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Synergies among Urban Heat Islands, Urban Dry Islands, and Heat Stress during heatwaves: evidences from the Bologna case study using the urbanized ICON model

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Outline of the presentation

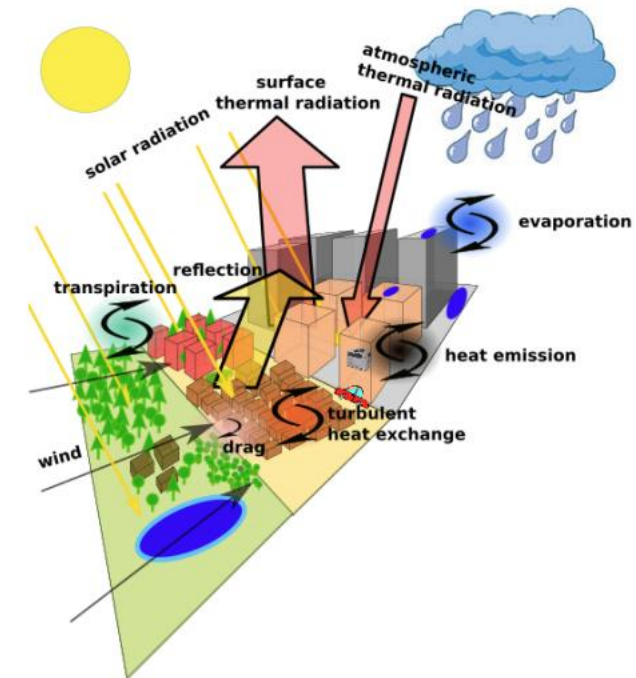
PP_CITTA: an history of success

- The establishment of TERRA_URB

TERRA_URB for climate applications:

- Bologna case study area and simulations setup
- UHI and UDI
- Coupling between UHI/UDI and heatstress with heatwaves

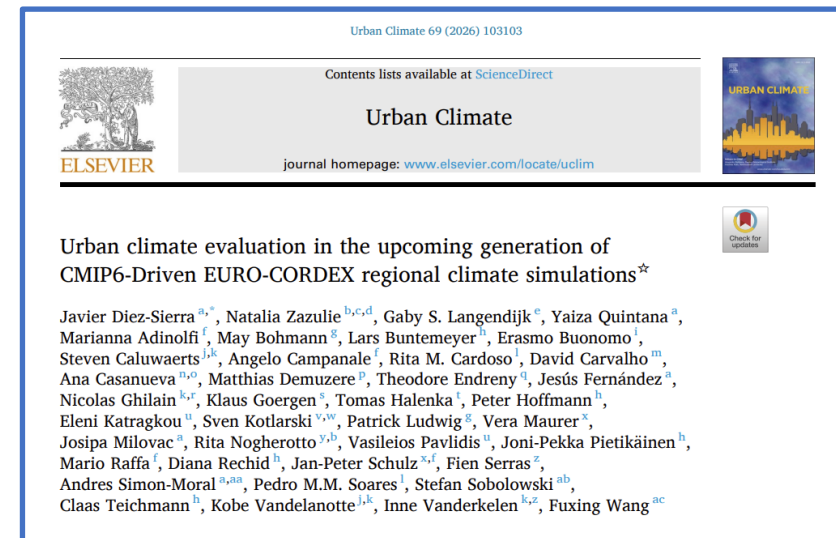
Conclusions and next steps



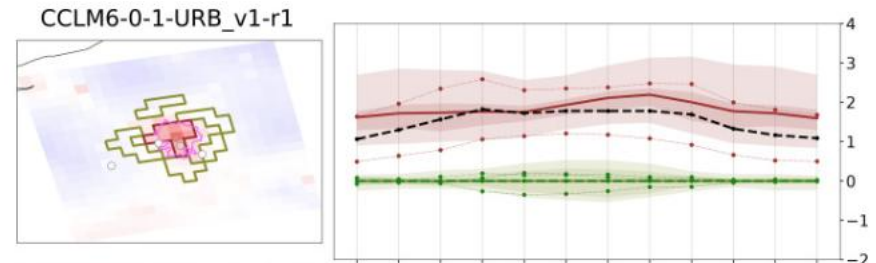
PP_CITTA, a history of success

The successful porting of TERRA_URB from COSMO to ICON demonstrates PP_CITTA's ability to develop and transfer advanced urban modelling capabilities within the ICON framework.

In a recent publication in *Urban Climate* on the evaluation of the next-generation EURO-CORDEX ensemble using different regional climate models, the COSMO-CLM model with the TERRA_URB parameterization was shown to capture key urban climate features, achieving performance comparable to, or even better than, more sophisticated urban parameterizations such as TEB or BEM-BEP. Read more at [10.1016/j.uclim.2026.103103](https://doi.org/10.1016/j.uclim.2026.103103).



Annual cycle of the UHI in Paris simulated with CCLM. The UHI from observations is shown in black, while the CCLM results are shown in red



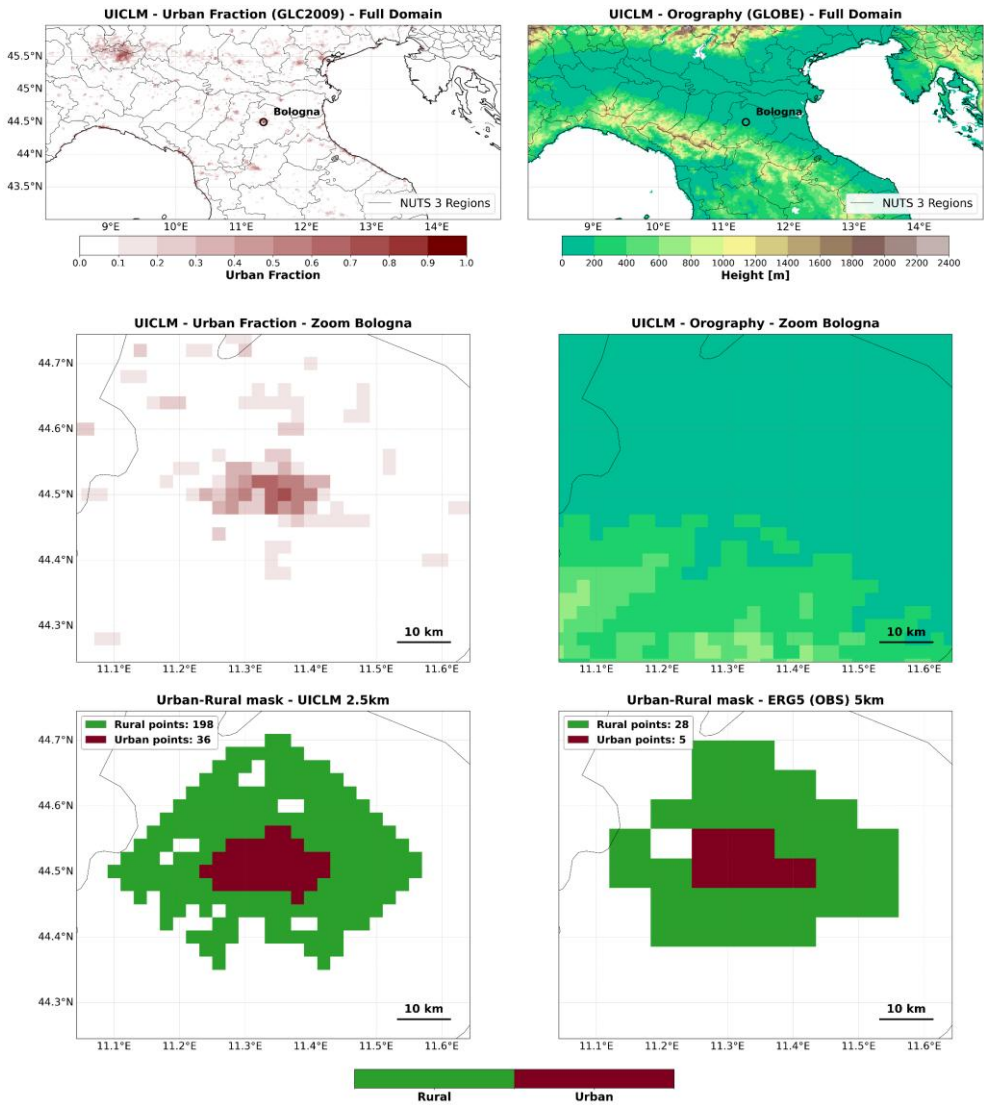
Bologna case study area



In the EU-funded **CARMINE** project, the **Bologna** area was selected as a case study because one of the main issues addressed is the coupling between the Urban Heat Island (UHI) effect and heatwaves, and its impact on vulnerable populations.

Model	ICON-CLM with TERRA_URB (UICLM)
Version	ICON release-2025.10-public
Boundary forcing	ERA5 reanalysis 0.25°x 0.25° (≈ 31 km)
Lateral Boundary Condition (LBC)	update frequency 6 h
Simulated Period	208-2024 (2018 as spinup)
Soil initializations	Temperature and moisture obtained by interpolation from ERA5
Horizontal resolution	0.0225° (≈ 2.5 km), R2B10 grid
Time step	20 s
N° vertical levels	65 (top model level elevation = 22 km)
Output frequency	1 h
Land surface scheme	Tiled TERRA (Schrodin and Heise, 2001; Schulz et al., 2016; Schulz and Vogel, 2020) with TERRA_URB parameterization (Wouters et al., 2016; Campanale et al., 2025)
Land use dataset	GlobCover2009 (Arino et al., 2012)
Evaluated variables	2m temperature (T_2M) and 2m relative humidity (RH_2M)

Setup used for the climate simulations. The most important activated parameterizations are based on the ICON-D2 configuration. The urban–rural mask was created using the algorithm provided by Diez-Sierra et al. (2025).

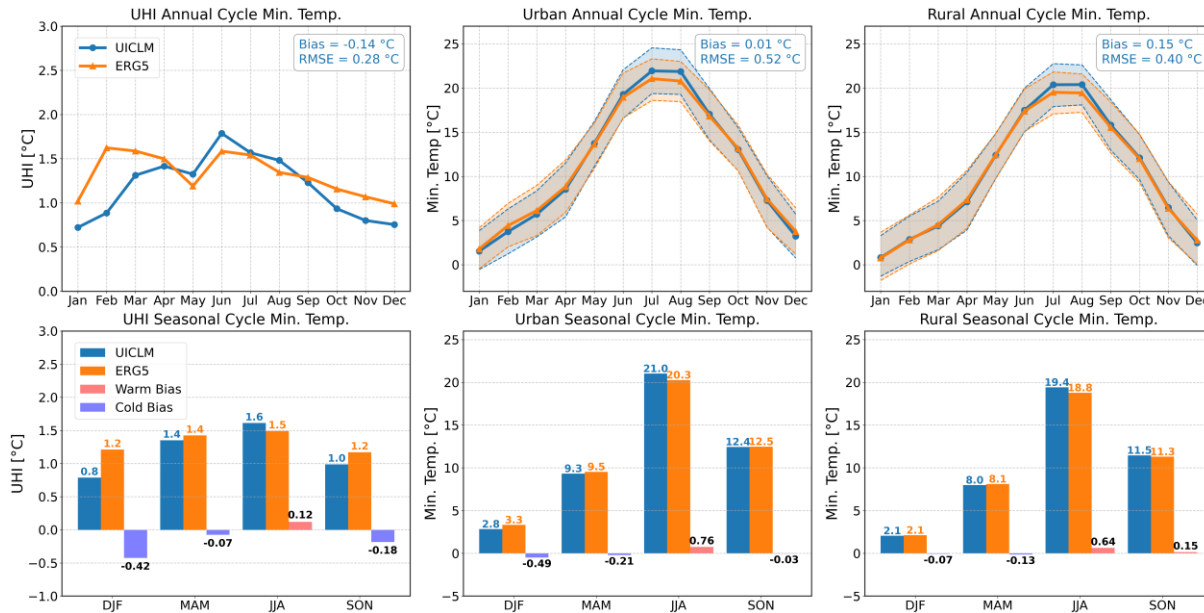


Urban-rural masks obtained for UICLM and ERG5 (observational dataset)

Temperature evaluation

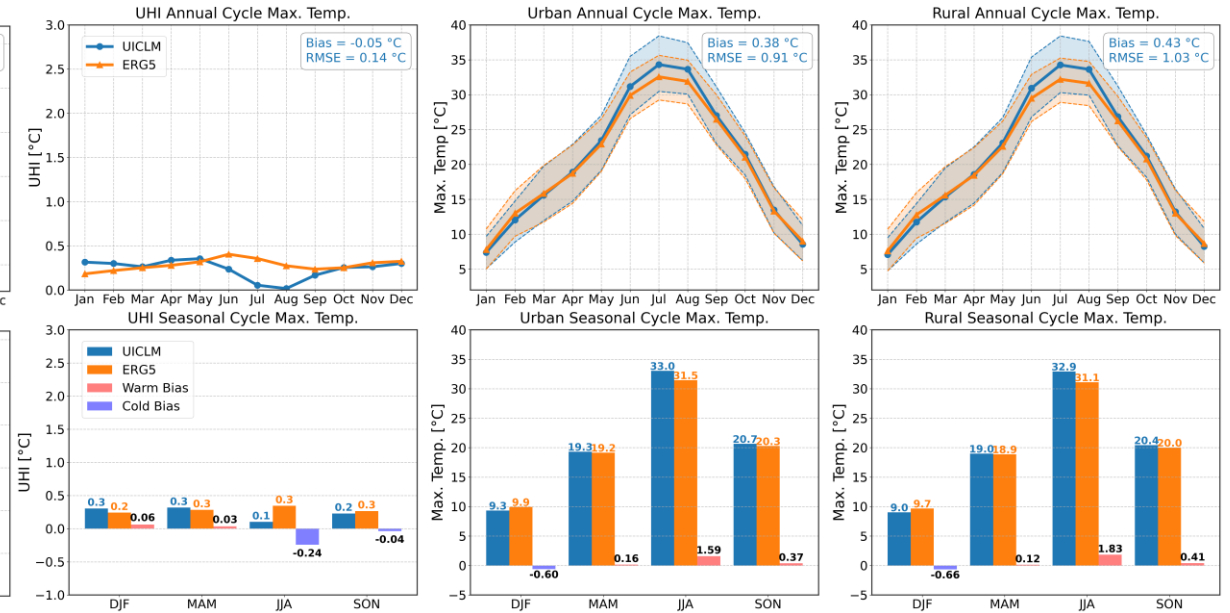


Annual cycle of nocturnal UHI and minimum temperature in urban and rural areas (the lower and upper dashed bands indicate the 15th and 85th percentiles, respectively)



- **UHI is a nocturnal phenomenon**, with peak values of 1.6 °C for UICLM and 1.5 °C for ERG5 reached in summer.
- **The intensity and seasonality of the signal are well reproduced by the urbanized ICON model.**
- A cold urban bias is observed in UHI DJF (possibly due to insufficient anthropogenic heat flux).
- A warm bias is observed in both urban and rural temperatures during summer.

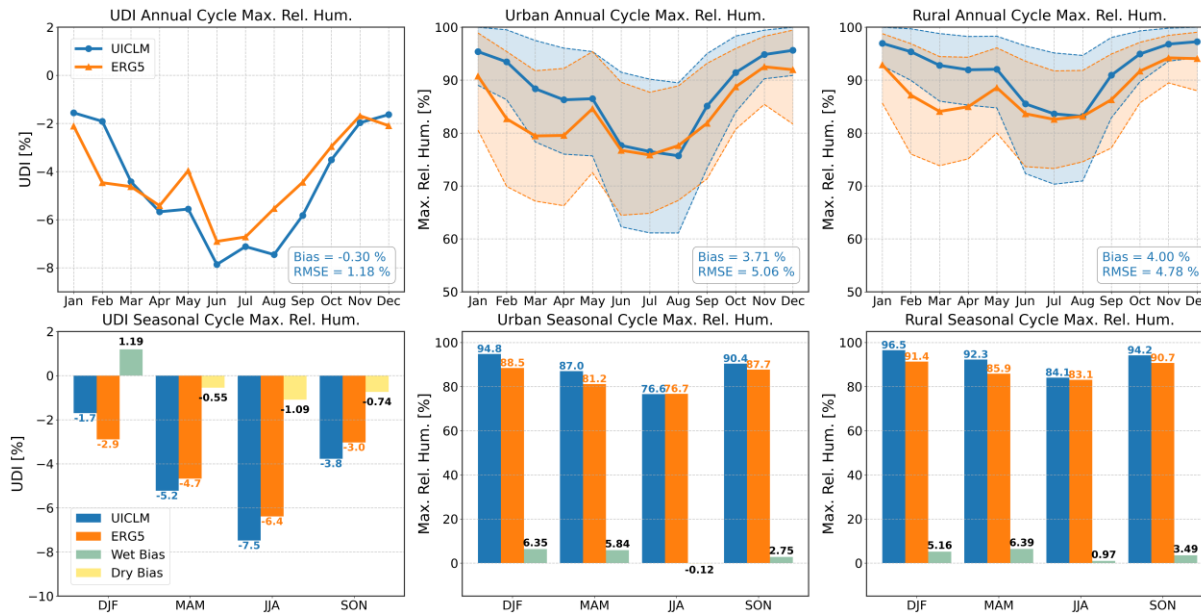
Annual cycle of diurnal UHI and maximum temperature in urban and rural areas (the lower and upper dashed bands indicate the 15th and 85th percentiles, respectively)



- **UHI shows lower intensity during the day, as expected, in both UICLM and observations.**
- During the day, a warm bias is observed in both urban and rural temperatures during summer, possibly related to lower soil moisture and an excessive partitioning of available energy into sensible heat flux rather than latent heat flux, resulting in reduced evapotranspiration (not shown here).

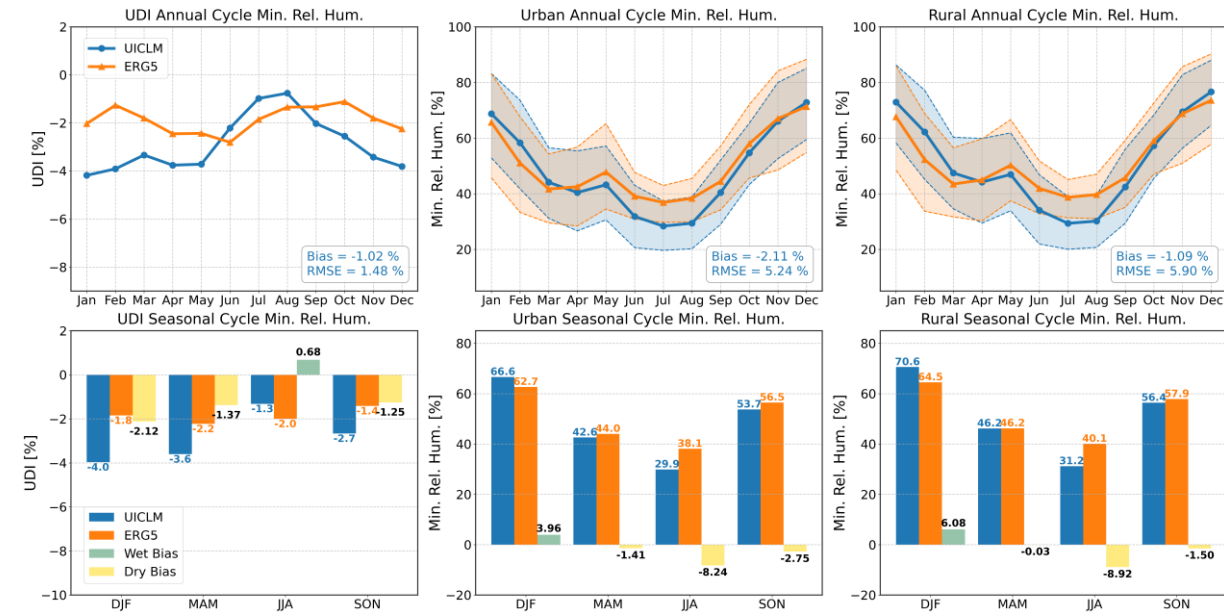
Relative humidity evaluation

Annual cycle of nocturnal UDI and maximum rel. humidity in urban and rural areas (the lower and upper dashed bands indicate the 15th and 85th percentiles, respectively)



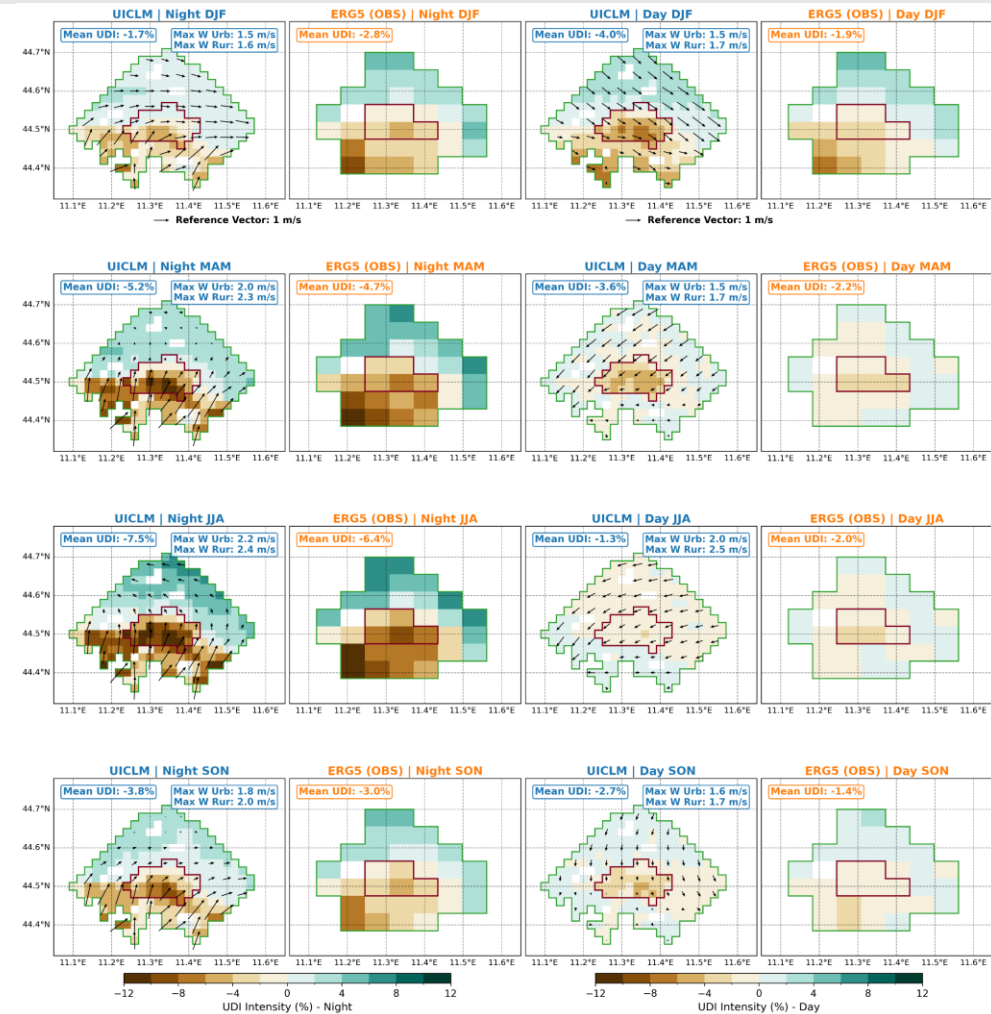
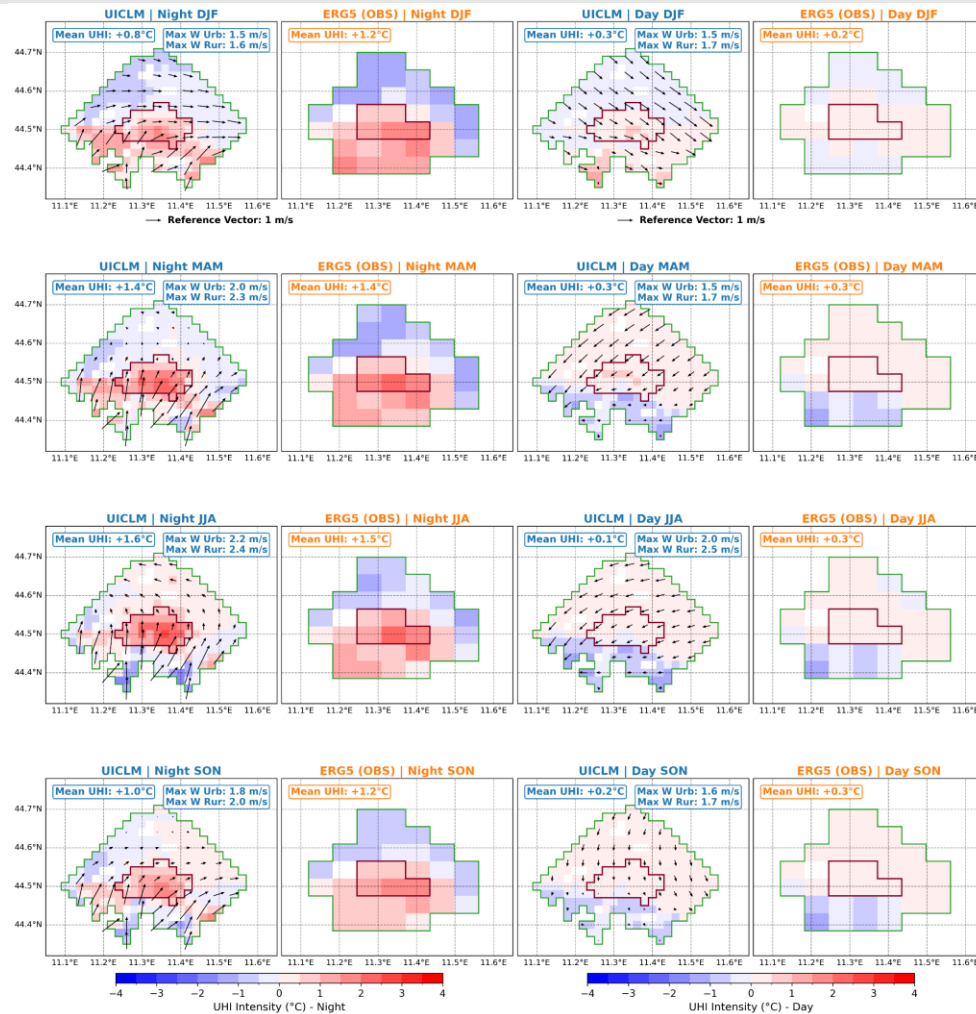
- **UDI is a nocturnal phenomenon**, with peak values of -7.5% for UICLM and -6.4 % for ERG5 reached in summer.
- **The intensity and seasonality of the signal are well reproduced by the urbanized ICON model.**

Annual cycle of diurnal UDI and minimum rel. humidity in urban and rural areas (the lower and upper dashed bands indicate the 15th and 85th percentiles, respectively)



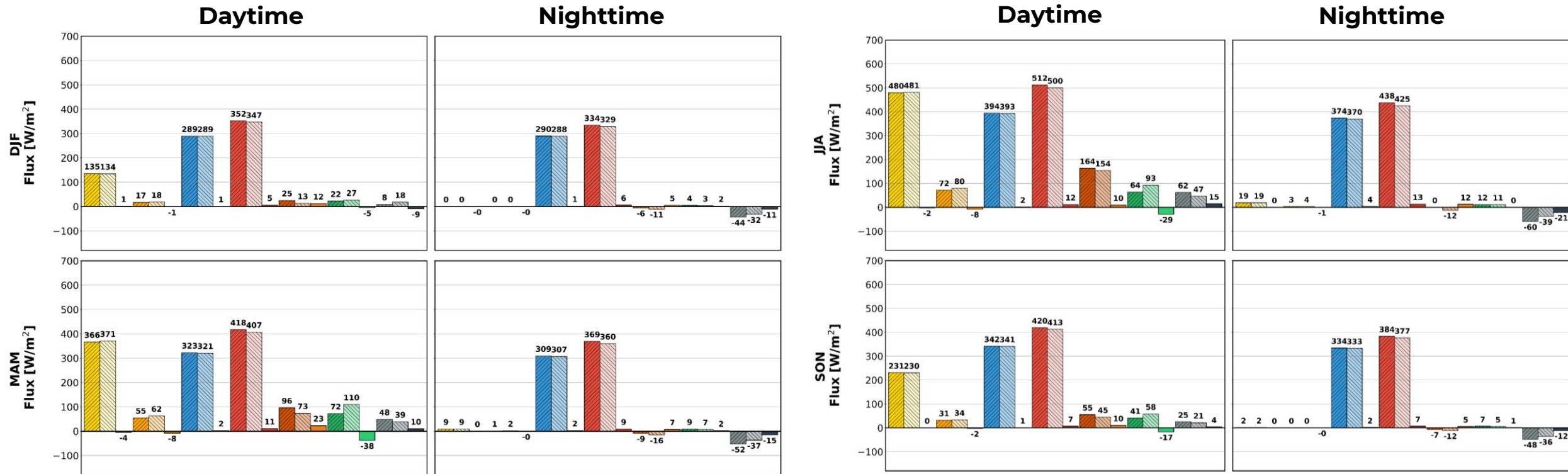
- **UDI shows lower intensity during the day, as expected, in both UICLM and observations.**
- During the day, a dry bias is observed in both urban and rural relative humidity during summer, possibly related to lower soil moisture and an excessive partitioning of available energy into sensible heat flux rather than latent heat flux, resulting in reduced evapotranspiration and dry atmosphere.

UHI and UDI representation



The spatial representation of UHI and UDI is obtained by subtracting the mean temperature and relative humidity values, averaged over rural points, from the corresponding temperature and relative humidity fields for both UICLM and ERG5.

Surface heat budget



Surface seasonal heat budget: $R_n = S + L + G$, where R_n is net radiation, S and L are sensible and latent heat fluxes, and G is the stored heat flux into the soil, rock, or urban fabric.

Net radiation is further decomposed as: $R_n = (SW_{\downarrow} - SW_{\uparrow}) + (LW_{\downarrow} - LW_{\uparrow})$.

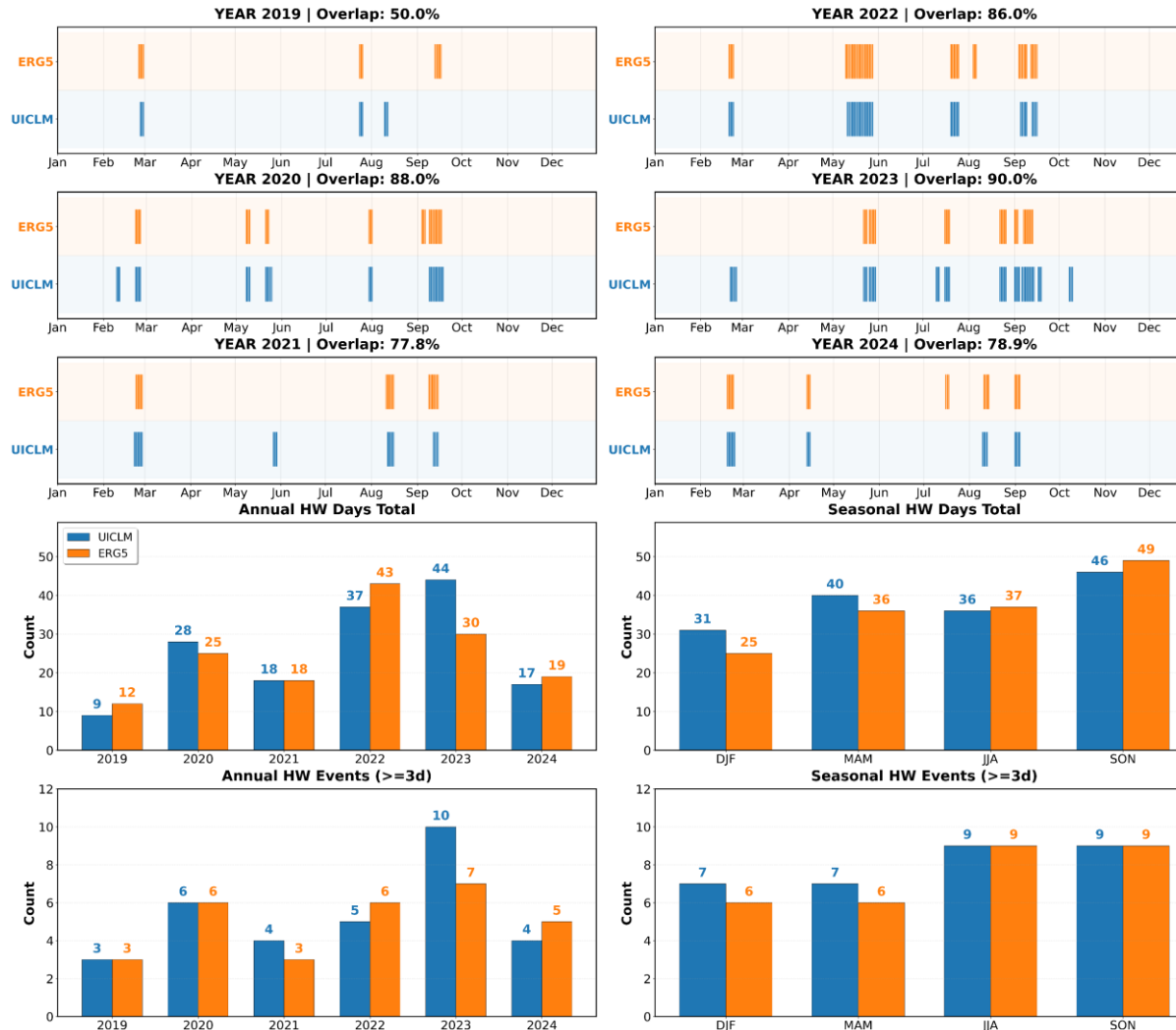
The reported flux are averaged for urban and rural points

- **Nocturnal UHI:** Mainly driven by daytime heat storage (positive G during the day) and its nocturnal release (negative G at night), which is partitioned into sensible heat and outgoing longwave radiation.
- **Diurnal UDI:** Mainly driven by differences in latent heat flux (and evapotranspiration) between urban and rural areas.

HW representation



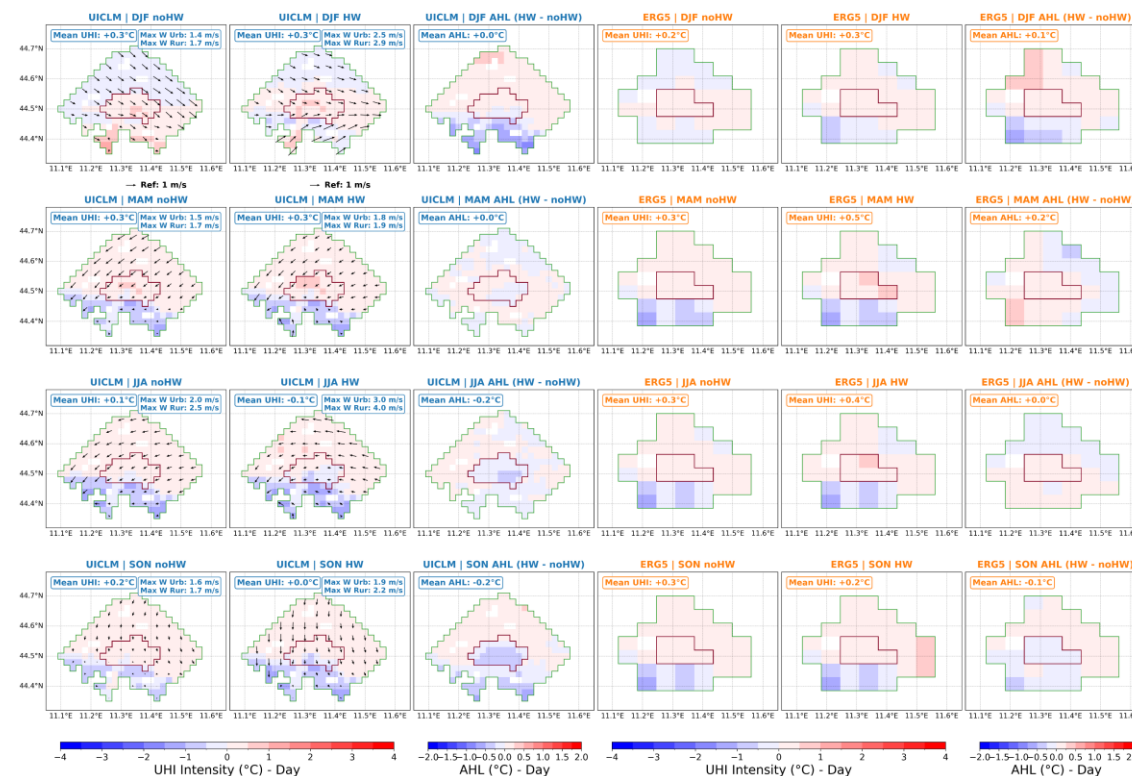
Overall temporal overlapping 2019-2024 (Ref: ERG5): 82.3%



A **heat wave** is defined as a period of **at least three consecutive days during which the daily maximum air temperature**, spatially averaged over both urban and rural grid cells within the Bologna area, **exceeds its seasonal 90th percentile** calculated over the entire 2019-2024 analysis period. All remaining days are classified as non-heatwave (noHW) conditions.

Overall, UICLM demonstrates exceptional skill in capturing the timing of extreme events, achieving a remarkably **high temporal overlap of 82.3% with ERG5** over the entire analysis period. On an annual basis, synchronization peaks at 90.0% in 2023 and remains consistently high across all years, ranging from 50.0% in 2019 to 88.0% in 2020.

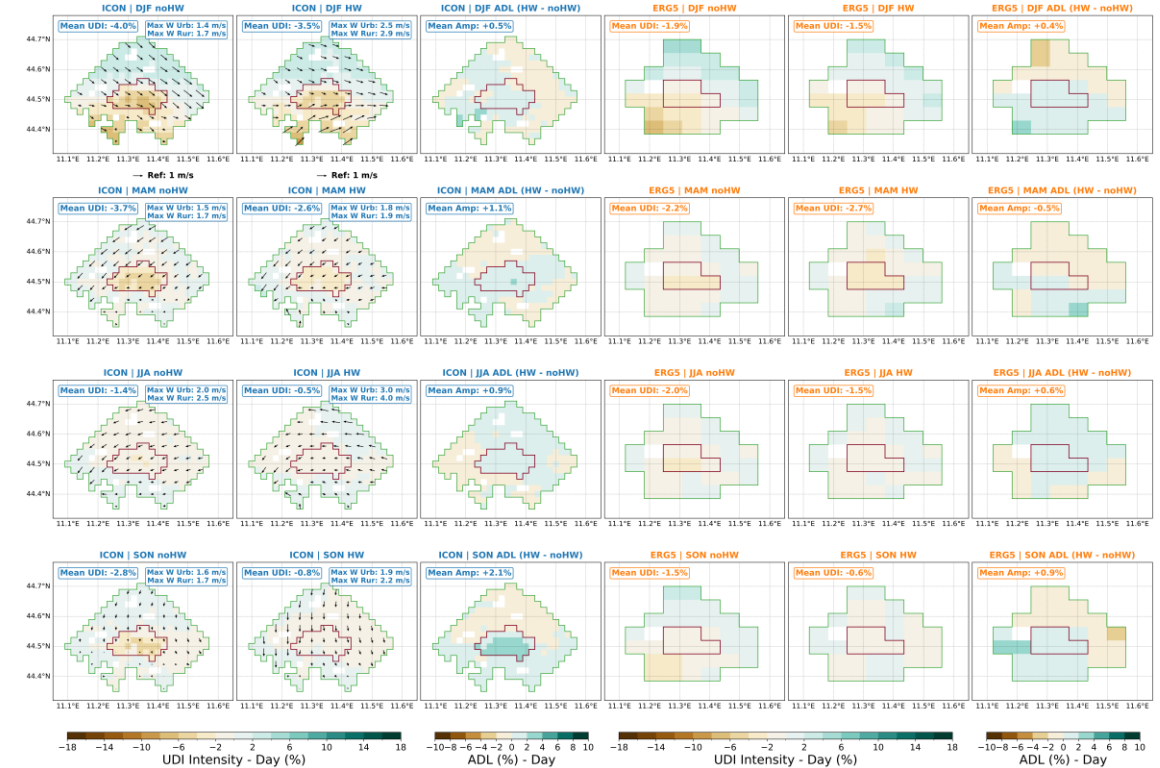
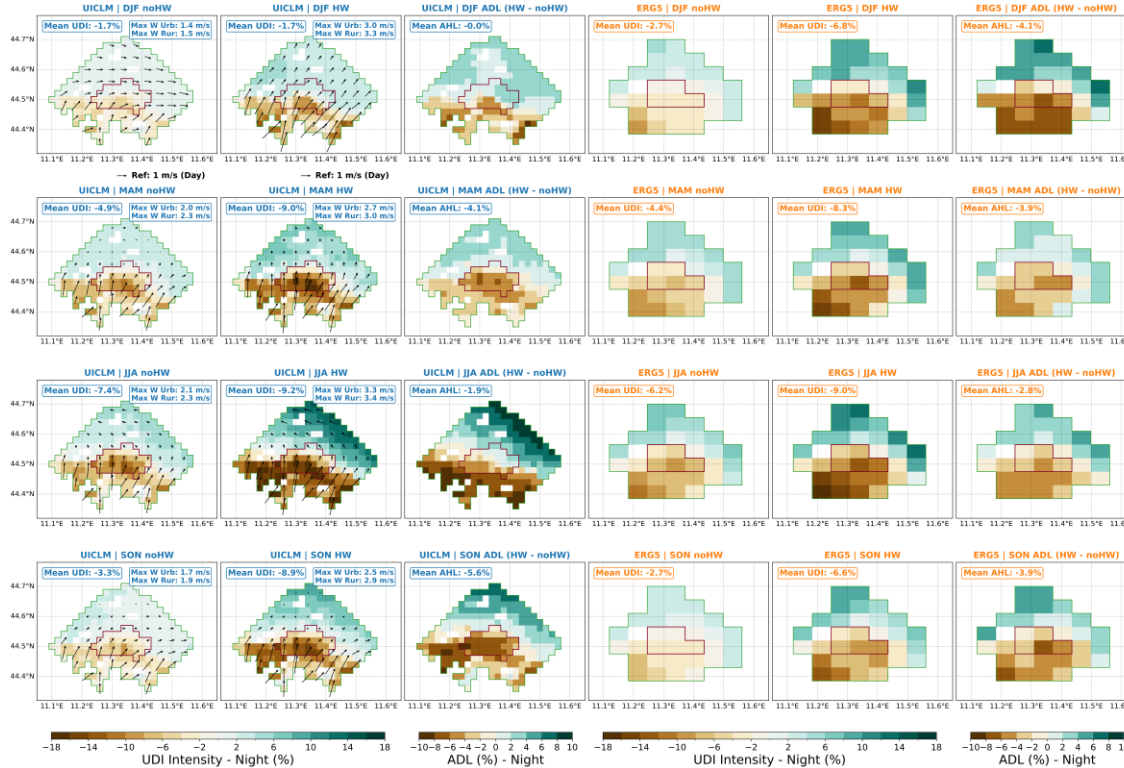
In highly anomalous years, such as 2022 and 2023, UICLM simulates high frequencies of HW days (37 and 44 days, respectively) that closely bracket the observed counts (43 and 30 days).



Spatial representation of diurnal UHI during HW and no-HW conditions for both UICLM and ERG5. The AHL (Added Heat Load) is defined as the difference between UHI|HW and UHI|no-HW, showing the increase in UHI intensity during HW conditions.

Heatwaves amplify nocturnal urban effects, with UHI reaching +1.9 °C in both UICLM (compared with +1.3 °C during noHW) and ERG5 (compared with +1.4 °C during noHW) during JJA, while showing weak or no amplification during the day.

UDI amplification



Spatial representation of nocturnal UDI during HW and no-HW conditions for both UICLM and ERG5. The ADL (Added Dry Load) is defined as the difference between UDI|HW and UDI|no-HW, showing the increase in UHI intensity during HW conditions.

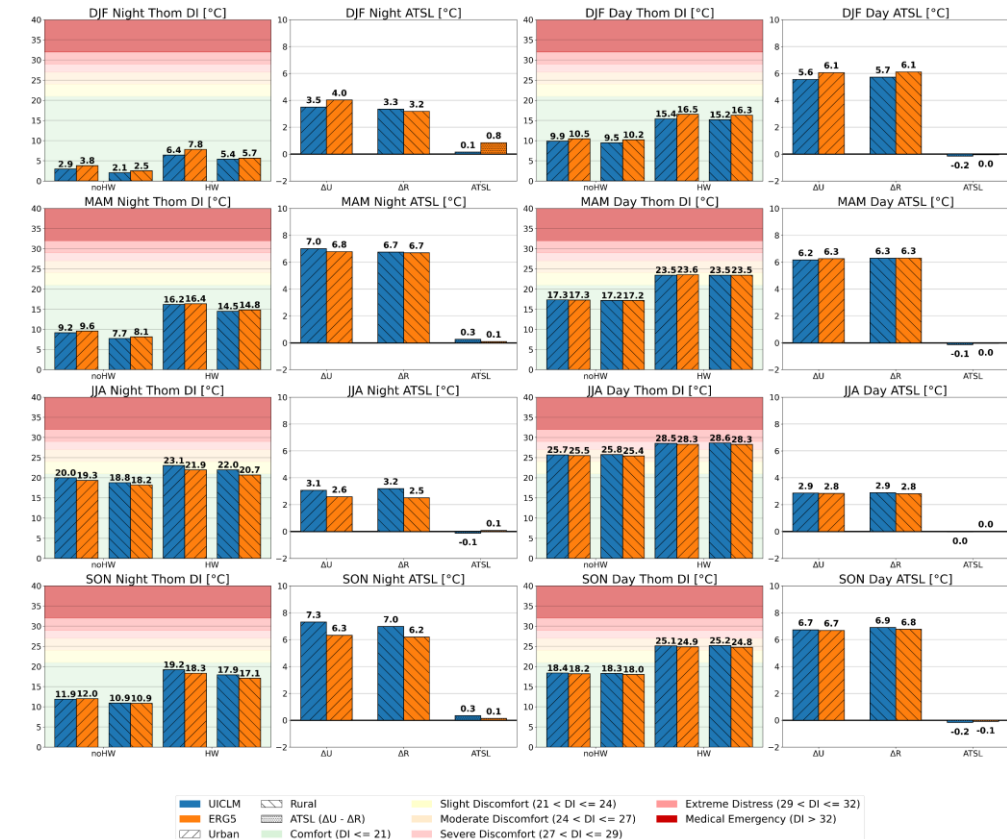
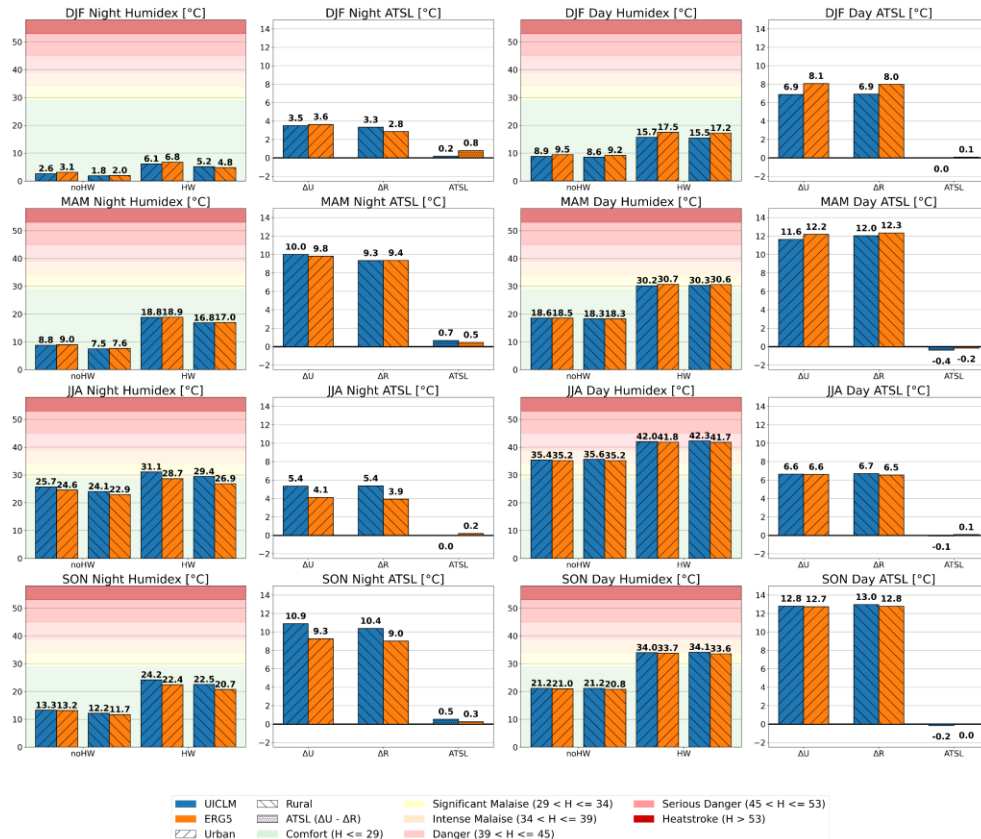
Spatial representation of diurnal UDI during HW and no-HW conditions for both UICLM and ERG5. The ADL (Added Dry Load) is defined as the difference between UDI|HW and UDI|no-HW, showing the increase in UDI intensity during HW conditions.

Heatwaves amplify nocturnal urban effects, with UDI reaching -9.2% in UICLM (compared with -7.4% during noHW) and -9.0% in ERG5 (compared with -6.2% during noHW) during JJA, while showing weak or no amplification during the day.

Heat stress analysis: Intensity



Heat stress indicators (Humidex and Thom) combine temperature and relative humidity, as a humid environment inhibits sweat evaporation, potentially leading to greater perceived thermal stress.

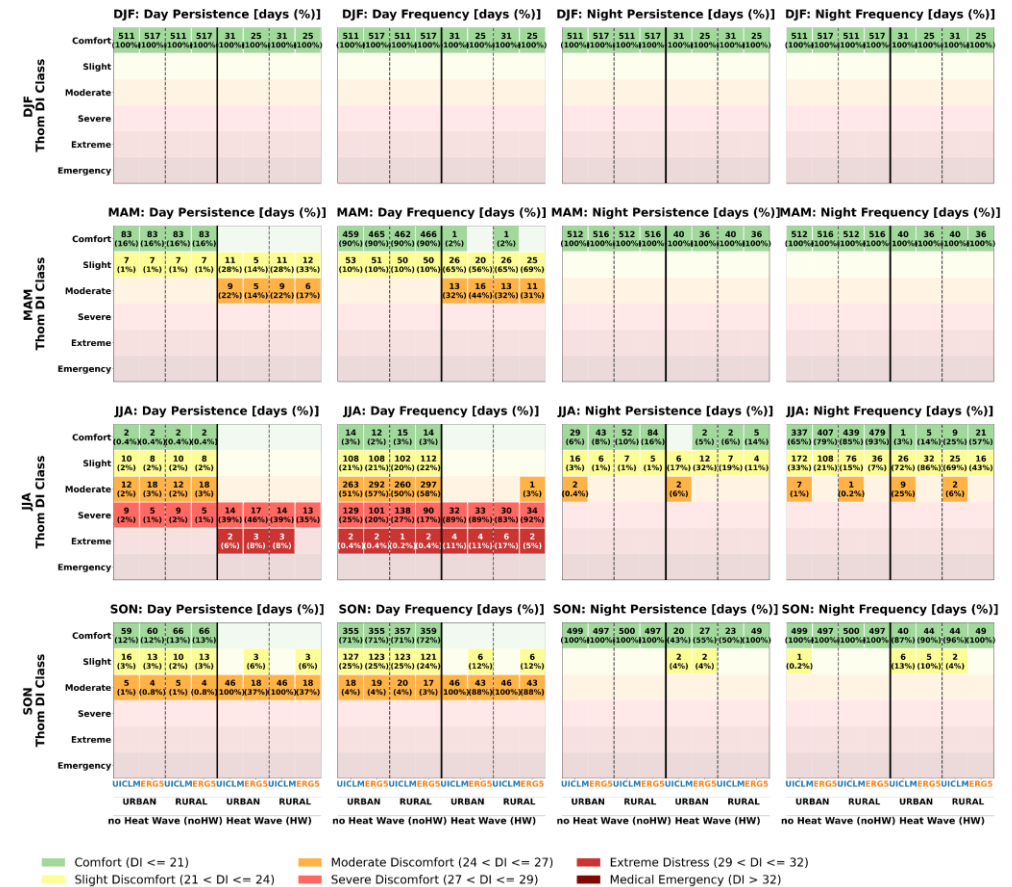
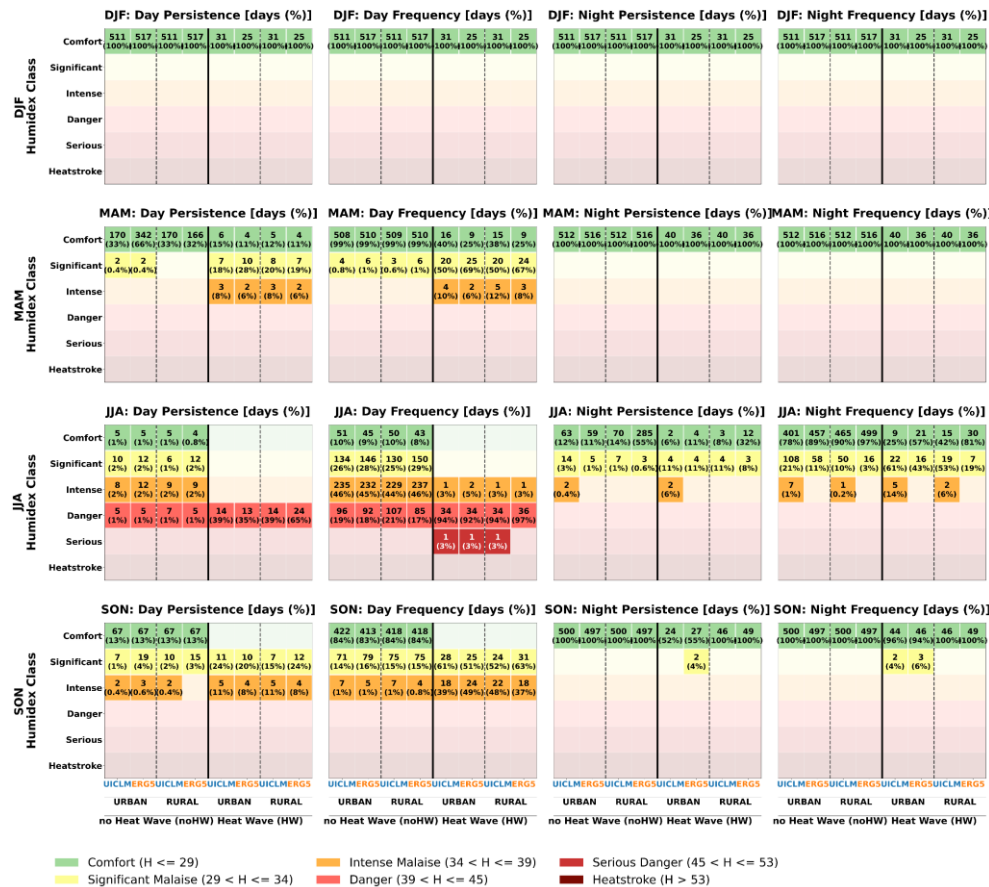


Seasonal intensity of the Humidex index for both UICLM and ERG5 over urban and rural areas. ATSL is calculated as the difference between Humidex during HW and no-HW conditions.

Seasonal intensity of the Thom index for both UICLM and ERG5 over urban and rural areas. ATSL is calculated as the difference between Thom during HW and no-HW conditions.

Thermal stress is mainly driven by synoptic heatwave forcing, with higher intensity during daytime HW conditions.

Heat stress analysis: frequency and persistency



Seasonal frequency and persistence of the Humidex index during HW and noHW conditions for UICLM and ERG5 over urban and rural areas, reported as relative (%) values (normalized with respect to the total duration of each risk class) and absolute values (days).

Seasonal frequency and persistence of the Thom index during HW and noHW conditions for UICLM and ERG5 over urban and rural areas, reported as relative (%) values (normalized with respect to the total duration of each risk class) and absolute values (days).

The major contribution of the city at night is reflected in the increased frequency and persistence of higher-risk categories (from comfortable to significant) during JJA HW conditions over urban areas compared with rural ones.

- UICLM reproduces the main urban climate features of the Bologna metropolitan area, capturing the seasonal and diurnal variability of UHI and UDI (paper in preparation; more details will be provided in that study).
- UHI is predominantly nocturnal, reaching +1.6 °C in UICLM vs +1.5 °C in ERG5 in summer, while daytime urban–rural differences remain weak. UDI is also stronger at night, reaching –7.4% in UICLM vs –6.2% in ERG5 under all weather conditions.
- Summer heatwaves amplify nocturnal urban effects, with UHI reaching +1.9 °C in both UICLM and ERG5, and UDI reaching –9.2% in UICLM vs –9.0% in ERG5.
- Thermal stress intensity is mainly driven by synoptic heatwave forcing during the day, whereas urban effects become more relevant at night, increasing the frequency and persistence of higher-risk conditions.
- Despite summer warm and dry biases during day, urban–rural contrasts are well captured, with UHI and UDI showing close agreement between UICLM and ERG5, indicating that the main mechanisms governing urban effects are well represented.
- UICLM provides a suitable framework for high-resolution urban climate studies, with potential applications to future climate projections and the assessment of compound heatwave, UHI and UDI impacts.
- Next steps: extend the analysis to climate projections to investigate whether UHI/UDI-heatwave interactions and associated thermal stress intensify under future warming, supporting the assessment of urban climate risks and adaptation strategies.

Thank you for your attention!
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