An Inexpensive Method for Validating Remotely Sensed Evapotranspiration

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ABSTRACT

A method is presented for estimating the actual evapotranspiration from short natural vegetation or agricultural crops. The method, which can be used to validate remotely sensed evapotranspiration, consists of equating the ET flux equations based on the generalized Penman-Monteith (GPM) combination method and a humidity gradient (HG) method. By equating the GPM and HG expressions, a single unknown parameter, either the bulk surface resistance (r_s) or aerodynamic resistance (r_a), can be determined. In the procedure, the value of the resistance factor is adjusted iteratively until the daily ET time series curves from the two methods approximately coincide. This paper provides an overview of the technical approach used, and presents results of comparisons between the new method and eddy covariance systems in Florida and Puerto Rico. The new method performed well compared to the eddy covariance systems, and has the advantage of being relatively inexpensive .

Key-Words: - Evapotranspiration, Penman-Monteith, humidity gradient, Bowen ratio, eddy covariance, weighing lysimeter, surface resistance, aerodynamic resistance

1. Introduction

Accurate estimates of actual evapotranspiration (ET) are costly to obtain. An inexpensive alternative is to estimate actual evapotranspiration by multiplying a potential or reference evapotranspiration by a crop coefficient (K_c) [1,2]. This approach has been promoted by the United Nations Food and Agriculture Organization (FAO) for more than 30 years through their Irrigation and Drainage Paper No. 24 [1] and more recently in Paper No. 56 [3]. Even though they have reported values for K_c for numerous crops, many crops grown in the world are not included in their lists, and coefficients for mixed natural vegetation are generally not available. Although crop coefficients derived in other parts of the world can be used to provide approximate estimates of evapotranspiration, the crop coefficient in fact depends upon the specific crop variety and other local conditions [4].

To avoid the need for using crop coefficients a direct approach can be used to estimate actual evapotranspiration. Current methods for estimating actual evapotranspiration include weighing lysimeter, eddy covariance, and Bowen-ratio methods. Each of these methods has certain limitations. A meteorological method is described in this paper which provides an estimate of the actual ET from short natural vegetation or agricultural crops and is less expensive than the other methods mentioned above. The specific objectives of this study were to describe a relatively inexpensive method for estimating actual evapotranspiration that can be used to validate remotely sensed values of evapotranspiration; and to present results from validation studies conducted in Florida and Puerto Rico

2. Methods

2.1 Data Analysis

The method used in this study consisted of equating the ET flux equations based on the generalized Penman-Monteith (GPM) combination method [3] with a humidity gradient (HG) method [5]. In the procedure, the value of one of the resistance factors (either the aerodynamic resistance, r_a, or the bulk surface resistance, r_s) is adjusted iteratively in the two equations until their ET time series curves approximately coincide. A similar approach was used by Alves et al. [6] in which an independent estimate of ET was derived from the Bowen ratio method, r_a was obtained from a theoretical equation, and r_s was obtained by inversion of the Penman-Monteith equation.

The GPM combination equation is given as follows [3]:

$$ET = \frac{\Delta \cdot (R_n - G) + \rho_a \cdot c_p \cdot \frac{(e_s - e_a)}{r_a}}{\lambda \cdot \left[\Delta + \gamma \cdot \left(1 + \frac{r_s}{r_a} \right) \right]} \quad (1)$$

where Δ is the slope of the vapor pressure curve, R_n is the net radiation, G is the soil heat flux density, ρ_a is the air density, c_p is the specific heat of air, γ is a psychrometric constant, T is the air temperature at 2 m height, u_2 is the wind speed at 2 m height, e_s is the saturated vapor pressure and e_a is the actual vapor pressure, r_a is the aerodynamic resistance and r_s is the bulk surface resistance.

Evapotranspiration can also be estimated by means of a humidity gradient equation,

$$ET = \rho_a \cdot K_w \cdot \frac{d}{dz} q \quad (2)$$

where ρ_a is the density of air, q is the specific humidity of the air, z is the vertical spatial coordinate and K_w is the transfer coefficient for water vapor in the atmosphere. The functional form of equation 2 used in this study is given below:

$$ET = \left(\frac{\rho_a \cdot c_p}{\gamma \cdot \rho_w} \right) \cdot \frac{(\rho_{vL} - \rho_{vH})}{(r_a + r_s)} \quad (3)$$

where ρ_w is the density of water, ρ_v is the water vapor density of the air, and L and H are vertical positions above the ground. The water vapor densities were calculated using the ideal gas equation. All other variables were defined previously.

In this study L and H were 0.3 m and 2 m above the ground, respectively. Equation 3 is essentially identical to the latent heat flux equation presented by [5, equation 15.9] except that their formulation was based on the vapor pressure deficit (VPD). The VPD is the saturated air vapor pressure minus the actual vapor pressure. In our formulation we rely only on actual vapor pressures. It is important to note that the resistance factors in equation 3 are identical to those used in equation 1.

The method, which effectively combines equations 1 and 3, allows for the solution of r_s. In this study, the value of the aerodynamic resistance (r_a) is estimated using the following equation [3]:

$$r_a = \frac{\ln\left[\frac{(z_m - d)}{z_{om}}\right]\cdot\ln\left[\frac{(z_h - d)}{z_{oh}}\right]}{k^2\cdot u_2} \qquad (4)$$

where z_m is the height of wind measurement, z_h is the height of humidity measurement, d is zero plane displacement height equal to 0.67 h, h is crop height, z_{om} is roughness length governing momentum transfer equal to 0.123 h, z_{oh} is roughness length governing transfer of heat and vapor equal to 0.1 z_{om}, and k is the von Karman's constant (0.41). Allen et al. [3] reported that equation 4 and the associated estimates of d, z_{om} and z_{oh} are applicable for a wide range of crops. Equation 4 is restricted to neutral stability conditions, i.e., where temperature, atmospheric pressure, and wind velocity distribution follow nearly adiabatic conditions (no heat exchange). A study of surface and aerodynamic resistance performed by [7] determined that equation 4 will produce reliable estimates of r_a for small crops.

In this study the bulk surface resistance is estimated by a trial and error procedure, which consists of adjusting the value of r_s until the time-series plots of ET (during the daylight hours) from equations 1 and 3 approximately coincide. Adjustment of the average daily r_s value is considered acceptable when the values of the integrated daily total ET from the two equations are within 0.01 mm.

2.2 Field Data Analysis

Climatological data were saved on a Campbell Scientific (CS) CRX10 data logger every 10 seconds. Net radiation was measured using a NR Lite Net Radiometer. Wind speed was measured 3 m above the ground using a MET One 034B wind speed and direction sensor. The wind speed at 3 m was adjusted to the 2 m height using the logarithmic relation presented by [3]. Soil water content was measured using a CS616 Water Content Reflectometer. Soil temperature was measured using two TCAV Averaging Soil Temperature probes, and the soil heat flux at 8 cm below the surface was measured using a HFT3 Soil Heat Flux Plate.

An initial test using two temperature/relative humidity (Temp/RH) sensors simultaneously, positioned at the same height in close proximity revealed non-constant differences in RH between the two sensors. Differences in RH ranged from -5% to +8.5%. Errors of this magnitude were unacceptable for use in estimating the vertical humidity gradient. Therefore, to obtain accurate estimates of the humidity gradient, a single Temp/RH sensor (Vaisala HMP45C) was used, which was automatically moved between two vertical positions (0.3 m and 2 m) over short time periods (2 minutes).

An automated elevator device was developed for moving the Temp/RH sensor between the two vertical positions [8]. The device consisted of a PVC plastic frame with a 12 volt DC motor (1/30 hp) mounted on the base of the frame. One end of a 2-m long chain was attached to a shaft on the motor and the other end to a sprocket at the top of the frame. Waterproof limit switches were located at the top and bottom of the frame to limit the range of vertical movement.

The new method was verified by comparing ET results for April 5th and 6th, 2005, with an eddy covariance system at the University of Florida (UF) Plant Science Research and Education Unit (PSREU) near Citra, Florida. The eddy station was located in the center of a 23 ha bahia grass field and the shortest distance from the station to the edge of the field was 230 m.

A second validation was conducted in grass and sweet corn fields located at the University of Puerto Rico Agricultural Experiment Station at Lajas, PR. Comparisons for the grass were made on December 21, 22, and 23, 2006, and on January 3, 9, 10 and 11,

2007. Comparisons for the sweet corn were made on June 6, 7, 8, 9, 10 and 11, 2007.

A Campbell Scientific CSAT3 3D Sonic Anemometer and KH20 krypton Hygrometer are the major instruments used in the eddy covariance systems. The anemometer measured wind speeds and the speed of sound using three pairs of non-orthogonal sonic transducers to detect any vertical wind speed fluctuations. The anemometer was set up facing the prevailing wind to minimize the negative effect by the anemometer arms and other supporting structures. The frequency of the CSAT3 is 10 Hz with an output averaged every 30-minutes. The KH20 Krypton Hygrometer was mounted 10 cm away from the center of the CSAT3, with the source tube (the longer tube) on the top and the detector tube (the shorter tube) on the bottom. The output voltage of the hygrometer is proportional to the attenuated radiation, which is in turn related to vapor density. The frequency of the hygrometer is 10 Hz with an average output every 30-minute.

The eddy covariance-derived 30-minute latent heat fluxes were corrected for temperature-induced fluctuations in air density [9], for the hygrometer sensitivity to oxygen [10], and for energy balance closure. Sensible heat fluxes were corrected for differences between the sonic temperature and the actual air temperature [11]. Both the sensible and latent heat fluxes were corrected for misalignment with respect to the natural wind coordinate system [12]. The Bowen-ratio method was used to close the surface energy balance relationship [13]. Flux and atmospheric measurements were logged using a CR23X datalogger. During certain periods, such as early mornings and after precipitation, the hygrometer measurements were not available due to the moisture obscuring the lens. The data analysis was conducted for daytime measurements, based on the available energy for evapotranspiration.

3. Results

For convenience, the equipment used in this study involving a standard weather station and an elevator device for obtaining the temperature and humidity gradients, will be referred to as the "ET station". To estimate the ET using data from the ET station the following steps were used:

1. The data were read into a spreadsheet macro which, among other things, separated the "up" and "down" humidity and temperature data, and calculated actual vapor pressures.
2. The aerodynamic resistance (r_a) was estimated using equation 4.
3. The ET estimates from equations 1 and 3 were plotted together on the same graph, and the value of r_s was adjusted until the two datasets approximately coincided. The two datasets were considered to be in agreement when their total daily ET was within 0.01 mm of each other.

Table 1 lists the estimated daily ET data from the eddy covariance system and the ET station for 15 dates at locations in Florida and Puerto Rico. The ET estimates by the two methods were in reasonably good agreement. The average ratio of the ET from the eddy system and the ET station was 1.03. Figures 1 through 3 show ET from the eddy systems plotted against ET from the ET station. The average coefficient of determination (r^2) was 0.87.

4. Conclusion

The ET estimates by the two methods were in reasonably good agreement. Because of the relatively low cost of the method described in this paper numerous stations could be deployed over a region with the purpose of validating or calibrating remote sensing estimates of ET. The system described in this paper is approximately 20 and 7 times less expensive than the weighing lysimeter and eddy covariance methods, respectively. The Bowen Ratio method, although relatively inexpensive, nevertheless is about twice the cost of the system described in this paper.

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Date	Vegetation	Location	Eddy Covariance ET (mm)	ET station (mm)	ET_{eddy} / $ET_{station}$
4/5/2005	Grass	Florida	3.92	4.11	0.95
4/6/2005	Grass	Florida	3.78	3.66	1.03
12/21/2006	Grass	Puerto Rico	2.89	2.85	1.01
12/22/2006	Grass	Puerto Rico	5.14	4.60	1.12
12/23/2006	Grass	Puerto Rico	3.80	3.40	1.12
1/3/2007	Grass	Puerto Rico	3.09	2.82	1.10
1/9/2007	Grass	Puerto Rico	2.00	2.10	0.95
1/10/2007	Grass	Puerto Rico	2.90	2.50	1.16
1/11/2007	Grass	Puerto Rico	2.20	2.20	1.00
6/6/2007	Corn	Puerto Rico	5.40	5.60	0.96
6/7/2007	Corn	Puerto Rico	5.97	6.00	1.00
6/8/2007	Corn	Puerto Rico	6.39	6.32	1.01
6/9/2007	Corn	Puerto Rico	7.00	7.60	0.92
6/10/2007	Corn	Puerto Rico	6.90	6.10	1.13
6/11/2007	Corn	Puerto Rico	5.70	6.10	0.93
Average					1.03

Tbl. 1. Comparison of daily ET determined from eddy covariance system and the ET station for 15 dates from 2005 to 2006 in Florida, PR

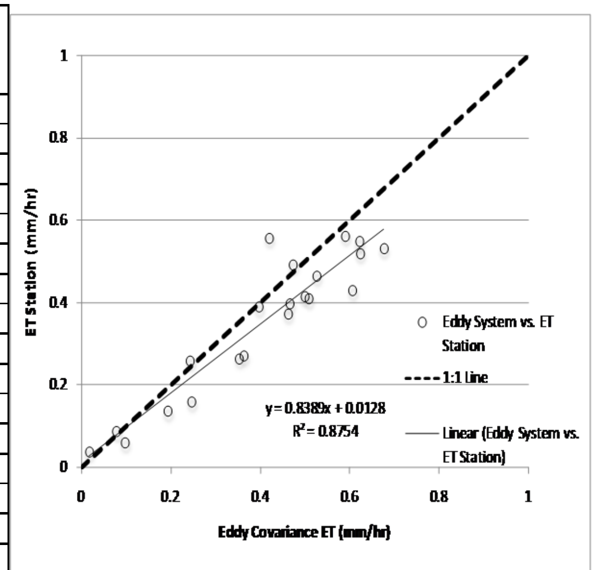

Fig. 1. Daily grass evapotranspiration estimated using the eddy covariance system and ET station on April 5th and 6th, 2005 at the University of Florida Plant Science Research and Education Center near Citra, Fl.

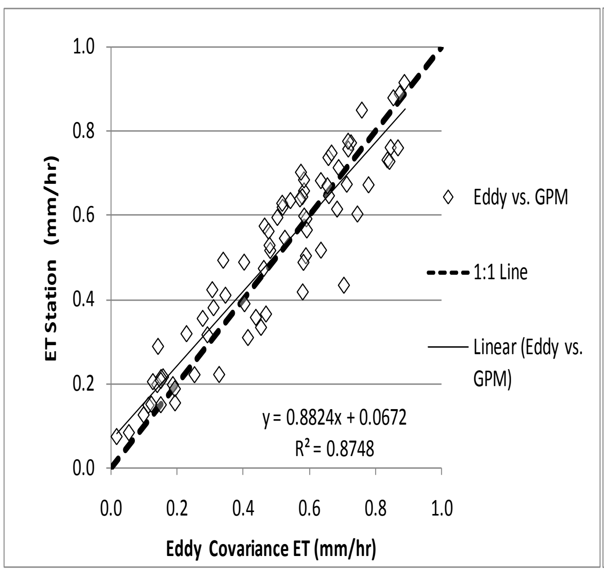

Fig. 2. Daily corn evapotranspiration estimated using the eddy covariance system and ET station for June 6, 7, 8, 9, 10 and 11 2007 at the University of Puerto Rico Agricultural Experiment Station, Lajas, PR.

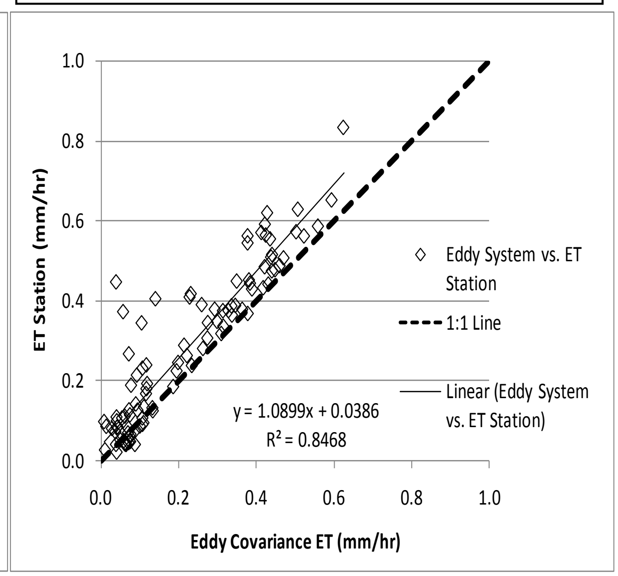

Fig. 3 Daily grass evapotranspiration estimated using the eddy covariance system and ET station for December 21, 22, 23 2006, and January 3, 9, 10 and 11 2007 at the University of Puerto Rico Agricultural Experiment Station, Lajas, PR.