Agricultural and Forest Meteorology, 62 (1992) 205–218
Elsevier Science Publishers B.V., Amsterdam

Development and evaluation of continuously weighing mini-lysimeters

C. Susan B. Grimmond[a], Scott A. Isard[b] and Mark J. Belding[a]

[a]*Climate and Meteorology Program, Department of Geography, Indiana University, Bloomington, IN 47405, USA*

[b]*Department of Geography, University of Illinois, Urbana, IL 61801, USA*

(Received 20 April 1992; revision accepted 13 July 1992)

ABSTRACT

Grimmond, C.S.B., Isard, S.A. and Belding, M.J., 1992. Development and evaluation of continuously weighing mini-lysimeters. Agric. For. Meteorol., 62: 205–218.

Micrometeorological methods for measuring evapotranspiration are based on the assumption that the water vapor flux is constant with respect to height within the first few meters above the ground, and consequently are not applicable where an area is not extensively homogeneous. An increasing emphasis on energy and water flux studies in heterogeneous terrain (e.g. urban and hilly environments) has created a need to develop alternative approaches to quantify the latent heat flux. Lysimetry is an established alternative that permits the direct measurement of evapotranspiration from the ground surface and thus can provide accurate point estimates of the latent heat flux in heterogeneous environments. To date, the continuously weighing lysimeters that have been developed and extensively tested are large (surface area generally greater than 2 m^2), stationary and expensive to construct and maintain. These instruments are also inappropriate for most geographic studies of energy and water budgets in heterogeneous environments because knowledge of the spatial variability of evapotranspiration and quantification of the horizontal transport of moisture and heat require multiple, simultaneous flux determinations. This research tests two continuously weighing, portable mini-lysimeters ($< 0.2\ m^2$) designed for practical application in heterogeneous environments. The performance of the lysimeters are compared with evaporative flux measurements obtained using eddy correlation instrumentation from an extensive homogeneous surface. The soil moisture status of the monolith and the stomatal resistance of the plants within the lysimeter are compared with simultaneous measurements from the surrounding grass field. The results show that the evaporative flux, soil moisture and stomatal resistance measurements from both lysimeters compare favorably with measurements that are representative of their surroundings.

INTRODUCTION

Methods for measuring the evaporative flux using micrometeorological techniques are well developed for extensive, horizontal surfaces with uniform

Correspondence to: C. Susan B. Grimmond, Department of Geography, Indiana University, Bloomington, IN 47405, USA.

surface cover and small roughness (e.g. Haugen, 1973; Brutsaert, 1982; Oke, 1987). Under these conditions, micrometeorological techniques are known to yield values for the moisture and heat exchanges that are consistent with the principles of Monin–Obukhov similarity theory (MOST), a scheme which relates the surface turbulent fluxes and corresponding profiles in one-dimensional, semi-empirical scaling functions (e.g. Arya, 1988; Stull, 1988; Sorbjan, 1989). The turbulent fluxes are generally measured in the lower atmosphere either directly via eddy correlation or indirectly using profile methods such as the aerodynamic or Bowen ratio–energy balance approaches (see Oke, 1987 for an overview). The latter two methods depend upon the assumption that the diffusivities for momentum, heat and moisture are similar; an assumption that has proven to be of restricted validity. Operationalization of the micrometeorological approaches requires that tower-observations of evapotranspiration be conducted in the 'constant flux layer' within the lowest few meters of the atmosphere. Two conditions must be met in order to obtain accurate measurements of evapotranspiration using these one-dimensional concentration or diffusivity micrometeorological approaches (Oke et al., 1989). First, the instrument height must be large relative to the height and horizontal spacing of the surface elements so that the contribution of the elements is effectively combined into an integrated signal. Second, there must be a large homogeneous fetch in the upwind direction to achieve horizontal homogeneity of humidity and temperature, and thus a 'constant flux layer' over the measurement site. A number of studies have shown that the turbulent fluxes within this constant flux layer can vary less than 10% with height (see Panofsky, 1973) and thus flux measurements obtained within this layer are often representative of the energy and moisture exchanges between the Earth's surface and the atmosphere below the instrument level. The time required to obtain suitable averages of turbulent states depends on instrument height and atmospheric stability. The range of temporal scales contributing to the transport of entities is well defined and sampling guidelines are available (Wyngaard, 1973).

Where the scale of interest does not include extensive homogeneous surfaces, the constant flux layer generally does not have sufficient depth to accurately measure evapotranspiration with micrometeorological methods. An alternative approach is lysimetry. Lysimeters have been used in many different environments (see Aboukhaled, 1982 for a review) to obtain direct point measurements of evapotranspiration. Large lysimeters (i.e. surface area $> 2\,m^2$) are the standard instrument for measuring evapotranspiration (Slatyer and McIlroy, 1961). Recently many researchers have used 'mini-lysimeters' in field studies (Clark et al., 1984; Rosenthal et al., 1985; Wight et al., 1986; Dugas and Bland, 1989; Isard and Belding, 1989). Mini-lysimeters have the advantage that they: (1) permit the measurement of the evaporative flux from smaller areas; (2) create less disturbance to the environment of interest during installation; (3) are considerably cheaper to install than the large ones, and thus more than one mini-lysimeter can be deployed in an area to study the spatial variability of evapotranspiration.

The number of potential sources of error associated with using lysimeters to measure evapotranspiration are substantial. There are errors associated with the mechanics and electronics of the lysimeter. Water loss from the plant population in a lysimeter may not be representative of evapotranspiration from surrounding vegetation. The area of exposed plant canopy may exceed the lysimeter surface area. The non-vegetated edge between the soil–plant monolith within the lysimeter and the surrounding area increases turbulence in the layer of air immediately above the lysimeter. Finally, the walls of the lysimeter may impact the thermal regime of the soil and vegetation within the lysimeter. In general, the effect of each of these sources of error on the accuracy of evapotranspiration measurements is inversely related to the surface area of the lysimeter (Dugas and Bland, 1989).

Latent heat flux measurements from most mini-lysimeters have not been adequately compared with concurrent flux measurements using micrometeorolgical techniques in appropriate field situations (e.g. Oke, 1979; Suckling, 1980; Isard and Belding, 1989). In a recent study, Dugas and Bland (1989) compared measurements from three lysimeters with surface areas of 0.18, 0.75 and 3.0 m^2. Water loss was periodically monitored by manually connecting the lysimeters to an electronic load beam. The accuracy and resolution of the measurements of evapotranspiration from the small lysimeters were much less than would have been achieved if a portion of the mass of the lysimeters was either counterbalanced with weights or electronically offset before the signal was sampled by the data logger. The temporal resolution of their evapotranspiration measurements was 5–29 days and thus there is a further need to evaluate the accuracy and repeatability of mini-lysimeter measurements at temporal scales ranging from hours to days.

The objective of this paper is to present the results of an evaluation of two continuously weighing mini-lysimeters ($< 0.2\,m^2$ surface area) with hourly resolution of the flux determinations.

METHODS

Lysimeter design

The design criteria for the mini-lysimeters developed in this project are that they be: (1) able to continuously monitor evapotranspiration at the resolution of an hour; (2) easily and rapidly deployed; (3) re-deployable (i.e. portable); (4) economical to construct and install. To meet these requirements as well as those of lysimeters in general (see Slatyer and McIlroy, 1961; Aboukhaled, 1982), a number of constraints must be optimized.

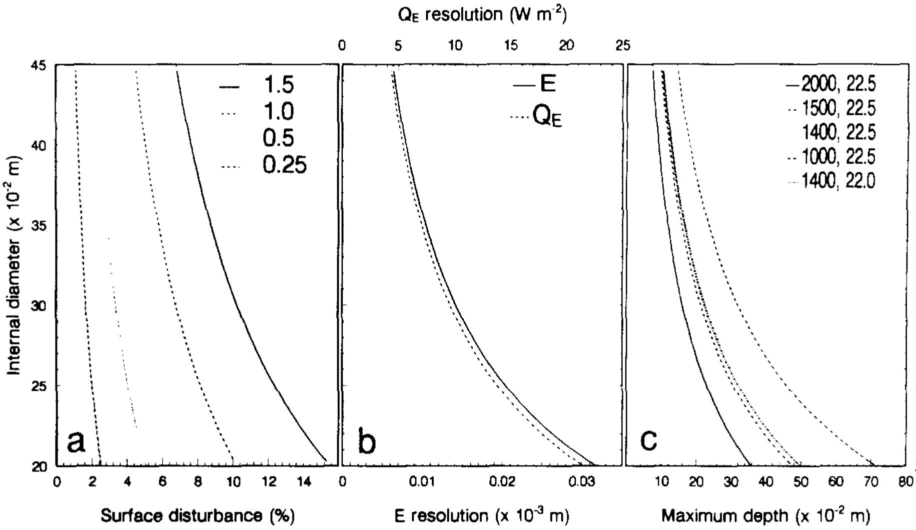

Fig. 1. Relations for optimizing mini-lysimeter design with respect to internal diameter ($2r_i$). (a) Surface disturbance as defined by eqn. (1). The total distance between the outside edge of the outer container and the inside edge of the inside container ($r_0 - r_i$) are plotted against $2r_i$ for values of ($r_0 - r_i$) ranging between 0.25×10^{-2} to 1.5×10^{-2} m. (b) Resolution of the mini-lysimeters determined as a mass and a flux (approximately 20°C). (c) Maximum depth of the monolith with varying ρ_b(kg m^{-3}) and W_{max}(kg).

As with all lysimeters, installation should cause minimal disturbance to the environment and the soil structure inside the lysimeter must resemble closely that of the surrounding area. Site disturbance is minimized in mini-lysimeter installation by not utilizing heavy earth moving equipment, which has the added benefit of reducing installation cost. The monolith must be kept intact to ensure that it has the same hydrological characteristics as its surroundings. When site and monolith disturbances are minimal, mini-lysimeters can be used immediately following installation. In contrast, the time interval between installation and collection of high quality flux data with large lysimeters can be as long as 12 months (Campbell, 1989).

To minimize surface disturbance during operation owing to the lysimeter hardware, circular containers with minimum wall thickness for holding the soil monolith (inner container) and lining the walls of the pit (outer container) are desired. The surface disturbance, from the amount of non-vegetated surface owing to the containers, increases with increasing width of the disturbed surface and decreasing diameter of the monolith surface (Fig. 1(a)). This follows from the ratio of these two surfaces

$$\text{Surface disturbance (\%)} = \left[\frac{(r_0^2\pi) - (r_i^2\pi)}{(r_i^2\pi)}\right] \times 100 \tag{1}$$

where r_o and r_i are outside and inside diameters of the outer and inner containers, respectively. Figure 1(a) shows how surface disturbance of airflow near the lysimeter and to the thermal regime of the soil and vegetation within the lysimeter could be minimized. However, the walls of the lysimeter container must be sufficiently strong (i.e. thick) to support the monolith and ensure that the walls do not deform. In addition, there must be no contact between the inner and outer containers.

Automatic monitoring of the mass of the lysimeter monolith is achieved via a straingauge load cell connected to a data logger. As the environment in which it is deployed is often damp, the load cell must survive long term 'wash down' situations. A logistical constraint associated with the use of a load cell is that they are manufactured at pre-determined capacities; thus, the choice of load cell capacity has to be optimized with the other constraints. Obviously, the monolith plus container has to weigh less than the capacity so that the receipt of water does not overload the load cell. The resolution of a lysimeter for mass exchange (E) is a function of surface area (or diameter for a cylindrical lysimeter) for a given signal measurement resolution. Thus with an increase in lysimeter diameter the resolution of measurement improves (Fig. 1(b)). In lysimeter design there is a trade-off between maximizing the surface area in order to maintain or improve the resolution, and maximizing the depth to ensure adequate rooting depth for the plants, while still being able to lift an intact soil monolith with minimal disturbance to the surroundings. The dimensional constraints for the lysimeter follow from the relation between the monolith radius (r_i), maximum depth (d_{max}), maximum weight (W_{max}) or load cell capacity, and the bulk density (ρ_b) of the material

$$d_{max} = \frac{W_{max}}{r_i^2 \pi \rho_b} \tag{2}$$

because the weight of the monolith is the product of its bulk density and volume (the relation for which brings eqn. (2) back to its basic form), as the diameter of the lysimeter increases, the maximum depth for a given W_{max} and ρ_b decreases (Fig. 1(c)).

The specifications of the two lysimeters (LY1 and LY2) used in this study are given in Table 1 and a schematic is presented in Fig. 2. The load cell (Interface, Scottsdale, AZ, single point I load cell model SP-I 50 lb–22.7 kg) signals were monitored by a Campbell Scientific (CSI) 21X Micrologger (Logan, UT). The mini-lysimeters in this study are designed for use in areas where horizontal runoff is negligible and thus the primary drainage component from the lysimeter is vertical. For this application the bottoms of the mini-lysimeters were sealed forcing drainage to zero. Changes in mass were monitored at 60 s intervals and averaged for 5 min periods. Evapotranspiration was determined on an hourly basis from the differences of load cell weight at the beginning of and end of each period. The hourly latent heat flux from

TABLE 1

Specifications of the mini-lysimeters

	Lysimeter 1 (LY1)	Lysimeter 2 (LY2)
Weighing mechanism	(Interface Inc single point I load cell model SP-I 50)	
Internal diameter (m)	0.2795	0.2744
Surface area (m^2)	0.06136	0.05914
Depth (m)	0.265	0.198
E resolution ($\times 10^{-3}$m)	0.0163	0.0169
Q_E resolution approximately 20°C (W m^{-2})	11.1	11.5

the lysimeters (Q_{El}, $W m^{-2}$) was calculated as

$$Q_{El} = [P + \Delta W(\rho A)^{-1}]L_v \quad (3)$$

where P is the precipitation (m h^{-1}), A is the surface area (m^2), ρ is the density of water (kg m^{-3}), L_v is latent heat of vaporization (J kg^{-1}) and ΔW is change

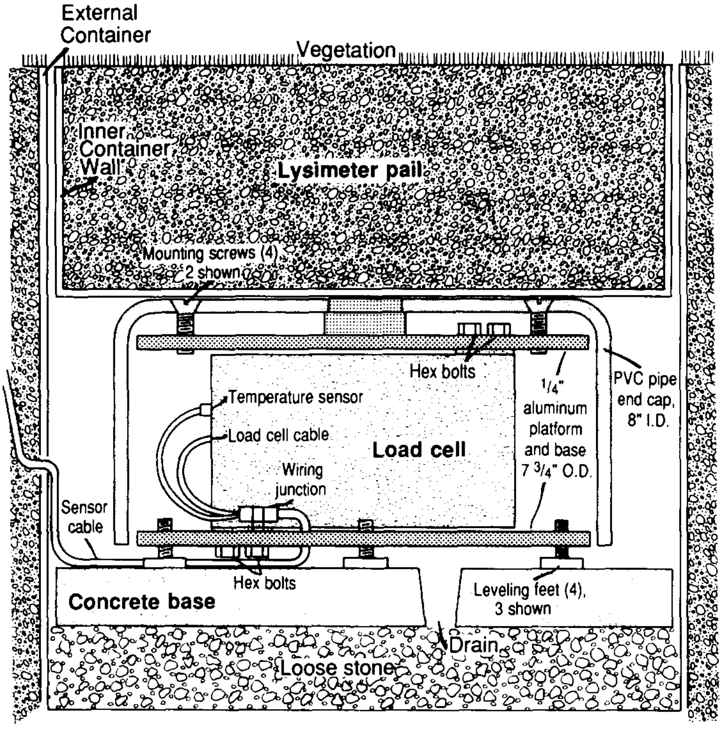

Fig. 2. Lysimeter design (modified from Isard and Belding, 1989).

in weight ($kg\,h^{-1}$) given as

$$\Delta W = \frac{LCS_t - LCS_{t+1}}{CF} \quad (4)$$

where LCS is the load cell signal (mV) and CF is the calibration factor ($mV\,kg^{-1}$). CF is determined by frequent application of known weights on the monolith and recording the signal response. This should be done at a time of day when evapotranspiration and wind speeds are negligible. The energy flux in eqn. (3) can be converted to a depth of water by omitting L_v.

The probable absolute measurement error for the lysimeters attached to a CSI 21X using the full bridge with excitation compensation instruction (Instruction 9), following the approach of Cook and Rabinowicz (1963), is 28 and 29 $W\,m^{-2}$, at 20°C, for LY1 and LY2 respectively.

Measurement program

Two lysimeters of slightly different dimensions were used to assess both the accuracy and repeatability of the design. The performance of the two lysimeters was evaluated in terms of the evaporative flux, soil moisture status, and vegetation stomatal resistance. Measurements were conducted 17 July–4 August 1991 (year/day: 91/198 to 91/216) over an extensive horizontal field in Bloomington, Indiana. July was slightly warmer and sunnier than normal, with approximately half the normal precipitation. This precipitation occurred in the first part of the month before measurements began. August was also warmer than normal, but less sunny with about normal monthly precipitation, which occurred in the middle of the month. Because no appreciable precipitation fell during the study period, restriction of drainage from the lysimeter bottom was unlikely to be an important source of measurement error. The soil at the site is a loamy udorthent (United States Department of Agriculture (USDA) Soil Conservation, 1981). The site is sufficiently homogeneous in the horizontal to meet the fetch requirements for the micrometeorological eddy correlation techniques. The vegetation in the field is a mixture of short grasses that were allowed to grow without mowing throughout the study period. Because of the drought conditions, the height of the grasses only increased from approximately 0.1–0.2 to 0.2–0.3 m during the study period.

The eddy correlation approach was used to evaluate the evaporative flux independent of the lysimeters. The required vapor flux and vertical wind velocity were measured with a CSI Krypton Hygrometer KH20 and a CSI Sonic Anemometer and fine wire thermocouple system CA27, respectively. Measurements from the two instruments were recorded on a CSI 21X Micrologger which has the capability to measure fast response signals, calculate the instantaneous departures of the vertical wind velocity (w') and vapor flux (q') from their respective means, and perform the covariance calculations between the fluxes to allow the determination of latent heat flux from

$$Q_E = L_v \overline{w'q'} \quad (5)$$

Fifteen minute flux determinations were used to compute hourly fluxes. Corrections were made for variations of oxygen absorption by the sensor and air density (Webb et al., 1980; Tanner and Greene, 1989).

To compare the soil moisture status within the lysimeters with that of the surrounding areas, it is necessary to employ a non-destructive sampling method that does not disturb the monolith within the lysimeter. Time domain reflectometry (TDR) was used to assess soil moisture (Topp et al., 1980; Ledieu et al., 1986). Vertical rods (0.15 m) were installed in each lysimeter and at six locations in the surrounding field which were monitored daily with a Soil Moisture Equipment Corporation (Santa Barbara, CA) Trase 6000 XI system.

Measurements of stomatal resistance were used to compare plant water status inside and outside the lysimeters. Daily measurements were taken at the same locations as the soil moisture measurements with a Delta T Devices (Burwell, Cambridge, UK) AP4 porometer. A minimum of two replicates were made at each site. Only grasses abundant within the lysimeter (and thus the surrounding field) were selected for porometry.

EVALUATION

Evapotranspiration measurements by the two lysimeters (LY1 and LY2) and eddy correlation (KH) approach are compared and evaluated using statistical (Table 2) and graphical techniques (Fig. 3). The flux estimates from the three systems were similar and decreased throughout the precipitation-free study period. The root mean square error (RMSE) for comparisons of LY1 and LY2 to KH were 49.3 W m^{-2} and 38.1 W m^{-2}, respectively. The unsystematic RMSE was the major component of this error in all cases. The measurements from the two lysimeters fall on either side of the eddy correlation results. As noted above, the probable absolute measurement error for each lysimeter attached to a CSI 21X data logger is 28–29 W m^{-2}. The equivalent error for the KH is unknown. The difference in the means of LY1 and LY2 is within this probable absolute measurement error. The MBE for comparisons of LY1 and LY2 to KH were +7.2 W m^{-2} and −3.0 W m^{-2}, respectively. LY1 averaged slightly greater Q_E than did LY2, which was expected as LY1 was 0.067 m deeper than LY2 (Table 1). In general the statistical comparisons (Table 2) indicate that LY2 performed in a manner more similar to the eddy correlation approach than did LY1. This is counter-intuitive as the deeper lysimeter (LY1) would a priori be expected to perform closest to KH if the KH is taken as closest to 'true'. If, however, the KH underestimates turbulent fluxes, as has been suggested by Tanner et al. (1985)

TABLE 2

Statistical comparison of evaporative flux determined from the Lysimeters (LY1 and LY2) and Krypton hygrometer (KH)
(a) For hours when all three systems were operating

n = 154	KH	LY1	LY2
Mean (W m^{-2})	71.1	78.3	68.1
Standard Deviation (SD) (W m^{-2})	67.7	93.9	78.9
Maximum (Max) (W m^{-2})	259.4	306.9	273.2
Coefficient of determination (r^2)		0.75	0.77
Intercept linear regression (a) (W m^{-2})		−7.3	−4.5
Slope of linear regression (b)		1.20	1.02
Mean Bias Error (MBE) (W m^{-2})		7.2	−3.0
Root Mean Square Error (RMSE) (W m^{-2})		49.3	38.1
RMSE — systematic ($RMSE_{SY}$) (W m^{-2})		15.5	3.3
RMSE — unsystematic ($RMSE_{USY}$) (W m^{-2})		46.8	37.9
Mean Absolute Error (MAE) (W m^{-2})		39.8	27.4
Willmott's (1981) index of agreement (d)		0.90	0.93
Nash and Sutcliffe's (1970) goodness of fit (N&S)		0.47	0.68

(b) For hours when at least two systems were operating

	LY1 vs. KH		LY2 vs. KH		LY1 vs. LY2	
n (h)	188		231		320	
	LY1	KH	LY2	KH	LY2	LY1
Mean (W m^{-2})	106.5	84.8	60.7	65.9	43.3	44.6
SD (W m^{-2})	112.6	75.3	72.5	54.6	84.5	98.4
Max (W m^{-2})	374.0	263.6	273.2	259.4	375.8	459.8
r^2	0.79		0.77		0.89	
a (W m^{-2})	−6.35		−4.37		7.18	
b	1.33		0.98		0.81	
MBE (W m^{-2})	21.7		−5.2		−1.3	
RMSE (W m^{-2})	61.1		34.8		33.4	
$RMSE_{SY}$ (W m^{-2})	33.1		5.3		18.6	
$RMSE_{USY}$ (W m^{-2})	51.3		34.4		27.7	
MAE (W m^{-2})	48.9		27.3		25.1	
d	0.89		0.93		0.96	
N&S	0.34		0.71		0.88	

based on energy balance closure, the performance of the deeper LY1 may in fact be closest to the 'true' latent heat flux.

The time series (Fig. 3(b)) suggests that Q_E from the lysimeters was greater than from KH in the earlier part of the measurement period, but as the vegetation within the area became more stressed, owing to a lack of rainfall, the Q_E measured by the lysimeters became less than that from the KH. Dewfall, which was observed at the site most mornings, was indicated by the lysimeters, however, the KH rarely indicated its occurrence (Fig. 3(b)).

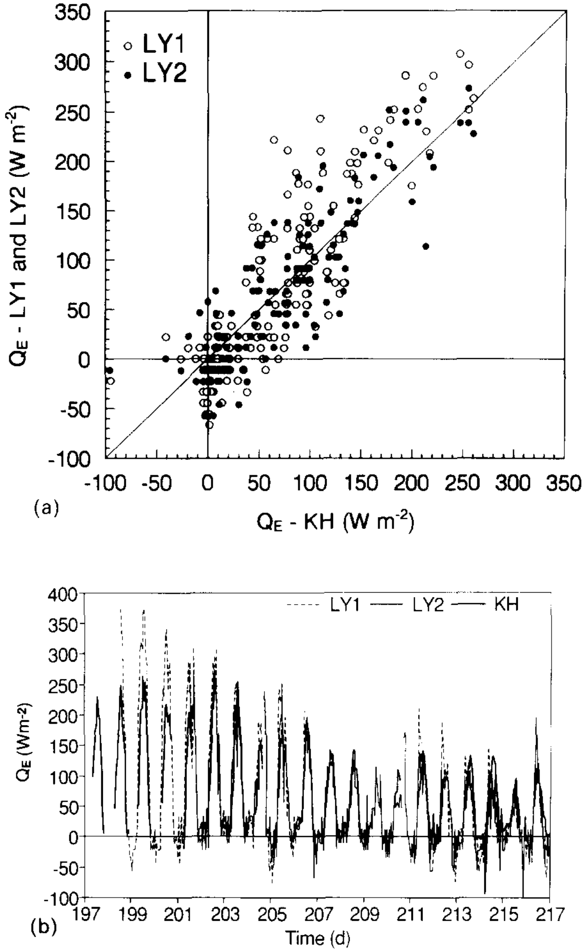

Fig. 3. Hourly evaporative flux determined by eddy correlation (KH) and lysimetry (LY1 and LY2). (a) Scatter plot for hours when all three systems were operational. (b) Time series for the observation period.

TDR measurements revealed a steady decline in soil moisture at all sites during this precipitation-free period (Fig. 4). The trend of soil moisture in both lysimeters and in the surrounding field were similar throughout the study period. During the first half of the period, desiccation within the lysimeters was close to the mean of the measurements from the surrounding field. In contrast, during the latter half of the period when evapotranspiration was very small, soil moisture within the lysimeters was similar to the lowest soil moisture measurements from the field. In the latter part of the period the errors in measurement are probably of the same magnitude or larger than the actual soil moisture measurements. Errors in TDR measurements are the

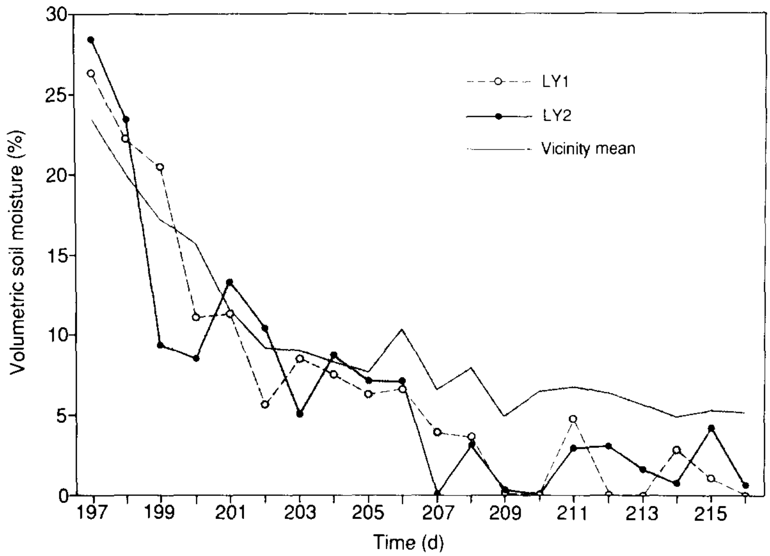

Fig. 4. Mean volumetric soil moisture for top 0.15 m of soil within the lysimeters (LY1 and LY2) and within their vicinity. The shaded area indicates the range of soil moisture in the vicinity.

probable explanation of the apparent increase in soil moisture during this rain-free period.

The variability in stomatal resistance of vegetation throughout the precipitation-free period (Fig. 5) was large. Stomatal resistance increased slightly toward the end of the period. Measurements of stomatal resistance of the plants within the lysimeters were similar to corresponding measurements from the surrounding vegetation. Observations of stomatal resistance were discontinued after 91/211 owing to the highly stressed nature of the vegetation in the lysimeters.

DISCUSSION AND CONCLUSIONS

Measurements of the evaporative flux, soil moisture and stomatal resistance from both mini-lysimeters were similar to corresponding measurements from the surrounding field. The lysimeters were tested during an extensive precipitation-free period when soil moisture at the study site was similar to conditions during the severe drought experienced throughout the Midwest during July and August 1988. Even at the end of the 3 week period, the RMSE for comparisons between LY1 and LY2 with KH are 45.0 and 43.0 W m^{-2} and the MBE between LY1 and LY2 is -3.4 W m^{-2}. Differences among the three systems were similar to those reported for other instrument comparisons (see for example Halliwell and Rouse, 1989).

We conclude that the mini-lysimeters developed and tested in this study

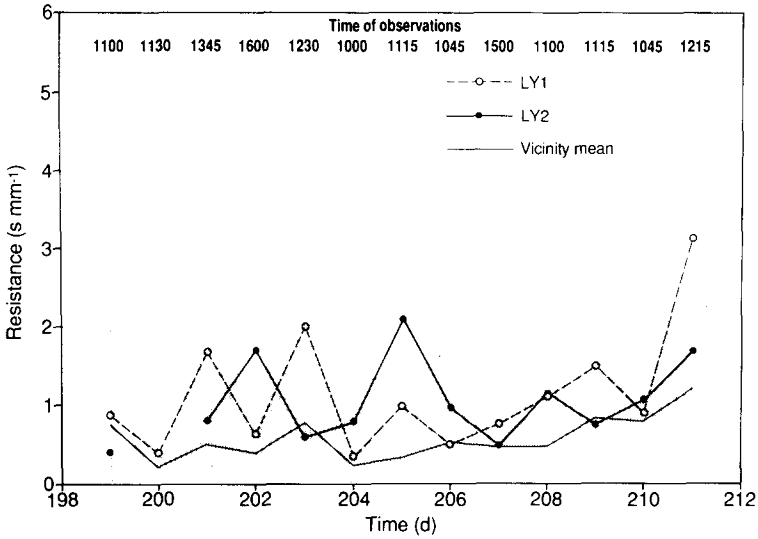

Fig. 5. Mean stomatal resistance within the lysimeters (LY1 and LY2) and within their vicinity. The shaded area indicates the range of stomatal resistance in the vicinity. The time of the observations, to the closest 15 min period, is indicated at the top of the graph for each day.

provide relatively accurate and reliable measurements of latent heat flux. However, it should be noted that the mini-lysimeter flux measurements have not been evaluated over long time periods (i.e. months and years) and thus these results are only strictly applicable for short-term (days to weeks) studies. One limitation of these systems is that the vegetation must have a rooting depth less than the depth of the mini-lysimeter container. Assuming that a data logging device is available, the only major cost associated with the lysimeter is the load cell (approximately $300), bringing the total cost of the mini-lysimeter to less than $600 excluding labor.

Recent emphasis on understanding fluxes of heat and water vapor in heterogeneous environments (e.g. urban, alpine, wetland and land reclamation sites) has necessitated the development of portable and inexpensive instruments that can be deployed efficiently to estimate spatial and temporal variations in these important fluxes. Often these areas are characterized by surface cover that is patchy at the micro-scale but can be treated as a homogeneous unit when the surfaces are integrated to the local-scale to meso-scale. Generally, the heterogeneity in these environments causes micro-scale advection to be a significant term in both the water and energy balances. For this reason, measurements at multiple sites are needed to quantify the latent heat flux and micrometeorological techniques are often inapplicable for measuring the energy fluxes. The mini-lysimeters developed and evaluated in this study provide a portable and economical instrument for continuous automatic monitoring of evapotranspiration at the resolution of an hour.

ACKNOWLEDGMENTS

Special thanks are due to Dr C.J. Souch (Indiana University, IN) and Dr H.A. Cleugh (Macquarie University, Australia) for input to all aspects of this study; M. Demanes, D. Dishman, A. Johnson and M. Mattix for help in the field. Dr T.R. Oke (University of British Columbia) provided the initial funding for development of an original prototype of the mini-lysimeters. This research was funded by US National Science Foundation grants SES-8921919 and SES-9144227.

REFERENCES

Aboukhaled, A., 1982. Lysimeters. FAO Irrigation and Drainage Paper, 39.

Arya, S.P.S., 1988. Introduction to Micrometeorology. Academic Press, San Diego, CA, 307 pp.

Brutsaert, W., 1982. Evaporation into the Atmosphere. D. Reidel, Boston, MA, 299 pp.

Campbell, D.I., 1989. Energy balance and transpiration from tussock grassland in New Zealand. Boundary-Layer Meteorol., 46: 133–152.

Clark, G.A., Reddell, D.L., Adams, R.F. and McBurnie, J.C., 1984. Evaluation of mini-lysimeters for deficit irrigation studies. ASAE Technical Paper, 84-2621.

Cook, N.H. and Rabinowicz, E., 1963. Physical measurement and analysis. Addison-Wesley, Reading, MA, 312 pp.

Dugas, W.A. and Bland, W.L., 1989. The accuracy of evaporation measurements from small lysimeters. Agric. For. Meteorol., 46: 119–129.

Halliwell, D.H. and Rouse, W.R., 1989. A comparison of sensible and latent heat flux calculations using the Bowen ratio and aerodynamic methods. J. Atmos. Oceanic Technol., 6: 563–574.

Haugen, D.A., 1973. Workshop on Micrometeorology. Am. Meteorol. Soc., Boston, MA, 392 pp.

Isard, S.A. and Belding, M.J., 1989. Evapotranspiration from the alpine tundra of Colorado, USA Arctic Alpine Res., 21: 71–82.

Ledieu, J., de Ridder, P., de Clerck P. and Dautrebande, S., 1986. A method of measuring soil moisture by time domain reflectometry. J. Hydrol., 88: 319–328.

Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part I — A discussion of principles. J. Hydrol., 10: 282–290.

Oke, T.R., 1979. Advectively-assisted evapotranspiration from irrigated urban vegetation. Boundary-Layer Meteorol., 16: 167–174.

Oke, T.R., 1987. Boundary Layer Climates, 2nd Edn. Methuen and Company, London, 435 pp.

Oke, T.R., Cleugh, H.A., Grimmond, S., Schmid, H.P. and Roth, M., 1989. Evaluation of spatially averaged fluxes of heat, mass and momentum in the urban boundary layer. Weath. Clim., 9: 14–21.

Panofsky, H.A., 1973. Tower micrometeorology. In: D.H. Haugen (Ed), Workshop on Micrometeorology. Am. Meteorol. Soc. Boston, MA, pp. 151–176.

Rosenthal, W.R., Arkin, G.F. and Shouse, P.J., 1985. Water deficit effects on sorghum transpiration. National conference on advances in evapotranspiration, ASAE, St Joseph, MI, pp. 159–169.

Slatyer, R.O. and McIlroy, I.C., 1961. Practical Microclimatology. CSIRO, Melbourne, 310 pp.

Sorbjan, Z., 1989. Structure of the atmospheric boundary layer. Prentice Hall, Englewood Cliffs, 317 pp.

Stull, R.B., 1988. An introduction to boundary layer meteorology. Kluwer Acacemic Publishers, Boston, MA, 666 pp.

Suckling, P.W., 1980. The energy balance microclimate of a suburban lawn. J. Appl. Meteorol., 19: 606–608.

Tanner, B.D. and Greene, J.P., 1989. Measurement of sensible and water vapor fluxes using eddy correlation methods. Final Report for US Army Dugway Proving Ground, Dugway UT., Task Assignment M-6 of Contract DAAD09-87-D-0038 with H.E. Cramer Company, Salt Lake City, UT.

Tanner, B.D., Tanner, M.S., Dugas, W.A., Campbell, E.C. and Bland, B.L., 1985. Evaluation of an operational eddy correlation system for evapotranspiration measurements. National conference on advances in evapotranspiration, ASAE, St Joseph, MI, pp. 87–99.

Topp, G.C., Davis, J.L. and Annan, A.P., 1980. Electromagnetic determination of soil water content: measurement in coaxial transmission lines. Water Resour. Res., 16: 574–582.

United States Department of Agriculture Soil Conservation Service, 1981. Soil Survey of Monroe County, IN, US Department of Agriculture Soil Conservation Service.

Webb, E.K., Pearman, G.I. and Leuning, R., 1980. Correction of flux measurements for flux density effects owing to heat and water vapour transfer. Q.J.R. Meteorol. Soc., 106: 85–100.

Wight, J.R., Hanson, C.L. and Cooley, K.R., 1986. Modelling evapotranspiration from sagebush-grass rangeland. J. Range manage., 39: 81–85.

Willmott, C.J., 1981. On the validation of models. Physical Geog., 2: 184–194.

Wyngaard, J.C., 1973. On surface turbulence. In: D.A. Haugen (Ed), Workshop on Micrometeorology. Am. Meteorol. Soc., Boston, MA, pp. 101–149.