Estimating Daily Evapotranspiration in Puerto Rico using Satellite Remote Sensing

ERIC. W. HARMSEN[1], JOHN MECIKALSKI[2], MELVIN J. CARDONA-SOTO[3], ALEJANDRA ROJAS GONZALEZ[4] AND RAMÓN VASQUEZ[5]

[1]Department of Agricultural and Biosystems Engineering
University of Puerto Rico – Mayagüez Campus
P.O. Box 9030, Mayagüez, PR 00681
U.S.A.
eric.harmsen@upr.edu http://academic.uprm.edu/abe/PRAGWATER

[2]Department of Atmospheric Sciences
University of Alabama in Huntsville (UAH)
National Space Science and Technology Center (NSSTC)
U.S.A.
johnm@nsstc.uah.edu

[3]Department of Electrical and Computer Engineering
University of Puerto Rico – Mayagüez Campus
Mayagüez, PR 00680
U.S.A.
cardonam@gmail.com

[4]Department of Civil Engineering
University of Puerto Rico – Mayagüez Campus
Mayagüez, PR 00680
U.S.A
alejandra_rojaspr@yahoo.com

[5]Department of Computer and Electrical Engineering
University of Puerto Rico – Mayagüez Campus
Mayagüez, PR 00681,
U.S.A
reve@ece.uprm.edu

ABSTRACT: Evapotranspiration (ET) is an important component of the hydrologic cycle. Quantification of ET is essential for proper irrigation scheduling and water conservation efforts. A technique is presented in which satellite solar insolation estimates are used to predict daily reference evapotranspiration (ET_o) using the Penman-Monteith (PM), Preistly-Taylor (PT) and Hargreaves-Samini (HS) methods for Puerto Rico. In addition to solar insolation, other meteorological variables (e.g., net radiation, soil heat flux, air temperature dew point temperature and wind speed) are estimated. As an example of the methodology, ET_o was estimated over Puerto Rico for March 5, 2009 using the three methods. The results indicated relatively close agreement between the methods; however, the Penman-Monteith method produced the lowest values.

This paper also presents a comparison between estimated and observed solar radiation from April 1 through June 21, 2009, which indicates a need for calibration of the solar radiation remote sensing product. As a practical example of the use of the methodology, the Hargraeves-Samani ET_o was estimated for a crop season. The crop evapotranspiration (ET) was estimated by multiplying the ET_o by a crop coefficient (K_c). The goal of the analysis, which considered five different crops and seven locations, was to determine the cumulative seasonal water consumptive use. Determination of the seasonal water consumptive use is valuable for determining water supply infrastructure for farms and irrigation districts. 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

1 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^{-2} day^{-1} [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]). Remote sensing of ET has several important advantages over the use of pyranometer networks including large spatial coverage, relatively high spatial resolution, the availability of data in remote, inaccessible, regions, and in countries that may not have the means to install a ground-based pyranometer network [5]

The objective of this study was to develop an algorithm for estimating daily, high resolution (1-km), crop reference evapotranspiration (ET_o) over Puerto Rico. Three radiation-based ET_o methods will be tested and compared. A practical example is given in which the seasonal consumptive water use is determined for five different vegetable crops at seven locations in western and southern Puerto Rico.

Harmsen et al. [6] have evaluated several climate change scenarios for Puerto Rico which indicates that the dry season may become drier and longer in the future. Therefore, a reliable remote sensing evapotranspiration product for Puerto Rico will become increasingly valuable for supporting water resources studies in the future. Such a product can be combined with quantitative precipitation estimation (QEP) methods such as the National Oceanic and Atmospheric Administration's (NOAA) Hydro_Estimator [7, 8], with the goal of performing water budgets at the watershed scale.

2 Methods

In this study we will estimate the ET flux using the Penman-Monteith [1], Priestly-Taylor [9] and Hargreaves-Samani [10] 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. [11]. Input required for the Penman-Monteith was based on procedures developed for Puerto Rico by Harmsen et al. [12].

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 [13]. The Penman-Monteith method is given by the equation [14]:

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

where Δ is 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}], γ is psychrometric constant [kPa °C^{-1}], T is mean daily air temperature at 2 m height [°C], u_2 is wind speed at 2 m height [m s^{-1}], 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^{-1} and an albedo of 0.23.

The Priestly-Taylor equation (PT) represents a simplification of the Penman equation [15, 16] and is valid for humid conditions:

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

where α 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 [17]. In this study a value of 1.3 was used.

The Hargreaves-Samani (HS) reference evapotranspiration equation is

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

in which ET_o 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. [12] 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. [18], 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 and southern Puerto Rico. These sites include coastal and mountainous conditions (Fig, 1).

Figure 1. Locations of NRCS SCAN weather stations in Puerto Rico.

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 [12]. 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. [18] 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_o calculation.

Solar radiation (R_s) was estimated with the radiative transfer model of Diak et al. [11] 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. [19] were used to calculate extraterrestrial radiation (R_a), R_n and G.

3 Results

In this section we present the ET_o estimates based on the PM, PT and HS methods for March 5th, 2009. Table 1 shows the weather information for the seven SCAN stations in Puerto Rico for this day and Fig. 1 shows the locations of the SCAN weather stations. Fig. 2 shows a visible satellite (GOES) image at 15:15 local time (19:15 UTC), indicating large-scale cloud bans 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). Fig. 3 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 5th, 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

Fig. 4 shows the estimated average air temperature distribution in Puerto Rico on March 5th, 2009. The average air temperature was based on the regression method of [18] which relates temperature with surface elevation (Fig. 5). The estimated vs. observed average air temperature are shown in Fig. 6. The regression equation was used to estimate the average air temperature in Fig. 4.

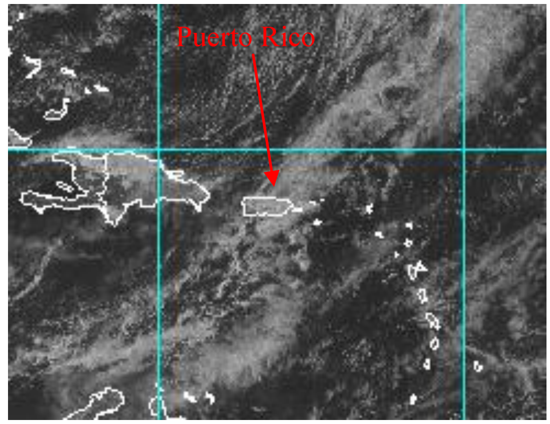

Fig. 2. Visible satellite image of Caribbean region at 15:15 local time (19:15 UTC).

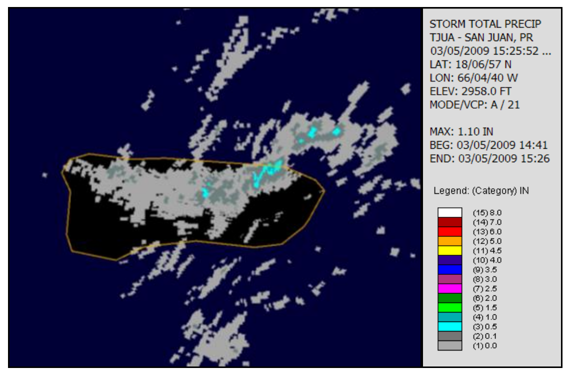

Fig. 3. NEXRAD radar storm total precipitation in inches over Puerto Rico at 15:26 local time (19:26 UTC).

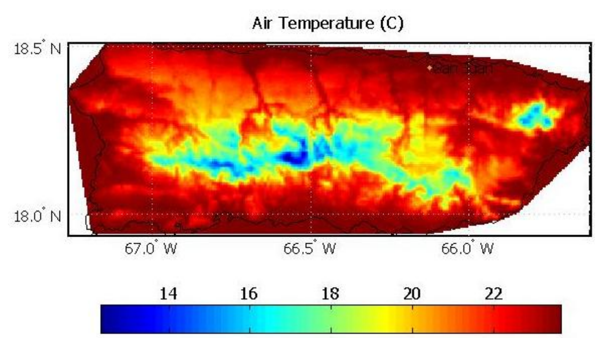

Fig. 4. Estimated average air temperature on March 5th, 2009.

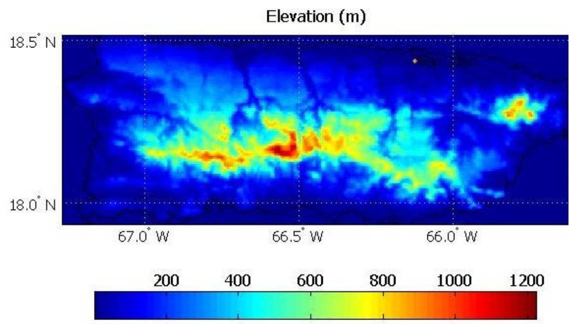

Fig. 5. Surface elevation in Puerto Rico.

Fig. 7 shows the distribution of solar insolation across Puerto Rico on March 5th, 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 (Fig. 3).

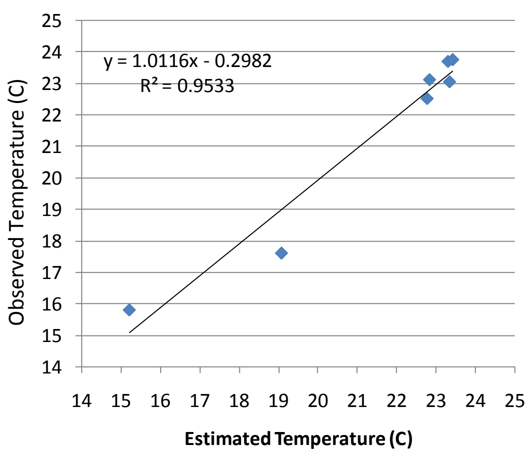

Fig. 6. Estimated versus observed daily average temperature at the seven SCAN stations in Puerto Rico. The regression equation was used to estimate air temperature in Fig. 3.

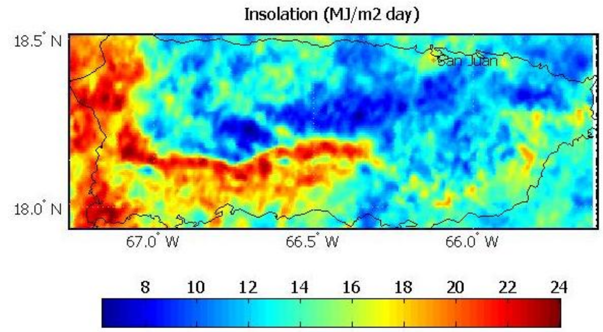

Fig. 7. Integrated daily solar insolation for Puerto Rico on March 5th, 2009.

Figures 8, 9 and 10 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 (Fig. 7). 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 (Fig. 3), and where solar insolation was the lowest.

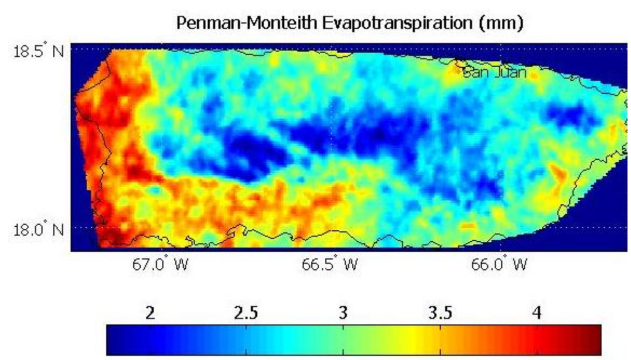

Fig. 8. Penman-Monteith ET_o distribution in Puerto Rico for March 5th, 2009.

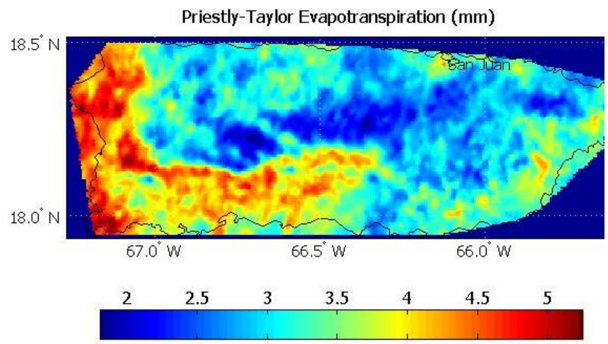

Fig. 9. Priestly-Tailor ET_o distribution in Puerto Rico for March 5th, 2009.

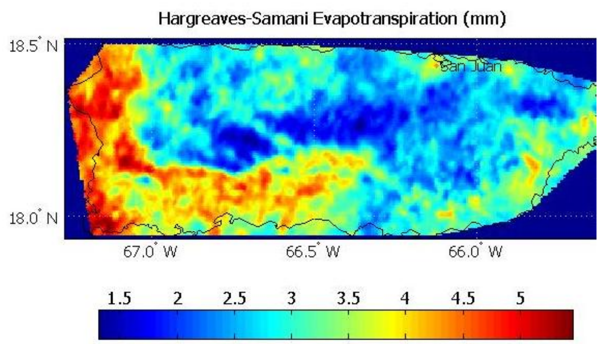

Fig. 10. Penman-Monteith ETo distribution in Puerto Rico for March 5th, 2009.

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 [20]. All values for March 5th 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 7.9 MJ/m^2 day and 10.17 MJ/m^2 day W/m^2, respectively, and observed and estimated average daily temperatures were 15.8 and 15.2 C, respectively.

Table 2. ET_o estimated by PM, PT and HS methods for March 5th, 2009 compared with the long-term average ET_o calculated with the Puerto Rico ET (PRET) computer program [20].

			ET_o			
Station	**Ele. (m)**	**Latitude**	**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

3.1 Example Application – Seasonal ET Estimation

An example application is provided below in which seasonal evapotranspiration is estimated for five different vegetable crops: Tomato (*Lycopercicum esculantum*), Sweet Corn (*Zea mays*), Squash (*Cucurbita Maxima*), Lettuce (*Lactuca sativa*) and Sweet Pepper (*Capsicum annuum*). The seasonal ET estimates were performed at the locations associated with the seven SCAN weather stations (Fig. 1). Remotely sensed solar radiation data for April 9-11, 23, May 8-10, 18-28 were missing. Therefore, the evapotranspiration for these days were estimated using the measured solar radiation from the SCAN weather station, except in the case of Combate, where no weather station data were available for the period of interest. Therefore, in the case of Combate, the missing remote sensing solar radiation data were estimated using a linear interpolation between the “last” and “next” days when remotely sensed solar radiation data were available.

The actual crop evapotranspiration was estimated from the relation [1]:

$$ET = K_c\, ET_o \qquad (6)$$

where ET is crop evapotranspiration and K_c is the evapotranspiration crop coefficient. In this example, ET_o was estimated using the Hargreaves-Samani equation (equ. 3), which depends only on the solar radiation and average daily air temperature. The remote sensing approach was found to overestimate on average the daily solar insolation, as shown in Figure 11. Therefore, in this example the estimate of solar radiation was improved by using the best-fit exponential regression equation:

$$R_{s\_obs} = 4.0371 \cdot e^{0.0665 \cdot R_{s\_est}} \quad (4)$$

where R_{s_obs} represents an estimate of the observed solar radiation, and R_{s_est} is the remotely sensed solar radiation. The data in Fig. 11 includes data from the Fortuna, Bosque, and Mayaguez sites. Data from Isabela, Maricao and Guilarte appear to be unreliable and therefore were not used in the regression analysis (equ. 6), and data from Combate was not available. Maricao and Guilarte weather stations are located in forests and shading of the pyranometers likely occurred. In the case of Isabela, the solar insolation data is reported in units of Langley and when converted to MJ/m^2day are suspiciously low, and therefore were not used.

The estimation procedure for air temperature based on surface elevation was improved using the following linear regression equation based on the best-fit curve shown in Figure 12.

$$T_{avg\_obs} = 0.8295 \cdot \left(T_{avg\_est} \right) + 3.6156 \quad (5)$$

where T_{avg_obs} represents an estimate of the observed temperature and T_{avg_est} is the estimated air temperature.

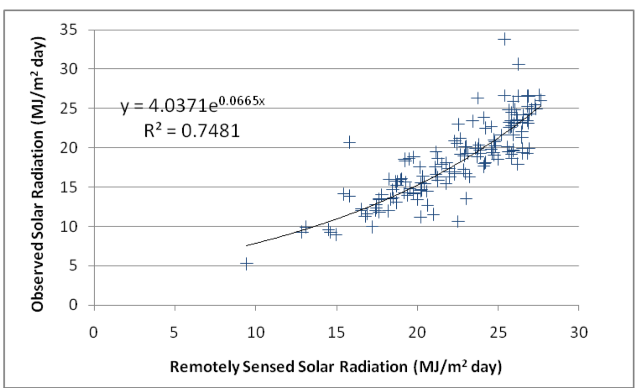

Figure 11. Estimated and observed solar radiation from six of the SCAN weather station sites (Combate observed data not available). A best-fit exponential curve is include along with the data.

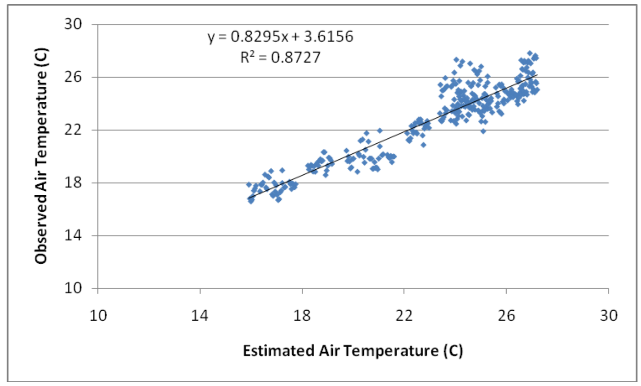

Fig. 12. Estimated and observed average air temperature at six of the SCAN weather stations (Combate observed data not available). A best-fit linear regression curve is include along with the data.

The crop coefficients (Fig. 13) were determined by the FAO method [1]. The initial K_c value of 0.45 was based on mainly soil evaporation assuming 20 mm of irrigation every 4 days. The length of the growing season in each case was 80 days with the initial, developmental, mid and end crop growth stages equal in duration (20 days each).

As an example, Fig. 14 shows the daily reference evapotranspiration and crop evapotranspiration for sweet pepper at Fortuna. The evapotranspiration data is observed to be highly variable which is consistent with the observed variability of the solar radiation (Fig. 15). Table 3 lists the seasonal ET for each of the five crops and the seven locations. Sweet Corn at Combate exhibited the maximum consumptive water use (277 mm), while the minimum consumptive water use (191 mm) was associated with Squash at Guilarte. The information contained in Table 3 is valuable for determining pumping water supply infrastructure for farms and irrigation districts.

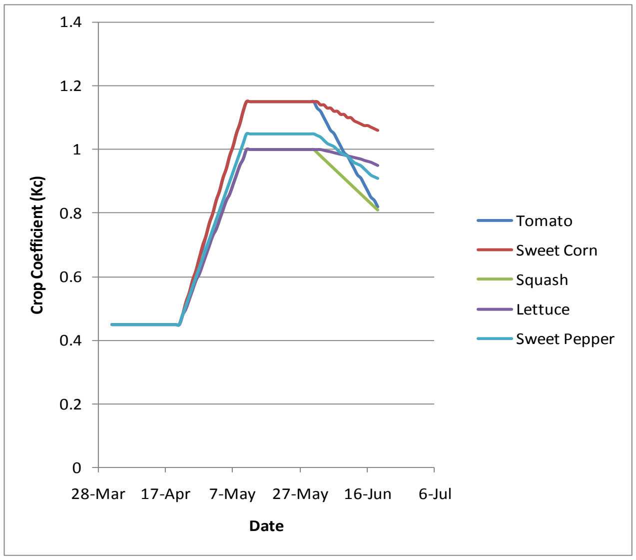

Fig. 13. Evapotranspration crop coefficients for Tomoto, Sweet Corn, Squash, Lettuce and sweet pepper from April 1 – June 21, 2009.

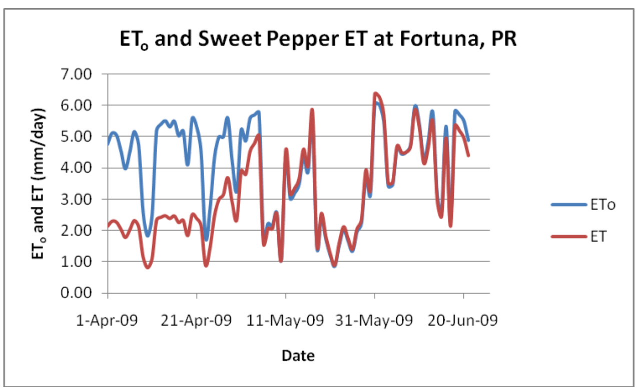

Fig. 14. Reference evapotranspiration (ET_o) and sweet pepper evapotranspiration (ET) during the growing season (April 1-June 21, 2009) at Fortuna, PR.

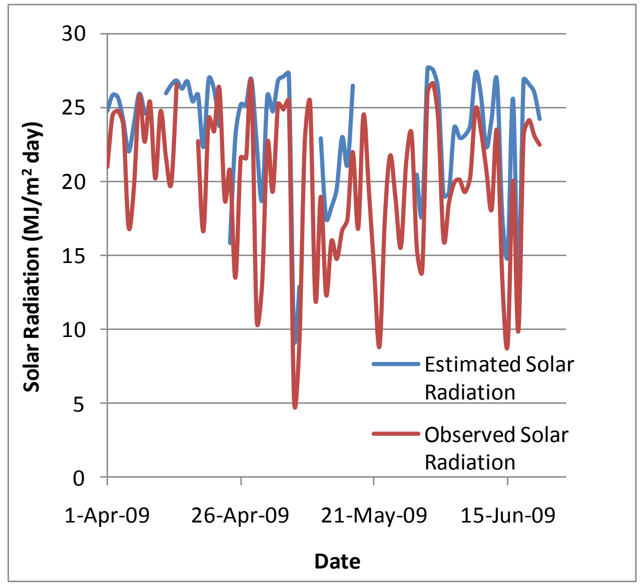

Fig. 15. Esimated and observed solar radiation during the period April 1 through June 21, 2009 at Fortuna, PR.

Table 3. Seasonal evapotranspiration for five crops at the seven SCAN sites during a crop season (April 1 – June 21, 2009).

	Seasonal Evapotranspiration (mm)						
Crop	Isabela	Maricoa	Guilarte	Fortuna	Combate	Mayaguez	Bosque
Tomato	217	207	198	263	283	232	291
Sweet Corn	228	219	208	277	297	243	305
Squash	200	191	183	242	259	212	267
Lettuce	206	198	189	251	268	219	276
Sweet Pepper	210	201	192	255	273	223	280

3.2 Method Limitations

The remote sensing technique did a relatively poor job of estimating solar radiation as can be seen from Fig. 11. The data exhibit a relatively large degree of scatter (r^2 = 0.75) and there is a positive bias which results in overestimate by the remote sensing procedure. In future work, we plan to apply the three step calibration methodology described by Paech et al. (2009) to the solar insolation product in Puerto Rico. The method follows the following steps: 1) comparison with ground-based pyranometer measurements on clear (non-cloudy) reference days, 2) correcting for a bias related to cloudiness, and 3) deriving a monthly bias correction factor. According to the authors, in Florida this resulted in a significant reduction in bias errors and a very robust ET product. Since much of Florida is characterized by convective storms, similar to Puerto Rico, there is hope that this technique may work well in Puerto Rico.

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 for this method.

Air temperature was estimated as described in the Section 2. As can be seen from Fig. 6, there was excellent agreement between the estimated and observed temperatures at the seven SCAN sites on March 5th with a r^2 = 0.95. However, when the estimation procedure was evaluated over the period from April 1 – June 21, 2009, the r^2 dropped to 0.87. Note also that these stations are limited to locations in western and southern Puerto Rico. Future efforts should incorporate observations from northern and eastern Puerto Rico.

4 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 ETs were estimated for Puerto Rico for March 5th, 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.

A practical example application of the methodology was presented in which the seasonal consumptive water use for five crops were determined at the seven SCAN weather station sites in western and southern Puerto Rico. In the analysis, solar radiation was estimated using an exponential calibration equation which related the remotely sensed solar radiation with the observed solar radiation. The calibration equation was based on data from three of the study sites (Fortuna, Mayaguez and Bosque). The results indicated that the maximum seasonal water use occurred for Sweet Corn at Combate (277 mm) and the minimum seasonal water use was associated with Squash at Guilarte (191 mm).

Several improvements could be pursued in future research, including the incorporation of spatially variable wind speed, calibration of the insolation algorithm for Puerto Rico based on the three-step approach Paech et al. [5], improvement of the dew point temperature estimation, estimation of short-term (sub-hourly) reference ET, and estimation of the effective crop coefficient based on the Normalized Difference Vegetation Index (NDVI) for estimating actual evapotranspiration.

Acknowledgements

This material is based on research supported by NOAA-CREST (NA17AE1625), NSF-CASA, NASA-IDEAS and USDA Hatch (H-402). We would also like to thank Vanessa Acaron and Jayson Maldonado, participants in the Research Experiences for Undergraduates (REU) Program, for conducting the comparison between observed and estimated data.

References:

[1] Allen, R. G., L. S. Pereira, Dirk Raes and M. Smith, *Crop Evapotranspiration Guidelines for Computing Crop Water Requirements.* FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome. 1998, pp. 300.

[2] Sumner, D. M, C. S. Pathak, J. R. Mecikalski, S. J. Paech, Q. Wu, and T. Sangoyomi, Calibration of GOES-derived Solar Radiation Data Using Network of Surface Measurements in Florida, USA. *Proceedings of the ASCE World Environmental and Water Resources Congress 2008 Ahupua'a. 2008.*

[3] Gowda, P. H., J. L. Chávez, P. D. Colaizzi, S. R. Evett, T. A. Howell, and J. A. Tolk, Remote sensing based energy balance algorithms for mapping ET: Current status and future challenges. *Transactions of the American Society of Agricultural and Biological Engineers.*Vol. 50(5). 2007, pp. 1639-1644.

[4] Allen, R. G., M. Tasumi, R. Trezza, C. W. Robison, M. Garcia, D. Toll, K. Arsenault, J.M.H. Hendrickx, and J. Kjaersgaard, Comparison of Evapotranspiration Images Derived from MODIS and Landsat along the Middle Rio Grande. *Proceedings of the ASCE*

World Environmental and Water Resources Congress 2008 Ahupua'a.

[5] Paech, S. J., J. R. Mecikalski, D. M. Sumner, C. S. Pathak, Q. Wu, S. Islam, and T. Sangoyomi, ., 2009. A calibrated, high-resolution OES satellite solar insolation product for a climatology of Florida evapotranspiration, J. *of the American Water Resources Association* (in press).

[6] Harmsen, E. W., N. L. Miller, N. J. Schlegel and J. E. Gonzalez, 2009. Seasonal Climate Change Impacts on Evapotranspiration, Precipitation Deficit and Crop Yield in Puerto Rico, *J. Agricultural Water Management* 96, 1085–1095.

[7] Ramírez-Beltran, N.D, Kuligowski, R.J., Harmsen, E., Castro, J.M., Cruz-Pol, S., Cardona-Soto, M. (2008). Rainfall Estimation from Convective Storms Using the Hydro-Estimator and NEXRAD. *WSEAS TRANSACTION on SYSTEMS*. No. 10, Vol. 7, pp 1016-1027.

[8] Harmsen, E. W., S. E. Gomez Mesa, E. Cabassa, N. D. Ramirez Beltran, S. C. Pol, R. J. Kuligowski ,R. Vasquez, 2008. Satellite Sub-Pixel Rainfall Variability. *WSEAS TRANSACTIONS on SIGNAL PROCESSING*. Issue 8, Volume 7, Pages 504-513.

[9] Priestly, C.H.B. and R.J. Taylor. On the assessment of surface heat flux and evaporation using large scale parameters. *Mon.Weath. Rev*. 1972, pp. 100:81-92.

[10] Hargreaves, G. H. and Z. A. Samani, Reference *Crop* Evapotranspiration from Temperature. *Appl. Eng. Agric.*, ASAE. 1(2). 1985,. pp.96-99.

[11] Diak, G. R., W. L. Bland, and J. R. Mecikalski, *A note on first estimates of surface insolation from GOES-8 visible satellite data, Agric. For. Meteor*., 82, 1996, pp. 219–226.

[12] Harmsen, E. W., M. R. Goyal, and S. Torres Justiniano, Estimating Evapotranspiration in Puerto Rico. J. *Agric. Univ. P.R.* 86(1-2). 2002, pp. 35-54.

[13] Jensen, M. E., R. D. Burman, and R. G. Allen. *Evapotranspiration and irrigation water requirements*. ASCE Manuals and Reports on Engineering Practice No. 70. 1990, pp. 332.

[14] Harmsen, E. W., V. H. Ramirez Builes, M. D. Dukes, X. Jia, J. E. Gonzalez And L. R. Pérez Alegía, 2009. A Ground-Based Method for Calibrating Remotely Sensed Surface Temperature for use in Estimating Evapotranspiration. *WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT*. Issue 1, Volume 5, January. pp 13-23.

[15] Penman, H.L., Natural evaporation from open water, bare soil, and grass, *Proc. R. Soc., London.* Vol. A193. 1948, pp. 120-145.

[16] Penman, H.L., *Vegetation and Hydrology*, Tech. Comm. 53. Commonwealth Bureau of soils, Harpenden, England. 1963.

[17] Morton, F.I. Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. *Journal of Hydrology*, 66. 1983, pp. 1-76.

[18] Goyal, M. R., E. A. González, C. Chao de Báez, Temperature versus elevation relationships for Puerto Rico. *J. Agric. UPR* 72(3). 1988, pp. 449-467.

[19] Allen, R. G., I. A. Walter, R. Elliott, R. Howell, D. Itenfisu and M. Jensen, R. L. Snyder, The *ASCE Standardized Reference Evapotranspiration Equation*. Environmental and Water Resources Institute of the American Society of Civil Engineers. 2005, pp. 57.

[20] Harmsen, E. W. and A. Gonzaléz, Technical Note: A Computer Program for Estimating Crop Evapotranspiration in Puerto Rico, *J. Agric. UPR.* 89(1-2). 2005, pp. 107-113.