A Ground-Based Method for Calibrating Remotely Sensed Surface Temperature for use in Estimating Evapotranspiration

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ABSTRACT

A method is presented for estimating hourly actual evapotranspiration from short natural vegetation or agricultural crops. The method, which can be used to calibrate 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. 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. An example is presented in which the average surface temperature of a grass-covered field, located at the University of Puerto Rico Agricultural Experiment Station at Rio Piedras, PR (located within the San Juan metropolitan area), obtained by NASA's airborne Advanced Thermal and Land Applications Sensor (ATLAS), was corrected to provide accurate estimates of ET using a flux gradient equation.

Key-Words: - Evapotranspiration, Penman-Monteith, humidity gradient, eddy covariance, remote sensing, surface resistance, aerodynamic resistance, surface temperature

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 [1, 2, 3] by a crop coefficient (K_c) [4, 5]. 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 [6]. 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 [7].

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, scintilometer, 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 hourly actual evapotranspiration that can be used to calibrate remotely sensed surface temperature for use in estimating evapotranspiration; and to present results from validation studies conducted in Florida and Puerto Rico (PR). An example is also presented in which the average remotely sensed surface temperature, obtained as part of an urban heat island study in San Juan, PR, is corrected for use in a humidity gradient evapotranspiration flux equation.

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 [6] with a humidity gradient (HG) method [8]. 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 in the two equations until their ET time series curves approximately coincide. A similar approach was used by Alves et al. [9] 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 [6]:

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

where ET is evapotranspiration [mm/hr], Δ is the slope of the vapor pressure curve [kPa °C^{-1}], R_n is net radiation [MJ m^{-2} day^{-1}], G is soil heat flux density [MJ m^{-2} day^{-1}], ρ_a is air density [[kg m^{-3}], c_p is the specific heat of air [MJ kg^{-1} °C^{-1}], γ is the psychrometric constant [kPa °C^{-1}], T is air temperature at 2 m height [°C], u_2 is wind speed at 2 m height [m s^{-1}], e_s is saturated vapor pressure [kPa], e_a is actual vapor pressure [kPa], r_a is aerodynamic resistance [s m^{-1}], and r_s is bulk surface or canopy resistance [s m^{-1}].

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

$$ET = \left(\frac{\rho_a \cdot c_p}{\gamma \cdot \rho_w}\right) \cdot \frac{\left(\rho_{vL} - \rho_{vH}\right)}{\left(r_a + r_s\right)} \quad (2)$$

where ρ_w is the density of water [kg m^{-1}], ρ_v is the water vapor density of the air [kg m^{-1}], and L and H are vertical positions above the ground [m]. The water vapor densities were calculated from the actual vapor pressures and air temperatures 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 2 is essentially identical to the latent heat flux equation presented by Monteith and Unsworth [8, equation 17.3].

The method, which effectively combines equations 1 and 2, allows for the solution of r_s. In this study, the value of the aerodynamic resistance (r_a) is estimated using the following equation [6]:

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

where z_m is the height of wind measurement [m], z_h is the height of humidity measurement [m], d is zero plane displacement height equal to 0.67 h [m], h is crop height [m], z_{om} is roughness length governing momentum transfer equal to 0.123 h [m], z_{oh} is roughness length governing transfer of heat and vapor equal to 0.1 z_{om} [m], and k is the von Karman's constant (0.41). The variable ζ is defined as r_a u_2. Allen et al. [6] reported a value of ζ equal to 208 for a theoretical reference grass with a height h = 0.12 m.

Equation 3 and the associated estimates of d, z_{om} and z_{oh} are applicable for a wide range of crops [6]. A study of surface and aerodynamic resistance performed by [10] determined that equation 3 will produce reliable estimates of r_a for small crops. The equation is restricted to neutral stability conditions, i.e., where temperature, atmospheric pressure, and wind velocity distribution follow nearly adiabatic conditions (no heat exchange). Atmospheric stability conditions can be determined using the Richardson Number:

$$R_i = \frac{g \cdot \Delta t}{T} \cdot \frac{\Delta z}{(\Delta u)^2} \qquad (4)$$

where g is acceleration of gravity [9.8 m s^{-2}], Δt and Δu are, respectively, the temperature [°C] and wind velocity [m s^{-1}] differences between levels z_1 and z_2 [Δz, m], and T is the average absolute temperature [°K] [9]. The critical value R_i is usually taken as 0.25, although suggestions in the literature range from 0.1 to 1.0.

In this study, the value of r_s is obtained by a graphical procedure in which successive adjustments are made to r_s until the time-series plots of ET (during the daylight hours) from equations 1 and 2 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, Inc.[1] (CSI) CRX10 data logger every 10 seconds. Net radiation was measured using a CSI NR Lite Net Radiometer. Wind speed was measured 3 m above the ground using a CSI 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 CSI CS616 Water Content Reflectometer. Soil temperature was measured using two CSI TCAV Averaging Soil Temperature probes, and the soil heat flux at 8 cm below the surface was measured using a CSI 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

[1] Reference to a commercial product in no way constitutes an endorsement of the product by the authors.

differences in RH between the two sensors. Differences in RH ranged from -5% to +8.5% (Fig. 1). 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) every 2 minutes.

An automated elevator device was developed for moving the Temp/RH sensor between the two vertical positions [11]. 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 sprocket on 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.

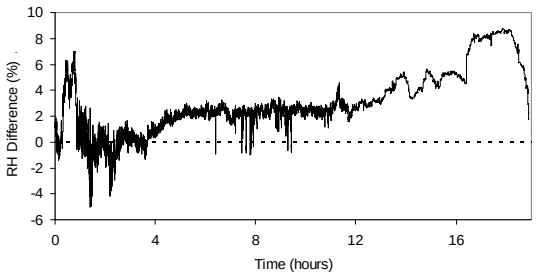

Fig. 1. Difference between RH measured by two RH sensors held in close proximity.

For automating the elevator device, a Moeller EASY412-DA-RC™ Programmable Logic Controller (PLC) was used which is composed of "n" inputs and "n" relay outputs. To program the device, a ladder logic was used which is a chronological arrangement of tasks to be accomplished in the automation process. The Temp/RH sensor was connected to the elevator device, which measured RH and temperature in the up position for two minutes then changed to the down position where measurements were taken for two minutes, and the process continued indefinitely until the experiment was ended. When the elevator moves to the up position it activates the limit switch which sends an input signal to the PLC. That input tells the program to stop and remain in that position for two minutes. At the same time it activates an output which sends a 5 volt signal to the control port C2 in the CR10X data logger in which a small subroutine is executed. This subroutine assigns a "1" in the results matrix which indicates that the temperature and relative humidity correspond to the up position. At the end of the two minutes period the elevator moves to the down position and repeats the same process, but in this case sending a 5 volts signal to the data logger in the control port C4, which then assigns a "2" in the results matrix.

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 PR 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 CSI CSAT3 3D Sonic Anemometer and CSI 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.

Additionally, other meteorological and environmental variables were measured including: air temperature, relative humidity, wind speed and direction, soil temperature, soil heat flux, precipitation (tipping bucket), net radiation, and incoming solar radiation.

The eddy covariance-derived 30-minute latent heat fluxes were corrected for temperature-induced fluctuations in air density [12], for the hygrometer sensitivity to oxygen [13], and for energy balance closure. Sensible heat fluxes were corrected for differences between the sonic temperature and the actual air temperature [14]. Both the sensible and latent heat fluxes were corrected for misalignment with respect to the natural wind coordinate system [15]. The Bowen-ratio method was used to close the surface energy balance relationship [16]. Flux and atmospheric measurements were logged using a CSI 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 AND DISCUSSION

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 3.
3. The ET estimates from equations 1 and 2 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.

As an example, Fig. 2 shows the short-term estimates of ET on April 6th, 2005 at the PSREU near Citra, Florida. The total daily ET for both methods (GPM and HG) was 3.66 mm, the final value of r_s was 154 s m^{-1}, and ζ equaled to 191, based on a grass height of 15 cm. Based on our experience, the HG method is generally much more variable than the GPM method. The fluctuations in the GPM ET data in Fig. 2 were primarily due to fluctuations in the net radiation and the actual vapor pressure difference between the two vertical positions (Fig. 3). It is interesting to note that the HG ET data, which is a function of the water vapor density gradient and the wind velocity (via r_a), follows the pattern of the GPM method quite well, and the GPM ET data were well correlated with net radiation.

Figure 4 shows a 15-minute period of RH readings. The figure also shows the value of the square wave (i.e., the value 1 or 2 sent from the PLC to the data logger). A square wave value of 1 signified that the Temp/RH sensor was in the up position and a 2 signified that the Temp/RH sensor was in the down position. Figure 3 shows the actual vapor pressures for April 6th, 2005, separated into the up and down positions as determined by the spreadsheet macro.

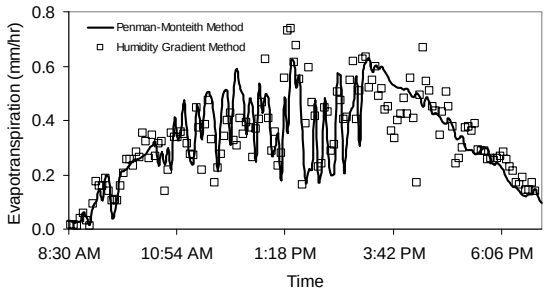

Fig. 2. Example of the actual ET using the GPM and HG equations obtained on April 6, 2005 at the University of Florida Plant Science Research and Education Center near Citra, FL.

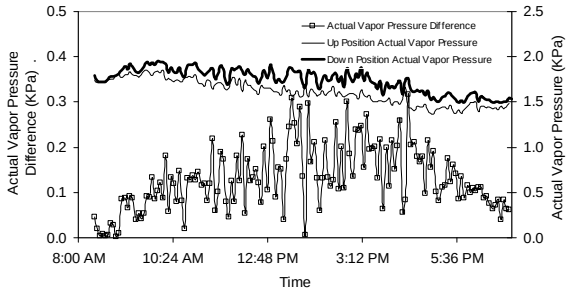

Fig. 3. Example of the estimated actual vapor pressure in the up and down positions, and the vapor pressure difference between the two vertical positions measured at on April 6, 2005 at the University of Florida Plant Science Research and Education Center near Citra, FL.

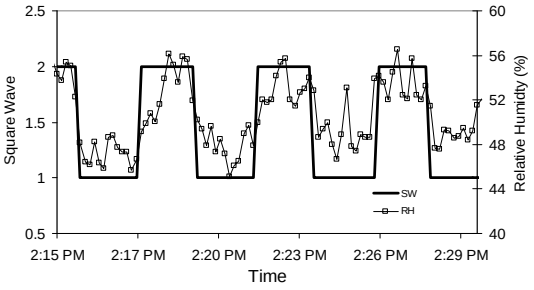

Fig. 4. Example of the measured relative humidity for a fifteen-minute period measured on April 6, 2005 at the University of Florida PSREU near Citra, FL. A 1 on the square wave axis indicates that the RH /temperature sensor was in the up position (2 m) and a 2 indicates that the sensor was in the down position (0.3 m).

3.1 ET Station Validation

Table 1 lists the estimated daily ET (expressed in mm) from the eddy covariance systems 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 error was 3%, and the maximum positive and negative errors were 13% and -8 percent, respectively.

Figures 5 through 7 shows the half-hour ET (expressed in mm/hr) from the eddy systems and ET station. The average coefficient of determination (r^2) was 0.87. As an example, Fig. 8 compares the corn evapotranspiration from the ET station and eddy covariance system between 7:30 am and 6:00 pm on June 7, 2007 at the UPR Agricultural Experiment Station, Lajas, PR.

The ET station tended to underestimate ET, relative to the eddy covariance system, for larger values of ET for the test with grass in Florida (Fig. 5). Some of the bias observed in the result may be attributable to violations in the assumption of neutral stability atmospheric conditions, required for use of equation 3. However, most of the higher ET values occurred during the middle of the day when Ri values were less than 0.1, indicating stable atmospheric conditions (Fig. 9).

The ET station performed well during the test with corn in PR (Fig. 6), although considerable scatter is observed in the data as reflected by the r^2 of 0.875. The ET station tended to over-estimate ET slightly, relative to the eddy covariance system, for the entire ET range for the test with grass in PR (Fig. 7). The average over-estimation was approximately 0.05 mm hr^{-1}. The poor condition of the grass (patchy), due to the dry conditions, may have contributed to this result. The poor performance of the GPM has been noted for low values of leaf area index [17].

The ET estimates from the ET station and eddy covariance 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, 10 and 7 times less expensive than the weighing lysimeter, scintilometer, 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. In the next section an example is presented in which surface temperature derived from a NOAA remote sensing instrument is calibrated for use with a simple humidity gradient-type ET equation.

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

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

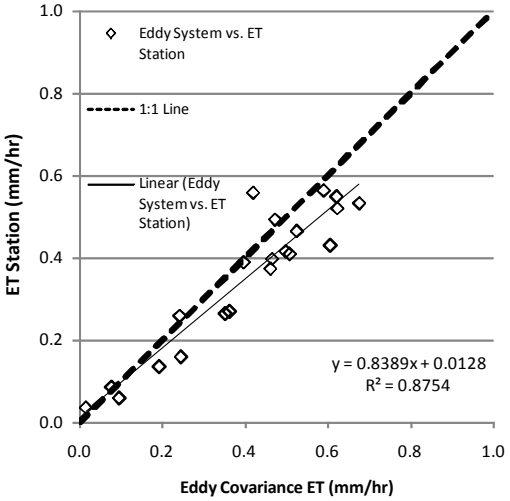

Fig. 5. Half-hour values of grass evapotranspiration (expressed in mm/hr) estimated using the eddy covariance system and ET station on April 5th and 6th, 2005 at the University of Florida Plant Science Research and Education Center near Citra, FL.

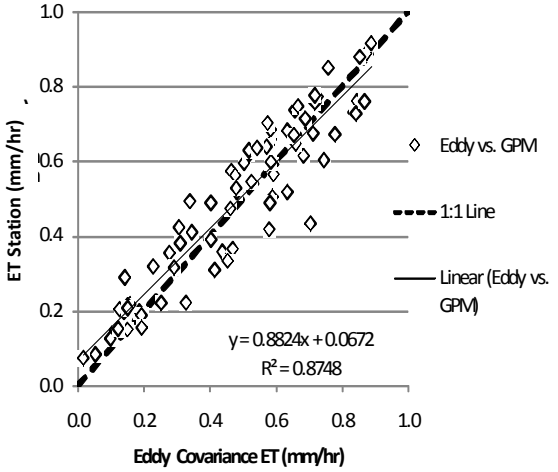

Fig. 6. Half-hour values of corn evapotranspiration (expressed in mm/hr) estimated using the eddy covariance system and ET station for June 6, 7, 8, 9, 10 and 11 2007 at the University of PR Agricultural Experiment Station, Lajas, PR.

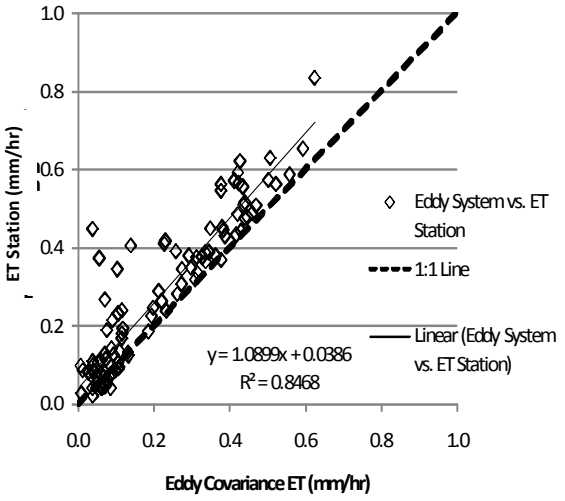

Fig. 7. Half-hour values of grass evapotranspiration (expressed in mm hr^{-1}) estimated using the eddy covariance system and ET station for December 21, 22, 23 2006, and January 3, 9, 10 and 11 2007 at the University of PR Agricultural Experiment Station, Lajas, PR.

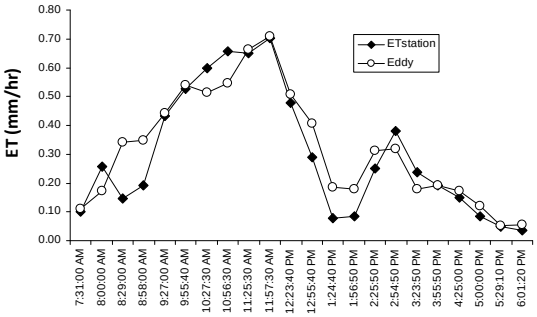

Fig. 8. Comparison of corn evapotranspiration determined by means of the ET station and eddy covariance system on June 7, 2007 at the UPR Agricultural Experiment Station, Lajas, PR.

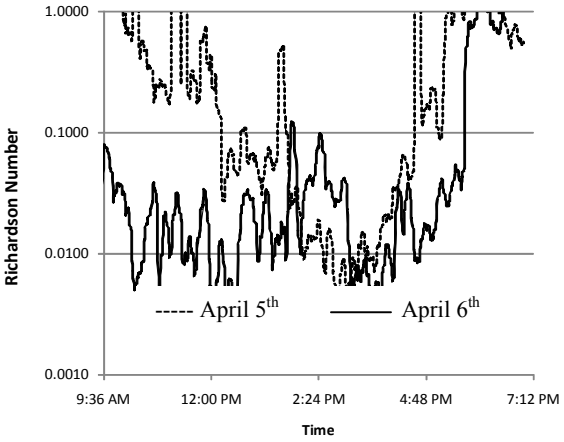

Fig. 9. Calculated Richards Number (R_i) on April 5th and 6th, 2005.

3.2 Calibration of ATLAS Surface Temperature for estimating Evapotranspiration

The ability to estimate short-term fluxes of water vapor from a growing crop or natural vegetation is necessary for calibrating estimates from remote sensing techniques, such as NASA's Advanced Thermal and Land Applications Sensor (ATLAS). On February 11th through February 16th, 2004, the airborne ATLAS instrument was used to evaluate the urban heat island effect within the San Juan Metropolitan area [18]. To calibrate energy flux estimates from ATLAS, a ground study was conducted at the University of PR Agricultural Experiment Station at Rio Piedras, PR (located within the metropolitan area). The ET station was located on a grass-covered field in the Jardin Botanica Sur. The objective of this study was to calibrate the ATLAS surface temperatures so that accurate values of evapotranspiration (or latent heat flux) from vegetated areas could be estimated with a humidity gradient flux equation. Various efforts have been made to estimate the vapor flux using remote sensing techniques (e.g., [19, 20, 21, 22, 23]). These methods typically rely on an equation of the following form [20]:

$$ET = \left(\frac{\rho_a \cdot c_p}{\lambda \cdot \gamma}\right) \cdot \left(\frac{\rho_{vs} - \rho_{va}}{r_l}\right) \quad (4)$$

where ρ_{va} is water vapor density of the air based on measurements of air temperature and RH at the ground surface, ρ_{vs} is water vapor density at the evaporating surface (via the vapor pressure), based on surface temperature obtained by remote sensing, and r_l is the average leaf stomatal resistance (s m^{-1}). All other parameters have been previously defined.

Figure 10 shows the surface temperature image of the study area (circled) and the surrounding vicinity obtained from the ATLAS instrument on February 11th, 2005, at 2:25 PM. In one pixel of 5 square meters (resolution of the ATLAS instrument), in which the ET station was located, the average air temperature, average soil temperature and ATLAS surface temperature were 28.9°C, 27.9°C and 32.0°C, respectively. The average surface temperature derived from the ATLAS instrument for a group of twelve contiguous pixels (300 m^{-2}) within the study area was 33.0°C.

In this study, r_l was set to 100 sm^{-1}, appropriate for well watered grass [6], ρ_{va} was based on the actual vapor pressure of the air 2 m above the ground and ρ_{vs} was based on the actual vapor pressure near the ground surface. A ground surface temperature was obtained by trial and error adjustment of temperature in equation 4 (via the vapor pressure) until the ET equaled the ET obtained from the ET station (0.53 mm hr^{-1}). The corrected value of the surface temperature was considered to be the effective surface temperature ($T_{ST\text{-}eff}$). A

surface temperature correction factor (STCF) was obtained from T_{ST}-$T_{ST\text{-}eff}$. The STCF can be subtracted from all T_{ST} pixel values in the San Juan area obtained during the field campaign for use in calculating evapotranspiration for similar land surface conditions (i.e., grass). Using this approach, an effective surface temperature of 29.45°C was obtained. Therefore, the average correction to the ATLAS surface temperature was 33.0 °C – 29.45 °C = 3.76 °C.

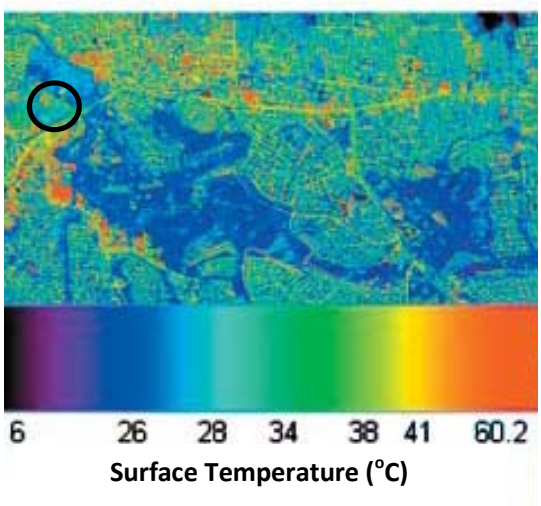

Fig. 10. ATLAS surface temperature image. Circled area is the study area where the ET station was located.

4. Conclusion

A ground-based method was described for estimating actual, short-term (sub-hourly) evapotranspiration. The ET estimates from the ET station and eddy covariance 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.

An example was provided in which the surface temperature from an urban heat island study conducted in San Juan, PR, using NASA's ATLAS remote sensing instrument, was calibrated for use in a simple humidity gradient-type evapotranspiration equation. A surface temperature correction factor of 3.76 °C was obtained.

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