A Method for Direct Assessment of the "Non Rainfall" Atmospheric Water Cycle: Input and Evaporation From the Soil

Article *in* Pure and Applied Geophysics · May 2012

DOI: 10.1007/s00024-011-0328-9

CITATIONS
12

READS
130

6 authors, including:

Kudzai Farai Kaseke
University of California, Santa Barbara
24 PUBLICATIONS **196** CITATIONS
SEE PROFILE

Anthony Jan Mills
C4 EcoSolutions
108 PUBLICATIONS **1,596** CITATIONS
SEE PROFILE

Karen Esler
Stellenbosch University
267 PUBLICATIONS **4,735** CITATIONS
SEE PROFILE

Joh R. Henschel
National Research Foundation, South Africa
166 PUBLICATIONS **2,792** CITATIONS
SEE PROFILE

Pure Appl. Geophys.

DOI 10.1007/s00024-011-0328-9

Pure and Applied Geophysics

A Method for Direct Assessment of the "Non Rainfall" Atmospheric Water Cycle: Input and Evaporation From the Soil

Kudzai Farai Kaseke,[1,4,6] Anthony J. Mills,[2] Roger Brown,[3] Karen J. Esler,[1] Johannes. R. Henschel,[4] and Mary K. Seely[5]

Abstract—"Non rainfall" atmospheric water (dew, fog, vapour adsorption) supplies a small amount of water to the soil surface that may be important for arid soil micro-hydrology and ecology. Research into the direct effects of this water on soil is, however, lacking due to instrument and technical constraints. We report on the design, development, construction and findings of an automated microlysimeter instrument to directly measure this soil water cycle in Stellenbosch, South Africa during winter. Performance of the microlysimeter was satisfactory and results obtained were compared to literature and fell within the expected range. "Non rainfall" atmospheric water input into bare soil (river sand) was between 0.88 and 1.10 mm per night while evaporation was between 1.39 and 2.71 mm per day. The study also attempted to differentiate the composition of "non rainfall" atmospheric water and results showed that vapour adsorption contributed the bulk of this input.

Key words: "Non rainfall" atmospheric water, dew, vapour adsorption, microlysimeter.

1. Introduction

"Non rainfall" atmospheric water (fog, dew, vapour adsorption) supplies a small but critical amount of water to arid zones (Malek *et al.*, 1999; Kidron, 2000), promoting biological decomposition and nutrient recycling in the upper few centimetres of the soil profile (Whitford, 2002). The ecological significance of this water input is highlighted by the fact that in some arid environments, dew and fog input equals or exceeds annual rainfall and is the sole source of liquid water for plants (Agam and Berliner, 2006).

Despite its acknowledged importance, there is no international standard for measuring this input directly into the soil (Zangvil, 1996; Brown *et al.*, 2008). This is primarily because of the small fluxes involved which pose difficulties for measurement (Scott, 1962; Jacobs *et al.*, 2002; Ninari and Berliner, 2002). Monteith and Unsworth (1990), estimated the theoretical dew maximum at 0.40 mm per night. Thus, instrumentation with a minimum resolution of less than 0.10 mm would be ideal for such studies (Agam and Berliner, 2006). However, achieving this degree of accuracy in a highly mobile soil environment is difficult given the potential interferences from inter alia wind, animals and drifting sand (Brown *et al.*, 2008).

Lack of agreement on the very definition of "non rainfall" atmospheric water and its vectors has further compounded the problem of lack of appropriate instrumentation (Noffsinger, 1965; Zangvil, 1996). Several methods and instruments have been developed to measure this water, e.g., fog collector (Schemenauer and Cereceda, 1994), cloth plate method and Duvdevani blocks (Kidron, 2000). These methods are useful in that they provide proxy measurements for inter-site comparisons (Berkowicz *et al.*, 2001), but are limited in their application because they rely on artificial collecting surfaces which differ from the natural receiving substrate

[1] Department of Conservation Ecology and Entomology, Stellenbosch University, P. Bag X1, Matieland 7602, South Africa. E-mail: faraikaseke@gmail.com; kje@sun.ac.za
[2] Department of Soil Science, Stellenbosch University, P. Bag X1, Matieland 7602, South Africa. E-mail: mills@sun.ac.za
[3] Climate Analysis Systems Group, University of Cape Town, P. Bag X3, Rondebosch 7701, South Africa. E-mail: brown.roger@gmail.com
[4] Gobabeb Research Centre, P. O. Box 953, Walvis Bay, Namibia. E-mail: joh.henschel@gobabeb.org
[5] Desert Research Foundation of Namibia, 7 Rossini Street, Windhoek, Namibia. E-mail: Mary.seely@drfn.org
[6] 26 Gobvu Road, Zengeza 3, Chitungwiza, Zimbabwe.

Published online: 19 May 2011

(soil) surface. They, therefore, tend to under- and/or over-estimate "non rainfall" atmospheric water input direct into the soil (Berkowicz *et al*., 2001; Ninari and Berliner, 2002; Heusinkveld *et al*., 2006).

Human reliance for observation is an additional handicap that makes these traditional methods of instrumentation unsuitable for studies in remote or sparsely populated areas (Jacobs *et al*., 2002). There is, therefore, a need for the development of automated instrumentation for "non rainfall" atmospheric water studies (Heusinkveld *et al*., 2006) and, according to Ninari and Berliner (2002), the loadcell microlysimeter method is the most promising approach. The microlysimeter method is an in situ method that directly measures mass loss or gain (Heusinkveld *et al*., 2006) and residence time of water derived from "non rainfall" atmospheric sources (Brown *et al*., 2008) in a soil sample.

1.1. Microlysimeter Design and Specifications

The microlysimeter method has been applied to evaporation studies from the soil surface of irrigated crops (Storlie and Eck, 1996). However, design specifications were meant for a high evaporation flux after irrigation (Boast and Robertson, 1982), whilst "non rainfall" atmospheric water cycles involve a much smaller latent heat flux (Ninari and Berliner, 2002). Design and specifications of the microlysimeter method for high evaporation fluxes are thus unsuitable for "non rainfall" atmospheric water studies and consequently require adjustments. Figure 1 shows a schematic of the microlysimeter developed for this study which is based on the automated loadcell microlysimeter design by Heusinkveld *et al*. (2006) and Brown *et al*. (2008).

We used a Tedea-Huntleigh 1004 (1,500 g) aluminium single point low capacity loadcell, dimensions (110 × 10 × 33) mm. Excitation with 10 V DC is stated as 7.69 mV which translates to 0.0051 mV g^{-1}. Temperature variation of the loadcell can cause significant errors to loadcell output (Storlie and Eck, 1996). However, these temperature effects on loadcell output can be buffered by installing the loadcell below ground. This measure significantly reduced temperature variation on the loadcell but we still needed to account for the effect of the remaining temperature variation on loadcell output. We thus housed the loadcell in a chamber with an aluminium base plate (10 mm thick) and sides/top of polyvinylchloride (PVC) (5 mm thick). The PVC acted as an additional heat buffer to the loadcell from lateral and vertical heat flow from the surface and surrounding soil. Assuming 100% thermal conductivity by the aluminium base plate, loadcell temperature variation should be similar to that of the underlying soil. Based on these assumptions we calculated and compensated for the temperature error effect on loadcell output (Storlie and Eck, 1996). A small depression was carved onto the base plate to allow the loadcell to bend, and an overload screw was inserted on the loading end of the loadcell through the base plate to protect against overload and damage to the loadcell (Heusinkveld *et al*., 2006).

Vertical heat conduction towards the loadcell from the surface was further reduced by attaching the soil-sample dish to the loadcell via a 180 mm non-conductive plastic pipe (Heusinkveld *et al*., 2006). This connecting pipe slotted into a plastic holder on the loading end of the loadcell, further reducing heat conduction from the surface (Fig. 1). The connecting pipe also reduced dead weight exerted on the loadcell by microlysimeter components keeping the unit within loadcell capacity. The connecting tube encased the connecting pipe and limited any lateral movement due to air turbulence affecting the sample dish at the surface. The connecting pipe also slotted into a cap on the underside of the sample dish, that was designed with a 5 mm protruding ridge (overflow protector) at the bottom. The purpose of the ridge was to divert possible overflow from the sample dish from running down the connecting pipe directly into the loadcell compartment, thereby ensuring a dry environment in the loadcell compartment.

Theoretically, microlysimeters provide an absolute reference for latent heat fluxes provided that the soil and heat balance of the microlysimeter are similar to those of the surrounding area (Ninari and Berliner, 2002). Microlysimeter casing affects thermal transfer between surrounding soil and the sample in the microlysimeter (Evett *et al*., 1995). Sample dishes constructed from high thermal conducting materials do result in lower soil sample surface

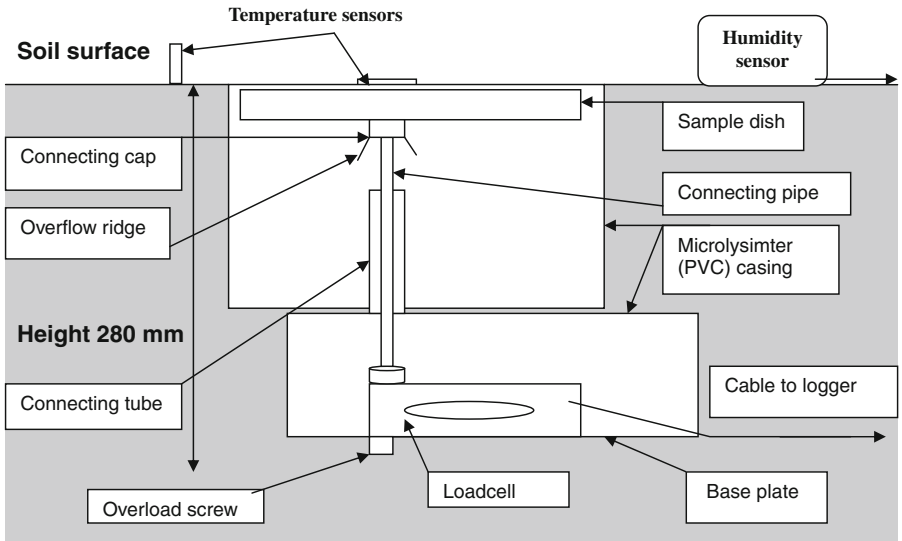

Figure 1
A schematic illustration of the automated loadcell microlysimter, designed following Heusinkveld *et al*., (2006) and Brown *et al*., (2008)

temperature in the microlysimeter compared to adjacent soils (Evett *et al*., 1995). During the day, these materials conduct heat away from the surface of the sample and the reverse occurs at night. This energy reduction may result in lower evaporation estimates from metal microlysimeters during the day than actual field evaporation (Evett *et al*., 1995). It is, therefore, impossible to eliminate material influences on the sample, but selection of low thermal conducting materials could minimise the influence of the microlysimeter on the soil sample (Storlie and Eck, 1996). According to Walker (1983), there is no significant temperature difference between soil samples in plastic sample dishes and the adjacent soil. Evett *et al*. (1995) recommended the use of PVC which has a similar thermal conductivity to that of a dry mineral soil to construct sample dishes. Sample dishes used for this study were constructed from 2 mm transparent polypropylene to minimise material influences on sample temperature (Evett *et al*., 1995; Heusinkveld *et al*., 2006).

Insufficient depth and surface of the sample dish can significantly affect the soil heat balance through distortion of water and temperature profiles in the sample (Ninari and Berliner, 2002). However, according to Jacobs *et al*. (1999), the daily moisture cycle is confined to the upper 2–3 cm of the soil profile and there is no significant difference between sample dish depths ranging between 30 and 70 mm. We thus adopted a 35 mm sample dish depth, as a shallower depth would block vapour transport to deeper soil layers and lead to possible under- and or over-estimation of "non rainfall" atmospheric water input (Heusinkveld *et al*., 2006). A larger depth would exert more dead weight onto the loadcell and decrease loadcell sensitivity. In theory, small sample dishes exacerbate edge effects. However, Daamen *et al*. (1993) found no evidence to support this after testing dish sizes ranging from 50 to 210 mm in diameter. Larger sample dish sizes passively amplify the signal (Brown *et al*., 2008) and reduce the aerodynamic edge effects (Heusinkveld *et al*., 2006) provided the dead weight is kept within loadcell capacity. We settled for a 140 mm diameter plastic soil-sample dish for this study.

Francis *et al*. (2007) pointed to the possibility of moisture recharge from below the soil surface (capillary rise and overnight distillation processes). It was thus necessary to physically isolate the microlysimeter sample from below ground moisture recharge by using a non-porous sample dish. Physical isolation of the sample ensures that water input into the sample is from the atmosphere and not from below ground (Brown *et al*., 2008). Heusinkveld *et al*. (2006) noted the need for automated instrumentation for "non rainfall" atmospheric water studies, given the

handicap of traditional methods which rely on human observation and are unsuitable for remote areas (Jacobs *et al*., 2002). Our microlysimeter was therefore fully automated, capable of repeated measurements and solar powered. After compensating for temperature error effects on loadcell output and isolating the sample from below ground moisture recharge, it was assumed that the remaining weight change would reflect "non rainfall" atmospheric water input and evaporation from the soil sample.

1.2. Vector Definitions

"Non rainfall" atmospheric water in arid ecosystems is supplied via three vectors namely: fog, dew and vapour adsorption (Agam and Berliner, 2006). However, for the duration of this study, no fog was observed. It is, nonetheless, important to define dew and vapour adsorption as used in this particular study.

Dew is the natural condensation of water vapour into liquid droplets on a sufficiently cooled substrate surface (Stone, 1963; Beysens, 1995; Awanou and Hazoume, 1997; Malek *et al*., 1999). It is a phase transition on the soil–plant–atmosphere interface affecting energy balance. Dew formation is dependent on the receiving substrate characteristics (Beysens, 1995), occurring when the substrate surface equals or falls below ambient dew point temperature but is above freezing point, otherwise frost forms (Ashbel, 1949; Beysens, 1995; Agam and Berliner, 2006).

Vapour adsorption is a reversible interfacial physical process resulting from differential forces of attraction and repulsion between vapour molecules and soil particles (Agam and Berliner, 2006). It occurs as a result of vapour movement from the atmosphere into the soil due to the establishment of a vapour gradient between the two. Although there are two types of adsorption—physical and chemical—physical adsorption is dominant in the soil because the energy available under natural conditions cannot support chemical adsorption (Hillel, 1998). This study makes no attempt to distinguish between osmotic effects due to salinity and strict vapour adsorption. Instead, their combined effect is collectively referred to as vapour adsorption or hygroscopic uptake.

In theory, conditions conducive for one input vector preclude the others from occurring concurrently (Brown *et al*., 2008). Dew formation occurs when the receiving substrate surface temperature equals or falls below ambient dew point (Beysens, 1995), and vapour adsorption occurs when a vapour gradient is established between the atmosphere and the soil, independent of dew point temperature (Brown *et al*., 2008). Therefore, the receiving substrate (soil) surface temperature can be used to distinguish between dew and vapour adsorption input (Agam and Berliner, 2006). According to our study, input that occurred when soil surface temperature was below ambient dew temperature was classified as dew and if temperature was above ambient dew point this was classified as vapour adsorption.

2. Materials and Methods

The microlysimeters were calibrated in the laboratory and the effect of temperature variation on loadcell output was calculated (Fig. 2). The temperature response graph was calculated by exposing the microlysimeters to varying temperature regimes (range 20.7–26.3°C) whilst loaded with a standard 500 g mass. Calibration of the microlysimeter unit showed that for the dimensions of the loading dish used in this study, the minimum resolution of the loadcell was 0.038 g equivalent to a depth of 0.0026 mm of water.

After laboratory calibrations, field trials were conducted from 11 to 23 July 2008 at Stellenbosch University farm (S33 56.577 E18 51.152).

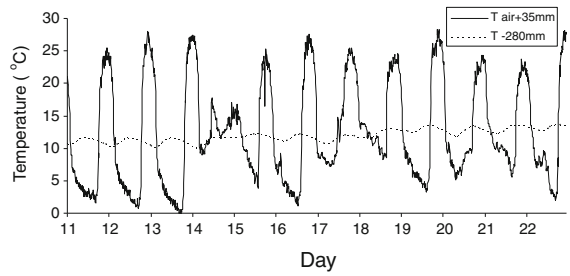

Figure 2
Temperature profiles 35 mm above ground and 280 mm below ground, Stellenbosch, July 2008. *T*-280 mm was taken as the loadcell temperature profile

Stellenbosch experiences a Mediterranean climate and is located about 50 km east of Cape Town, South Africa, 119 m a.s.l. Summers are dry and sunny averaging 30°C, while winters are warm averaging 18°C (midday) and 6°C at night; rainfall ranges between 600 and 800 mm year^{-1}.

The microlysimeters were positioned in the soil, with the sample dishes—filled with river sand (<2 mm)—flush with the surface. Dallas Semiconductor DS18820+ temperature sensors (resolution 0.1°C) were placed at loadcell depth (Fig. 1), the surface of the soil sample and 35 mm above ground level. A maxi control temperature humidity combo sensor was used to monitor relative humidity at ground level and sampling interval for all instruments was set at 10 min for the entire test period. These data allowed calculation of dew point at the soil surface using the equation by Berry (1945):

$$\text{Dew point} = ((0.66077 - \log \text{EW}) \text{ x } 237.3/(\log \text{EW} - 8.16077))$$

where

$$\log \text{EW} = 0.66077 + (7.5 \text{ x } T/(237.3 + T)) + \log_{10}(\text{RH}) - 2$$

where T is atmospheric temperature (°C) and RH relative humidity (%).

The microlysimeter unit was solar powered using a single 12 V 26 Ah battery recharged by a 10 W photovoltaic cell connected to our specially designed data logger. The power pack and logger were placed above ground to prevent flooding and south of the microlysimeter to prevent shadow casting onto the samples which would influence the temperature regime of the sample.

3. Results and Discussion

Different temperatures affected loadcell performance (output) in the laboratory. An increase in loadcell temperature of +0.1°C resulted in a corresponding mass change equivalent to −0.00185 mm of water. This relationship followed the linear regression ($y = -0.0185x$, $R^2 = 0.9811$, $p < 0.01$). Temperature variation of the loadcell can cause significant errors to loadcell output (Storlie and Eck, 1996) and given the small fluxes involved in "non rainfall' atmospheric water measurements it is therefore important to compensate for the effect of temperature variation on loadcell output.

Temperature profiles of the air 35 mm above the soil surface exhibited high variation with a diurnal range of over 31°C, while the soil temperature at loadcell depth (280 mm) had a diurnal range of less than 2°C (Fig. 2). This is in agreement with Whitford (2002), who states that temperature variation at depths 150–450 mm is less than 3°C. However, temperature variation at loadcell depth over the test period was 3.6°C and this could have been related to the water status of the soil (wet and drying) during the period. Assuming efficient thermal conductivity by the aluminium base plate (Fig. 1), the soil temperature profile at loadcell depth would be similar to that of the actual loadcell (Fig. 2). Based on this assumption, we took the soil temperature profile at loadcell depth (Fig. 2) as the loadcell temperature profile and substituted it into the temperature error effect (linear regression equation $y = -0.00185x$, $R^2 = 0.9811$, $p < 0.01$).

Data were obtained for 10 of the 12 days as the equipment was given 24 h to stabilise before collecting data. The day the microlysimeters were installed, 10 July 2008, rain was received and resulted in saturated (wet) soil at the beginning of data collection on 11 July 2008. There were no significant differences among the three microlysimeters [$F_{(2.997)} = 0.011$, $p = 0.989$] and the three outputs were consequently averaged to give one set of results for each day (e.g. Fig. 3).

Since the soil samples were isolated from below-ground moisture, and we compensated for the temperature error effect on loadcell output, we could assume that the resultant mass change from the microlysimeters reflected "non rainfall" atmospheric water input and subsequent evaporation. Figure 3 shows "non rainfall" atmospheric water cycles for 12 and 13 July and clearly distinguishes two phases typical of the cycle: input (y) and evaporation (z). Classification denotes the phase dominant process, reflecting either a net gain or loss of water from the sample. The jagged graph (Fig. 3) indicates that the system is dynamic, with alternate periods of input and evaporation regardless of the phase. According to

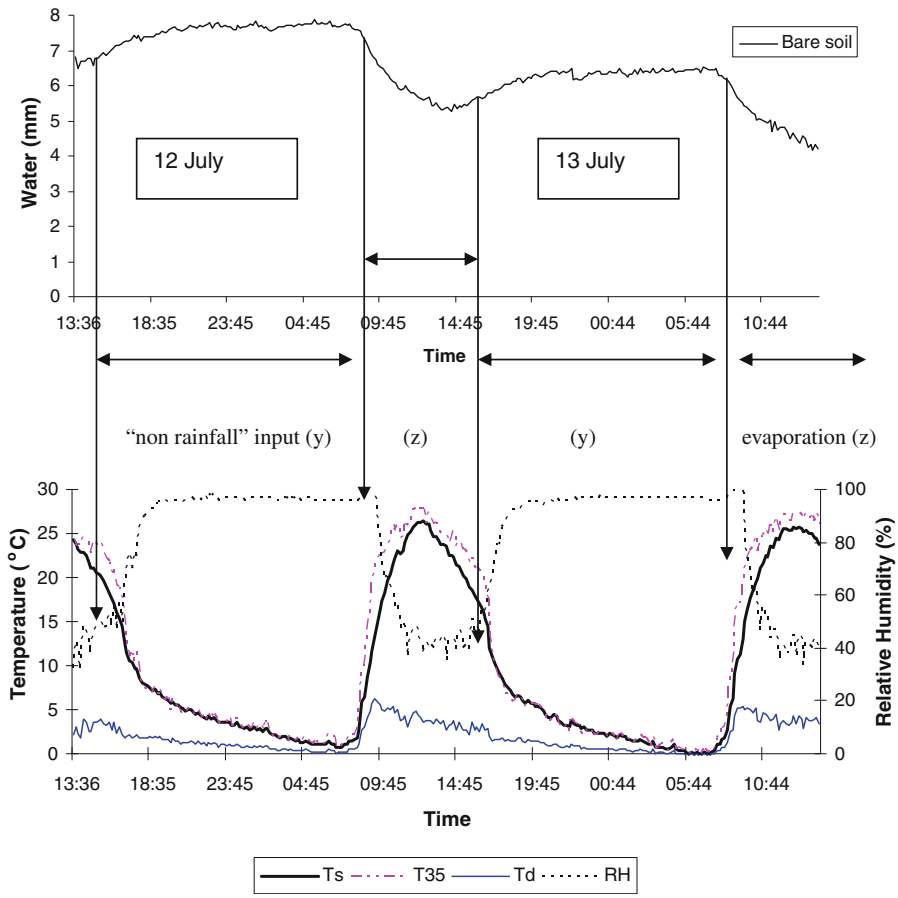

Figure 3
Typical "non rainfall" atmospheric water cycles with associated meteorological data, for 12 and 13 July 2008. T_s Soil surface temperature, T_{35} air temperature, T_d dew point temperature, RH relative humidity at soil surface

AGAM and BERLINER (2004), the evaporative phase precedes and determines "non rainfall" atmospheric water input into soil e.g. evaporation on 12 July was from the morning until mid afternoon of the same day, while "non rainfall" atmospheric water input was from mid afternoon on the 13th until the morning of the 14th July 2008.

Ambient humidity at the soil surface and air temperature 35 mm above the soil surface reveal the different phases when water input or evaporation dominate (Fig. 3). An increase in air and soil temperature decrease ambient humidity, generating a vapour gradient from soil to atmosphere—evaporative phase—resulting in a net loss in sample (soil) water content (Fig. 3). A decrease in air and soil temperatures is accompanied by an increase in ambient humidity, reversing the vapour gradient from soil to atmosphere—input phase—resulting in a net gain in soil water content (Fig. 3). We expected that soil surface temperature would be higher than that 35 mm above the soil surface, but the opposite was the case (Fig. 3). This may have been because of the high soil water content in the sample.

"Non rainfall" atmospheric water input into the sample was calculated from the moment input exceeded evaporation, e.g. on the 13th, this was from 1535 h until the next morning when evaporation exceeded input at 0837 h (Fig. 3). Commencement of the input phase was due to vapour adsorption because dew point temperature had not been attained by the soil surface on both days (Fig. 3). Fog was absent and therefore not included. Although conditions were more favourable for vapour adsorption than dew formation, dew nonetheless did form for a few

minutes in the early morning when the soil surface temperature attained dew point temperature (Fig. 3).

"Non rainfall" atmospheric water input was calculated in two ways: net and total input. The net input method is the principle behind the manual microlysimeter method that was used by Danalatos *et al.* (1995): net input = max (y) − min (z), where y = soil water content at the end of the input phase and z = soil water at inception of input phase.

Total "non rainfall" atmospheric water input on the other hand is a summation of all input during the input phase excluding any evaporation that may have taken place during this period. Table 1 shows net and total input for each of the ten "non rainfall" atmospheric water cycles. There were significant differences between net (0.94 mm, SD 0.11, SE 0.03) and total (3.16 mm, SD 0.77, SE 0.24) "non rainfall" atmospheric water input [ANOVA: $F_{(4.414)} = 80.04$, $p < 0.01$] and total input was 3.4 times net input. This difference could be explained by the difference in calculation in that total input does not take evaporation during this phase into account while net input includes it, therefore net input will always be lower than total input (Table 1).

Although we made some changes to the design of the microlysimeter, the design was based on that of Heusinkveld *et al.*, (2006) and was an improvement on the model by Brown *et al.*, (2008). Both authors performed manual calibrations that were compared to the automatic microlysimeter and results showed a high level of agreement between the manual and automatic microlysimeters. We, therefore, felt it was unnecessary to make any field calibrations and instead opted to compare our results to those in the literature; in particular, we referenced the work of Danalatos *et al.* (1995), which was conducted in a similar environment using manual microlysimeters. Danalatos *et al.* (1995) reported net "non rainfall" atmospheric water input into soil ranging from 0.90 to 2.60 mm per night during winter which is comparable to our results which ranged from 0.76 to 1.10 mm per night in winter. We were therefore confident that our equipment performed relatively well and that the data generated was comparable to similar studies under similar conditions.

Heusinkveld *et al.* (2006) noted the need for automated instrumentation for "non rainfall" atmospheric water studies due to some handicaps of the traditional methods (Jacobs *et al.*, 2002). A major example of these handicaps is that the duration of "non rainfall" atmospheric water input is always predetermined by the researcher e.g. 1900–0700 h (Li, 2002) but Brown *et al.* (2008) demonstrated that the input phase occurs prior to sunset and can last beyond the 0700 h mark. In the current study Fig. 3, the input phase on the 12th began around 1506 h and lasted until 0755 h the following morning, while on the 13th it began around 1535 h and lasted until 0837 h the following morning. This demonstrates that predetermined input durations are not necessarily true. It is, however, important to acknowledge that the duration of the "non rainfall" atmospheric water input is dependent on site, season and soil properties.

Increasing ground level humidity increased the cumulative "non rainfall" atmospheric water input directly into the soil (Fig. 4). As humidity at the soil

Table 1

Input into and evaporation from the soil sample in mm for the ten "non rainfall" atmospheric water cycles, July 2008

Date	Net input	Total input	Vapour adsorption	Dew	Net evaporation	Total evaporation
11	1.04	4.00	2.96	1.04	1.88	3.52
12	1.09	3.11	2.56	0.56	2.29	4.20
13	1.03	3.03	2.61	0.43	2.34	3.04
14	0.88	2.40	1.86	0.54	2.14	3.60
16	0.82	4.52	3.20	1.32	1.54	3.59
17	0.99	2.67	1.89	0.77	2.71	4.35
18	0.76	1.98	1.68	0.29	2.25	4.31
19	0.90	3.72	1.98	1.74	2.26	4.02
20	0.85	2.72	1.93	0.79	2.11	3.90
21	0.98	3.40	3.01	0.38	1.39	2.72

surface increased beyond 30%, there was an increase in soil water due to "non rainfall" atmospheric water input—vapour adsorption. Soil surface humidity above 30% could have been higher than the humidity in the soil pores resulting in a vapour pressure difference between the air and the soil. This vapour pressure difference would have resulted in vapour movement from the air into the soil—input phase. This input would, in theory, continue until humidity in the soil pores was at equilibrium with ground level humidity or saturated. At ground level humidity above 95%, cumulative "non rainfall" atmospheric water input experienced a secondary increase leading to a possible peak in soil water content under these conditions—dew formation (Fig. 3).

There has been little or no attempt to differentiate "non rainfall" atmospheric water input from the different vectors due to lack of appropriate instruments. Instead, research has tended to silo vectors together (Jacobs *et al.*, 2002; Sharan *et al.*, 2007; Brown *et al.*, 2008). This study attempted vector differentiation in the field using data derived from the total "non rainfall" atmospheric water input calculation and definitions of the vectors given in Sect. 1.2. This differentiation was successful in that it revealed the composition of this input and allowed determination of the significance of each vector to soil microhydrology. Vapour adsorption was the dominant input vector during this period and supplied on average 2.369 mm of water (75% of total input) which was about three times more input compared to dew formation (0.785 mm of water or 25% of total input). This may have been because environmental conditions are more favourable to vapour adsorption than dew formation (Agam and Berliner, 2004, 2006), and this is also demonstrated in Fig. 3, where the soil surface temperature only briefly attained dew point temperature. Low dew input and duration (Fig. 3) confirm the findings of Ninari and Berliner (2002) who concluded that dew formation is a rare occurrence on soils.

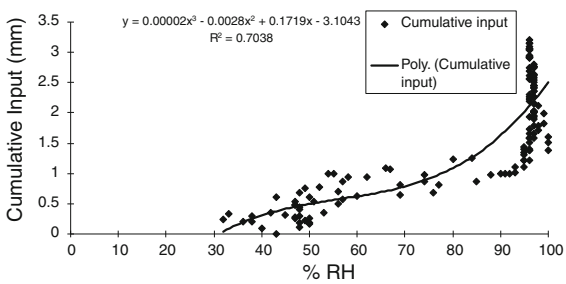

Figure 4
The effect of ground level humidity on cumulative "non rainfall" atmospheric water input directly into bare soil

A drawback of the vector differentiation method applied to this study is that it is dependent on the sampling interval used. A relatively long sampling interval (10 min) reduced accuracy. If, for example, 9 min input were vapour adsorption and the final minute was dew, then all input in that sampling interval was classified as dew input. However, we acknowledge that a shorter sampling interval would increase accuracy of vector differentiation.

Despite the drawback mentioned above, an advantage of the automated microlysimeter method is that it enables observations of the reverse process—evaporation—and has been used in this manner to quantify small influxes (Agam and Berliner, 2004). Evaporation from a bare soil surface is the evaporation of water surrounding the soil particles as thin films and filling the pore spaces between them (Aydin *et al.*, 2005). Evaporation from bare soils is an important process although generally, soil evaporation models describe vegetated areas rather than bare soils (Aydin *et al.*, 2005). The automated microlysimeter method is not a model but a direct method that can be used to measure evaporation from a bare soil surface.

Evaporation was calculated from the moment evaporation exceeded input 0755 h on 13 July 2008 until the inception of the input phase 1535 h on the same day (Fig. 3). This experimental set up allowed two methods of calculation for evaporation from the soil surface—net and total evaporation similar to "non rainfall" atmospheric water input. Net evaporation is the difference between soil water content at the inception of the evaporative phase and at the end of evaporative phase; net evaporation $= a - b$, where $a =$ soil water content at the inception of the evaporative phase and $b =$ soil water content at the end of the evaporative phase.

Total evaporation, on the other hand, is the summation of all evaporation from the evaporative phase excluding any input that may have occurred during this phase. Table 1 shows evaporation from the

sample for each of the ten "non rainfall" atmospheric water cycles. There were significant differences [ANOVA: $F_{(4.414)} = 59.98$, $p < 0.01$] between total (3.73 mm, SD 0.54, SE 0.17) and net evaporation (2.09 mm, SD 0.39, SE 0.12) with the former experiencing 1.8 times more input compared to the latter (Table 1). This could have been because total evaporation is a summation of all evaporation during the evaporative phase and does not take into account any input during the phase unlike net evaporation. The net evaporation range for this study 1.39–2.71 mm day^{-1} was similar to that reported by Danalatos *et al.* (1995) 0.90–2.20 mm day^{-1} under similar conditions and this demonstrates the high performance of the equipment and appropriateness of the methods used in this study.

Net and total "non rainfall" atmospheric water input into the sample was less than net and total evaporation from the same sample. These results mean there was a net loss in soil water (net method = 1.15 mm and total method = 0.57 mm) from the samples and this is justified by the fact that the study commenced with saturated (wet) soil after rains experienced on 10 July 2008. Therefore, even though "non rainfall" atmospheric water input was added into the soil, it was less than the amount of water that would be lost via evaporation from the soil due to its high water content. From 11 to 15 July there was a gradual decrease in soil water content in the sample due to high evaporation caused by the high soil water content which exceeded "non rainfall" atmospheric water input. At the same time, daily evaporation progressively decreased as the sample dried. This could have been because as the sample dried from the surface, the resulting dry layer could have acted as a buffer reducing the rate of evaporation from underlying soils.

The sudden increase in wetness from 15 to 16 July (Fig. 5) was due to a rainfall event that saturated the sample once more and almost flooded the microlysimeter as water levels almost rose to the level of the connecting tube (Fig. 1). Had this water reached this level, it would have spilled over and found its way into the loadcell compartment where it would have damaged the loadcell. After this rainfall event, evaporation once again exceeded "non rainfall" atmospheric water input leading to the observed decrease in soil water content (Fig. 5). We decided to terminate the study earlier than anticipated due to weather forecasts that predicted heavy bouts of rainfall after 23 July 2008.

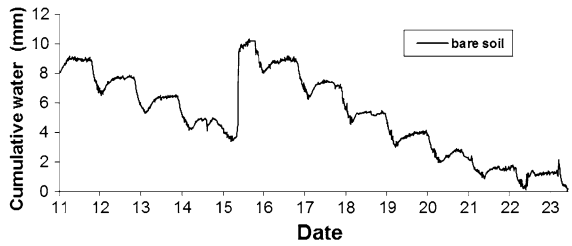

Figure 5
Diurnal changes in soil water content measured from soil in microlysimeters, Stellenbosch, July 2008

4. Conclusions

Caution is to be exercised in microlysimeter construction, e.g. selection of materials to limit material influence on the energy balance of the samples and temperature effects on loadcell output (Storlie and Eck, 1996). The experimental results obtained from the automated microlysimeter developed for this study were comparable and consistent with those obtained using the manual microlysimeter method in the literature (Danalatos *et al.*, 1995). On average the input phase of the "non rainfall" atmospheric water cycle began late in the afternoon (1610 h) and ended after sunrise (0837 h) similar to that reported by Brown *et al.* (2008). This implies that manual methods underestimate "non rainfall" atmospheric water input because the start and end times are predetermined and do not necessarily capture the full period of input.

This experimental setup enabled the determination of the composition of "non rainfall" atmospheric water directly into soil. Under the prevailing meteorological conditions at Stellenbosch during July 2008, vapour adsorption was the dominant input vector supplying three times more input compared to dew. This confirms previous observations that dew formation is a rare occurrence on soils (Ninari and Berliner, 2002).

Despite the automated microlysimeter being the most promising in situ method for "non rainfall"

atmospheric studies (Agam and Berliner, 2006), the instrument has some drawbacks. Firstly, because of the limited loading dish depth and capacity the instrument is not suited for heavy bouts of rainfall which could lead to flooding and damage of the instrument. Secondly, a relatively long sampling interval (10 min) reduced accuracy. If, for example, 9 min were vapour adsorption and the final minute was dew then all input in that sampling interval was classified as dew input. Despite these drawbacks, the instrument and the methods developed provide inroads into determining the significance of different water input vectors in ecological processes in arid zones.

Acknowledgments

This study was financially supported by the National Research Foundation of South Africa (NRF). The authors would also like to thank Dr. J. Irish and Prof M. Fey for their input and Glen Newins and Brian Mulder for construction and development of the equipment.

References

Agam, A., and Berliner, P.R. (2004), *Diurnal water content changes in the bare soil of a coastal desert*, J. Hydrometeorol. *5*, 922-933.

Agam, A., and Berliner, P. R. (2006), *Dew formation and water vapour adsorption in semi arid environments – A review*, J. Arid Environ. *65*, 572-590.

Ashbel, D. (1949), *Frequency and Distribution of Dew in Palestine*, Geographical Review, *39*, 291-297.

Awanou, C.N. and Hazoume, R.P. (1997), *Study of natural condensation of atmospheric humidity*, Renewable Energy, *10*, 19-34.

Aydin, M., Yang, S., Kurt, N., and Yano, T. (2005), *Test of a simple model for estimating evaporation from bare soils in different environments*, Ecol. Modelling, *182*, 91-105.

Berry, F. A., Handbook of meteorology, (McGraw-Hill Book Company, 1945).

Beysens, D. (1995), *The formation of dew*, Atmos. Res. *39*, 215-237.

Berkowicz, S.M., Heusinkveld, B.G., and Jacobs, A.F.J. (2001), Dew in arid ecosystem: ecological aspects and problems in dew measurement, Proceedings, 2nd International Conference on Fog and Fog Collection, 301-304.

Boast, C.W., and Robertson, T.M. (1982), *A "microlysimeter" method for determining evaporation from bare-soil: description and laboratory evaluation*, Soil Sci. Soc. Am. J. *46*, 689-696.

Brown, R., Mills, A.J., and Jack, C. (2008), *Non-rainfall moisture inputs in the Knersvlakte: Methodology and preliminary findings*, Water SA. *34*, 275-278.

Daamen, C.C., Simmonds, L.P., Wallace, J.S., Laryeak, B., and Sivakumar, M.V. (1993). *Use of microlysimeters to measure evaporation from sandy soil*, Agric. and Forest Meteorol. *65*, 159-173.

Danalatos, N.G., Kosmas.,C.S., Moustakas, N.C., and Yassoglou. N. (1995), *Rock fragments II. Their impact on soil physical properties and biomass production under Mediterranean conditions*, Soil Use Mgt. *11*, 121-126.

Evett, S.R., Warrick, A.W., and Matthias, A.D. (1995), *Wall material and capping effects on microlysimeter temperatures and evaporation*, Soil Sci. Soc. Am. J. *59*, 329-336.

Francis, M., Fey, M., Prinsloo, H., Ellis, F., Mills, A., and Medinski, T. (2007), *Soils of Namaqualand: Compensations of aridity*, J. Arid Environ. *70*, 588-603.

Heusinkveld, B.G., Berkowicz, S.M., Jacobs, A.F.G., Holstag, A.M. and Hillen, W.C. (2006), *An automated microlysimeter to study dew formation and evaporation in arid and semi arid regions*, J. Hydrometeol. *7*, 825-832.

Hillel, D., Environmental Soil Physics (Academic Press, San Diego, USA, 1998).

Jacobs, A.F.G., Heusinkveld, B.G., and Berkowicz, S.M. (1999), *Dew deposition and drying in a desert system: a simple simulation model*, J. Arid Environ. *42*, 211-222.

Jacobs, A.F.G., Heusinkveld, B.G., and Berkowicz, S.M. (2002). *A simple model for potential dewfall in an arid region*, Atmos. Res. *64*, 285-295.

Kidron, G.J. (2000). *Analysis of dew precipitation in three habitats within a small arid drainage basin, Negev Highlands, Israel*, Atmos. Res., *55*, 257-270.

Li, X.Y. (2002), *Effects of gravel and sand mulches on dew deposition in the semiarid region of China*, J. Hydrol. *260*, 151-160.

Malek, E., McCurdy, G., and Giles, G. (1999), *Dew contribution to the to the annual water balances in semi-arid desert valleys*, J. Arid Environ. *42*, 71-80.

Monteith, J., Unsworth, M., Principles of environmental physics (Routledge New York, USA, 1990)

Ninari, N., and Berliner, P.R. (2002), *The role of dew in the water and heat balance of bare loess soil in the Negev desert: quantifying the actual dew deposition on the soil*, Atmos. Res. *64*, 323-334.

Noffsinger, T.L. Survey techniques of measuring dew. In Humidity and Moisture, 2 (ed. Wexler. A..) (Reinhold, New York, 1965).

Sharan, G., Beysens, D., and Milimouk-Melnytchouk, I. (2007), *A study of dew water yields on galvanised iron roofs in Kothara (north-west India)*, J. Arid Environ, *69*, 259-269.

Schemenauer, R.S., and Cereceda, P. (1994), *Fog collection's role in water planning for developing countries*, Natural Resources Forum, *18*, 91-100.

Scott, D. (1962), *An instrument measuring dew deposition,* Ecology, *43*, 341-342.

Stone, E.C. (1963), *The ecological importance of dew*, The Quarterly Review of Biology, *38*, 328-341.

Storlie, C.A., and Eck, P. (1996), *Lysimeter-based crop efficient for young highbush blueberries*, Horticultural Sci. *31*, 819-822.

WALKER, G.K. (1983). *Measurement of evaporation from soil beneath crop canopies*, Can. J. Soil Sci. *63*, 137-141.

WHITFORD, W.G., Ecology of desert systems. (Elsevier Science Ltd., 2002)

ZANGVIL, A. (1996), *Six years of dew observation in the Negev Desert, Israel*, J. Arid Environ, *32*, 361-372.

(Received November 16, 2010, revised April 14, 2011, accepted April 18, 2011)