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Research paper

Estimating non-rainfall-water-inputs-derived latent heat flux with turbulence-based methods

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A R T I C L E I N F O

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A B S T R A C T

Non-rainfall water inputs (NRWI) are a significant water source in drylands. Small latent heat flux (λE) involved in the formation and evaporation of NRWI presents measurement challenges. Microlysimeters (MLs) are a point measurement that was previously shown to be accurate for detecting NRWI. In an attempt to upscale these measurements, two turbulence-based methods were examined. Their larger spatial extent is potentially an important improvement over the ML point measurements. However, accumulation of NRWI largely occurs during the night, during which strong stable conditions are typical for many drylands. This may challenge turbulence-based methods.Therefore the applicability of such methods for monitoring NRWI needs to be carefully examined before being disseminated for use. In this research, NRWI-derived λE obtained by an eddy-covariance (EC) and a surface layer scintillometer (SLS) using the energy balance approach were tested against ML measurements over a bare soil in the Negev Desert during the dry summer season. The microlysimeter, the EC, and the SLS all recorded similar diurnal dynamics of λE but, compared to the ML measurements, the EC tended to underestimate the λE flux while the SLS (with ancillary measurements) over estimated λE. Closures of 93% and 89% for the ML and the EC respectively are indicative of the EC underestimation. In the case of the SLS, under the research conditions, the large magnitude of soil heat flux (G) and the divergence of its calculation by two different methods, make G a prime suspect. However, a question still remains as to the accuracy of the scintillometer-derived *H*.

1. Introduction

Non-rainfall water inputs (NRWI), i.e., a gain of water to the surface soil layer that is not from rainfall, are comprised of fog deposition, dew formation, or water vapor adsorption, depending on local meteorological conditions. In drylands, NRWI are known to significantly contribute to the water cycle (Agam et al., 2004; Agam and Berliner, 2006, 2004; Danalatos et al., 1995; Kidron et al., 2000; Kidron et al., 2002; Kosmas et al., 2001, 1998; Ramírez et al., 2007; Verhoef et al., 2006), as the annual amount of NRWI can exceed that of rainfall and even constitute the sole source of liquid water during the long dry summer (Evenari, 1986; Jacobs et al., 1999; Lange et al., 1998, 1992). It has been suggested that NRWI may contribute to biogeochemical dynamics by promoting microbial activity and nutrient recycling in the upper few centimeters of the soil profile (Whiteford and Spanu, 2002), leading to consumption and emission of three major greenhouse gases: CO_2, N_2O, and CH_4 (Baldock et al., 2012; Grover et al., 2012; Smith et al., 2003).

However, the small magnitude of the λE fluxes involved in the formation and evaporation of NRWI challenges their measurement. In an attempt to overcome this challenge, various methods for measuring the duration and quantity of NRWI have been developed, especially for dew formation (Uclés et al., 2013). Direct measurements of dew mostly consist of the use of artificial condensation plates (Andrade, 2003; Beysens et al., 2005; Bunnenberg and Kühn, 1977; Duvdevani, 1947; Gillespie and Duan, 1987; Jacobs et al., 1994; Jacobs et al., 1990; Kidron et al., 2000, 2011; Li, 2002; Liu and Foken, 2001; Lomas, 1964; Pedro and Gillespie, 1982; Rao et al., 2009; Ye et al., 2007). These approaches are valid for comparing between different atmospheric conditions, but are strongly affected by the characteristics of the condensation plate and are thus not applicable for representing the amount of NRWI absorbed by the soil (Ninari and Berliner 2002).

An alternative method for quantifying both dew and water vapor absorption is the microlysimeter (ML). A ML is a cylindrical column of undisturbed soil sample installed such that its surface is level with the surrounding soil and is exposed to the atmosphere. Changes in the ML mass are translated into changes in the amount of water in the soil sample, or their equivalent latent heat flux (λE) exchange. The surface

Abbreviations: NRWI, nonrainfall water inputs; ML, microlysimeter; EC, eddy covariance; SLS, surface layer scintillometer

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area, the column depth, and the wall material of the ML should be carefully defined in order to keep the thermal balance in the ML similar to that in the surrounding soil (Ninari and Berliner, 2002). Several NRWI studies applied periodical manual weighing of MLs, attempting to capture the time of minimum and maximum weight to determine daily amounts of water addition (Jacobs et al., 1999; Rosenberg, 1969; Sudmeyer et al., 1994; Waggoner et al., 1969). However, the exact time at which they occur is difficult to accurately estimate, which may result in an underestimation of NRWI (Uclés et al., 2013). Continuous automatic weighing is therefore advantageous and has been used in several studies to monitor NRWI (Brown et al., 2008; Heusinkveld et al., 2006; Ninari and Berliner, 2002; Uclés et al., 2013). While a continuous measurement imposes some additional technical challenges, it provides the rate of accumulation in addition to the total mass gain, without the need to be present in the field. If correctly constructed, this method provides an absolute reference for water balance measurements (Evett et al., 2012). However, being a point measurement, it is limited and cannot represent the natural spatial variability. Given the large heterogeneity of soils, upscaling from point measurement to larger scales is necessary to fully understand the environmental factors controlling NRWI.

Turbulence-based methods (e.g., eddy-covariance and scintillometry) can be used directly or indirectly to measure the latent heat flux (λE) resulting from the formation and evaporation of NRWI at a significantly larger footprint. The larger spatial extent of these methods is potentially an important improvement over the ML point measurements. However, while having a larger footprint, attempting to measure NRWI-derived λE is challenging. Accumulation of NRWI largely occurs during the night, when conditions are typically stable and λE is relatively small. This often results in a significant uncertainty in the λE measurement (Kustas et al., 1994). Therefore the applicability of such methods for monitoring NRWI needs to be carefully examined before implementation. In this research, NRWI-derived λE obtained by an eddy-covariance (EC) and a surface layer scintillometer (SLS) were tested against ML measurements over a bare soil in the Negev Desert during the dry summer season.

The EC method is a turbulence-based method widely applied for direct λE measurements. It relies on high-frequency measurements of wind vertical speed with a 3-dimensional anemometer, combined with a fast response measurement of the gas concentration (e.g., water vapor), resulting in calculations of turbulent fluxes within the atmospheric boundary layer (Burba, 2013). Calculation of the flux requires an averaging time of at least 10, but typically 30 min during which stationarity is assumed (Hartogensis et al., 2002). Since the formation of NRWI is assumed to be non-stationary, examination of the suitability of the EC for measuring NRWI is required.

A turbulence-based method that does not rely on the assumption of stationarity is scintillometry. Scintillometry theory has been adapted to measure sensible heat flux (H) over path lengths ranging from 50 m to 5 km. To derive λE, ancillary measurements are required. Several methods were proposed to combine different ancillary measurements with the scintillometer (Van Kesteren et al., 2013), the most commonly used of which is the energy balance approach. According to this approach, λE can be calculated as the residual of the surface energy balance equation (Brutsaert, 1982):

$$\lambda E = R_n - G - H \tag{1}$$

Where H has been previously defined, R_n is net radiation; G is soil heat flux conducted into or from the soil; all components are in W m^{-2} and are positive when directed towards the soil surface, and negative when directed away from the soil surface. To utilize the energy balance approach with scintillometry measurements, R_n and G need to be measured. The overall error magnitude in λE calculations is thus the accumulated measurement errors of the three components.

The intrinsic error magnitude of typical net radiometers used to measure R_n is 5–7% (Culf et al., 2004). The representative sample area of the net-radiometer compared to the footprint of the other components of the energy balance can also yield errors in λE estimates. The net-radiometer footprint depends on the measurement height, but generally its footprint is significantly smaller than the scintillometer footprint, and much larger than the point measurement of G. Errors in G are much more substantial and can reach 50% (Foken, 2008), and the spatial divergence can be significant (Kustas et al., 2000).

In this study we examined the capability and limitations of both turbulence-based methods to estimate latent heat flux.

2. Materials and methods

2.1. Site description

A field experiment was carried out at the Jacob Bluestein Institutes for Desert Research, Ben-Gurion University of the Negev, in the heart of the Negev desert in Israel (30°51′ N, 34°46′ E, 470 m above the sea level) over a bare soil covered by a thin crust, with sparse and dry annual grasses and several dormant perennials spread away of the measurement system (> 100 m). The top soil is sandy loam with an average bulk density of 1400 kg m^{-3} (Moombe, 2014) and 12% clay content. The research site is characterized by an arid climate with long-term average annual precipitation of 93 mm (IMS, 2012) and a ratio of precipitation to potential evaporation of 0.04 ~ 0.05 (Zhang et al., 2013). Mean daily maximum and minimum temperatures in August are 33 °C and 19.2 °C, respectively, and 15.4 °C and 4.5 °C in January (IMS, 2007). The prevailing winds are from west-north-west and north-west, derived by the sea breeze that regularly carries water vapor from the Mediterranean Sea (about 80 km from the site) during the afternoon (Fig. 1). The study was conducted during the dry summer season, from May to October, 2014, during which no precipitation events were recorded, except for a very minor event on 26–27 September, 2014 that was not detected by the rain gage. Over a fetch of ~400 m in the direction of the prevailing wind direction, the field was homogeneous with a flat topography.

2.2. Measurements and analysis

A fully equipped micrometeorological station was set up for continuous measurement of background meteorological conditions and all energy balance components (Fig. 2). Measurements of background meteorological conditions, i.e., incoming solar radiation, air temperature and humidity, and wind speed and direction, were conducted at 0.1 Hz and recorded as 30-min averages.

Net radiation was measured at 2.4 m height with a 4-way net radiometer (CNR1, Kipp and Zonen, Holland) at 0.1 Hz in a four separate components mode − incoming and reflected shortwave radiation, and incoming and outgoing longwave radiation.

Soil heat flux was assessed using two methods: the calorimetric method and the combination method (sometimes referred to as the calorimetric heat storage correction method (Sauer and Horton, 2005). Three soil heat flux plates (HFT3, Campbell scientific, USA) were buried 5 cm below the surface, and next to each plate self-made T-type thermocouples were placed at depths of 0, 1, 2, 3, 4, 5 cm. Additional soil temperatures were measured at a depth of 10, 15, 20, 30, 40, 50 cm. Data were sampled every 30 s for all above mentioned measurements, 30-min averages were recorded using CR5000 and CR21X dataloggers, (Campbell scientific, Logan Utah, USA).

Soil water content, required to compute the volumetric heat capacity of the soil, was determined by a 24-h field campaign during which soil water content was measured gravimetrically every two hours at interval depths of 0–1, 1–2, 2–3, 3–4, 4–5, 5–10, 10–15, and 15–20 cm and in addition, at depths of 20–30, 30–40 and 40–50 cm at 6:00 and 12:00. The very dry soil conditions (2–4% volumetric water content (VWC in percent) at the uppermost soil layer) along with the lack of

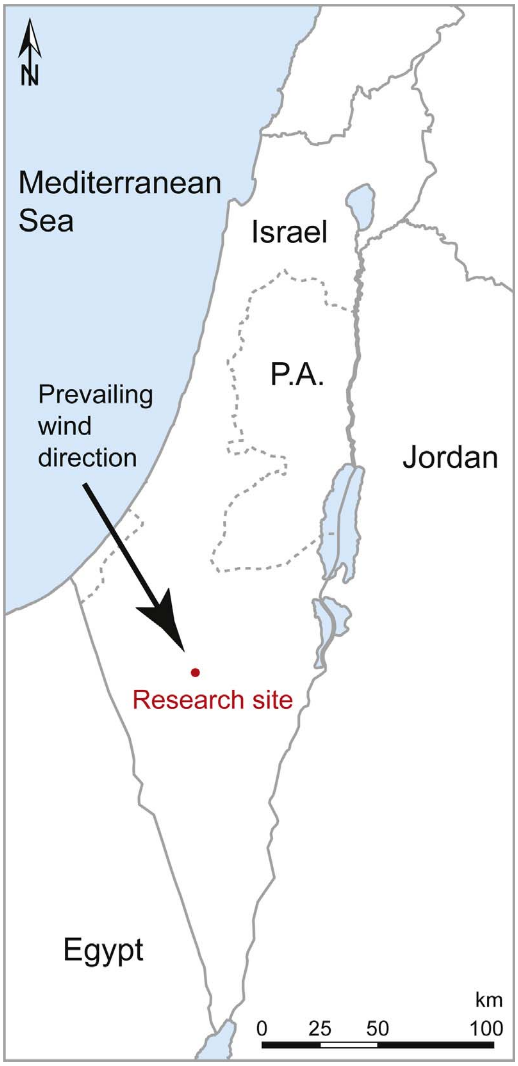

Fig 1. A map indicating the research site location (30°51′ N, 34°46′ E).

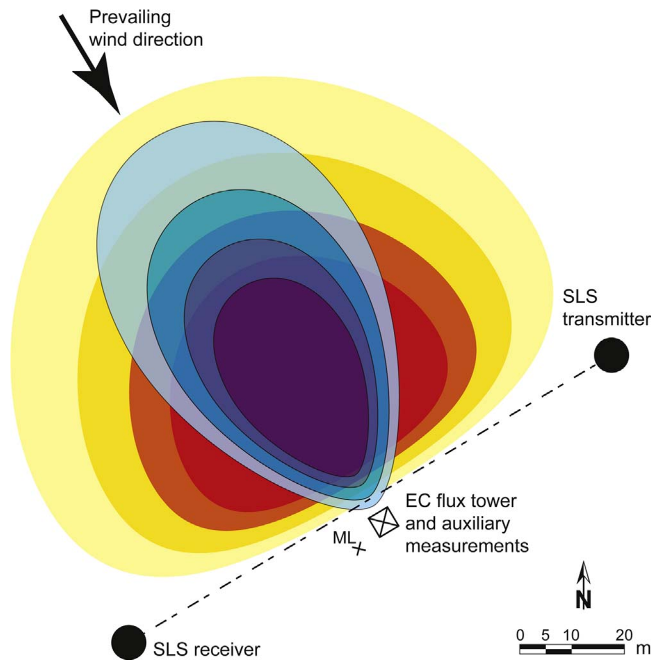

Fig. 2. Top view of the experiment design. The transmitter and receiver of the surface layer scintillometer (SLS) are placed at a distance of 100 m. The eddy covariance (EC) flux tower, microlysimeter, and complementary meteorological measurements are placed in the middle of the SLS path. The approximated footprints of SLS and EC are illustrated by warm and cold colors for the SLS and EC, respectively. Increase in hue saturation indicates greater contribution to the measured flux.

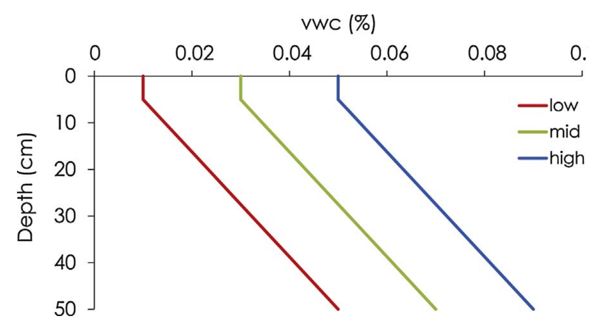

Fig. 3. Values of volumetric water content (VWC) profile used for the sensitivity analysis of soil heat flux calculations. The predetermined profile is in green (mid); Red and blue are 2% lower (low) and higher (high) VWC value, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

instruments that can accurately and continuously detect such small changes at the dry end of the scale, compelled the use of a VWC profile that was kept constant throughout the experiment, with 3% VWC at the 0–5 cm depth, linearly increasing from 3% to 7% VWC for the 5–50 cm depths.

The volumetric heat capacity of the soil (C_v) was determined following (De Vries, 1963):

$$C_v = (1.94 \cdot q_m + 2.5\theta_c + 4.19\theta_w) \cdot 10^6 \tag{2}$$

where θ_m is the volumetric fraction of mineral; θ_c is the volumetric fraction of the organic matter; and θ_w is the volumetric fraction of water.

Sensitivity analysis was performed to test the error magnitude in soil heat flux introduced due to the assumed constant VWC profile. The measured VWC profile used for the calculations is shown in green in Fig. 3. Soil heat flux calculations were then conducted with VWCs ranging ± 2% from the measured water content at each depth.

Latent heat flux was directly measured with two methods: a microlysimeter (ML) and an EC system; and was indirectly quantified using a SLS and ancillary measurements. The microlysimeter was set next to the EC flux tower in the middle of the scintillometer path so that the footprint of all three methods is centered at the same point (Fig. 2). An undisturbed soil sample was excavated and inserted into a PVC tube with a diameter of 20 cm and a depth of 48 cm. The bottom of the soil core was insulated using 2 cm thick polystyrene foam and the sides were covered with insulation material, to minimize heat transport laterally and to/from the bottom of the ML sample (Ninari and Berliner, 2002). The sample was then placed on a digital scale (GP30KS, A & D, CITY, Japan) that continuously monitored the sample's mass. The scale had a resolution of 0.1 g, equivalent to 0.003 mm water or 8.8 W m^{-2}. The sample's mass was recorded every 30 s. To prevent dew formation on the edges of the cylinder, a flexible plastic cover was placed over the gap between the soil sample and the surrounding soil. ML data processing included removing readings that contained digital noise. Every 30 min, one-hour recordings (120 samples) were averaged around the target time (half an hour before and half an hour after). Mass differences between time steps were translated into equivalent water depth changes (mm) and latent heat fluxes. Given the homogeneity of the research area, and since the ML was proved to accurately measure NRWI on the soil surface (Ninari and Berliner, 2002), the ML served here as the reference for the EC and SLS measurements.

The EC flux tower was composed of a 3D sonic anemometer (CSAT3, Campbell Scientific, USA) and an open path infrared gas analyzer

(LI7500, LiCor, USA). The EC system was installed at a 1 m height facing north-west. Data were acquired at 10 Hz and stored on a CR5000 datalogger (Campbell Scinetific, USA). Post-processing included despiking according to the algorithm developed by Goring and Nikora (2002), correction for water vapor concentration and crosswind effects on sonic temperature (Liu et al., 2001; Schotanus et al., 1983), 2D coordinate rotation correction (Tanner and Thurtell, 1969), frequency response correction (Massman, 2000), and the correction for buoyancy effects described by Webb et al. (1980). In addition to the latent heat flux, sensible heat flux was also directly measured with the EC system.

A surface layer scintillometer (SLS40, Scintec, Germany) was installed at a height of 1 m above the soil surface with a path length of 100 m almost perpendicular to the prevailing wind, with the flux tower slightly off of the middle of the path (Fig. 2). The sampling frequency was 50 kHz, data were logged every 10 s, and stored using the scintillometer's software (SRun1.14). SLS data were post processed to calculate H and u_*. Since the scintillometer cannot detect the direction of the flux (Odhiambo and Savage, 2009a, 2009b), the direction of the flux (upward/downward) and the stability conditions were determined by the net radiation direction: unstable and negative flux (upward) for $R_n \geq 0$ and stable and positive flux (downward) for $R_n < 0$. The stability functions followed Thiermann and Grassl (1992), and Savage (2009). Spikes of u_* and H resulting from malfunction of the instrument were excluded. The latent heat flux was derived as the residual of the energy balance equation (Eq. (1)) with the energy balance components R_n and G derived as described above.

2.3. Energy balance closure test

Theoretically, the energy flux leaving the surface is equal to the energy flux received at the surface (Brutsaert, 1982). Based on this basic law, the accuracy of energy balance measurements can be tested using the energy balance closure, where the sum of the net radiation and the soil heat flux (often termed as the available energy) is equal to the turbulent fluxes ($H + \lambda E$).

In practice, closure is rarely achieved from field measurements (Foken, 2008). Typically, in micrometeorological studies, independent measurements of the fluxes are only 70–90% of net radiation (Heusinkveld et al., 2004). The different techniques used to derive the energy balance components were tested in various combinations, using the energy balance closure test to determine the best combination of measurement methods.

3. Results and discussion

Two time periods representing typical meteorological conditions, for which a full dataset exists, were selected: 4 days in September 2014 with mostly clear skies and some scattered clouds throughout different parts of the day, and 3 clear sky days in October 2014 (Fig. 4). The wind speed in the area varies from about 0.3 m s^{-1} in the early morning to ~5 m s^{-1} in the afternoon. The predominant wind is northwestern coming from the Mediterranean Sea area (Figs. 1 and 4) carrying moisture resulting in an increase in the water vapor pressure, simultaneous to a decrease in air temperature (Fig. 4). This sets the conditions for water vapor adsorption.

To assess the applicability of the turbulence-based methods, i.e., the EC and the SLS, for monitoring NRWI-derived λE, and especially since the SLS method is indirect and based on ancillary measurements of R_n and G, all components of the energy balance need to be carefully evaluated:

3.1. Net-radiation

The 4-way net-radiometer is to date the most reliable instrument to quantify net radiation, albeit known to underestimate R_n by about 3–5% (Culf et al., 2004). The net-radiometer was set up next to the EC system, in the middle of the SLS path over a representative and undisturbed area. There is thus less doubt involved in its measurement. Following is an analysis and of the measurements of soil, sensible, and latent heat fluxes, and a discussion on how they affect the NRWI-derived λE estimates.

3.2. Soil heat flux

The result from the sensitivity analysis for the effect of VWC (ranging between +2% and −2% VWC) on G showed an average difference of 4.4 W m^{-2}, equivalent to 5.5% of the flux, for soil heat flux derived by the calorimetric method and an average difference of 8.4 W m^{-2}, equivalent to 3.5% of the flux, for soil heat flux derived by the combination method. Note that in computing the percentage error, the transition times when the soil heat flux reverses and the fluxes are very small were excluded to avoid bias.

A greater soil heat flux was estimated using the calorimetric method compared to soil heat flux computed using the combination method (Fig. 5). The calorimetric method relies on soil water content across the entire profile. Under very dry conditions, it is difficult (or impossible) to accurately and continuously measure soil water content. However, under the very dry conditions at the site, only small changes are expected in soil water content. Thus the potential miscalculation of soil heat flux due to errors in soil water content measurement are likely not significant.

The combination method only requires knowledge of soil water content for the soil layer above the plate (top 5 cm in this case). Utilization of this method may thus reduce the measurement uncertainty. However, it has its own set of drawbacks. The soil heat flux plates, although claimed to be generic and suitable for all soil types, may have slightly different thermal properties than those of the soil, which may cause deflection of the flux, resulting in either divergence or convergence of the flux into the plate. The plate may also cause a divergence of water flow, even at the vapor phase (Massman, 1992; Sauer and Horton, 2005; Van Loon et al., 1998).

Based on these intrinsic differences between the methods, the obtained differences in their estimates (Fig. 5) were expected. Since both methods have pros and cons it was difficult to *a-priori* define which of the two is preferable for dry bare soil as will be further discussed below.

3.3. Sensible heat flux

Sensible heat flux was measured with two independent methods − the EC and SLS − which yielded very similar fluxes (Fig. 6). Unreasonable peaks were measured by the SLS around sunset and sunrise, when H is very small and the flux changes direction. This was observed as well by De Bruin et al. (2002) who found large errors in H during the transition hours, explained by contributions of water vapor when evaluating the temperature structure parameter (C_T^2) from the structure function constant (C_n^2). When H becomes zero while evaporation, though small, is still non-zero, systematic errors in the calculation of H were observed.

Overall, a scatterplot between EC- and SLS-derived H (H_{EC} and H_{SLS}, respectively) resulted in a slope of 0.93 and correlation coefficient of 0.94 (Fig. 7), indicating that H_{SLS} was somewhat smaller compared to H_{EC}. Several previous studies also reported good agreement between the two methods (De Bruin et al., 2002; Hartogensis et al., 2002; Odhiambo and Savage, 2009a, 2009b). Some studies reported the same underestimation of H_{SLS} compared to H_{EC} (Hartogensis et al., 2002; Savage, 2009) while others reported overestimation of H_{SLS} (De Bruin et al., 2002; Odhiambo and Savage, 2009a, 2009b; Van Kesteren et al., 2013; Watts et al., 2000). (Savage, 2009) showed that the use of various empirical functions in the MOST analysis may result in −30% to 28% error in the estimation of sensible heat flux, In this case, the MOST formulation described by Thiermann and Grassl (1992) and Savage (2009) was used. The good agreement between H_{SLS} and H_{EC} implies

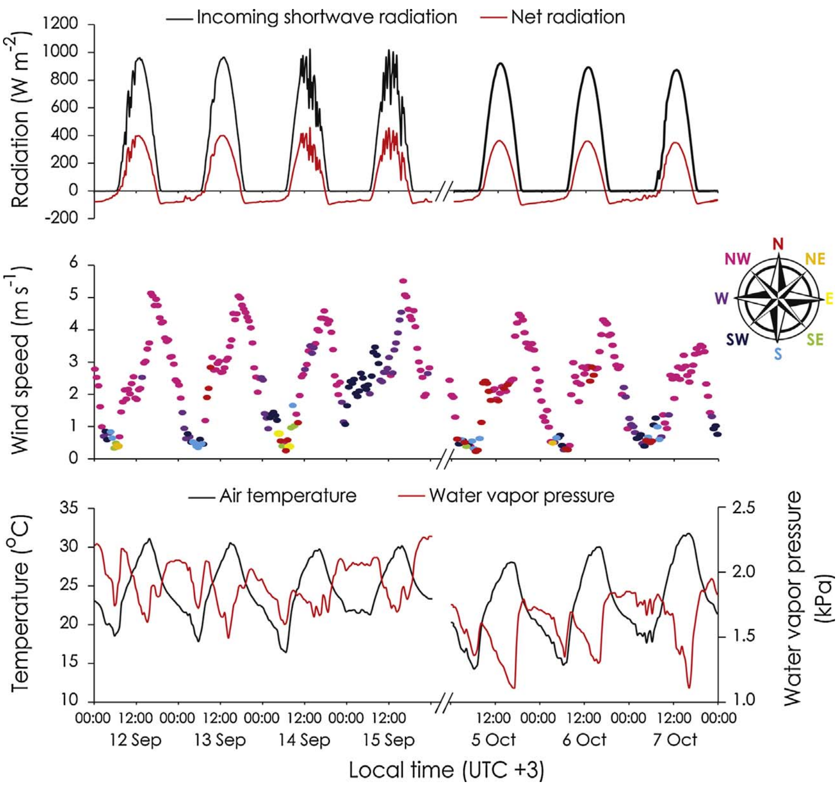

Fig. 4. Meteorological conditions at the experimental site for two selected time periods.

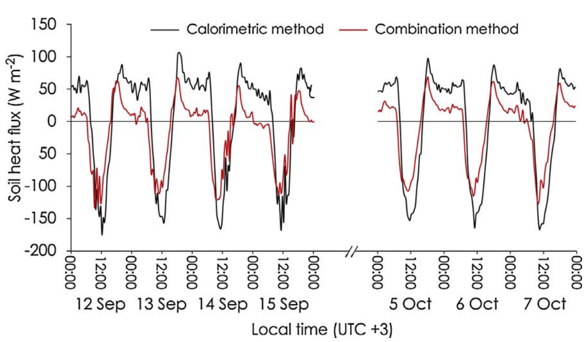

Fig. 5. 30 min average of the soil heat flux computed by the calorimetric method and by the combination method.

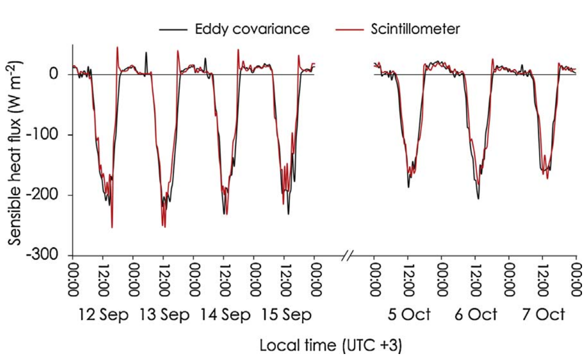

Fig. 6. 30 min average of sensible heat flux measured with eddy covariance and the surface layer scintillometer.

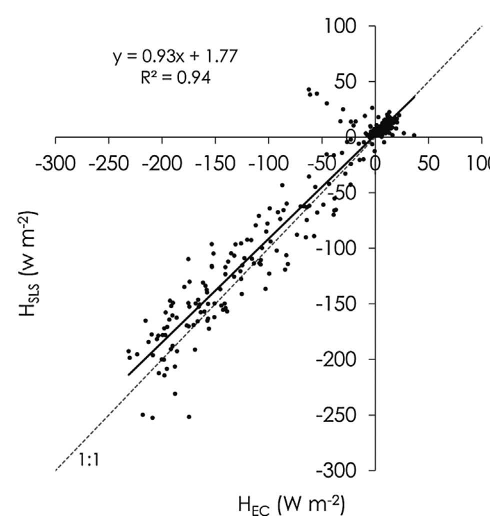

Fig. 7. The correlation between the sensible heat fluxes measured by the eddy covariance (H_{EC}), and the surface layer scintillometer (H_{SLS}); the solid line is the linear regression line, and the dash line is a 1:1 line.

that this formulation is suitable for the research conditions. However, it is possible that the EC underestimated H (Culf et al., 2004), and accordingly the SLS also underestimated H.

The theoretical principles and the instrumentation used in these two methods are different, and the methods are completely independent of each other. The good agreement between them thus provides a robust proof for the accuracy of the measurements of sensible heat flux, and, along with the fact that their footprint is rather different (Odhiambo and Savage, 2009a, 2009b), implies that the study area is reasonably homogeneous.

3.4. Latent heat flux

The mass change of the microlysimeter showed a consistent diurnal pattern, with an increase starting between 1600 and 1700 (UTC +3) in the afternoon when the sea breeze reaches the area and brings moister air (Fig. 8). The mass increase continued throughout the night and immediately after sunrise started decreasing as the soil sample lost water to evaporation. A similar phenomenon was reported by Agam

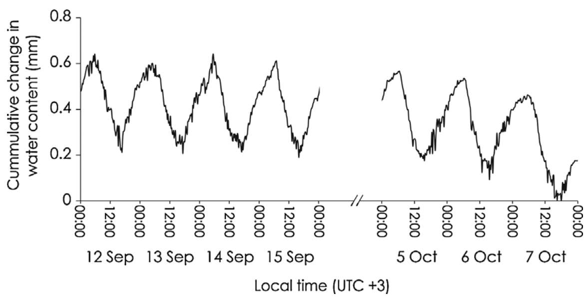

Fig. 8. Cumulative change in water content. Changes were determined relative to the lowest mass point, which was set at zero.

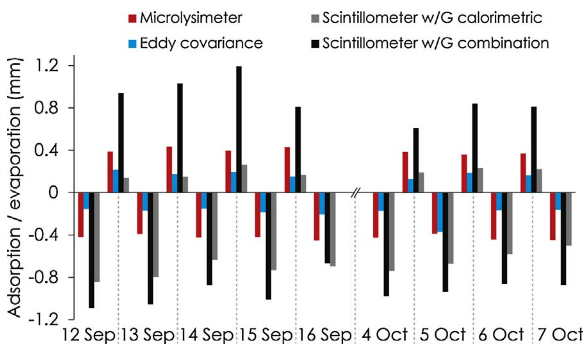

Fig. 9. Daily total adsorption (positive) and evaporation (negative) measured by the different methods.

and Berliner (2004) for a loess soil 25 km north of the research site (at the Mashash experimental farm).

In September, the daily cumulative adsorption and daily cumulative evaporation were similar, summing up to 0.41 mm day^{-1} adsorption and to 0.42 mm day^{-1} evaporation (Fig. 9), indicating no total gain or loss of water during this period. In October, the daily cumulative adsorption (0.37 mm day^{-1}) was somewhat smaller compared to the daily cumulative evaporation (0.43 mm day^{-1}, Fig. 9) resulting in an overall decrease in mass from day to day (Fig. 8). This was the result of a very light rain that occurred a week prior to this measurement period. Analysis of the gravimetric water content measurements agreed well with the microlysimeter results, with 0.38 mm day^{-1} water vapor adsorption and 0.41 mm day^{-1} of evaporation, all occurring at the first 5 cm of the soil (data not shown).

As a previously proved successful method for monitoring NRWI (Agam et al., 2004; Ninari and Berliner, 2002), the microlysimeter served as the reference to which the other methods were compared. To allow for the comparison, the microlysimeter mass measurements were converted into hourly latent heat fluxes. Three turbulence-based methods were compared to the latent heat flux derived by the microlysimeter (λE_{ML}): the eddy-covariance-derived latent heat flux (λE_{EC}), and two methods based on the scintillometer measurements of H, applying the energy balance equation (Eq. (1)); with G computed with the combination method ($\lambda E_{SLS\text{-}comb}$), and with the calorimetric method ($\lambda E_{SLS\text{-}cal}$). The daily cumulative amounts of adsorption and evaporation are presented in Fig. 9 and the hourly fluxes are presented in Fig. 10.

The diurnal pattern of λE_{EC} followed closely that of λE_{ML} but with a smaller magnitude. The daily cumulative adsorption was 0.17 mm day^{-1}, nearly half of the measured amount by the microlysimeter. The daily cumulative evaporation was similar to the daily cumulative adsorption (0.19 mm day^{-1}), indicating that while the eddy covariance does not capture the entire magnitude of the flux, it does describe the dynamics accurately (Figs. 9 and 10). The underestimation of both the latent and sensible heat fluxes has been previously reported (Culf et al., 2004), the results presented here are no exception.

The latent heat fluxes computed as the residual of the energy

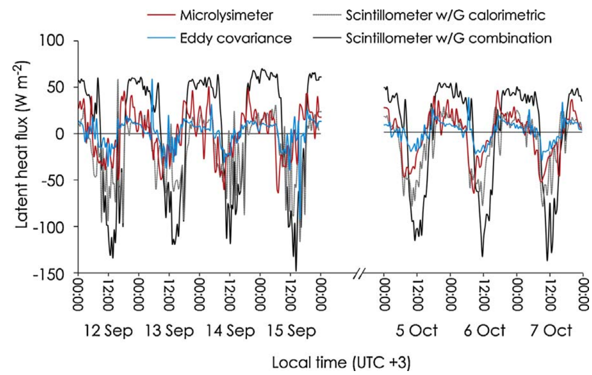

Fig. 10. 30 min averages of measured latent heat flux.

balance equation using the scintillometer with the two methods for deriving G revealed large differences between these methods. The daily cumulative evaporation for both methods was significantly larger compared to the microlysimeter (an average of 0.69 and 0.93 mm day^{-1} for the calorimetric and the combination methods respectively). The daily cumulative adsorption derived by the combination method had the same magnitude of the cumulative evaporation, similarly to results obtained by the microlysimeter and the eddy covariance methods, only with a larger magnitude. The calorimetric method, on the other hand, resulted in much smaller daily cumulative adsorption compared to evaporation, implying an overall drying of the soil, a phenomenon that was moderately observed in the second period but was not observed in the first period (Figs. 9 and 10).

Extraction of latent heat flux as a residual from scintillometery and ancillary measurements accumulates all potential errors. Errors in R_n due to accumulation of dirt/dust on the net-radiometer's domes, damaged domes, or levelling, as well as potential differences in the effect of radiative heating on the up- and down-facing longwave sensors, were assumed negligible (Payero et al., 2003; Savage, 2009). The good agreement between the EC-derived and the SLS-derived sensible heat fluxes provides confidence in their values, implying that errors in the latent heat flux are likely not attributed to errors in the sensible heat flux. Errors in soil heat flux thus remain the main suspect for the large discrepancy between the scintillometer-based methods and the microlysimeter.

Previous comparisons between eddy-covariance-derived and scintillometer-derived (based on the energy balance equation) latent heat fluxes revealed a good agreement between the two methods (Savage, 2009; Savage et al., 2010; Van Kesteren et al., 2013). However, these studies were conducted in different climate zones, with a significant fraction of vegetation cover, where the latent heat flux is a larger component of the energy balance whereas the soil heat flux is a substantially smaller component. Over bare dry soil, soil heat flux can reach up to 50% of net radiation (Heusinkveld et al., 2004; Idso et al., 1975) and therefore an error in soil heat flux can translate into a significant error in the latent heat flux.

The underestimation of latent heat flux measured by the eddy-covariance and the over estimation derived from the scintillometer (both methods) is intriguing. The eddy covariance method is known to underestimate both latent and sensible heat fluxes (Twine et al., 2000). In fact, in many cases, it is assumed that the underestimation is due to miss-capturing of the largest and smallest eddies, and thus when applying a closure correction on the data, the residual is split between the two fluxes according to the Bowen ratio (Lee, 1998; Twine et al., 2000). Following this line of thinking, if the latent heat flux measured by the eddy covariance is underestimated, it is likely that the sensible heat flux is underestimated as well. Given the very good agreement between sensible heat flux measured by the eddy covariance and that measured by the scintillometer, one may conclude that the scintillometer is also underestimating sensible heat flux. If both the net radiation and the soil

Table 1
Linear regression analysis of the correlation between the turbulent fluxes ($H + \lambda E$) and the available energy ($R_n + G$). R_n is net radiation; G is soil heat flux; H and λE are sensible and latent heat flux, respectively. Subscripts stand for: EC − eddy covariance; SLS − surface layer scintillometer; ML − microlysimeter; cal − calorimetric method; comb − combination method.

	$H_{EC} + \lambda E_{EC}$		$H_{EC} + \lambda E_{ML}$		$H_{SLS} + \lambda E_{ML}$	
	slope	R^2	slope	R^2	slope	R^2
$R_n + G_{cal}$	0.89	0.95	0.93	0.94	0.90	0.91
$R_n + G_{comb}$	0.65	0.97	0.68	0.94	0.64	0.90

heat flux are accurate, an underestimation of the sensible heat flux would result in an overestimation of latent heat flux.

The large degrees of freedom prevent reaching a concrete conclusion on what is the contribution of each of the energy balance components to the deviation of latent heat fluxes from the fluxes measured by the microlysimeter. Exploring the energy balance closure using all possible combinations (excluding the scintillometer-based latent heat fluxes) revealed that the best closure (93%) was obtained with soil heat flux calculated with the calorimetric method, sensible heat flux from the eddy covariance, and latent heat flux from the microlysimeter (Table 1). Soil heat flux measured with the combination method significantly deteriorated the closure, potentially implying its inapplicability under the research conditions.

4. Conclusion

In this study, the main goal was to obtain the latent heat flux resulting from NRWI formation and consequent evaporation. Evaluating these small fluxes is complex and challenging. The microlysimeter, the eddy covariance, and the scintillometer all recorded similar diurnal dynamics of latent heat flux but, compared to the ML measurements, the eddy covariance tended to underestimate the flux and the scintillometer (with ancillary measurements) over estimated λE. Given the relatively homogeneous research site, the ML, albeit being a point measurement potentially not capturing the natural heterogeneity, served as the best measurement technique and yielded the best closure (93%). The eddy covariance, in comparison, yielded a closure of 89%.

When applying the energy balance approach to derive latent heat flux from scintillometry measurements, it is important to bear in mind the accumulation of errors. In this case, given the large magnitude of G and the small magnitude of λE, miscalculation in G may translate into a large error in the estimation of λE. Based on the closure test, the calorimetric method seems to better estimate G in dry bare soil. A question still remains as to a potential source of error in the scintillometer-derived H. If indeed the EC underestimated both the latent and sensible heat fluxes and since there was a good agreement between the EC-derived and the SLS-derived H, than the scintillometer also underestimated H, contributing to the overestimation of latent heat flux. Future research will be conducted to inquire the possible combination of turbulence properties measured by the scintillometer and high-frequency measurements of water vapor concentration in the mid-path of the scintillometer to directly derive the latent heat flux, obviating the need for measurements of net radiation and soil heat flux.

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