Exchange coefficients in an agrivoltaic power plant model

How convective exchange coefficients vary between 2D & 3D crop models coupled to CFD?

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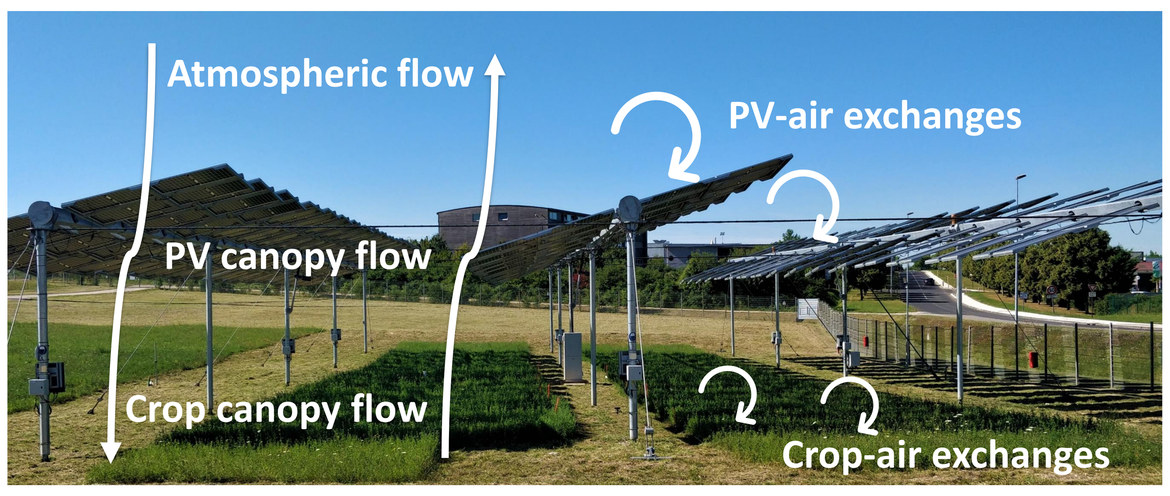
Context

Agrivoltaics (APV) integrates photovoltaic (PV) energy generation and agricultural production on the same land. The goal is to accelerate the renewable energy transition while protecting crops from climate change. A coupling between a crop model, a Computational Fluid Dynamic (CFD) solver, and a 3D radiation model has been developed to simulate soil-plant-atmosphere energy and water exchanges in heterogeneous microclimates. It ultimately aims at understanding how APV power plants impact crop growth. In such a model, exchange coefficients are key parameters as they convert energy into temperature or evaporated water, thereby influencing both crop and PV yields.

- **Which convective exchange coefficient model is the most appropriate in APV conditions?**



2D crop model

The crop is modeled as the bottom surface boundary condition of the 3D CFD domain.

Surface model assumptions:

- plant height is small compared to the cell size;
- only vertical exchanges are considered;
- crop impact on air modeled with a wall law.

Convective exchange resistance $r_{a\to c}$:

- Shear stress exponential decrease (Raupach, et al., 1981)

$$r_{a\to c} = \frac{P_{r_t}}{l_m}\frac{h_{exc}}{(1-e^{-\eta})^{0,5}u_a^*}$$

- Crop exchange height h_{exc}
- Turbulent Prandtl number P_{r_t}
- Turbulent mixing length l_m
- Exponential extinction factor η
- Atmosphere friction velocity u_a^*

Crop impact on the air flow:

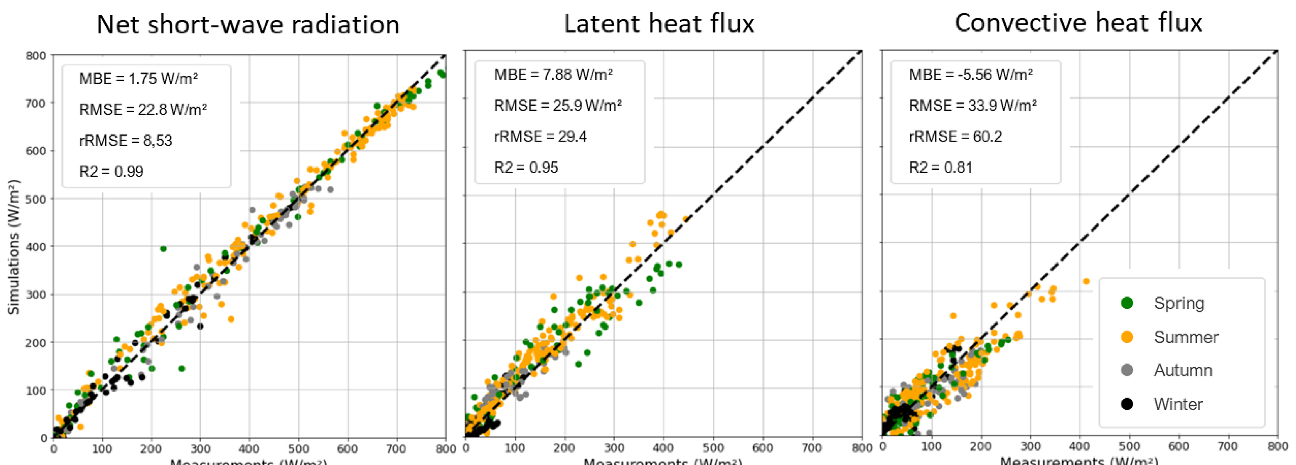
- Exchanges modeled by a rough wall-law (Jacobson, 2005)

$$z_0 = h_c(1-0{,}91e^{-0{,}0075LAI})$$

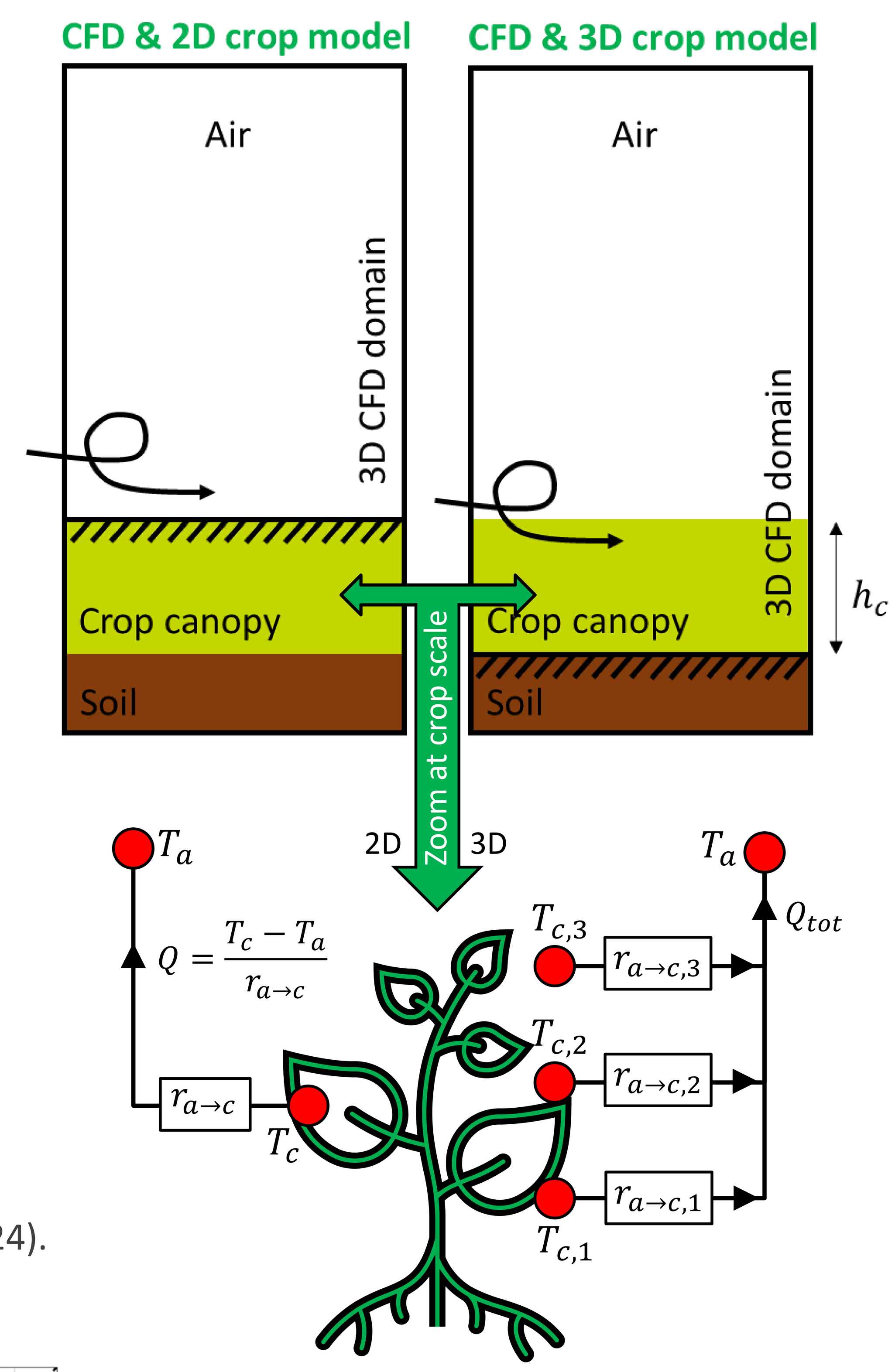
- Dynamic roughness z_0
- Crop canopy height h_c
- Leaf Area Index LAI

Evaluation on ICOS Lusignan experimental data

- 20-days sunny and cloudy conditions, (Beauclair, et al., 2024). Root mean square error (RMSE) < 30 W/m² in average.



(to be published)



Convective flux comparison

$$Q = \frac{T_c - T_a}{r_{a\to c}} \quad \overset{2D \quad 3D}{\longleftrightarrow} \quad Q_{tot} = \sum_i \frac{T_{c,i} - T_a}{r_{a\to c,i}}$$

$$\frac{1}{r_{a\to c}} \quad \overset{2D \quad 3D}{\longleftrightarrow} \quad \frac{1}{r_{a\to c,eq}} = \sum_i \frac{1}{r_{a\to c,i}}$$

- Crop temperature T_c
- Air temperature T_a
- Convective flux Q
- Crop level « i »

3D crop model

The crop is virtually defined in the 3D CFD domain.

Volume model assumptions :

- some cells contain both plants and air;
- random distribution of leaves inside plant-related cells;
- exchanges between plant and air in the same cell.

Convective exchange resistance $r_{a\to c}$:

- Canopy-related velocity correlation (Thom, et al., 1967)

$$r_{a\to c} = \frac{C}{(C_d LAI)^{0,5}}\frac{1}{\|\boldsymbol{u}\|}$$

- Empirical parameter $C \approx 22$
- Leaf drag coefficient C_d
- Leaf Area Index LAI
- Wind speed magnitude $\|\boldsymbol{u}\|$
- Leaf characteristic length l_{leaf}

Different from literature's formulas that are based on single isolated leaf experiments and have no canopy-related parameters! $r_{a\to c} = 130 l_{leaf}^{0,5}\|\boldsymbol{u}\|^{-0,5}$ (Grylls, et al., 2021)

Crop impact on the air flow:

- Exchanges modeled by source terms (Katul, et al., 2004) that are added in the equations of Navier-Stokes and the k-ε turbulence model.

$$\begin{cases} \boldsymbol{S_u} = \rho C_d LAI\|\boldsymbol{u}\|\boldsymbol{u} \\ S_k = \frac{1}{2}\rho C_d LAI[\beta_d\|\boldsymbol{u}\|^3 - \beta_d\|\boldsymbol{u}\|k] \\ S_\varepsilon = \frac{1}{2}\rho C_d LAI\left[C_1\|\boldsymbol{u}\|^3\frac{\varepsilon}{k} - C_2\|\boldsymbol{u}\|\varepsilon\right] \end{cases}$$

- Leaf drag coefficient C_d
- Mass density ρ
- Wind speed vector $\boldsymbol{u}$
- Turbulent kinetic energy k
- Turbulent dissipation ε
- Model constants β_p, β_d, C_1, C_2

How to evaluate the 3D crop model ?

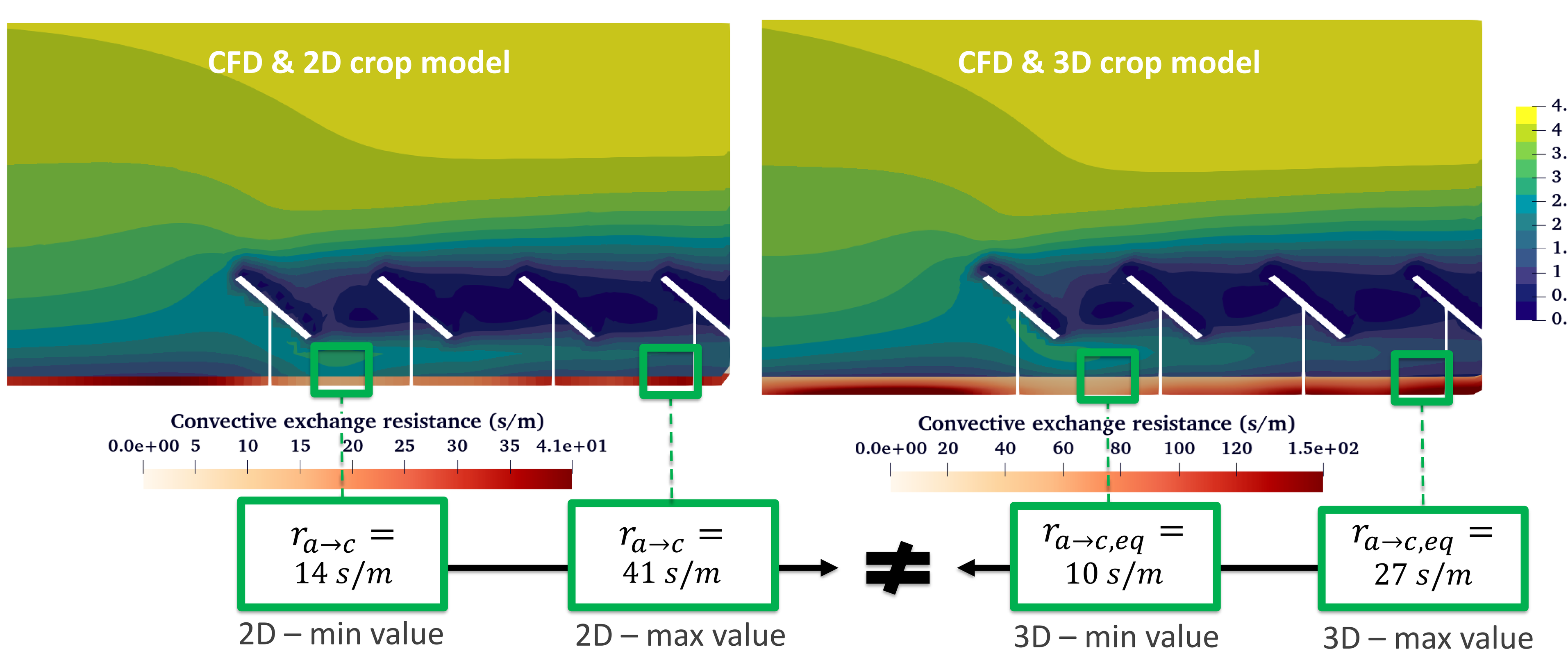
- Using overall energy fluxes √
- **How to evaluate temperature, energy and water exchanges at eachcrop level? Where to find experimental data?**

Simulations with PV panels

Simulation of 4 rows of PV panels (dimensions of a panel array: height 5m, length 6m, width 20m, tilt 40°, spacing 8m), on a 1M-cell cartesian mesh, using the CFD solver code.saturne.

Pre-calibration on 1m high homogeneous crop in open-field conditions giving similar resistances.

- **How PV panels modify the velocity field and influence the exchange coefficients?**



Conclusion & Perspectives

- **Validated coupling of a 2D crop model, code.saturne, and a 3D radiation model (to be published).**
- **Same convective exchange coefficient values between the 2D and the 3D crop models in open-field conditions.**
- **In presence of PV panels, almost the same velocity fields above the crop although a finer mesh for the 3D crop model and different plant to air exchange approaches.**
- **In presence of PV panels, 3D velocity penetration within the crop canopy only for the 3D crop model, leading to different convective exchange coefficients compared to the 2D crop model.**
- **Some doubts about convective exchange resistance formulas for 3D crop models. Which one to choose?**
- **How to the evaluate the convective exchanges in 3D crop models? Is there any open-source data?**

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