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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 surface

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Abstract

During nighttime, latent heat fluxes to or from the soil surface are usually very small and the absolute amounts of dew deposition are accordingly very small. The detection of such small fluxes poses serious measurement difficulties. Various methods for measuring dew have been described in the literature and most of them rely on the use of artificial condensing plates with physical properties that are very different from those of soil surfaces. A system that detects the actual dew deposition *on the soil surface* under natural conditions would be advantageous and microlysimeters (MLs) appear to be the obvious answer. The objectives of this work were to test the adequacy of microlysimeters to estimate condensation amounts, and to compare these amounts with those measured by a Hiltner dew balance in order to validate the long term data collected using the latter. The research was carried out at the Wadi Mashash Experimental Farm in the Northern Negev, Israel, during two measurement periods. A micro-meteorological station was installed in the field next to a modified Hiltner balance. A microlysimeter with an undisturbed soil sample was placed nearby. During the first period, the depth of the microlysimeter was 15 cm while at the second period it was 55 cm. The results show that for measuring dew, the minimum depth of a microlysimeter should exceed the depth at which the diurnal temperature is constant, which for a dry loess soil in the Negev Desert is 50 cm.

Keywords: Dew; Microlysimeter; Desert; Bare soil

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1. Introduction

Dew in arid and semi-arid ecosystems is considered to be of great importance (Atzema et al., 1990) and is a water source for the bacteria of biological crusts (Lange et al., 1992, 1998) and for plants (Pitacco et al., 1992; Mabbayad and Watson, 1995). It is therefore of interest to quantitatively describe its role in the short (daily) and long (seasonal) term water balance of arid environments.

During the night, the latent heat flux towards the soil surface is very small, and therefore the amounts of dew deposition are very small as well. This fact poses some very special technical measurement difficulties. Various methods for measuring dew are described in the literature, most of them using artificial condensing plates with varying physical properties (Duvdevani, 1947; Lomas, 1965; Noffsinger, 1965; Bunnenberg and Kuhn, 1980; Zangvil and Druian, 1980; Severini et al., 1984; Janssen et al., 1991; Jacobs et al., 1994; Zangvil, 1996; Kidron, 1998; Liu and Foken, 2001). One of these methods is the Hiltner dew balance (Lambrecht) which was used for several years in the Negev desert (Zangvil and Druian, 1980; Zangvil, 1996) to continuously record dew deposition. The Hiltner dew balance is based on the continuous weighing of an artificial condensation plate that hangs from a beam 2 cm above the soil surface. This device is very convenient and simple to use, yet its adequacy has to be proved since the energy balance of its condensation plate is completely different from that of the soil surface above which it is installed due to the fact that: (1) it hangs above the soil surface, the air gap thus effectively isolating it from the soil; (2) the properties of the material of which the condensation plate is made (a thin plastic plate) are very different from those of the soil; and (3) the dew condensing on the plate accumulates on it, while dew formed on the soil surface may infiltrate into the soil.

The Hiltner dew balance could, therefore, be considered as a “potential dew” gauge, whose results are probably mainly correlated to atmospheric conditions. These limitations apply as well to the other methods mentioned above. A method that detects the actual dew deposition *on the soil surface* under natural conditions is clearly needed. We propose to examine the adequacy of a microlysimeter (ML) for this purpose.

MLs have been widely used to measure evaporation from the soil surface of irrigated crops (Shawcroft and Gardner, 1983; Lascano and van Bavel, 1986; Plauborg, 1995), and their use for dew measurements has been suggested (Sudmayer et al., 1994; Jacobs et al., 2000). Typically, an undisturbed soil sample (a representative vertical section of the soil profile) is inserted into a small cylinder open at the top. The ML is inserted back into the soil with its upper edge level with the soil surface and weighed continuously. For bare soil, any change in weight reflects a flux. The recommended materials and dimensions for MLs have been determined for cases in which the evaporation flux after irrigation was of interest. In these cases, the soil is saturated or close to saturation, and the latent heat flux is relatively large (Boast and Robertson, 1982).

Theoretically, the ML will provide the absolute reference for latent heat fluxes, as long as the soil and the heat balance of the ML are similar to those of the surrounding area. The heat balance of the soil sample can be significantly affected by insufficient surface area, insufficient depth and wall material:

(1) *Small surface area*. A small diameter may result in edge problems. Boast and Robertson (1982) and Walker (1983) used MLs with a diameter of 7.6 cm. and wall thickness of 3 mm; Evett et al. (1995) used a ML with a 8.5 cm diameter and wall thickness of 3.5 mm. There are no reports on the effect a change in diameter has on the representativity of the ML.

(2) *Insufficient depth*. In a shallow ML distorted water and temperature profiles may occur which may result in heat and water fluxes to be different from those in the surrounding soil. Boast and Robertson (1982) tested the effect of ML depth on evaporation. They concluded that for periods of 1–2 days, the 7 cm depth ML was accurate enough to describe evaporation from the soil shortly after irrigation (heat flux was not measured).

(3) *Wall material*. The performance of ML in the field is strongly affected by the thermal conductivity of the wall (λ_w). λ_w should be equal or smaller than the thermal conductivity of the surrounding soil (λ_s) to eliminate vertical heat conduction through the ML cylinder and therefore minimizing horizontal heat flux in the deeper layers of the sample. Evett et al. (1995) found that PVC is the best material among those they tested.

The soil heat flux (in both the ML sample and the surrounding soil) has to match the latent and sensible heat fluxes from the boundary layer at the soil surface. The energy-balance of bare soil at the soil–atmosphere interface is:

$$NR + G + H + E = 0 \tag{1}$$

in which all fluxes are positive when directed towards the soil surface (the interface) and measured in (W m^{-2}): *NR*—net radiation; *E*—latent heat flux (negative for evaporation and positive for condensation); *H*—sensible heat flux; *G*—soil heat flux.

Rewriting the energy balance equation, the latent heat flux (*E*) can be derived:

$$E = -(NR + G + H). \tag{2}$$

The sensible heat flux (*H*) can be computed by the stability corrected aerodynamic equations (Brutseart, 1982):

$$H = \frac{\rho C_p u_z k \Delta T}{[(\ln(Z_u/Z_0) - \psi_m(Z_u))(\ln(Z_1/Z_2) - (\psi_h(Z_1) - \psi_h(Z_2)))]} \tag{3}$$

in which: ρ—dry air density (kg m^{-3}); C_p—heat capacity of the air (J K^{-1} kg^{-1}); u_z—mean horizontal wind speed (m s^{-1}) as measured at height *Z* (m); *k*—von Karman constant (=0.41); ΔT—air temperature difference between Z_1 and Z_2 (°K); Z_0—the roughness length (m); ψ_m and ψ_h are the stability corrected functions at the pointed height for momentum and latent heat flux respectively.

The soil heat flux (*G*) can be calculated by:

$$g_{j+1/2} = C_v \frac{(T^i_{j+1} + T^{i+1}_{j+1}) - (T^i_j + T^{i+1}_j)}{2} \frac{dZ}{dt}$$

$$G = \sum_{j=1}^{n} g_{j+1/2} \tag{4}$$

in which $g_{j+1/2}$ is the mean heat gain/loss for a soil layer of thickness dZ (m) between depths j and $j+1$ for time interval dt (s) (between i and $i+1$); C_v—volumetric heat capacity of the layer (J K^{-1} m^{-3}); T—soil temperature (K); n—number of soil layers.

The daily mean value of G is often one or more orders of magnitude smaller than the remaining terms in the energy-balance equation (Eq. (1)) (Brutseart, 1982). This is not the case during shorter periods of time during which it may be one of the dominating fluxes. The soil heat flux (G) can therefore play a very important role in the energy balance at the soil surface during nighttime.

The soil surface temperature is influenced by both the atmospheric and the soil conditions and is one of the main factors that determine whether dew will deposit or not. Small changes in soil surface temperature of the ML sample, when compared to the surrounding soil, could result in preferential dew deposition if its surface is slightly cooler than the surrounding, or the opposite. It is very important, therefore, to ensure similar temperature profiles (and consequently similar soil heat fluxes) inside the ML and in the surrounding soil. Provided the soil sample is undisturbed and representative of the area, similar temperature profiles will yield equal surface temperatures and hence guarantee that the latent heat fluxes measured with the ML represent the surrounding soil.

The objectives of this work were to test the adequacy of MLs to estimate dew deposition, and to compare the dew deposition measured with it to that measured by a Hiltner dew balance in order to validate the long term data collected by the latter in the research area.

2. Materials and methods

The research was carried out at the Wadi Mashash Experimental Farm in the Northern Negev, Israel (31°08′N, 34°53′E; 400 m.a.s.l.). Mean annual rainfall at the farm is 115 mm, most of which occurs between October and April. Long-term maximum and minimum temperatures for January are 14.7 and 4.8 °C; for July they are 32.4 and 18.6 °C. Class A pan evaporation is 2500–3000 mm year^{-1}. The soil is a sandy loam Aridisol (Loess) with 10% clay, 54% silt and 36% sand.

Measurements were carried out during two periods. The first period was from day of the year (DOY) 87–126 (March 29 to May 7), 2000 and the second from DOY 163–235 (June 12 to August 23), 2001. During both measuring periods the following were measured: Incoming and reflected short-wave radiation using two pyranometers (LI2003S, Campbell Scientific[1]); two net-radiometers (Q-7, Campbell Scientific[1]) installed 1.5 m above soil surface; wind speed at four heights (2, 1, 0.5, 0.25 m), using cup-anemometers (014A Met-One[1]); Soil heat flux at three different locations in the field with heat flux plates (HFT-3, Campbell Scientific[1]) at depth of 5 cm and measuring temperatures above them at 1 cm intervals. We replaced the mechanical weighing system of the Hiltner balance by connecting the weighing arm to a load-cell, thereby reducing the

[1] Trade or company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the authors.

time lag of the original setup. The modified Hiltner dew-balance was placed in close proximity to the ML and its condensing plate was protected from wind using the original windshield designed for this device.

During the first measuring period, the sensible heat flux was measured using six interchangeable self-designed aspirated psychrometers measuring dry-bulb temperatures. A ML was built out of a PVC cylinder (thermal conductivity of ~ 0.1 W m^{-1} K^{-1}) with 7 mm thickness, 25 cm diameter and 15 cm length. An *undisturbed* soil sample was taken by digging a trench around the desired sample area, to reduce the pressure on the soil crust. The ML cylinder was then forced into the soil by applying pressure with a hydraulic jack and the ML with the soil sample was dug out and positioned above a scale so that the top end of the sample was level with the soil surface. The output of the scale was registered automatically every half hour by a palm computer (48GX, Hewlett Packard[1]). The resolution of the scale was 1 g and the ML surface area was 490 cm^2, yielding a resolution of 0.02 mm (in equivalent depth of water) or 27.78 W m^{-2} (in energy terms). One set of seven differentially connected thermocouples was inserted radially at a depth of 2 cm in the ML soil sample to measure lateral temperature gradient; another set of six thermocouples was inserted at depths of 15, 10, 5, 3.75, 2.5 and 1.25 cm inside the ML, to compare its vertical temperature gradients to those measured in the surrounding soil.

During the second period, the aspirated psychrometers were replaced by a sonic anemometer (CA27, Campbell Scientific[1]) and a deeper ML used. The dimensions of the new PVC ML had a diameter of 18.6 cm and 55 cm of effective depth with an additional 5 cm of polypropylene insulation. A scale with a maximum weighting capacity of 30 kg and resolution of 0.1 g (HP 30K, A&D[1]) was used. The resolution of the deeper ML was 0.004 mm (in equivalent depth of water) or 5.11 W m^{-2} (in energy terms). Temperatures in the ML and in the surrounding soil were measured from 50 to 5 cm depth in 5 cm intervals and every 1 cm from 5 cm to soil surface.

Temperatures in the soil and in the ML, and the weight of the Hiltner condensation plate were measured for the last 2 min of every half hour. All data excluding the above were measured every 10 s and averaged half hourly. Data was measured and collected by a data-logger (23X, Campbell Scientific[1]).

3. Results and discussion

Latent heat flux measured with the Hiltner dew balance (Hiltner) and the 15 cm depth ML (ML_{15}) together with the latent heat flux calculated using the Energy-Balance equation (EB) for one representative day of the first measurement period (day of year (DOY) 105–106, 16–17 April 2000) are presented in Fig. 1. Positive values represent condensation and negative values represent evaporation. The latent heat fluxes measured with the Hiltner and the ML_{15} are similar, while the EB computations yield much larger amounts of condensation. A good agreement between the Hiltner and the ML_{15} was observed as well for the total condensation per night during the first measurement period, while EB yielded condensation amounts that were much higher than those of the Hiltner and the ML_{15} (Fig. 2).

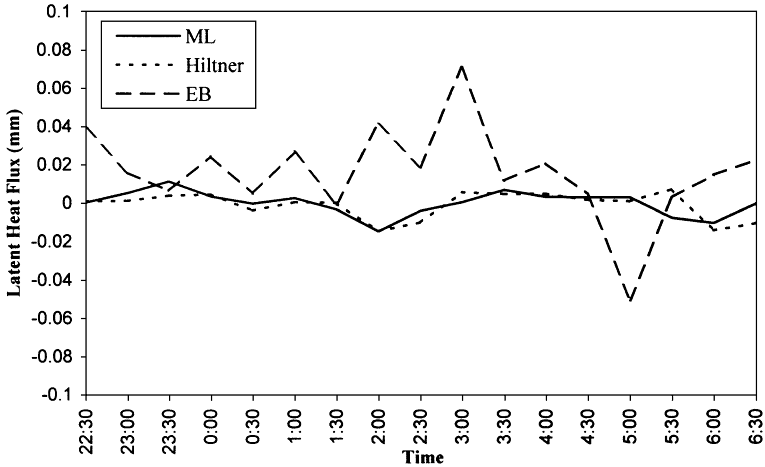

Fig. 1. Latent heat flux as measured by the Hiltner dew balance (Hiltner) and the microlysimeter (ML), and as calculated from the energy-balance equation (EB), for DOY 105–106, 2000, a representative day of the first measurement period.

As mentioned previously, it is unlikely to assume that the Hiltner dew balance can accurately describe the actual condensation on the soil surface. The ability of the ML_{15} to correctly detect the latent heat fluxes at the surrounding soil surface can, therefore, be questioned. One of the critical conditions to ensure the representativity of the ML_{15} is that a similarity in the temperature profiles close to the soil surface exists. Reliable measurements of surface temperature are difficult to obtain even when an infra-red thermometer is used due to the sensitivity of the former to even extremely small changes of wind speed. We compared therefore the temperatures of the ML_{15} and the surroundings at 1 cm depth

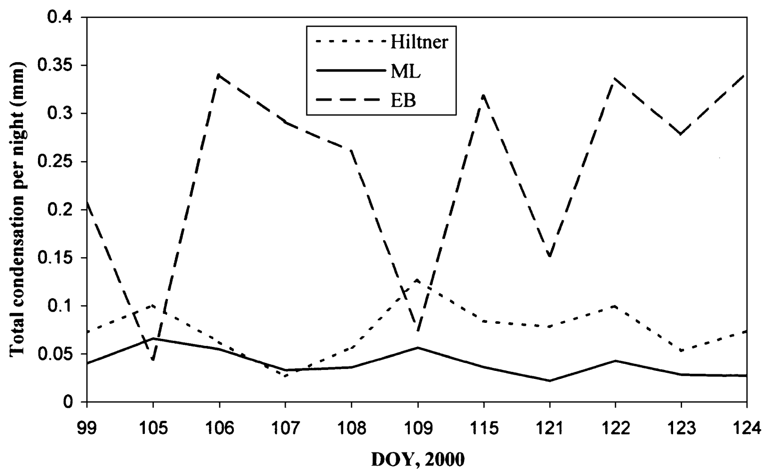

Fig. 2. Total condensation per night measured by the Hiltner dew balance (Hiltner) and the microlysimeter (ML) and calculated with the energy-balance equation (EB), for the first measurement period.

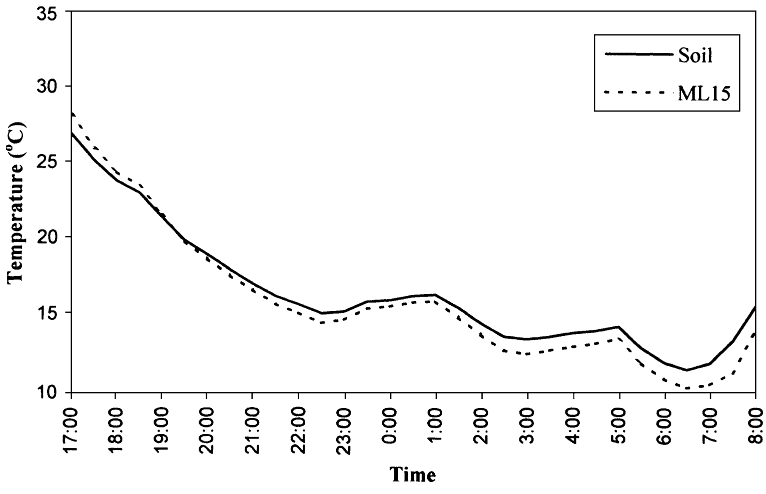

Fig. 3. Soil temperature at 1 cm depth inside (ML) and outside (Soil) the microlysimeter, for the 15 cm depth microlysimeter, measured at DOY 105–106, 2000 (first measurement period).

(Fig. 3). During the day, the ML_{15} is warmer than the surrounding soil and cooler during the night. These differences are probably amplified at the soil surface.

Two possible mechanisms may explain these temperature differences: (1) lateral heat flux exchange between the ML_{15} and the surroundings, and (2) insufficient depth of the ML, thus preventing the conduction of heat from or to the deeper soil layers. In Fig. 4, the lateral and vertical temperature gradients inside the ML_{15} are compared. The lateral gradient, measured at 2 cm depth in the ML is very small when compared to the vertical gradient at that depth, especially during the night (order of 0.0001 °C m^{-1}). Outward

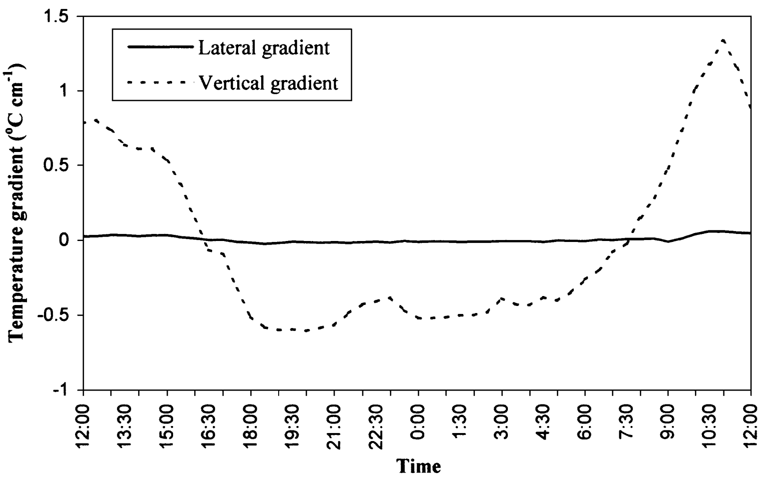

Fig. 4. Lateral and vertical temperature gradients inside the microlysimeter, measured at DOY 105–106, 2000 (first measurement period).

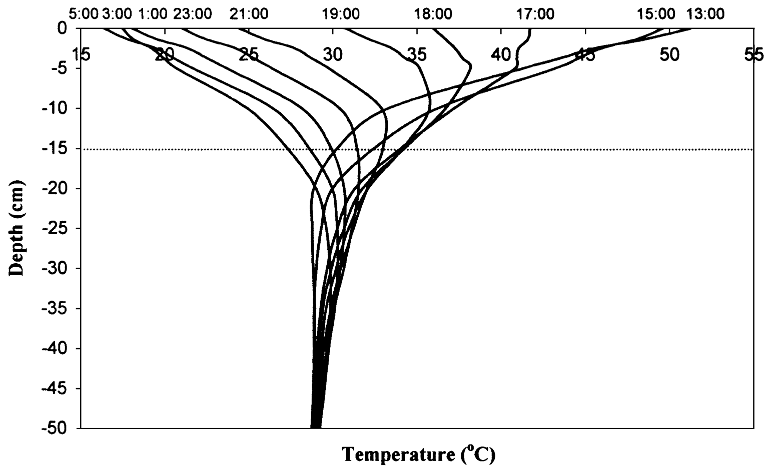

Fig. 5. Temperature profiles in the soil for different hours of the day, as measured on DOY 183, 2001 (beginning of the second measuring period).

radial flux of heat can therefore not explain the preferential cooling of the soil sample inside the ML_{15} during the night. This cooling can, therefore, only be explained by the lack of deeper layers that could contribute to the upward heat flux and therefore prevent the temperature drop. It appears that heat storage below 15 cm plays an important role, and in order to determine the required depth of MLs in dew-related studies the temperature profile from the soil surface to a depth of 50 cm was measured during nights during which dew was recorded. The rationale of this examination being that the depth of the ML should exceed the shallowest depth at which the daily temperature is constant. In Fig. 5, several

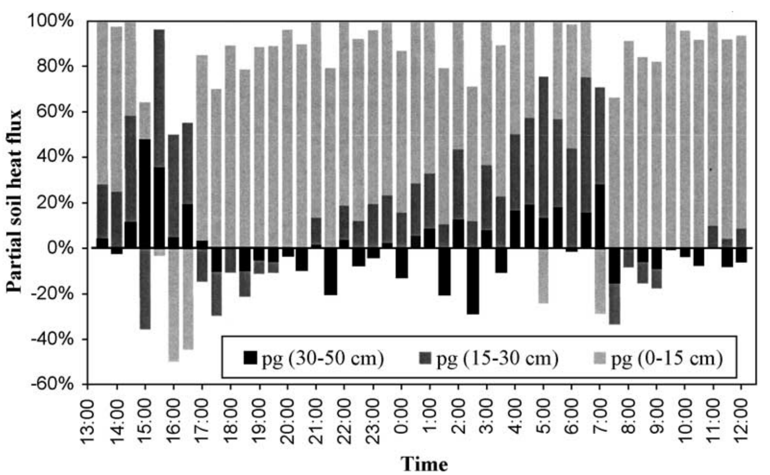

Fig. 6. Partial contribution of the different soil layers (pg 0–15, 15–30, 30–50 cm) to the total soil heat flux, for DOY 183, 2001 (second measurement period).

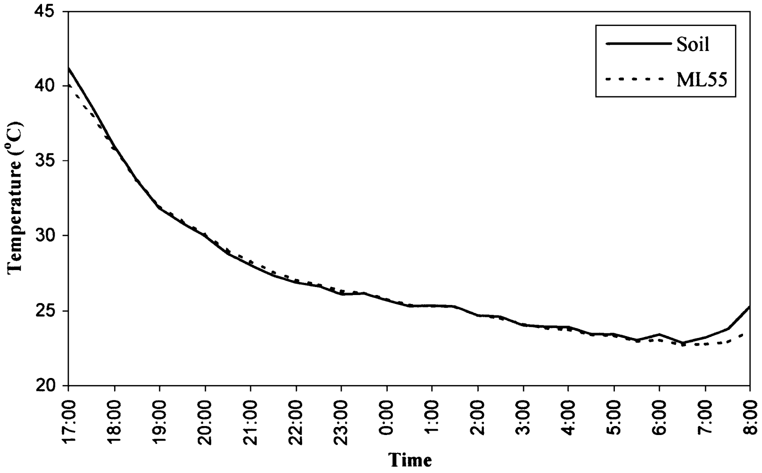

Fig. 7. Soil temperature at 1cm depth inside (ML) and outside (Soil) the microlysimeter, for the ML_{55}, measured at DOY 245–246, 2001 (second measurement period).

soil temperature profiles as measured at the beginning of the second measuring period (DOY 183, 2001), are presented. It is very clear that a relatively large heat flux can be expected at 15 cm depth. In Fig. 6 the partial contribution of the different soil layers is presented. The partial contribution of each layer was calculated as the change in its heat storage ($g_{j+1/2}$) divided by the total soil heat flux (G), during the corresponding time interval (Eq. (2)). The increasingly important role of the 15–30 cm layer as from 21:00 until sunrise is noteworthy as well as the fact that during some periods during the night the layers below 15 cm contribute even more than 60% of the total flux. It is important to note

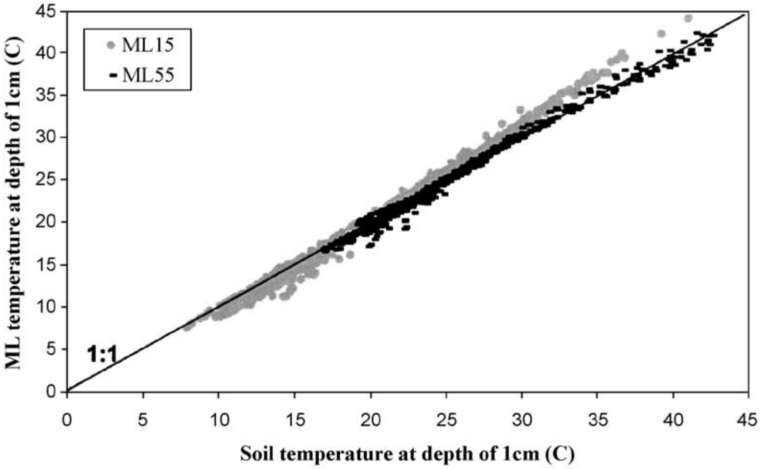

Fig. 8. Temperatures at 1 cm depth inside both ML_{15} and ML_{55} plotted versus the surrounding soil temperature at the same depth for all measured nights (from 17:00 to 8:00, every half hour).

Table 1
Summary of results from linear regression analysis and comparison of slopes between the temperatures inside the MLs (both 15 and 55) and the surrounding soil temperatures, for depths of 1 and 5 cm

	Depth (cm)	N	Slope	Intercept	R^2	P, comparison of slopes	P, comparison of coefficients	P, comparison of slopes to 1
ML_{15}	1	1349	1.133	− 2.475	0.994	0.0000[a]	0.0000[a]	0.0000[a]
ML_{55}	1	565	1.019	− 0.439	0.990			0.394
ML_{15}	5	1349	1.230	− 4.667	0.982	0.0000[a]	0.0000[a]	0.0000[a]
ML_{55}	5	565	1.037	− 1.668	0.986			0.133

[a] Slopes/coefficients are significantly different.

here that the soil was very dry during this measurement period (average volumetric water content of the upper 5 cm of the soil was 2.1%), and that the conduction of heat in the soil would be higher for higher volumetric water contents. This implies that if the whole profile would be wetter, the depth at which the daily temperature remains constant may be below 50 cm.

As a result of these findings we built a 55-cm deep ML (ML_{55}). To keep the lateral gradient as small as possible, the PVC tube was thermally insulated by wrapping it in glass wool. The daily course of the soil temperature at 1 cm depth inside and outside the ML_{55} is presented for a characteristic night in Fig. 7. The temperature differences are now much smaller than those recorded for the ML_{15}. The better correspondence between measurements inside and outside the ML for the ML_{55} can be gleaned from the results presented in Fig. 8 and in Table 1. In Fig. 8, temperatures at 1 cm depth inside both ML_{15} and ML_{55} are plotted versus the corresponding surrounding soil temperature at the same depth for all measured nights (from 17:00 to 8:00, at half hourly intervals). Table 1 shows the results of the linear regression analysis between the temperatures inside and outside the MLs (both

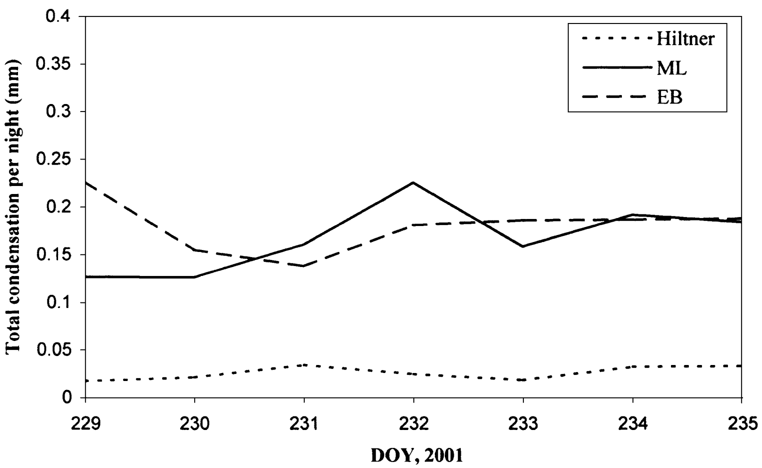

Fig. 9. Total condensation per night measured by the Hiltner dew balance (Hiltner) and the microlysimeter (ML) and calculated from the energy-balance equation (EB), for the second measurement period.

ML_{15} and ML_{55}), for both 1 and 5 cm depths. This pattern repeats for the whole profile. These results leave no doubt as to the fact that the ML_{55} represents the surrounding soil better than the ML_{15}.

Comparing the total condensation measured by the Hiltner, the ML_{55} and the computed latent heat flux (EB), (Fig. 9), a completely different pattern than that presented in Fig. 2 emerges. The ML_{55} and the EB seem to agree rather well. It seems, therefore, that a deeper ML resolves the apparent lack of agreement between atmospheric and soil measured fluxes as appeared to be the case from the results obtained with ML_{15}.

We suggested that the values registered by the Hiltner balance could be referred as "potential dew deposition", thus implying that larger dew amounts than those that actually condense on the soil surface should be detected by the balance. From our results it appears that the opposite is the case: the Hiltner balance underestimated total condensation. No surface wetting was evident during visual inspect of the soil surface on several occasions during which dew was registered by the Hiltner balance. This would indicate that water vapor is adsorbed within the soil profile, even though the soil surface temperature does not drop to dew point. Hints for the existence of this mechanism can be found already in a theoretical analysis of Philip (1957) and in articles of Kosmas et al. (1998, 2001).

4. Conclusions

The use of a ML appears to be the most accurate method to measure dew deposition *on the soil surface*. Nevertheless, it appears that the ML specifications for measuring evaporation published to date are not sufficient in the case of measuring condensation. We have shown that for measuring dew, the minimum depth of a ML should be the depth at which the diurnal temperature is constant in order to ensure similar temperature profiles inside and outside the ML. For a dry loess soil in the Negev Desert, a minimum depth of 50 cm is required. Furthermore, our results indicate that during the night water vapor is adsorbed within the soil profile, even though the soil surface temperature does not drop to dew point and no surface wetting is evident. This process, which appears to be important at least for the area in which we carried out our trials, cannot be quantified with the Hiltner dew balance and casts serious doubts about the usefulness of the latter for the estimation of total absorption of water from the atmosphere by the soil profile.

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