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Surface renewal performance to independently estimate sensible and latent heat fluxes in heterogeneous crop surfaces

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SUMMARY

Surface renewal (SR) analysis is an interesting alternative to eddy covariance (EC) flux measurements. We have applied two recent SR approaches, with different theoretical background, that from Castellví (2004), SR_{Cas}, and that from Shapland et al. (2012a,b), SR_{Shap}. We have applied both models for sensible (H) and latent (LE) heat flux estimation over heterogeneous crop surfaces. For this, EC equipments, including a sonic anemometer CSAT3 and a krypton hygrometer KH20, were located in two zones of drip irrigated orchards of late and early maturing peaches. The measurement period was June–September 2009. The SR_{Cas} is based on similarity concepts for independent estimation of the calibration factor (α), which varies with respect to the atmospheric stability. The SR_{Shap} is based on analysis of different ramp dimensions, separating the ones that are flux-bearing from the others that are isotropic. According to the results obtained here, there was a high agreement between the 30-min turbulent fluxes independently derived by EC and SR_{Cas}. The SR_{Shap} agreement with EC was slightly lower. Estimation of fluxes determined by SR_{Cas} resulted in higher values (around 11% for LE) with respect to EC, similarly to previously published works over homogeneous canopies. In terms of evapotranspiration, the root mean square error (RMSE) between EC and SR was only 0.07 mm h^{-1} (for SR_{Cas}) and 0.11 mm h^{-1} (for SR_{Shap}) for both measuring spots. According to the energy balance closure, the SR_{Cas} method was as reliable as the EC in estimating the turbulent fluxes related to irrigated agriculture and watershed distribution management, even when applied in heterogeneous cropping systems.

1. Introduction

Precision in sensible (H) and latent heat (LE) flux estimation is important due to their great contribution to precipitation, plant growth, and the amount and locations of surface water runoff. Water use for irrigation purposes is the most important demand to be considered in watershed management. Irrigated agriculture should rely on evapotranspiration (ET) measurements. Together with increasing needs for more arable land and less water use per crop product, there has been a notable improvement in instrumentation, methods and approaches to estimate ET. In order to spread scientifically approved techniques into commercial practice, simpler approaches are preferred. Furthermore, in the absence of possibilities to apply direct measurements of turbulent fluxes such as eddy covariance (EC) or lysimeter measurements of ET losses, surface renewal (SR) (Paw U et al., 1995) has been proposed as a reliable alternative ET estimation method.

The energy balance closure is used as a standard procedure to independently evaluate scalar flux estimates derived by micrometeorological methods (Wilson et al., 2002). Where closure is not achieved, flux measurements need to be interpreted to account for inconsistency with conservation principles (Kustas et al., 1999). Several reasons for the lack of closure of the surface energy budget in EC measurements have been discussed by Mahrt (1998): (1) lack of coincidence of the source areas (leaves and soil surface) among various flux components measured very near to a surface; (2) flux divergence arising from transport that is not one-dimensional such as insufficient fetch; (3) non-stationarity of the measured time series; (4) turbulent dispersive fluxes arising from organized planetary-boundary-layer circulations that may have preferred locations so that the mean vertical velocities at an instrument location may be systematically different from zero, hence giving rise to a vertical advective flux; and (5) systematic bias in instrumentation (Twine et al., 2000).

When using the SR method, some of the uncertainties related to EC instrumentation could be avoided: no orientation limitations,

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no leveling requirement, no shadowing or instrumentation separation issues, etc. Likewise, despite Castellví (2012) showed that in practice the fetch requirements for SR are similar as for the EC method, Castellví and Snyder (2009a) showed that the SR method can be operated at any height (roughness or inertial sublayer) and thus the SR is less stringent to the fetch requirements when a sonic anemometer is avoided. In other words, the SR equipment is more adjustable to the specific conditions of fetch (Castellví, 2012). Methodologically, SR is based on canopy layer turbulence and the time–space scalar field associated with the dominance of turbulent coherent structures. Numerous authors (Paw U et al., 1995; Snyder et al., 1996; Spano et al., 1997, 2000; Chen et al., 1997a,b; Castellví and Martinez-Cob, 2005; Zapata and Martínez-Cob, 2001; Zhao et al., 2010) have used a simple version of the SR method based on analyzing ramp-like patterns in the temperature time series to estimate H. It was proved to be applicable in a wide range of natural surfaces. In this case latent heat flux (i.e. ET expressed in energy terms) was obtained as the residue of the energy balance equation. Detailed theory behind the SR analysis basics and early advances are described in previous works by Paw U et al. (1995, 2005), Snyder et al. (1996), and Spano et al. (1997).

The main challenge facing the SR method is deriving the calibration factor (α), thus making SR dependent on other direct surface exchange measurements such as EC. According to some important studies in the topic (Paw U et al., 1995; Snyder et al., 1996; Katul et al., 1996; Duce et al., 1998; Castellví, 2004), α for sensible heat flux depends on the measurement height, stability conditions, canopy architecture and size and design of the wire if thermocouples are used. When it comes to estimating α, different explanations and methods have been proposed in order to derive repeatable procedures to correct the SR flux results. Namely, Paw U et al. (1995) proposed that the need for calibration arises from uneven coherent structure heating. Afterwards, Castellví (2004) proposed combining SR analysis with similarity theory to auto-calibrate SR, which requires also average wind speed measurements. One study over rice field demonstrated the feasibility of applying the Castellvi (SR_{Cas}) principles to independently derive H and LE (Castellví et al., 2006). Another study over rangeland grass used SR_{Cas} to estimate three scalar fluxes, demonstrating energy flux densities higher than the ones derived by the EC method: 4%, 18% and 10% for H, LE and carbon dioxide (Fp) fluxes, respectively (Castellví et al., 2008). Castellví et al. (2006, 2008) showed that this SR_{Cas} estimations improved energy balance closure when applied over homogeneous crop surfaces.

Recently, Shapland et al. (2012a, 2012b) proposed a SR method (SR_{Shap}) for independent flux estimation by distinguishing the larger turbulent coherent structures responsible for the flux interchange from the smaller non-flux-bearing isotropic turbulence. Shapland et al. (2012b) applied this approach for the H estimation over bare soil, sorghum and teff grass fields. Their approach demonstrated that no calibration was needed under the unstable atmospheric conditions. Under the hypothesis that the smallest scale turbulent structures (Scale One) mix the larger scale coherent structures (Scale Two), which are responsible for direct energy and mass exchange, α values are shown to be about 1.00.

To our knowledge, no other results have been reported on the application of the SR_{Cas} or SR_{Shap} approaches for calculating LE over heterogeneous canopies, where the turbulence can be enhanced by the presence of an uneven ground cover and the assumptions behind similarity theory may not be fulfilled. Thus, we have employed both SR_{Cas} and SR_{Shap} analyses in drip-irrigated peach orchards to estimate independently H and LE flux densities over the data collected by EC equipments. An EC installation was set up in each of two different peach orchards with distinct cultivars to provide a dataset to evaluate performance and applicability of the SR_{Cas} and SR_{Shap} methods over such a heterogeneous crop surface when compared to EC values as a reference. The SR_{Cas} calculation requires high frequency temperature measurements and mean horizontal wind speed data. For SR_{Shap} calculation, only high-frequency scalar measurements are needed.

2. Materials and methods

2.1. Crop, site and instrumentation

Two EC stations were run from 1 June to 30 September 2009 at a commercial orchard La Herradura in Caspe (NE Spain, middle Ebro River Basin) to measure the surface energy balance components in two drip-irrigated peach orchards. 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 orchard 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 topography was rough, with elevation ranging from 120 to 200 m above the mean sea level (Fig. 2). Peaches represented 154 ha out of 227 ha total in the orchard. About 51 and 52 ha were cropped to early and late maturing peaches, respectively (Fig. 1). The remaining crops were cherries and apricots.

The first EC station (ST1) was set in a late peach zone (41°17′40″N latitude, 0°00′24″E longitude), and the second EC station (ST2) was set in an early peach zone (41°18′21″N latitude, 0°00′26″E) (Fig. 1). Both late and early peach zones included several cultivars with similar phenological characteristics. Row orientation was north to south and canopy height was about 2.5 m for both orchards. The tree and row spacing were 3.75 m and 5.75 m for the late peaches, respectively, and 3.0 m and 5.0 m for the early peaches, respectively.

The soil down to 1.2 m depth was characterized by moderate to low average values of readily available water (70–110 mm) depending on the stoniness of a particular zone within the orchard (Zapata et al., 2013). Field capacity and wilting point were 0.29 and 0.13–0.14, respectively. Drip irrigation was applied daily. Two polyethylene irrigation laterals were used to irrigate each row of trees, one lateral at each side of the row. Turbulent (non-pressure compensating) emitters were used with a design discharge of 4 l h^{-1}. Emitters were extruded in the laterals at 1 m intervals. The discharge volume was 24 l h^{-1} $tree^{-1}$ for early peaches and 30 l h^{-1} $tree^{-1}$ for late peaches. Table 1 lists the monthly irrigation amounts during the measurement period. Due to their distinct phenological development (Table 2), late peaches received more irrigation water from June to September compared to the early peaches. Pruning and flower and fruit thinning practices were applied seasonally. Herbicides were applied to control weed growth and thus to minimize the presence of understory vegetation between the tree rows.

Both micrometeorological stations consisted of a sonic anemometer (Campbell Scientific, CSAT3), a krypton hygrometer (Campbell Scientific, KH20), 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). Two data loggers (Campbell Scientific, CR3000) were 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 anemometers were placed pointing towards the northwest, about 315° from north clockwise in late peaches and 308° from north clockwise in early peaches, as this is the most predominant wind direction in the middle Ebro River area (Martínez-Cob et al., 2010). In addition, a previous study of the wind rose recorded at a nearby