Monitoring Free-Water Evaporation at Automated Weather Stations

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28 November 1994 and 12 April 1995

ABSTRACT

The automation of weather stations necessitates an alternative approach to the traditional manual measure of free-water evaporation made using a class A pan. This study compared commercially available water-level sensing transducers mounted on class A pans to manual measurements using a class A pan. Measurements of free-water evaporation with two automated transducers over a 24-h period resulted in mean differences of 0.23 and 0.98 mm. Hourly measurements for free-water evaporation allowed examination of the correlation between principal weather elements and evaporation. Evaporation from the pan was highly correlated with wind speed at night ($r = 0.86$) and with air temperature during the day ($r = 0.75$). In addition, it was found that during the summer some 33% of the daily free-water evaporation occurred at night. For a 24-h period, accumulated free-water evaporation was highly correlated with air temperature ($r = 0.85$), net radiation ($r = 0.81$), incoming solar radiation ($r = 0.80$), and wind speed ($r = 0.69$).

1. Introduction

Advances in data-logging technology have allowed the automation of weather stations, drastically reducing the manpower required, and hence the cost to monitor meteorological conditions. However, in the automation process measurements of evaporation, traditionally made using a class A pan, are often abandoned because sensing devices have not been readily available. The design of sensors to monitor free-water evaporation from pans are numerous (Phene and Campbell 1975; Bloemen 1978; Ambrus et al. 1981; van Haveren 1982; Chow 1994) and is discussed by Chow (1994). Despite the many approaches developed, only recently have there been commercially produced sensors available to permit a network application.

The measure of free-water evaporation from a pan, E_p, continues to serve a need in hydrology, forestry, and agriculture. In the past E_p has been useful as an indicator of lake and reservoir evaporation (Kohler and Parmele 1967; Hanson 1989). A common use of E_p is in irrigation scheduling (Doorenbos and Pruitt 1977), which requires simple and inexpensive equipment to gauge evaporation. The measurement is converted using locally derived crop coefficients to a measure of water use by a crop. However, using E_p to determine potential evapotranspiration (PET) and/or actual evapotranspiration (AET) (de Jong and Tugwood 1987; Yin 1988), warrants some caution. For example, Chiew and McMahon (1992) concluded that daily E_p and PET were poorly correlated. Earlier evidence also indicated poor correlations between E_p and AET (Staple and Lehane 1954; Army and Ostle 1956). The relationship of E_p and PET to AET is more tenuous as the surface dries, as dry soil conditions not only reduce evaporation from the soil surface (Bond and Willis 1970) but also induce plant water stress, reducing transpiration. Furthermore, high air temperatures, while increasing E_p, can bring about stomatal closure and a reduction in AET.

The primary objective of this study is to examine two commercially available sensors for measuring free-water evaporation from class A pans at automated weather stations. Since these sensors measure hourly evaporation rates, differences between daytime and nighttime evaporation are examined in relation to diurnal meteorological variables.

2. Methods

In April 1992, two class A pans (1.2-m diameter by 0.25 m deep) were set on wooden platforms with the open edge 50 cm above the surrounding ground level. These pans were located 2 m apart within the weather station enclosure at the Agriculture and Agri-Food Canada Research Centre in Lethbridge, Alberta (49°42′N, 112°47′W, elevation 899 m). On one pan, a commercial water-level sensor (model MN-2B, BCP Electronics, Clovis, California)[1] was mounted on the outside edge. The sensor consisted of a small tank con-

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[1] Use of brand names and suppliers is not an endorsement of these products. Other commercially available instruments may be equally satisfactory.

taining a float attached to a leaf spring with a surface-mounted strain gauge. The water in the tank and class A pan were connected by a hose. A second commercial level sensor (model 3003, Sierra-Misco Inc., Berkeley, California), consisting of a tank, float, and chain assembly that turned a 1000Ω potentiometer was attached to a second pan. The tank was located on a level platform and connected to the pan using a metal pipe. The output signals from the transducers were recorded on a data logger (model CR21X, Campbell Scientific, Logan, Utah). Free-water evaporation was calculated as the difference between mean hourly water levels, accumulated for 24 h ending at 0800 MST to correspond to manual measurements of daily free-water evaporation.

During April and May 1992, the water levels in the two automated pans were reset manually at 0800 MST to a reference height (6.4 cm below the open edge). The amount of water added (or removed) was compared to measurements from the water-level transducers after 27 April when ice was no longer present. In June 1992, solenoids (controlled by the data logger) were used to automate the filling of the pans at 0800 MST only when the water level was below a reference height. While the solenoid was activated the water level was monitored every 5 s; the solenoid was closed when the water level reached the reference height. A measurement of the actual height of water was recorded after allowing water levels between the pan and sensor wells to stabilize for 15 min. The reference level was set to allow approximately 20 mm of evaporation and 10 mm of rainfall (lower and upper linear limit of MN-2B sensor). To prevent rain from raising the water level above the upper range of the sensors, an overflow L-shaped plastic pipe was installed in the wall of the pan with the inside opening positioned below the water level to eliminate water loss due to wave action. In this manner, evaporation could be monitored immediately after rain with a minimum of data lost.

Daily accumulated evaporation was compared with 0800 MST measurements made using a third, noninstrumented class A pan in the weather station enclosure. The duration of the experiment (1 April–31 October) corresponded to the season in which manual measurements of free-water evaporation are made at weather stations in Canada.

Significance of the mean difference between automated and manual measurement of E_p was examined using a paired Student's t-test (Snedecor and Cochran 1980). The significant mean differences were then examined using accuracy analysis (Allen and Raktoe 1981) that further partitions differences to bias, regression, and random errors. Bias error indicates the tendency to consistently overestimate or underestimate. A regression error exists if the slope of the paired values is different from 1 and a random error results from scatter between paired values.

3. Results

a. Accuracy of daily estimates using automated pans

The mean difference between mean daily class A pan evaporation using the strain gauge transducer and the manual measurement was 0.23 mm (Table 1), which was not significant ($P < 0.05$). Most of the difference (94%) was due to random error and not to bias or regression errors. Compared to the manual measurements, the potentiometer transducer was less accurate than the strain gauge transducer and the mean difference of 0.98 mm (Table 1) was significant ($P < 0.05$). Most of the difference was attributed to bias (47%) and random (50%) errors. During a calibration check of the sensors (Fig. 1), it was observed that a change in direction of the pan level during filling or removal of water resulted in hysteresis, which we speculate was due to a change in the shape of the water meniscus on the float. For the potentiometer transducer, an additional error may be due to inexact meshing the float-chain-potentiometer assembly.

b. Diurnal free-water evaporation using an automated pan

Recording of hourly values of E_p enables the underlying influence of the environment to be examined in more detail than is possible using daily totals. For example, 24-h evaporation totals were the same (9.9 mm) on 17 and 19 August 1992 (Table 2). The daytime global irradiance under clear sky conditions was similar (6.1 and 6.5 MJ), as was the mean wind speed at pan height (2.0 m s^{-1}). Mean daytime air temperature on 17 August was slightly higher (24.6° vs 23.0°C) and vapor pressure was a little less (1.19 vs 1.26 kPa) than on 19 August and as a result evaporation was slightly higher (6.9 vs 5.4 mm). On 19 August, wind speed at pan height increased sharply from 2.3 m s^{-1} at 1900

TABLE 1. Differences between manual and automated daily pan evaporation measurements.

Paired *t* test	Potentiometer	Strain gauge
n	31	17
x—manual	8.57	10.93
x—automated	9.55	10.70
Difference	0.98	0.23
R^2	0.95	0.93
t	5.24*	0.94 NS
Accuracy analysis		
Bias (%)	47	5
Regression (%)	3	1
Random (%)	50	94

Key: *n*, number of daily samples; *x*—manual, mean evaporation (mm) for all days measured by manually filling; *x*—automated, mean evaporation (mm) for all days measured with a transducer; R^2, coefficient of determination; *t*, Student's t-test; NS, not significant ($P > 0.05$); * significant ($P < 0.05$).

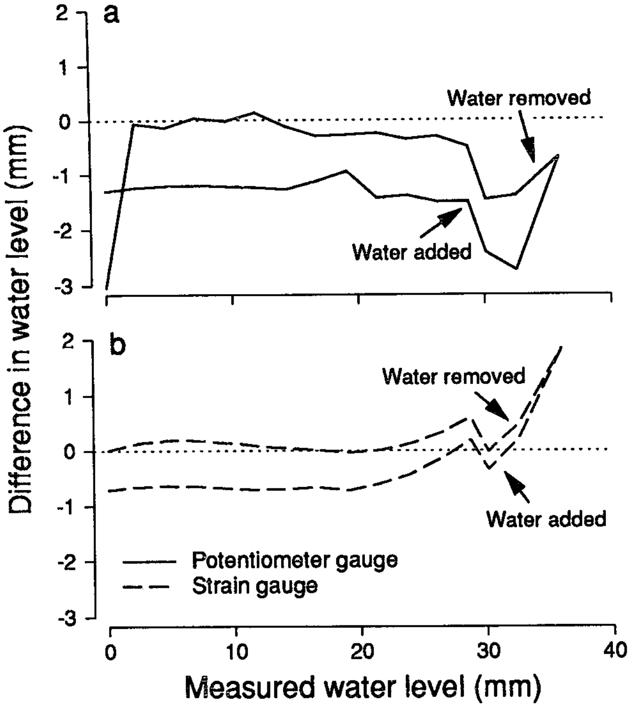

FIG. 1. Differences in water level measured manually and electronically during calibration check of (a) potentiometer and (b) strain gauge transducers showing hysteresis as water was removed and then added.

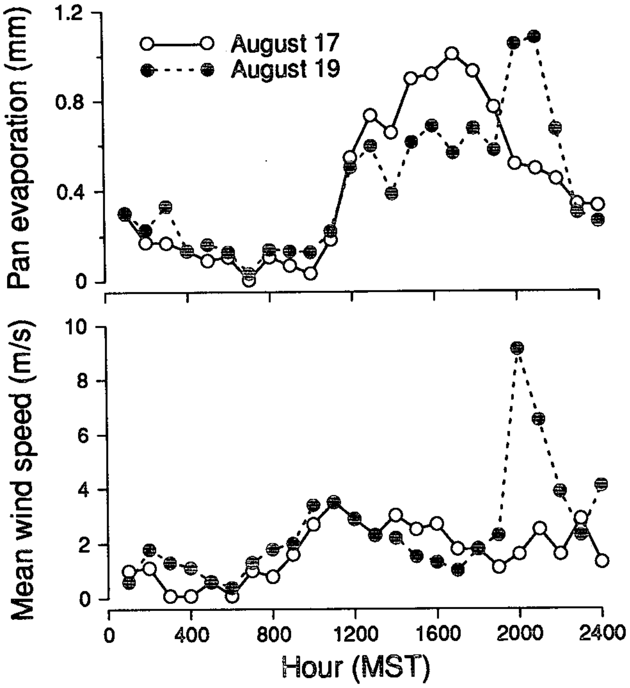

FIG. 2. Mean hourly pan evaporation and wind speed at pan height on 17 and 19 August 1992.

to 9.1 m s^{-1} at 2000 MST (Fig. 2). During this period of higher wind speed, pan evaporation nearly doubled.

Evaporation during the night on 17 and 19 August was 30% (3.0 mm) and 45% (4.5 mm) of the 24-h total evaporation. On average, for nine clear days in August (Table 2), the nighttime evaporation accounted for 33% of the 24-h total (2.7 vs 8.3 mm). Chapman and Kininmonth (1972) reported that 8%–36% of the 24-h daily evaporation occurred during the night in parts of Australia's Northern Territory during the dry season. The value increased to 50% in the wet season. Nighttime evapotranspiration, on the other hand is lower, about 1.7% (calm) and 14% (windy) of the 24-h evaporation for an irrigated alfalfa field in Utah (Malek 1992). The diurnal differences indicate the influence of stomatal closure in reducing water loss and the difficulty in using E_p when estimating evapotranspiration.

Correlations between the automated pan evaporation (using strain gauge sensor) and weather factors for the days shown in Table 2 are shown in Table 3. For 24-h E_p totals, the best correlation was with mean air temperature ($r = 0.85$), followed by net radiation and incoming solar radiation ($r = 0.81$ and 0.80, respectively). This result is expected given the dependency of daily air temperature and net radiation on incoming solar radiation. The relationship of 24-h E_p with wind speed ($r = 0.69$) was weaker than that with temperature and radiation. In contrast, E_p was highly correlated with wind speed at night ($r = 0.86$), while net radiation ($r = 0.57$), air temperature ($r = 0.49$), and vapor pressure ($r = 0.26$) were less important. During the daytime, E_p had the strongest relationship with air temperature ($r = 0.75$), while those with wind speed ($r = 0.34$) and net radiation ($r = 0.26$) were much weaker. Vapor pressure at screen height was poorly correlated with the 24-h and daytime E_p, although the relationship was negative, as anticipated.

TABLE 2. Daytime and nighttime pan evaporation and atmospheric conditions for nine clear-sky days in August 1992.

	Daytime					Nighttime			
Day	E_p	U_p	T_a	e_a	S↓	E_p	U_p	T_a	e_a
9	6.1	3.2	19.5	0.60	7.4	2.4	0.9	10.8	0.79
10	4.8	2.1	18.1	0.89	7.2	2.0	0.3	10.7	0.89
11	4.4	1.5	20.2	0.92	7.1	2.1	0.2	11.2	1.01
14	8.5	2.2	29.2	0.97	6.8	2.4	1.0	18.4	1.42
15	5.3	1.2	26.2	1.18	6.7	3.1	1.0	17.5	1.29
16	4.7	2.0	22.5	1.32	6.6	2.9	1.1	17.4	1.38
17	6.9	2.0	24.6	1.19	6.1	3.0	1.3	17.5	1.24
19	5.4	2.0	23.0	1.26	6.5	4.5	3.1	14.9	1.01
30	4.2	4.1	16.1	0.83	5.9	2.1	1.5	9.7	0.79
Mean	5.6	2.3	22.1	1.08	6.7	2.7	1.2	14.2	1.09
SD	1.4	0.9	4.1	0.24	0.5	0.8	0.8	3.6	0.25

Key: E_p, total pan evaporation (mm); U_p, mean wind speed (m s^{-1}) at pan height; T_a, mean air temperature (°C) at screen height; e_a, mean vapor pressure (kPa) at screen height; S↓, total incoming solar radiation (kJ).

TABLE 3. Correlation coefficients for daytime and nighttime pan evaporation and atmospheric conditions for nine clear-sky days in August 1992.

	Correlation coefficient				
	U_p	T_a	e_a	$S\downarrow$	R_n
E_p 24-h	0.69	0.85	−0.07	0.80	0.81
E_p nighttime	0.86	0.49	0.26	−0.39	0.57
E_p daytime	0.34	0.75	−0.02	0.04	0.26

Key: E_p, total pan evaporation (mm); U_p, mean wind speed (m s^{-1}) at pan height; T_a, mean air temperature (°C) at screen height; e_a, mean vapor pressure (kPa) at screen height; $S\downarrow$, total solar irradiation (kJ); R_n, net radiation (kJ).

Others (Baier and Robertson 1965; Hobbs and Krogman 1965) have found significant correlations between vapor pressure deficit and evaporation. The strong correlation in these previous studies may be related to the dependence of the vapor pressure deficit on maximum temperature, as reported by Baier and Robertson (1965).

The poor correlation of E_p and radiation during the daytime is attributed to the influence of stored energy in the class A pan over periods of less than a day. Since maximum water temperature, hence heat storage, occurs later in the day than peak incoming solar radiation, poor correlation is expected. Over a 24-h period, however, storage is less important and the integration of 24-h radiation determines, for the most part, the energy available for evaporation (Table 3).

4. Conclusions

Measurements of free-water evaporation by commercially available sensors, from the minimum data gathered in our study, indicate that these sensors are within 0.23 and 0.98 mm of manual measurements. The lower range of this difference is not statistically significant and is similar to the reporting unit of Environment Canada's manual observation of pan evaporation (0.2 mm).

Free-water evaporation was highly correlated with weather factors. During the day, air temperature was the key factor, and at night wind speed was most important. Over a 24-h period, incoming solar radiation, and hence net radiation and air temperature, along with wind speed, were highly correlated with free-water evaporation from the class A pan.

It is recommended that automation of the class A pan with water-level sensing transducers be implemented to measure pan evaporation at automated weather stations. Commercially available sensors not only permit a standardizing of sensors for weather station networks but also provide information on the diurnal behavior of free-water evaporation as a function of environmental driving forces.

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