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Observing actual evapotranspiration within a hilly watershed: case study of the Kamech site, Cap Bon peninsula, Tunisia

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Abstract: There is a strong need for long term observations of land surface fluxes, especially the latent heat flux (λE), or actual evapotranspiration (ETa), a key component of both the surface energy balance and the hydrological cycle. The eddy covariance (EC) method is widely used to provide measurements of land surface fluxes. However, missing data are inherent to EC measurements and several gap-filling methods have been proposed. Nevertheless, observing ETa by EC and testing gap-filling methods in hilly watersheds received little attention. This study aimed at obtaining continuous ETa time series from EC measurements collected within a small hilly watershed, which implied adapting gap-filling techniques to these particular conditions. The experiment took place within the agricultural watershed Kamech (Northeast Tunisia) which belongs to the OMERE environmental observatory. A 9.6-meter-high EC flux tower was installed in the center of the 2.45 km^2 area watershed. Sensible and latent heat fluxes data collected from 2010 to 2013 were quality controlled. The software REddyProc was used to gap-fill the fluxes at hourly timescale. To account for the combined effects of wind direction and topography, REddyProc was applied after separating the two dominant wind directions, which notably improved the estimated fluxes. Aggregating the hourly λE estimates at daily and monthly timescales allowed analyzing the temporal variability of ETa over the seasons and between years.

Keywords: actual evapotranspiration; hilly watershed; eddy covariance; gap filling; ORE OMERE; Tunisia

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1. Introduction

In many regions of the world, water scarcity is an important issue for socio-economical development, and efficient management of water resources is required in order to ensure water and food security [1]. Actual evapotranspiration (ETa), which corresponds to the sum of soil evaporation and vegetation transpiration, is a key land surface process that significantly drives hydrological budget [2], vegetation functioning and resulting agricultural production [3], as well as boundary layer processes and regional climate [4]. Further, ETa is strongly influenced by global change, including (1) climate forcing such as rainfall and evaporative demand and (2) anthropogenic forcing such as land use and agricultural systems [5, 6]. Therefore, accurate and consistent estimates of ETa are required to tackle the challenges related to water resource management. Besides, long-term observations of ETa within small watersheds are mandatory for diagnosing the combined effects of the involved processes (i.e., climate forcing, vegetation functioning and hydrological cycle). These observations are also needed for prognosticating future trends by using modelling approaches that involve calibration and simulation procedures [7]. Additionally, long-term observations of ETa over small watersheds are useful as ground truth for validating remotely sensed products [8].

To ensure accurate and continuous observations of ETa over small watersheds, the eddy covariance (EC) method is the reference technique for measuring the sensible (H) and latent (λE) heat fluxes, where λE corresponds to ETa. The EC method has been tested and proven for a worldwide variety of land surface conditions, including crops, forests, snow, water bodies, urban areas, as well as mountainous and flat areas [9]. EC method has several advantages such as high temporal resolution at hourly scale and spatial integration over large areas [10]. However, EC measurements often experience large portions of missing data, as the consequence of sensor or power failures, maintenance and calibration procedures, improper weather conditions, and rejection of data induced by quality checks [9]. Gap filling methods are therefore necessary to obtain continuous series of land surface fluxes over seasonal or inter-annual periods. In order to provide accurate estimates of H and λE when data are missing, several gap-filling methods have been proposed. These methods rely on ancillary information in time or space: the mean diurnal variation method [11], the regression method [12,13], the evaluation of two-week average Priestley–Taylor coefficient [14,15], the look-up table method [11] and the multiple imputation [16]. Most of gap filling methods were devoted to carbon dioxide measurements, for homogenous surfaces over flat or mountainous areas.

Hilly areas are widespread throughout the world. They experience intensification of rainfed agriculture, since topographical conditions permit the mobilization of water resources [17, 18, 19, 20]. They depict strong spatial heterogeneities, because of family farming that induces very small fields. For hilly and heterogeneous cropping systems, the conditions that drive ETa (i.e., radiative, wind and turbulence regimes, vegetation patterns) can be different from those occurring for homogenous surfaces over flat / mountainous areas. For instance, it is necessary to adapt correction methods for EC measurements [21,22], or to account for footprint changes according to wind direction.

The existing gap-filling methods have not been examined over hilly cropping systems. This is all the more critical that the latter are likely to provide different relationships between ancillary information and flux measurements than those observed on homogeneous areas over flat / mountainous terrains. When dealing with hilly cropping systems, the wind direction is an important parameter for two reasons. First, the combined effects of hilly topography and wind direction induced changes in airflow streamlines and turbulent fluxes [23]. Second, when observing fluxes at the field scale in the same study area, [21] and [22] reported the existence of two dominant wind directions, and demonstrated the necessity to discriminate these two wind directions when processing the EC data. Thus, the gap filling methods are likely to provide different relationships between ancillary information and flux measurements, when considering different wind directions. This induces the necessity to evaluate the existing gap-filling methods for EC data collected over hilly cropping systems, and to adapt these methods if necessary.

In the context of providing long-term observations of ETa, the current study aimed at evaluating a simple, robust, available and widely used gap-filling method, for obtaining complete time series of ETa measurements over hilly cropping systems. We used a nearly four-years long EC measurements dataset, collected from a flux tower within an agricultural watershed. The latter was typified by hilly topography, and the footprint of the flux tower measurements integrated a patchwork of crop fields. The crops were rainfed, which minimized advection processes induced by changes in soil moisture. We evaluated the gap-filling method proposed by [24], which is world widely distributed through the REddyProc package. We evaluated this method on λE for ETa, but also on H that is used to estimate water status indicators (e.g. Bowen ratio, evaporative fraction). We compared the performance of the gap-filling method when used in its original version and when adapted to the conditions of hilly and heterogeneous cropping systems, i.e. by discriminating between wind directions. Finally, daily and monthly values of ETa were documented and analyzed.

The paper is structured as following. Section 2 present the experimental strategy (site description, experimental design, data collection and processing, implementation and evaluation of the gap-filling method) as well as the experimental conditions, with a focus on meteorology. Section 3 reports and discusses (1) the comparison of the performances of the original and adapted versions of the gap-filling method, as well as (2) the obtained times series of ETa estimates at the daily and monthly timescales. Conclusion discusses main outputs and future investigations.

2. Materials and methods

2.1. Site description

The experiment took place within the agricultural Kamech watershed, located in the Cap Bon peninsula in northeastern Tunisia (36°52′40″ N, 10°52′40″ E). Kamech watershed belongs to the long-term environmental research observatory OMERE (a French acronym for Mediterranean Observatory of Water and the Rural Environment). OMERE studies the impacts of anthropogenic forcing and climate change on hydrology, erosion, and water quality (http://www.obs-omere.org). In the context of the OMERE observatory program, measuring evapotranspiration ETa at the watershed scale was recognize as a key research objective for the following reasons. On the one hand, ETa is the main component of the hydrological balance in semiarid regions, up to 80% at the yearly timescale. On the other hand, ETa is rarely measured directly, and it is usually estimated indirectly from the hydrological balance closure or from meteorological measurements.

The climate is Mediterranean sub-humid. Annually averaged precipitation and Penman-Monteith reference crop evapotranspiration over the 2004-2014 period are 680 mm and 1366 mm, respectively. A detail analysis of these meteorological observations is given in Section 2.4.

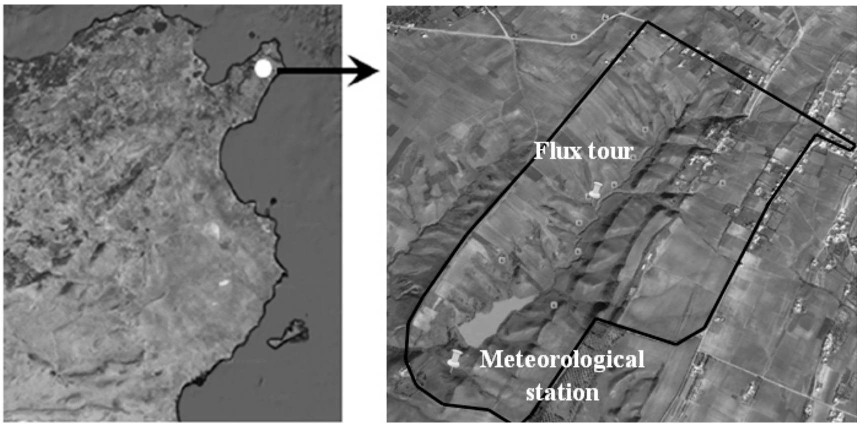

Figure 1. The Kamech watershed. Left: localization of the Kamech watershed in the Cap Bon peninsula, northeastern Tunisia. Right: aerial map of the Kamech watershed with the localization of the flux tour and of the meteorological station.

The Kamech watershed has an area of 2.45 km^2. The watershed topography is globally V shaped from its middle to the outlet (Figure 1), around a valley oriented from northwest to southeast. The slopes are irregular, especially on the southern rim, which has natural embankments induced by sandstone hogbacks. The altitude ranges between 94 m and 194 m asl. The slopes range between 0 % and 30 %, the quartiles being 6%, 11% and 18%. The soils have sandy-loam textures, with depths ranging from 0 to 2 m according to the location within the watershed and to the local topography [17]. Most of the crops were rain-fed. They include winter cereals (durum and bread wheat, barley, oat, and triticale) and legumes (chickpeas and fava beans), which can be either harvested or grazed. The steepest parts of the watershed are covered by natural vegetation and used as rangeland for livestock. Sowing of crops starts in November and the maximum vegetation growth appears in spring, the vegetation height rarely exceeding 1 m. From the end of June (summer season) until the end of October (autumn season), the Kamech watershed is mostly under conditions of bare soil.

2.2. Experimental design and data acquisition

2.2.1. Instrumental design

The meteorological station is located at 36°52′10.5″ N, 10°52′6.3″ E, 108 m asl., near the catchment outlet. The measurements of ETa at the watershed scale are collected from an eddy covariance (EC) device set up on a 9.6 m-height flux tower. Installed in 2010, the flux tower is located at 36°52′39.0′′N, 10°52′36.4′′E, 115 m asl., close to the center of the watershed (see Figure 1). In the current study, we focused on the data collected between March 2010 and August 2013.

2.2.2. Meteorological station

The meteorological station measured: (1) the solar irradiance with a SP1110 pyranometer (Skye, UK); (2) the air temperature and humidity with an HMP45C probe (Vaisala, Finland); (3) the wind speed with an A100R anemometer (Vector Instruments, UK); (4) the wind direction with a W200P wind vane (Vector Instruments, UK). The instruments were installed 2 m above ground (1 m for the pyranometer), following the standard of the World Meteorological Organization for agro-meteorological measurements. All sensors were connected to a CR10X data-logger (Campbell Scientific, USA). Variables were sampled at 1 Hz and stored as 30 minutes averages.

2.2.3. Eddy covariance flux tower

The eddy covariance (EC) tower was equipped with sensors installed at 9.6 m above the soil surface for measuring the turbulent fluxes. A three-dimensional sonic anemometer (CSAT3, Campbell Scientific, USA) measured wind speed in the three directions and air temperature at a 20 Hz frequency. The sonic anemometer was vertically set up and oriented relative to North West. An open path gas CO_2 / H_2O analyzer (LI-7500, Li-Cor Biosciences, USA) measured concentrations of water vapor and CO_2 at a 20 Hz-frequency. A thermo-hygrometer HMP45C sensor (Vaisala, Finland) measured air temperature and air humidity at a 1 Hz-frequency. All sensors were connected to a datalogger (CR3000 Campbell SC, USA) and were power supplied by photovoltaic panels connected to batteries. Data from the fast sensors (CSAT3 and LI-7500) were stored at 20 Hz frequency. Data from the slow sensor (HMP45C) were averaged over 15 minutes intervals.

2.3. EC flux calculations and quality control

2.3.1. Calculating convective fluxes

The sensible heat (H) and latent (λE) heat fluxes were calculated over 30 minutes intervals from the sonic anemometer and the gas analyzer data, by using the ECpack library version 2.5.22 [25]. Most of the instrumental corrections proposed in the ECpack library were applied. These corrections aimed to (1) account for the distance between the sonic anemometer and the gas analyzer (2) account for the evolution of the average values over the calculation interval; (3) correct the temperature measured by the anemometer for the variations of the sound speed with air humidity; (4) correct the frequency response and path averaging. When measuring fluxes by using the EC technique, it is conventional to rotate the sonic coordinate system. For this, we used the double rotation correction [26] implemented in ECpack.

For the current study, we considered both the nighttime and daytime data. The resulting 30-minutes flux data had a footprint of 18 ha on average, corresponding to an along-wind length of 970 m and an across-wind width of 210 m. Given the averaged field size within the experimental site was 0.5 ha, the measurement footprint integrated several crop fields. Further, the crop fields around the flux tower were representative of the crop fields within the 2.45-km^2 size Kamech watershed (wheat, favabean, oat and rangeland).

2.3.2. Quality control

The quality control of the 30-minutes flux data was performed using two standard tests that are routinely employed over flat and sloping terrains, i.e., the Steady State test and the Integral Turbulence Characteristics test. These tests permitted to ensure that the theoretical requirements for the EC measurements were fulfilled [27]. On the same site, [21,22] applied these tests over EC datasets collected under conditions of hilly topography, and reported good energy balance closure for the selected data. We kept the high and good quality classes as defined by [28] and [29], since these two classes are considered as suitable for long-term observations.

Before quality control, the rate of missing because of experimental failures (deficient energy supply, sensors malfunctioning) ranged between 20% and 57% for H, and between 28% and 81% for λE (see Table 1). The rate of missing data after quality control filtering ranged between 44% and 69% for H and between 66% and 92% for λE. The rates of missing data before and after quality control filtering were similar to those reported in former studies that addressed missing data from flux tower with EC devices. In terms of gap temporal distribution that might directly impacts the performances of gap filling methods, we identified 4 long periods with continuously missing data for H: from 12/15/2010 to 01/25/2011, from 11/24/2011 to 03/02/2012, and from 02/01/2013 to 03/30/2013, and for λE: from 05/01/2010 to 06/04/2010, from 12/15/2010 to 01/25/2011, from 11/24/2011 to 03/29/2012, from 10/10/2012 to 05/28/2013.

Table 1. Summary of the available flux data available, for the sensible (H) and latent (λE) heat fluxes. The number of 30-min intervals correspond to the number of days of the experiment. The rates of missing data are given as percentages of the number of 30-min intervals. Missing raw measurements are due to experimental failures. Missing after QC correspond to the sum of missing raw measurements and data eliminated by quality control (section 2.3.2). Missing data after gap-filling are given for both way of applying REddyProc: without separating the wind directions (REP), and after separating the wind directions (RNS, see section 2.5.2).

years	number of days	number of 30-min intervals	missing raw measurements		missing after QC		missing after gap-filling REP		missing after gap-filling RNS	
			H	λE	H	λE	H	λE	H	λE
2010	306	14687	20%	31%	44%	78%	0%	0%	0%	0%
2011	365	17520	25%	28%	48%	66%	11%	11%	11%	11%
2012	366	17568	30%	53%	53%	81%	16%	36%	16%	36%
2013	243	11664	57%	81%	69%	92%	0%	61%	24%	75%
total	1280	61439	31%	46%	53%	78%	8%	25%	12%	28%

2.4. characterization of the climatic conditions

The local climatic conditions during the experiment are given in Figure 2, which presents, for the four years of the experiment, the monthly average of the main of the main climatic variables as measured by the meteorological station: solar incoming radiation, air temperature, water pressure deficit, wind speed, reference evapotranspiration and rainfall amounts. As a typical Mediterranean site, two constrating periods were clearly distinguished: a relatively cold and humid period (from October to April) and a hot and dry period (from May to September). Monthly averages of solar radiation, air temperature and wind speed exhibits little inter-annual variability. Water vapour deficit inter-annual variability was higher (higher values of VPD during the summers of 2011 and 2012, lower values of VPD during the summer of 2013) that induced similar variations of the reference evapotranspiration ET$_0$. Wind speed has a rather high averaged value, around 4 m.s^{-1}, and did not present any seasonal variations. As usual for a Mediterranean site, rainfall amounts exhibited a high seasonal variability, with almost no rain during summer (june to august) and higher rainfall amounts in autumn, winter and spring. For each month, the inter-annual variability of the rainfall amounts was high, with is also commonly observed in Mediterranean areas.

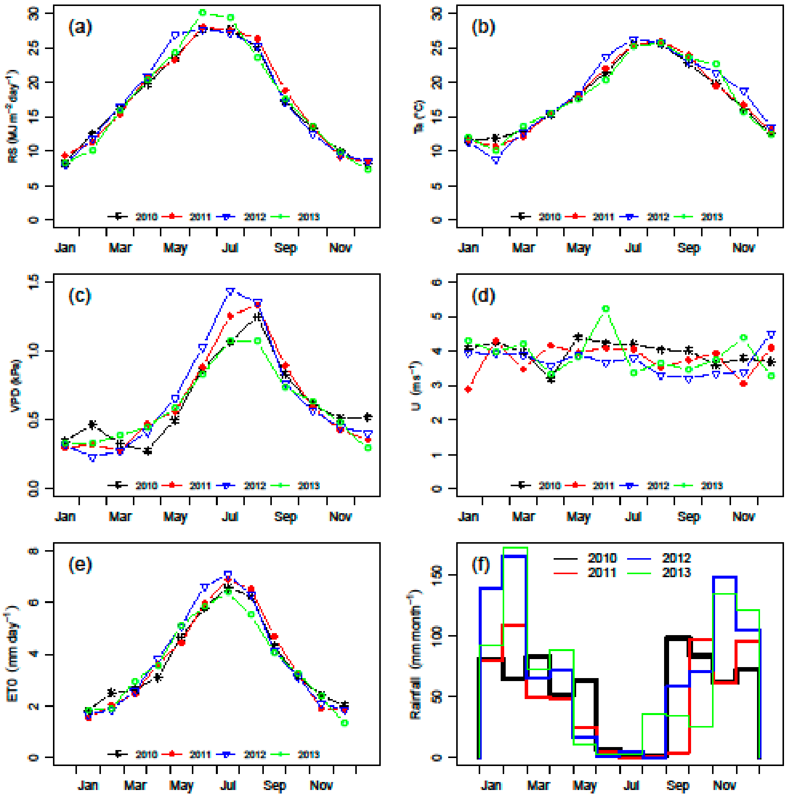

Figure 2. Climatic conditions during the four years of the experiment, recorded at the meteorological station: (a) Incoming solar radiation; (b) air temperature; (c) water vapour deficit; (d) wind speed; (e) reference evapotranspiration; (f) rainfall amounts. Values in (a) to (e) are the monthly averages, values in (f) are cumulated rainfall amounts.

Figure 3 shows the wind rose deduced from wind speeds and directions recorded hourly at the meteorological station. As no systematic seasonal variation of the wind direction was observed, Figure 3 covers the four years of the experiment. Two dominant wind directions were clearly distinguished: a northwestern sector, with winds coming from directions between southwest (220°)

and east-northest (70°) directions (clockwise degrees, north is 0°) and a southern sector, with winds coming from the other directions. These two sectors will be hereafter refered to as NW and S, respectively. The NW winds were more frequent (66%) than the S winds (34%). Even if the variability of wind speeds was low at the monthly time scales (Figure 2), we could observe high speeds at hourly time scale, higher than 8 m.s^{-1}, especialy for NW winds.

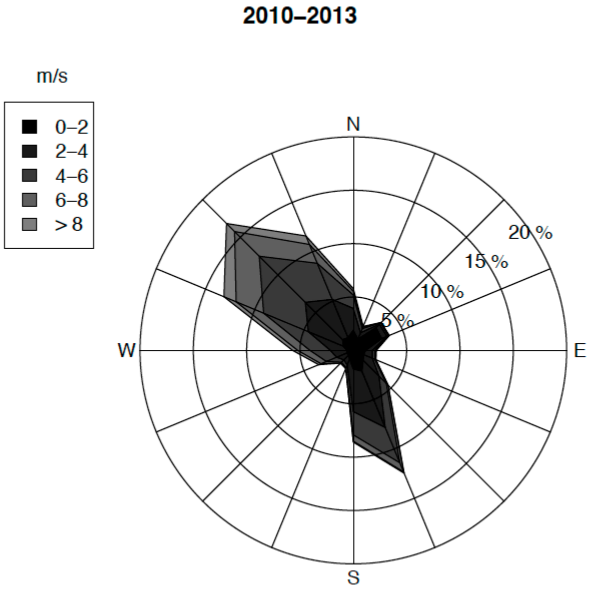

Figure 3. Distribution of the wind directions throughout the four years experiment. The wind rose indicates the occurrence of wind speeds for 16 wind directions.

2.5. Method for gap filling EC data

2.5.1. REddyProc gap filling method

In this study, the gap filling method proposed by [24] was chosen. This choice was motivated by the following reasons. First, this method was tested and proven for a worldwide variety of land surface conditions, in the context of the FLUXNET network. Second, this method does not involve much ancillary information, as it only requires meteorological data. Third, this method is world-widely spread through the R package labeled REddyProc that was developed by [24] at the Max Planck Institute for Biogeochemistry Institute.

This package relies on a gap-filling technique similar to that proposed by [11], and additionally includes (1) the co-variation of fluxes with meteorological variables, and (2) the temporal auto-correlation of the fluxes. In this method, three different conditions are identified one after another [24] :

- Step 1: all meteorological data of interest are available (solar incoming radiation Rs, air temperature Ta, and vapor pressure deficit VPD). The missing values of H or λE are replaced by the average value under similar meteorological conditions for a given time window. Similar meteorological conditions correspond to Rs, Ta and VPD values that do not deviate by more than 50 W.m^{-2}, 2.5 °C, 0.5 kPa, respectively. If no similar meteorological conditions are present within a 14 days time window centered on the date of interest, the time window is extended to 28 days.
- Step 2: Rs only is available. The same approach is taken, and similar meteorological conditions correspond to Rs values that does not deviate by more than 50 W.m^{-2}. The time window is 14 days centered on the date of interest.

- Step 3: all meteorological data are missing. The missing value of H or λE are replaced by values derived at the same time of the day from a mean diurnal course (MDC). The latter are computed on the date of interest when possible, or from the two adjacent days otherwise.

If after these three first steps any value cannot be filled, the procedure is repeated with incremental increases of the window sizes until the value can be filled. This incremental procedure is stopped when no replacement value is found in a 210 days window. As a consequence, continuously missing data for a period of more than 105 days cannot be gap-filled.

2.5.2. Adapting the REddyProc method to hilly cropping systems

REddyProc was applied to fill gaps within incomplete times series of H and λE measurements, labeled H_{ORI} and λE_{ORI} hereafter, by using the meteorological data collected at the local meteorological station: global radiation, air temperature and vapour pressure deficit. The time series of H and λE measurements to be completed were quality controlled data (see section 2.3.2).

- First, REddyProc was applied in its original version without discriminating the two dominant wind directions (classical way). The obtained gap-filled data were labeled H_{REP} and λE_{REP}.

- Second, REddyProc was applied after discriminating the collected data under conditions of north-west (NW) and south (S) winds. We split the complete time series in two datasets. The NW (respectively S) dataset included the H_{ORI} and λE_{ORI} data collected under NW (respectively S) wind conditions. REddyProc was applied over each of these two datasets. The two resulting gap-filled datasets were finally merged. The obtained energy fluxes were labeled H_{RNS} and λE_{RNS}.

3. Results and discussion

3.1. Application of REddyProc

3.1.1. Impact of taking into account the wind direction in REddyProc

The existence of two dominant wind directions on the Kamech watershed might have an effect on the land surface fluxes measured at the flux tower. First, with different wind directions, the fluxes originated from different surfaces, that might have different vegetation covers. Second, the meteorological conditions might be different under NW and S winds. Third, as the flux tower was located near the bottom of the northern rim of the Kamech watershed, NW winds induced descending air flows, whereas S winds induced ascending air flows. On the same hilly site, [21,22] highlighted the importance of considering the wind direction when conducting eddy covariance flux measurements. Therefore, the REddyProc gap-filling procedure was applied in two different manners: without or with discriminating between the two dominant wind directions (see section 2.5.2).

Figure 4 presents the comparison of the sensible and latent heat fluxes estimated by REddyProc after separating the wind directions (fluxes labelled RNS) and without separation (fluxes labelled REP), at hourly, daily and monthly time scales.

At hourly time scale and under NW winds, the sensible heat flux estimates H_{REP} and H_{RNS} were very similar, with a regression line close to the 1:1 line (slope = 1.07, intercept = 1.9), and a small dispersion (RMSE = 11.0 $W.m^{-2}$). Conversely, under south winds, applying REddyProc without separating the wind directions (H_{REP}) distinctly overestimated the sensible heat flux estimates (H_{RNS}) obtained after discriminating the wind directions (slope = 0.81, intercept = -1.9), with a slightly larger dispersion (RMSE = 15.7 $W.m^{-2}$). Very similar results were obtained for the latent heat flux estimates: λE_{REP} and λE_{RNS} were very close under NW winds (slope = 1.05, intercept = -0.5), with a small dispersion (RMSE = 12.2 $W.m^{-2}$), whereas under S winds, λE_{REP} overestimated λE_{RNS} (slope = 0.81, intercept = 3.8), again with a slightly larger dispersion (RMSE = 18.9 W.m^{-2}). These results clearly demonstrate the need of accounting for the wind direction when gap-filling land surface fluxes at hourly time scale, over hilly conditions.

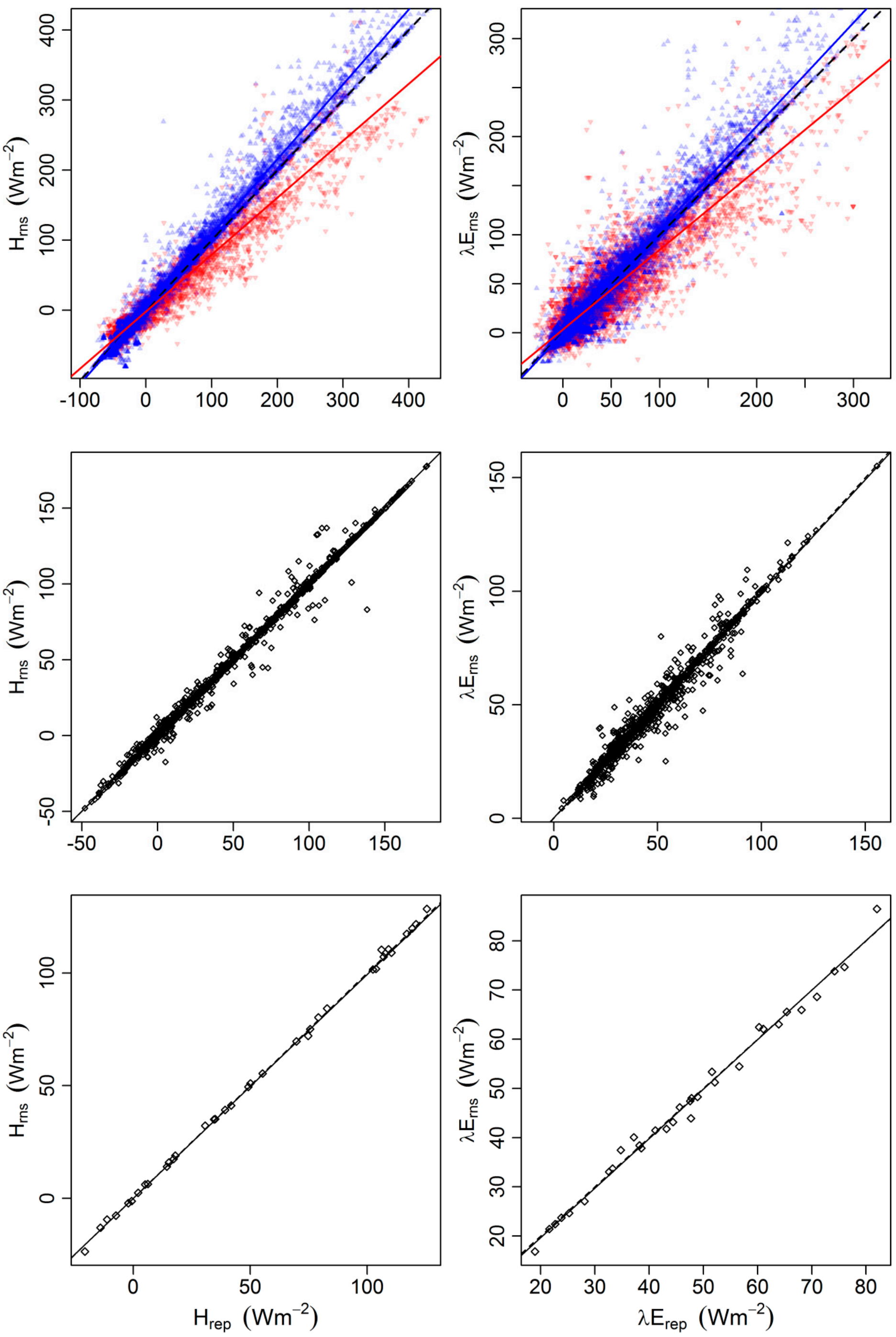

Figure 4. Comparison of the fluxes estimated by REddyProc applied after separating the wind directions (RNS) vs. without separation (REP). Left column: sensible heat fluxes (H); Right column: latent heat fluxes (λE); First line: hourly fluxes (30-min intervals); fluxes under NW winds are in blue; fluxes under S winds are in red; Second line: Fluxes integrated at daily time scale; Third line: fluxes integrated at monthly time scale; Continous line: regression line; Dashed lines: 1:1 lines.

Under NW winds, REddyProc without (REP) or with (RNS) discriminating between wind directions leaded to very similar estimates of the fluxes H and λE. As the NW wind sectors were more frequent (66% in our dataset), the classical way of applying REddyProc (REP) was likely to often replace missing flux data under S winds, by flux data obtained under NW winds.

Hourly flux data were integrated at the daily time scale. Application of REddyProc without (REP) and with (RNS) discriminating between wind directions leaded to very similar results at the daily time scale, for H as well as for λE (see Figure 4): the regression lines between RNS and REP flux estimates were very close to the 1:1 line, and the corresponding RMSE (4.5 and 4.6 $W.m^{-2}$ for H and λE, respectively), were lower than those obtained at the hourly time scale. This decrease of the dispersion can be related to the fact that REddyProc provided unbiased estimates of the fluxes. Furthermore, the fluxes obtained at the daily time scale integrated estimates of the missing flux data provided by REddyProc (REP or RNS), and actually measured flux data, the latter not varying with the way REddyProc was applied.

Further, the daily flux data were integrated at the monthly time scale. As expected, we did not observe any effect of the way the REddyProc procedure was applied (REP vs. RNS), for both H and λE. The dispersion around the regression line was low: 1.3 and 1.7 $W.m^{-2}$ for H and λE, respectively.

3.1.2. Gap filling rates obtained

The percentages of missing data remaining after application of REddyProc are given in the four last columns of Table 1, for both ways of applying REddyProc (REP and RNS). REddyProc was able to gap-fill missing flux data most of the time, except when the duration of the periods with missing data were to long. During the experiment, four period of disfonctioning of the flux tower were identified:

1. In May and June 2010, the LI-7500 analyser experienced a 34 days-long failure, preventing the measurement of λE. REddyProc was able to gap-fill all the missing λE data.
2. In December 2010 and January 2011, the flux tower experienced a 41 days-long failure, preventing the measurement of H and λE. REddyProc was able to gap-fill all the missing H and λE data.
3. From November 2011 to March 2012, the flux tower experienced several failures, preventing the measurement of H and λE, for 99 and 126 days, respectively. Gap-filling of missing data was only partial, leading to a 99 days long period with no gap filling for both H and λE.
4. From October 2012 to May 2013, the flux tower experienced several failures, preventing the measurement of H and λE, for 57 and 224 days, respectively. REddyProc was able to gap-fill all the missing H data, but λE data were not gap-filled during 221 days.

The way of applying REddyProc, without (REP) or with (RNS) separating the wind directions, had no influence on the rate of gap-filled data (see Table 1), except in 2013, when a failure of the wind wane of the meteorological station occurred concurrently to the failure of the flux tower. This prevented the application of the RNS method, whereas the REP method remained applicable.

3.2. Seasonal variations of daily surface fluxes

The seasonal evolution of the sensible (H) and the latent (λE) heat fluxes, at daily time scale, is presented on figure 5, along with the evolution of the evaporative fraction EF, evaluated as:

$$EF = \lambda E / (H + \lambda E), \quad (1)$$

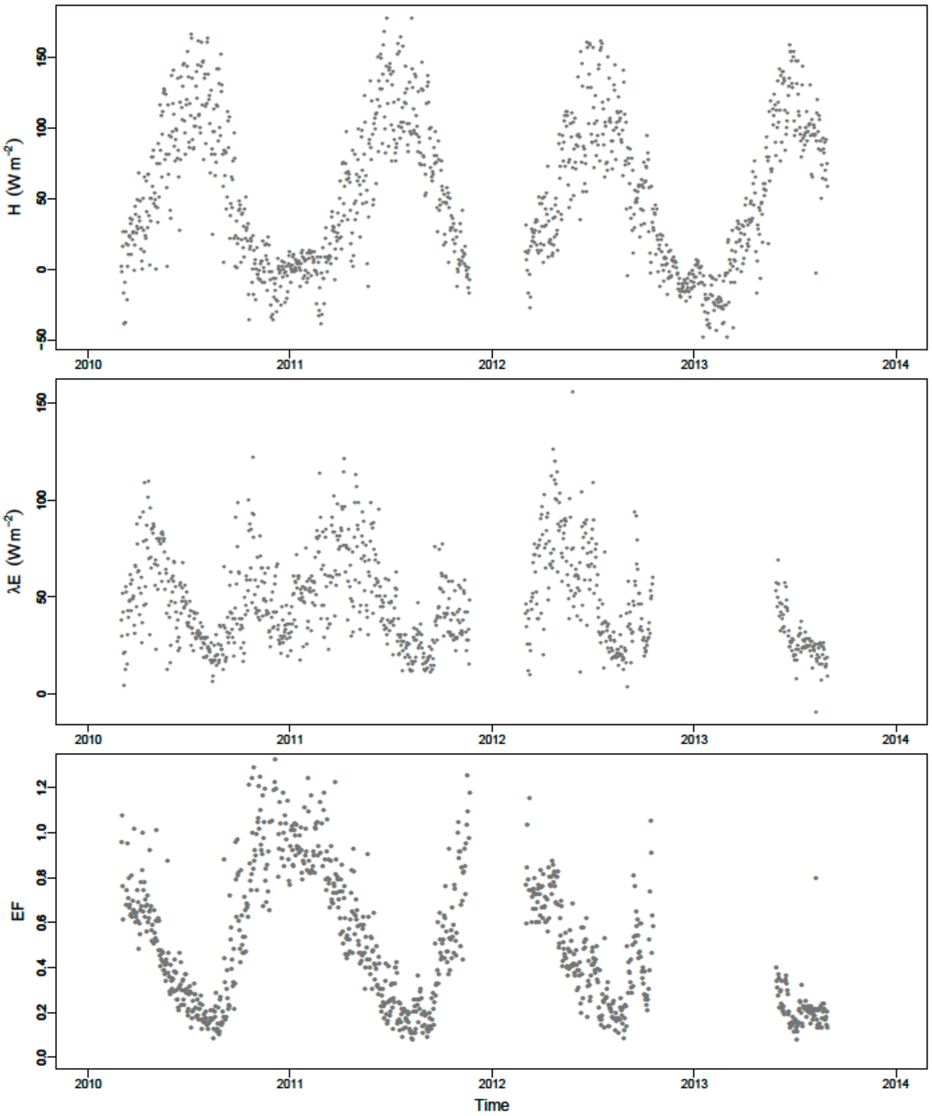

Figure 5. Seasonal evolution of the land surface fluxes at daily time scale. (a) Sensible heat flux (H); (b) Latent heat fluxes (λE); (c) Evaporative fraction. Both fluxes were gap-filled by REddyProc, without separating the wind directions (REP).

Following the evolution of the incoming solar radiation and of the air temperature, the daily values of sensible heat flux H exhibited a regular evolution over the seasons, with maximum values, around 170 W.m^{-2}, in summer (June to August) and minimum values in winter (November to February). Negative values of the sensible heat flux could be observed during winter, down to -50 W.m^{-2}.

The daily values of latent heat flux λE increased from winter to spring, reaching its maximum in April, when the development of the vegetation and soil moisture availability permitted high levels of evapotranspiration, around 120 W.m^{-2}, which correspond to 3.5 mm.day^{-1}. With the maturation and scenescence of the canopies, along with the decrease of the rainfall amounts, the latent heat flux decreased rapidly from the end of spring to summer, reaching very low values in August, down to 15 W.m^{-2} (0.5 mm.day^{-1}). With the start of the rainy season, the latent heat flux increased in fall, then decreased during winter with the decreases of the incoming solar radiation and of the air temperature.

The seasonal evolution of the evaporative fraction EF was rather regular, with low values, between 0.1 and 0.2, during summer, and with high values, between 0.8 and 1.2, during winter, the EF values exceeding unity corresponding to the periods during which the sensible heat flux was negative.

The sensible and the latent heat fluxes, as well as the evaporative fraction, exhibited large day-to-day variability, that could be ascribed to the variability of meteorological conditions, including rainfall events that could induce an increase of the latent heat flux during the following days.

The gap filling of the flux data by the REddyProc method was possible during the whole experiment, except for the periods 3 and 4 given in section 3.1.2.

3.4. Monthly evapotranspiration

Daily latent heat fluxes λE were monthly averaged, which permitted to reduce the day-to-day variability observed at the daily time scale, and converted in actual evapotranspiration units (mm.day^{-1}). Figure 6 presents the seasonal evolution of actual evapotranspiration (ETa) and of its ratio to reference evapotranspiration ET_0, the latter being deduced from measurements at the meteorological station (see section 2.4). Actual evapotranspiration ETa followed a classical behaviour for Mediterranean rainfed crops, increasing from 1 - 1.5 mm.day^{-1} in winter to 2.5 - 3 mm.day^{-1} in April. From the end of spring to summer, ETa regularly decreased, reaching a minimum below 1 mm.day-1 in August. During fall, ETa increased again, as a consequence of rainfall events that are usual during that part of the year, then decreased in winter, as a consequence of the decrease of both the incoming solar radiation and the air temperature.

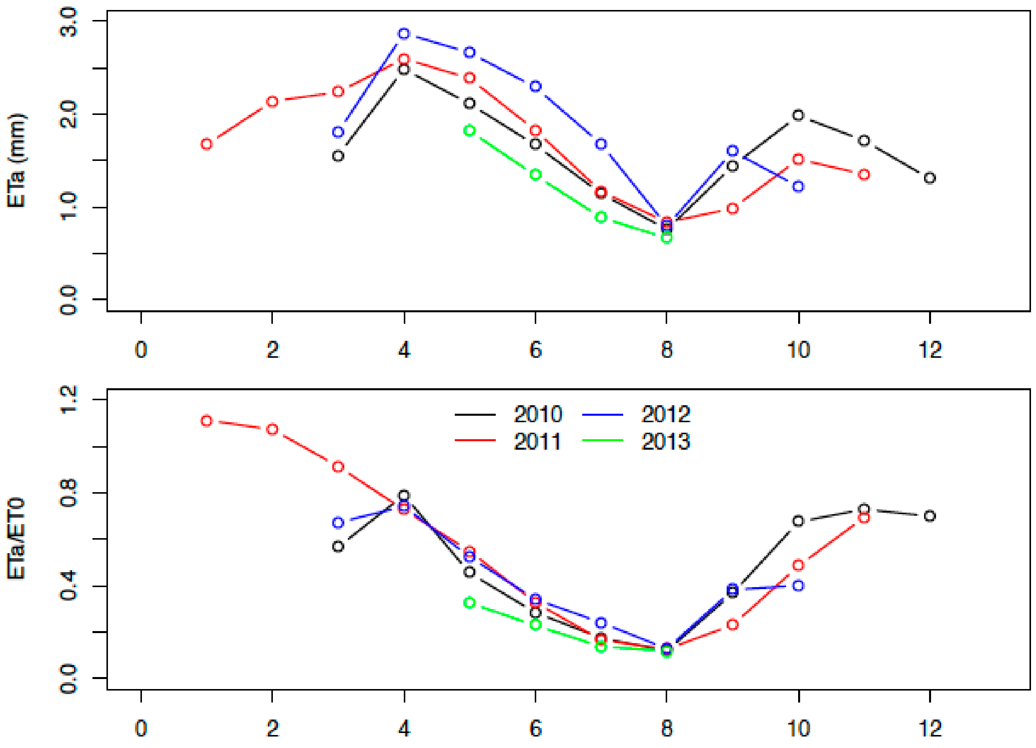

Figure 6. Seasonal evolution of the actual evapotranspiration at monthly time scale, during the four years of the experiment. (a) Actual evapotranspiration ETa; (b) Ratio of actual evapotranspiration to reference evapotranspiration ET_0.

Regarding the inter-annual variability, examining the ratio of the actual evapotranspiration ETa to the reference evapotranspiration ET_0 permits to account for the variability of the climatic demand. As an example, the actual evapotranspiration was slightly higher in May 2012 than in May 2013, despite reference evapotranspirations were almost equal. The ratio ETa/ET_0 was clearly very sensitive to the rainfall amonts occuring during the fall, with an increase of ETa/ET_0 arising sooner during the wet Septembers of 2010 and 2012 than during the dry September of 2011.

4. Conclusions

This study aimed at obtaining continuous time series of actual evapotranspiration from EC measurement collected during nearly four years, within an hilly watershed covered by rainfed crops, in a Mediterranean context. This agricultural watershed was typified by the existence of two dominant wind directions, that might interact with the hilly topography. The REddyProc method was choosen to gap-fill the missing flux data that are inherent to the eddy-covariance method, but was adapted to our particular conditions by separating the flux dataset between the two dominant wind directions. It was demonstrated that at hourly timescale, it was necessary to discriminate between wind directions. Conversely, the fluxes obtained with or without discriminating wind directions were very similar at daily and monthly timescales.

The analysis of the time series of the sensible and latent heat fluxes integrated at daily time scale emphasized the high consistency of the land surface fluxes obtained over this hilly watershed. At monthly timescale, the actual evapotranspiration ETa deduced from EC measurements exhibited a very good consistency with the reference evapotranspiration ET_0 measured at the meteorological station, with clear and coherent seasonal variations of the ratio ETa/ET_0. Our results gave great confidence in the observation of land surface fluxes by EC measurements over a small hilly watershed. These flux time series could be further used for validating hydrological models, or for testing water management scenarios to mitigate the effect of global change.

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Abbreviations

The following abbreviations are used in this manuscript:

λE: latent heat flux
asl: above sea level
EC: eddy covariance
EF: evaporative fraction

ET_0: Penman-Monteith reference evapotranspiration
ETa: actual evapotranspiration
H: sensible heat flux
NW: northwest wind sector (220° to 70°)
OMERE: french acronym for the Mediterranean Observatory of Water and Rural Environment
REP: REddyProc applied without discriminating wind directions (classical way)
RNS: REddyProc applied after discriminating wind directions (NW / S)
(R)RMSE: (relative) root mean squared error
Rs: incoming solar radiation
R^2: coefficient of determination
S: south wind sector (70° to 220°)
Ta: air temperature
VPD: water vapour pressure deficit

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