UNCERTAINTY DUE TO HYGROMETER SENSOR IN EDDY COVARIANCE LATENT HEAT FLUX MEASUREMENTS

Antonio Martínez-Cob[2], Kosana Suvočarev[1, 2]

[1] Corresponding author. E-mail: suvocarev@eead.csic.es. Phone: +34 976716075.

[2] Dept. Suelo y Agua, Estación Experimental Aula Dei, CSIC, Avda. Montañana 1005, 50059 Zaragoza, Spain.

ABSTRACT

Half-hour latent heat flux (LE) was measured over an early-maturing peach orchard (*Prunus persica* L.) by two different hygrometers: 1) infrared gas analyzer (IRGA) (Li-COR, model Li-7500); and 2) ultraviolet hygrometer (Campbell, KH20). A good agreement between LE obtained with the IRGA (LE_{IRGA}) and the KH20 (LE_{KH20}) hygrometers was observed. During rainy periods, LE_{IRGA} and LE_{KH20} were not reliable due to failure of the instruments caused by water drops standing over the sensors heads. Filtering out rainy periods improved the similarity between LE_{IRGA} and LE_{KH20}: mean estimation error, 6.2 W m^{-2}; root mean square error, 21.3 W m^{-2}; and refined index of agreement, 0.919. Even though the IRGA hygrometer is generally recommended, when economic constraints exist, the KH20 hygrometer can be used with similar confidence.

KEYWORDS

Latent heat flux; Eddy covariance; Infrared gas analyzer; Krypton hygrometer; Error analysis

1. INTRODUCTION

Improved management of irrigation water and several other hydrological issues requires an accurate knowledge of actual evapotranspiration (ET_a) of both crops (optimal or stressed conditions) and natural vegetation. Several methods exist for ET_a measurement and estimation (Hatfield et al., 2005). ET_a represents the water depth consumed by a plant surface (cropped or natural). This variable can also be represented in terms of an energy flux, the latent heat flux (LE), which represents the amount of energy per unit time required to evaporate a unit of water. The eddy covariance (EC) approach has been the preferred LE measurement method because of its accuracy and theoretical background. It entails fewer assumptions and is more direct than other micrometeorological methods, and the equipment can be easily moved from place to place in contrast to weighing lysimeters (Hatfield et al., 2005; Foken, 2008; Aubinet et al., 2012).

The EC method requires the high-frequency, fast-response measurements of the turbulent fluctuations of vertical wind speed and water vapor molar concentration. The former are measured by means of three-dimensional sonic anemometers. The latter are commonly measured by means of optical measuring methods based on Lambert-Beer's law (Foken, 2008). Hygrometers with ultraviolet (UV) and infrared (IR) radiation absorption are generally used. The appropriate operating range of vapor pressure is different for these two types of hygrometers. In addition, the calibration characteristics can change during the application time and, in this respect, the hygrometers working in the UV range are more affected than those in the IR range (Foken, 2008). Several commercial UV and IR hygrometers are available.

There have been several previous valuable sensor intercomparison experiments for characterizing the uncertainties of turbulence measurements but most of them only considered the three-dimensional sonic anemometers (Mauder et al., 2006). Mauder et al. (2006; 2007) have compared the effect of the hygrometer in the uncertainty of turbulence measurements. Mauder et al. (2006, 2007) evaluated the performance of different EC systems, each system being the combination of a three-dimensional sonic anemometer and a hygrometer sensor. These authors reported that the deviations within the EC systems using an UV hygrometer were larger than those within the EC systems using an IR hygrometer likely due to the sensitivity of the UV detector window to scaling effects and to corrosion of electrical contacts through condensing water in the sensor's enclosure, both effects causing shifts in the calibration curves. However, Mauder et al. (2006) did not test separately the uncertainty due to the hygrometer to that due to the sonic anemometer. In addition, the deviations between EC systems were in part (around 10 to 15 %) due to the different data analysis software packages. The results published by Mauder et al. (2007) were affected by technical problems due to application of one of the first serial numbers of IR hygrometer.

Currently most EC sites use open-path IR hygrometers, also known as infrared gas analyzers (IRGA), that record high-frequency fluctuations of both H_2O and CO_2 concentrations (Munger et al., 2012). However, the cost of an IRGA hygrometer, such as the LI-7500 (Li-COR, Lincoln, Nebraska, USA), is about three times the cost of an UV hygrometer, such as the KH20 (Campbell Scientific, Logan, Utah, USA). The goal of this paper was the comparison of LE obtained from two different hygrometers (a LI-7500 and a KH20) combined with the same three-dimensional sonic anemometer and using the same data analysis software package. In this way, the effect of the hygrometer in the uncertainty of turbulence measurements was evaluated without being affected by the sonic anemometer or the data analysis approach. The aim was answering the question whether the KH20 hygrometer can be as accurate as the IRGA hygrometer to get measured LE values.

2. MATERIAL AND METHODS

The measurements were carried out at a commercial early maturing peach (*Prunus persica* (L.) Batsch) orchard located in the stone-fruit orchard farm La Herradura (Caspe, Zaragoza, Spain). Measurements took place in 2010, from 27 Apr. to 5 May, 13 to 18 May, and 9 to 16 June. The experimental site was characterized by relatively high winds (long-term annual average wind speed at 2 m above ground is 3.1 m s^{-1}) and semiarid climate (long-term annual precipitation and reference evapotranspiration, 315 and 1392 mm, respectively) (Martínez-Cob and Faci, 2010).

The farm La Herradura was located next to a meander of the Ebro River, near to where the river forms a lake upstream of the Mequinenza dam (Fig. 1). The orchard topography was rough, with elevation ranging from 120 to 200 m above the mean sea level. Within the footprint of the micrometeorological tower the terrain is sloping down towards the point where the measurements were set, at 120 m above the mean sea level. Gradual rise occurs in the direction of the fetch limit, which is at 150 m above the mean sea level. Early maturing peaches represented about 51 ha (41 ha in the study zone) out of 227 ha total in the farm (Fig. 1). An EC station was set near the south east corner of the early maturing peach zone (41°18’21’’ N latitude, 0°00’26’’ E) (Fig. 1). This zone included several cultivars with similar phenological characteristics. Row orientation was north to south and canopy height was 3.0 m. The tree and row spacing were 3.0 m and 5.0 m, respectively.

The EC station consisted of a sonic anemometer (Campbell Scientific, CSAT3), a krypton hygrometer (Campbell Scientific, KH20), an infrared gas analyzer (IRGA) (Li-COR, Li-7500), a net radiometer (Kipp & Zonen, NR-Lite), an air temperature and relative humidity probe (Vaisala, HMP45C), four soil heat flux plates (Hukseflux, HFP01) and two soil temperature sensors (Campbell Scientific, TCAV). A data logger (Campbell Scientific, CR3000) was used to monitor these different sensors. All instruments except the soil sensors were placed on the top of a tower, at z = 6.9 m above the ground.

The sonic anemometer was placed pointing towards the northwest, about 308° from north clockwise, as this is the mid-point of the predominant wind direction range in the middle Ebro River area (Martínez-Cob et al., 2010). The Krypton hygrometer was installed at about 0.15 m horizontal distance, downwind the CSAT3. Similarly, the IRGA hygrometer was installed about 0.10 m horizontal distance downwind the Krypton hygrometer, i.e. about 0.25 m downwind the CSAT3. Both hygrometers were slightly shifted behind downwind the CSAT3; the IRGA hygrometer was slightly tilted as recommended by manufacturer. The Krypton hygrometer was calibrated at the factory and IRGA hygrometer was calibrated in laboratory using a dew point generator (LI-610, LiCor Inc.). Both calibration procedures took place during spring 2010. The net radiometers were placed oriented towards south. Soil heat flux plates were buried at 0.1 m depth, two in between rows and the other two in the row. Each soil temperature probe had four thermocouples (chromel-constantan), buried into pairs at 0.03 m and 0.06 m depth above each soil heat flux plate.

Sensors were monitored at a 10 Hz frequency. The 10 Hz raw data included wind speed at the x and y horizontal axes and at the z vertical axis, sonic temperature, CO_2 concentration, H_2O concentration recorded from the krypton (ρ_{h_KH20}) and the

IRGA (ρ_{h_IRGA}) hygrometers, air temperature and vapor pressure recorded from the Vaisala probe, net radiation, soil heat flux at 0.1 m soil depth (four sites) and soil temperature at 0.03-0.6 m depth (two sites). The datalogger processed online the raw data to get 30-min averages of turbulent fluxes following the basics of the EC method (Foken, 2008; Aubinet et al. 2012; Campbell Scientific, 2013): a) latent heat flux from the covariance of the fluctuations of vertical wind speed and ρ_{h_KH20} (LE_{KH20}); b) latent heat flux from the covariance of the fluctuations of vertical wind speed and ρ_{h_IRGA} (LE_{IRGA}); c) sensible heat flux (H) from the covariance of the fluctuations of vertical wind speed and sonic temperature; and d) net photosynthesis from the covariance of the fluctuations of vertical wind speed and CO_2 concentration. Values of LE_{KH20} and LE_{IRGA} were corrected online using the Webb, Pearman and Leuning (WPL) correction; additionally, the values of LE_{KH20} were corrected online to take into account the presence of oxygen which also absorbs the UV radiation emitted by the krypton hygrometer (Campbell Scientific, 2013). Likewise, 30-min averages of air temperature, vapor pressure, net radiation, horizontal wind speed and compass wind direction, soil heat flux at 0.1 m depth (four sites) and soil temperature at 0.03-0.06 m depth (two sites) were computed online and stored for further analysis. The EC station also included a rain gauge (Campbell, ARG100) to record 30-min total precipitation. The 30-min average soil heat flux values were corrected offline as described by Allen et al. (1996) using the average soil temperature values to get soil heat flux at the soil surface at each site; later, the four 30-min soil heat flux values obtained were averaged to get a single value.

For each half hour period, the cumulative normalized contribution to fluxes (CNF, %) was estimated following Burba y Anderson (2010) as follows:

$$CNF = exp\left[\frac{-U\,(z-d)}{u^*\,x_L\,k}\right] \qquad (1)$$

Where U is average wind speed (m s^{-1}), u^* is friction velocity (m s^{-1}); z is measurement height (6.9 m in this case); d is zero plane displacement (m), k is the von Kárman’s constant (0.4) and x_L is the upwind fetch distance (m); d was estimated as d = 2/3 h_c (Burba and Anderson, 2010), where h_c is the crop height (3 m in this case). Eq. (1) was used to determine which x_L distance provided CNF ≥ 80 % for most half-hour periods inside the appropriate range of wind directions.

LE_{KH20} and LE_{IRGA} were compared by simple regression analysis and several error statistics were computed following Willmott et al. (2012): mean estimation error (MEE), root mean square error (RMSE), and refined index of agreement (d_r). No comparison was performed between ρ_{h_KH20} and ρ_{h_IRGA} as the KH20 manufacturer claims that this hygrometer is not suitable to provide measurements of absolute H_2O concentrations, but H_2O concentration fluctuations and thus LE when used with a sonic anemometer (Campbell Scientific, 2010).

3. RESULTS AND DISCUSSION

Rainfall was irregularly distributed as it is typical in semiarid climates. A total of 34.6 mm were recorded in the study period, but 92.5 % was recorded in three rainfall events: 2 May (21:00 Universal Time Coordinated, UTC) to 3 May (22:30 UTC), 9 June (5:00 UTC) to 10 June (2:00 UTC), and 12 June (14:00 to 16:00 UTC).

Table 1 lists the percentage of half-hour periods for which the CNF (computed from Eq. 1) was above 80 % as a function of x_L. At first glance, Table 1 indicates that the appropriate fetch distance could be 500 m. However, the irregular shape of the orchard, and the relatively rough topography precluded such large fetch distance for most compass wind directions. It is also necessary to take into account that Eq. (1) computes CNF for neutral atmospheric conditions but that a shorter fetch distance is required for unstable atmospheric conditions (Burba and Anderson, 2010). Thus a conservative compromise between these different criteria led us to select an upwind fetch distance of 425 m as appropriate for this study. For x_L = 425 m, about 60 % of the half-hour periods had a CNF above 80 % (Table 1).

Once an upwind fetch distance was selected, a visual inspection of Fig. 1 selected a compass wind direction range of 240 to 330° assuring that the selected fetch distance of 425 m was available. A total of 874 half-hour periods were recorded during the three measurement periods. However, only a total of 438 half-hour periods (about 50 %) were retained for further analysis. Even though Eq. (1) only applies for neutral atmospheric conditions and unstable atmospheric conditions have lower fetch requirements, selecting a shorter fetch distance (i.e. less than 425 m) for the rest of compass wind directions was not possible as the EC station was located in the southeast corner of the orchard (Fig. 1). This stresses the difficulties for practical applications of the EC method that can be found in areas of relatively rough topography due to the important limitations imposed by the large fetch requirements and the varying compass wind direction along the season. Nevertheless, that limited data set still was large enough for the main goal of this study.

Fig. 2 displays the half-hour values of LE_{KH20} and LE_{IRGA} retained for analysis as a function of time. In general terms, there was a good agreement between both datasets of LE. The equation for the simple linear regression of LE_{IRGA} (dependent variable y) on LE_{KH20} (independent variable x) was y = 23.1 + 0.899 x with a coefficient of determination R^2 = 0.772. The MEE and RMSE were 14.3 and 43.5 W m^{-2}, respectively, while the d_r was 0.856. It was particularly noticeable the agreement for the period 13 to 18 May. During this period, the meteorological conditions (high wind speed, high net radiation, absence of precipitation and dryness) likely led to better development of atmospheric turbulence and thus high-size eddies. Thus, it is likely that the sonic anemometer and both hygrometers sampled at a higher extent the same eddies. The absence of precipitation in this period precluded the presence of water drops standing over the hygrometer heads disturbing the corresponding measurements. For the other two periods, 27 Apr. to 5 May and 9 to 16 June, the agreement between LE_{KH20} and LE_{IRGA} was somewhat worse. The lack of agreement was particularly noticeable during the periods for which rainfall events were recorded, 2 to 3 May, 9 to 10 June, and 12 June. During these rainy periods, the LE_{IRGA} values were much higher than the LE_{KH20} values, which were close to 0 (Fig. 2). The presence of water drops standing over the head of the KH20 and IRGA disturbed the corresponding readings of these sensors. According to Foken (2008), UV hygrometers (as the KH20) are more suited for measuring low absolute humidity and their optical windows are treated with hygroscopic material which also may affect the readings of these type of sensors when humidity is high as it occurs during and just after rainfall events. In addition, the KH20 sensor head was surrounded by a short flange that could retain a shallow water layer standing over the head during rainfall events, while this flange was absent around the IRGA sensor head. Also, data from open path IRGAs become erroneous when the turbidity of the window exceeds a given threshold, usually caused by accruing water (Haslwanter et al., 2009).

Therefore, a second filtering step was performed to remove rainy half-hour periods from further analysis. After this, 387 half-hour periods were kept for a further comparison of LE_{KH20} and LE_{IRGA}. Fig. 3 shows the simple linear regression of LE_{IRGA} (dependent variable y) on LE_{KH20} (independent variable x) for these 387 half-hour periods. There was a close agreement between both datasets even though there was still some discrepancy for a few instances (no clear reason for it could be found). The regression slope was not significantly different than 1 although the intercept was significantly different than 0 ($\alpha = 0.05$). The MEE and RMSE were 6.2 and 21.3 W m^{-2}, and the d_r was 0.919. These statistics indicate that the agreement between LE_{KH20} and LE_{IRGA} in this work was better than that reported by Mauder et al. (2006, 2007). Namely, IRGA hygrometer used by Mauder et al. (2007) was one of the first serial numbers of the LI-7500 IRGA sensor type and had some technical problems. The results by Mauder et al. (2006) are based on comparison between the instruments mounted at different micrometeorological towers. Consequently, they reported higher RMSE values of 28.5 and 37.7 W m^{-2}, respectively, and higher intercept values and regression slopes of 0.98 and 1.17. One should take into account that the differences between LE_{KH20} and LE_{IRGA} reported by Mauder et al. (2006, 2007) included not only the uncertainty due to the hygrometer sensor but also those due to the sonic anemometer (they compared combinations of sonic anemometers and hygrometers) and post-processing software packages. In general, there is a tendency for the LE_{IRGA} values to be slightly higher than the LE_{KH20} values.

Thus the energy balance closure for LE_{IRGA} was slightly better than that for LE_{KH20} (data not shown). It was in both cases within reported values for different canopies according to Wilson et al., (2002) and Stoy et al.(2013).

The results found in this paper suggest that both types of hygrometers can provide similar results with similar uncertainty as long as ‘optimal’ measurement conditions occur. The slightly better energy balance closure found for LE_{IRGA} is not enough to conclude that the IRGA hygrometer clearly provided better measured LE values. Thus when economic constraints exist, the KH20 hygrometer can be also used with confidence. In terms of LE, there is not a clear superiority of the IRGA hygrometer.

The main advantage of using this hygrometer would be for those studies for which CO_2 concentrations are also required.

4. CONCLUSIONS

The LE values obtained with two different types of hygrometer, IRGA and KH20, were quite similar in general terms. The largest differences were found during rainy periods. When filtering out those rainy periods, the similarity between LE_{IRGA} and LE_{KH20} was high. The statistics MEE, RMSE and d_r were 6.2 W m^{-2}, 21.3 W m^{-2}, and 0.919, respectively. Therefore, whenever economic constraints exist, the KH20 can be used with confidence.

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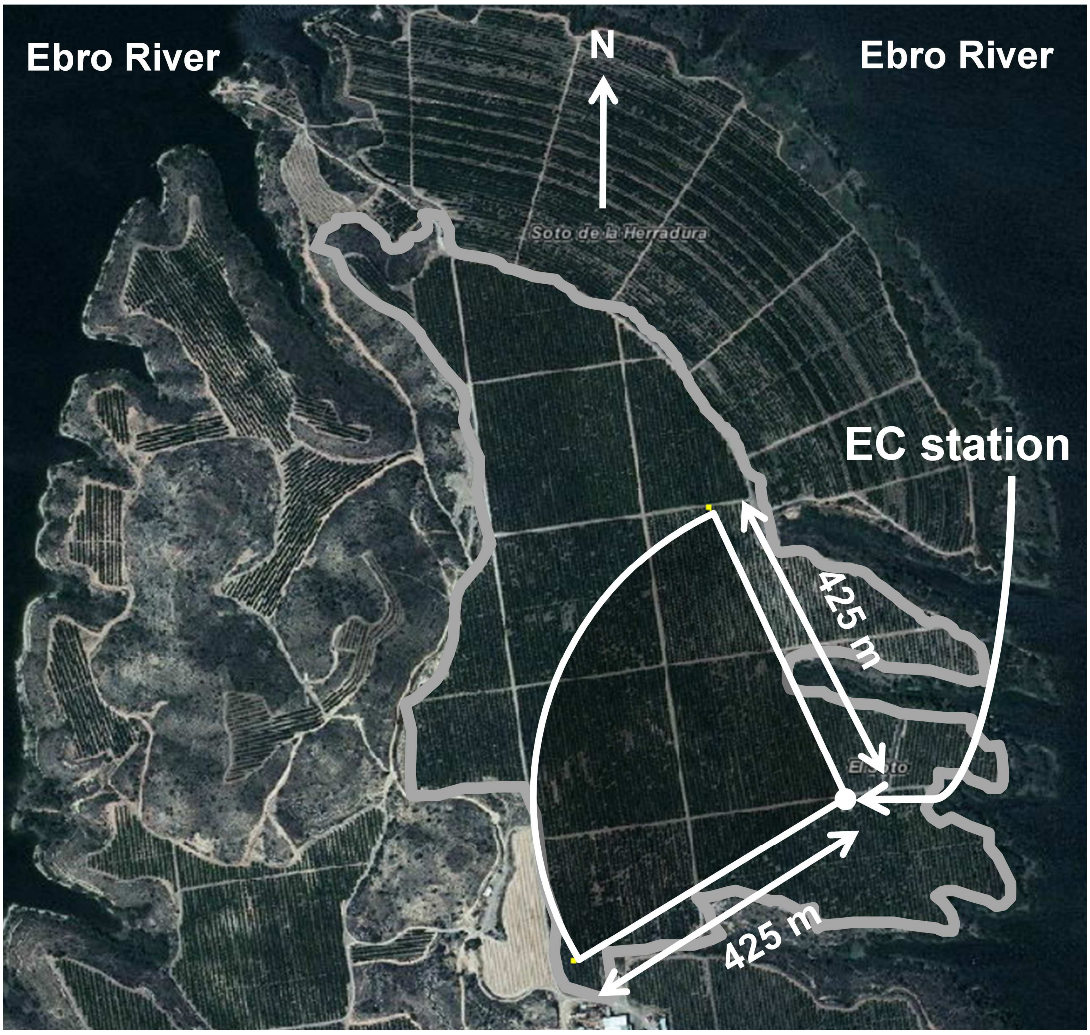

Fig. 1. Early-maturing peach orchard at the fruit-stone commercial orchard La Herradura (Caspe, Zaragoza, Spain). The location of the eddy covariance and the area within which fetch requirements are accomplished is also displayed.

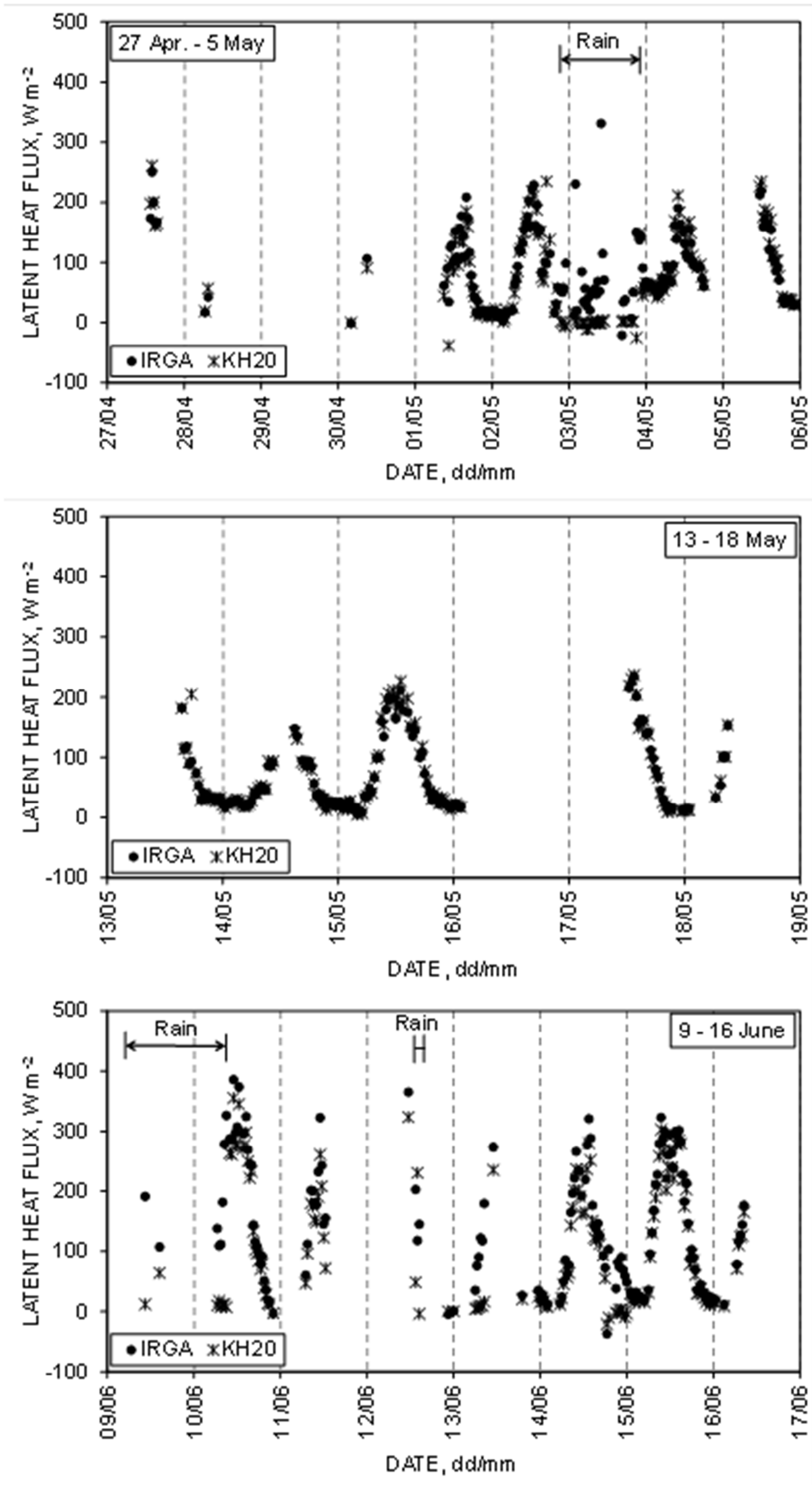

Fig. 2. Half-hour values of latent heat flux measured with a Campbell KH20 hygrometer (LE_{KH20}) and a Li-Cor Li-7500 infrared gas analyzer (LE_{IRGA}). The duration of the main rainfall events is also displayed.

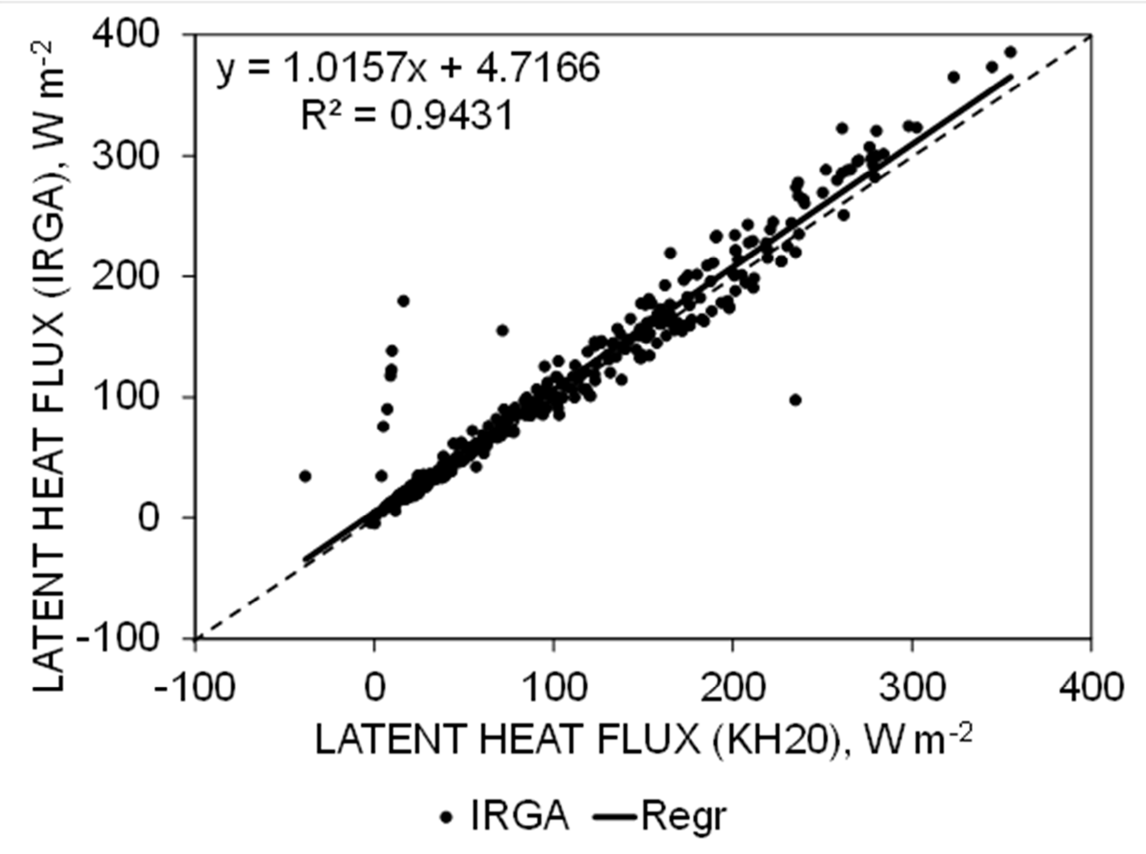

Fig. 3. Half-hour values of latent heat flux measured with a Campbell KH20 hygrometer (LE_{KH20}) versus those measured with a Li-Cor Li-7500 infrared gas analyzer (LE_{IRGA}) after excluding rainy half-hour periods from those displayed on Fig. 2.

Table 1. Percentage of half-hour periods (N_{CNF80}) for which the cumulative normalized contribution to fluxes was above 80 % as a function of upwind fetch distance (x_L).

x_L, m	350	375	400	425	450	475	500
N_{CNF80}, %	19.4	34.6	51.9	59.6	64.8	69.8	73.9