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3D Radiation in PALM with TenStream

S. Schubert[1,2], F. Jakub[3], M. Salim[1,2], B. Mayer[3]

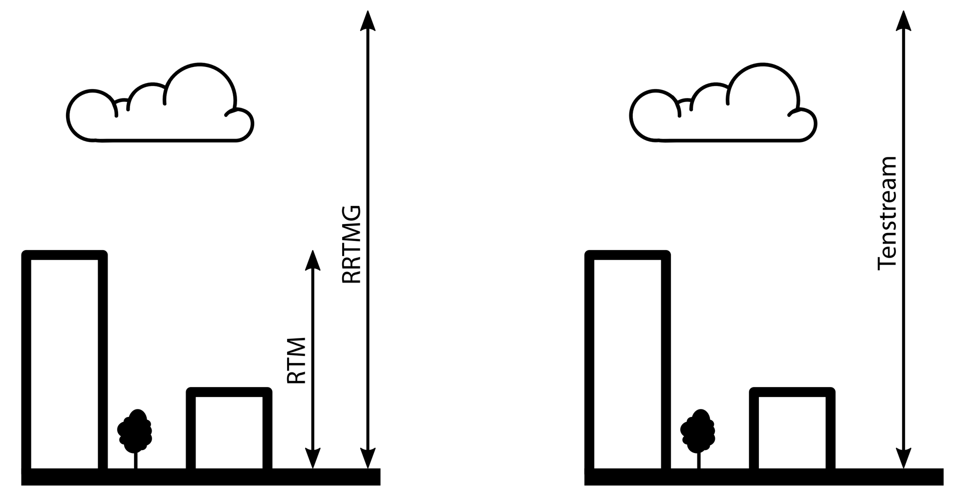
[1]Institute of Ecology, Technische Universität Berlin; [2]Geography Department, Humboldt-Universität zu Berlin; [3]Meteorological Institute, Ludwig-Maximilians-Universität München

Introduction

When applied to urban areas, PALM currently uses the 1d atmospheric radiation scheme RRTMG coupled to the surface-based, 3d radiation scheme RTM within the urban canopy layer (fig. 1a). This approach combines realistic results with a relatively low computational demand (Resler et al. 2021). This approach has the following main limitations:

- atmospheric heating rates assume horizontal homogeneity
- no consideration of atmospheric constituents within canopy
- 3d effects of clouds not considered

These issues are solved by the newly implemented 3d atmospheric radiation scheme Tenstream (fig. 1b).



(a) RRTMG (1d atmospheric radiation transport) coupled to RTM (3d surface based radiation transport within the canopy layer)

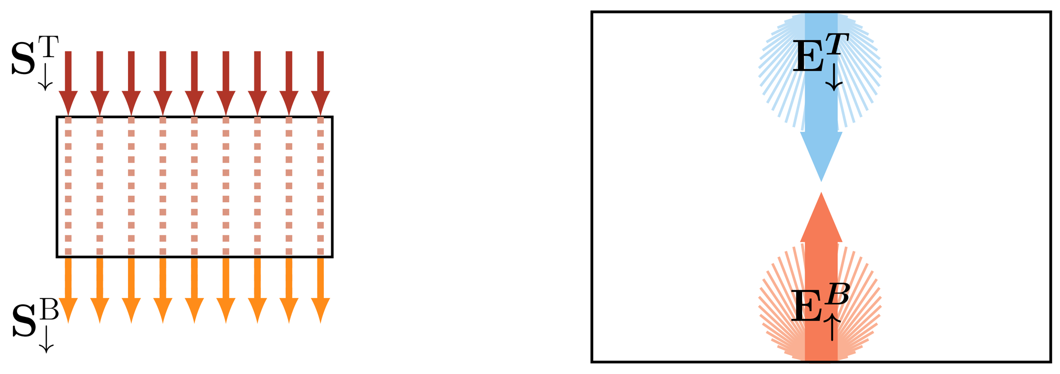
(b) Tenstream: 3d atmospheric radiation transport

Figure 1: Schematics of the currently available radiation schemes in PALM when applied to urban areas: (a) is the default approach while (b) is the newly developed approach.

Details of RRTMG+RTM and Tenstream

Rapid Radiative Transfer Model for GCMs (RRTMG) (Mlawer et al. 1997; Oreopoulos and Barker 1999)

- radiation transport in 1d atmospheric column from top of the domain to the surface
- considers atmospheric constituents
- average values for the PALM domain



(a) Direct downward radiation stream

(b) Diffuse downward and upward radiation streams

Figure 2: Discretization of radiation transport through atmospheric grid cells in RRTMG

Radiative Transfer Model (RTM) (Resler et al. 2017; Krč et al. 2021)

- shadows and visibility between surface elements within canopy → 3d structure
- input at top of canopy from RRTMG
- atmospheric constituents not considered
- resolved vegetation considered
- non-cyclic boundary conditions

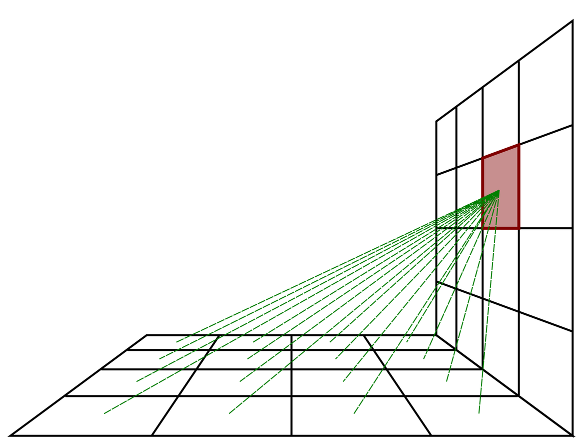
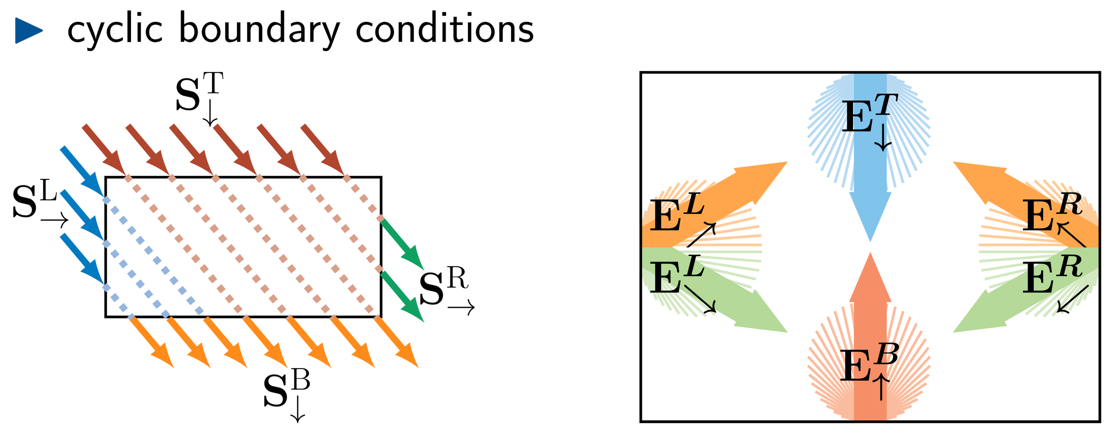


Figure 3: Principal discretization of radiation transfer between surface elements (Krč et al. 2021)

Tenstream (Jakub and Mayer 2015; Jakub and Mayer 2016)

- radiation transport in 3d between atmospheric grid cells
- atmospheric constituents considered
- resolved vegetation considered
- cyclic boundary conditions



(a) Direct downward and right-pointing radiation stream

(b) Diffuse streams through the top of the bottom of the grid cell as well as into the upper and lower hemisphere through each side of the grid cell

Figure 4: Discretization of radiation transport through atmospheric grid cells in Tenstream (Jakub and Mayer 2015). For illustration purposes, the third dimension is omitted, reducing the number of streams for direct radiation in (a) from 3 to 2 and for diffuse radiation in (b) from 10 to 6.

Buildings and resolved vegetation in Tenstream

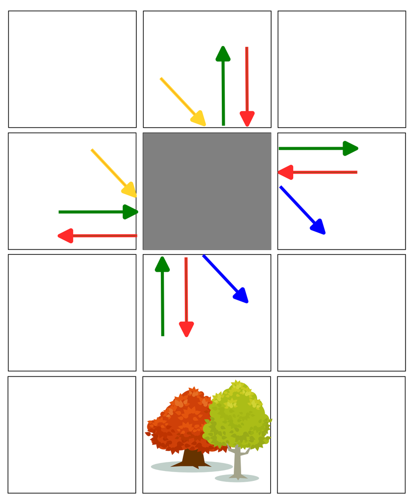


Figure 5: Building grid cells and resolved vegetation in Tenstream

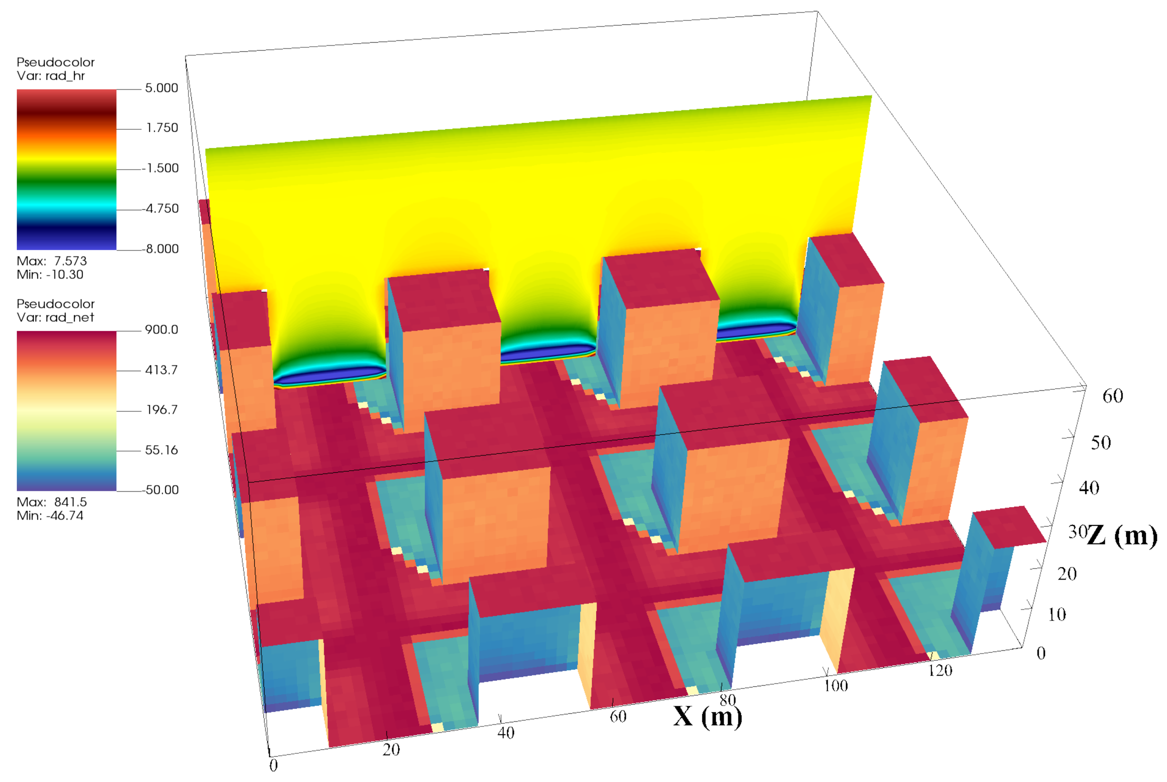
- building cells have 6 sides each with albedo and surface temperature
- shortwave direct radiation (direct sunlight) is blocked
- diffuse radiation is fueled by scattered shortwave radiation and thermal emission
- resolved vegetation is implemented as homogeneous grid cell property derived from leaf area index and vegetation albedo

Idealized simulations

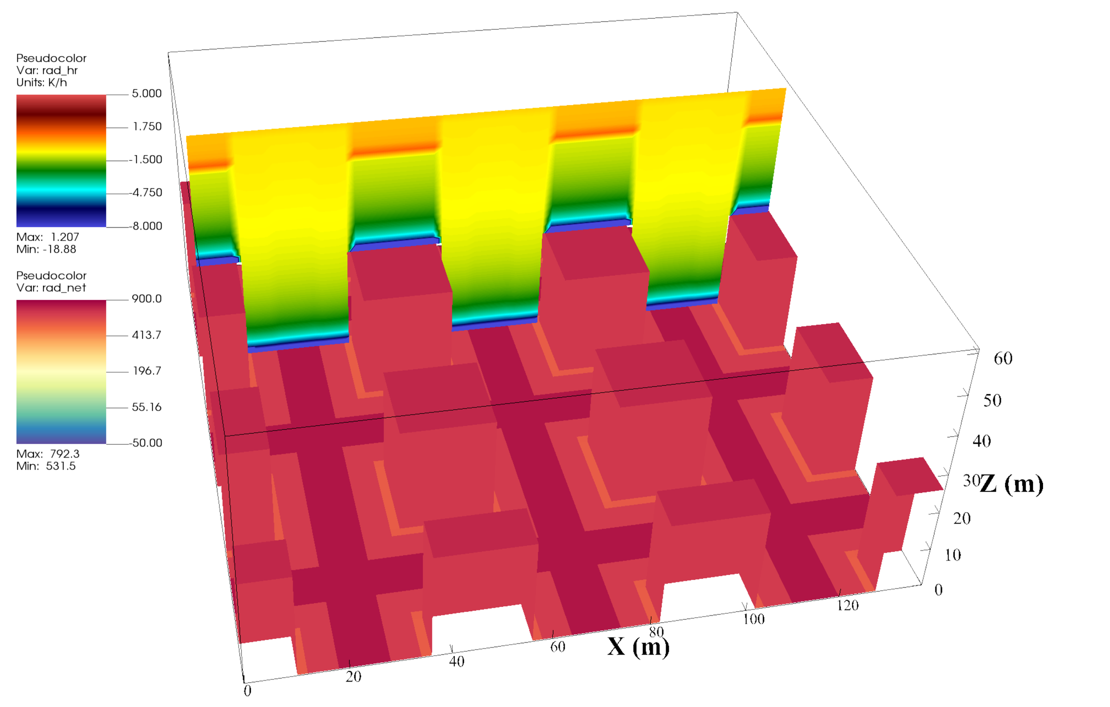
Idealized simulations are conducted with

- regularly arranged buildings with height of 25 m
- clear-sky conditions
- 2m grid spacing

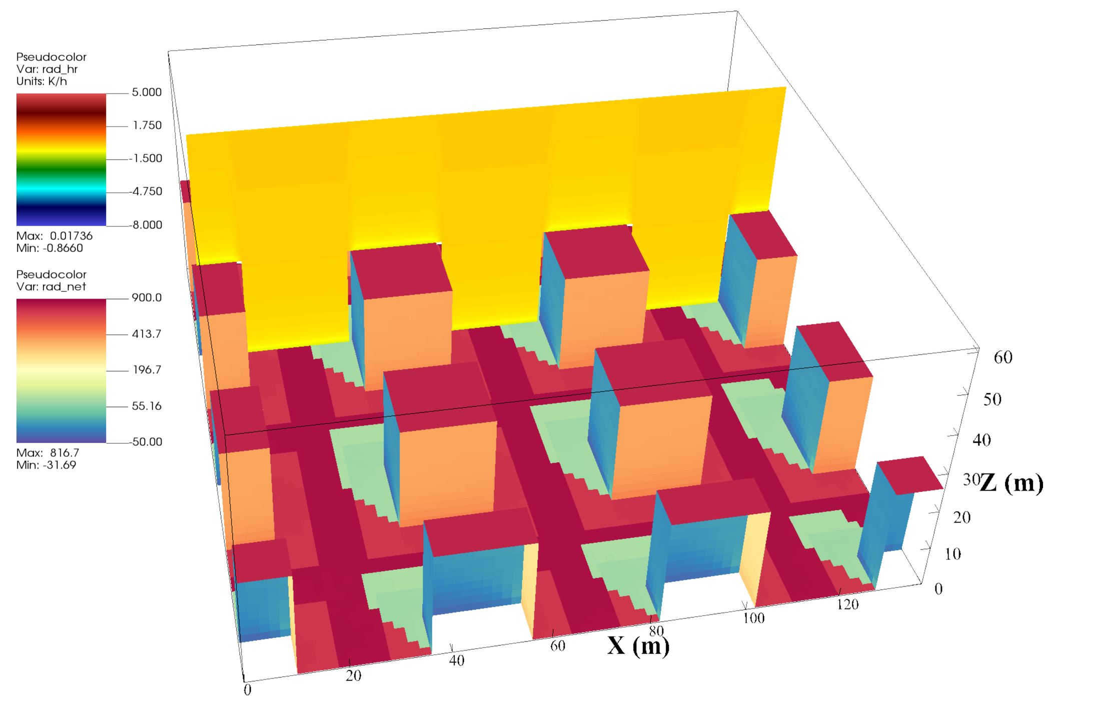
Results from simulations with either RRTMG+RTM or Tenstream are compared with the reference simulation using a Monte Carlo based raytracing approach (Mayer and Kylling 2005).



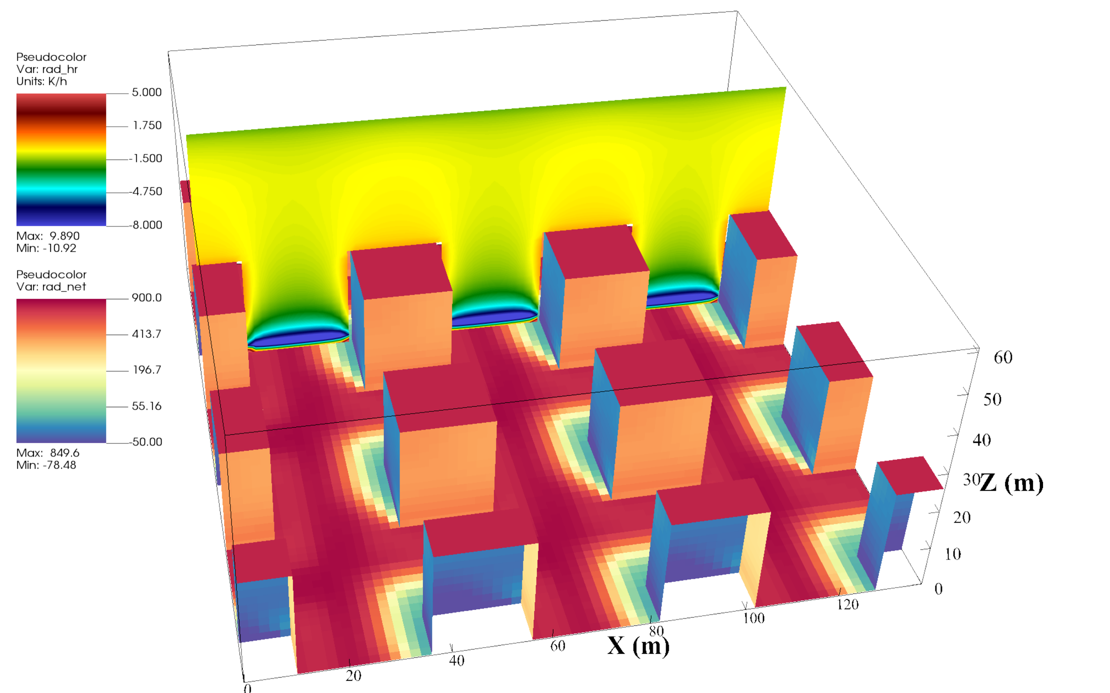
(a) Monte Carlo based raytracing as reference



(b) RRTMG



(c) RRTMG+RTM



(d) Tenstream

Figure 6: Daytime net radiation (colour on surfaces) and atmospheric heating rates (vertical cross section) from the idealized simulations with different radiation schemes

Performance of the idealized simulations

Simulation with RRTMG:

- neglects: illumination and emission of walls, blocking of radiation from the sun, scattering between surfaces
- large deviations from reference (tab. 1)

Simulation with RRTMG+RTM:

- much improved surface fluxes compared to RRTMG only (tab. 1)
- still large bias and RMSE

Simulation with Tenstream:

- numerical diffusion leads to smoothing of shadows
- all details of radiance field not captured with 10 streams
- both net radiation and heating rates improved considerably compared to RRTMG+RTM (tab. 1)

	surface net radiation		heating rates	
	RMSE	bias	RMSE	bias
RRTMG	107%	75%	257%	36%
RTM	24%	-1%	170%	-90%
Tenstream	17%	0.1%	26%	6%

Table 1: Root-mean-squared-error (RMSE) and bias of the surface net radiation and the atmospheric heating rates when comparing the idealized simulations with the Monte Carlo based reference simulation

Computational demand

Tenstream has a considerably higher computational demand than RRTMG+RTM (fig. 7). Approaches to reduce the computational demand are currently evaluated, though (fig. 7): Limitation of numerical iterations to solve the linear system of radiation transfer equations and a reduction of spectral integration samples.

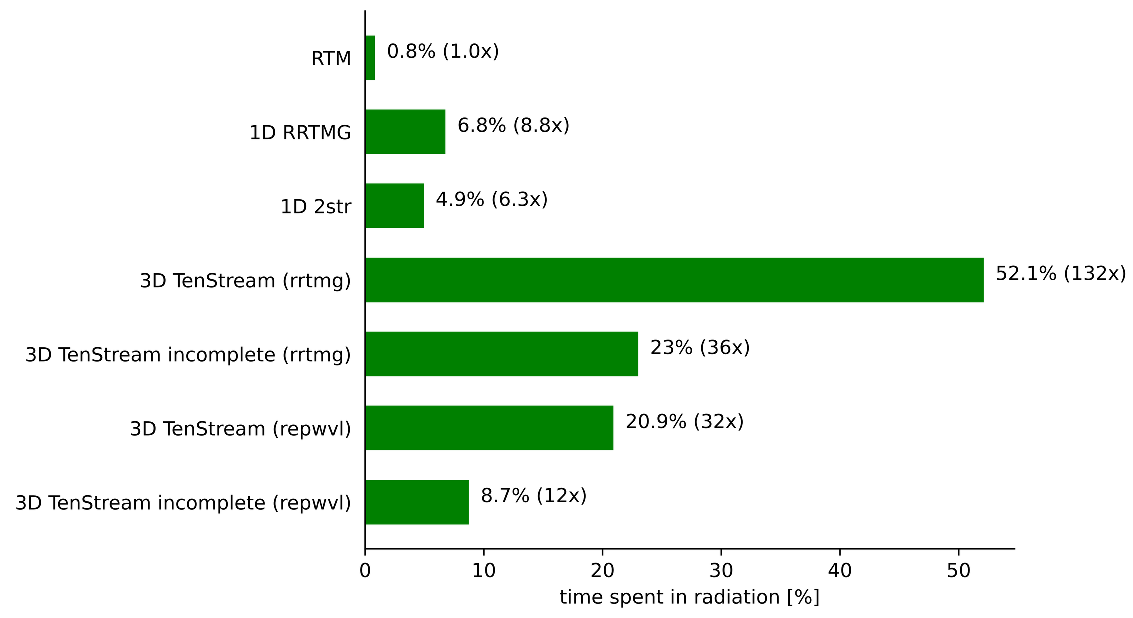


Figure 7: Typical performance of the different radiation schemes relative to the time needed by RTM. "3D TenStream (rrtmg)" is the current implementation. "incomplete" refers to a limitation of numerical iterations while "repvwl" refers to a reduction of spectral integration samples. Note that the values vary a lot for different set-ups and hardware configurations.

Outlook

We are currently working on:

- tuning of the Tenstream performance
- detailed evaluation with Monte Carlo based simulations and data from a measurement campaign by Schneider et al. ([UC]², Module B, TP2, fig. 8)

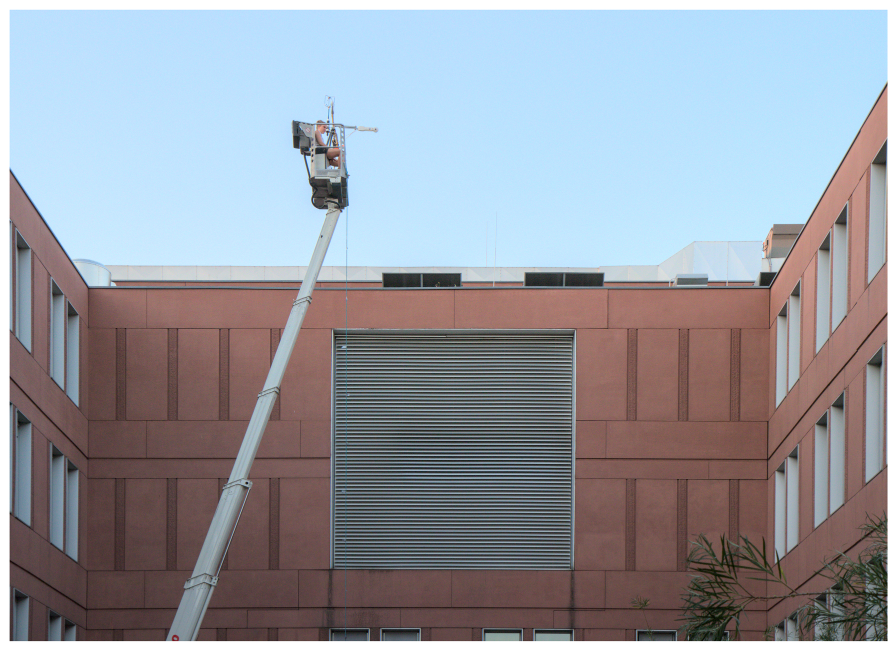


Figure 8: Measurement of radiation fluxes in all spatial directions on 2021-06-18 in Adlershof, Berlin ([UC]², Module B, Schneider, TP2)

References

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schubert.2@tu-berlin.de, fabian.jakub@physik.uni-muenchen.de, salim@tu-berlin.de, bernhard.mayer@lmu.de