Modelling T_{mrt} in a complex urban environment using a convolutional encoder-decoder network

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We present a novel and fast computing deep learning approach using a convolutional encoder-decoder network (U-Net) to predict maps of pedestrian level (1.1 m a.g.l.) T_{mrt} at a building-resolved scale (1 x 1 m). Therefore, we emulate the physical model SOLWEIG by training the U-Net on SOLWEIG model outputs.

As a demonstration case, U-Net is applied to model hourly T_{mrt} in the city center of Freiburg at 1 x 1 m resolution for two complete 30-year periods (1961 – 1990, 1991 – 2020) driven by hourly ERA5 reanalysis data.

1. Background

T_{mrt} is a driving factor of daytime human thermal comfort and underlies great spatial and temporal variabilities, especially in complex urban areas. Various micro scale (building-resolving) models exist to model T_{mrt} in urban environments. However, these models are computationally expensive, albeit to varying degrees. This means, study area and time might be very limited depending on spatial and temporal resolution. While this is sufficient for case studies where micro-level processes are modelled for different neighborhoods in limited time periods, projections of climate change impacts are not possible. To overcome these computational drawbacks of physical models, we present a deep learning approach based on convolutional encoder-decoder (U-net – Ronneberger *et al.*, 2015) for modelling T_{mrt} in complex urban areas.

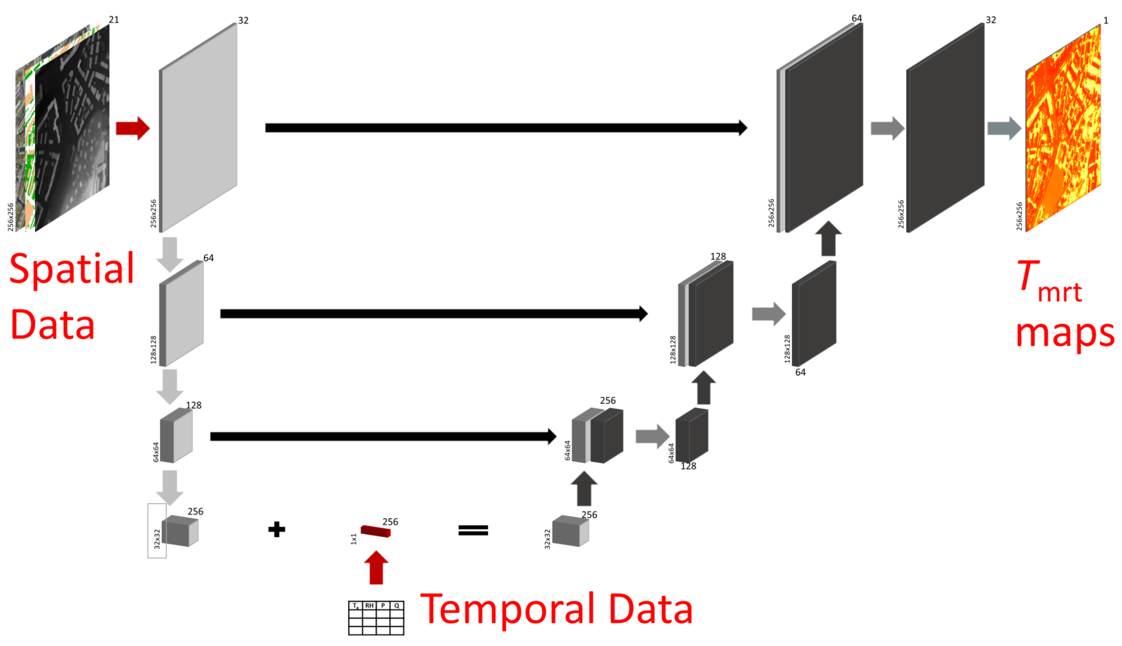
2. Methods

We use an U-Net to emulate SOLWEIG (Lindberg *et al*., 2008). This means SOLWEIG is used to create T_{mrt} training maps as response data for the U-Net. Training data covers 62 areas (500 x 500 m) located in Freiburg im Breisgau, Germany, and 80 days (hourly resolution). Temporal and spatial predictors are the same for both models. Temporal data is obtained from an urban weather. Spatial data contains a digital elevation model, digital surface model, land cover classes, and sky view factor maps. Spatial data is received from LIDAR data, orthophotos, urban atlas and open street maps.

Model validation is conducted in two steps: in **step 1**, SOLWEIG and U-Net are pointwise validated on 6-directional radiation measurements; in **step 2**, the U-Net is area-wide validated against SOLWEIG. Measurement data is from a T_{mrt} measuring campaign in 2007 / 2008.

Computational benchmarking of the two models is conducted by predicting 720 time steps of T_{mrt} maps, which corresponds to one month of hourly predictions or 5 days of 10-min presanctions.

To demonstrate a potential application, the trained U-Net is then applied to model long-term (60 years at hourly resolution) T_{mrt} for an area with a 500 x 500 m extent at a resolution of 1 m for the city center of Freiburg, Germany. For that purpose, ERA5-Land hourly data are used from 1960 to 2020.



Schematic representation of the U-Net.

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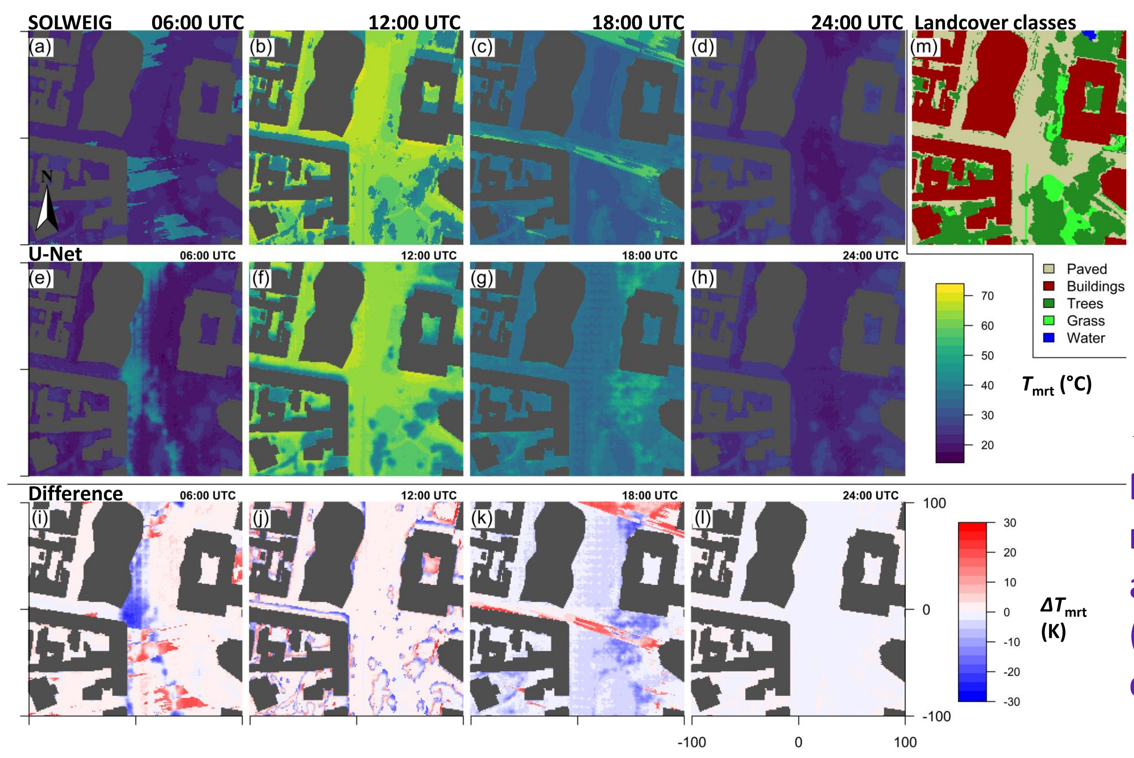
3. Results & Discussion

Both models show sufficient success in modelling T_{mrt}. SOLWEIG and U-Net are able to predict T_{mrt} in complex urban environments with an mean absolute error (MAE) of 4.4 K for SOLWEIG and 4.3 K for U-Net **(step 1 validation)**, which is in line with MAE values of SOLWEIG from literature.

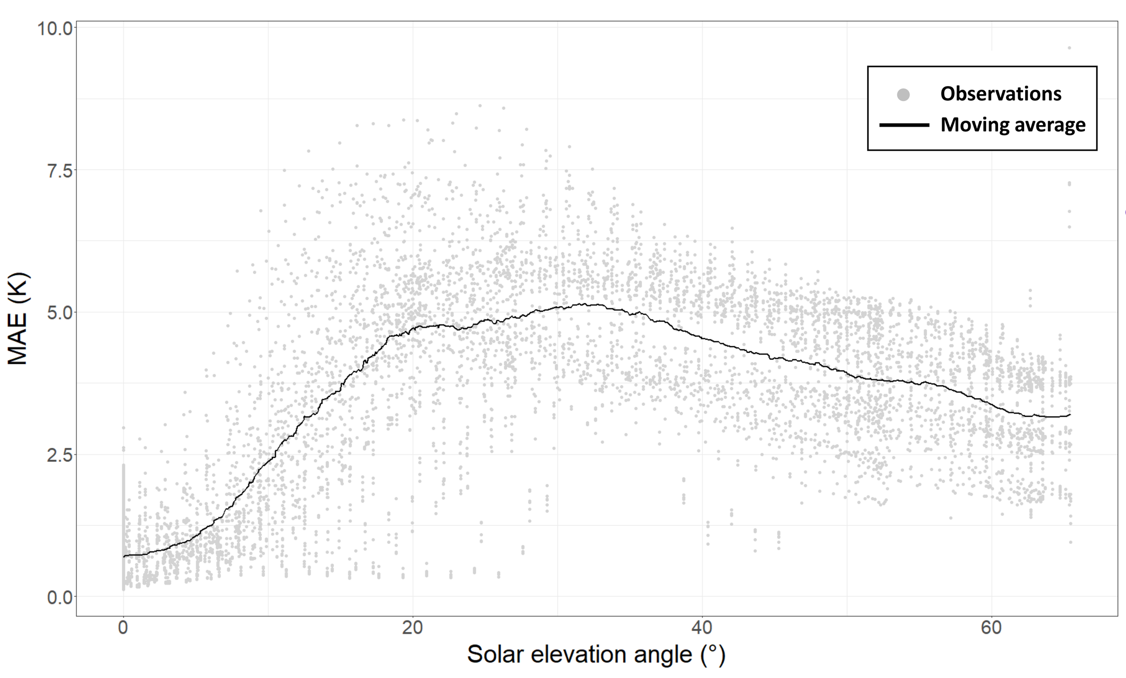
Evaluation metrics of SOLWEIG and the U-Net. Mean absolute error (MAE) and root mean squared error (RMSE) of SOLWEIG, U-Net, and measurements.

	Step 1 Validation			Step 2 Validation
	U-Net *vs.* Measurements	SOLWEIG *vs.* Measurements	U-Net *vs.* SOLWEIG	U-Net *vs.* SOLWEIG
MAE (K)	4.3	4.4	2.3	2.4
RMSE (K)	5.7	6.0	4.6	3.8

Model accuracy of the U-Net is high at 2.4 K (MAE – **step 2 validation**). Model accuracy varies between different test areas and days, while shadow patterns and solar elevation angle have the highest impact on accuracy. The U-Net performs better in open areas than in complex built-up environments because of the more complex shadowing. The limitations of the U-Net modelling T_{mrt} at the transition from shadow to sun can also be seen in the figure below. In addition, the highest prediction errors occur in the morning and evening. The main reason for these diurnal error cycles is complex shadow patterns for low solar zenith angles. Low solar zenith angles create long shadowing of buildings and trees and thus affect a larger area. As the U-Net has its highest errors at the transition from shadow to sun, large errors and errors in a larger area occur under these circumstances.



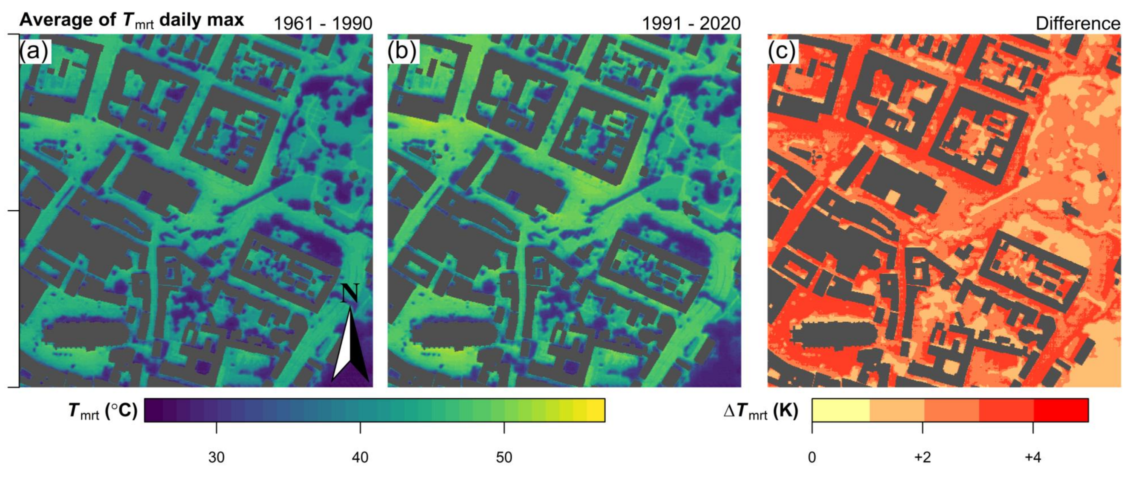
Modelled T_{mrt} maps at a height of 1.1 m a.g.l. and a spatial resolution of 1 x 1 m by SOLWEIG (a – d) and U-Net (e – h), as well as the difference (i – l) for four time steps of a clear summer day (July 17, 2007) in the city center of Freiburg. Figure (m) shows land cover classes of the area**.** North arrow can be seen in figure (a).



MAE of the U-Net as a function of solar elevation angle. Each point (observations) represents a MAE value for one timestep and one area. The black line represents the moving average value of MAE (window size of 2.5°).

The U-Net is about 22 times faster than SOLWEIG when saving predictions in GeoTIFF format. However, if the predictions are stored only in NumPy arrays, the U-Net is up to 38 times faster. For pure statistics, calculated directly from the predictions, the U-Net is up to 130 times faster.

Results of the 60-year predictions show that summertime daily maximum T_{mrt} at pedestrian level increased on average by 2.6 K (1.1. – 4.0 K), whereas summertime daily maximum air temperature increased by only 1.5 K from period one to period two. In addition, days with area-wise averaged $T_{mrt} \geq 60$ °C tripled from period one to period two. Maximum T_{mrt} increase is stronger on non-tree covered paved areas than on tree covered grassy areas (2.9 K and 1.7 K).



Predictions of the U-Net. Maps of average daily maximum T_{mrt} of the three summer months June, July, and August for 1961-1990 (a) and 1991-2020 (b) and the differences (c) in a 500 x 500 m subset of central Freiburg.

4. Conclusion

- The U-Net is able to **emulate** a micro-meteorological physical model with **computational superiority** (22 times faster with MAE of 2.4 K).
- Model accuracy varies between different test areas and days, while **shadow patterns** and **solar elevation** angle have the highest impact on accuracy.
- Improvement of the overall model results depends also on the performance of SOLWEIG, as SOLWEIG and U-Net perform similar compared to measurement data.
- The U-Net enables spatially differentiated, **long-term climate change detection** in complex urban environments.

References

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