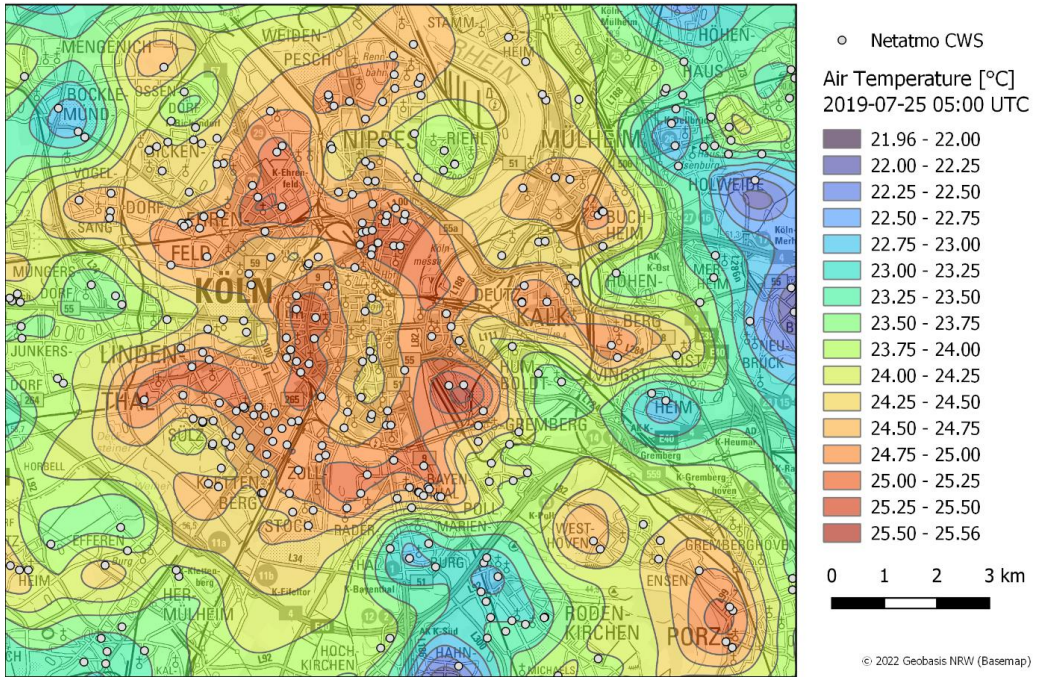
- Combine LST with SAT, UAV, crowdsourced data, models
- Towards human-centric metrics (HI, UTCI at scale)
- Use AI for integration and efficient models
- Interdisciplinary collaboration essential



Crowdsourcing

- Citizen weather station (CWS) data from privately-owned, non-professional, low-cost stations connected to the Internet.
- Rigorous quality control of CWS data is essential prior to any application

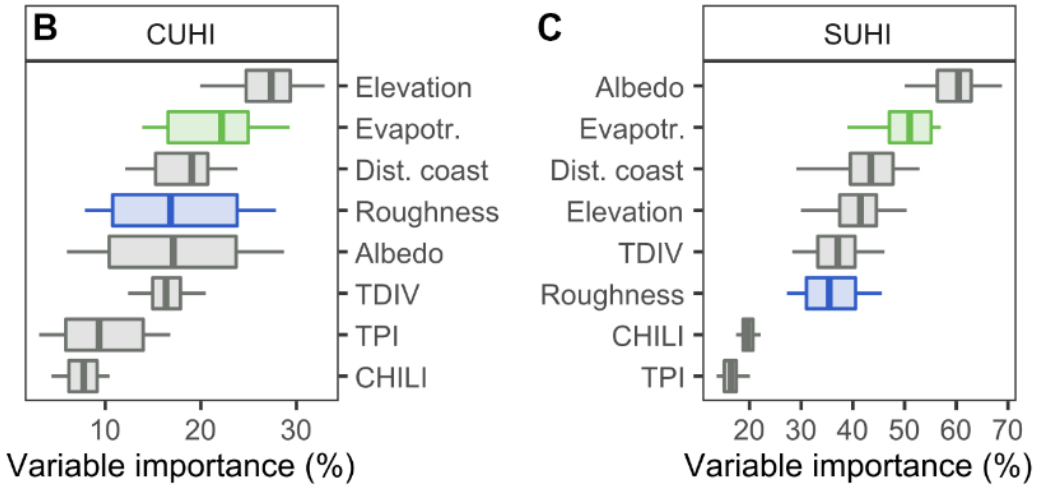
https://www.netatmo.com/

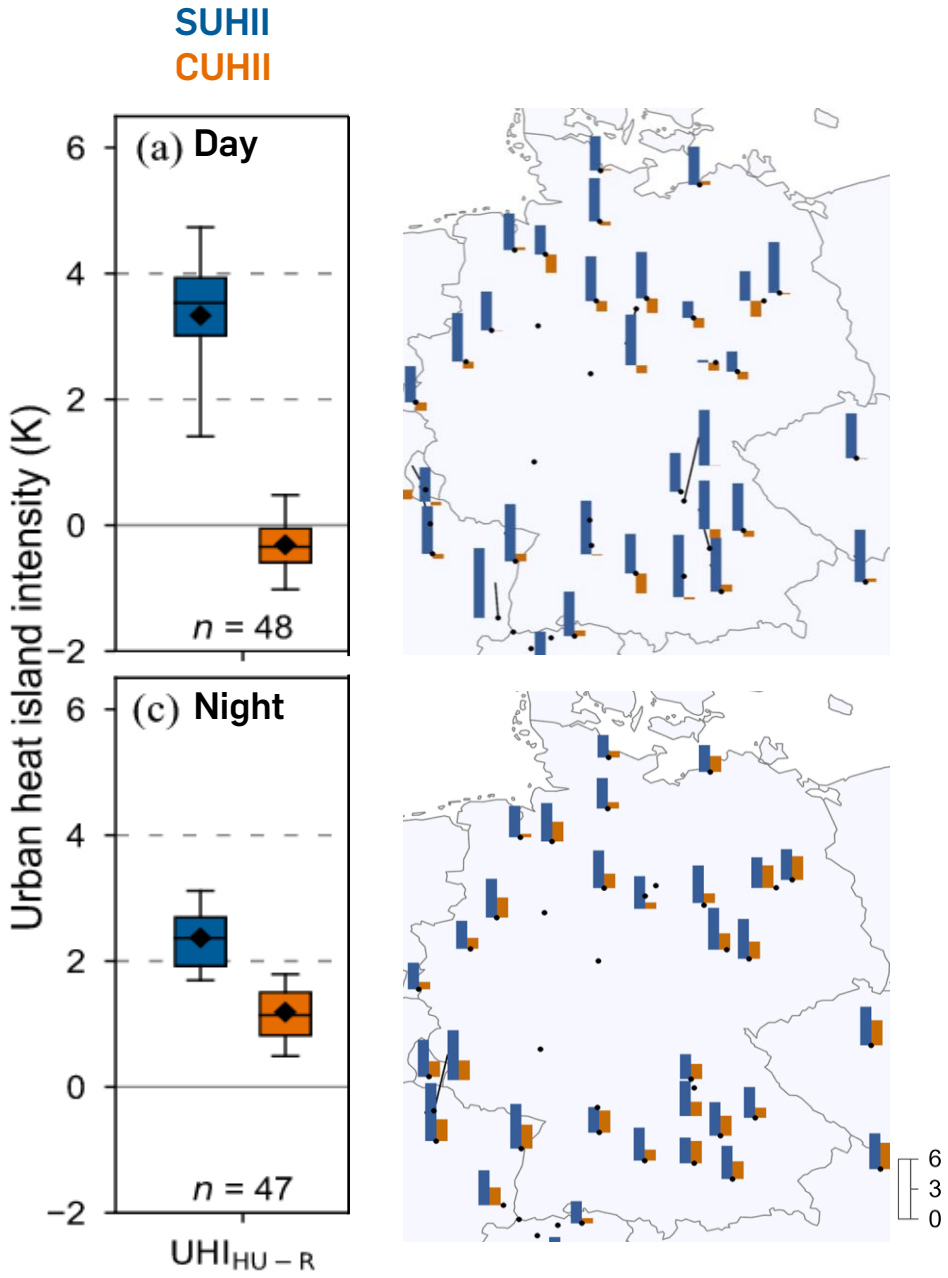


Fenner D, Bechtel B, Demuzere M, Kittner J and Meier F (2021) CrowdQC+—A Quality-Control for Crowdsourced Air-Temperature Observations Enabling World-Wide Urban Climate Applications. Front. Environ. Sci. 9:720747. doi: 10.3389/fenvs.2021.720747

CUHI vs. SUHI Intensity

- SUHI intensity exceeds CUHI both during the day and during the night:
  - **10:30:** -0.2 K vs. 3.6 K *(mean of all cities)*
  - **22:30:** 1.2 K vs. 2.3 K
- The correlation between the SUHI and CUHI intensities is low to moderate:
  - **10:30:** 0.24 ($p<0.050$)
  - **22:30:** 0.46 ($p<0.001$)
- Different determinants:

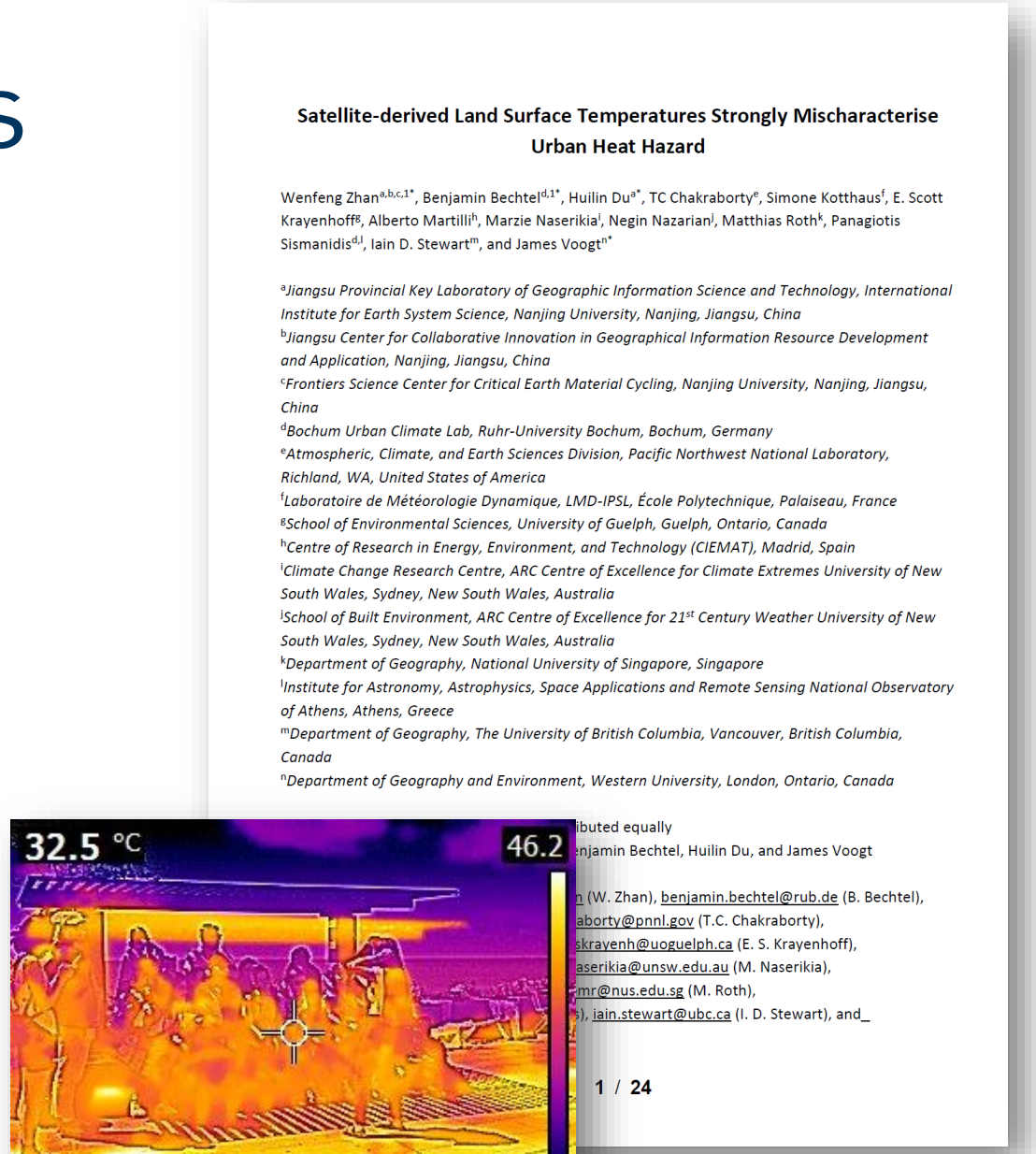




Source: **Krelaus et al., 2024; Venter et al., 2021**

Take home messages

- Cities are going to invest trillions in climate adaptation
- Reliable metrics are essential for planning and heat monitoring
- Traditional observations leaves large gaps
- LST is tempting but flawed and potentially dangerous if used carelessly for policy
- Daytime LST is … complicated. And not too policy relevant
- Interdisciplinary exchange needed
- **Cool People, not pixels!**



Satellite-derived Land Surface Temperatures Strongly Mischaracterise Urban Heat Hazard

Wenfeng Zhan[a,b,c,1*], Benjamin Bechtel[d,1*], Huilin Du[a*], TC Chakraborty[e], Simone Kotthaus[f], E. Scott Krayenhoff[g], Alberto Martilli[h], Marzie Naserikia[i], Negin Nazarian[j], Matthias Roth[k], Panagiotis Sismanidis[d,l], Iain D. Stewart[m], and James Voogt[n*]

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[g]*School of Environmental Sciences, University of Guelph, Guelph, Ontario, Canada*
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[m]*Department of Geography, The University of British Columbia, Vancouver, British Columbia, Canada*
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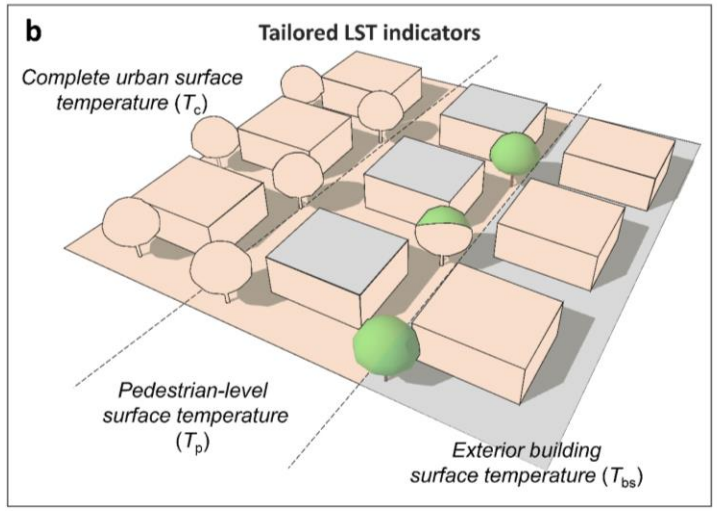
1 / 24

Misuse in Building Energy & Design

- LST not representative of building load
- Roofs dominate, walls under-sampled
- Insulation paradox: hot roof, low energy demand



Note: UCL: Urban canopy layer; SAT: Surface air temperature; LST: Land surface temperature; HI: Heat index; UTCI: Universal thermal climate index; UHI: Urban he

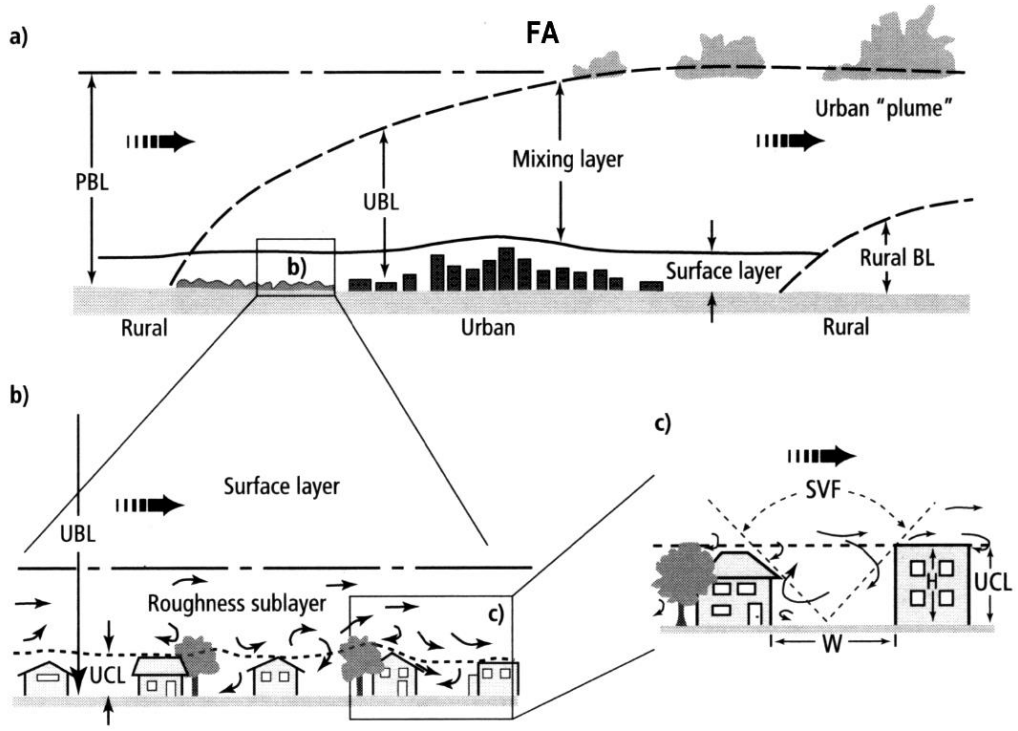
Fig. 2b (application-specific LST indicators: Tc, Tp, Tbs)

Brave new world?

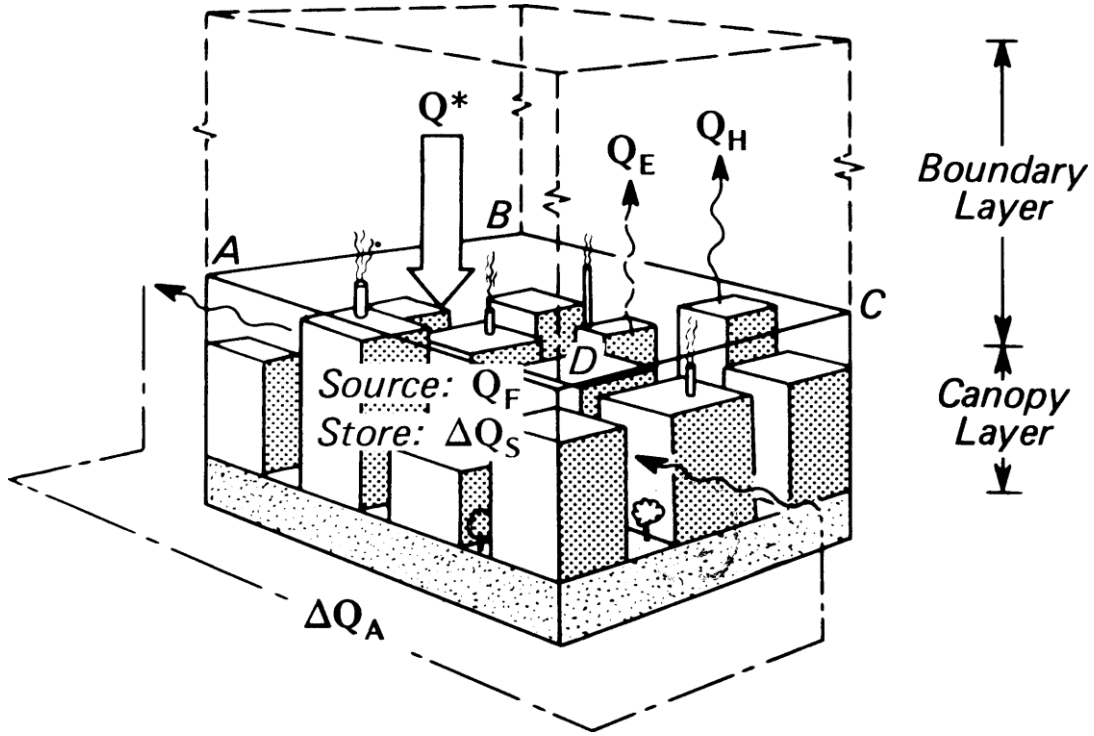
Image created with DALL-E

Zentrale Wirkungskomplexe

Aerodynamik

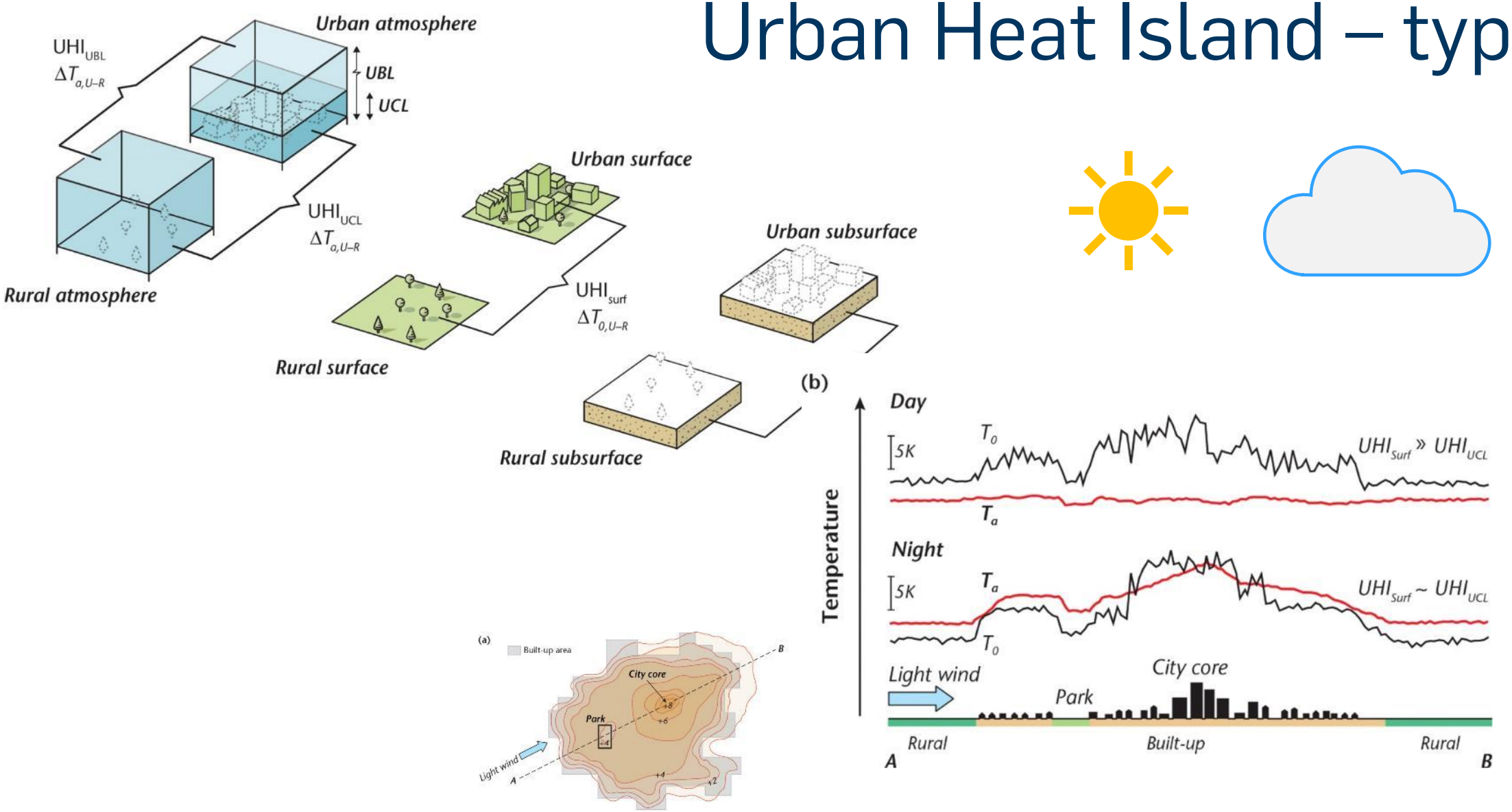


Urbane Energiebilanz



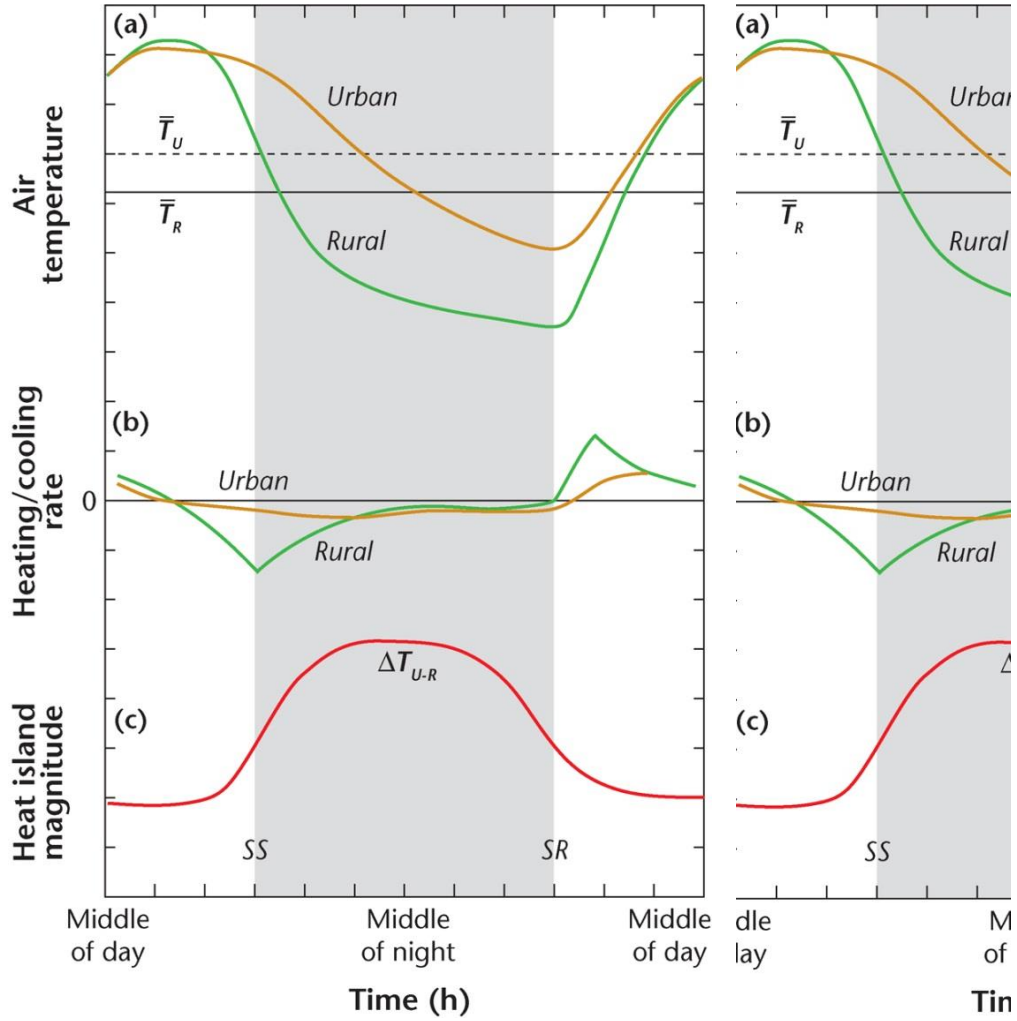
Links: Oke 1997, Kuttler 2004
Rechts: Oke 1987

Urban Heat Island – types



Oke et al. 2017

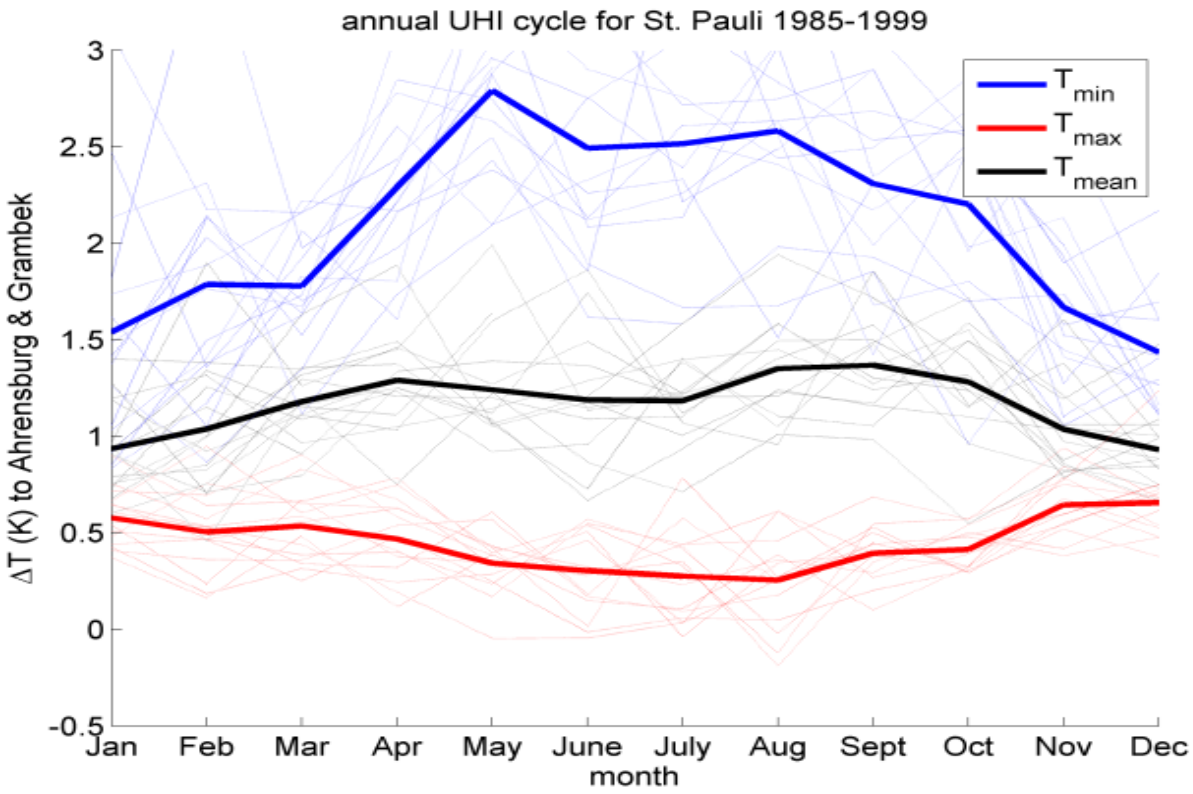
Zeitlicher Verlauf 1: Tagesgang



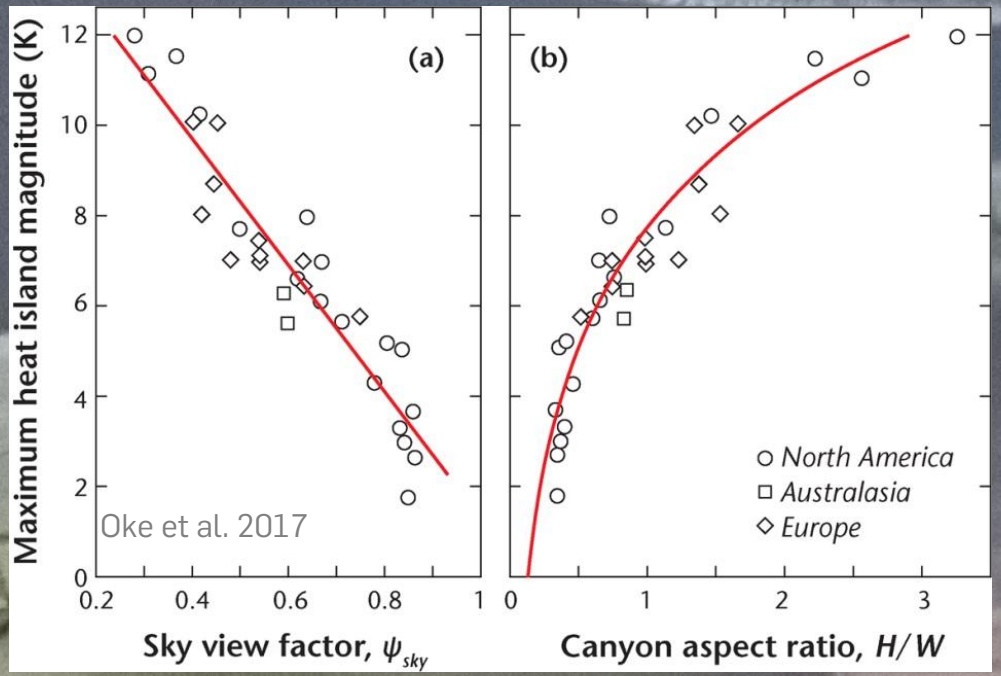
- Tags kleine UHI (oder sogar negativ)
- Abends reduzierte Abkühlung in der Stadt (Speicher, reduzierte Ausstrahlung)
- Nachts vor Sonnenaufgang: starke UHI
- Morgens: langsamere Erwärmung der Stadt (Material, Speicher)

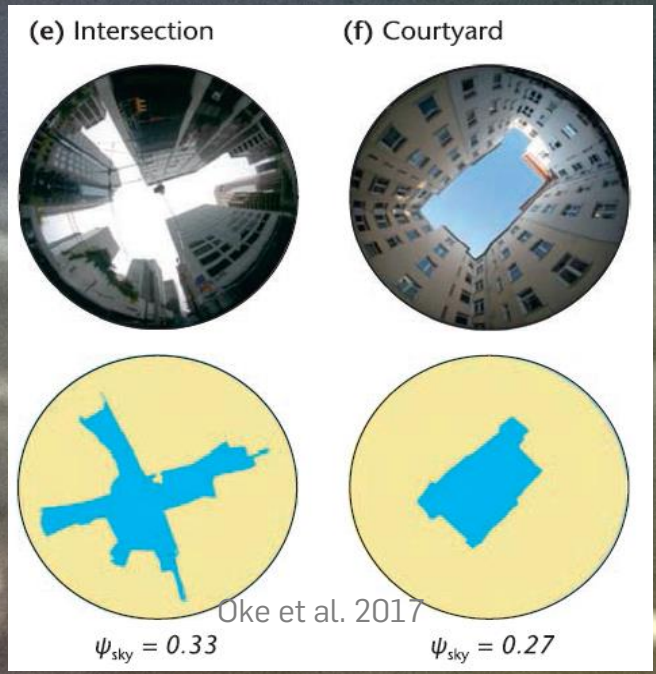
Oke et al. 2017

Zeitlicher Verlauf 2: Jahresgang

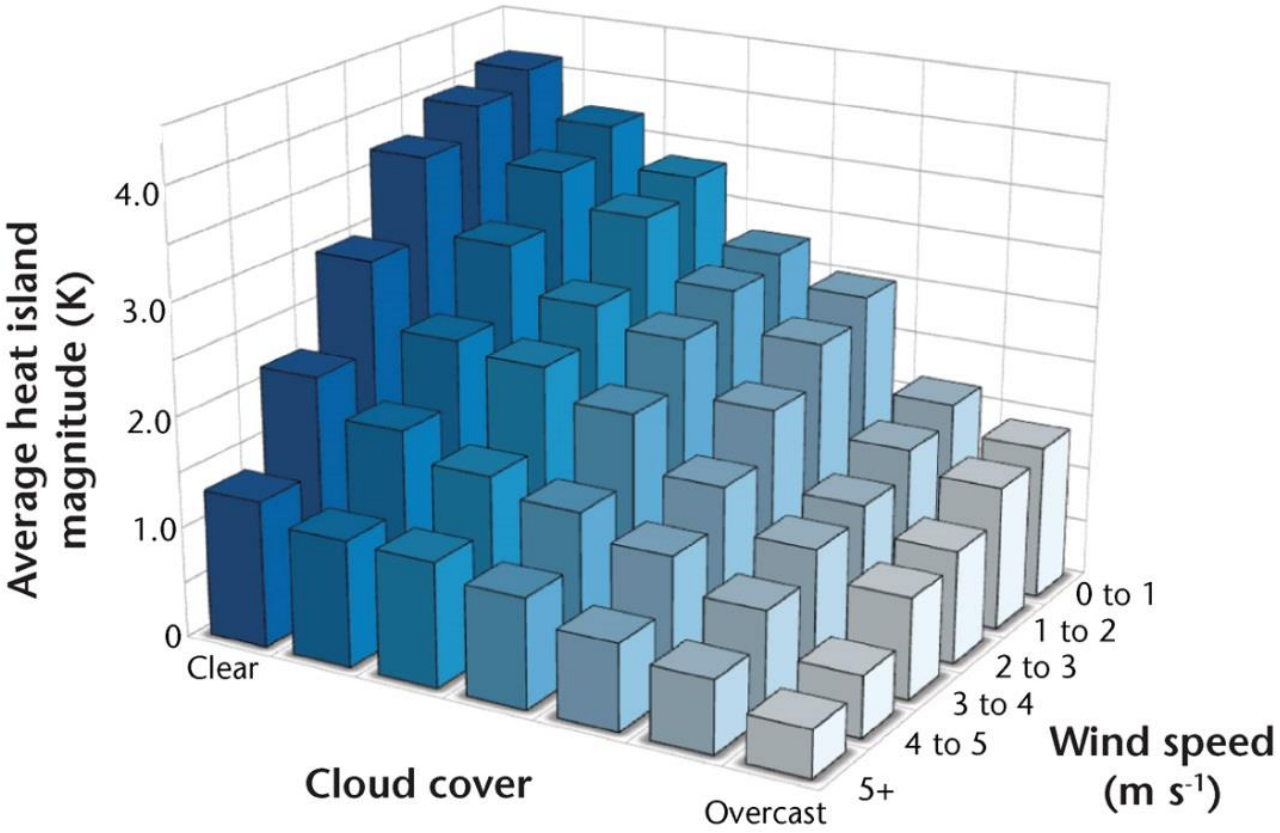


- Strahlungsantrieb (Einstrahlung, Tageslänge)
- Vegetationsperiode → Bowen Ratio (Q_H/Q_E)
- Geringer Einfluss des anthropogenen Wärmestroms Q_F (in unseren Breiten maximal im Winter)
- Wetter: Wind, Wolken, Niederschlag (Bodenfeuchte)

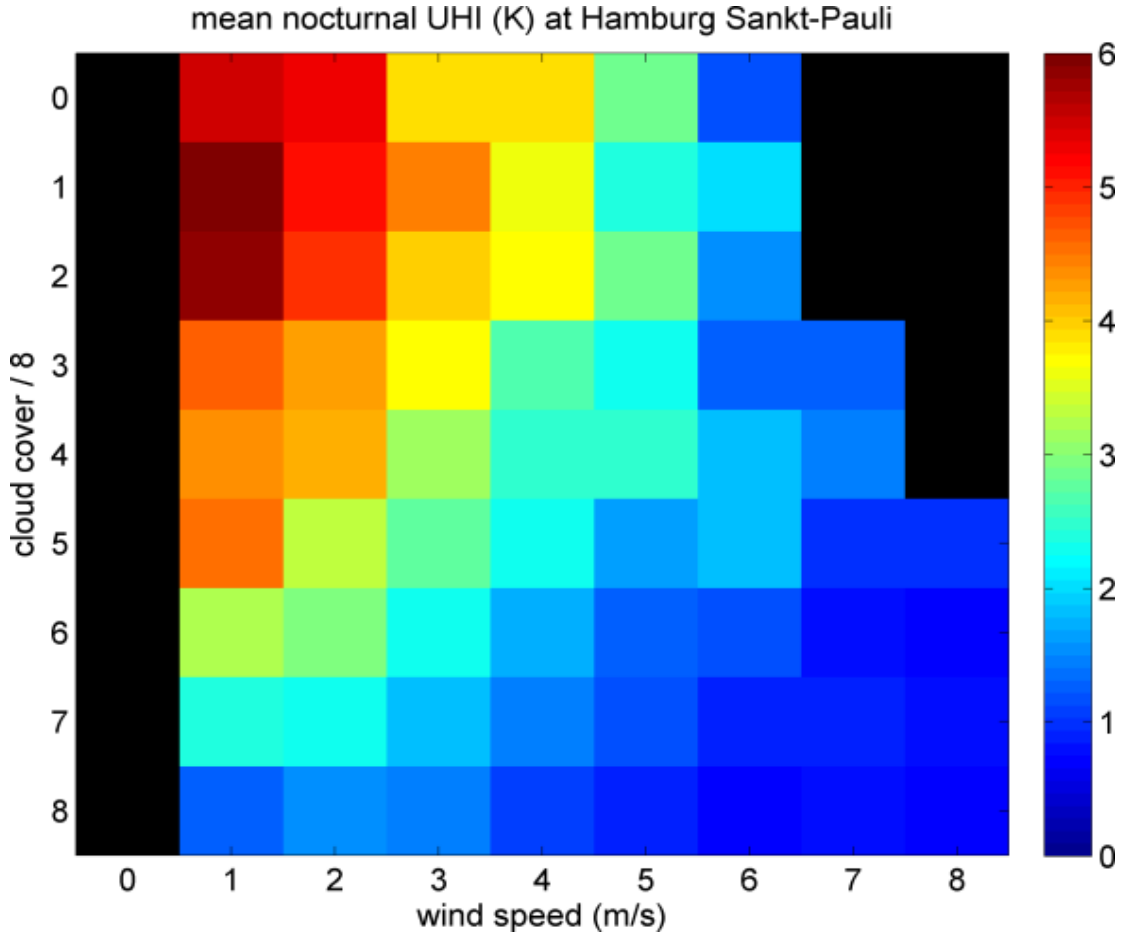

Maximum heat island magnitude (K)
(a)
(b)
Sky view factor, ψ_{sky}
Canyon aspect ratio, H/W
North America
Australasia
Europe
Oke et al. 2017


(e) Intersection
(f) Courtyard
ψ_{sky} = 0.33
ψ_{sky} = 0.27
Oke et al. 2017

Weather influence



Orlando



Hamburg

Oke et al. 2017, Arnds et al. 2017

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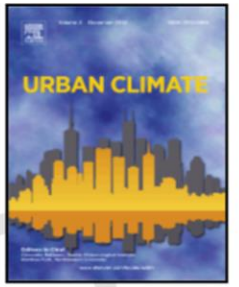
journal homepage: www.elsevier.com



Is the Urban Heat Island intensity relevant for heat mitigation studies?

Alberto Martilli [a,*], E. Scott Krayenhoff [b,1], Negin Nazarian [c,1]

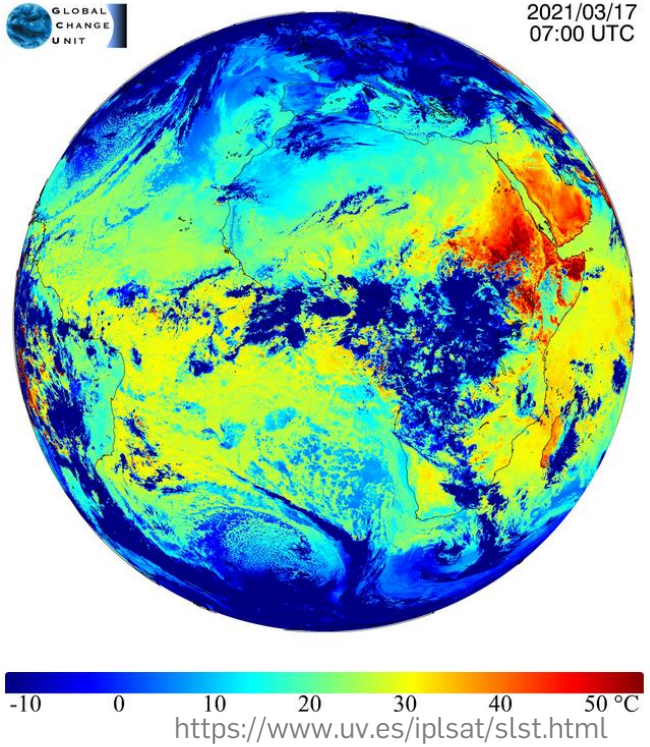
[a] *Department of Environment, CIEMAT, Madrid, Spain*
[b] *School of Environmental Sciences, University of Guelph, Guelph, Canada*
[c] *Faculty of Built Environment, University of New South Wales, Sydney, Australia*

Intra-urban differences?

ABSTRACT

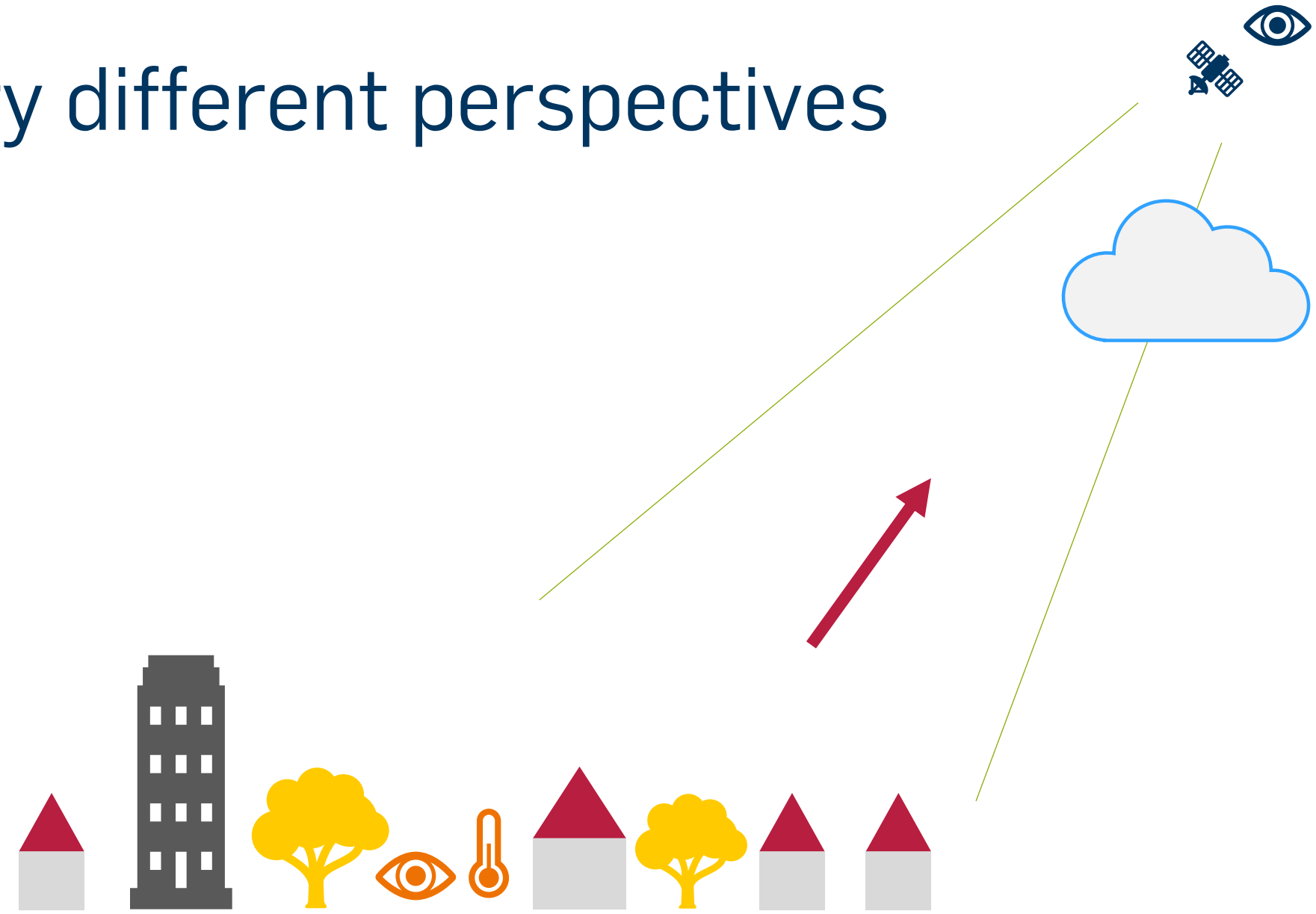
The Urban Heat Island concept is often used to describe 'excess' heat associated with urban areas, and is therefore frequently considered to be a negative phenomenon that requires mitigation. In this short communication we use clear examples to show that this is not necessarily true. Furthermore, we demonstrate that the Urban Heat Island intensity has little relevance for urban heat mitigation, and suggest the term "urban heat mitigation" to more accurately describe strategies aimed at cooling cities. We conclude with the research questions that, in our view, should guide future studies in the fields of urban thermal climate and heat mitigation. These questions are primarily rooted in the assessment of differences of climate responses between built Local Climate Zones in different climatic and geographical contexts.

PROOF

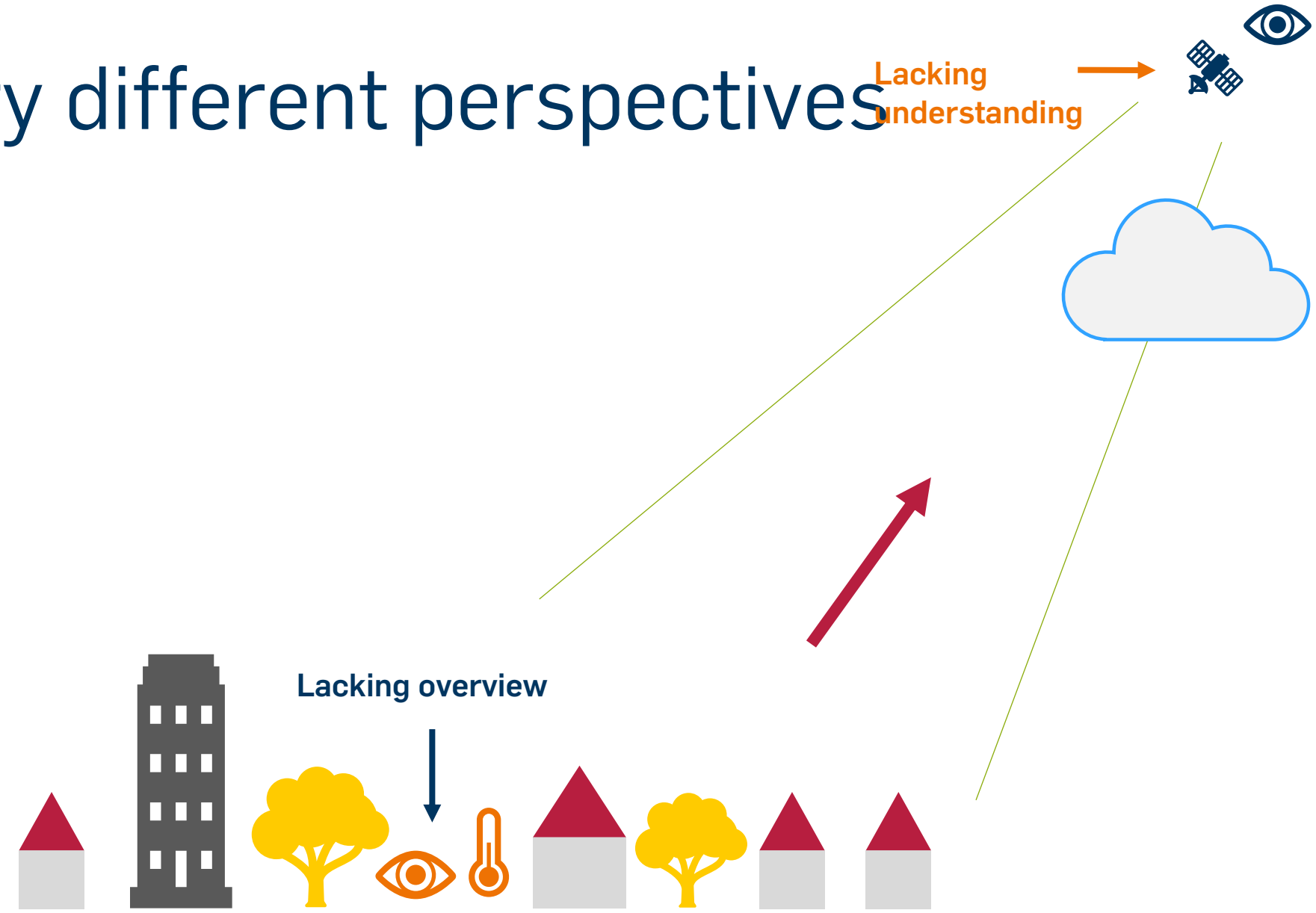


- A. Middel, E. S. Krayenhoff, *Science of The Total Environment*. **687**, 137–151 (2019).
- Oke et al. (2017)

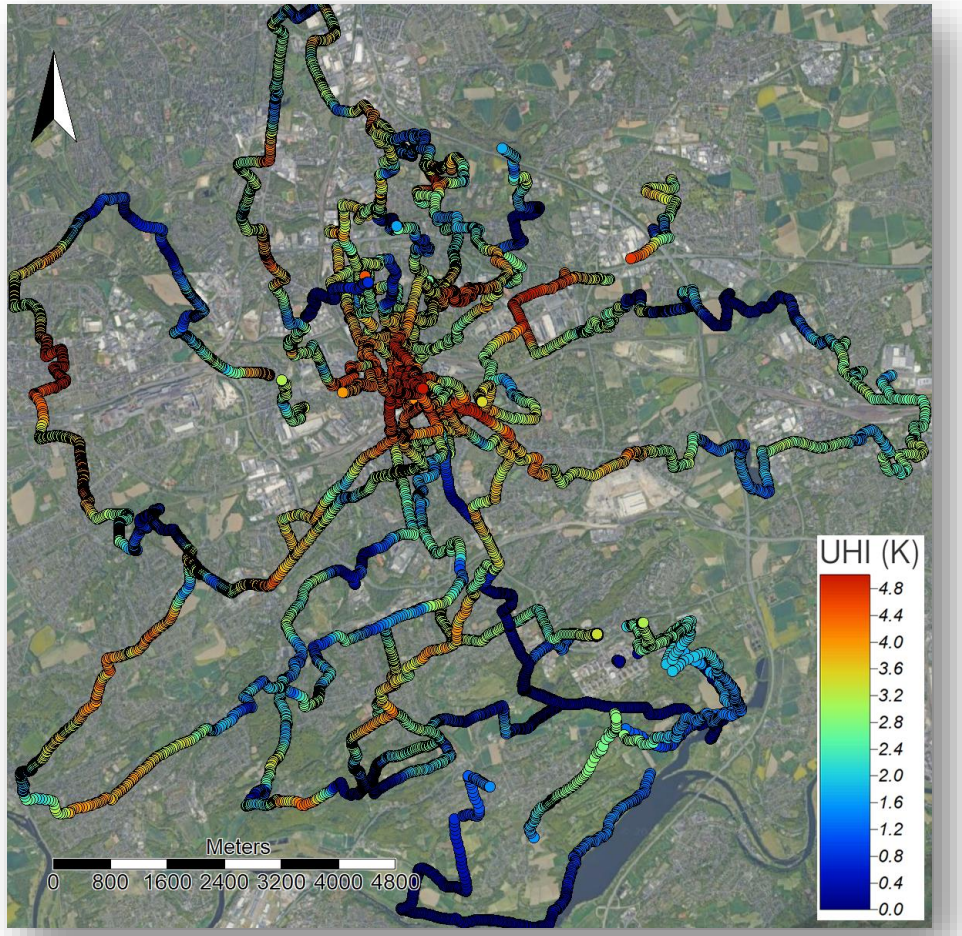
Very different perspectives

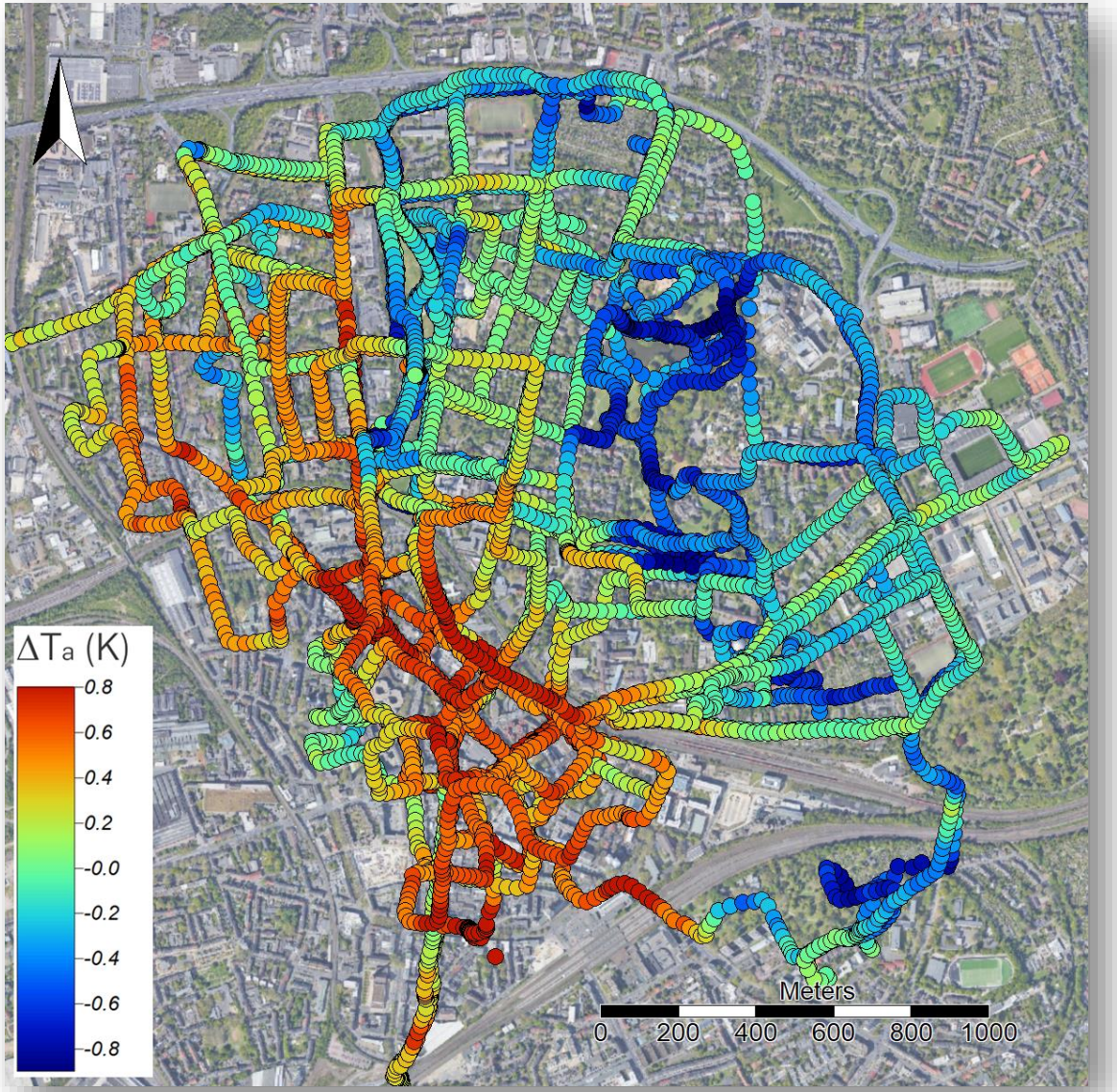


Very different perspectives



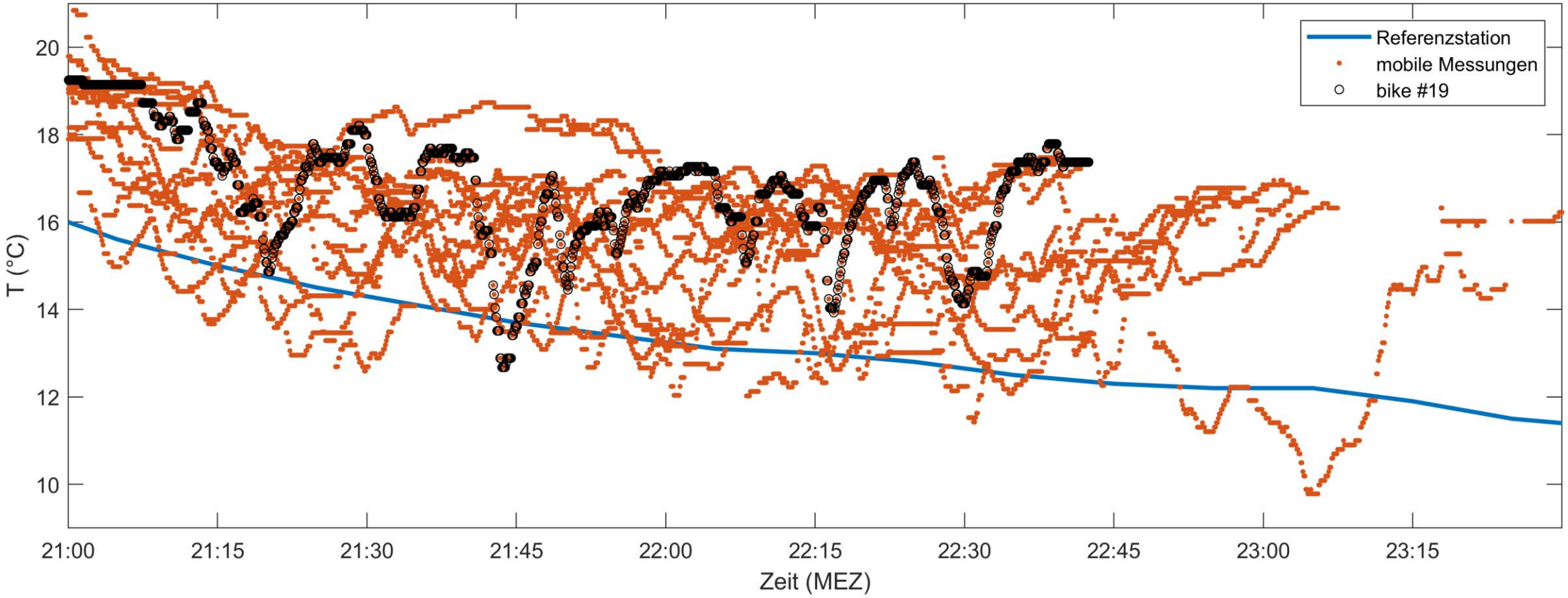
Crowdbike results





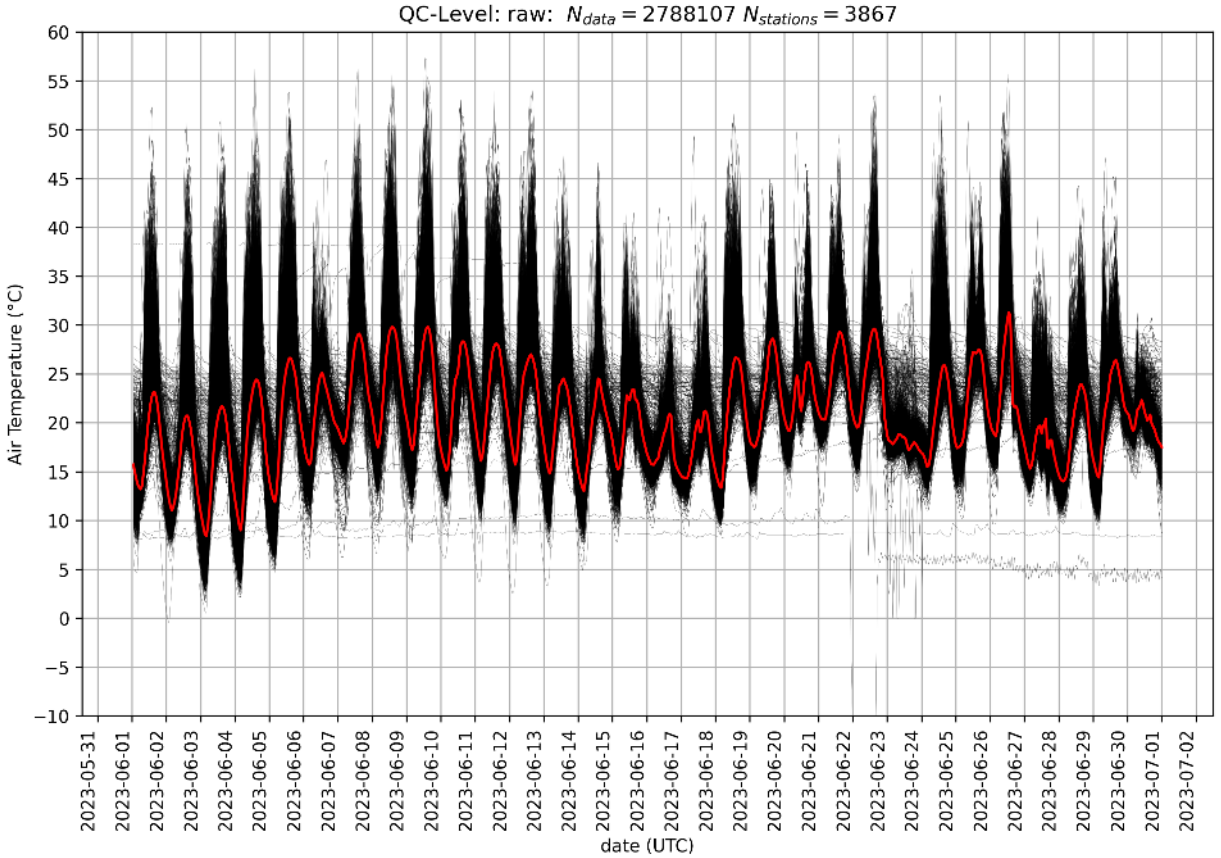
Quelle

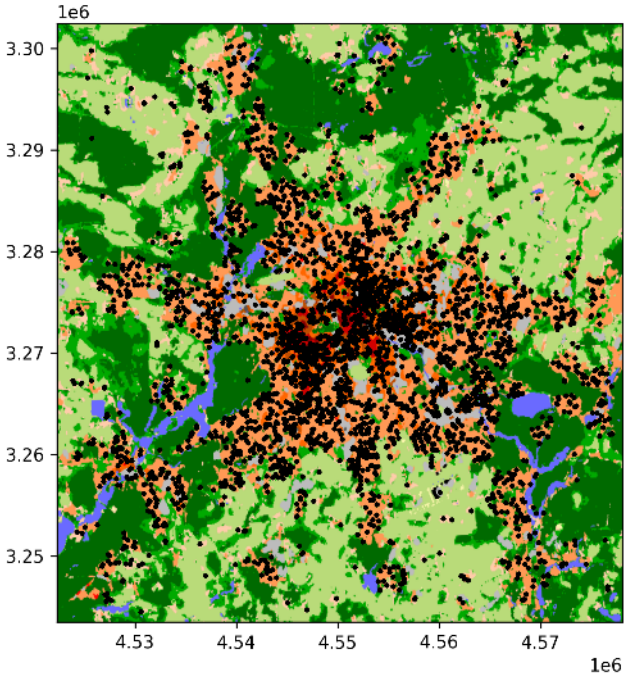
Problem of mobile observations



Quelle

Berlin: Quality Control – from raw data



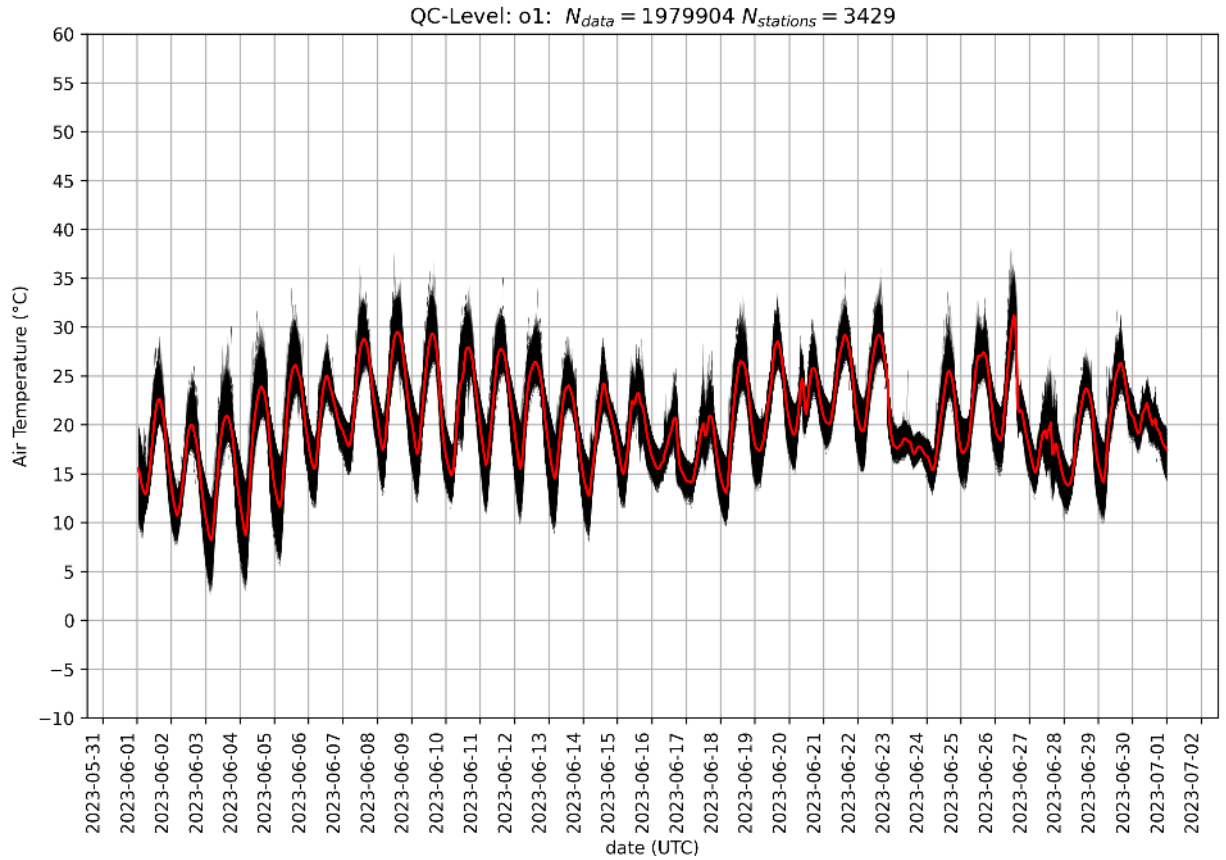


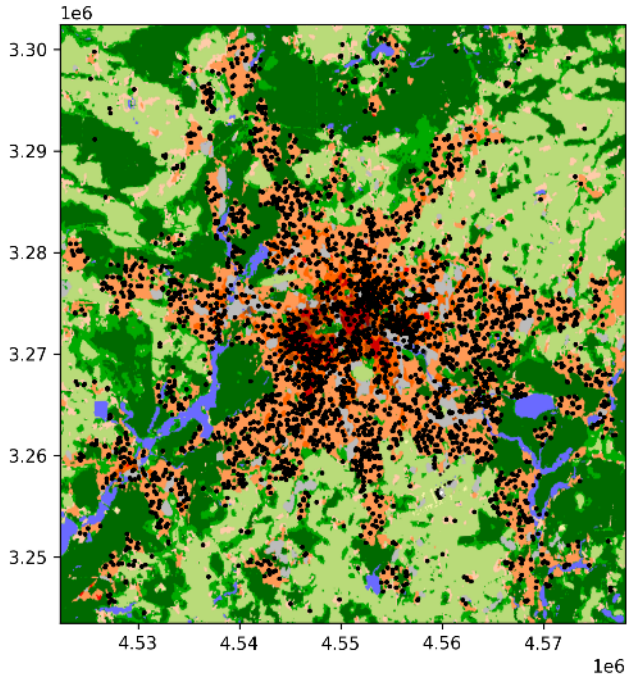
(Background map: Demuzere et al. 2022)

CrowdQC+: https://github.com/dafenner/CrowdQCplus

Fenner, D., et al. (2021). CrowdQC+—A Quality-Control for Crowdsourced Air-Observations Enabling World-Wide Urban Climate Applications. Frontiers in Science, 9. https://doi.org/10.3389/fenvs.2021.720747

Berlin: Quality Control – to quality controlled data





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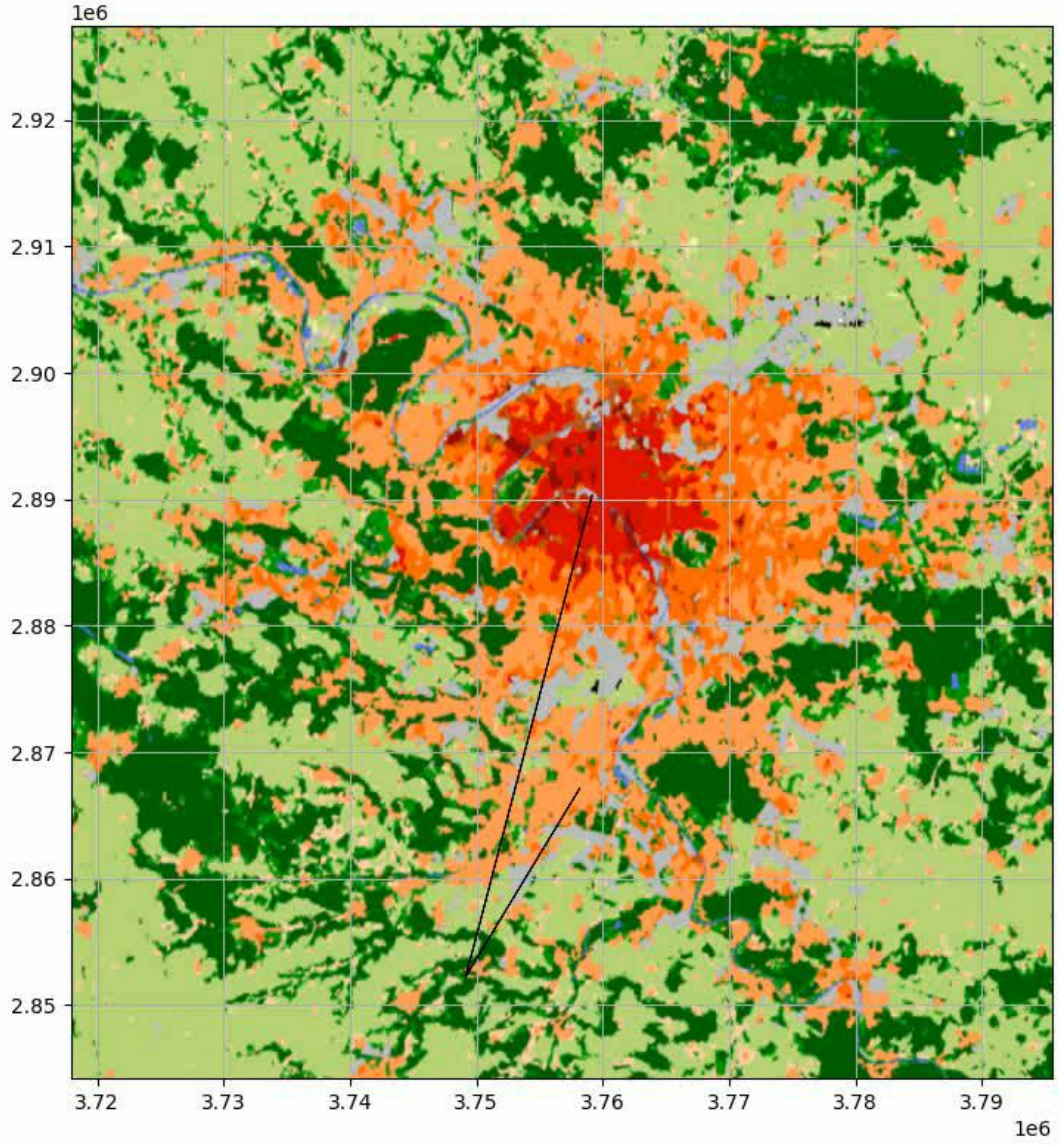
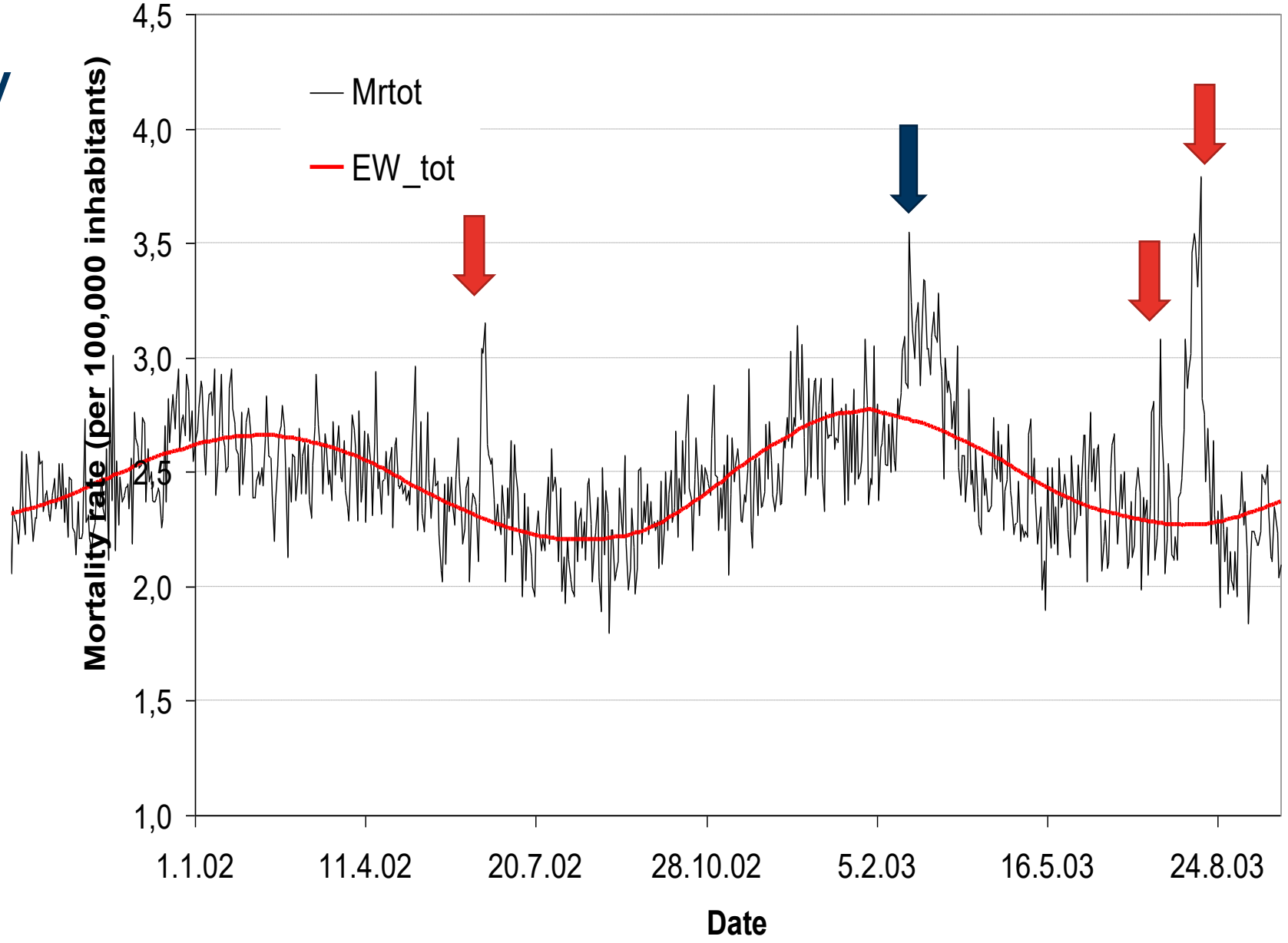
Metadata - Where did the station go when?

- Paris between 2019 - 2023
- Stations move
  - Initial position incorrect
  - Owner moves
  - Station is sold
  - ...
- Bi-weekly tiled scans of 257 regions

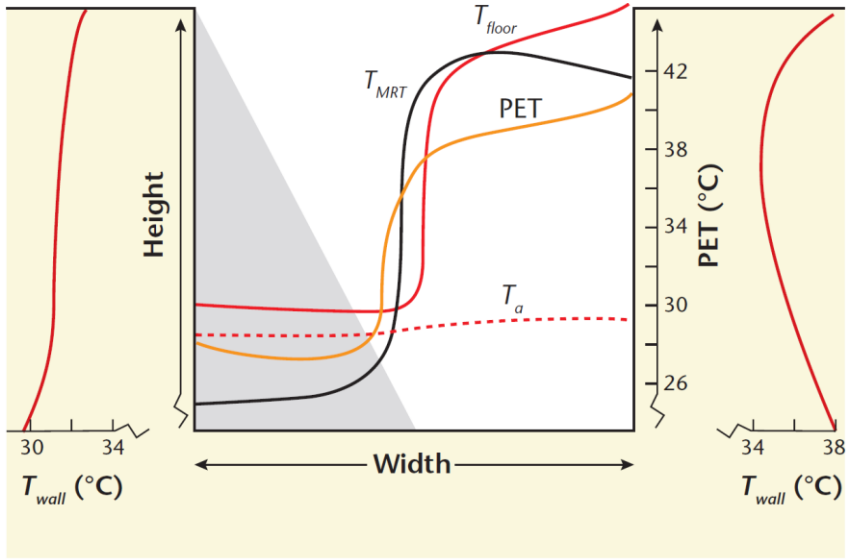


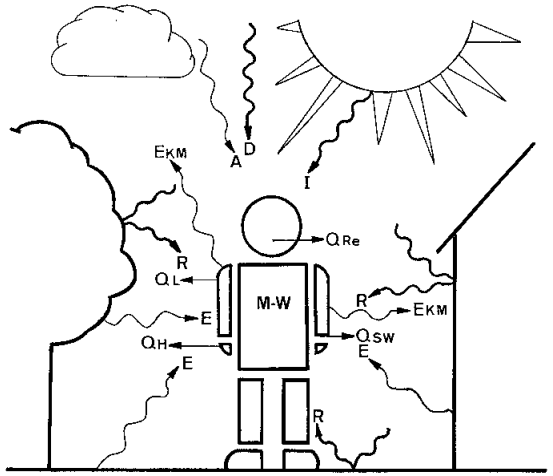
Mortality



Schär & Jendritzky (2003), Nature

Thermal comfort and exposure



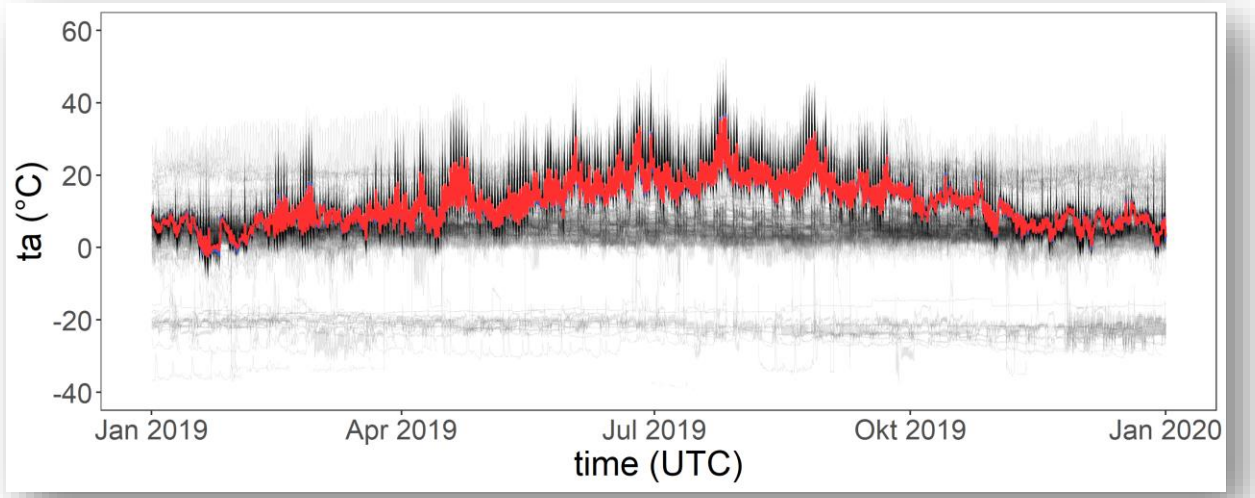


Oke et al. 2017

CrowdQC+

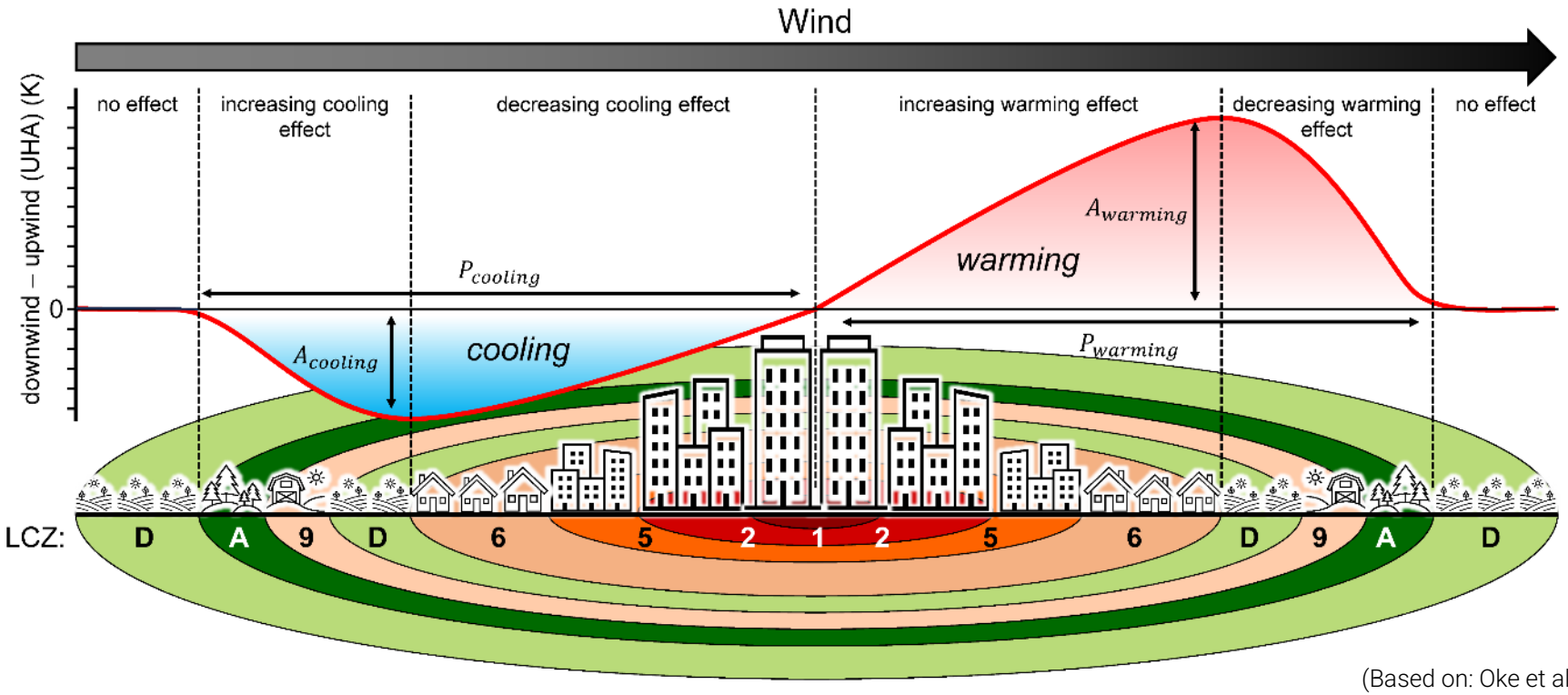
- statistically-based without reference data
- applicable for air temperature or other near-normally-distributed data
- applicable to “any” region
- applicable in near-real time
- user-friendly application in R
- open source code

Amsterdam, raw data



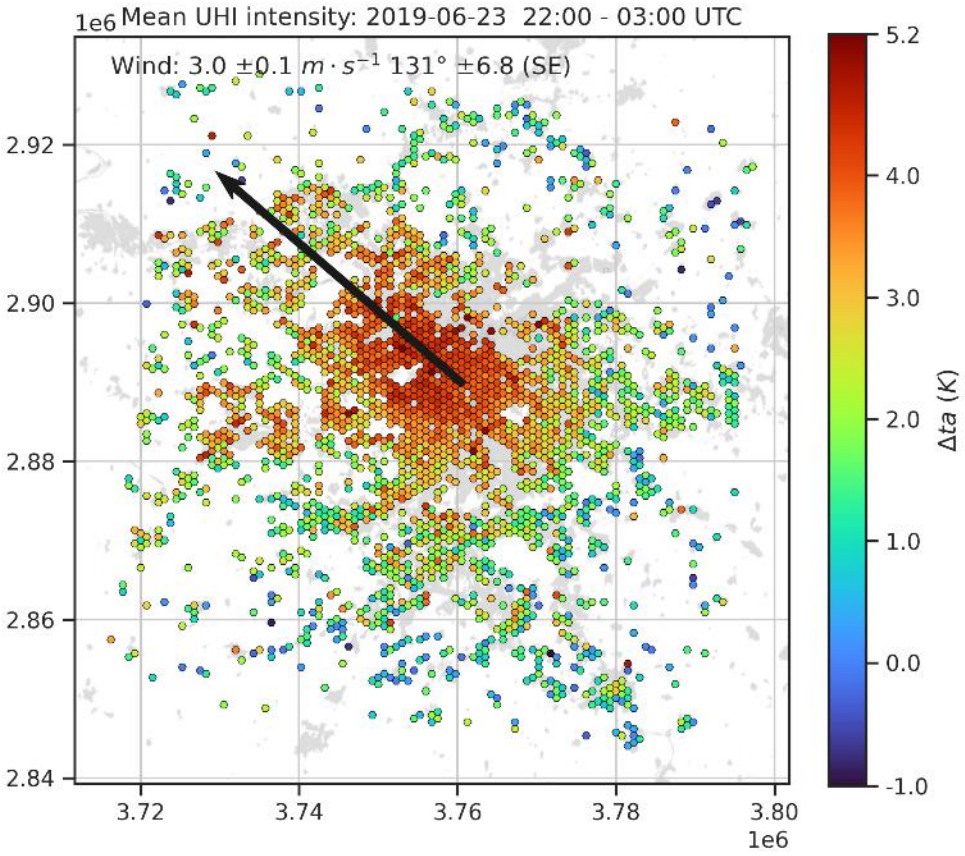
Fenner et al. 2021, Meier et al. 2017

UHA as a theoretical concept

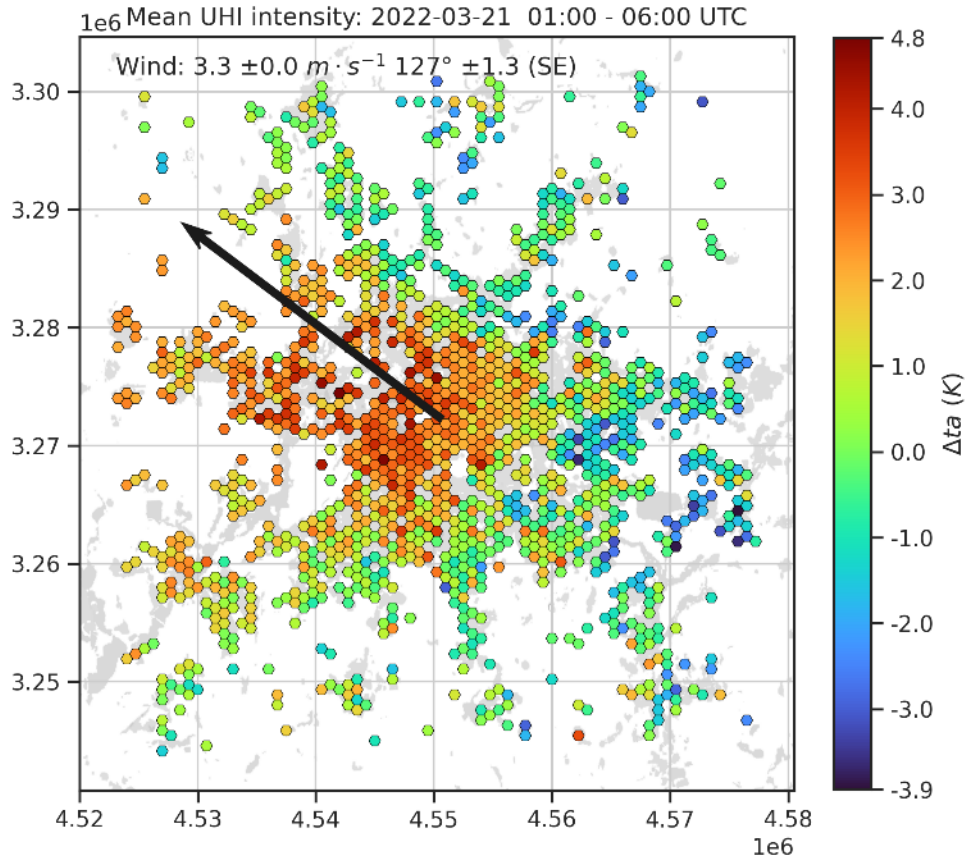


(Based on: Oke et al. 2017)

Situations with strong UHA

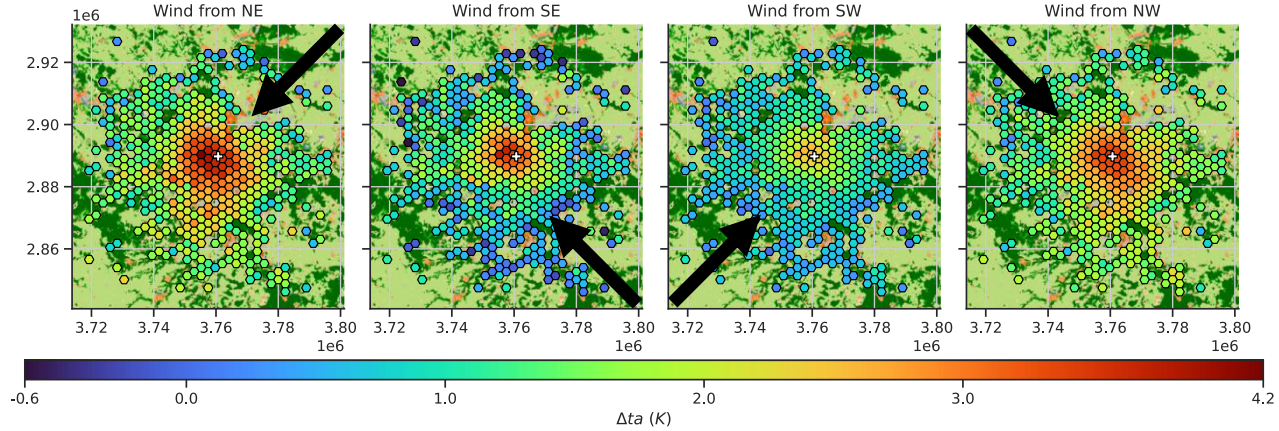


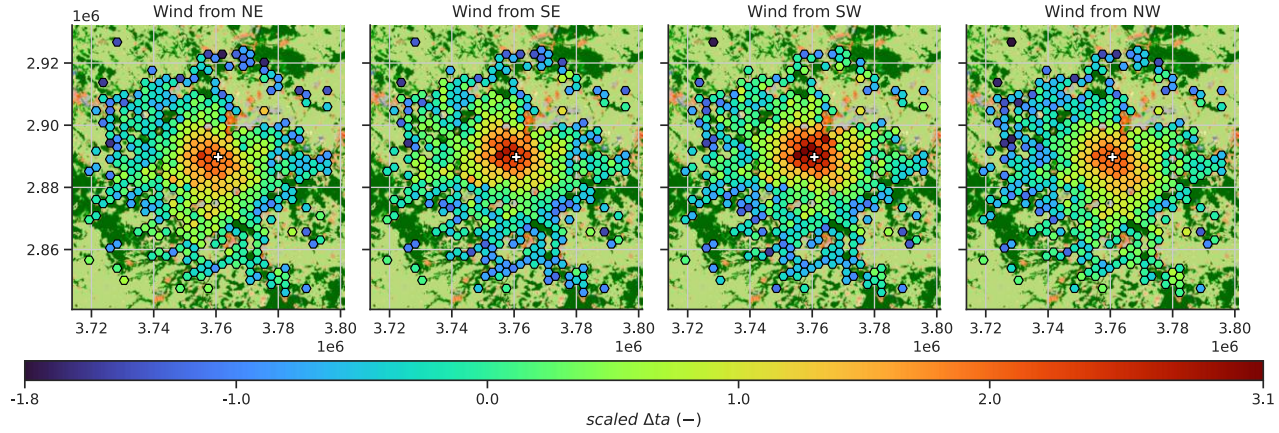
Paris

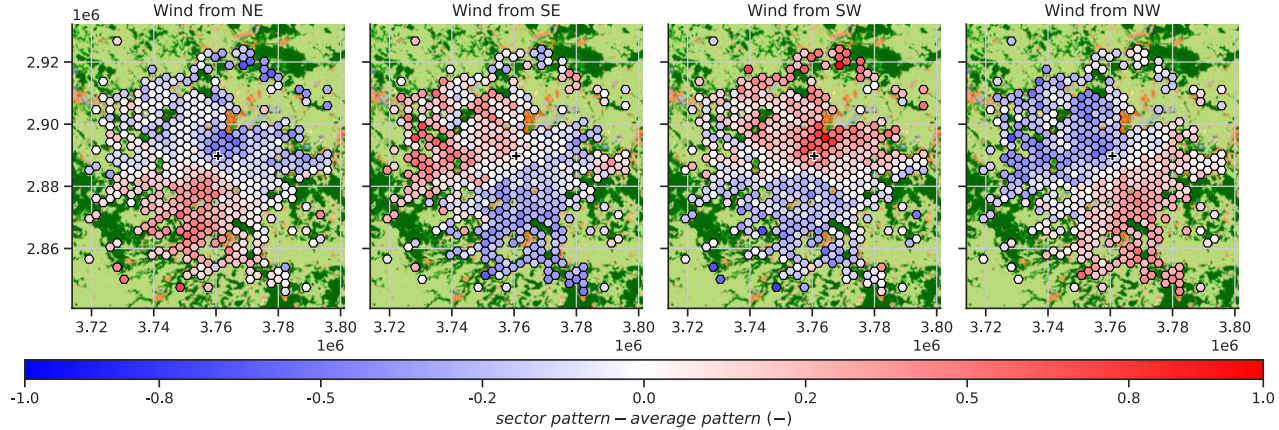


Berlin

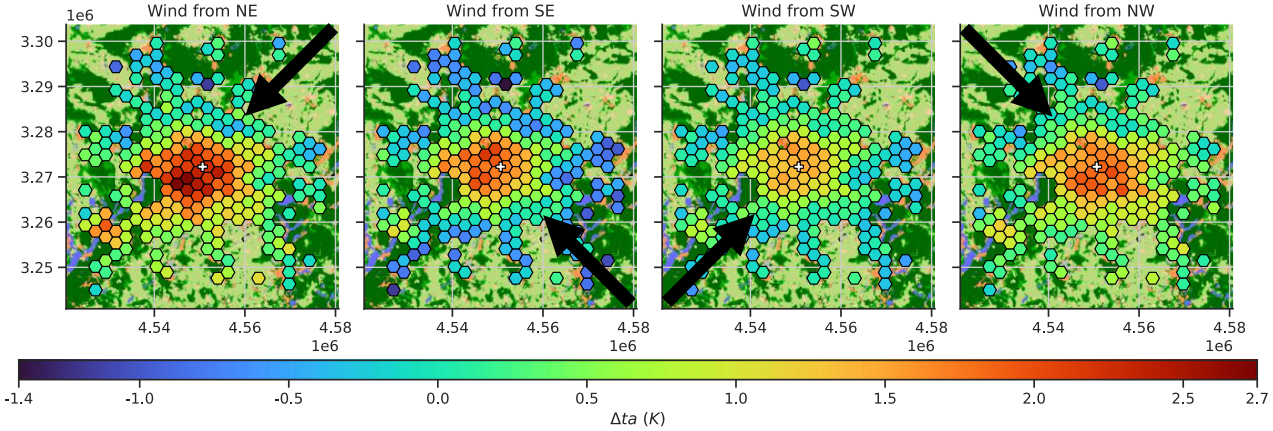
Paris (France)

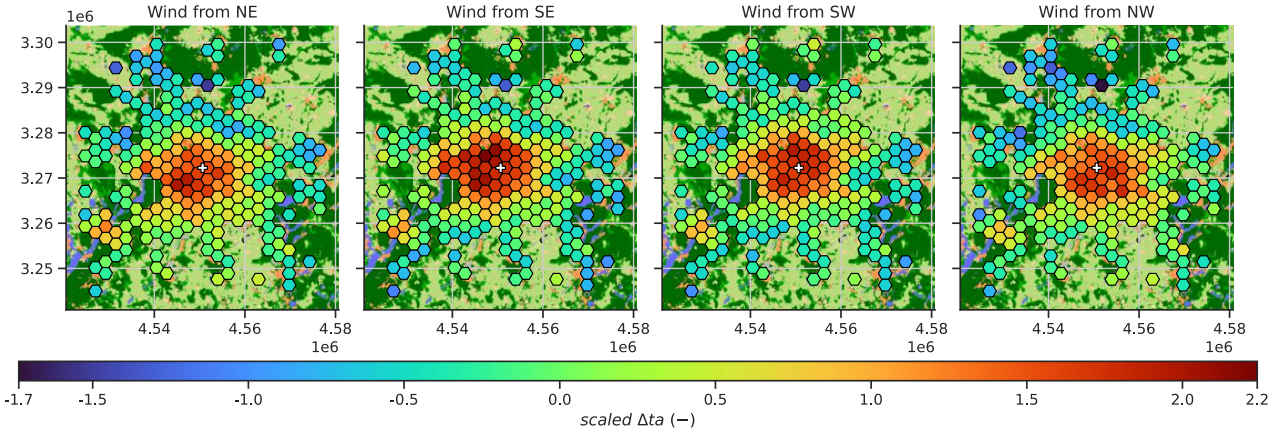


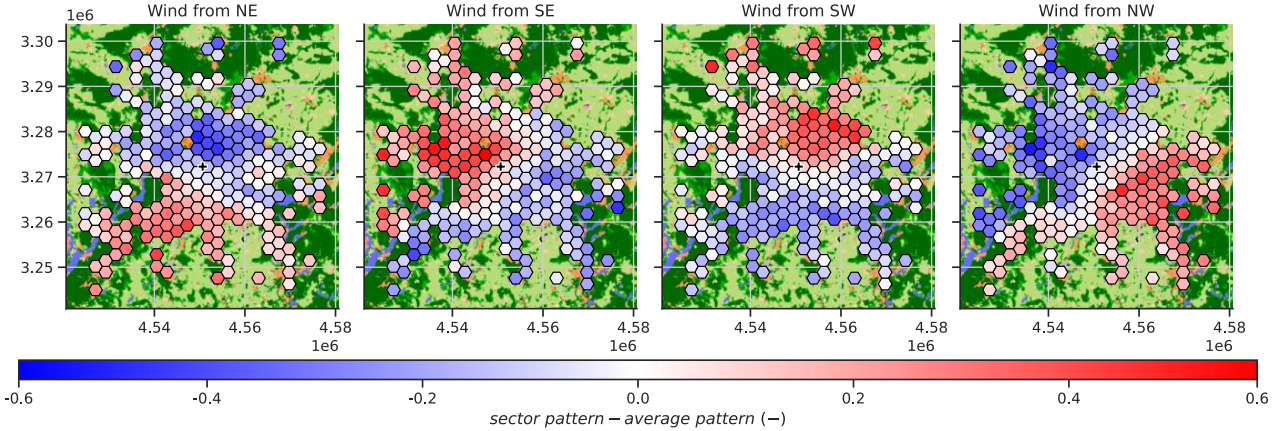


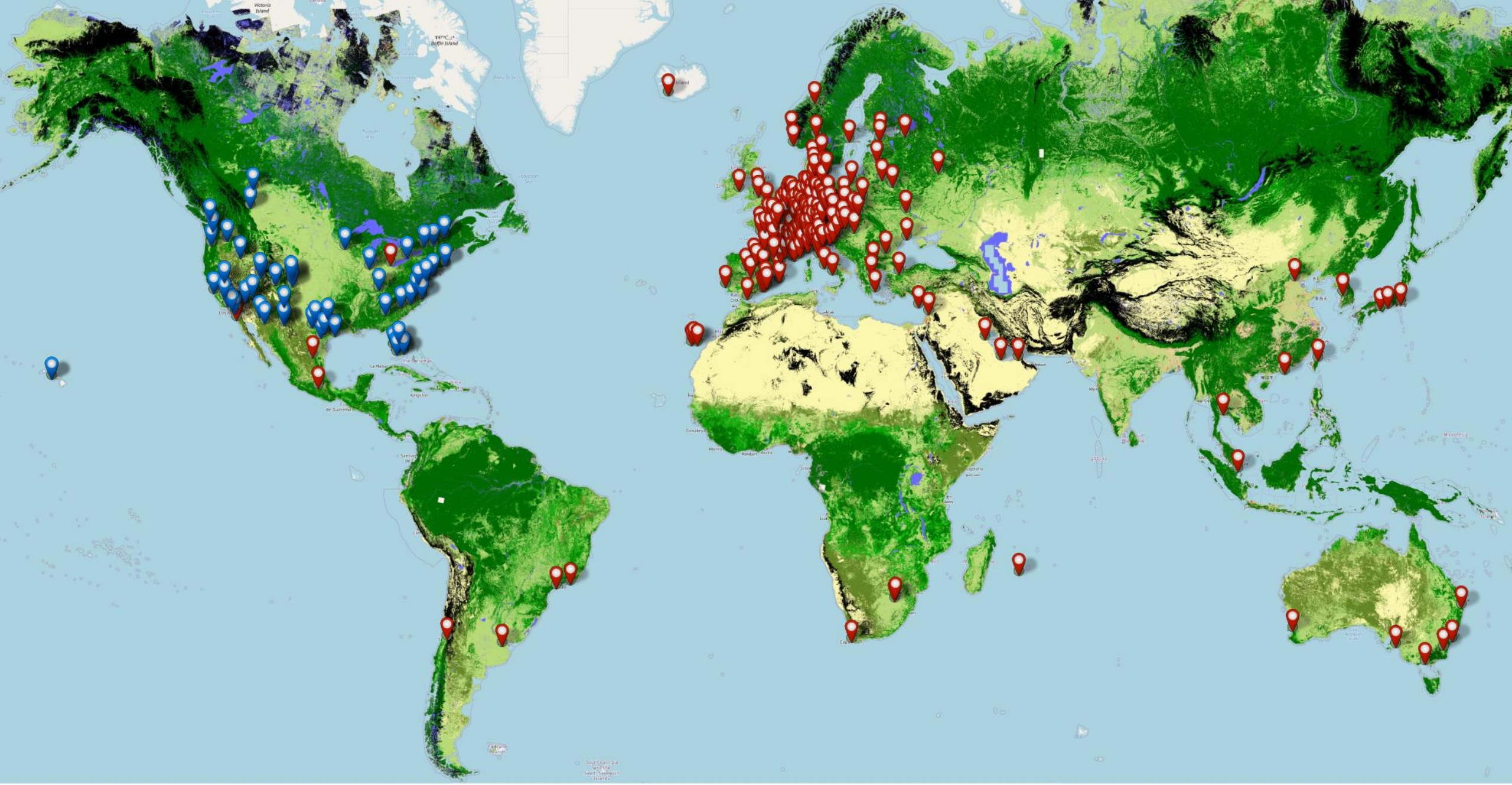


Berlin (Germany)

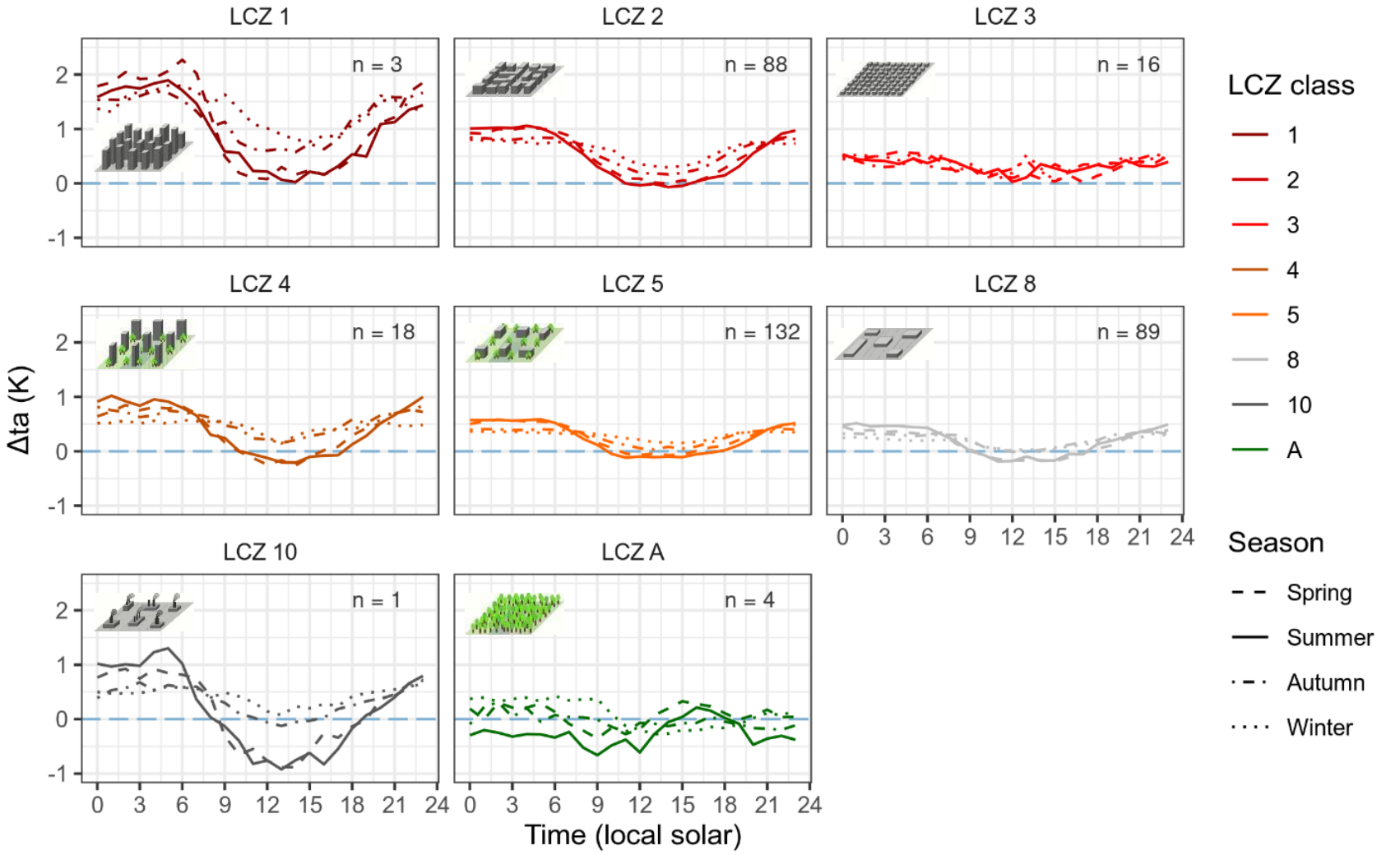







mesonet & netatmo scan areas
netatmo scan areas

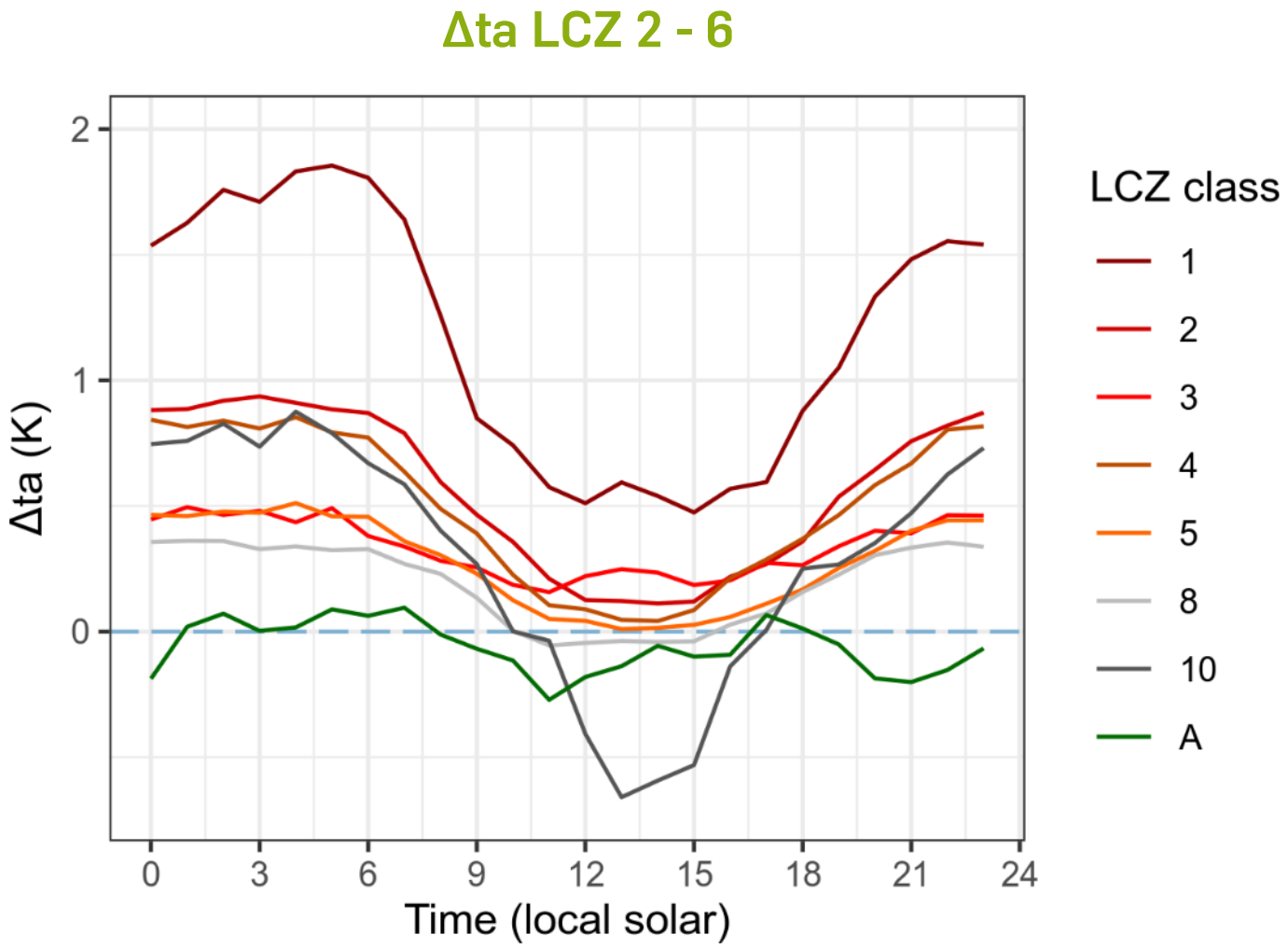
Intra-urban differences, per season



Aggregated over all cities (per LCZ and season)

Δta LCZ x – 6

Intra-urban differences



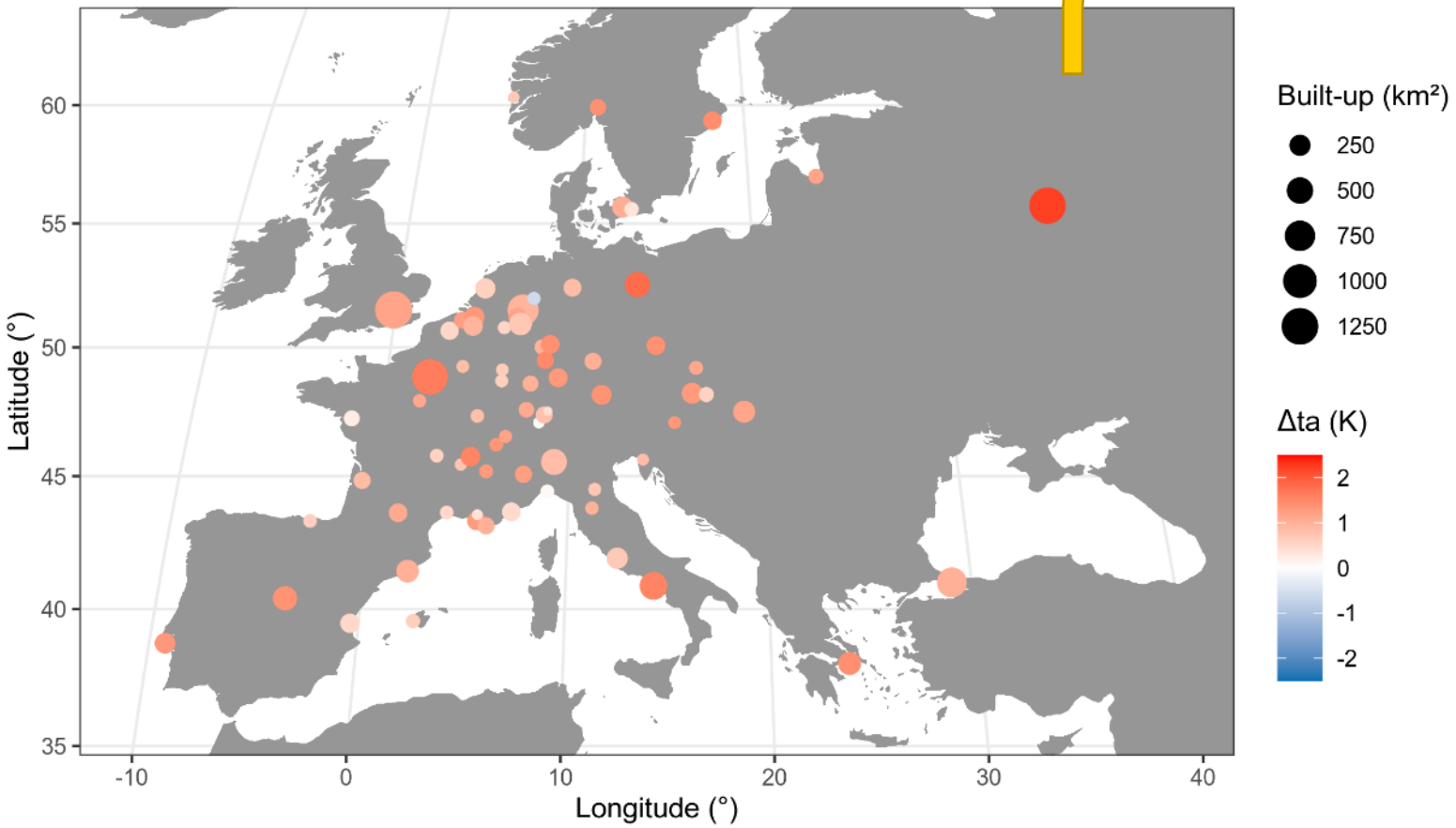
Aggregated over all cities (per LCZ)

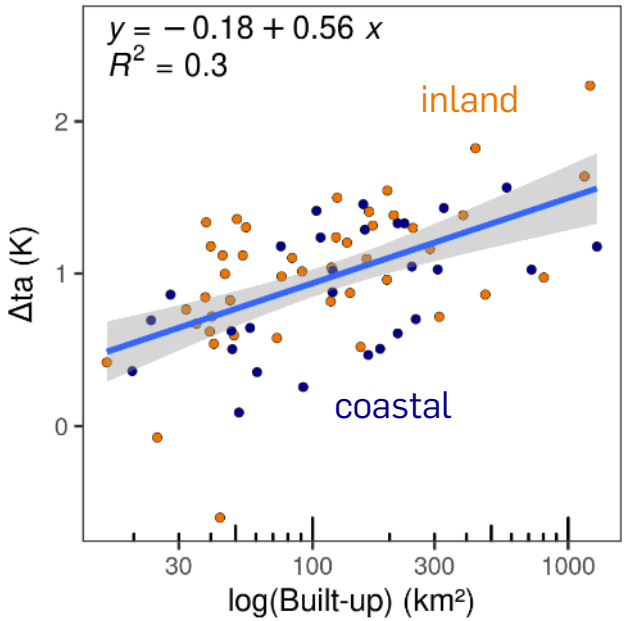
Oke (1973) revisited

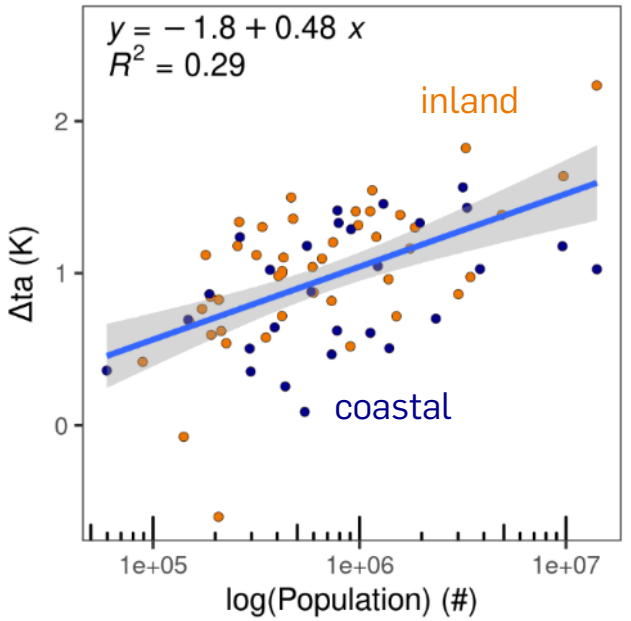
CITY SIZE AND THE URBAN HEAT ISLAND

T. R. OKE

Δta LCZ 2 - 6, 01-04 h, JJA

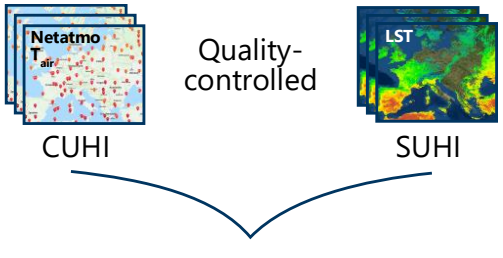






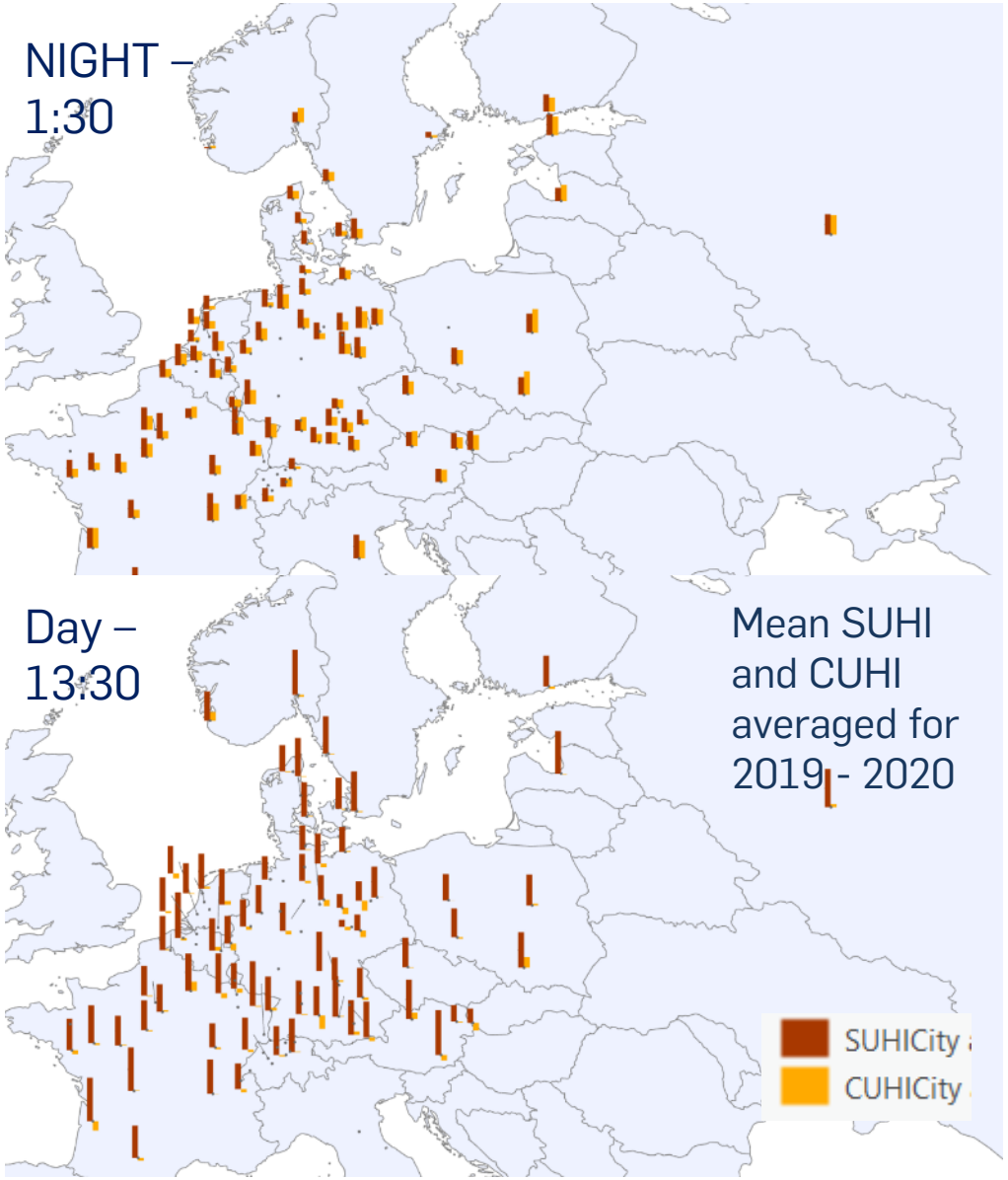
Fenner et al., in prep.

Vergleich



Urban density classes:

HU: high-density urban
LU: low-density urban
R: rural



Krelaus, Apfel (2022) MSc Thesis: Surface and canopy urban heat island magnitudes in Europe – uncovering differences within the diurnal cycle and sensitivity towards urban classification

10 shades of urban