BUCSS 2022

Urbanization, human dynamics and and climate change

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Albert-Ludwigs Universität Freiburg

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Photo: A. Christen

Population growth

We live in an age of a rapidly increasing world population and urbanization, which leads to unprecedented and long-term changes on our planet.

Urban landscape in Mexico City (Photo: P. Lopez Luz , based on Oke et al., 2017)

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Food security

Securing food for the growing world population is a global challenge in this century, also associated with water (over-)use and additional greenhouse gas emissions.

Harvester in industrial agriculture (Photo: A. Christen)

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Energy and fossil fules

Currently, 80% of global energy is still tied to fossil fuels, adding more CO_2 to the atmosphere - the main cause of anthropogenic climate change.

Urban power plant Berlin-Lichterfelde in the year 2005 (Photo: A. Christen)

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Pollution

Fossil fuel combustion has other direct impacts - The World Health Organization (WHO) estimates that about 7 million people die as a result of air pollution per year - one in eight deaths worldwide.

Smog in Los Angeles, USA (Photo: A. Christen)

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Human activities concentrate in cities

If we want to address these challenges and transform our society and economy to a more sustainable future, a key role will play cities.

Night over Seattle, USA (Photo: A. Christen)

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Today's lecture

- What are trends in global urbanization and how are they related to climate?
- How are cities are connected to **climate change**?
- How are urbanization and urban dynamics **affecting the urban climate system**?
- How is the climate system **affecting urban and human dynamics**?

Grand societal challenges and solutions are concentrated in cities

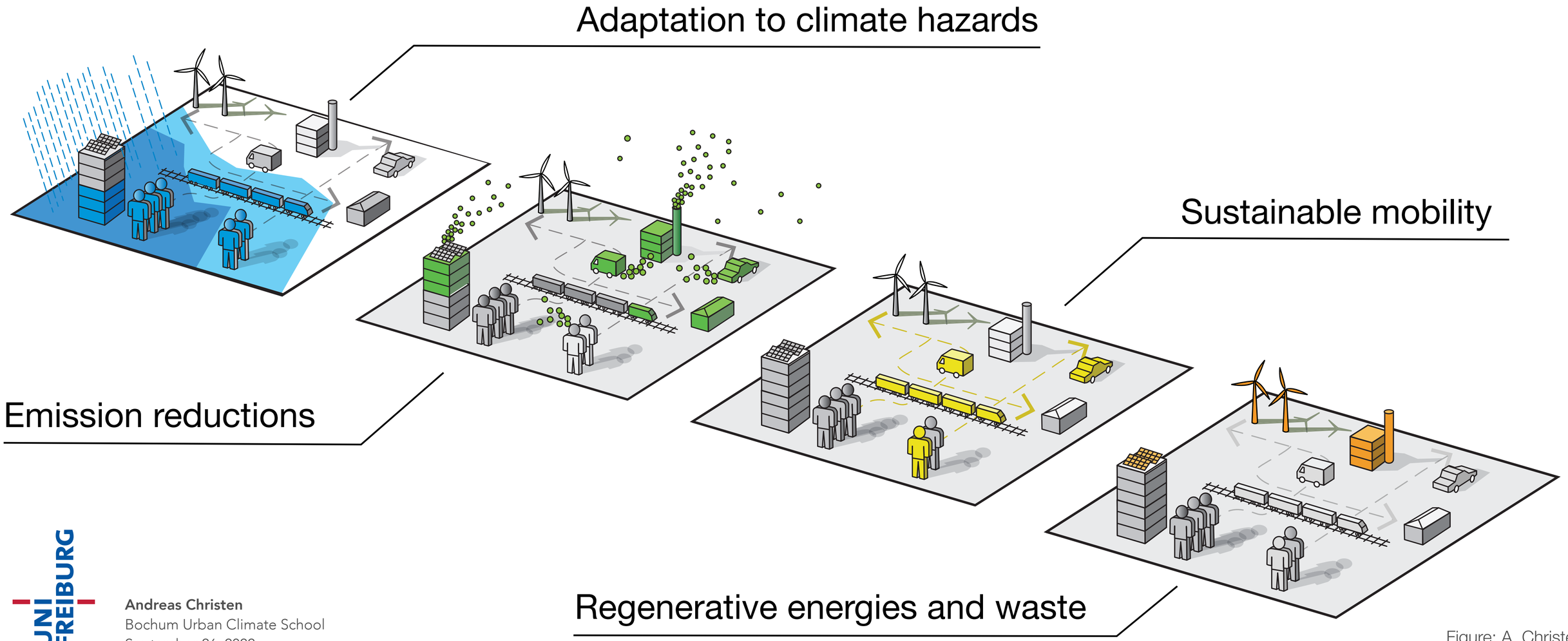

Figure: A. Christen

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Transformative cities

Cities are key when it comes to mitigating climate change and environmental impacts. Cities are places of innovation, efficiency and leadership - that's why they were successful in the first place.

Freiburg, Germany (Photo: A. Christen)

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Vulnerable cities

Cities are also often most vulnerable to climate change, they need to adapt to future climate and environmental hazards and risks, including heat, floods, and severe weather.

Floods along the Ciliwung River in Jakarta, Indonesia, in 2020 (Photo: Dimas Ardian/Bloomberg)

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Urban form and function impact urban climates

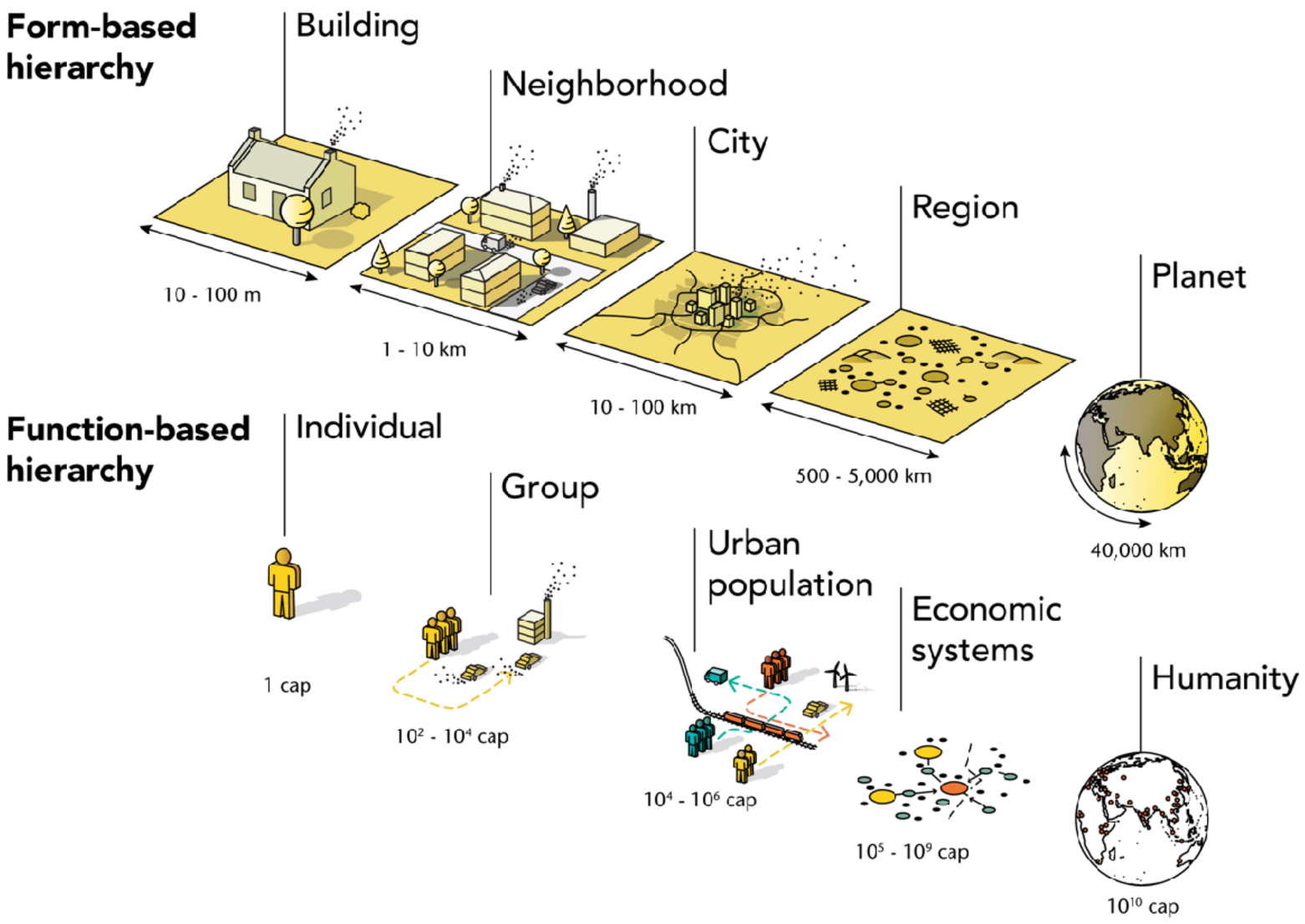

Figure: A. Christen

Two way coupling in urban climate science

Climate change

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Extreme events

Urban climate

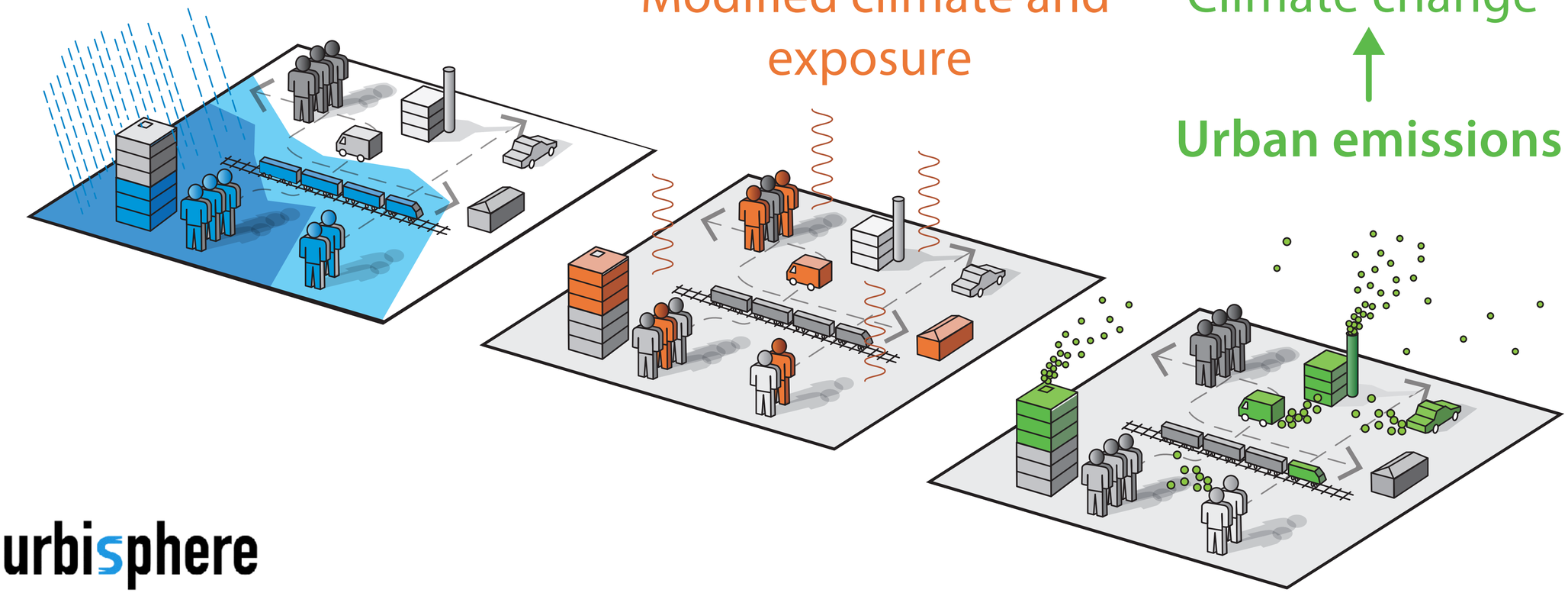
↕

Modified climate and exposure

Climate change

↑

Urban emissions



urbisphere

coupling dynamic cities and climate

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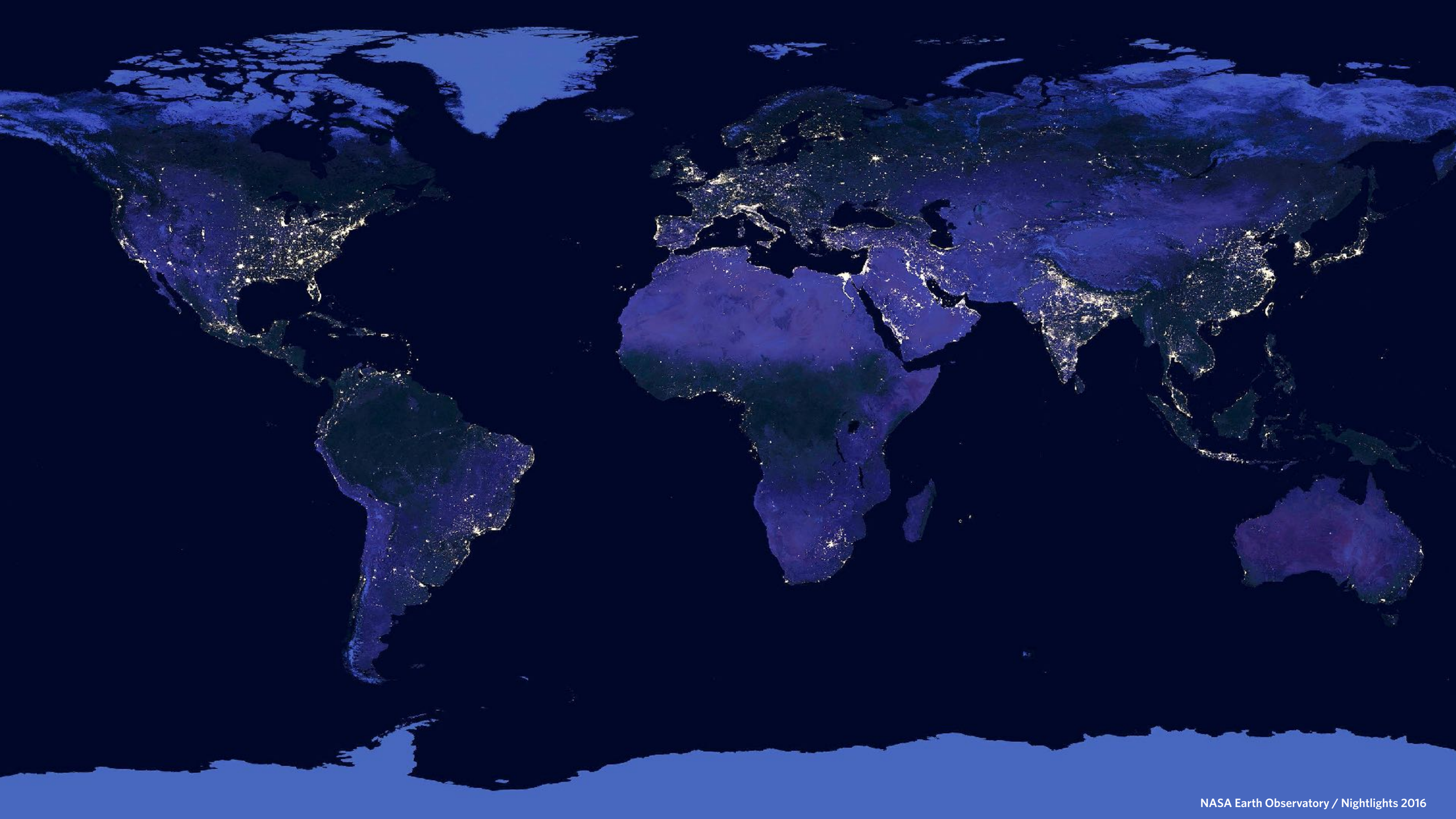
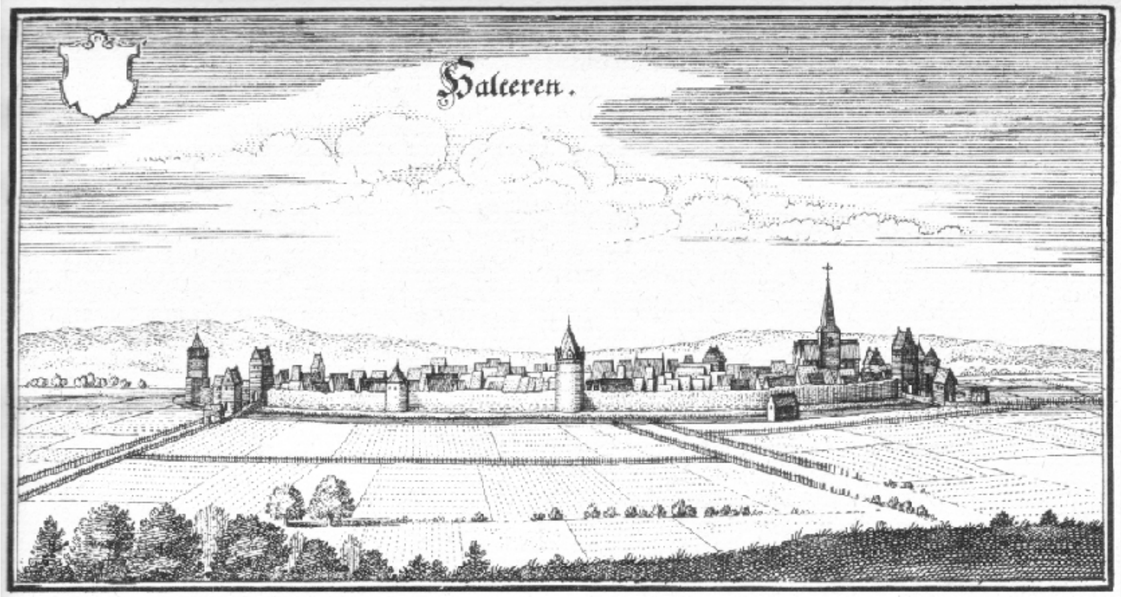
Figure: A. Christen



NASA Earth Observatory / Nightlights 2016

Cities and climate

City of Heilbronn and hinterland, (copper engraving)



In the past, cities **thrived in preferred climates** with **predictable weather** that provided secure access to water, food, and fuel.

Under climate change, with changing technology, or with uncontrolled, rapid expansion, cities increasingly **face new challenges** and may be exposed to **unexpected atmospheric hazards**.

Ex-tropical storm Fiona in Atlantic Canada this weekend (CBC)

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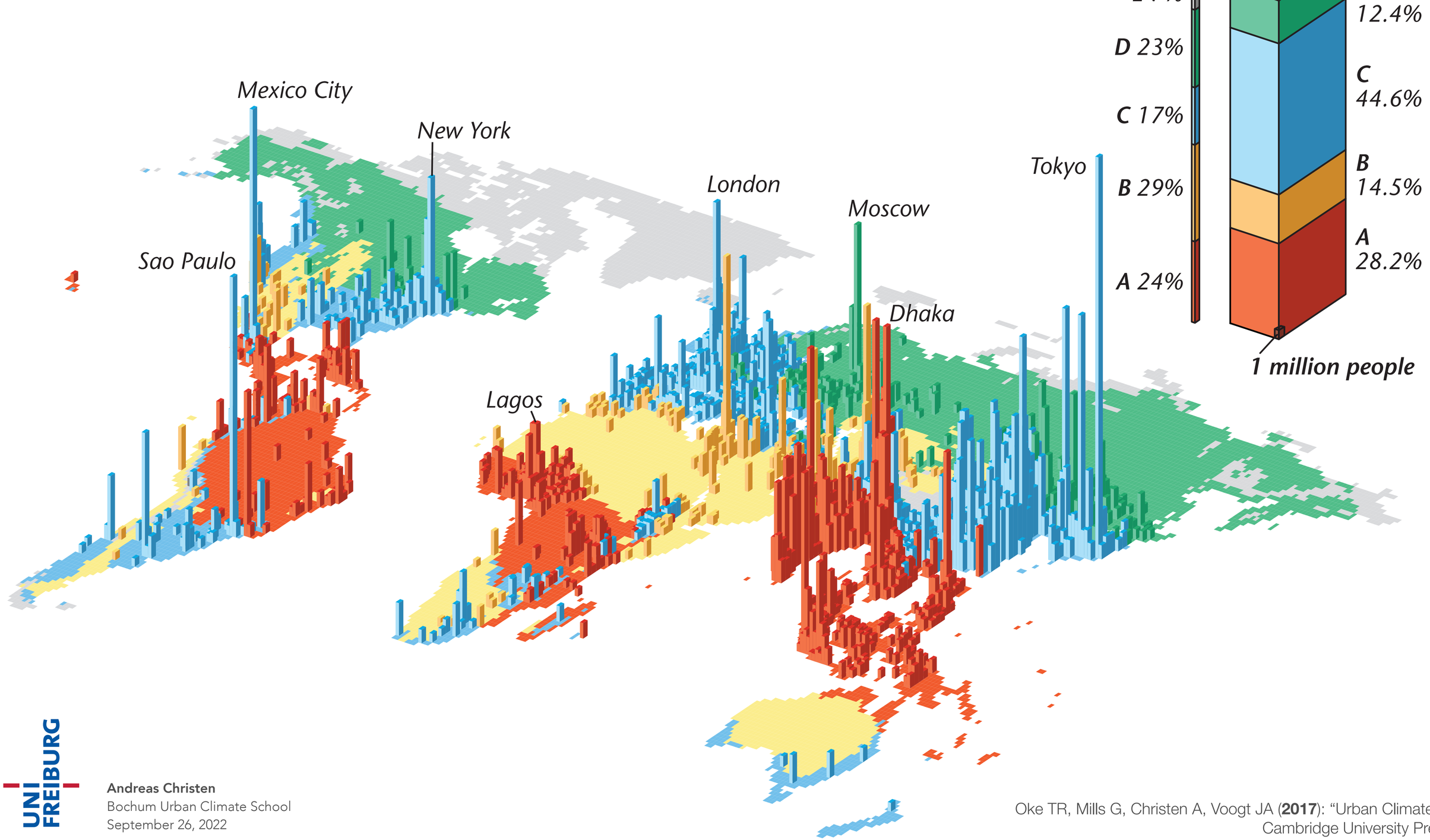

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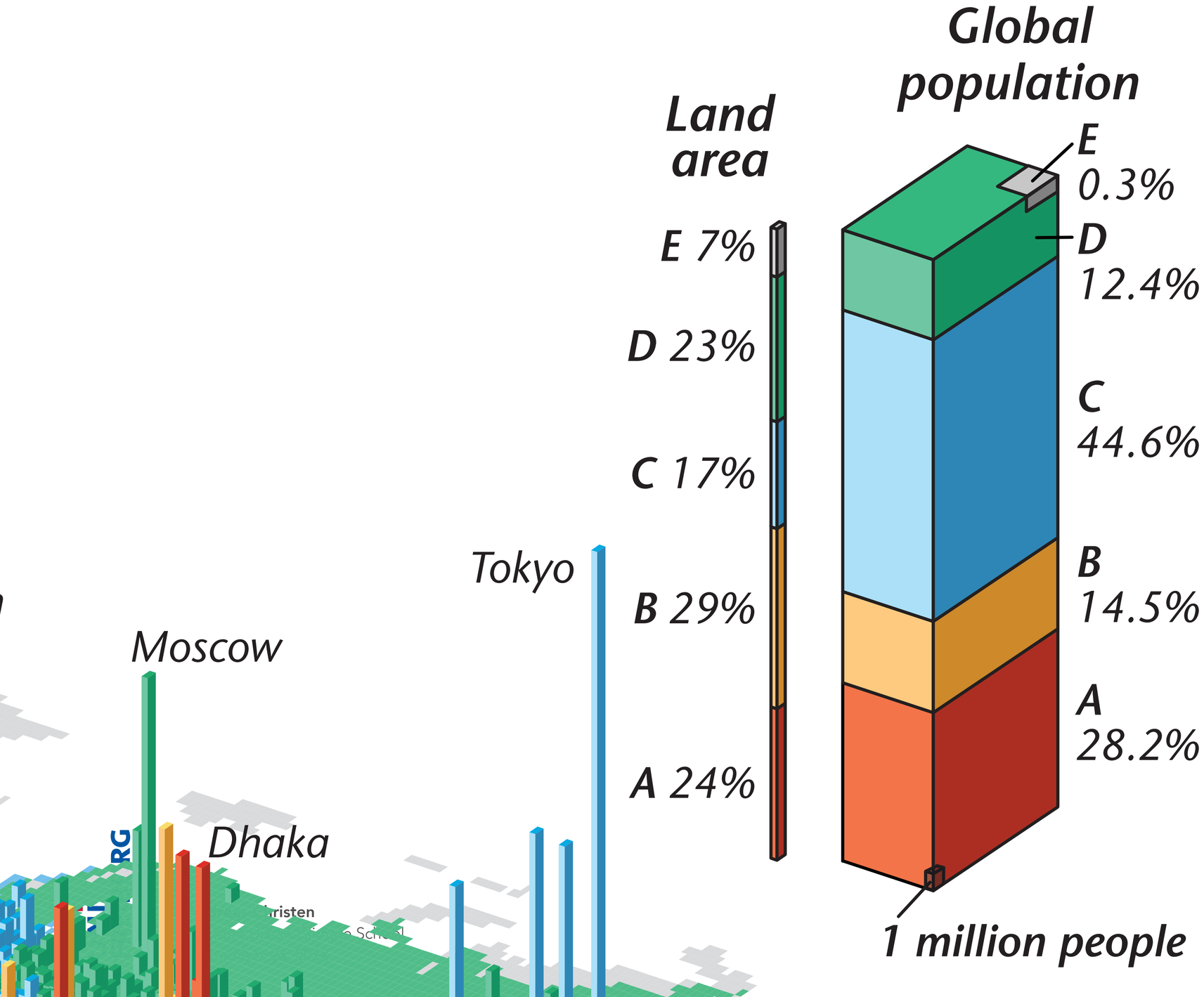
Oke TR, Mills G, Christen A, Voogt JA (**2017**): "Urban Climates", Cambridge University Press



Oke TR, Mills G, Christen A, Voogt JA (**2017**): "Urban Climates", Cambridge University Press

Mismatch between **global land area** and global **population** is obvious:

Essentially there are no settlements below 0°C average temperature (<1%), but 20% of global land mass is below 0 °C.

Also large areas of the land mass are below 300 mm annual precipitation (30%) but lack of water resources make also this part of the planet less populated (7% of population only).

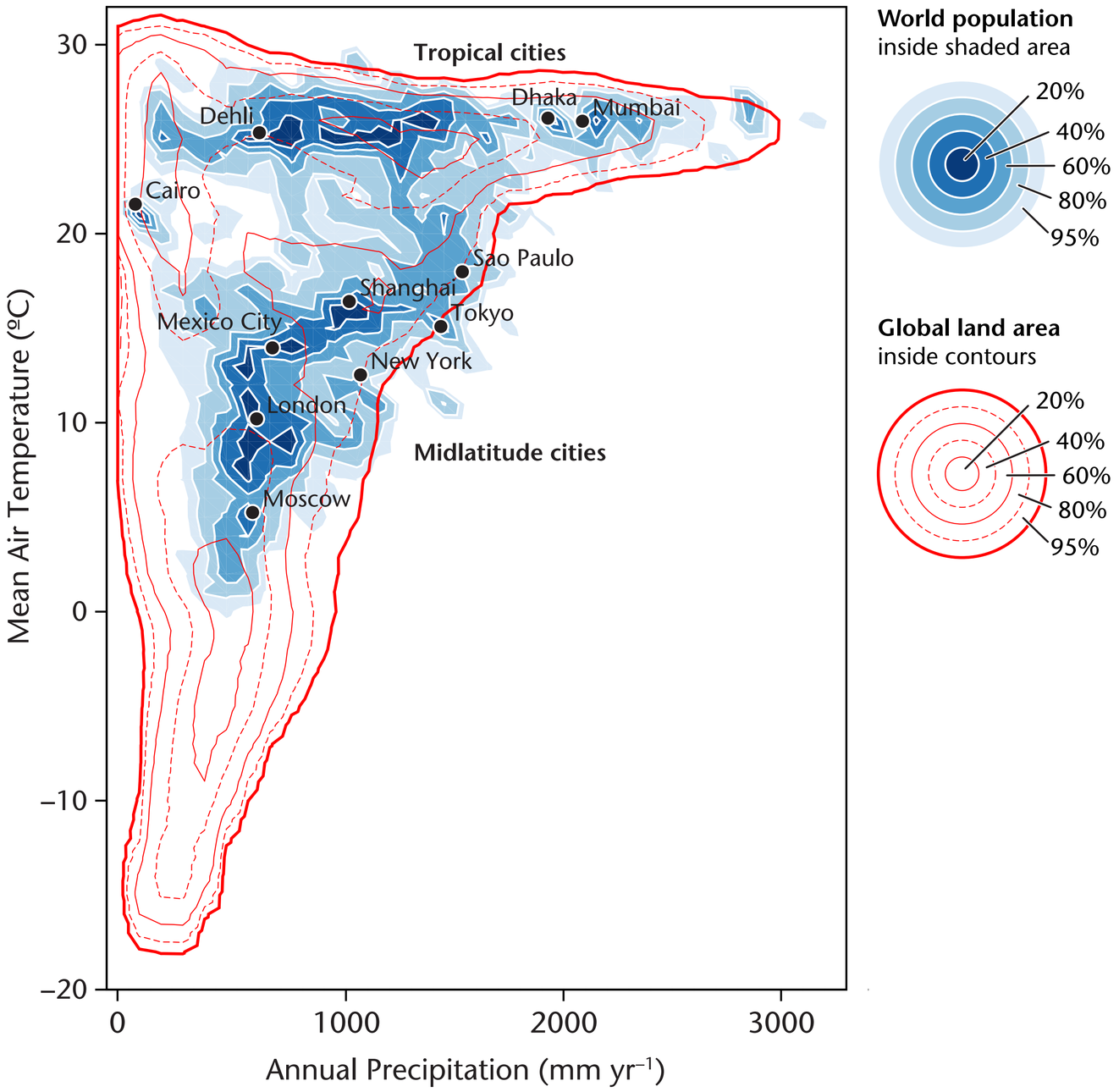


Figure: A.Christen

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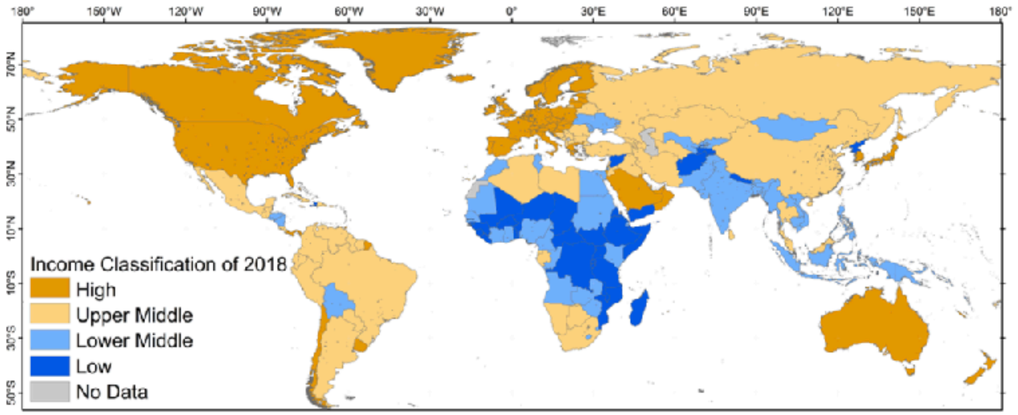
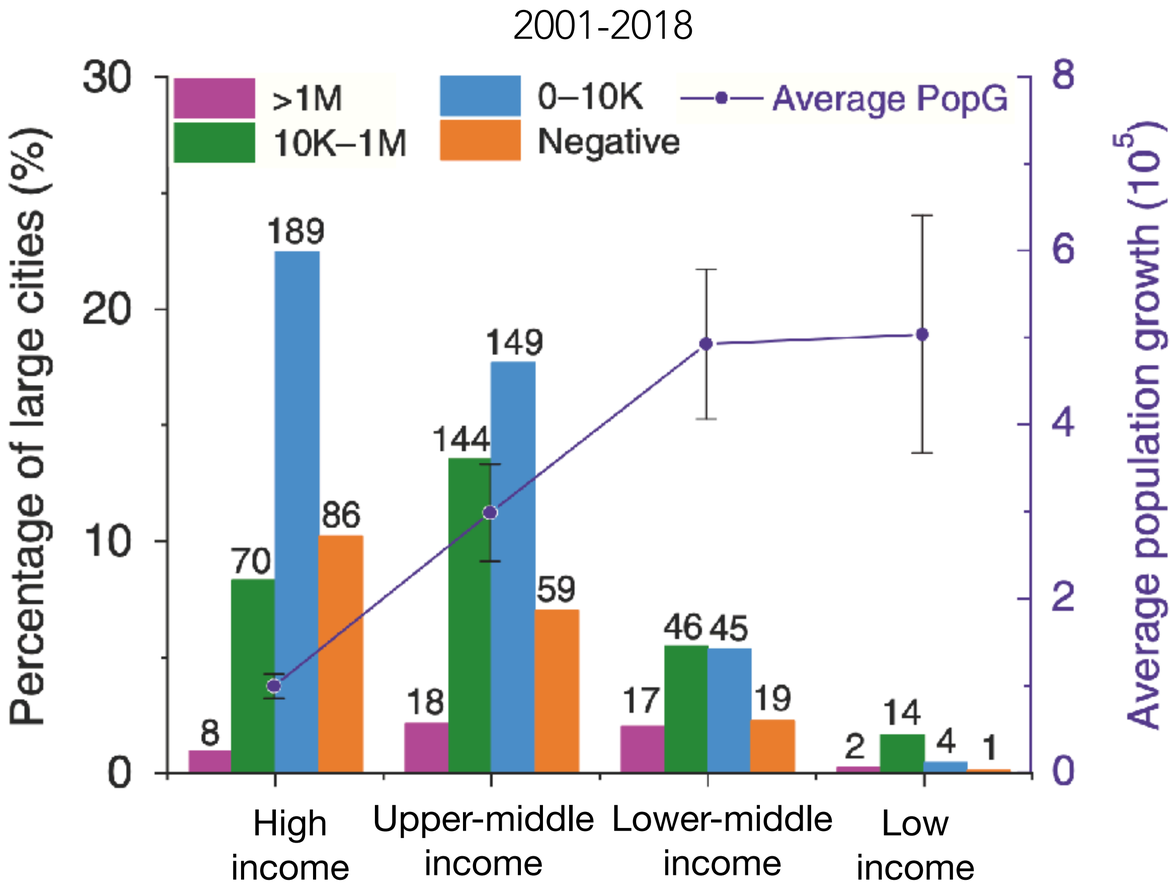
Urban population growth

Large cities in the low-income and lower-middle-income countries had the highest urban **population growth** in the two recent decades (since 2000):





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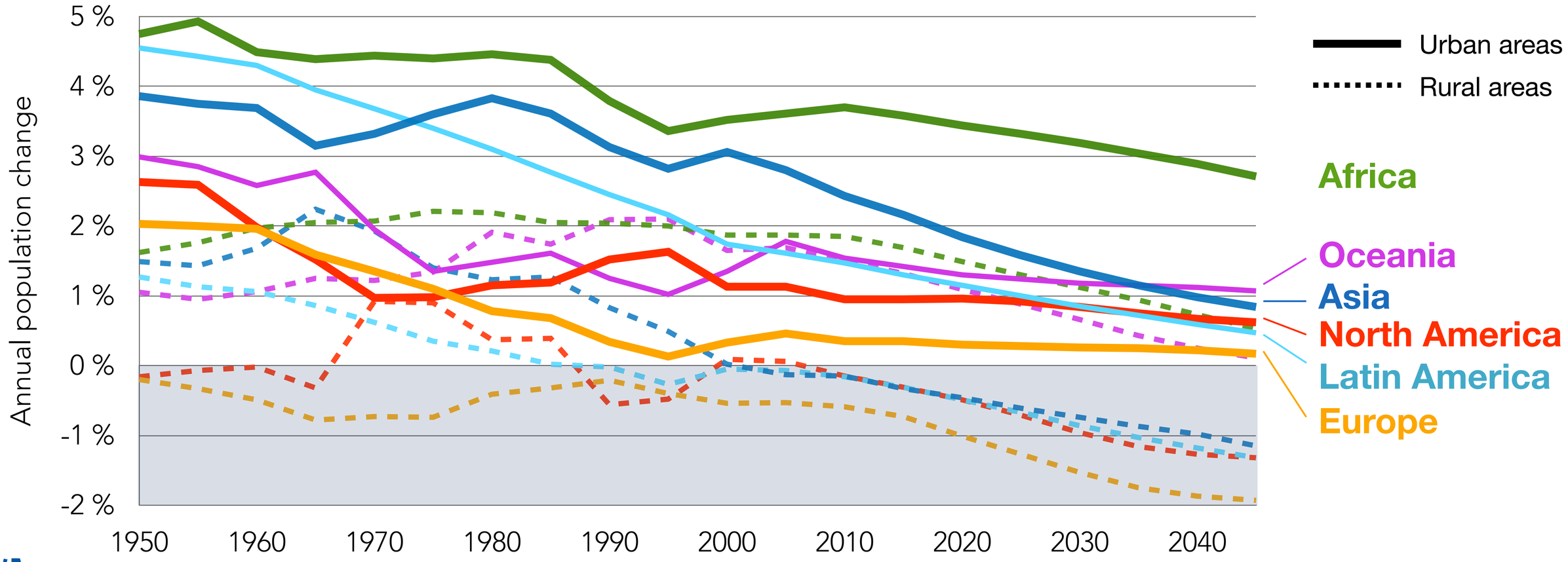
Source: Sun et al. (2020). Nature Communications (2020)11:5366

Rate of population growth by continent



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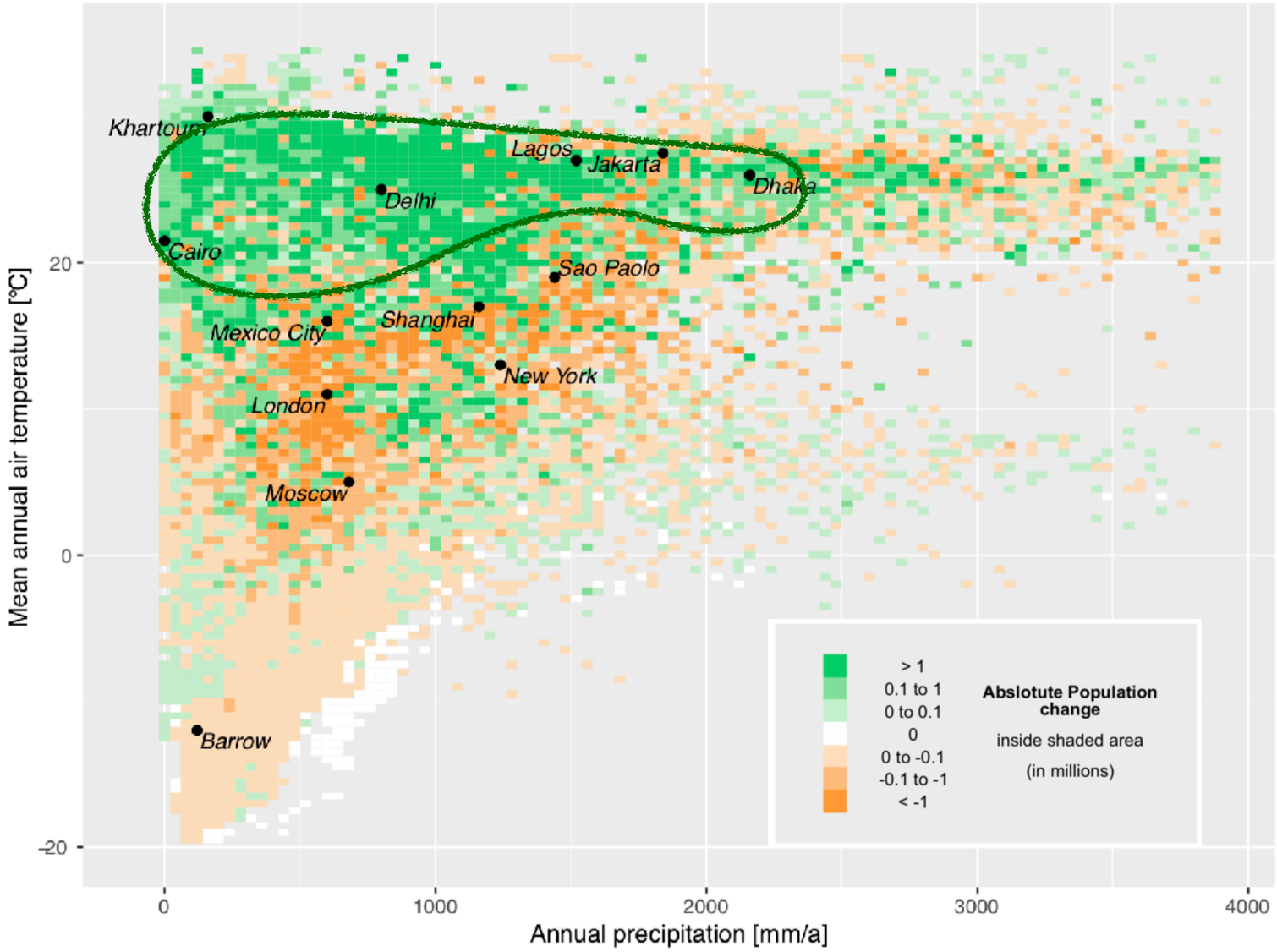
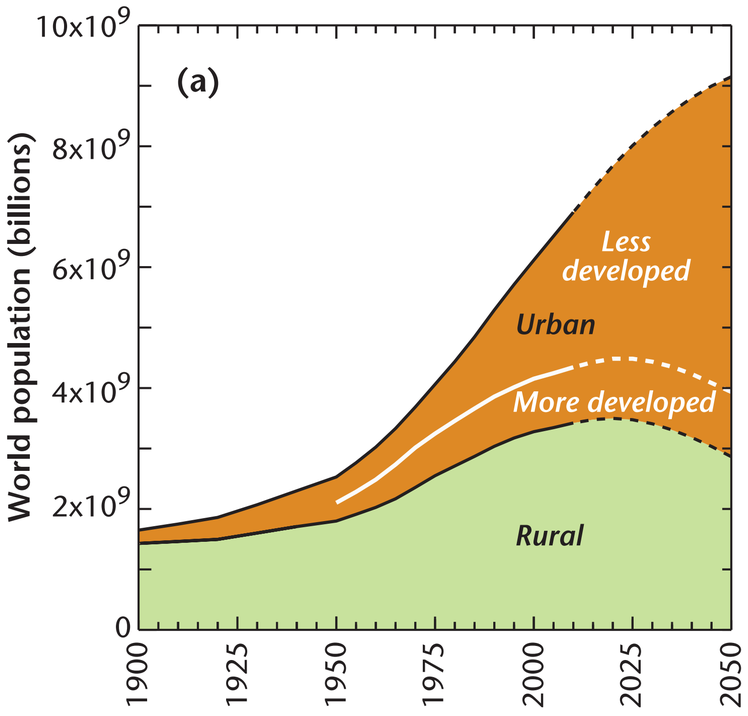
Data source: UN World Urbanization Prospects 2018

Future global population projections



Source: Reimers, Thesis Uni Freiburg, 2019

Population growth will be intensified in hot and **tropical cities** of the Global South primarily.



Source: Oke at al. 2017

Climate change affecting cities differently

All cities will become on average warmer due to **global climate change** (here shown are four RCPs = representative carbon pathways), albeit at different rates.

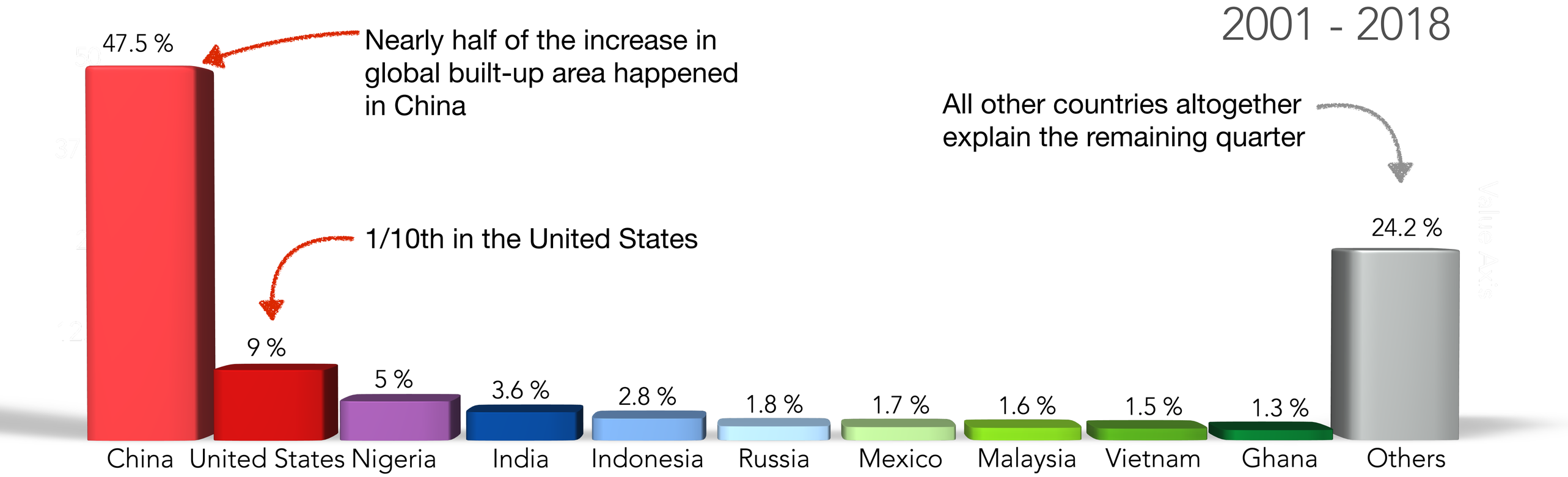
This does **not** yet include urban effects such as urban heat islands!

Source: Reimers, Thesis Uni Freiburg, 2019

Sealing of soils in Quebec City (Photo: A. Christen)

Changes in urban built-up areas

The global urban built-up areas increased from 2001 with 7.47×10^5 km^2 to 8.0×10^5 km^2 in 2018. In the upper-middle-income countries, increase in bult-up area was more than three times that of the high-income countries.



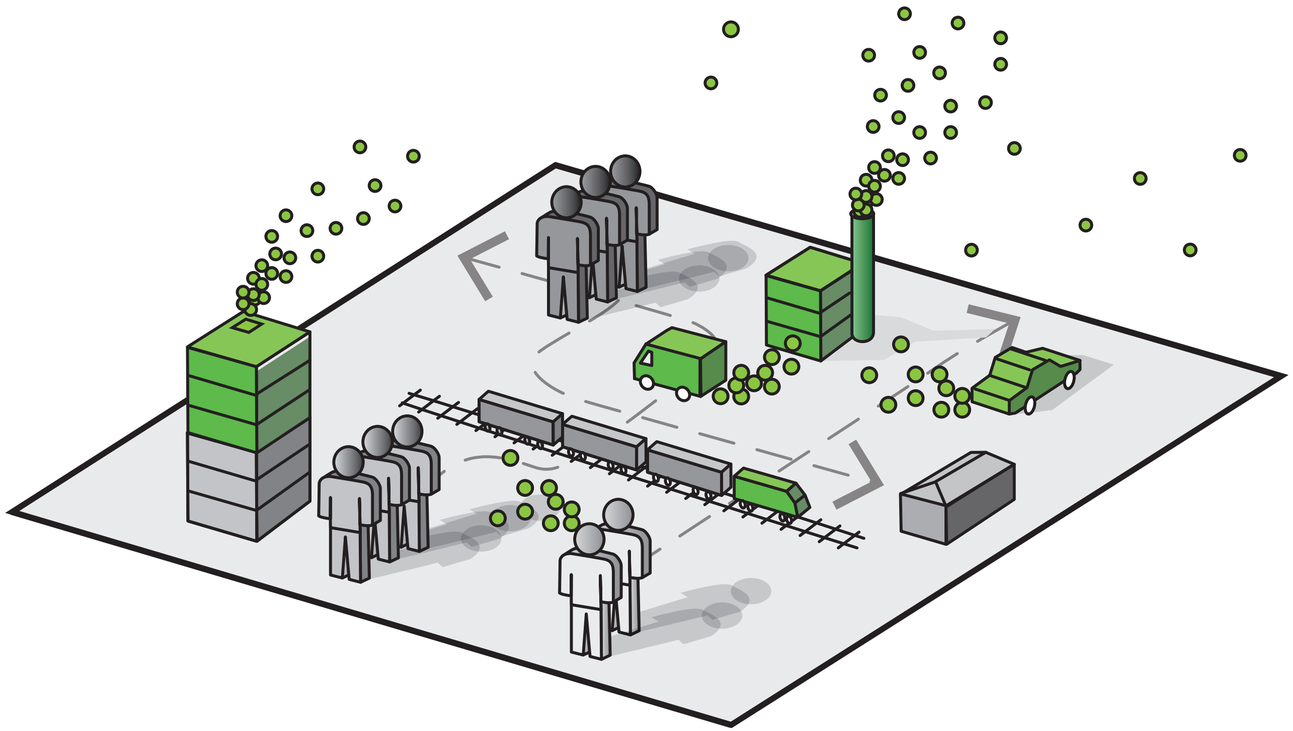
Source: Sun et al. (2020). Nature Communications (2020)11:5366

Fossil fuel emissions in the upper Rhine valley (Photo: A. Christen)

Climate change

↑

Urban emissions



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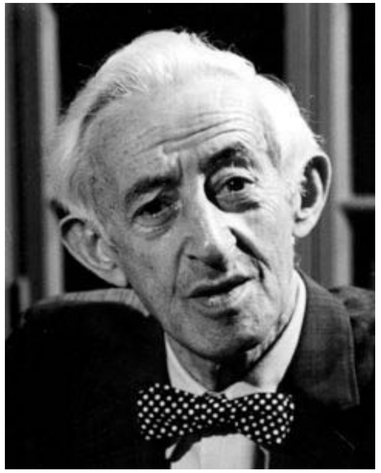
The concept of the urban metabolism

Metabolism - ‘The process in living organisms whereby substances are transformed into tissue with an attendant release of energy and waste’

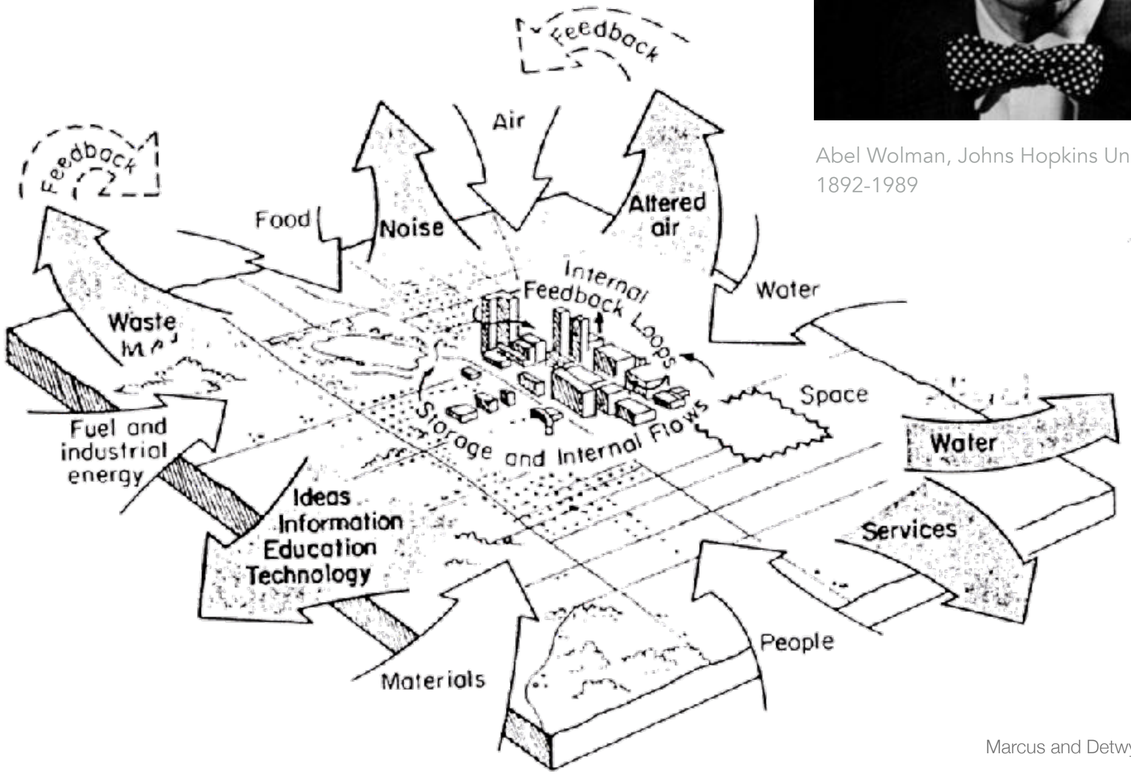
Analogy – the city as a organism with its own ‘urban metabolism’

Wolman (1965) first used this analogy which can be defined as “the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste.”

Wolman (1965) The metabolism of cities. *Sci. Am.* 213:179-90.

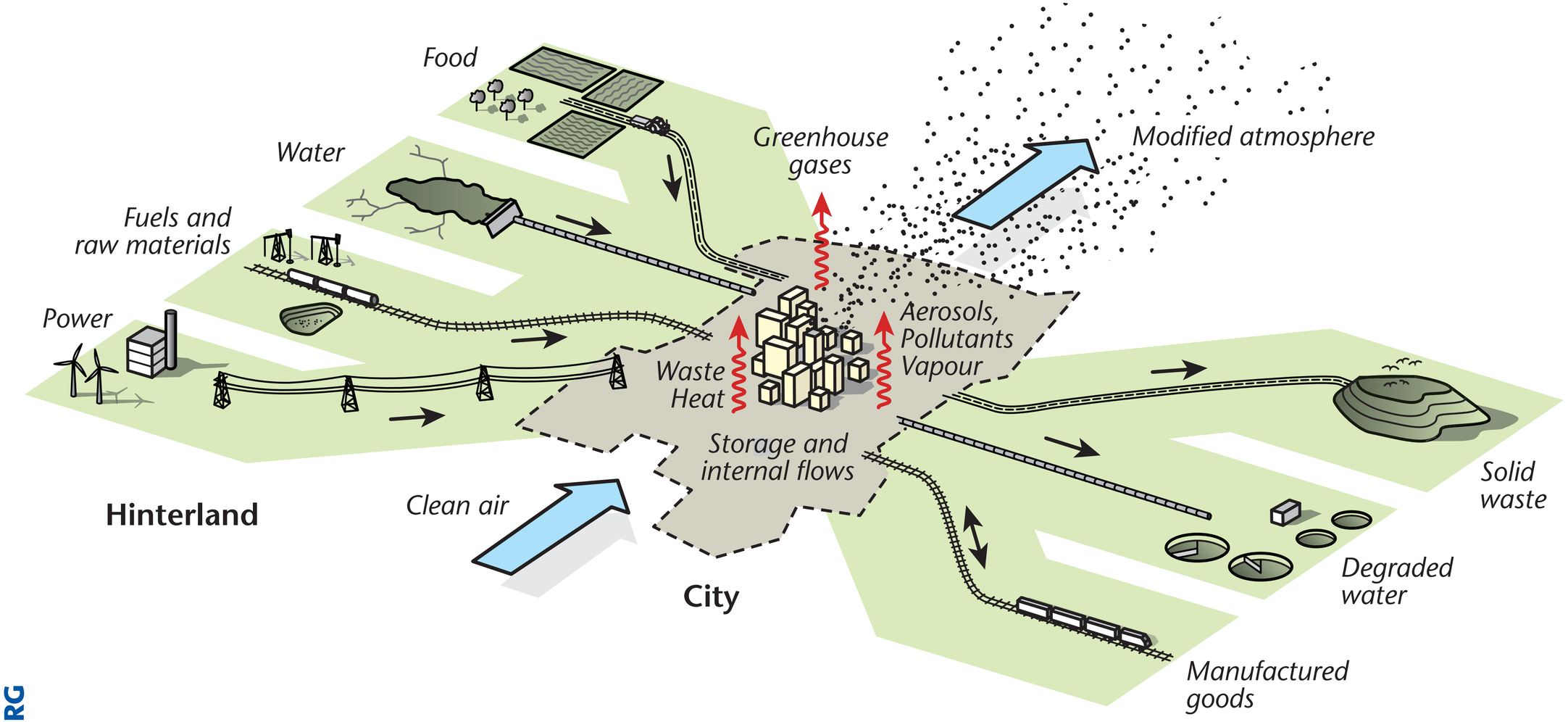


Abel Wolman, Johns Hopkins University, US
1892-1989



Marcus and Detwyler (1972)

The connectivity between city and its footprint



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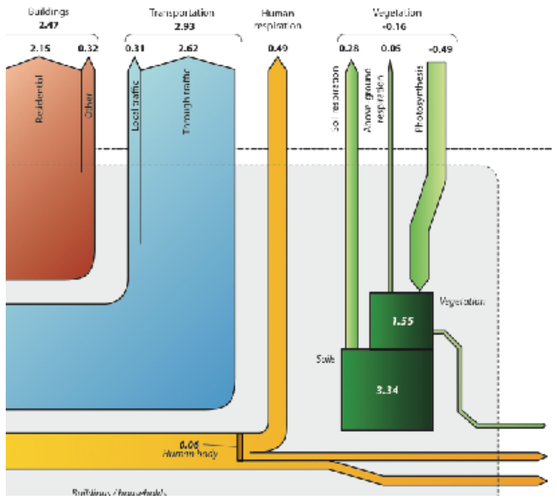
Oke TR, Mills G, Christen A, Voogt JA (**2017**): “Urban Climates”, Cambridge University Press

Urban metabolism controls urban climate



The metabolism of a city can be described by **mass** and **energy flows**.

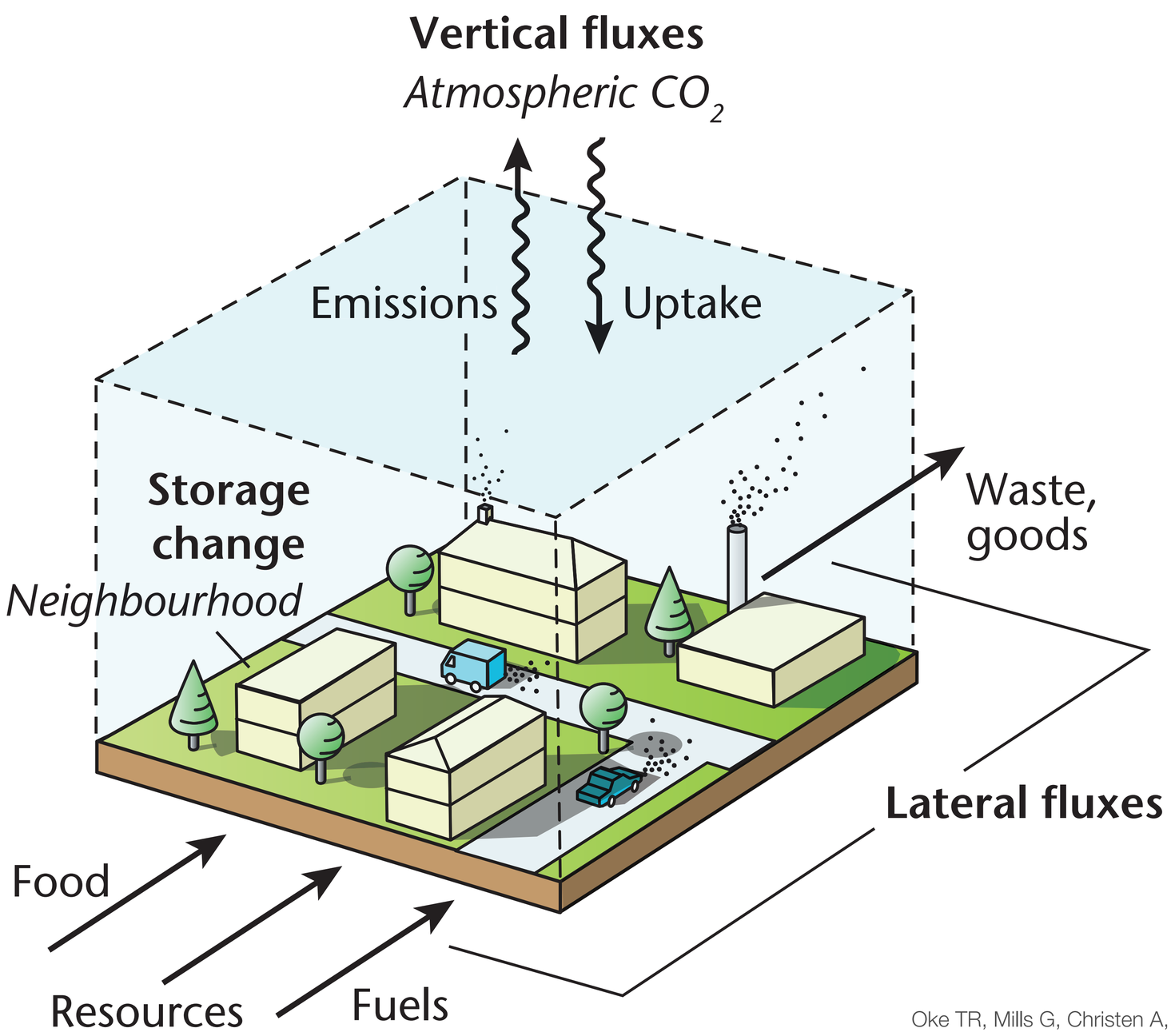
Climate-relevant **injections** into the urban atmosphere (called **emissions**) result from the release of waste by-products, combustion of energy sources, manufacturing, irrigation, construction, etc.

The magnitude of these emissions **varies according to human activity cycles** (time, day of the week, season, cultural practice, technology).

Eddy covariance tower

Urban Eddy Covariance tower in Vancouver, Canada (Photo: A. Christen)

Eddy Covariance System on top of urban measurement tower in Vancouver, Canada (Photo: R. Ketler)



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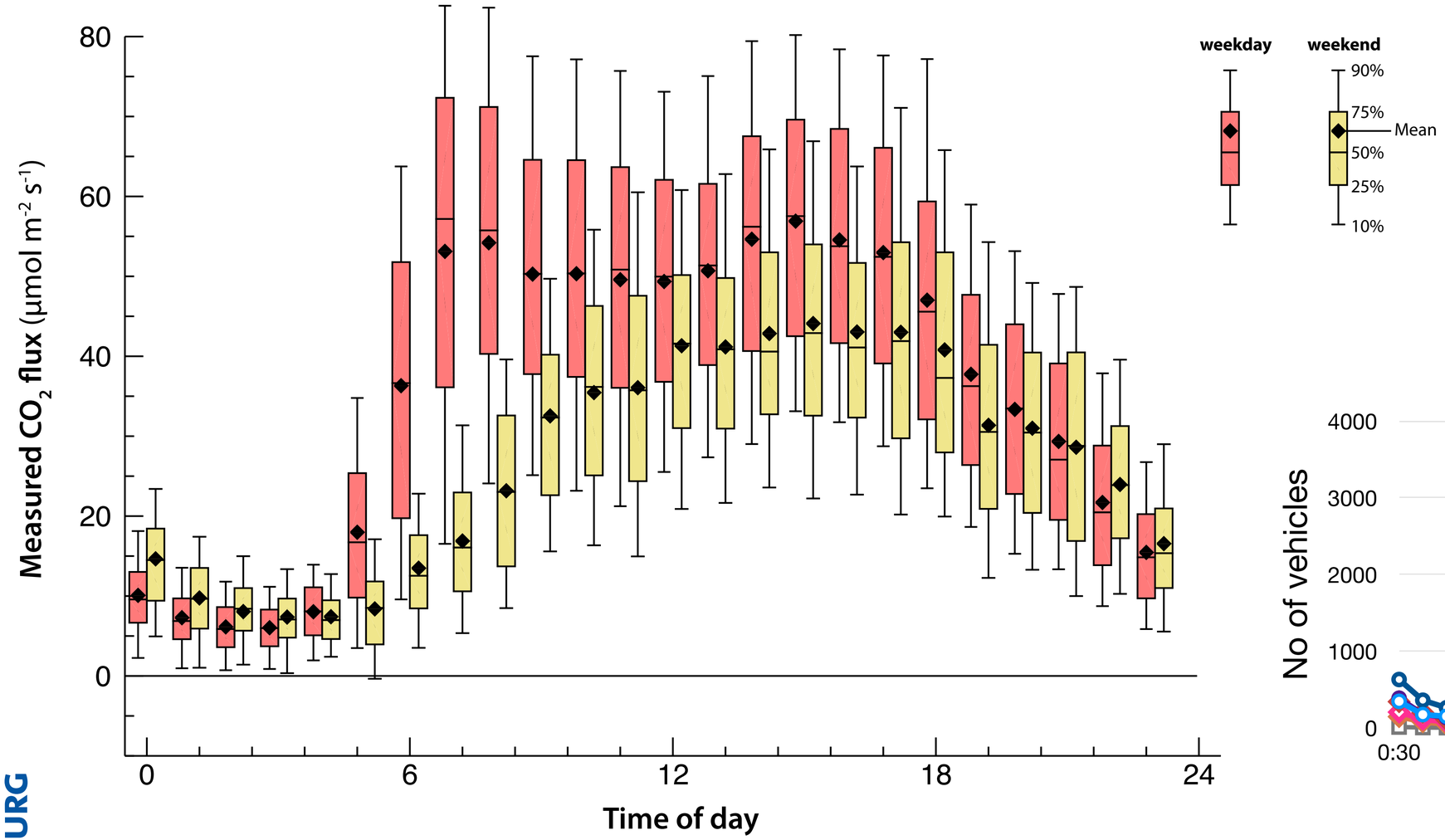
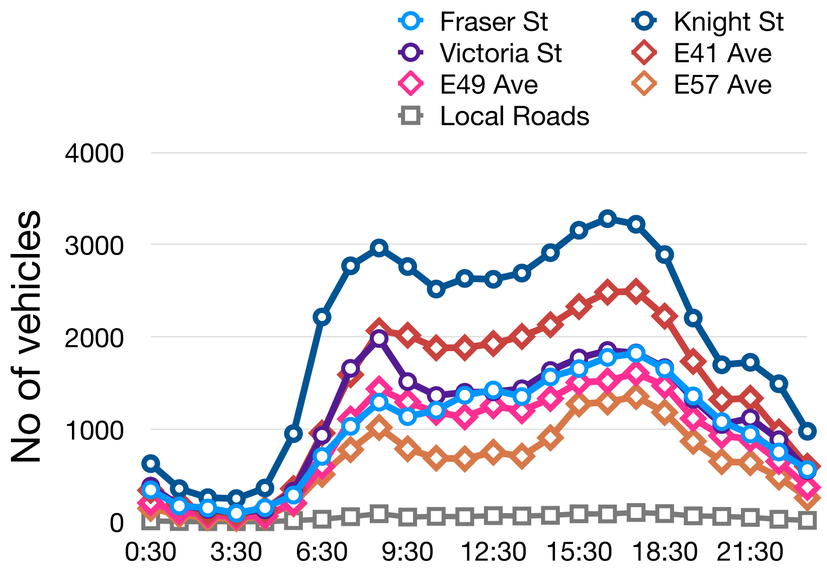
Diurnal course of the measured CO_2 fluxes





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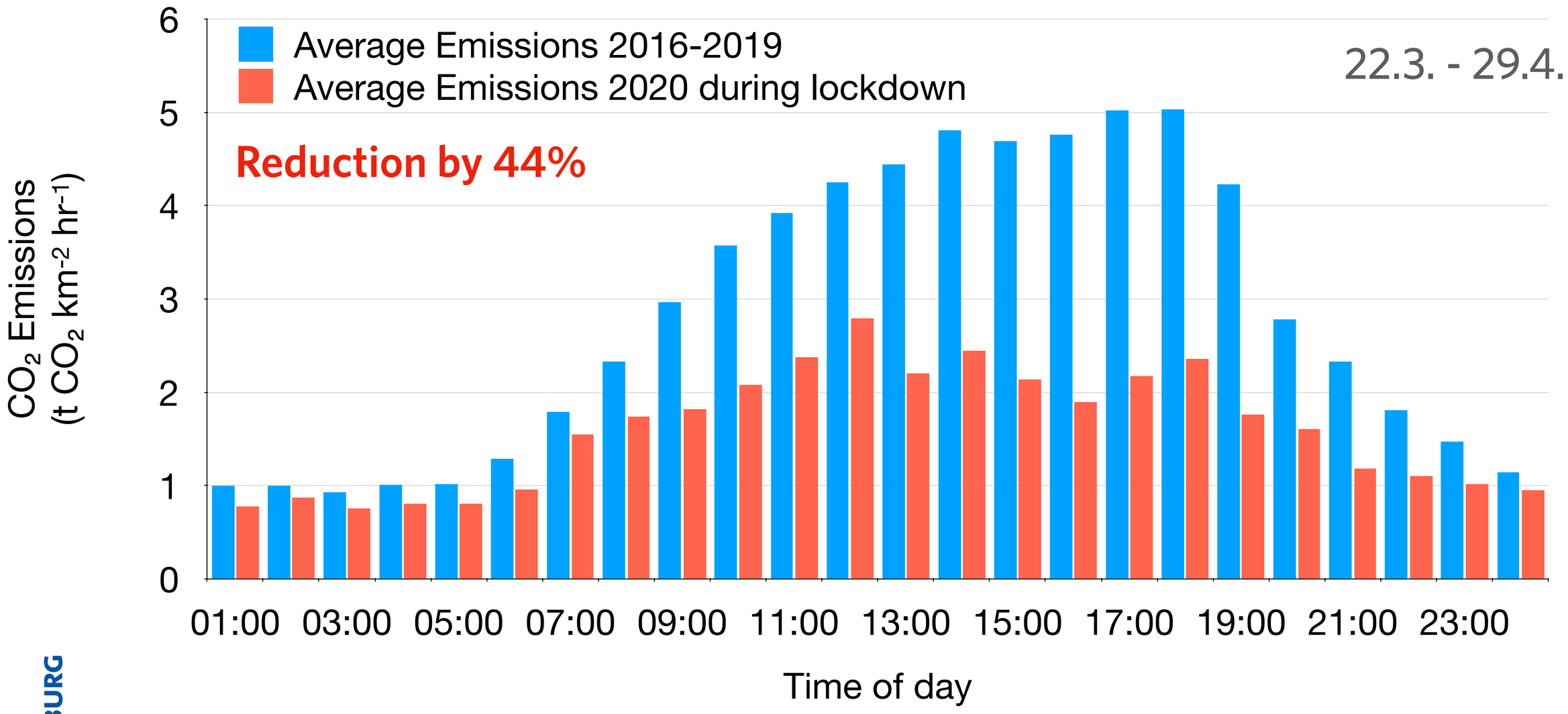
Christen A. (2014): 'Atmospheric measurement techniques to quantify greenhouse gas emissions from cities'. *Urban Climate*, 10 (P2), 241–260.

Urban Eddy Covariance system in Basel, Switzerland (Photo: R. Vogt, Uni Basel)

CO_2 Emissions in Basel during COVID-19



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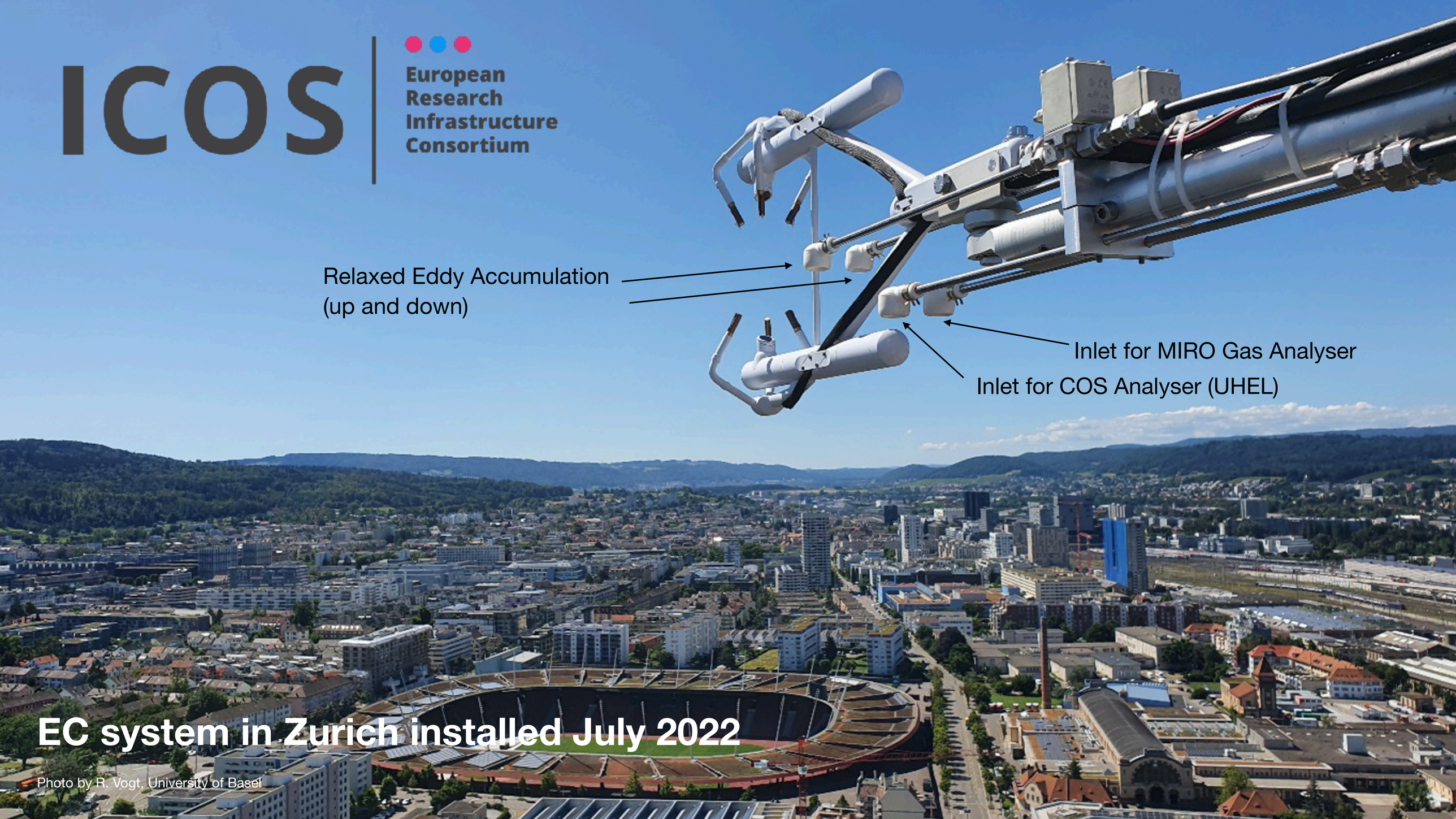
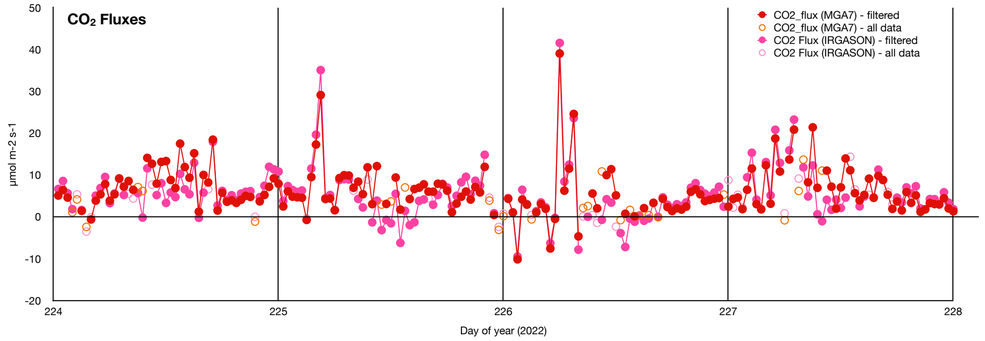
Dataset: *R. Vogt, Atmosphärenwissenschaften, Universität Basel.*

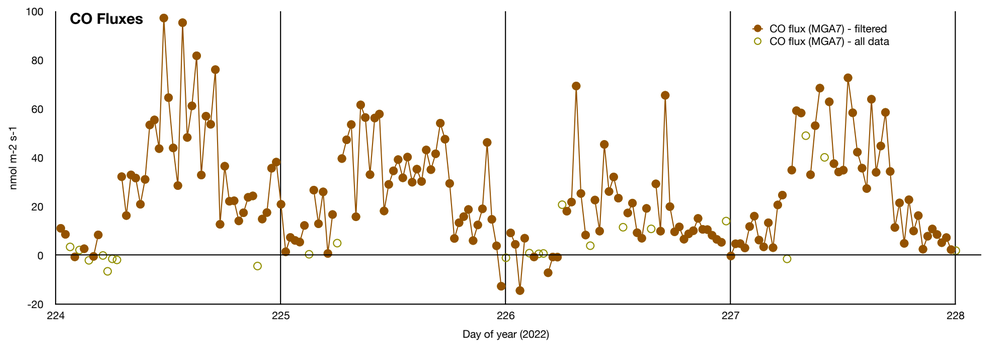


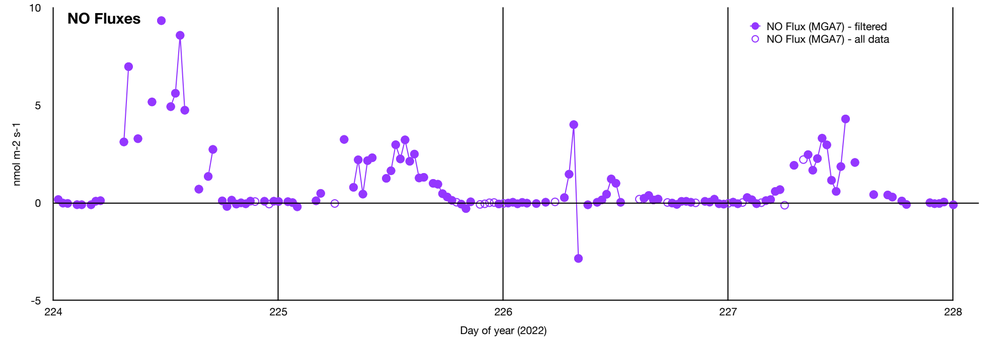
EC system in Zurich installed July 2022

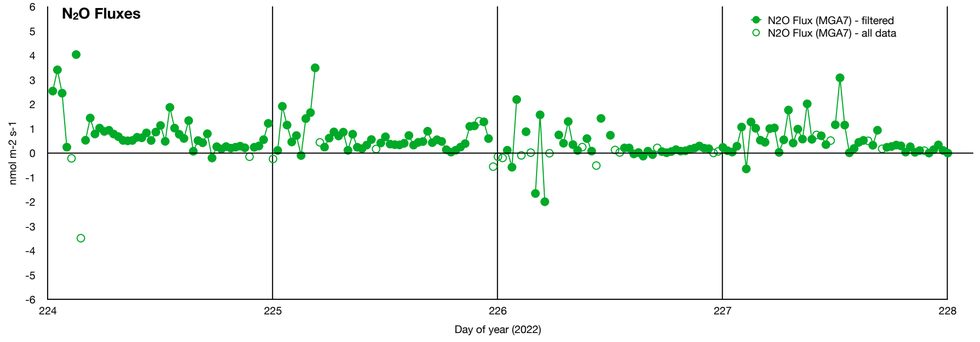
Photo by R. Vogt, University of Basel

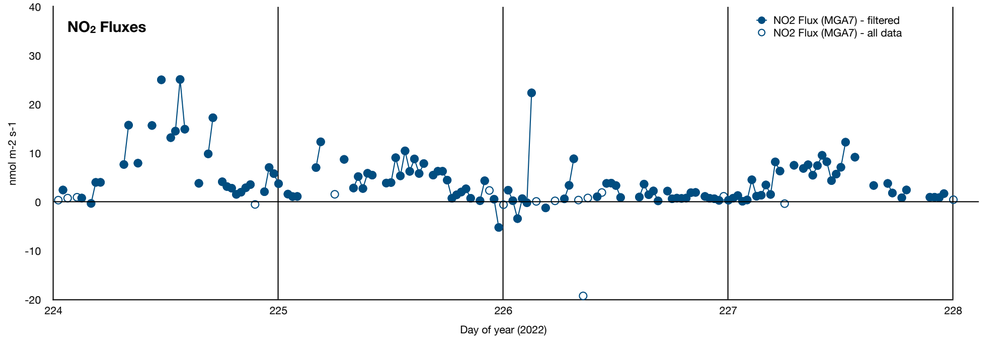
ICOS European Research Infrastructure Consortium

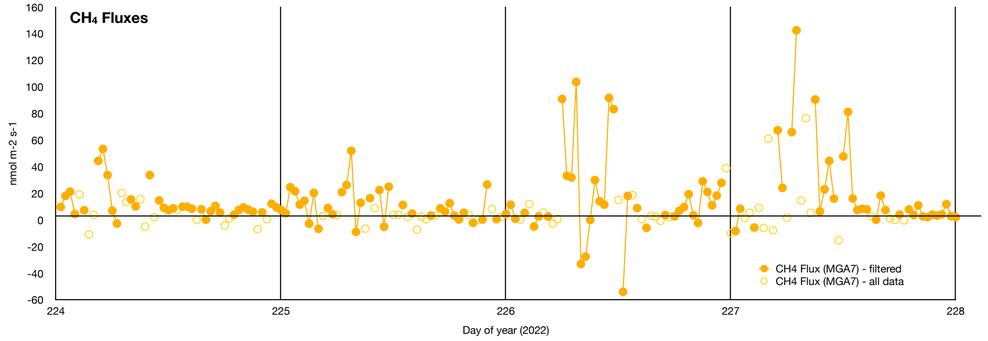












This is preliminary data processed using Eddy Pro without detailed spectral loss calculations and no advanced filtering. Data authors: Josh Hashemi, Dominik Brunner, Lukas Emmenegger, Leena Järvi, Ville Kasurinen, Samuel Hammer, Morten Hundt, Giacomo Nicolini, Dario Papale, Pascal Rubli, Jesse Soininen, Simone Sabbatini, Stavros Stagakis, Roland Vogt, Matthias Zeeman, Andreas Christen. Credits: ICOS Cities / PAUL H2020 Project, ICOS HO, MIRO AG.

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Monitoring fossil fuel emissions from cities

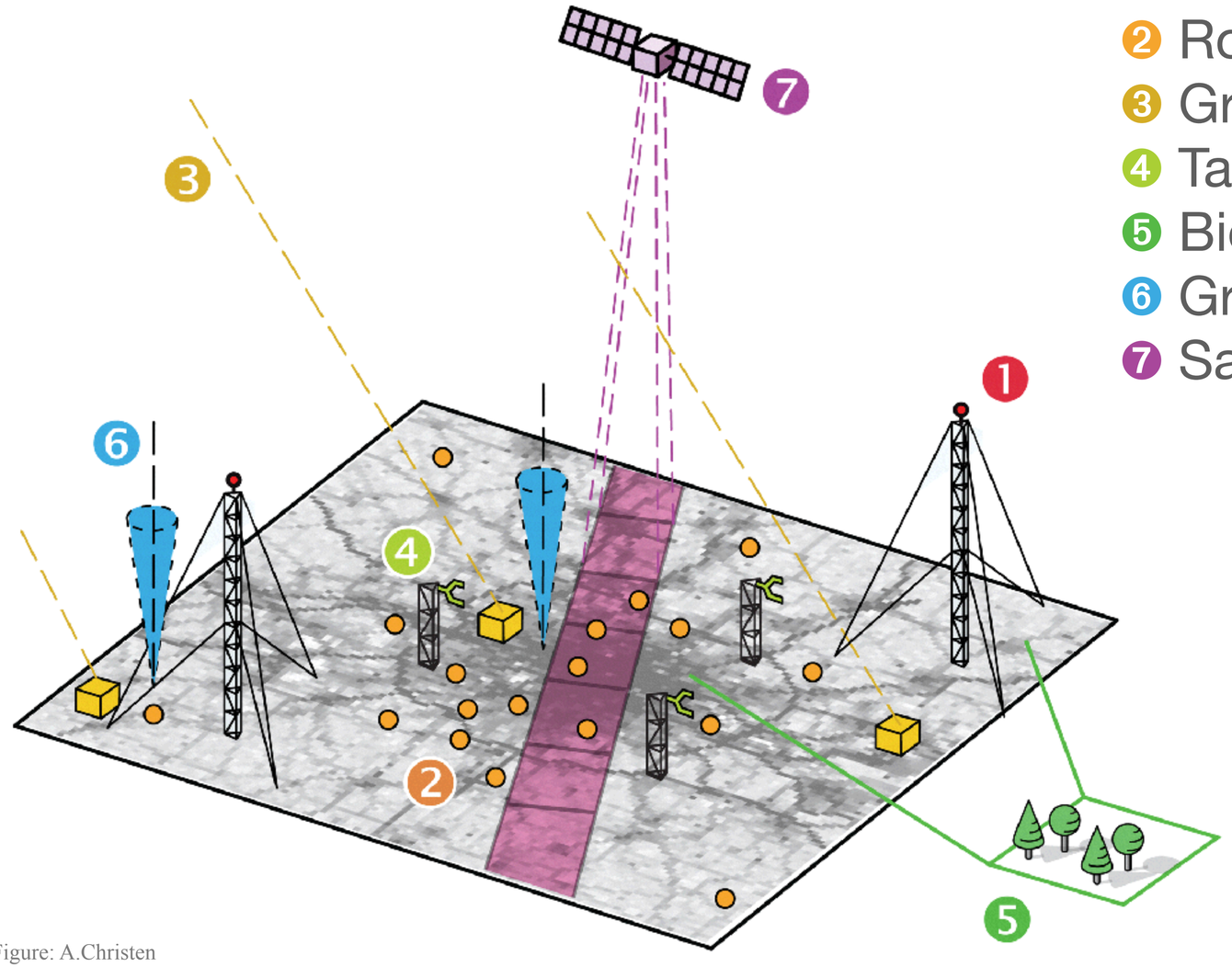

Figure: A.Christen

1. High-precision tall tower concentrations
2. Roof- and street-level networks
3. Ground-based total column network
4. Tall eddy covariance towers
5. Biogenic process observations
6. Ground-based wind and meteorology
7. Satellite total column observations

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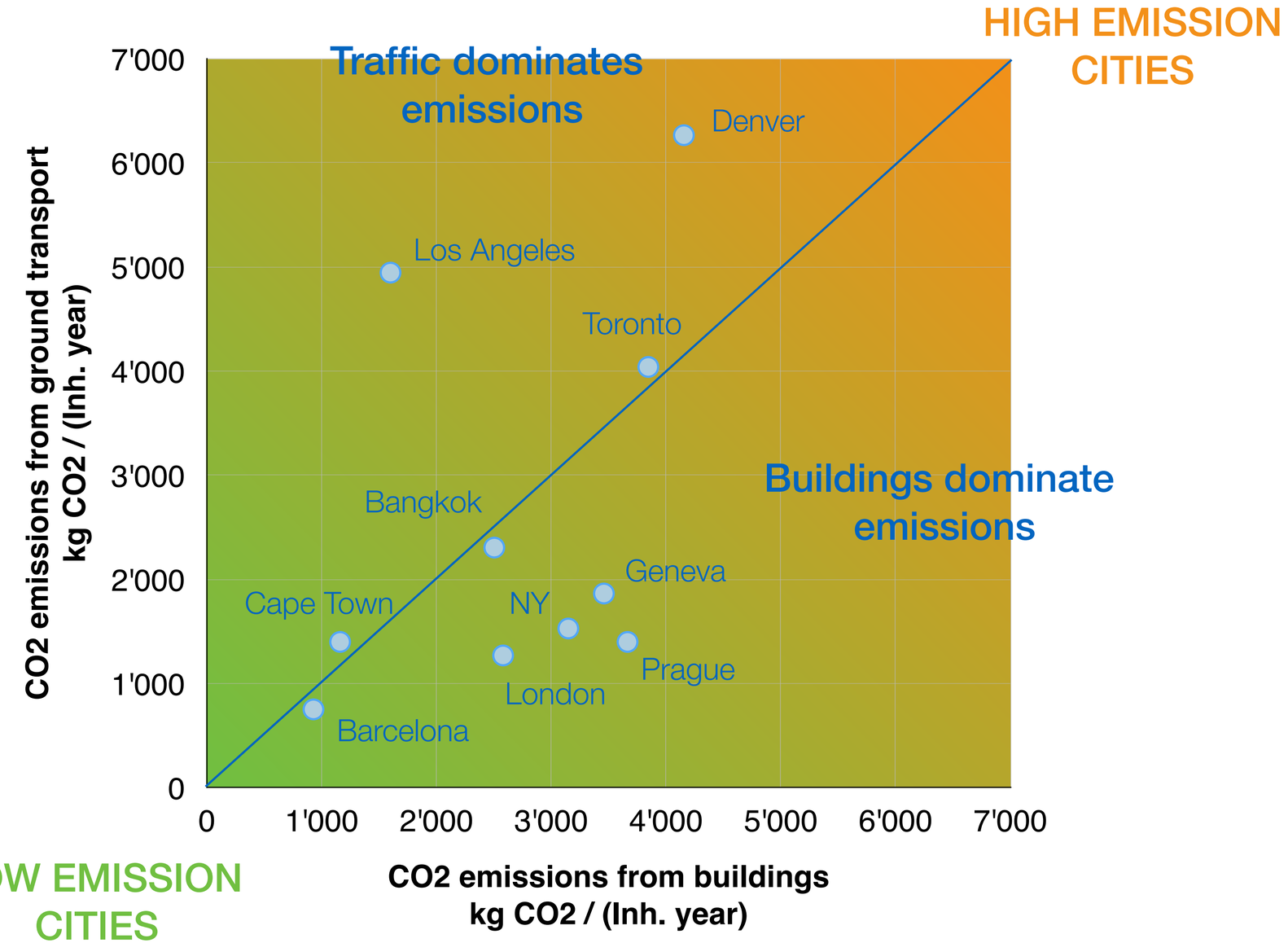
CO_2 Emissions from world cities



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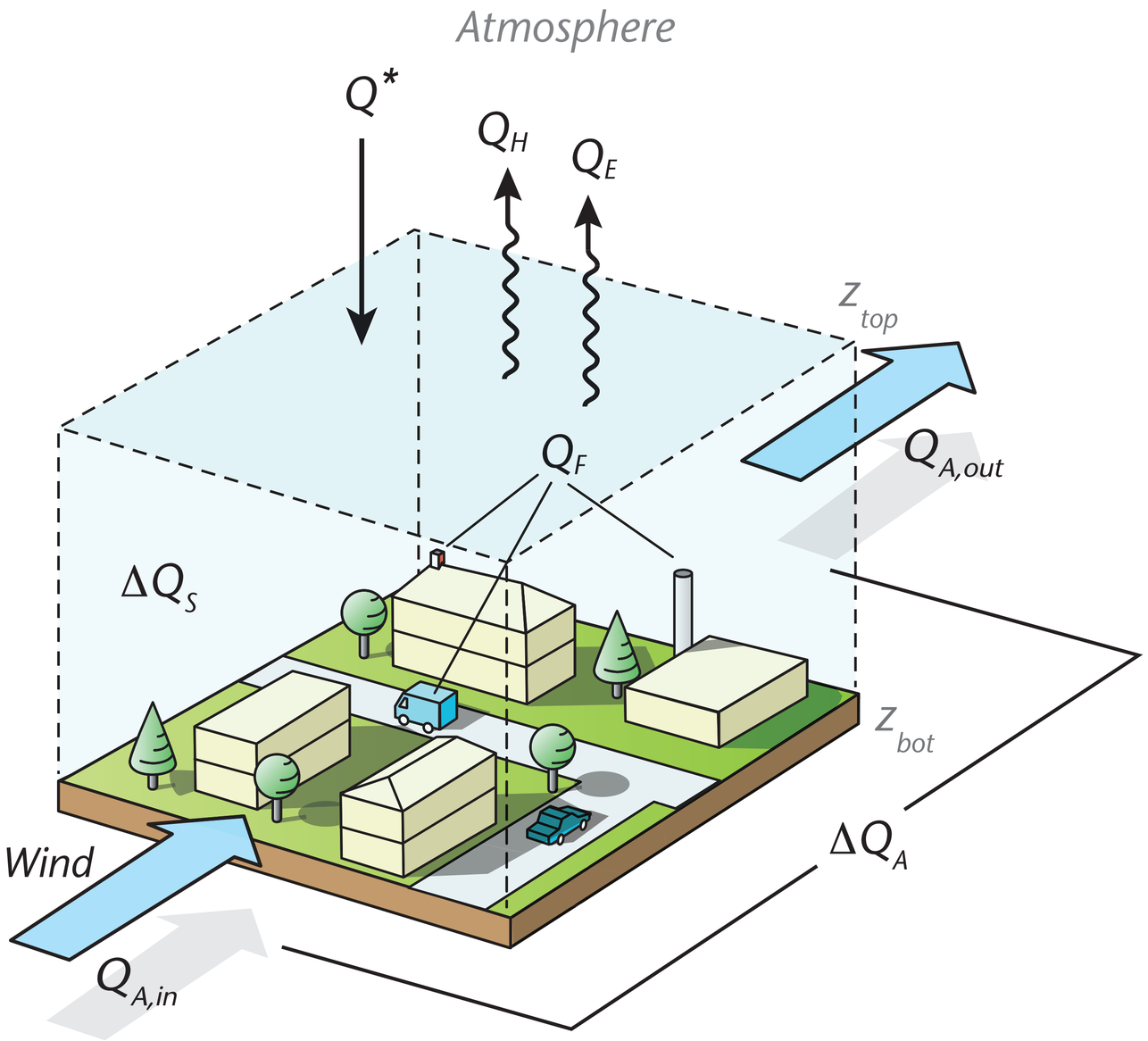
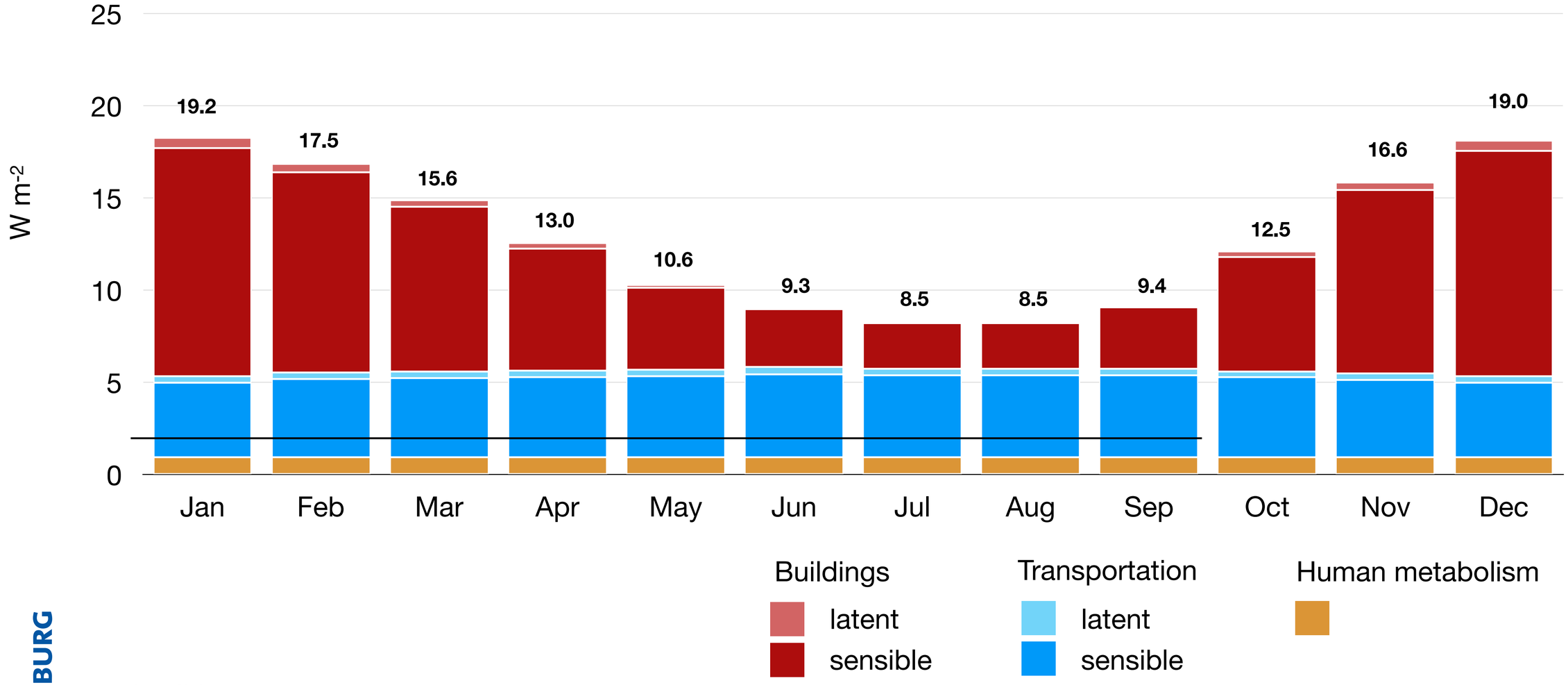


$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

Oke TR, Mills G, Christen A, Voogt JA (**2017**): "Urban Climates", Cambridge University Press

Annual variation of anthropogenic heat emissions



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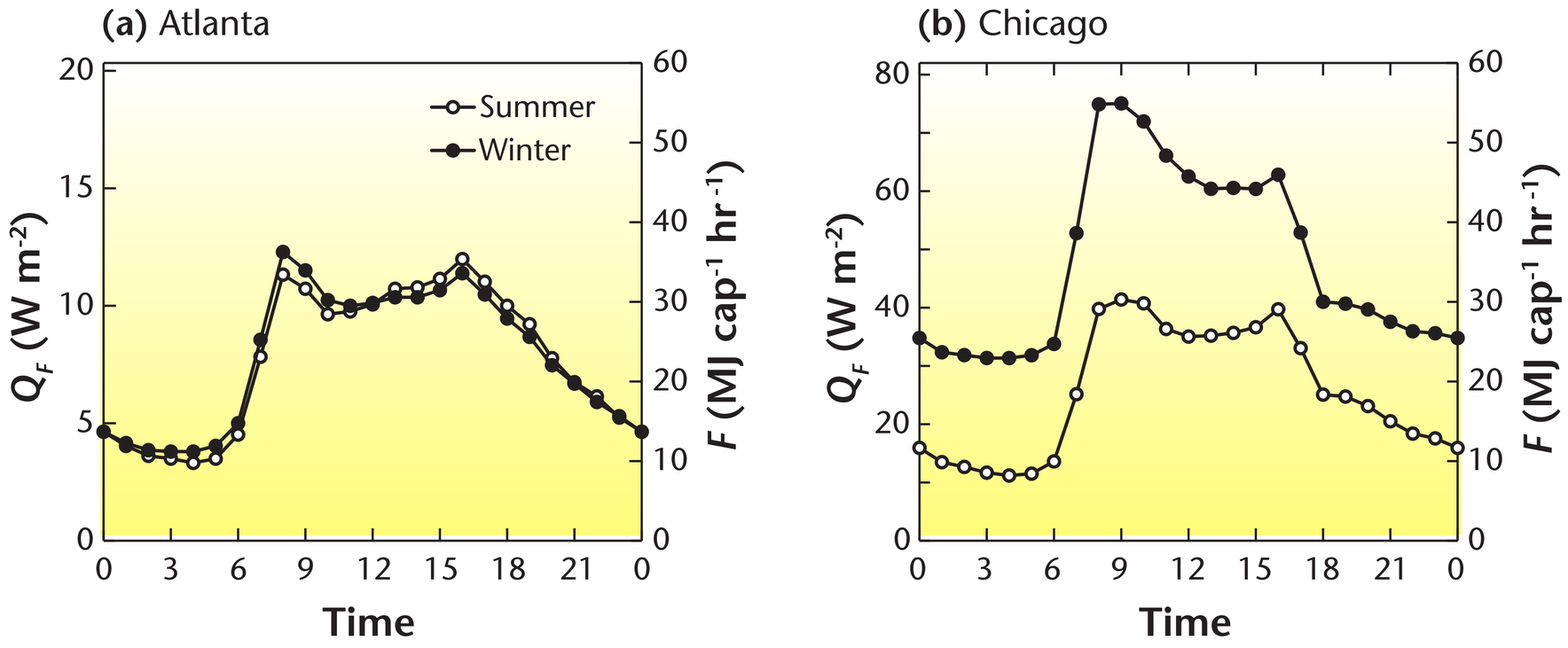
Christen A. and Van der Laan M.

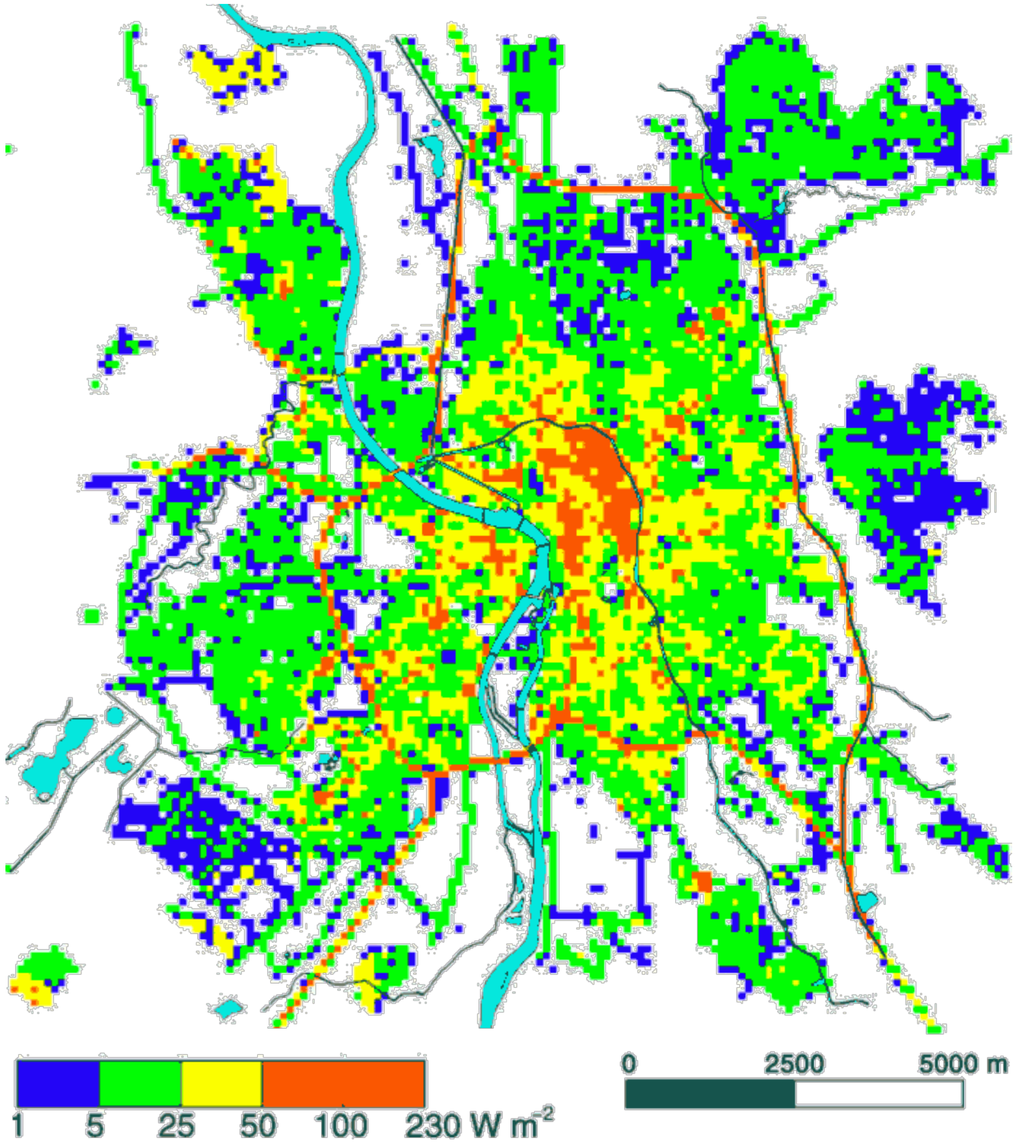
Diurnal course of anthropogenic heat emissions



Data from Sailor and Liu, 2004

Oke TR, Mills G, Christen A, Voogt JA (**2017**): "Urban Climates", Cambridge University Press

Spatial distribution of anthropogenic heat



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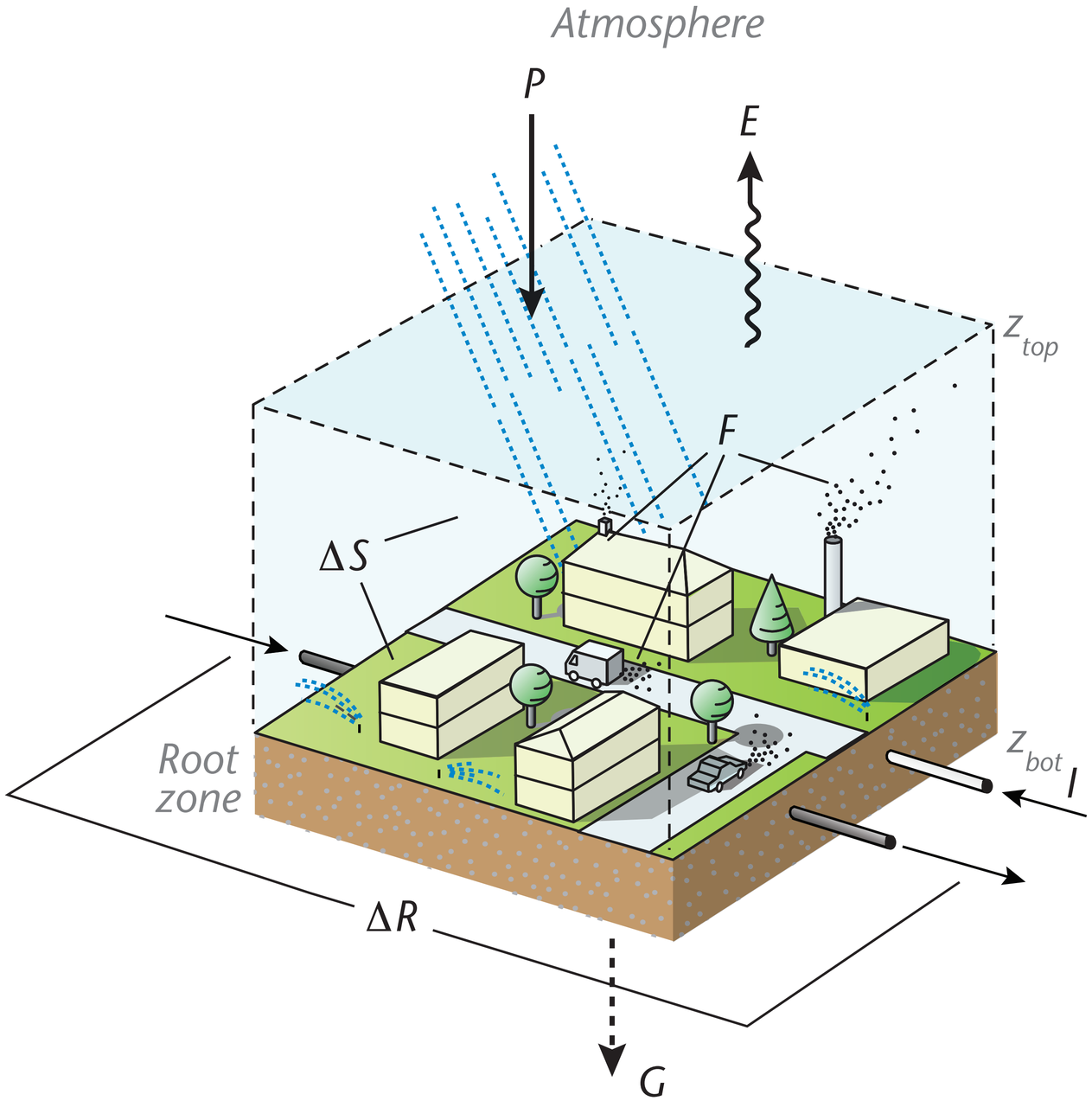

$$P + I + F = E + \Delta S + G + \Delta R$$

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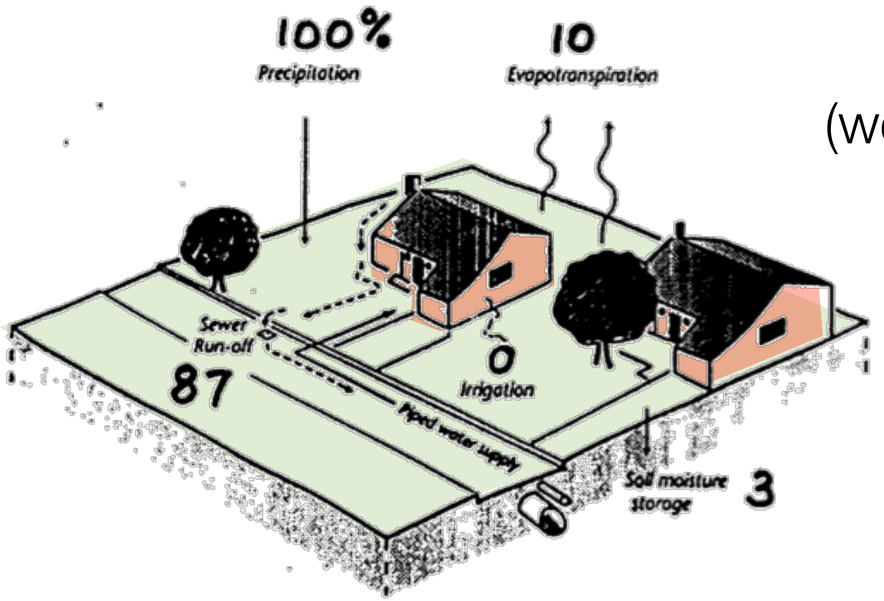
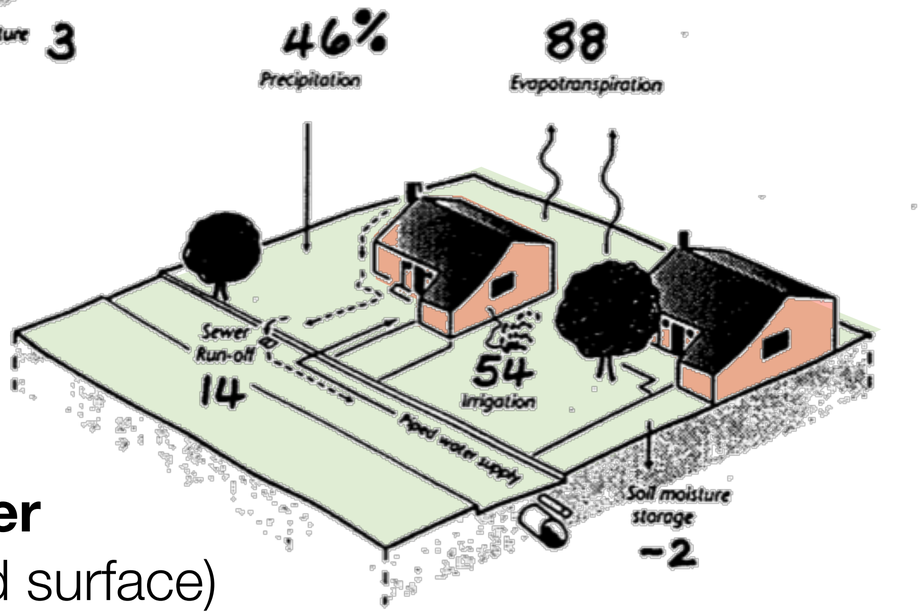
Oke TR, Mills G, Christen A, Voogt JA (**2017**): "Urban Climates", Cambridge University Press

Irrigation of urban lawns (Photo: A. Christen)

Seasonal changes to the water balance



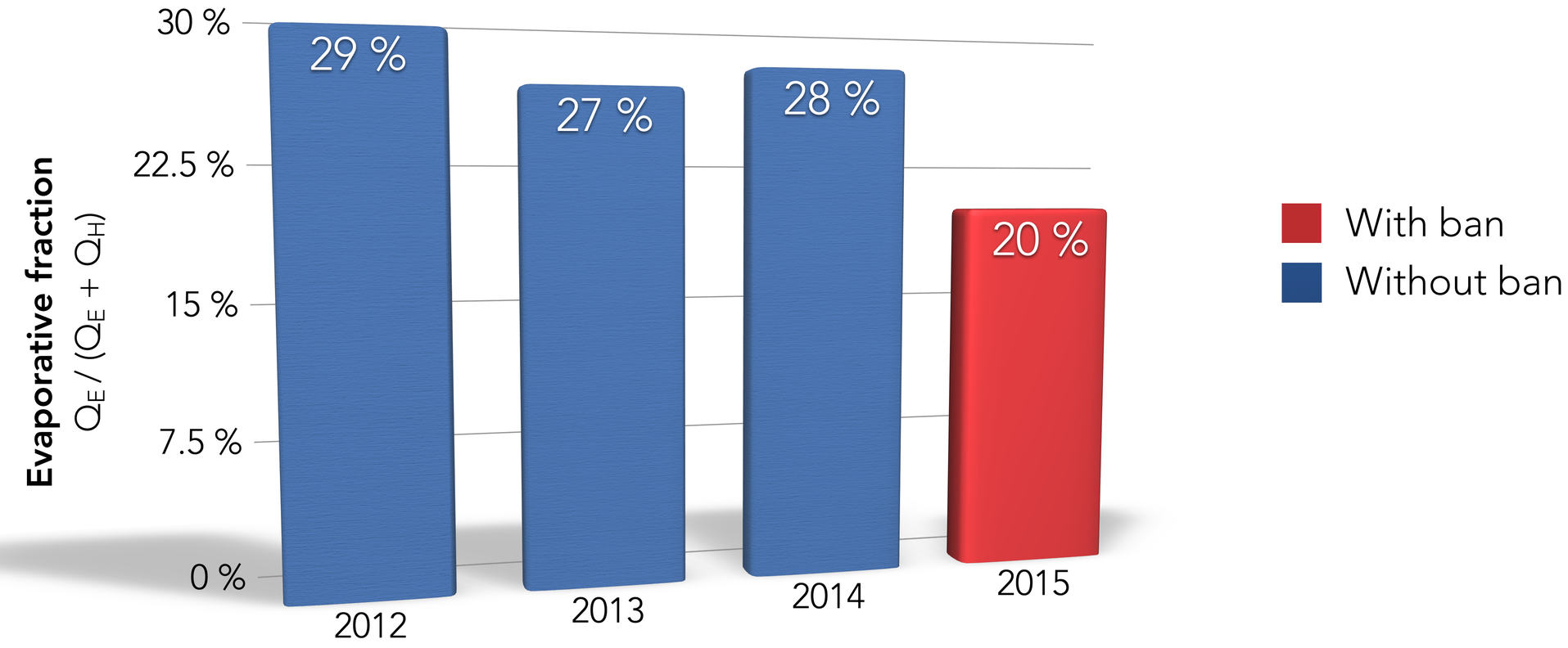
Winter
(wet surface)



Summer
(moist, irrigated surface)

Grimmond and Oke, 1986

Lawn sprinkling ban in summer 2015
reduced evapotranspiration from city



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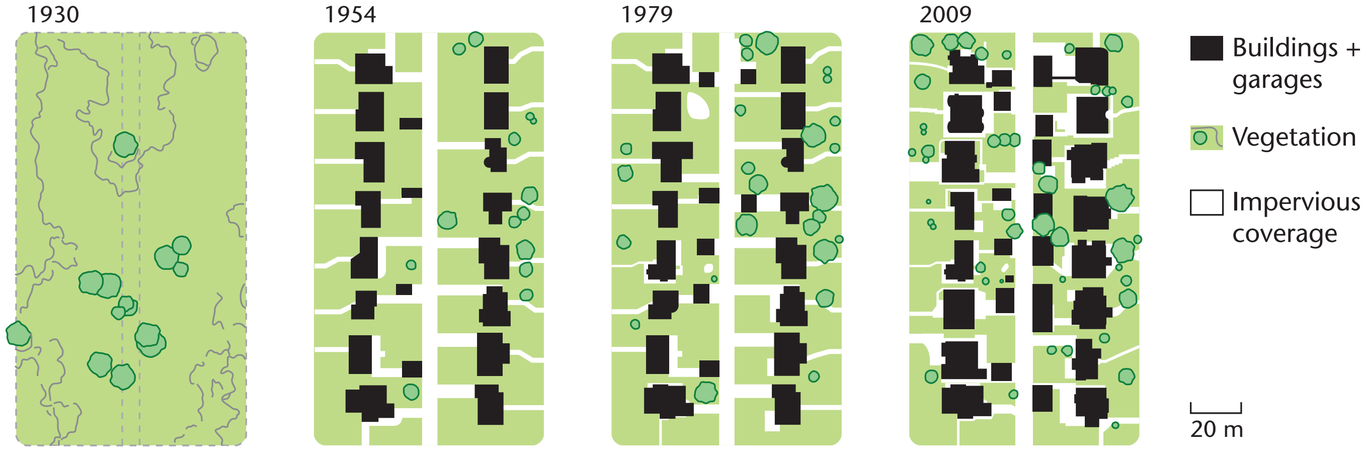
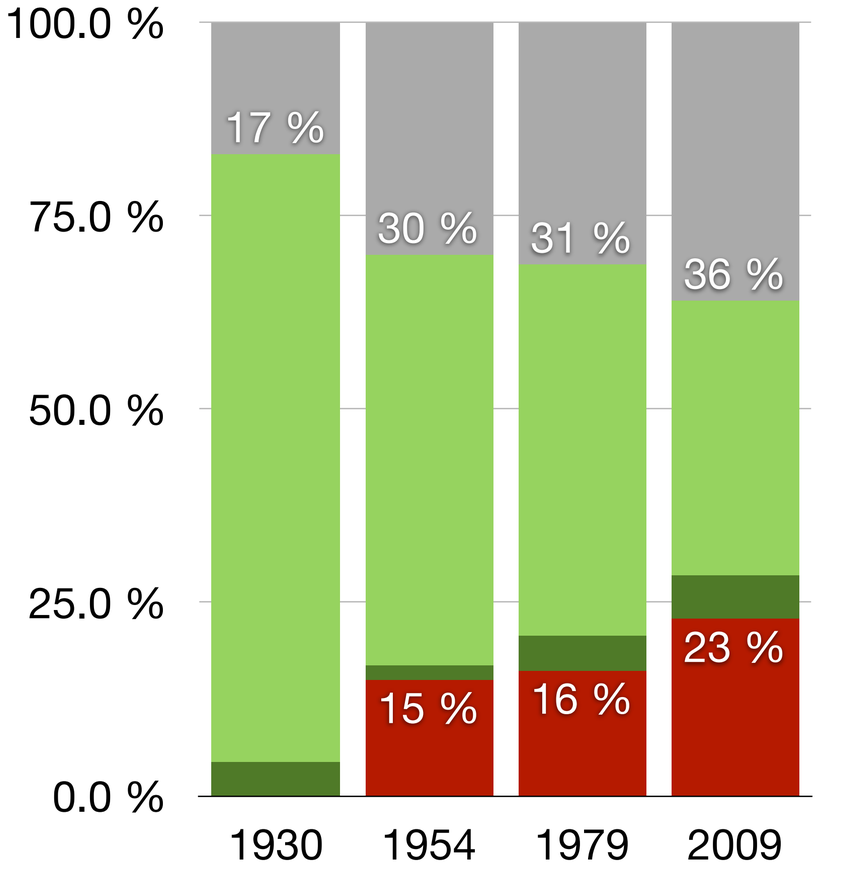
Based on data **measured on UBC's flux tower 'Vancouver Sunset'** (JJA average for all years).

Long-term changes to the water balance





Impervious (Streets, sidewaks etc.)
Ground vegetation
Trees
Houses and garages

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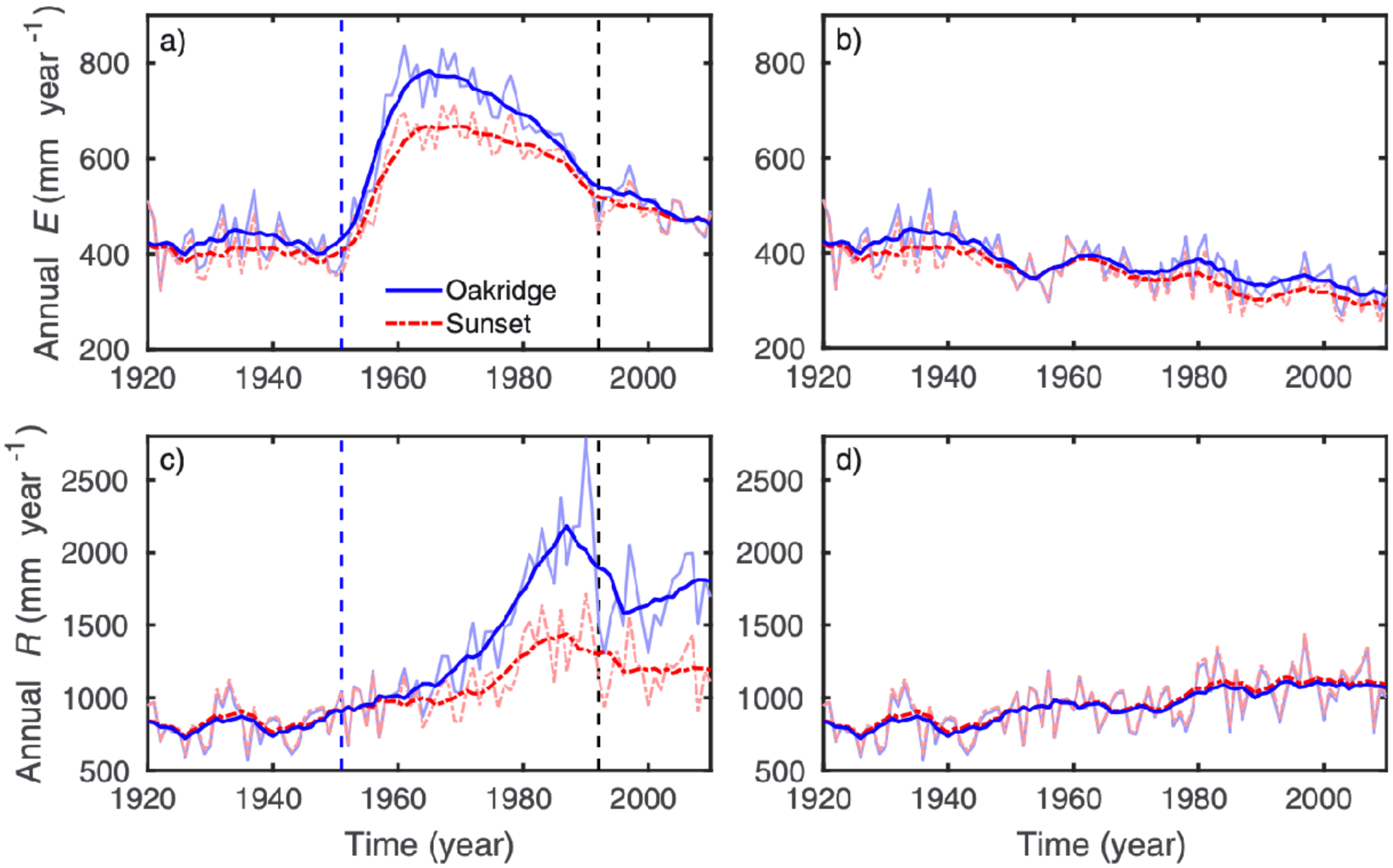
How urbanization affects the water balance



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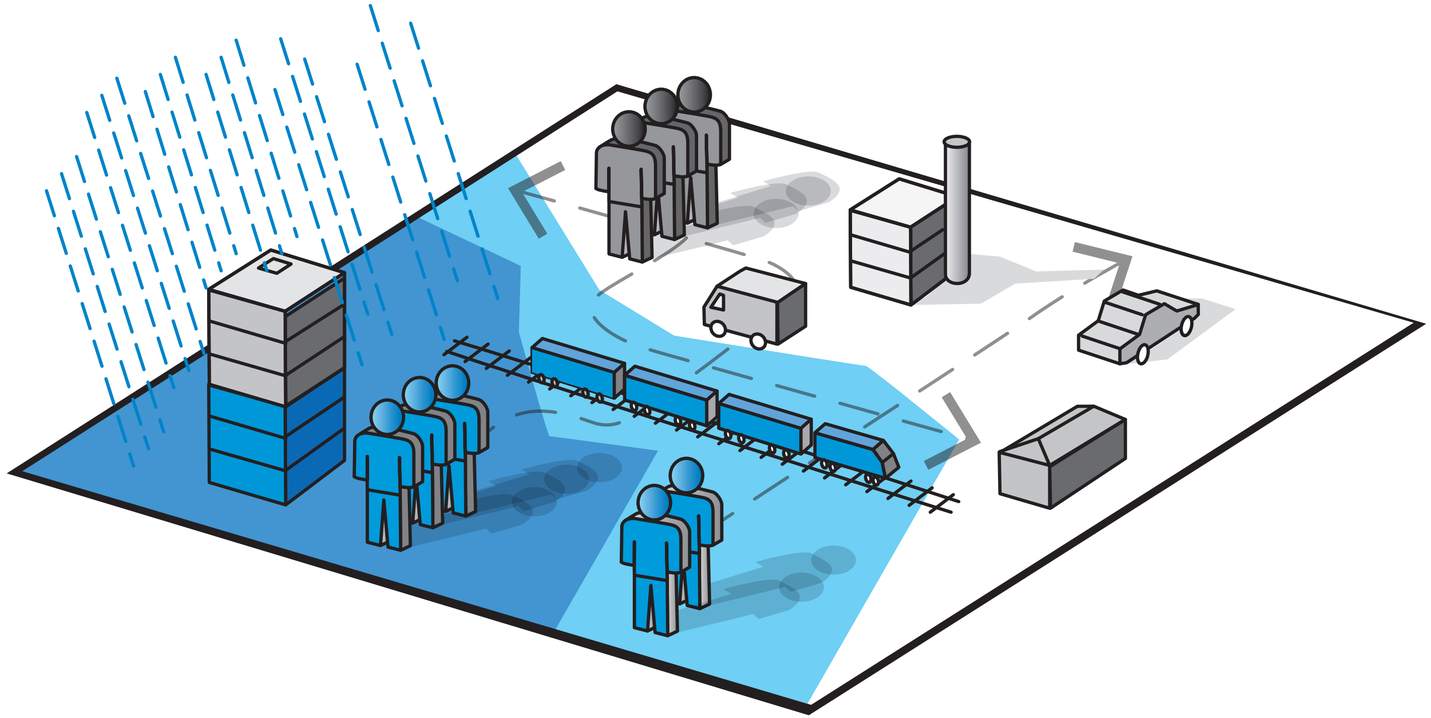
Kokkonen TV, Grimmond CSB, Christen A, Oke TR, Järvi L, **2018**: Changes to the Water Balance Over a Century of Urban Development in Two Neighborhoods: Vancouver, Canada. *Water Resources Research*, 54, 6625 - 6642.

Industrial Snow in the Netherlands (Quelle: NASA)

Climate change

↓

Extreme events



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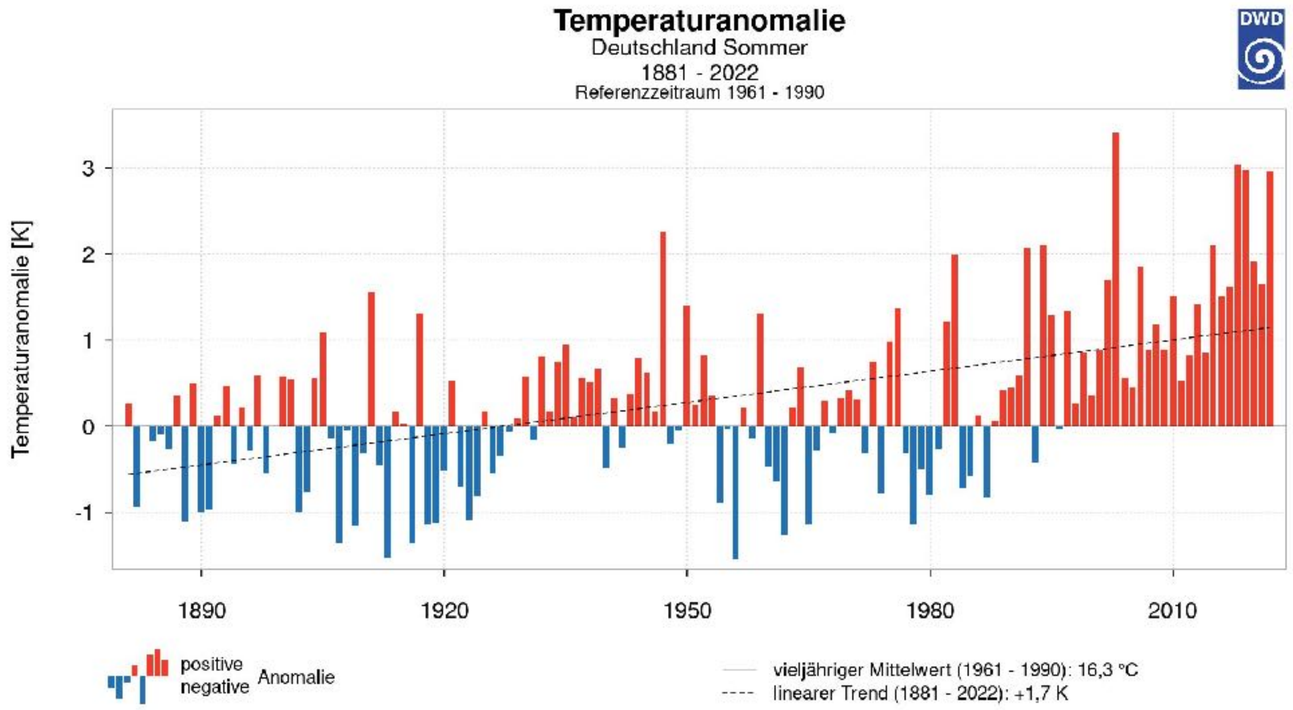
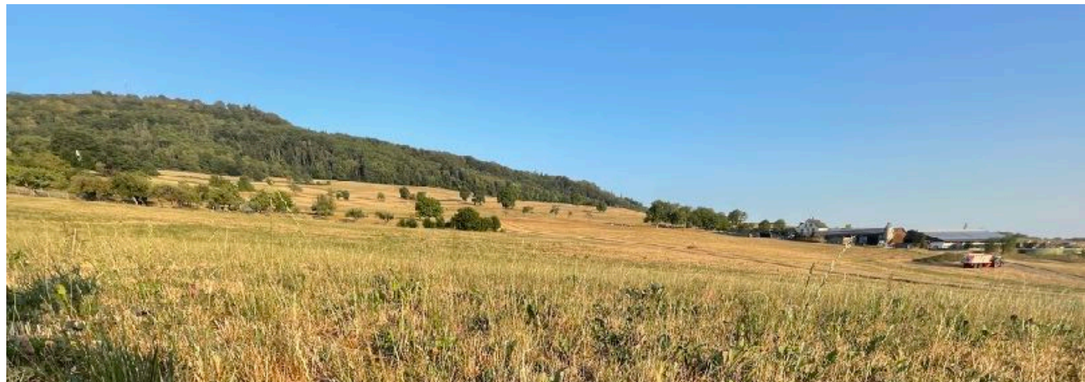
Summer 2022 in Germany



Most sunshine ever - since measurements began. Summer 2022 was one of the four warmest summers since 1881, with a temperature increase of 2.9 K compared to the multi-year average and below-average precipitation.



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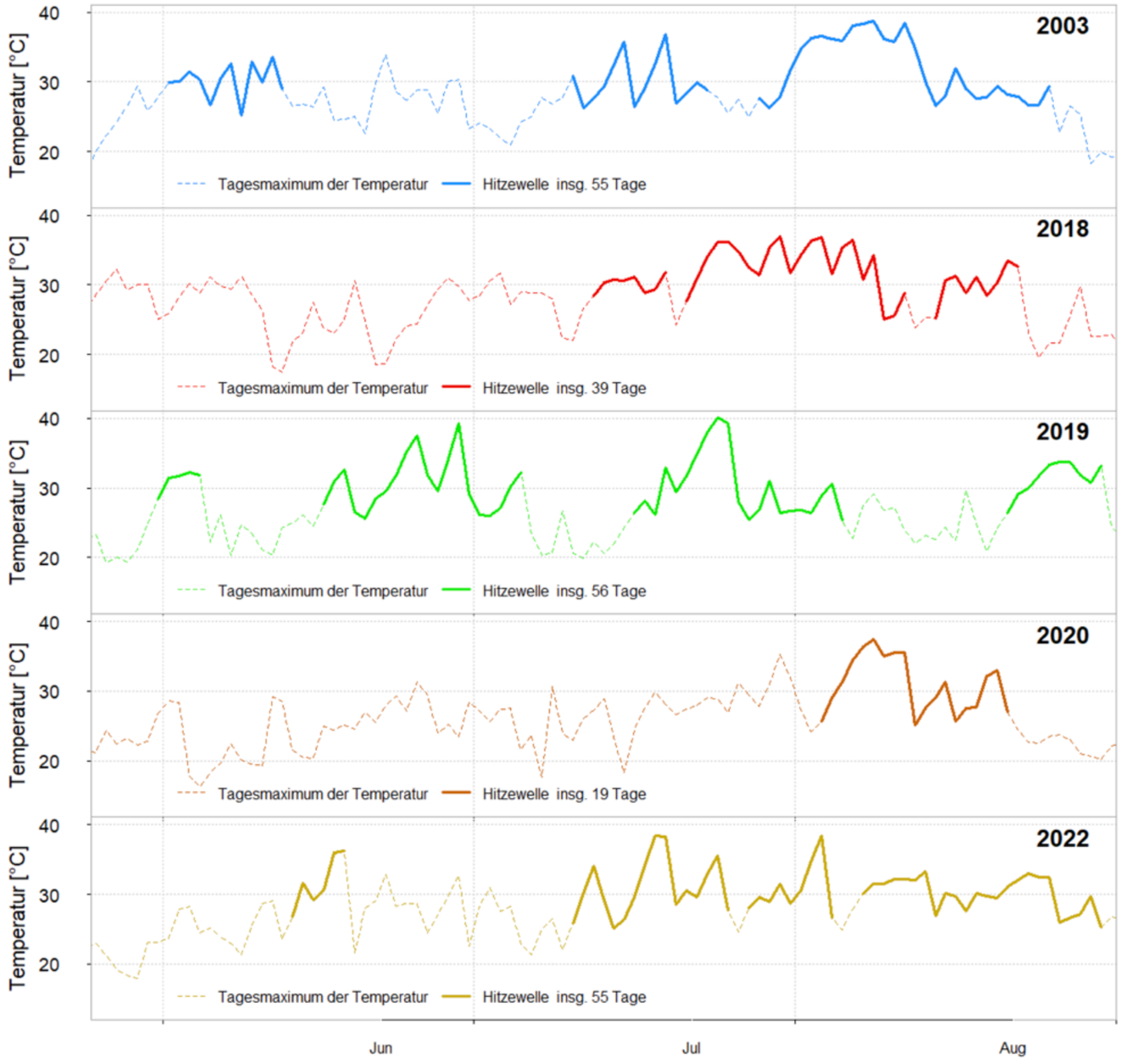
In Frankfurt, Germany, we counted 55 days with a heat-wave, comparable to 2003.



Deutscher Wetterdienst
Wetter und Klima aus einer Hand

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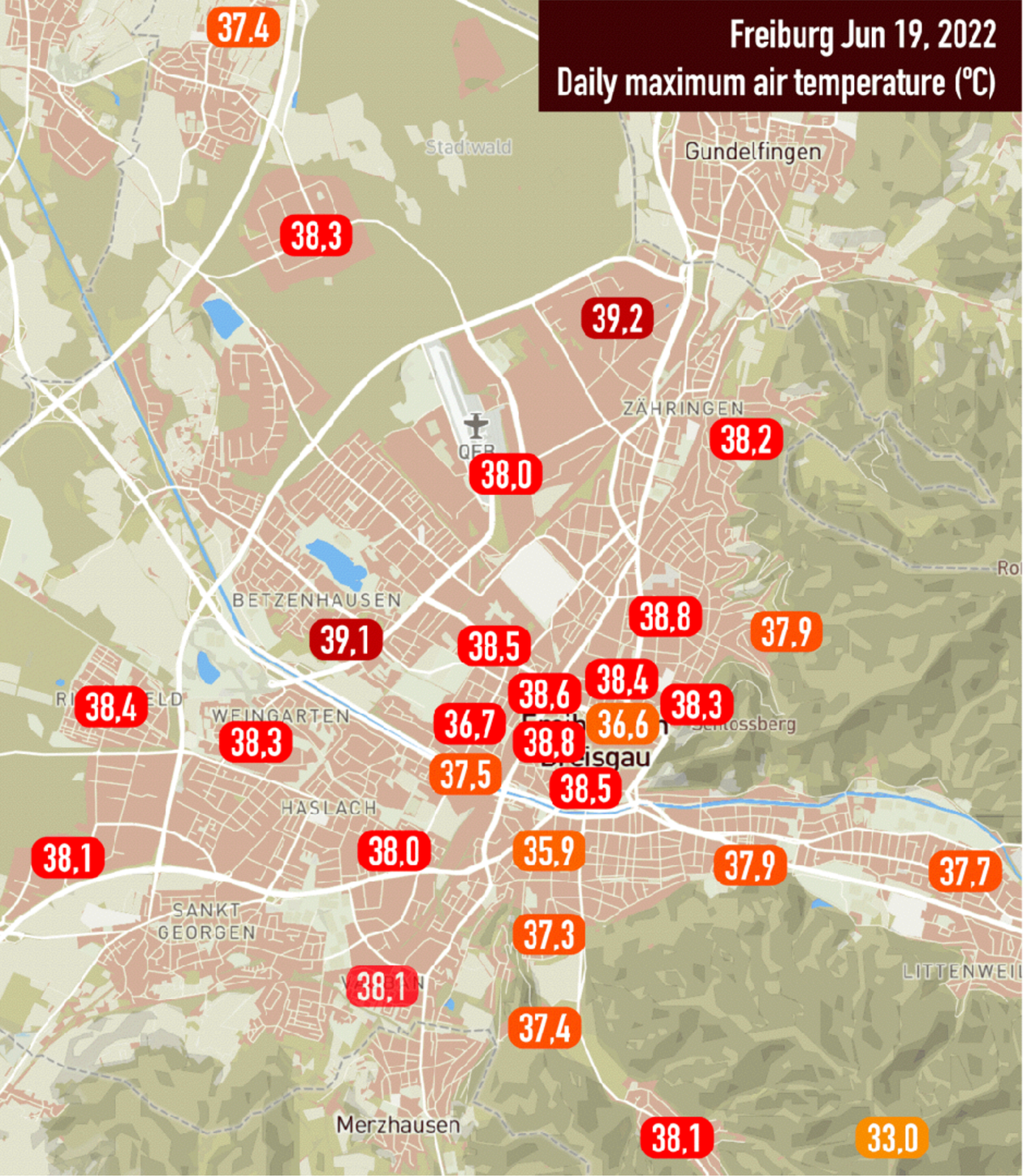
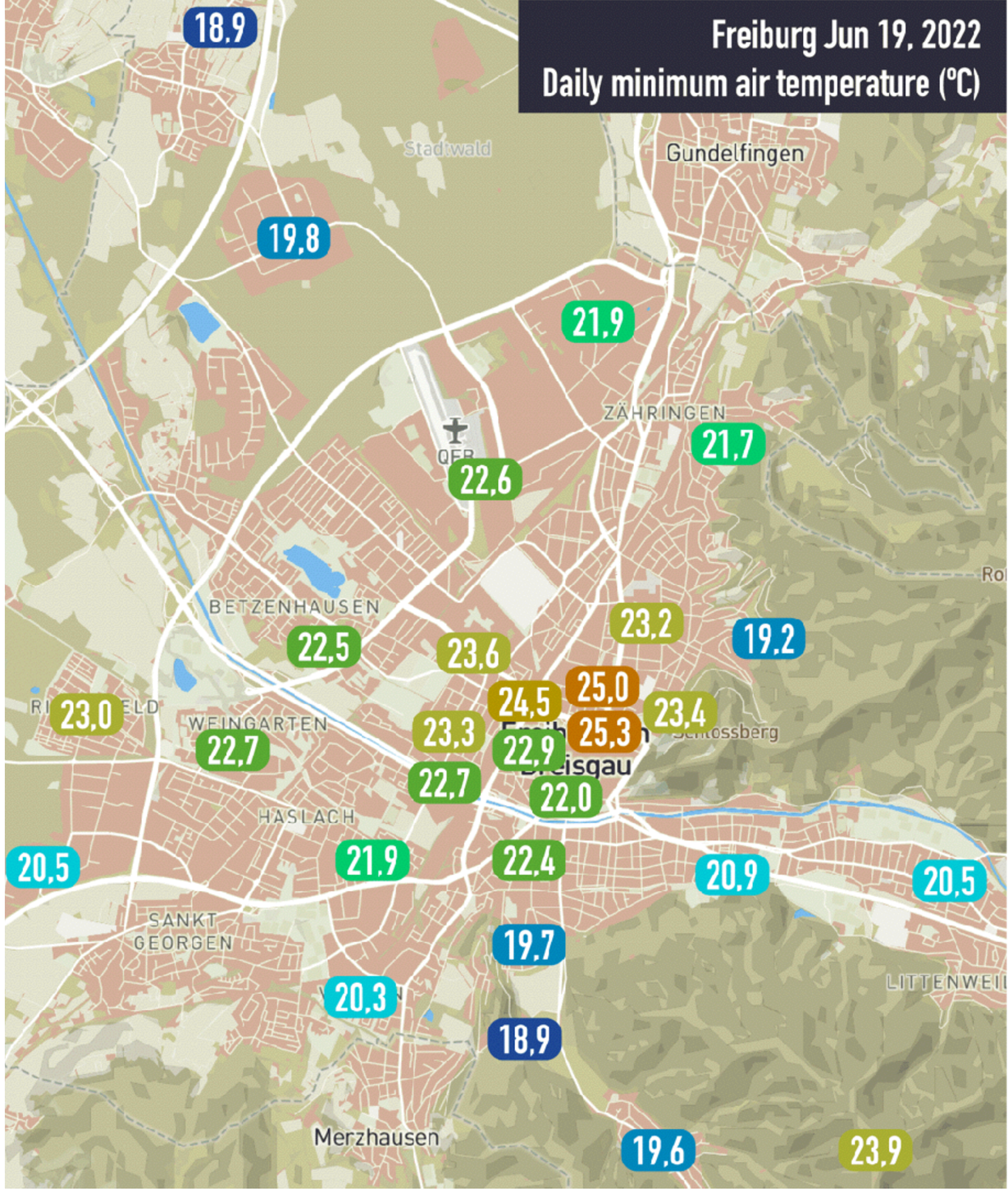
urbisphere

Tier I station
precipitation, temperature, humidity, global radiation, wind, globe temperature, pressure, air quality

Tier II station
Precipitation, temperature, humidity


Freiburg Jun 19, 2022
Daily maximum air temperature (ºC)
37.4
38,3
39.2
38,2
38,0
38,8
37,9
39,1
38,5
38,4
38,6
38,4
38,3
36,7
36,6
38,8
37,5
38,5
38,3
38,1
38,0
35,9
37,9
37,7
37,3
38,1
37,4
38,1
33,0
Stadtwald
Gundelfingen
ZÄHRINGEN
BETZENHAUSEN
WEINGARTEN
HASLACH
SANKT GEORGEN
Merzhausen
Schlossberg
LITTENWEI


Freiburg Jun 19, 2022
Daily minimum air temperature (ºC)
18.9
19,8
21,9
21,7
22,6
22,5
23,6
23,2
19,2
23,0
24,5
25,0
23,4
22,7
23,3
22,9
25,3
22,7
22,0
20,5
21,9
22,4
20,9
20,5
19,7
20,3
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Stadtwald
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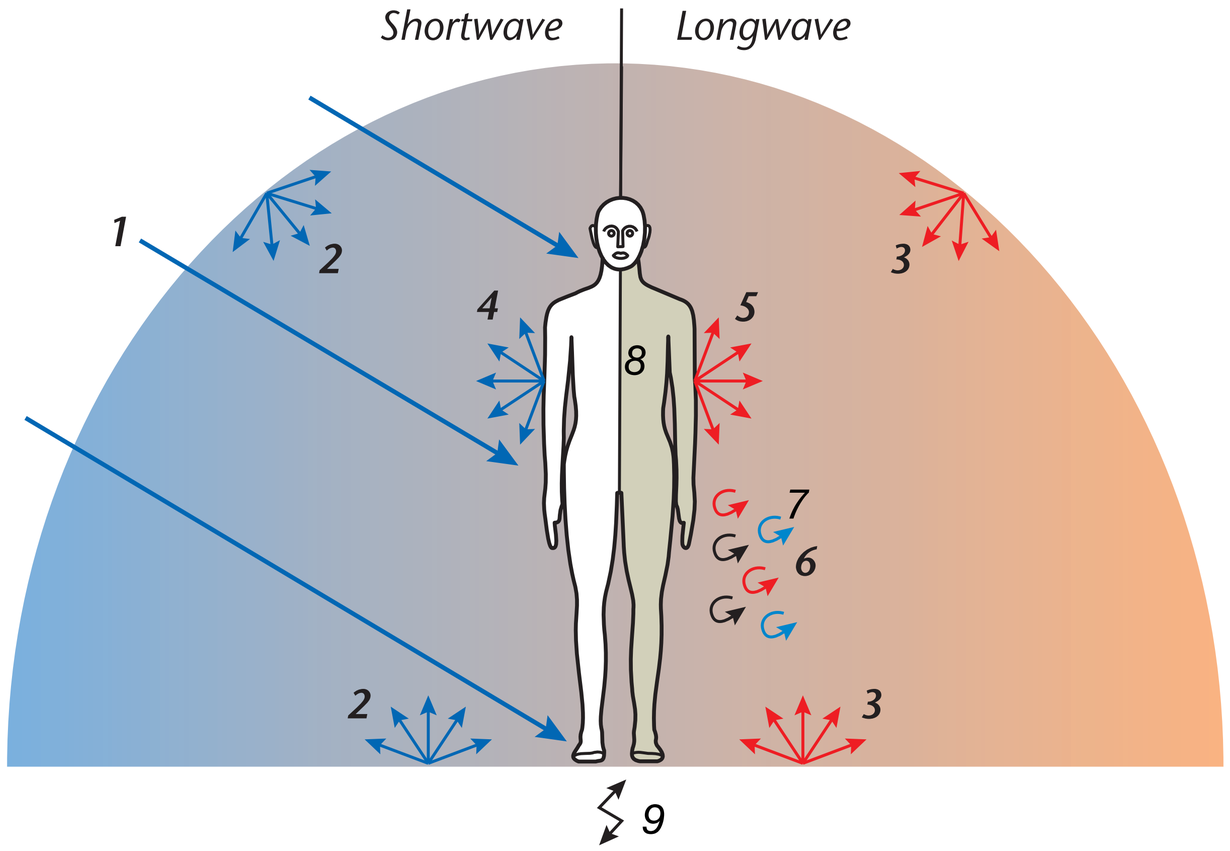
ZÄHRINGEN
BETZENHAUSEN
WEINGARTEN
HASLACH
SANKT GEORGEN
Merzhausen
Schlossberg
LITTENWEI

Thermal comfort



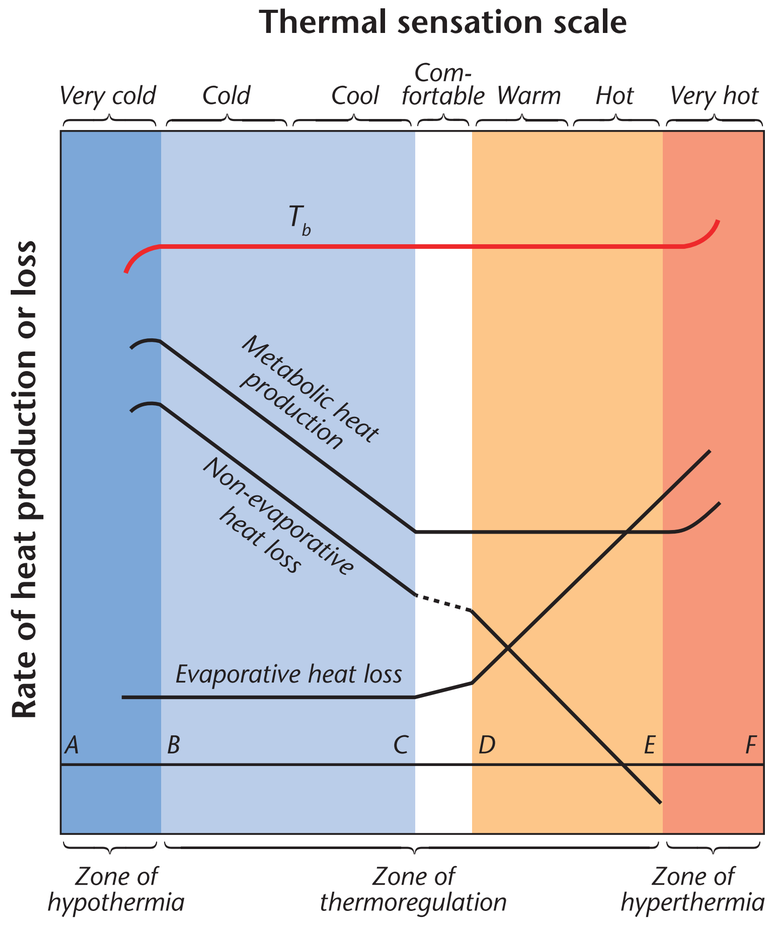
1 Direct solar irradiance incident on human body
2 Diffuse solar irradiance incident on human body
3 Long-wave irradiance incident on human body
4 Short-wave reflectance of human body
5 Long-wave emittance of human body
6 Sensible heat exchange of body
7 Latent heat exchange of body (sweating etc.)
8 Metabolic heat generation in body
9 Conductive heat between body and materials

Source: Oke at al. 2017 (modified)

Thermophysiological response

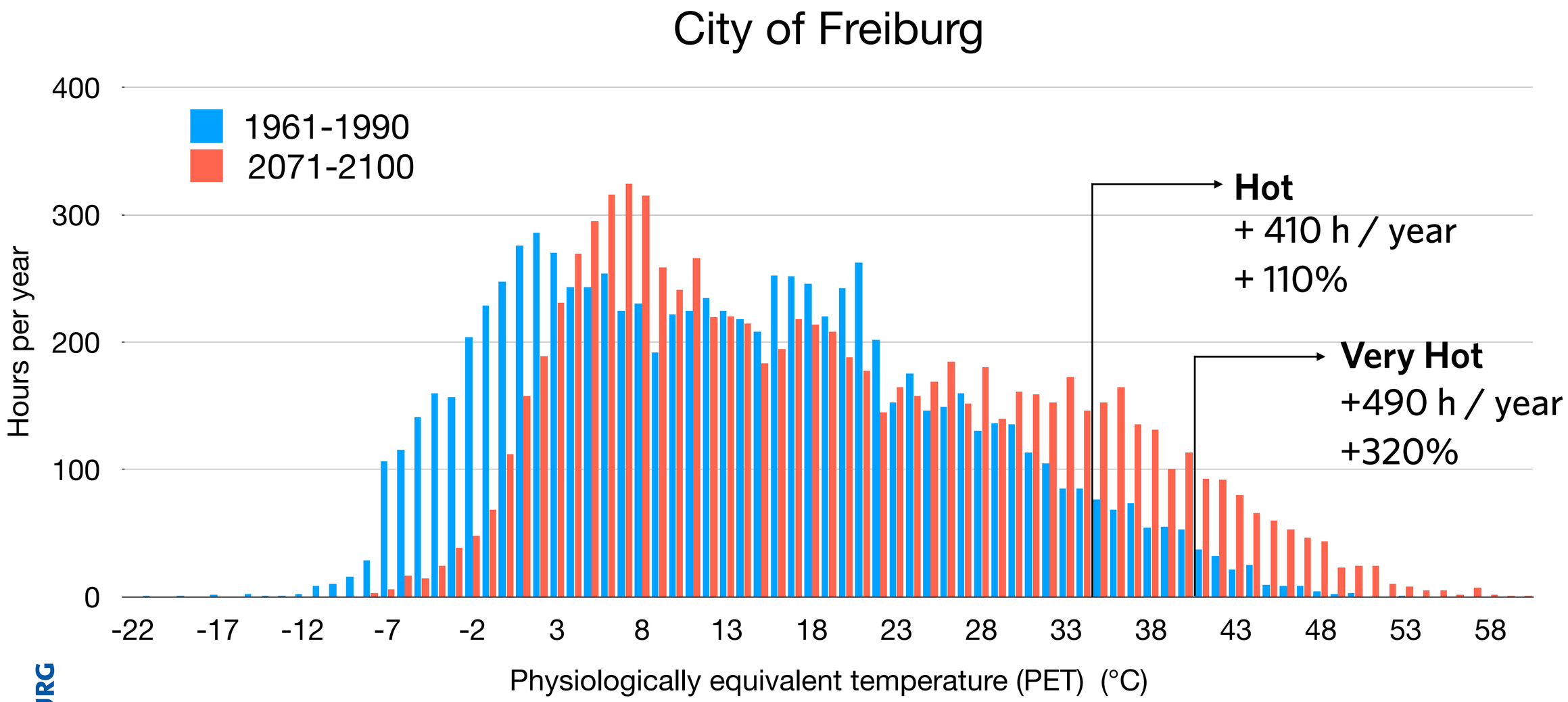
A number of **thermal indices** exist that aim at quantifying human thermal comfort including heat stress (e.g. PET, UTCI, Wind Chill, PMV)

PET	Thermophysiological stress level
<4 °C	extreme cold stress
4 °C to 8 °C	strong cold stress
8 °C to 13 °C	moderate cold stress
13 °C to 18 °C	light cold stress
18 °C to 23 °C	no thermal stress
23 °C to 29 °C	light heat stress
29 °C to 35 °C	moderate heat stress
35 °C to 41 °C	strong heat stress



Source: Oke at al. 2017 (modified)

Climate projections



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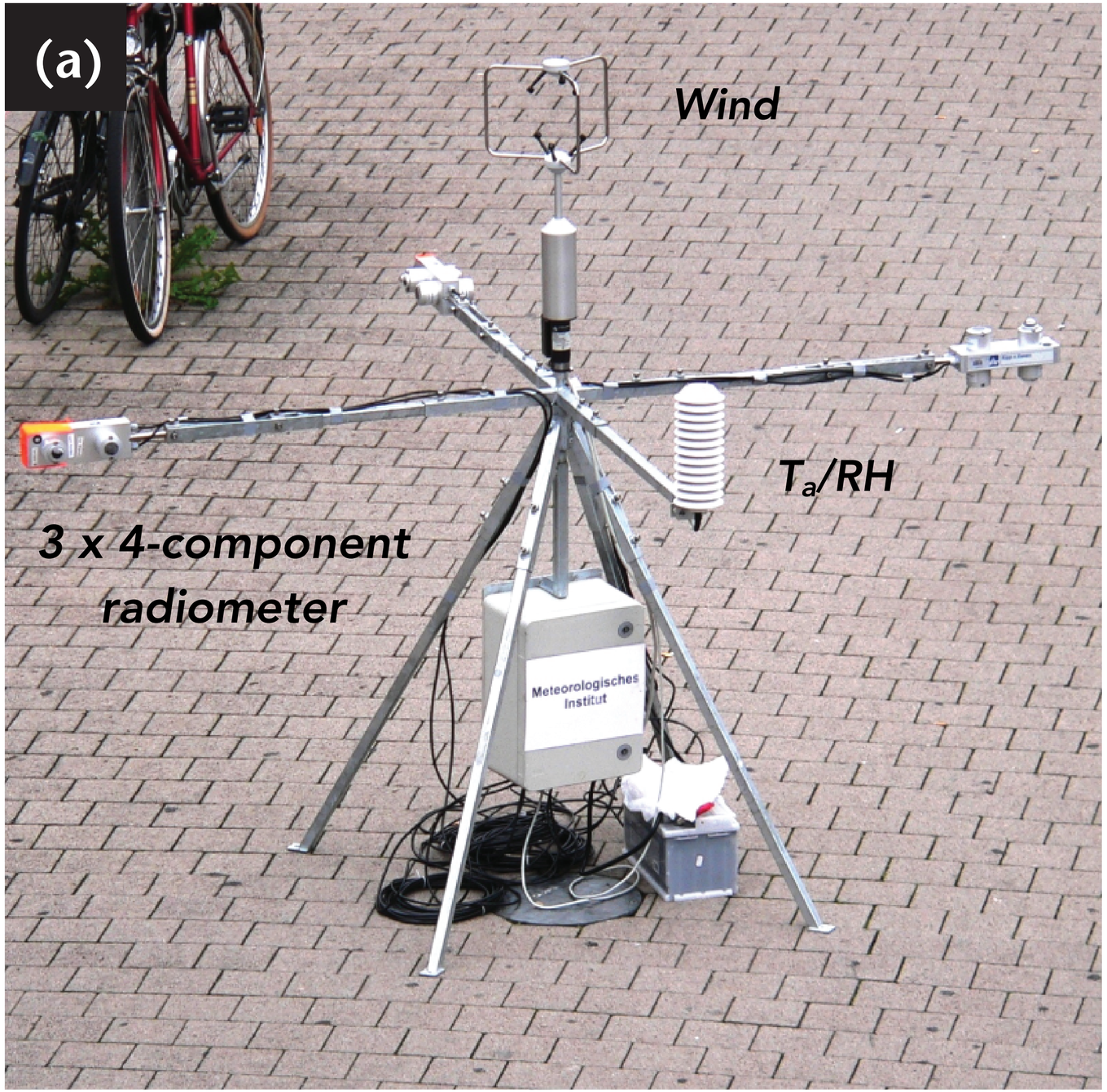
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung
klimazwei
Risiken mindern · Chancen nutzen

Data Source: Matzarakis und Endler, 2010

Consequently, any assessment of thermal comfort needs to consider a number of **environmental** and also **activity / clothing** variables.

The variables needed are not routinely measured at standard weather and climate stations.

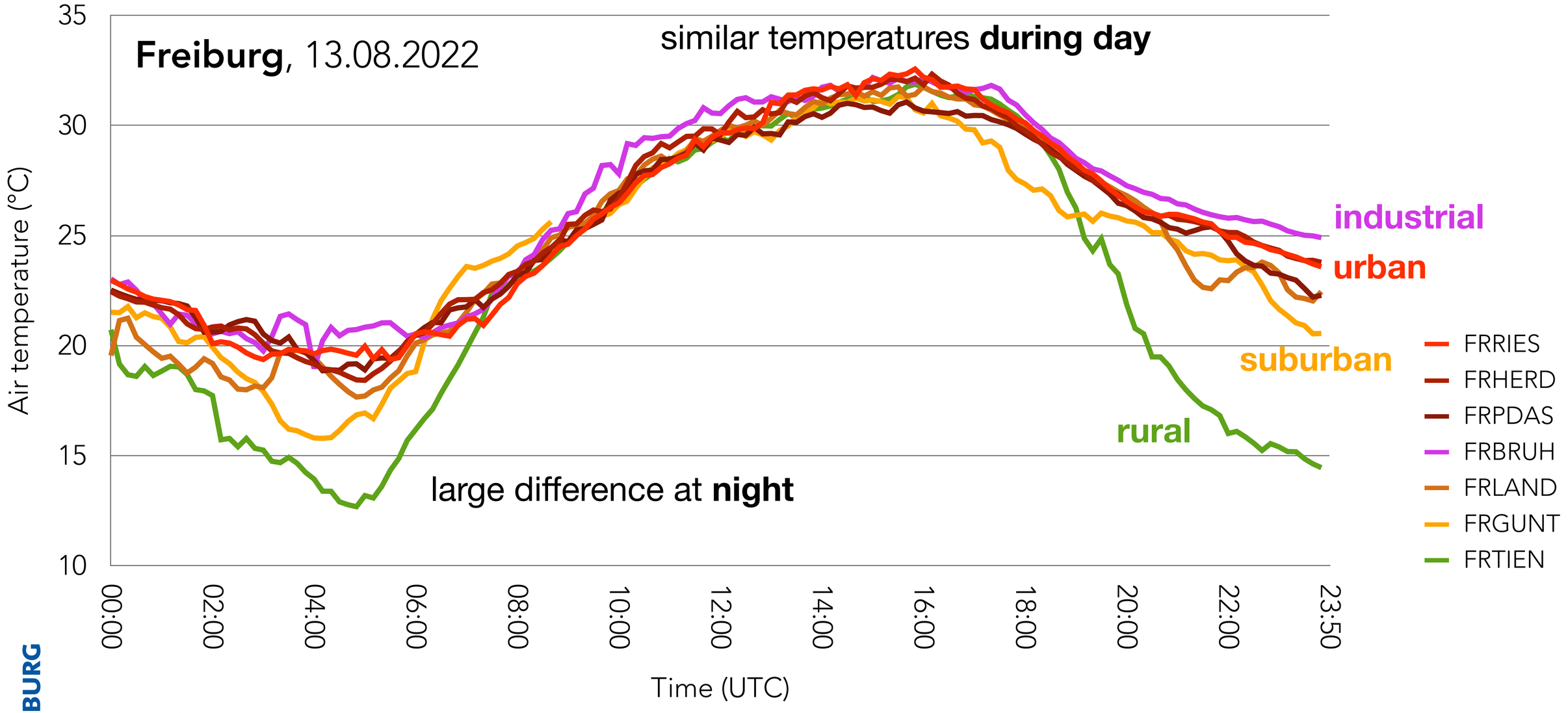
▶ Research observations using 6-sided radiation measurements to measure mean radiant temperatures in Freiburg.



Source: Helmut Mayer

Urban biometeorology station (Photo: A. Christen)

Air temperatures



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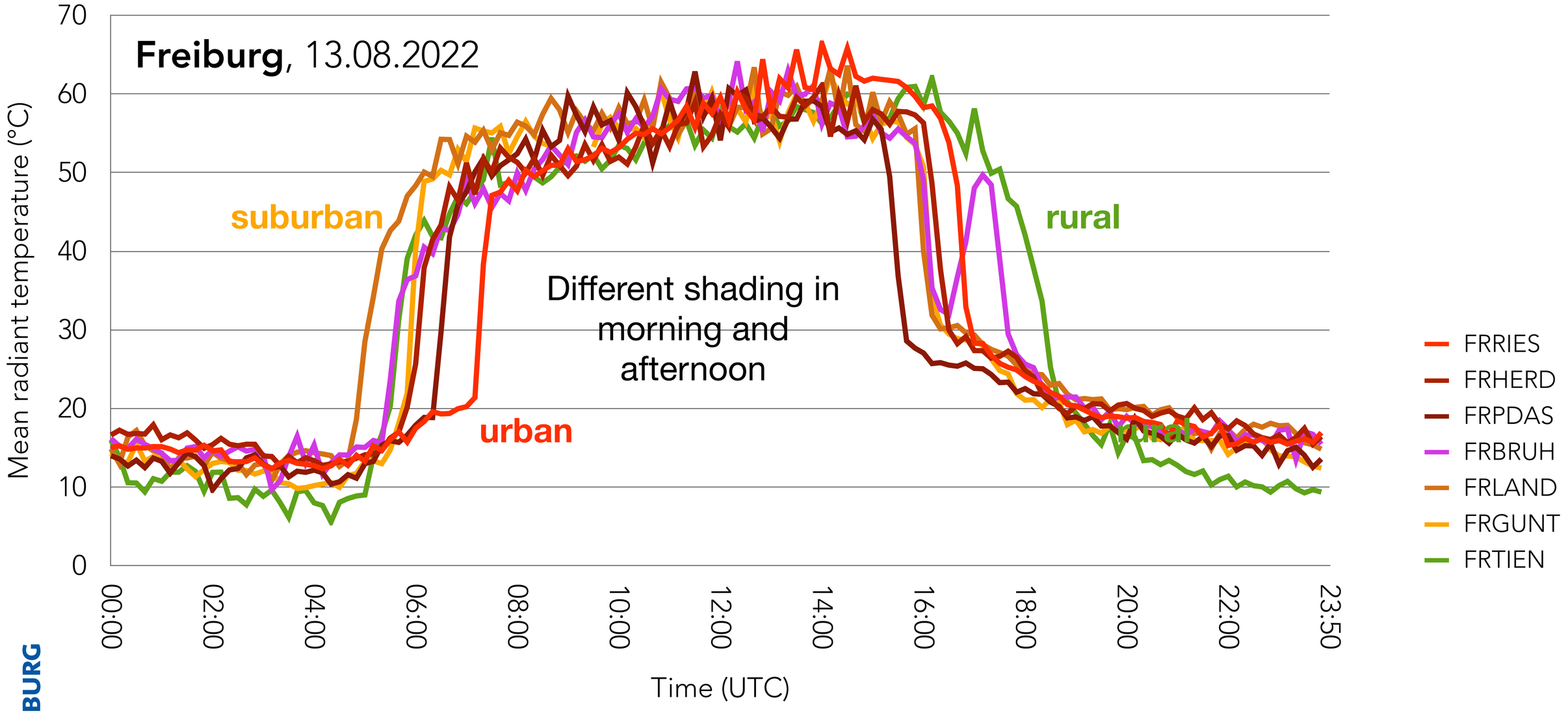
Mean radiant temperature



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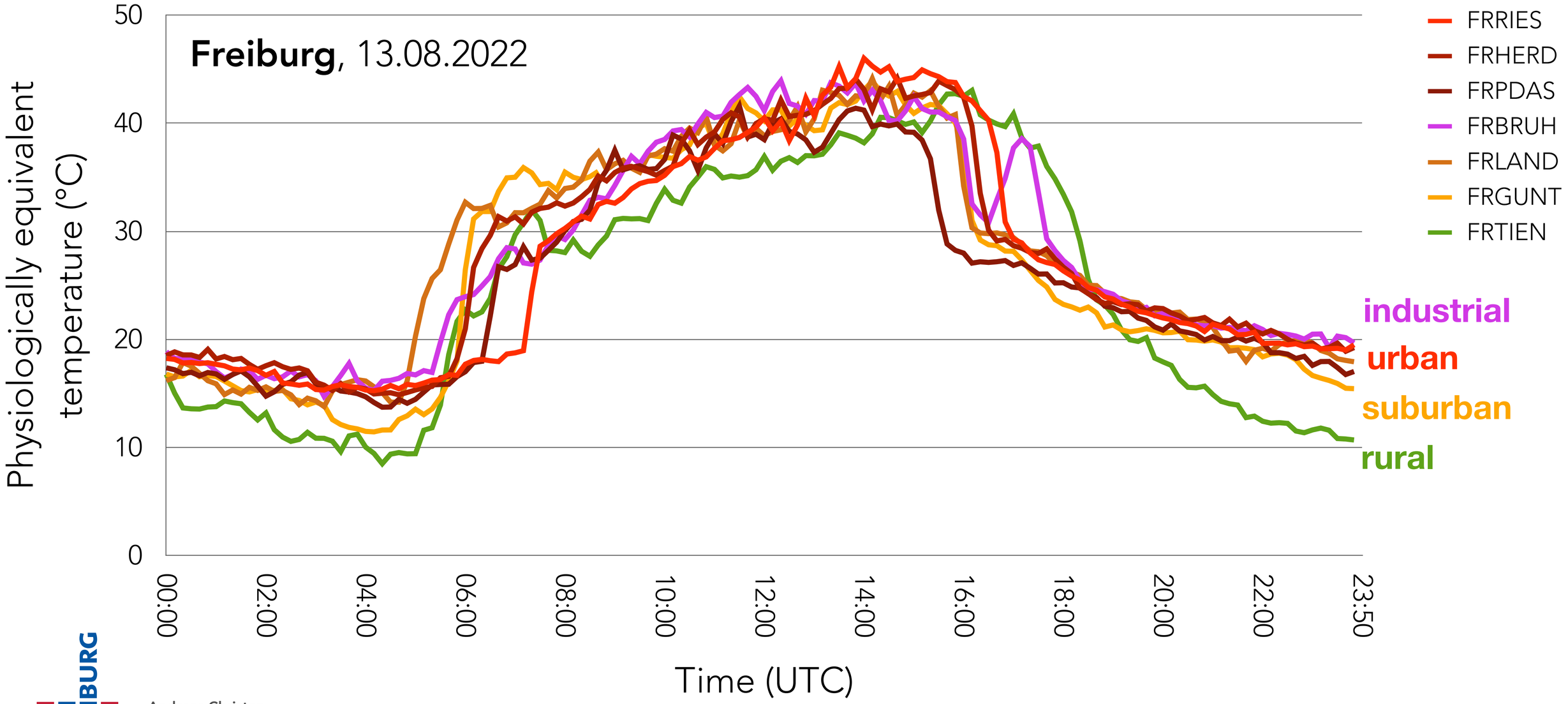
PET



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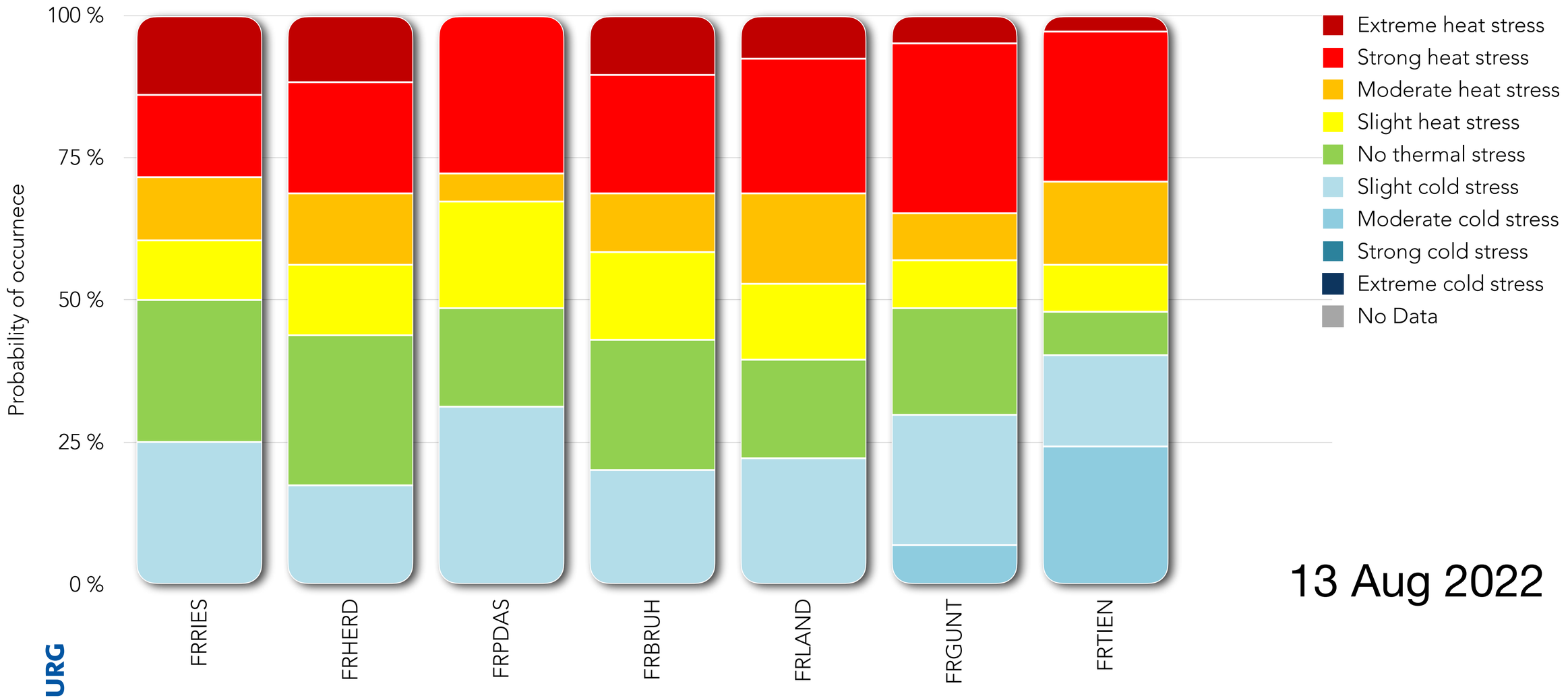
Differences in PET across Freiburg



13 Aug 2022

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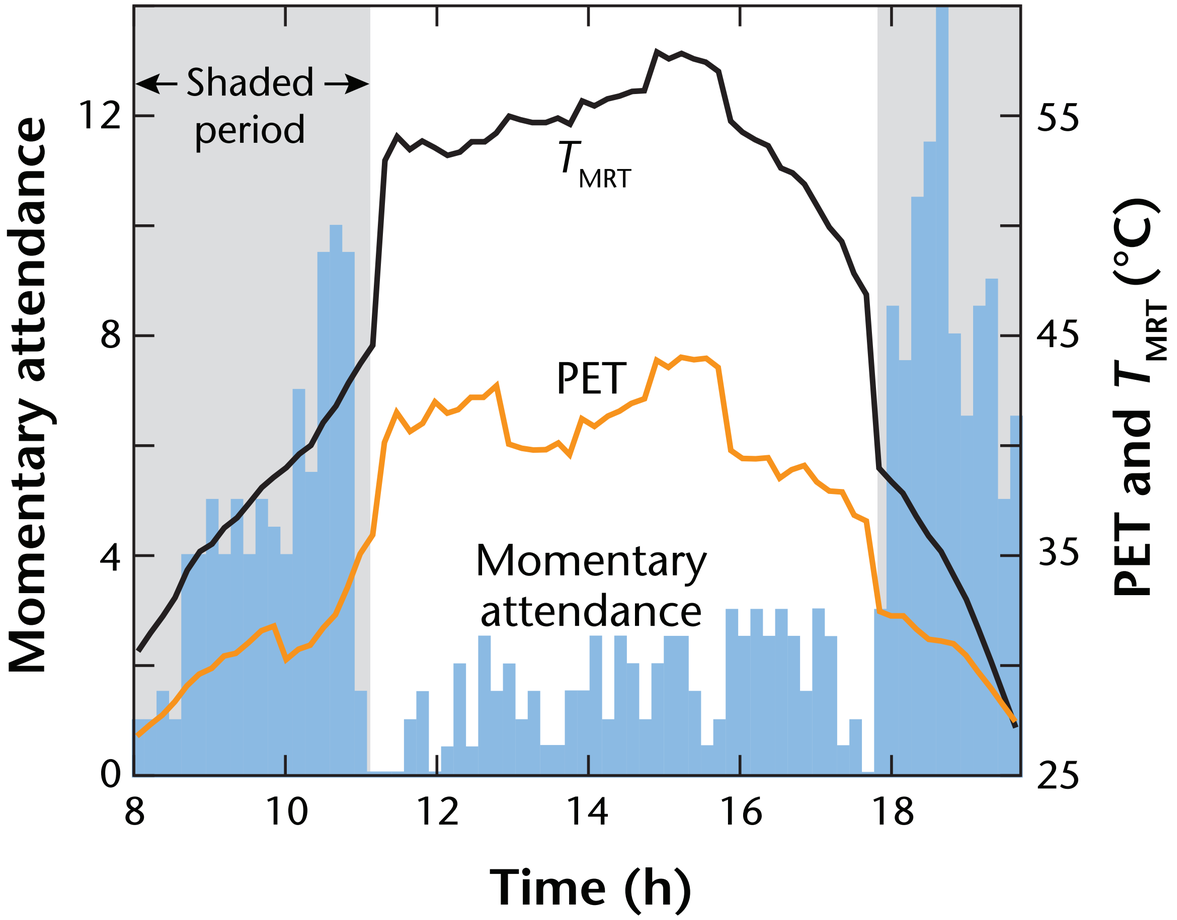
Human adaptive capacity

Assessment of the influence of daily shadings pattern on human thermal comfort and attendance on a public space in Rome during a sunny and warm August day.

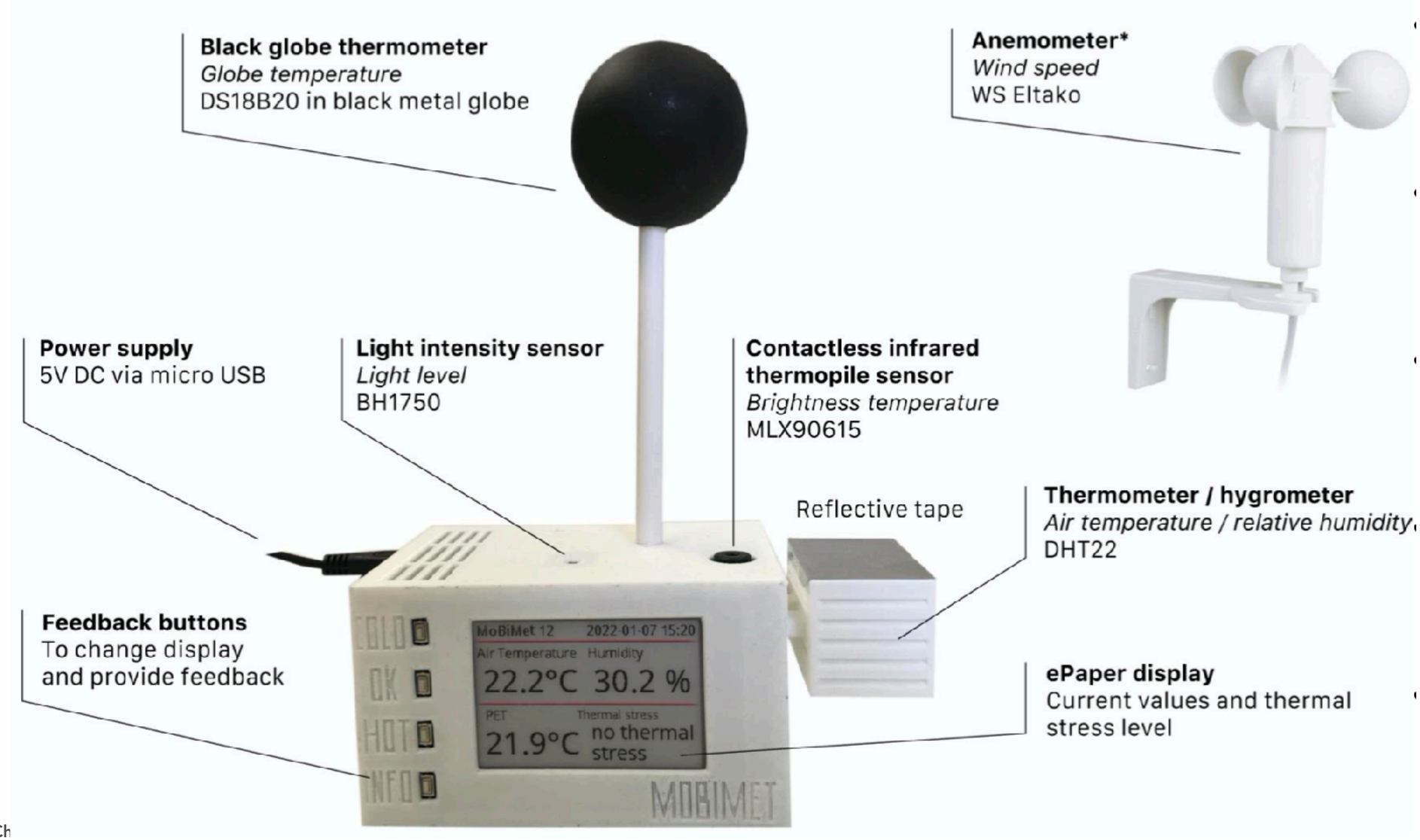
Momentary attendance = people in place (not walking through) for 10 minutes.



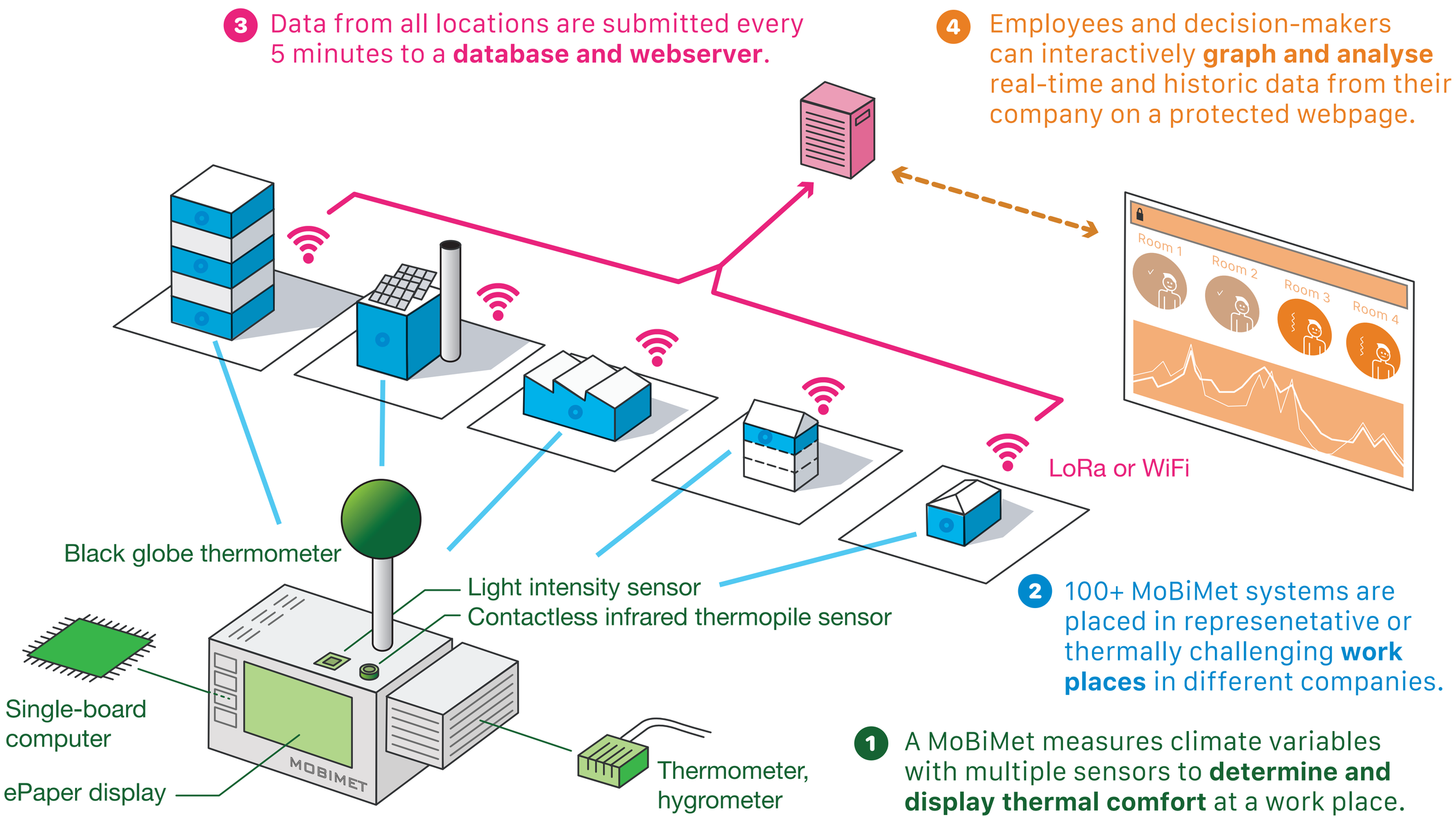
(Source: Oke et al. 2017 after Martinelli et al., 2015).

Mobile biometeorology ("MoBiMet") low-cost sensors (Photo: A. Christen)

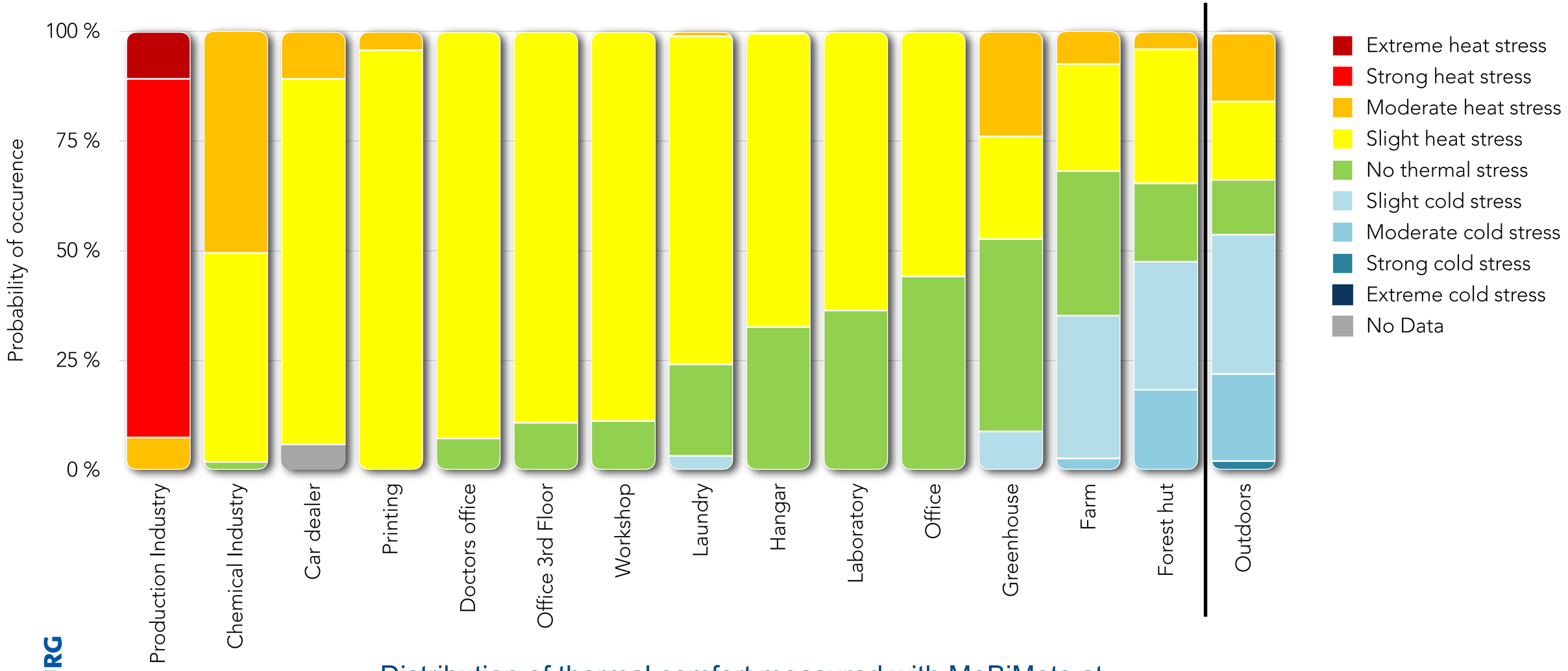
MoBiMet Prototype



Sulzer et al., 2022


3 Data from all locations are submitted every 5 minutes to a **database and webserver**.
4 Employees and decision-makers can interactively **graph and analyse** real-time and historic data from their company on a protected webpage.
Room 1
Room 2
Room 3
Room 4
LoRa or WiFi
Black globe thermometer
Light intensity sensor
Contactless infrared thermopile sensor
Single-board computer
ePaper display
MOBIMET
Thermometer, hygrometer
2 100+ MoBiMet systems are placed in represenetative or thermally challenging **work places** in different companies.
1 A MoBiMet measures climate variables with multiple sensors to **determine and display thermal comfort** at a work place.

Differences in indoor PET across Freiburg



Distribution of thermal comfort measured with MoBiMets at different workplaces in Freiburg during a cloudless week from September 2 to 9, 2021.

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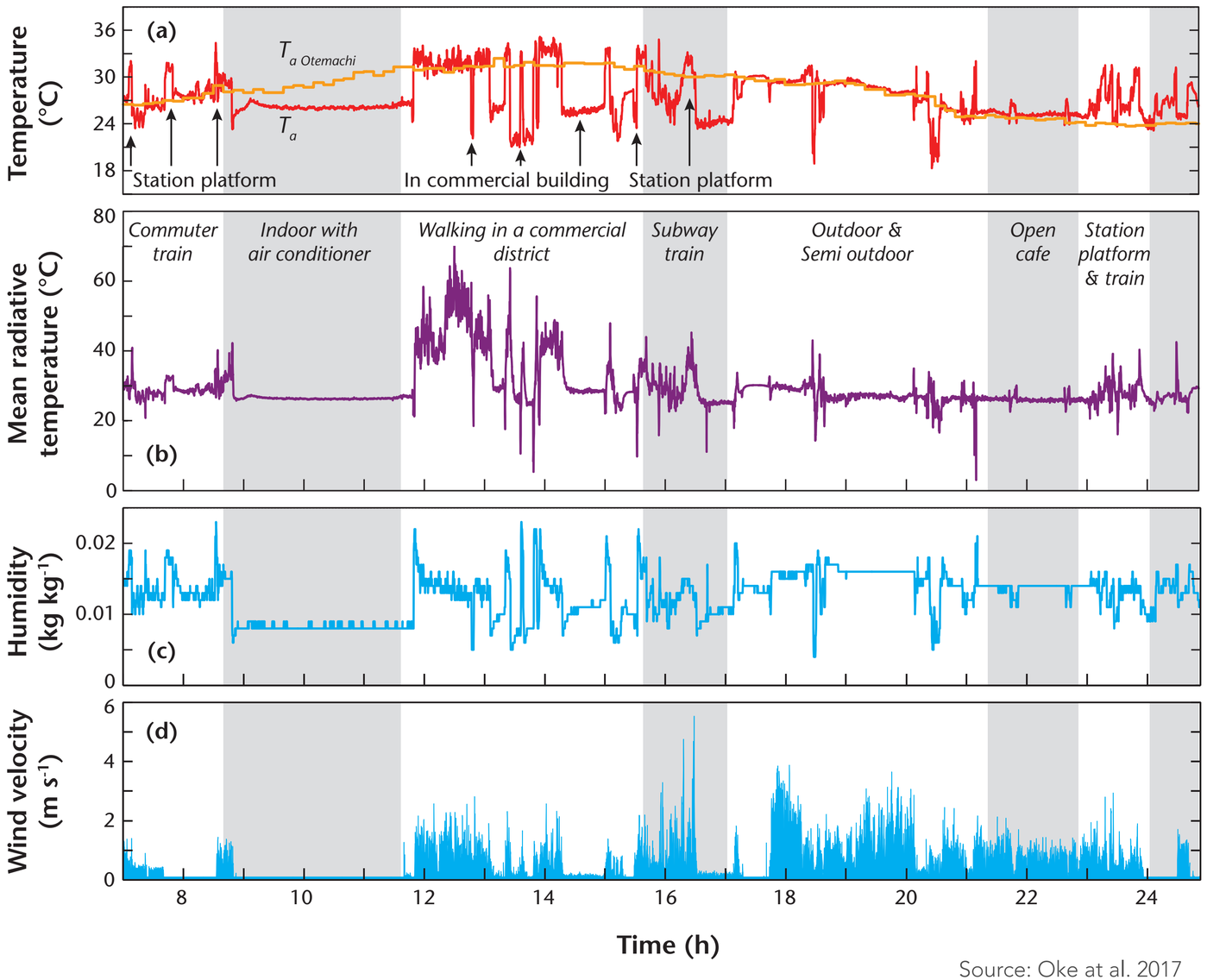
Data Source: Sulzer et al., 2022

Need for agent-based observations

People are mobile and experience transient environ-ments.



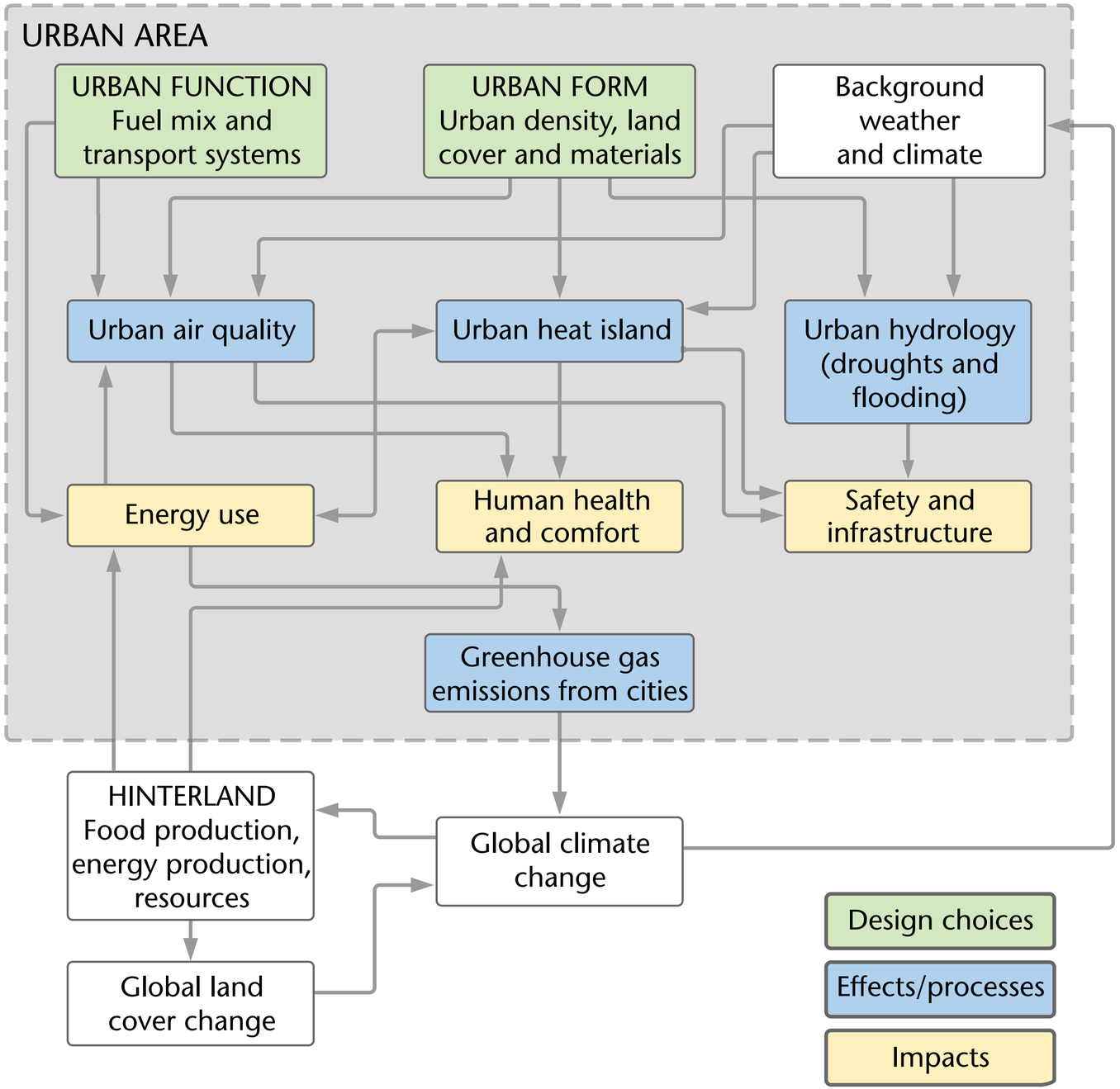
Source: Oke at al. 2017

Differential adaptive capacity

People can **move** through an urban environment, but for different individuals, their **degree of freedom** can be different and accessibility to healthy environments can be limited based on socio-economic disparities (differential **adaptive capacity**)

Big challenge to incorporate this in urban climate sciences, opens new field of **urban climate justice**.

Marginalised groups during a heat wave in Canada, Emergency cooling centres (Photos: CBC)



Oke TR, Mills G, Christen A, Voogt JA (**2017**): "Urban Climates", Cambridge University Press

Urban **design choices** will have effects on **urban heat, air quality, hydrology and emissions** and are interlinked with **impacts** on **urban health, energy use and safety.**

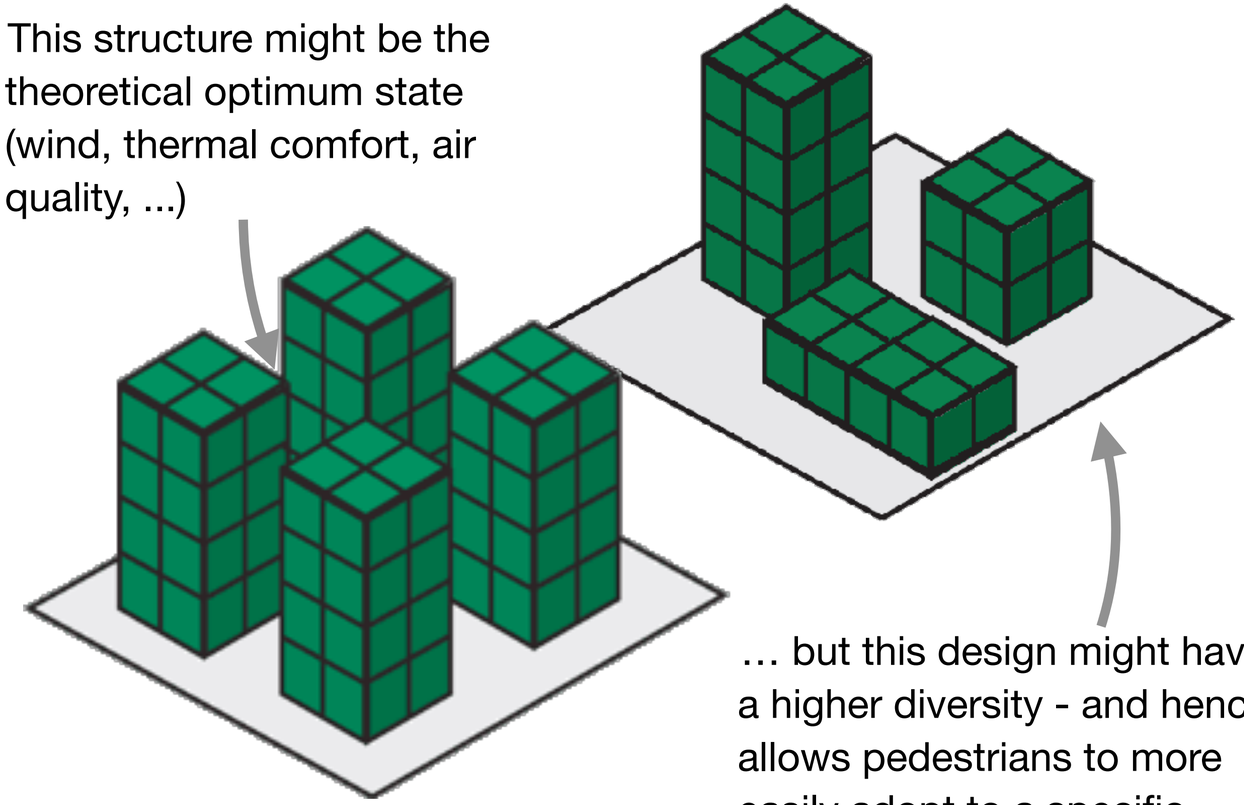
Urban design is therefore a powerful tool for local climate adaptation and allows to increase the resilience of cities to extreme atmospheric events and climate change.

Dynamic and diverse urban climate design

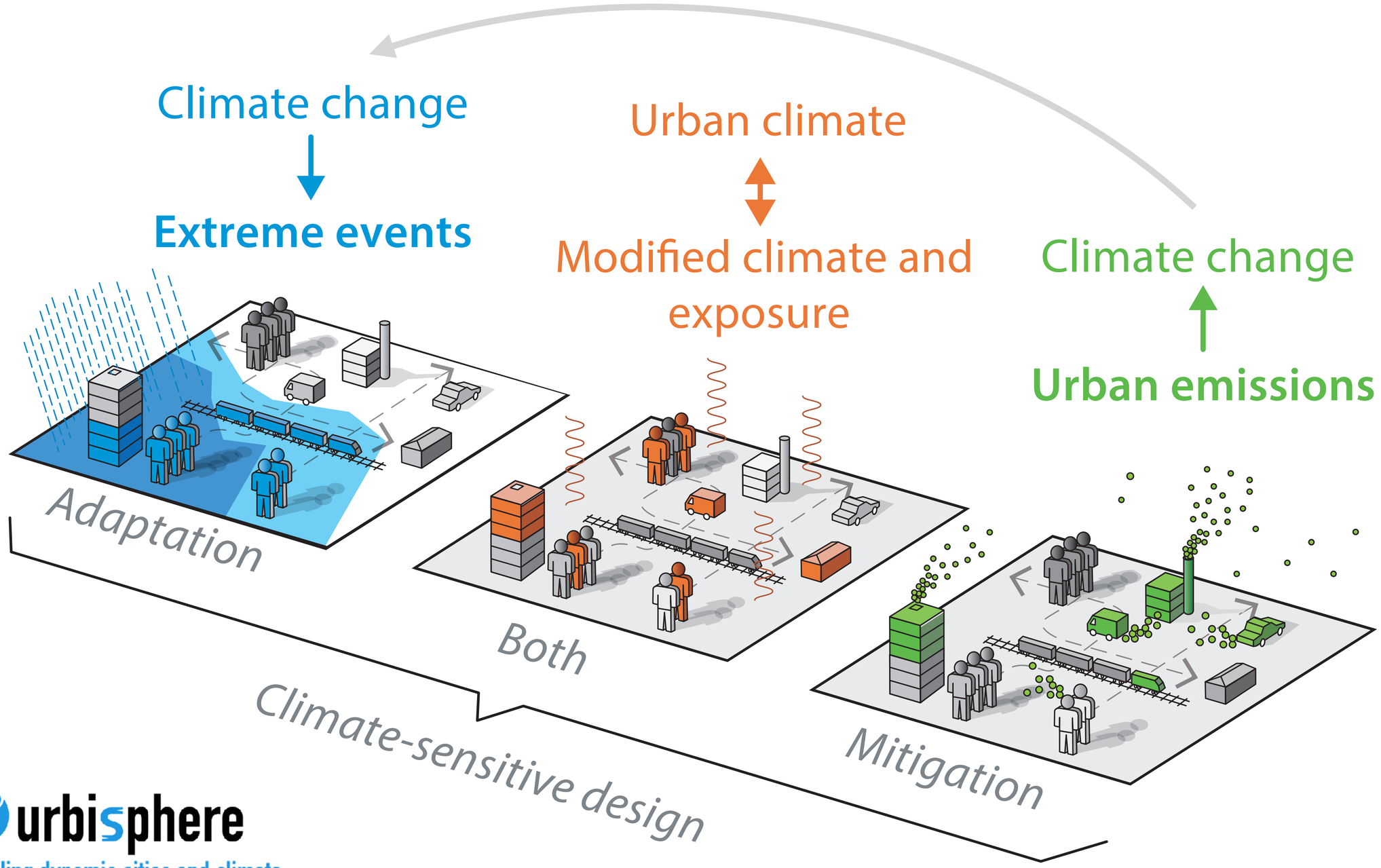
Generate multi-purpose spaces, flexible and diverse design approaches to adapt to climate change.

Multi-use open spaces and flood retention ponds. Photo: Dar Group (World Bank)

This structure might be the theoretical optimum state (wind, thermal comfort, air quality, ...)



… but this design might have a higher diversity - and hence allows pedestrians to more easily adopt to a specific stress situation by providing a choice.



urbisphere
coupling dynamic cities and climate

erc

Take home messages

- Global **urbanization** results in am increasingly **larger share of humans living in cities** - highest urbanization and population growth in the Global South. Historically, urbanization was closely tied to climate and climate variability, no longer the case but this makes cities **more dependent** on energy, water and food imports.
- The **urban metabolism** is a concept to understand, quantify and predict the human impacts on the atmosphere at the scale of cities - Human dynamics are linked to **emissions** of greenhouse gases, heat and water vapour.
- Impact on urban populations: Large microscale variability of heat exposure. People can **move** but their **degree of freedom** differs and the **accessibility** (adaptive capacity) of comfortable micro-environments can be limited - big challenge: **urban climate justice**.
- Solutions: Provide assessments and forecasts **at the scale of decision making**, and in the long-term create **diverse**, **adaptive** and **multi-use urban spaces** through design, planning and governance.

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@envmet

Thank you for the invitation

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Dr. James Voogt, Western University
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(Photo: Andreas Christen)

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