Two types of CO_2 advection transport on a gentle forested slope

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Context

The Net Ecosystem Exchange of an ecosytem (NEE) can be written as:

$$NEE = \left(\overline{w'c'}\right)_{h_{eco}} + \int_0^{h_{eco}} \frac{\partial \overline{c}}{\partial t} dz + \int_0^{h_{eco}} \left(\overline{u}\frac{\partial \overline{c}}{\partial x}\right) dz + \int_0^{h_{eco}} \left(\overline{w}\frac{\partial \overline{c}}{\partial z}\right) dz$$

$$F \qquad S \qquad HA \qquad VA$$

where F **: is the turbulent flux of CO2 above the canopy, measured by the eddy-covariance technique**

S **: Storage below the measurement height**

HA **and** ***VA*** **: horizontal and vertical advection**

Under stable atmospheric conditions over forests, it is commonly found that F + S underestimate the NEE due to important and non-measured HA and VA.

Objectives

In this study we used CO_2 concentration ([CO_2]), wind and temperature measurements performed with a 2D array of sampling points spread throughout the height of the forest in order to:

- **describe how gravitational flows can transport CO_2**
- **determine to which extent advection terms can offset the night flux underestimation in stable atmospheric condition.**

Site description

- The research is conducted at the **Vielsalm experimental site (Belgium)**. The uniform slope is of 3%. The two dominant species on the site (27 m tall beech and 35 m tall Douglas fir) are forming two sub-plots. The main tower is placed at their interface. The understorey is very sparse or absent.
- In stable atmospheric conditions, **gravitational flows**, that are decoupled from air motion above the canopy, develop in the trunk space (Aubinet et al., 2003 & Heinesch et al., 2007).

Material

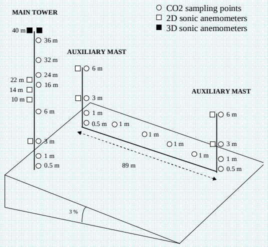


Fig. 1: Experimental set-up

- 20 CO2 sampling points, LICOR 6262, multiplexer with rotating cycle of 200s;
- 2 3D sonic anemometers (Gill R2 and R3)
- 8 2D sonic anemometers (home-made)
- 10 thermocouples distributed evenly on the whole canopy height.

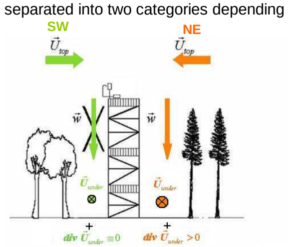
The main data set was obtained during a summer campaign in 2002 (930 half-hours with gravitational flows). The horizontal transect was situated in the Beech sub-plot, along the slope direction.

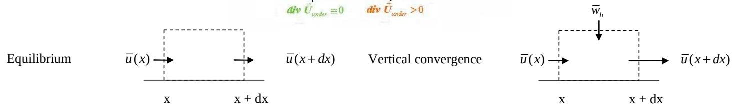
Results

Two gravitational flow patterns and their impact on the CO_2 concentration field

- The gravitational flow events can be separated into two categories depending on the ambient wind direction.

Fig. 2: Schematic representation of air flow patterns (slope is perpendicular to the sheet)





For **SW ambient winds** (green curves),

- No vertical velocity component is detected above the canopy (Fig. 3),
- Near zero divergence of horizontal wind in the trunk space (Fig. 4).
- Flat vertical profile of temperature in the gravitational sublayer (0-20 m; Fig. 5),

→ minor role of buoyant forces in the momentum budget

→ constant flow along the slope (equilibrium situation).

- No dilution → the enrichment due to the sources leads to a slightly positive horizontal [CO_2] gradient (Fig. 6).

For **NE ambient winds** (orange curves),

- A downward velocity component is detected above the canopy (Fig. 3),
- A positive divergence of horizontal wind in the trunk space (Fig. 4).
- 0.5℃ inversion of the vertical profile in the gravitational sublayer (0-20 m ; Fig. 5),

→ the buoyant forces play a dominant role in the momentum budget

→ flow acceleration along the slope (vertical convergence situation).

- Mixing of air with air poorer in CO_2 coming from the top the dilution effect is more important than the source impact → negative horizontal gradient of [CO_2] (Fig. 6).

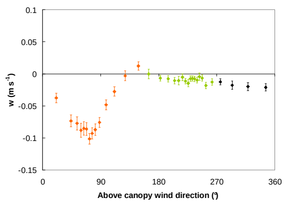


Fig. 3:Mean and standard error of the vertical velocity as a function of the incoming ambient wind direction in stable conditions

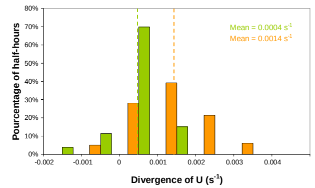


Fig. 4: Divergence of U in the trunk space

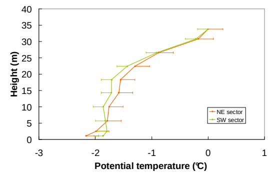


Fig. 5: Vertical profile of potential air temperature in nocturnal stable conditions and under clear sky.

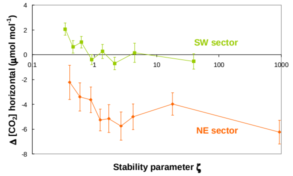


Fig. 6: Evolution with stability of the along slope [CO2] difference at 1 m height in conditions of gravitational flows.

CO_2 Budget : Comparison of turbulent flux, storage and advection

- The comparison of all the fluxes is made for stable atmospheric conditions and for the **NE ambient winds**, where the non-turbulent fluxes are more pronounced.

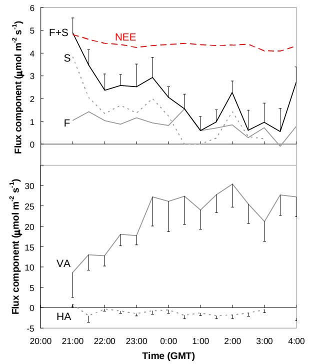


Fig. 7: Mean flux component evolution during stable nights with NE ambient winds

- NEE is estimated around 5 µmol m^{-2} s^{-1} (using F in turbulent conditions).
- F stays below 1.5 µmol m^{-2} s^{-1}, far below the expected NEE. The addition of S does not offset the underestimation of the NEE, except in the beginning of the night (Fig. 7a).
- The inclusion of the advection terms in the CO_2 budget would transform the night flux underestimation into a strong overestimation due to very important and unrealistic values of VA (Fig. 7b).
- However, VA presents a temporal evolution that is complementary with those of NEE underestimation.

→ This suggests that VA evolution is well described but that it is one order of magnitude too high.

→ This questions the hypothesis of *w* linear decrease with height commonly used to estimate VA (Lee, 1998, Finnigan, 1999). A more realistic exponential profile constrained by an estimation of *w* in the trunk space using the continuity equation (Fig. 8) lead to a more realistic night flux balance (Fig. 9).

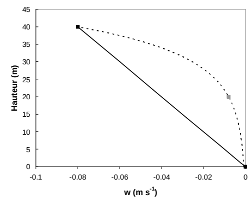


Fig. 8: Vertical profile of w

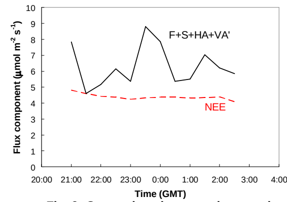


Fig. 9: Comparison between the complete CO_2 budget and NEE during stable nights with NE ambient winds (with exponential decrease of w with height)

Conclusions

- **A coherent picture emerges, linking the flow field and the [CO_2] field.**

→ This coherent picture reinforces the credibility of the particularly delicate measurements of w, horizontal gradients of CO_2 and divergence of horizontal wind speed,

→ it shows the mechanisms that bring CO_2 in or evacuate CO_2 out of the volume of measurement in conditions of gravitational flows.

- **The accuracy of VA estimations is severely hampered by the lack of information about the vertical profile of w. This problem introduces a huge uncertainty in the CO_2 budget of stable nights.**

- References : Aubinet et al., BLM 108, 2003; Finnigan, AFM 97, 1999; Heinesch et al., BLM 122, 2007; Lee, AFM 91, 1998.