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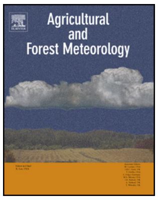

Uncertainty due to hygrometer sensor in eddy covariance latent heat flux measurements

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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.

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 in Mauder et al. (2007)

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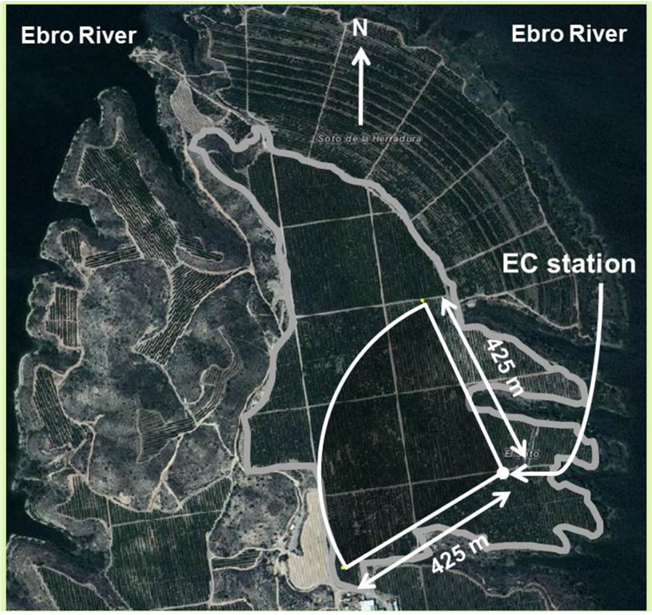

Fig. 1. Early-maturing peach orchard at the fruit-stone commercial orchard La Herradura (Caspe, Zaragoza, Spain). The location of the eddy covariance and the area within which fetch requirements are accomplished is also displayed.

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, UT, 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 April 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, LI-COR 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 ($\rho_{h\text{-KH20}}$) and the IRGA ($\rho_{h\text{-IRGA}}$) 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 $\rho_{h\text{-KH20}}$ (LE_{KH20}); (b) latent heat flux from the covariance of the fluctuations of vertical wind speed and $\rho_{h\text{-IRGA}}$ (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.