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Partial energy balance closure of eddy covariance evaporation measurements using concurrent lysimeter observations over grassland

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Abstract. With respect to the ongoing discussion on the causes of the energy imbalance and approaches to force energy balance closure a method had been proposed which allows the partial latent heat flux closure (Widmoser and Wohlfahrt; 2018). In the present paper, this method is applied to four measurement stations over grassland under humid and semi-arid climate, where lysimeters (*LY*) and eddy covariance (*EC*) measurements were taken simultaneously.

Results differ essentially from the ones quoted in literature. We distinguish between resulting *EC*-values weakly and strongly correlated to *LY*-observations as well as systematic and random deviations between *LY*- und *EC*-values. At the overall average, an excellent match could be achieved between *LY* and *EC*-measurements, which were partially closed with evaporation-linked weights. But there remain high differences between standard deviations of *LY*- and adjusted *EC*-values. For further studies we recommend data collected at time intervals even below half an hour.

No correlation could be found between correction evaporation weights and weather indices. Only for some datasets a positive correlation between evaporation and the correcting evaporation weight could be found. This effect appears pronounced for cases with high radiation and plant water stress.

Without further knowledge on the causes of energy imbalance one might perform full closure using equally distributed weights. Full closure, however, is not dealt with in this paper.

1 Introduction

During the last years several articles were published, in which lysimeter (*LY*) measurements were compared with eddy covariance (*EC*) measurements. A literature compilation on this can be found in Gebler et al. (2015). The increased interest in *LY*-*EC* comparison over the last couple of years may be related to the improvement of the *EC* and weighing *LY* measuring techniques.

Chavez and Howell (2009) hint at various error sources for *LY*- and *EC*-measurements. *EC*-observations on cotton fields in Texas with quarter-hourly measurements resulted in an energy balance gap of 73.2 to 78 %. Those gaps were closed assuming

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Bowen ratio preservation and correct measurements of the available energy. The comparison with *LY*-measurements on two fields reduced the differences from -41.4% to -28.8%, respectively from -34.1 to -26% with an accuracy of -0.03 ± 0.5 mm d^{-1} (≈ -0.9 ± 14 Wm^{-2}), respectively -0.1 ± 0.4 mm d^{-1} (≈ - 2.8 ± 11 Wm^{-2}). Negative values indicate that the lysimeter values were higher on average than *EC*-values.

Evett et al. (2012), using data from the same site as Chavez and Howell (2009), quotes errors of *EC*-measurements for latent heat flux with 1.9 to 2.7 mm d^{-1} (≈ 55 to 78 Wm^{-2}), for sensible heat flux with 1.4 to 1.9 mm d^{-1} (≈ 40 to 55 Wm^{-2}). Since those observations were made on cotton fields, an influence of the increasing plant height as against constant measurement height is suspected. After forced closure of the energy gap as done by Chavez and Howell (2009) differences between the two measurements methods were found from -17 to -19 % after correcting for plant growth, i.e. smaller than the ones mentioned by Chavez and Howell (2009).

In the same way, Ding et al. (2010) closed the energy gaps using half-hourly data on irrigated maize in an arid area in NW-China. There also, differences of daily measurements were reduced by forced Bowen ratio closure of the *EC*-gap. Differences could be reduced from -22.4% to -6.2%, the lysimeter measurements again being higher on average.

The following authors dealt with comparing measurements on grassland. Gebler et al. (2015) assumed that the energy balance deficit is caused by an underestimation of the turbulent fluxes only, which are corrected according to the evaporative fraction *LE/(LE+H)* averaged over 7 days. After correction, they find an agreement of *LY*-values with *EC*-values of 3.8 % (19 mm) over a year. The best agreements on the basis of monthly values during summer were obtained with less than 8 % of relative errors. The remaining differences are suspected to be due to different plant height within *EC*-fetch and the lysimeter. Mauder et al. (2018) evaluated two adjustment methods to close the energy balance: (1) the Bowen ratio preservation adjustment, following the approach of Mauder et al. (2013); (2) the method by Charuchittipan et al. (2014), which attributes a larger portion of the residual to the sensible heat flux. They also compare the *EC*-values with the results of the hydrological model GEO top 2.0 (Endrizzi et al.; 2014). They found that a daily adjustment factor leads to less scatter than a complete partitioning of the residual for every half-hour time interval. In contrast to the closure method used by the above quoted authors, Widmoser and Wohlfahrt (2018) achieved a partial latent heat closure of the energy balance by a direct comparison between *LY*- and *EC*-measurements, which is afterwards fully closed under the assumption of preservation of the Bowen ratio.

In this article, we concentrate on the partial evaporation closure of several datasets from four different stations by comparing concurrent *LY*- and *EC*-measurements. We close the energy gaps of the latent heat fluxes by applying the method used by Wohlfahrt and Widmoser (2013), which will be explained briefly in Sect. 2.5. The closing weights (*wL)* as well as systematic (*d*) and random deviations (d_{ran}) between *LY*- und *EC*-measurements will be presented. Results of the different datasets will be compared. The results differ essentially from the ones quoted in literature. Full closure will not be dealt with in this article.

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2. Material and methods

2.1 The data sets

Table 1 gives a list of the data used.

Table 1: Specifications of data used; *SM* denotes soil moisture

Name of station	Abbreviation	Country	Location	Observation period	Number of records used
Graswang	*G1*	Germany	47.57°N, 11.03°E; 864 m a.s.l.	02.03 – 31.10. 2013	1852
	G2			01.04 – 31.10. 2014	889
Fendt	*F1*	Germany	47.83°N, 11.06°E 597 m a.s.l.	01.03 – 24.10. 2013	720
	F2			01.04 – 31.10. 2014	846
Rietholzbach	*RHB*	Switzerland	47.37 °N, 8.99 °E, 795m a.s.l	01.05 – 30.10. 2013	920
Majadas	*M1* dry	Spain	39.56° N, 05.46 W 264 m.a.s.l.	15.05 – 12.10 2016	1103
	M2 dry season			15.05. – 25.08. 2017	1126
	M3 rainy season			25.08. 2017 – 05.01. 2018	823
	M4 dry season			21.04. – 03.09. 2018	1186
	M4 SMmoist			21.04. – 03.07. 2018	455
	M4 SMdry			04.07. – 03.09. 2018	731

In addition to the data of Table 1, we could use soil moisture informations. For Graswang, volumetric soil moisture was available as an average of three locations in 6 cm depth for each hour. For Majadas we could use half-hourly values measured in 40 cm depth.

Data were obtained from the following Institutions: (1) *RHB* from S.I. Seneviratne and M. Hirschi, Institute for Atmospheric and Climate Science, ETH Zurich, (2) *G* and *F* from M. Mauder, Institute of Technology (KIT-Karlsruhe), Garmisch-Partenkirchen, and R. Kiese, Institute for Technologie, Institute of Meteorology and Climate, both Germany; (3) *M* from O. Perez-Priego, Max Planck Institute for Biogeochemistry, Jena, Germany.

The stations *RHB, G* und *F* are within humid climate and represent typical grassland under agricultural use. For *G1*, *F1 and F2* measurements used were between 5 am and 8 pm with a time interval of one hour. The daytimes used for *G2*, also with time intervals of one hour, were reduced to 9 am to 4 pm for reasons given below (Sect. 2.4).

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The station Majadas represents a different situation in several aspects (Perez-Priego et al., 2015; Migliavacca et al., 2017):

- Climate: continental Mediterranean climate with winter rains (mean annual rainfall: ca 700 mm, mainly from November until May) and long dry periods during summer.
- Observation time was restricted from 9 am to 4 pm with half-hourly intervals. (Sect. 2.4)
- Plants: typical wood pasture (*Iberian Dehesa*) with low-intensity grazing by cows.
- The vegetation is dominated by an herbaceous stratum (dominated by species of grass, forbs and legumes (e.g. *Tolpis barbata, Anthoxanthum aristatum, Ornithopus compressus, Trifolum striatum, Lotus parviflorus and Plantago lagopus*) covered by oak trees (mostly *Quercus Ilex*) with low-density spacing (ca 20 trees per ha, i.e. 500 m^2/tree, i.e. ca 23 m average distance between trees).
- Lysimeter values are the mean of four lysimeter measurements.

2.2 Possible errors of lysimeter observations

Lysimeters can achieve measurement accuracies between ca ± 15 to ± 20 Wm^{-2} (≈ 0.5 to 0.7 mm d^{-1}), depending on their construction. Furthermore, hydraulic conditions (cylinder walls, soil conditions, ground water table) of the lysimeter do not correspond with the undisturbed surrounding. In addition to these systematic errors, random errors may occur due to instabilities caused by wind gusts. One may also note that lysimeter observations generally do not include negative values (condensation). The influence of wind and dew on lysimeter observations is described in Meissner et al. (2007) and Ruth et al. (2018). The theoretical accuracy of lysimeter measurements can be calculated from the surface area and weighing accuracy. For the *RHB*-lysimeter (operational since 1976), a systematic accuracy of about 0.03 mm/h (approx. ± 20Wm^{-2}) is quoted by Hirschi et al. 2017. All other lysimeters of this study are of the type TERENO Soil Can (METER Group AG, Munich, Germany; described by Gebler et al., 2015 and Mauder et al., 2018). Their calculated systematic accuracy is around 0.02 mm h^{-1} (approx. ± 15 Wm^{-2}).

2.3 Possible errors of *EC*-observations.

Systematic measuring errors of the latent heat flux (*LE*) may be around ± 30 Wm^{-2}, of sensible heat flux (*H*) around ± 13 Wm^{-2}, of available radiation (*A*) (net radiation minus the soil heat flux minus heat storages) around ± 12 Wm^{-2} (Alfieri et al., 2012). Errors caused by non-closure of the energy balance $\varepsilon = A - (LE+H)$ are not included in the estimates given above. The ε-errors result as the sum of *A-, LE-* und *H-* errors and may be around ± 55 Wm^{-2}.

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2.4 Data selection

High quality data were at disposal from all the observation stations. Still we had to dismiss 2 to 5% of the *EC*-measurements - mostly for morning and evening hours with high instability of turbulent fluxes. We sorted them out on the basis of the Out-of-Bound concept introduced by Wohlfahrt and Widmoser (2013), which excludes physically unrealistic measurements. Furthermore, data showing big differences between *LY*- and *EC*-measurements (i.e. > 300 Wm^{-2} ≈> 0.44 mm hr^{-1}) along with strong wind gusts (> 2.0 ms^{-1}), as well as early morning values with high air humidity and high dew formation were also excluded, thus reducing the original data sets for another 5% at the average.

The overall data selection led to a reduced number of early morning and late evening data as compared to the number of data available for the rest of the day. That means that results for around sunrise and sunset are generally less reliable. In case of *G2* the morning and evening data had to be reduced to such an extent that we decided to evaluate only data from 9 am to 4 pm. For Majadas, all morning data were omitted for this reason. The numbers of data given in Table 1 correspond to the data analyzed below.

2.5 Evaluation of weights *wL* by regression (partial closure)

Wohlfahrt and Widmoser (2013) introduced a simple framework for studying the energy imbalance (ε), i.e.

$$\varepsilon = A - H - LE \tag{1}$$

They proposed three dimensionless weights (*wA*, *wH* and *wL*) for the terms on the RHS of Eq. (1) which obey the following two constraints: (i) each weight is bound between zero and unity and (ii) the three weights sum up to unity.

Provided these weights are known, the terms on the RHS of Eq. (1) can be corrected for the lack of energy balance closure as:

$$cA = A - wA\varepsilon \tag{2a}$$
$$cH = H + wH\varepsilon \tag{2b}$$
$$cLE = LE + wL\varepsilon \tag{2c}$$

In this paper, we are concerned only with the evaluation of *wL* (Eq. 2c) by regressing the difference between *LY* and *EC* latent heat fluxes as a function of the energy imbalance:

$$LY - LE = wL\varepsilon + d, \tag{3}$$

where *wL* represents the slope of the best-fit linear relationship and the y-intercept (*d*) can be interpreted as a systematic difference between *LY* and *EC* latent heat flux measurements. The random difference follows from

$$d_{rand} = LY - (LE + wL\varepsilon + d) \tag{4}$$

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For regression, data were binned according to *LE*-size in such a way that for each bin the same number of data pairs (*LY*-*LE*) vs ε, see Eq. (3), was available. The number of bins, i.e. 5 to 14, depended on the number of data per dataset at disposal. At least 90 data-pairs entered each regression.

2.6 Used parameters

The results of the partial energy closure will be represented by the following parameters:

- *DLoL* = *LY* - *oLE* as difference between observed *LY*- and *EC*-observed *oLE*-values.
- *DLcL* = *LY* - *cLE* as difference between observed *LY*- and corrected *cLE*-values: *cLE* = *LE* + *wL* ε.
- *DLaL* = *LY* – *aLE* as difference between observed *LY* - and adjusted *aLE*-values: *aLE* = *cLE* +*d*

Furthermore we list the

- systematic deviations *d*, see intercept in Eq. (3)
- $\varepsilon_{red}/\varepsilon$ as a measure for the relative ε, remaining after adjustment; ε_{red} = (1-*wL*)
- weights *wL*

One may note that the *DLaL*-values correspond to the remaining differences after *LE* adjustment to the *LY*-data and as such may be interpreted as random deviations d_{rand} or noise.

3. Results

3.1 Basic evaporation characteristics

Tables 2a and 2b give means and standard deviations (*SD*) of the observed *oLE*-, the corrected *cLE*-, the adjusted *aLE*- and *LY*- evaporations for the analyzed periods and stations along with energy balance deficit ε and correlation coefficients between *LY*- and *LE*-data.

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180 **Table 2a: Basic evaporation characteristics for the humid stations (ρ = correlation coefficient)**

		G1	*G2*	*F1*	*F2*	*RHB*
oLE Wm^{-2}	*mean*	*153.2*	*149.1*	*107.3*	*133.3*	*139.3*
	SD	*99.5*	*78.3*	*95.1*	*73.3*	*100.7*
	ρ(LY,oLE)	*0.894*	*0.879*	*0.963*	*0.912*	*0.887*
ε Wm^{-2}	*mean*	*64.38*	*100.16*	*59.15*	*87.03*	*25.87*
	SD	*57.81*	*56.78*	*66.52*	*57.75*	*54.50*
cLE Wm^{-2}	*mean*	*179.7*	*176.3*	*129.5*	*163.9*	*146.2*
	SD	*114.5*	*95.9*	*114.4*	*85.0*	*105.2*
	ρ(LY,cLE)	*0.913*	*0.887*	*0.980*	*0.936*	*0.896*
aLE Wm^{-2}	*mean*	*185.5*	*175.5*	*113.7*	*167.1*	*148.3*
	SD	*110.1*	*89.8*	*115.4*	*84.2*	*104.3*
	ρ(LY,aLE)	*0.915*	*0.889*	*0.982*	*0.936*	*0.898*
LY Wm^{-2}	*mean*	*184.3*	*173.4*	*113.7*	*167.3*	*149.9*
	SD	*118.2*	*104.1*	*118.1*	*88.9*	*115.3*

One may note that *F1* has the lowest evaporation rate among the humid stations. This will influence the following results throughout.

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Table 2b: Basic evaporation characteristics for the Majadas stations (ρ = correlation coefficient)

		M1	*M2*	*M3*	*M4 all*	*M4 moist*	*M4 dry*
oLE Wm^{-2}	*mean*	*69.1*	*92.7*	*41.0*	*100.0*	*165.2*	*59.1*
	SD	*77.0*	*64.1*	*31.1*	*81.8*	*69.8*	*59.2*
	ρ(LY,oLE)	*0.928*	*0.867*	*0.771*	*0.910*	*0.723*	*0.943*
ε Wm^{-2}	*mean*	*125.78*	*133.58*	*122.41*	*161.62*	*181.12*	*149.40*
	SD	*52.39*	*54.52*	*51.56*	*60.21*	*72.26*	*47.40*
cLE Wm^{-2}	*mean*	*110.5*	*160.6*	*64.3*	*181.0*	*304.0*	*99.1*
	SD	*120.0*	*99.4*	*35.5*	*130.3*	*97.1*	*85.5*
	ρ(LY,cLE)	*0.957*	*0.926*	*0.803*	*0.967*	*0.898*	*0.959*

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aLE Wm^{-2}	*mean*	*105.4*	*152.6*	*69.6*	*177.1*	*301.9*	*96.8*
	SD	*104.2*	*92.0*	*35.0*	*132.8*	*91.7*	*87.2*
	ρ(LY,aLE)	*0.960*	*0.930*	*0.807*	*0.969*	*0.913*	*0.959*
LY Wm^{-2}	*mean*	*103.6*	*153.3*	*68.9*	*177.0*	*300.8*	*99.9*
	SD	*110.3*	*99.1*	*42.2*	*137.8*	*101.5*	*94.3*

3.2 Differences between means and standard deviations of *LY*- and *EC*-measurements

Tables 3a and 3b show the differences between LY- and EC-parameters of Tables 2a and 2b.

Table 3a: Parameter differences (*LY* – *EC*) for humid stations

Parameter		*G1*	*G2*	*F1*	*F2*	*RHB*
DLoL Wm^{-2}	mean	*31.12*	*24.32*	*6.41*	*33.94*	*10.63*
	SD	*18.62*	*25.85*	*23.06*	*15.58*	*14.60*
DLcL Wm^{-2}	mean	*5.05*	*-3.10*	*-15.75*	*3.35*	*3.70*
	SD	*3.71*	*8.24*	*3.71*	*3.90*	*10.07*
$DLaL = d_{rand}$ Wm^{-2}	mean	*-0.98*	*-1.34*	*0.67*	*0.18*	*1.60*
	SD	*8.06*	*14.33*	*2.70*	*4.73*	*10.94*

Table 3b: Parameter differences (*LY-EC*) for Majadas station; semi-arid (*moist* and *dry* are related to soil moisture content)

Parameter		*M1*	*M2*	*M3 rainy*	*M4*	*M4 moist*	*M4 dry*
DLoL Wm^{-2}	mean	*34.47*	*60.62*	*27.91*	*77.18*	*135.58*	*40.73*
	SD	*33.29*	*34.99*	*11.19*	*55.99*	*31.69*	*35.06*
DLcL Wm^{-2}	mean	*-6.92*	*-7.29*	*4.61*	*-0.74*	*-3.20*	*0.74*
	SD	*-9.47*	*-0.25*	*6.78*	*7.49*	*4.32*	*8.76*
$DLaL = d_{rand}$ Wm^{-2}	mean	*-1.81*	*0.70*	*-0.75*	*1.47*	*-1.16*	*3.08*
	SD	*6.02*	*7-08*	*7.22*	*5.06*	*9.73*	*7.13*

For all stations, the *DLoL*-averages are positive, i.e. the *LY*-observations are higher on average than the *EC*-observations. For the humid stations *F1*and *RHB* the *DLoL*-deviations are below the measurement accuracy. The *DLcL*- and *DLaL*-values are all below the measurement accuracy for the humid as well as the semi-arid stations.

3.3 Parameters obtained by the *LY-EC*-comparison

Tables 4a and 4b present the parameters *d* (intercept = systematic deviation), $\varepsilon_{red}/\varepsilon$ and *wL* as obtained by applying Eq. (3).

Table 4a: Parameters for humid stations

Parameter		*G1*	*G2*	*F1*	*F2*	*RHB*
d (intercept) Wm^{-2}	mean	*6.03*	*1.75*	*-16.42*	*3.17*	*2.11*
	SD	*7.02*	*9.25*	*6.55*	*3.47*	*5.23*
$\varepsilon_{red}/\varepsilon$	mean	*0.616*	*0.759*	*0.686*	*0.649*	*0.688*
	SD	*0.079*	*0.151*	*0.114*	*0.033*	*0.168*
wL	mean	*0.384*	*0.241*	*0.314*	*0.351*	*0.312*
	SD	*0.079*	*0.151*	*0.114*	*0.033*	*0.168*

Table 4b: Parameters for Majadas station; semi-aride (*moist* and *dry* are related to soil moisture content)

Parameter		*M1*	*M2*	*M3 rainy*	*M4*	*M4 moist*	*M4 dry*
d (intercept) Wm^{-2}	mean	*-5.11*	*-8.00*	*5.36*	*-2.21*	*-2.05*	*-2.34*
	SD	*17.90*	*12.02*	*4.43*	*12.31*	*15.30*	*4.64*
$\varepsilon_{red}/\varepsilon$	mean	*0.678*	*0.506*	*0.809*	*0.515*	*0.230*	*0.726*
	SD	*0.282*	*0.222*	*0.039*	*0.290*	*0.079*	*0.182*
wL	mean	*0.322*	*0.494*	*0.191*	*0.485*	*0.770*	*0.274*
	SD	*0.282*	*0.222*	*0.039*	*0.290*	*0.079*	*0.182*

The systematic deviations means *d* between *LY*- und *EC* are all within the measurement accuracy of *LY* with around ± 20 Wm^{-2}, respectively ± 15 Wm^{-2} except for *F1,* which is quite close to it.

3.4 Reduction of the *LY-LE*-differences by adjustment expressed in percentages.

Tables 5a and 5b give the average and standard deviation differences between *LY*- and *EC*-values as expressed in percentages of *LY*. The improvements made visible by comparing the differences before and after adjustments. As such, they may also be compared to the quotations in Chavez and Howell (2009), Ding et al. (2010) and Evett et al. (2012).

Table 5a: Comparison of the *LY-EC*-differences (means: upper 2 lines; Standard deviations: lower 2 lines) before and after adjustment of the *EC*-values, humid

adjustment	calculation	*G1*	*G2*	*F1*	*F2*	*RHB*
before	100*mean(*LY-oLE)*/mean(*LY*) %	*16.9*	*14.0*	*5.6*	*20.3*	*7.1*
after	100*mean(*LY-aLE*)/mean(*LY*) %	*-0.5*	*-0.8*	*0.6*	*0.1*	*1.1*
before	100* [SD(*LY)-SD(oLE*)]/SD(*LY*) %	*15.8*	*24.8*	*19.5*	*17.5*	*12.7*
after	100* [SD(*LY)-SD(aLE*)]/SD(*LY*) %	*6.8*	*13.8*	*2.3*	*5.3*	*9.5*

Table 5b: Comparison of the *LY-EC*-differences (means: upper 2 lines; Standard deviations: lower 2 lines) before and after adjustment of the *EC*-values, Majadas

adjustment	calculation	*M1*	*M2*	*M3*	*M4*	*M4 SMmoist*	*M4 SMdry*
before	100*mean(*LY-oLE)*/mean(*LY*) %	*33.3*	*39.5*	*40.5*	*43.6*	*45.1*	*40.8*
after	100*mean(*LY-aLE*)/mean(*LY*) %	*-1.7*	*0.5*	*-1.1*	*-0.8*	*-0.4*	*3.1*
before	100* SD(*LY-oLE*)/SD(*LY*) %	*30.2*	*35.3*	*26.5*	*40.6*	*31.2*	*37.2*
after	100* SD(*LY-aLE*)/SD(*LY*) %	*5.5*	*7.1*	*17.1*	*3.7*	*9.6*	*7.6*

3.5 Differences between *LY*- and observed, corrected and adjusted *EC*-measurements averaged for daytime-hours.

Figures 1a und 1b show the mean daytime cycle of observed hourly differences *LY - oLE (*denoted as *DLoL* in Tables 3a und 3b) at the individual stations. The averaged *DLoL*-differences appear low for the humid data sets and declining towards the afternoon. The Majadas-observations are higher and show a tendency of peaks around noon for the dry season.

Figures 2a and 2b give the corresponding differences between *LY*- and corrected *EC*-measurements, i.e. $DLcL = LY - LE + wL\varepsilon$.

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Figures 3a and 3b demonstrate the *DLaL*- values as differences between *LY*- and adjusted *EC*-measurements *aLE,* respectively the random deviations d_{rand}. The *DLaL* differences (= random deviations d_{rand}) for all stations are within the *LY*-measurement accuracy of ± 15, respectively of ± 20 Wm^{-2} and may be neglected.

3.6 Systematic deviations averaged for daytime-hours

Figures 4a and 4b present the systematic deviations *d* between *LY* and *oLE.* The systematic deviations for the humid stations are within the *LY*-measurement accuracy of ± 15 respectively of ± 20 Wm^{-2} and may be neglected with exception of the slight negative deviation of *F2.* For *M4 d*-values are clearly below the measurements accuracy.

3.7 Averaged hourly daytime values for *wL*

Figures 5a and 5b show averaged daytime-hour-values of the weights *wL*. Figure 5a gives the humid *wL*-data for bins ranging from 6 (G2) to 12 (G1, F1, F2) and 14 (RHB). The *wL* data for Majadas in Fig. 5b used bins varying between 5 and 12. We distinguish between the drying periods (about March to August) in red and yellow as well as the one "rainy" period *M3* (end of August 2017 to beginning of January 2018) in blue. Figure 5b also splits M4 into a period with "high soil moisture" (20.04. to 23.06., red line with blue triangles) and a "low soil moisture" (01.07. to 04.09., red line with yellow triangles). Both periods are under high temperatures and very sparse rainfall. For soil moisture, see Fig. 6b.

All humid averaged values of daytime-hours of *wL* are roughly within the range of around 0.2 und 0.4. Their standard deviation is highest in the hours around noon (not shown), and not as expected during sunrise and sunset hours. For Majadas, variations in the various datasets are higher, especially for the drying period (i.e. no rainfall, but still high soil moisture) of M4 (topmost line in Fig. 5b).

3.8 Temporal patterns

3.8.1 *wL* in time

Figures 6a and 6b show two different situations for the development of *wL* in time under varying soil moisture. Whereas Fig. 6a presents a limited dry period under humid conditions (*G1*), Fig. 6b demonstrates a gradually drying situation over 212 weeks (20.04. to 04.09. 2018) for *M4*.

3.8.2 Deviations in time

Figures 7a and 7b illustrate the *EC*-deviations from the *LY*-values before (light green) and after (blue) *EC*-adjustments along the analyzed time period for *F2* (7a) and *M4* (7b). They demonstrate again the remaining high variation.

3.9 Correlations between *wL* and different evaporation terms

Tables 7a and 7b show correlation coefficients between *wL* and three estimates of evaporations.

Table 7a: Correlation coefficients between *wL* and corrected *cLE*, adjusted *aLE* and *LY*; humid

wL vs	*G1*	*G2*	*F1*	*F2*	*RHB*
cLE	*0.764*	*0.612*	*0.708*	*-0.120*	*-0.300*
aLE	*0.827*	*0.723*	*0.720*	*-0.14*	*-0.344*
LY	*0.764*	*0.612*	*0.708*	*-0.12*	*-0.331*

Table 7b: Correlation coeffiecients between *wL* and corrected *cLE*, adjusted *aLE* and *LY*; Majadas

wL vs	*M1*	*M2*	*M3*	*M4 all*	*M4 moist*	*M4 dry*
cLE	*0.922*	*0.850*	*0.155*	*0.903*	*0.413*	*0.960*
aLE	*0.902*	*0.812*	*0.044*	*0.884*	*0.264*	*0.953*
LY	*0.865*	*0.756*	*0.032*	*0.859*	*0.238*	*0.916*

For 7 out of 11 datasets, including all three dry periods of Majadas, the correlation coefficients are rather high. We could however not find correlations between *wL* and other weather indicators or combinations of them (not shown).

4. Discussion

The method applied offers two results: (1) corrected *cLE*-values as given by $cLE = oLE + wL\ \varepsilon$ and (2) adjusted *aLE*-values as given by $aLE = cLE + d$. One may consider *cLE* as *weakly linked* to the *LY*-measurements via the *wL*-regression and *aLE* as strongly linked to *LY* via both *wL* as well as *d*. Differences between the two range between 1 and 15 Wm^{-2} (Tables 3), i.e. within the measurement accuracies.

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In general, *LY*- measured data are higher than data based on the *EC*-method. This is in accordance to literature (e.g. Chavez and Howell, 2009). They differ surprisingly little in humid climate with around 10 to 30 Wm^{-2} (0.35 to 1.0 mm d^{-1}) in contrast to the difference at the dry station Majadas with around 30 to 60 Wm^{-2} (1.0 to 2.1 mm d^{-1}).

The adjustment of the *LE*- to the *LY*-data expressed by the differences *DLaL* hint at a nearly perfect match for the means (Tables 3). They are all in the range of the measurements accuracies. All standard deviations given by the difference SD(*LY*) – SD(*aLE*), respectively SD(*cLE*), however, increase with adjustments, but remain less than SD(*LY*) (see SD for *DLoL*- and *DLaL*-values in Tables 3a and 3b).

The adjustments reached in this paper are higher (Tables 5) than the ones quoted by

- Chavez and Howell (2009) with reductions of *LY-EC*-differences from 41.4% to 28.8%, respectively from 34.1 to 26% with an accuracy of ≈ 0.9 ± 14 Wm^{-2}, respectively ≈ 2.8 ± 11 Wm^{-2}
- Evett et al. (2012), mentioning *LE-EC*-measurements errors within ≈ 55 to 78 Wm^{-2}, which were reduced after forced closure of the energy gap to *LY* - and *LE-EC* differences between 17 and 19 % and
- Ding et al. (2010), quoting that differences between *LY*- and *LE-EC*-measurements could be reduced from 30.2 to 10.3%.

It surprises that the systematic deviations *d* between *LY*- and *EC* measurements (Tables 4a and 4b) are within the measurements accuracies with exception to *F1,* which, however, is very close to it. For the humid regions *d* is positive (4 cases) as well as negative (1 case). For Majadas *d* is positive only for *M3,* measured during rainy season. For *M4* the *d*-values are distinctly below measurement accuracy (Table 4b; Fig. 4b). One could expect a more pronounced difference of *d* for the two different measurements devices (*RHB* and TERENO lysimeters).

The energy gaps are in the range of 25 to 100 Wm^{-2} for the humid stations. They are much higher for Majadas with around 120 to 180 Wm^{-2}. The gaps ε reduce to about 50 to 80% after partial energy closure. They appear rather constant (around 70%) for the humid regions and vary more for Majadas, for which the most striking variations, i.e. 23% and 72.6% respectively, occur with *M4* during high and low soil moisture (Tables 4a und 4b, lines ε_{red}).

The calculated *wL*-values appear nearly independent of daytime hours (Fig. 5a and 5b). Data from humid climate gave hourly averaged *wL*-values within a narrow range of 0.2 to 0.4. The corresponding values for Majadas show wider variations. During the non-rainy-season, they differ more substantially for *M4* with high soil moisture (*wL* around 0.78) and low soil soil moisture (*wL* around 0.25). We cannot give any explanation for this.

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Standard deviations of wL for daytime hours averages change little, but we were surprised to find the highest daily average standard deviations of wL at noon (Fig. 5b). We would have expected them to take place in morning and evening, when there are (1) less data available and (2) the energy fluxes are less stable.

Since wL-values are partly positively correlated to the height of evaporation (Tables 7a and b) and seem to depend to some extent on seasons (Fig. 6a and 6b), one might conclude that the high standard variations are rather related to weather conditions. No clear picture, however, can be drawn on this aspect.

We also could not find any explanation for other specific cases found, like the unexpected drop of d-values for $G2$ (Fig. 4a).

5. Summary and conclusions

The applied partial closure gives, according to our knowledge, so far the best adjustments of EC- to LY-measurements. The method gives two results for improved LE-estimates, one weakly linked and one strongly linked to the LY-readings. Their differences appear negligible in view of the inaccuracies of the input data. The method also allows a distinction between systematic (d) and random deviations (d_{rand}) for the first time, probably. The wL-weight-averages are rather stable during daytime. The systematic deviations d and random deviations (Tables 3) are all below or very close to measurements accuracies.

For the future, one should try to increase the information of LY- as well as EC-measurements. In a first step we recommend to perform the comparison of LY and EC based on 5 to 10 minutes intervals of lysimeter readings instead of currently one/half hour, and center the EC averaging window accordingly. We expect an improvement of the accuracy of wL-, d- and d_{rand} estimates thereby. The benefit of using higher resolved lysimeter data is described in Ruth et al. (2018).

In long terms, one may think of improving measurements accuracies of relevant input data. Lysimeter-measurements should include negative values (condensation) and consider the influence of wind. The former can be realized by including rain observation on a high temporal scale to identify a mass increase in the absence of rain, i.e., dew formation (Ruth et al.; 2018). As long as no improvements are realized, as a pragmatic solution for full energy balance closure we recommend closing by attributing one third of the gap ε to each of the three weights. This is common practice in land surveying. This recommendation is supported by the fact that we found generally rather constant wL-values during daytime between 0.2 and 0.4.

6. Data availability

The data basis for the presented analyses is available at https://doi.org/10.3929/ethz-b-000420733. The dataset consists of the half-hourly or hourly, respectively, time series of lysimeter and eddy covariance evapotranspiration, as well as ancillary data described in the text, from Fendt (2013-2014), Graswang (2013-2014), Majadas (2016-2018) and Rietholzbach (2013).

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Author contributions

Peter Widmoser initiated the study, conducted the analyses and wrote a first version of the manuscript. Dominik Michel revised the article and put it into shape for publication.

Competing interests

The authors declare that they have no conflict of interest.

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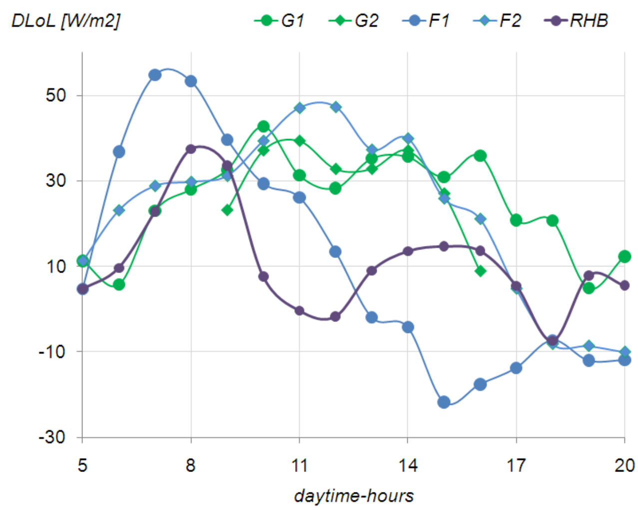

Figure 1a: ***DLoL = LY - oLE*** **as a function of daytime hrs; humid.**

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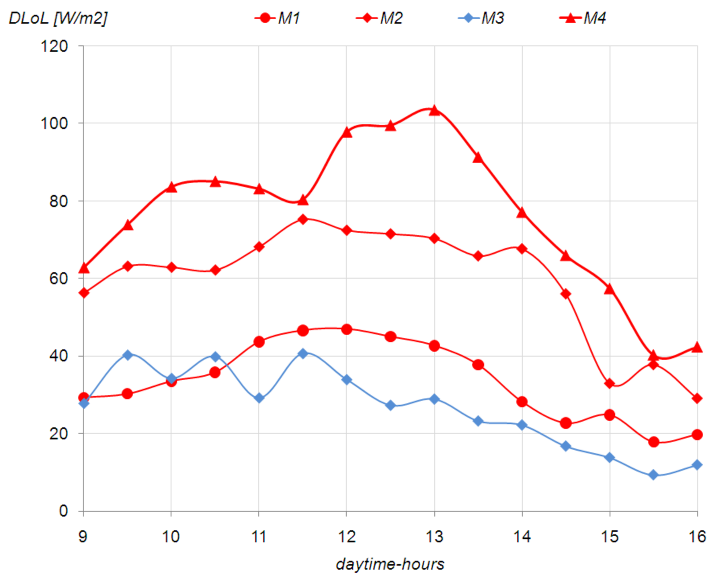

Figure 1b: ***DLoL = LY - oLE*** **as a function of daytime hrs; Majadas; red: dry; blue: wet season.**

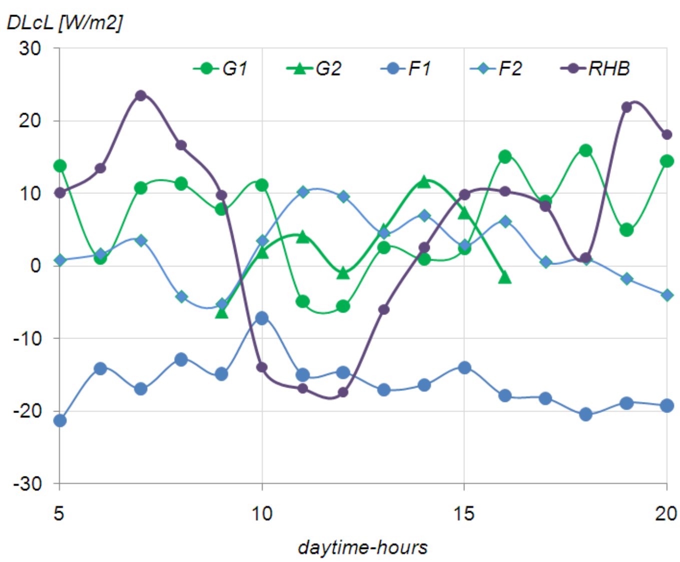

Figure 2a: Differences ***DLcL=LY – cLE*****; humid.**

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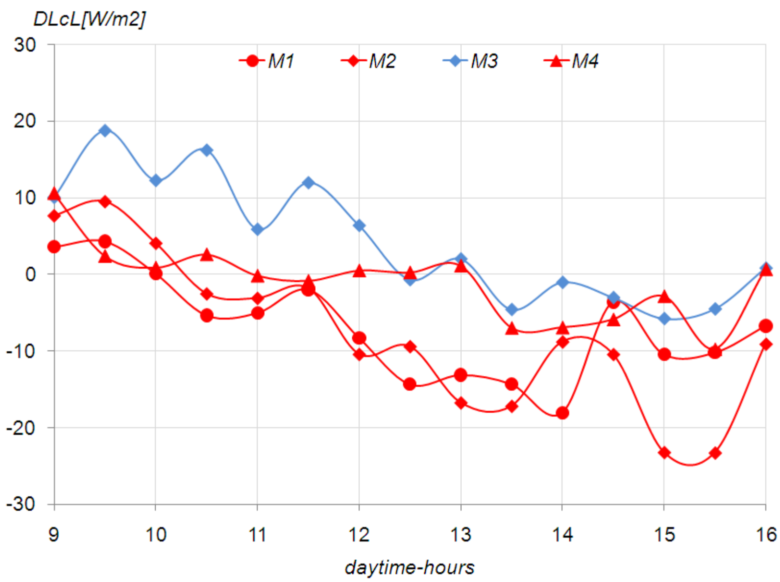

455 **Figure 2b: Differences DLcL= LY – cLE; Majadas red: dry; blue: wet season.**

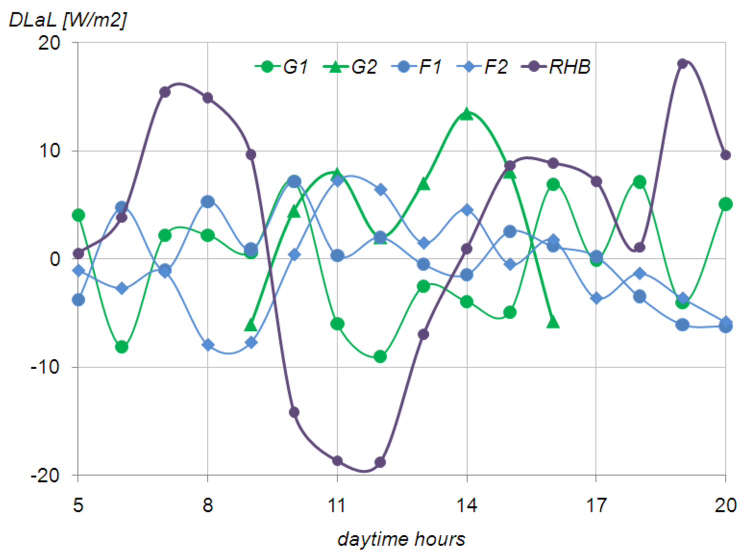

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Figure 3a: *DLaL* between *LY* and *LE*-values as a function of daytime hrs; humid.

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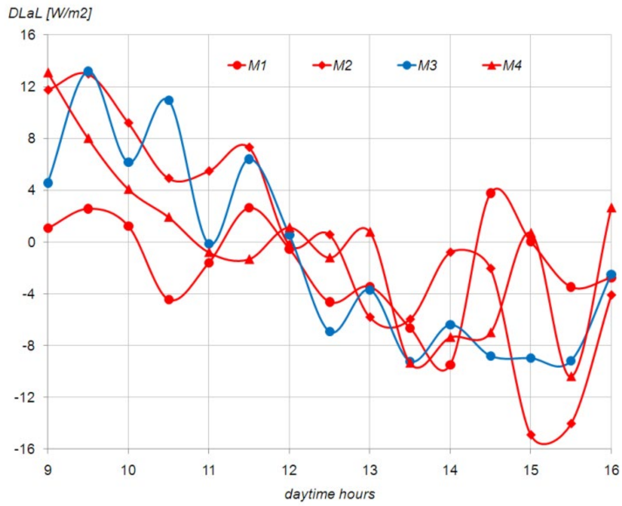

Figure 3b: *DLaL* between *LY* and *LE*-values as a function of daytime hrs, Majadas; red: dry; blue: wet season.

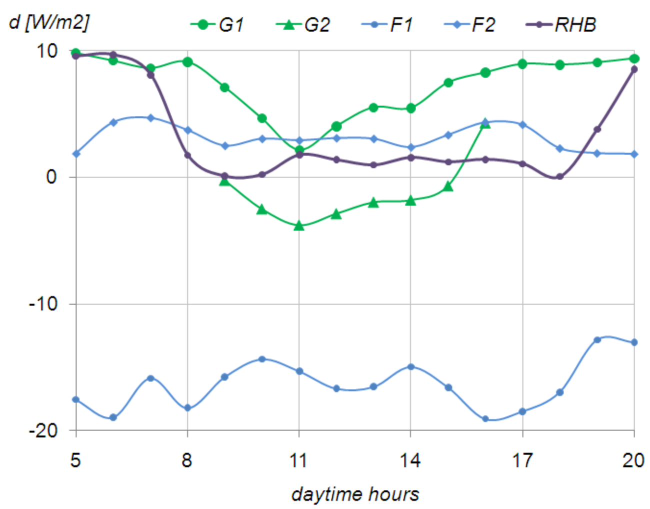

Figure 4a: Systematic differences *d* between *LY* and adjusted *aLE*; humid.

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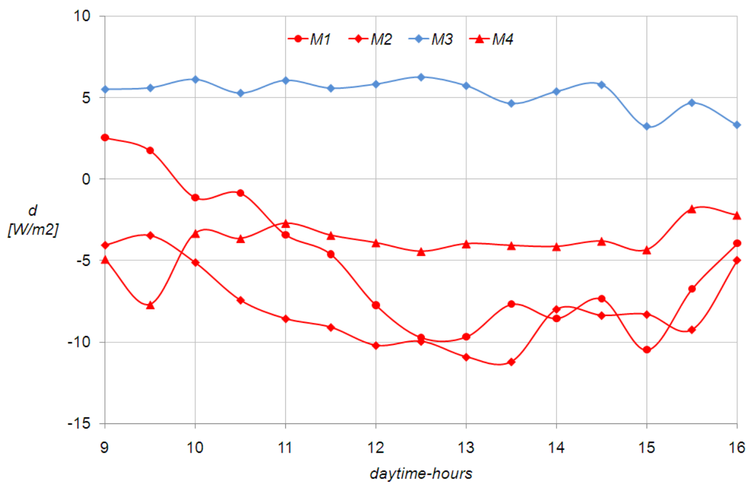

Figure 4b: Systematic differences *d* between *LY* and adjusted *aLE*; Majadas red: dry season; blue: rainy season.

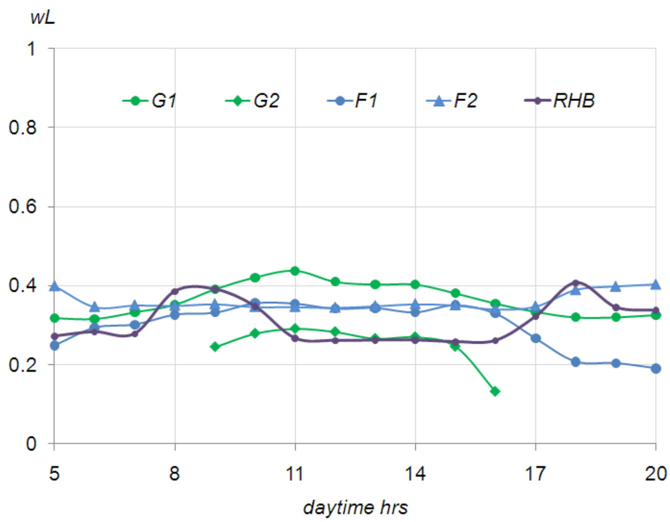

Figure 5a: Averaged daytime-hours values for *LE*-weights *wL*; humid.

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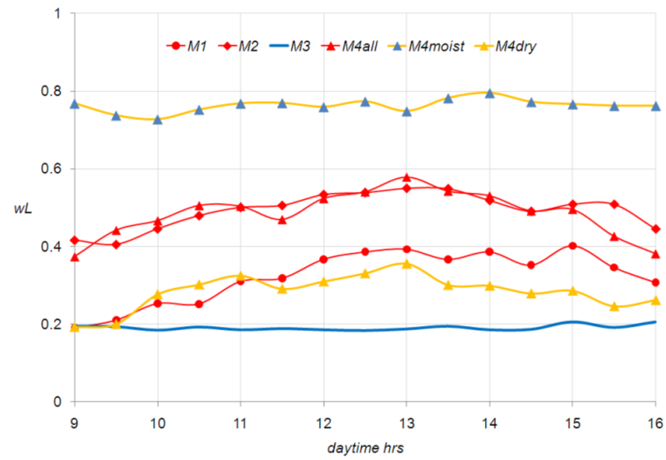

Figure 5b: Averaged values daytime-hours for *LE*-values *wL* in Majadas red: dry; blue: wet season. *M4* split into the period "high soil moisture" (20.04. to 23.06., yellow line, blue triangles) and "low soil moisture" (01.07. and 04.09., yellow line, yellow triangles).

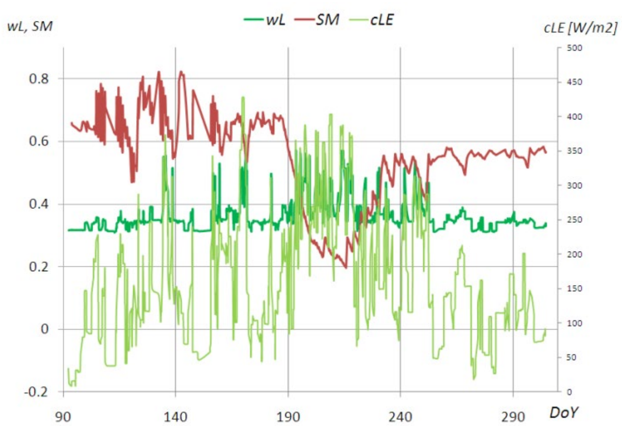

Figure 6a: Development of *wL* (smoothed, dark green), *cLE* (smoothed, light green) and soil moisture (brown) including a dry spell in 2013 for *G*, humid.

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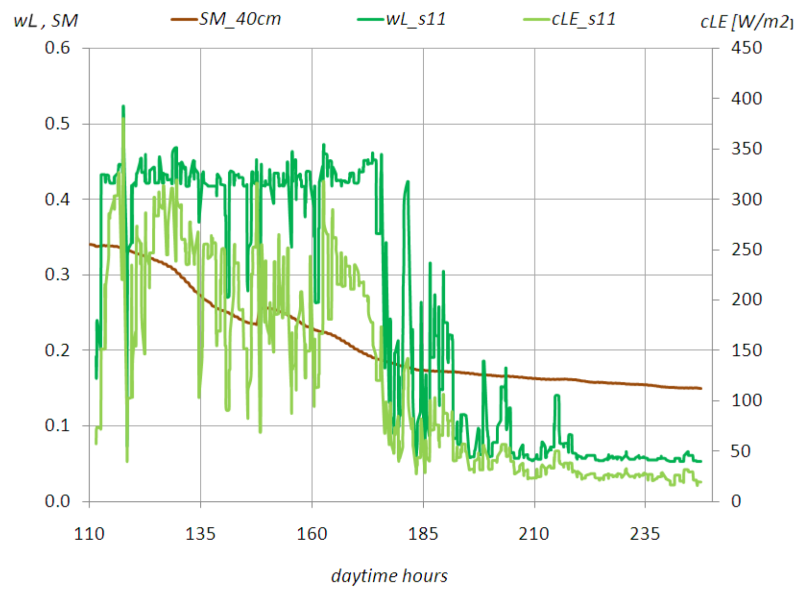
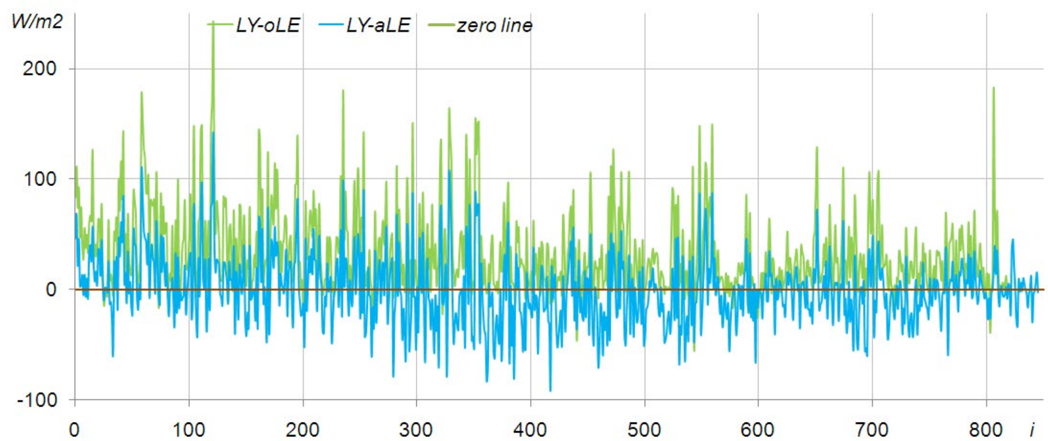


495 **Figure 6b: Development of *wL* (dark green) and corrected *LE* (*cLE*; light green) along with soil moisture (*SM*, brown) from 21.04. to 04.09. 2018 for *M4*, semi-arid.**



500 **Figure 7a: *EC*-deviations from *LY*-observations before (green) and after (blue) *EC*-adjustments along observation period for station *F2*.**

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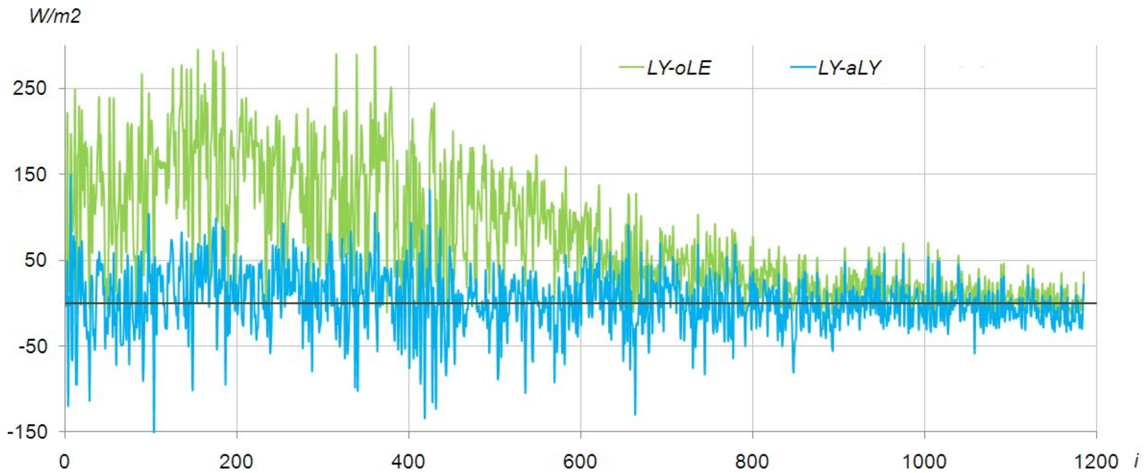

Figure 7b: *EC*-deviations from *LY*-observations before (green) and after (blue) *EC*-adjustments along observation period for station *M4*.

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