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A GROUND-BASED PROCEDURE FOR ESTIMATING LATENT HEAT ENERGY FLUXES[1]

Eric Harmsen[2], Richard Díaz[3] and Javier Chaparro[3]

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2. Associate Professor, Dept. of Agricultural and Biosystems Engineering, University of Puerto Rico-Mayagüez Campus, eric_harmsen@cca.uprm.edu
3. Undergraduate and Graduate Research Assistants, respectively, University of Puerto Rico – Mayagüez Campus.

ABSTRACT

The ability to estimate short-term fluxes of water vapor from the land surface is important for validating latent heat flux estimates from high resolution remote sensing techniques. A new, relatively inexpensive method is presented for estimating the ground-based values of the surface latent heat flux or evapotranspiration.

The method used in this study consists of equating two different evapotranspiration flux equations; one based on the Penman-Monteith energy method and the other on the vapor gradient method. The resulting equation has a single unknown parameter, the bulk surface resistance (r_s). Because r_s can not be solved for explicitly, in the procedure, the value of r_s is adjusted iteratively in the two equations until their ET curves approximately coincided.

In this paper, the methodology was applied to a set of meteorological data collected from a grass-covered field on February 11, 2004, at the University of Puerto Rico's Agricultural Experiment Station, Rio Piedras, PR. The estimated bulk surface resistance was determined to be 90 s m^{-1}, and the total evapotranspiration for the 8-hour study was 3.6 mm and 3.7 mm for the energy-based and vapor gradient-based equations, respectively. The estimated value of the bulk surface resistance is consistent with other studies.

INTRODUCTION

Various efforts have been made to estimate the latent heat flux using remote sensing techniques (e.g., Jarvis 1981; Luvall et al., 1990; Holbo and Luvall, 1989; Quattrochi and Luvall, 1990; Turner and Gardner, 1991). These methods typically rely on an equation of the following form (Luvall et al., 1990):

$$LE = \left(\frac{\rho \cdot c_p}{\gamma}\right) \cdot \frac{(VD_a - VD_s)}{R_s} \quad (1)$$

where LE is latent heat flux (MJ m^{-2} day), ρ is density of air (kg m^{-3}), c_p is specific heat of air (MJ kg^{-1} ^{o}C^{-1}), VD_a is water vapor density of the air (kg m^{-3}), VD_s is saturated water vapor density of the air at the vegetation canopy, based on surface temperature obtained by remote sensing (kg m^{-3}), γ is psychrometric constant (kPa ^{o}C^{-1}), and R_s is stomatal resistance (s m^{-1}).

To validate LE estimates from remote sensing techniques, LE must be determined at the ground surface. In this paper LE will be expressed as a quantity of water evaporated per unit time, otherwise known as the evapotranspiration (ET) and is expressed in units of mm per hour. LE and ET are related by the latent heat of vaporization (2.45 MJ per kg of water). Current ground-based ET measurement techniques include: weighing lysimeter, eddy covariance, and the water balance methods. Each of these methods is expensive and has certain disadvantages. In this study ET was determined using a new ground-based procedure based on the less expensive yet sufficiently accurate energy balance and vapor gradient methods.

METHODS

Data Analysis

The methods used in this study consisted of equating the ET flux equations based on the Penman-Monteith (PM) energy method with a vapor gradient method. By equating the two equations, a single unknown parameter, bulk surface resistance (r_s), could be solved for. In the procedure, the value of r_s was adjusted iteratively in the two equations until their ET time series curves approximately coincided.

The PM energy equation is given as follows (Allen et al., 1998):

$$ET = \frac{\Delta \cdot (R_n - G) + \rho_a \cdot c_p \cdot \frac{(e_s - e_a)}{r_a}}{\lambda \cdot \left[\Delta + \gamma \cdot \left(1 + \frac{r_s}{r_a} \right) \right]} \quad (2)$$

where Δ is slope of the vapor pressure curve (kPa^oC^{-1}), R_n is net radiation (MJ m^{-2} hr^{-1}), G is soil heat flux density (MJ m^{-2} hr^{-1}), ρ_a is air density (kg m^{-3}), c_p is specific heat of air (MJ kg-1 ^{o}C-1), γ is psychrometric constant (kPa^oC^{-1}), T is air temperature at 2 m height (^{o}C), u_2 is wind speed at 2 m height (m/s), e_s is the saturated vapor pressure and e_a is the actual vapor pressure (kPa), r_a is the aerodynamic resistance (s m^{-1}) and r_s is bulk surface resistance (s m^{-1}). The two resistance factors in equation 2 are shown schematically in the Figure 1.

In this study the aerodynamic resistance will be estimated from the following equation (Allen et al., 1998):

$$r_a = \frac{\ln\left[\frac{(z_m - d)}{z_{om}}\right] \cdot \ln\left[\frac{(z_h - d)}{z_{oh}}\right]}{k^2 \cdot u_2} \quad (3)$$

where z_m is height of wind measurement 2 m), z_h is height of humidity measurement (2 m), d is zero plane displacement height is 0.67 h, z_{om} is roughness length governing momentum transfer is 0.123 h, z_{oh} is roughness length governing transfer of heat and vapor is 0.1 z_{om}, k is von Karman's constant (0.41), and h is crop height (0.12 m). Allen et al. (1998) have reported that equation 3 and the associated estimates of d, z_{om} and z_{oh} are applicable for a wide range of crops. Equation 3 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 Kjelgaard and Stockle (2001) determined that equation 3 will produce reliable estimates of r_a for small crops.

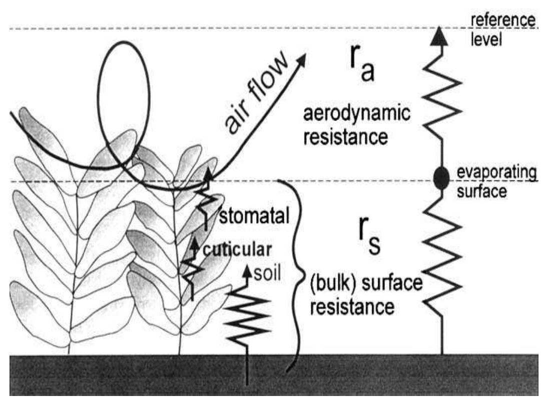

Figure 1. Simplified representation of the (bulk) surface resistance and aerodynamic resistances for water vapor flow (from Allen et al., 1998).

Evapotranspiration can also be estimated by means of a vapor gradient equation as given below:

$$ET = \left(\frac{\rho_a \cdot c_p}{\gamma \cdot \rho_w} \right) \cdot \frac{(VD_L - VD_H)}{(r_a + r_s)} \quad (4)$$

where ρ_w is density of water, VD_L is absolute vapor density at height L and VD_H

is absolute vapor density at height H. In this study L and H were 0.3 m and 2 m, respectively. All other variables were previously defined.

Field Data Collection

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% (see Figure 2). Errors of this magnitude are clearly unacceptable for use in estimating the vertical humidity gradient. Therefore, to obtain accurate estimates of the humidity gradient, a single Temp/RH sensor (CS HMP45C) was used, which was manually moved between two vertical positions (0.3 m and 2 m) over short time periods (2 minutes). The vapor densities (VD) were estimated from the temperature and RH data, which were recorded by the data logger every 10 seconds.

Climatological data were saved on a Campbell Scientific (CS) CRX10 data logger every 10 seconds. Net radiation was measured using a CS NR Lite Net Radiometer. Wind speed was measured at 30 cm and 3 m above the ground, respectively. The upper sensor was a MET One 034B wind speed and direction sensor. The lower wind speed was measured using a HOBO wind speed sensor. The wind speed at 3 m was adjusted to the 2 m height using the logarithmic relation presented by Allen et al. (1998). 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. Soil heat flux at the soil surface was estimated using the average soil temperature, soil heat flux at 8 cm and water content data.

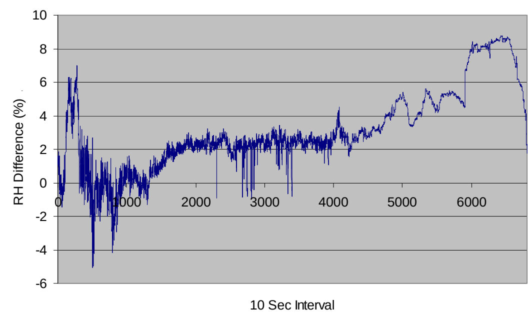

Figure 2. Differences in measured RH between two sensors located in close proximity, 2 meters above the ground.

RESULTS AND DISCUSSION

Figure 3 shows an example of some RH data collected from the single Temp/RH sensor located in a field of grass at the University of Puerto Rico (UPR) Experiment Station in Rio Piedras, PR, during February 2004 (Harmsen and Díaz, 2004). Figure 4 shows the estimated ET for the same day based on equations 2 and 4, respectively. Note that the measured vertical air temperature gradient was negligible, confirming the presence of aerodynamically stable conditions during the study (Figure 5).

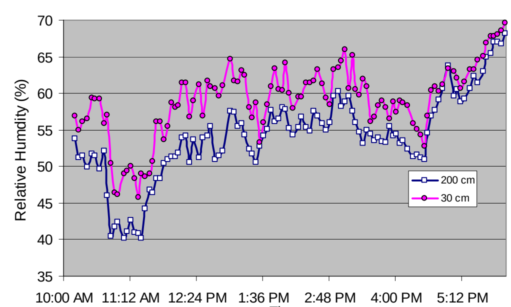

Figure 3. Measured relative humidity at 0.3 m and 2 m above the ground between 10 AM to 6 PM on February 11, 2004.

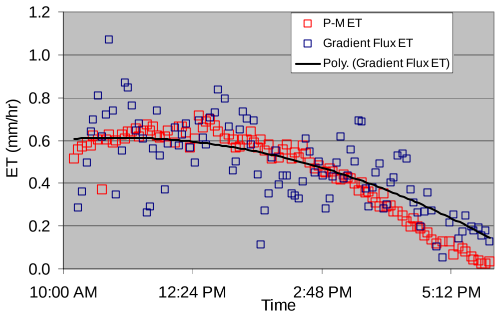

Figure 4. Calculated latent heat flux using equations 2 and 4 from 10 AM to 6 PM on February 11, 2004.

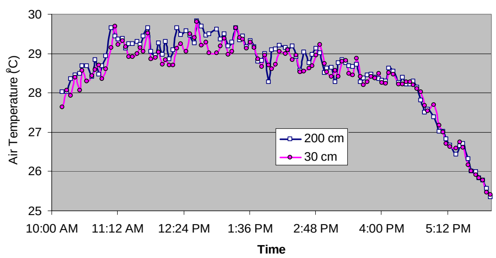

Figure 5. Measured air temperature at 0.3 m and 2 m above the ground between 10 AM to 6 PM on February 11, 2004.

The ET results from equation 4 indicated much more temporal variation than the ET estimated using equation 2. The probable cause of this variation is that equation 4 is more sensitive to variations in wind speed (via the aerodynamic resistance factor) than equation 2. Figure 6 shows the variation in wind speed at the study site at 0.3 and 2 m heights, respectively, during the eight hour test.

To improve comparison of the two methods, a best-fit 2nd order polynomial equation was developed for the equation 4 data and the polynomial curve was then compared with the P-M curve (Figure 4). The best-fit value of r_s was found to be 90 s m^{-1}. This value of r_s is consistent with the imaginary reference grass defined by the United National Food and Agriculture Organization (FAO), having a value of r_s equal to 70 m/s (Allen et al., 1998). The total estimated vapor flux for the eight-hour study period was 3.6 mm and 3.7 mm from equations 2 and 4, respectively.

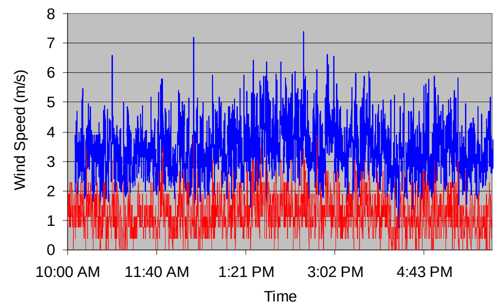

Figure 6. Measured wind speed from 10 AM to 6 PM on February 11, 2004. The lower plot is for wind speed measured at 0.3 m above the ground. The upper plot is for wind speed at 2 m above the ground (adjusted from 3 m data).

FUTURE WORK

Manually moving the Temp/RH sensor between the two vertical positions was very labor intensive. Therefore, an apparatus for automatically moving the Temp/RH sensor has been developed at the University of Puerto Rico. The apparatus consists of an aluminum frame with a 12 volt DC motor attached at its base. One end of a chain is connected to a sprocket on the motor and the other end connected to a sprocket at the top of the frame. The 2 m frame height was selected because this is the standard reference height defined by the FAO for estimating evapotranspiration with the Penman-Monteith equation (Allen et al., 1998).

Limit switches are located at the top and bottom of the frame which are contacted when the Temp/RH sensor, attached to the chain, is raised or lowered. A programmable logic controller (PLC) is used to hold the sensor in the "up" position (2 m) for a 2 minute period, during which RH measurements are recorded every 10 seconds. At the end of the 2 minute period, the RH sensors is lowered (travel time approximately 10 seconds) to the "down" position (0.3 m) and held for 2 minutes while Temp/RH data is recorded. This sequence of movements is continued for periods of up to one or two days. The CR10X weather station data logger has been programmed to communicate with the PLC and to record the vertical position of the Temp/RH sensor. This information is important during the post-processing phase when the "up" data is separated from the "down" data in order to calculate the humidity gradient.

Future work also includes validation of the new methodology by comparing ET estimates with estimates from a soon-to-be-installed NASA eddy covariance system located in Lajas, PR (L. Pérez Alegría, personal communication).

During 2005, the measurement system will be used to validate LE estimates from the Moderate Resolution Imaging Spectroradiometer (MODIS) for four different vegetation types. The spatial resolution of MODIS is 250 m, however, with an interpolation technique developed at the University of Puerto Rico, it will be possible to obtain resolutions on the order of 65 m or 1 acre in area.

SUMMARY AND CONCLUSIONS

A method was presented for estimating ground-based values of evapotranspiration or the latent heat flux. The methodology will be useful for validating latent heat flux estimates based on remote sensing techniques. The methods used in this study consisted of equating the ET flux equations based on the Penman-Monteith (PM) energy method with a vapor gradient method. By equating the two equations, a single unknown parameter, bulk surface resistance (r_s), could be solved for. In the procedure, the value of r_s was adjusted iteratively in the two equations until the ET curves approximately coincided.

The method was applied to ground-based meteorological data measured on February 11, 2004 at the University of Puerto Rico Agricultural Experiment Station located at Rio Piedras, PR. The estimated bulk surface resistance was 90 s m^{-1}, and the total evapotranspiration for the 8-hour study was 3.6 mm and 3.7 mm for the energy-based and vapor gradient-based equations, respectively. To reduce the labor associated with manually moving the Temp/RH sensor between the two vertical positions, an apparatus is currently under development to automate the process.

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