An Automated Microlysimeter to Study Dew Formation and Evaporation in Arid and Semiarid Regions

BERT G. HEUSINKVELD
Meteorology and Air Quality Group, Wageningen University, Wageningen, Netherlands

SIMON M. BERKOWICZ
Minerva Arid Ecosystems Research Centre, Institute of Earth Sciences, Hebrew University of Jerusalem, Jerusalem, Israel

ADRIE F. G. JACOBS, ALBERT A. M. HOLTSLAG, AND WILLY C. A. M. HILLEN
Meteorology and Air Quality Group, Wageningen University, Wageningen, Netherlands

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ABSTRACT

The development of a simple and low-cost portable weighing microlysimeter that makes use of a load cell for automated recording and for studying daily dew formation, rate of accumulation, and subsequent evaporation in arid or semiarid regions during rainless seasons is presented. The sampling cup is 3.5 cm deep, with the load cell itself situated at 20-cm depth to minimize temperature effects. The device was tested in a sand dune experimental station situated near Nizzana, northwest Negev Desert, Israel, during which extensive micrometeorological measurements were collected. One microlysimeter was placed in a playa and a second was installed on the stabilized midslope of an adjacent linear sand dune. To assess the performance of the load cell microlysimeters (LCM), one pair of manual microlysimeters was installed next to each LCM. A third pair was installed at a point between the LCMs and a fourth pair above the midslope LCM. Sixteen overnight measurements were carried out within a 6-week period. The LCM could measure dew with an error of ±0.02 mm. The daily dew variation in the samples during the 16 overnight measurements ranged up to 0.2 mm on stable dune slopes but up to 0.4 mm on the playa. This difference is attributed to the playa's high silt and clay content and salinity. Dew formation and accumulation were found to occur long before the soil-surface temperature reached the dewpoint temperature of the air. The cost of building this microlysimeter, excluding labor, is about $175 (U.S.).

1. Introduction

Insights into the exchange processes of heat and mass in arid and semiarid environments require that reliable measurements can be made of dew and its subsequent evaporation. The absolute amounts, however, are small and are not likely to exceed 0.4 mm per evening (Jacobs et al. 2000a). It is thus not surprising that attempts to evaluate the multiple roles dew plays in the environment and in ecosystems have been hindered by the very difficulty of dew measurement. Approaches have included destructive sampling, moisture-absorbing material, dewdrop size calibrations, electrical surface wetness circuits, and assessment of dew on proxy surfaces (Berkowicz et al. 2001; Richards 2004). Single measurements taken near sunrise will, at best, provide only maximum dew amounts for the particular surface under study. This does not take into account possible drying during the evening. However, dew onset, accumulation (and rate), and evaporation can be of primary interest, for example, in agriculture where dew is a factor in the development of plant diseases (Wallin 1967). There is a need for dew sensors to allow repetitive measurements to be performed, but with a capability for automated recording at desired time intervals.

The exchange process of water between the soil surface and the atmosphere plays an important role in arid

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Corresponding author address: B. G. Heusinkveld, Meteorology and Air Quality Group, Wageningen University, Duivendaal 2, NL-6701 AP Wageningen, Netherlands.
E-mail: Bert.Heusinkveld@wur.nl

regions (Malek et al. 1999), especially during lengthy rainless seasons. In this period dew (and sometimes fog, depending on the location) is the only source of water. Desert arthropods, such as isopods, ants, and beetles, rely on dew as a significant moisture source (Broza 1979; Moffett 1985) and desert landsnails become active when the soil is wet from dew (Nevo et al. 1981). Spiderwebs can be laden with dew on heavy-dew evenings, contributing to webs breaking due to the increased load (Brackenbury 1997). Desert soil faunas, such as nematodes, are sensitive to dew deposition on a soil surface (Steinberger et al. 1989). Larmuth and Harvey (1978) found that desert seedling distribution in a reg desert of Morocco was greatest near a stone and speculated on the role of stones as both a dew collector and funnel of dew. Dew may also contribute to seed germination and assist in the adhesion of dust and fine materials to surfaces. Gutterman and Shem-Tov (1997) noted that certain desert plants have seeds that develop a mucilaginous layer when wetted and can then adhere to a soil surface. They believe that although dew wetting is insufficient to cause seed germination, it may help in priming the seed. Other studies have focused on water stress recovery by desert plants from dew (Munne-Bosch et al. 1999; Munne-Bosch and Alegre 1999). In addition, in many desert areas biological sand crusts play a major role in stabilizing sand dunes (Danin et al. 1989). The development of such crusts is largely determined by water availability for the crust organisms, which is the key parameter controlling the activity of the microbial crust community (Harel et al. 2004). Nocturnal dew can be a major source of water for these organisms (Jacobs et al. 2000a).

In the present study, dew formation and evaporation on flat surfaces as well as on a slope were of special interest. A search of electronic catalogs led to the investigation of load cells as a basic sensor with which to construct a simple and inexpensive weighing microlysimeter. A load cell is an electronic device that measures the deformation of a piece of metal by means of a strain gauge; that is, the resistance changes when stretched. Examples of load cell use range in applications from Grimmond et al. (1992) for a vegetated surface, Jackson (1996) for an aeolian sediment trap, Scott et al. (2002) on effects of soil trampling on evapotranspiration, and Sear et al. (2000) to record bedload transport in streams.

The advantage of a microlysimeter method is that it is a direct measure of soil water loss/gain. There are a number of studies where microlysimeters have been used for determining evaporation. Daamen et al. (1993) reviewed various microlysimeter designs. They tested microlysimeters that ranged from 51 to 214 mm in diameter and 100 to 200 mm in depth. Although they concluded that all of the microlysimeters performed similarly, they did not report if they were sensitive enough to measure dew. Exposure of the edge of the sampling cup cannot be avoided and thus the edge will stick out a few millimeters above the surrounding soil surface. As edges can enhance turbulent transport, a small diameter lysimeter will have a greater edge-to-diameter ratio. Daamen et al. (1993), however, did not find evidence for this.

There were several considerations in working in a desert area for the purposes of our research. First, the study site in the northwest Negev Desert of Israel experiences dew approximately 200 evenings per year (Evenari et al. 1982; Zangvil 1996) and can reach up to 0.4 mm per night even in the hot, dry summer (Jacobs et al. 2000a). In addition, the hot, rainless period is usually 6 to 7 consecutive months (i.e., from April to October), but up to 9 consecutive months during a drought year (Berkowicz 2003).

Meteorological and manual microlysimeter measurements in the research site were first carried out in September–October 1997 (Jacobs et al. 1999, 2000a,b, 2002). The data revealed that the latent heat fluxes are substantial and that they followed a daily pattern resulting from dew. The number of dew evaporation measurements using the manual microlysimeters was limited since the measurements were very time consuming. It required that the manual microlysimeters' soil samples be repeatedly removed from their respective locations and weighed within an on-site shielded sensitive balance (Mettler, PM1200, Switzerland, 0.001-g accuracy) (powered by car batteries and recharged by solar panels) that had been placed inside a box to protect against wind effects. These manual measurements were either initiated about 2 h before sunset to about 1300 local time (LT) the following day (until no weight changes occurred), or from about 1 h before sunrise to about 1300 LT. The lysimeters were weighed at 30-min intervals around sunrise and sunset because of rapid dew accumulation/drying, and then at 1–2-h intervals. One difficulty in carrying out such measurements is the need to remove and replace the manual microlysimeters. This required carefully cleaning them before weighing in order to remove any soil material that may have attached itself to the sides or base.

Such measurements are laborious and exhausting, which may partly explain why modern dew research (post-1970) has lagged behind other areas in meteorology. Hence, an inexpensive recording device can be a welcome tool for both short- and long-term dew measurements. In this paper, the development of an automated microlysimeter is presented including results ob-

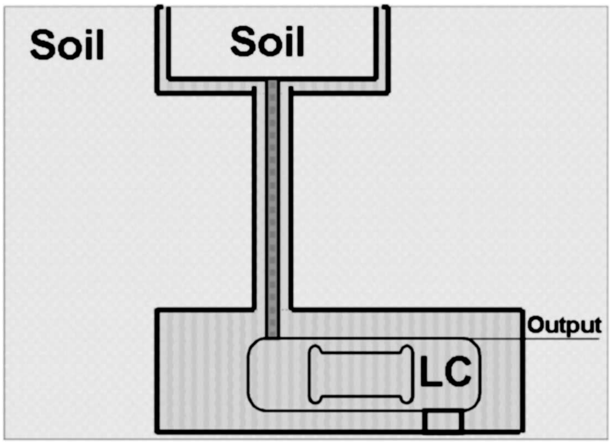

FIG. 1. Sketch of microlysimeter construction. The top of the load cell (LC) is 0.22 m below the surface.

tained from an experimental campaign held in the Negev Desert in September–October 2000 to study dew onset, accumulation, and evaporation.

2. Load cell microlysimeter (LCM) specifications and design

The instrument was designed as a portable, lightweight, and inexpensive sensor that could be used either in the field or under laboratory conditions. The design and specifications needed were based, in part, on experience and data obtained during a dew-measurement field campaign carried out in 1997 (Heusinkveld et al. 2004; Jacobs et al. 1999, 2000a). The load cell is manufactured by Vishay Tedea-Huntleigh (Switzerland; http://www.tedea-huntleigh.com). A low-capacity, single-point load cell was used, model 1042, 1-kg rated capacity, made of anodized aluminum with dimensions 150 mm × 39 mm × 20 mm. It has a humidity-resistant coating. The total error is given as 0.02% of the applied load. There is internal electronic temperature compensation, but the remaining temperature dependence cannot be neglected. The temperature effect as specified by the manufacturer is $\pm 0.001\%\ \mathrm{K}^{-1}$ on output of load versus temperature, and the effect on the offset is $\pm 0.004\%\ \mathrm{K}^{-1}$ of the rated output. Thus for a sampling cup of 140-mm diameter weighing 1 kg, the temperature effect in equivalent units in depth of water as dew is $3.2\ \mu\mathrm{m\ K}^{-1}$. This was tested in a temperature-controlled oven over a range of 20°–70°C and the company specifications were found to be correct.

The LCM was thus designed to avoid these temperature problems. Figure 1 contains a sketch of the sensor and Fig. 2 shows the LCM on a base plate (left panel) and protective housing (right panel), respectively. The exposed surface area of the LCM contains a transparent plastic polypropylene dish (2-mm-thick walls) that can hold a sample 140 mm in diameter and 35 mm deep. Although a larger diameter would reduce aerodynamic edge effects, this would also increase the size and weight of the sample.

The sampling cup depth of 35 mm was based on previous dew measurements at the Nizzana field site, comparing 10-, 30-, and 75-mm-deep manual microlysimeters (polyvinylchloride, diameter 70 mm, walls 3 mm). The results showed that there were no differences between the 30- and 75-mm-deep microlysimeters (Jacobs et al. 1999; but see also Evett et al. 1995). A shallower microlysimeter dish would block vapor transport to deeper soil layers and collect less dew. The dish base has a small cap that fits into a central plastic support pipe to ensure the dish is balanced on the load cell below. The plastic pipe has a low heat conduction coefficient, which limits heat conduction toward the load cell. Polyvinylchloride (PVC) material, 5 mm thick, was used to house the load cell and protect the sampling dish. Figure 2 (right panel) shows the load cell attached to the housing base plate. The base plate can be made of PVC, but also in aluminum to ensure better thermal contact with the soil below. We recognize that this housing material and bottom cap will affect the thermal transfer between the soil and the microlysimeter sample (Evett et al. 1995). A small depression was carved into the base plate (Fig. 2, left panel) to allow the load cell to bend. A screw can be inserted into a threaded hole in the loading end of the load cell for overload protection.

The load cell itself is installed (Fig. 1) at a depth of 220 mm (top of load cell), much deeper than the depth of the soil sampling cup. Figure 3 shows a typical diurnal pattern of the soil temperature profile variation in the field site to be less than 5°C at 200-mm depth during summer. Assuming that the temperature variation in the load cell will be similar to that of the soil below the load cell, one can estimate a temperature error effect on the load cell output (Storlie and Eck 1996), that is, a maximum error of 0.015 mm of equivalent dew amount. Because of the insulating open space above the load cell and the poor temperature-conducting plastic shaft that connects the load cell to the soil sampling cup, it is expected that the temperature variation is lower. Therefore, no corrections were made for the remaining temperature effect.

The output was recorded using a Campbell Scientific 21X datalogger (Campbell Scientific, United States). The measurement technique was a 6-wire full bridge with excitation lead compensation with a resolution of

FIG. 2. (left) Load cell affixed to a PVC base plate. An aluminum base plate option is also shown (note the depression to allow the load cell to bend). (right) Microlysimeter showing the empty plastic sampling dish and protective cover for rain or storage.

0.1 g. The mass was monitored at 5-s intervals and was averaged every 15 min.

The soil cores for the sampling cup were prepared in the following way: A PVC pipe of the same diameter and depth as the sampling cup was placed on the study surface. The pipe was then tapped until flush with the surface. The soil around the pipe was then exposed by digging and a flat plate was inserted horizontally at the base of the exposed pipe. The surface was then covered by another plate and the entire core was lifted and inverted. The top plate was removed and the sampling cup was placed over the core and pushed down. Then the core was inverted again, revealing the original surface. A hole was excavated beneath the site where the core was extracted. The load cell housing was installed and soil was backfilled to the edge of the housing at the soil surface. The dish and protective PVC casing limits heat exchange from the surrounding soil and is obviously not suited for situations under rainfall. In such cases, the dish should be covered with a cap. However, our design could be used for light rains of a few millimeters, as long as the water percolation does not reach the dish base. This can be determined by removing the transparent dish and visual examination of the base.

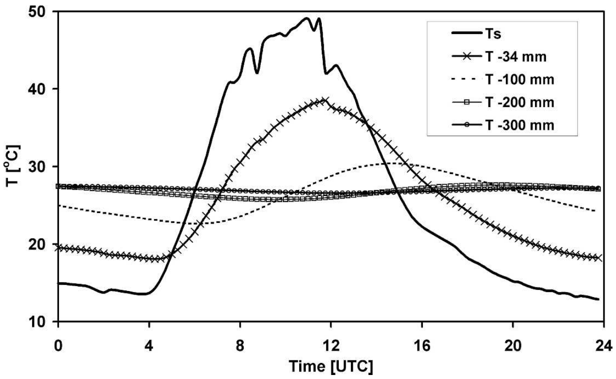

FIG. 3. Measured temperature variation in a playa soil at the surface, T_s, and at various depths, 30 Sep 1997. Local solar time is UTC + 2 h 18 min.

3. Field site description

Two load cell microlysimeters were tested during a 6-week field campaign held in September–October 2000, in the Hebrew University of Jerusalem Minerva Arid Ecosystems Research Center (AERC) sand dune experimental station (30°56′N, 34°23′E; elevation 190 m msl) situated near Nizzana, northwest Negev Desert, Israel. The Mediterranean Sea lies about 40 km to the northwest. The average annual rainfall of the region is about 100 mm, with a coefficient of variation of about 40%, and occurs primarily in winter between December and February (Sharon et al. 2002). The measurement campaign took place near the end of the hot, rainless summer. The soil water recharge by rain is low. During the period October 1999–March 2000, the site received only 35 mm of rainfall, with 8 mm in March

2000 distributed over four small showers. The only major rainfall occurred in late January 2000 (18 mm).

The dune field encompassing Nizzana consists of sparsely vegetated linear dunes 10 to 25 m high and up to 125 m wide. The dune crests are mobile but the dunes themselves are stable. The dunes are elongated west–east, which is the resultant of the direction of the strongest winds (Sharon et al. 2002). Although the climate is classified as arid, the dune slopes can have a perennial vegetation cover of up to 30% and even up to 50% near footslopes (Tielbörger 1997). Biological crusts form on the dune slopes and tend to cover the open areas between shrubs (Littmann and Ginz 2000). The interdune corridors are between 50 and 150 m wide and contain a mixture of wide, flat playa surfaces, gently sloping stretches, many small hillocks, and remnants of eroded ancient dunes.

Dew formation and evaporation on two terrain types were assessed on a dune slope covered with biological crusts and in a flat playa area situated near the foot of the dune. The playa consists of a thick compacted layer of silt and clay, though the first few millimeters can contain 35% fine sand (Pfisterer et al. 1996). This material was deposited during temporal inundations caused by strong winter rains.

4. Field instrumentation

The meteorological measurements were made 10–30 m away from the microlysimeters, depending on the sensor. Monitoring of the radiation budget, by measuring the shortwave and longwave radiation separately, was performed with Kipp radiometers at an interval of 15 min. The incoming and reflected shortwave radiation was monitored by two solarimeters (Kipp CM14, the Netherlands), and the incoming and emitted longwave radiation was monitored by two pyrgeometers (Kipp CG1, the Netherlands). The sensible and latent heat fluxes were measured by the eddy correlation (EC) technique using a 3D sonic anemometer (Campbell Scientific, CSAT3, United States) and a fast humidity sensor (Li-Cor, Li-7500, United States), mounted at a height of 3 m.

The temperature profile was monitored at 0.5 and 1.5 m with aspirated psychrometers (Pt-100 resistance thermometers). Wind speed was measured at two heights (2 and 5 m) with small sensitive microcup anemometers (length distance 1.2 m). Soil temperatures were measured at 2-, 50-, and 100-mm depths with Pt100 (platinum wire) homemade resistance thermometers. Soil surface temperature was monitored with a pyrometer (Heimann KT15, Germany).

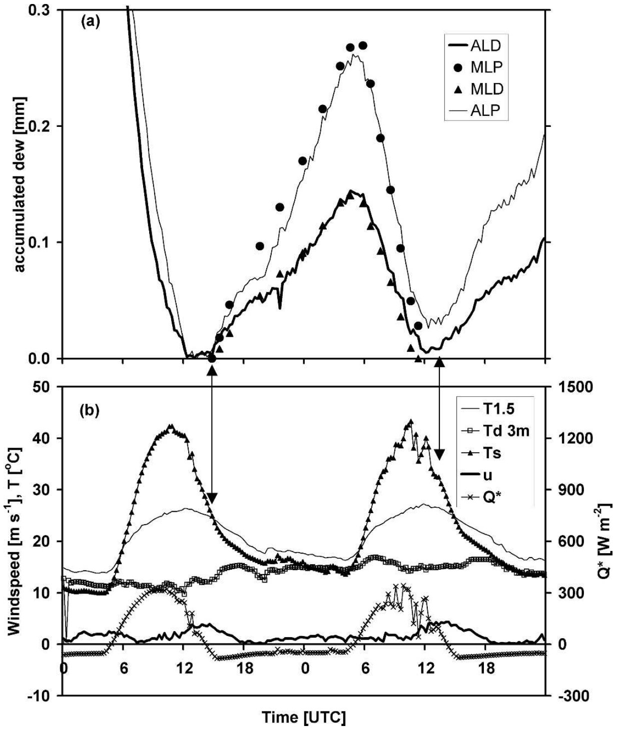

FIG. 4. (a) Automatic microlysimeter on dune midslope (ALD), automatic microlysimeter on the playa (ALP), manual microlysimeter on dune midslope (MLD), manual microlysimeter on the playa (MLP), 16–17 Oct 2000. (b) Meteorological data for 16–17 Oct 2000: $T_{1.5}$ air temperature at 1.5 m, T_s surface temperature, T_d dewpoint at 3 m, u wind speed at 3 m, and Q^* net radiation. Local solar time is UTC + 2 h 18 min. Arrows point to the start of the dew formation process.

Four pairs of manual microlysimeters (MLS) (Boast and Robertson 1982), 30 mm deep and 70 mm in diameter, were installed along a 32-m transect running from the flat playa to the upper dune slope. The first pair (MLS-1) was next to the playa load cell, the second set (MLS-2) was near the dune footslope (13 m away from the playa load cell), the third set (MLS-3) was next to the load cell on the dune midslope (11 m above MLS-2), and the fourth pair (MLS-4) was 8 m farther upslope. In total, 16 overnight measurements were carried out using the manual microlysimeters.

5. Results and discussion

An example of the load cell performance is provided in Fig. 4a, together with relevant meteorological data (Fig. 4b). The sensitivity of the LCM is demonstrated for yearday 290 (16 October 2000). This day experienced the first rain of the season, a drizzle of 0.3 mm followed by dew. This rain was not registered by the station's manual rain gauges or rain recorder, but was detected on both LCMs. The remaining water in the

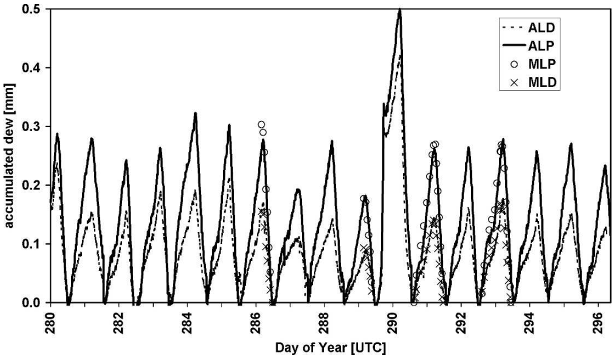

FIG. 5. Daily dew formation and evaporation measured using the automatic microlysimeters: Automatic microlysimeter on dune midslope (ALD), automatic microlysimeter on the playa (ALP), manual microlysimeter on the playa (MLP), and manual microlysimeter on dune midslope (MLD).

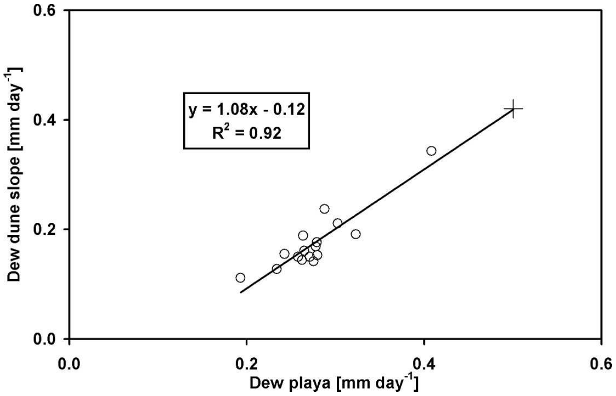

FIG. 6. Ratio between automatic microlysimeter on dune midslope and automatic microlysimeter on the playa. The "+" data point contains 0.3-mm light rain, and the "o" data points contain dew only.

manual and LCMs could be attributed to the water that did not evaporate on the cooler day that followed the dew night. The MLS and LCM dew data were found to differ by less than 5%. Of interest is the contrast between the playa and dune midslope dew accumulation amounts. The dune midslopes receive about 34% less dew (on average) than on the playa soil (Figs. 5 and 6). This pattern was found for both the manual and recording microlysimeter data. The three pairs of MLS stations on the slopes, however, differed between themselves by less than 6% with no clear preference for slope position (i.e., top, middle, and footslope). The average difference in dew recorded within the pairs of manual microlysimeters was 8%, with an individual high of 14%. This is consistent with data obtained from a previous field campaign in 1997 on the same slope (Jacobs et al. 2000a).

To explain the large difference between the playa and dune slope dew yields, we suggest that it can be attributed to the playa's characteristic high silt, clay, and salinity levels. The dune slope surfaces, in contrast, have grain size distribution medians of 90 μm for the 2–4-mm-thick crust and 230 μm for the coarse sand below the crust (Verrecchia et al. 1993; Pfisterer et al. 1996). The dew formation process is controlled by the available energy (i.e., net radiation minus soil heat flux) and the vapor pressure gradient between the free atmosphere and the soil (Monteith 1957). It is the vapor pressure gradient that is affected by the soil composition and soil moisture content. On a dry soil surface, dew formation will not always be visible as free surface water, but it will be bound in capillaries and adsorbed by the soil. Therefore, vapor pressure deficit at the soil atmosphere interface need not be zero during a dew episode, although for a free water surface this would be valid. The measurements support this; for example, in Fig. 4 the dew formation process starts (see arrows) while $T_s - T_d > 10°\mathrm{C}$. The dew water will first contribute to the filling of fine soil capillaries. When the smaller soil capillaries fill up, it will increase the vapor pressure of the soil pores. During the dew formation process, the vapor pressure deficit will start to differ in both soil types and this will result in a difference in dew amount. This is evident from Fig. 6, where the difference between the dew on the dune slopes to that on the playa was greater for nights with less dew. However, this is only valid when the soil is not saturated at the start of the dew formation process. Note that salinity will also increase the vapor pressure deficit in the soil pores and thus enhance dew yield. The playas are saline because of ponding (and subsequent evaporation) of rain and runoff water that collect there. In contrast, on the dune slopes rain can cause salts to be removed by runoff or flushed beneath the surface. To exclude microclimatic conditions as the cause of the 34% difference in dew yields between dune slope and playa, a playa soil sample in an MLS was transposed with one from the dune slope. The MLS with the dune slope sample placed on the playa also had dew amounts about 34% less than the playa sample transposed to the dune slope. Hence, spatial variation of microclimate could not explain the large difference in dew yields between playa and dune slope.

6. Conclusions

The development of inexpensive and portable recording microlysimeters to study minor changes in near-surface soil moisture content can make a valuable contribution to dew research. The total accuracy of the LCM tested here, as based on manufacturer's specifications and oven testing, was ±0.02 mm of equivalent dew. The LCM's compact size and light weight allows the sensor to be installed in a variety of settings and landscapes, and not just on flat surfaces.

The daily dew variation during the study period ranged from 0.1 to 0.2 mm on stable dune slopes but up to 0.4 mm on the playa soils. Both the LCM and MLS data suggest that dew formation on bare soil is influenced by soil properties (silt and clay content and salinity). The playa dew amounts were about 34% higher, on average, than on the dune slopes. The soil composition may help to explain why such surfaces can absorb moisture even when the soil surface temperature is more than 10°C higher than the dewpoint temperature of the free atmosphere.

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