Radiation modelling as a first step into a numerical simulation of vegetation-atmosphere interactions in urban canyons

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Introduction

- Urbanisation impacts Earth's systems by increasing CO_2 emissions, creating Urban Heat Islands, and affecting climate, energy use, and public health.
- Urban climate mitigation and adaptation strategies need a thorough understanding of the mechanisms controlling the microclimate in cities.
- Urban climate modelling enables researchers to explore different scenarios and interventions within a controlled setting without having to rely on sparse in situ weather stations.
- We are developing a **simple**, and therefore light, *3D ecophysiological model* for urban climate analysis, representing tree canopies and **solids** (buildings and terrain) as **3D voxels**.
- We present the 3D radiation model to estimate the radiation reaching the canopy surface of each vegetation voxel.

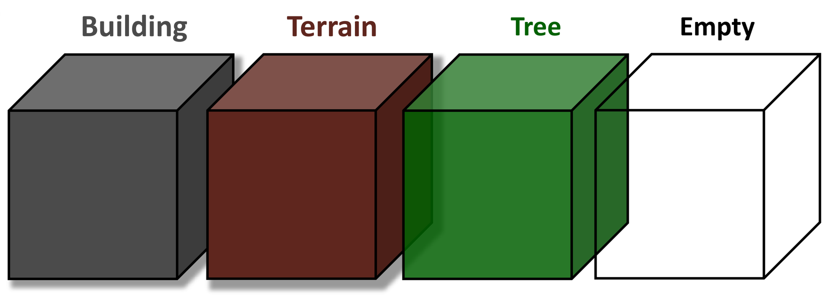


Fig. 1 – The four types of isometric cubic voxels present in our model.

Study Area

We focus on one small area around the University of Basel where we have installed meteorological stations to measure atmospheric variables, including incoming and outgoing shortwave and longwave irradiance.

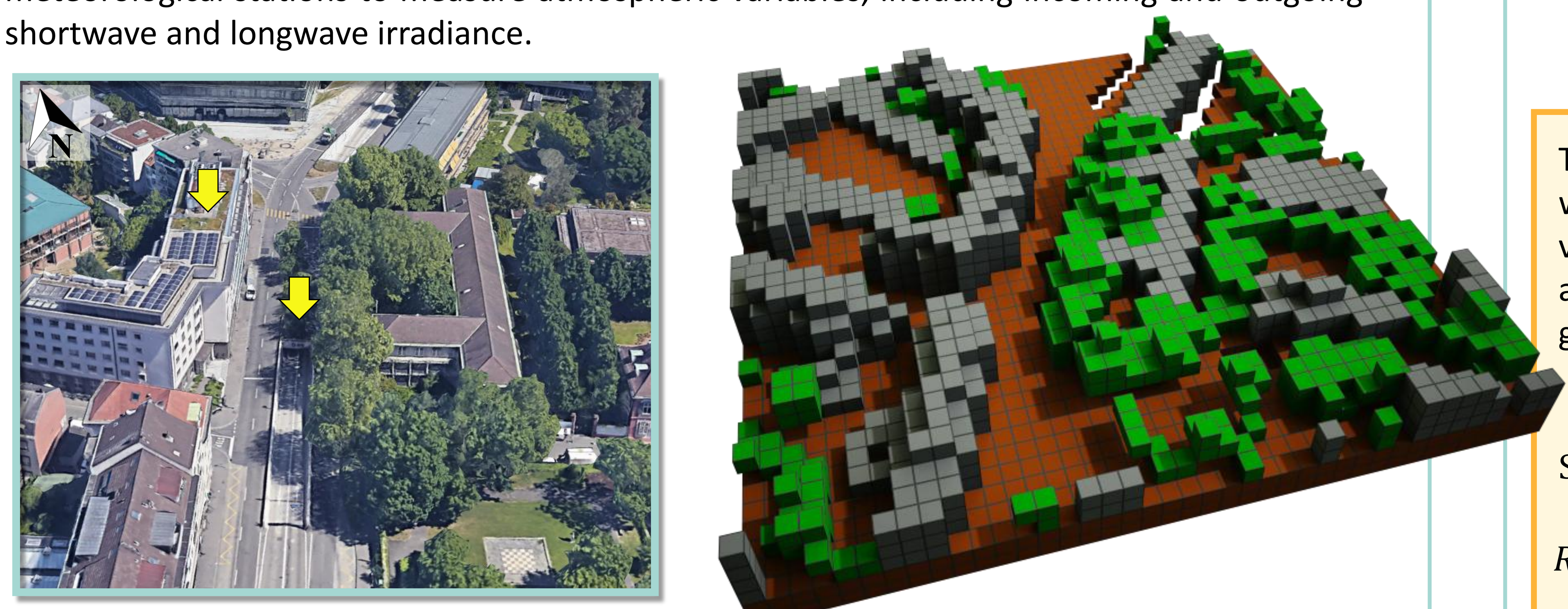


Fig. 2 – Comparison between an aerial view (Google Earth) of the considered neighbourhood and the 3D modelled version of the same area with voxels of the four different types. The red arrows in the left picture show the locations of the roof and street stations.

Results

- Converting a continuous space into a finite grid of discrete voxels causes discretization errors, such as the modelled direct irradiance being blocked at a shifted time compared to what happens in the urban canyon. This causes the clusters' displacement from the median visible in the hourly average in Fig. 4.
- In urban canyons with buildings on both side, the displacement of shadows usually happens twice a day in opposite directions, therefore daily means average out that error.

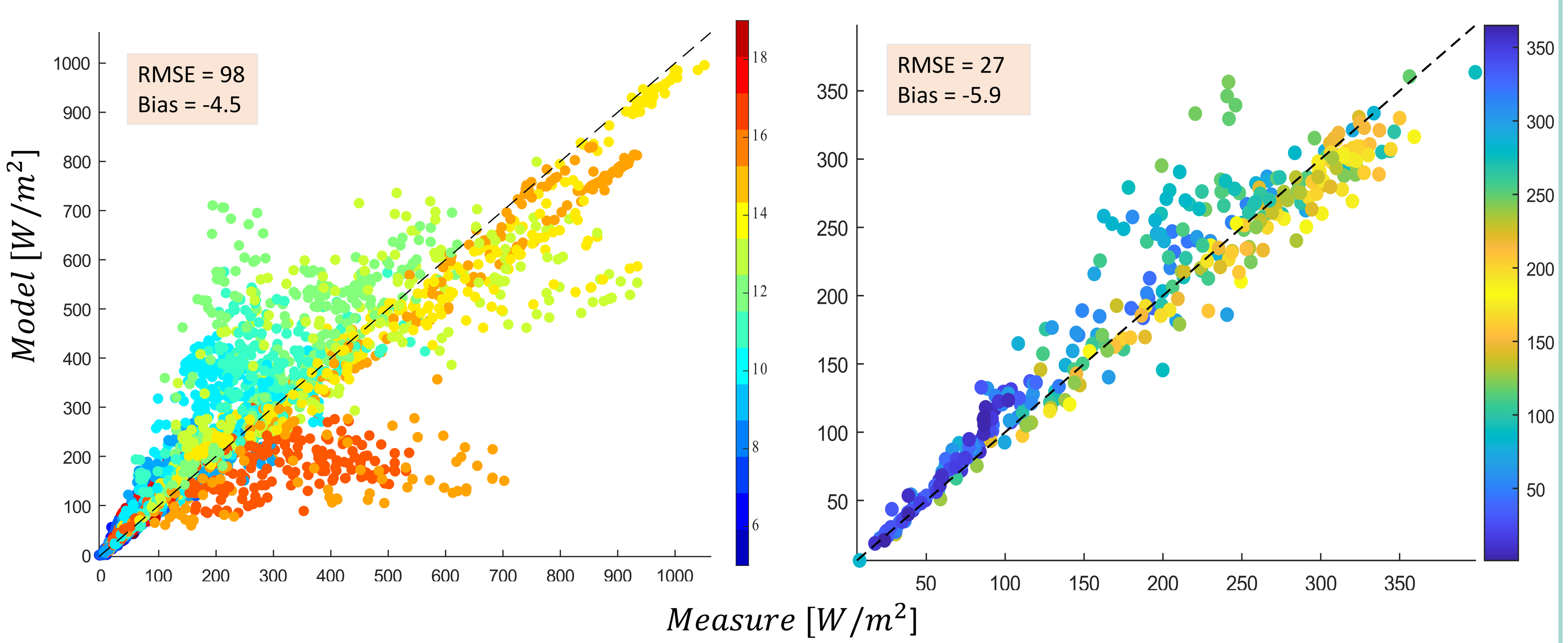


Fig. 4 – Comparison of simulated street-level incoming shortwave radiation against measured data for 2023. On the left we have hourly average colour-coding according to the hour of the day (UTC +1). On the right we have daily average colour-coding according to the day of the year.

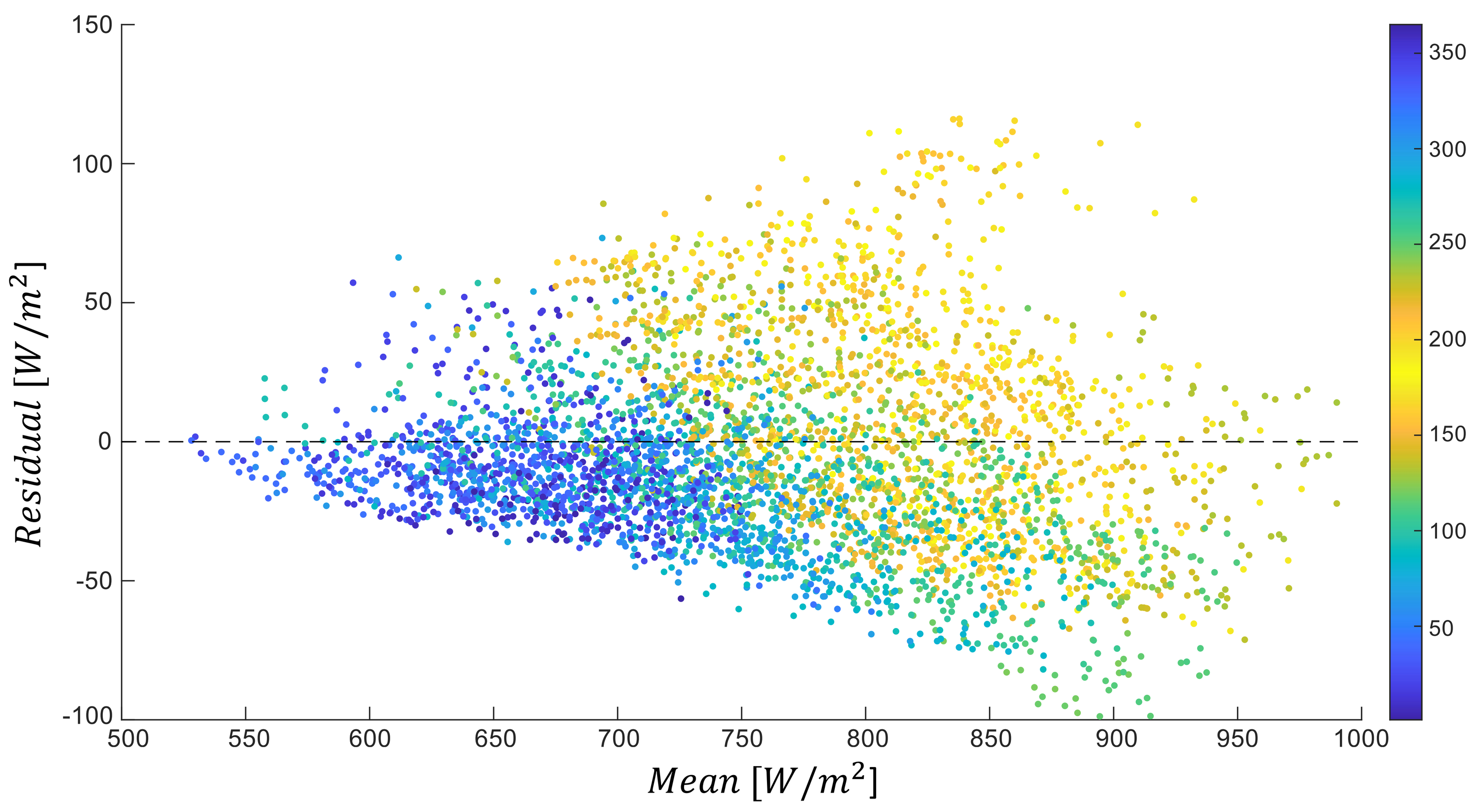
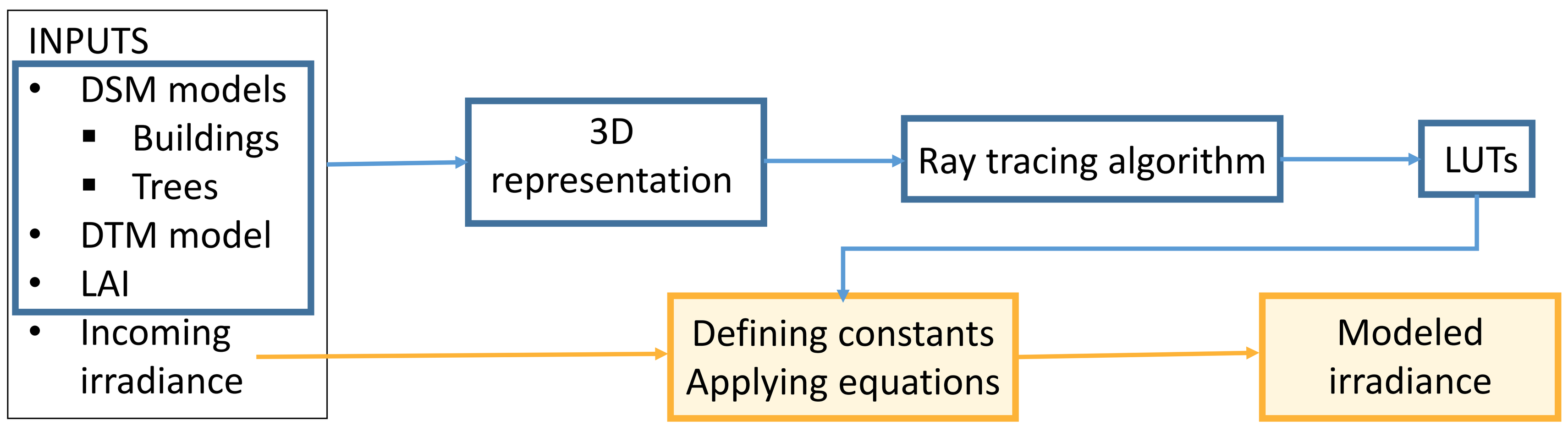


Fig. 5 – Mean of Measured and Computed longwave at street level (M+C/2) versus the residual (M-C) during daylight hours for 2023. We can see that for large daily mean fluxes we have larger residuals. The average daily absolute relative error is 2.3%, with a standard deviation of 1.4% and the correlation between daily mean flux and daily errors is just 0.11. Therefore the percentage bias remains nearly constant.

Radiation Model



- Geospatial data are used to develop a 3D model of the study area and a ray tracing algorithm determines directions that are blocked or intercepted by tree canopies to determine useful variables, such as the Sky View Factor (SVF), shortwave reflection (R) and longwave contributions (LW) .
- The Leaf Area Index (LAI) intercepted by radiation is also determined by the same algorithm and is used to determine the transmittance (τ), which is the fraction of incident light transmitted through a tree voxel.
- This information for each voxel is stored in Look Up Tables (LUTs) and subsequently used in the relevant equations to compute incoming radiation without recomputing the geometry.

To compute physical quantities, we first calculate several spatial variables. As seen in Fig. 3, these are derived from our model's geometric construction.

$$\mathrm{SVF} = \sum \frac{\sin(\varphi_{free})}{T \cdot \sum \sin(\varphi)}$$

$$R_{\mathrm{dir}} \propto \sum S / \sin(\alpha)$$

$$R_{diff} \propto \sum SVF_{solid}/\mathrm{N}$$

$$SW_{\mathrm{dir}} = SW_{\mathrm{dir}} \downarrow \cdot \sin(\phi) \cdot \tau_{\mathrm{dir}} \cdot \mathrm{S}$$

$$SW_{diff} = SW_{diff} \downarrow \cdot \mathrm{SVF} \cdot \tau_{diff}$$

$$SW_{\mathrm{r}} = \sum_{seen\ voxel} R_{\mathrm{dir}} + R_{diff}$$

$$LW = LW_{sky} + LW_{solid} + LW_{trees}$$

$$LW_{sky} \propto \mathrm{SVF} \cdot \tau_{diff}$$

$$LW_{solid} \propto \sin(\beta) \cdot f(T_b)$$

$$LW_{trees} \propto LAI \cdot \tau_{\mathrm{tree}}$$

φ_{free} : elevation of unblocked directions (yellow and blue arrows)
T : total number of considered azimuth directions
φ : elevation of the considered direction
S: 1 if the sun's direction is unblocked (blue arrow); 0 if shadowed by a solid voxel (red arrows)
α : angle between voxel and tree (pink arrow)
SVF_{solid} : SVF of the solid voxel seen by the tree
N : number of solid voxels seen by the tree
$SW_{\mathrm{dir}} \downarrow$: measured direct shortwave on roof
ϕ : sun elevation (blue arrow)
$SW_{diff} \downarrow$: measured diffuse shortwave on roof
β : angle between voxel and tree (orange arrow)
T_b : temperature of the solid voxel, dependent on S

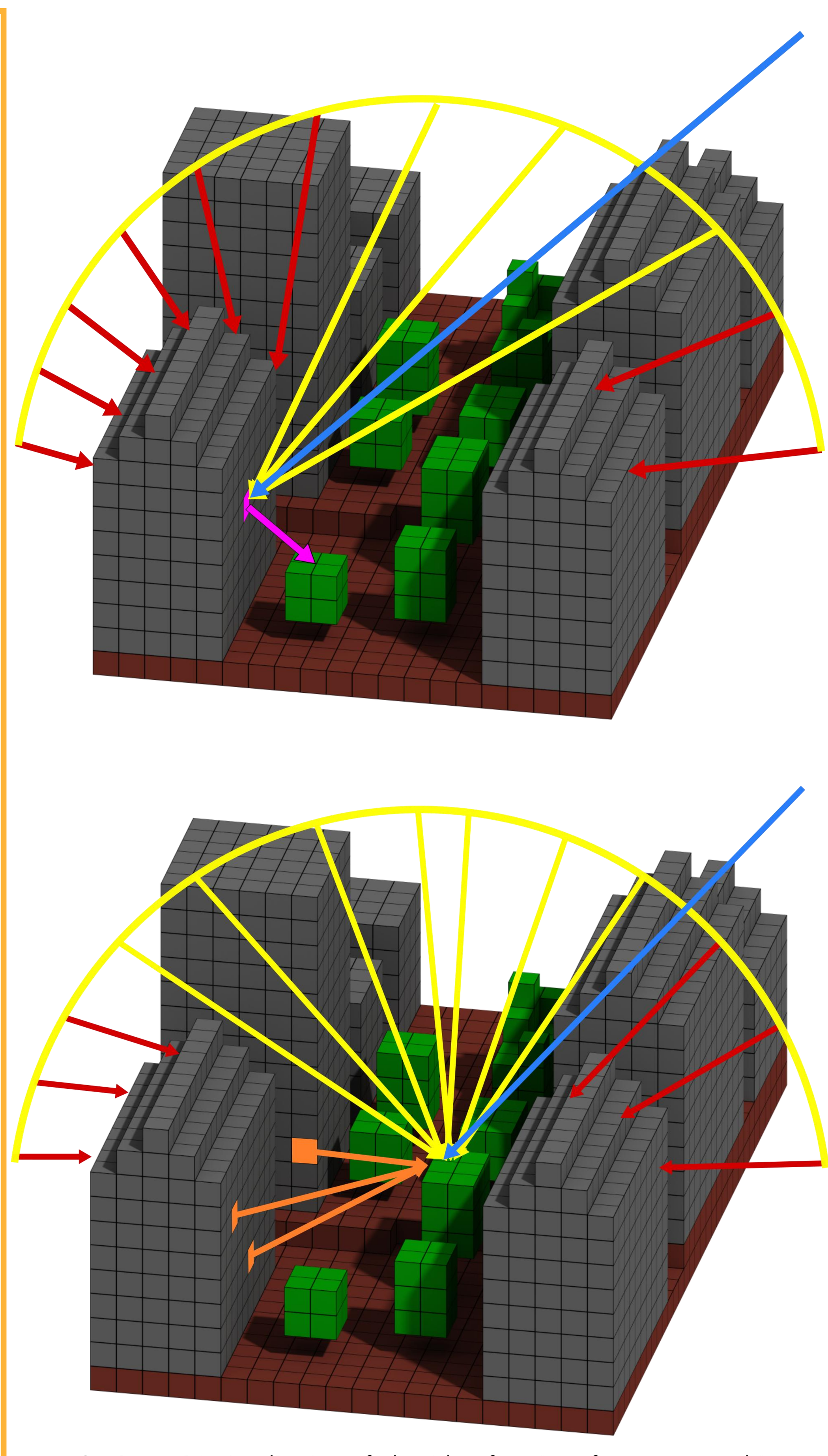


Fig. 3 – A 3D visualisation of algorithm functions for a tree voxel in an urban canyon. The colours of the arrows indicate: blue, the direct shortwave from the sun direction; orange, the thermal emission of solid voxels; yellow, directions free to the horizon; red, blocked directions. The pink arrow shows one of the voxels seen by the tree and the reflection path connecting them.

Conclusions and future work

- In Basel's urban canyon, our computationally efficient approach predicts daytime shortwave and longwave irradiance.
- The results show errors caused by several modelling effects such as discretization and simplifications, but these errors are comparable to other models reported in the literature.
- Radiation fluxes are simulated at very high resolutions and this might allow us to simulate **leaf-level process** more precisely.
- The model will be further evaluated using two additional street level micrometeorology stations and an ongoing thermal camera campaign in street in urban canyon.

References:

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