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Water use in a sugar-cane plantation

Running title: Sugar-cane water use

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Abstract

The evapotranspiration (E) from a sugar-cane plantation in the southeast Brazil was measured by the eddy covariance method during two consecutive cycles. These represented the second (393 days) and third year (374 days) re-growth (ratoon). The total E in the first cycle was 829 mm, accounting for 69% of rainfall; while in the second cycle it was 690 mm, despite the total rainfall (1353 mm) being 13% greater. The ratio of E to available energy, the evaporative fraction, exhibited a smaller variation between the first and second cycles: 0.58 and 0.51, respectively. The estimated interception losses were 88 and 90 mm, respectively, accounting for approximately 7% of the total rainfall. The sugar-cane yield in the second cycle (61.5±4.0 t ha^{-1}) was 26% lower than the first cycle, as well as lower than the regional average for the third ratoon (76 t ha^{-1}). The below average yield was associated with less available soil water at the beginning of the cycle, with the amount of rainfall recorded during the first 120 days of re-growth in the second cycle being 16% of that recorded in the first (203 mm).

Introduction

During the last decade global biofuel production has increased. This has occurred mainly in the United States and Brazil (Qin *et al.*, 2011); most of the industrial ethanol produced in the world is made either from corn in the United States or sugar-cane in Brazil (Waclawovsky *et al.*, 2010).

The increasing demand for production of biofuels as an alternative to fossil fuel burning is promoting the conversion of existing agricultural areas (Loarie *et al.*, 2011). This trend may intensify with the introduction of second generation biofuels (lignocellulosic), unless they are based on waste biomass or the land-use changes occur in abandoned agricultural lands (Fargione *et al.*, 2008).

However, high growth rates are likely to be associated with high evapotranspiration rates (e.g. Hall et al, 1998), and the impacts on water resources of widespread bioenergy-crop planting of should be addressed. These impacts should be included in any energy or economic cost-benefit analysis of biofuel production (Das et al., 2011).

Currently, the area of the world under sugar-cane is approximately 20 million hectares. This area is spread over 70 countries (Galdos *et al.*, 2009), but the leading country is Brazil with 9.5 million hectares in 2009. Nearly 60% of this area is found in São Paulo state (Pinheiro *et al.*, 2010). The average sugar-cane yield in the southeast of Brazil attained after the first year of establishment in rain-fed conditions is 104 t ha^{-1}, the productivity of the re-growth from the stubble, known as the ratoon crop (Cuadra *et al.*, 2012), decreases at a rate of approximately 10% per year between the four successive harvests (ratoons). This reduction is mainly due to the cumulative stool damage during harvest (Bull, 2000). When it falls beyond about 70 t ha^{-1} the plantation is re-established (Macedo *et al.*, 2008).

To meet the growing demand for biofuel, future sugar-cane expansion in Brazil will probably occur in some low rainfall areas, where the crop may be expected to exhibit some water stress (Manzatto *et al.*, 2009; Waclawovsky *et al.*, 2010; Marin *et al.*, 2011); this is already the case in the western region of São Paulo state where the replacement of pasture has been going on for the last 15 years (Martinelli and Filoso, 2008).

The eddy-covariance method offers the capability of directly measuring the evapotranspiration, including the evaporation of intercepted rainfall and from soil during the time when the canopy cover is not complete, and at the characteristic field-scale of crops (Suyker and Verma, 2009; Denmead *et al.*, 2010). In this study we present two years of eddy-covariance data, covering two complete annual cycles of a representative sugar-cane plantation. The objectives are to establish the controls of climate (rainfall, soil water content and saturation deficits) on the crop development, to assess its water use, and to clarify its likely effect on the regional water budget – an important issue (Loarie *et al.*, 2011), as the water availability is considered the major cause of inter-annual yield variation (van den Berg *et al.*, 2000).

Materials and Methods

1-Site

The sugar-cane plantation, which belongs to the company Usina Santa Rita (USR), was situated in Luiz Antonio municipality in São Paulo State, Brazil (21^o 38' S, 47^o 47' W at 552 m altitude). The distance between planting rows was 1.4 m. The continuous area (> 400 ha) exhibited a small slope of less than 2% and was surrounded by pasture, citrus fruit orchards and the native savanna forest (Cerrado). The soil (Typic Haplustox) texture fractions are 22% clay, 74% sand and 3% silt, and the mean dry bulk density (d_b) down to 2.6 m depth is 1500 kg m^{-3}. Compaction resulting from previous mechanical harvesting has created a denser layer between 10 cm and 25 cm (d_b = 1636 kg m^{-3}). The available soil water between the potentials of -0.01 and -1500 kPa was 136 mm in the first meter.

The mean annual precipitation (from the years 1971 to 2007) and standard deviation is 1517±274 mm with the maximum in December (274±97 mm) and the minimum in July and August (27±34 mm). The mean annual temperature is 22 ºC, varying from 24 ºC in January to 19 ºC in July.

The sugar cane was planted in 2003 and there had been two previous harvests with stubble burning in the years 2004 and 2005. The data reported here covered the first cycle of second re-growth (ratoon), which started on 14 April of 2005 and extended to the harvest on 11 May 2006; and the second cycle or third ratoon that finished on 20 May 2007 (DoY 140). The length of each cycle was thus 393 and 374 days, respectively.

2-Instrumentation

Fluxes of momentum, sensible (H) and latent heat (LE) were measured by a three-dimensional sonic anemometer (R2A, Gill, UK) installed at the top of a 9 m lattice tower (0.5 m cross-section) and a closed-path infra-red gas analyzer (IRGA, LI6262, LICOR, USA). The air was pumped (KNF Neuberger, Germany) at a rate of 5 l min^{-1}, from an input co-located with the sonic anemometer through to the IRGA down 10 m of polyethylene tubing (4 mm internal diameter). The tubing was heated to keep it warmer than the ambient air and the air passed through two 1.0 µm pore-size membrane filters (Gelman Acro 50, Pall Corporation, USA). The IRGA reference was connected to a nitrogen gas cylinder and the calibrations were performed every two weeks. All the raw data (21 Hz) were stored on a data-logger flash card (CR1000, Campbell SI, USA) for subsequent analysis.

During 30 days in 2007 (DoY 100-130), an open-path IRGA (LI7500, LICOR, USA) was available for comparison with the closed-path system. It was deployed below the sonic anemometer at an angle of approximately 30^o with the vertical.

The air temperature, humidity (HMP45 Vaissala) and rainfall (Hydrological Inst.) were measured at 6 m height. The net radiation (R_n, LITE, Kipp and Zonen, The Netherlands), incident and reflected fluxes of photosynthetically active radiation (PAR, LITE, Kipp and Zonen, The Netherlands) and global solar radiation (R_g, CM3,Kipp and Zonen, The Netherlands) were collected by sensors installed on a horizontal mast 2.5 m away from the tower at 7 m height. The soil heat flux (G) was measured using four plates (REBS, USA) installed in different rows and inter-rows. The soil water content (SWC) was measured by 10 reflectometers (CS615, Campbell SI, USA) installed in a vertical profile, with each sensor representing layers of 30 cm, down to 3 m depth.

3-Data processing

The covariances between vertical wind speed (w), and the sonic temperature and the water vapor were obtained from the fluctuations relative to 30 minute block averages. Coordinate rotation (Kaimal and Finnigan, 1994) was applied to force the mean w=0. The water vapor time of travel down the sampling tube was assessed by continuously computing the absolute maximum correlation coefficients between w and a range of delayed signals (Moncrieff *et al.*, 1997). The frequency response corrections were empirically derived based on the low-pass filter technique (see Massman and Lee, 2002; Sakai *et al.*, 2004). The cospectral transfer function (H_{wq}) was calculated as the ratio of the measured normalized cospectrum of water vapor flux to the normalized cospectrum of heat flux ($H_{wq} = [Co(\overline{w'q'})/\overline{wq}]\,[Co(\overline{w'Ts'})/\overline{wTs})]^{-1}$). The characteristic time constant response (τ_s) was obtained following Mammarella *et al.* (2009) supposing the water vapor was measured by a first-order response sensor ($[1+(2\pi\,\tau_s\,f)^2]^{-1}$, where f is the natural frequency). Because the time lag was applied before the calculation of covariances, the sensor separation and phase-shift were already corrected (see Ibrom *et al.*, 2007).

The water vapor fluxes obtained from the open-path system were corrected for density fluctuations (Webb *et al.*, 1980) and the self-heating effect (Burba *et al.*, 2008).

The heat storage (S) in the air was approximated by the background variation of air temperature and humidity (see the profiles in maize by Santos *et al.*, 2011), and the biomass heat storage was calculated assuming that the aboveground biomass was in equilibrium with the air (see Meyers and Hollinger 2004). At intervals of approximately 20 days all the aboveground biomass (stalks, green and dead leaves) was sampled in ten random plots of 1 m along the planting lines, representing areas of 2.4 m^2. Sub-samples containing 10% of the fresh weight were oven-dried at 60 ^oC until a constant weight was reached. The leaf area indices of green (L_g) and dead (L_d, senesced) leaves were calculated from the sampled dry biomass and the specific leaf area of green (10.2 m^2 kg^{-1}) and dead (9.6 m^2 kg^{-1}) leaves.

4-Gap filling

Missing half hourly fluxes amounted to 20% during the first year of measurements and 18% in the second year, within the range reported for other sites (Falge *et al.*, 2001; Cabral *et al.*, 2010). The longest gap of 15 consecutive days was due to power failure after a lightning storm – a very common occurrence in this region. Due to the growth of the plants, for small gaps we used the mean diurnal variation (Falge *et al.*, 2001) over a five day non-overlapping window. When the sensible heat fluxes (H) were available the missing LE were estimated from the energy balance as the residual (see energy balance closure results), if not LE was obtained from the relationships between LE and R_n, fitted over variable time windows as a function of the data gaps. The soil water content (SWC) was simulated during the periods when it was not available by the model Hydrus1D (Šimůnek *et al.*, 2008), forced with the measured rainfall and evaporation data.

5-Bulk canopy and aerodynamic conductances

The bulk canopy conductance (g_c) was obtained from the inverse Penman-Monteith equation (Monteith, 1965) (see Cabral *et al.* 2003; Sakai *et al.* 2004), with the aerodynamic conductance for momentum transfer (g_a) being based on the wind speed and the sonic-anemometer friction velocity (u_*), following Gash *et al.* (1999). The calculations were performed for daylight hours between 08-17 h on dry days, i.e. without rainfall in the preceding 48 hours. Under these conditions it can be assumed (based on the observed nearly exponential decay of soil evaporation) that evaporation came predominantly from the vegetation (see Grace *et al.* 1998; Ryu *et al.* 2008).

6-Wet canopy evaporation

The evaporation of intercepted rainfall was obtained as the residual ($LE = R_n - H - G - S$) in the energy balance equation (see Gash *et al.* 1999; van der Tol *et al.* 2003). We tested the performance of the sonic anemometer during rainfall based on the linear relationship between u_* versus the standard deviation of vertical wind speed (Cabral *et al.*, 2010; van der Tol *et al.*, 2003). The residual LE was summed during rainfall events with more than 0.5 mm hr^{-1} and after, for as long as the vapor pressure deficit was lower than 0.7 kPa, under the assumption that, as the transpiration decreases during wet canopy conditions (see Tolk *et al.* 1996; Bosveld and Bouten 2003; Kume *et al.* 2008), the measured fluxes represented water from intercepted rainfall.

Results

1 – Fetch, flux corrections and energy balance closure

The peak distance from the measuring point to the maximum contributing source area (Hsieh *et al.*, 2000) estimated for a canopy height (h_c) of 0.5 m varied from 12 m (unstable conditions) to 120 m (stable conditions) and when h_c was 4 m, from 8 to 40 m respectively. The fetch around the tower consisted of sugar-cane plantation in all directions within a diameter of approximately 500 m. During unstable conditions the cumulative source contribution achieved was >90%.

The ensemble normalized cospectra of water vapor fluxes (LE) are presented in Figure 1a, calculated over three periods when the sugar cane was fully developed and therefore with the maximum attenuation of high frequency eddies. The estimated characteristic time constant of the first-order response sensor (τ_s) was: 0.5 s when the closed-path tubing was new, observed just before the harvest in 2005; 0.85 s one year later (2006); and 1.5 s two years later (2007). In the worst cases which represented the maximum attenuation in heat fluxes obtained by the application of the estimated τ_s the resultant water vapor flux losses were between 15% and 19%. However the comparison between the LE fluxes measured with the closed-path without corrections (LI6262) versus the open-path system (LI7500) during 30 days in April-May of 2007, and shown in Figure 1b indicated that on average the closed-path LE fluxes were underestimated by 5%.

The slope of the energy balance closure relationship ($H + LE = R_n - G - S$) forced through the origin without LE flux corrections was 0.83 (R^2=0.902; p=0.01), but after the data were spectrally corrected (Figure 2) the closure achieved was 0.97 (R^2=0.88, n=29624) and not significantly different from unity (p=0.01).

<<Place Figure 1 about here>>

<<Place Figure 2 about here>>

2 - The climate, soil water content and canopy development

Daily averages of air temperature, humidity and saturation deficit are presented in Figure 3a. The air temperatures, which ranged from 12 to 27 ºC, did not limit the sugar-cane development (Campbell et al., 1998; Keating et al., 1999). Vapor pressures as high as 2.6 kPa were recorded in summer, while in winter values as low as 0.7 kPa were attained, the corresponding saturation deficits varied from 0.12 to 2.4 kPa. The lower winter temperatures were a consequence of passing cold fronts and were followed by periods with rising temperatures, lower vapor pressures and higher saturation deficits.

The daily totals of rainfall (Figure 3b) were characteristic of the region: summer rainfall days with some exhibiting more than 50 mm day^{-1} and a dry winter, disrupted by passing cold fronts as already noted above. The ranges of daily soil water content (SWC) in the three layers depicted in Figure 3b were 89-217 mm (0-0.9 m), 169-379 mm (0-1.8 m) and 282-610 mm (0-3.0 m), respectively and were recorded in the winter and summer of the second cycle.

The reflection coefficients (albedo) for PAR and Global fluxes were calculated as the ratios between daily totals of reflected and incident flux densities (see Fritschen, 1967) and are presented in Figure 3c. The comparison with the mean daily albedo obtained as the average of the measurements between 11 and 13 hr gave somewhat smaller results for PAR (slope=0.95; R^2=0.98) and global (slope=0.93; R^2=0.74) radiation fluxes.

The estimated one-sided green (L_g) and senesced (L_d) leaf area indices, as well the canopy height, are shown in Figure 3d. The PAR albedo (ρ_{PAR}) exhibited a steady decrease from 0.12, just after the previous harvest to 0.05 when the L_g achieved was 3.2 m^2 m^{-2}. Besides the saturation in ρ_{PAR} the L_g still increased and this was detected by the global radiation albedo (ρ_G). Nonetheless, L_g and ρ_{PAR} data exhibited the significant relationship: $\rho_{PAR} = 0.0775L_{\mathbf{g}}^{\mathbf{-0.2255}}$ (r^2=0.88 p=0.01).

There was a delay in L_g of nearly two months between cycles, because the minimum albedo (~0.05) in the first cycle was observed in October of 2005, while in the second cycle it was recorded in January of 2007; however the L_g values achieved were nearly the same 3.8 and 3.6, respectively.

The decrease observed during the final phase of the cycles (approximately the last 50 days) was the consequence of herbicide (glyphosate) aerial spraying; this is a common pre-harvest practice whose objective is to enhance the sucrose accumulation in sugar-cane stalks (see Dalley & Richard Jr, 2010).

<<Place Figure 3 about here>>

3-Available energy and turbulent fluxes

The time series of daily totals (water equivalent, mm day^{-1}) of evapotranspiration (E) and available energy ($A_v = R_n - G - S$) are shown in Figure 4. Low E values (0.1 mm day^{-1}) were observed in the initial phase of the re-growth; the maximum attained was

5.3 mm day^{-1} when the plantation was fully developed. The overall averages and standard deviations of E in each cycle were 2.1±1.1 and 1.8±1.4 mm day^{-1}, respectively. The water equivalent of the sensible heat fluxes (H) is indirectly displayed in Figure 4 as the difference between A_v and E, and whose range was from -0.1 to 5.4 mm day^{-1} with the overall averages being 1.6±0.6 and 2.1±0.9 mm day^{-1}, respectively. Bowen ratios (β=H/LE) as high as 5 were found at the beginning of the cycles, particularly in the second cycle, but a β of around 0.4 was representative of the fully developed plantation.

<<Place Figure 4 about here>>

The monthly totals (water equivalent, mm month^{-1}) of fluxes are depicted in Figure 5. The evapotranspiration (E) followed the available energy (A_v) and both were reduced in the summer by the cloudy conditions and rainfall. These conditions were more intense in the second cycle (2007).

<<Place Figure 5 about here>>

The total rainfall recorded in the first cycle (1194 mm) was below the long-term average minus one standard deviation (1517±274 mm) as well 12% lower than the total observed in the second cycle (1353 mm) which was considered normal, i.e. within one standard deviation of the long term average. However the cumulative rainfall during the initial 120 days of the first cycle (203 mm) was six times the recorded total in the second cycle. The long term averages and standard deviations relative to April-July and May-August totals, which represent the first 120 days of each cycle, were 190±96 mm and 142±85 mm, respectively. Thus, while the initial 120-day period of the first cycle received the average rainfall, the second cycle received rainfall (32 mm) well below the average.

The cumulative E measured by the eddy-covariance system (Table 1) during the first (392 days) and second (373 days) cycles was 829 mm and 685 mm, respectively. These figures represent the second and third year re-growth of a sugar-cane plantation. The total E in the first cycle accounted for 69% of rainfall, while it was 51% in the second cycle despite the total rainfall (1353 mm) being 13% greater. The evaporative fraction (E/A_v) varied between 0.17 and 0.72 and the overall averages and standard deviations in each cycle were 0.57±0.07 and 0.45±0.19, respectively. Because the wet canopy evaporation (Figure 5) was obtained as the residual in the energy balance equation, we tested the performance of the sonic anemometer during rainfall for 573 rainy 30-minute periods; the fitted slope of the linear relationship between u_* versus the standard deviation of vertical wind speed was 1.20 (R^2=0.83), close to the "universal" value and assuring the sonic anemometer was not affected by the rainfall. The number of days in each cycle with rainfall was 112 (28%) and 141 days (38%), and the amount of rainfall recorded overnight represented 58% (697 mm) and 64% (641 mm) of the total rainfall in each cycle, respectively. In terms of the parameters of Gash's analytical rainfall interception model (Gash *et al.*, 1995), the overall average rainfall ($\overline{R}$) and wet canopy evaporation rate ($\overline{E}_w$) were 3.6 mm hr^{-1} and 0.15 mm hr^{-1}, respectively. The observed maximum monthly total interception (Figure 5) was 33 mm in January of 2007 and the cumulative interception losses in each cycle were 88 and 90 mm, respectively, accounting for approximately 7% of the total rainfall (see Table 1).

<<Place Table 1 about here>>

4 – Sugar-cane yields

Since planting in 2003, the observed sugar-cane yields (stalks fresh-weight, Table 2) reached the regional averages during the first three harvests (UNICA, 2011), despite the inter-annual variation in the total rainfall. However the second-cycle yield (61.5±4.0 t ha^{-1}) was 26% lower than the first cycle as well lower than the average for the third ratoon (76 t ha^{-1}).

The amount of rainfall received during the initial 120 days of growth (Table 2) give us an indication why the expected yields were achieved with the exception of the third ratoon. The cumulative E recorded during the initial 120 days of the first cycle was 157 mm (Figure 5), therefore as long as the cumulative rainfall approximately attained this amount (157 mm) or the soil water content at the beginning of the cycle was nearly the field capacity (~140 mm m^{-1}) the probability of achieving the average yield increases.

The water use efficiency (WUE) calculated as Yield/E was 101 kg ha^{-1} mm^{-1} in the first cycle and 90 kg ha^{-1} mm^{-1} in the second, implying a reduction of 11% in WUE. The total rainfall received over the hypothetical fourth ratoon (Table 2) was normal (1710 mm), as was the amount of rainfall recorded for the initial 120 days of re-growth (204 mm).

<<Place Table 2 about here>>

5 - Bulk canopy and aerodynamic conductances

<<Place Figure 6 about here>>

We have calculated the hourly averages of aerodynamic conductance (g_a) and bulk canopy conductance (g_c) over days within distinct L_g intervals, the results are shown in Figure 6(a,b). The mean g_a (Figure 6a) increased from 20 to approximately 80 mm s^{-1} in part in response to the change in canopy structure (Figure 3d), but also due to the decrease in the distance between the canopy top and the sonic anemometer (9 m).

The hourly averages of g_c ranged from 1 to 60 mm s^{-1} (Figure 6b) and followed the increase in L_g (see Figure 3d). In order to verify whether there was a relationship between g_c and saturation deficit (D), the estimated hourly g_c values obtained under high irradiance conditions (PAR>1000 μmol m^{-2} s^{-1}) were normalized by the daily green leaf area index (L_g) from Figure 3d; these results are displayed in Figure 7. The ratio, g_c/L_g, represents the canopy conductance on a leaf area basis and the averages calculated over D intervals exhibited a strong potential relationship ($g_c/L_g = 16.0D^{-0.8904}$, R^2=0.8345).

The mean hourly aerodynamic conductance (g_a) calculated over friction velocity (u_*) intervals also exhibited a good relationship with u_* as shown in Figure 8. The linear fittings were obtained on days covering two intervals of L_g, which represented the initial and fully developed phases of the sugar-cane plantation. u_* was also well correlated with the wind speed (u), the fit was given by $u_* = 0.097u + 0.088$, R^2 = 0.9876.

<<Place Figure 7 about here>>

<<Place Figure 8 about here>>

The dependence of evapotranspiration on g_c (see autocorrelation issue, Suyker and Verma, 2008) was assessed by plotting the ratios of daily measured E against the FAO reference crop evapotranspiration (E_o) using Eq. 6 of Allen *et al.* (1998) with the measured available energy (Figure 9). The ratios exhibited a sharp decrease for g_c< 15 mm s^{-1} (L_g ~2) and achieved values around unity for the fully developed canopy.

<<Place Figure 9 about here>>

Discussion

1-Flux Corrections

The spectral corrections were comparable to the corrections reported by Sakai *et al*. (2004) above grassland and Mammarella *et al*. (2009) during the summertime in a forest, from 10%–15%, increasing with the u_* (Aubinet *et al.*, 2001) and the relative humidity (see Ibrom *et al.*, 2007; Mammarella *et al*., 2009); at the sugar-cane site although the relative humidity was higher during the summer the LE fluxes were also higher, which decreases the relative magnitude of the corrections.

2-Surface characteristics

The early senescence and reduced L_g (Figure 3d) observed in the second cycle are typical responses to water stress in sugar cane (Inman-Bamber and Smith, 2005). As reported by Roberts *et al.* (1990), this response can be reversed by a compensatory growth after re-watering. However the effects during the establishment of the crop possibly have more pronounced consequences for production (Robertson *et al.*, 1999), perhaps because at that time the deep roots were yet to be reestablished (see Smith *et al.* 2005; Battie Laclau and Laclau 2009). Based on the soil-water drying period in the winter of 2006 (Figure 3b) we found that the root system extracted water from a layer of 2.1 m depth just before the harvest, and from 1.2 m afterward.

3-Conductance

The daily patterns of sugar-cane canopy conductance for a given L_g varied little; similar results were found by Roberts *et al.* (1990) and Inman-Bamber and McGlinchey (2003) who used a fixed value of 25 mm s^{-1} when estimated the sugar-cane reference evaporation. The relationship between g_c and the saturation deficit (D, Figure 7) showed that for D greater than 1.5 kPa the canopy conductance was lower than 12.5 mm s^{-1} which is characteristic in C_4 plants (Polley *et al.*, 1992). The evapotranspiration was significantly reduced (Figure 9) when g_c was lower than 15 mm s^{-1} (L_g ~2), this has already been observed in C_4 crops (Steduto and Hsiao, 1998; Suyker and Verma, 2008). Based on the ratio (E/E_o) which represents a measure of the crop coefficient (Allen *et al.*, 1998), the maximum attained sugar-cane evapotranspiration approached the reference evapotranspiration; this result contrasts with that from Inman-Bamber and McGlinchey (2003) who found a coefficient of 1.25 was representative of the fully developed crop (see Denmead *et al.*, 2009).

4-Wet canopy evaporation

The average wet canopy evaporation ($\overline{E}_w$ = 0.15 mm hr^{-1}) observed above the sugar-cane plantation was the same as the optimized value obtained by Finch and Riche (2010) in a *Miscanthus* plot and within the range (0.1 to 0.2 mm hr^{-1}) of estimates based on the Penman-Monteith equation (van Dijk and Bruijnzeel, 2001). However we measured the sugar-cane interception loss at 7%, which was much lower than the 25% found by Finch and Riche (2010) and the 18% reported by van Dijk and Bruijnzeel (2001) for a maize, cassava and rice mixed-crop growing in humid tropical conditions; although these authors also measured an interception loss of 8% in another plot of mixed maize and cassava, closer to our results. These high interception losses may be a consequence of the measurements being taken in small plots with more exposure to the wind, in contrast to the extensive area of sugar cane used here.

The energy balance equation terms are prone to uncertainty, an issue which must addressed in order to give confidence in the residual LE estimates. During daylight rainy conditions the typical values of fluxes were approximately: R_n ~ 200 W m^{-2}; S ~ 4 W m^{-2}; G ~ 20 W m^{-2} and H ~ 60 W m^{-2}. The other estimated errors are in: R_n of 5% (Kohsiek *et al.*, 2007); S and G of 10 W m^{-2} (Oncley *et al.*, 2007) and H of 10% (Mauder *et al.*, 2007). Assuming that the errors are independent the maximum residual LE error would be approximately 18 W m^{-2} or 16% of LE (116 W m^{-2}). However the rainfall interception measurements also have large uncertainties as argued by Muzylo *et al.* (2009); for an accuracy of 2.5% in gross rainfall and throughfall, and with the interception loss being 7% of gross rainfall, the expected error in the measured interception is approximately 22%.

The estimated 7% interception loss implies that approximately 93% of the rainfall reaches the soil either directly as throughfall or indirectly as stemflow. The soil evaporation measured by Denmead *et al.* (1997) in a sugar-cane plantation without mulching accounted for approximately 40% of total evaporation while the green leaf area index (L_g) was <2.5; although the total leaf area is greater because the senesced leaves also remain attached to the stalks in the sugar-cane (see Fig. 3d) and therefore contribute to the canopy closure (Singles *et al.*, 2008). Thus practices like the system of trash-blanketing (Denmead *et al.*, 2010; Farine *et al.*, 2011), as opposed to the burnt-cane system representative of the conditions in Brazil, can effectively reduce this non-productive water loss (see Pereira *et al.*, 2006).

Even though the sugar-cane originated in the tropics, cultivation is spread over 70 countries with significant production in subtropical regions where the growth is limited by periods of the year exhibiting low temperatures and rainfall (Campbell *et al.*, 1998). The data presented here showed that rain-fed, sugar-cane evapotranspiration was driven by the available energy when the canopy was fully developed and the maximum attained E approached the reference evapotranspiration. The total E achieved in the water limited second cycle of the sugar-cane (690 mm) was similar to the annual E obtained in an Amazonian pasture (647±144 mm) by Sakai *et al.* (2004) and represented 41% of the annual rainfall (1597 mm), whilst the total E measured in the first sugar-cane cycle was 20% greater and exhibited the same order of the increase (0.43 mm day^{-1}) estimated by Loarie *et al.* (2011) on conversion of other crops or pasture to sugar-cane.

Based on the stalks moisture content (approx. 70%) the sugar-cane water use efficiency on a dry-weight basis (WUE_d) was 36.6 and 26.7 kg ha^{-1} mm^{-1} in each cycle, respectively. These values are comparable to soybean (average 31 kg ha^{-1} mm^{-1}) reported by Suyker and Verma (2009) and maize (29.7 kg ha^{-1} mm^{-1}) by Hickman et al. (2010) who also obtained considerably lower WUE_d for two perennial grasses: Miscanthus (19.7 kg ha^{-1} mm^{-1}) and Switchgrass (9.7 kg ha^{-1} mm^{-1}). However Suyker and Verma (2009) also observed higher WUE_d in maize (52 kg ha^{-1} mm^{-1}). High irrigated sugar-cane yields (260-299 t ha^{-1}) were obtained in the northeast of Brazil characterized by low precipitation and high solar radiation due to low cloudiness (Waclawovsky *et al.*, 2010). Although irrigation can be used to increase the yields of dryland crops it is likely to be preferentially used in the production of high-value food agriculture instead of biofuel feedstocks (Farine *et al.*, 2011).

These results should be representative of evapotranspiration under the conditions found in the areas where sugar-cane expansion is planned in Brazil, and the crop is not traditionally grown, as in the central region and parts of the northeast (Marin *et al.*, 2011), with some of them having low rainfall (Manzatto *et al.*, 2009).

As pointed out by Hickman *et al.* (2010) and already observed by Loarie *et al.* (2011) large-scale plantings of bioenergy crops could potentially increase E, thereby decreasing surface temperatures, increasing humidity, precipitation and cloud cover. These indirect land use changes effects (Zenone *et al.*, 2011) could be enhanced, because the sugar-cane is one of the crops whose productivity is not expected to decline due to the climate change predictions (Buckeridge *et al.*, 2011) as the increase in temperature, and the CO_2 fertilization effect which would delay the onset of drought due to the reduction in the stomatal conductance (Oliver *et al.*, 2009).

However our results showed that the sugar-cane agricultural system is less adapted to adverse growing conditions (see Schwalm *et al.*, 2010) because the lack of soil water resulting from the low rainfall at the initial phase of the sugar-cane re-growth limited the evapotranspiration.

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Tables

Table 1 – Summary of total fluxes (water equivalent, mm) recorded in each sugar-cane cycle, whose length (days) is shown between parentheses.

Cycle	Rainfall (mm)	Evapotranspiration (mm)	Available Energy (mm)	Rainfall interception (mm)
1 (393 days)	1194	829	1429	88
2 (374 days)	1353	685	1339	90

Table 2 – Sugar-cane yields (stalks fresh weight) measured by the mill (USR) and the regional averages (UNICA, 2011). The hatched columns exhibit the cycles measured in this work.

	Cane Plant	1st Ratoon	**2nd Ratoon Cycle 1**	**3rd Ratoon Cycle 2**	4th Ratoon
Stalks Fresh Weight	2003-2004	2004-2005	**2005-2006**	**2006-2007**	
Yield at Mill ($t\ ha^{-1}$)*	101.8 ± 4.91	95.9 ± 4.7	**83.4 ± 5.5**	**61.5 ± 4.0**	
Regional average	104.8	94.2	**83.1**	**76.5**	71.3
Total Rainfall (mm)	1950	1475	**1194**	**1353**	1710
Initial 120 days rainfall (mm)	177	257	**203**	**32**	204

*Mean and standard deviation of five plots around the flux tower

Figure Legends

Figure 1 – (a) Ensemble normalized cospectra of heat ($\overline{w'T'}$) and water vapor ($\overline{w'q'}$) fluxes representing three periods when the closed-path tubing was: new; one year and two years old. The thick line represents the inertial sub-range decay proportional to the natural frequency ($f^{-4/3}$); (b) relationship between the water vapor fluxes measured by the closed-path system (LI6262) without corrections versus the open-path (LI7500) during April-May of 2007, and the fitted line through the origin (y=1.05x, R^2=0.97).

Figure 2 – Relationship between the sum of heat and water vapor (H+LE) fluxes (30 min) spectrally corrected versus the available energy ($A_v = R_n – G – S$). The slope of the linear fit forced through the origin was H+LE=0.97 A_v, R^2=0.90, n=29812.

Figure 3 – Time series of (a) daily averages of air temperature (black dotted line), vapor pressure (black thin line) and saturation deficits (grey line); (b) daily totals of rainfall (grey bars); soil water content (0-0.9 m, thin black line; 0-1.8 m, thck black line; 0-3.0 m, dotted line); (c) daily albedo of PAR (triangles), global radiation (circles); (d) Leaf Area Index of green leaves (L_g, black line); dead leaves (L_d, grey line) and canopy height (H_c, dotted line).

Figure 4 – Time series of daily totals (water equivalent, mm day^{-1}) of available energy (A_v, dark area) and evapotranspiration (E, grey area).

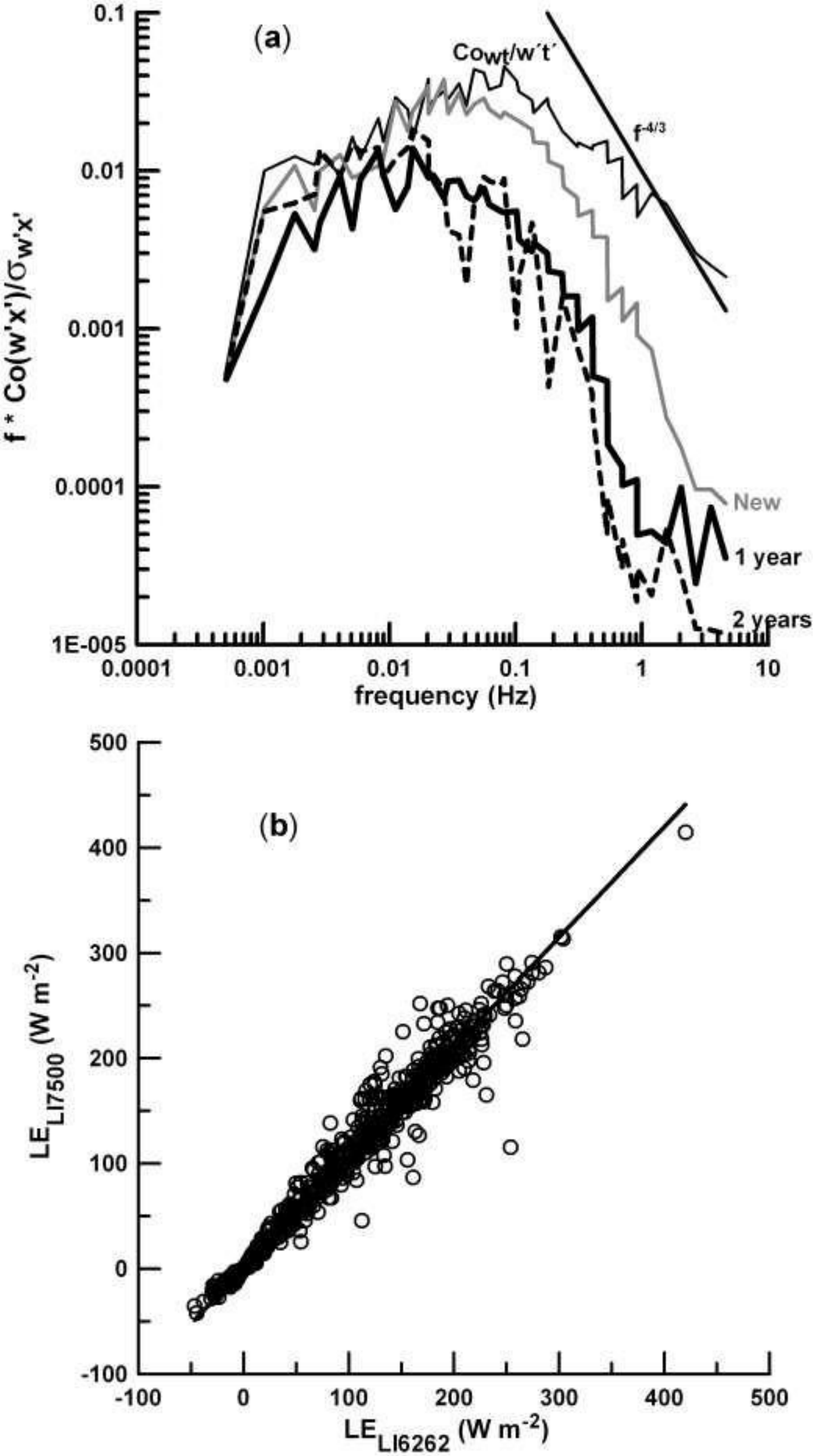
Figure 5 – Monthly totals (water equivalent, mm month^{-1}) of available energy (A_v, circles), Evapotranspiration (grey squares), Rainfall (triangles) and Interception (grey diamonds).

Figure 6 – Hourly averages of (a) aerodynamic (b) and bulk canopy conductance calculated over distinct time periods as given by the mean green leaf area index (L_g): Lg=0.2 (black circles); Lg= 0.7 (empty squares); Lg =1.1 (empty circles); Lg =2.3 (black diamonds); Lg =3.8 (grey squares); Lg =5.8 (black triangles). For clarity, the figures contain the standard errors only for upper and lower values of conductance.

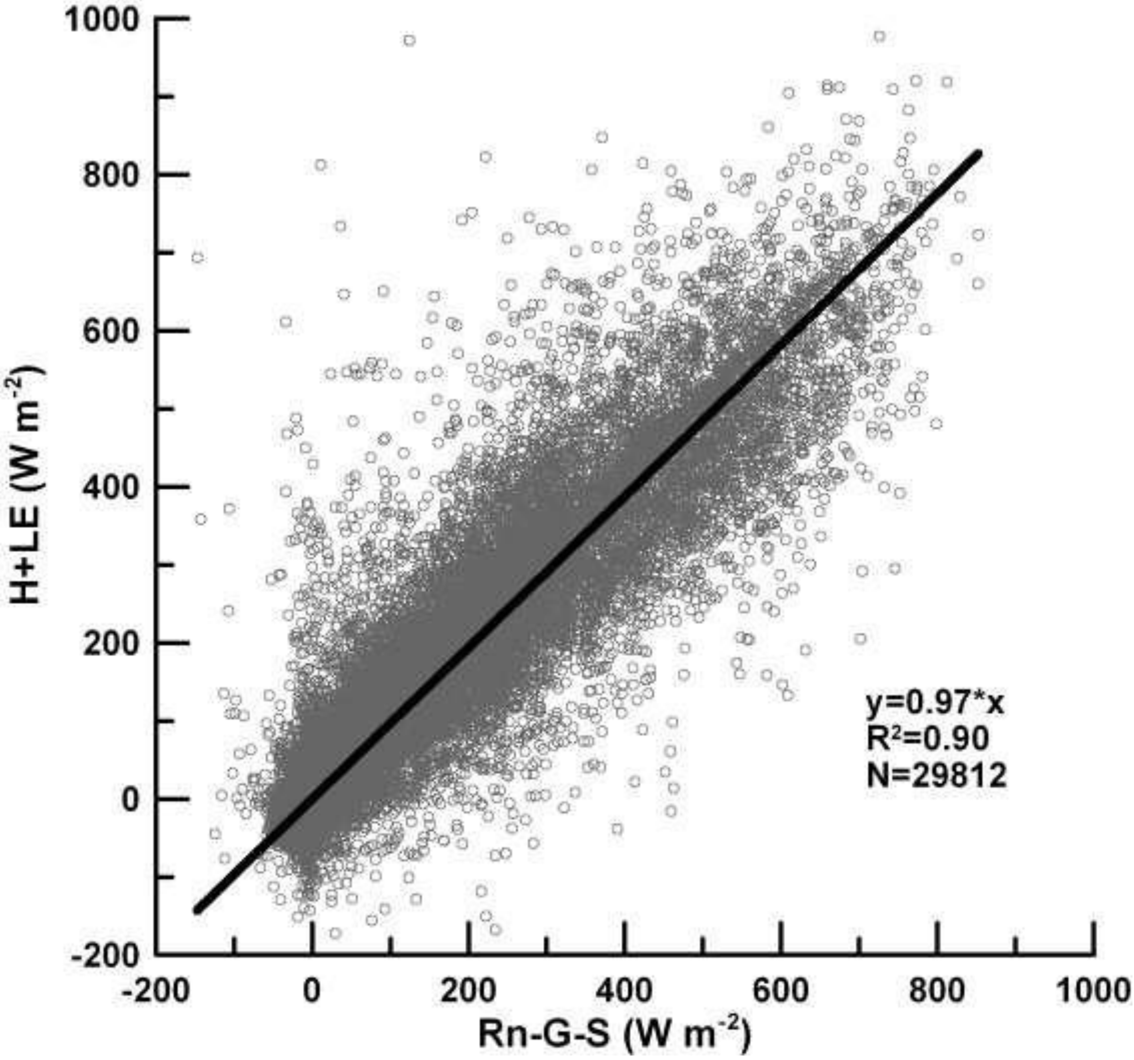
Figure 7 – Canopy conductance (g_c/L_g) divided by the leaf area index (L_g) during high insolation conditions (PAR>1000 µmol m^{-2} s^{-1}) versus saturation deficits (D, kPa). The black circles represent the averages over saturation deficits intervals and the bars are the standard errors.

Figure 8 – Mean aerodynamic conductances (g_a, mm s^{-1}) versus friction velocity (u_*) calculated when L_g<0.5 (circles) and L_g>4 (triangles).

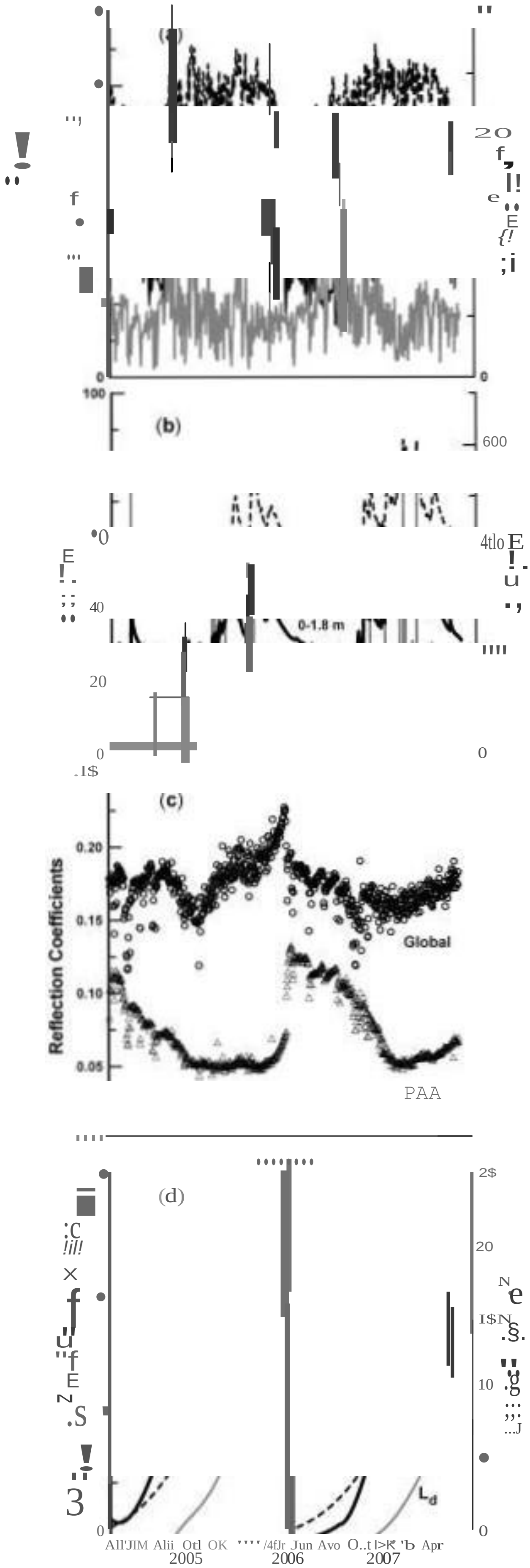
Figure 9 – Ratios of daily totals of evapotranspiration (E) by the reference evapotranspiration (E_o) versus canopy conductance (g_c), for cycle 1 (circles) and cycle 2 (diamonds). The average points (filled circles) were calculated over g_c intervals for both cycles and the bars are the standard deviations.



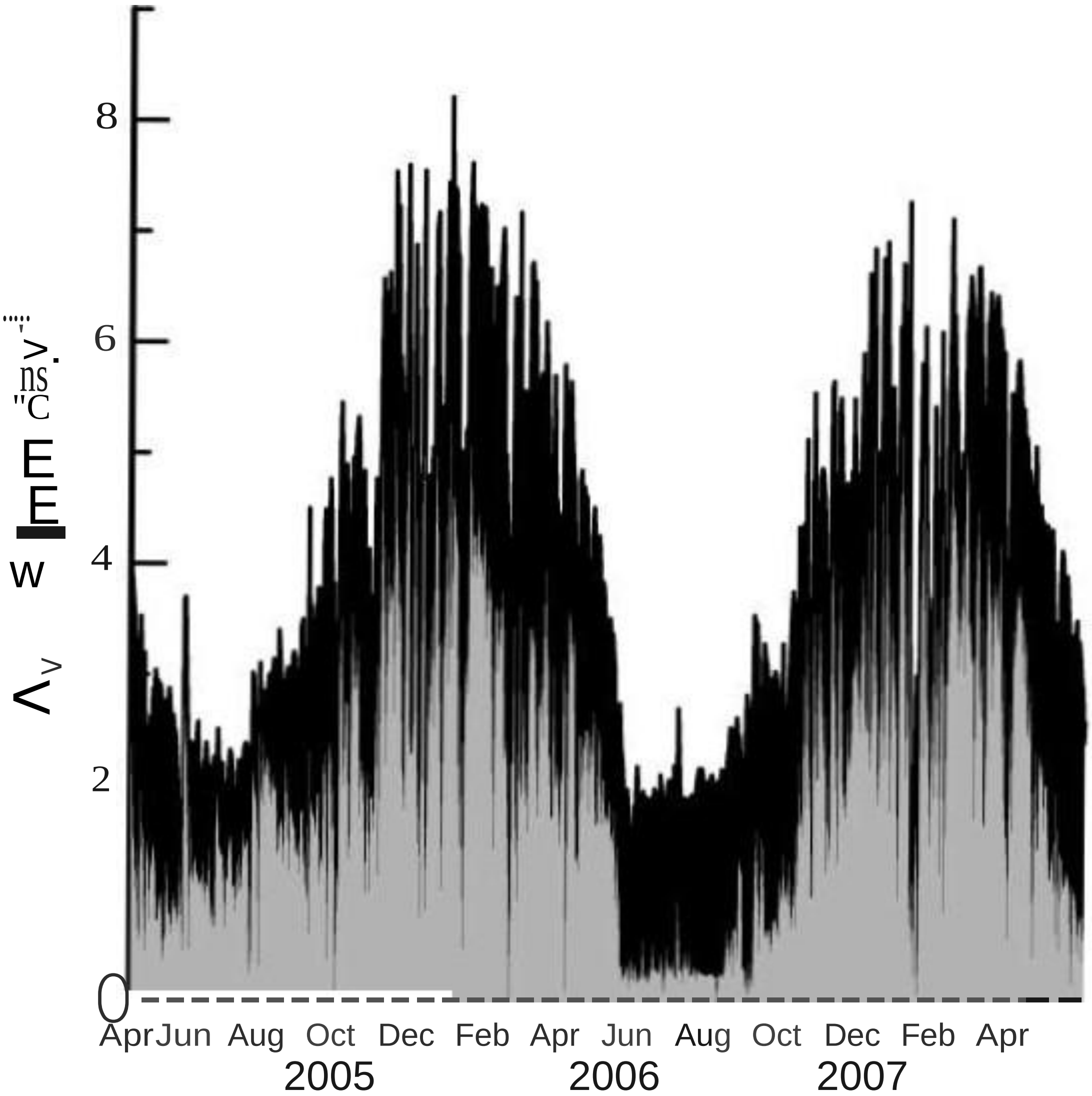
(a)
Cowt/w´t´
f-4/3
New
1 year
2 years
f * Co(w'x')/σw'x'
0.1
0.01
0.001
0.0001
1E-005
0.0001
0.001
0.01
0.1
1
10
frequency (Hz)
(b)
LELI7500 (W m-2)
LELI6262 (W m-2)
500
400
300
200
100
0
-100
-100
0
100
200
300
400
500

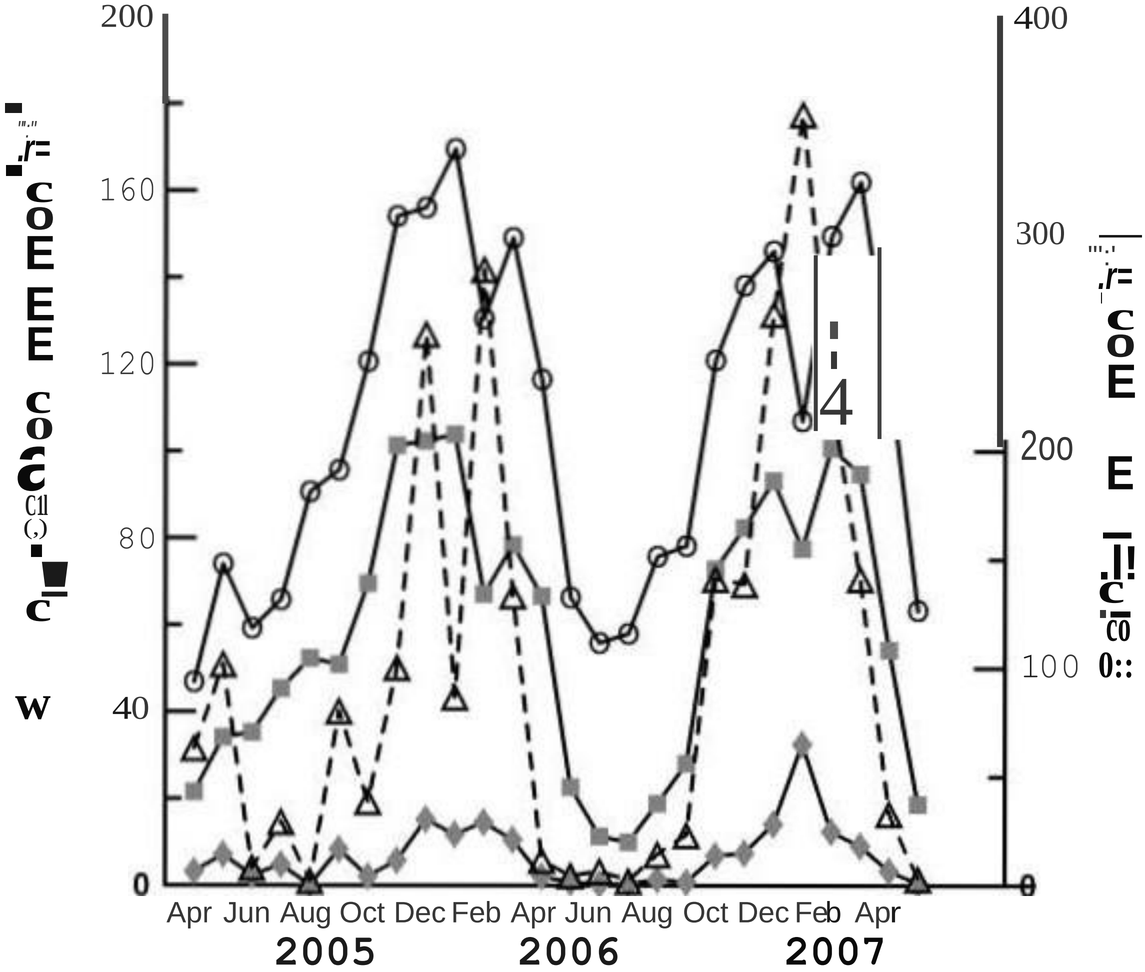


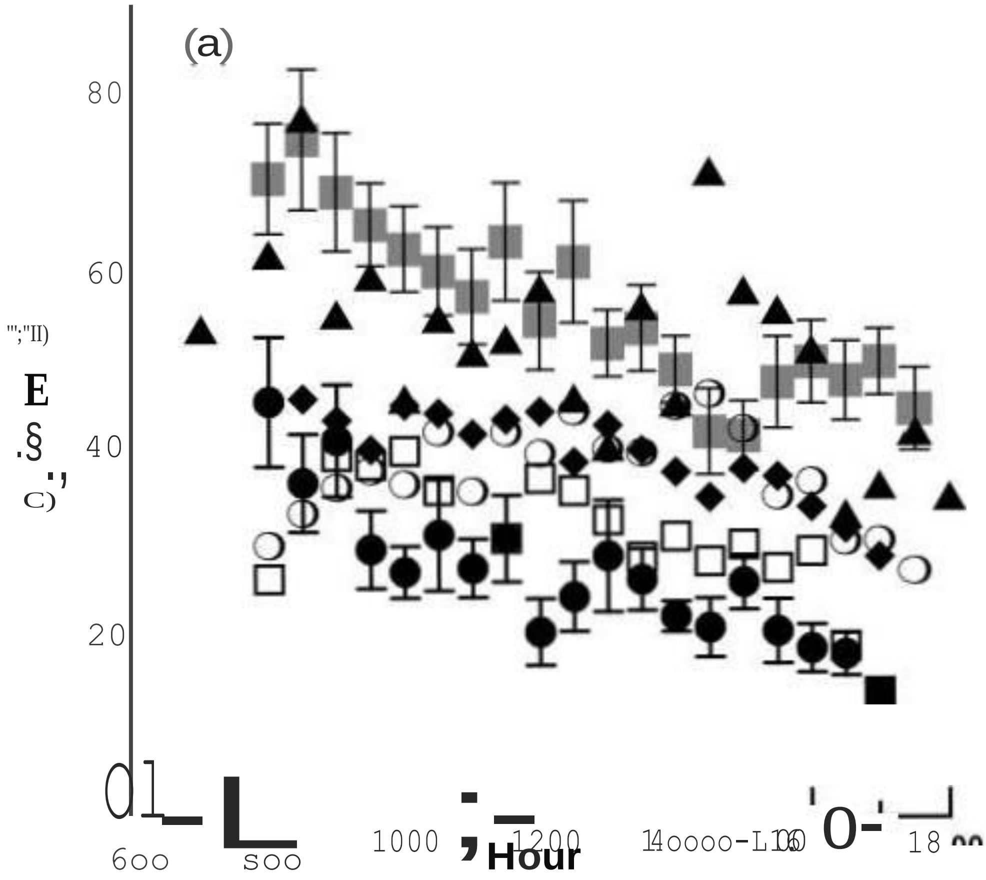
1000
800
600
400
200
0
-200
H+LE (W m-2)
-200
0
200
400
600
800
1000
Rn-G-S (W m-2)
y=0.97*x
R²=0.90
N=29812

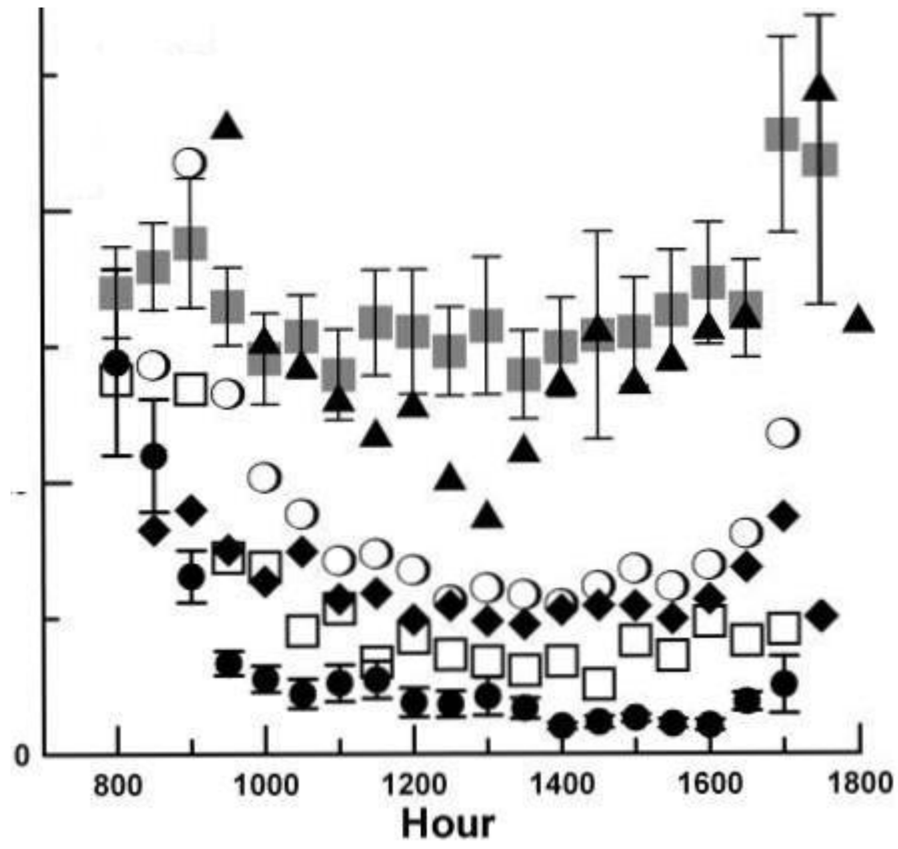


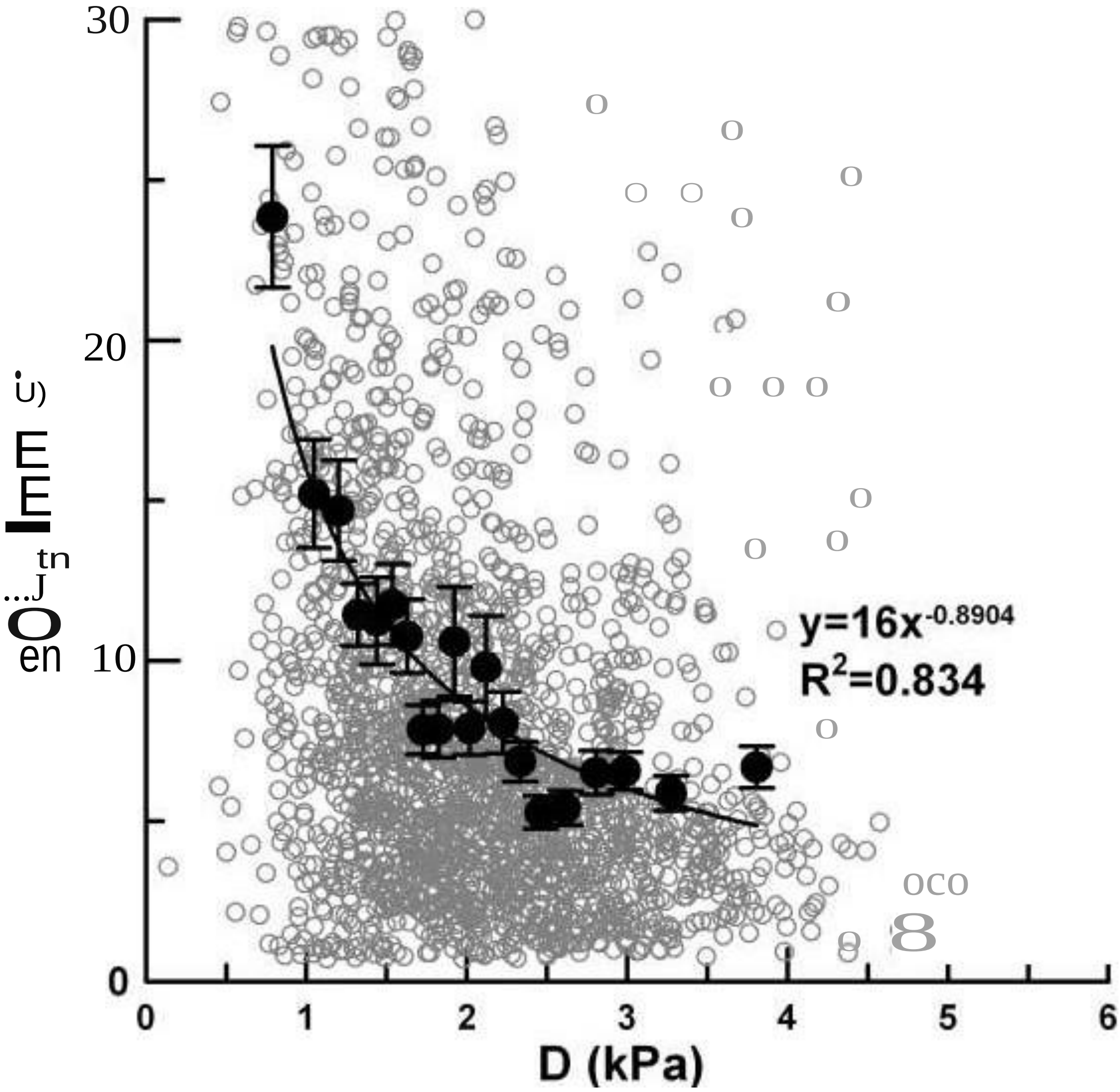
(a)
(b)
0-1.8 m
(c)
Reflection Coefficients
0.20
0.15
0.10
0.05
Global
PAA
(d)
2005
2006
2007


8
6
4
2
0
Apr Jun Aug Oct Dec Feb Apr Jun Aug Oct Dec Feb Apr
2005
2006
2007

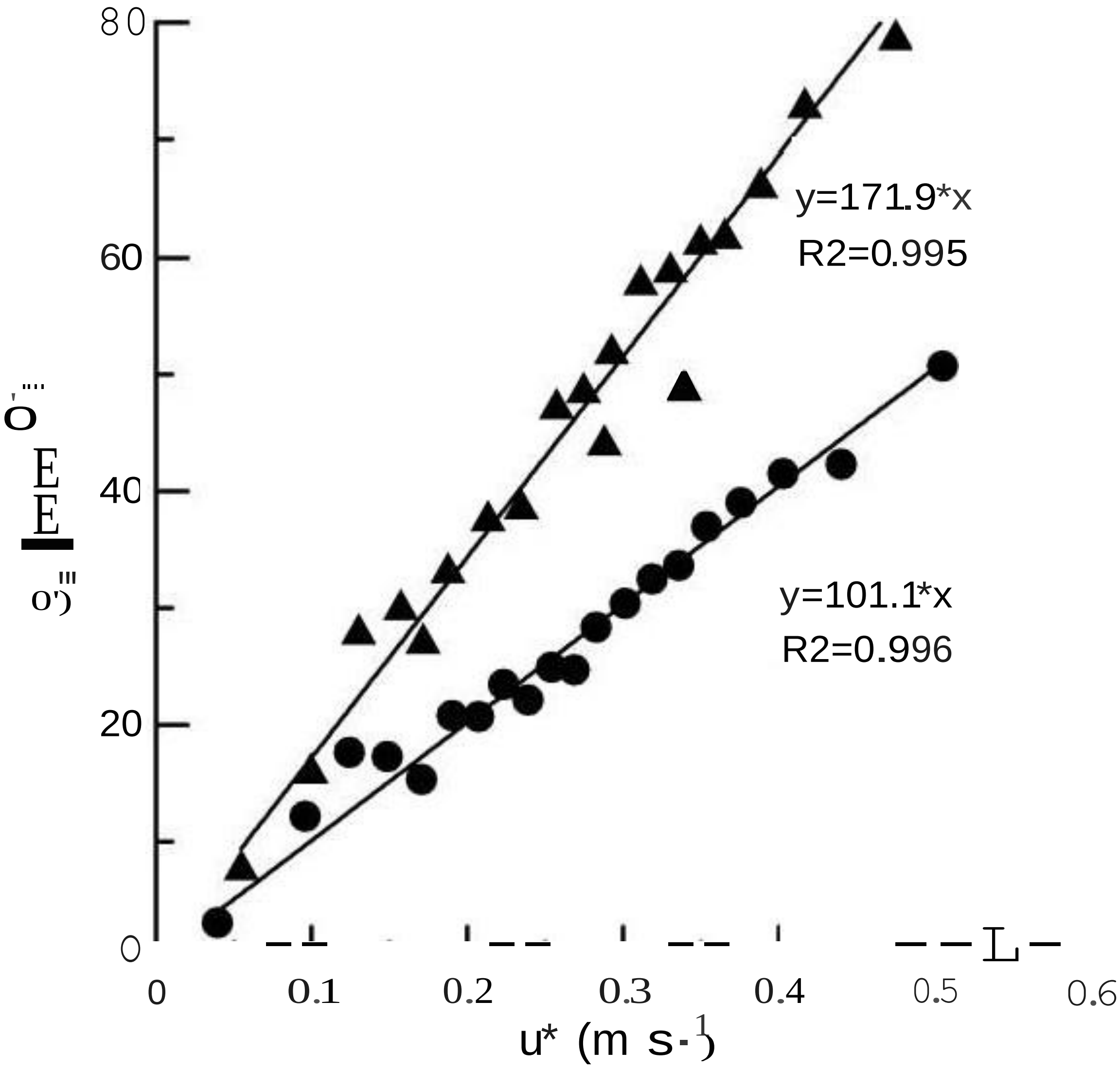

200
160
120
80
40
0
400
300
200
100
0
Apr Jun Aug Oct Dec Feb Apr Jun Aug Oct Dec Feb Apr
2005
2006
2007



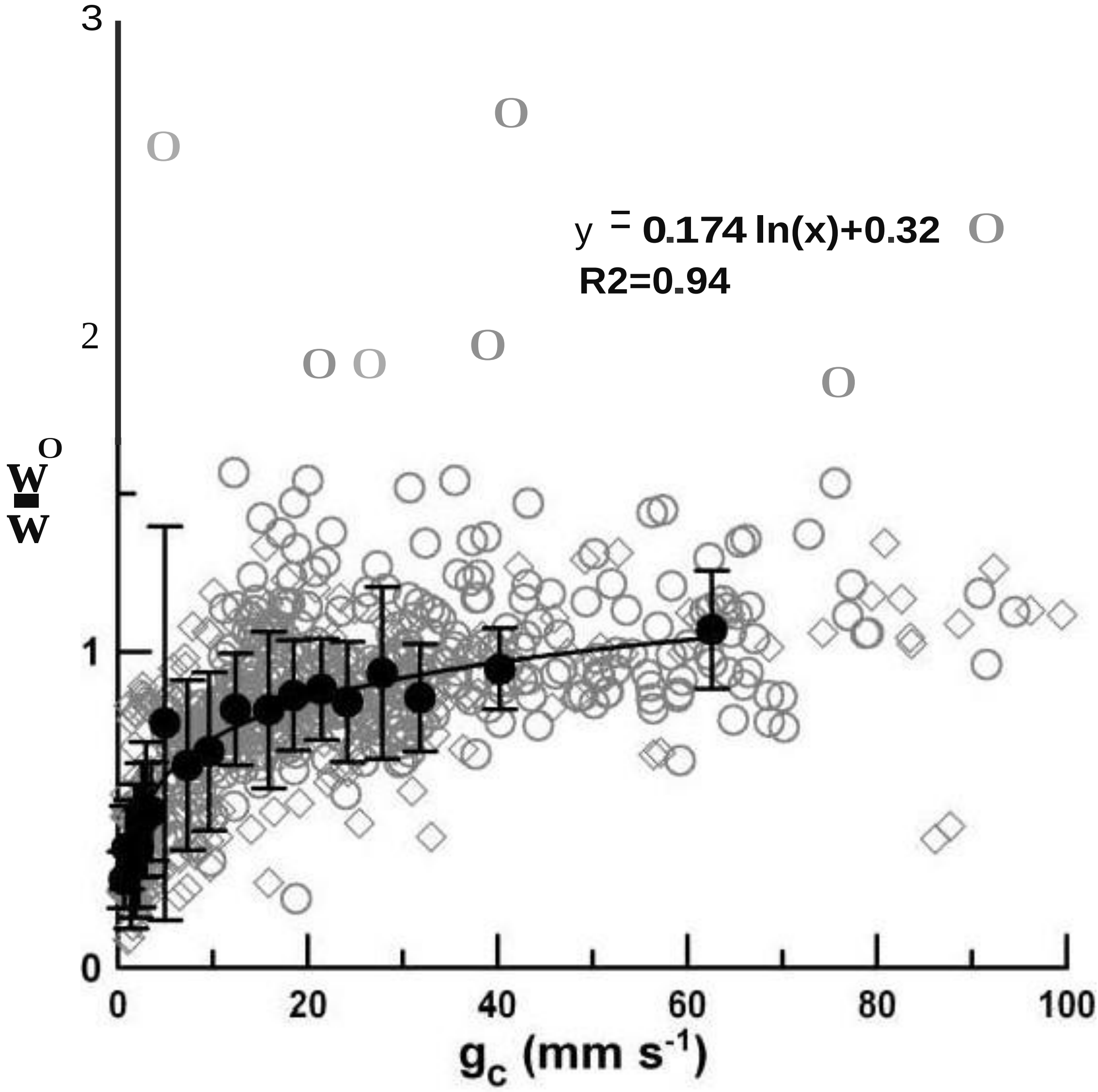




y=16x^-0.8904
R^2=0.834
D (kPa)



80
60
40
20
0
y=171.9*x
R2=0.995
y=101.1*x
R2=0.996
0
0.1
0.2
0.3
0.4
0.5
0.6
u* (m s-1)



3
2
1
0
y = 0.174 ln(x)+0.32
R2=0.94
0
20
40
60
80
100
g_c (mm s^{-1})