Wind regimes above and below a dense oil palm canopy: Detection of decoupling and its implications on CO_2 flux estimates

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Christian Stiegler[1], Tania June[2], Christian Markwitz[1], Nicoló Camarretta[1], Ashehad Ashween Ali[1], Alexander Knohl[1,3]

[1]Bioclimatology, University of Göttingen, Göttingen, Germany
[2]Department of Geophysics and Meteorology, Bogor Agricultural University, Bogor, Indonesia
[3]Centre of Biodiversity and Sustainable Land Use (CBL), University of Göttingen, Göttingen, Germany

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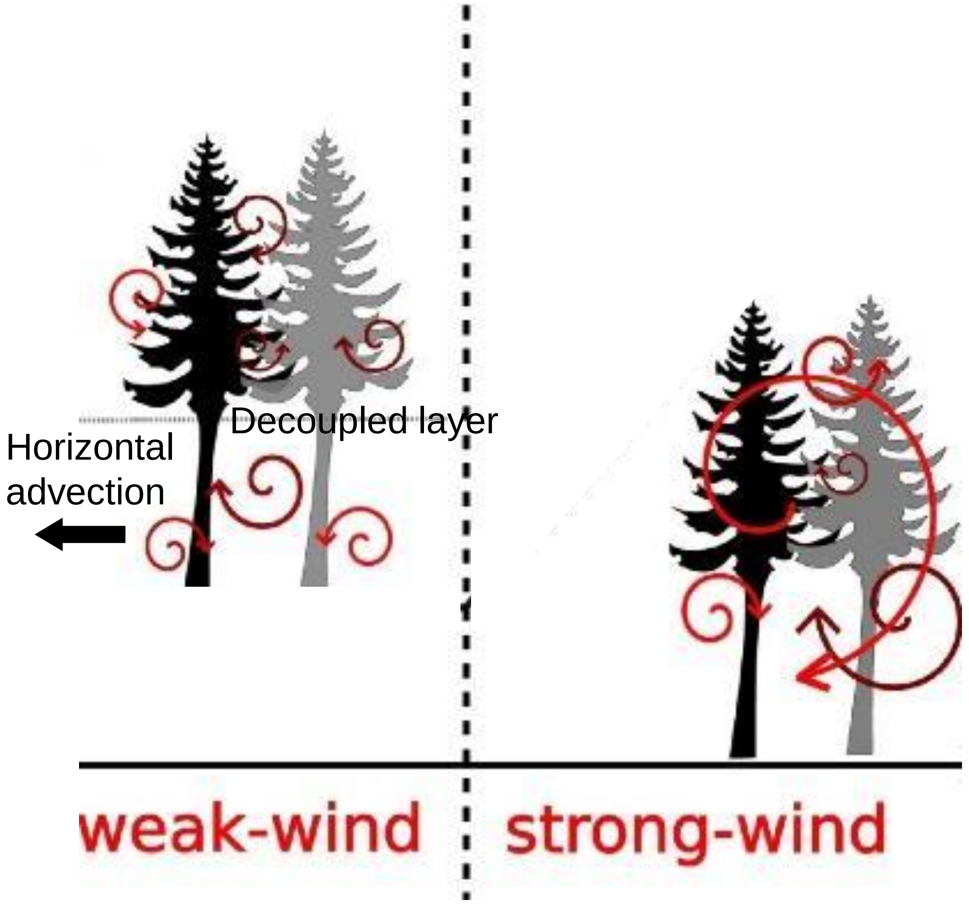
Decoupling

- Especially during night, calm weather conditions in tall vegetation canopies, such as forest or oil palm, may result in the formation of an isolated layer near the surface, which is decoupled from the above-canopy air layer.
- When decoupling occurs, there is a high potential that above-canopy measured carbon dioxide (CO_2) based on eddy covariance (*EC*) measurements might not represent the true ecosystem CO_2 flux as below-canopy respiration might be undetected by the *EC* system.

Schematic representation of air mixing within tall vegetation canopies



Adapted from Freundorfer et al., 2019, *Agricultural and Forest Meteorology* 279.

Study aim

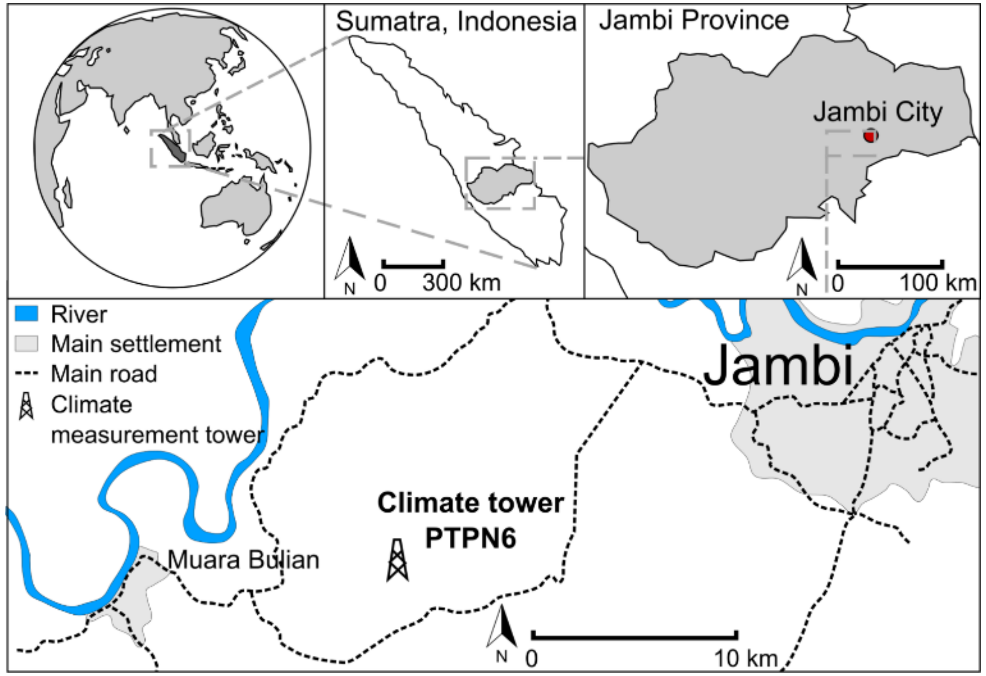
- **Investigate wind dynamics** of a mature oil palm (*Elaeis guineensis* Jacq.) plantation in tropical lowland Jambi Province (Sumatra, Indonesia).
- **Assess** the **strength of turbulent mixing** as an estimator for the degree of above- and below-canopy coupling by using eddy covariance (*EC*) measurements.
- **Explore** the potential **implications of decoupling** and horizontal below-canopy flow on the above-canopy derived net ecosystem exchange (*NEE*).
- Explore the **characteristics of vertical CO_2 concentration** in the oil palm plantation.

EC-tower within the studied oil palm plantation.

Study site

Our study has been conducted in a mature commercial oil palm plantation in tropical lowland Jambi Province (Sumatra, Indonesia). Palms were planted in 2002, with 156 palms per hectare, and reach an average height of 12 meters.

Study location



Stiegler et al., 2019, *Biogeosciences* 16.

Drescher et al., 2016, *Phil. Trans. R. Soc. B* 371.

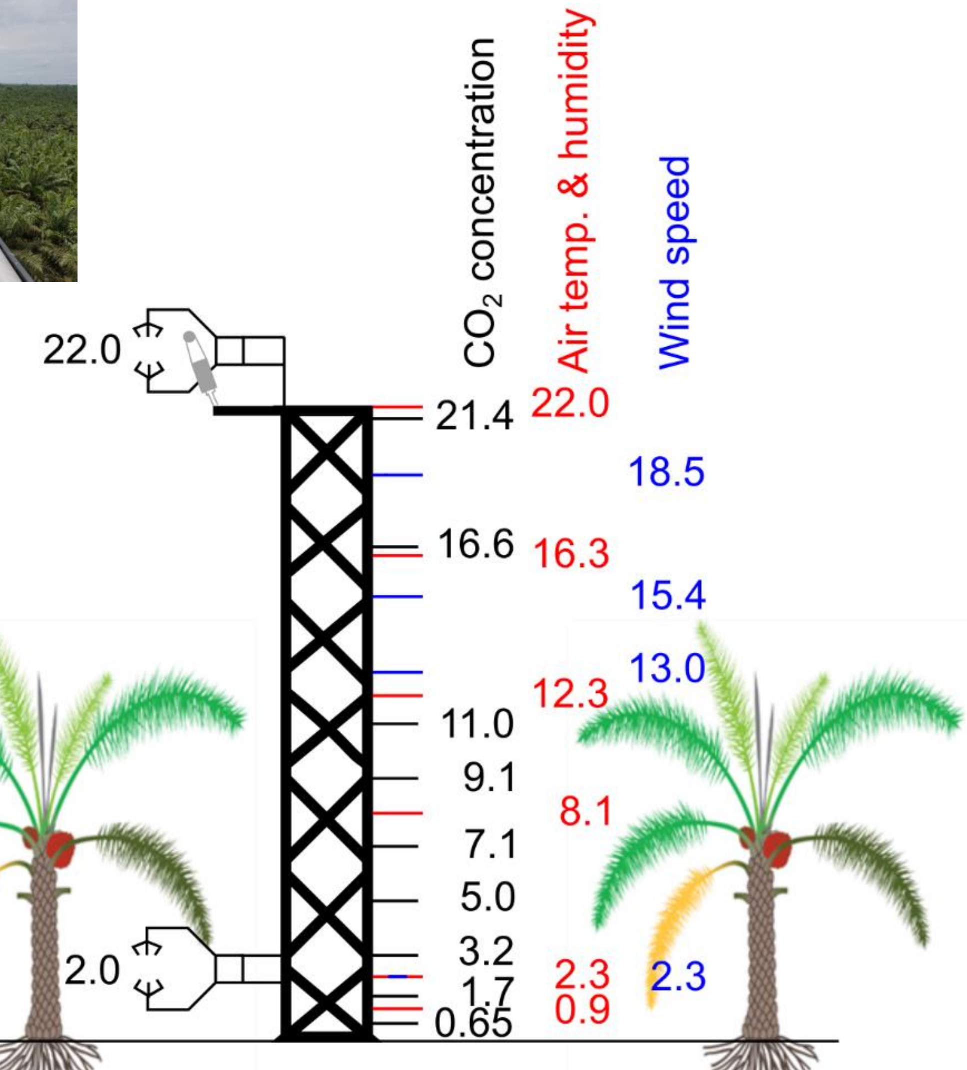
Clough et al., 2016, *Nature Communications* 7.

Video of oil palm plantation and measurement tower

Data collection & processing; Identification of decoupling & flux filtering

- Flux data were obtained from August 2017 to July 2020 by two eddy covariance (*EC*) systems
- Three approaches based on *EC* derived wind measurements to identify decoupling:
    1. Threshold based on friction velocity (u^*)
    2. Threshold based on the correlation between the standard deviation of below vs. above-canopy vertical wind speed (σ_w)
    3. Threshold based on dynamic stability of the atmosphere (bulk Richardson number, Ri_b)
- Thresholds were derived with R-package ”*strucchange*”. Filtered *EC-data* was gapfilled using REddyProc (MPI Jena, Germany) to derive cumulative CO_2 fluxes
- Meteorological parameters and CO_2 concentration were measured at various heights along the tower

Climate tower & measurement heights



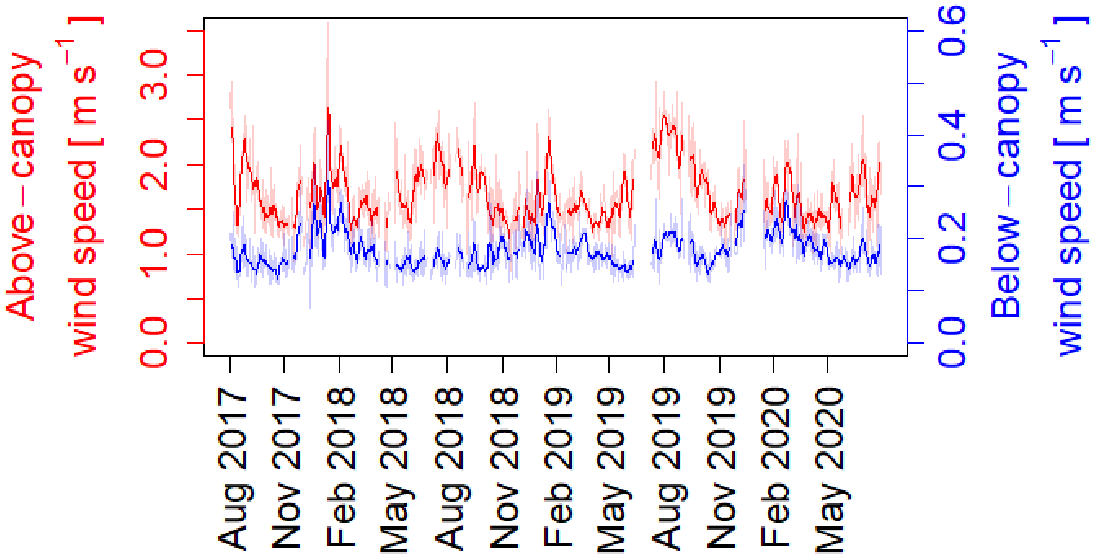
Stiegler et al., 2019, *Biogeosciences* 16.
Meijide et al., 2017, *Agric. For. Meteorol.* 239.

Wind speed

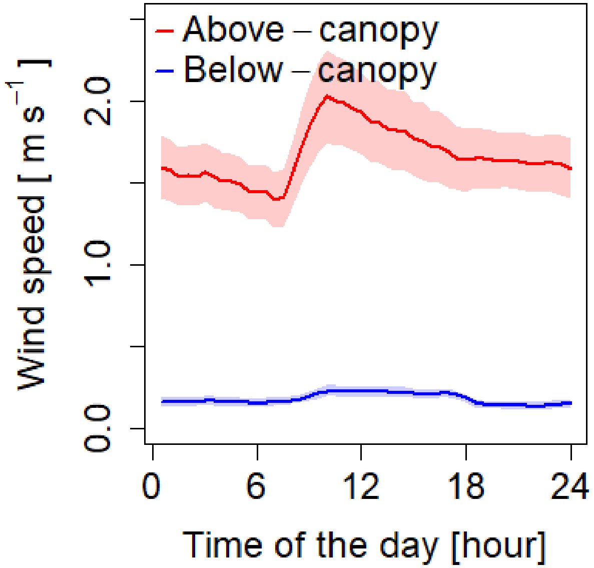
Probability density function of above- and below-canopy wind speed

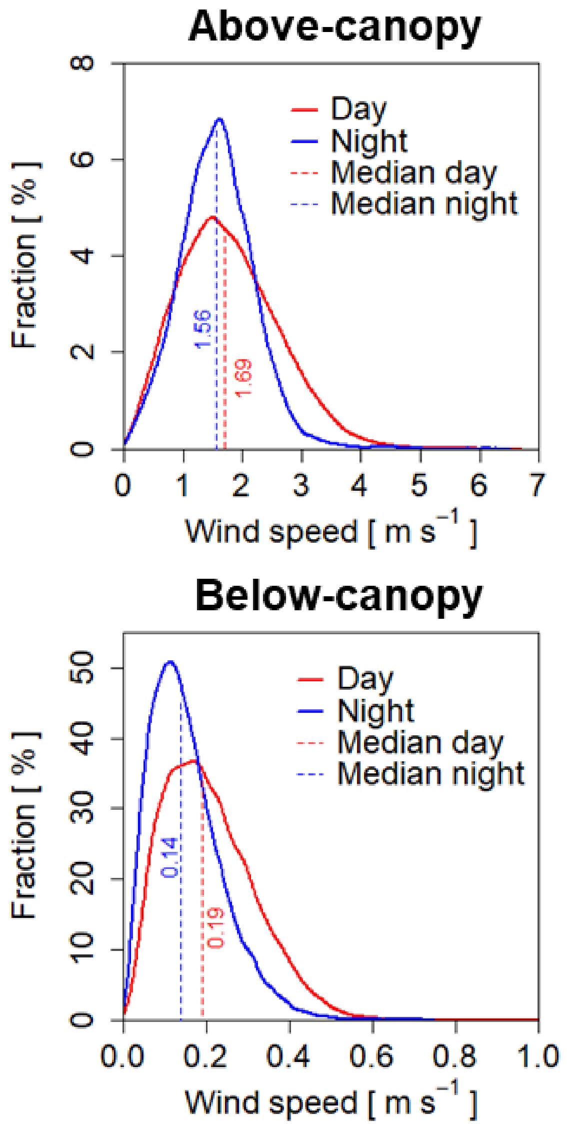
- Wind speed is generally low in the oil palm plantation. Winds peak around noon and reach their minima shortly before sunrise
- Below the oil palm canopy, calm conditions strikingly dominate, especially during night

Daily average wind speed



Diel horizontal wind speed

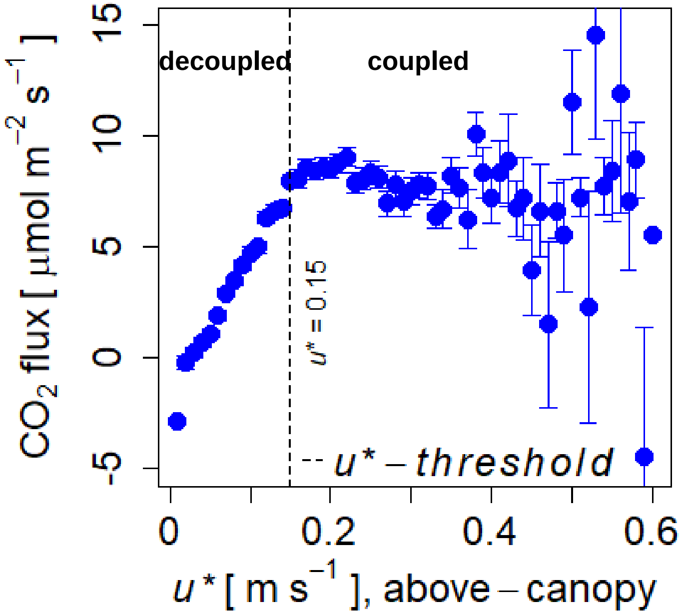




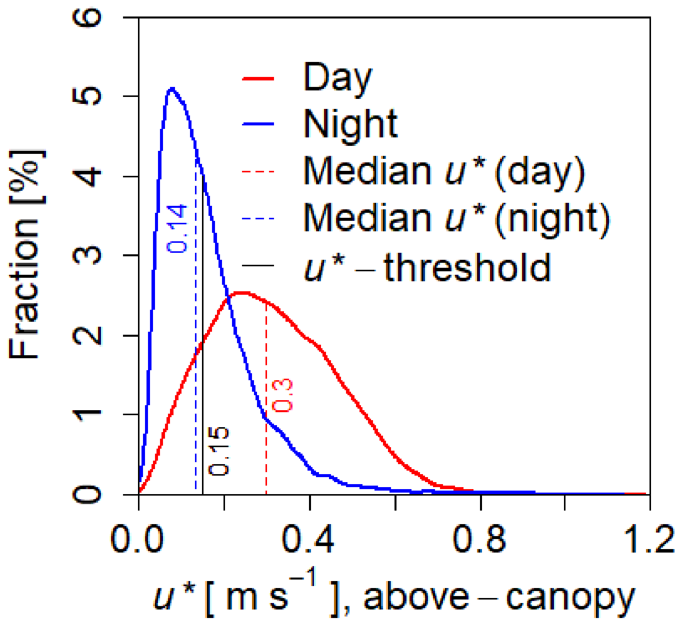
Friction velocity (*u**)

- At higher nocturnal above-canopy turbulence strength (*u** > 0.15 m s^{-1}) nocturnal above-canopy CO_2 flux levels off, indicating transition from decoupling to coupling at this threshold

Nocturnal above-canopy *u and CO_2 flux**



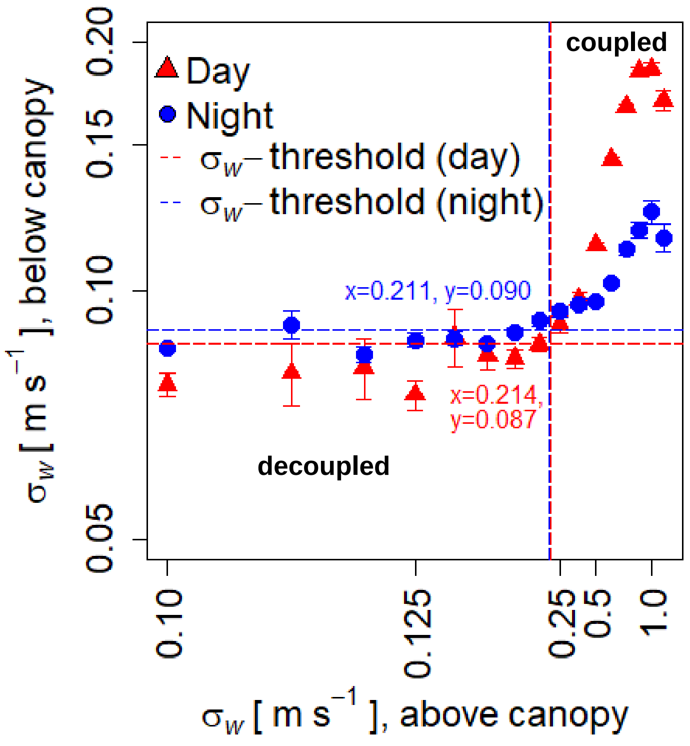
Probability density function of above-canopy *u*



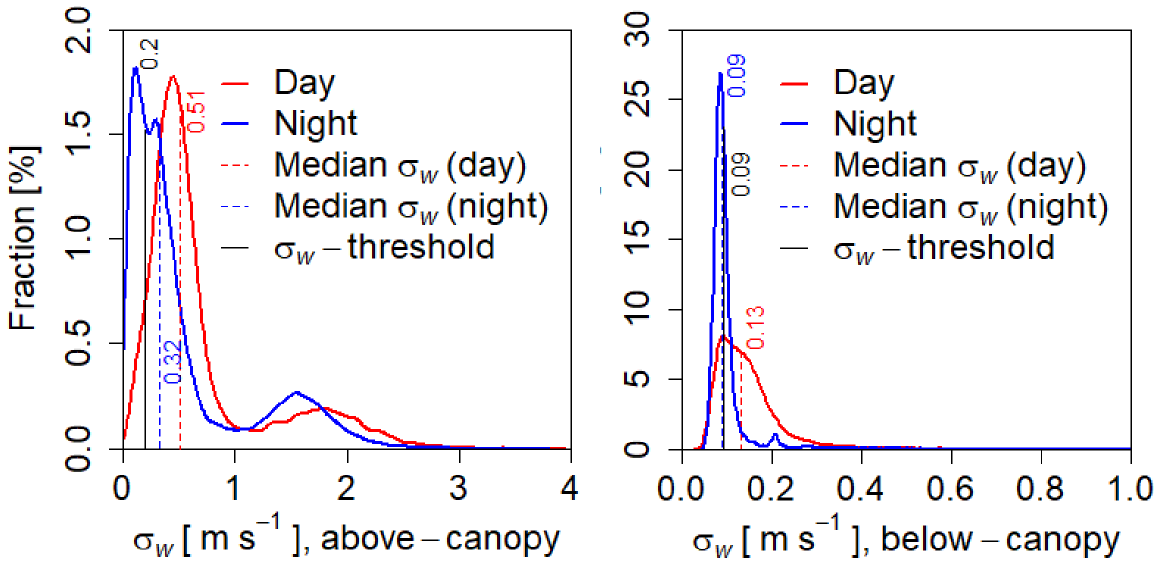
Correlation between the standard deviation of below- vs. above-canopy vertical wind speed (σ_w)

- The correlation between above- and below-canopy σ_w breaks down at thresholds of ~0.21 m s^{-1} and ~0.09 m s^{-1}, respectively, indicating possible transition between decoupling to coupling between the two measurement heights at these thresholds

Standard deviation of vertical wind speed



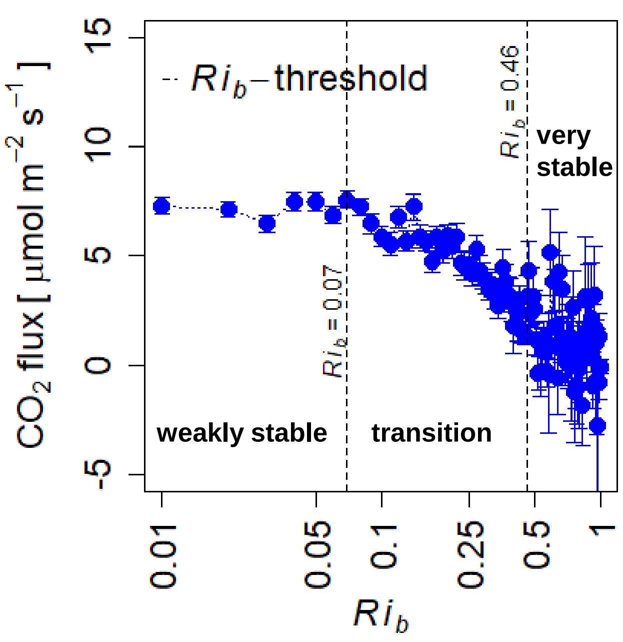
Probability density function of above- and below-canopy σ_w



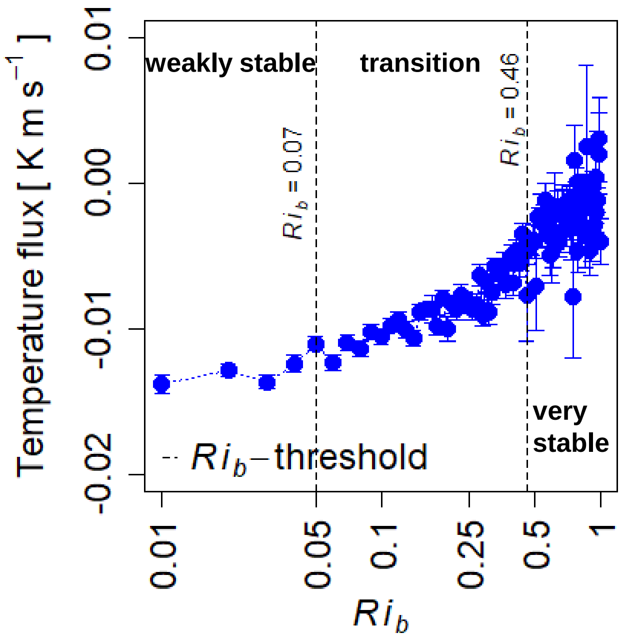
Dynamic stability of the atmosphere (bulk Richardson number, Ri_b)

- Based on the bulk Richardson number (Ri_b) and its relationship between nocturnal CO_2 net ecosystem exchange (*NEE*) and temperature flux (kinematic heat flux) we found three distinct stable boundary-layer regimes in our data set
- Fluxes decrease rapidly with increasing Ri_b and non-turbulent flow becomes increasingly important, with decoupling occurring at very stable conditions

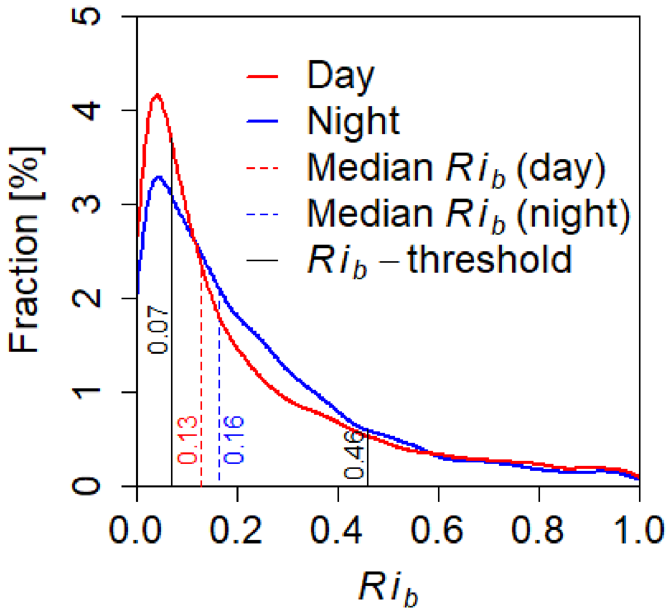
CO_2 flux and Ri_b



Temperature flux and Ri_b



Probability density function of Ri_b



Overview CO_2 flux filtering approaches (non-gapfilled)

- On average, ~45% of CO_2 fluxes were removed due to filtering, most of them during night
- The σ_w filtering approach yielded highest daytime *NEE* (CO_2 uptake) while the *u**-filtering approach yielded highest nocturnal respiration

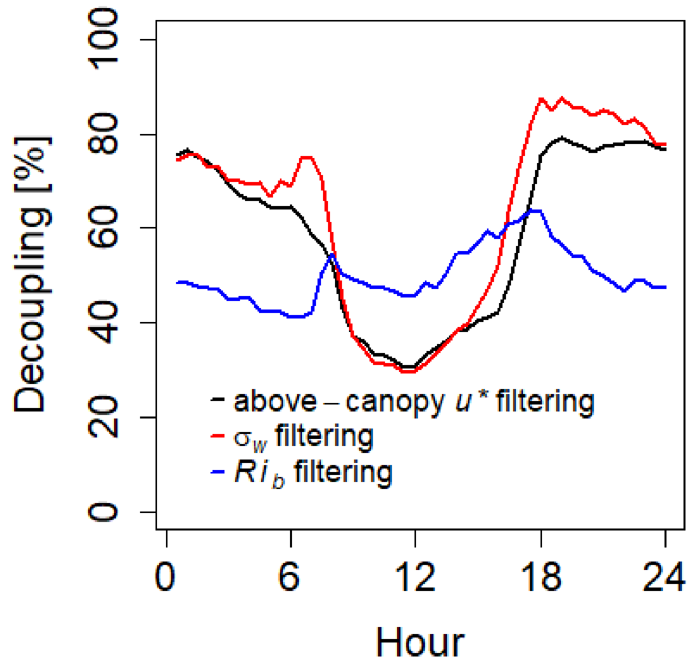
Filtering approach	Decoupling threshold	Percentage of CO_2 fluxes removed compared to unfiltered data (prior to gap filling)	CO_2 flux ± standard deviation [µmol m^{-2} s^{-1}]			Coupling between above- and below-canopy air layer [%]	
			Average	Day	Night	Day	Night
Original data	-	-	-3.92 ± 14.66	-13. 21 ± 13.15	6.05 ± 8.24	-	-
u* (friction velocity), above-canopy	u* < 0.15 m s^{-1}	33.5	-7.40 ± 15.73	-14.74 ± 12.61	8.12 ± 8.93	86.0	43.0
σ_w (standard deviation of above- and below-canopy vertical wind speed)	*Above-canopy:* σ_w < 0.214 m s^{-1} (day) & <0.211 m s^{-1} (night) *Below-canopy:* σ_w < 0.087 m s^{-1} (day) & 0.09 m s^{-1} (night)	41.3	-9.19 ± 15.42	-16.43 ± 11.70	7.11 ± 9.05	93 (above-canopy), 80 (below-canopy	68 (above-canopy), 44 (below-canopy)
Ri_b (bulk Richardson number)	*Weakly stable:* Ri_b < 0.07 *Stable regime:* Ri_b > 0.46	59.8	-2.66 ± 14.63	-12.60 ± 13.50	6.52 ± 8.23	86.0	85.0

Overview CO_2 flux filtering approaches.

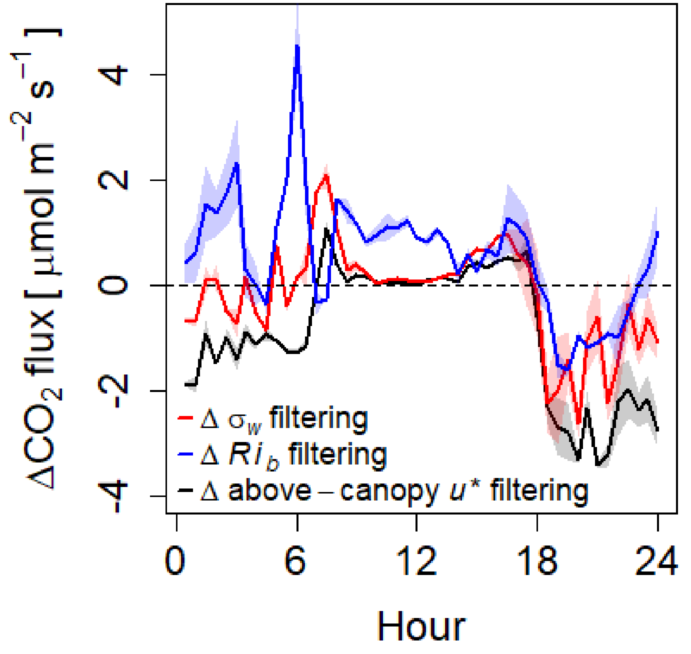
Diel characteristics of decoupling and CO_2 fluxes, accumulated carbon

- The short periods after sunrise and before sunset are crucial for the breakdown and development of decoupling or coupling between above- and below-canopy air layers. They are also those times of the day (together with night conditions), when differences in *NEE* between the different flux filtering approaches are most apparent

Diel percentage of decoupling



Absolute differences of CO_2 fluxes in relation to non-filtered data



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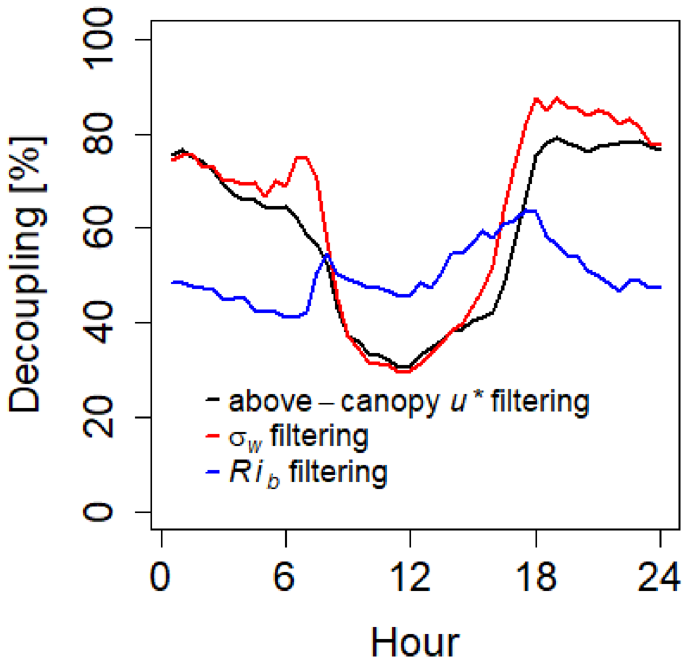
- In 2019, σ_w filtered data yielded highest accumulated carbon while Ri_b filtered data yielded lowest accumulated carbon. Differences in accumulated carbon are up to 251.5 gC m^{-2}

Diel percentage of decoupling



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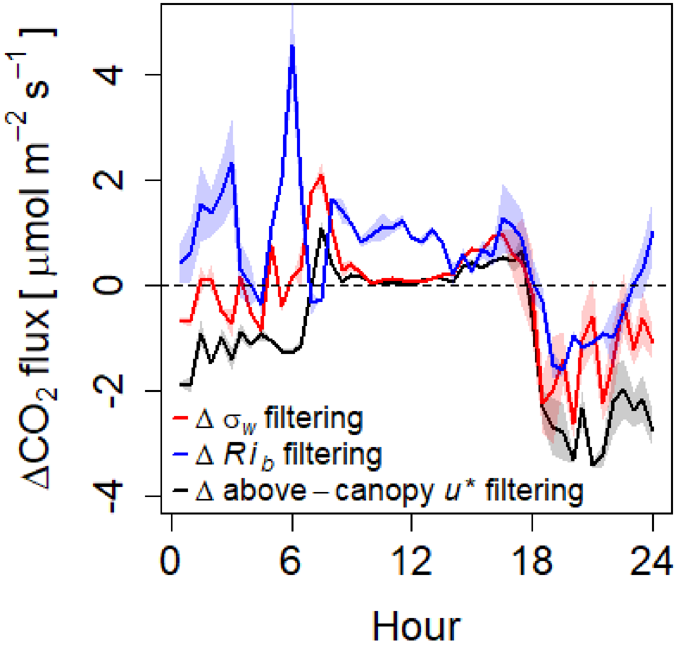
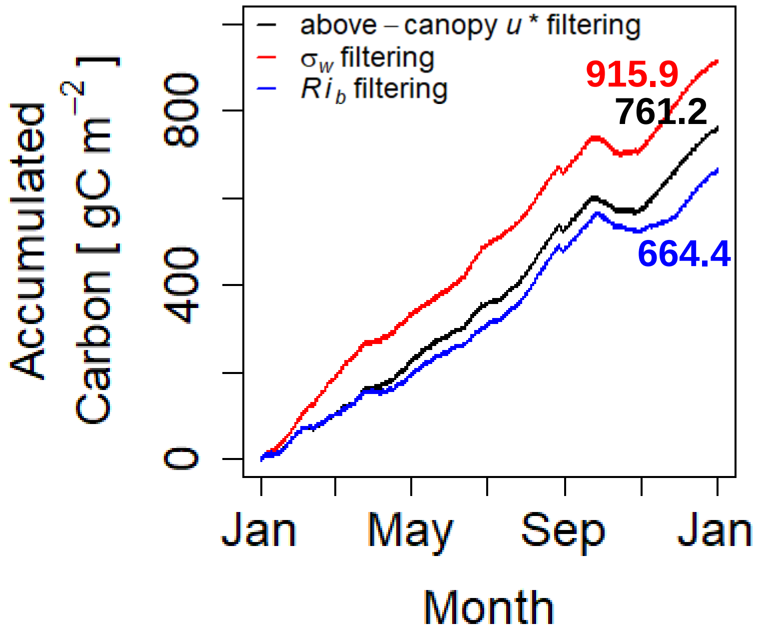


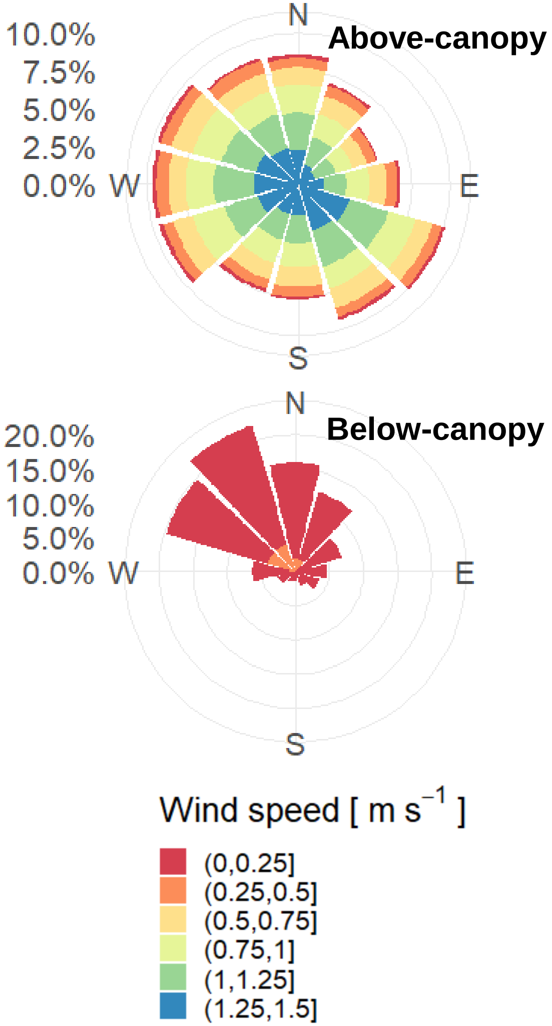
Accumulated carbon (2019)



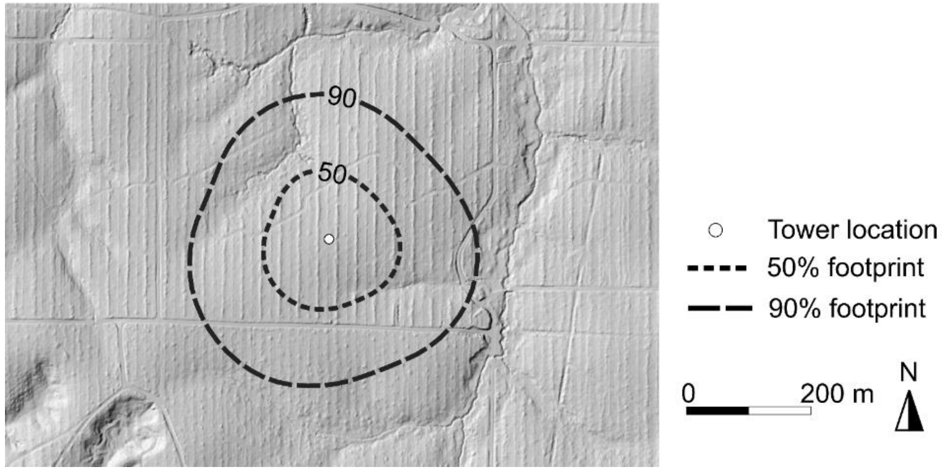
Is the below-canopy flow topically induced?

- A preferential wind sector from northwest (~315º) for below-canopy wind and buoyancy forcing is clearly visible
- Lowering terrain (from the tower's perspective in ~90º to ~150º) and a slope of 3º within the footprint area of the *EC*-tower, may already be enough to create thermally-induced drainage flow

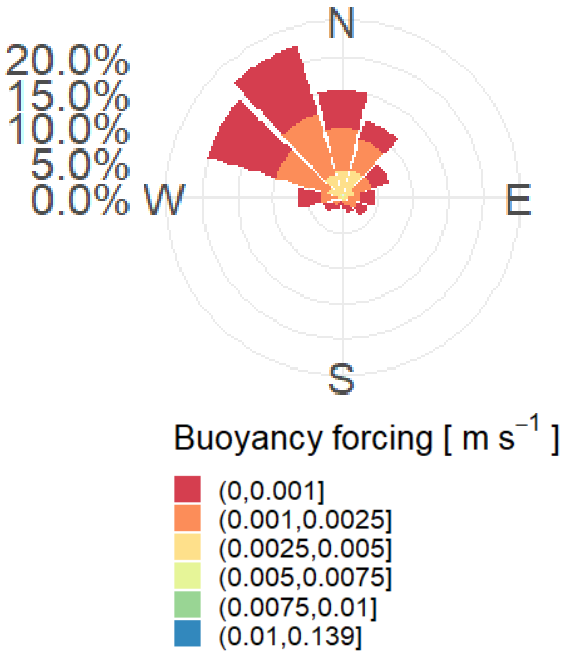
Wind roses for low above-canopy wind conditions and Ri_b >0.07



Hillshade map (from DEM) and EC footprint areas



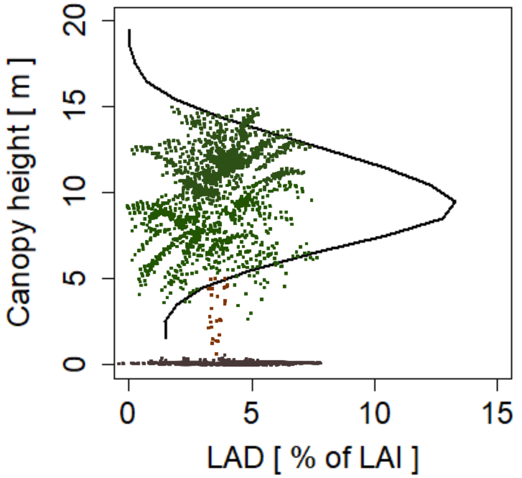
Buoyancy forcing in dependency of below-canopy wind direction



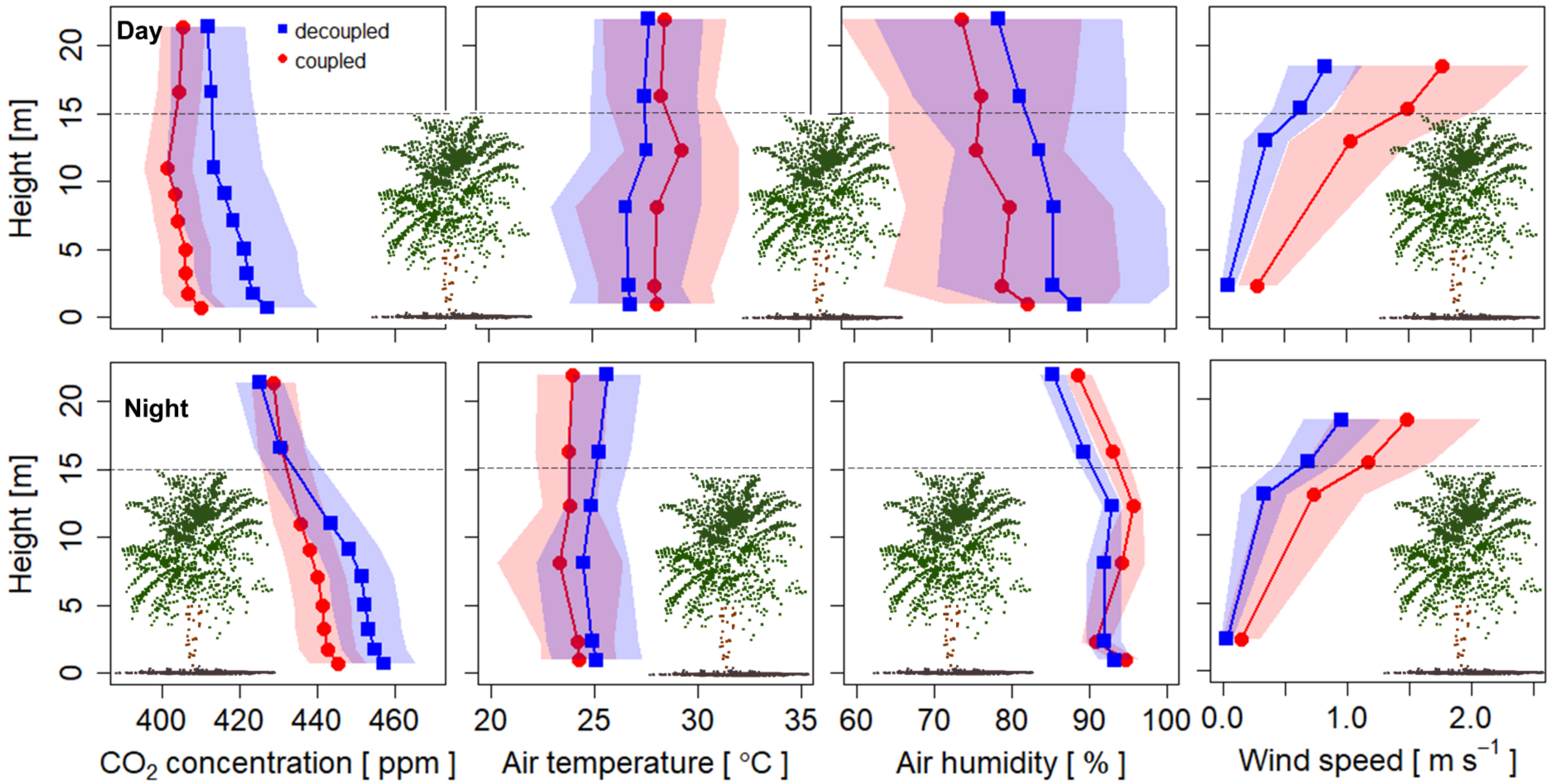
Vertical structure of the air layer

- The oil palm canopy marks a clear boundary for the behavior of CO_2 concentration and wind
- The canopy is nearly always stably stratified, expressed by the temperature increase in the upper parts of the canopy. Under low-wind conditions, such stably stratified atmosphere potentially stimulates decoupling

Leaf area density (LAD) of oil palm



Vertical profiles of CO_2 concentration and meteorological parameters



Summary & conclusion

- Wind speeds above and below the oil palm canopy are generally low
- Threshold analyses showed that during night, decoupling may occur frequently and up to 48% of measured nocturnal CO_2 fluxes fall within such decoupling periods
- Sensitivity in detection of decoupling is highly dependent on the applied method, with σ_w filter being most sensitive in the detection of decoupling
- CO_2 flux filtering approaches yield substantial differences in accumulated carbon
- A slope of 3º within the footprint area of the *EC*-tower, may already be enough to create thermally-induced drainage flow
- The canopy is nearly always stably stratified, expressed by the temperature increase in the upper parts of the canopy. Under low-wind conditions, such stably stratified atmosphere potentially may stimulate decoupling

Take-home message

- Decoupling of above- and below-canopy air layers needs to be investigated and considered, especially in such low-wind tropical ecosystems and when eddy covariance data is used as reference for fluxes of tall vegetation or for modelling approaches

THANK YOU FOR YOUR ATTENTION!

QUESTIONS?

@BioclimGoe
@efforts_crc990
@stiegler_chr

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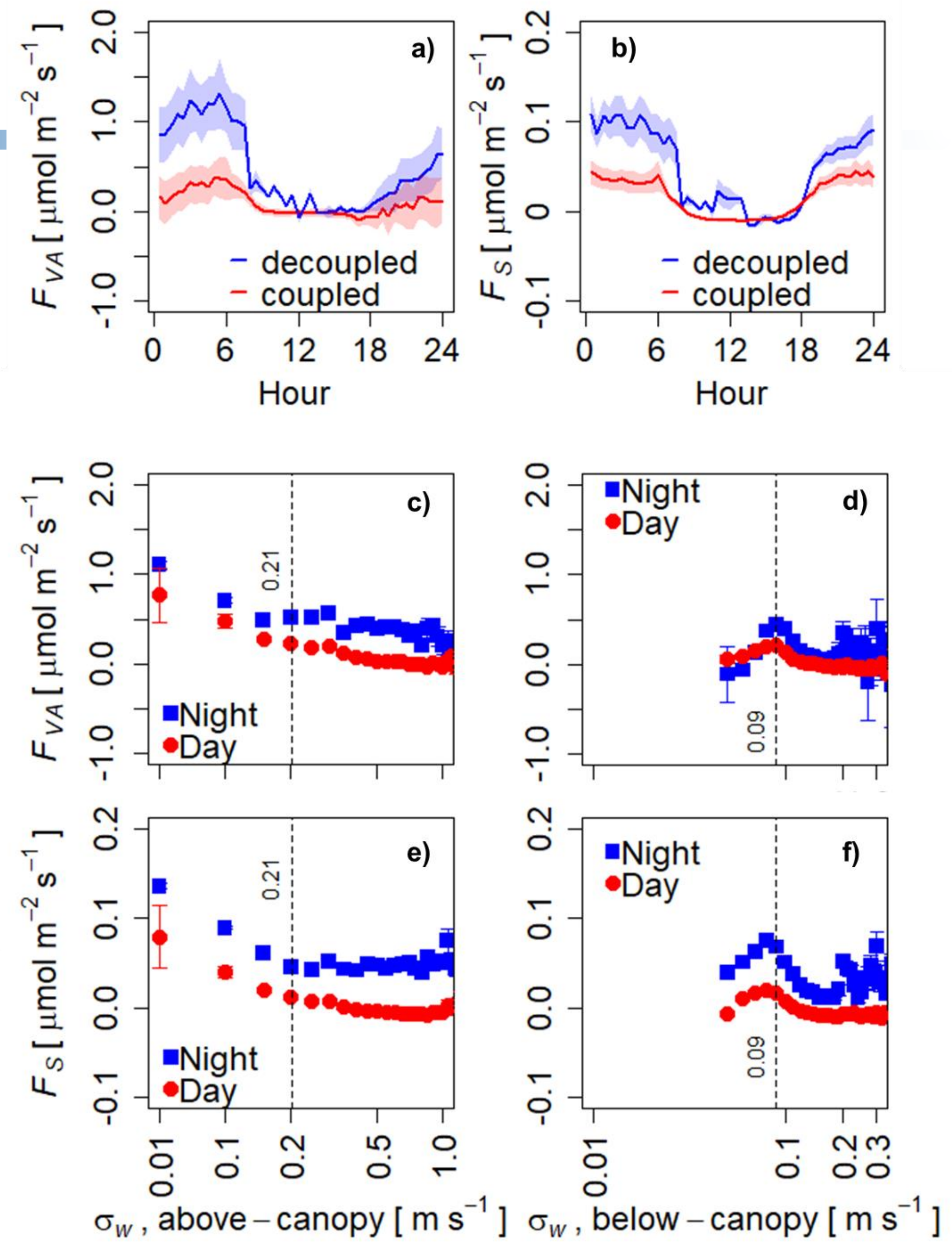
CO_2 vertical advection (F_{VA}) and storage fluxes (F_S)

- The magnitude of F_{VA} and F_S peaks shortly before dawn, when CO_2 concentration reaches its diel maximum, and both vertical and horizontal wind speed approach their diel minima
- At low σw, F_{VA} and F_S show a decreasing trend with increasing above-canopy σ_w
- Below the canopy, an initial increase of F_{VA} and F_S at σ_w < $\sigma_{w\ threshold}$ may be linked to increasing, but still decoupled, below-canopy turbulent transport



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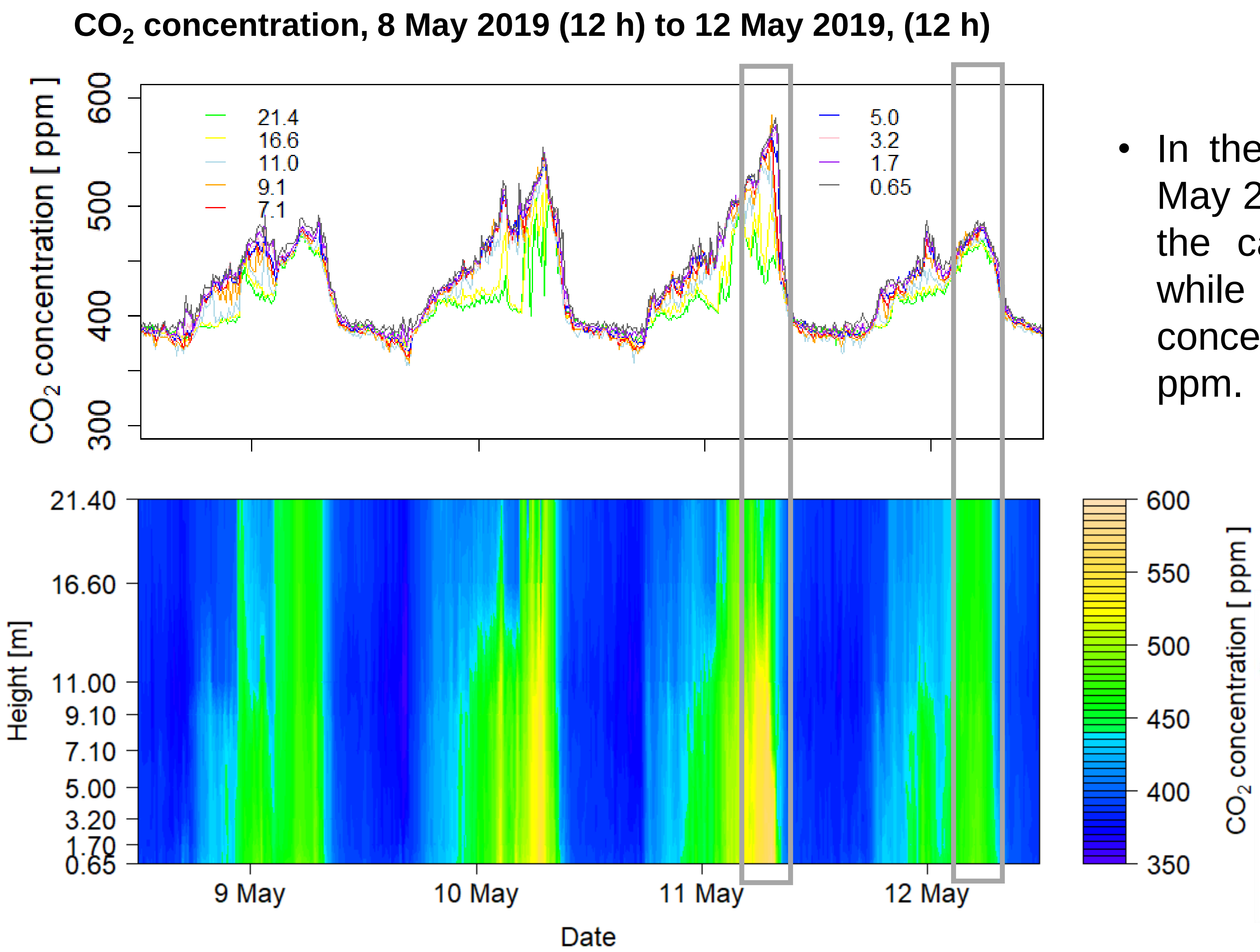
Ri_b (bulk Richardson number)	*Weakly stable:* Ri_b < 0.07 *Stable regime:* Ri_b > 0.46	59.8	-2.19 ± 13.91	-12.45 ± 12.20	8.08 ± 5.26	86.0	85.0

Overview CO_2 flux filtering approaches.

CO_2 concentration, 8 – 12 May 2019

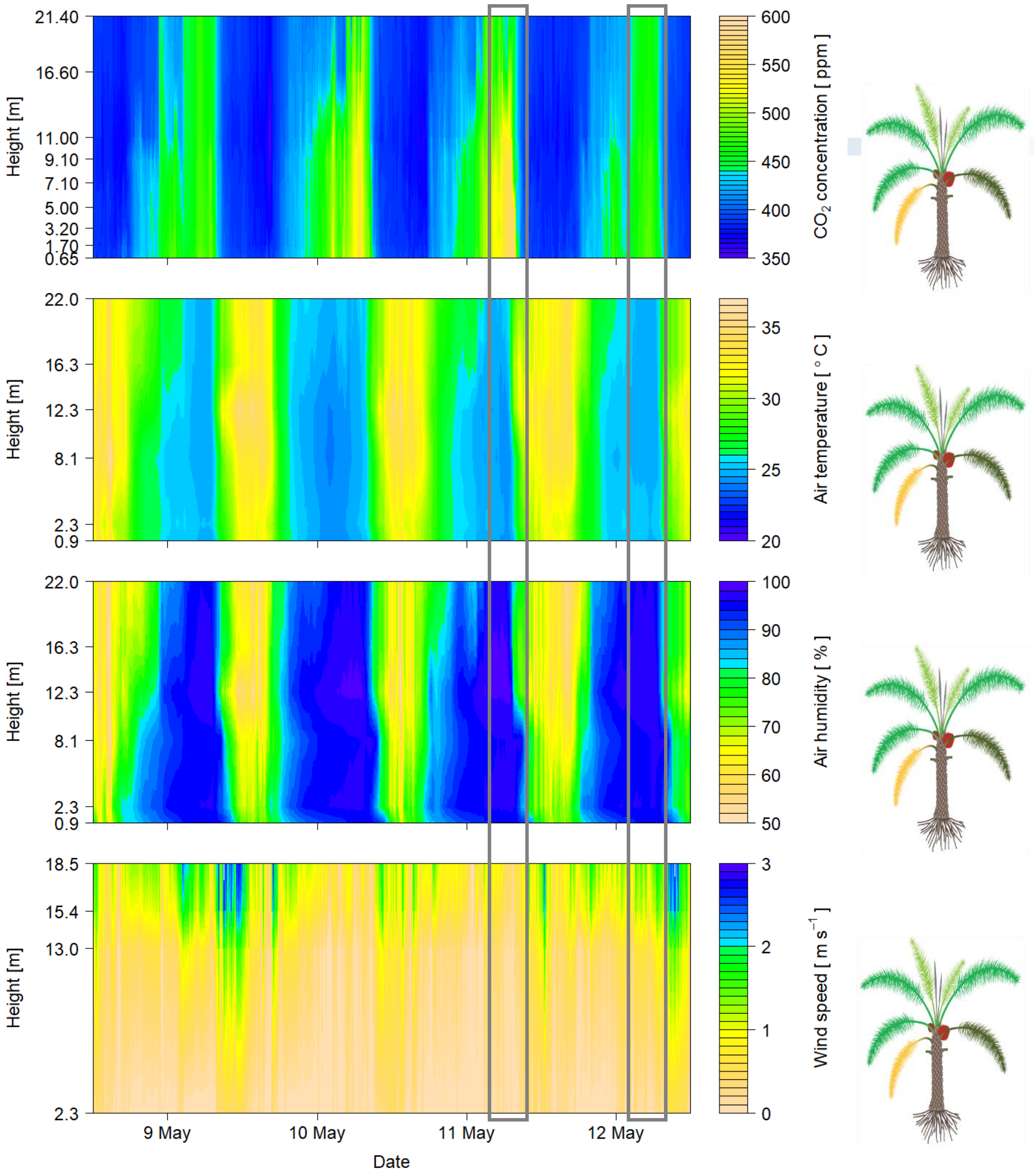


CO_2 concentration profile during the period 8 May 2019 (12 h) to 12 May 2019, (12 h)

- In the morning hours of 10 and 11 May 2019, CO_2 concentrations below the canopy reach up to 580 ppm while above-canopy CO_2 concentration remains below 500 ppm.

CO_2 concentration & micrometeorological conditions, 8 – 12 May 2019

- Nights with high CO_2 concentration:
  - Calm conditions dominate in all vertical profiles
  - Air temperature is lower and air humidity is higher compared to nights with lower CO_2 concentration



CO_2 concentration, air temperature, air relative humidity, and wind speed profile during the period 8 May 2019 (12 h) to 12 May 2019, (12 h).