Final Scientific Report on
"Decrease of uncertainty of natural grassland's carbon dioxide exchange"
(OTKA PD 105944)

Introduction

Several research projects aimed to investigate the energy, water and CO_2 exchange of different ecosystems, for which eddy covariance (EC) technique has become a widespread tool in the last decades (Aubinet et al., 2000; Baldocchi, 2003; Kutsch et al., 2010; Soussana et al., 2007). With this technique the net ecosystem exchange (NEE), the resultant of photosynthetic carbon uptake and respiratory carbon loss, can be measured.

Based on the mass conservation equation it can be deduced that the NEE is the sum of the turbulent CO_2 flux (*cflux*), the rate of change of storage (*RCS*) below the measuring height and the horizontal and vertical advection (Baldocchi, 2003; Loescher et al., 2006). The advection terms are usually neglected, partly because they are assumed to be zero over homogenous terrain and partly because it is hard to measure them (Aubinet et al., 2000). The easiest way to calculate RCS is to assume the concentration (and its change in time) being constant with height below the measuring level (1 level approach). This approach can be used at any EC station due to availability of continuous CO_2 concentration measurements. However, it was clear from our own measurements that the CO_2 concentration profile is usually not constant with height and RCS can be underestimated when using the approach of constant concentration change with height (Nagy et al., 2011). Measurement of CO_2 concentration profile, on the other hand requires an additional measurement setup.

In the case of tall vegetation RCS measurements are routinely done, but in the case of short vegetation it is often neglected (Jia et al., 2014; Mudge et al., 2011; Shimizu et al., 2015; Tang et al., 2003; Zhang et al., 2007) based on the assumption that its positive values after sunset and negative values at dawn cancel each other when calculating daily and yearly sums (Aubinet et al., 2000; Baldocchi, 2003). On the other hand, (Nieveen et al., 2005) measured RCS over short canopies and found it negligible.

One of the frequently discussed problems related to EC measurements is the possible underestimation of fluxes at night time when the turbulence is diminished or vanished (Aubinet et al., 2000; Goulden et al., 1996). Comparison of night time EC fluxes to soil respiration measured with chambers support the underestimation of R_{eco} by EC based fluxes since R_{eco} in the low range (below 2 μmol CO_2 m^{-2} s^{-1}) was similar to or smaller than soil respiration (Nagy et al., 2011), however soil respiration is only a part of R_{eco}. Alike, eddy covariance fluxes were lower than chamber estimates of ecosystem respiration (in a forest), but the mean night estimates from the two techniques were correlated within a year (r^2 from 0.18 to 0.60) according to Speckman et al. (2015). Nevertheless, in the case of a scrub-oak ecosystem Dore et al. (2003) found that chamber-based measurement of ecosystem respiration at night did not significantly differ from EC based estimate of R_{eco} in six out of 12 measurement periods and for the other periods the maximum difference was 1.1 μmol $m^{-2}s^{-1}$, with an average of 0.72 ± 0.09 μmol $m^{-2}s^{-1}$.

On one hand, the underestimation is commonly corrected by u_* filtering, which relies on the rejection of data under a – usually site specific – threshold of friction velocity (u_*) derived from the investigation of the NEE-u_* relationship. Rejected data will then be replaced by modelled data based on the NEE-temperature function during the gap-filling procedure. The basic idea behind is that during the calm night conditions the turbulence is less than required to thoroughly mix the air layers below the measurement height, resulting in underestimation of night NEE fluxes (Aubinet et al., 2000). The routine use of the procedure has been questioned partly because of the difficulties related to the proper choice of the u_* threshold (Acevedo et al., 2009; Falge et al., 2001) and partly because of the weaknesses in the basis of this correction. There were attempts to standardize the threshold selection method (Gu et al., 2005; Reichstein et al., 2005), but the theoretical background remained debated. For example, Papale et al. (2006) argues that u_* correction is only applicable if the CO_2 accumulated during low turbulence conditions is removed by drainage or advection, otherwise it will be double counted when it is carried (and measured by the EC system) by the turbulence initiated at dawn. To avoid the double counting of the CO_2 flux data must be corrected by the storage term and u* filtering can be performed only afterwards (Aubinet et al., 2002; Papale et al., 2006).

Neglecting of advection and drainage flows in low wind conditions (when they contribute significantly to the mass balance) might introduce serial systematic bias in estimates of NEE (van Gorsel et al., 2007), on the other hand. Advection is small relative to the vertical turbulent flux (van Gorsel et al., 2007; van Gorsel et al., 2008, 2009) and RCS (and Reco) reaches its maximum in the few hours after sundown. They assumed this (maximum) peak to occur because during still conditions at the evenings there is ususally a period when there are no flows (either horizontal or vertical) to remove the stored CO_2.

These maximal R_{eco} values showed good agreement with independent chamber based respiration measurements and with R_{eco} estimates from light response curves (van Gorsel et al., 2009). However, according to their revised calculations net ecosystem exchange of a wet sclerophyll forest was reduced by 560 gC m^{-2} on annual basis (van Gorsel et al., 2008). This discrepancy seems to be too large to accept without doubts.

Measuring site and setup

Our research group is measuring the CO_2 exchange of a sandy grasslands since 2002 by the means of EC technique. The measurement had been supported by FP5 (Greengrass) and FP6 (Carboeurope IP) research projects. Measurements investigating the effect of grazing on the carbon balance at the sandy grassland site was supported by AnimalChange (FP7) project.

The measuring site is situated at the central part of the country on the Hungarian Great Plain, in the Kiskunság National Park near Bugacpuszta. (46.69°N, 19.60°E, 106.4 m a.s.l.) The spatial extent of the continuous grass cover is 550 ha. The terrain is not completely homogenous due to surface undulations. The maximum difference in altitude is 2 m, affecting soil water dynamics (Fóti et al., 2014). The soil type is sandy chernozem, with high (similar to 90%) sand content. The mean annual (10 years average) temperature and sum of precipitation are 10.4°C and 562 mm, respectively.

The EC station is equipped by a CSAT3 sonic anemometer (*Campbell Scientific Inc.)* and by a Li-Cor 7500 open path IRGA *(LI-COR Inc)*. Besides eddy-covariance measurements the following micrometeorological variables are measured:

- temperature (HMP35AC, *Vaisala)*,
- relative humidity(HMP35AC, *Vaisala)*,
- gloabal and reflected radiation (Schenk piranometer, *Schenk Gmbh*, CMP3 *Campbell Scientific Inc.)*,
- net radiation (Q7 Net Radiometer, NR Lite, *Campbell Scientific Inc.)*,
- photosynthetically active radiation (PAR), reflected PAR, *Campbell Scientific Inc.)*,
- soil temperature (105T Thermocouple probe, *Campbell Scientific Inc.)*,
- soil water content (CS616 Water Content Reflectometer, *Campbell Scientific Inc.)*,
- soil heat flux (HFP01 Heat Flux Plate, *Campbell Scientific Inc.)*.

Data is measured and recorded by a CR5000 data logger (*Campbell Scientific Inc.).*

Methods

The calculation of CO_2 fluxes is based on high frequency (10 Hz) measurement of wind speed, temperature, water vapour and CO_2 concentration data. Spike detection and removal are done after Vickers and Mahrt (1997). The values considered as spikes are replaced by linear interpolation. To calculate fluctuations from the raw data series linear detrending is performed. The disturbance effect of sensor heads is influenced by the angle between the wind vector and horizontal plane, the so called angle of attack. To avoid errors caused by this error our database is calibrated after van der Molen et al. (2004). The error caused by the inaccurate levelling of the sonic anemometer is corrected by the planar fit method (Wilczak et al., 2001) 3D coordinate rotation is then applied according to these corrected mean wind speeds. From the corrected raw wind speed data the turbulent flux of CO_2 is calculated by the following equation.

$$cflux = \rho\overline{w'CO_2'}, \qquad (1)$$

where *w* is the vertical wind speed components, CO_2 is the carbon dioxide concentration and ρ is the air density, variables with commas in superscript denote fluctuations.

As the dataset of the turbulent fluxes is not continuous (the ratio of available data was about 35% at daytime, while it is only 30% during night) calculation of yearly sums of NEE, R_{eco} and GPP requires gap-filling. The method is based on empirical functions of environmental variables and fluxes (response curves). Filling the daytime gaps a non-linear function between PAR and daytime CO_2 fluxes is used:

$$cflux = \frac{\alpha\beta PAR}{\alpha PAR+\beta} + R_{eco}, \qquad (2)$$

where PAR represent photosynthetically active radiation, and α, β and R_{eco} are the fitted parameters with physical meaning: α apparent quantum yield, β is GPP at light saturation and R_{eco} is ecosystem respiration(Falge et al., 2001a). For night time data the temperature response curve of respiration is used:

$$R_{eco} = R_{ref}e^{E_0\left(\frac{1}{56.02}-\frac{1}{t+46.02}\right)}, \qquad (3)$$

where t is temperature in °C, R_{ref} is a reference respiration at 10°C and E_0 is a parameter related to activation energy (Lloyd and Taylor, 1994). These functions are fitted on data within a time window of ±3 days of the day in concern. If the fit does not converge, the time window is increased by ±3 days, if there is no statistical significant fit for even a 15 days-long time window, gaps are filled with the mean diurnal variance (MDV) method. The window size is increased in every step by ±3 days, until it reached the pre-defined maximum (32 days). If there was not enough data to determine the MDV series, then missing points in MDV were filled by interpolation. For data gaps in January, February, November and December only the MDV method is used, since in this month the relationship between PAR and F_c is weak. Temperature response curves are fitted throughout the whole year since they are necessary to the flux partitioning. From this temperature response curves and the half-hourly temperature data R_{eco} is estimated for daytime, and gross primary productivity is calculated as follows:

$$GPP = -NEE + R_{eco} \qquad (4)$$

The uncertainty of the annual sum was calculated by a Monte-Carlo method. Artificial gaps were generated into the 1 year long dataset, and were filled afterwards. The length of gaps and their distribution was the same as in the original dataset. The usual number of runs in Monte Carlo simulations is 10000, but according to Verbeeck et al., (2006) 2000 runs are sufficient, as the standard deviation is already converging at that number of runs. The above statement was proven to be valid for our dataset as well, so for one given year 2000 runs were performed, and uncertainty was calculated as the standard deviation of the yearly sum of NEE, R_{eco} or GPP calculated in the different runs.

Starring from the conservation equation, assuming stationarity and horizontal homogeneity of turbulence, moreover neglecting horizontal and vertical advection, NEE can be written as the sum of the turbulent CO_2 flux (cflux) measured by the EC system and the RCS calculated from the CO_2 concentration profile (Aubinet et al., 2000):

$$NEE = cflux + RCS. \qquad (5)$$

Fluxes are interpreted according to the micrometeorological sign convention, i.e. R_{eco} and accumulation of CO_2 are represented by positive values, while CO_2 uptake by the vegetation and depletions are negative.

Tasks accomplished during the project:

1. Establishment of a CO_2 concentration, wind speed, temperature and relative humidity profile measuring system.

The EC system operating at Bugac was completed by a 5-level (0.2, 0.5, 1, 2 and 4m) CO_2 concentration profile measuring system. The measurements of the rate of change of storage below the level of the EC system was started in June, 2013. The gas analyzer (Li-820, carbon dioxide analyzer) required to the measuring system was already available when applying for the grant. Other necessary equipment (CR1000 data logger, CFM100 compact flash memory modul, AM16/32 multiplexer, valves, tubes, air-pumps, flow meters) was purchased in the first year of the project.

According to the initial routine, air sampling was switched between the measurement heights in every 20 seconds, while the carbon dioxide concentration was measured in every second. The carbon dioxide concentration for the last 10 seconds was averaged by the data logger and stored on the compact flash card. A whole measuring cycle took two minutes, i.e. a given level was sampled in every two minutes, and there was a 40 seconds long pause at the end of the measuring cycle. The rate of the sampling flows were also measured and stored. The flow rate was found to change and became critically low from time to time. It was assumed that the blockage was caused by dew formation, so as a first attempt, water traps were installed in Summer, 2014. As the volume of the traps increased also the time period for sampled air to reach the gas analyser, the measuring cycle had to be extended to five minutes, and the time of switching between the sampling levels to 40 seconds. Unfortunately, low flow rates were still detected, furthermore the system was totally plugged in July, 2014 caused by the failure of the filter (Balston DFU) at the inlet of the gas analyser. After replacing the filter flow rates returned to the expected range.

To extend the carbon dioxide concentration profile system into flux-profile system it was complemented by a wind speed profile system (3 levels: 1, 2 and 4m)in July, 2013 and temperature and relative humidity (RH) profile system in September, 2014. The temperature and relative humidity sensors *(CS215 temperature and RH probe, Campbell INC.)*, were bought within the frame of this project. Windspeed was measured by A100LK anemometers *(Vector Instruments Ltd.)* Temperature, RH and wind speed were sampled in every second and averaged in every five minutes by the data logger and stored on the compact flash card.

2. Calculation of half-hourly storage fluxes

From the raw CO_2 concentration dataset half-hourly averages and standard deviations were calculated and stored in ASCII files on daily basis. To account for the delay caused by the changes in the flow rate, a delay term was calculated and used in the half-hourly averaging routine. Temperature, RH and wind speed were also averaged half-hourly and stored on daily basis in ASCII files.

Rate of change of storage was calculated according to (Aubinet et al., 2005),

$$RCS = \int_0^h \frac{dc}{dt} dz, \qquad (6),$$

where *h* is the height of the EC measurements, *c* is carbon dioxide concentration, *t* is for time and *z* for height. The integration of the concentration change at the different sampling heights was performed numerically using the trapezoidal rule. RCS is also routinely calculated from the single point CO_2 concentration measurements (EC system), assuming spatially (vertically) constant concentration change between the ground and the level (height) of the EC system. In this analysis RCS was calculated from the uppermost level of the concentration profile measurements as well, to compare the two approaches. In the case of the single point approach the rectangular rule was used for numerical integration.

3. Improvement of the gap-filling routine

According to the research plan reconsideration of the gap-filling algorithm was the other component of decreasing the uncertainty of the carbon balance measurements. It was planned by introducing a new variable (soil water content, SWC) into the temperature response function according the following equation:

$$R_{eco} = R_{ref} e^{E_0\left(\frac{1}{56.02} - \frac{1}{t+46.02}\right) + \left(-0.5\left(\ln\frac{SWC}{SWC_{opt}}\right)^2\right)}, \qquad (7)$$

where R_{ref} and E_0 are reference respiration at 10°C and activation energy, respectively. SWC_{opt} denotes soil water content optimum value for respiration (Balogh et al., 2011; Lloyd and Taylor, 1994). The function was fitted for one year long periods of the whole dataset (since 2002), but it was overestimating the ecosystem respiration and introduced serious bias into the estimation of annual sum of NEE, R_{eco} and GPP. Therefore eq. 3. was used in the analysis.

Since the relatively poor fit of the temperature response curves was caused by the low data availability at night, implementation of an other kind of temperature curve were not a promising option. The other way to improve the goodness of fit was the increase of the time window, but in that case seasonal variation is introduced in to the variation of the dataset in a given time window. Instead, the fitted parameters of the response curves were considered as time series, they were filtered by rejecting data outside the interquartile range. To mitigate the effect of day to day variation of weather the time series were smoothed in a 3 day long window by boxcar average method. Afterwards gaps were filled by simple linear interpolation. With this method response curves were created for intervals when the initial fit was failing because of missing data (Fig 1. and 2.).

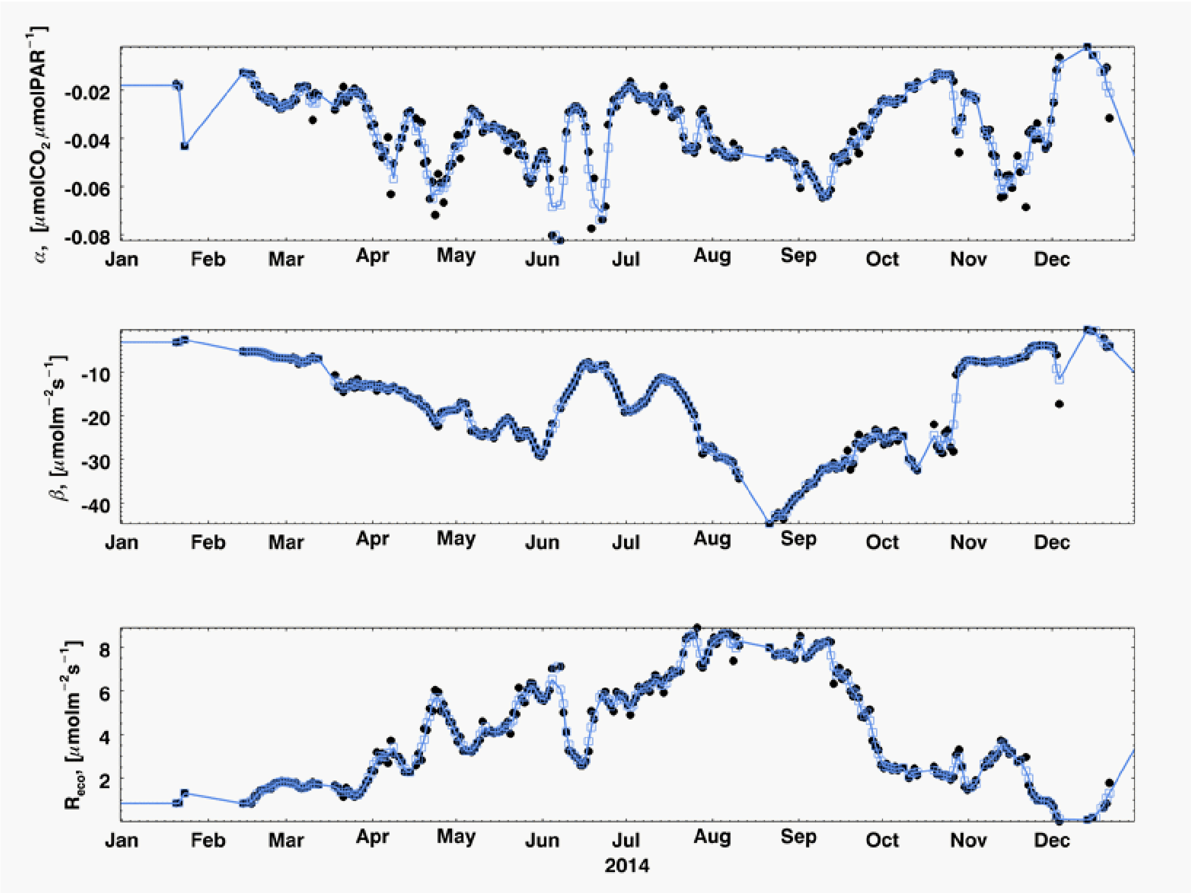

Fig. 1. An example for the interpolated parameters of the light response curve. α: apparent quantum yield, β: GPP at light saturation and R_{eco}: ecosystem respiration. Black dots are original fitted parameter values, light blue squares are the filtered (interquartile range) and smoothed (3 day boxcar averages) values, and blue line is the interpolated time series.

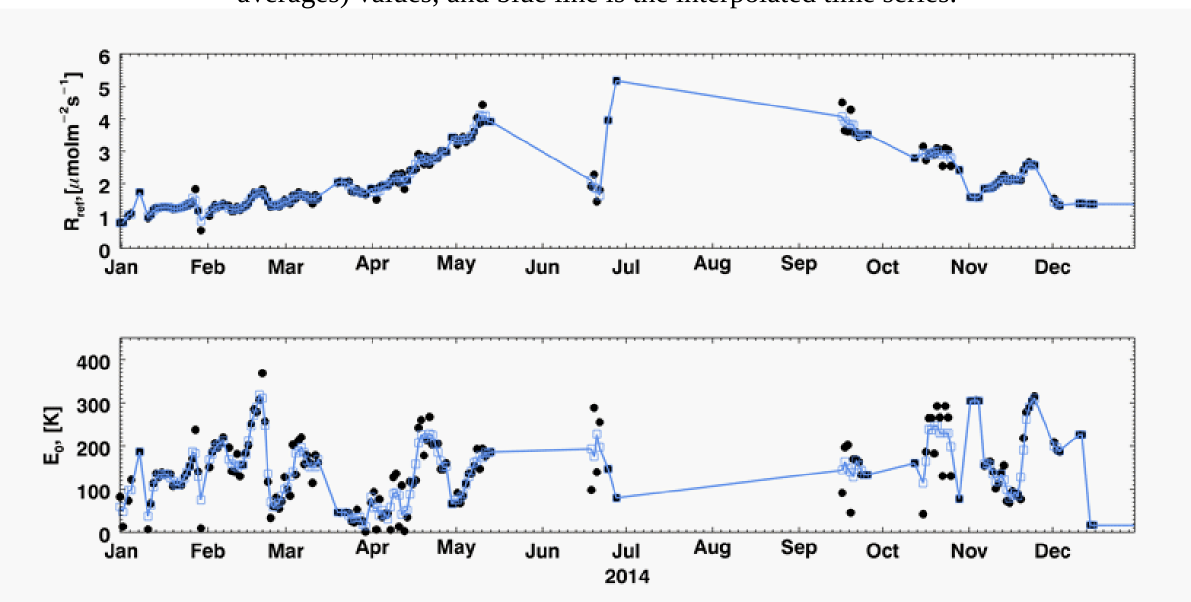

Figure 2. An example for the interpolated parameters of the temperature response curve. R_{ref}: reference respiration at 10°C and E_0: a parameter related to activation energy. Black dots are parameter values from fitting the data, light blue squares are the filtered (interquartile range) and smoothed (3 day boxcar averages) values, and blue line is the interpolated time series. Failure of the fit of the temperature response curve caused long gaps (June, from July to September) in the time series of the parameters.

4. Measurement of soil respiration by chambers

Automatic soil respiration measurements (Nagy et al., 2011) were performed in two intervals during the project, July-December, 2013 and March-May, 2014. These data were used as a bottom constraint for R_{eco}, when addressing the problem of low night time eddy fluxes during still conditions.

Results and discussion

Comparison of the different calculation methods

RCS calculated from the two different approaches, one level (EC height) vs. concentration profile measurement was compared for the period of July 2013 - June 2015. The slope of the overall linear regression between the storage fluxes calculated by the two approaches (1 level approach vs. profile measurements) was 0.94 (regression not shown on Fig. 3.), suggesting that the profile approach was underestimating RCS contradicting to theoretical considerations.

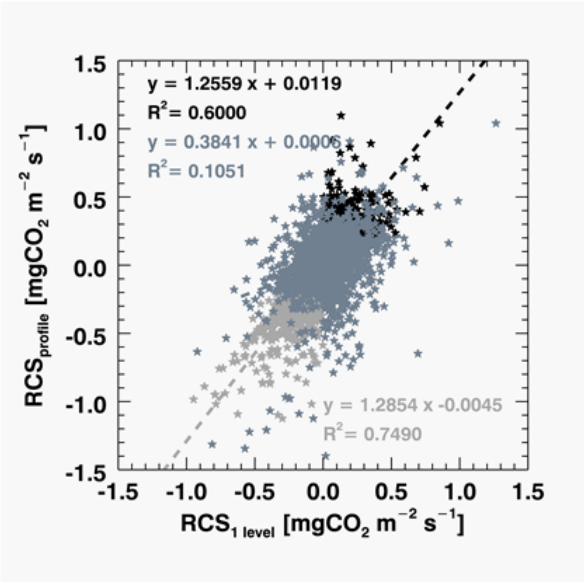

Fig. 3. Linear regression between rate of change of storage (RCS) calculated from one-point concentration measurement ($RCS_{1\ level}$) and concentration profile ($RCS_{profile}$) measurements. Points were divided into three groups according to the CO_2 concentration change: 1. Increase of CO_2 at all levels accumulation (accumulation, black stars), 2. decrease of CO2 at all levels (depletion, light grey stars), 3. mixed situation (dark grey stars).

As a next step concentration change profiles were classified into three groups: 1. when the concentration is increasing at all heights (black stars on Fig. 3., e.g. RCS build up usually during the first half of the night), 2. when the concentration is decreasing at all heights (light grey stars on Fig. 3., depletion of CO_2 usually at dawns) and 3. mixed situations (dark grey stars on Fig. 3.). The measured RCS fluxes were nearly equally distributed between the three groups. Linear regression analysis in the three different groups showed that the RCS calculated from the concentration profile measurements was by 26% and 28% higher than RCS calculated by 1 level approach during build up (group 1) and depletion (group 2), respectively (Fig. 3.). In the mixed situations linear regression between the two kinds of RCS was not statistically significant, since in this cases the chosen numerical integration method had a great influence on the value of RCS.

Another classification, considering the shape of the concentration change curve was also done (figures shown in Appendix 1 and 2). Positive (accumulation) and negative (depletion) RCS values were handled separately. In cases when the concentration was increasing below the measuring height of the EC system, and the change was monotonously decreasing with height (Appendix 1, Class A), RCS calculated from the concentration profile measurements was about 95% higher, than RCS calculated from them 1 level approach. However, in cases when the concentration was decreasing with time, and the concentration also decreased with height (Appendix 2, Class A) the single point approach resulted 38% smaller RCS than the profile measurements. On the other hand, when concentration change was not monotonous the profile method tended to underestimate RCS as compared to the single level approach (Appendix 1, Class C1, D1, E1, F4).

The effect of RCS on NEE

The process of CO_2 accumulation and depletion below the measuring level of the EC system is illustrated by the mean diurnal variance (MDV) of RCS calculated for both approaches. In the vegetation period (May, 2014 in this example) after sunset turbulence was usually becoming weaker, in which situation CO_2 respired by the vegetation was starting to be accumulated near the ground. This corresponds to large positive RCS fluxes (Fig. 4., left pane). After 2-3 hours this RCS was decreasing considerably, ie the rate of accumulation is getting slower, which was most probable due to drainage flows (Van Gorsel et al., 2007; van Gorsel et al., 2009). After sunrise the accumulated CO_2 is leaving the system either due to photosynthetic uptake by the vegetation or by developing turbulence. Distinction between these two processes may be based on the sign (direction) of the fluxes in these periods. If it is positive then CO_2 is most probably is leaving the system by turbulence, and if it is negative then it is taken up by the vegetation. The question however remaining in both cases is related to the fact that these fluxes are related to CO_2 amounts transported into the control volume in earlier periods.

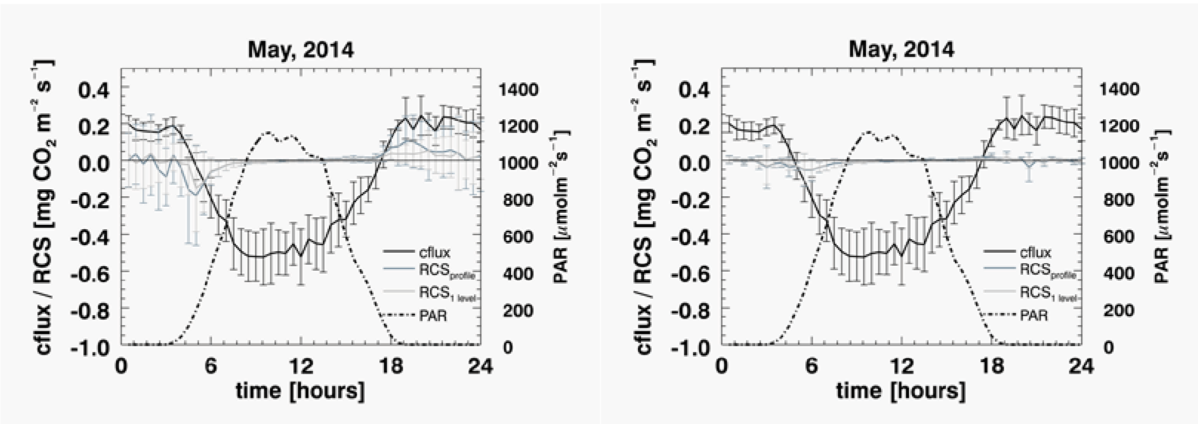

Fig 4. Mean diurnal variation (MDV) of PAR, RCS, turbulent CO_2 flux (cflux) and NEE in May 2014 at Bugac. *Left pane:* all the measured RCS fluxes were used when calculating the MDV. *Right pane:* MDV of RCS values associated to valid turbulent fluxes.

Although, when calculating NEE (the sum of the turbulent flux and RCS) only part of this information was used i.e. only those RCS fluxes (half hours) were considered where cflux was also available. The right panel of Fig 4. shows the storage actually taken into account and the difference between cflux and NEE, which is similarly negligible as found by Aubinet et al.,

(2005) and Nieveen et al., (2005). This also means that the considerable storage measured by the profile system is not captured at all by the EC system, neither when accumulating, and more importantly, nor when it is flushed out. According to the right pane of Fig. 4. the MDV of the RCS curves calculated by the two method was not different, suggesting that when RCS correction is applied the one level approach is a reliable choice. On the other hand, the methodology (storage correction applied only if valid turbulent fluxes are for the half hour in concern are available) largely decreases the effect of storage (RCS is small if turbulent fluxes occur).

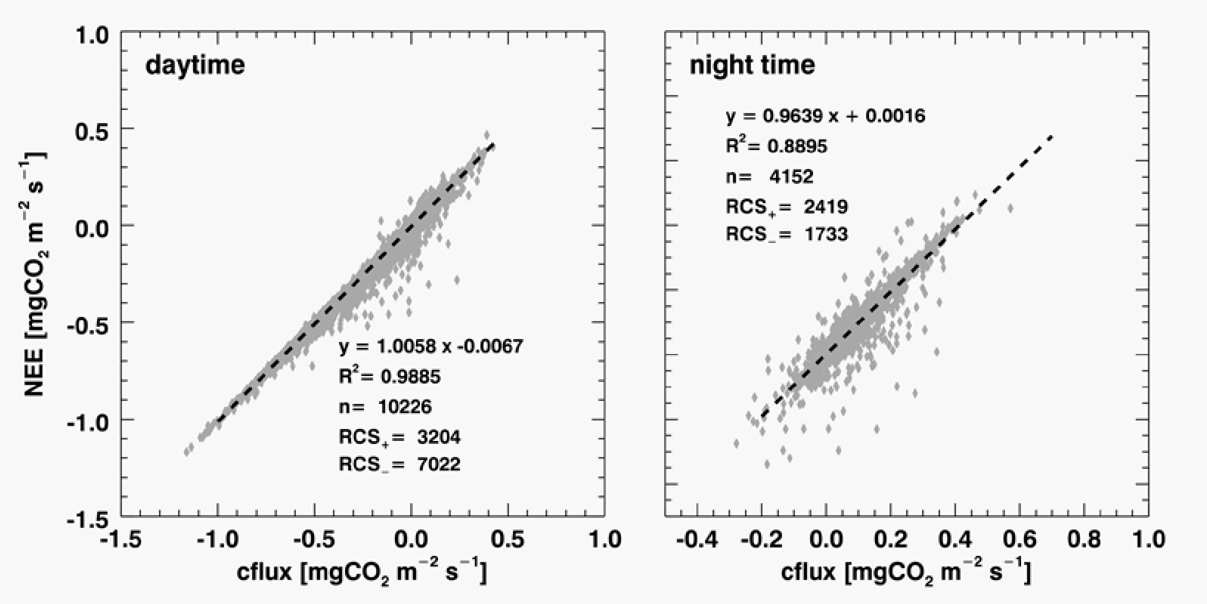

Fig. 5. Linear regression between turbulent CO_2 flux and NEE (cflux + RCS) for daytime and night time separately.

On the other hand the apparently negligible difference between the MDV series of cflux and NEE (storage corrected flux) typically present from sunrise to early morning in active periods (i.e. May)) caused considerable difference in the annual sum of NEE, R_{eco} and GPP. The difference ($NEE_{storage}$ – $NEE_{no\_storage}$) was -82 gC m^{-2} $year^{-1}$ (31% bias as compared to the balance based on data not considering storage) for the year 2014. From the linear regression of NEE vs. turbulent flux (corrected vs. uncorrected fluxes) it also seems that taking into account RCS has only a minor effect on the half-hourly fluxes. Daytime fluxes were increased by 0.6% according to the slope of the linear regression (Fig. 5.) of the whole dataset (July, 2013 – June, 205) while night time fluxes became 4% lower after storage correction. The decrease (stronger sink activity) of the annual sum was caused by the fact that the majority of valid fluxes (69% of the daytime cflux) was corrected by a negative RCS. Moreover, the decrease of night time fluxes (due to RCS correction) caused the annual sum of ecosystem respiration to be decreased by 35 gC m^{-2} $year^{-1}$ (-3%). This induced a 47 gC m^{-2} $year^{-1}$ (4%) increase in the estimate of the annual sum of GPP in 2014.

	uncertainty [gC m^{-2} $year^{-1}$]		
	NEE	**R_{eco}**	**GPP**
without RCS	26	15	28
with RCS	28	17	31

Table 1. Uncertainty of NEE, R_{eco} and GPP as calculated by the Monte-Carlo method.

Uncertainty of the yearly sums was calculated by the Monte Carlo method described in the methods section. The values calculated for the dataset with and without RCS are similar (Table 1.). Furthermore, the values lie within the same range as the uncertainties for the gap-filling method used earlier (Pintér, 2009). Based on this analysis, RCS measurements used as a correction factor (storage correction) did not affect the uncertainty of the annual sum of NEE, R_{eco} and GPP.

Implementation of RCS measurements into the annual net ecosystem exchange estimate

The usual low data availability at night, the underestimation of night time fluxes and the accumulation of CO_2 below the measuring height of the EC system are coupled. RCS is usually low, when the wind speed is above a given threshold and the surface layer is well mixed, so aerodynamic criteria necessary for valid turbulence measurement are met. The contrary is true when turbulent mixing is weak. In these cases RCS is usually significant and the turbulent fluxes are not available/valid (Lavigne et al., 1997). According to Massman and Lee (2002) RCS is not fully accounting for the lack of turbulent flux at low wind conditions. Furthermore, Goulden et al. (1996) found that rate of CO_2 accumulation during low wind situations over forests was only 20-30% of turbulent exchange measured during windy intervals.

As positive RCS values reflect the rate of accumulation of CO_2 above the canopy their use as an alternative estimate of R_{eco} might be reasonable. Moreover, our measurements performed over a grassland (short vegetation on a plain) showed half-hourly RCS being of the same magnitude or even higher (more positive) than the intercept of the light response curve used as an estimate of R_{eco}. To illustrate this, positive RCS values (accumulation periods) during low turbulence conditions (u_{1m} < 1 ms^{-1}) and the intercept of the light response curve are presented on Fig. 6. RCS was also averaged for each night for the half-hours when the wind speed was below 1 ms^{-1}, this curve much closer to the R_{eco} estimated from the intercept. Because of the unknown contribution of advection and/or drainage flows to these fluxes the underestimation of R_{eco} is highly possible.

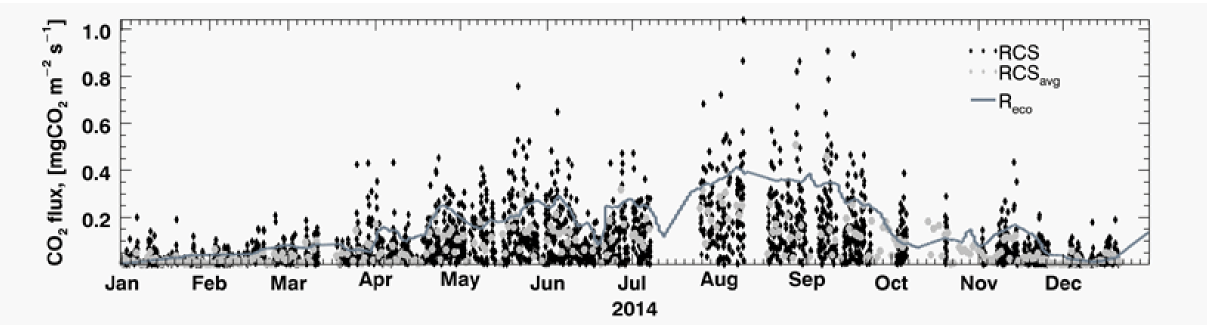

Fig. 6. Comparison of measured RCS, averaged RCS and R_{eco} estimated as the intercept of the light response curve.

An other method to use the RCS fluxes to correct for night time underestimation of (turbulent) fluxes was suggested by van Gorsel et al. (2007, 2009), namely deriving R_{eco} estimates as the maximum of early NEE (the sum of turbulent flux and RCS) and build temperature response curves to estimate daytime R_{eco} and/or fill the night time gaps. In our case only one response curve (for the whole year) could be built due to the low availability (especially during summer) of night time measurements. In their study due this approach annual NEE of a wet sclerophyll forest was reduced by 560 gC m^{-2} $year^{-1}$ (van Gorsel et al., 2008). According to our calculations the sink (2014) strength would be reduced by as much as 170 gC m^{-2} $year^{-1}$, a value which is comparable to the annual sink capacity. The biggest concern about this method might be that it is apparently using only one temperature response curve for the whole year, which is not to be preferred according to Reichstein et al. (2005) since the short and long time temperature sensitivity (E_0 parameter) of the response curve differs significantly. However, especially in the case of our dataset, splitting the data into subintervals (e.g. montly) was not possible because the low data availability (3-4 available maximum R_{eco} values in July and August) and the narrow temperature range made the fit impossible.

Summary and conclusions

- Accumulation and depletion of CO_2 (rate of change of storage, RCS) below the level of EC measurement at a semi-arid grassland are represented by fluxes of similar magnitude as that of the turbulent fluxes measured by the EC method. The maximum of the positive peak (representing the accumulation at early nights) was 1.1 $mgCO_2m^{-2}s^{-1}$ while the negative peak reached -1.35 $mgCO_2$ $m^{-2}s^{-1}$.
- RCS calculated from CO_2 concentration profile gave larger estimate as compared to calculated from CO_2 concentration at one (upper most) level in 65% of cases, while RCS was similar in 24% of the cases. Considering annual NEE sums the difference between application of the two methods was negligible.
- In practice, implementation of RCS fluxes into the annual net ecosystem exchange estimate means the correction of the valid turbulent fluxes by this term. RCS fluxes not associated to a valid turbulent flux are not included (Fig. 4.). As a result absolute values of daytime fluxes were increased by 0.6%, while those of night time fluxes decreased by 4% (Fig 6.).
- While from this point of view the RCS fluxes were found negligible as reported by Aubinet et al., (2005) and Nieveen et al., (2005), the annual NEE sum was modified by -82 $gCm^{-2}year^{-1}$. This might be a systematic bias caused by the fact that negative RCS values (depletion of CO_2) in the morning are more often taken into account (due to higher frequency of valid fluxes in this, than in the other parts of the day) than positive RCS (accumulation) at (early) night. Because of this selective systematic bias implementation of RCS fluxes into annual net ecosystem exchange estimate is not straightforward.
- After all, considering the source and similar order of magnitude positive RCS fluxes (as compared to R_{eco}) are seemingly promising candidates for estimating night time R_{eco}, the decrease of RCS during night supports the presence of advection flows and the unknown magnitude of these makes RCS unreliable estimate of R_{eco}.

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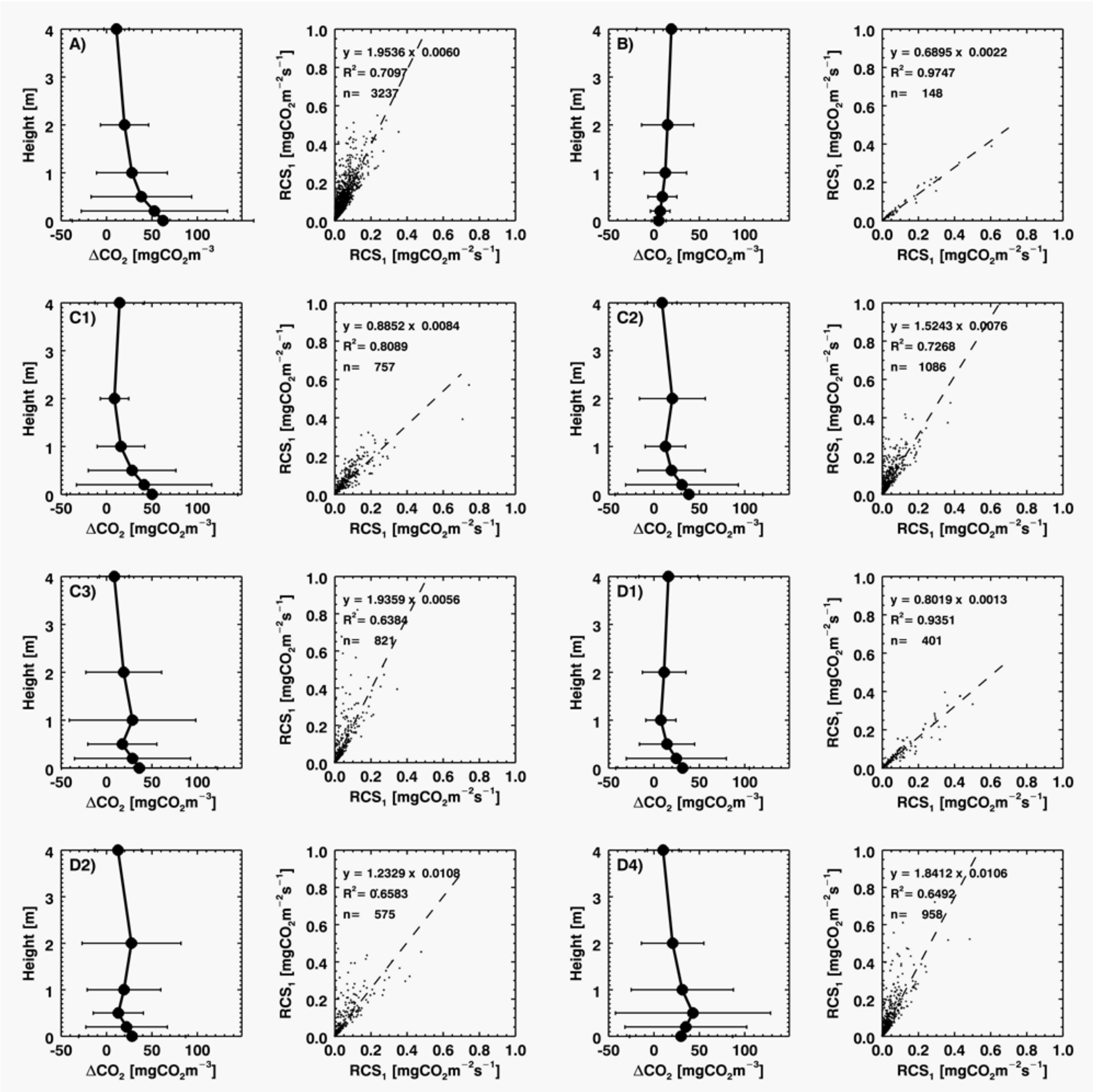
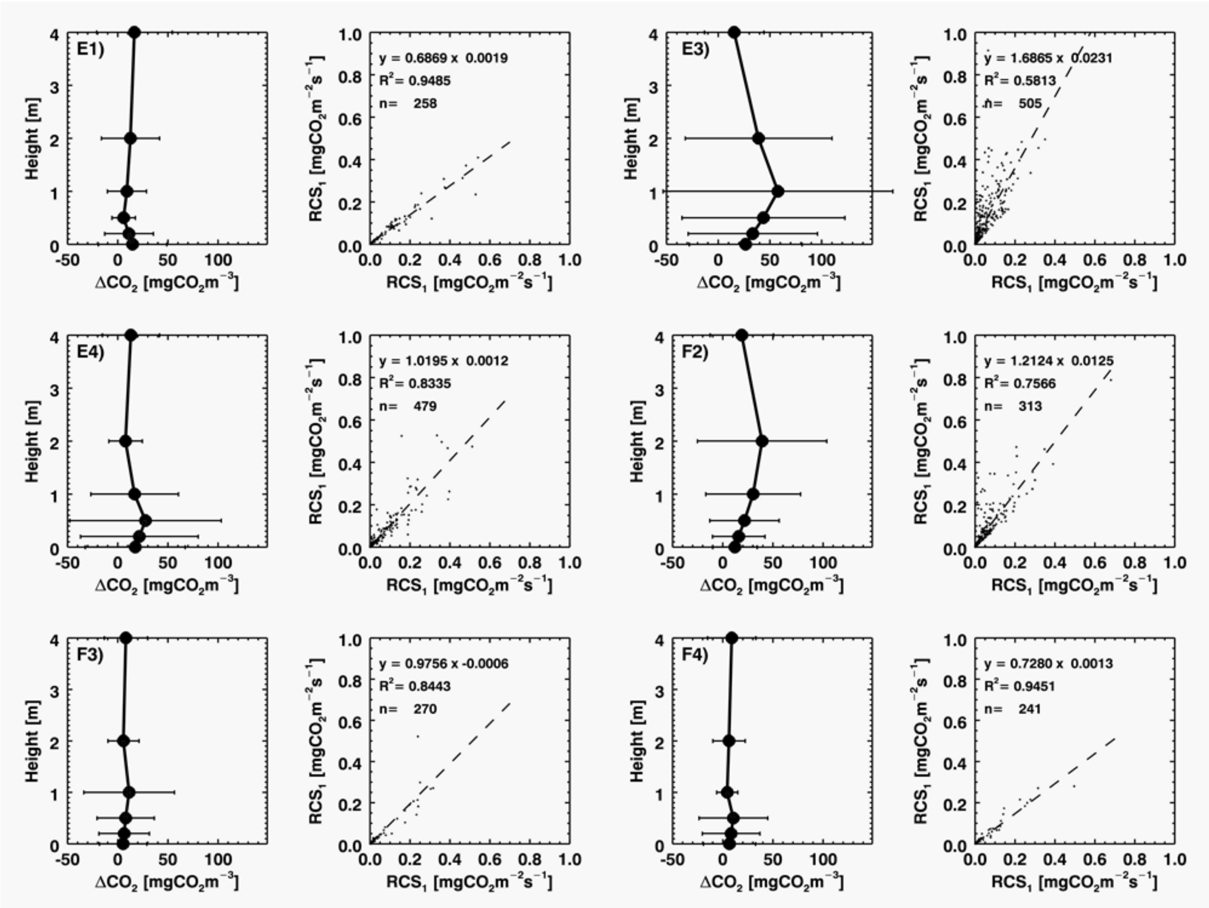
Appendix 1

Classification of CO_2 accumulation (positive RCS) events according to the vertical shape of the concentration change. Figures in the 1st and 3rd column represents the vertical change of concentration change. The scatter plot diagrams in the 2nd and 4th column shows the regression between RCS calculated from the concentration profile measurements (RCS_p) and from the 1 level approach (RCS_1) in the different classes. Class A: monotonously decreasing concentration change, Class B: monotonously increasing concentration change, Class C: 1 concentration change is bigger than its neighbour, C1: ΔCO_2 at 2 m is bigger than at 4m, C2: ΔCO_2 at 1 m is bigger than at 0,5m, etc. Class D: two concentration changes were bigger than the neighbours, Class E: three concentration changes were bigger than the neighbours, Class F: four concentration changes were bigger than the neighbours.

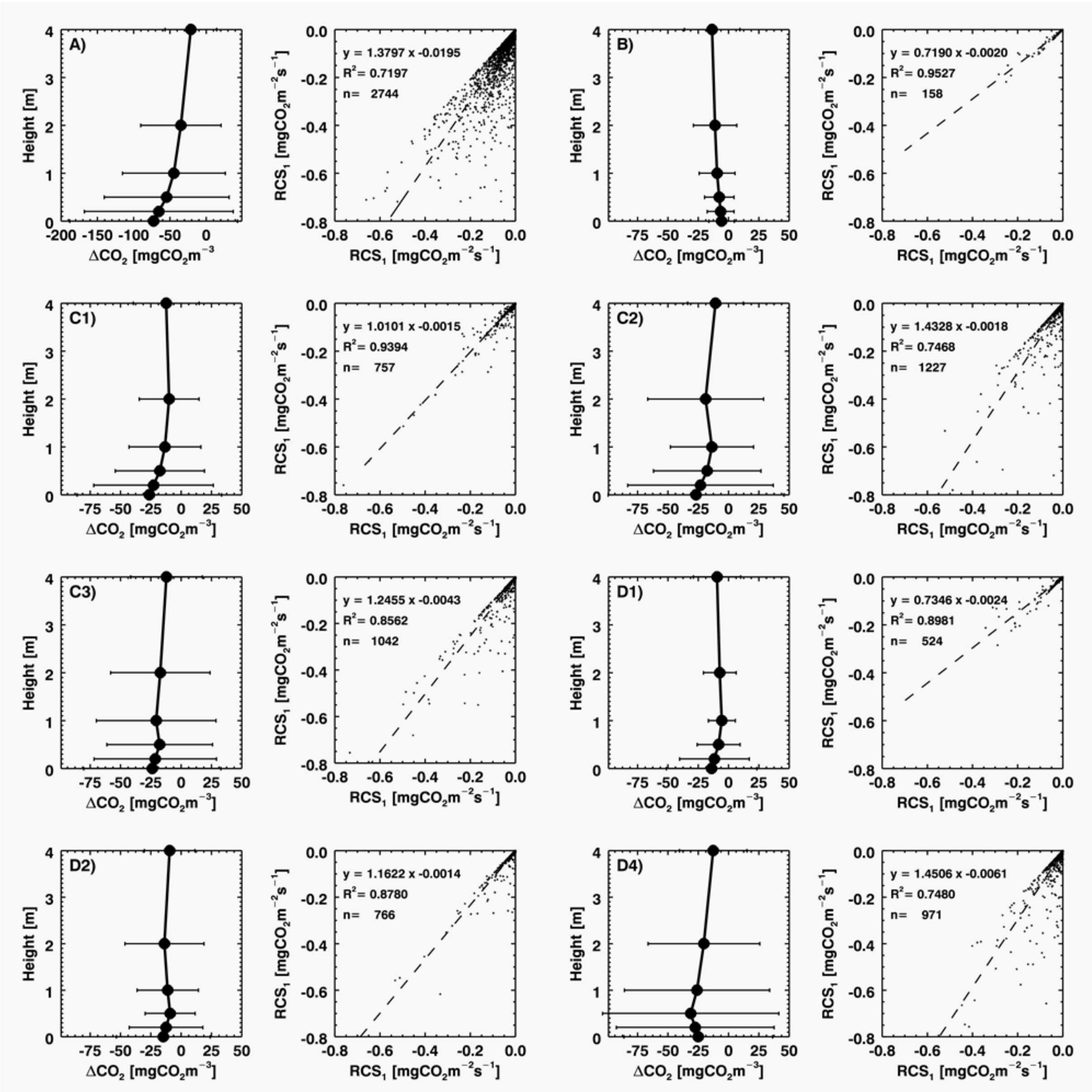


Appendix 1 continued



Appendix 2

Classification of CO_2 depletion (negative RCS) events according to the vertical shape of the concentration change. Figures in the 1st and 3rd column represents the vertical change of concentration change. The scatter plot diagrams in the 2nd and 4th column shows the regression between RCS calculated from the concentration profile measurements (RCS_p) and from the 1 level approach (RCS_1) in the different classes. Class A: monotonously increasing concentration change, Class B: monotonously decreasing concentration change, Class C: concentration change in one level is bigger than its neighbour, C1: ΔCO_2 at 2 m is smaller than at 4m, C2: ΔCO_2 at 1 m is smaller than at 0,5m, etc. Class D: two concentration changes were smaller than the neighbours, Class E: three concentration changes were smaller than the neighbours, Class F: four concentration changes were smaller than the neighbours.



Appendix 2 continued