Comparative Performance of Two Reversing Bowen Ratio Measurement Systems

J. H. McCaughey, D. W. Mullins and M. Publicover

Department of Geography, Queen's University, Kingston, Ontario, Canada K7L 3N6

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ABSTRACT

This paper reports on the results of a comparative experiment between two Bowen ratio measurement systems conducted at the Petawawa National Forestry Institute, Chalk River, Ontario, in 1985. Both systems interchange the positions of the psychrometers in the vertical. One, termed the pivot system, turns the psychrometers through 180° over a fixed separation distance, and inverts them in the process. It is also capable of orienting the psychrometers into the wind. The other, termed the elevator system, interchanges the psychrometers by moving them up and down two adjacent vertical tracks in a fixed orientation. The experiment lasted eight days, and the weather conditions varied from clear and dry to overcast. On the basis of hourly values of evapotranspiration, the agreement between the systems is within 10% for daytime values. When period totals are considered, this agreement improves to better than 5% for most days. There was no improvement shown by allowing the pivot system to orient into the wind. The elevator system is superior for two principal reasons. First, the separation distance between the psychrometers is easily varied to accommodate different sites. Second, during reversal there is no disturbance of the wet-bulb reservoirs which might lead to an oversupply of water to the sensors.

1. Introduction

It has now become common practice to use reversing temperature-difference measurement systems to measure the Bowen ratio in the field (e.g., McNeil and Shuttleworth, 1975; Munro, 1980). This is in response to the need to cancel the likely systematic errors associated with the measurement of either temperature or temperature difference at fixed measurement levels. The reversing system designs consist of two basic models: the pivot and the elevator. In the pivot model the reversal of the psychrometers is accomplished by the rotation of a vertical arm through 180°. Of necessity in this system the psychrometers at either end of the vertical arm are inverted during reversal which can cause a problem with oversupply of water to the wet-bulb sensor. Also, a potential difficulty exists as a result of an asymmetry in the errors associated with the temperature difference measurements which are height-dependent and therefore not cancelled completely by the interchange mechanism (Spittlehouse and Black, 1981). In contrast, the elevator system reverses by moving the psychrometers along either one or two vertical supports where at no time is the orientation of either psychrometer changed. McCaughey and Brintnell (1984) described the performance of a pivot system installed at Petawawa, Ontario in 1981 and 1982. This system, called the RTDMS (Reversing Temperature Difference Measurement System), recently has been changed into an elevator system with much more flexibility in terms of ease of measurement. In this paper we describe the features of the elevator RTDMS and report on the results of a week-long comparison experiment when both versions of the RTDMS were operated side-by-side on a clear-cut site at the Petawawa National Forestry Institute (PNFI), Chalk River, Ontario (45°58′N, 77°25′W).

In the RTDMS the Bowen ratio ($\beta = Q_h/Q_e$) is solved from

$$\beta = [(S/\gamma + 1)(\Delta\theta_w/\Delta\theta) - 1]^{-1}, \qquad (1)$$

where Q_e and Q_h are the latent and sensible heat fluxes respectively, S is the slope of the saturation vapor pressure vs temperature curve at the wet-bulb temperature (T_w), γ is the psychrometric constant, $\Delta\theta_w$ and $\Delta\theta$ are the potential wet- and dry-bulb temperature differences over height Δz, respectively. Angus and Watts (1984) noted that the Bowen ratio method is reliable and gives satisfactory results under moist conditions. However, under very dry surface conditions ($\beta > 10$) the method fails, mainly because of the very small values of ΔT_w and the difficulty of measuring them to an accuracy of ± 0.001°C which is required to preserve an accuracy of $\pm 10\%$ in β. Field measurement systems are not capable of such accurate temperature difference measurements.

Implicit in Eq. (1) is the assumption that the eddy diffusivities for sensible heat (K_h) and water vapor (K_w) are identical. This is not the case if the sensible heat flux is directed down towards the surface and the water vapor flux is upwards (Warhaft, 1976). Such conditions prevail when an advective inversion exists (Lang et al., 1983; Verma et al., 1978). Under these conditions, the simple Bowen ratio is not appropriate, but as yet there is no general way to account for the departure from similarity (Brost, 1979; Hicks and Everett, 1979).

The β is used in association with the energy balance of the surface to solve for Q_e and Q_h, as

$$Q_e = (Q^* - Q_g - Q_s)/(1+\beta), \quad (2)$$

$$Q_h = [\beta/(1+\beta)](Q^* - Q_g - Q_s), \quad (3)$$

where Q^* is net radiation, Q_g is the soil heat flux, and Q_s is the heat storage in the biomass and in the canopy air from the surface to the height of measurement of Q^* (positive when heat is transferred to storage). Aston (1985) found that the evapotranspiration from a young eucalypt forest measured by the Bowen ratio method gave satisfactory results which agreed with a weighing lysimeter. Here β was found from a reversing system, and different separation distances between the psychrometers of 3, 6 and 9 m gave equally satisfactory results. He noted the importance of knowing the value of the hourly biomass heat storage, not measured for the eucalypt forest, in the estimation of hourly evapotranspiration.

2. System design

The design of the pivot RTDMS is documented in McCaughey and Brintnell (1984). This system was constructed to orient itself into the wind using a large vane assembly in order to minimize any possible interference of the system itself with the temperature gradients being measured. We will comment in detail on the design modifications of this system which led to the elevator RTDMS. The elevator system was built for work over a variety of surface types with differing heights and surface roughnesses. Hence, it was important to have a system which was flexible enough for the operator to be able to set the separation distance (Δz) between the psychrometers. Also, for work over forests, where the vertical temperature gradients are small, a very large Δz is required. Beyond a Δz of around 3 m, the pivot system becomes an unattractive alternative because of the need for a fairly massive, and therefore heavy, center-point bearing assembly to withstand the high torque imposed on the system during reversal. The current elevator RTDMS has been operated successfully with separation distances as large as 8 m.

The basic design features of the elevator RTDMS are shown in Fig. 1. Each of the two psychrometers is attached to a separate vertical track by means of a cart assembly, and both are moved up and down by a 12 V reversing motor (Globe, type EM-15) located in a housing at the base of the tracks. The motor turns a 40 cm diameter drive wheel attached to the psychrometer carts with steel cable running around an idler wheel at the top of the tracks. The movement of the carts is stopped when either of them trips the magnetic switches positioned at the base of the tracks. One switch controls clockwise rotation while the other controls counterclockwise rotation of the motor. Each cart has a magnet attached to an arm which extends below it, and as the magnet parallels the switch, the switch opens, interrupts the power to the motor, and stops the movement of the psychrometers. The closer the switches are to the center-point of the RTDMS the smaller is the separation distance. There is essentially no disturbance of the psychrometers during the interchange except their slow movement along the tracks. They are not flipped over, as occurs in the pivot system, and more importantly, the wet-bulb reservoir does not invert, thereby preventing an oversupply of water to the sensor.

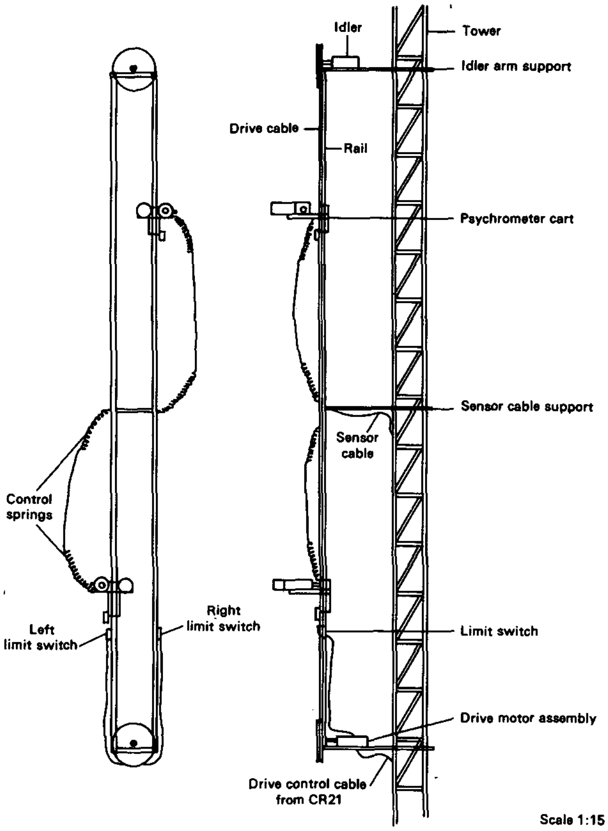

FIG. 1. Schematic of the elevator Reversing Temperature Difference Measurement System.

The timing of the elevator RTDMS is controlled by the field data system. To date, we have used Campbell Scientific systems: CR21, CR7 and 21X, with a simplified reversing circuit that incorporates a relay driver (model A21)—a marked improvement over earlier versions of the system. These had an independent timer (McCaughey, 1981) which would lose synchronization with the clock in the data system, thereby causing contamination of the data.

Wet- and dry-bulb temperature differences are measured with copper–constantan thermopiles, and the corresponding absolute temperatures are measured by a single thermocouple imbedded in the hot side of each thermopile. It is necessary to designate the "hot" (positive) and "cold" (negative) side of each thermopile in the RTDMS because, to preserve the accepted sign of a negative average temperature gradient under lapse conditions, the system must start in the hot-side-up position. Either 5- or 10-junction thermopiles are used depending upon the resolution of the recording system. The system must be capable of resolving down to a temperature difference of at least 0.01°C accurately. Each thermopile is calibrated separately over a temperature difference range of ±5°C at an ambient temperature of 20°C. The calibration facility consists of two constant temperature circulating baths (Neslab RTE-5), and a platinum resistance thermometer (PRT) is used as a standard (Rosemount sensor 104 MB and linear bridge 414L). One of the baths is used as a stable reference, and its temperature is measured at the start and end of the calibration run with the PRT. The other bath's temperature is varied to give an average of six calibration points above and below 20°C. The line of best fit to the twelve points is used as the calibration of the sensor. A typical calibration of one of the sensors, a 10-junction thermopile used in the Petawawa field experiment, is

$$\Delta T = -0.0187 + 0.00247 \cdot \Delta V$$

$$r^2 = 0.999, \quad \text{rmse} = 0.006°\text{C}, \qquad (4)$$

where ΔT is the temperature difference (°C), ΔV is the output (μV) of the sensor, r^2 is the coefficient of determination, and rmse is the root-mean-square error of the line (°C).

At Petawawa in 1985, both versions of the RTDMS had identical psychrometers (McCaughey and Brintnell, 1984) with aspiration rates of 5.4 m s^{-1}, measured in the laboratory.

3. Field experiment

Between 28 August and 4 September 1985 at PNFI, both versions of the RTDMS were set up side-by-side on a flat, clear-cut site covered primarily by 0.8 m-high bracken fern, which showed signs of senescence. Within 100 m of the experimental tower in the prevailing wind direction (NW), were 25 randomly spaced young spruce trees between 1 and 2 m in height. A complete description of the fetch characteristics of this site is given in McCaughey (1985), McCaughey and Brintnell (1984), and Mullins (1986). The bottom level of measurement was 1.0 m, and the separation distance between the psychrometers was 1.5 m.

The elevator system was oriented with the psychrometers pointing NW in the direction of maximum fetch. The pivot system was "free," i.e., allowed to rotate into the wind from 28 August until 1000 local time 1 September. It was then stabilized and also oriented NW.

Supporting data on soil moisture content, horizontal windspeed, wind direction and sky condition were monitored (Table 1). Windspeed and wind direction were measured at the level of the top psychrometer with a Gill 3-cup anemometer and microvane (models 12102 and 12302, respectively). Hourly windspeeds varied from 0.2 to 3.6 m s^{-1}, with daytime values of around 2 to 3 m s^{-1} and nighttime values of around 0.3 to 0.5 m s^{-1}. Soil moisture was determined gravimetrically from two soil samples taken at 0900 each day. Only one day, 31 August, was completely clear; the rest were a mixture of complete overcast (3 September) and cloudy or cloudy–bright (2 September).

Net radiation was measured with a Middleton net pyrradiometer (model CN-1) mounted at 5 m and continuously purged with dry nitrogen. The soil heat flux was measured with the combination method which involves measuring the flux at a depth of 5 to 10 cm and estimating the heat storage above the plates using the calorimetric method (Tanner, 1963). This approach minimizes errors associated with the heat flux plates interfering with heat and moisture flow in the soil (Kimball et al., 1976). The soil heat flux was measured with five Thornthwaite flux plates (model 610) connected in series and buried to a depth of 0.10 m. The thermal conductivity of these heat flux plates is 0.335 W m^{-1} °C^{-1}, and they were calibrated in a medium

TABLE 1. Summary of conditions during the comparison period, 28 August to 4 September. Daily mean values of soil moisture (X_w), windspeed (u), wind direction, air temperature (T), and vapor pressure deficit (VPD) are reported.

Date	X_w (% vol.)	u (m s^{-1})	Wind direction	T (°C)	VPD (kPa)	Sky condition
28	19.3	0.744*	NNW to NW*	9.5*	101.3*	Cloudy
29	16.0	0.593	Variable	9.6	93.8	Cloudy
30	20.1	1.206	Variable	11.9	127.6	Cloudy (am) Cloudy–bright (pm)
31	20.0	1.088	Variable	11.1	198.0	Clear
1	19.9	1.118	Variable	11.1	81.2	Haze
2	19.0	1.356	N to NW	13.7	105.6	Cloudy–bright
3	16.0	1.151	Variable	13.1	20.7	Overcast
4	14.5	1.670*	NNW to NW*	20.6*	122.2*	Overcast (am) Cloudy–bright (pm)

* Sample period averages: 1800 to 2400 local time 28 August and 0000 to 1600 4 September.

with the same thermal conductivity (W. Superior, personal communication). Two thermocouples at 0.01 and 0.075 m, positioned above one of the plates, measured the mean soil temperature which was used along with the soil's heat capacity to calculate the heat storage above the level of the plates. The soil's heat capacity was determined from an experimentally derived value of the heat capacity of the dry soil plus the daily value of soil moisture (De Vries, 1963).

Ideally, when using soil heat flux plates, their thermal conductivities should be the same as that of the surrounding soil. Depending on the ratio of transducer to medium conductivity, significant errors can result in the measured heat flux (Philip, 1961). In this experiment, the thermal conductivity of the soil was not measured. However, given that the soil moisture by volume varied only from 14% to 20% (Table 1), and the daily mean soil temperature fluctuated from 12° to 15°C, there should not have been a large change in the soil's thermal conductivity during the course of the experiment. Mogensen (1970) showed that the calibration factor of a flux plate changes as a linear function of the soil's thermal conductivity. The thermal conductivity of his plate was 0.37 $\mathrm{W\ m^{-1}\ {}^\circ C^{-1}}$ which is very close to the value for the plates used in this experiment. Assuming that the thermal conductivity of the Petawawa soil is double the value for the plate (0.67 $\mathrm{W\ m^{-1}\ {}^\circ C^{-1}}$), then the error in the measured soil heat flux, caused by differences in the thermal conductivities of the plate and the soil, would be a maximum of 20% (Mogensen, 1970).

The heat storage in the biomass was found from measurements of biomass temperature with a 5-junction parallel thermocouple plus the measured standing biomass (0.335 $\mathrm{kg\ m^{-2}}$).

The reversals of each RTDMS were timed for each half hour starting on the hour. The pivot system was controlled with a 12 V timer (McCaughey and Brintnell, 1984), whereas the elevator RTDMS was controlled with a CR21. The temperature differences from both systems were recorded on a CR5 data system as 5-minute averages. The absolute temperatures were recorded as hourly averages on a separate CR5. For the pivot system, the first five minutes after reversal were considered as an adjustment period and these data were dropped from the analysis. In the case of the elevator system, the 5-minute samples before and after reversal were dropped because the CR21 programming characteristics required that the system reverse one minute before the full hour and half-hour, i.e., at 29 and 59 minutes after the hour. This drawback is not present if either a CR7 or 21X is used as the timing device because they have more flexible programming capabilities. The hourly average temperature differences from the pivot system were found from the data recorded from 5 to 30 minutes and 35 to 60 minutes past the hour using the method first documented by Tanner (1960). In the case of the elevator system, the sample periods used were 5 to 25 minutes and 35 to 55 minutes past the hour.

It is felt that the elevator RTDMS has several advantages over the pivot system which can be summarized as follows:

1) the interchange motion is smooth and steady with no high torque placed on any part of the linkage;
2) the orientation of the psychrometers does not change during reversal, thereby avoiding the possibility of differing radiation loads on the 'top' and 'bottom' of the psychrometers;
3) there is no danger of overfeeding water to the wet-bulb sensors as a result of interchanging the position of the psychrometers;
4) the separation distance between the psychrometers is easily varied to accomodate sites with different boundary layer depths.

McCaughey (1981) found the pivot design system performed satisfactorily when compared to a weighing lysimeter and to another reversing system. Thus, confidence can be placed in the values of β from this design. However, to date, no comparative performance data exist for the elevator RTDMS, and no information exists on the improvement, if any, in the estimate of β from the pivot system as a result of the orientation of the intakes of the psychrometers into the wind which negates any possibility of the supporting structure's influencing the thermal stratification of the air being sampled (Mollo-Christensen, 1979).

Figure 2 shows the hourly values of evapotranspiration from the elevator RTDMS ($Q_{e(e)}$) and the pivot system ($Q_{e(p)}$) for the six full days of the experimental period. The value of $Q_{e(p)}$ at 0900 local time 31 August is missing because of required adjustment to the mechanism. At 1900 on this day, both values of evapotranspiration are incorrect because of the unstable behavior of both systems during this transition period. Such instability is expected, and it is interesting to note that this was the only occurrence during the comparison period. The night of 29/30 August shows aberrant values from 0000 to 0600 as a result of the occurrence of prolonged drizzle and fog which eradicated stable temperature gradients over the site. These seven hours are dropped from further analysis. Up to 1000 1 September the pivot RTDMS was free to rotate. As can be seen, the wind directions during this period varied from NW (when the psychrometers of both systems were parallel and facing the wind), to SE (when the directions of the psychrometers were 180° out of phase), and the wind was blowing from the back of the psychrometers through the tower for the elevator system. There is no systematic deviation in the values of the elevator system under such conditions, and it is reasonable to conclude that both systems are sampling the temperature gradients satisfactorily. Therefore, the orientation capability of the pivot system is not improving the estimate of Q_e. Furthermore, after 1000 1 September, when both

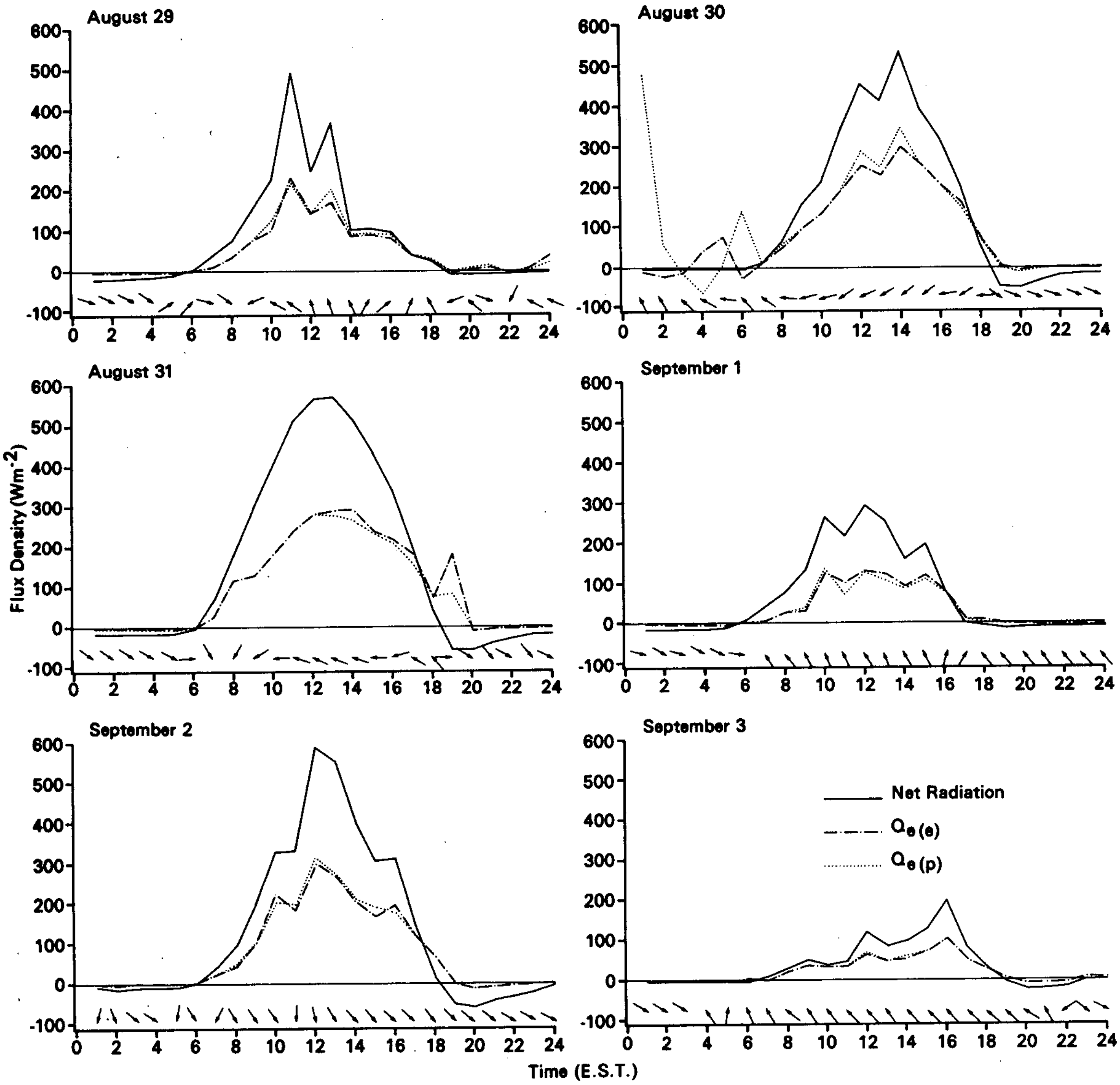

FIG. 2. Diurnal values of evapotranspiration from the pivot ($Q_{e(p)}$) and elevator ($Q_{e(e)}$) Bowen ratio systems, and net radiation, PNFI, 1985. Mean hourly wind direction is shown for each hour.

systems were oriented in the same direction, there is no systematic shift in the values from the pivot system, even when the wind was blowing from behind the psychrometers during most of 3 September.

The fractional discrepancy between the values from the two systems is apparent from Fig. 3. The agreement between the system values is very acceptable and there are only seven hours in which the fractional discrepancy exceeds 10%, when $Q_e > 50$ W m^{-2}. McIlroy and Dunin (1982) argued that an agreement within ±10% to 20%, for daytime hourly values of Q_e from nominally identical systems, is a reasonable expectation not only for Bowen ratio systems but also for lysimeters (McIlroy and Angus, 1963). Osmolski and Gay (1983) found Q_e values from two identical Bowen ratio reversing systems deviated less than 30 W m^{-2} for flux densities as high as 700 W m^{-2}. Also, Blad and Rosenberg (1974) found good agreement between the Bowen ratio method and a lysimeter except for periods of warm air advection when the Bowen ratio method underestimated Q_e by about 20%. On the basis of these criteria the two versions of the RTDMS are performing very well. It is also encouraging that there is an equal spread of values around the 1:1 line which shows no systematic nature to the discrepancies between the system values. On the last full day of the experiment, 3 September, the net radiation values are very low as a result of the generally overcast conditions, but the Q_e values from both systems are in near perfect agreement.

Table 2 summarizes the comparative performance

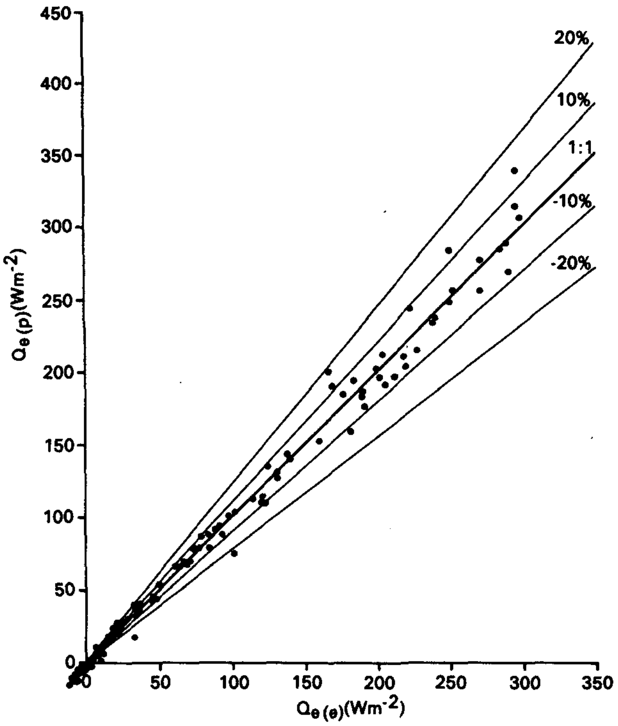

FIG. 3. Hourly values of evapotranspiration from the pivot and elevator Bowen ratio systems, PNFI, 1985.

between the system values of Q_e, Q_h and β on the basis of period totals. As expected, the agreement between the two values of Q_e is improved compared to that for hourly data; the discrepancies are <5%, except for 1 September when the values agree to within 10%. Comparing the totals for the first period, when the pivot system was free to rotate into the wind, to the second period, when it was stabilized, there is agreement to within 2% in the values of Q_e. For the whole 8-day sample, there is no discernible difference between the convective flux values from either system.

4. Conclusions

The two versions of the RTDMS, a pivot and an elevator design, were compared over a period of eight days at Petawawa, Ontario. The agreement between the evapotranspiration values from both systems was excellent on both an hourly, generally within 10%, and daily, generally within 5%, basis. There was no apparent difference in the performance of the pivot system when it was allowed to rotate into the wind compared to times when it was stabilized and facing in the same direction as the elevator system. Therefore, the effort required to build and operate such a system does not appear to be warranted.

The elevator RTDMS is superior to the pivot system in terms of its flexibility. The separation distance between the psychrometers is easily varied to accomodate different measurement situations. For forested sites, where the temperature differences are very small, the separation distance can be increased to at least 8 m if the fetch conditions warrant such a deep adjusted boundary layer. Finally, the interchange mechanism on this system does not invert the psychrometers, thus

TABLE 2. Summary of period totals (MJ m^{-2}) for 28 August to 4 September of Q_e and Q_h from the elevator and pivot Bowen ratio systems. Subscripts (e) and (p) indicate elevator and pivot systems respectively, and $\Delta Q_e = Q_{e(e)} - Q_{e(p)}$. From 28 August until 1000 local time 1 September the pivot system was free to rotate into the wind.

Date	Hours included	$Q_{e(p)}$	$Q_{h(p)}$	β	$Q_{e(e)}$	$Q_{h(e)}$	β	ΔQ_e	$\Delta Q_e/Q_{e(e)}$
28	18–24	0.357	−0.741	−2.076	0.371	−0.755	−2.035	0.014	0.038
29	01–24	3.996	2.170	0.543	3.799	2.367	0.623	−0.197	−0.052
30	07–24	7.138	3.627	0.508	6.813	3.950	0.580	−0.325	−0.048
31	01–24*	7.220	5.762	0.798	7.511	5.471	0.728	0.291	0.039
1	01–10	0.681	0.636	0.934	0.615	0.702	1.141	−0.066	−0.107
1	11–24	2.229	1.832	0.822	2.464	1.597	0.648	0.235	0.095
2	01–24	6.818	4.615	0.677	6.708	4.724	0.704	−0.110	−0.016
3	01–24	1.714	0.837	0.488	1.676	0.876	0.523	−0.038	−0.023
4	01–16	6.406	4.455	0.695	6.515	4.346	0.667	0.109	0.017
Totals while: pivot system free		19.392	11.454	0.591	19.109	11.735	0.614	−0.283	−0.015
pivot system stabilized		17.167	11.739	0.684	17.363	11.543	0.665	0.196	0.011
Totals for both periods		36.559	23.193	0.634	36.472	23.278	0.638	−0.087	−0.002

* 0900 and 1900 dropped from sample.

removing any possibility of disturbing the water delivery to the wet-bulb sensors.

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