

Monitoring Indoor Climate Extremes involving Residents and IoT

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Objectives

- Collect empirical data on **indoor heating levels** in low-cost housing across two neighbourhoods (Choba and Wattville) near Johannesburg;
- Document **building characteristics** that influence indoor thermal performance;
- Generate evidence-based insights to inform **regulations and retrofitting strategies** for climate-resilient housing
- Generate **a dataset for further analysis** and **as the foundation for a statistical model** to predict indoor climate



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- Project leadership
- Field team coordination
- Survey administration
- Sensor installation
- Community engagement



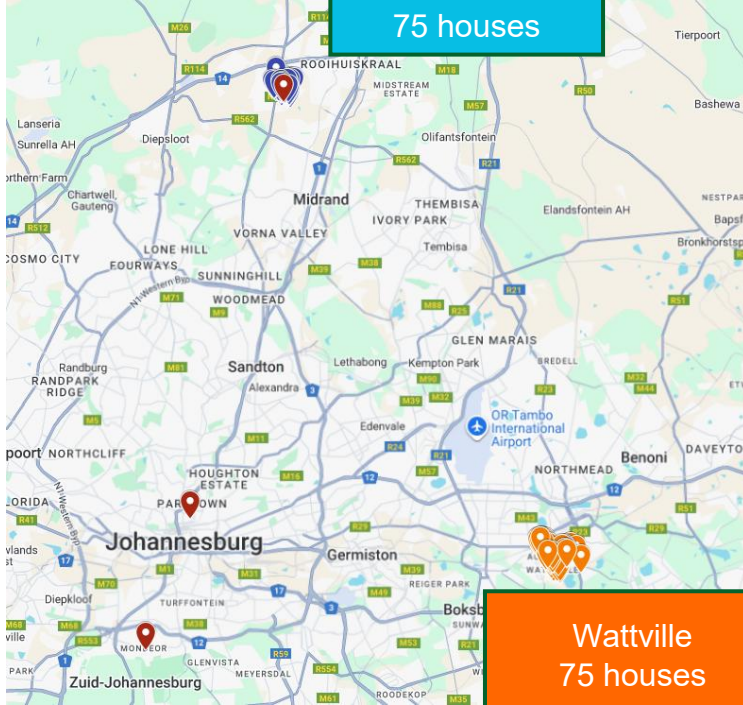
- Measurement campaign design
- Building-characteristics survey design
- Dashboard implementation
- Data analysis



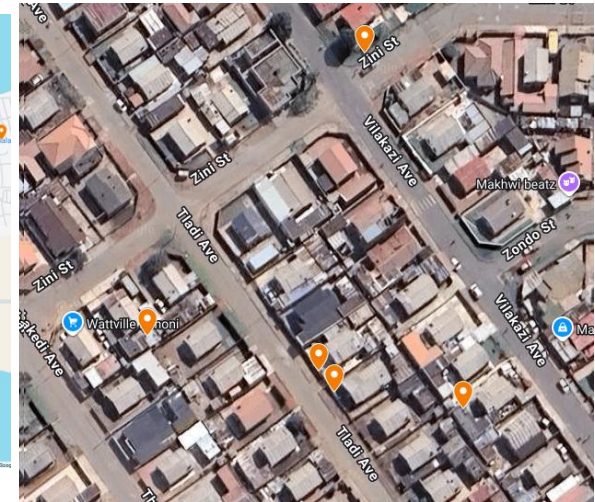
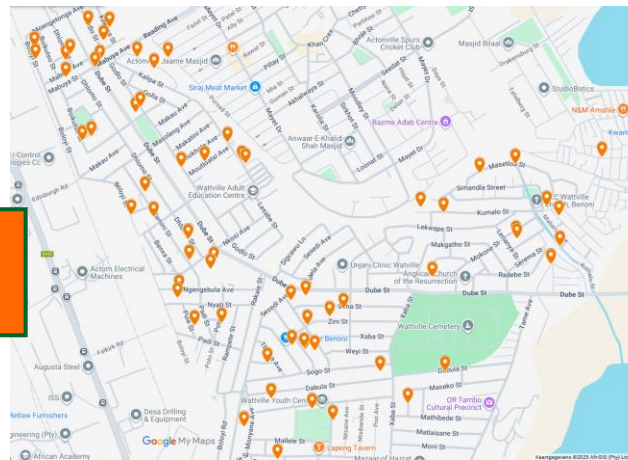
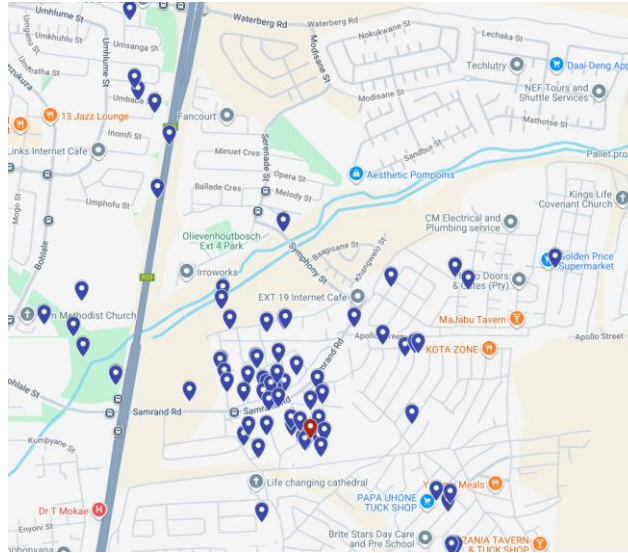
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Setting

Choba
75 houses



Wattville
75 houses



vito

planact

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Building characteristics

- Use of clappia surveys

🔍 Walls and floor

Floor material *

☐ Dirt/Earth ☐ Tile ☐ Wood ☒ Concrete ☐ Stone

☐ Epoxy Coating ☐ Bamboo ☐ Carpet ☐ Other

☐ Not Applicable

Walls material *

☐ Earth/Clay ☐ Clay & Dung ☐ Wood

☐ Stone or Bricks or concrete ☐ Plaster or Stucco ☒ Metal Panels

☐ Not applicable

These are the primary exterior walls of the house. Do not include inside walls

🔍 Doors and widows

Only count doors and windows that lead directly outside; do NOT include interior ones

Doors *

☐ 0 ☒ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

☐ 7 ☐ 8 ☐ 9 ☐ 10 ☐ More

Number of doors of the house. Do not count the ones that are NOT giving to outside.

Windows *

☐ 0 ☐ 1 ☒ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

☐ 7 ☐ 8 ☐ 9 ☐ 10 ☐ More

Number of windows of the house. Do not count the ones that are not giving to outside.

🔍 Front wall

This is the wall with the entrance door

Number of windows *

☐ 0 ☒ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Picture of front wall *

Door-to-wall ratio (in %) *

Number of doors

☐ 0 ☒ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Number of doors on the Front wall. Do not count the ones that are not giving to outside.

Type of window *

☐ None ☒ Fixed Windows ☐ Bars in front of window

☐ Sliding Windows ☐ Casement Windows

☐ Louvered/Shutter Windows ☐ Not applicable

Window-to-wall ratio (in %) *

Building Dimensions and Form

Length
Width
Height
Orientation

Construction Materials and Thermal Properties

Walls material
Roof material
Type of roof
Roof colour
State of roof
Floor material

Insulation and ventilation

Ventilation Type
Ceiling under roof

Windows and Doors

Doors total
Windows front
Windows total
Window-to-wall ratio
Type of window
Doors front
Door-to-wall ratio

Surrounding Environment and Shading

Facade numbers
Density of surrounding houses
Density surrounding vegetation
Trees in neighbourhood
Trees close to house
Trees covering roof

Other

People living in house
Sensor in kitchen



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Indoor heat measurements

- IoT sensors for near-real-time monitoring
- Market analysis and field test in both neighbourhoods before full deployment (October 2025)
- Sensor: Dragino S31B-NB
 - Temperature
 - Humidity
 - NB-IoT connectivity
- Pre-configured by IoT360 (South Africa), including SIM card management



Indoor heat measurements

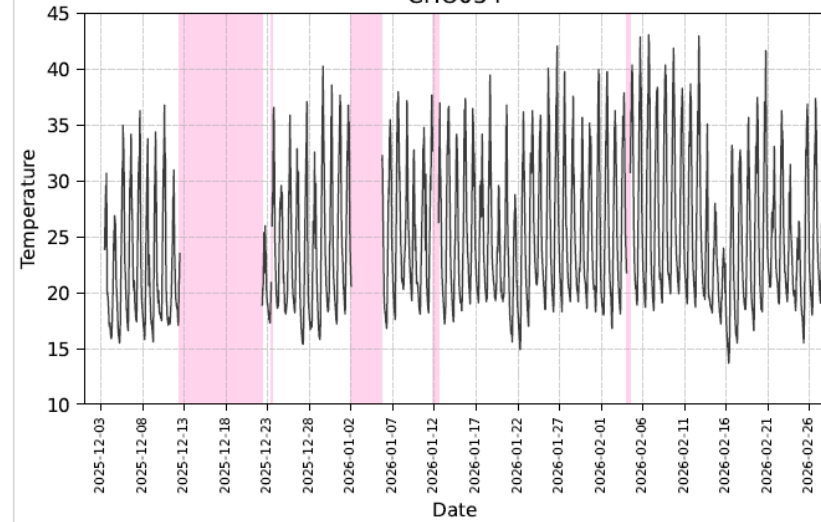
- Standardised installation protocol
 - Mounted at 1.5–2 m height, away from the roof
 - On the coolest wall of the house (south-facing)
 - Away from windows
 - Insulated cardboard enclosure to shield the sensor from radiant heat
- Data used: 01/09/2025 – 30/04/2026 (longer dataset available)



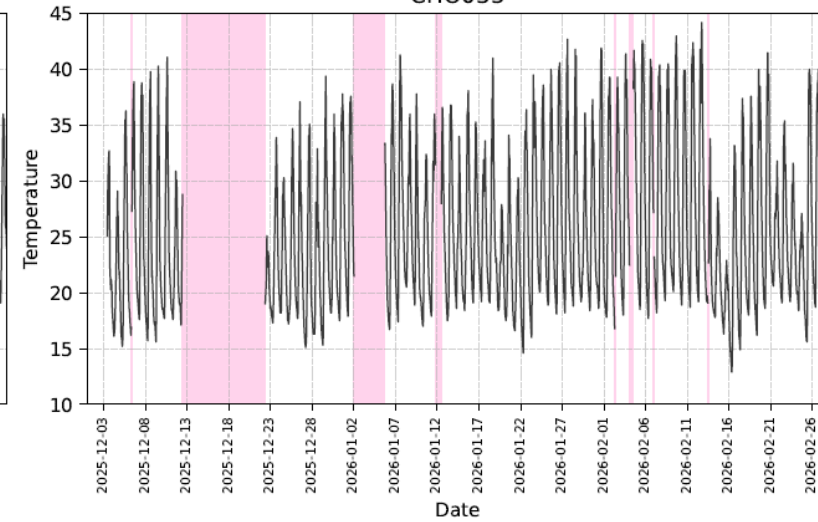
Examples of deployment of sensors in two of the study houses

Indoor heat measurements: examples of sensor measurements

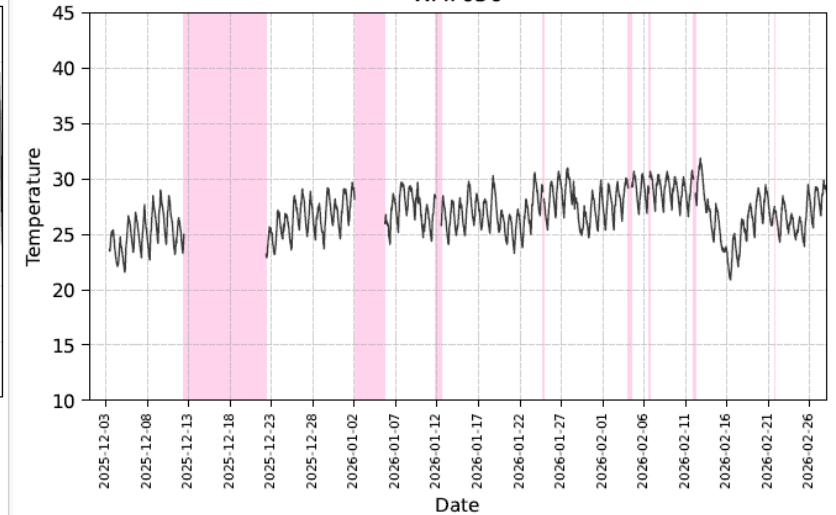
CHO034



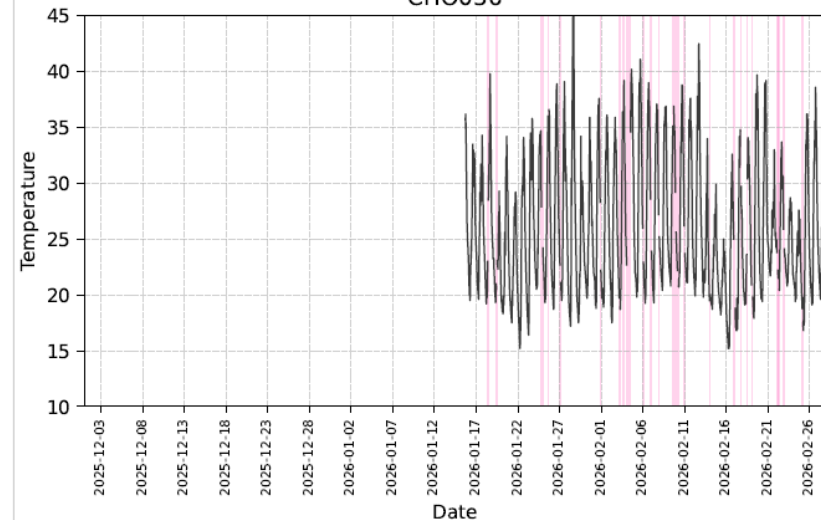
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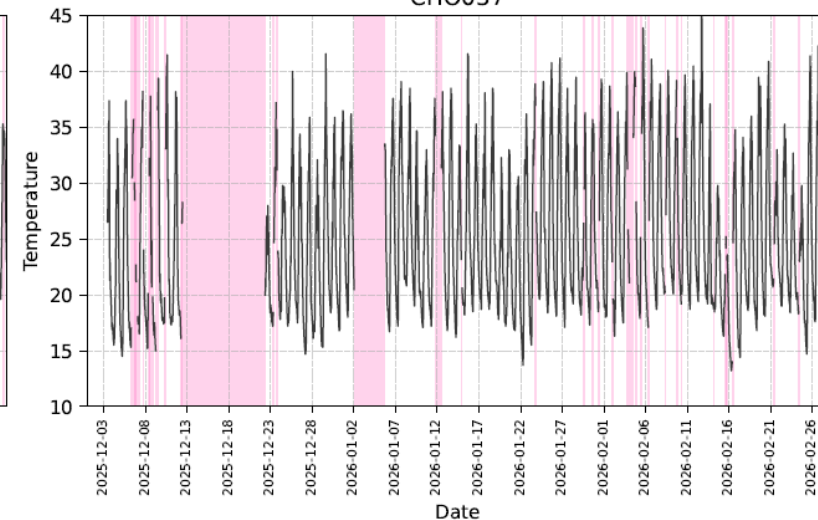
WAT050



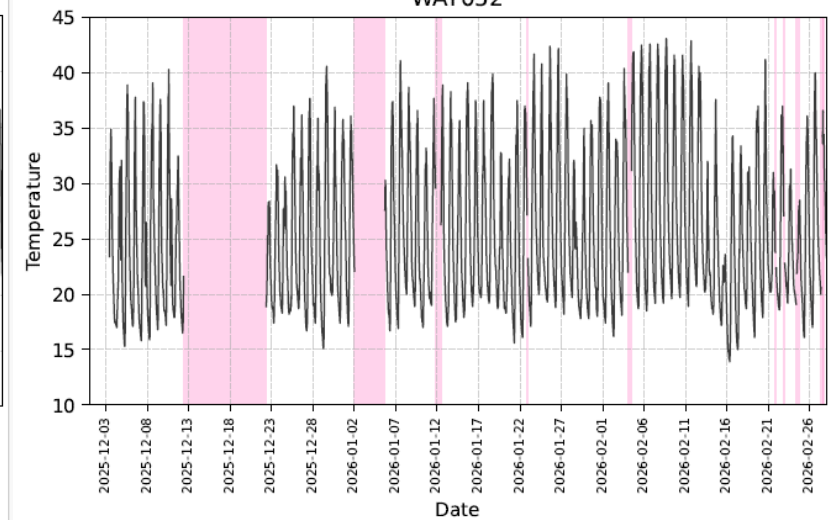
CHO036



CHO037



WAT052



Missing data

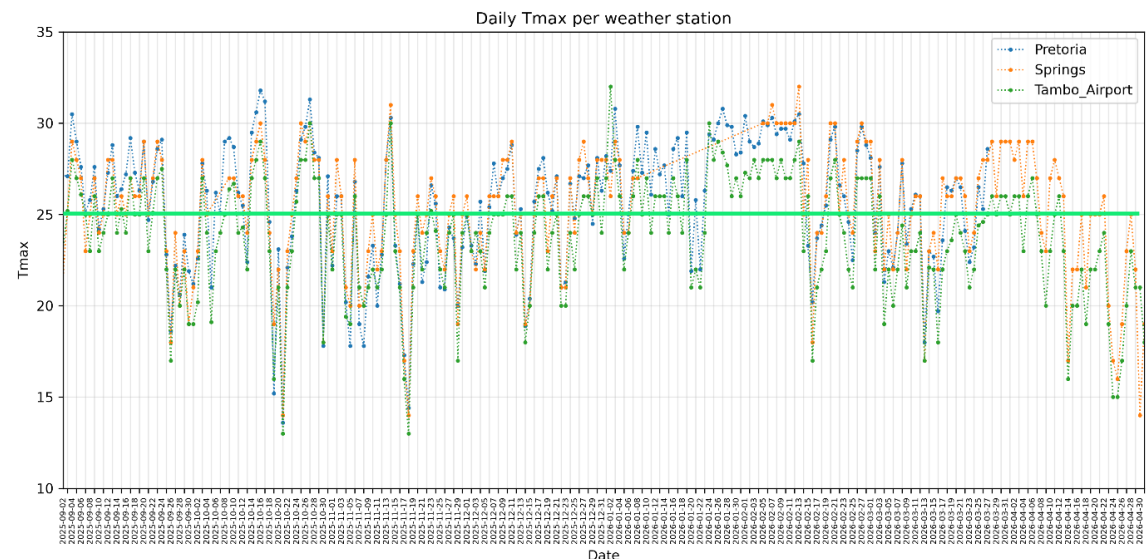
- Causes
 - Depleted batteries on delivery
 - Transmission gaps
 - Late SIM payments → connectivity suspended
 - No backfill: buffered data not resent after reconnection
 - Weak signal → rapid battery drainage



After data processing: 132 of 152 houses yielded usable data; 124 were analysed.

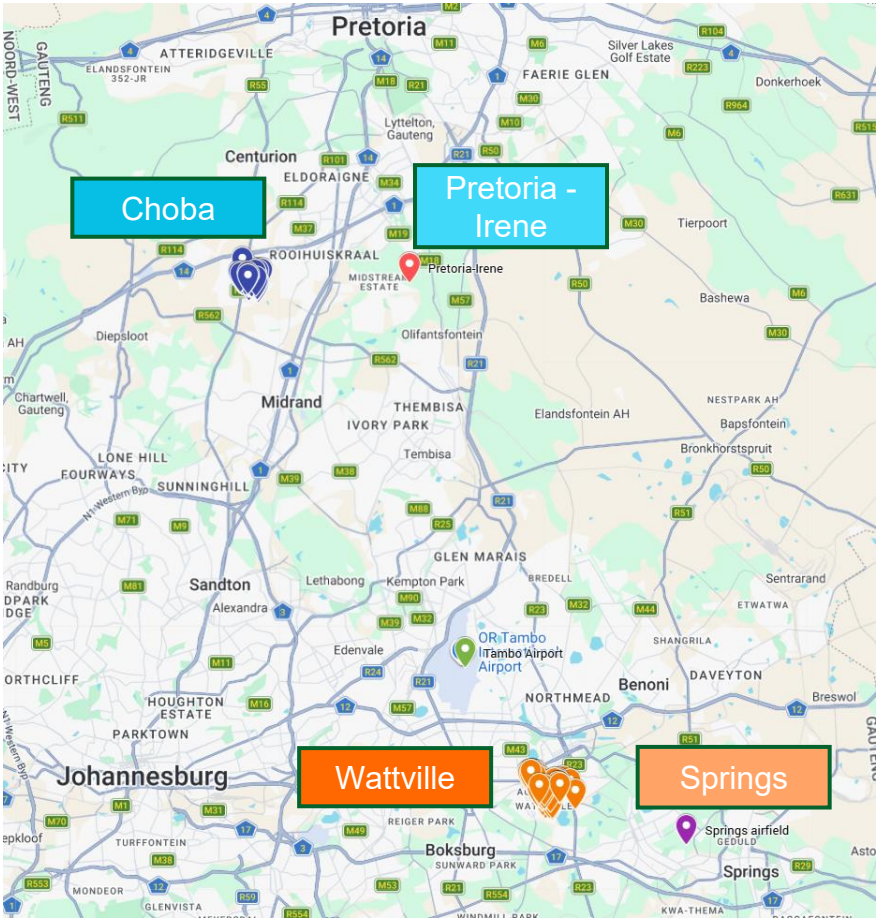


Outdoor temperatures



	Springs	Pretoria
Maximum	32.0	31.8
Mean	18.4	20.4
Minimum	5.0	0.0
Mean daily maximum	25.2	25.6
Number of days > 25°C	134	131

Source: GHCN database/ NOAA / National Centers for Environmental Information (NOAA/NCEI)
(<https://www.ncei.noaa.gov/maps/hourly/>)



Typical houses

	Choba	Wattville
Surface (m²)	9.4	16.6
Walls material		
Metal Panels	43	12
Stone or Bricks or concrete	10	21
Plaster or Stucco	1	25
Clay & Dung	11	0
Others	8	1
Roof material		
Corrugated metal	65	26
Clay or concrete tiles	3	22
Asbestos Sheets	0	11
Slate	3	0
Wood Shingles/Shakes	2	0
Type of roof		
Flat	58	17
Pitched	11	42
Others	4	0
Ceiling under roof		
Yes	14	40
No	59	19

- **67** houses have metal roofs and in most cases metal walls. 13 houses have clay walls

→ **metal(clay)/metal** houses [*“metal”*]

Most of them are in **Choba**.



- **36** houses have stone, brick or concrete walls which are in many cases plastered. Roofs are mostly covered with tiles or asbestos sheets

→ **stone/no-metal** houses. [*“masonry”*]

Most of these houses are in **Wattville**.



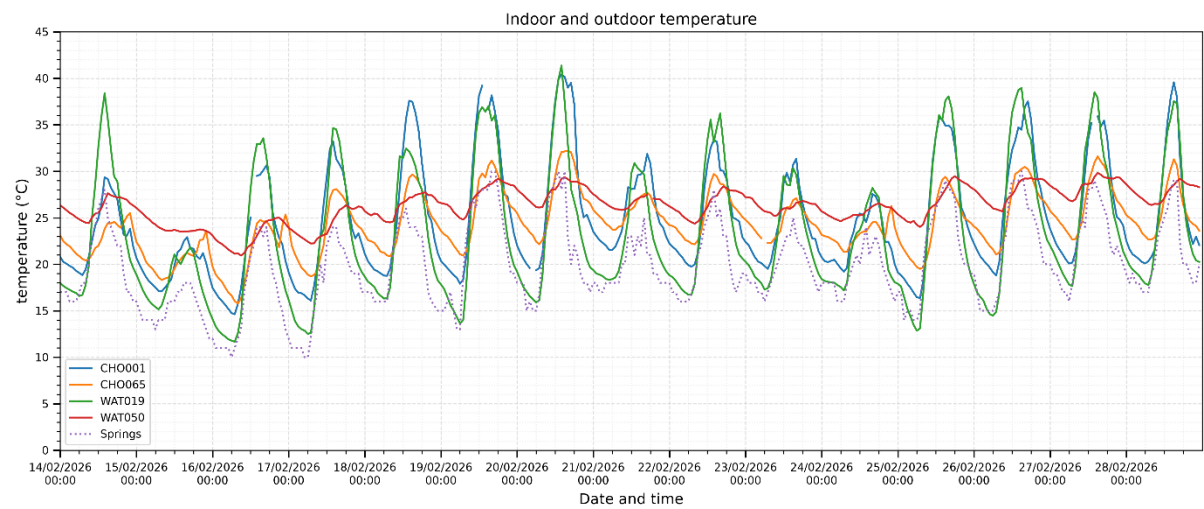
- **21** houses with (sometimes plastered) stone, brick or concrete walls and with corrugated metal roofs

→ **stone/metal**

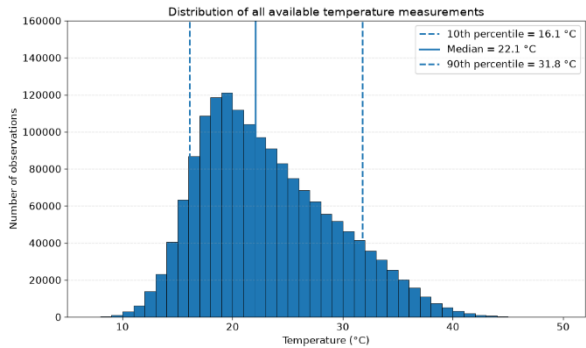
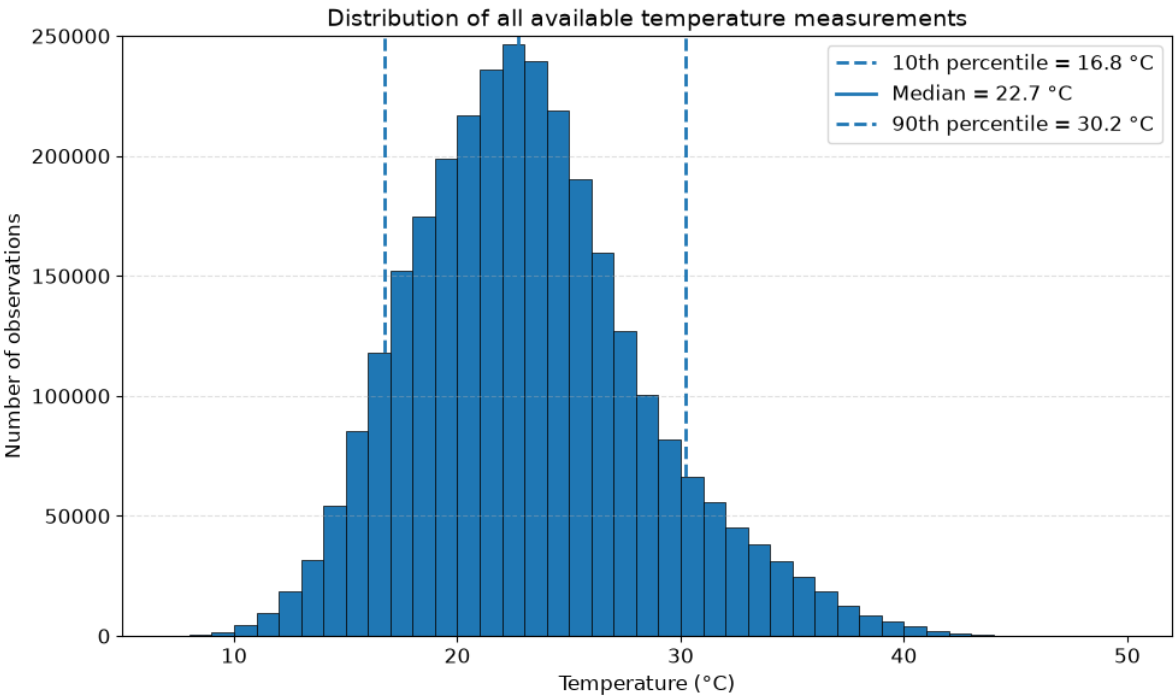


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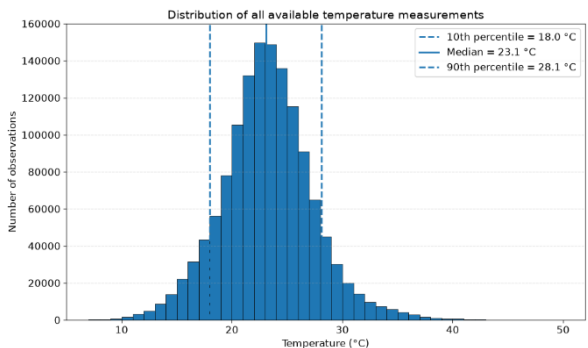
Indoor heat measurements: overview



Indoor temperatures recorded in a few houses in the second half of February 2026 compared with the outdoor temperature recorded at the Springs weather station.



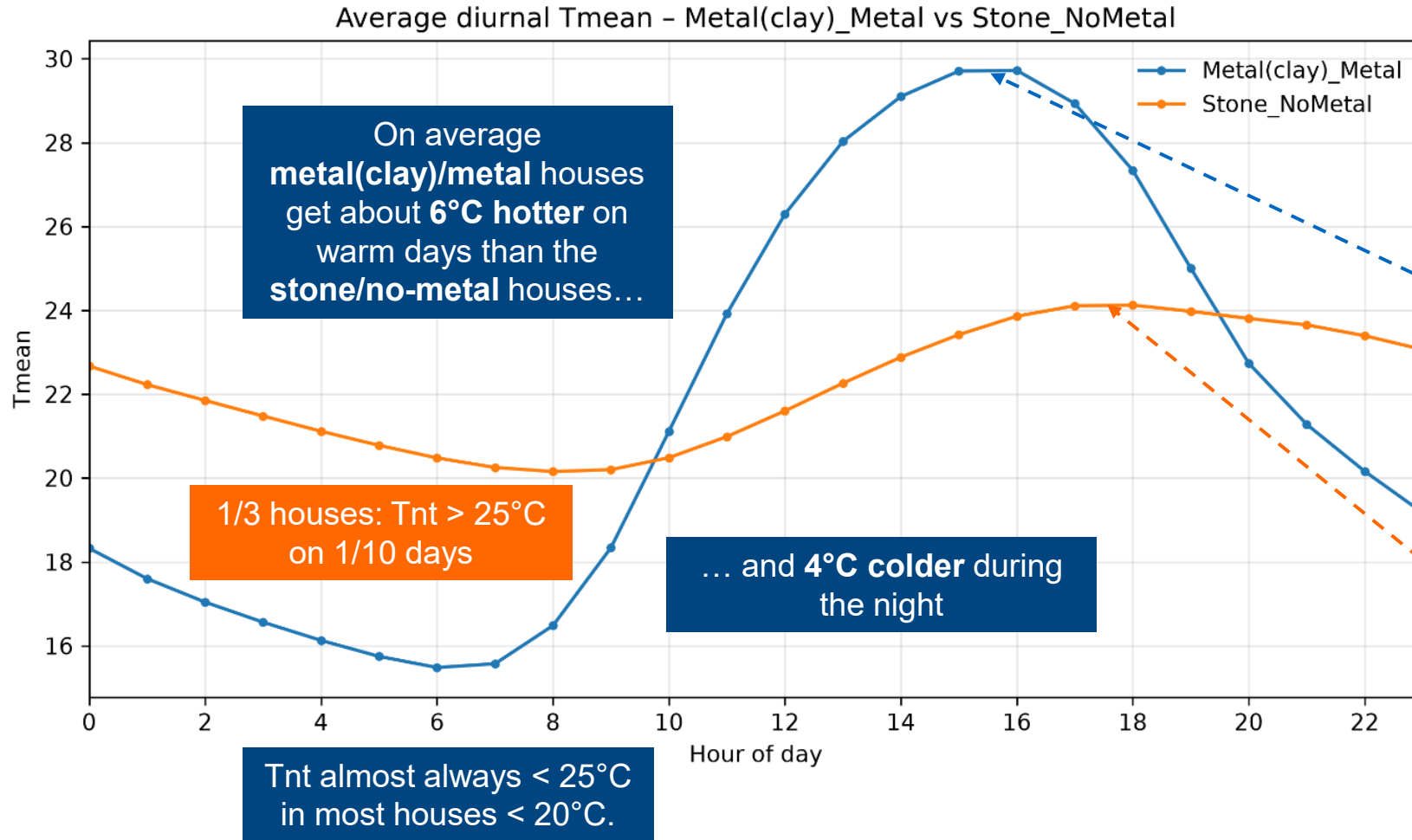
Choba



Wattville



Average diurnal patterns for different house types



Indoor heat indicators per house

daily maximum temperature Tmax

- p90_Tmax: 90th percentile of all daily maximum temperatures: *“the temperature that is exceeded in the house on one out of ten warm days”*
- p50_Tmax: the median of the daily maximum temperature: *“the temperature that is exceeded in the house on one out of two warm days”*

daily minimum night-temperature Tnt (the Tnt for day x is the minimum temperature in the night following day x)

- p90_Tnt
- p50_Tnt

(daily cumulative exceedance of a threshold (i.e., 25°C)

$$T_{\text{exc}} = \sum_{h=\text{main window}} \max(T_h - T_{\text{threshold}}, 0) \quad)$$

Dealing with missing data

Linear interpolation of small gaps < 2h → limited impact on p50_Tmax, p90_Tmax

Trade off: maximise number of houses, minimise bias

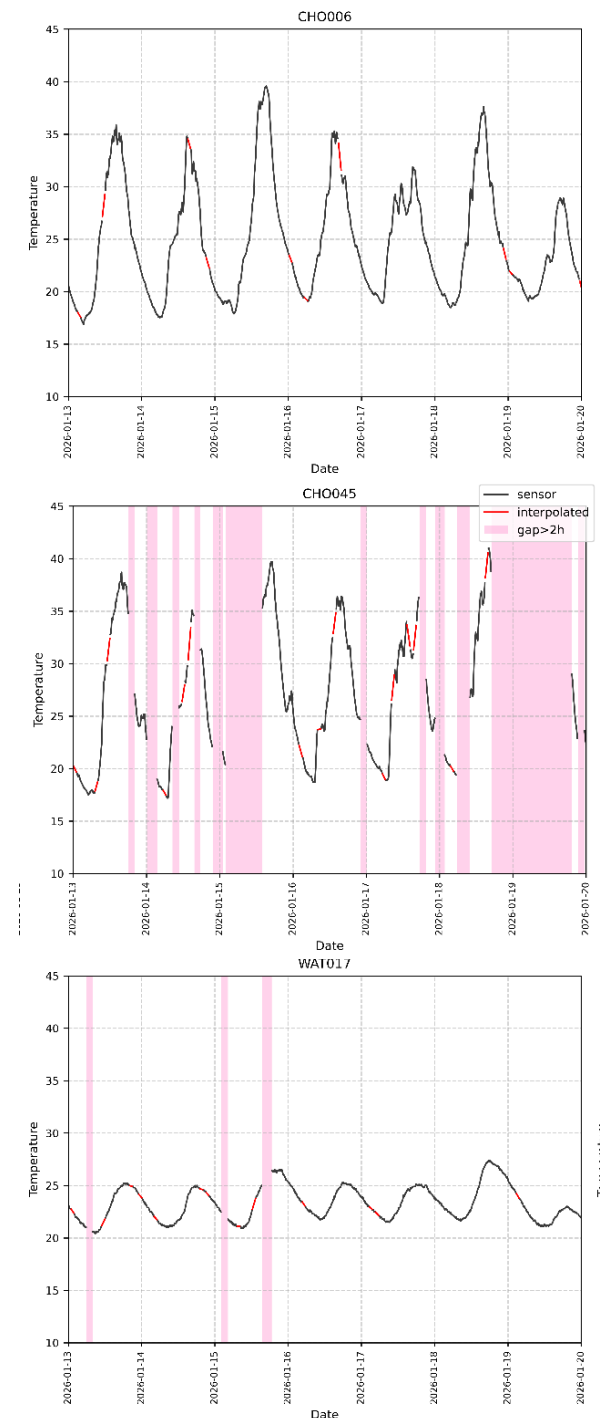
→ use warm days : Tmax outdoor > 25°C → 165 days

→ house included for further analysis if sufficient data available on >20% of total warm days

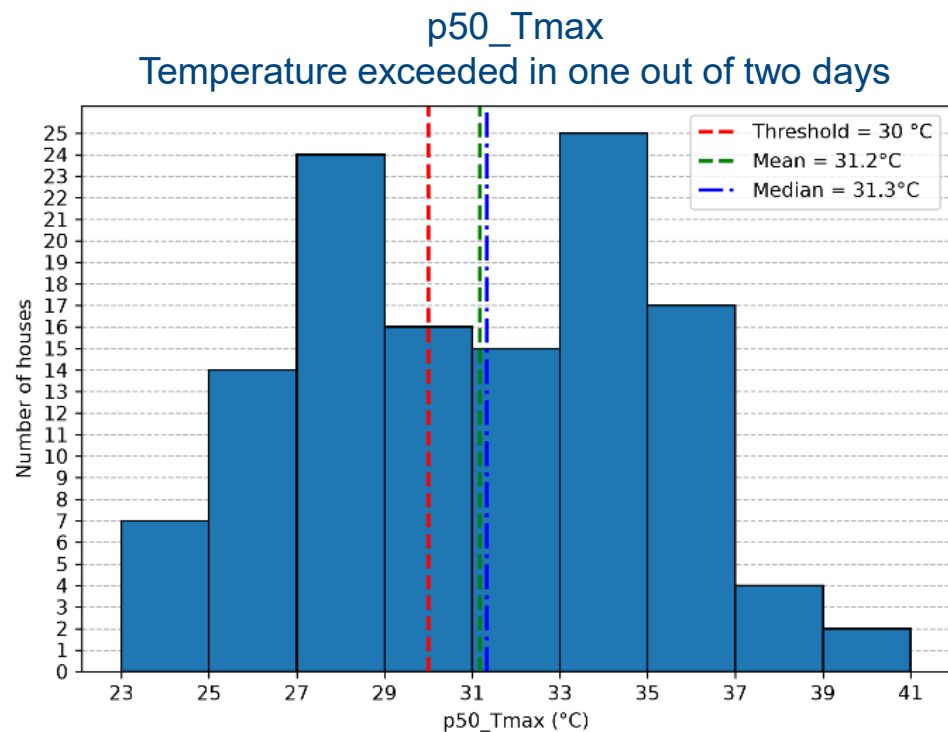
→ 124 houses

Some bias related to data availability

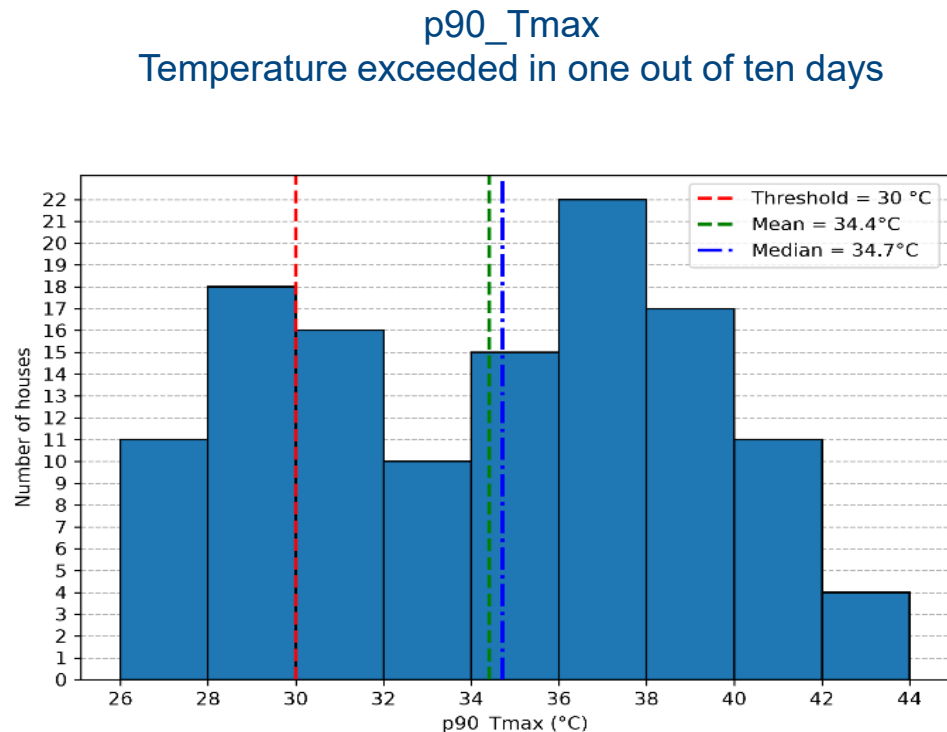
- 14 houses → 0.5 – 1.0 °C
- No systematic bias for neighbourhood or house type



Indoor heat indicators per house



In 74 houses the temperature exceeds 30°C in one out of two warm days.



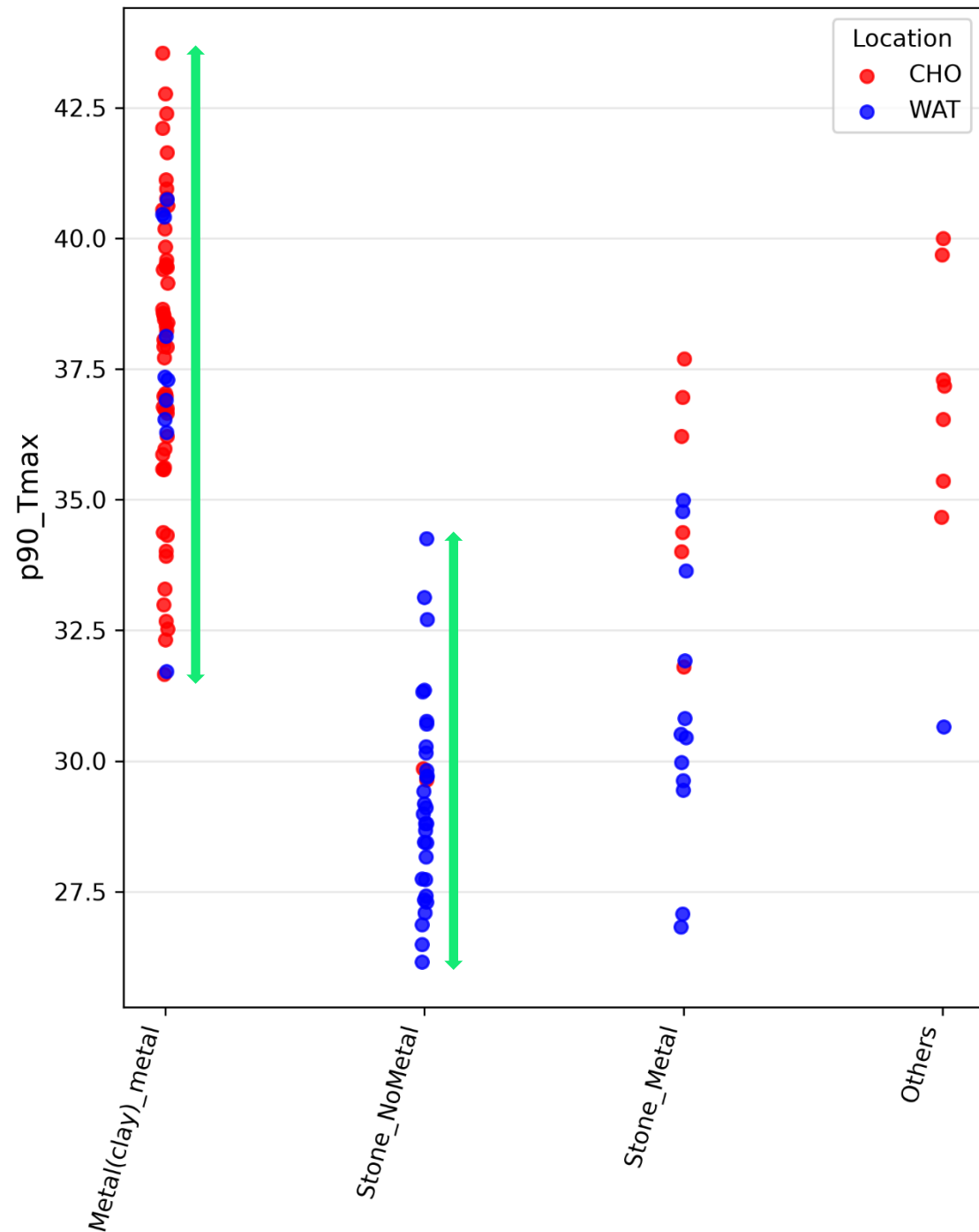
In 95 houses the temperature exceeds 30°C in one out of ten warm days.

In 15 houses the temperature even exceeds 40°C in one out of ten warm days.

Indoor heat indicators per house type



$p90_Tmax + 8.4^{\circ}C$



Comfort temperatures and acceptable temperature ranges

ASHRAE Standard 55-2010

based on the prevailing mean outdoor temperature = mean temperature on the previous days (minimum 7 to maximum 30 days).

- The prevailing temperatures (for a 7-days period) for the considered period range from 14.2 to 22.1°C with an average of 18.5°C.
- For 18.5°C → comfort temperature = 23.5°C, acceptable range 20.0 - 27.0°C
- For 22.1°C → comfort temperature = 24.7°C, acceptable range 21.2 to 28.2°C.

Association of building characteristics with indoor temperature

Univariate linear regression

N = 121	House type	Walls material	Type of roof	Roof material	Ceiling	Floor material	Windows total	Surface	Density houses	State of roof	WTW ratio*	DTW ratio**
R-squared	0.66	0.63	0.50	0.47	0.42	0.41	0.36	0.19	0.12	0.12	0.08	0.04
F-statistic	75.1	48.6	58.3	34.9	84.5	41.4	16.6	27.2	8.2	8.1	10.3	4.5
F-statistic p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.035

- No significant associations with orientation of the house, the presence of trees close to the house, or the presence of trees in the neighbourhood (trees covering the roof: only 4 houses)
- Analysis on subgroups: house types
 - stone/no-metal houses → roof material: tiles versus asbestos (-2.6°C)
 - metal houses: none

[Elastic net regression]

Association ≠ Causality !

No association ≠ No effect

Association of building characteristics with indoor temperature

Association ≠ Causality !

- **High correlation:** walls material, roof material, roof type, ceiling, floor

	Type of roof	
Walls material	Flat	Pitched
Metal Panels	49	4
Stone or Bricks or concrete	11	20
Plaster or Stucco	0	26
Clay & Dung	10	1
Wood	1	1
Earth/Clay	2	1
Not applicable	2	0
Total	75	53

$\Delta=6.4^{\circ}\text{C}$

	Floor material		
Walls material	Concrete	Tile	Carpet
Metal Panels	34	6	12
Stone or Bricks or concrete	10	21	0
Plaster or Stucco	2	24	0
Clay & Dung	11	0	0
Other/rare	6	1	1
Total	63	52	13

$\Delta=5.9^{\circ}\text{C}$

Association of vegetation and trees with indoor temperature

No association ≠ No effect

Variables related to vegetation and trees are not associated with the indoor temperature *in this study*

- Trees can have an overall effect on the **outdoor air temperature**.
 - To have an effect trees should be present in high densities
 - In Wattville and Choba trees and vegetation are sparse, and the effect on the outdoor air temperature is negligible.
- Trees can also provide local cooling through **direct shading**.
 - Only four houses in the sample have trees covering the roof → too few to assess the effect of shading on the indoor temperature.
 - Presence of vegetation and trees is only recorded in qualitative terms. Nearby-tree indicators do not quantify the actual shade on roofs, walls or windows.

Association of building characteristics with indoor temperature

	House type	Walls material
R-squared	0.66	0.63
F-statistic	75.1	48.6
F-statistic p-value	0.000	0.000

	Walls material Roof material		Walls material Roof material Surrounding houses	
R-squared	0.68		0.70	
Adjusted R-squared	0.66		0.68	
F-statistics	F	PR(>F)	F	PR(>F)
- model	34.2	0.000	29.1	0.000
- walls	18.3	0.000	17.2	0.000
- roof material	6.3	0.001	6.4	0.001
- surrounding houses			4.2	0.017

	Category	Coefficient	Std_error	t_value	p_value
	Intercept	37.8	0.37	102.7	0.000
Walls material	Reference: Metal Panels				
	Plaster or Stucco	-5.9	0.80	-7.4	0.000
	Stone or Bricks or concrete	-5.5	0.80	-6.9	0.000
	Clay & Dung	-1.5	0.87	-1.7	0.097
	Other / rare	-1.5	1.08	-1.4	0.157
Roof material	Reference: Corrugated metal				
	Clay or Concrete Tiles	-3.4	0.78	-4.4	0.000
	Asbestos Sheets	-1.4	0.99	-1.4	0.161
	Other / rare	-0.9	1.36	-0.7	0.510
Surrounding houses	Reference: Semi-packed				
	Fully packed	2.5	0.92	2.7	0.007
	Isolated/ open	-0.7	0.94	-0.7	0.488

High to extremely high indoor temperatures are common

- In half of the houses the temperature exceeds 30°C on one out of two warm days.
- In a quarter of the houses 35°C is exceeded on one out of two warm days.
- In one out of ten houses the temperature exceeds 40°C on one out of ten days.
- Most of these houses are in Choba.
- However, also in Wattville the temperature exceeds 30°C in a quarter of the houses on one out of two warm days

→ way above the acceptable temperatures

The number of warm and very warm days is expected to **increase in the future**



Large differences are related to thermal properties of building materials

- Houses in Choba are (considerably) hotter during the day (on average 6 to 7°C) and colder at night.
- Differences are mainly explained by the different house types: houses with (mainly) metal walls and metal roofs which are dominant in Choba versus masonry houses with tile or asbestos roofs in Wattville
- Overall higher thermal mass and better insulation of the stone/no-metal houses. Houses with heavier wall and roof constructions are expected to have higher thermal inertia and heat storage, resulting in slower indoor temperature responses to outdoor temperature fluctuations during the day as well as during the night.

The included variables account for 2/3 of the observed variability in indoor heat

- House types and construction patterns account for 2/3 of the observed variability
- Differences in indoor heating are largely associated with the walls or the roof material
- No absolute causal effect or magnitude of effect
 - Roof material and walls material are highly correlated.
 - Difference associated with different walls or roof materials may be caused partially by other strongly correlated variables such as the type of roof, the presence of a ceiling, the floor material ...
 - The precise contribution of each correlated characteristic remains uncertain.
 - The fact that some houses are fully packed seems to have an effect independent from walls and roof material.

1/3 of the observed variability in indoor heat is not accounted for

- **Actual ventilation and occupant behaviour**
 - Timing and duration of actual ventilation
 - Use of doors and windows, possibility of cross-ventilation, ventilate safely and privately.
 - Occupants may be absent during (large part of) the day with windows and doors closed.
- **Internal heat gains**
 - Cooking, presence of people in the house, use of appliances
- **Actual thermal properties of the house**
 - not fully captured by the broad material labels or the insulation and ventilation categories.
- **Shading by surrounding houses and vegetation**
 - not fully captured by the qualitative descriptions.
- **Location of the sensor inside the house**
 - sensors closer to radiant surfaces (e.g., metal roofs), cooking activities, windows or doors.
- **Measurement uncertainty**



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