Micro-climate modeling applied to agrivoltaics

CFD and a radiation model coupled to a Soil/Plant/Atmosphere model

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Context

The constantly increasing world energy demand leads to severe stresses on our society. Climate is changing, and extreme weathers put pressure on the agricultural field. Agrivoltaics is the combination of photovoltaic electricity and agricultural production on the same surface. It is a promising solution to overcome the lack of surface dedicated to energy production while protecting crops. Designing agrivoltaic (APV) systems requires a comprehensive understanding of the impact of photovoltaic panels on the micro-climate and on the plant growth.

- **A 3D multi-physics model able to reproduce the interactions between the atmosphere, the plants, and the soil is needed to assess the performance of agrivoltaic systems.**

Models

1. 3D Navier Stokes + humidity to compute the local air temperature (T), humidity (q), pressure (P), and wind speed ($\boldsymbol{u}$):
Finite volume method

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \nabla.(\rho \boldsymbol{u}) = 0 \\ \dfrac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla.(\boldsymbol{u} \otimes \rho \boldsymbol{u}) = \rho \boldsymbol{g} - \nabla P + \nabla.(\mu \nabla \boldsymbol{u} - \rho \boldsymbol{\mathcal{R}}) \\ C_p \dfrac{\partial \rho T}{\partial t} + C_p \nabla.(\rho T \boldsymbol{u}) = \nabla.(\lambda \nabla T - \rho \boldsymbol{\mathcal{R}}_T) + ST_T \\ \dfrac{\partial \rho q}{\partial t} + \nabla.(\rho q \boldsymbol{u}) = \nabla.(K_q \nabla q - \rho \boldsymbol{\mathcal{R}}_q) + ST_q \end{cases}$$

2. 3D radiation model to compute the SW_{net} and LW_{net} for obstructed skies and complex crop geometries:
Discrete Ordinate Method

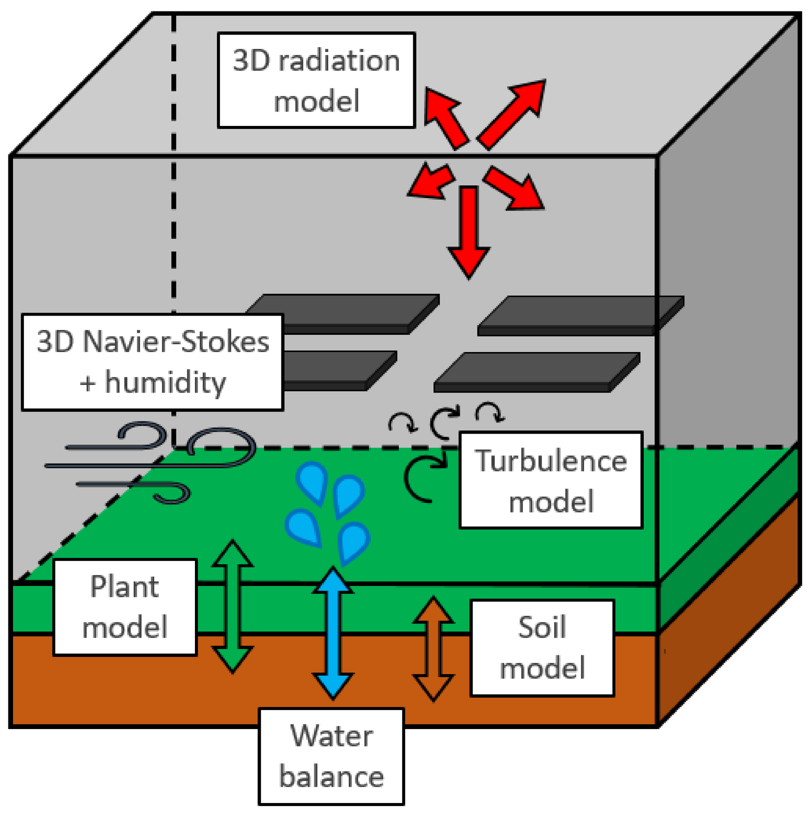
3. Plant model using a stomatal conductance (g_{CO2}):
Soil/plant/atm continuum model [1]

$$g_{CO2} = g_0 + \frac{a A_{SW}}{c_i - \Gamma} f_{\Psi_{LE}}$$

4. Turbulence model to capture the local turbulent exchanges (LE and H) between the air, and the crops:
$k - \epsilon$ turbulence model & surface model

$$LE = f(\boldsymbol{\mathcal{R}}_q, \nu_t, g_{CO2}, crop\ geometry)$$

$$H = f(\boldsymbol{\mathcal{R}}_T, \nu_t, crop\ geometry)$$



5. Soil model, with an energy balance (for T_s) and a water balance (for θ):
2-layers force restore model [2]

$$c_{p,s} \frac{\partial T_s}{\partial t} = SW_{net} + LW_{net} + LE + H + G$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(rK \frac{\partial \Psi_{LE}}{\partial r} \right)$$

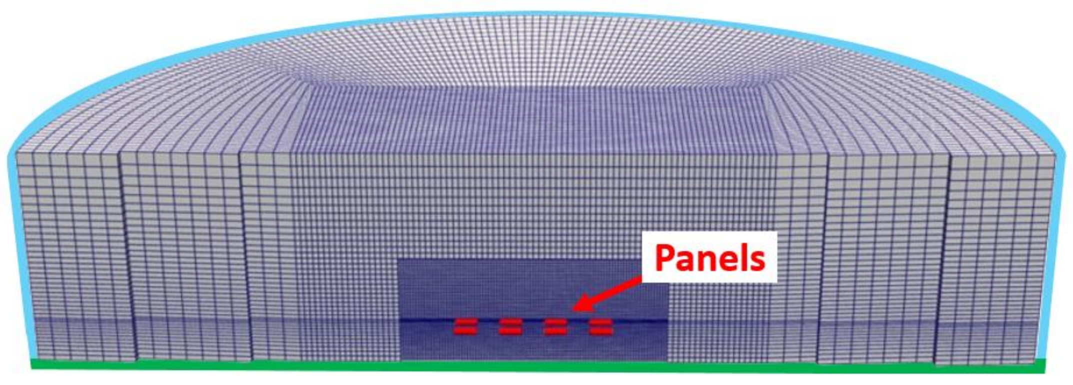
6. Update the boundary conditions soil/crop → air (for T, q, and u). Then, restart at 1.

ρ is the density, μ is the dynamic viscosity, C_p is the specific heat, λ is the thermal conductivity, ST_T and ST_q are source terms, K_q is the humidity conductivity, $\boldsymbol{\mathcal{R}}_u$ $\boldsymbol{\mathcal{R}}_T$ and $\boldsymbol{\mathcal{R}}_q$ are the Reynolds turbulent tensors, g_0 and a are photosynthesis model constants, A_{SW} is the photon assimilation rate, c_i and Γ are CO2 concentrations, $f_{\Psi_{LE}}$ is a water stress factor, ν_t is the turbulent kinematic viscosity, $c_{p,s}$ is the soil heat capacity, G is the conduction exchange, θ is the soil water content, r is the radial length, K is the soil hydraulic conductivity, and Ψ_{LE} is the water potential.

Simulation software

- **Code_saturne**

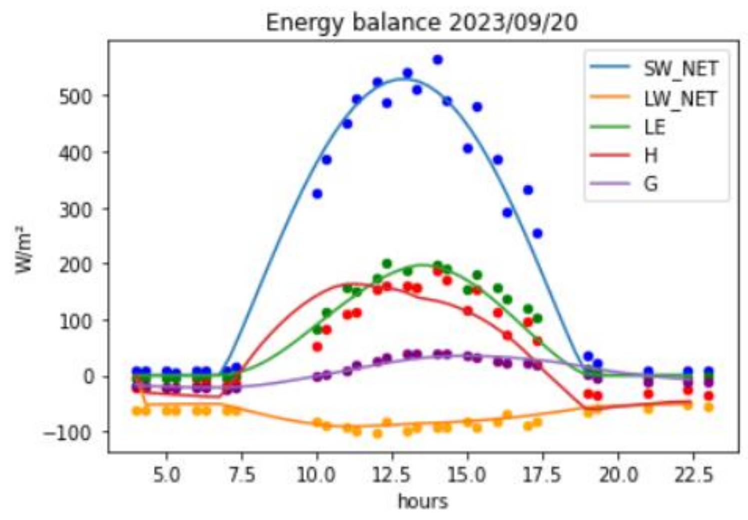
A highly parallelizable computational fluid dynamic code, with an Unsteady-RANS solver and an implicit time step numerical scheme. Using highly non-uniform cylindrical meshes with hexahedral cells. Atmospheric profiles following Monin-Obukhov theory on the sides and at the top of the domain.

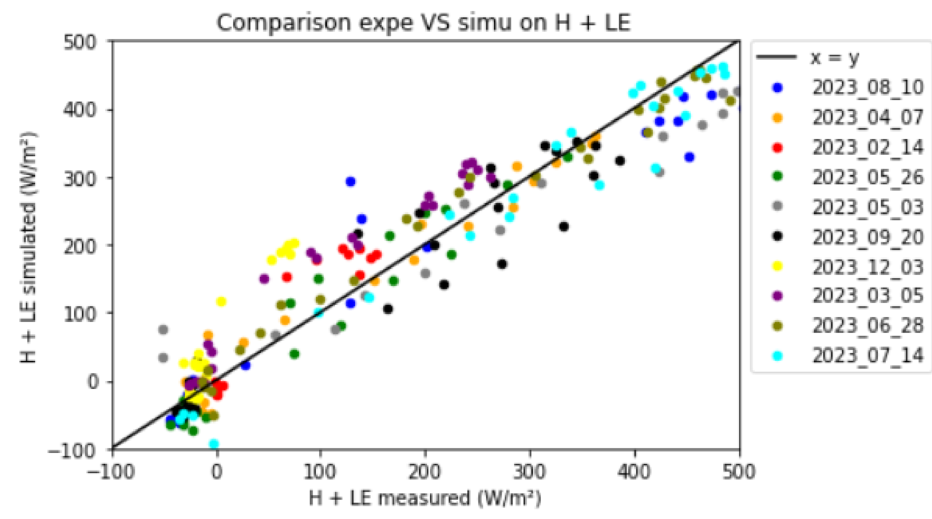


Validation

First of all, the model (–) is validated on open field experimental data (●) of grassland, from Integrated Carbon Observation System (ICOS) data, France, Lusignan [3].
Net solar radiation (SW_NET), net infra-red radiation (LW_NET), turbulent latent exchange (LE), turbulent convective exchange (H), and conduction exchanges (G).

- **Mean relative error < 20%.**





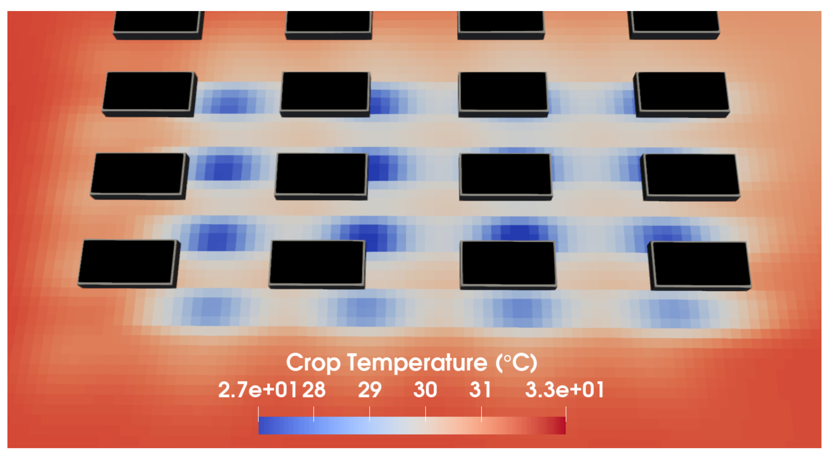
Results for APV systems

The ultimate goal of this model is to predict the impact of any agrivoltaic (APV) systems on the plant growth along chosen days.
Simulation case of heat waves, 2023-08-03, on alfalfa.

- $\Delta T_{crop} \simeq 5°C$ **between the shaded crop and the full sun crop.**
- **The simulation captures the impact of APV systems on key factors for the plant growth: the radiation, the water stress, and the thermal stress.**

AgriPV lab [4], Les Renardières, EDF, France

Code_saturne simulation, 16 panels



Conclusion & Perspectives

- **A detailed model composed of a radiation model, an atmospheric and fluid CFD solver, a plant model, a soil model, and a water model.**
- **Validation successfully carried out on ICOS data.**
- **The model can simulate 3D, non-stationary, and highly heterogeneous interactions between the crop, the soil, and the atmosphere for complex agrivoltaic geometries.**

- **Future validation on various APV systems (AgriPV lab, on crop temperature).**
- **Sensitivity analysis of the exchange coefficients according to the crop architectures and the photovoltaic panel geometries.**
- **Study of the stomatal conductance and the plant water potential response delay to a quick transition to shade.**
- **Add obstructed sky considerations in crop models such as DSAAT, or STICS.**

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