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Ventilation of subterranean CO_2 and Eddy covariance incongruities over carbonaceous ecosystems

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Abstract

Measurements of CO_2 fluxes with Eddy Covariance (EC) systems are ongoing over different ecosystems around the world, through different measuring networks, in order to assess the carbon balance of these ecosystems. In carbonaceous ecosystems, characterized by the presence of subterranean pores and cavities, ventilation of the CO_2 accumulated in these cavities and pores can act as an extra source of CO_2 exchange between the ecosystem and the atmosphere. In this work we analyse the effect of the subterranean heterogeneity of a carbonaceous ecosystem on measurements of CO_2 fluxes by comparing measurements from two EC systems with distinct footprints. Results showed that both EC systems agreed for measurements of evapotranspiration and of CO_2 in periods when respiratory and photosynthetic processes were dominant (biological periods), with a regression slope of 0.99 and 0.97, respectively. However, in periods when the main source of CO_2 comes from the ventilation of subterranean pores and caves (abiotic periods) agreement is not good, with a regression slope of 0.6. Ground-penetrating radar measurements of the sub-surface confirmed the existence of high sub-surface heterogeneity that, combined with different footprints, lead to differences in the measurements of the two EC systems. These results show that measurements of CO_2 fluxes with Eddy covariance systems over carbonaceous ecosystems must be taken carefully, as they may not be representative of the ecosystem under consideration.

1 Introduction

The importance of characterising the global carbon cycle is clear, since CO_2 is the principal greenhouse gas after water vapour (Schimel, 1995). In this context, accurate measurements of net carbon exchange between terrestrial ecosystems and the atmosphere are very important as terrestrial ecosystems are the main driver of global interannual variability in atmospheric CO_2 (Friend et al., 2007). The Eddy Covariance technique produces a direct measure of CO_2 exchange between the atmosphere and terrestrial ecosystems, and is therefore an indispensable tool to assess carbon ecosystem exchange (Matross et al., 2006; Baldocchi, 2003).

The net CO_2 flux between the terrestrial surface and the atmosphere has generally been interpreted as a biological flux due to photosynthetic and respiratory processes. However, over carbonaceous substrates, recent works highlight the role of geochemical rock weathering (dissolution and precipitation) processes in the total surface-atmosphere CO_2 exchange (e.g.: Emmerich, 2003; Mielnick et al., 2005; Kowalski et al., 2008; Serrano-Ortiz et al., 2009). After rain events, infiltrating water dissolves the soil CO_2, acting as a CO_2 sink by reducing the CO_2 emissions, and percolates downward. The CO_2-enriched water seeping through fissures of bedrock creates new pores, fissures and even macropores (caves) that characterise karstic systems. Therefore, pores, fissures and cavities near the surface can accumulate high concentrations of soil-derived CO_2 (Bourges et al., 2001; Wood, 1985) that can be isolated from soil-atmosphere exchange flows. Later, through the venting of these subterranean spaces, the gaseous CO_2 stored can be exchanged with the atmosphere (Weisbrod et al., 2009; Benavente et al., 2009). Therefore, the ventilation of caves and fissures in carbonaceous ecosystems can yield an abiotic (in the sense that it is not directly produced by a biological process, like photosynthesis or respiration) source of CO_2 affecting the net ecosystem exchange (NEE), that under certain conditions can be as important as the biological processes traditionally considered (Kowalski et al., 2008; Serrano-Ortiz et al., 2009).

Measurements of net ecosystem exchange with the Eddy Covariance (EC) technique require sufficient fetch, meaning that the underlying vegetation extends homogeneously upwind for an extended distance (Baldocchi, 2003). This is a requirement met by nearly all EC used in different measuring networks around the world, such as FLUXNET (Baldocchi et al., 2001). However, when the flux has not only superficial, but also a subterranean source, as happens with the CO_2 coming from the venting of pores and caves, then the subterranean heterogeneity can affect the fetch requirements of the EC measurements. According to this, in carbonaceous ecosystems it is important to analyse the reliability of EC measurements, as the presence of a subterranean source of CO_2, with a high spatial and temporal heterogeneity, can lead to net ecosystem exchange measurements that are not representative of the whole ecosystem. Moreover, the role of carbonaceous ecosystems in the global carbon balance is highlighted by the fact that carbonaceous substrates outcrop on ca. 12–18% of the water-free Earth (Ford and Williams, 1989).

In order to analyse the reliability of EC measurements in carbonaceous substrates, in this work we compared the measured fluxes of a carbonaceous ecosystem from two EC systems with distinct footprints. We differentiated between periods where photosynthesis and respiration were the main processes affecting the NEE (biological periods), versus those where the ventilation of subterranean pores and caves (abiotic periods) was the main process occurring (Serrano-Ortiz et al., 2009). We also compared the evapotranspiration flux from the two EC systems, as transpiration and evaporation are processes that are not strongly affected by subterranean heterogeneity. We expect that when the ecosystem fluxes are only dependent on the surface heterogeneity (as is the case of evapotranspiration and CO_2 fluxes caused by photosynthesis and respiration) both EC systems measure similarly. However, when abiotic CO_2 fluxes predominate, subsurface heterogeneity will yield differences between the CO_2 fluxes measured by the EC systems. Measurements of Ground penetrating radar (GPR) were also made to confirm the subterranean spatial heterogeneity of the carbonaceous ecosystem.

2 Material and method

2.1 Site description

The carbonaceous ecosystem studied in this work was located in the instrumented area of "El Llano de los Juanes", a sub-humid Mediterranean shrubland plateau located in the Sierra de Gador (Almeria, Southeast Spain; 36°55′41.7′′ N; 2°45′1.7′′ W), at 1600 m altitude and 25 km from the coast. The Sierra de Gádor consists of Triassic carbonate rocks (Vallejos et al., 1997), while in "El Llano de los Juanes" these carbonate rocks are mainly dark limestone, with 98±2% calcite (X-ray diffraction analysis). In this ecosystem, bare soil, gravel and rock represent 49.1% of the ground cover. Vegetation is sparse, with predominance (as % of ground cover) of three perennial species, *Festuca scariosa* (lag.) *Hackel* (18.8%), *Hormathophilla spinosa* (L.) *Kupfer* (6.8%) and *Genista pumila* (Vierh) *ssp. pumila* (5.5%). The extent of fetch is several hundreds of meters from the EC tower in every direction. More detailed site information can be found in Serrano-Ortiz et al. (2007).

2.2 Eddy covariance and micrometeorological measurements

Measurements of CO_2 (F_c) and energy fluxes (both latent heat, or evapotranspiration, *LE*, and sensible heat, *H*) were carried out using two Eddy Covariance Systems (EC_1 and EC_2) installed on two towers with a 10 m separation (Fig. 1). Each system consisted of a three-axis sonic anemometer (CSAT-3, Campbell Scientific Inc., Logan, UT, USA; hereafter CSI) for measuring windspeed (3D) and sonic temperature, and an open-path infrared gas analyser (LI-COR 7500, Lincoln, NE, USA) for measuring CO_2 and water vapour densities. Measurements were recorded at 10 Hz by a data logger (CR23X, CSI) that calculated and stored means, variances and co-variances every 15 min. Eddy fluxes calculated from density covariances (Webb et al., 1980) and two coordinate rotations (McMillen, 1988) were carried out in post-processing, as well as the conversion to half-hour means following Reynolds' rules (Moncrieff et al., 1997). Measurements of CO_2 fluxes and *LE* with friction velocity lower than 0.2 m s^{-1} were eliminated from the analysis to avoid possible underestimation due to low turbulence (Serrano-Ortiz et al., 2009).

The two systems, EC_1 and EC_2, were installed from late July to mid-October on towers separated by 10 m, and at heights of 2.75 m and 3.4 m, respectively. This height ensured that measurements were representative of the ecosystem's surface. Previously, to ensure that there were no significant differences between EC_1 and EC_2 due to instrument errors, both systems were installed on the same tower during 12 days, at a height of 2.80 m. The comparison between the data of the two EC systems was done considering only daytime data, to avoid uncertainties due to the erratic behaviour of night-time turbulent fluxes.

In addition, soil water content (SWC) was measured with a water content reflectometer (CS615, CSI) and precipitation was quantified with a tipping bucket (0.2 mm) rain gauge (model 785 M, Davis Instruments Corp., Hayward, CS, USA). These measurements were made every 10 s, and stored every 15 min in the CR23X data-logger.

2.3 Footprint analysis

A footprint analysis was carried out to compare the source areas of the two EC systems, both when EC_1 and EC_2 were installed in the same tower and when they were in separate towers. The Flux Source Area Model (FSAM) of Schmid (1994, 1997), widely used as a tool for estimating the source area of Eddy covariance measurements (e.g.: Goeckede et al., 2004; Scott et al., 2003; Baldocchi et al., 2001) was selected. We compared the 50% source area boundaries, as they include the point of maximum source weight, and according to Schmid (1997) a flux source point located within or outside the 50% source area boundaries would have to be from 5 to 10 times stronger than the point of maximum source weight, in order to achieve a similar response on the EC sensors. Therefore, we considered that the 50% source areas were appropriate to compare the flux source areas of both EC systems.

The FSAM model calculates the source area of a given sensor as a function of the height of the sensor, the atmospheric stability conditions and the lateral wind speed fluctuations. In this context, three input parameters are used: $(z_r - d)/z_0$, $(z_r - d)/L$ and σ_v/u_*, where z_r is the height of the EC tower, d the displacement height, L the Obukhov length, σ_v the standard deviation of cross-wind velocity fluctuations, z_0 the roughness length and u_* the friction velocity. While $(z_r - d)/z_0$ is constant for the same z_r, and σ_v/u_* is very stable, the stability factor $(z_r - d)/L$ has a range of values according to the atmospheric conditions that determine the dimensions of the resulting source areas. Therefore, $(z_r - d)/L$ and σ_v/u_* were calculated for each half hour, and separated in two groups: data with unstable atmospheric conditions ($(z_r - d)/L < -0.01$) and data with near neutral atmospheric conditions ($-0.01 < (z_r - d)/L < 0.01$) (ranges taken from Monteith and Unsworth, 1990). Notice that there were no data with stable conditions, as stable conditions occur at night, whereas only daytime data were considered.

In order to obtain the maximum and minimum dimensions of the 50% source areas, considering that these dimensions vary mainly due to $(z_r - d)/L$, we ran the FSAM model using the minimum and maximum values of $(z_r - d)/L$ and an averaged σ_v/u_*, for each range of stability conditions. This was done both for the period when EC_1 and EC_2 were on the same tower, and for the period when they were in separate towers. Table 1 summarizes the values of the parameters used to run FSAM.

The values of z_0 and d were calculated from the relations with the average plant height of the ecosystem (h=0.5 m), as proposed by Shuttleworth and Gurney (1990).

2.4 GPR measurements

In order to investigate the presence and location of caves and pores in the subsurface of the footprint area of the two EC systems, measurements were made with a GPR (Ground-penetrating radar) system in a 80 m×30 m area to the Northeast of the towers (Fig. 1). This area included the maximum source weighted points (according to the footprint analysis mentioned before) for both EC systems, for the main wind directions coming from the North to East directions.

Seven profiles, 80 m long and with 5 m separation, were measured using a GPR proEX (Malå, Sweden) equipped with a shielded antenna of 250 MHz central frequency, applying time windows of 200 ns, 5 cm measurement steps, a sampling frequency of 1551 MHz, and 898 samples per scan. For the soil type of the measured site, i.e. limestone, the average speed is 0.1 m/ns, this being the value used for all the profiles carried out in reflection mode. According to the average speed and the recording time window, the depth of investigation was between 5 and 8 m.

2.5 Comparison of flux measurements between EC systems

To assess the agreement of the fluxes measured by EC_1 and EC_2 we used different methods. On one hand, we calculated the linear regression between the fluxes measured by EC_1 and EC_2. On the other hand, we calculated the root mean square error (ε) as:

$$\varepsilon = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(F_{1,i} - F_{2,i}\right)^2} \tag{1}$$

where $F_{1,i}$ and $F_{2,i}$ are the ith fluxes (either F_c or LE) measured by EC_1 and EC_2, respectively. As the units of ε are different for F_c and LE, to have a notion of the magnitude of the ε and be able to compare them, we calculated the relative root mean square error (ε_r) relating this parameter to the average of F_1 for the whole data set:

$$\varepsilon_r = \frac{\varepsilon}{\overline{F_1}} \cdot 100 \tag{2}$$

In the case of F_c, the average does not give a notion of the magnitude in μmol m^{-2} s^{-1} of the F_c data for the whole data set, due to the presence of positive and negative values. To avoid this effect, $\overline{F_1}$ was calculated as the average of the absolute values of F_c for the whole data set. In the case of LE, $\overline{F_1}$ was a normal average, due to the absence of negative LE values, as only daytime data were considered.

Comparison of fluxes from EC_1 and EC_2 was done for the whole period studied. However, as mentioned in the Introduction, another comparison between F_c fluxes was done, differentiating between biological and abiotic periods. Following Serrano-Ortiz et al. (2009) we considered biological periods with SWC >15% and Bowen ratio (H/LE) lower than 4, and abiotic periods with SWC<15% and Bowen ratio higher than 4.

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3 Results

For the period where both EC systems were on separate towers, the values of *LE* measured ranged between ca. 160 W m^{-2} and −60 W m^{-2}, while F_c ranged between ca. 6 μmol m^{-2} s^{-1} and −5 μmol m^{-2} s^{-1} (Fig. 2). The values of SWC and precipitation (Fig. 2) showed that before the 12 September the SWC was very constant (around 10% vol.) but after the important precipitation event on that day (more than 40 mm), SWC reached 30%, and remained above 15%. This change in SWC is reflected in higher values of *LE*, and the beginning of a transition in F_c from positive (CO_2 release) to negative (CO_2 uptake). According to the criteria for separating between biological and abiotic periods mentioned in the previous section, the abiotic period lasted from the 29 July until the first rain event on the 12 September, when the biological period is considered to have begun (Fig. 2).

For the period where EC_1 and EC_2 were on the same tower, both systems showed good agreement for F_c (F_{c2}=1.05 F_{c1}+0.08, R^2=0.97; ε=0.32 μmol m^{-2} s^{-1}), and fair agreement for *LE* (LE_2=0.87LE_1+1.98, R^2=0.93; ε=7.28 W m^{-2}).

Figure 3 shows the linear regressions for *LE* and F_c between the two EC systems installed on separate towers. These results show that the agreement between EC_1 and EC_2 was better for *LE* (slope = 0.99) than for F_c (slope=0.82) (Table 2). The ε_r for *LE* was 33%, while the ε_r for F_c was up to 74%.

Figure 4 represents the linear regressions between F_{c1} and F_{c2} for the biological and abiotic periods. Results showed clearly better agreement for the biological period than for the abiotic period. Moreover, the ε for the abiotic period was 15.4% higher than the ε for the whole dataset, while the ε for the biological period was 21.7% lower than the ε for the whole dataset (Table 2).

Figure 5 represents the maximum boundaries of the 50% source areas calculated with the FSAM for each EC system mounted in separate towers, both for the data with unstable conditions and for the data with near neutral conditions. Also represented are the wind directions, separated into intervals of 45°. Unstable conditions represented more than 75% of all data, and for these data the dominant winds came from between the North and East directions (60%). The upwind source area boundaries for these wind direction differed by up to 30 m. For neutral conditions, representing less than 25% of the data, the main wind direction was from the South (33% of the data), and as can be seen in Fig. 5, the upwind source areas boundaries for that wind direction differed by less than 9 m. As expected, for the period when both EC systems were mounted on the same tower, the boundaries of the source areas of both EC systems were the same, with differences of less than 1 m (data not shown). Therefore, the footprint analysis showed that for certain wind directions, the source areas of the two EC systems mounted in separate towers were different (Fig. 5).

Figure 6 represents the radargramme of one of the seven profiles done with a GPR to survey the subsurface for the possible presence of caves and fractures. As already indicated, the profiles were done along an 80 m per 30 m area at the North-east of the towers (Fig. 1). According to the above source area analysis, the area measured with the GPR was located within the boundaries of the source areas of both towers, for at least 45% of the total data. The radargrammes showed three distinctive zones: i) A shallow zone with a thickness between 0–2 m, marked by multiple reflections and limited by a bedding plane (labelled B in Fig. 6) – this region is characterized by strong vertical fracturing and cracks; ii) A deeper zone below, where the absence of strong reflections could be caused by the homogeneity of the material (A in Fig. 6) or due to the attenuation of the signal; and iii) A possible cavity between two bedding planes (labelled C in Fig. 6). Although a more thorough survey should be done to determine the exact location of fractures and caves, these results reveal the existence of discontinuities of the rock, bedding planes and fractures in the subsurface of the measured area.

4 Discussion and conclusions

Measurement of turbulent fluxes with Eddy covariance systems requires a sufficient fetch to generate an internal boundary layer where fluxes are constant with height

(Kaimal and Finnigan, 1994). To match this requirement, Eddy covariance systems are mounted on towers at a height within this boundary layer, and in areas with uniform vegetation, with no strong discontinuities that can affect the EC measurements in a way that they no longer are representative of the whole area. However, this has worked when measuring fluxes from scalars (CO_2, water vapour or temperature) whose main sources come from the surface, either soil surface or vegetation.

Recent works have shown evidence of the existence of a subterranean source of CO_2 coming from the ventilation of pores and caves located in the sub-surface of carbonaceous ecosystems (Kowalski et al., 2008; Emmerich, 2003; Baldini et al., 2006). Moreover, Weisbrod et al. (2008) have demonstrated the existence of a convective exchange mechanism between fractures and atmosphere in an arid area with a high level of porosity in the soil. In the same carbonaceous area considered in this paper, Kowalski et al. (2008) indicated that this sub-surface source of CO_2 is stronger during dry periods when the low soil water content enhances this leakage of sub-surface CO_2 through the soil pores. This so called abiotic source of CO_2 can be predominant during dry periods, when the biological processes occurring on the surface are limited, vegetation is considered to be senescent, and heterotrophic respiration can be neglected (Eliasson et al., 2005; Serrano-Ortiz et al., 2009).

According to these considerations, in this paper we present evidence of the effect of the spatial heterogeneity of the CO_2 sub-surface abiotic source on the Eddy covariance (EC) system CO_2 flux measurements on a carbonaceous area. At first, comparing the measured evapotranspriation (LE) and CO_2 flux (F_c) of two separate EC towers, results show that the agreement is better for LE, a surface-dependent flux (through transpiration and soil surface evaporation), than for F_c (Fig. 3 and Table 2). Moreover, if we compare F_c from the two EC in periods with predominance of biological surface processes (biological periods), with higher SWC that favour photosynthesis and respiration, we can see that the agreement between both systems is very good (Fig. 4 and Table 2). The presence of positive F_c data in this period, indicating release of CO_2, can be due to high respiration rates after a rain event (Schwinning and Sala, 2004).

When the comparison of F_c between EC_1 and EC_2 is done during periods with predominance of ventilation sub-surface processes (abiotic periods), results show a clear disagreement between the two EC systems (slope=0.6 and ε=0.95 μmol m^{-2} s^{-1}, in Table 2).

This disagreement during abiotic periods can be explained by the spatial heterogeneity of the pores and fractures through which CO_2 outflows. The analysis of the source areas of the two EC systems show that for certain wind directions, the source areas of the two EC systems located in separate towers are different (Fig. 5). Hence, if the source area of one of the EC includes an outflow of CO_2, this tower will measure a different amount of CO_2 flux than the other tower during the abiotic period. To reinforce this explanation, radar measurements confirm the presence of fractures and caves in the subsurface, whose distribution is not uniform (Fig. 6). Moreover, the gaseous CO_2 stored in a certain cave or pore in the soil can outflow from a point located at a distance from the cave or pore where it originated. Therefore, not only the spatial heterogeneity of the carbonaceous subterranean porespace, but especially of the outflow points, must be taken into account when measuring the surface-atmosphere CO_2 exchange in carbonaceous areas.

Though efforts have been made to use an EC system to locate and quantify surface CO_2 outflows (Lewicki et al., 2009), results were not conclusive. Therefore, measurements of CO_2 fluxes with EC towers over carbonaceous ecosystems must be interpreted with care, as they may not be representative of the whole area, since these ecosystems have additional sources of CO_2 due to ventilation processes across fissures, pores and caves. Thus, in these ecosystems with a high subsurface heterogeneity, the carbon balance measured only with Eddy covariance measurements should be corroborated with additional techniques.

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Table 1. Values of parameters used to run the FSAM model. FSAM was run for the period when EC_1 and EC_2 were installed in the same tower, and when they were installed in separate towers. Runs 1, 2, 5 and 6 used the minimum and maximum $(z_r - d)/L$ obtained during unstable conditions, and runs 3, 4, 7 and 8 used the minimum and maximum $(z_r - d)/L$ obtained during neutral conditions.

			EC_1			EC_2		
	Atmospheric conditions	runs	$\frac{(z_r-d)}{L}$	$\frac{(z_r-d)}{z_0}$	$\frac{\sigma_v}{u_*}$	$\frac{(z_r-d)}{L}$	$\frac{(z_r-d)}{z_0}$	$\frac{\sigma_v}{u_*}$
Same tower	Unstable	1	−0.104	38.9	3.26	−0.105	38.9	3.03
		2	−0.011	38.9	3.26	−0.01	38.9	3.03
	Neutral	3	−0.01	38.9	4.33	−0.009	38.9	4.3
		4	0.0005	38.9	4.33	0.0006	38.9	4.3
Separate towers	Unstable	5	−0.9	37.5	3.6	−0.98	47.5	3.66
		6	−0.01	37.5	3.6	−0.01	47.5	3.66
	Neutral	7	−0.01	37.5	4.19	−0.01	47.5	4.74
		8	0.003	37.5	4.19	0.003	47.5	4.74

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Table 2. Parameters of the linear regressions (slope and y-intercept), coefficient of determination (R^2), the root mean square error (ε) and the relative root mean square error (ε_r) obtained by comparing F_c and LE measured with EC_1 and EC_2. Y-intercept and ε values for F_c and LE are in $\mu mol\,m^{-2}\,s^{-1}$ and $W\,m^{-2}$, respectively. Parameters were obtained for the total set of data (n=665), and for the biological (n=248) and abiotic periods (n=252), separately.

		slope	y-intercept	R^2	ε	ε_r (%)
Total data	LE	0.99	2.5	0.71	14.23	33.3
	F_c	0.82	−0.39	0.76	0.82	74.0
Biological period	F_c	0.97	−0.3	0.81	0.64	57.9
Abiotic period	F_c	0.60	−0.26	0.73	0.95	85.4

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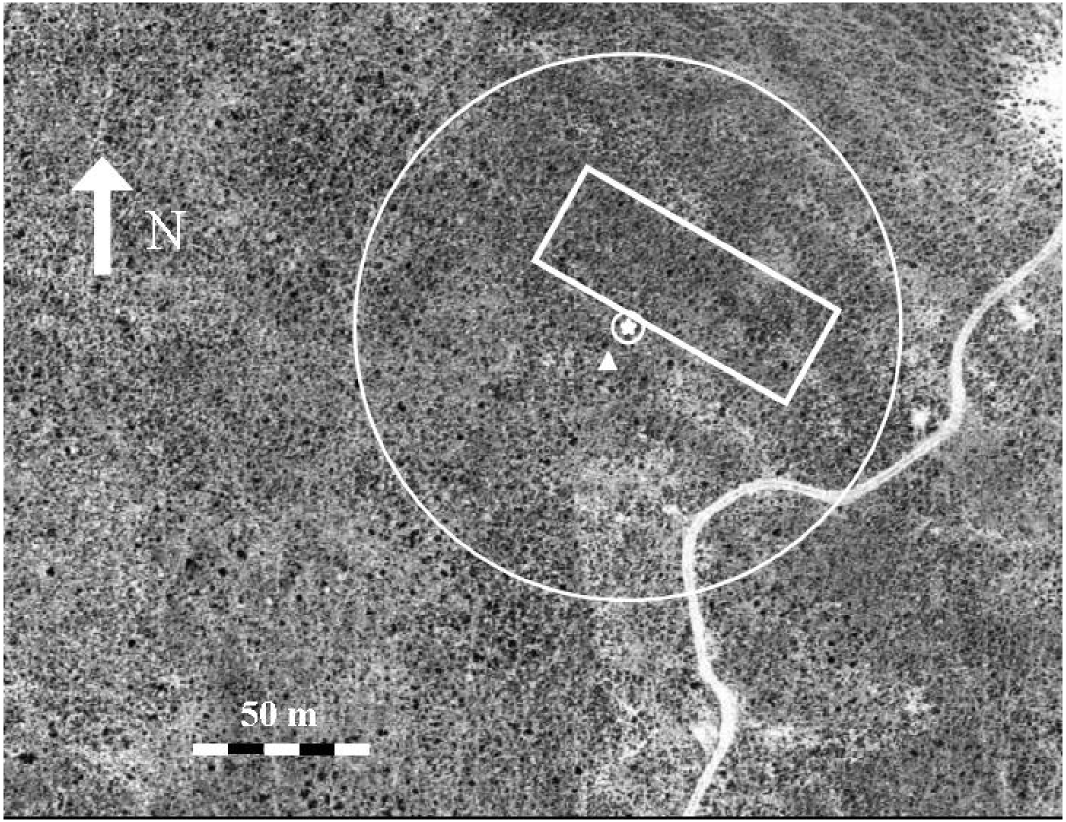

Fig. 1. Schematic image of the measuring site, and the position of the two EC (EC_1: triangle; EC_2: star). Also is indicted the rectangular area measured with the GPR, and the boundaries of the source area of EC_2 obtained with the footprint analysis (see Fig. 5 – unstable conditions).

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Ventilation of subterranean CO_2 and Eddy covariance incongruities

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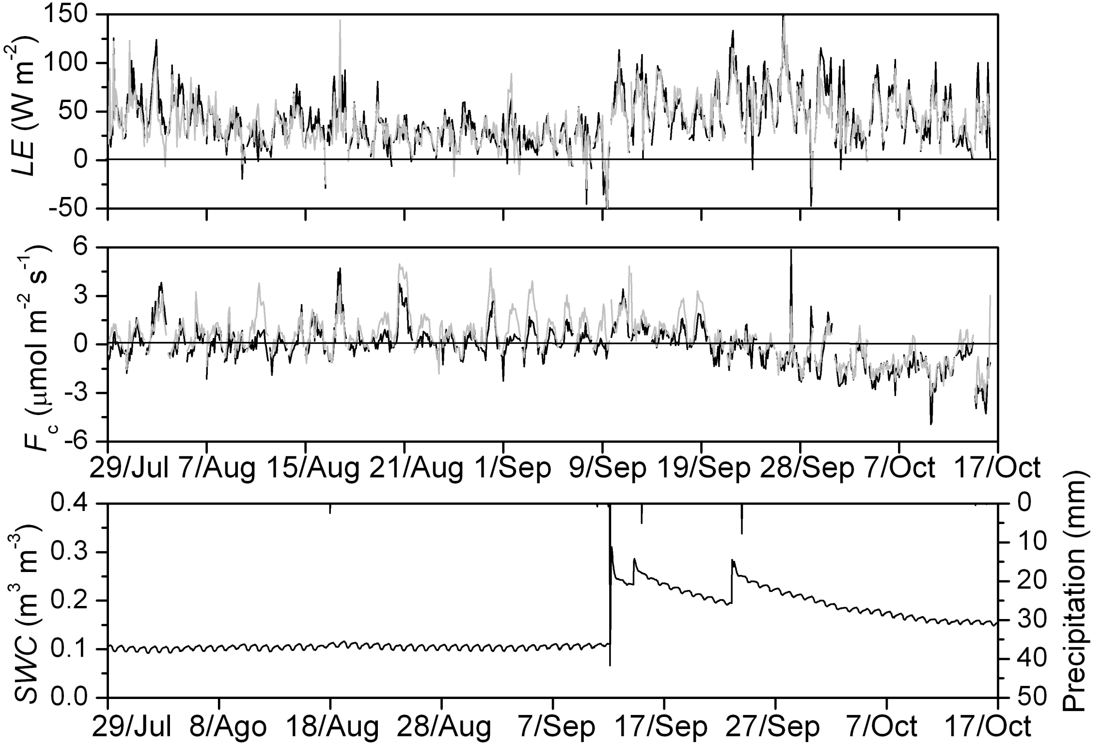

Fig. 2. Values of diurnal *LE* and F_c measured every 30 min by EC_1 (grey line) and EC_2 (black line) for the period from end of July to mid October, when both systems were located on two separate towers. Soil Water Content (SWC) and precipitation are also represented. Notice that *LE* and F_c are diurnal data (no night-time data are shown) from non-continuous days – as no gap-filling was used – while SWC and precipitation are continuous data for the whole period.

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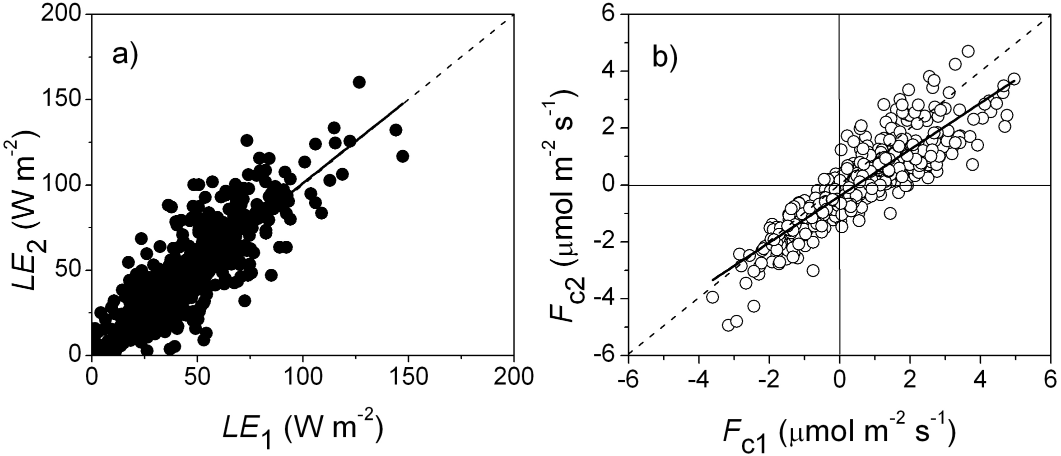

Fig. 3. Linear regressions between *LE* **(a)** and F_c **(b)** measured with EC_1 (x-axis) and EC_2 (y-axis) for the period where they were on separate towers. The regression line (solid line) and the 1:1 line (discontinuous line) are shown.

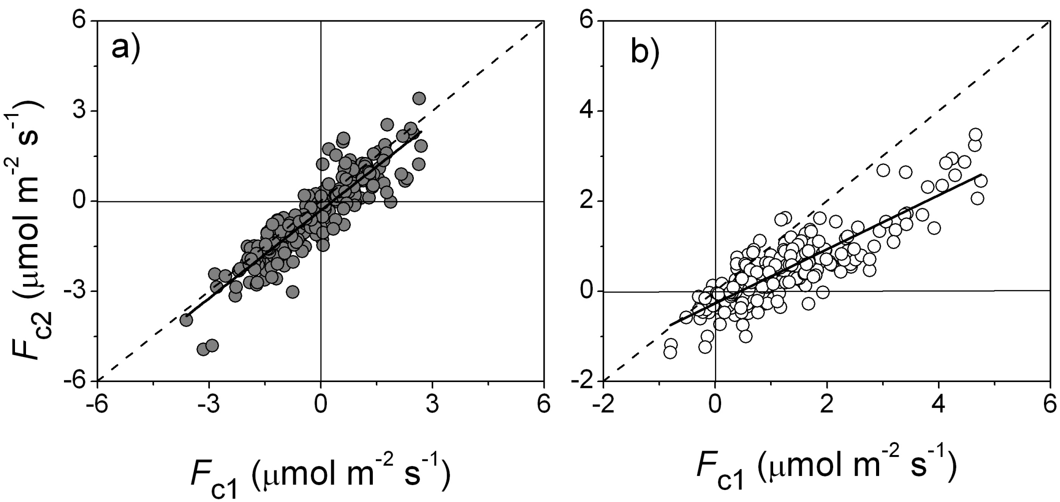

Fig. 4. Linear regressions between F_c measured with EC_1 (x-axis) and EC_2 (y-axis), for the biological period **(a)** and abiotic period **(b)**. The regression line (solid line) and the 1:1 line (discontinuous line) are shown.

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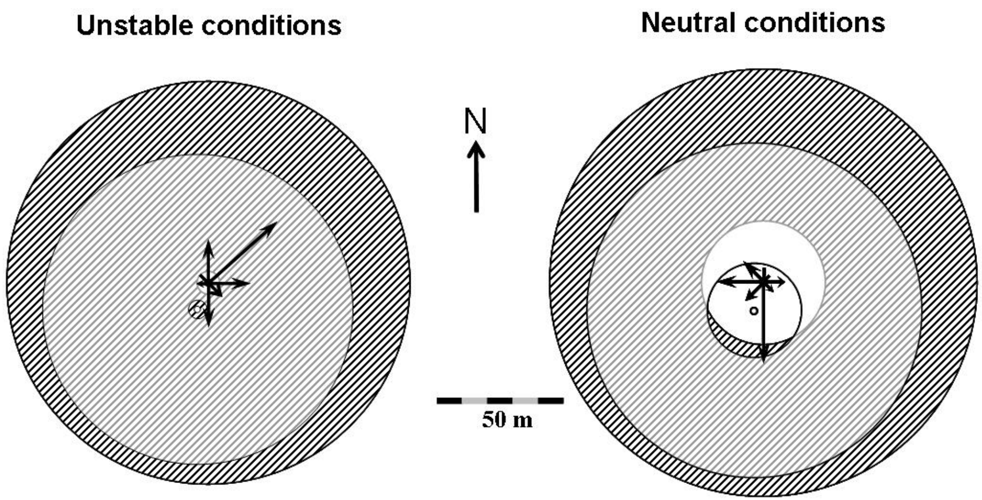

Fig. 5. Schematic representation of the boundaries of the 50% source areas for EC_1 and EC_2, when they were on separate towers, for periods with unstable atmospheric conditions and periods with near-neutral atmospheric conditions (see Material and Method for a more detailed explanation). The source area of EC_1 is light white, and the source area of EC_2 is white with black stripes. The arrows indicate the direction from where the wind is coming, separated in 45° angles, being the length of the arrow the proportion of the total data coming from that specific 45° wind direction.

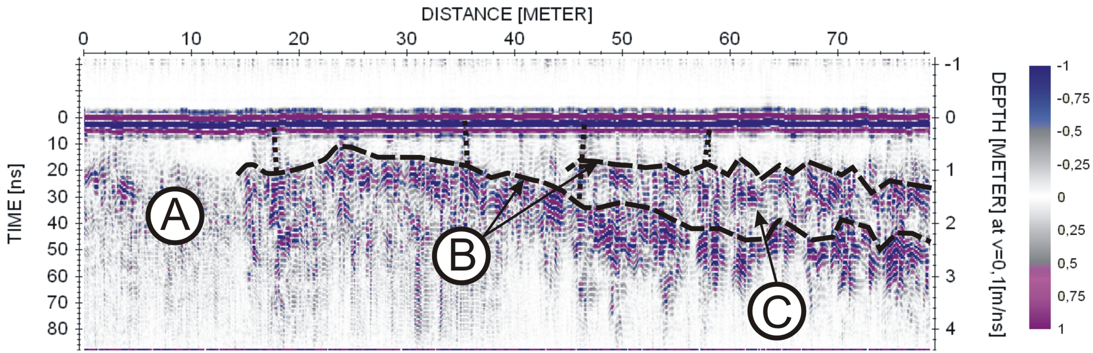

Fig. 6. Radargramme of one of the seven 80 m profiles carried out with a GPR, to the Northeast of the EC towers (location of the area surveyed with the GPR is shown in Fig. 1). A: massive and compact limestones, B: bedding plane, C: possible cavity. Vertical dotted lines indicate fractures and cracks.