Special Section: HOBE

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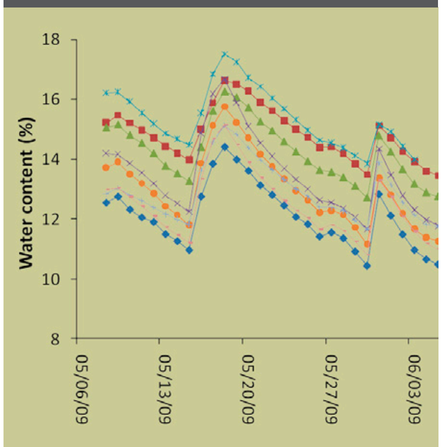

Daily root zone soil moisture depletion, measured using time domain reflectometry (TDR), was compared with daily accumulated water vapor loss, using the eddy covariance (EC) technique. The two approaches were in good agreement during dry periods, indicating that TDR-based evapotranspiration rates can be used for evaluating EC-measured evapotranspiration rates.

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Comparing Evapotranspiration Rates Estimated from Atmospheric Flux and TDR Soil Moisture Measurements

Measurements of water vapor fluxes using eddy covariance (EC) and measurements of root zone soil moisture depletion using time domain reflectometry (TDR) represent two independent approaches to estimating evapotranspiration. This study investigated the possibility of using TDR to provide a lower limit estimate (disregarding dew evaporation) of evapotranspiration on dry days. During a period of 7 wk, the two independent measuring techniques were applied in a barley (*Hordeum vulgare* L.) field, and six dry periods were identified. Measurements of daily root zone soil moisture depletion were compared with daily estimates of water vapor loss. During the first dry periods, agreement between the two approaches was good, with average daily deviation between estimates below 1.0 mm d^{-1}. Toward the end of the measurement period, the estimates of the two techniques tended to deviate due to different source areas contributing to the flux estimates. With certain limitations, TDR-based evapotranspiration estimates are a promising approach for confining EC-based evapotranspiration.

Abbreviations: EC, eddy covariance; LAI, leaf area index; TDR, time domain reflectometry.

Evapotranspiration is a major component of the water balance of natural and managed ecosystems and affects processes such as biomass accumulation and groundwater recharge. The daily evapotranspiration loss from an ecosystem is difficult to measure accurately, and several approaches have been applied at different scales and compared to obtain a reliable estimate (Kelliher et al., 1992; Rana and Katerji, 2000; Wilson et al., 2001; Verstraten et al., 2008).

Eddy covariance above-canopy measurement of water vapor flux provides one of the most reliable and widely applied methods for estimating short- and long-term total evapotranspiration (Baldocchi et al., 1988; Wilson et al., 2002; Suyker and Verma, 2008). Although in principle a simple technique, great care must still be taken in analyzing the EC flux data to account for nonideal measurement conditions (Massman and Lee, 2002; Ibrom et al., 2007; Mahrt, 2010).

Time domain reflectometry is a widely applied technique for the nondestructive measurement of soil water content due to its flexibility, accuracy, and the possibility for automated measurement of several probes simultaneously (Topp and Reynolds, 1998; Robinson et al., 2003; Topp and Ferré, 2004; Robinson et al., 2008). The TDR-based observations of root zone soil moisture dynamics have often been used to support the calibration and evaluation of root water uptake models (Musters and Bouten, 2000; Jansson et al., 1999; Ladekarl et al., 2005; van der Keur et al., 2001; Schelde et al., 1998) but have only in very few cases been used directly for estimating evapotranspiration rates (Wilson et al., 2001; Young et al., 1997).

Wilson et al. (2001) compared estimates of stand evapotranspiration in a mixed deciduous forest and found a positive correlation between estimates based on EC and on the soil water budget; however, the data were highly variable. The EC-based estimates were generally a little higher than estimates based on soil water content measurements to a depth of 0.75 m—assumed to be the maximum rooting depth. During a 6-d dry period, Young et al. (1997) found good agreement between estimated water loss from a grass-covered weighing lysimeter and the accumulated water loss estimated from vertically installed 0.8-m TDR probes.

We note that detailed and frequent soil moisture observations are valuable because they provide an independent estimate of soil water depletion, comparable to evapotranspiration, during dry periods in which precipitation, irrigation, and drainage are negligible. Soil moisture observations that embrace the entire root zone will account for all root water uptake plus soil surface evaporation. Within 24-h cycles without precipitation, only minor initial wet canopy evaporation will be unaccounted for by a daily soil moisture budget. The prospects for comparing soil-moisture-based evapotranspiration with estimates provided by above-canopy micrometeorological techniques have hardly been explored. The objective of this study was to compare 53 d of daily estimates of evapotranspiration from an agricultural field using the two independent techniques: TDR soil moisture measurement and EC water vapor flux measurement, and to evaluate the possible application of TDR-based evapotranspiration estimates to confine EC-based evapotranspiration estimates. If the approach is successful, it could provide a useful additional quality control tool in micrometeorological flux studies where the degree of energy balance closure has often been adopted as a quality control measure on latent (and sensible) heat fluxes (Wilson et al., 2002; Foken, 2008; Mahrt, 2010).

Materials and Methods

Study Site and Period

The TDR and EC measurements were performed in an agricultural field ("focus field") during the period 5 May to 26 June 2009. The agricultural crop was winter barley (cv. Anisette) that had been established during September 2008 and was harvested on 21 July 2009. The field was located within the Skjern River catchment near Herning in central Jutland, Denmark. The soil was a Spodosol—a coarse sand below a 0.30-m organic topsoil—located on the glaciofluvial sandy outwash plains of the most recent European glaciations. Soil porosities in the upper 1 m of the profile ranged between 0.35 and 0.40. The soil water holding capacity was small: available soil water (between pF 2.0 and pF 4.2, equivalent to pressure heads between 100 and 15,850 cm) was 19% (v/v) in the upper 20 cm of the plow layer and only 6% (v/v) in the remaining part of the root zone, necessitating frequent irrigation to maintain crop growth during most growing seasons. The groundwater level was located well below the root zone, at a depth of approximately 5 m.

Time Domain Reflectometry System for Measuring Root Zone Water Content

A self-contained TDR system, TC36, was developed. The TC36 includes a compact PC unit, a TDR100 TDR instrument (Campbell Scientific, Logan, UT), and a 36-channel multiplexer. The TC36 software includes options for generating and testing multiprobe parameter sets and making automated measurements of soil moisture content as described in the user's guide (Thomsen, 2006). The user's guide also includes details on probe design and field installation. In manual test mode, the user is presented with graphs showing the acquired and analyzed traces for real-time quality assurance and optimization of parameters controlling trace acquisition and analysis. The software used for data acquisition, analysis, and storage (Thomsen, 1994) is similar to software developed by Baker and Allmaras (1990) and Heimovaara and Bouten (1990).

For this experiment, eight measurement probes, installed vertically from the surface, were included. The probes were a balanced type including a balancing and impedance matching (50–200-Ω) pulse transformer (Spaans and Baker, 1993). The pulse transformer was placed in the probe head, connecting the RG58 low-loss coaxial cable and the probe rods made from 0.006-m-diameter stainless steel. To include the entire root zone (soil profile studies estimated this to be 0.65 m at maximum), a probe length of 0.75 m was selected. Because of a hard and stony layer at approximately the 0.5-m depth, probe installation was difficult, adding to the variability in measured water content. The TDR probes were installed in a group in the middle of the field, spaced approximately 0.25 m apart and occupying an area of 1 m^2. Probe cables were 20 m long to exclude edge effects from the fenced area that included the EC mast, the TDR system, and other meteorologic installations.

The TDR observations were available during 5 May to 26 June 2009, when harvest was approaching.

Eddy Covariance Measurements of Water Vapor Fluxes

A three-dimensional sonic anemometer (R3–50, Gill Instruments Ltd., Lymington, UK) was installed to take measurements at 12.5 m above the soil surface. The instrumented mast was installed close to the center of the field. Measurements were taken at a frequency of 10 Hz. A membrane pump (N 89 KNDC, KNF Neuberger, Freiburg, Germany) with a nominal pumping capacity of 9 L min^{-1} moved air from a tube inlet close to the sonic anemometer into an infrared gas analyzer (LI-7000, LI-COR, Lincoln, NE) that measured the mole fraction of H_2O and CO_2 at a nominal frequency of 10 Hz. The tube had an inner diameter of 6 mm and was 20 m long. The air passed through a 1-μm Gelman filter in front of the inlet to the LI-7000, which was changed every 2 mo on average. All data were stored on a datalogger (CR3000, Campbell Scientific, Logan, UT) and transferred to Copenhagen University on a daily basis.

The delay time for the CO_2 and H_2O signals, as calculated from the best correlation with the vertical wind component, was 6.5 s on average. Taking the tube dimensions and the average cell pressure in the LI-7000 of 9.4 kPa into consideration, this corresponds to a true flow rate of 5.6 L min^{-1}, a response time of 0.12 s, and a cutoff frequency of 1.37 Hz. The relatively low cutoff frequency was not considered a major problem because of the relatively smooth surface and the relatively large measurement height of 12.5 m (Eugster and Zeeman, 2006). Nevertheless, a frequency response correction (Moore, 1986) was essential and was included in the flux calculations. The turbulent flux of H_2O was calculated from the covariance between the vertical wind speed and the H_2O concentration, averaged across 30 min, using the Alteddy software, version 3.5 (Alterra, Univ. of Wageningen, Wageningen, the Netherlands). The fluxes were corrected for errors caused by the tilt of the anemometer relative to the mean streamline coordinate system by use of the planar fit method (Wilczak et al., 2001). In this way, the modification of the wind field by the presence of the other installations at the site was accounted for. Following a quality check using the criteria proposed by Foken et al. (2004), the gaps caused by a few hours with rejected data were filled according to Moffat et al. (2007). All water vapor fluxes were accumulated to daily values (mm d^{-1}).

The average distance to the point in the field with the highest flux contribution, as well as the cumulative contribution of an area up to a certain distance, was calculated using the equations of Schuepp et al. (1990), taking the stability correction method of Dyer (1974) into account and assuming a typical Monin–Obukhov length of $L = -40$ m. The leaf area index (LAI) at the focus field was measured with an optical sensor (LAI-2000, LI-COR, Lincoln, NE). Every third week, six above-canopy readings and 24 below-canopy readings were taken in the focus field of winter barley and seven neighboring fields that were cropped with spring or winter barley. Additional measurements were taken in the pine forest northeast of the focus field. All data obtained for the same crop type were averaged. The "green LAI" for the barley crops was calculated on the basis of a visual examination of the average number of green leaves per plant in relation to the total number of leaves as seen by the LAI-2000.

Precipitation and Irrigation

Precipitation was measured using a tipping bucket rain gauge (RIMCO 7499, McVan Instruments, Mulgrave, VIC, Australia) located 50 m south of the flux station. The bucket size of 0.1 mm allowed the calculation of precipitation amounts and intensities at a fine time resolution. Irrigation of the barley crop was performed by the farm manager three times before and four times during the measurement period, on 18 April, 30 April, 3 May, 15 May, 30 May, 7 June, and 18 June. On each of these dates, the irrigation amount reported by the farmer was 22 to 25 mm.

Results and Discussion

Precipitation Records for Identification of Dry Periods

During periods with no or very little precipitation, the TDR observations provided an estimate of the soil water depletion as a result of evapotranspiration. This implicitly assumes no downward transport of water taking place during the dry periods investigated here. Similarly, upward capillary flux from below the zone monitored by TDR should be negligible. For the sandy and fast-draining soil at the site, we considered both conditions fulfilled. To evaluate the performance of TDR-based evapotranspiration estimates, we classed days with a maximum precipitation of 1.0 mm as dry. Six individual dry periods could be identified from the available data series, ranging in duration from 2 to 6 d (Fig. 1). In the simple soil water balance calculations based on 24-h differences in TDR-observed soil moisture, the small contributions from minor showers on dry days were incorporated as infiltrating water after allowing 0.2 mm for interception loss.

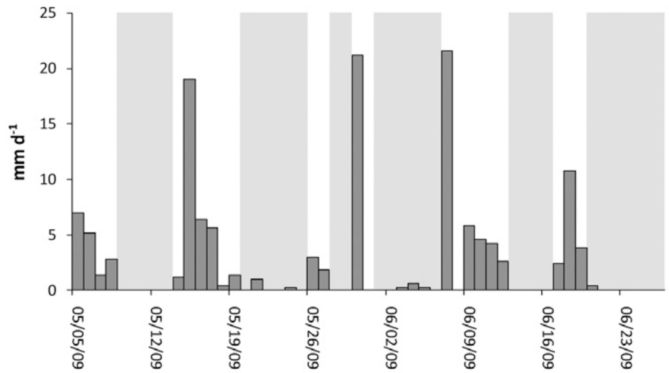

Fig. 1. Precipitation and irrigation events during the experimental period from 5 May to 23 June 2009. Six periods identified as dry are shaded.

Averaging Frequent Time Domain Reflectometry Observations

The original TDR soil water content measurements were made at 15-min intervals. Figure 2 demonstrates the diurnal development of water content (individual observations) for three probes during 6 d. The three probes selected represent a range in the measurement uncertainty of individual probes. Probe 4 shows a development in water content with very little scatter, while Probe 2, followed by

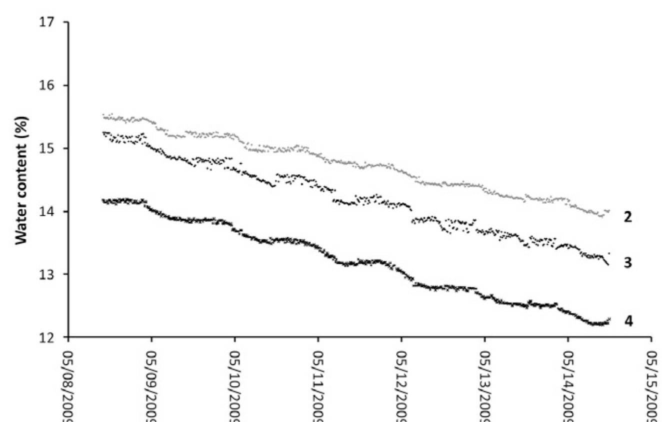

Fig. 2. Time domain reflectometry (TDR) based observations of soil water content at 15-min time resolution (raw data) from 8 to 15 May 2009. Three probes are shown; Probe 4 was very stable while Probes 2 and 3 exhibited more noisy readings, requiring filtering of the data to estimate diurnal changes in soil water content. On the *x* axis, tick marks indicate 1200 h.

Probe 3, shows increasing scatter, although with the same diurnal development as Probe 4. The varying amount of scatter was due to small differences in probe manufacture, producing slightly different entry points of the TDR trace of individual probes and leading to varying degrees of minor instability in the automated TDR trace analysis.

For each probe, we calculated hourly averages of soil water content, and Fig. 3 shows the range in hourly water contents observed within the relatively small area (1 m^2) during the entire period. The spatial variability in soil moisture within a managed agricultural field can be considerable and several replicates are required to resolve this variability (Thomsen et al., 2007; Brocca et al., 2010). For our water balance calculations, we considered only daily changes, i.e., stepwise 24-h reductions in average water content, and the observed water content dynamics generally progressed in parallel for the individual probes.

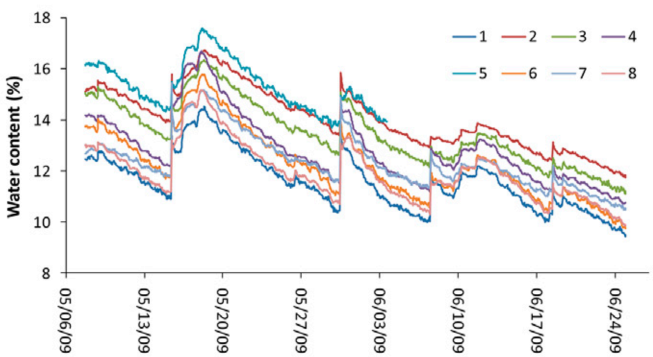

Fig. 3. Time domain reflectometry (TDR) measured soil water content at 1-h time resolution during the entire period from 6 May to 24 June 2009. Diurnal evolution in water content was evident for many of the eight probes. Four irrigation events on 15 and 30 May and 7 and 18 June caused clear increases in soil water content in the 0- to 0.75-m soil layer.

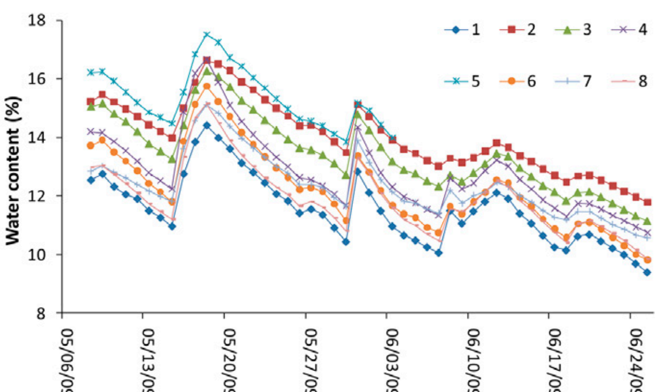

Fig. 4. Time domain reflectometry (TDR) data for 6 May to 24 June 2009 prepared for water balance calculations: daily TDR-based observations of soil water content at 0200 h for the eight individual TDR probes. Values are means of 15-min observations between 0000 and 0345 h.

Figures 2 and 3 demonstrate how the TDR method was capable of resolving relatively small changes in water content. Changes during 1 d of 0.2% (v/v) or more were detectable, equivalent to a "detection limit" of average water loss throughout the 0.75-m measurement depth of 1.5 mm d^{-1}. It may also be seen from Fig. 2 and 3 how soil water contents stabilized at an almost constant level after 0000 h, so we calculated, for each probe, the mean nighttime soil moisture content at 0200 h as means of 15-min observations between 0000 and 0345 h. The resulting daily time step (Fig. 4) soil water contents were calculated to enable the calculation of daily depletion in soil water content for a direct comparison with daily accumulated water vapor fluxes. In principle, the comparison between measurement techniques could be made at an even smaller time step than 24 h; however, root water uptake, assumed to make up a large proportion of the observed soil water depletion, could be expected to be slightly delayed in time compared with observed evapotranspiration, as also observed in studies involving sap flow and considerations of internal water storage in plants (Stockle and Jara, 1998; Köstner et al., 1992). Hence, 24 h was considered the smallest possible time step for a comparison between techniques.

Comparing Evapotranspiration Estimates

While EC observations ran continuously during May through July 2009, the time slots available for comparison were constrained by the availability of TDR observations during dry periods. Figure 5 shows the EC- and TDR-based evaporation estimates for all available dry days. In Table 1, the accumulated values for the six periods are given.

Table 1 indicates that EC estimates were generally higher than TDR estimates and that deviation between techniques on a daily basis was quite small during all periods but Period 6. Figure 5 reveals more disparity than Table 1, with TDR estimates sometimes being higher than the EC estimate. Agreement between techniques was generally good during Periods 1 to 4. For Periods 5 and 6, the discrepancy between techniques tended to increase and single-day deviations eventually exceeded 1 mm d^{-1}.

A possible reason for the increasing discrepancy toward the end of the period may be that different source areas contributed to the measured fluxes. While the TDR-based estimate always reflected conditions within the winter barley field close to the EC mast, the footprint of the flux measurements would sometimes extend into surrounding fields cropped with spring barley, as well as heath and pine forest toward the north and northeast, the latter having an average LAI of 2.4. The simple footprint model of Shuepp et al. (1990) provided an estimate of the effective distance seen by the flux mast (the flux source area) and a corresponding cumulative flux contribution with distance: 50% of the flux originated within 250 m of the mast and 80% of the flux originated within 800 m of the mast.

In Fig. 6, daily deviations between evapotranspiration estimates are shown as a function of wind direction. The largest deviations occurred for Periods 5 and 6 with winds from the east and northeast

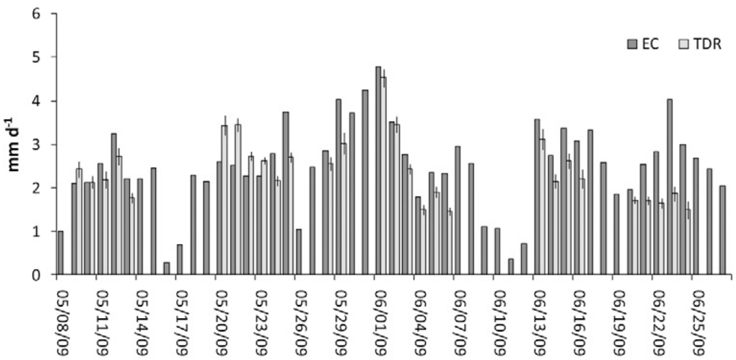

Fig. 5. Eddy covariance (EC) and time domain reflectometry (TDR) based estimates of daily evapotranspiration from 8 May to 25 June 2009. For TDR-based estimates, only dry days (precipitation <1 mm and days not following irrigation events) were considered. The TDR-based observations are shown with standard errors of the mean.

directions. The source area in these directions, extending beyond the border of the field at a distance of 250 m from the mast, was heterogeneous, including heath, sparse pine forest, orchards, and a spring barley field. While the winter barley crop began maturing and senescing toward the middle and end of June 2009, the surrounding areas were still actively transpiring. We observed the development in green LAI in the winter and spring barley crops and found that on 2 June 2009, the green LAI of spring barley and winter barley were similar (4.1 and 4.7, respectively). Three weeks later, on 25 June, the green LAI of spring barley was four times that of winter barley (2.2 vs. 0.5), illustrating the rapid senescence of winter barley in June.

Limitations and Prospects of Evapotranspiration Estimates Based on Time Domain Reflectometry

We concluded that the two estimates of evapotranspiration on dry days were initially in good agreement, but with EC often reporting the higher evapotranspiration. The TDR estimate accounts for net soil water depletion, while even for days without measurable precipitation the EC net evapotranspiration estimate may include minor evaporation of morning dew from the vegetation, a positive water flux that is not necessarily counteracted by dew formation toward the end of the day. Hence, we expect the TDR estimate to constitute a lower limit of evapotranspiration during a 24-h cycle, and, consequently, TDR estimates can be used for confining EC observations. To allow a valid confinement, a number of requirements must be met: (i) a dry day, (ii) similar source areas, (iii) knowledge of the root zone depth, and (iv) TDR observations embracing all soil moisture changes in the root zone. The first requirement can easily be determined from rainfall records. With regard to the second, this requires a sufficient number of replicates of TDR observations to resolve the variability within the field seen by the EC observations. As demonstrated, however, even if the observed soil moisture spans a wide range in water contents, daily or periodic changes in water content are less variable. The third requirement calls for maximum root depth studies before deciding on the measurement depth of the TDR probes. With regard to the fourth requirement, it should be noted that with increasing length of vertically installed TDR probes, it becomes increasingly difficult to resolve small changes in water content because the average soil moisture content throughout the extent of the probe will change only a little on a daily basis. Thus for deeper root zones than the present one, TDR-based estimates may only be possible for longer time intervals.

Table 1. Six dry periods and the observed accumulated soil water depletion (determined by time domain reflectometry [TDR]) and accumulated water vapor flux (determined by eddy covariance [EC]). Deviations were calculated in relation to the number of days in the period and the accumulated water vapor flux.

Period	Dry period in 2009	Accumulated water depletion†	Accumulated water vapor flux	Mean daily deviation	Relative deviation
		mm			%
1	9–13 May	11.2 (0.6)	12.2	0.2	8
2	20–25 May	17.1 (0.6)	16.2	−0.2	−6
3	28–29 May	5.6 (0.4)	6.9	0.7	19
4	1–6 June	15.3 (0.6)	17.5	0.4	13
5	13–16 June	10.1 (0.8)	12.7	0.7	20
6	20–24 June	8.4 (0.5)	14.3	1.2	41

† Standard error of the mean in parentheses.

Conclusions

While acknowledging the limitations listed above, we found TDR-based evapotranspiration estimates a promising approach to confining (lower limit) EC observations of water vapor fluxes. The lower limit confinement is due to the fact that during a dry 24-h or longer cycle, only a possible initial wet canopy evaporation will be unaccounted for by the TDR method, while root

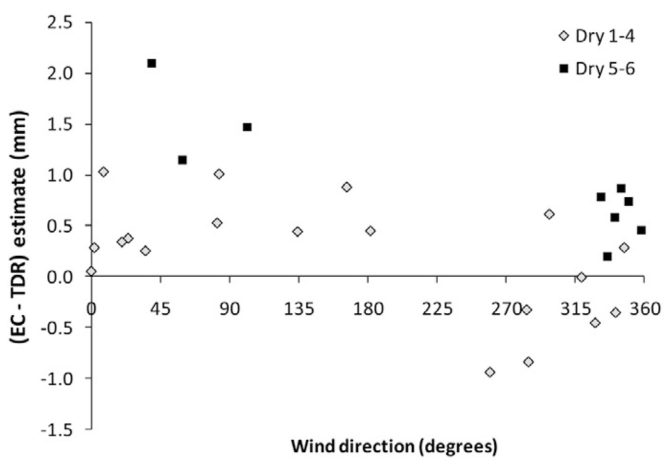

Fig. 6. Deviation between daily eddy covariance (EC) and time domain reflectometry (TDR) based evapotranspiration estimates as a function of wind direction. Dry periods in 2009 were: 1, 9–13 May; 2, 20–25 May; 3, 28–29 May; 4, 1–6 June; 5, 13–16 June; and 6, 20–24 June.

water uptake leading to canopy transpiration and soil surface evaporation will be accounted for by soil moisture measurements comprising the entire root zone. Likewise, the TDR-based evapotranspiration can confine other "top-down" evapotranspiration estimates based on above-canopy micrometeorological techniques and thus has the potential to serve as an additional quality control tool within micrometeorological flux studies. The present study is a first indication of the possibilities of the approach and should be succeeded by an analysis of longer time series of observed evapotranspiration, possibly on other soils and vegetation types, and accompanied by a full footprint analysis to identify time periods when flux source areas are similar and TDR and EC estimates are directly comparable.

Acknowledgments

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