Can agrivoltaic systems protect the plants against frost?

Journée scientifique ICEO/SIRTA
2025/06/24

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What is an agrivoltaic[1] (APV) system ?

[1] C. Dupraz, et al., Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes, Renewable Energy, 2010

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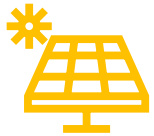
Combine **electricity production**  and

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Combine **electricity production** and **agricultural production** on the **same surface.**

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Credit to Shengrui Yao, COLLEGE OF AGRICULTURAL

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Frequency & intensity[2] ↗

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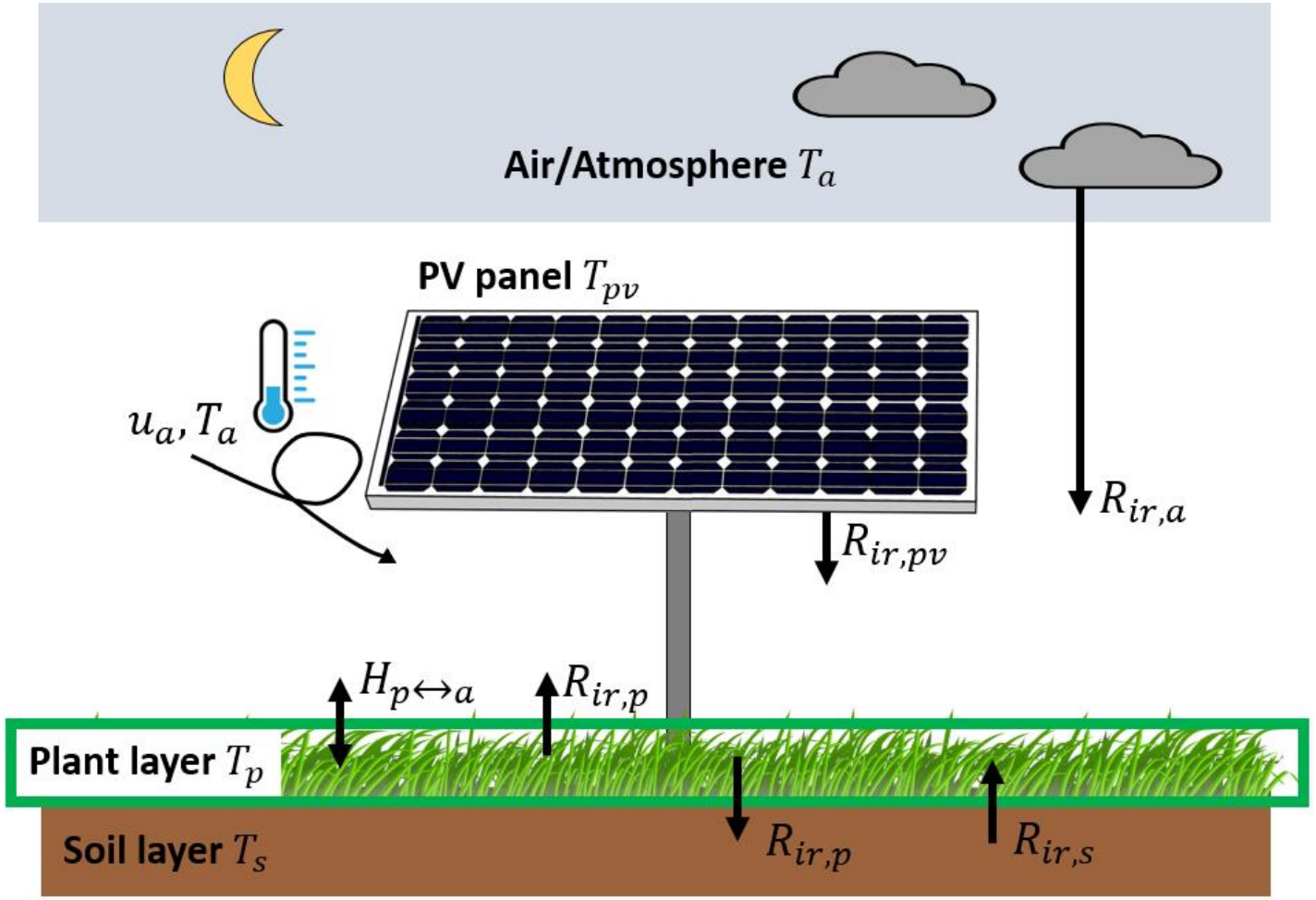
[1] Gels de printemps en vergers, Sud Arbo

[2] J. R. Lamichhane, Rising risks of late-spring frosts in a changing climate, Nature Climate Change, 2021

How to precisely estimate plant temperature?

Theory during night-time



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Theory during night-time

Energy balance at plant layer[1]

Net radiation ⟵ $R_{net,p} = H_{p\leftrightarrow a}$

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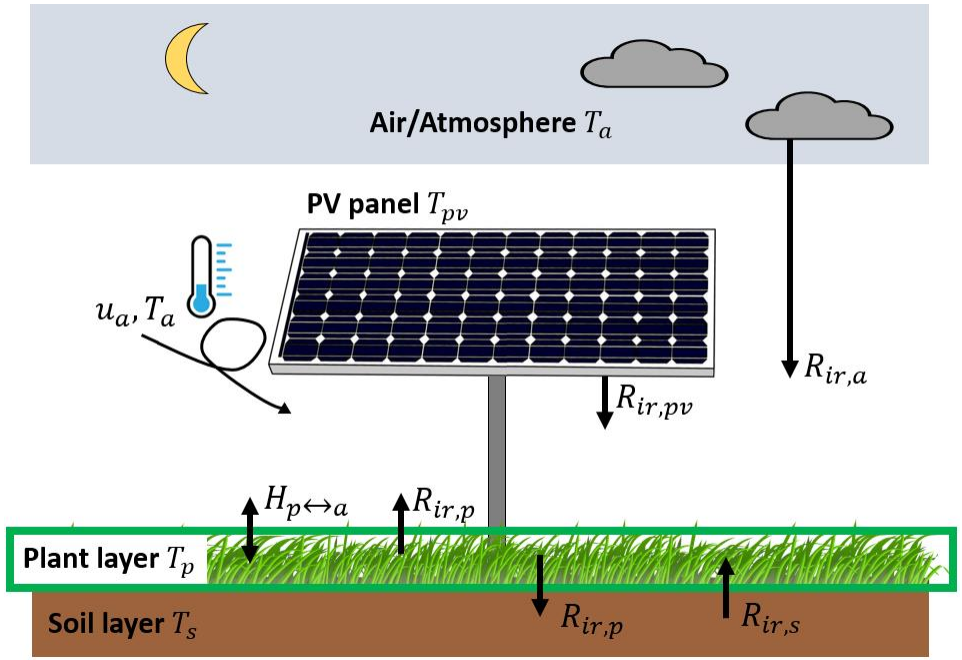

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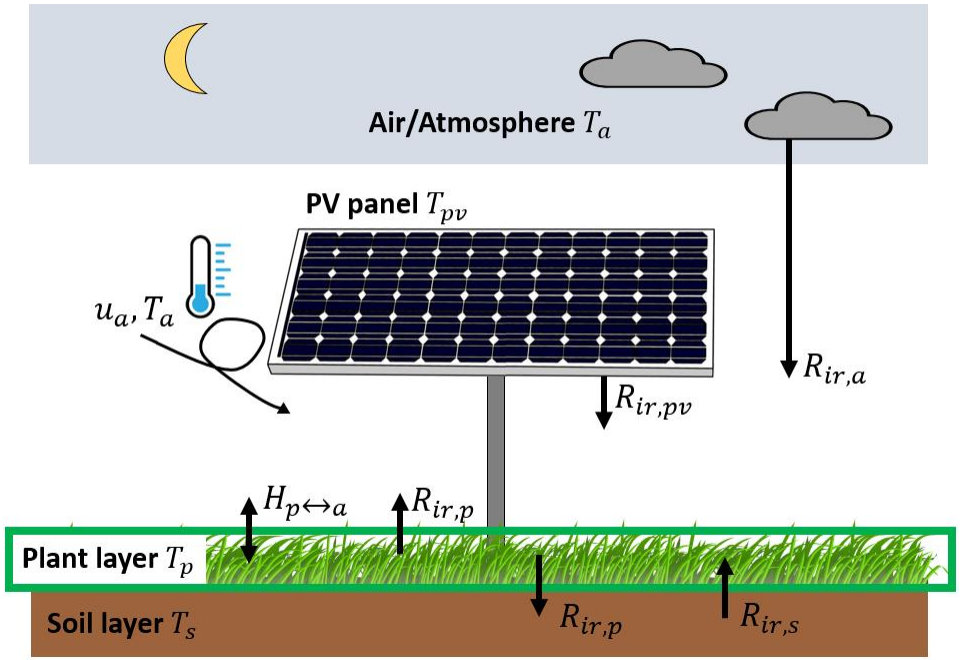

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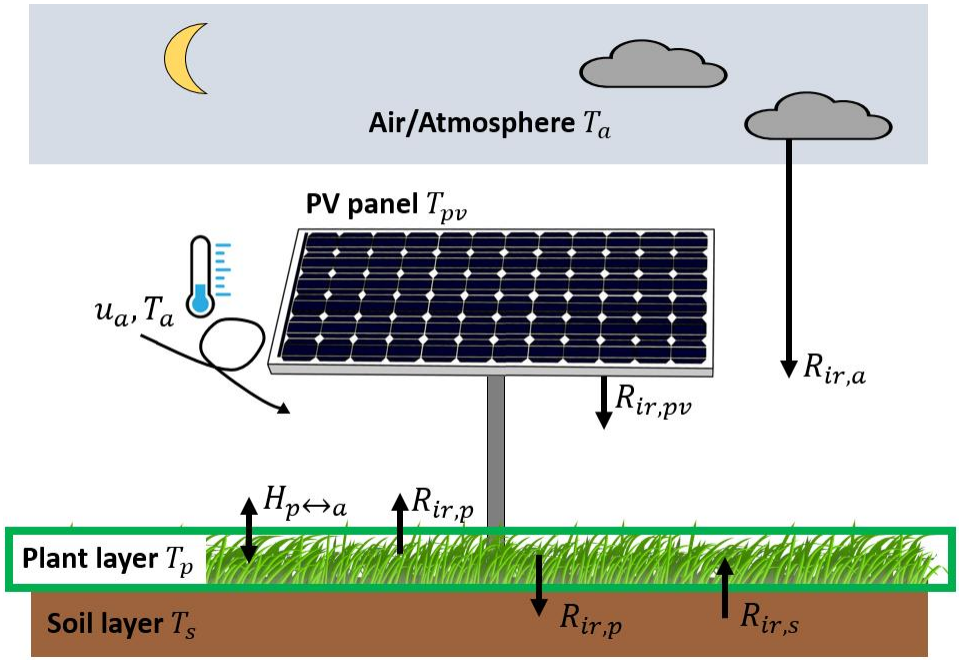
Sensible heat flux

$$H_{p\leftrightarrow a} = \frac{\rho c_p}{r_c}(T_{plant} - T_{air})$$



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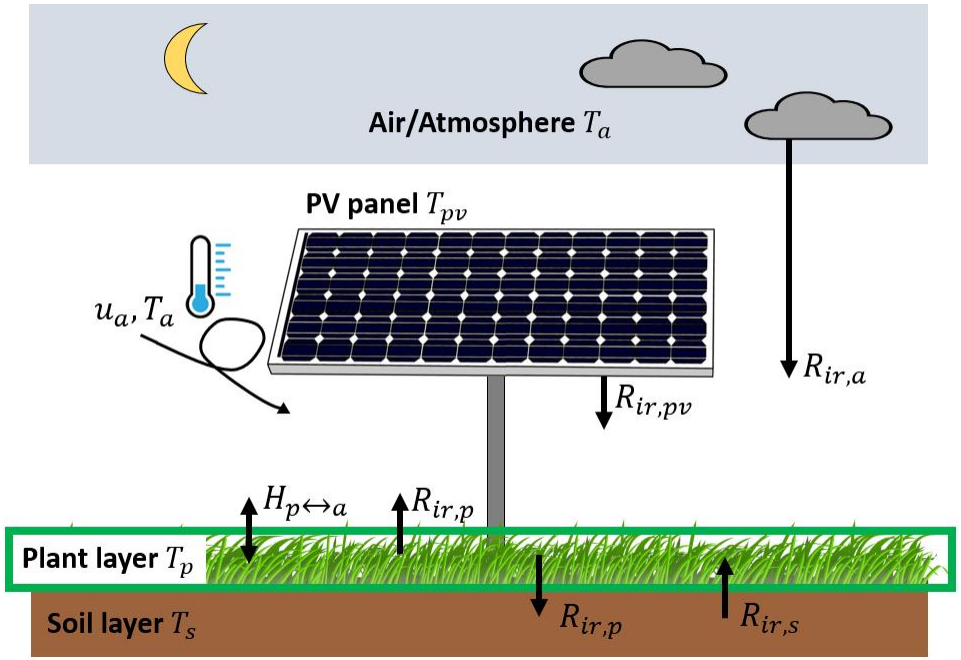

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$$H_{p\leftrightarrow a} = \frac{\rho c_p}{r_c}(T_{plant} - T_{air}) \qquad r_c = f(u, u^*, plant\ geometry)$$

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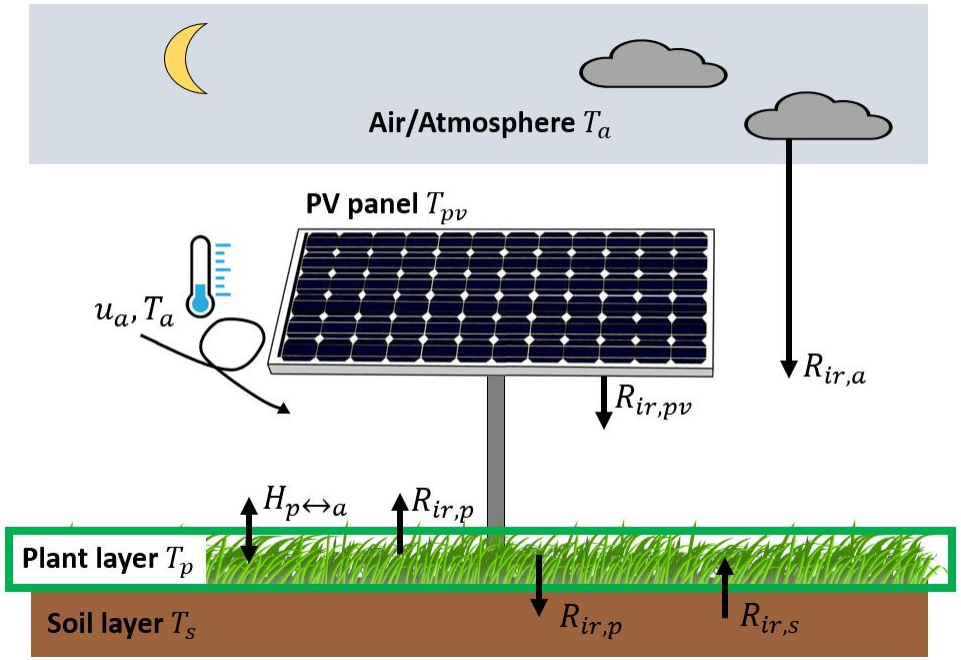

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Which physical quantities are involved?

- **Infrared (IR) radiation**
- **Air temperature**
- **Wind speed**

Which systems are involved?

- **Atmosphere and air**
- **PV panel**
- **Plants**
- **Soil**

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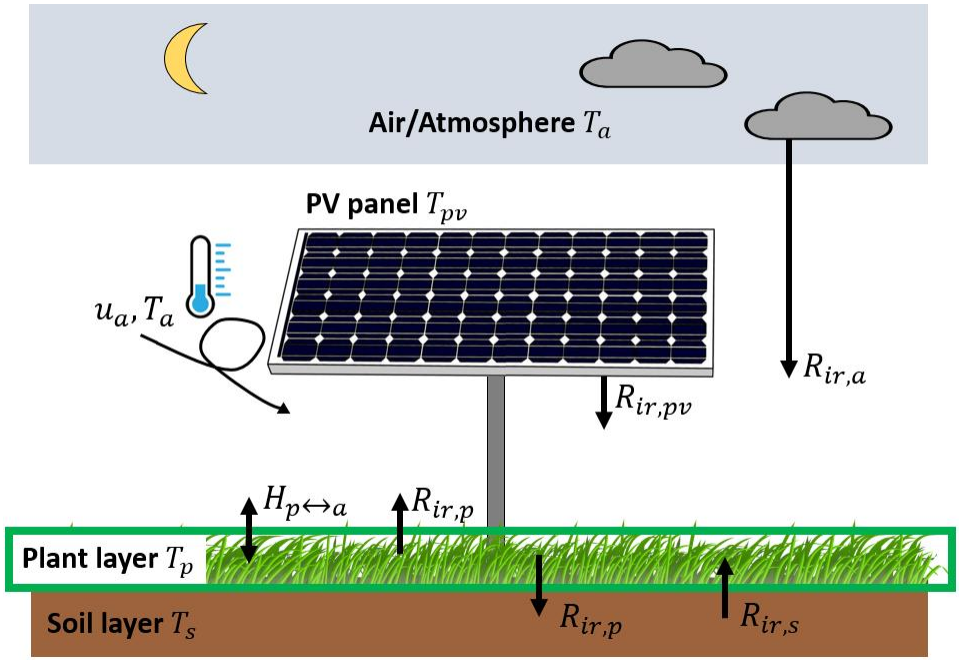
How to precisely estimate plant temperature?
Theory during night-time – Case of white frost



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$$H_{p\leftrightarrow a} = \frac{\rho c_p}{r_c}(T_{plant} - T_{air}) \quad \approx 0°C$$

$$r_c = f(u, u^*, plant\ geometry) \quad < 1\ m/s$$

Which physical quantities are involved?

- **Infrared (IR) radiation**
- **Air temperature**
- **Wind speed**

Typical values of IR radiation:

- **At** $T \approx 0°C$, $R_{ir} = \epsilon\sigma T^4 \approx 300\ W/m^2 \quad \Rightarrow \quad R_{net} \approx -50 W/m^2$

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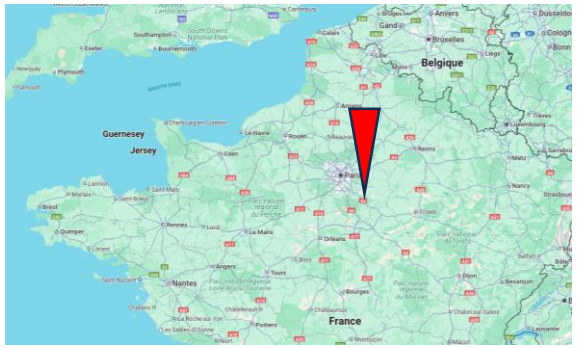

Measurements
AgriPV @ EDF lab les Renardières

APV power plant dimensions:

- Spacing 12m
- Height 5m
- 3 rows
- 16 columns
- 40% covering

Measurements:

- Winter & Spring 2025
- Every 1 minute

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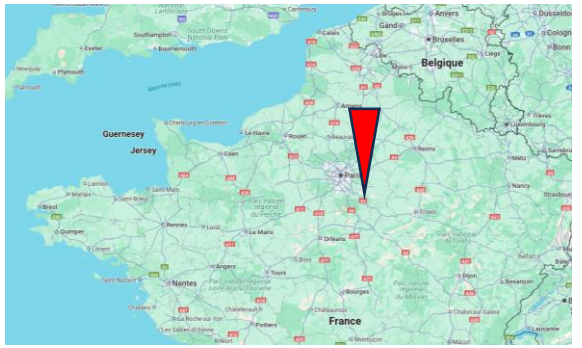

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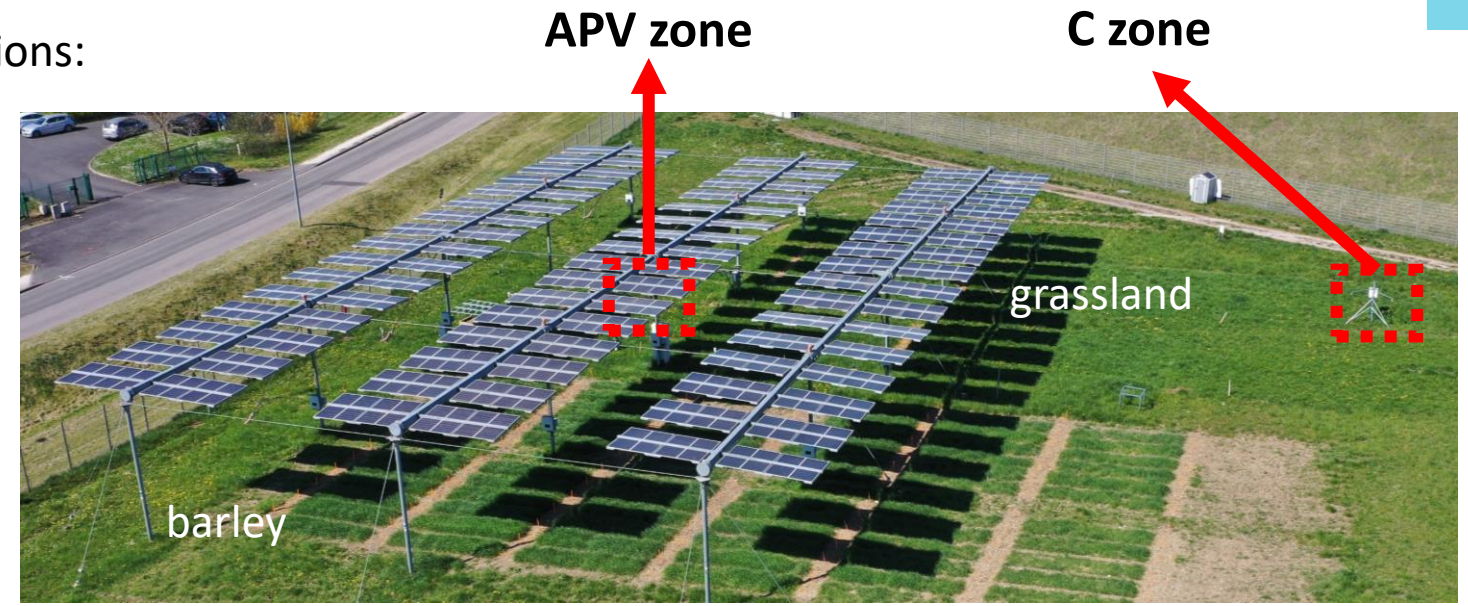

NR01 solar & IR sensors

SI-111-SS IR radiometers

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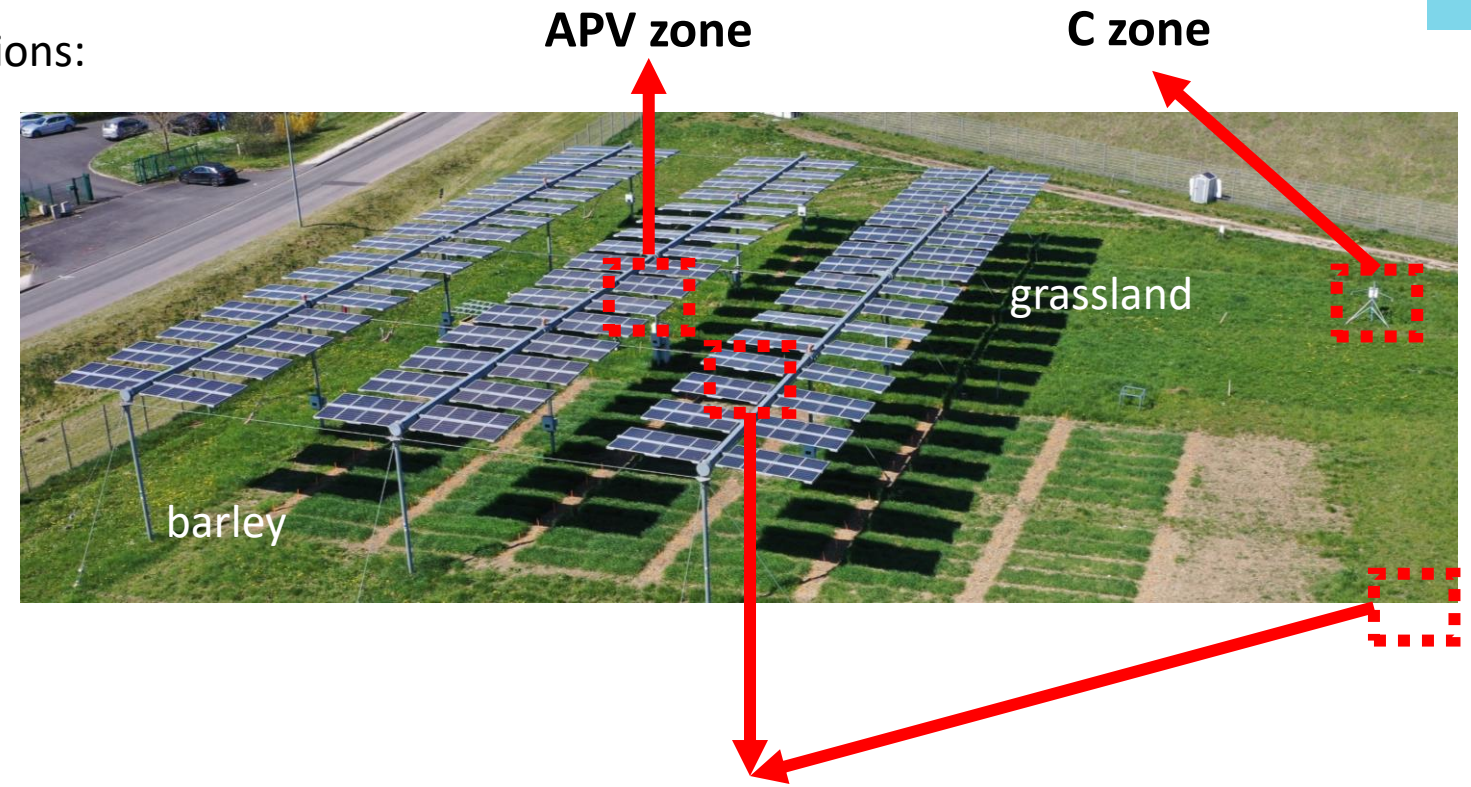

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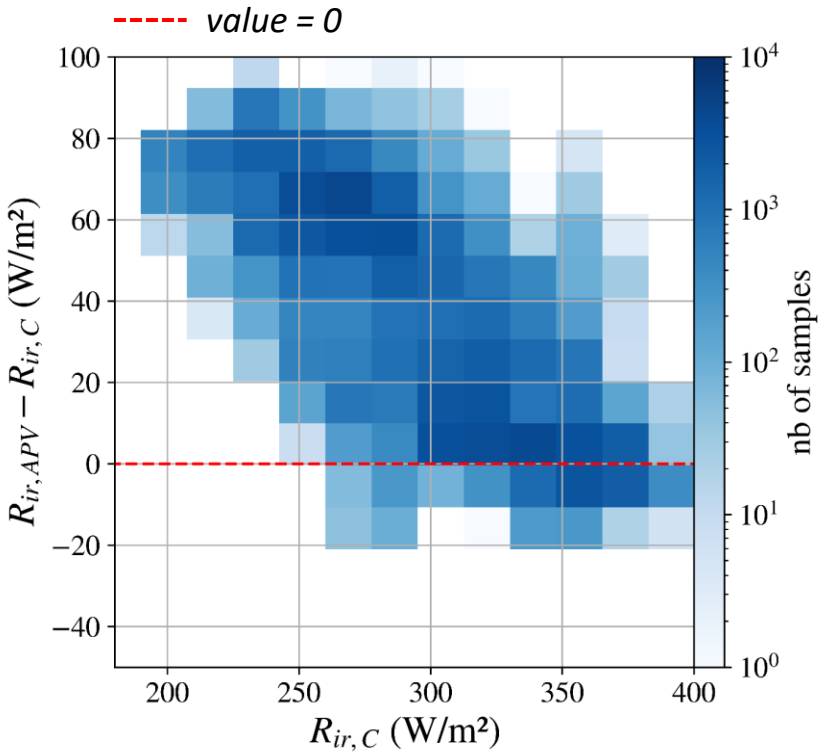

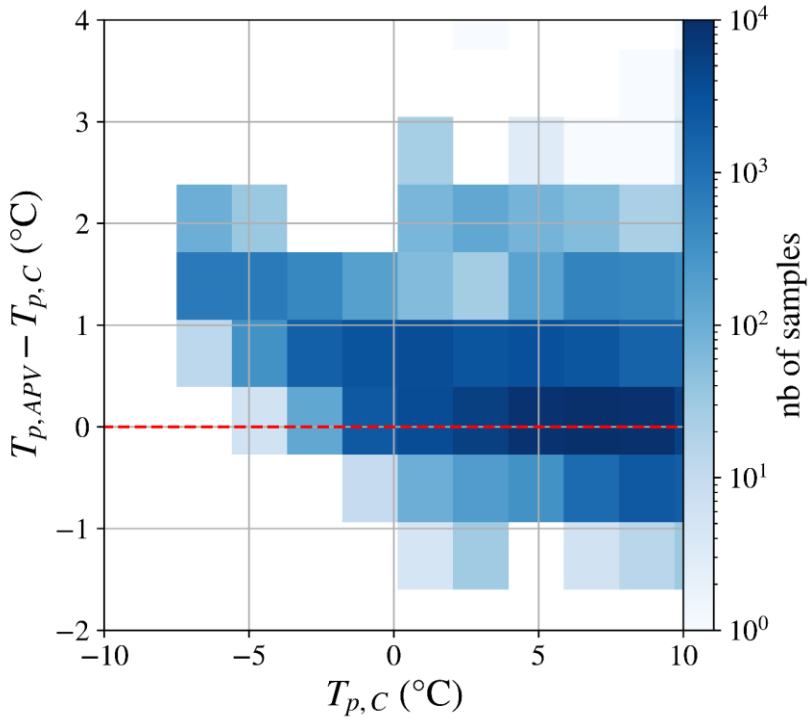

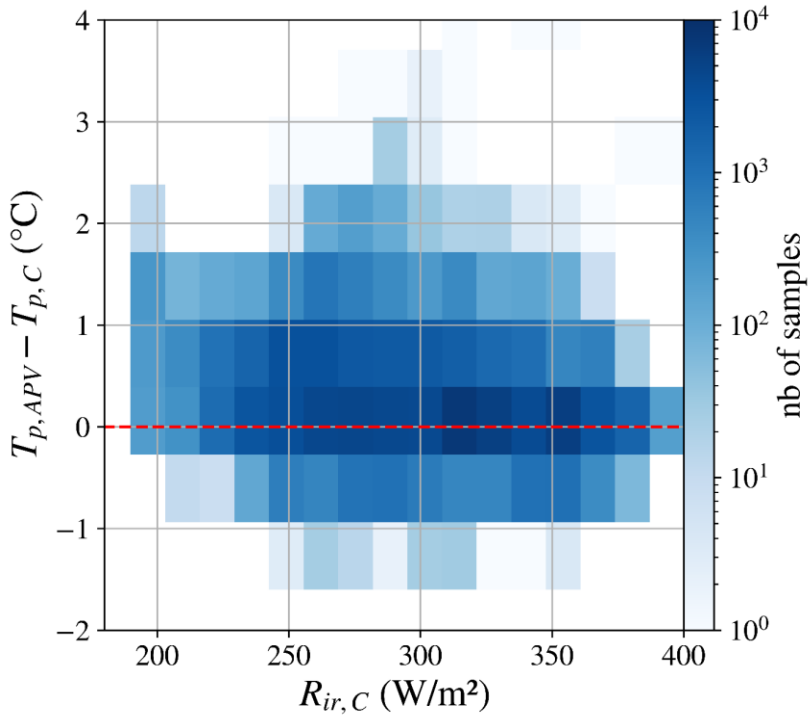

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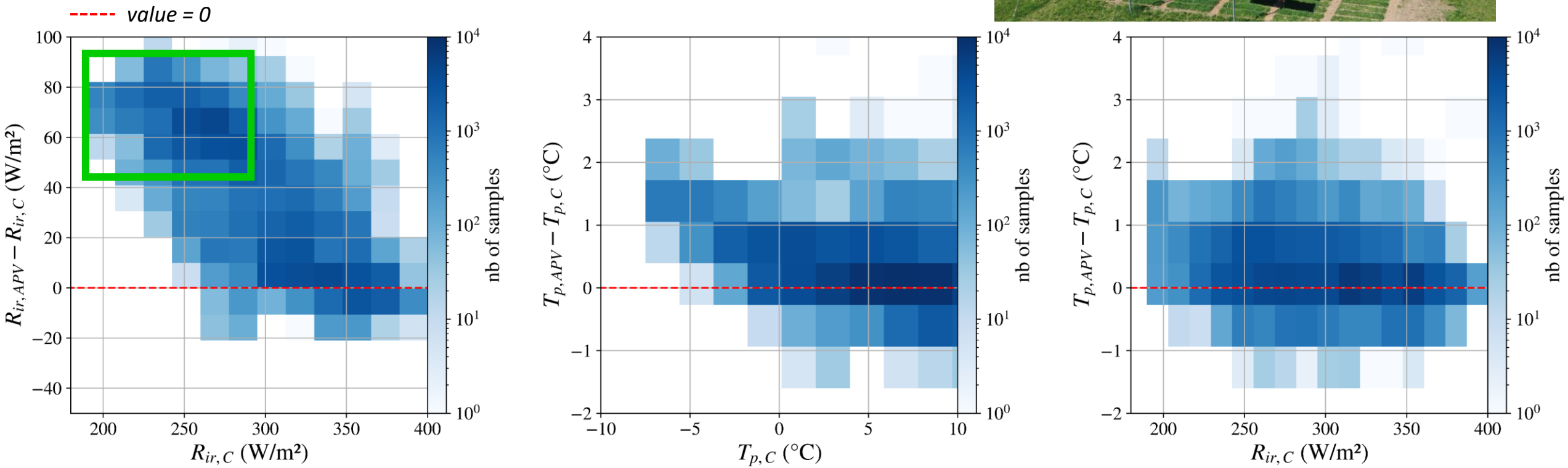

➢ **When $R_{ir,C} < 250\ W/m^2$, $R_{ir,APV}$ is increased by up to $80\ W/m^2$**

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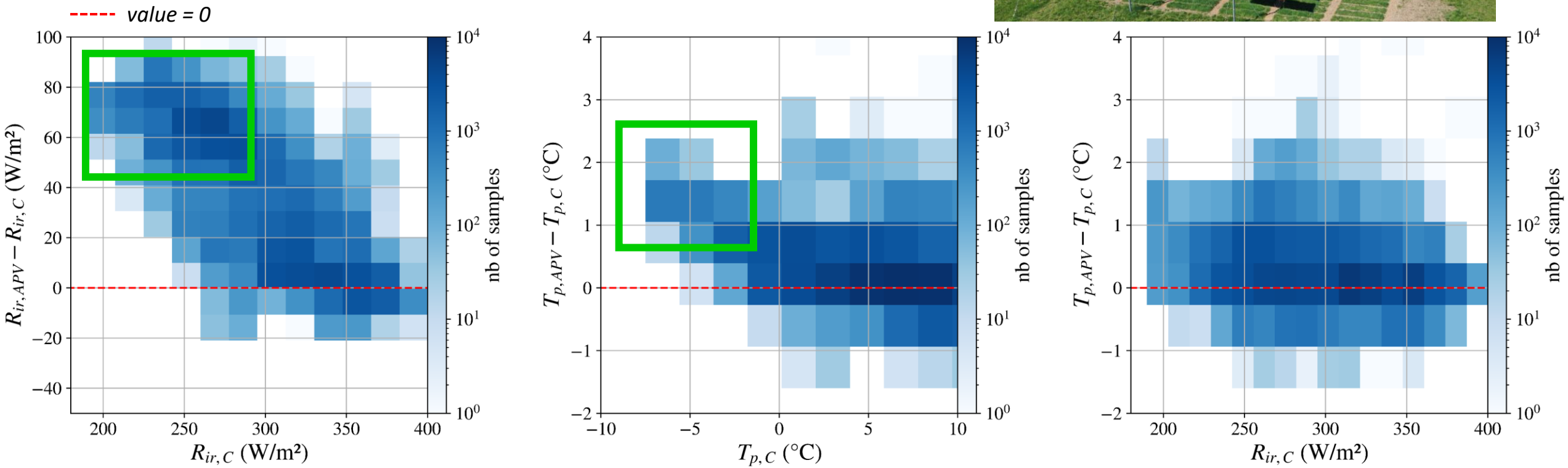
Infrared radiation



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- When $T_{p,C} < 0°C$, $T_{p,APV}$ is increased by up to $2°C$

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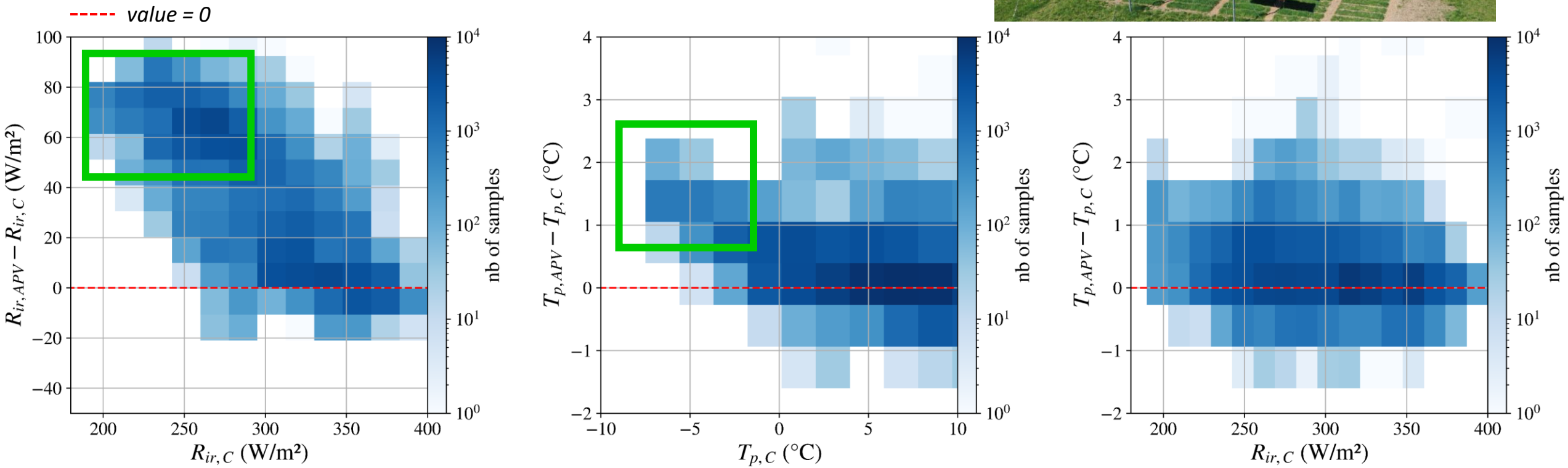

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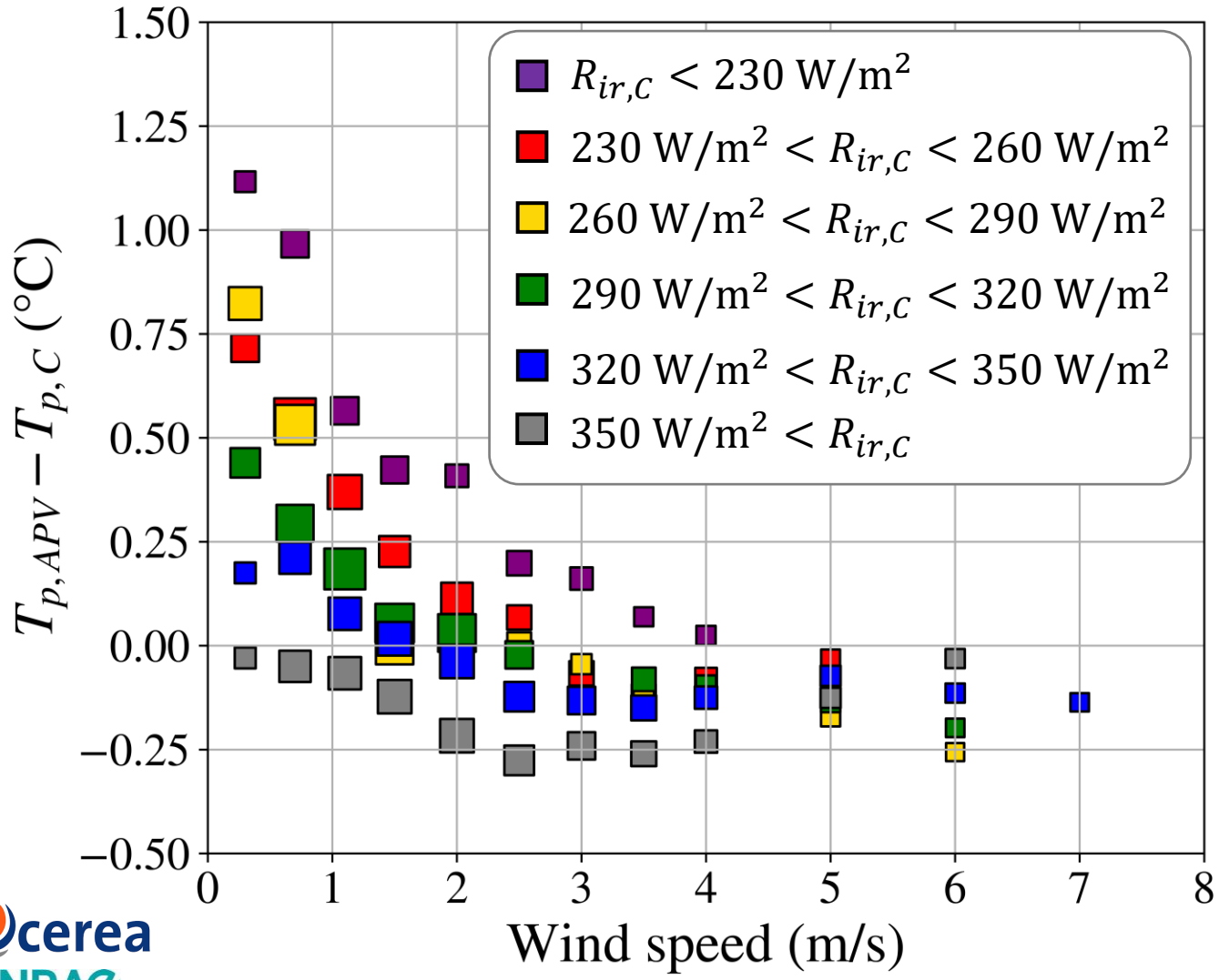
- When $T_{p,C} < 0°C$, $T_{p,APV}$ is increased by up to $2°C$
- Measuring R_{ir} is not enough to explain this increase in temperature

Measurements
Impact of microclimate on plant temperature



The size of the squares depend on the number of samples.

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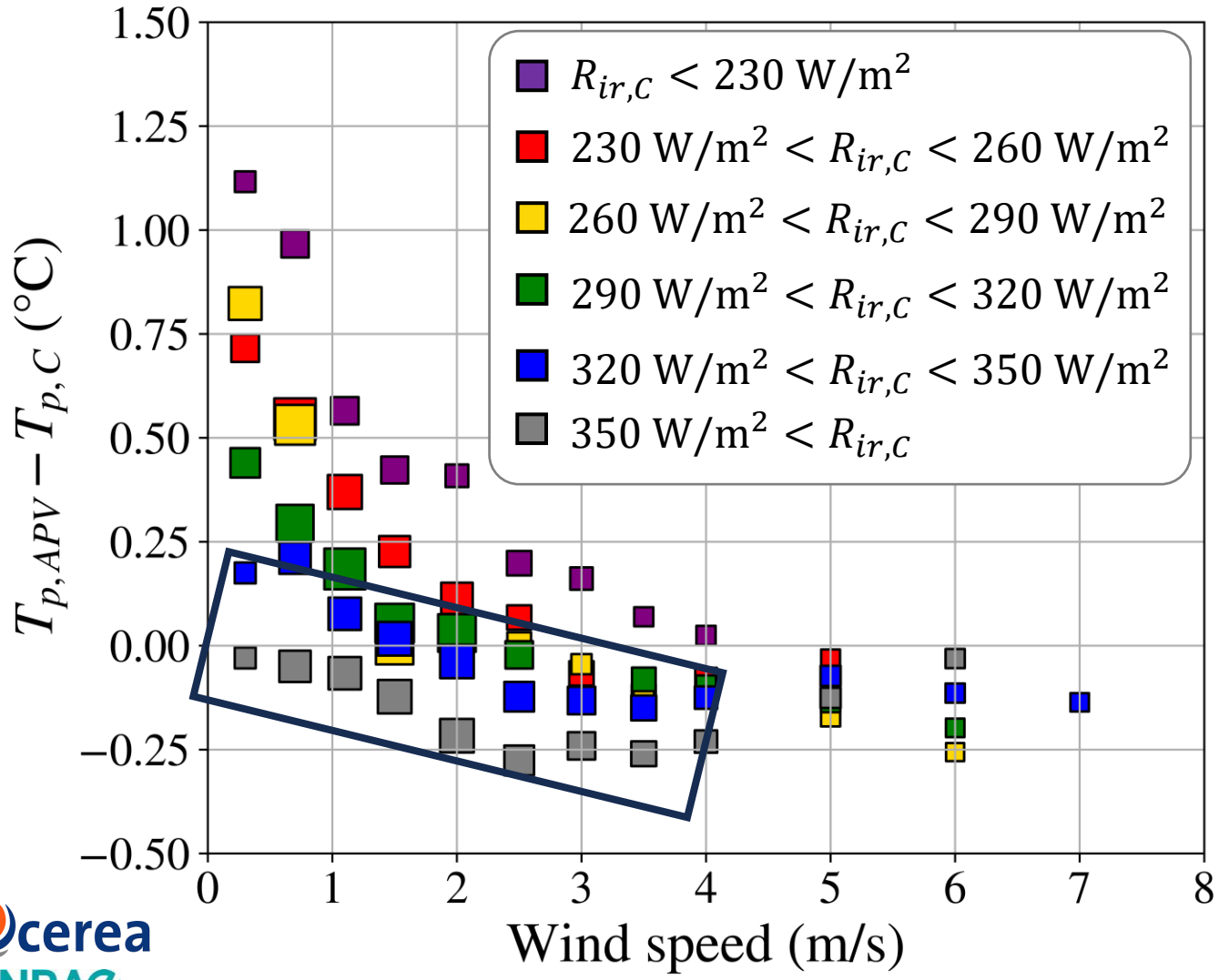

In average:

- **If cloudy sky $\Delta T_p \approx 0°C$**

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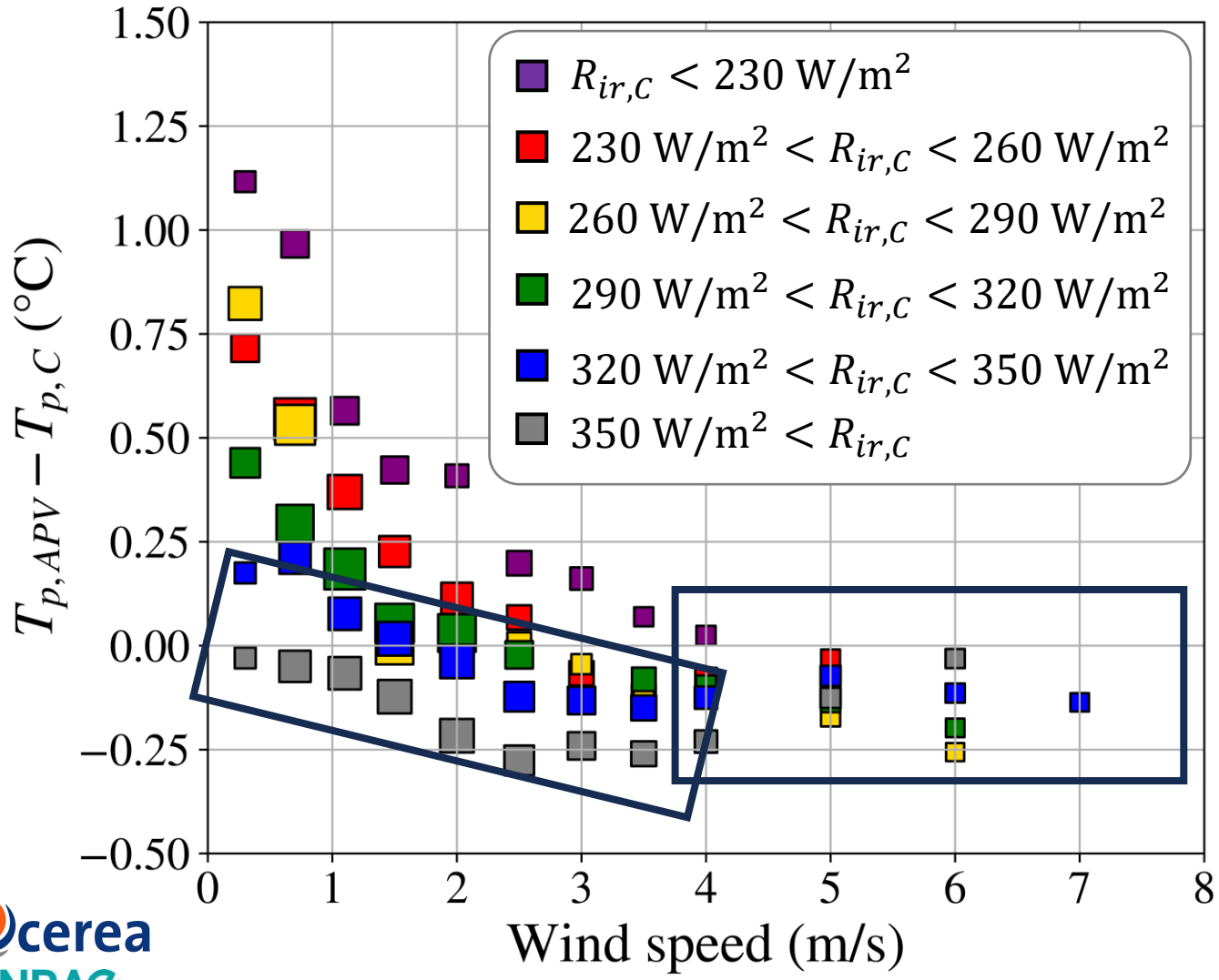

In average:

- **If cloudy sky $\Delta T_p \approx 0°C$**
- **If strong wind $\Delta T_p \approx 0°C$**

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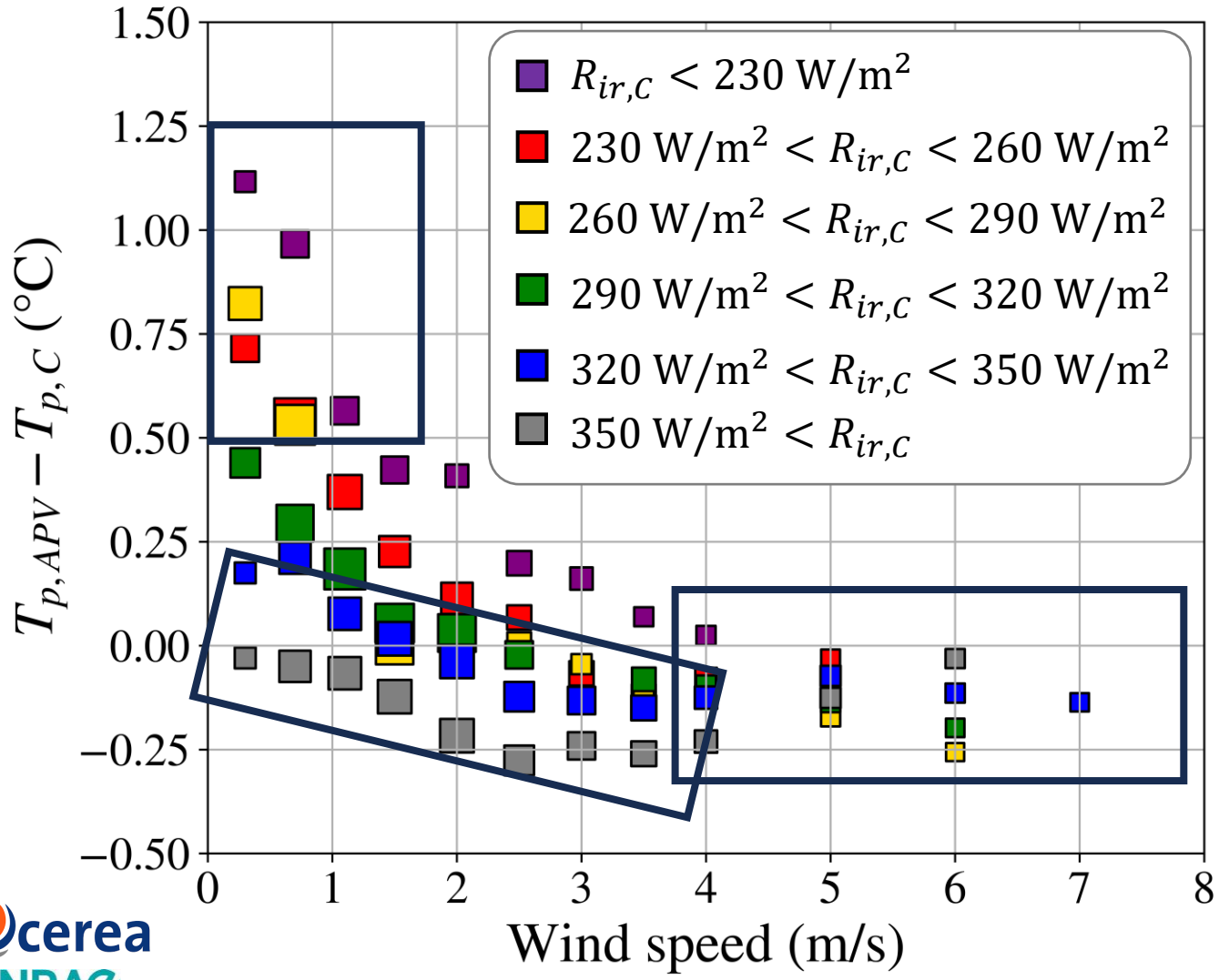

In average:

- **If cloudy sky $\Delta T_p \approx 0°C$**
- **If strong wind $\Delta T_p \approx 0°C$**
- **If clear sky and no wind $\Delta T_p \approx 1°C$**

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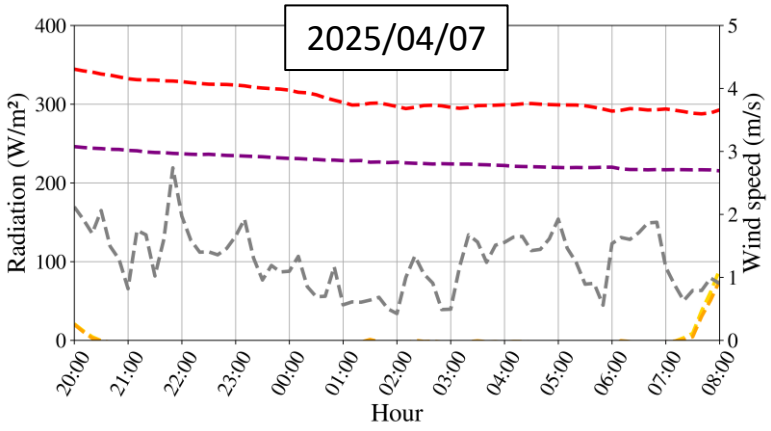
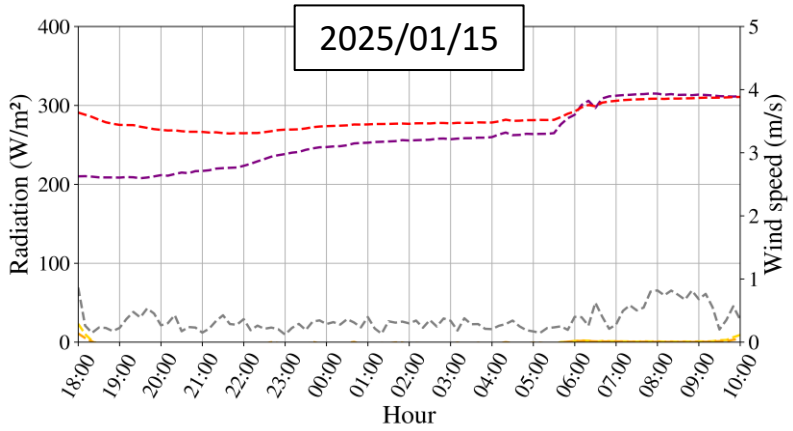
Measurements
Plant temperature time series APV VS C





- Infrared radiation APV zone
- Infrared radiation C zone
- Solar radiation
- Wind speed

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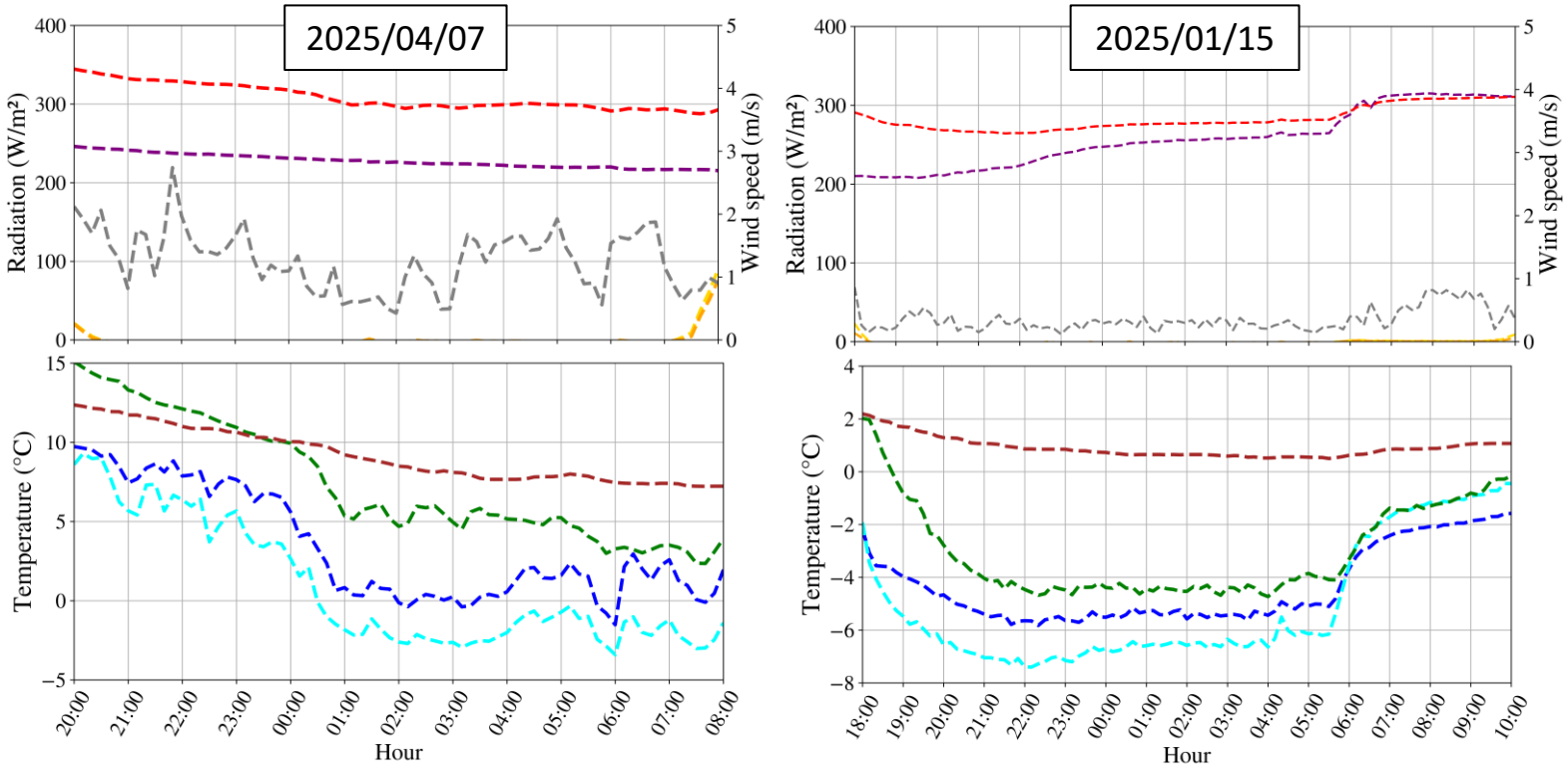

- Infrared radiation APV zone
- Infrared radiation C zone
- Solar radiation
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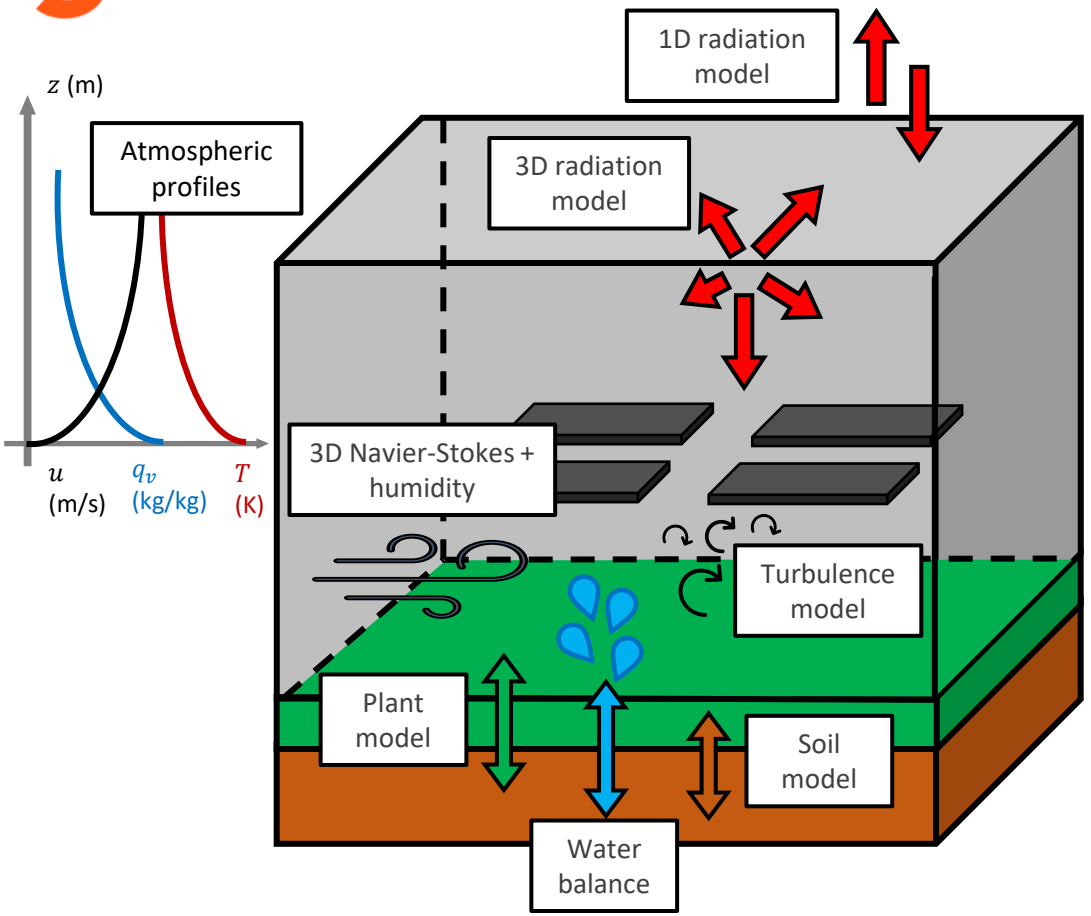
- Plant temperature APV zone
- Plant temperature C zone
- Air temperature
- Soil temperature

- $T_{p,APV} - T_{p,C} > 2°C$ **during these two frost occurences**
- **Neither soil temperature, nor air temperature seem relevant parameters to estimate frost intensity**

Numerical study
Numerical set-up – PV[1] and plant[2] models

code_saturne



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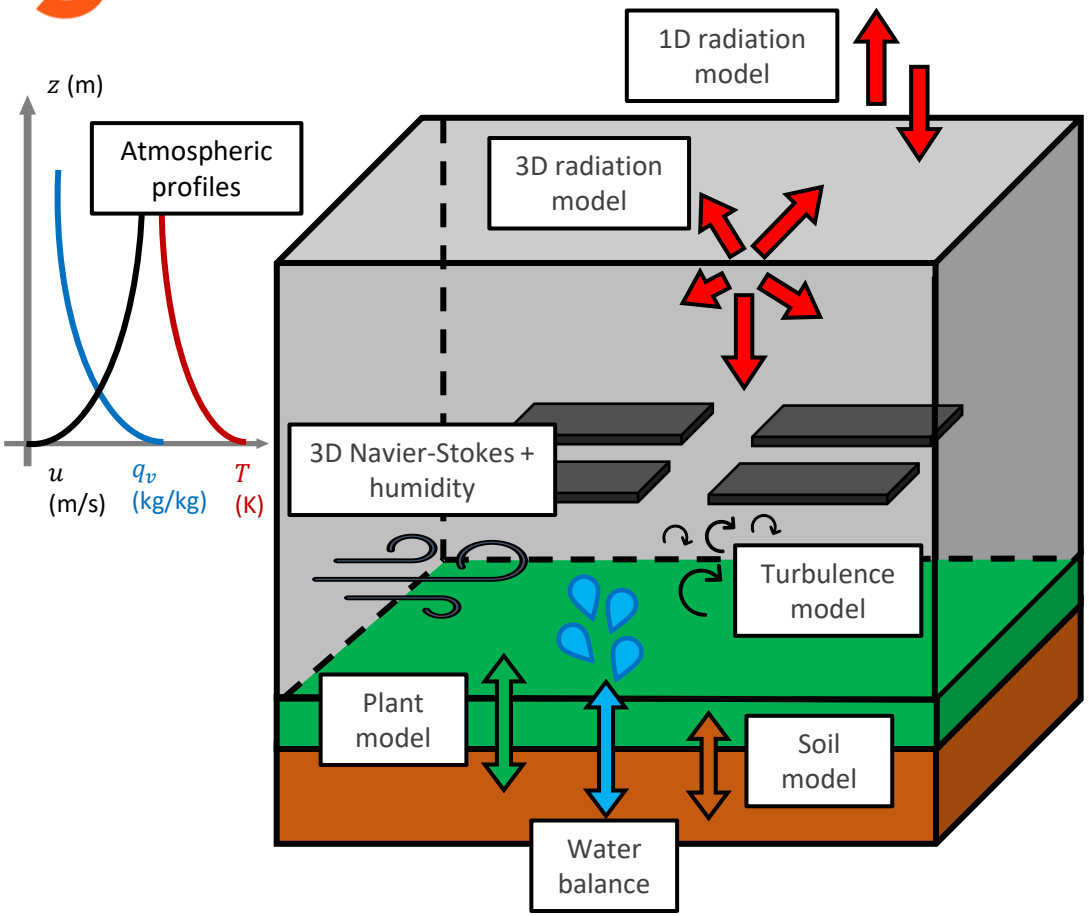

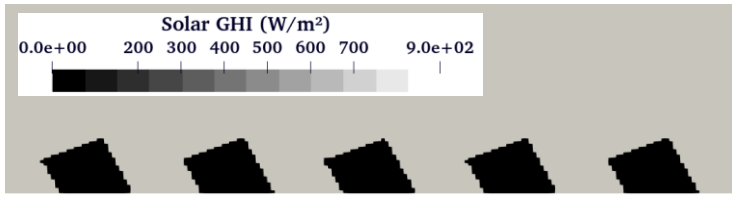

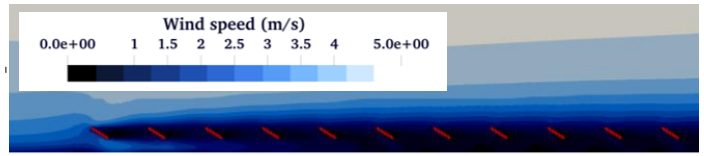

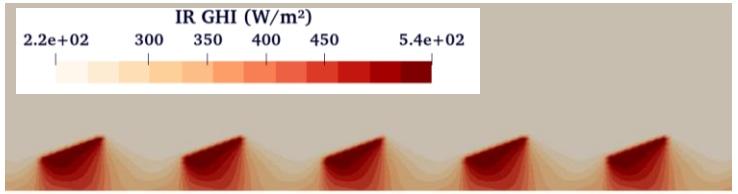

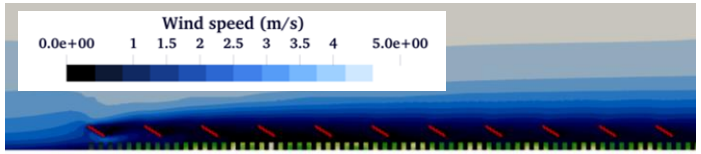

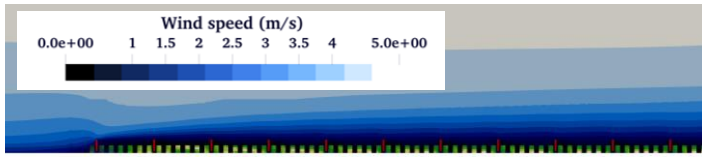

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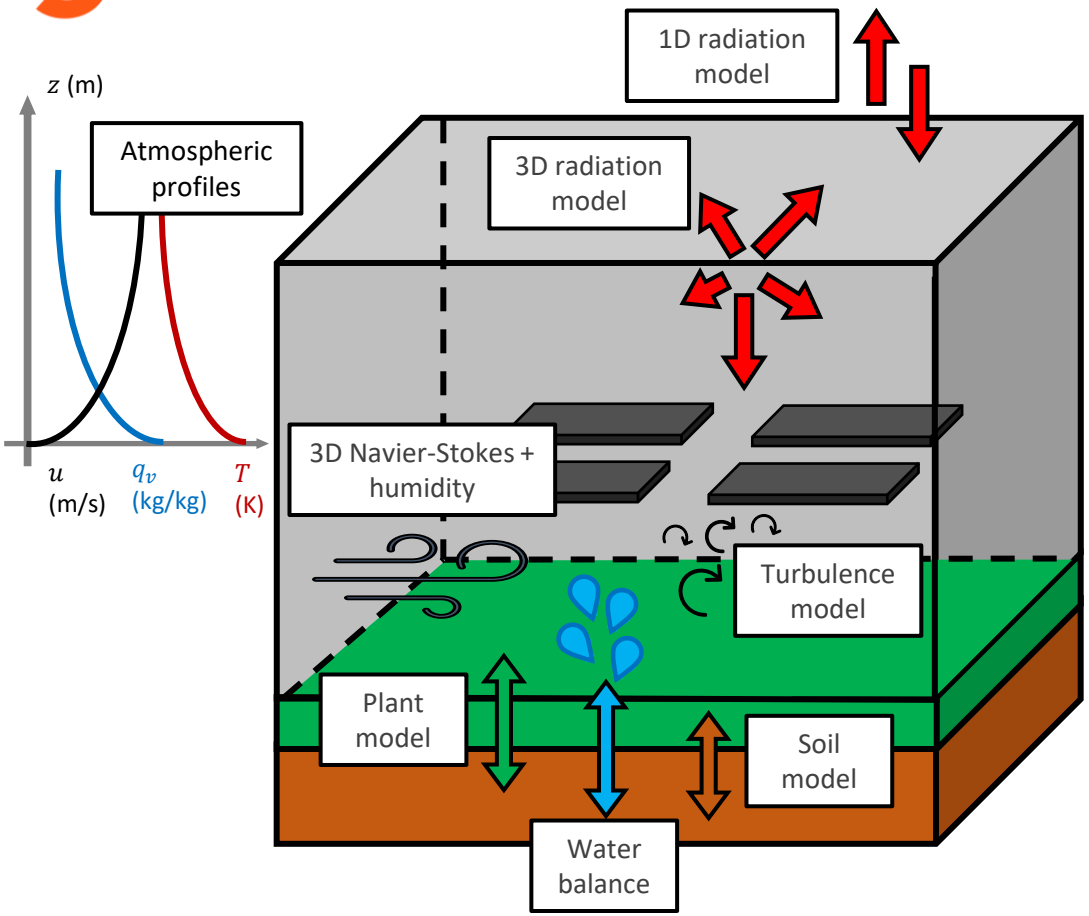
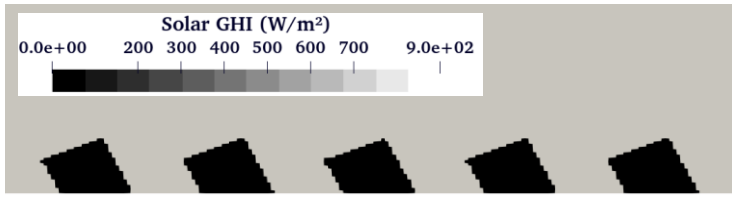
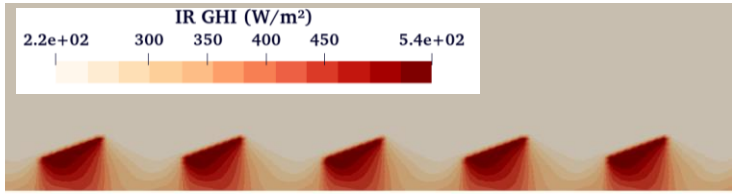
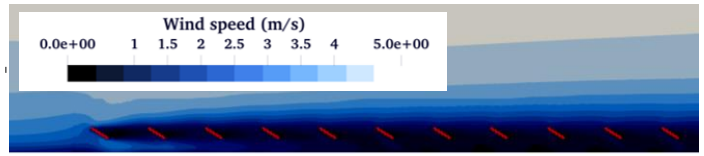
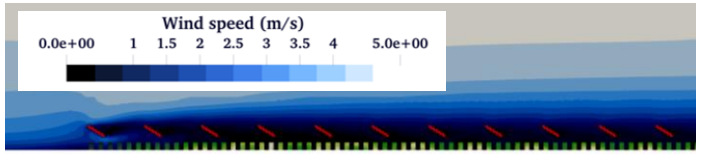
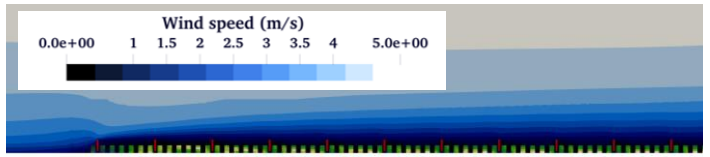


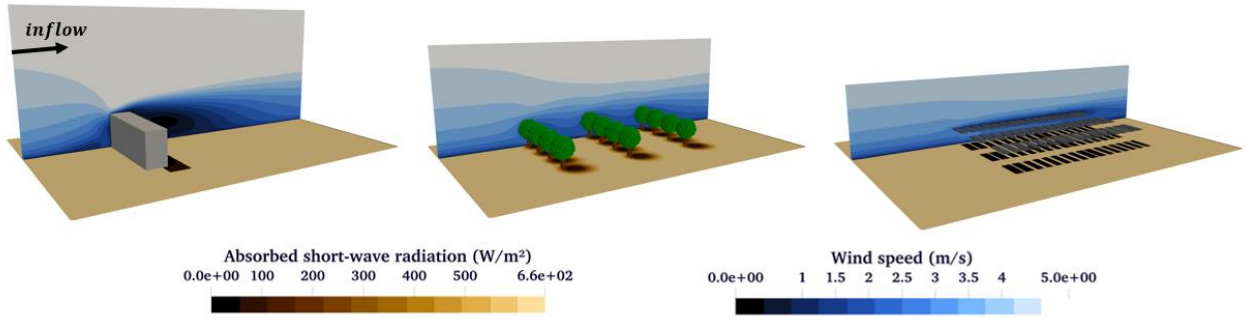


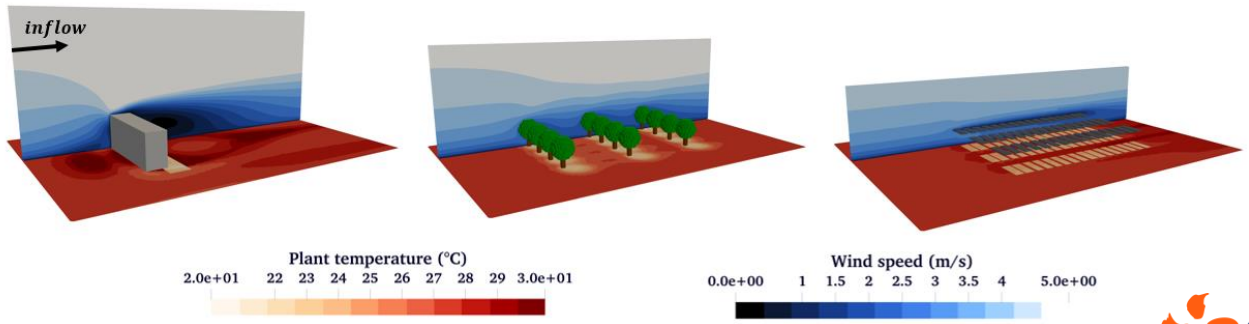








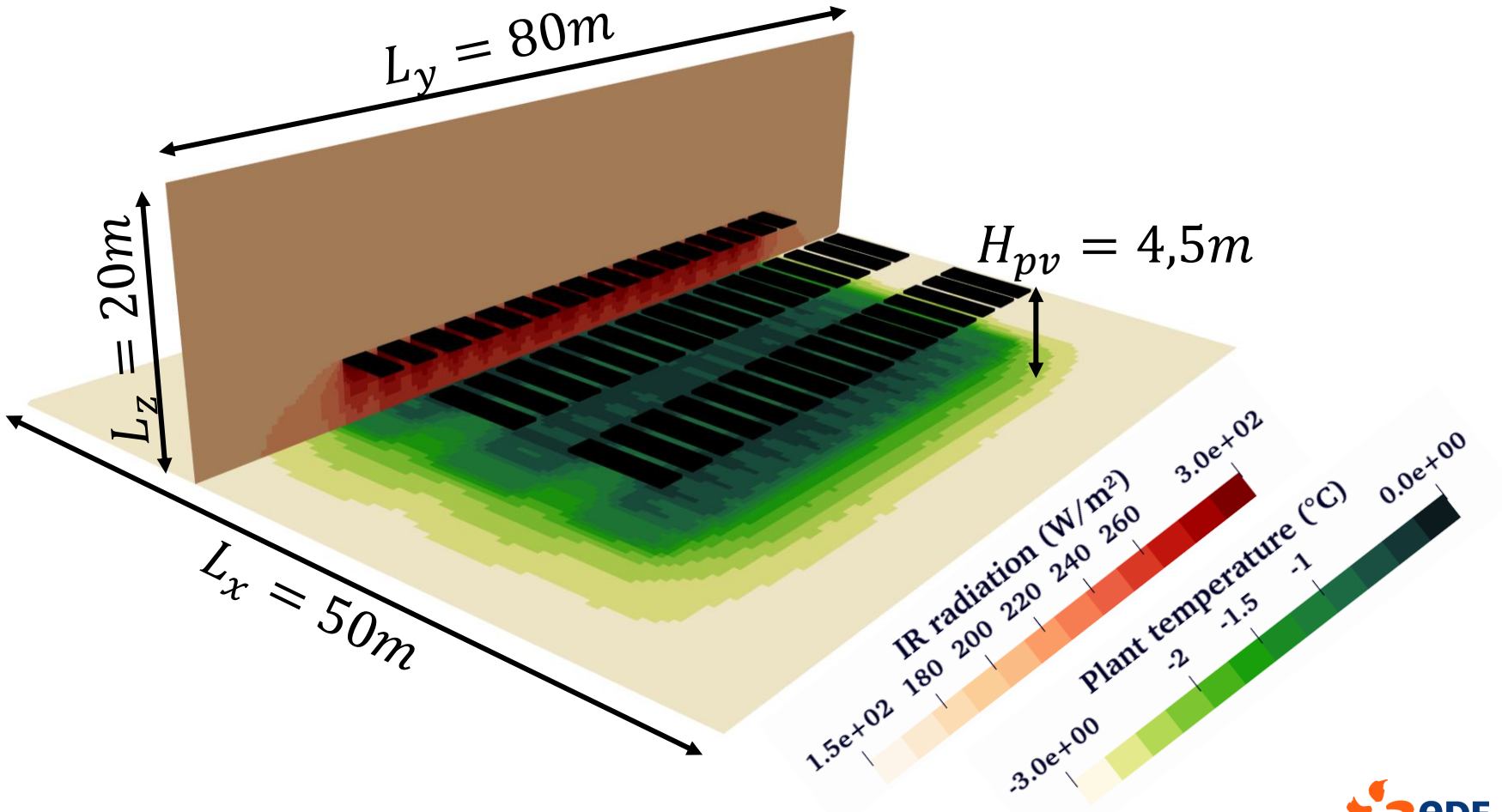




[1] J. Vernier, et al., Solar Energy, 2025 [2] J. Vernier, et al., Agricultural and Forest Meteorology, Under review

Numerical study
3D results

code_saturne



Simulations are first validated based on the measurements

Heterogeneity:

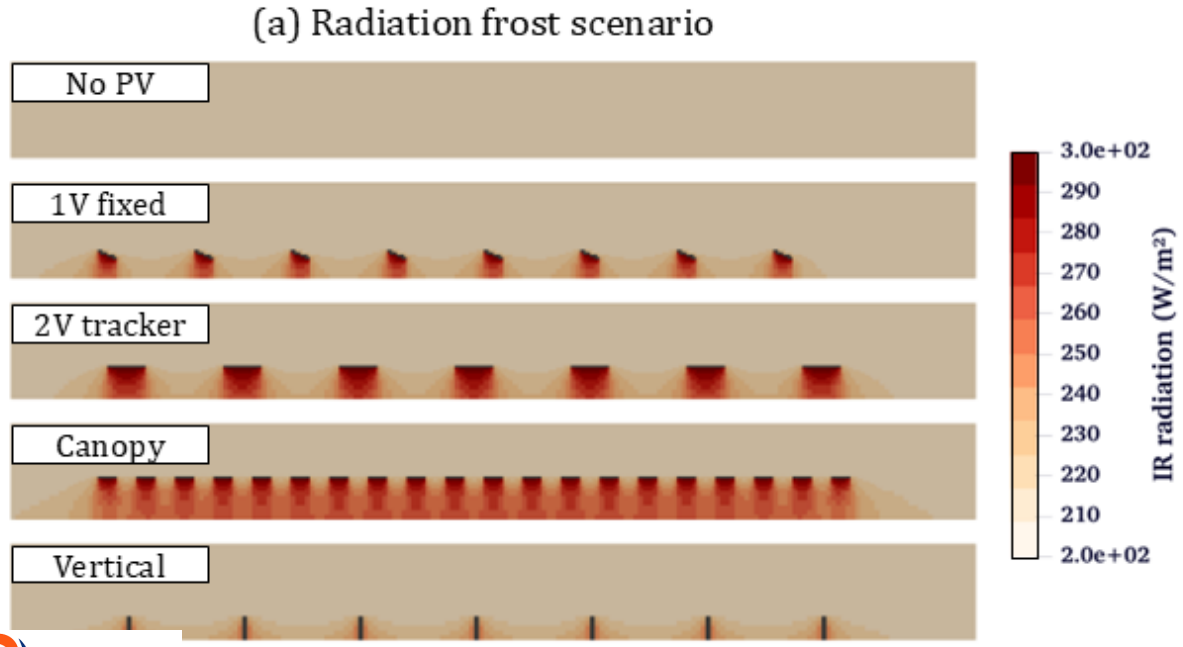
- **APV VS control zone**
- **Below VS between PV**

Numerical study
Sensitivity analysis

Radiation frost

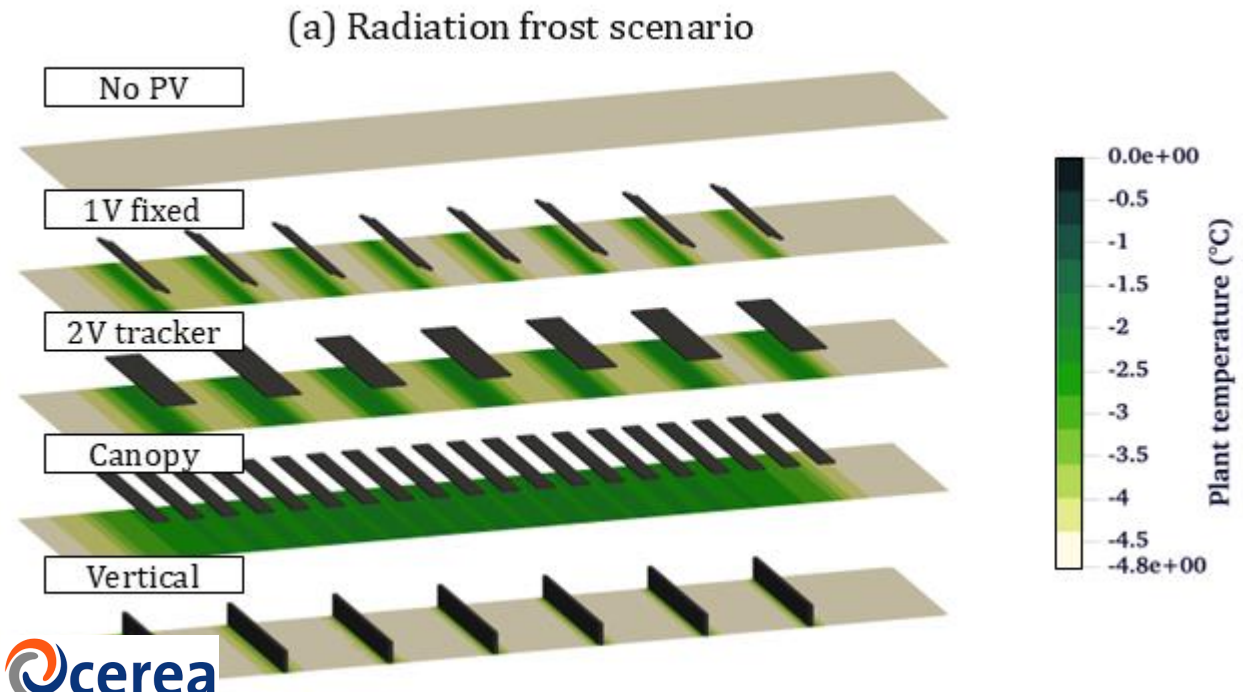
Numerical study
Sensitivity analysis

Radiation frost



Numerical study
Sensitivity analysis

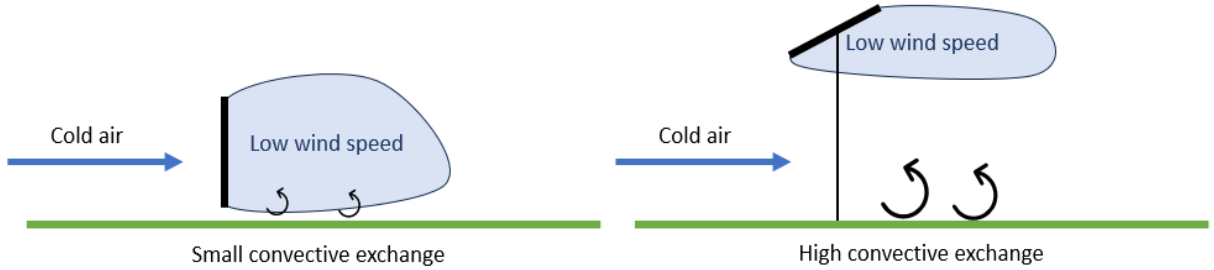
Radiation frost

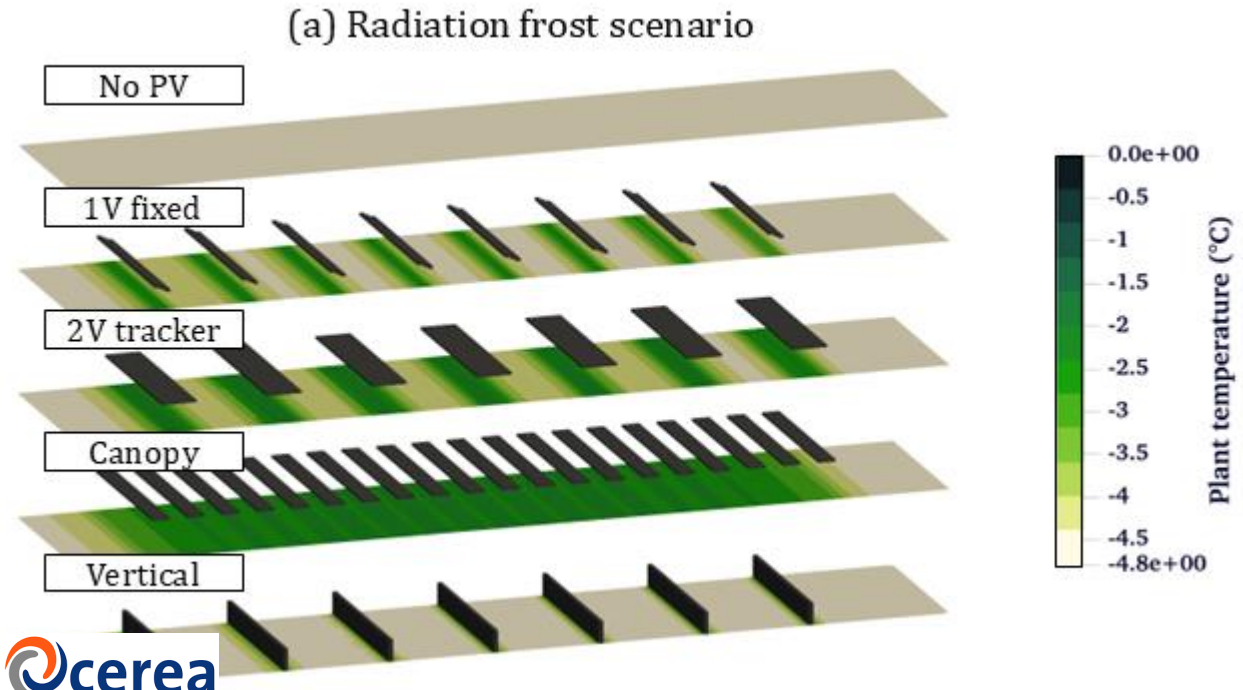


Numerical study
Sensitivity analysis

Radiation frost

Convection frost

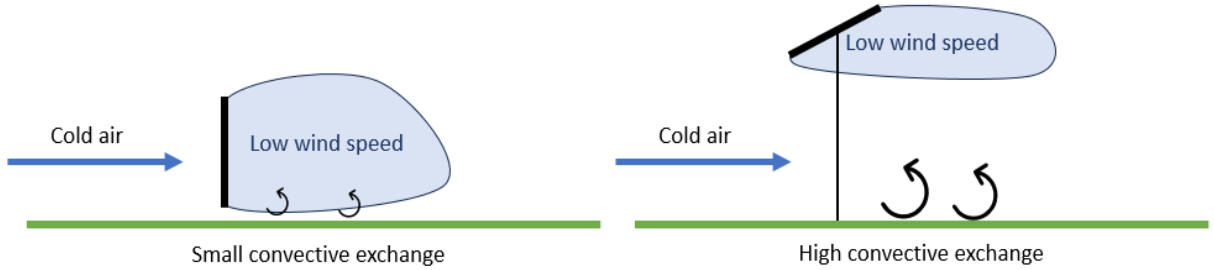


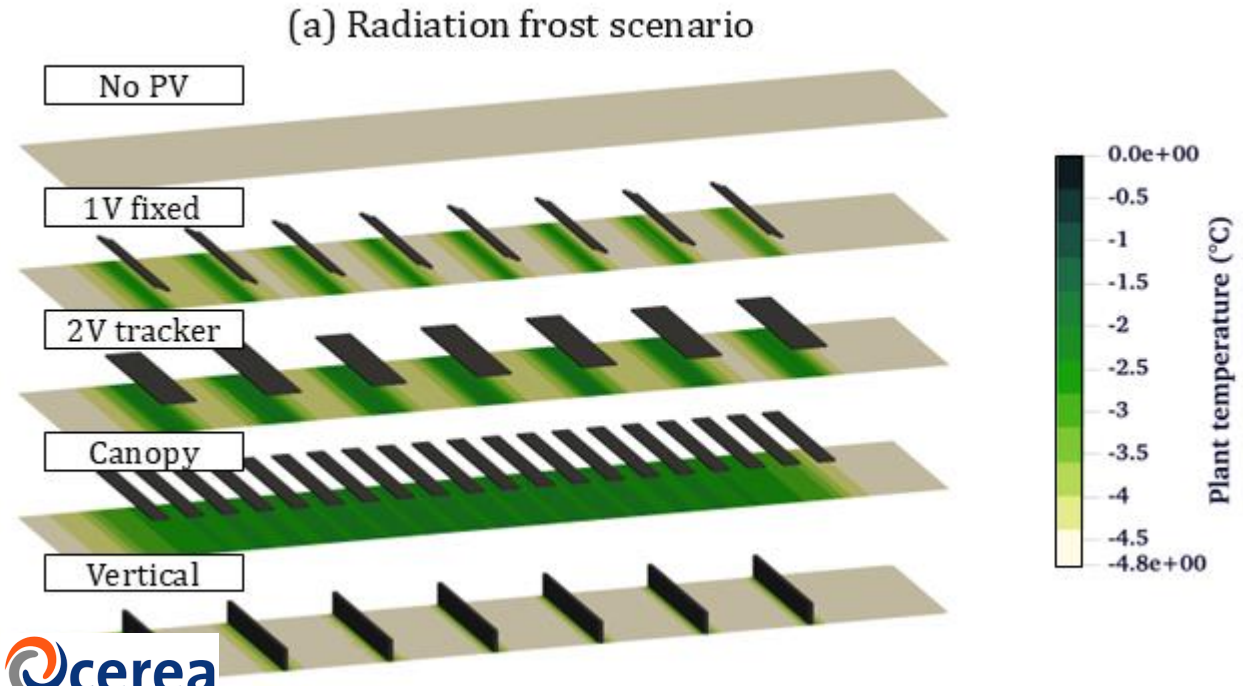


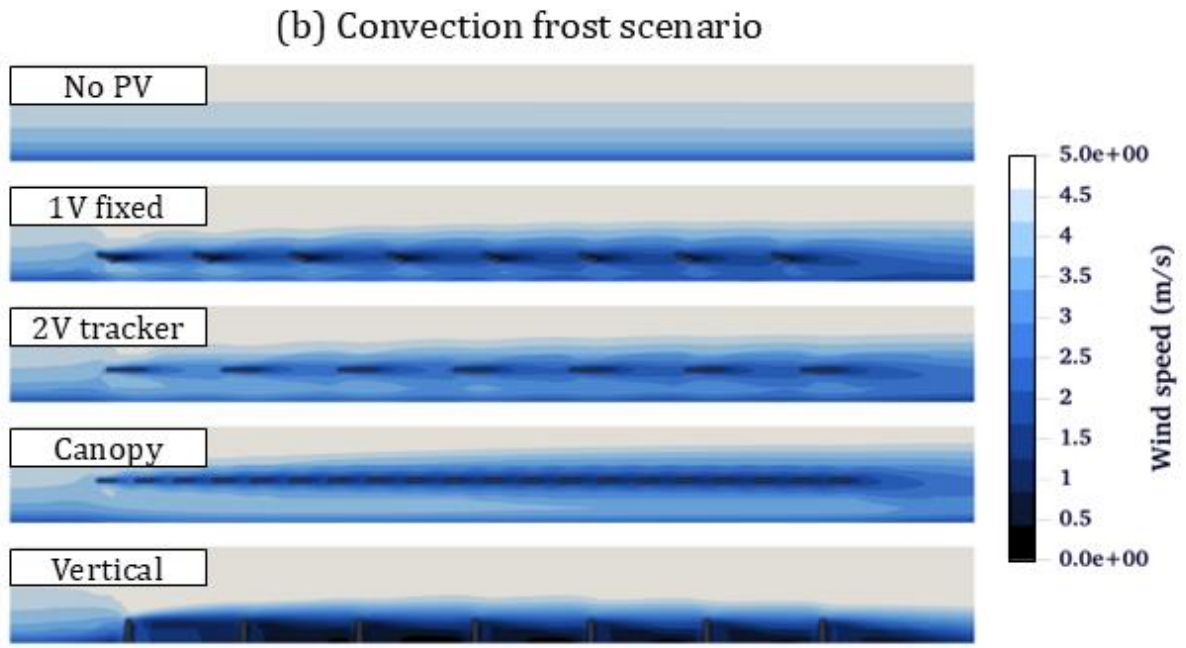
Numerical study
Sensitivity analysis

Radiation frost

Convection frost



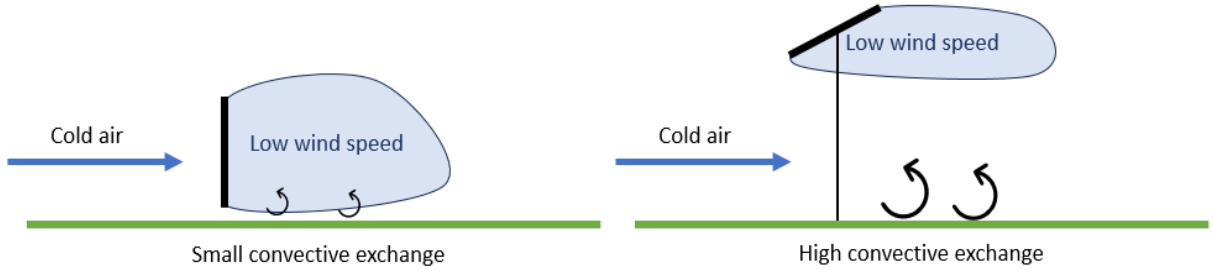




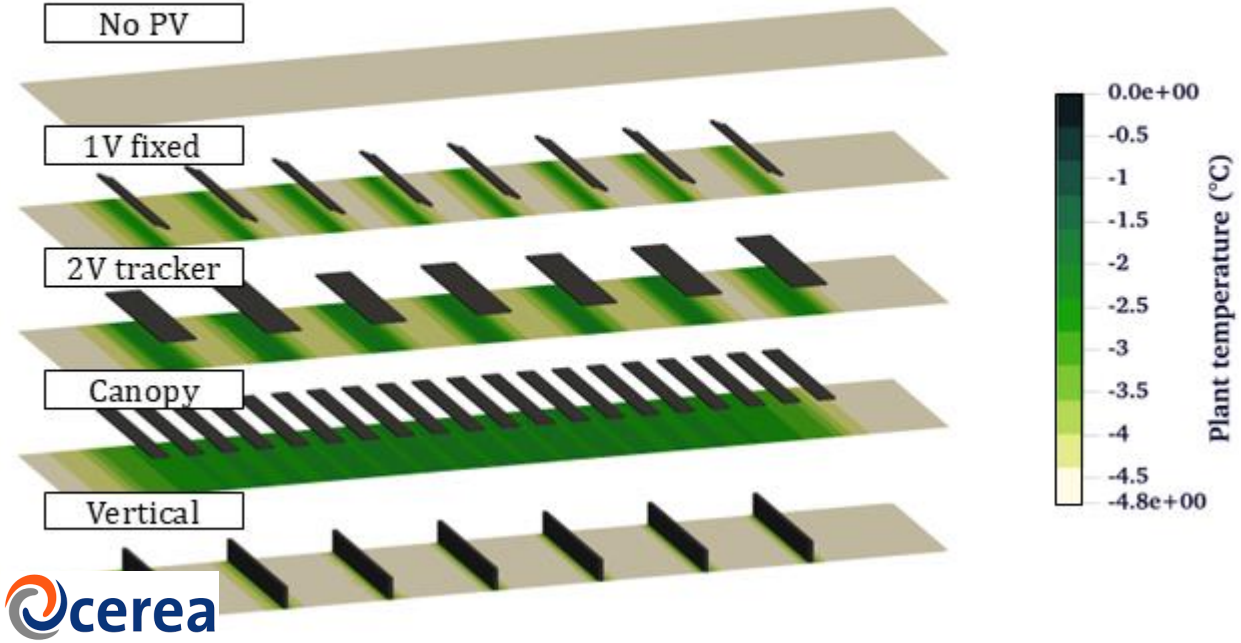
Numerical study
Sensitivity analysis

Radiation frost

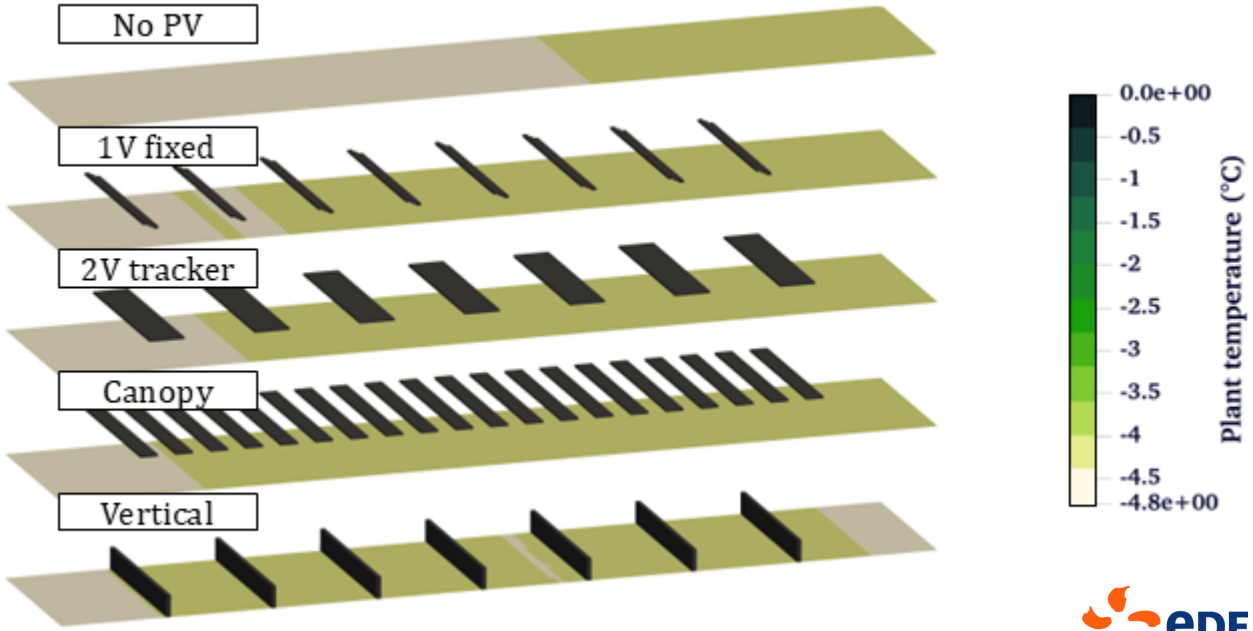
Convection frost



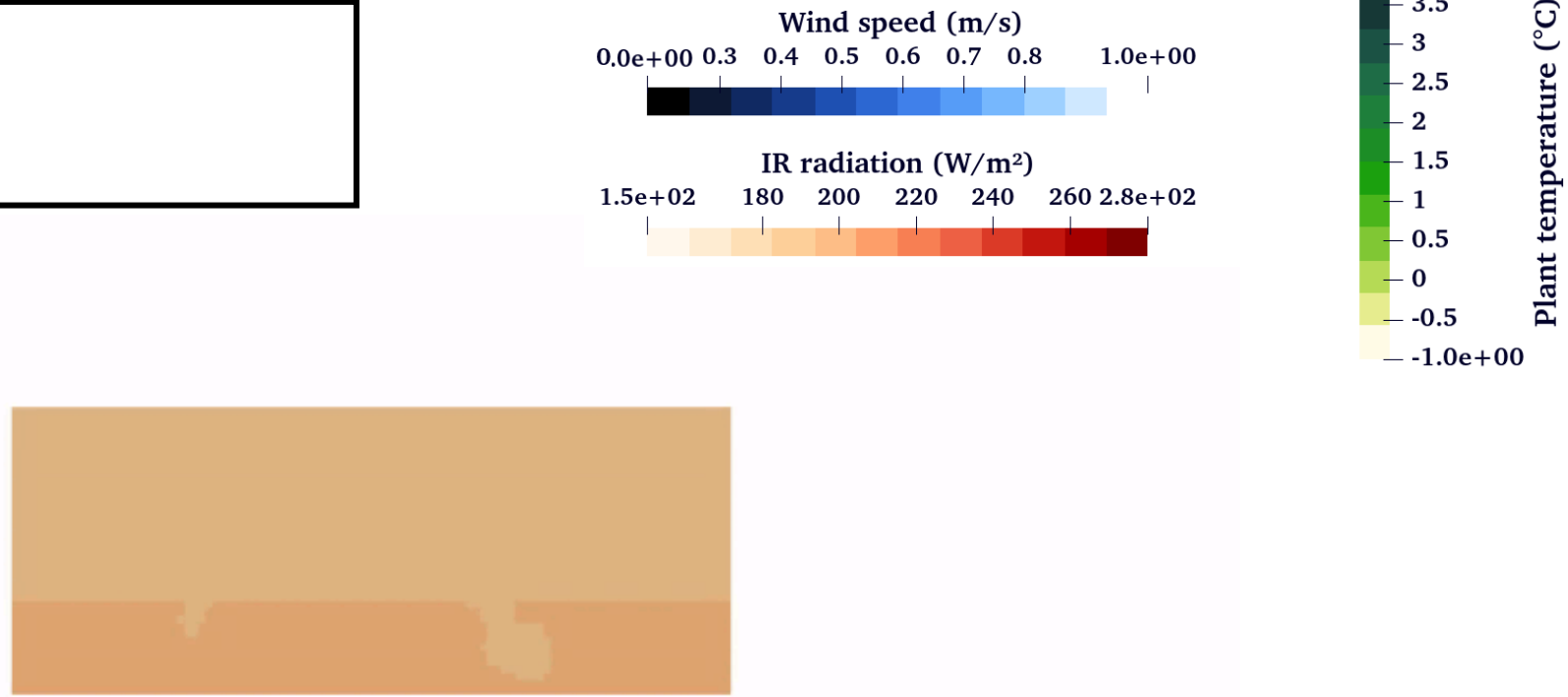
(a) Radiation frost scenario



(b) Convection frost scenario



Conclusion



- *Measurements show that PV panels protect plants against white frost (radiation frost) and do not worsen black frost (convection frost).*
- *Neither air temperature, nor soil temperature seem relevant parameters to study frost intensity.*
- *Optimal APV geometry could be found using the coupling of models in code_saturne.*

Next steps:

- ❑ *To be included in crop models (STICS, or DSSAT).*
- ❑ *Frost study using a 3D plant model → for apple trees or vineyards.*

Thank you for listening!

Any questions?

→ Junni Luo poster n.27 on an airflow study at SIRTA APV power plant, which questions standard energy and water exchange models!

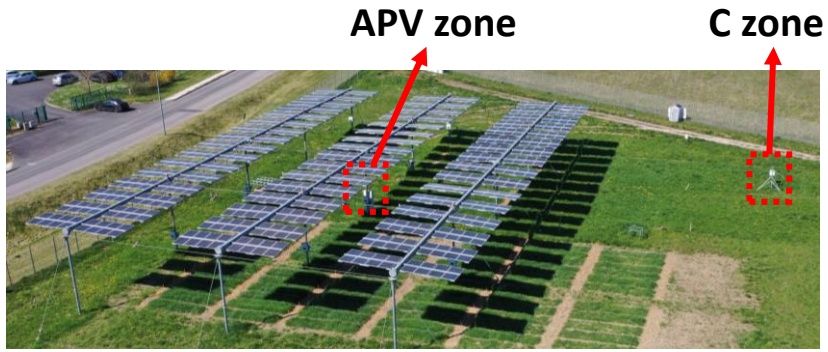
Do you want to learn more about agrivoltaic modelling?

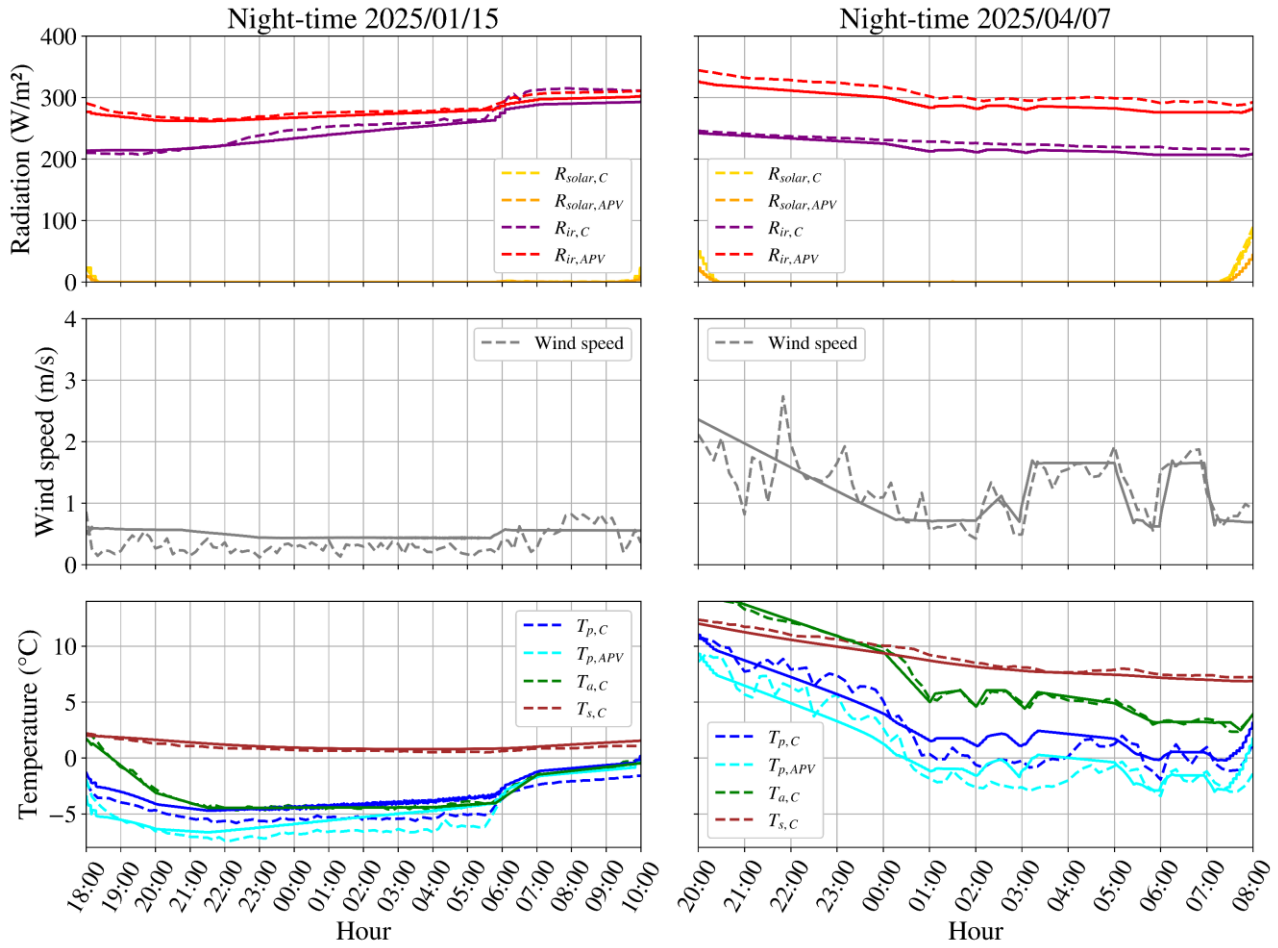
Already published:
J. Vernier, et al., An innovative method based on CFD to simulate the influence of photovoltaic panels on the microclimate in agrivoltaic conditions, Solar Energy, 2025 *https://doi.org/10.1016/j.solener.2025.113571*

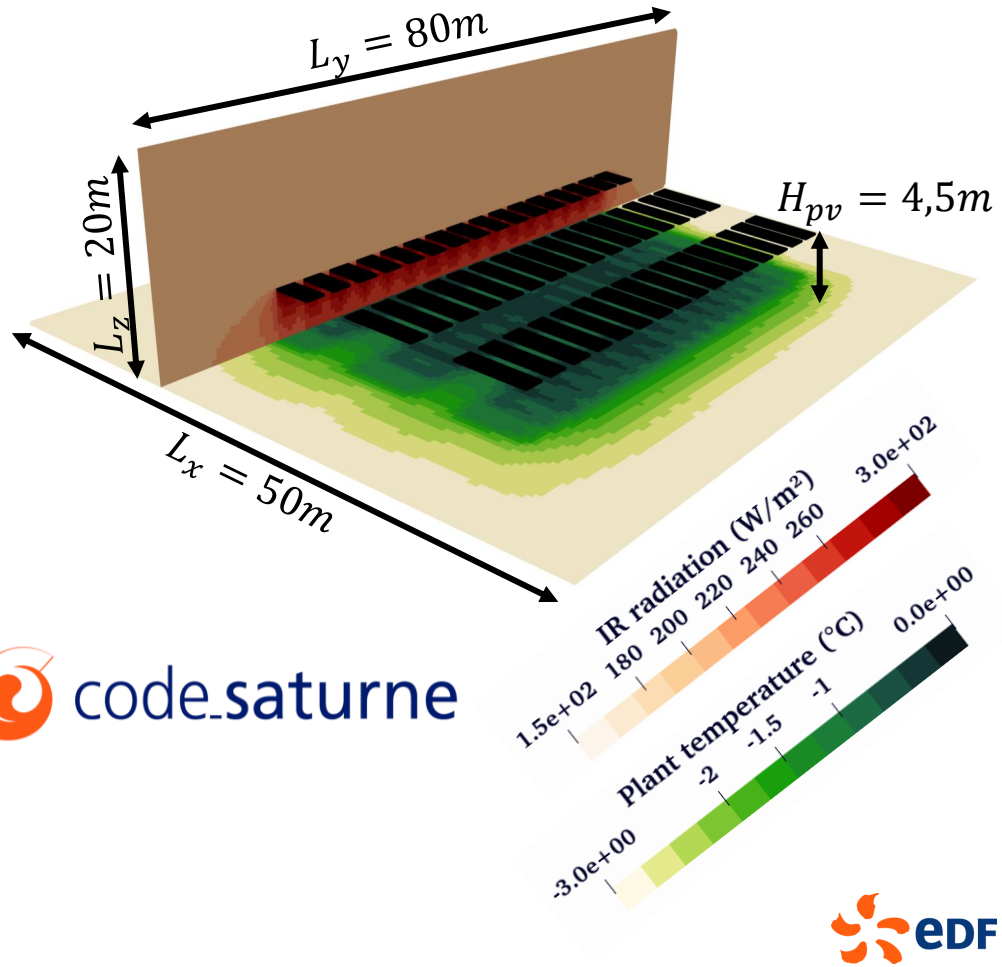
Under review:
J. Vernier, et al., A Soil-Plant-Atmosphere Continuum model coupled to CFD to simulate plant energy and water exchanges in heterogeneous microclimates, *https://ssrn.com/abstract=5209927*

J. Vernier, et al., How to Model Wind Flows in Vegetative Canopies and Plant-Air Convective Heat Exchanges? A Special Focus on Agrivoltaics

Numerical study
Evaluation against measurements



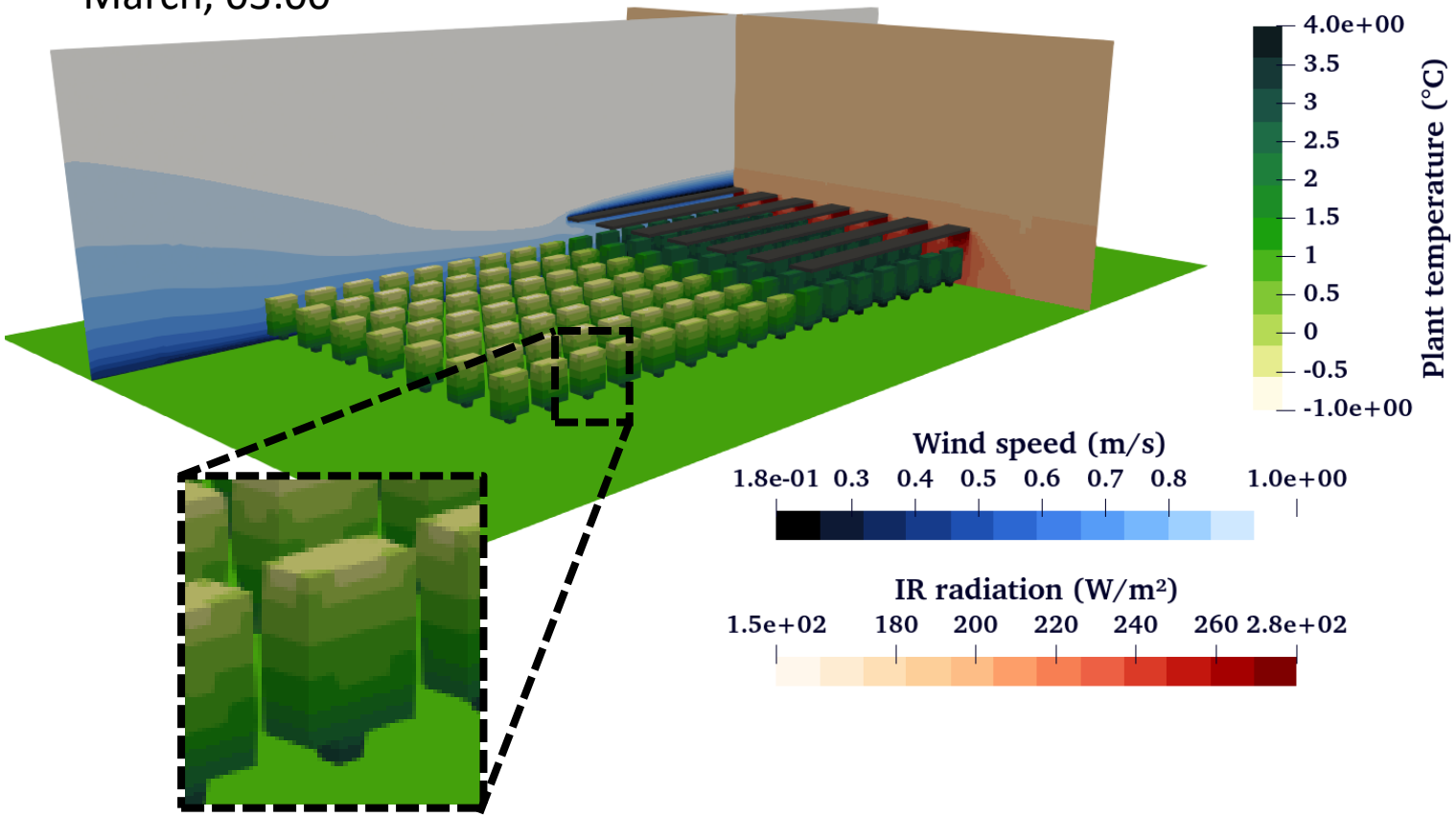




code_saturne

Numerical study
3D plant modelling

March, 03:00



- Consider more complex plants!
- Higher protection as the apple trees are located closer to the PV panels
- Impact of frost first at the surface