GenHack 2025

Phase 3: Metrics & Quantitative Insight

Discrepancies

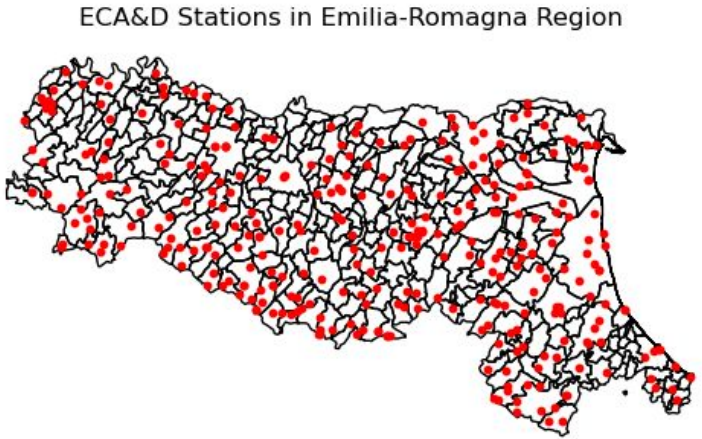
Goal – Understanding Temperature Discrepancies

Sentinel satellite temperatures often differ from weather station data.

- Weather stations are the ground truth, but sparse;
- Sentinel covers everywhere but is less precise.

Why Emilia Romagna?

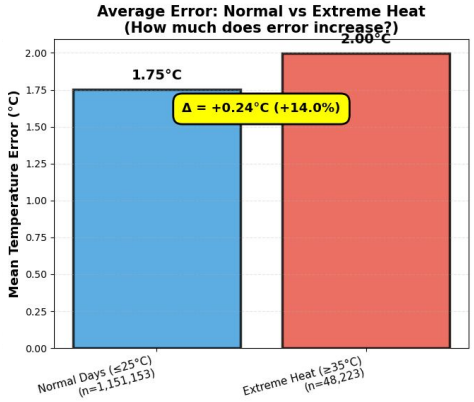
- High density of weather stations across the region
- Large urban agglomerations ideal for studying urban heat effects
- Stations are spatially well distributed, enabling reliable comparisons

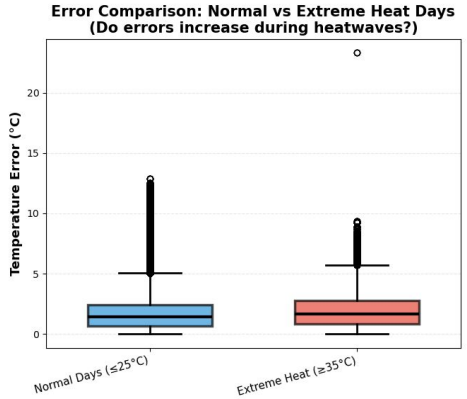


Do Satellite Errors Increase During Heat Waves?

During heat waves, satellite temperature estimates become less accurate.

- Satellites slightly underestimate on normal days but severely during extreme heat (**+1.8°C**).
  When ERA5 reports 38°C, ground truth may be ~40°C.
- Current satellite systems have critical biases exactly when accurate data is most needed for public health protection.
- With p = 6.12e-281, the independent t-test shows the difference is statistically unquestionable.





Which Stations Have the Largest Errors?

As expected, the largest temperature errors occur in areas with NDVI < 0.5, corresponding to dense urban zones.

SOUID	HGHT	ECA_TX	ERA5_t2m	NDVI	temp_diff
95625.0	1794.0	9.767949	17.321503	0.403827	-7.553554
916134.0	2165.0	6.950680	13.817970	0.291629	-6.867291
118225.0	1662.0	9.881128	15.970561	0.377859	-6.089433

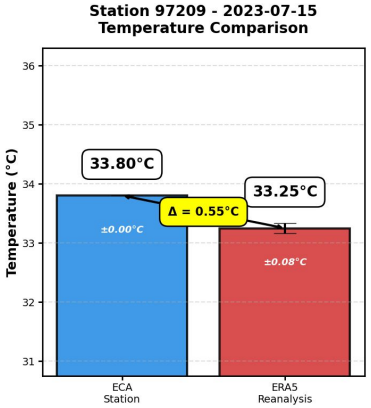
Error metric

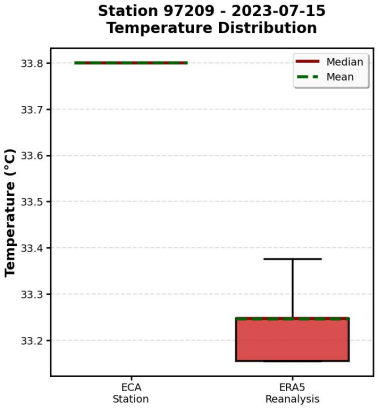
Absolute error: |ECA_TX - ERA5_t2m|

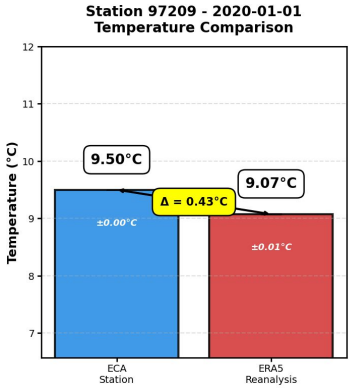
Which Season Have the Largest Error?

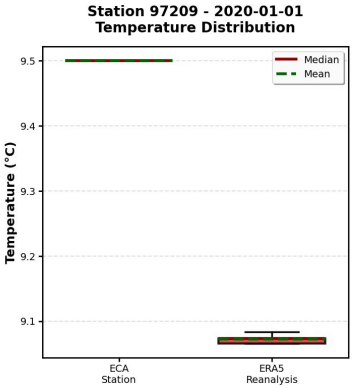
Observations:

- **Summer**:
  Absolute error: Δ = 0.55°C
  Distribution shows ERA5 underestimates the temperature, with a wider spread compared to the station;
- **Winter**:
  Absolute error: Δ = 0.43°C
  Distribution is narrower, indicating smaller variability and smaller bias, as seasonal extremes and urban heat effects are less pronounced.









Metrics used to evaluate discrepancies

The **Urban Heat Island** (UHI) index was defined as the temperature difference between each pixel and the mean temperature of rural pixels, identified as those with an **NDVI above 0.5**.

Temperature data from ECA meteorological stations served as ground truth to assess discrepancies caused by ERA5's coarser spatial resolution. After computing the UHI for both ERA5 pixels and ECA stations, discrepancies were quantified as the absolute difference between their respective UHI values.

UHI Discrepancy	
Mean	1.20 °C
Standard Deviation	1.22 °C
Max	8.40 °C
Percentage Error	
Mean	40.06%
Standard Deviation	40.95%
Min	0.20%
Max	199.88%

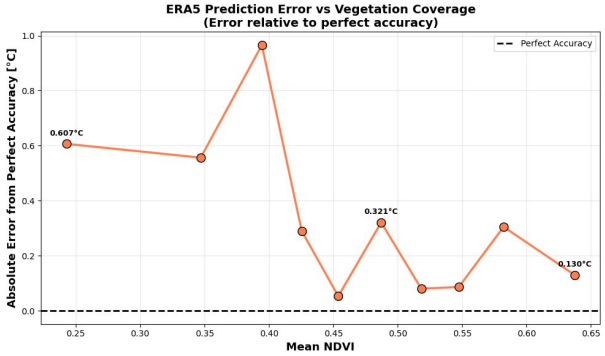
$$\mathrm{UHI} = T_x - \overline{T}_{\mathrm{rural}} \qquad \Delta_{\mathrm{UHI}} = \left|\mathrm{UHI}_{\mathrm{ERA5}} - \mathrm{UHI}_{\mathrm{ECA}}\right|$$

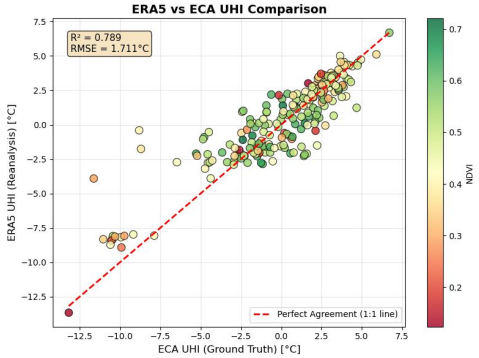
Correlation between urbanization and error

A central hypothesis of the study is that **ERA5's accuracy degrades as urbanization increases**.

This is validated through NDVI gradient analysis, which demonstrates a clear pattern: as vegetation decreases and urban density rises, the absolute error between ERA5 and ground truth grows substantially.

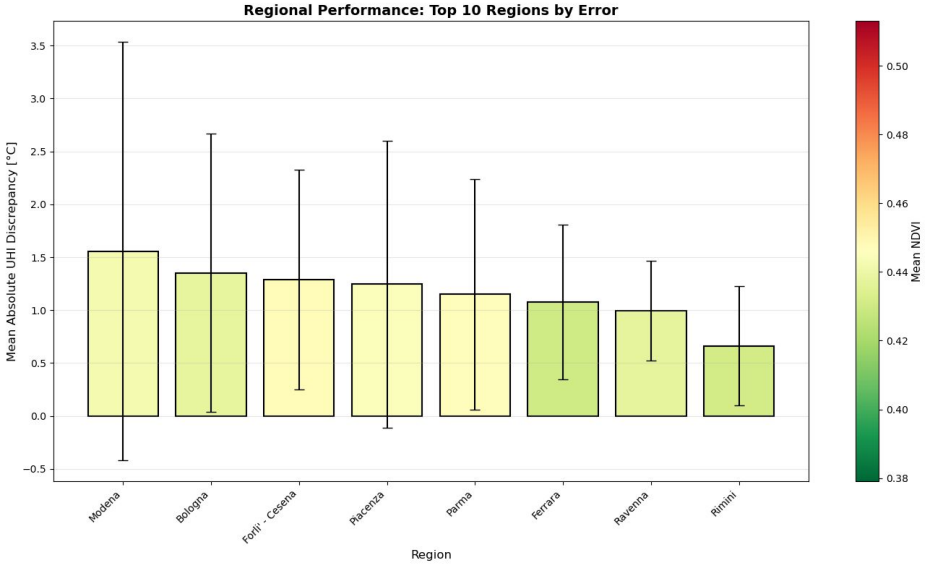
Urban stations consistently show larger discrepancies, regardless of the actual UHI magnitude, while rural stations maintain near-perfect agreement.





Province analysis

The **error** is not random; it **is strongly linked to land cover**, with urban stations showing much higher absolute and percentage errors than their rural counterparts. The coarse spatial resolution of ERA5, which averages temperatures over large grid cells, fails to capture the localized heat effects that ground stations detect, especially in built-up areas.



Plots and regional summaries show that provinces with larger cities, like **Bologna** and **Modena**, experience the highest discrepancies.

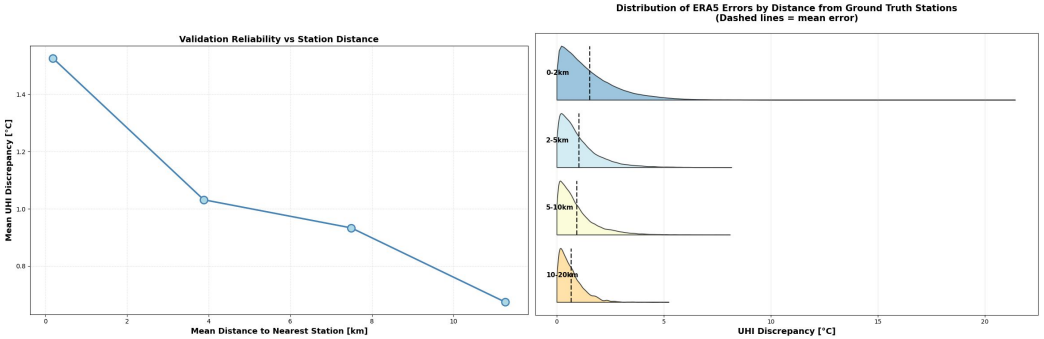
Spatial Dependence of ERA5 Error

Errors between ERA5 and ground-truth temperatures are largest near weather stations, where local thermal variability is accurately measured.

Ground-truth data were **interpolated** onto the NDVI grid using a **nearest-neighbor** method, meaning that as distance from stations increases, the interpolated temperatures lose precision and no longer capture fine-scale UHI patterns.

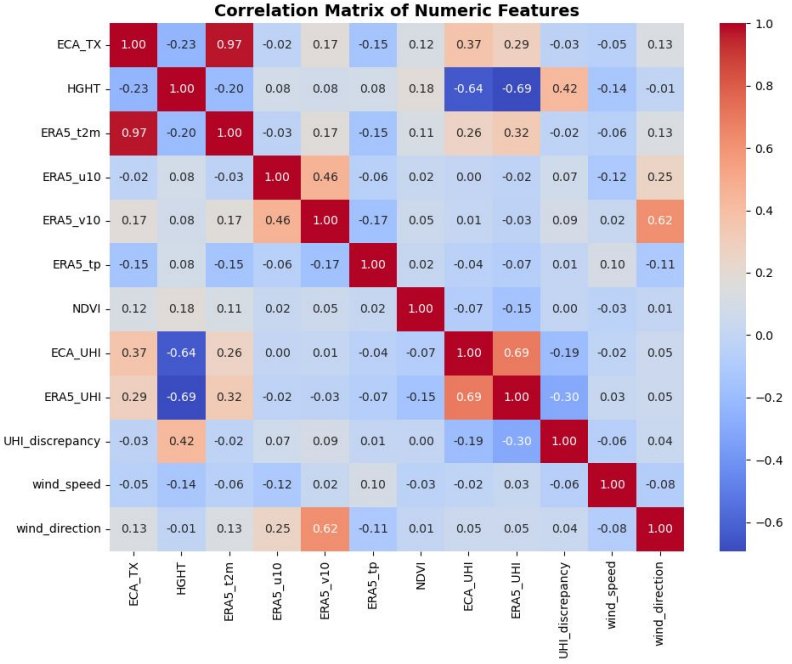
This makes ERA5 appear more accurate at greater distances, producing artificially lower errors. A denser station network is therefore essential to reduce interpolation uncertainty and improve UHI evaluation.

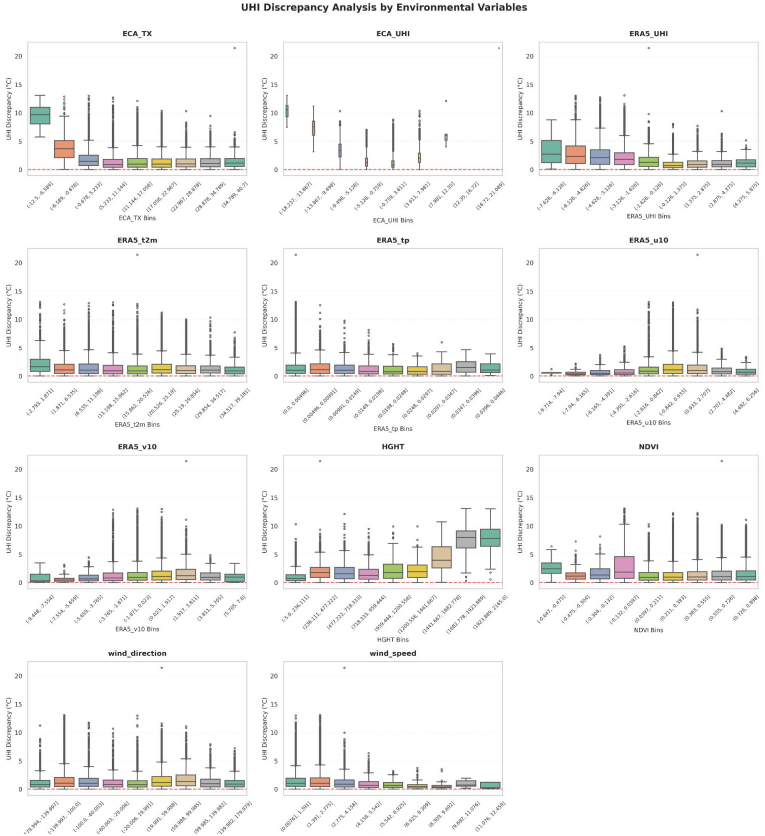
In the plots, a few unusually high error values were intentionally kept rather than removed to show the real though rare impact that distance can have on discrepancies.



Emilia-Romagna region general analysis

Considering every province in Emilia-Romagna region, previously seen:





Conclusion

The study demonstrates that **ERA5 systematically fails to capture the thermal signature of urban environments** due to its coarse spatial resolution.

The role of vegetation (NDVI): there is a direct link between land cover and model performance:

- **High Error:** Dense urban areas (NDVI ~0.2) show the largest prediction discrepancies.
- **High Accuracy:** Rural areas (NDVI ~0.8) show near-perfect alignment.

While ERA5 remains useful for regional-scale climate analysis, it cannot replace high-resolution **ground station networks**, which are **irreplaceable for local urban heat monitoring**.