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***Satellite-Based Daily Evapotranspiration Estimation in Puerto Rico***

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**Abstract:** A technique is presented in which satellite solar insolation estimates are used to predict daily reference evapotranspiration ( $ET_o$ ) using the Penman-Monteith (PM), Priestly-Taylor (PT) and Hargreaves-Samani (HS) methods for Puerto Rico. For this approach, average, minimum and maximum daily air temperatures were obtained from a regression procedure that depends on surface elevation and day of the year. The air temperature was adjusted using actual daily temperatures from several locations in PR. Dew point temperature was assumed to be equal to the daily minimum temperature, and a value of 1.9 m/s was assumed for wind speed. As an example,  $ET_o$  was estimated for March 5, 2009 using the three methods, with the Penman-Monteith method producing the lowest values. This research represents a preliminary step in the development of an  $ET_o$  product for PR. This product is a potentially valuable tool for conducting water resource studies and for supporting irrigation scheduling efforts.

Key-Words: - GOES, satellite, remote sensing, Penman-Monteith, Priestly-Taylor, Hargreaves-Samani, evapotranspiration

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## INTRODUCTION

Determination of evapotranspiration is important for evaluation of hydrologic resources of a region, and evaluating irrigation requirements. Because of the inter-relation between components of the hydrologic cycle, evapotranspiration is important in the evaluation of soil water content, surface runoff, and aquifer recharge. Evapotranspiration (ET) is defined as the combination of evaporation from soil and plant surfaces, and transpiration from plant leaves. Evaporation is the process whereby liquid water is converted to water vapor and removed from the evaporating surface [1]. Transpiration is the vaporization of liquid water contained in plant tissues and its subsequent removal to the atmosphere. Crops predominately lose water through small openings in their leaves called stomata. Evapotranspiration can be expressed in units of mm/day (or in/day), or as an energy flux in units of MJ m<sup>-2</sup> day<sup>-1</sup> [1]. Evapotranspiration is important because it is often the largest component of the hydrologic cycle after rainfall. Under arid conditions, potential ET can easily exceed rainfall.

Remote sensing methods for estimating ET are needed for tropical conditions. Various techniques have been developed based on radiation methods (e.g. [2]) and surface energy budgets (e.g., [3, 4]).

The objective of this study was to develop an algorithm for estimating daily, high resolution (1-km), crop reference evapotranspiration (ET<sub>o</sub>) over Puerto Rico. Three radiation-based ET<sub>o</sub> methods will be tested and compared.

## METHODS

In this study we will estimate the ET flux using the Penman-Monteith [1], Priestly-Taylor [5] and Hargreaves-Samani [6] methods, in combination with a solar radiation product of the GOES-12 satellite. Solar radiation was derived using the radiative transfer model of Diak et al. [7]. Input required for the Penman-Monteith

was based on procedures developed for Puerto Rico by Harmsen et al. [8].

Of the three methods, the Penman-Monteith (PM) method is generally regarded as superior because it takes into account the major variables which control evapotranspiration [1], and the method has been rigorously validated under diverse conditions throughout the world [9]. The Penman-Monteith method is given by Allen et al. (1998) as:

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \left( \frac{900}{T + 273} \right) \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \quad (1)$$

where  $\Delta$  is slope of the vapor pressure curve [kPa °C<sup>-1</sup>],  $R_n$  is net radiation [MJ m<sup>-2</sup> day<sup>-1</sup>],  $G$  is soil heat flux density [MJ m<sup>-2</sup> day<sup>-1</sup>],  $\gamma$  is psychrometric constant [kPa °C<sup>-1</sup>],  $T$  is mean daily air temperature at 2 m height [°C],  $u_2$  is wind speed at 2 m height [m s<sup>-1</sup>],  $e_s$  is the saturated vapor pressure and  $e_a$  is the actual vapor pressure [kPa]. Equation 1 applies specifically to a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec m<sup>-1</sup> and an albedo of 0.23.

The Priestly-Taylor equation (PT) represents a simplification of the Penman equation [10, 11] and is valid for humid conditions:

$$ET_o = \alpha \cdot \frac{\Delta \cdot (R_n - G)}{(\Delta + \gamma)} \quad (2)$$

where  $\alpha$  is the Priestly-Taylor constant equal to 1.26, and the other variables/parameters were previously defined. A value of 1.32 has been recommended for estimates from vegetated areas as a result of the increase in surface roughness [12]. In this study a value of 1.3 was used.

The Hargreaves-Samani (HS) reference evapotranspiration equation is

$$ET_0 = 0.0135 R_s (T + 17.8) \quad (3)$$

in which  $ET_0$  and solar radiation (insolation),  $R_s$ , are in the same equivalent units of water evaporation [ $L T^{-1}$ ], and  $T$  is mean temperature in degrees C. Harmsen et al. [8] reported good agreement between the PM and HS methods for 34 locations in Puerto Rico.

Daily average temperature was estimated using the regression equations of Goyal et al. [13], which relate temperature to elevation in Puerto Rico. The equations provide values of daily mean temperature for each month of the year. The monthly data were regressed to obtain a polynomial equation relating the day of the year with air temperature. The average daily air temperature was “nudged” based on the actual average daily temperature measured from the Natural Resource Conservation Service (NRSC) Soil Climate Analysis Network (SCAN) sites in western Puerto Rico. These sites include coastal and mountainous conditions.

An average value of 1.9 m/s was used for wind speed in the PM model based on the published average winds speeds for the six NOAA Climate Divisions for Puerto Rico [8]. This value is close to the world-wide average value of 2 m/s recommended by the FAO [1] in the absence of observed data.

Saturated and actual vapor pressures are estimated based on the average and dew point temperatures, respectively. For convenience, in this study the dew point temperature was assumed to be equal to the minimum temperature based on the regression method for minimum temperature of Goyal et al. [13] and nudged using actual air temperature data from the seven SCAN stations. For humid conditions, use of minimum temperature for dew point temperature is generally a valid assumption. For the drier south and southwest part of Puerto Rico, however, the assumption may lead to errors in the  $ET_0$  calculation.

Solar radiation ( $R_s$ ) was estimated with the radiative transfer model of Diak et al. [7] using

data from the visible-channel of the GOES satellite. More information on this  $R_s$  product can be found in Sumner et al. [2]. The methods presented in Allen et al. [14] were used to calculate extraterrestrial radiation ( $R_a$ ),  $R_n$  and  $G$ .

## RESULTS

In this section we present the  $ET_0$  estimates based on the PM, PT and HS methods for March 5<sup>th</sup>, 2009. Table 1 shows the weather information for the seven SCAN stations in Puerto Rico for this day. Figure 1 shows a visible satellite (GOES) image at 15:15 local time (19:15 UTC), indicating large-scale cloud bands covering the region. The National Weather Service in San Juan reported haze, fog and light rain during the day. The National Weather Service (NWS) reported severe rain in Vaga Alta, Puerto Rico with flooding reported at 15:38 local time (19:38 UTC). However, other locations in Puerto Rico experienced little or no rainfall during the day (Table 1). Figure 2 shows the NEXRAD radar total storm rainfall at 15:26 local time (19:26 UTC), indicating rain bands extending across a significant portion of the island.

Table 1. Weather information from the seven SCAN stations on March 5<sup>th</sup>, 2009.

Site	Isabela	Maricao	Guilarte	Fortuna	Combate	Mayaguez	Bosque
Elevation (m)	15	746	1019	28	10	14	165
Rainfall (mm)	2.8	1.8	14.7	0.0	0.0	1.5	0.0
Average Temperature (C)	23.1	17.6	15.8	23.7	23.8	23.1	22.5
Minimum Temperature (C)	21.9	15.9	14.0	20.6	21.3	21.4	19.5
Maximum Temperature (C)	24.4	18.8	16.9	27.0	27.4	25.4	26.7
Relative Humidity (%)	77.4	96.6	97.1	75.7	68.5	79.6	78.8
Wind Speed (m/s)	4.8	2.3	0.8	2.4	0.9	0.8	0.05
Solar Radiation (W/m2)	255	215	92	304	332	304	211

Figure 3 shows the estimated average air temperature distribution in Puerto Rico on March 5<sup>th</sup>, 2009. The average air temperature

was based on the regression method of [13] which relates temperature with surface elevation (Figure 4). The estimated versus observed average air temperature are shown in Figure 5. The regression equation was used to estimate the average air temperature in Figure 3.

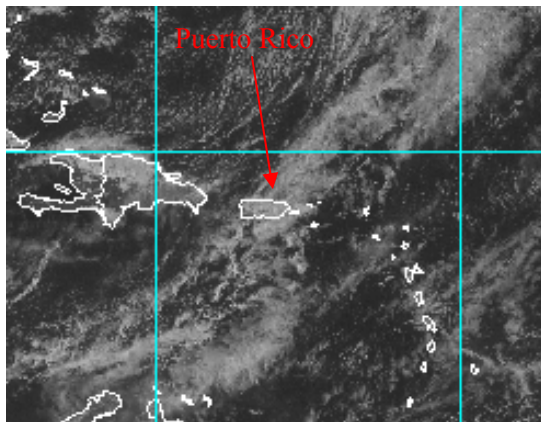


Figure 1. Visible satellite image of Caribbean region at 15:15 local time (19:15 UTC).

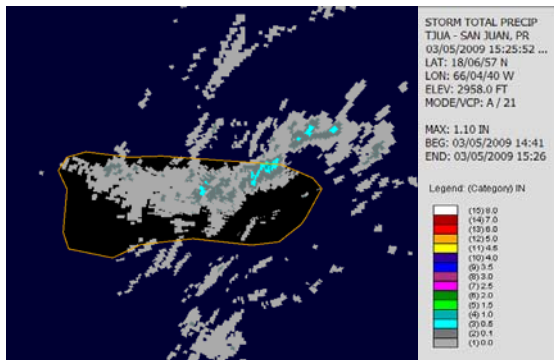


Figure 2. NEXRAD radar storm total precipitation in inches over Puerto Rico at 15:26 local time (19:26 UTC).

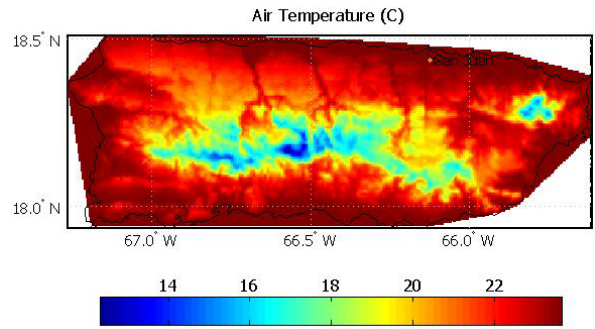


Figure 3. Estimated average air temperature on March 5<sup>th</sup>, 2009.

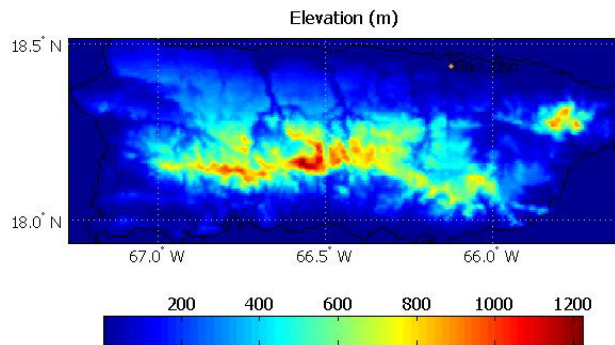


Figure 4. Surface elevation in Puerto Rico.

Figure 6 shows the distribution of solar insolation across Puerto Rico on March 5<sup>th</sup>, 2009. The figure indicates that the west and south west parts of the island received significantly more solar insolation than central, northern and north eastern Puerto Rico. The southeast received an intermediate level of solar insolation. This spatial pattern of the solar insolation is apparent in the NEXRAD radar storm total precipitation distribution (Figure 2).

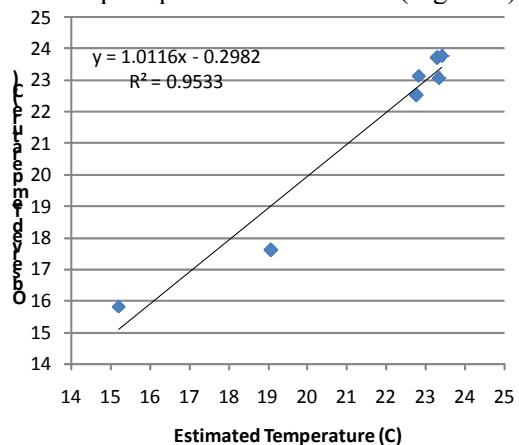


Figure 5. Estimated versus observed daily average temperature at the seven SCAN stations in Puerto Rico. The regression equation was used to estimate air temperature in Figure 3.

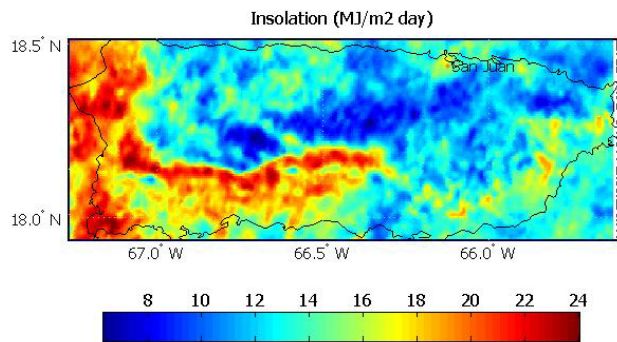


Figure 6. Integrated daily solar insolation for Puerto Rico on March 5<sup>th</sup>, 2009.

Figure 7, 8 and 9 show the daily  $ET_o$  estimated using the PM, PT and HS methods, respectively. The  $ET_o$  spatial distributions closely match the solar insolation pattern (Figure 6). In general the three methods are in good agreement. The PM method produced the lowest  $ET_o$  values, as compared to the PT and HS methods (see differences in the figure color bars). The lowest  $ET_o$  values occur in the mountain areas associated with the lowest air temperatures (Figure 3), and where solar insolation was the lowest.

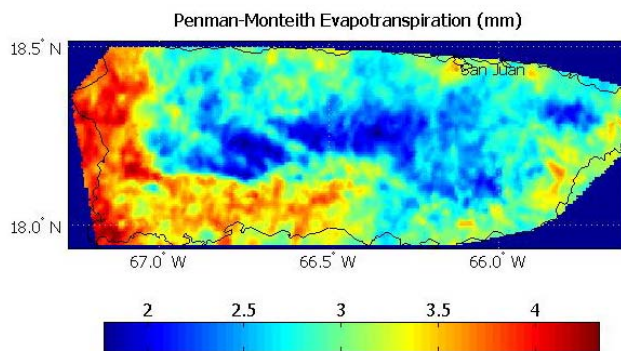


Figure 7. Penman-Monteith  $ET_o$  distribution in Puerto Rico for March 5<sup>th</sup>, 2009.

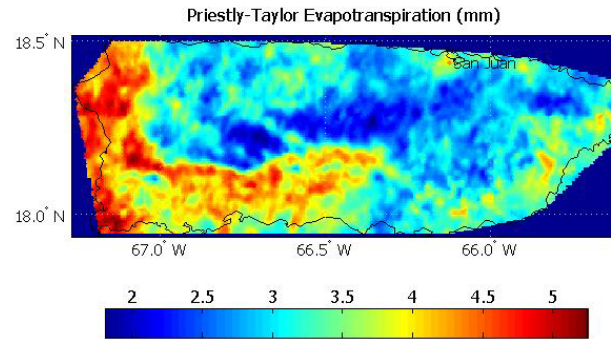


Figure 8. Priestly-Taylor  $ET_o$  distribution in Puerto Rico for March 5<sup>th</sup>, 2009.

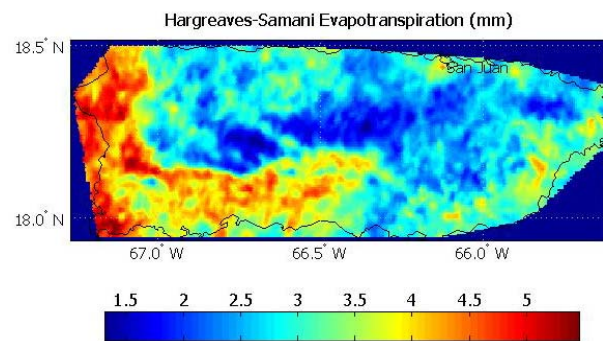


Figure 9. Penman-Monteith  $ET_o$  distribution in Puerto Rico for March 5<sup>th</sup>, 2009.

Table 2 compares the PM, PT and HS  $ET_o$  values at the SCAN stations with the long-term average  $ET_o$  as calculated by the computer program PRET [15]. All values for March 5<sup>th</sup> were lower than the long-term average values (PRET). The lowest value of  $ET_o$  was associated with the Guilarte site where the observed and estimated solar radiation were 92 and 118  $W/m^2$ , respectively, and observed and estimated average daily temperatures were 15.8 and 15.2 C, respectively.

#### METHOD LIMITATIONS

Theoretically, the PM method is the most accurate of the three; however, numerous assumptions were made in developing the input for the PM method. For example, the wind speed was assumed to be 1.9 m/s over the entire island. Table 1 indicates that average daily wind speeds at the SCAN stations varied between

0.05 to 4.8 m/s, with an average of 1.2 m/s. Future efforts need to incorporate spatially varied wind speed. Air temperature was estimated as described in the Methods section. As can be seen from Figure 5, there was excellent agreement between the estimated and observed temperatures at the seven SCAN sites. However, these stations are limited to locations in western Puerto Rico. Central, northern and northeastern Puerto Rico received relatively low levels of insolation as compared to west and southern Puerto Rico, and consequently the estimated air temperatures in those areas may be over estimated.

Table 2.  $ET_0$  estimated by PM, PT and HS methods for March 5<sup>th</sup>, 2009 compared with the long-term average  $ET_0$  calculated with the Puerto Rico ET (PRET) computer program [15].

Station	Ele. (m)	Latitude	$ET_0$			
			PRET	PM	PT	HS
Isabela	15	18.28	4.7	3.8	3.6	3.7
Maricao	746	18.15	3.9	3.8	4.1	4.3
Guilarte	1019	18.15	3.7	2.4	2.3	1.9
Fortuna	28	18.03	5.0	3.9	3.7	3.9
Combate	10	17.98	5.0	3.8	3.6	3.8
Mayaguez	14	18.22	4.5	3.9	3.8	4.0
Bosque	165	17.97	5.1	3.4	3.1	3.0

### SUMMARY AND CONCLUSIONS

A remote sensing-based technique is presented for estimating evapotranspiration in Puerto Rico. The method relies on solar insolation derived from the GOES satellite. Temperature is estimated from a regression approach which is a function of surface elevation and day of the year. Temperatures are further adjusted using actual daily temperatures from several locations in Puerto Rico. Reference  $ET_0$ s were estimated for Puerto Rico for March 5<sup>th</sup>, 2009, a day with scattered clouds and rainfall. The Penman-Monteith, Priestly-Taylor and Hargreaves-Samani methods in general produced similar results, with the Penman-Monteith producing the lowest values. Several improvements could be pursued in future research, including the incorporation of spatially variable wind speed, calibration of the insolation algorithm for Puerto Rico, improvement of the dew point temperature

estimation, estimation of short-term (sub-hourly) reference  $ET_0$ , and estimation of the effective crop coefficient based on the Normalized Difference Vegetation Index (NDVI) for estimating actual evapotranspiration.

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