ESTIMATING EVAPOTRANSPIRATION IN THE CARIBBEAN REGION USING SATELLITE REMOTE SENSING

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ABSTRACT: In early 2009, collaboration between the University of Puerto Rico-Mayagüez Campus and the University of Alabama in Huntsville resulted in the availability of a solar radiation satellite remote sensing product for Puerto Rico, the Dominican Republic, Haiti and Cuba. The half-hourly and daily-integrated data are available at 1 km resolution for Puerto Rico and 2 km resolution for the other islands. These data are extremely valuable for the purpose of analyzing water resource-related problems. In this paper we describe the technical approach for estimating reference evapotranspiration (ET), actual ET, surface runoff, deep percolation and soil moisture content. Results of estimated reference ET are presented for Puerto Rico, Haiti and the Dominican Republic. Actual ET, surface runoff, deep percolation and soil moisture content estimates are presented for Puerto Rico. This research represents a preliminary step in the development of a suite of remote sensing products that are potentially valuable tools for conducting water resource studies at the island scale.

Key words: satellite remote sensing, solar radiation, evapotranspiration, water balance, Caribbean

INTRODUCTION

Remote sensing methods for estimating ET are needed for tropical conditions. Various techniques have been developed based on radiation (e.g., Sumner et al., 2008) and surface energy budget methods (Evett et al., 2007, Allen et al., 2008). In this study a solar radiation based methodology is used for estimating ET. Remote sensing of solar radiation has several important advantages over the use of pyranometers networks including large spatial coverage, relatively high spatial resolution, and the availability of data in remote, inaccessible regions and countries that may not have the means to install a ground-based pyranometers network (Sumner et al., 2008). The objective of this study is to introduce a new ET remote sensing product for Puerto Rico, Haiti and the Dominican Republic. The development of the methodology has advanced more quickly in Puerto Rico; therefore, the information presented here can be considered a prototype of what is being developed for the other two countries (i.e., Haiti and the Dominican Republic).

TECHNICAL APPROACH

Reference ET is estimated with the original radiation-based Hargreaves formula (Hargreaves, 1975 and Hargreaves and Samani, 1982):

$$ET_O = 0.0135 \cdot (R_s \cdot 0.408) \cdot (T_a + 17.8) \tag{1}$$

where R_s is solar radiation and T_a is the average daily air temperature. The 0.408 value converts the solar radiation from units of MJ/m^{2}day to mm of water per day.

The daily actual evapotranspiration (ET_a) was obtained by converting the latent heat flux (LE) for each 1 km^2 pixel to an equivalent depth of water using the latent heat of vaporization. The LE was estimated using the following equation (Monteith and Unsworth, 2007):

$$LE = \frac{\rho \cdot C_p \cdot (e_o(T_s) - e(T_a))}{\gamma \cdot (r_a + r_s)} \tag{2}$$

where ρ is the density of dry air, C_p is the specific heat of air, γ is psychrometric constant, $e_o(T_s)$ is the saturated vapor pressure at the effective surface temperature T_s, $e(T_a)$ is actual vapor pressure at the air temperature T_a, and r_a and r_s are aerodynamic and surface resistances, respectively. Vapor pressures were calculated with the equation: $e = 0.6018(\exp[(17.27T)/(T+237.3)]$ (Allen et al., 1998), where T is temperature. Air temperature (T_a) was obtained from lapse rates calibrated for Puerto Rico by Goyal et al. (1988) with regression equations relating average air temperature with surface

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elevation. To verify the appropriateness of using the estimated air temperature, comparisons were made with measured air temperature at two coastal locations (Isabela and Fortuna) and two mountain locations (Guilarte and Maricao) in Puerto Rico during the ten day period of analysis (June 20-June 29, 2010), and a high correlation between measured and estimated air temperature was obtained ($T_{a,measured} = 1.062$ $T_{a,estimated}$ - 0.78, coefficient of determination, $r^2 = 0.94$).

The effective surface temperature is difficult to obtain from remote sensing, since the satellite brightness temperature obtained may be that of the cloud top and not the ground surface, if clouds are present. Therefore, T_s was obtained by an implicit approach similar to that described by Lascano and van Bavel (2007). In this study, the surface energy balance was employed and the single unknown variable (T_s) was obtained using the recursive root function **fzero** in MatLab (Ver. 10) (http://www.mathworks.com). After obtaining the value of T_s for each pixel, the values of LE and H are calculated. The form of the surface energy balance used in this study is shown below:

$$R_n - LE(T_s) - H(T_s) - G = 0 \tag{3}$$

where R_n is the net radiation, G is the soil heat flux, assumed to be zero for the daily analysis, and H is the sensible heat flux,

$$H = \frac{\rho \cdot C_p \cdot (T_s - T_a)}{r_a} \tag{4}$$

Net radiation is obtained from the calculation procedure presented by Allen et al. (1998), which requires solar radiation (R_s) and albedo (α), which in this study are derived from the radiative transfer model of Diak et al. (1996) using half-hourly data from the visible channel of NOAA's GOES-13 satellite. More information about the R_s and α remote sensing products can be found in Sumner et al. (2008). To evaluate the solar radiation product for Puerto Rico, a comparison was performed between pyranometers and the remotely sensed solar radiation (in the corresponding pixels) for six locations (Mayagüez, Isabela, Maricao, Guilarte, Fortuna and Bosque Seco) between April 2009 and June 2010.

Aerodynamic resistance (r_a) was calculated with the following equation (Yunhao et al., 2001):

$$r_a = r_{ao} \cdot \phi + r_{bh} \tag{5}$$

where r_{ao} is the aerodynamic resistance under conditions of neutral atmospheric stability (Allen et al., 1998):

$$r_{ao} = \frac{\ln\left[\dfrac{(z - z_{disp})}{z_o}\right] \cdot \ln\left[\dfrac{(z - z_{disp})}{(0.1) \cdot z_o}\right]}{k^2 \cdot u} \tag{6}$$

In (6) z is the virtual height at which meteorological measurements are taken, in this study assumed to be within the inertial sublayer and equal to $1.5(z_o/0.13)$ (Monteith and Unsworth, 2007). The roughness length (z_o) and the zero plane displacement (z_{disp}) for various land use/vegetation categories were obtained from ATMET (2005). The term ($z_o/0.13$) is equivalent to the canopy height (h). The parameter k is Von Karman's constant (k = 0.41). Six-hour values of wind speed for Puerto Rico, obtained from the National Weather Service's National Digital Forecast Database (NDFD, 2010), were averaged to obtain the daily average wind speed (u). Although the wind speed is a model forecast, it is the best source of spatially distributed wind speed over the island. The atmospheric stability coefficient is estimated from (Yunhao et al., 2001):

$$\phi = \left[1 - \frac{\left[\eta \cdot (z - z_{disp}) \cdot g \cdot (T_s - T_a)\right]}{T_o \cdot u^2}\right] \tag{7}$$

where g is acceleration of gravity, and the coefficient η is commonly taken as 5 (Yunhao et al., 2001). The temperature T_o is the average of the values of T_s and T_a. The excess resistance $r_{bh} = 4/U^*$, where the friction velocity is $U^* = k\ u\ /\ \ln[(z - z_{disp})/z_o)]$. Surface or canopy resistance (r_s) was estimated using the equation of Ortega-Farias et al. (2008):

$$r_S = \frac{\rho \cdot C_p \cdot VPD}{\Delta \cdot (R_n - G) \cdot C_F} \cdot \left(\frac{\theta - \theta_{WP}}{\theta_{FC} - \theta_{WP}} \right)$$

(8)

where Δ is the slope of the saturation vapor pressure curve at the mean temperature, VPD is the vapor pressure deficit, C_f is a calibration coefficient equal to 1 in this study, θ is volumetric soil moisture content in the root zone, and θ_{FC} and θ_{WP} are the volumetric soil moisture content at field capacity and wilting point, respectively. Values of field capacity and wilting point were obtained from regression equations based on percent sand, silt and clay presented by Cemek et al. (2004). Percentages of sand, silt and clay for Puerto Rico were obtained from the Soil Survey Geographic (SSURGO) Database of the USDA Natural Resource Conservation Service (http://soils.usda.gov/survey/geography/ssurgo/).

A water balance was performed in each of the 1 km^2 pixels with the equation:

$$SMD2 = PRECIP - ET_a - RO - DP + SMD1$$

(9)

where SMD1 and SMD2 are the depths of water in the soil profile at the beginning and end of the day (24 hours), respectively, PRECIP is rainfall, ET_a is the actual evapotranspiration (described above), RO is surface runoff and DP is deep percolation or the soil water that passes below the root zone. The water balance analysis is performed over the soil profile depth equal to root depth (R_{depth}). Root depth for various land use/vegetation categories were obtained from ATMET (2005). The 24-hour rainfall is obtained from NOAA's Advanced Hydrologic Prediction Service (AHPS) website (http://water.weather.gov/precip/). In Puerto Rico, the source of the AHPS rainfall is NEXRAD radar and rain gauge data. Runoff is estimated using the Curve Number method of the Soil Conservation Service (SCS, 1972):

$$RO = (PRECIP - 0.2S)^2 / (PRECIP + 0.8S)$$

(10)

$$S = [(25400 / CN) - 254]$$

(11)

where S is the maximum potential difference between rainfall and runoff at the moment of rainfall initiation, CN is the curve number which is a proportion of rainfall converted to runoff, and is adjusted for antecedent soil moisture conditions (Fangmeier et al., 2006).

An initial value of SMD2 is calculated with a modification of equation 9: $SMD2_i = PRECIP - ETa - RO + SMD1$. If the Value of $SMD2_i$ is larger than the depth of water in the soil profile at field capacity (FCD), then DP = $SMD2_i$ - FCD and the value of SMD2 is equal to FCD. If however, $SMD2_i$ < FCD, then DP = 0, and SMD2 = $SMD2_i$.

RESULTS AND DISCUSSION

Remotely sensed solar radiation from the GOES satellite was compared with daily integrated solar radiation from pyranometers located at six locations in western Puerto Rico during the period from April 2009 to June 2010. Figure 1 shows the measured data plotted against the remotely sensed data. The observed scatter is considerably greater than Sumner et al. (2008) obtained in Florida using the same method. In this study, the power function shown in Figure 1 was used to obtain values of R_s used in the calculations. Future efforts could take advantage of the expanded capabilities of the GOES-R instruments (anticipated launch date 2015) for possible improvement of the remote sensing algorithm for solar radiation under tropical conditions. It should also be noted that the pyranometers used for comparison may themselves be in error and need to be checked for accuracy.

Figure 2 and 3 show the estimated reference evapotranspiration (ET_o) for Puerto Rico, Haiti and the Dominican Republic, respectively, on June 29, 2010. Figure 4 shows the estimated actual evapotranspiration for Puerto Rico for the same day. By taking the ratio of ET_a to ET_o, the "crop" coefficient (K_c) was obtained (Figure 5). Estimated K_c values are between 0.3 and 0.9, which are quite reasonable. (Note, values of zero along the island/ocean interface are an artifact of the grid resolution, where a portion of the pixel may extend into the ocean. These anomalous values can be ignored.)
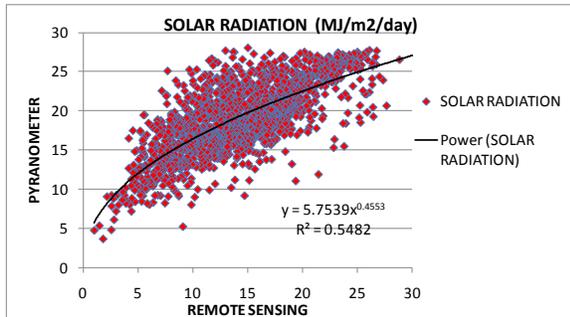
Figure 1. Comparison of solar radiation obtained from pyranometers at six locations in Puerto Rico and satellite remote sensing.
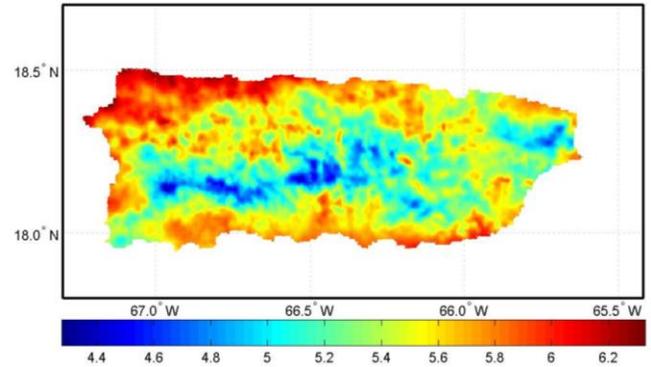

Figure 2. Estimated reference evapotranspiration (ETo) for Puerto Rico on June 29th, 2010.

Figure 6 shows the total rainfall that occurred in Puerto Rico on June 29, 2010. The figure indicates a relatively large amount of rain fell in the north central and northwestern portions of the island. In this study, CN values were not available; therefore a new CN map was developed for Puerto Rico based on land cover and soil hydrologic group obtained from the SSURGO data (Figure 7). Figure 8, 9 and 10 show the estimated surface runoff, deep percolation and soil moisture content on June 29, 2010. To initialize the analysis, a value of the soil moisture equal to the field capacity was set for each pixel on June 20th. Subsequently, the soil moisture was updated daily as described in the previous section. Due to abundant rainfall during the 10-day analysis period, the soil moisture was still very close to the field capacity throughout most of the island on June 29th.
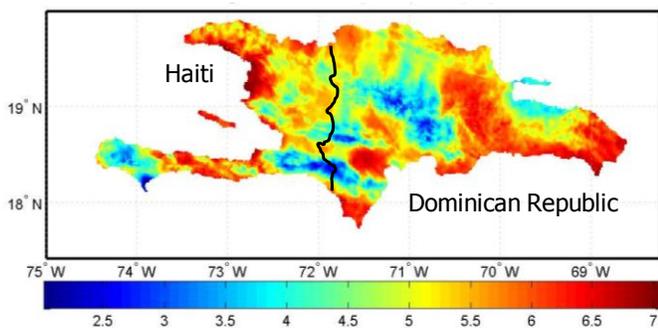

Figure 3. Estimated reference evapotranspiration (ETo) for Haiti and the Dominican Republic on June 29th, 2010.
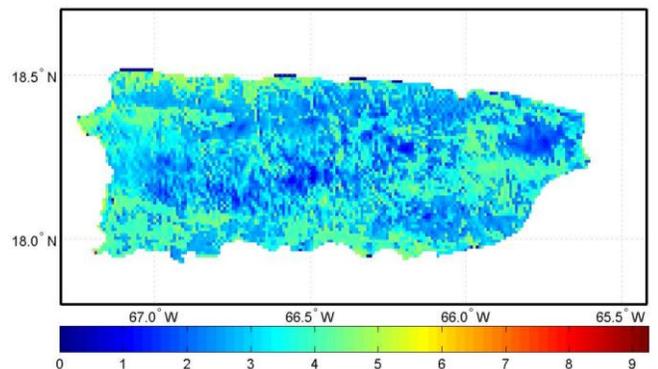

Figure 4. Estimated actual evapotranspiration (ETa) for Puerto Rico on June 29th, 2010.
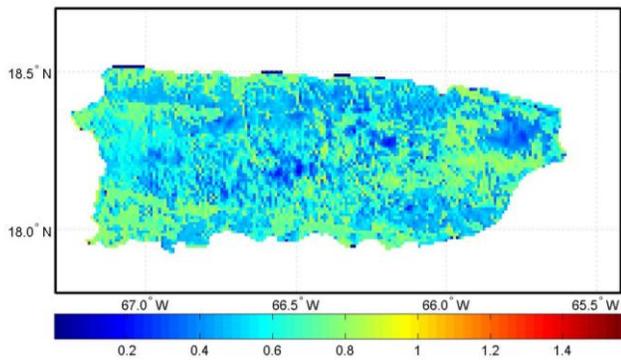
Figure 5. Estimate "crop" coefficient (K_c) over Puerto Rico on June 29, 2010.
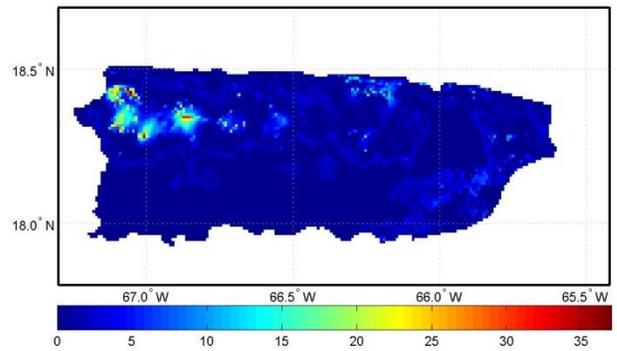

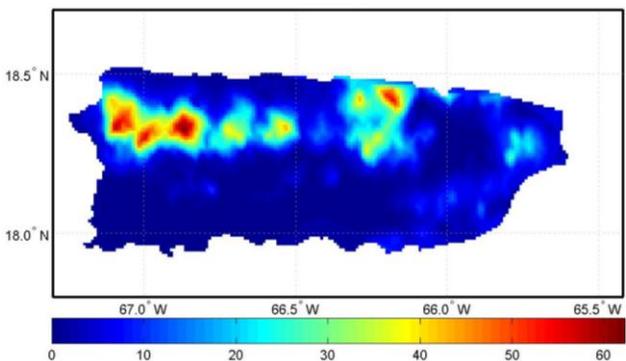Figure 8. Estimated surface runoff in Puerto Rico on June 29, 2010.

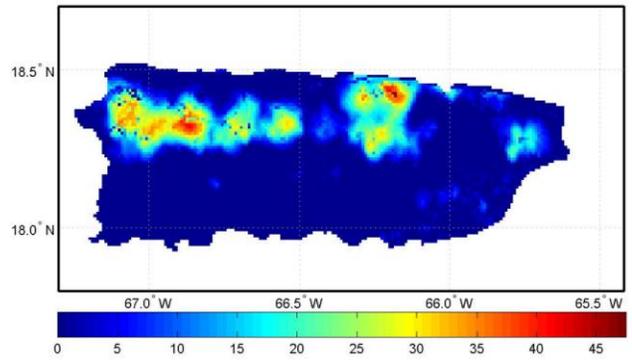Figure 6. AHPS rainfall over Puerto Rico on June 29, 2010.

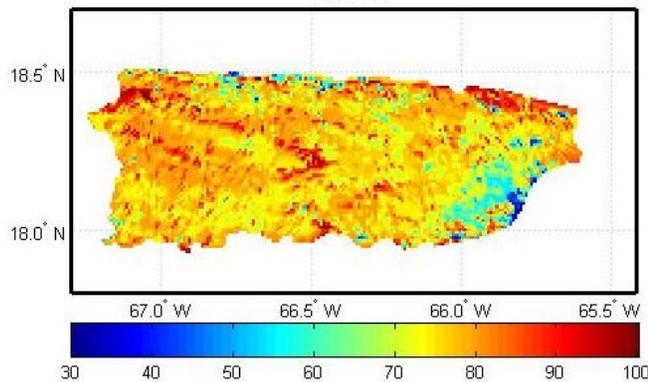Figure 9. Estimated deep percolation on June 29, 2010.
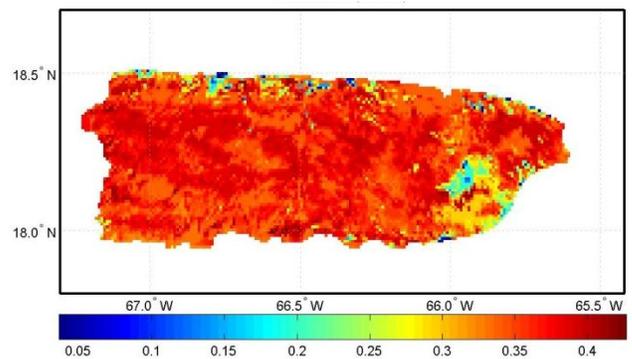

Figure 7. Curve Number map for Puerto Rico.

Figure 10. Estimated soil moisture in Puerto Rico on June 29, 2010.

SUMMARY

In this paper we describe a method for estimating reference evapotranspiration in Puerto Rico, Haiti and the Dominican Republic. A method for estimating the actual evapotranspiration and performing a water balance analysis over Puerto Rico is also described. A comparison of the measured solar radiation and satellite remotely sensed solar radiation indicated a relatively low coefficient of determination. Future efforts should investigate the quality of the pyranometers used in this study and possible improvement of the satellite algorithm. Estimates of reference evapotranspiration for June 29, 2010, were provided for Puerto Rico, Haiti and the Dominican Republic, and the estimated actual evapotranspiration, surface runoff, deep percolation and soil moisture content for Puerto Rico on the same day were presented.

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