

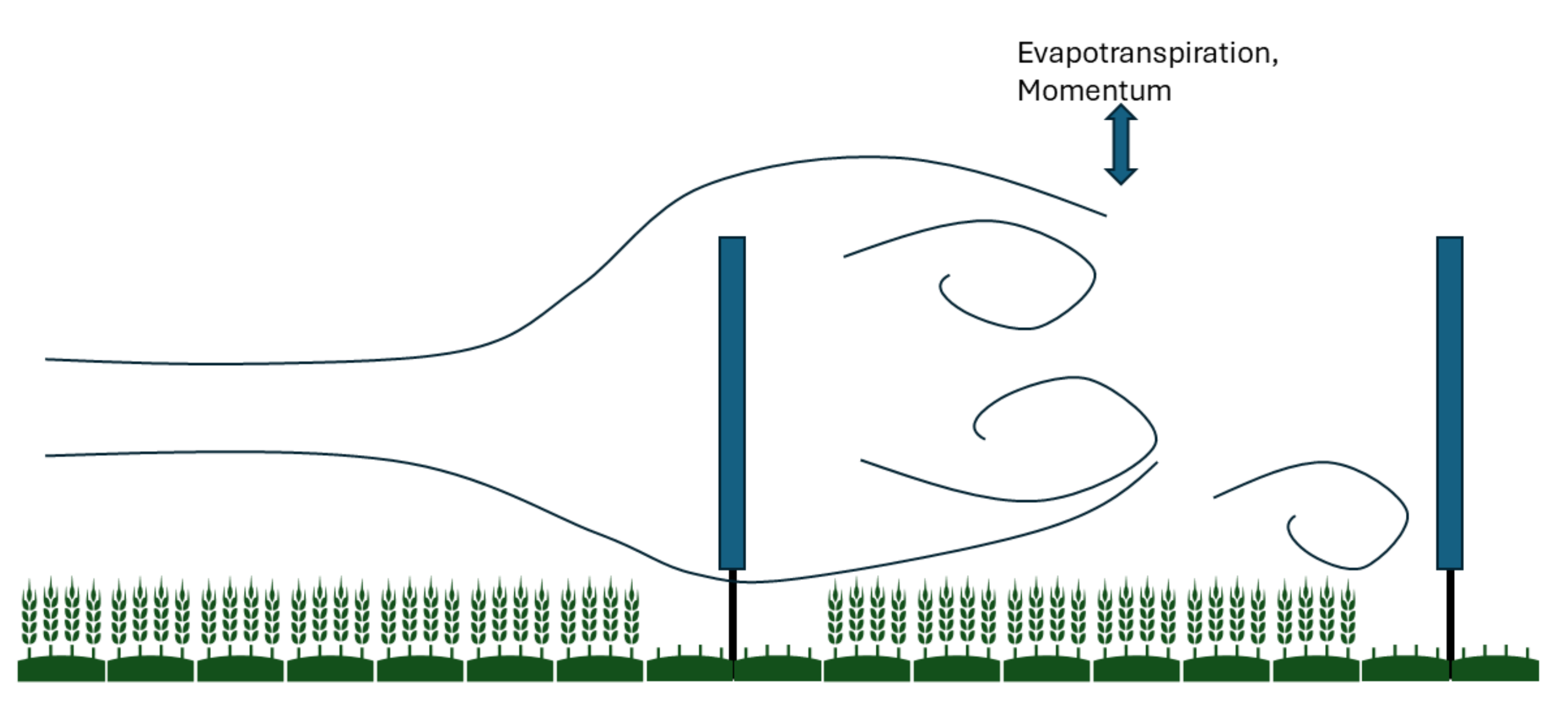
A Study of 3D Turbulent Wind Flow at the Centre of Vertical Agrivoltaics in Full-Grown Wheat Condition

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Agri-PV and microclimate

In the burgeoning field of sustainable energy solutions, the integration of photovoltaic modules into agricultural systems is a promising avenue. Agrivoltaics influences air flows, orchestrating a symphony of effects that affect the crop microclimate and consequently their growth and yield. This interaction encompasses changes in mean wind speed, shading patterns, turbulence levels and, ultimately control the evapotranspiration process. Vertical agrivoltaics is an interesting design because of its compatibility with agricultural equipment operation, its bimodal electricity production profile and the expected benefits of windbreak and shading effect on water balance [1]. Among the multitude of factors that determine the microclimate, the transport of scalars and momentum appears to be a key player, governed mainly by turbulent wind phenomena [2]. Few studies provide details on the impact of photovoltaic structures on the airflow around the crop. One study investigated the impact mean on airflow of a ground-mounted power plant with modules close to the horizontal (18° angle of attack of) using 2D anemometers at several different heights but the low measurement frequency (1/60 Hz) give no insight to effects on flow turbulence [3]. Others have studied the microclimate in a fixed PV shading system with an angle of 25°, measuring wind speed and direction using a mechanical 2D anemometer, which therefore has an inertia that introduces errors in high-frequency measurements [4]. In addition, as in the previous study, the lack of vertical velocity measurements means that turbulence is poorly captured. Therefore, this work investigates the impact of photovoltaic modules mounted on a vertical agrivoltaics structure on wind dynamics, with particular emphasis on the windbreak effect and turbulence pattern and transport in a 111 kWc demonstrator.



Material and methods

This study is based on a trial conducted in a TotalEnergies vertical agrivoltaic pilot located in Valpuseaux (France). The trial aims to study the windbreak effect and turbulence at the center of the demonstrator according to the wind direction. Data from a 3D sonic anemometer were collected at the center of the demonstrator, 2m above the soil. These were compared with another dataset collected on a second 3D sonic anemometer located in the reference zone 30m south of the last panel of the central array. The data were collected during the growing period of wheat.

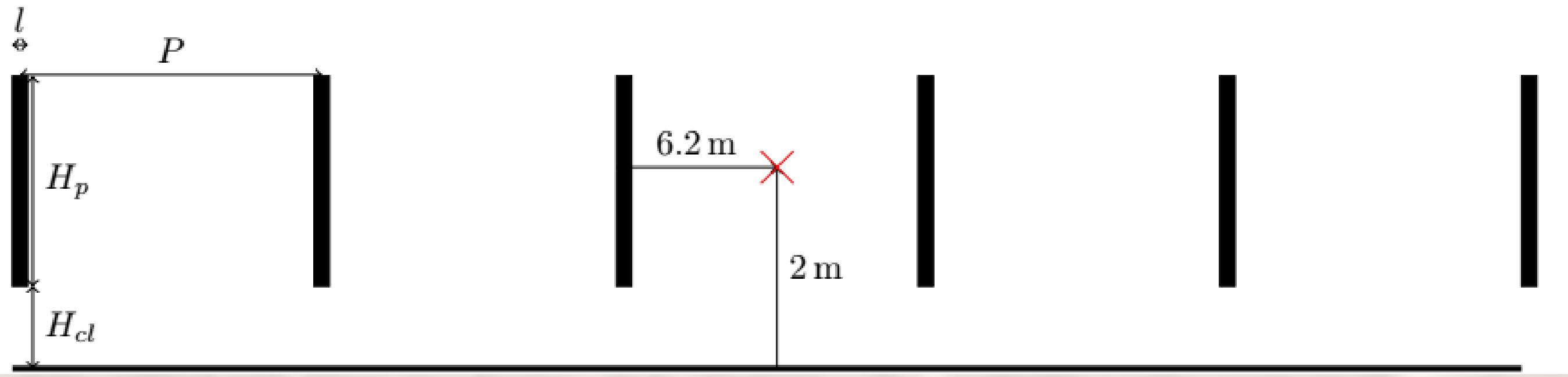


Figure 1 : Schematic diagram of the Valpuseaux agrivoltaic demonstrator and position of the 3D sonic anemometer within the demonstrator. The red cross indicates the position of the anemometer. P is the pitch distance (10 m). H_p is the panel height (2.087 m). H_{cl} is the clearance height (0.817 m). l is the row width (variable from 3 cm to 10 cm).

The turbulence transfer is characterised by the friction velocity calculated according to Kaimal and Finnigan [5] with the velocity eddy components :

$$u^* = \sqrt{u'w'}$$

Where u' is the horizontal eddy component and w' the vertical eddy component. To study the shear rate and the momentum transfer, we perform a quadrant-hole analysis (QH) [6, 7]. This consists of decomposing the shear stress into four parts according to the sign of the eddy components :

- $u' > 0$ and $w' > 0$: Outward interaction (S1)
- $u' < 0$ and $w' > 0$: Ejection (S2)
- $u' < 0$ and $w' < 0$: Inward interaction (S3)
- $u' > 0$ and $w' < 0$: Sweeps (S4)

Sweeps are downward gusts, and ejections are upward low-wind events. The contribution of each quadrant to the momentum transfer can be calculated as follows :

$$S_i = \frac{\langle u'w' \rangle_i}{|u'w'|}$$

Where the chevron notation indicates a conditional average and the over line notation indicates a temporal average. Outward and inward intersections have a positive conditional mean, unlike the other two quadrants.

References

[1] R. Bruhwyler et al., « Could Windbreak Effect Significantly Decrease Evapotranspiration in Vertical Agrivoltaics? », *AgriVoltaics*2022, 2022.
[2] M. B. Parlange, W. E. Eichinger, et J. D. Albertson, « Regional scale evaporation and the atmospheric boundary layer », *Reviews of Geophysics*, vol. 33, n° 1, p. 99-124, 1995, doi:10.1029/94RG03112.
[3] E. H. Adeh, J. S. Selker, et C. W. Higgins, « Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency », *PLOS ONE*, vol. 13, n° 11, p. e0203256, nov. 2018, doi:10.1371/journal.pone.0203256.
[4] H. Marrou, L. Guilioni, L. Dufour, C. Dupraz, et J. Wery, « Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? », *Agricultural and Forest Meteorology*, vol. 177, p. 117-132, août 2013, doi:10.1016/j.agrformet.2013.04.012.
[5] J. C. Kaimal et J. J. Finnigan, *Atmospheric Boundary Layer Flows: Their Structure and Measurement*. Oxford University Press, 1994.
[6] J. J. Finnigan, « Turbulence in waving wheat », *Boundary-Layer Meteorol*, vol. 16, n° 2, p. 213-236, juin 1979, doi:10.1007/BF02350512.
[7] Y. Brunet, « Turbulent Flow in Plant Canopies: Historical Perspective and Overview », *Boundary-Layer Meteorol*, vol. 177, n° 2, p. 315-364, déc. 2020, doi:10.1007/s10546-020-00560-7.

Take Home message

- Single point statistics of turbulent and mean wind flow characteristics in Agri-PV
- In the center of the demonstrator, Agri-PV acts as windbreak protection when wind is perpendicular but accelerate it when it is parallel
- Agri-PV acts as a second canopy system in terms of momentum transfer by increasing sweep events when the wind arrives perpendicular to the panels.
- Further work will investigate the spatial variability of these effects using numerical simulations

Results and discuss

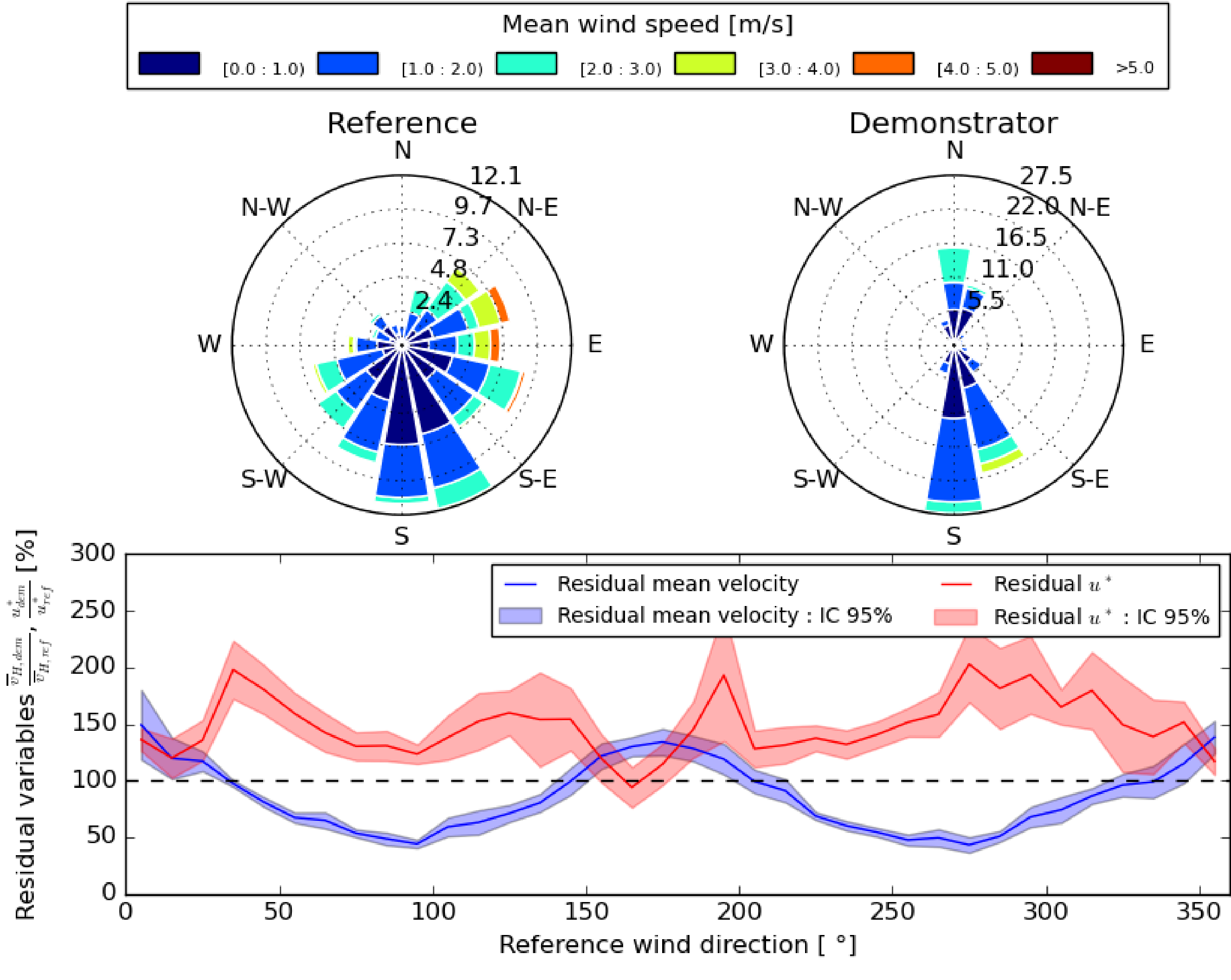


Figure 2 : Wind roses inside reference area and vertical agrivoltaics demonstrator and change in mean wind speed $\frac{\bar{v}_{H, dem}}{\bar{v}_{H, ref}}$ and friction velocity $\frac{u_{ref}^{dem}}{u_{ref}^{ref}}$ as a function of reference wind direction.

The wind roses illustrate that the mean wind at the center of the demonstrator is deflected towards the parallel to the photovoltaic arrays. The line graph presents the evolution of the ratio between the mean speed at the center of the demonstrator and that of the reference, as well as the ratio for the friction velocity, according to the direction of the reference wind. The variation of the mean speed (in blue) seems to follow a sinusoidal law with a decrease in speed when the direction of the reference wind is perpendicular to the photovoltaic arrays and an increase in speed when the direction is parallel. This increase is may be due to a Venturi effect caused by the canyoning of the flow with the photovoltaic arrays. This result should be compared [3] with those who did not observe this canyoning effect on steeply sloping panels. Friction velocity (u^* in red), and thus the momentum transfer, seems to increase overall inside the demonstrator compared to the reference zone, except when the direction is close to the parallel.

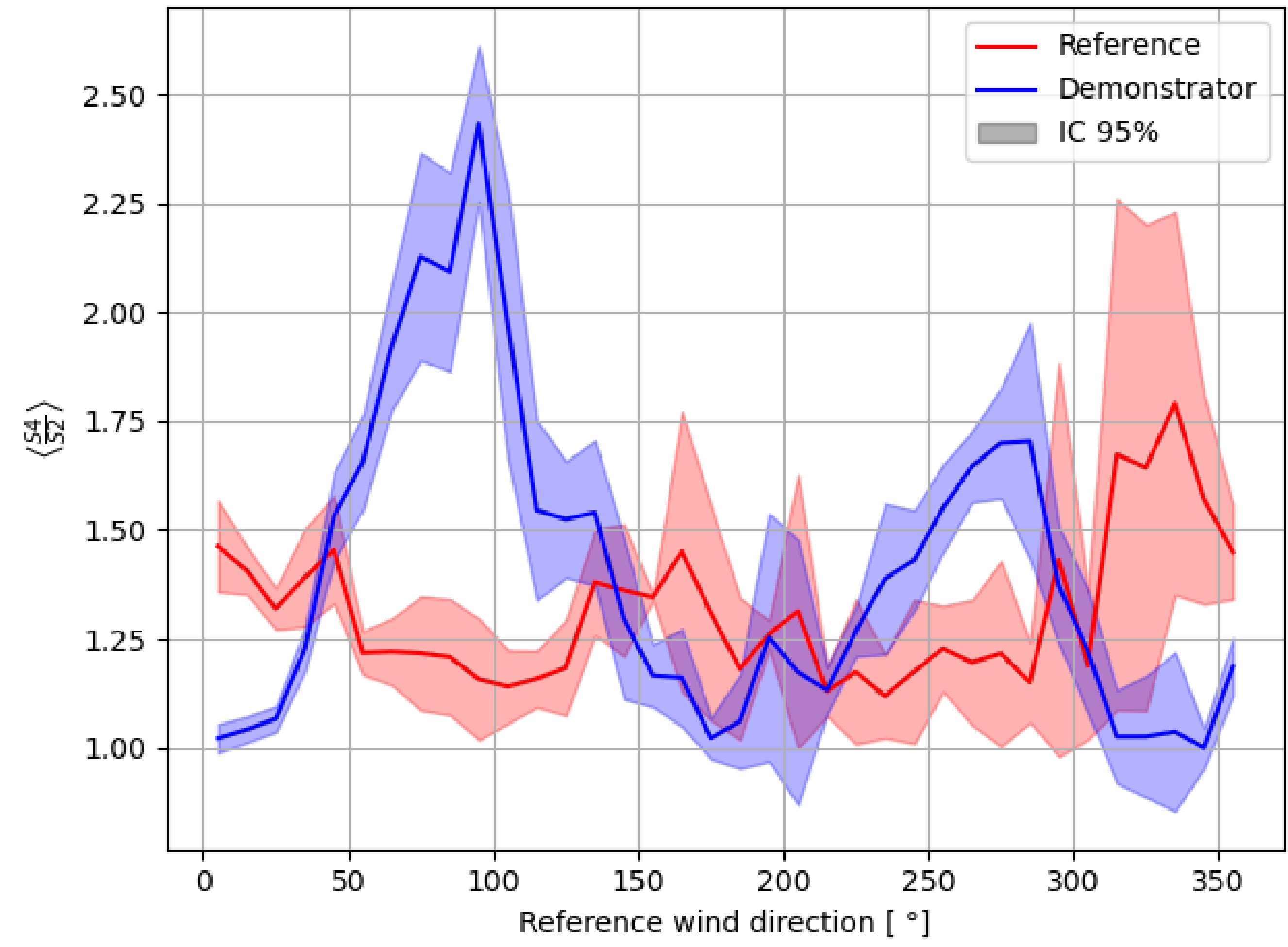


Figure 3 : Average of the ratios between sweeps and ejections $\frac{S_4}{S_2}$ for the reference anemometer and within the demonstrator as a function of the reference wind direction.

The Agri-PV system influences the ratio of sweep to ejection and acts like a second complex canopy. In fact, just above and within the canopy, the momentum transport is dominated by sweep events, whereas above the canopy, ejections take up some of the momentum and there is a balance between the two types of events, as shown in the figure 4. [7]. We can see that the Agri-PV structure increases the sweep when the wind is perpendicular but not when it is parallel, where it tends to reduce it (Figure 3). Photovoltaic structures therefore modify transport processes. In the future, we will be working on the impact of this modification on evapotranspiration and sensible heat, which are transported by the same mechanisms.

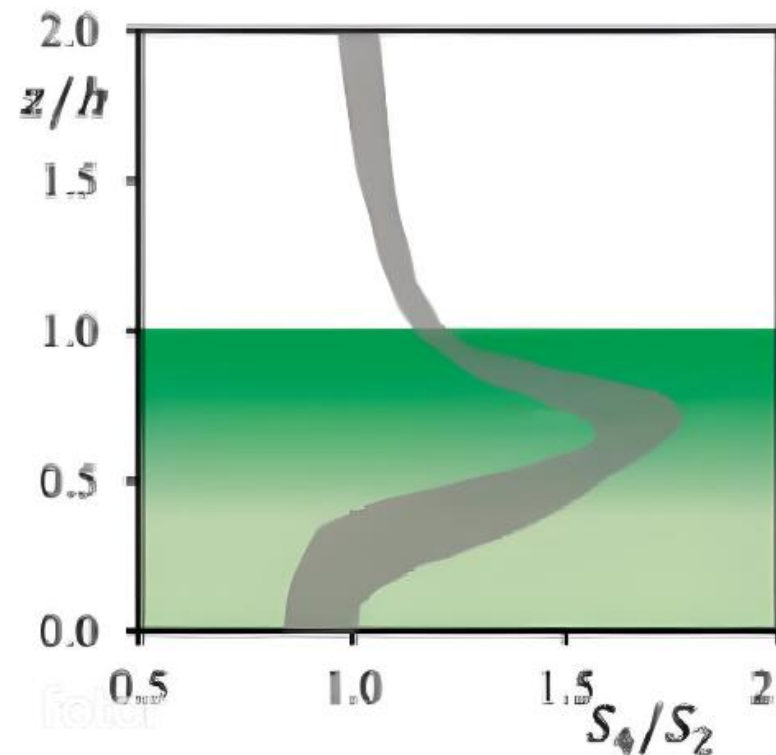


Figure 4 : Profile of the ratio between sweep (S4) and ejection (S2) in a plant canopy [7]. The grey band indicates the variability of this ratio over 12 canopies.