Test and Validation of Different Methods for Soil Moisture Estimation in Puerto Rico Soils

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER IN SCIENCE
In
CIVIL ENGINEERING
(Environmental and Water Resources Engineering)

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
May 2017

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Abstract

Resources available to retrieve accurate SM measurements are very limited in Puerto Rico. The objective of this project was to validate and downscale the AMSR2 SM products over Puerto Rico. For the validation, the 25km resolution SM from AMSR2 was compared with field measurements from each SCAN-NRCS stations in Puerto Rico. The validation revealed that 35% of the AMSR2 SM estimates behave similar to the SCAN-NRCS SM measurements with a correlation of 0.5363. To downscale the AMSR2 SM product, a simple linear equation was used to describe the relationship between the 25km SM and the three 1km resolution products from MODIS (Albedo, NDVI, and LST). The model provided a good fit with the AMSR2 SM with a correlation of 0.61 and an overall RMSE of 0.0050. Future work will include the optimization of the model and the addiction of other variables with hopes of improving the downscaled product.

Resumen

Los recursos disponibles para obtener mediciones precisas de SM son muy limitados en Puerto Rico. El objetivo de este proyecto fue validar y reducir la escala de los productos AMSR2 SM en Puerto Rico. Para la validación, la resolución de 25km SM de AMSR2 se comparó con las mediciones de campo para cada estación de SCAN-NRCS en Puerto Rico. La validación reveló que 35% de las estimaciones de AMSR2 SM se comportan de forma similar a las mediciones SCAN-NRCS SM con una correlación de 0.5363. Para reducir la escala del producto AMSR2 SM, se utilizó una ecuación lineal simple para describir la relación entre los 25km SM y los tres productos de resolución de 1km de MODIS (Albedo, NDVI y LST). El modelo proporcionó un buen ajuste con el AMSR2 SM con una correlación de 0.6102 y un RMSE global de 0.0050. El trabajo futuro incluirá la optimización del modelo y la adicción de otras variables para de mejorar el producto.

Dedication

I dedicate this work to my mother Vilma Olivieri Camacho, my father Reinaldo Nuñez Quilez, to Salimar Cordero Mercado, and to my friends, who have been my extended family, motivation, and inspiration through all the stages of my life.

Acknowledgements

It is imperative that I start giving thanks to my mother Vilma Olivieri Camacho and my father Reinaldo Nuñez Quilez, their love, support, and compassion are the solid foundation of my motivation and strength to go further in life. Also, I would like to take this opportunity to thank Dr. Rebecca Tirado Corbalá, who has been a great support and motivation since the beginning of this study. Also, I would like to thank Dr. Tarendra Lakhankar from NOAA-CREST, Dr. Amy Fisher from ERDC-GRL USACE, Mike Lewis also from ERDC-GRL USACE, and all the research colleagues who I had the wonderful opportunity to meet. All the knowledge and experience that they have entrusted me is a gift that I cherish every day. I also want to extend my gratitude to Ismael Pagán Trinidad and Miriam I. Hernandez Ruiz for their unconditional support in making this and many opportunities possible. Finally, I want to thank my advisor and mentor Dr. Jonathan Muñoz Barreto, for granting me the opportunity to be part of this team, for introducing me the principles of microwave remote sensing, for guiding me through this path, and for opening new doors for me to pursue further graduate studies.

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AMSR2 – Advanced Microwave Scanning Radiometer 2

GCOM-W1 – Global Change Observation Mission – Water 1

GOES-PRWEB – A water balance based model that estimates soil moisture in Puerto Rico

LST – Land Surface Temperature

NDVI – Normalized Difference of Vegetation Index

SCAN-NRCS – Soil Climate Analysis Network - Natural Resources Conservation Service

SM – Soil Moisture

SMAP – Soil Moisture Active Passive

SMOS – Soil Moisture and Ocean Salinity

1. General Introduction

The soil moisture (SM) content is the quantity of water accumulated in soil pores, usually recorded as percent or volume ratio (e.g. cm^3/cm^3) for different depths (e.g. 5cm, 10cm, 25cm). SM plays an important role in the water cycle, hydrologic modeling, agricultural activities, and environmental monitoring [1–6]. Hydrologic-modeling systems are very sensitive to changes in SM values for applications involving flood control and drought assessment [1]. In agricultural activities, best management practices and irrigation control can be optimized with continuous spatio-temporal SM measurements [7]. Predictions and results for environmental monitoring applications like climate change and weather forecasting have a high dependency on the accuracy of the SM data [5, 6, 8]. The spatio-temporal availability of accurate SM measurements rely on the quality of the instruments, frequency of retrieval, and management of the data [2]. There are three options for acquiring SM content; ground-based measurements, modeling predictions, or remotely sensed estimates [1, 3].

The SM measurements collected in the field, usually referred to as in-situ measurements, are commonly retrieved in high or low density networks of point measurements. The density of a network is determined by the quantity and assembling of instruments, the area of study, and the budget of the project. There are various instruments and techniques used to measure in-situ, a Time Domain Reflectometry (TDR) instrument measures the soil dielectric permittivity, a value that increases with higher water presence, and because of this it is frequently used to quantify SM [3, 9]. Another type of instrument used to collect in-situ measurements of SM are based on cosmic-ray detection. The Cosmic-ray Soil Moisture Observing System (COSMOS) measures the quantity of fast neutrons above the land surface, which have an inversely correlated relationship with SM due to kinetic energy loss. This kinetic loss happens when fast neutrons collide with hydrogen atoms found in wet land surfaces [9]. While in-situ measuring provides accurate products, the instruments can be difficult to calibrate and maintain without high technical knowledge, and the availability of an adequate network that meets the requirements for each individual project is very limited [1].

Soil moisture can be simulated at different spatio-temporal resolutions using modeling systems [3]. The quality of the simulation is tied to the accuracy of the in-situ data used as the training dataset and the right implementation of a validation and optimization process [3, 10, 11]. Some models used globally to simulate SM are the SM Accounting, SM Water Balance Model, and the Variable Infiltration Capacity (VIC) model [3, 12–15]. As an example of how these models work, the VIC model simulates SM based in correlations between land cover, SM storage capacity, topography, precipitation, and SM [12, 15]. A simulation can be performed for various spatio-temporal resolutions depending on the objective of the project [3], thus a poor availability of ground-based SM measurements will affect directly the process of validation and optimization [13].

Satellite-based microwave observations can retrieve SM estimates at different spatio-temporal resolutions [1, 3]. Passive microwave depends on the physical temperature and surface emissivity of the earth's surface. In principle, passive sensors, like radiometers, measure the thermal emission of the surface at the microwave wavelength, and translate that energy to brightness temperature [16, 17]. The response of the soil to an electromagnetic wave depends on its texture, surface roughness, organic matter content, iron-oxide content, and moisture content [18]. In general, radiative transfer models like the tau-omega (τ-ω) use the dielectric constant alongside other characteristics of the soil, such as an incident angle and brightness temperature, to estimate SM with remote sensing technologies [18, 19, 21]. The existing satellite-based SM products provide average values of SM at coarse spatial resolutions (ranging from 3km to 40km) [1]. However, at the current state, satellite-based products are not are not useful for hydrologic modeling and agricultural applications [1, 7].

1.1 Soil Moisture in Puerto Rico

The resources available in Puerto Rico to retrieve accurate SM measurements are very limited. Currently, the Soil Climate Analysis Network (SCAN) of the Natural Resources Conservation Service (NRCS) has eight stations around the island retrieving in-situ SM content (Figure 2). The data collection is available online (www.wcc.nrcs.usda.gov) and provides over five years of hourly and daily SM data. Simulated SM is available from the GOES-PRWEB model at 1km resolution, which uses a water and energy balance approach to simulate different hydrologic parameters such as surface runoff, stream flow, and SM. Remotely sensed SM data can be retrieved from the various missions such as the Soil Moisture Active Passive (SMAP), the Soil Moisture and Ocean Salinity (SMOS), or the Global Change Observation Mission – Water 1 (GCOM-W1) satellite system. This project will be based on data from the Advanced Microwave Scanning Radiometer 2 (AMSR2), a sensor carried by the GCOM-W1 satellite system. The AMSR2 is a microwave radiometer that estimates SM worldwide every two days at a 25km resolution [6, 22]. This product can be downloaded from the Earth Observation Research Center (EORC) of Japan Aerospace Exploration Agency (JAXA) website (https://gcom-w1.jaxa.jp) and is available in daily or monthly basis at 10km and 25km resolutions. Knowing that in Puerto Rico the topography, soil characteristics, land use, vegetation density, and weather varies significantly, it can be inferred that the averaged estimates of coarse resolution SM provided by the satellite system may not be accurate.

The spatio-temporal availability and accuracy of SM measurements are key elements to acquiring the best possible outcomes in applications involving hydrologic modeling, agricultural management, and weather monitoring. Unfortunately, in Puerto Rico, the NRCS is the only agency offering a SM product that has reliable historical data and that is available for the public. With only eight stations around the center and west part of the island, the scientific community is compelled to make corrections to these measurements or simply assume the values. Simulated SM from GOES-PRWEB is available for the entire island daily at 1km resolution, but is yet to be validated.

This project is meant to take notice of and to work on the assessment of the lack of availability of reliable spatio-temporal SM in Puerto Rico. The first objective is to validate the coarse resolution (25km) AMSR2 SM estimates by comparing its product with ground-based SM measurements provided by the SCAN-NRCS network over Puerto Rico. The second objective is to downscale the AMSR2 coarse spatial resolution of 25km SM products to a fine spatial resolution of 1km using the Normalized Difference of Vegetation Index (NDVI), the Land Surface Temperature (LST), and the albedo. All products are retrieved from the Moderate Resolution Imaging Spectroradiometer MODIS. This second part will include an alteration to the downscaling methodology which will consist on adding 1km resolution precipitation (P) from GOES-PRWEB as a variable. The third and final part of the project will be the validation of the downscaled products. In the validation, SM data for each SCAN-NRCS station will be compared with the 25km SM product from the AMSR2 sensor. In a general sense, the results generated in this project will offer a downscaled validated SM product from coarse resolution satellite-based estimates retrieved from the AMSR2.

2. Previous Publications

Various studies state the importance of SM, as it is an essential parameter of the water cycle, hydrologic modeling, agricultural activities, and weather monitoring applications [1–4]. While field measurements offer accurate SM values with low spatial coverage, satellite systems offer global averaged estimates of SM at low resolution [1]. Both means of SM retrieval have their unique advantages and disadvantages. While these instruments and systems may provide accurate or global measurements, both have serious limitations such as the availability of networks or very low resolution products that cannot be used for most applications [1, 16, 24].

Satellite-based SM products are estimations based on electromagnetic readings on different wavelengths that cover large footprints at a global scale and at low resolutions [1, 3]. Optical and thermal infrared spectral regions can be used to generate SM products [1]. Microwave radiometer systems can be identified as passive or active [16]. A passive microwave system, or radiometer, receives energy emitted from the Earth [23]. While active systems, or radars, emit radio waves towards the Earth and receives a reflection reading [16]. In a simple manner, a microwave sensor, whether passive or active, receives energy from Earth's surface, and estimates SM through a model that considers soil properties, weather, and dielectric constants from water-soil combinations, which are translated to SM estimates for approximately the first five centimeters of depth [1]. The dielectric constant (ρ_d) is an indicator of conductivity. In dry soils, usual values of the dielectric constant range from 3 to 8, the presence of water in soil can increase the dielectric constant value up to 80 [1, 16].

Satellite-based SM estimates are available daily from the AMSR-2 sensor, but the resolution is very low and for most applications that data is not viable [1, 12]. Different methods have been used to downscale satellite-based coarse SM products [2, 5, 12]. In a recent study, the 25km resolution AMSR2 product for a region in the northwest of China was downscaled with a method where a temperature-vegetation-drought index is derived from the Moderate-resolution Imaging Spectro-radiometer (MODIS) [5]. In a study made by Das [14], he suggested a downscale method which consists of simulating SM using a VIC model at the desired resolution. The VIC SM product was then upscaled to match the coarse resolution SM. The coarse resolution satellite based product was downscaled using the upscaled product and a data assimilation technique. Another study made by Ranney et al. (2015), in the Cache la Poudre catchment in Colorado, suggests an improvement for the Equilibrium Moisture from Topography (EMT) model, adding the vegetation and soil properties as variables to the estimation of SM for the downscaling of coarse resolution products, calling it the EMT + VS model [13]. In a study made by Djamai et al. (2016), a downscale methodology was applied to retrieve high resolution SM in Manitoba, Canada. This methodology consists on a combination of the Disaggregation based on Physical and Theoretical Scale Change (DISPATCH) algorithm with the Canadian Land Surface Scheme (CLASS) simulation software to estimate SM at a continuous time-series by using DISPATCH to downscale SMOS 40km SM products during cloud-free days and then using the CLASS to estimate SM on cloudy days [2]. Ray et al. (2010) downscaled the AMSR-E 25km resolution SM to enhance the results of a landslide model. This method consisted of a simple linear equation that described the relationship between the 25km resolution AMSR-E products with the 1km Normalized Difference of Vegetation Index (NDVI), Land Surface Temperature (LST), and albedo products from MODIS . [12].

3. Methodology

Puerto Rico consists of an archipelago with a land surface area of 8940km^2. The island is mostly mountainous and the elevation at the highest point is 1,338 meters (4,390 feet) from water level. In Puerto Rico, the soil type, land use, soil temperature, daily precipitation, impervious areas, and density of vegetation varies noticeably by the kilometer, therefore, it is expected that any average of a 25km resolution SM estimate cannot be representative of the area of coverage. The methodology of this project is meant validate and enhance the satellite-based SM product by downscaling the coarse resolution AMSR2 SM product to a finer resolution SM product.

The project started with the validation of all available of the 25km AMSR2 SM product for Puerto Rico using ground-based SM measurements from the SCAN-NRCS network. The second stage was the downscaling the AMSR2 SM from 25km to 1km resolution using MODIS 1km Albedo, NDVI, and LST. An alteration of the downscaling technique was included in the second stage, where the GOES-PRWEB 1km daily precipitation was considered as a variable in the downscaling equation. The final stage was validation of the downscaled 1km SM product for the original and altered equations using the SCAN-NRCS SM measurements. The methodology is presented as a brief flowchart in Figure 1.

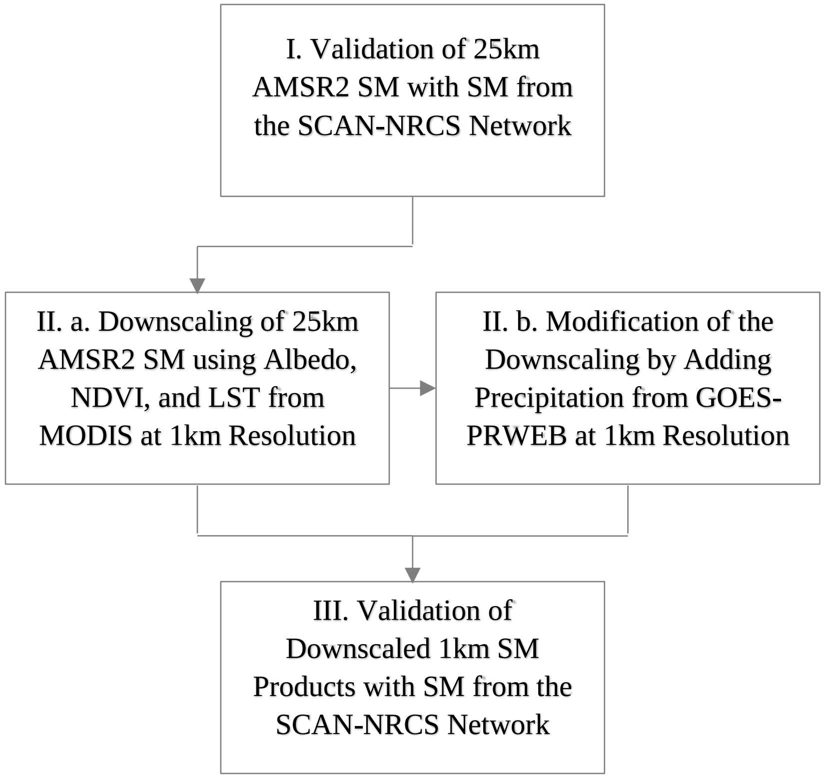


Figure 1. Project Flowchart.

3.1 Validation

For the validation process of the entire collection of 25km resolution AMSR2 SM products, all data available (from 2001 to 2016) from all the SCAN-NRCS stations over Puerto Rico was processed. To analyze the behavior of the AMSR2 SM products in terms of each individual SCAN-NRCS station, the location of each ground-based station was matched with the closest AMSR2 pixel centroid. Additionally, the SM data was filtered for all days where the SM bias does not exceed a range of ±0.15. In this study, the SM bias refers to the difference between ground measured and satellite-based SM. These values were analyzed with the coefficient of correlation or "R squared" (R^2) for each station. The R^2 measures the relationship in variability between the observed measurements and the estimated values [24]. R squared is calculated as shown in

Equation (1) ranges from 0 to 1, where 0 is a poor estimate and 1 is the best estimate. A value of $R^2 \geq 0.70$ is considered as a satisfactory estimation.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} e_i^2}{\sum_{i=1}^{n} \theta_{i,G}^2} = 1 - \frac{\sum_{i=1}^{n} \left[\theta_{i,G} - \theta_{i,S}\right]^2}{\sum_{i=1}^{n} \left(\theta_{i,G} - \bar{\theta}_{i,G}\right)^2} \tag{1}$$

where $e_i^2 = \left[\theta_{i,G} - \theta_{i,S}\right]^2$ is the squared difference or squared error between the ground-based (G) observations $\theta_{i,G}$ and the satellite-based (S) estimated values $\theta_{i,S}$ and $\bar{\theta}_{i,G}$ is the average value of the ground-based observations for all the instances studied.

3.2 Downscale

The AMSR2 product was downscaled to a finer 1km resolution to enhance the satellite-based continuous spatio-temporal SM measurements over Puerto Rico. The downscaling technique selected has been previously executed by Ray, et al. (2010) and first published by Chauhan et al. (2003). The technique suggests that remotely sensed SM retrieved from the AMSRE system at a 25km resolution can be downscaled to 1km resolution using a simple linear equation based on parameters calculated with a regression model that is based on three physical properties of 1km resolution retrieved from another satellite-based source, the (MODIS). The three physical properties are the albedo, the LST, and the NDVI. The Equation (2) presents the downscaling approach with these three MODIS parameters.

$$\theta_s = \sum_{i=0}^{i=n} \sum_{j=0}^{j=n} \sum_{k=0}^{k=n} a_{ijk} V^i T^j A^k \tag{2}$$

By establishing n equal to zero, the equation yields to Equation (3).

$$\theta_s = a_{000} + a_{100}A + a_{010}T + a_{001}V + a_{110}TA + a_{101}VA + a_{011}VT \tag{3}$$

The approach used in this project differs in that it will use coarse resolution SM from the AMSR2 (latest version of the AMSR systems), and 1km resolution daily precipitation data from GOES-PRWEB, which was added in the downscaling equation. Following this new approach, the variables was referred as follows; soil moisture as θ_s, albedo as A, LST as T, NDVI as V, daily precipitation as P, and the parameters calculated with a regression model are a_{ijk}. The equation used to downscale coarse resolution SM products was written as,

$$\theta_s = \sum_{i=0}^{i=n} \sum_{j=0}^{j=n} \sum_{k=0}^{k=n} \sum_{l=0}^{l=n} a_{ijkl} P^l V^i T^j A^k \tag{4}$$

By establishing $n = 1$, n is the number of pixels, the equation yields to Equation (5).

$$\begin{aligned} \theta_s = a_{0000} + a_{1000}A + a_{0100}T + a_{0010}V - a_{0001}P + a_{1100}TA + a_{1010}VA \\ - a_{1001}AP + a_{0110}VT - a_{0101}TP - a_{0011}PV \end{aligned} \tag{5}$$

The a_{ijkl} parameters are the connection between the fine resolution downscaled SM and the coarse resolution satellite-based SM products. These parameters are calculated with a multiple linear regression model that compares the aggregated values of the physical properties with the coarse resolution SM estimate. Each parameter was upscaled to match the 25km resolution of AMSR2. The upscale was performed as follows,

$$\begin{aligned} V_{25km} &= \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} V_{ij}}{mn} \qquad & T_{25km} &= \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} T_{ij}}{mn} \\ A_{25km} &= \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} A_{ij}}{mn} \qquad & P_{25km} &= \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} P_{ij}}{mn} \end{aligned} \tag{6}$$

where 25km is the resolution at which the physical parameters will be upscaled, m is the value for the i^{th} column of the 1km resolution grid inside the 25-kilometer resolution and n is the value for the j^{th} row of the 1km resolution grid inside the 25-kilometer resolution. Before validating the downscale with the in-situ data, the downscaled 1km product was first aggregated to match the 25km resolution of the pixel and analyzed by calculating R^2 and the Root Mean Square Error (RMSE). The RMSE is another indicator of the "goodness of fit" of a model, it is calculated as in Equation (7).

$$RMSE = \sqrt{mean(\theta_G - \theta_S)^2} \tag{7}$$

A t-statistic test was performed to determine the significance of each parameter in the downscaling equations. A t-statistic test was done to evaluate each regression coefficient. The null hypothesis states that when the t-value equals zero the coefficient is not significant, the alternative hypothesis states that the t-value is different than zero. The null hypothesis was rejected when the p-value is equal or less than the significant level (5%) meaning that the coefficient is significant to the model.

An F-statistic test was performed to evaluate the significance of the variances between the downscaled and coarse resolution SM to reinforce the deduction that the downscaling model provides a good fit. The null hypothesis of the F-statistic test states that the variances of the downscaled and coarse resolution SM are equal (F-value = 1). This hypothesis was rejected if the probability of the F-value is equal or less than the significance level (5%), meaning that the linear regression model used to determine the downscale provides a good fit.

3.3 Data

3.3.1 In-situ SM, precipitation, and LST from the SCAN-NRCS stations

The Soil Climate Analysis Network (SCAN) project of the Natural Resources Conservation Service (NRCS) has been collecting soil moisture and soil temperature since 1991 all over the United States. In the present day, the project has employed over 200 stations around the United States, mainly in agricultural areas. The stations are continuously providing ground-based measurements of soil moisture at different depths, precipitation, relative humidity, land surface temperature, solar radiation, wind velocity, wind direction, and barometric pressure. All available ground-based daily SM, precipitation, and land surface temperature data over Puerto Rico was downloaded for the eight SCAN-NRCS stations (Figure 2) from the NRCS-NWCC (National Water Climate Center) website in comma-separated values (.csv) format. The rest of this section provided a detailed overview of each SCAN-NRCS station in Puerto Rico.

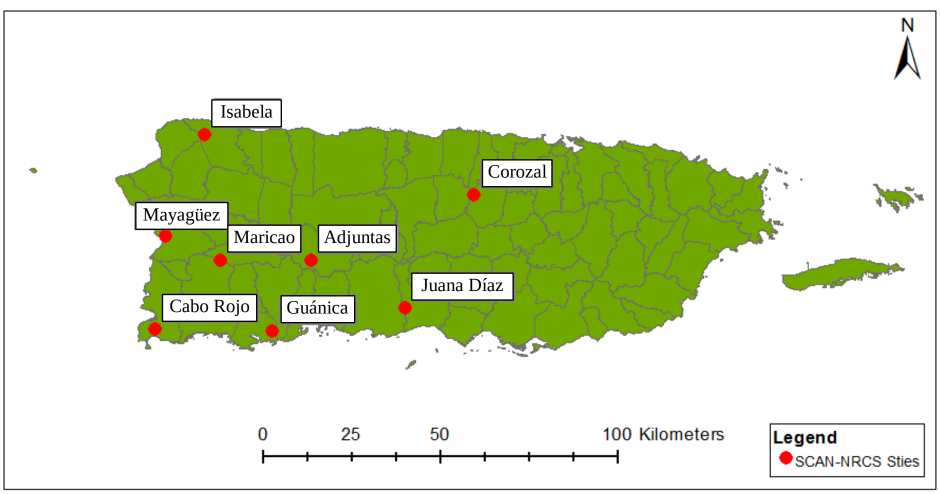


Figure 2. Location of all SCAN-NRCS stations over Puerto Rico.

- Adjuntas Station

The SCAN-NRCS Station 2045 was assembled in Adjuntas PR in 2001. It is located at latitude 18.15 and longitude -66.77. At that location, the elevation is about 3,345 feet above sea level. The soil is classified as Humatas clay (Very-fine, parasesquic, isohyperthermic Typic Haplohumults) (Table 2) and is composed of 6.5% sand, 29.8% silt, and 63.7% clay. The area is very dense in vegetation (pastures) with (Table 3) and in a 1km radius more than 80 percent of the area is forested and the slopes ranges from 40 to 60 percent (Table 2). Considering all the collected data from 2001 to 2017, the average SM, P, and LST were 0.398 cm^3/cm^3, 0.25 inches, and 19.7 ˚C, with a variance of 0.018, 0.132, and 5.05, respectively (Table 1).

Table 1. Adjuntas, basic statistics for the entire data collection 2001 to early 2017 for daily SM, Precipitation, and LST.

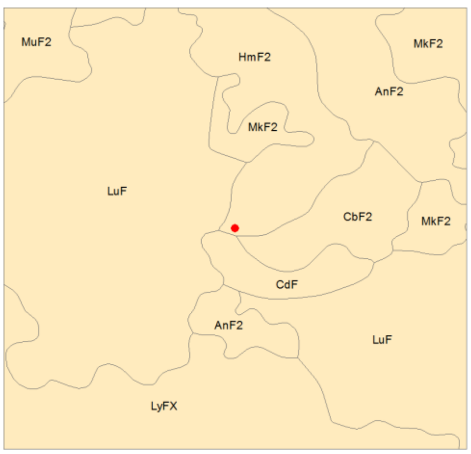
	Soil moisture (cm^3/cm^3)	Precipitation (in)	LST * (˚C)
Maximum	0.646	6.20	24.6
Minimum	0.119	0.00	10.0
Average	0.398	0.25	19.7
Mode	0.526	0.00	20.5
Variance	0.018	2.06	4.94
Standard Deviation	0.133	1.44	2.22

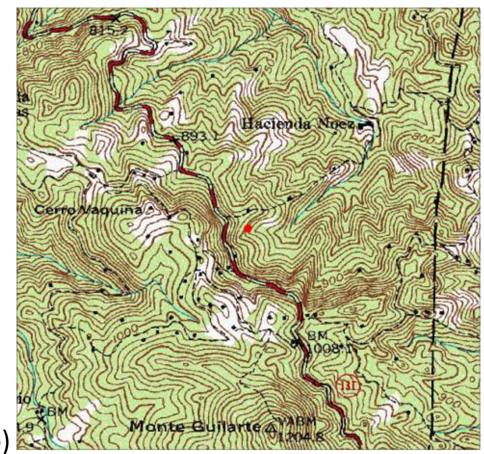
*LST= Land Surface Temperature.

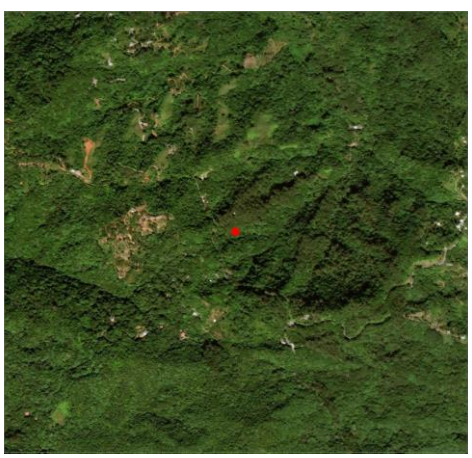
Table 2. Adjuntas, soil information inside the 1km buffer around the SCAN-NRCS station.

Map Unit Symbol	Map Unit Name	Acres in AOI*	Percent of AOI*
AnF2	Alonso clay, 40 to 60 percent slopes, eroded	101.9	10.3%
CbF2	Caguabo gravelly clay loam, 20 to 60 percent slopes, eroded	52.9	5.4%
CdF	Caguabo-Rock land complex, 20 to 60 percent slopes	29.1	2.9%
HmF2	Humatas clay, 40 to 60 percent slopes	104.5	10.6%
LuF	Los Guineos clay, 40 to 60 percent slopes	456.7	46.2%
LyFX	Los Guineos-Maricao association, steep	148.2	15.0%
MkF2	Maricao clay, 20 to 60 percent slopes	67.8	6.9%
MuF2	Mucara silty clay, 40 to 60 percent slopes, eroded	27.2	2.8%

*AOI = Area of interest

a) 

b) 

c) 

d) 

Figure 3. Adjuntas, a) Soil, b) Topography, c) Visual, and d) Station for a 1km buffer around the SCAN-NRCS station.

(Images retrieved March 31, 2017 from https://websoilsurvey.sc.egov.usda.gov, https://gdg.sc.egov.usda.gov, and ArcGIS)

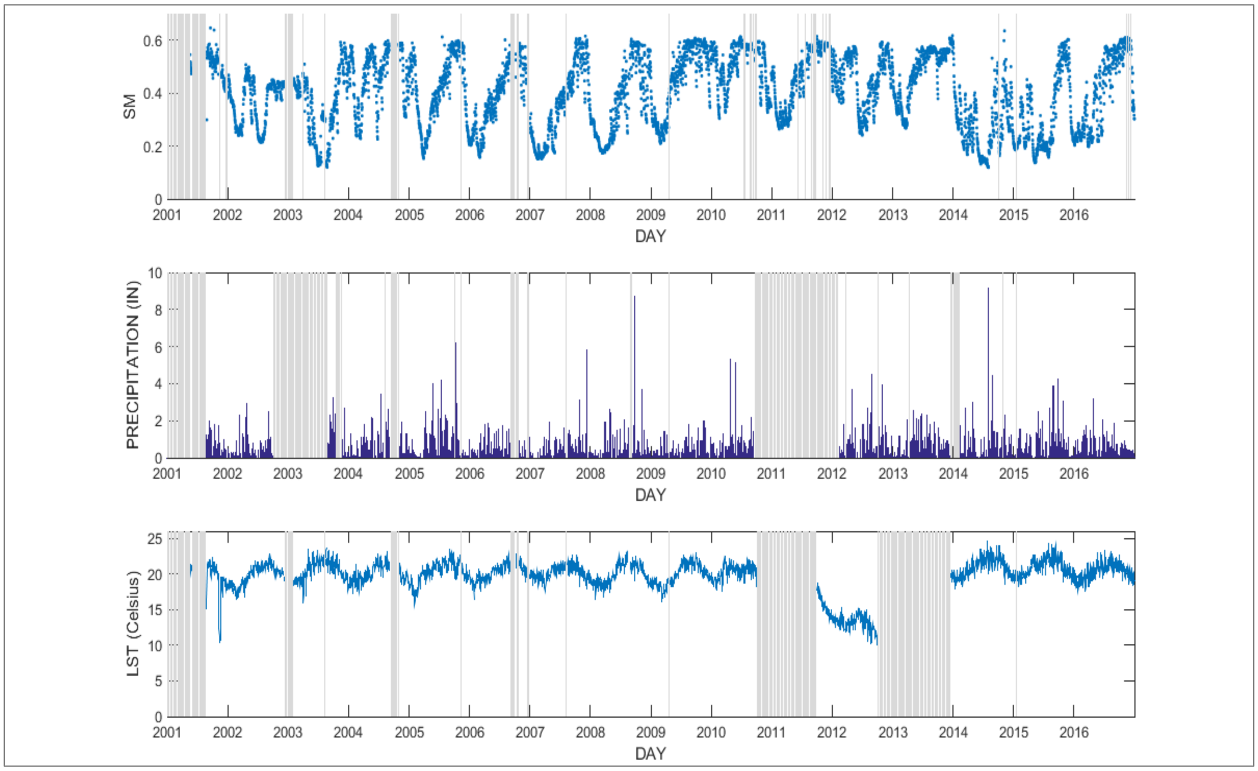


Figure 4. Adjuntas, all available SM, P, and LST. (Note: Gray lines are days without data)

- Cabo Rojo Station

The SCAN-NRCS Station 2066 was assembled in Cabo Rojo, PR in 2002. It is located in latitude 17.98 and longitude -67.17. At that location, the elevation is about 33 feet above the water level, the soil is classified as Melones clay (Fine, smectitic, isohyperthermic, Chromic Calcitorrerts) (Table 4) and is composed of 81.8% sand, 6.3% silt, and 11.9% clay. There is high density of small crops, and in a 1km radius the land use varies from residential, to agricultural, and to plains with small grass (Figure 5) with slopes ranging from 0 to 20 percent (Table 4). Considering all the collected data from 2002 to 2017, the average SM, P, and LST is 0.170 cm^3/cm^3, 0.09 inches, and 26.9 ˚C, with a variance of 0.005, 0.10 and 4.14, respectively (Table 3).

Table 3. Cabo Rojo, basic statistics for the entire data collection 2001 to early 2017 for daily SM, Precipitation, and LST.

	Soil moisture (cm^3/cm^3)	Precipitation (in)	LST * (˚C)
Maximum	0.491	5.60	32.4
Minimum	0.005	0.00	20.0
Average	0.170	0.09	26.9
Mode	0.128	0.00	27.9
Variance	0.005	0.10	4.14
Standard Deviation	0.072	0.32	2.03

*LST= Land Surface Temperature.

Table 4. Cabo Rojo, soil information inside the 1km buffer around the SCAN-NRCS station.

Map Unit Symbol	Map Unit Name	Acres in AOI *	Percent of AOI *
AtD	Altamira gravelly clay, 2 to 20 percent slopes	40.9	4.1%
GuB	Guayabo fine sand, 0 to 5 percent slopes	0.0	0.0%
GyB	Guayacan clay, 0 to 5 percent slopes	43.8	4.4%
GyC	Guayacan clay, 5 to 12 percent slopes	69.9	7.1%
GyD	Guayacan clay, 12 to 20 percent slopes	1.5	0.1%
LnA	Llanos Costa loam, 0 to 2 percent slopes	4.8	0.5%
LnB	Llanos Costa loam, 2 to 5 percent slopes	2.4	0.2%
LnC	Llanos Costa loam, 5 to 12 percent slopes	88.5	9.0%
MnC	Melones clay, 2 to 12 percent slopes	391.6	39.6%
Sa	Salt flats, ponded	1.6	0.2%
SsB	Sosa sandy loam, 2 to 5 percent slopes	332.8	33.7%
SsC	Sosa sandy loam, 5 to 12 percent slopes	3.1	0.3%
VaA	Vayas silty clay, 0 to 2 percent slopes, occasionally flooded	7.5	0.8%

*AOI = Area of interest

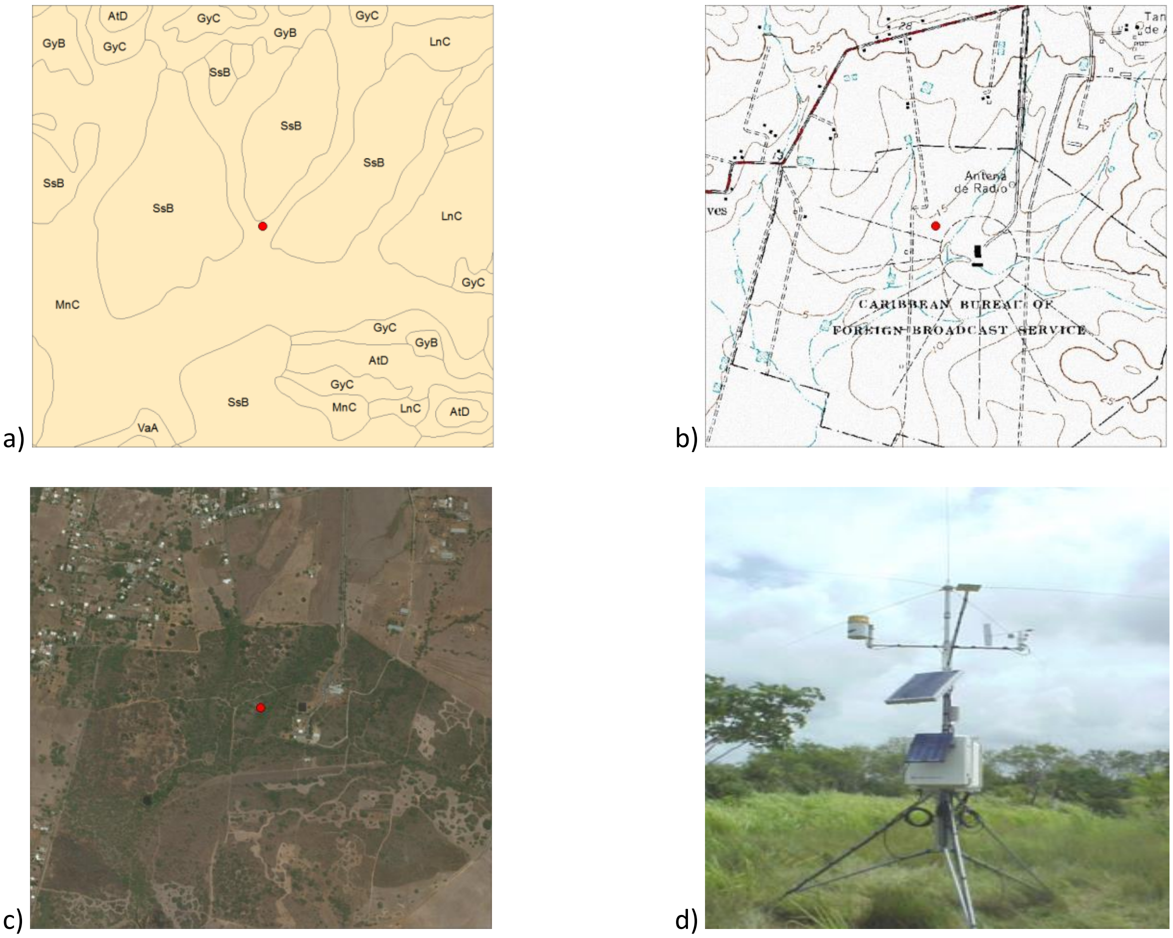


Figure 5. Cabo Rojo. a) Soil, b) Topography, c) Visual, and d) Station for a 1km buffer around the SCAN-NRCS station.

(Images retrieved March 31, 2017 from https://websoilsurvey.sc.egov.usda.gov, https://gdg.sc.egov.usda.gov, and ArcGIS)

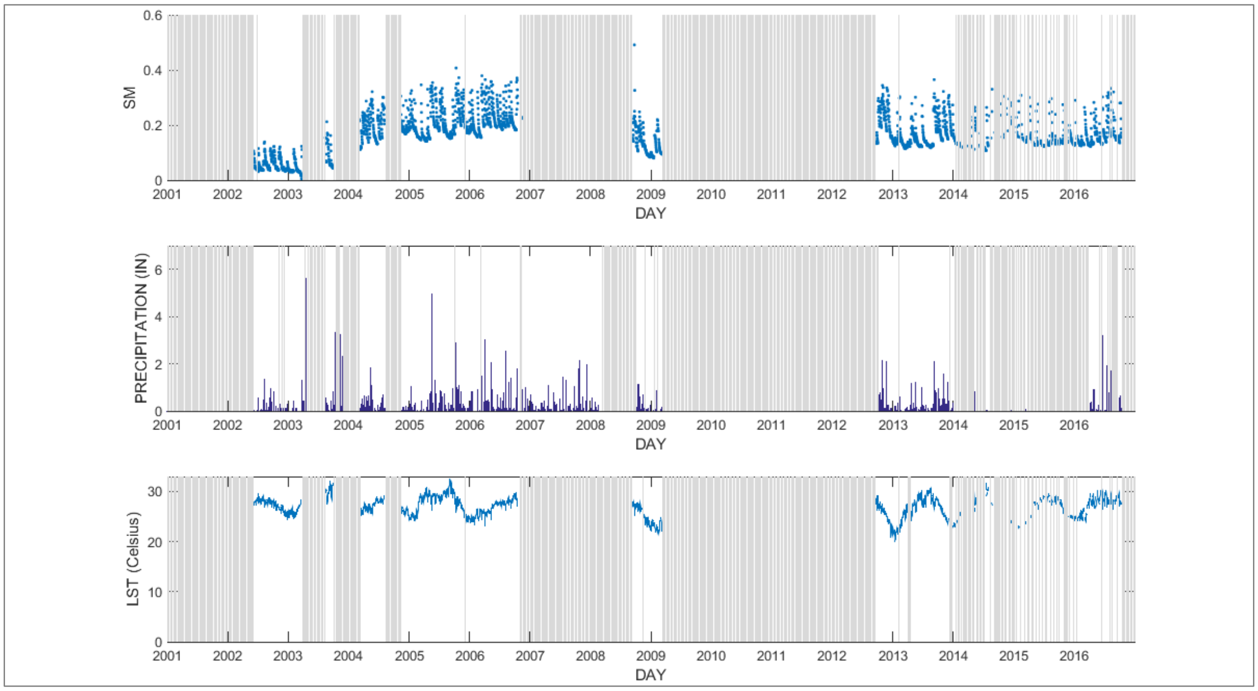


Figure 6. Cabo Rojo, all available SM, P, and LST data for the SCAN-NRCS station. (Note: Gray lines are days without data)

- Corozal Station

The SCAN-NRCS Station 2188 was assembled in Corozal, PR since 2012. It is located in latitude 18.32 and longitude -66.36. At that location, the elevation is about 852 feet above the water level, the soil is classified as Consumo clay (Fine, mixed, semiactive, isohyperthermic Typic Haplohumults) (Table 6). The station is placed in a small grass field with bushes around it, and the majority of the area at a 1km radius are forests, the rest are agricultural and residential areas (Figure 7) and slopes ranging from 5 to 60 percent (Table 6). Considering all the collected data from 2012 to early 2017, the average SM, P, and LST is 0.362 cm^3/cm^3, 0.20 inches, and 25.12˚C, with a variance of 0.015, 0.23, and 2.76 respectively (Table 5).

Table 5. Corozal, basic statistics for the entire data collection from starting date to early 2017 for daily a) SM, b) P, and c) LST.

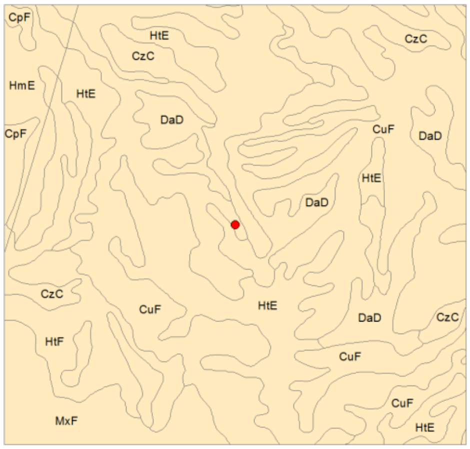
	Soil moisture (cm^3/cm^3)	Precipitation (in)	LST * (˚C)
Maximum	0.567	5.80	28.9
Minimum	0.118	0.00	21.3
Average	0.362	0.20	25.1
Mode	0.480	0.00	23.5
Variance	0.015	0.23	2.76
Standard Deviation	0.123	0.48	1.66

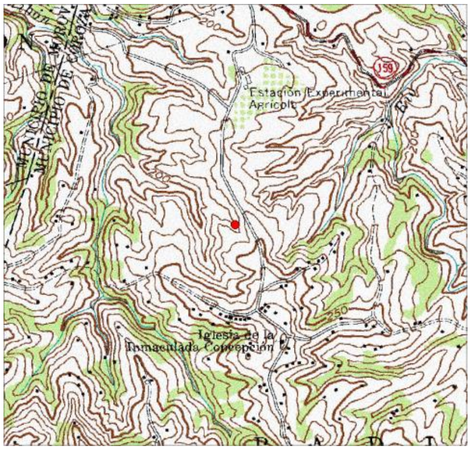
*LST= Land Surface Temperature.

Table 6. Corozal, soil information inside the 1km buffer around the SCAN-NRCS station.

Map Unit Symbol	Map Unit Name	Acres in AOI *	Percent of AOI *
CpF	Consumo clay, 40 to 60 percent slopes	18.9	1.9%
CrC	Corozal clay, 5 to 12 percent slopes	0.5	0.1%
HmE	Humatas clay, 20 to 40 percent slopes	26.4	2.7%
CuF	Consumo clay, 40 to 60 percent slopes	371.4	37.6%
CzC	Corozal clay, 5 to 12 percent slopes	135.7	13.7%
DaD	Daguey clay, 12 to 20 percent slopes	105.6	10.7%
Es	Estacion silty clay loam	0.2	0.0%
HtE	Humatas clay, 20 to 40 percent slopes	209.1	21.2%
HtF	Humatas clay, 40 to 60 percent slopes	58.5	5.9%
JnD2	Juncal clay, 5 to 20 percent slopes, eroded	0.3	0.0%
LaC2	Lares clay, 5 to 12 percent slopes, eroded	0.8	0.1%
MxF	Mucara clay, 40 to 60 percent slopes	61.0	6.2%

*AOI = Area of interest

a) 

b) 

c) 

c) 

Figure 7. Corozal. a) Soil, b) Topography, c) Visual, and d) Station for a 1km buffer around the SCAN-NRCS station.

(Images retrieved March 31, 2017 from https://websoilsurvey.sc.egov.usda.gov, https://gdg.sc.egov.usda.gov, and ArcGIS)

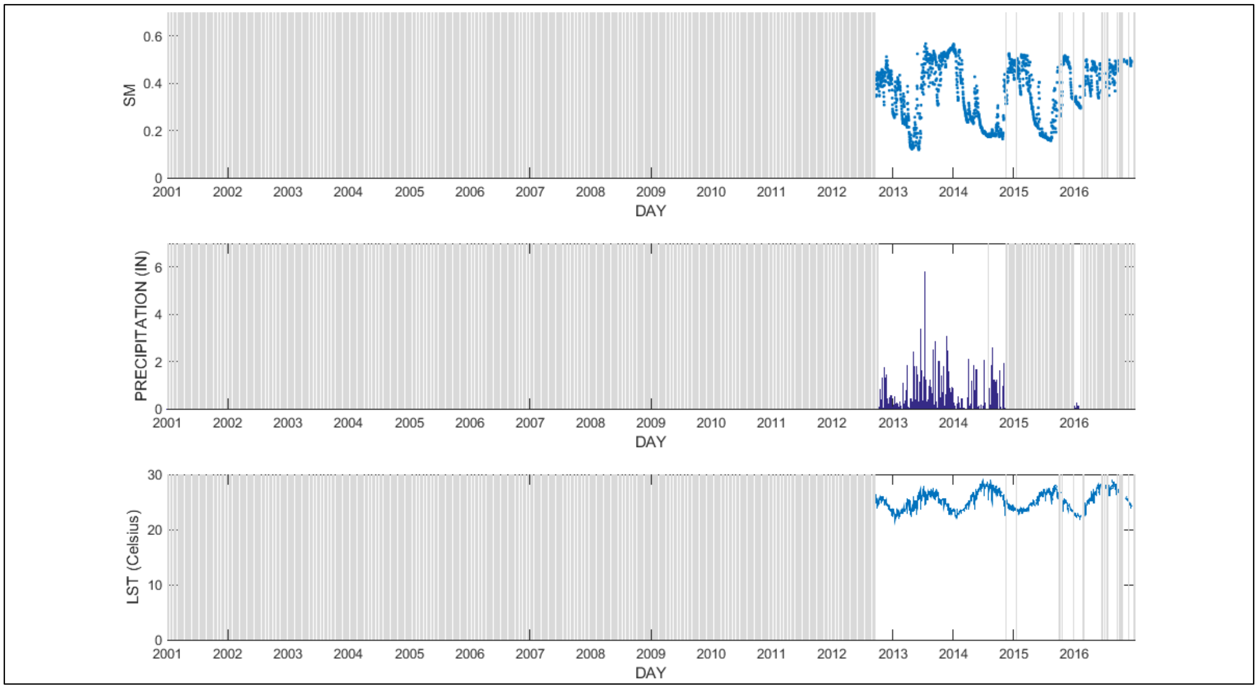


Figure 8. Corozal. All available SM, P, and LST data for the SCAN-NRCS station. (Note: Gray lines are days without data)

- Guánica Station

The SCAN-NRCS Station 2067 was assembled in Guánica, PR since 2002. It is located in latitude 17.97 and longitude -66.87. At those coordinates, the elevation is about 541 feet above the water level, the soil is classified as La Covana-Limestone outcrop-Seboruco complex (Table 8) and is composed of 79.7% sand, 12.0% silt, and 8.3% clay. The area is very dense in vegetation with small bushes, and in a 1km radius more than 90% of the land cover consists of small bushes and crops (Figure 9) and slopes changing from 5 to 60 percent (Table 8). Considering all the collected data from 2012 to January 1, 2017, the average SM, P, and LST have been 0.063 cm^3/cm^3, 0.10 inches, and 27.90 ˚C, with variance of 0.003, 0.32, and 3.17, respectively (Table 7).

Table 7. Guánica, basic statistics for the entire data collection from starting date to early 2017 for daily a) SM, b) P, and c) LST.

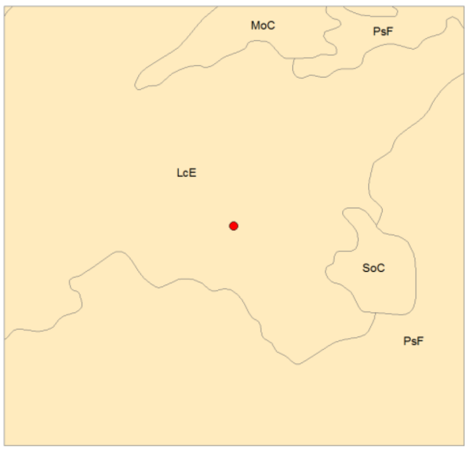
	Soil moisture (cm^3/cm^3)	Precipitation (in)	LST * (˚C)
Maximum	0.385	7.43	33.1
Minimum	0.000	0.00	22.0
Average	0.063	0.10	27.2
Mode	0.022	0.00	27.9
Variance	0.003	0.32	3.17
Standard Deviation	0.057	0.57	1.78

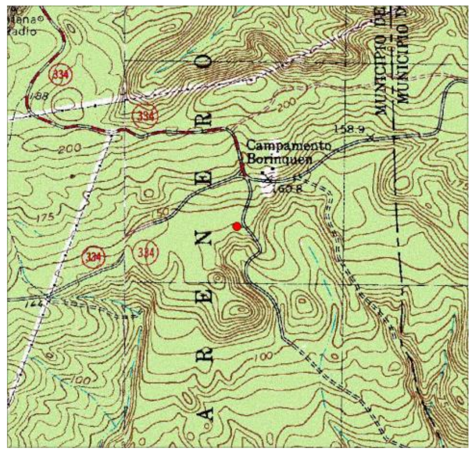
*LST= Land Surface Temperature.

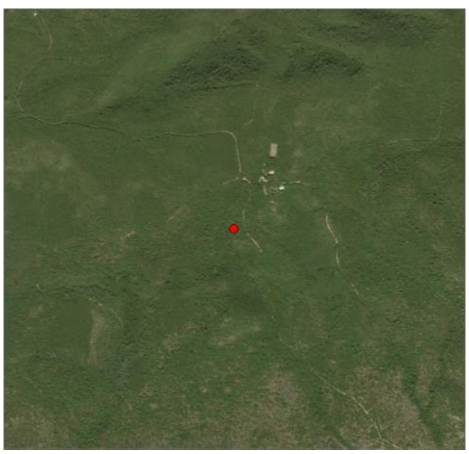
Table 8. Guánica. Soil information inside the 1km buffer around the SCAN-NRCS station.

Map Unit Symbol	Map Unit Name	Acres in AOI *	Percent of AOI *
LcE	La Covana-Limestone outcrop-Seboruco complex, 12 to 40 percent slopes	515.8	52.2%
MoC	Montalva clay, 5 to 12 percent slopes	40.1	4.1%
PsF	Pitahaya-Limestone outcrop-Seboruco complex, 40 to 60 percent slopes	403.0	40.8%
SoC	Seboruco silty clay loam, 2 to 12 percent slopes	29.4	3.0%

*AOI = Area of interest

a) 

b) 

c) 

d) 

Figure 9. Guánica. a) Soil, b) Topography, c) Visual, and d) Station for a 1km buffer around the SCAN-NRCS station.

(Images retrieved March 31, 2017 from https://websoilsurvey.sc.egov.usda.gov, https://gdg.sc.egov.usda.gov, and ArcGIS)

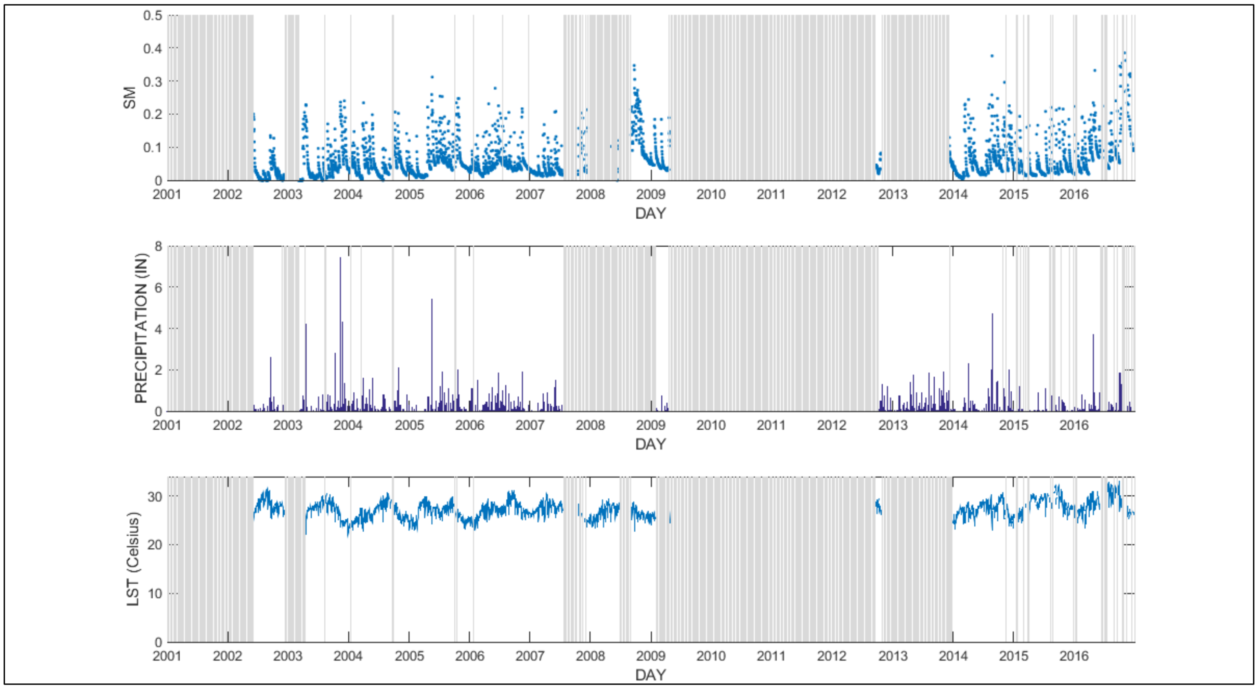


Figure 10. Guánica. All available SM, P, and LST data for the SCAN-NRCS station. (Note: Gray lines are days without data)

- Isabela Station

The SCAN-NRCS Station 2052 was assembled in Isabela PR since 2003. It is located in latitude 18.47 and longitude -67.04. At that location, the elevation is about 50 feet above the water level, the soil is classified as Coto Clay (Very-fine, kaolinitic, isohyperthermic Typic Eutrustox) (Table 10) and composed of 34.9% sand, 9.5% silt, and 55.6% clay. The area is moderately dense in vegetation with small grass, and in a 1km radius more the land use is divided in agricultural and residential areas (Figure 11) with mostly low slopes of 0 to 5 percent and some areas with 12 to 40 percent (Table 10). Considering all the collected data from 2003 to early 2017, the average SM, P, and LST have been 0.314 cm^3/cm^3, 0.15 inches, and 25.50 ˚C, with a variance of 0.009, 0.13, and 3.83, respectively (Table 9).

Table 9. Isabela. Basic statistics for the entire data collection from starting date to early 2017 for daily a) SM, b) P, and c) LST.

	Soil moisture (cm^3/cm^3)	Precipitation (in)	LST * (˚C)
Maximum	0.506	4.53	31.5
0Minimum	0.078	0.00	19.6
Average	0.314	0.15	25.5
Mode	0.370	0.00	27.4
Variance	0.009	0.13	3.83
Standard Deviation	0.095	0.36	1.96

*LST= Land Surface Temperature.

Table 10. Isabela. Soil information inside the 1km buffer around the SCAN-NRCS station.

Map Unit Symbol	Map Unit Name	Acres in AOI *	Percent of AOI *
BeB	Bejucos sandy loam, 2 to 5 percent slopes	36.2	3.7%
CtB2	Cotito clay, 0 to 5 percent slopes, eroded	37.2	3.8%
CuB2	Coto clay, 2 to 5 percent slopes, eroded	561.2	56.8%
Lo	Limestone outcrop	4.4	0.4%
Lr	Limestone rock land	60.0	6.1%
MsB	Matanzas clay, 2 to 5 percent slopes	16.0	1.6%
SaD	San German gravelly clay loam, 12 to 20 percent slopes	188.6	19.1%
SaE	San German gravelly clay loam, 20 to 40 percent slopes	50.5	5.1%
SeB	Santa Clara silty clay loam, 2 to 5 percent slopes	18.4	1.9%
SrD	Soller-Limestone rockland complex, 5 to 20 percent slopes	1.8	0.2%
TcB2	Tanama clay, 2 to 5 percent slopes, eroded	4.5	0.5%
TcC2	Tanama clay, 5 to 12 percent slopes, eroded	9.5	1.0%

*AOI = Area of interest

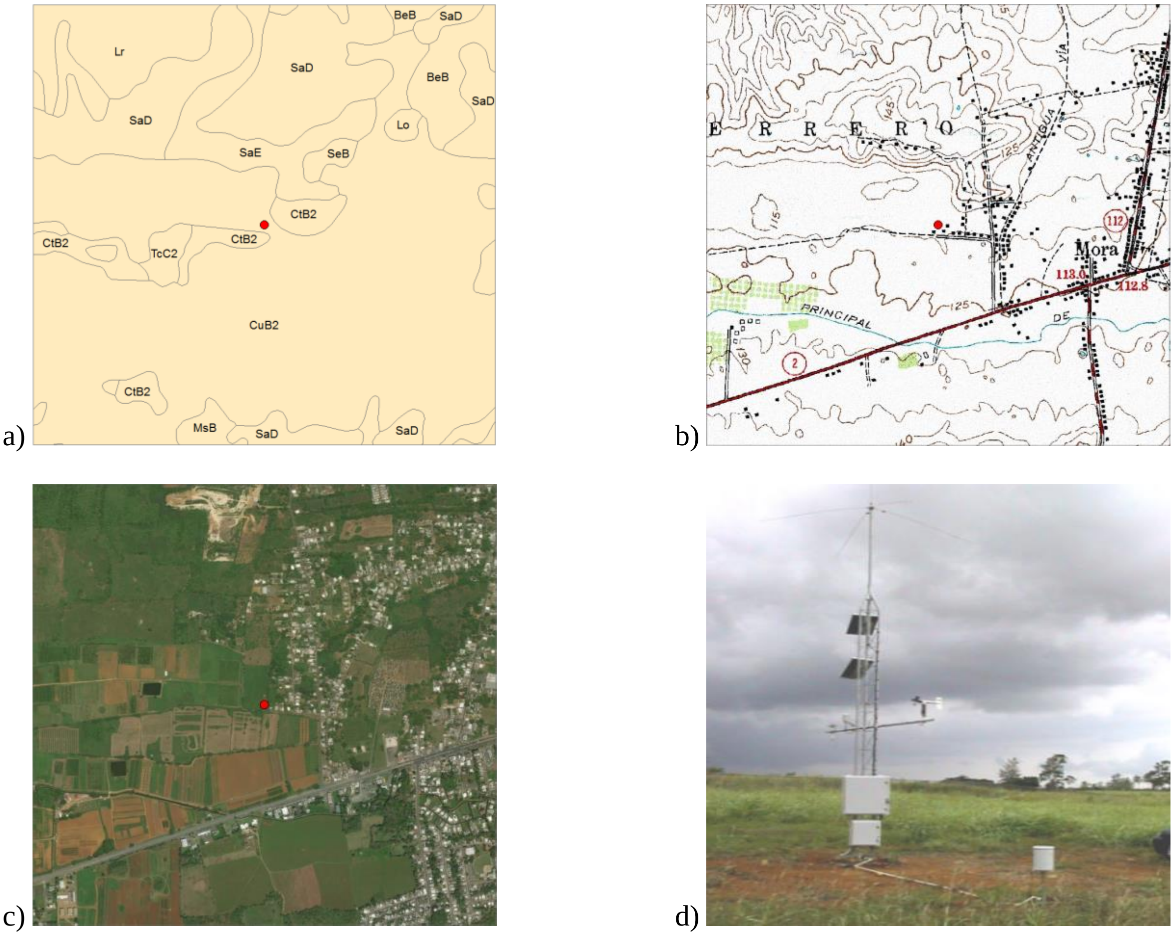


Figure 11. Isabela. a) Soil, b) Topography, c) Visual, and d) Station for a 1km buffer around the SCAN-NRCS station.

(Images retrieved March 31, 2017 from https://websoilsurvey.sc.egov.usda.gov, https://gdg.sc.egov.usda.gov, and ArcGIS)

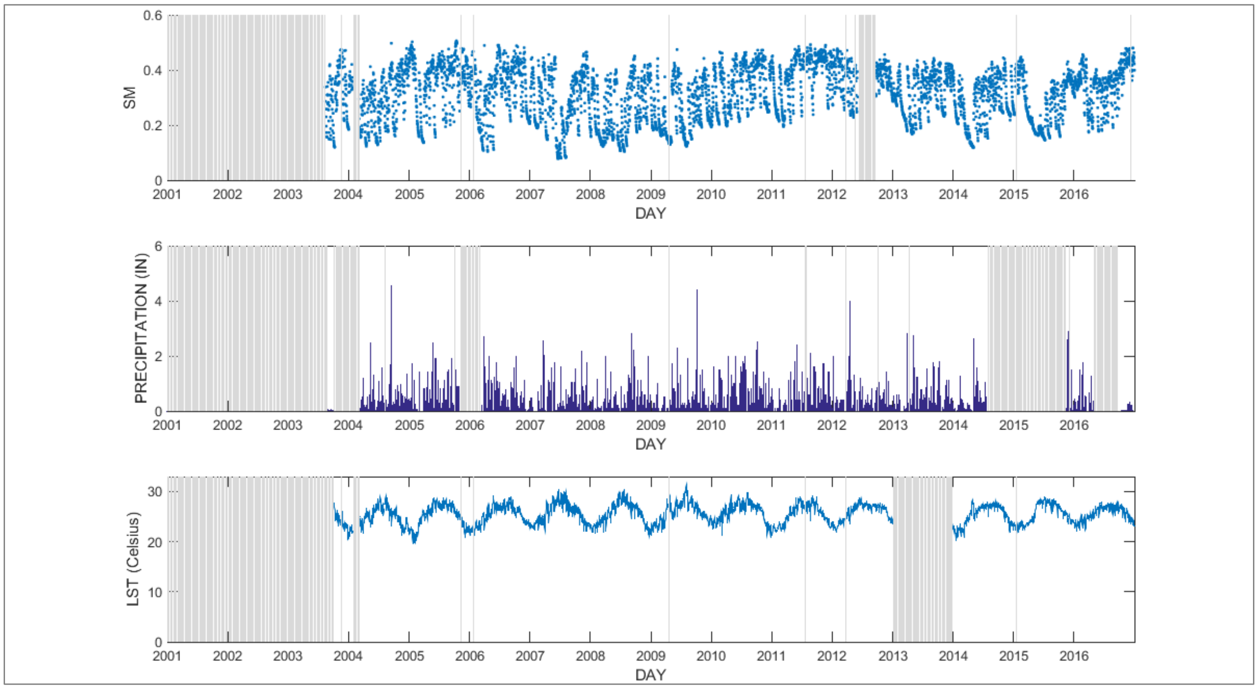


Figure 12. Isabela. All available SM, P, and LST data for the SCAN-NRCS station. (Note: Gray lines are days without data)

- Juana Díaz Station

The SCAN-NRCS Station 2122 was assembled in Juana Díaz, PR in 2007. It is located in latitude 18.03 and longitude -66.53. At that location, the elevation is about 93 feet above the water level, the soil type is classified as Jacaguas silty clay loam (Loamy-skeletal, mixed, superactive, isohyperthermic Fluventic Haplustolls) (Table 12), the area is agricultural with small grass, and in a 1km radius the land use is divided almost equally between residences, forest, and agricultural areas (Figure 13). Slopes in the area range from 0 in residential and agricultural areas to 60 percent in the forests (Table 12). Considering all the collected data from 2007 to early 2017, the average SM, P, and LST have been 0.299 cm^3/cm^3, 0.09 inches, and 27.82 ˚C, with a variance of 0.171, 0.35, and 2.54, respectively (Table 11).

Table 11. Juana Díaz. Basic statistics for entire data collection from starting date to early 2017 for daily a) SM, b) P, and c) LST.

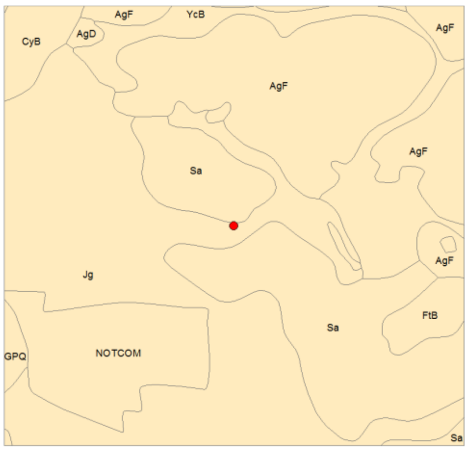
	Soil moisture (cm^3/cm^3)	Precipitation (in)	LST * (˚C)
Maximum	0.819	7.35	35.2
Minimum	0.112	0.00	21.1
Average	0.299	0.09	27.8
Mode	0.178	0.00	26.4
Variance	0.029	0.12	6.45
Standard Deviation	0.171	0.35	2.54

*LST= Land Surface Temperature.

Table 12. Juana Díaz. Soil information inside the 1km buffer around the SCAN-NRCS station.

Map Unit Symbol	Map Unit Name	Acres in AOI *	Percent of AOI *
AgD	Aguilita gravelly clay loam, 12 to 20 percent slopes	5.5	0.6%
AgF	Aguilita gravelly clay loam, 20 to 60 percent slopes	229.7	23.2%
CyB	Cuyon loam, 0 to 5 percent slopes	23.0	2.3%
FtB	Fraternidad clay, 2 to 5 percent slopes	19.3	2.0%
GPQ	Gravel pits, quarry	7.1	0.7%
Jg	Jacaguas silty clay loam	335.5	33.9%
NOTCOM	No Digital Data Available	89.7	9.1%
Sa	San Anton clay loam	187.4	19.0%
W	Water >40 acres	4.3	0.4%
YcB	Yauco silty clay loam, 2 to 5 percent slopes	86.8	8.8%

*AOI = Area of interest

a)


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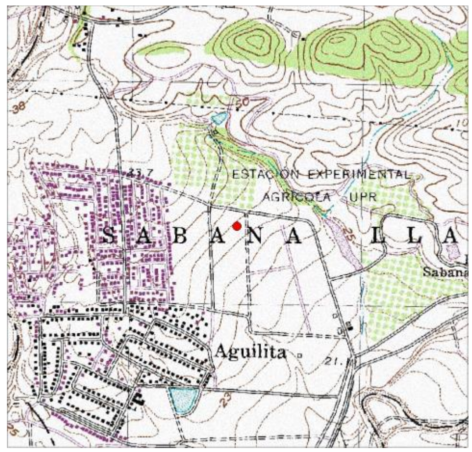


c)


d)


Figure 13. Juana Díaz. a) Soil, b) Topography, c) Visual, and d) Station for a 1km buffer around the SCAN-NRCS station.

(Images retrieved March 31, 2017 from https://websoilsurvey.sc.egov.usda.gov, https://gdg.sc.egov.usda.gov, and ArcGIS)

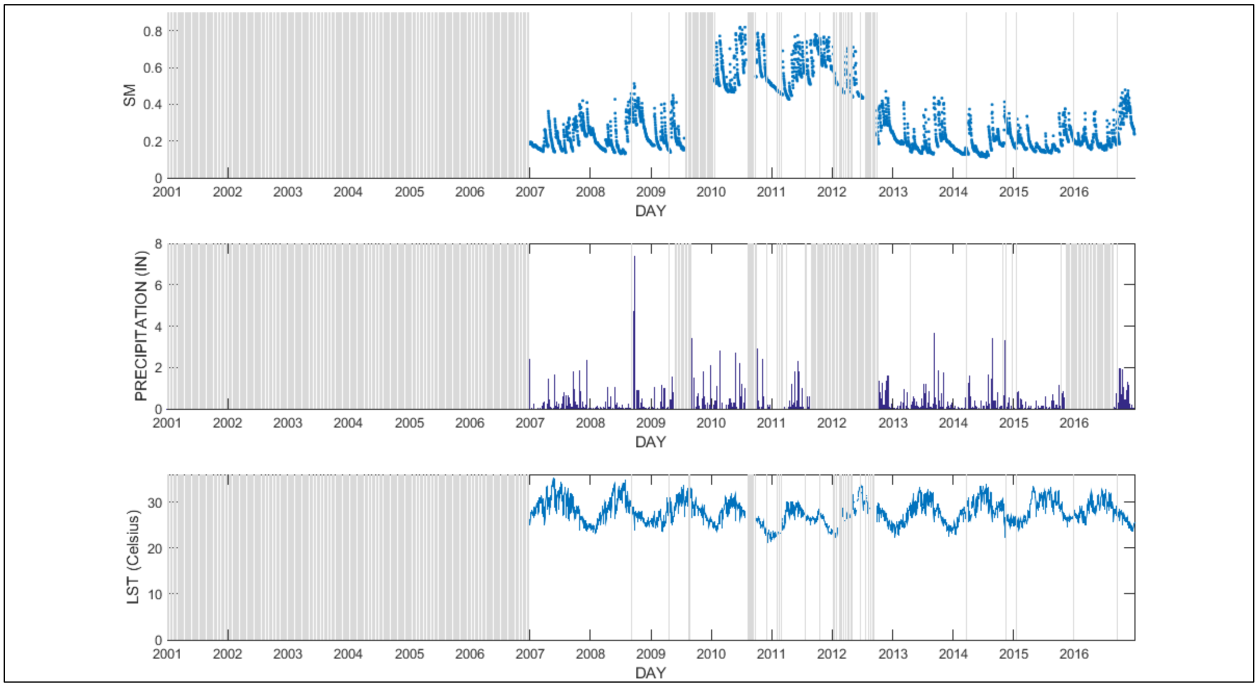


Figure 14. Juana Díaz. All available SM, P, and LST data for the SCAN-NRCS station. (Note: Gray lines are days without data)

- Maricao Station

The SCAN-NRCS Station 0015 was assembled in Maricao, PR in 2001. It is located in latitude 18.15 and longitude -67.00. At that location, the elevation is about 2450 feet above the sea level, the soil is classified as El Cacique-La Taina complex (Table 14) and is composed of 31.4% sand, 42.5% silt, and 26.1% clay. The area is very dense in vegetation with trees and tall crops; in a 1km radius more than 90% of the area are forests. The station is located very close to a river (Figure 15) and the slopes vary from 5 to 60 percent (Table 14). Considering all the collected data from the 2001 to early 2017, the average SM, P, and LST have been 0.175 cm^3/cm^3, 0.23 inches, and 20.91 ˚C, with a variance of 0.046, 0.24, and 1.42, respectively (Table 13).

Table 13. Maricao. Basic statistics for the entire data collection from starting date to early 2017 for daily a) SM, b) P, and c) LST.

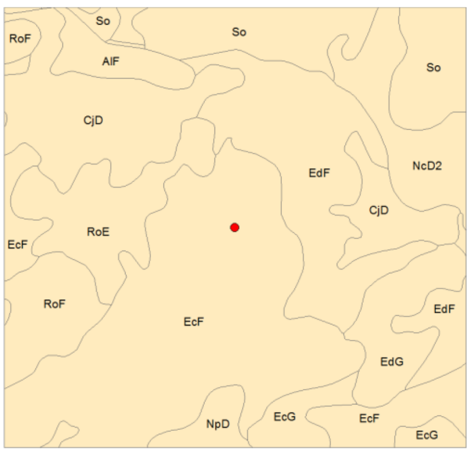
	Soil moisture (cm^3/cm^3)	Precipitation (in)	LST * (˚C)
Maximum	0.401	4.21	24.0
Minimum	0.000	0.00	17.6
Average	0.175	0.23	20.9
Mode	0.193	0.00	21.3
Variance	0.046	0.24	1.42
Standard Deviation	0.068	0.49	1.19

*LST= Land Surface Temperature.

Table 14. Maricao. Soil information inside the 1km buffer around the SCAN-NRCS station.

Map Unit Symbol	Map Unit Name	Acres in AOI *	Percent of AOI *
NcD2	Nipe clay, 5 to 20 percent slopes, eroded	57.3	5.8%
RsE2	Rosario clay, 20 to 40 percent slopes, eroded	4.3	0.4%
So	Serpentinite outcrop	99.7	10.1%
AlF	Aljibe-Guama-Indiera complex, 20 to 60 percent slopes	25.3	2.6%
CjD	Cerro Gordo mucky peat, 2 to 20 percent slopes	127.3	12.9%
EcF	El Cacique-La Taina complex, 20 to 60 percent slopes	316.1	32.0%
EcG	El Cacique-La Taina complex, 60 to 90 percent slopes	28.4	2.9%
EdF	El Descanso-Hoconuco complex, 20 to 60 percent slopes	146.9	14.9%
EdG	El Descanso-Hoconuco complex, 60 to 90 percent slopes	46.6	4.7%

*AOI = Area of interest

a)


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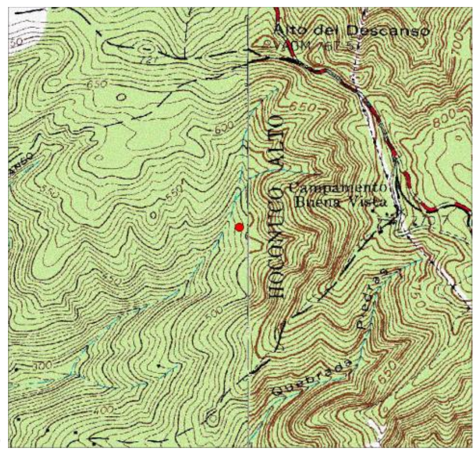
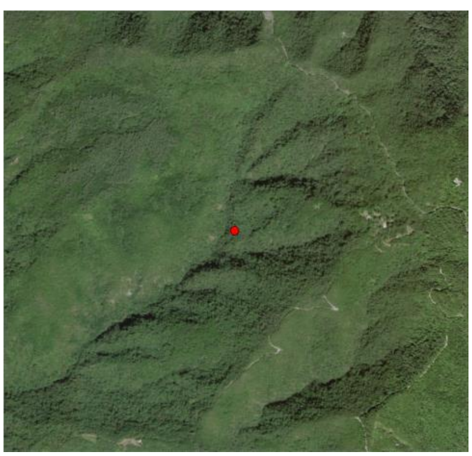


c)


d)


Figure 15. Maricao. a) Soil, b) Topography, c) Visual, and d) Station for a 1km buffer around the SCAN-NRCS station.

(Images retrieved March 31, 2017 from https://websoilsurvey.sc.egov.usda.gov, https://gdg.sc.egov.usda.gov, and ArcGIS)

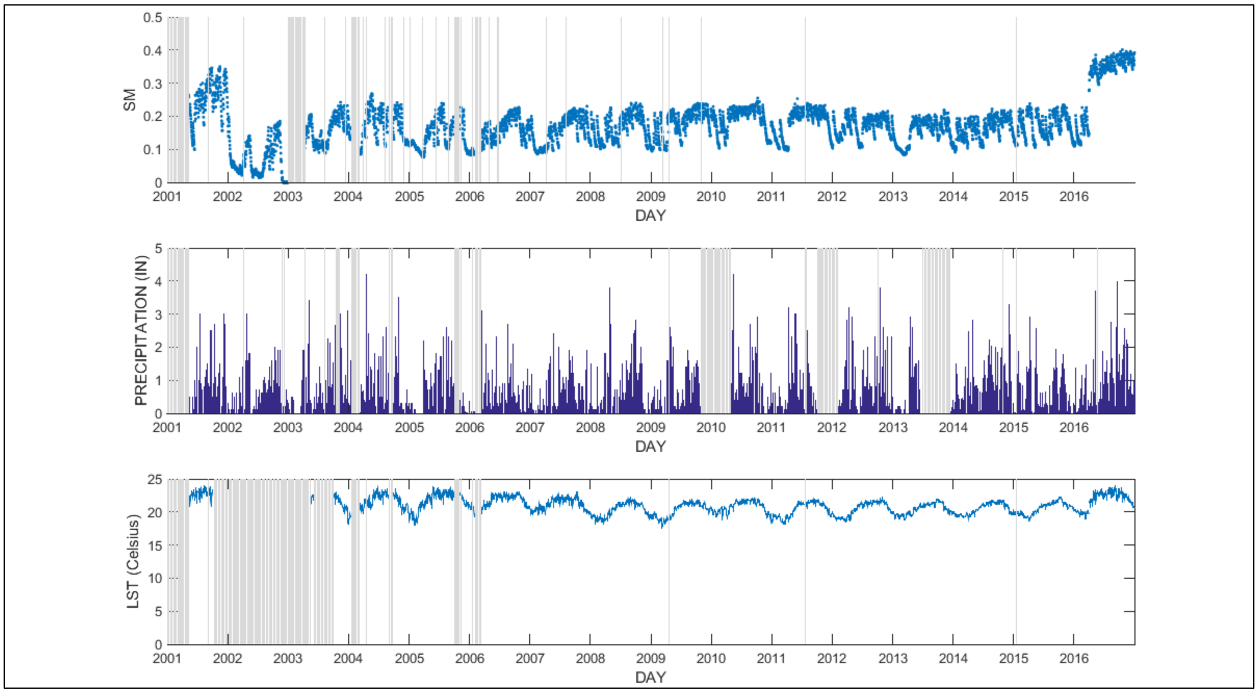


Figure 16. Maricao. All available SM, P, and LST data for the SCAN-NRCS station. (Note: Gray lines are days without data)

- Mayagüez Station

The SCAN-NRCS Station 2112 was assembled in Mayagüez, PR in 2006. It is located in latitude 18.21 and longitude -67.14. At that location, the elevation is about 45 feet above the sea level, the soil type is classified as Leveled clay land (Table 16) and is composed of 26.1% sand, 42.5% silt, and 31.4% clay. The station is located in the Tropical Agricultural Research Station (TARS) of the United States Department of Agriculture (USDA) and the area around a 1km buffer is mostly urban (Figure 17), with slopes ranging from 0 to 60 percent (Table 16). Considering all the collected data from 2006 to early 2017, the average SM, P, and LST have been 0.553 cm^3/cm^3, 0.19 inches, and 29.22 ˚C, with a variance of 5.32e-04, 0.175, and 3.46, respectively (Table 15).

Table 15. Mayagüez. Basic statistics for entire data collection from starting date to early 2017 for daily SM, P, and LST.

	Soil moisture (cm^3/cm^3)	Precipitation (in)	LST * (˚C)
Maximum	0.584	4.40	33.0
Minimum	0.454	0.00	24.6
Average	0.553	0.19	29.2
Mode	0.564	0.00	29.1
Variance	5.32e-04	0.18	3.46
Standard Deviation	0.023	0.42	1.86

*LST= Land Surface Temperature.

Table 16. Mayagüez. Soil information inside the 1km buffer around the SCAN-NRCS station.

Map Unit Symbol	Map Unit Name	Acres in AOI *	Percent of AOI *
An	Alluvial land	10.1	1.0%
Ba	Bajura clay	4.8	0.5%
Cn	Coloso silty clay loam	12.5	1.3%
CoE	Consumo clay, 20 to 40 percent slopes	107.5	10.9%
CoF2	Consumo clay, 40 to 60 percent slopes	5.1	0.5%
DaD2	Daguey clay, 12 to 20 percent slopes, eroded	83.4	8.4%
DaE2	Daguey clay, 20 to 40 percent slopes, eroded	26.3	2.7%
GPQ	Gravel, pits and quarries	7.5	0.8%
HmE2	Humatas clay, 20 to 40 percent slopes	58.3	5.9%
Lc	Leveled clayey land	332.2	33.6%
Le	Leveled clayey land, shallow	0.2	0.0%
Lf	Leveled land, frequently flooded	258.8	26.2%
Lm	Leveled sandy land	16.5	1.7%
MxE	Mucara clay, 20 to 40 percent slopes	46.8	4.7%
ToA	Toa silty clay loam, 0 to 2 percent slopes, occasionally flooded	17.8	1.8%
W	Water > 40 acres	0.5	0.0%
AgD	Aguilita gravelly clay loam, 12 to 20 percent slopes	5.5	0.6%
AgF	Aguilita gravelly clay loam, 20 to 60 percent slopes	229.7	23.2%
CyB	Cuyon loam, 0 to 5 percent slopes	23.0	2.3%
FtB	Fraternidad clay, 2 to 5 percent slopes	19.3	2.0%
GPQ	Gravel pits, quarry	7.1	0.7%
Jg	Jacaguas silty clay loam	335.5	33.9%
NOTCOM	No Digital Data Available	89.7	9.1%
Sa	San Anton clay loam	187.4	19.0%
W	Water >40 acres	4.3	0.4%
YcB	Yauco silty clay loam, 2 to 5 percent slopes	86.8	8.8%

*AOI = Area of interest

Figure 17. a) Soil, b) Topography, c) Visual, and d) Station for a 1km buffer around the SCAN-NRCS station.

(Images retrieved March 31, 2017 from https://websoilsurvey.sc.egov.usda.gov, https://gdg.sc.egov.usda.gov, and ArcGIS)

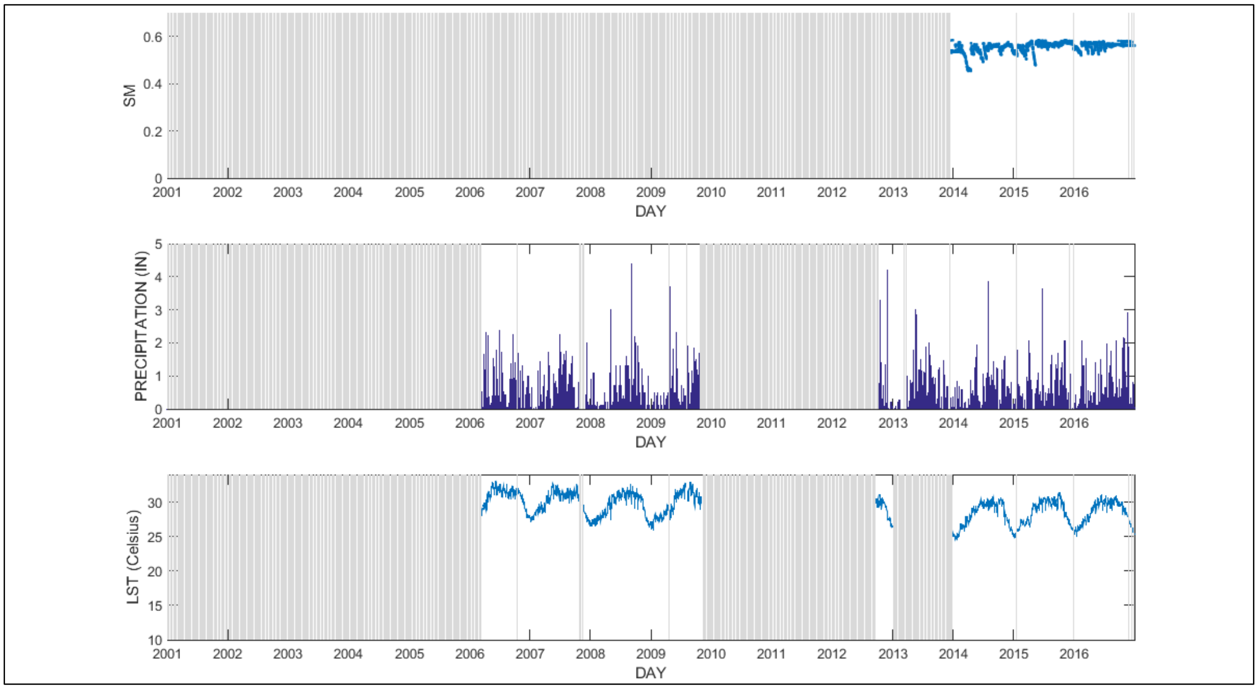


Figure 18. Mayagüez. All available SM, P, and LST data for the SCAN-NRCS station. (Note: Gray lines are days without data)

3.3.2 Satellite-based SM Estimates from the AMSR2 Sensor

The Global Change Observation Mission – Water 1 (GCOM-W1) (Figure 19) satellite system was launched in May 17th, 2012 to collect geophysical parameters (i.e., precipitation, sea surface temperature, and soil moisture content) and observe changes in water circulation [6, 22]. The GCOM-W1 system carries the Advanced Microwave Scanning Radiometer 2 sensor, which retrieves the radiometric waves emitted from Earth, data used to estimate SM at coarse resolution covering most of the globe's area every two days [6, 22]. The SM product provided by the AMSR2 can be retrieved from the Earth Observation Research Center (EORC) on the Japan Aerospace Exploration Agency (JAXA) website. The data can be downloaded in Hierarchical Data Format 5 (HDF5) for day and night readings, scene (referring to all the measurements taken half orbit between the North Pole and the South Pole with respect to the observation point [25]) or global map (10km and 25 km resolution), on a daily or monthly basis. For this project, all available daily 25km resolution SM estimates values during the day were retrieved and analyzed. A sample of the 25km resolution SM product over Puerto Rico is presented in Figure 20.

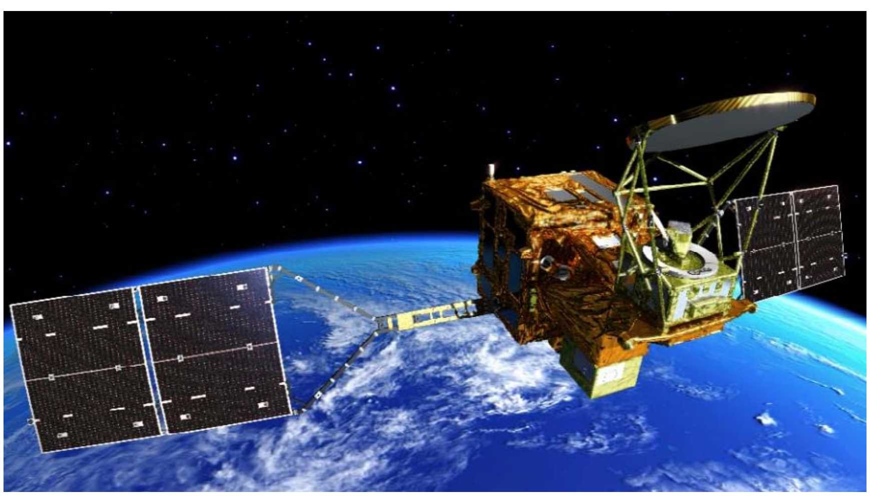


Figure 19. GCOM-W1 Shizuku (droplet in Japanese) satellite system, retrieved March 29, 2017, from http://global.jaxa.jp/projects/sat/gcom_w/index.html.

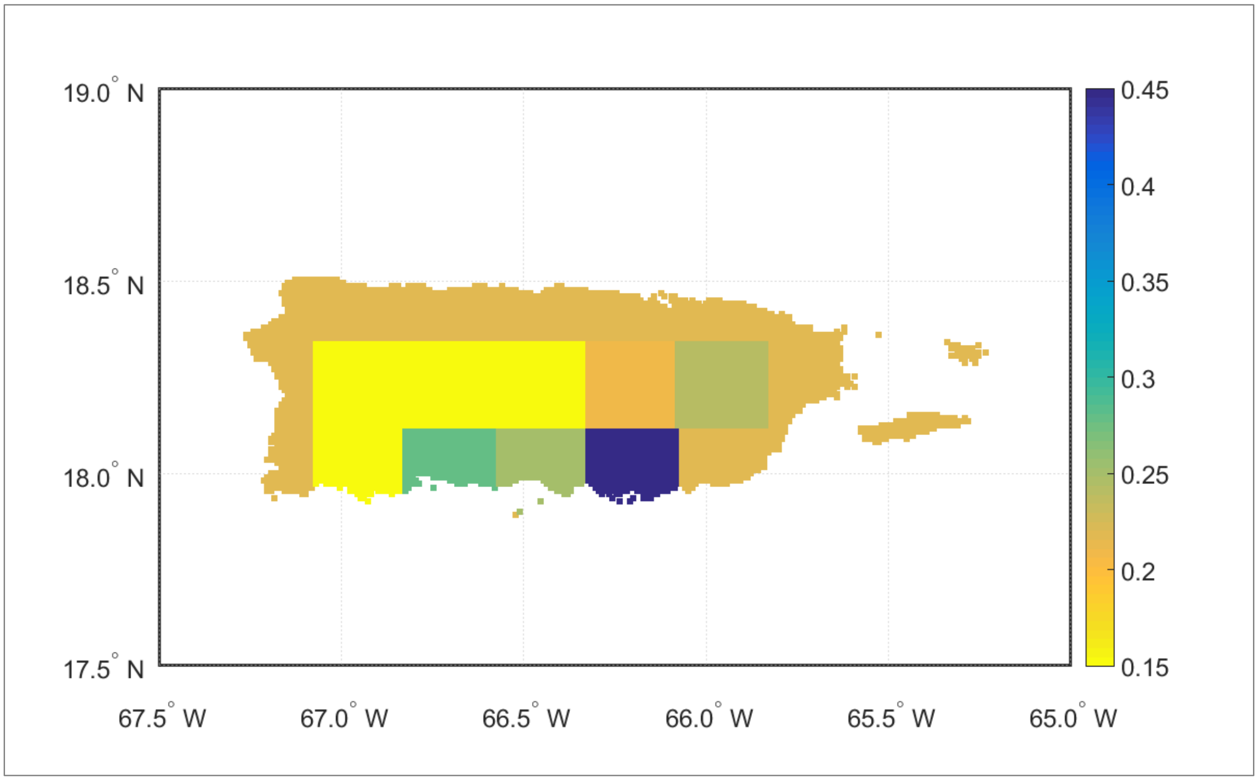


Figure 20. AMSR2 25km SM product for December 26, 2016.

3.3.3 Moderate Resolution Imaging Spectroradiometer (MODIS)

The MODIS instrument is a spectroradiometer that collects data for 36 different spectral bands and offer its products at a spatial resolution that varies from 500 to 5,600 meters. The products of MODIS are leaf area index, fractional photosynthetically active radiation, bidirectional reflectance distribution function, thermal anomalies and fire, temperature, emissivity, vegetation indices, gross and net primary productivity, and albedo. Two units of MODIS are currently collecting data, one is aboard the Terra satellite and the other in Aqua satellite system (Figure 21). These satellite systems are part of the NASA-centered international Earth Observing System (EOS). Both systems travel in a circular sun-synchronous polar orbit, a setting that allows the systems to go from north to south of Earth every 99 minutes (16 orbits per day), collecting data for the entire planet every one or two days. MODIS products of Albedo, LST, and NDVI at a 1km resolution were retrieved in HDF4 from the EOS for Puerto Rico in order to perform the downscaling of a 25km resolution SM from AMRS2 to a 1km resolution SM product. A sample of the Albedo, LST, and NDVI parameters over Puerto Rico is presented in Figure 22.

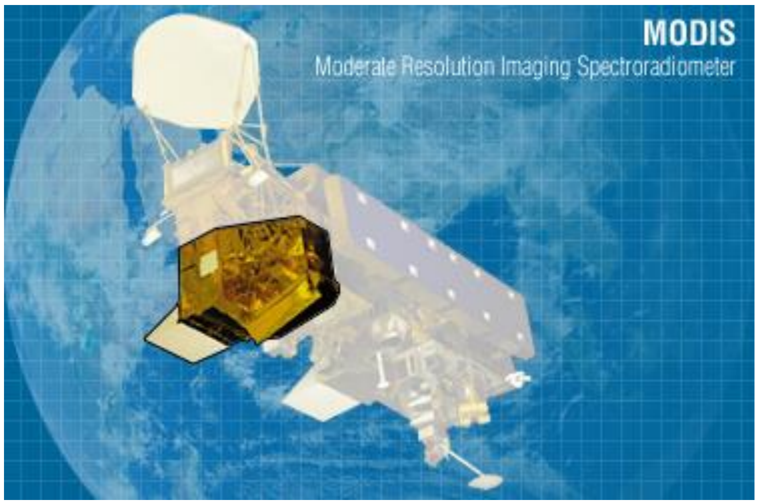


Figure 21. MODIS instrument carried by the Aqua satellite system. Retrieved February 21, 2017 from http://www.moisturemap.monash.edu.au

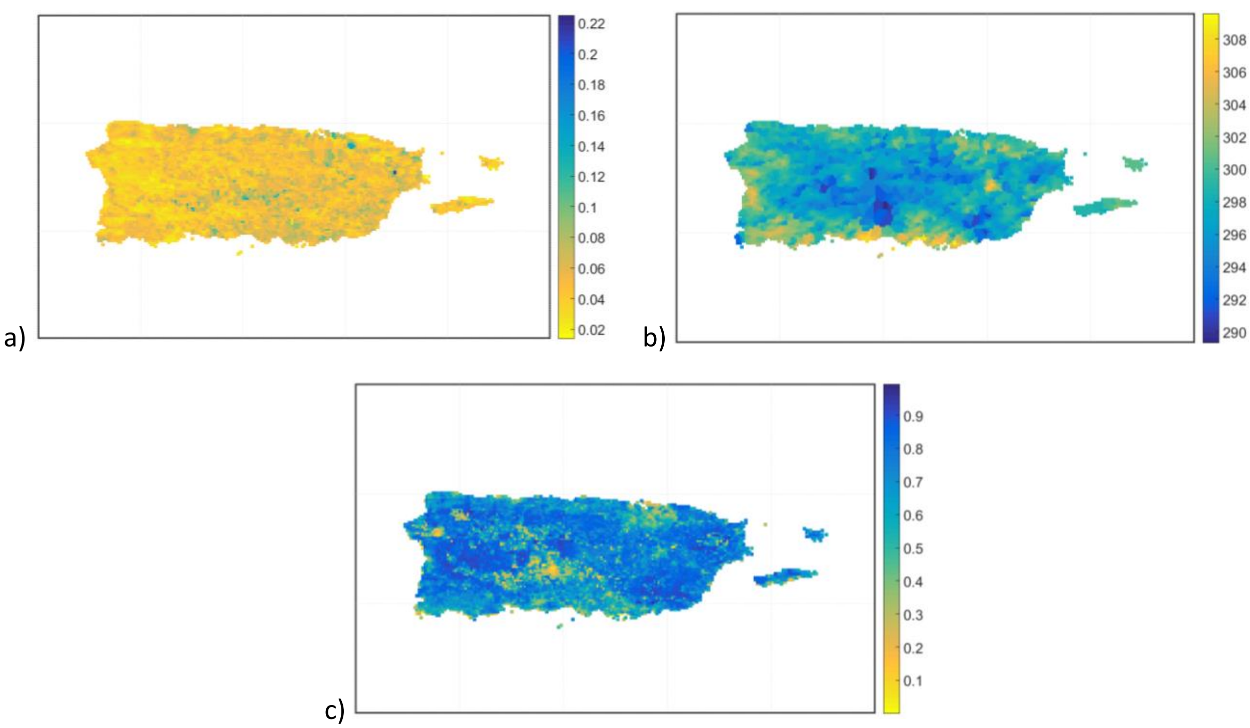


Figure 22. MODIS product at 1km resolution over Puerto Rico; a) Albedo, b) LST (K), and c) NDVI, for September 5, 2016.

3.3.4 Precipitation from GOES-PRWEB

Daily precipitation (Table 23) at 1km resolution is provided from the GOES-PRWEB model. The model GOES-PRWEB obtains 24-hour precipitation data from NOAA's Advanced Hydrologic Prediction Service (AHPS), then process the data and makes it available to download for csv format in the Puerto Rico Agricultural Water Management (PRAGWATER) website.

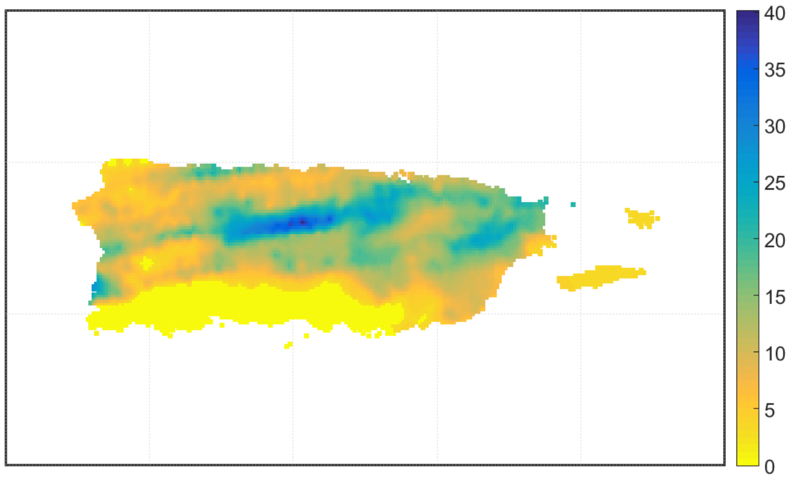


Figure 23. Rainfall event for September 5, 2016 from GOES-PRWEB.

4. Results and Discussion

4.1 Validation of 25km Resolution AMRS2 SM

The 25km resolution AMRS2 SM was compared with in-situ data from each SCAN-NRCS station in Puerto Rico. For each station, only the 25km pixels with the closest distance from their centroid to the station and with an error between ±0.15 in terms of SM were considered for comparison. The total number of days during which AMSR2 collected SM over Puerto Rico is 1148, this number will be compared with the quantity of data that had an error of ±0.15. The results of the validation and a brief discussion will be provided in the rest of this section.

- Adjuntas Station

The Adjuntas SCAN-NRCS station is located in a forested area, with high slopes, and clayey soils (Figure 3). High soil moisture is expected and can be observed in the SCAN-NRCS station data (Figure 4**Error! Reference source not found.**). A comparison of the full dataset of AMSR2 and NRCS shows that the satellite-based data is mostly underestimating SM in terms of the data collected in Adjuntas. This comparison is presented in Figure 24, from this comparison, only 25% of the satellite-based measurements achieved a bias of ±0.15. Now, while the overall average value of SM in Adjuntas is 0.3983, the data considered in this validation has an average SM of 0.2549. This indicates that, for this station, the sensor AMSR2 can provide an estimation having a bias of ±0.15 mostly for dry days. As seen in Figure 25, AMSR2 behaves similar to the in-situ measurements, but tends to underestimate, possibly due to the difference in resolution between the two systems. This also can be seen from the statistics since the average SM from AMSR2 is 0.2050 while the average of NRCS is 0.2549 and the correlation between both SM datasets is 0.8413 (Figure 26).

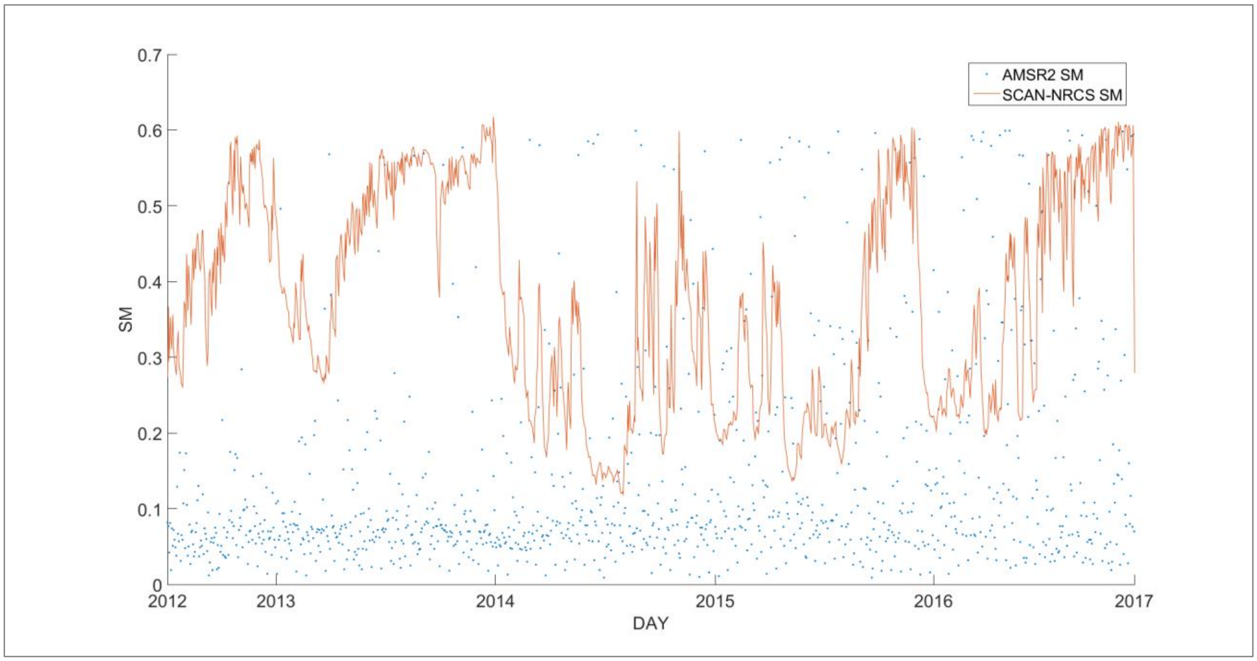


Figure 24. Adjuntas, comparison of all data available from AMSR2 SM and SCAN-NRCS SM.

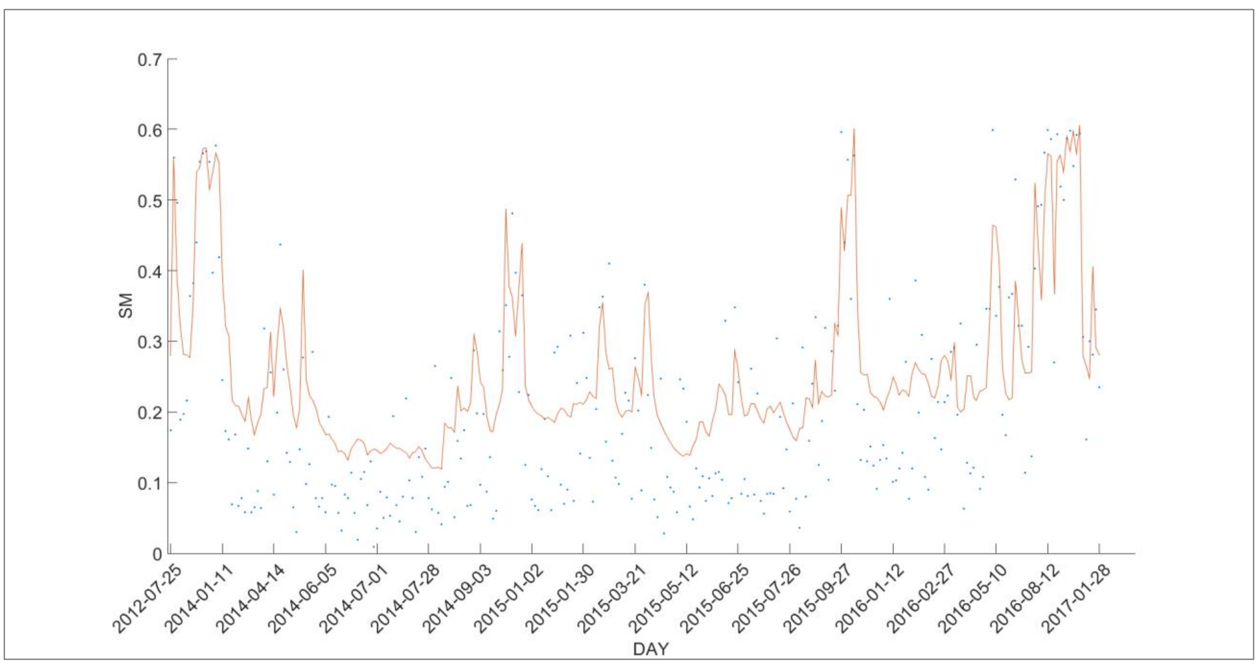


Figure 25. Adjuntas, comparison of 25km SM from AMSR2 with SM from SCAN-NRCS.

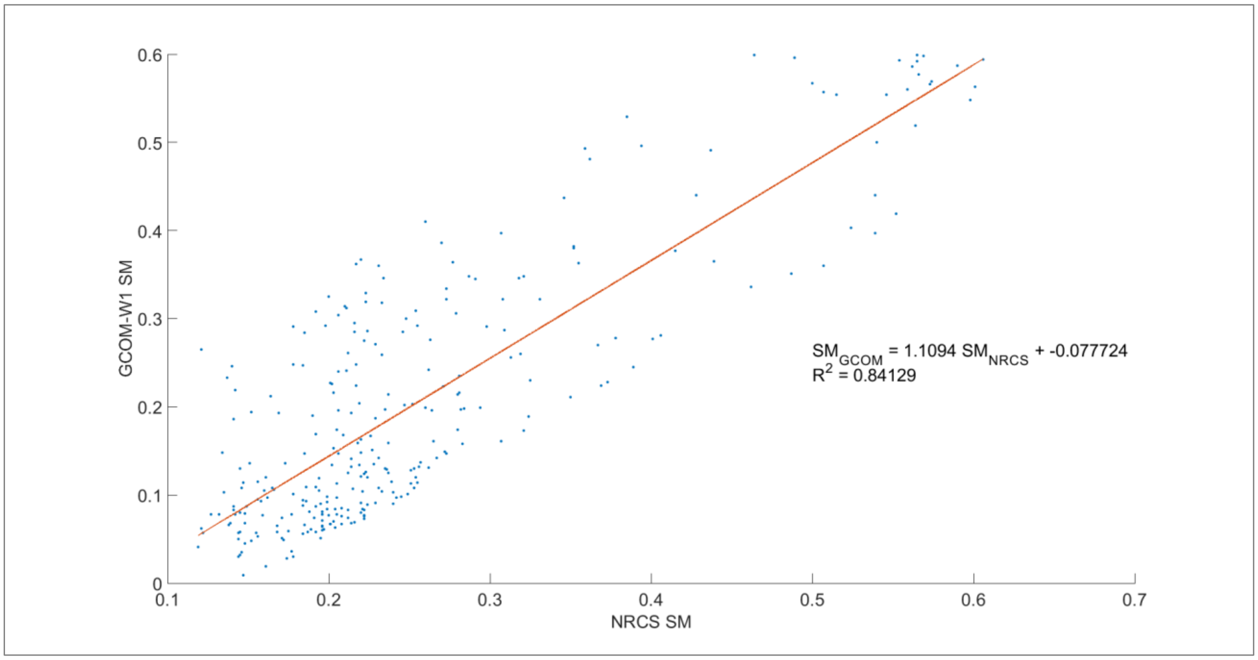


Figure 26. Adjuntas, correlation between AMSR2 SM and SCAN-NRCS SM measurements.

- Cabo Rojo Station

The Cabo Rojo SCAN-NRCS station is located in an agricultural area, with low slopes, low vegetation densities, and sandy soils (Figure 5). Low soil moisture is expected and can be observed in the SCAN-NRCS station data (Figure 6). A comparison of the full dataset of AMSR2 and NRCS (Figure 27) shows that the satellite-based data is mostly underestimating SM in terms of the data collected in Cabo Rojo. About 43% of the satellite-based measurements achieved a bias ±0.15. The overall and biased SM averages are 0.1699 and 0.1548, respectively. By comparing these values, it could be inferred that, for this station, the sensor AMSR2 can provide a moderately good estimation having bias of ±0.15. Though, Figure 28 reveals that, similar to Adjuntas, the satellite-based behaves similar to the in-situ measurements, but with a tendency to underestimate. This results in a correlation of 0.3027 as shown in Figure 29. Considering that Cabo Rojo is in the south-west part of the Island, in a region of higher temperatures, and observing the behavior of the data in Adjuntas, where it underestimated the SM values, it was expected that the comparison with Cabo Rojo would lead to higher correlations. Even though the correlations were low, the behavior of these 25km pixels that are located close to the southwest part of the island does describe a substantially drier environment compared to the results from Adjuntas, which is located closer to the center of the island, where lower temperatures and higher humidity is expected.

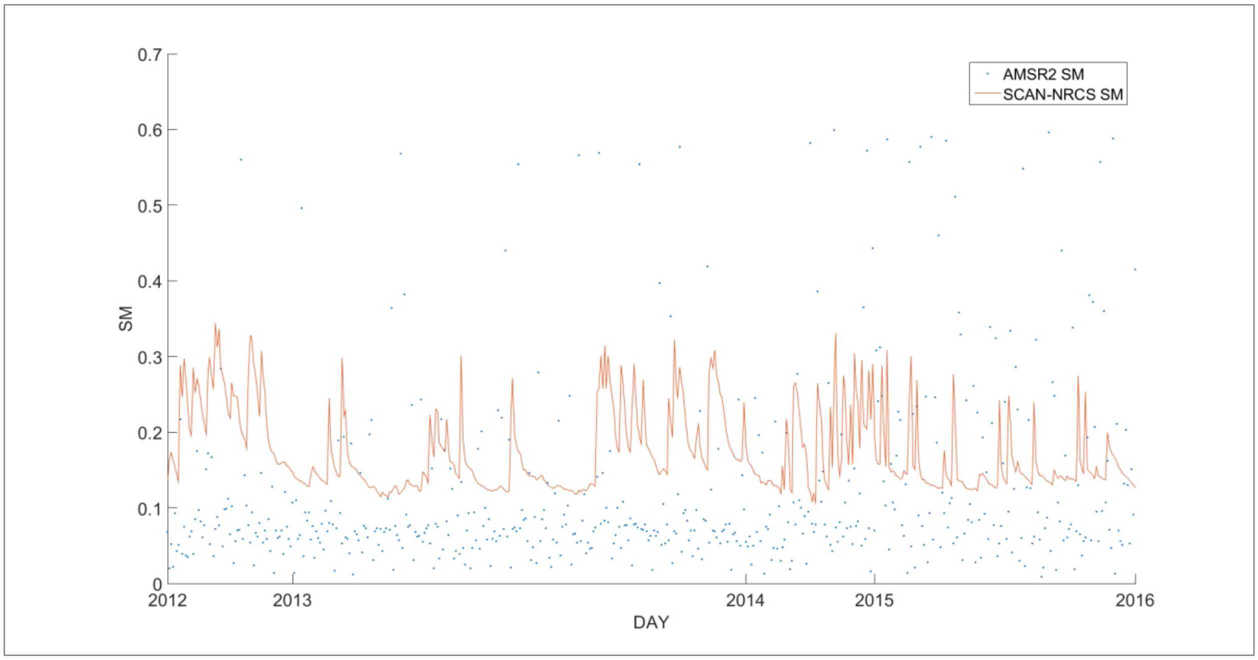


Figure 27. Cabo Rojo, comparison of all data available from AMSR2 SM and SCAN-NRCS SM.

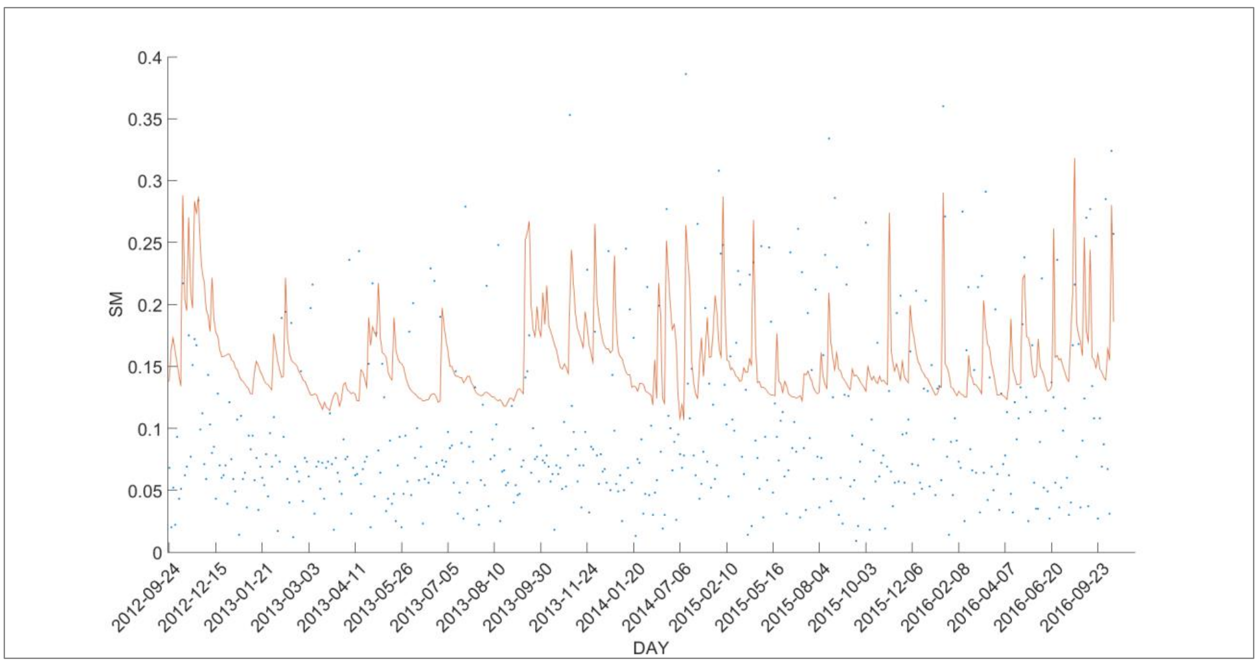


Figure 28. Cabo Rojo, comparison of 25km SM from AMSR2 with SM from SCAN-NRCS.

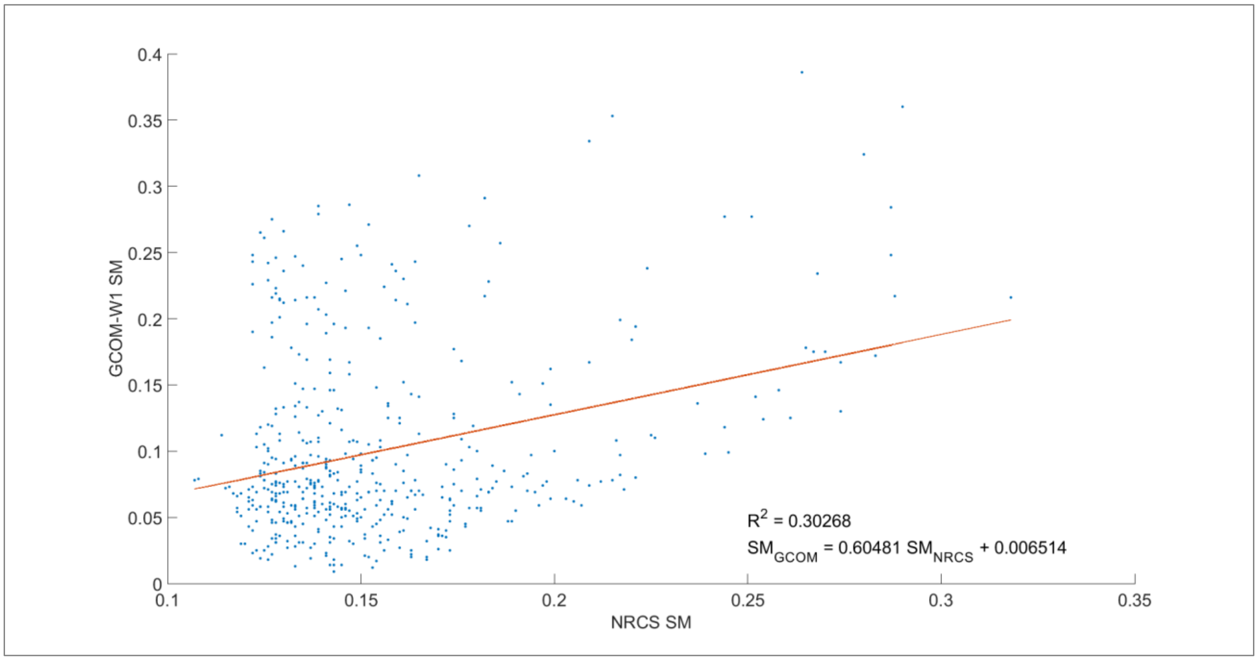


Figure 29. Cabo Rojo, correlation between AMSR2 SM and SCAN-NRCS SM measurements.

- Corozal Station

The Corozal SCAN-NRCS is located in the center of the island, a region that receives more precipitation during hurricane seasons (from June to November). Higher soil moisture is expected through the hurricane seasons each year, this can be observed in the SCAN-NRCS station data (Figure 8). A comparison of the full dataset of AMSR2 and NRCS (Figure 30) shows that the satellite-based data highly underestimates SM in terms of the in-situ data collected in Corozal. About 25% of the satellite-based measurements achieved a bias of ±0.15 (Figure 31). The ground-based overall and biased SM averages are 0.3621 and 0.2295, respectively, and the biased correlation is 0.7269 (Figure 32). Unlike the other stations, biased SM estimates from AMSR2 show a good fit compared to the ground-based data. Having a good correlation for this particular SCAN-NRCS station during summer seasons may be an indicative of AMSR2 producing accurate SM for the entire island during that same season.

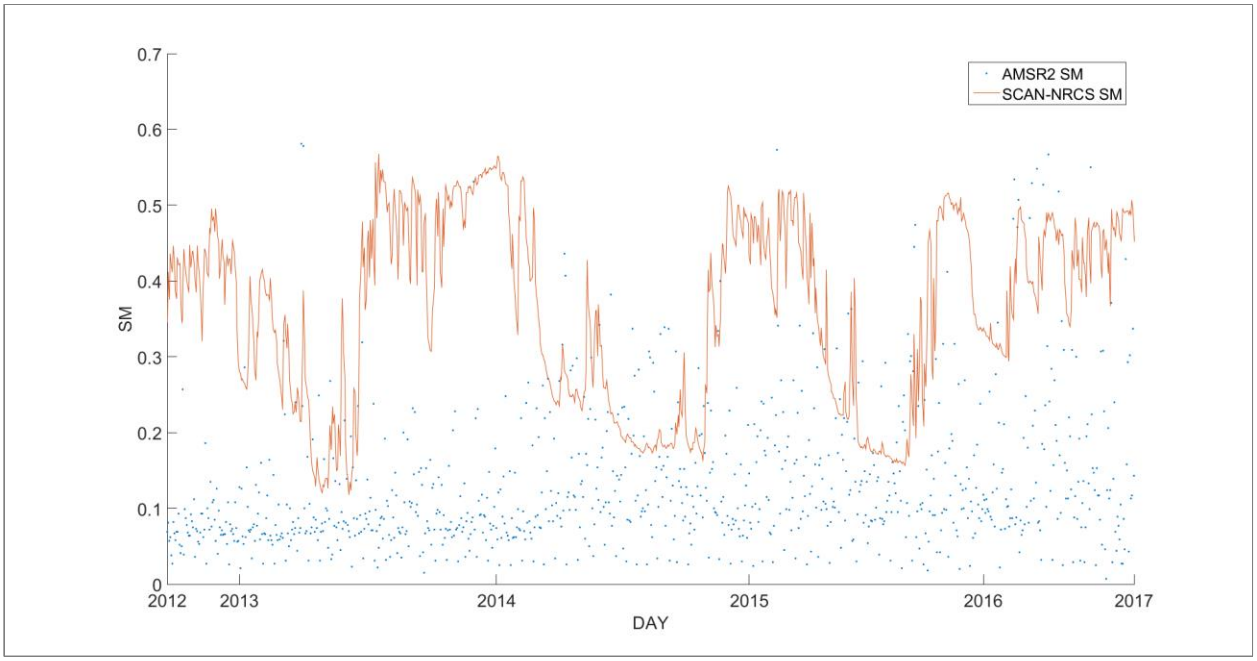


Figure 30. Corozal, comparison of all data available from AMSR2 SM and SCAN-NRCS SM.

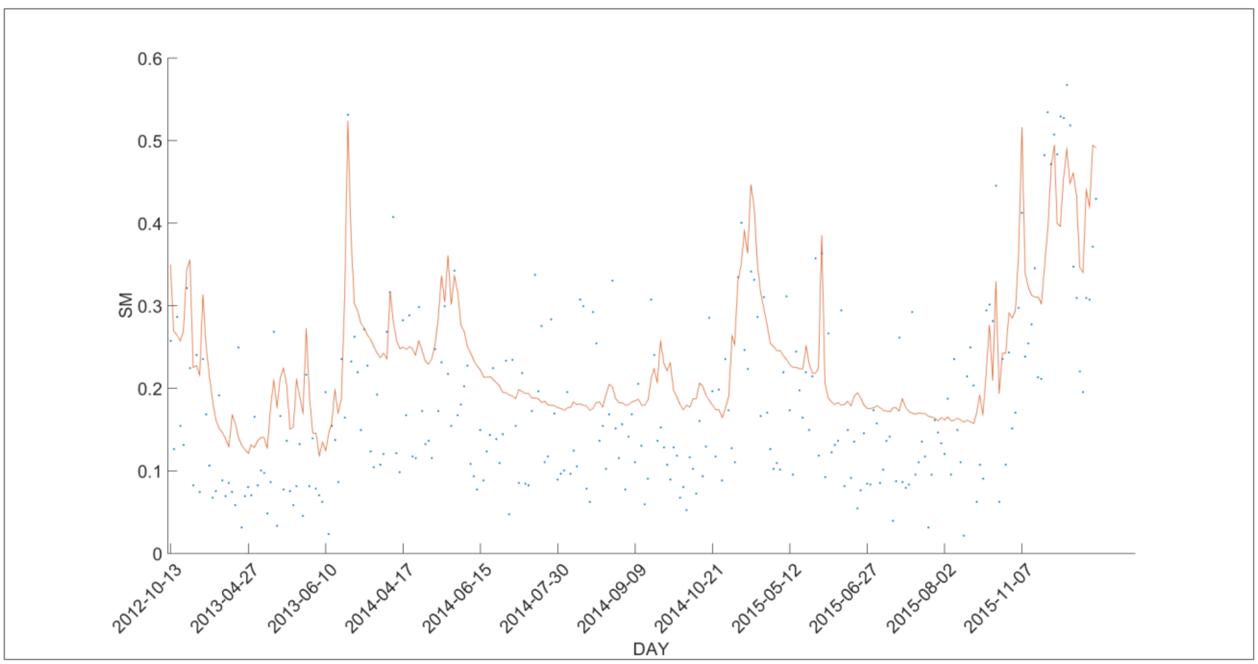


Figure 31. Corozal, comparison of 25km SM from AMSR2 with SM from SCAN-NRCS.

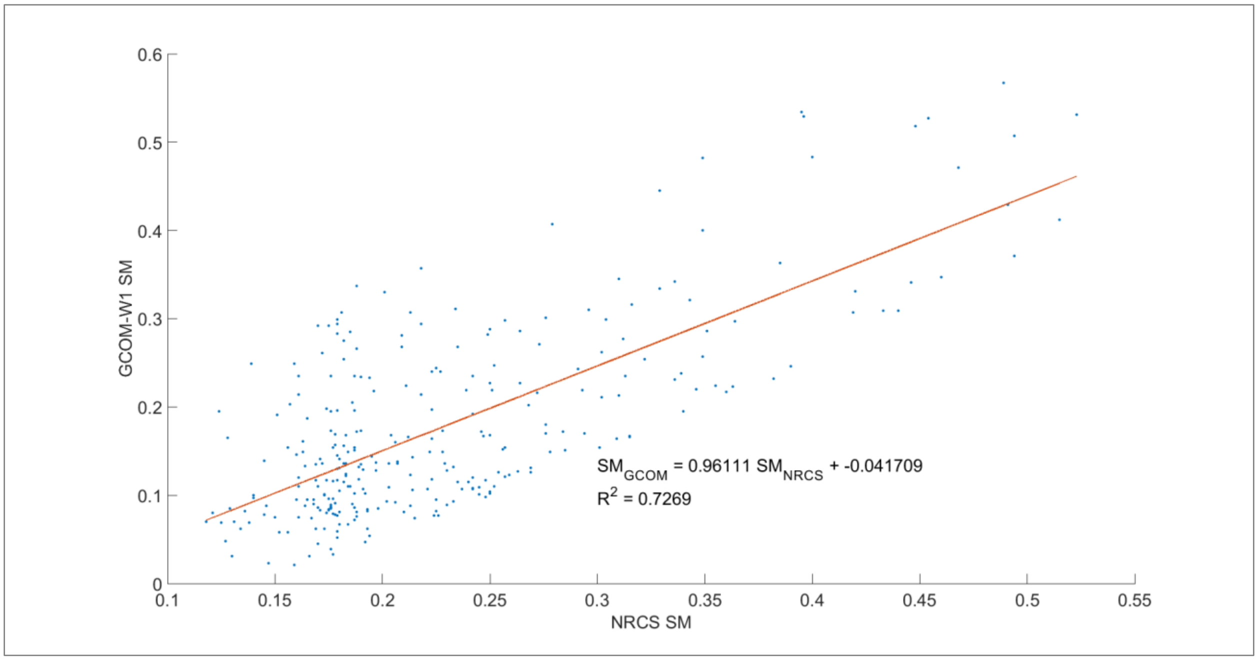


Figure 32. Corozal, correlation between AMSR2 SM and SCAN-NRCS SM measurements.

- Guánica Station

The Guánica SCAN-NRCS station is in an area known as the "Bosque Seco", which directly translates to "Dry Forest", with low slopes, high density of tall grass and small bushes, and about 79.7% of sandy soils (Figure 9). Very low soil moisture is expected all year except for hurricane season, this can be observed in the SCAN-NRCS station data (Figure 10). When plotting the full dataset of AMSR2 and NRCS SM for the other SCAN-NRCS stations is seemed like AMSR2 was underestimating most of the days. However, Figure 33 shows that the AMSR2 SM estimates are very close to the in-situ SM measurements. About 64% of the satellite-based measurements achieved a bias ±0.15 (Figure 34). It is expected that, for this station, AMSR2 will provide a good estimate of SM for both dry seasons and wetter seasons. The overall and biased SM averages are 0.0627 and 0.0669, respectively, and the correlation of the biased SM is 0.4075 (Figure 35). The correlation resulted from the values that for other stations are underestimates. However, AMSR2 is indeed showing a SM increase in wetter seasons and a decrease in drier seasons. This suggests that the only reason that the correlation is so low is because of the spatial resolution of the satellite-based sensor.

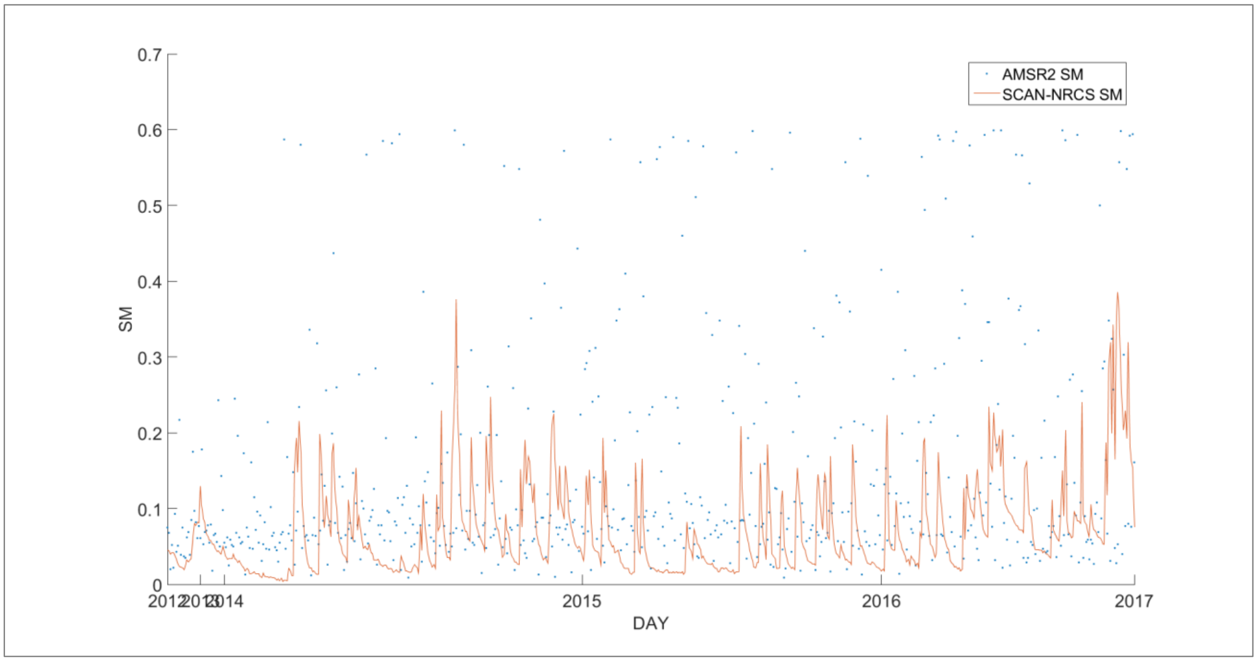


Figure 33. Guánica, comparison of all data available from AMSR2 SM and SCAN-NRCS SM.

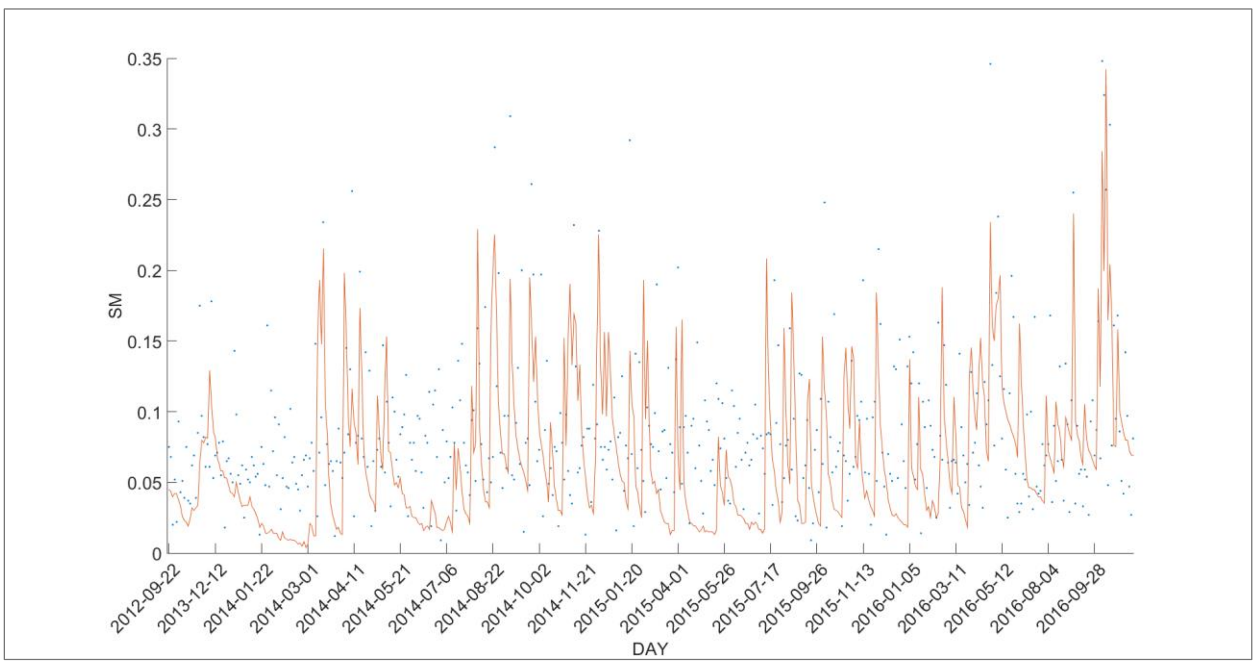


Figure 34. Guánica, comparison of 25km SM from AMSR2 with SM from SCAN-NRCS.

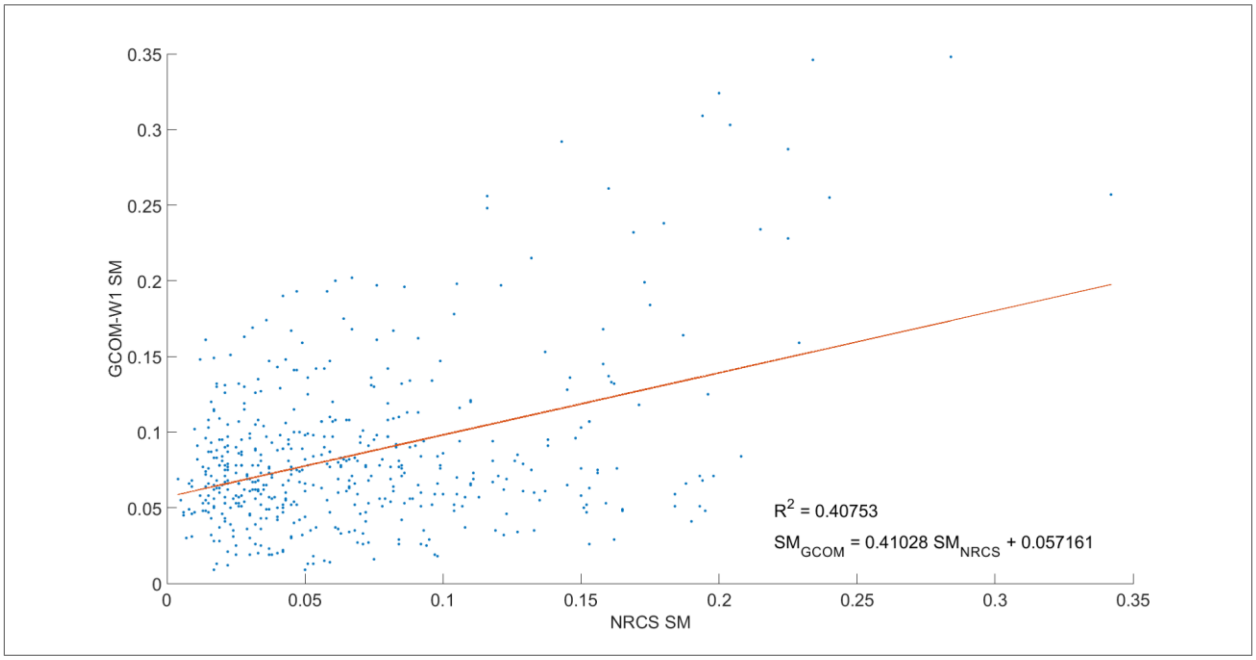


Figure 35. Guánica, correlation between AMSR2 SM and SCAN-NRCS SM measurements.

- Isabela Station

Isabela is in the north-west part of the island, in this region small precipitation events are common all year. The SCAN-NRCS station location is an agricultural area, with low slopes, and clayey soils (Figure 11). High soil moisture is expected and can be observed in the SCAN-NRCS station data (Figure 12). A comparison of the full dataset of AMSR2 and NRCS shows that the satellite-based data is mostly underestimating SM in terms of the data collected in Isabela. This comparison is presented in Figure 36, from this comparison, only about 28% of the satellite-based measurements achieved a bias of ±0.15 (Figure 37). While the overall average value of SM in Isabela is 0.3137, the biased average SM is 0.2499, and a correlation between the biased AMSR2 and NRCS SM datasets is 0.7532 (Figure 38). As seen in other stations, AMSR2 tends to underestimate a lot. However, AMSR2 manages provide a good estimate for a few days in wetter seasons, which indicates that the origin of the underestimates is the low resolution of the satellite-based sensor.

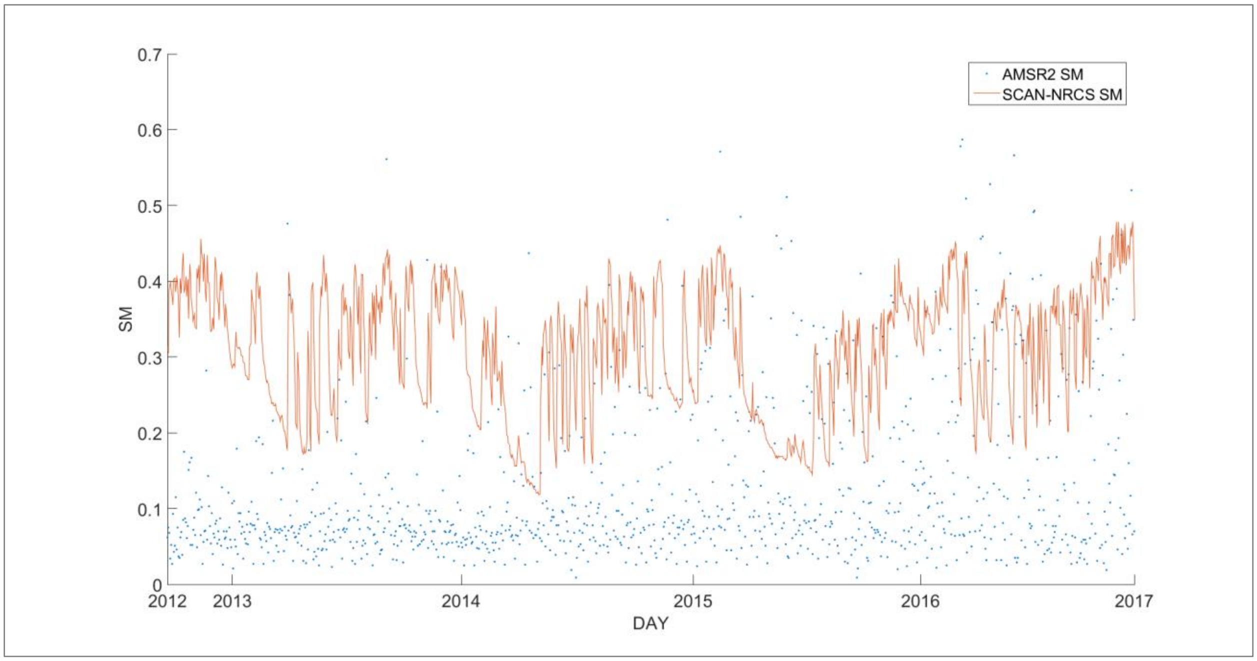


Figure 36. Isabela, comparison of all data available from AMSR2 SM and SCAN-NRCS SM.

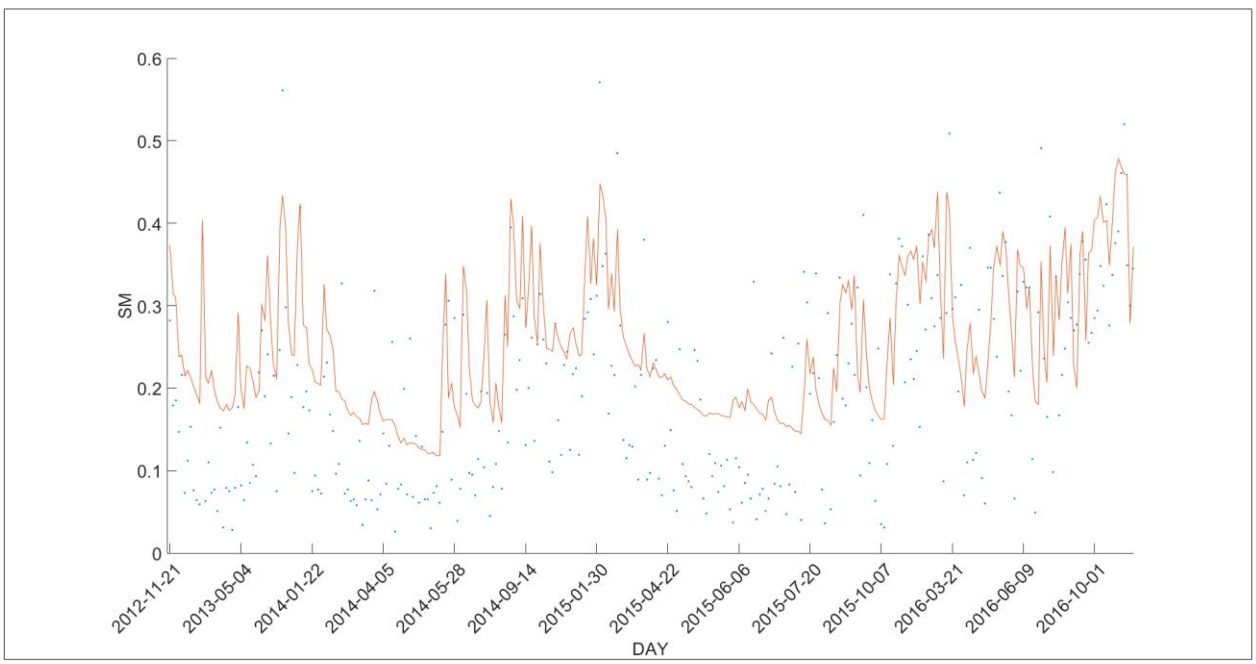


Figure 37. Isabela, comparison of 25km SM from AMSR2 with SM from SCAN-NRCS.

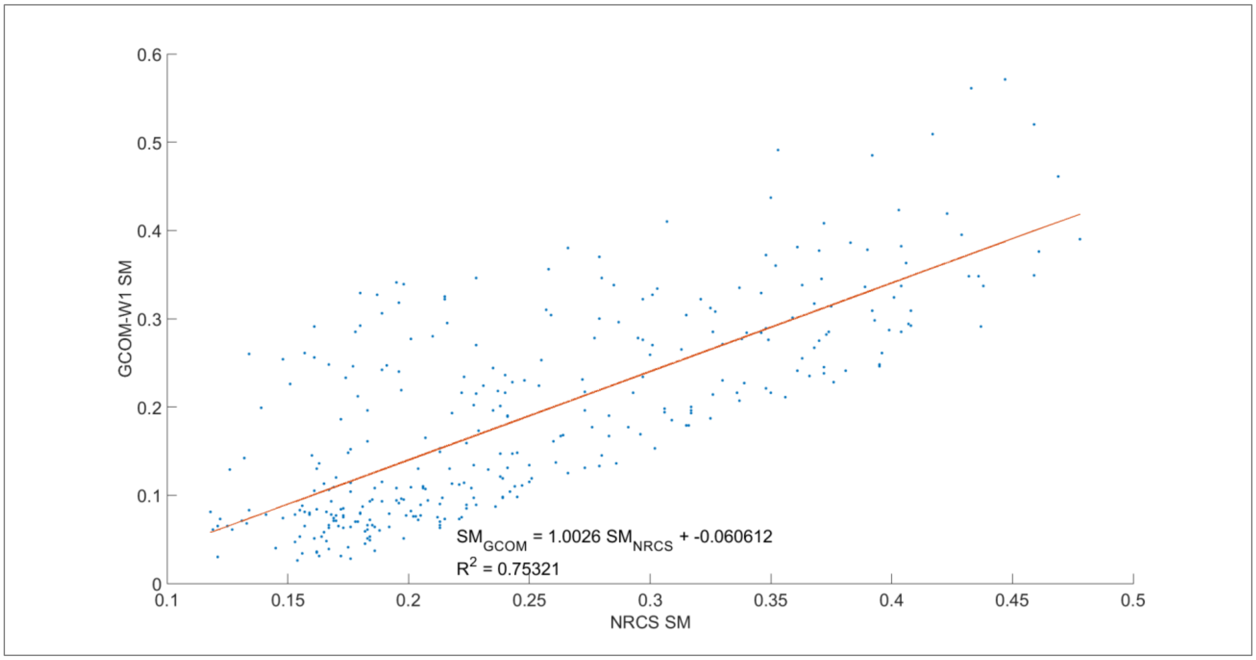


Figure 38. Isabela, correlation between AMSR2 SM and SCAN-NRCS SM measurements.

- Juana Díaz

Juana Díaz is in the south-central part of the island, a region known to be of hot weather but since it is close to the center there is higher probability of storm events during the year. The SCAN-NRCS station is in an agricultural, with low slopes, and clayey soils (Figure 13). A high frequency of precipitation events is expected and for soil moisture, low values are expected in dry days while a small increase is expected in wetter days. This behavior can be observed in the SCAN-NRCS station data (Figure 14). A comparison of the full dataset of AMSR2 and NRCS shows that the satellite-based data is mostly underestimating SM in terms of the data collected in Juana Díaz. This comparison is presented in Figure 39, from this comparison, only about 74% of the satellite-based measurements achieved a bias of ±0.15 (Figure 40). While the overall average value of SM in Isabela is 0.3983, the biased average SM is 0.1910, and a correlation between the biased AMSR2 and NRCS SM datasets is 0.4999 (Figure 41). Unlike the comparison with other stations, in Juana Díaz the AMSR2 SM estimates are overestimating more because the 25km pixel that is above Juana Díaz may be also covering part of the central part of the island, where humidity and frequency of precipitation events is higher.

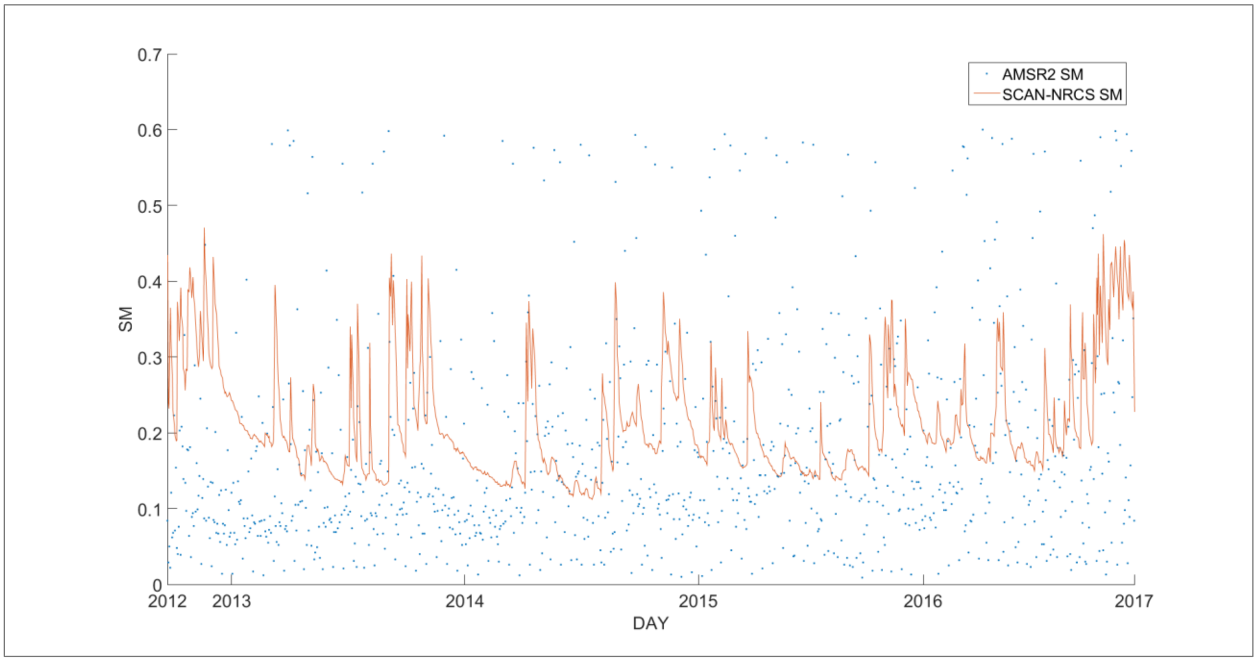


Figure 39. Juana Díaz, comparison of all data available from AMSR2 SM and SCAN-NRCS SM.

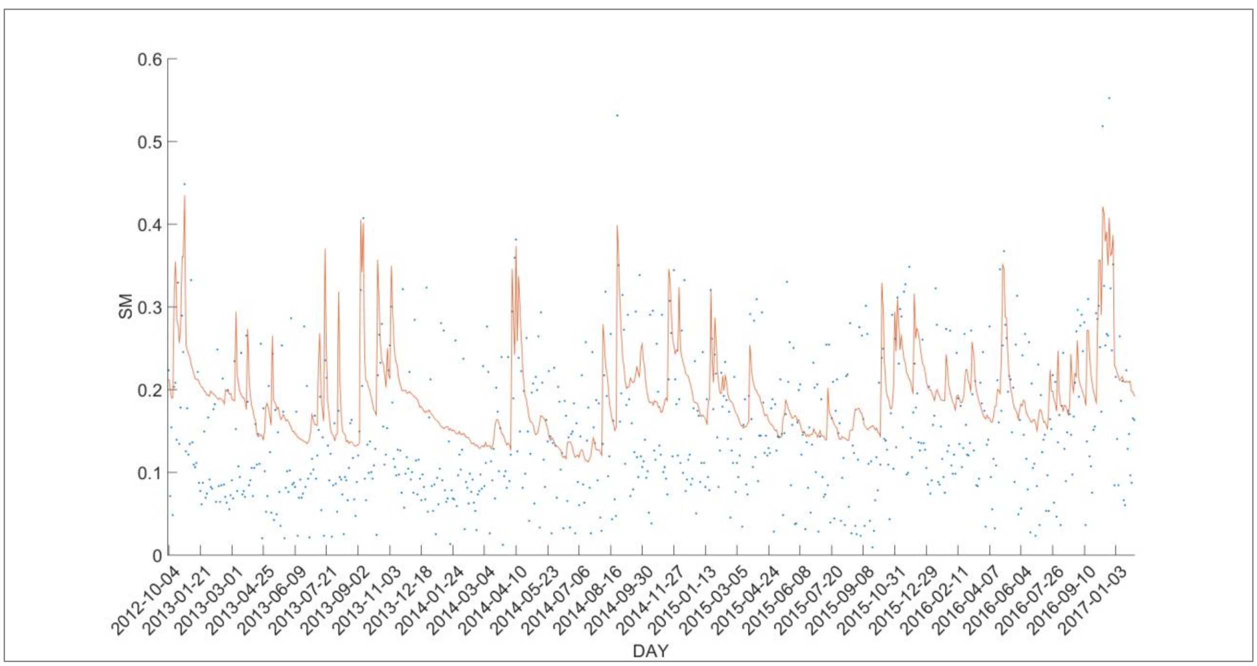


Figure 40. Juana Díaz, comparison of 25km SM from AMSR2 with SM from SCAN-NRCS.

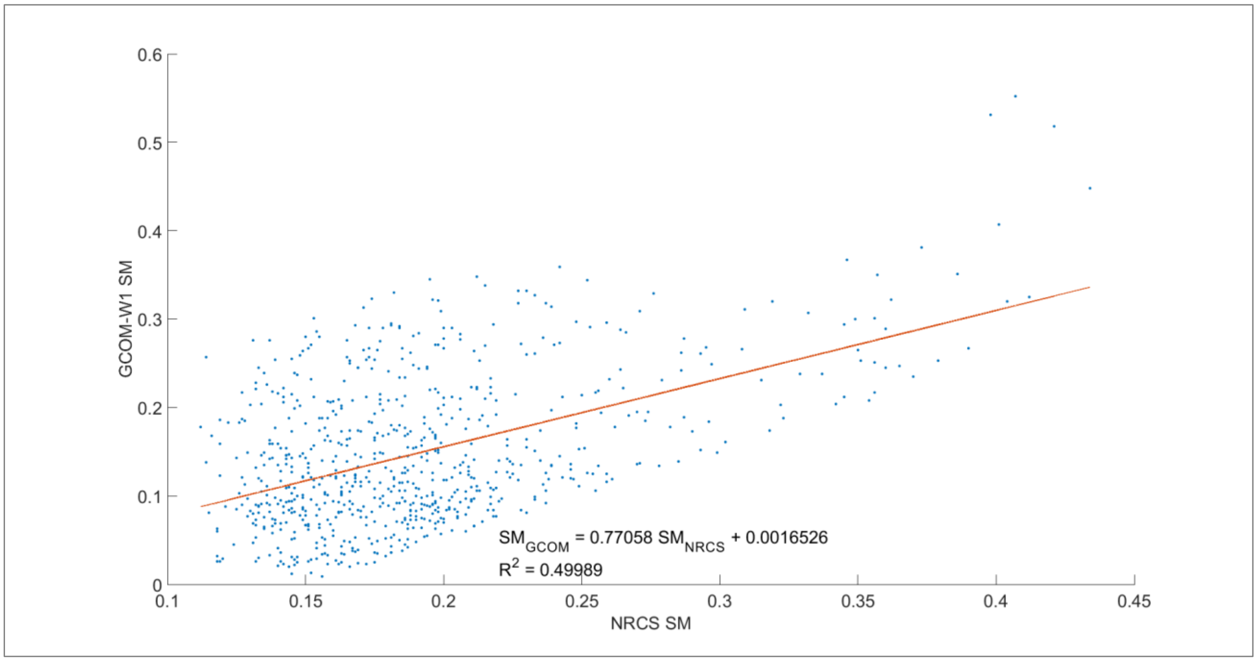


Figure 41. Juana Díaz, correlation between AMSR2 SM and SCAN-NRCS SM measurements.

- Maricao Station

Maricao is located in the west part of the island, an area where high frequency of storm events is common during the year. The SCAN-NRCS station is in a forested area, close to a river, and with a soil composed of 31.4% sand, 42.5% silt, and 26.1% clay (Figure 15). Infiltration due to soil composition and intervention of precipitation due to the high presence of trees will lead to lower daily soil moisture. This can be observed in the SCAN-NRCS station data (Figure 16). A comparison of the full dataset of AMSR2 and NRCS (Figure 42) shows that the overestimates produced by the satellite-based SM are more significant than the underestimates in terms of the in-situ data collected in Maricao. About 63% of the satellite-based measurements achieved a bias of ±0.15 (Figure 43). The ground-based overall and biased SM averages are 0.1745 and 0.1548, respectively, and the biased correlation is 0.3027 (Figure 44). The low correlation was expected, since lower SM content is expected in the station due to the soil and hydrological conditions of the area, and it is clearly not representative to a 25km resolution estimate.

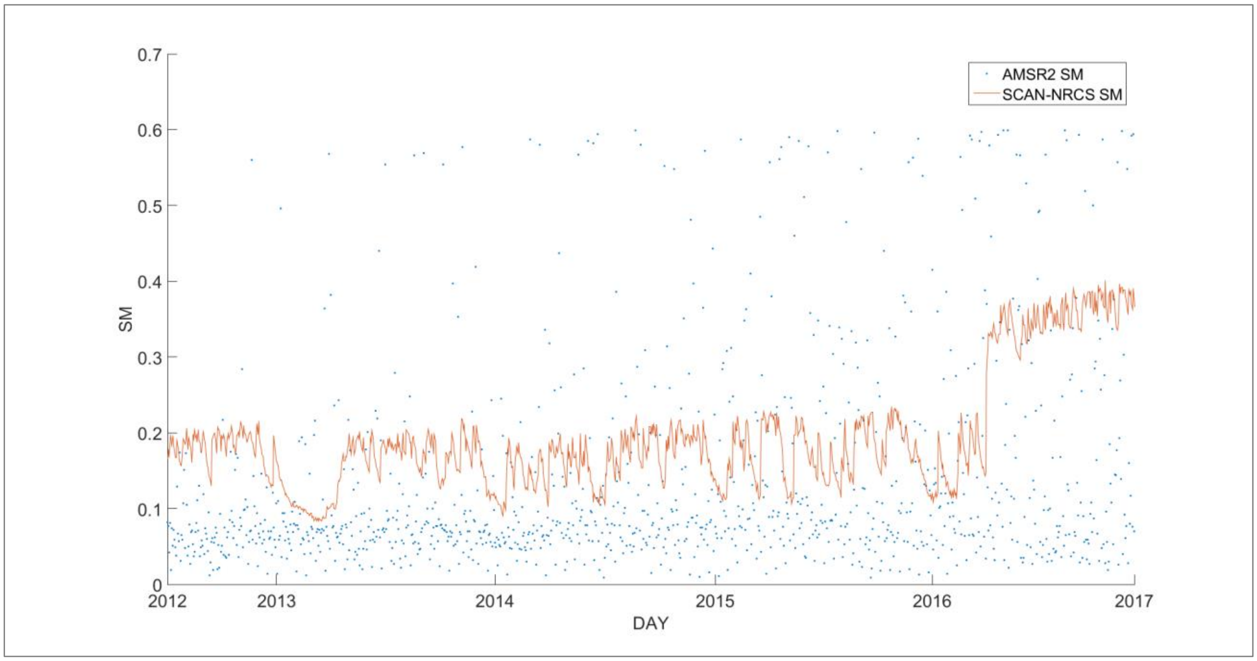


Figure 42. Maricao, comparison of all data available from AMSR2 SM and SCAN-NRCS SM.

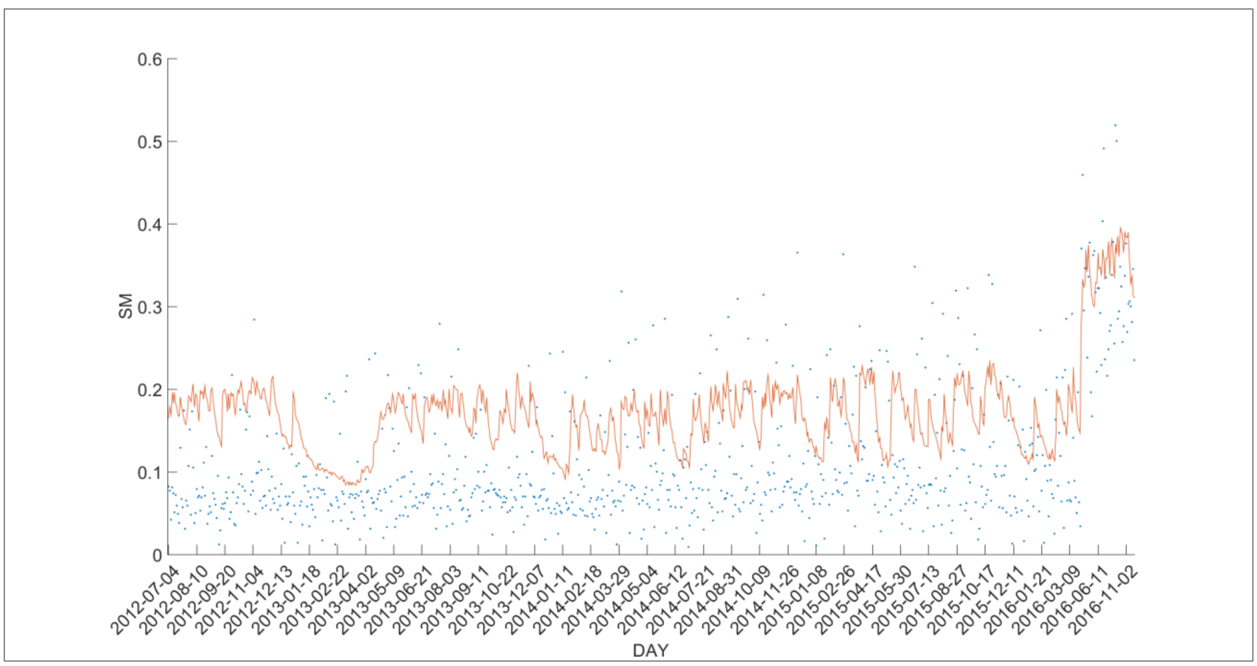


Figure 43. Maricao, comparison of 25km SM from AMSR2 with SM from SCAN-NRCS.

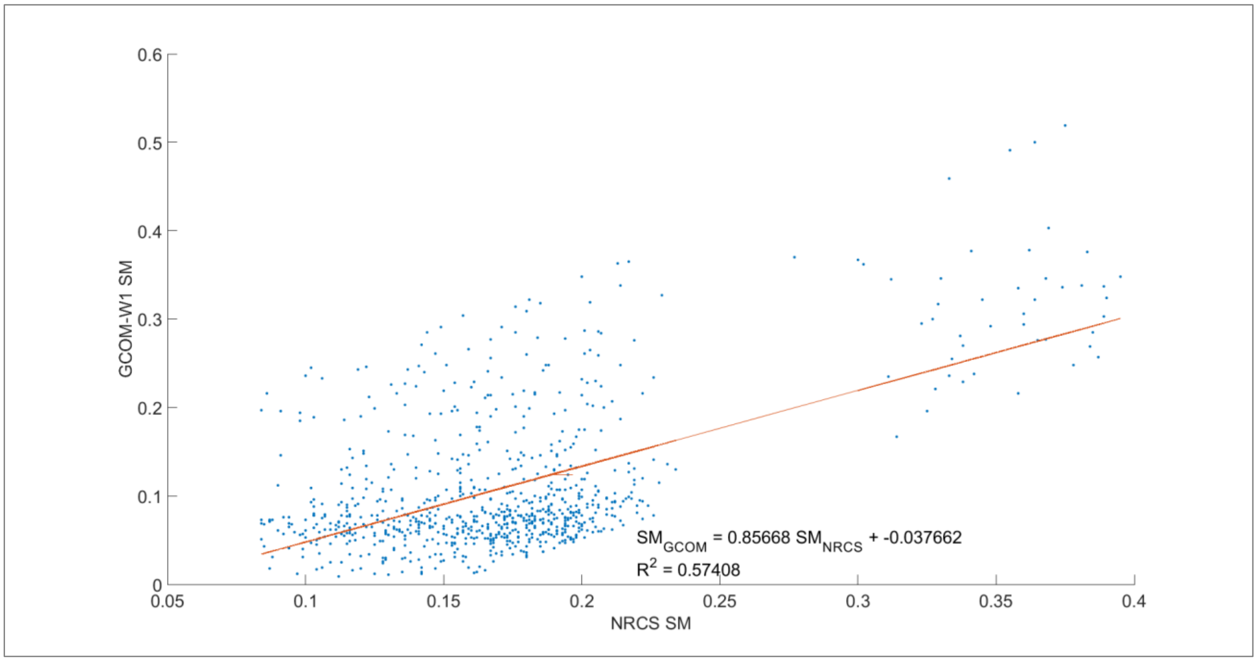


Figure 44. Maricao, correlation between AMSR2 SM and SCAN-NRCS SM measurements.

- Mayagüez Station

Mayagüez is located in the west part of the island, an area where high frequency of storm events is common during the year. The SCAN-NRCS station is in the Alzamora agricultural experimental station of the University of Puerto Rico of Mayagüez, the soil in that area is composed of 26.1% sand, 42.5% silt, and 31.4% clay, precipitation events are common and the vegetation density is low (Figure 17). High soil moisture is expected, however, the SCAN-NRCS station data (Figure 18) reveals high soil moisture for every day. Since the station is located in an agricultural area, it will be assumed that an irrigation system is affecting the measurements. A comparison of the full dataset of AMSR2 and NRCS (Figure 45) shows that AMSR2 underestimates in terms of the in-situ data collected in Mayagüez. Only 6% of the satellite-based measurements achieved a bias of ±0.15 (Figure 46). The ground-based overall and biased SM averages are 0.5533 and 0.5529, respectively, and the biased correlation is 0.4556 (Figure 47). This low correlation was expected since the ground-based SM describes an area that is constantly receiving a water inflow assumed to come from irrigation.

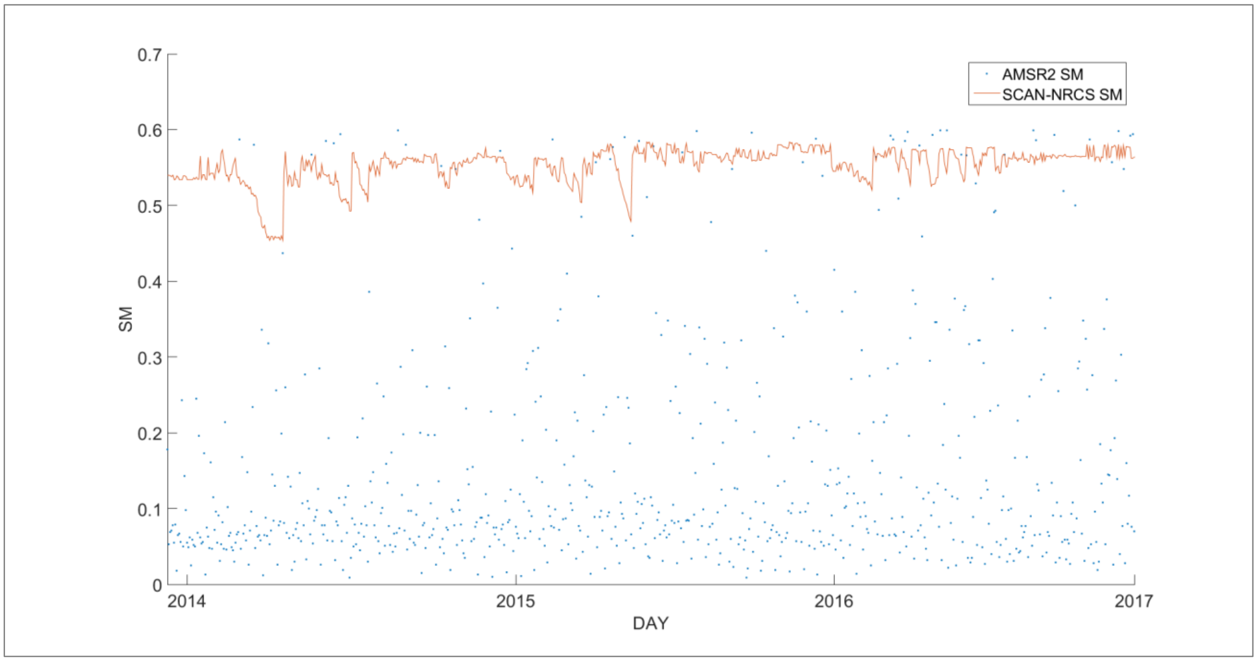


Figure 45. Mayagüez, comparison of all data available from AMSR2 SM and SCAN-NRCS SM.

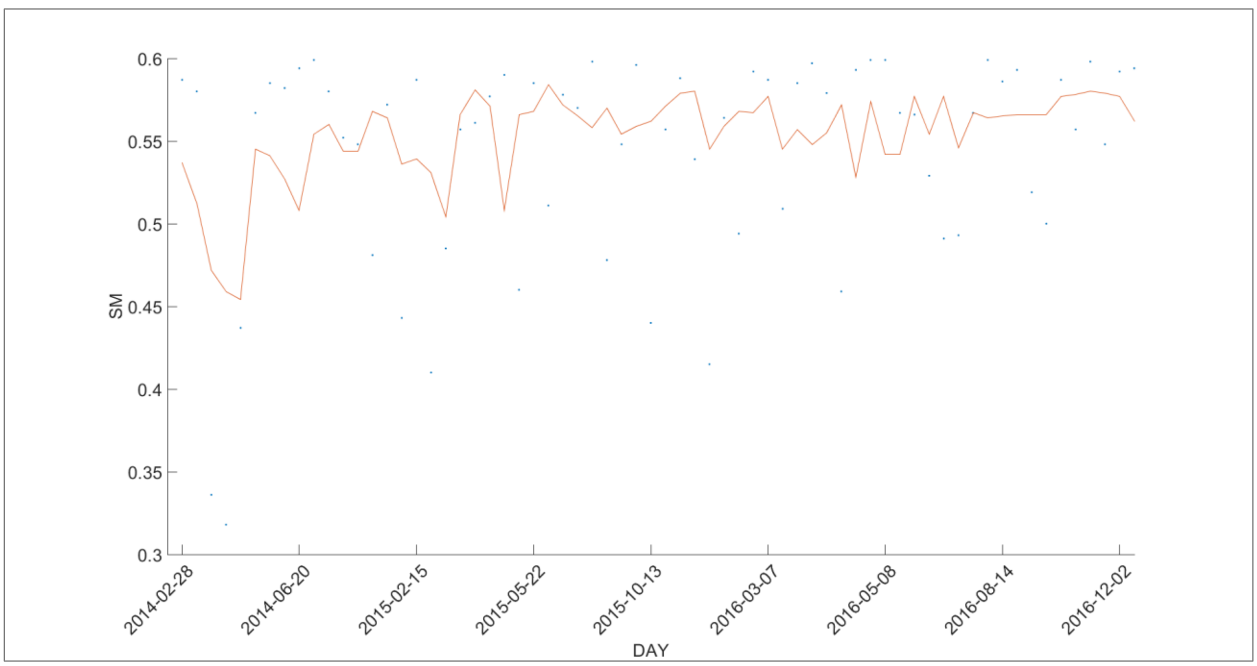


Figure 46. Mayagüez, comparison of 25km SM from AMSR2 with SM from SCAN-NRCS.

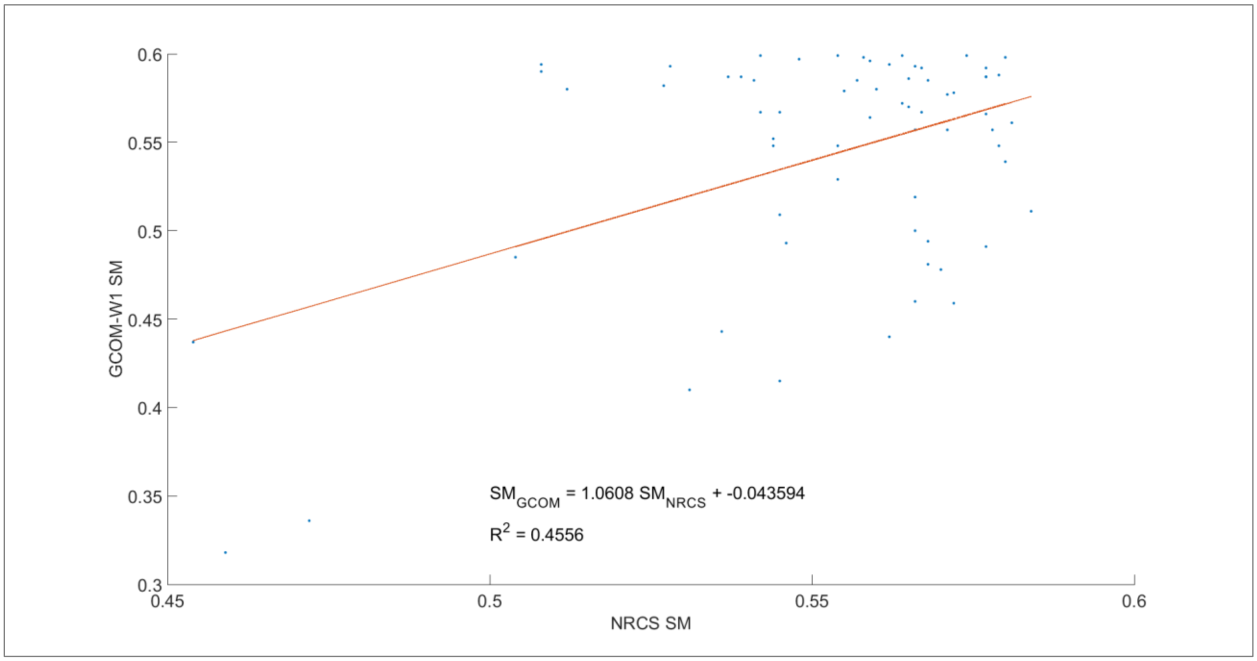


Figure 47. Mayagüez, correlation between AMSR2 SM and SCAN-NRCS SM measurements.

- Validation Summary

Table 18 provide the basic statics of the validation. These tables include the maximum, minimum, average, mode, variance, and standard deviation for all SM data from 2012-2016 on each SCAN-NRCS station and the compared AMSR2 SM values. For most SCAN-NRCS stations it can be observed that the AMSR2 maximum SM is very similar, while in the minimum, AMSR2 tends to underestimate. The average and mode are mostly below the medium SM value, this reinforce the hypothesis that AMSR2 tends to underestimate SM in Puerto Rico.

By comparing the average minimum distance from station to centroid with the correlation coefficients from Table 17, with more AMSR2 coverage above any SCAN-NRCS station, the correlation increases. When the coverage is mostly in an area kilometers away from the station, the correlation decreases. Also, the magnitude of the correlation depends on the quantity of values that are inside the error range. With fewer AMSR2 products behaving similarly to the ground-based SM, an increase in correlation is more likely.

Table 17. Average distance, frequency of biased, and correlation coefficient for the validation in each SCAN-NRCS station.

Station	Adjuntas	Cabo Rojo	Corozal	Guánica	Isabela	Juana Díaz	Maricao	Mayagüez
Average Minimum Distance: Station to Centroid	12.4km	32.0km	11.4km	14.2km	35.9km	13.1km	33.8km	32.1km
Percent inside ±0.15 error range	25%	43%	25%	44%	28%	64%	43%	6%
R^2	0.8417	0.3027	0.7269	0.4075	0.7532	0.4999	0.3027	0.4556

Table 18. Overall basic statistics for each SCAN-NRCS station validation.

Adjuntas	NRCS SM	AMSR2 SM
Maximum	0.6060	0.599
Minimum	0.1190	0.009
Average	0.2549	0.205
Mode	0.1960	0.078
Variance	0.0129	0.0225
Std. Deviation	0.1137	0.1500

Cabo Rojo	NRCS	AMSR2
Maximum	0.318	0.386
Minimum	0.107	0.009
Average	0.155	0.100
Mode	0.128	0.069
Variance	0.0012	0.0048
Std. Deviation	0.0348	0.0696

Corozal	NRCS	AMSR2
Maximum	0.523	0.567
Minimum	0.118	0.021
Average	0.230	0.179
Mode	0.179	0.136
Variance	0.0067	0.0117
Std. Deviation	0.0817	0.1080

Guánica	NRCS	AMSR2
Maximum	0.342	0.348
Minimum	0.004	0.009
Average	0.067	0.085
Mode	0.021	0.078
Variance	0.0027	0.0028
Std. Deviation	0.0521	0.0524

Isabela	NRCS	AMSR2
Maximum	0.478	0.571
Minimum	0.118	0.026
Average	0.250	0.190
Mode	0.213	0.216
Variance	0.0075	0.0133
Std. Deviation	0.0865	0.1152

Juana Díaz	NRCS	AMSR2
Maximum	0.434	0.552
Minimum	0.112	0.009
Average	0.191	0.149
Mode	0.145	0.094
Variance	0.0030	0.0071
Std. Deviation	0.0546	0.0842

Maricao	NRCS	AMSR2
Maximum	0.318	0.386
Minimum	0.107	0.009
Average	0.155	0.100
Mode	0.128	0.069
Variance	0.0012	0.0048
Std. Deviation	0.0348	0.0696

Mayagüez	NRCS	AMSR2
Maximum	0.584	0.599
Minimum	0.454	0.318
Average	0.553	0.543
Mode	0.566	0.587
Variance	0.0008	0.0041
Std. Deviation	0.0276	0.0643

4.2 Downscaling AMSR2 SM Product

The AMSR2 25km resolution SM product was downscaled to 1km resolution with a simple linear equation involving MODIS products for Albedo, NDVI, and LST. The average resultant downscaling equation for all AMSR2 data is shown in Equation (8). The regression model achieved a moderate correlation of 0.6102 and an overall RMSE of 0.0050, indicating that the model did a good fit with the AMSR2 estimates. To reinforce this statement R-squared was calculated and the F-statistic test was performed. The R-squared was 0.037 and the p-value of the F-statistic test was less than 0.0001, these results reinforce the statement that the model is providing a good fit.

$$\begin{aligned}\theta_s = 0.1503 + 1.33\times10^{-4}\ \mathrm{A} + 4.70\times10^{-5}\ \mathrm{T} - 1.06\times10^{-6}\ \mathrm{V} \\ - 4.28\times10^{-7}\ \mathrm{TA} + 7.31\times10^{-10}\ \mathrm{VA} - 2.31\times10^{-9}\ \mathrm{VT}\end{aligned} \tag{8}$$

Table 19 presents the averages of the value, squared error, t-statistic value, and P-value of each regression coefficient. This table shows that all p-values are below the significant level (5%), meaning that the null hypothesis if rejected for each coefficient, and all terms in the linear equation are significant.

Table 19. Downscaling. Calculated Values and T-Statistics of the Regression Coefficients.

Coefficient	Value	Squared Error	t-statistic Value	P Value (%)
a_{000}	0.1503	0.0053	49.1222	0.0014
a_{100}	1.3295×10^{-4}	3.66×10^{-5}	2.9769	0.1432
a_{010}	4.70×10^{-5}	1.84×10^{-5}	1.9657	0.1276
a_{001}	-1.0628×10^{-6}	6.67×10^{-7}	-1.6633	0.1113
a_{110}	-4.28×10^{-7}	1.01×10^{-7}	-3.2375	0.1354
a_{101}	7.31×10^{-10}	1.89×10^{-9}	-0.1246	0.2927
a_{011}	-3.20×10^{-9}	2.31×10^{-9}	0.1067	0.1160

The results from this downscale for September 5, 2016 are shown in Figure 48. The response of this model to the MODIS parameters was very promising, since the downscaled SM is attempting to react accurately to the rainfall event of that day (Figure 23).

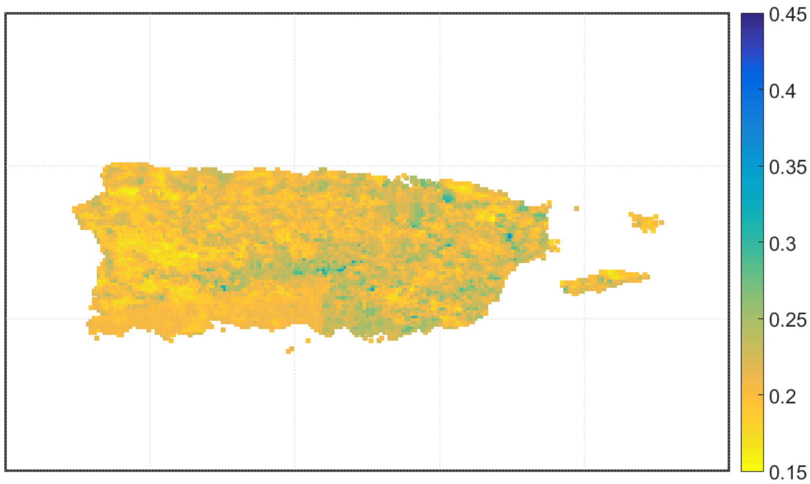


Figure 48. Downscaled AMSR2 SM Estimates for September 5, 2016.

A second downscaling was performed by adding 1km resolution precipitation from GOES-PRWEB to the equation. The resultant equation with its respective regression coefficients is shown in Equation (9).

$$\begin{aligned}\theta_s = {} & -0.1695 + 0.0053\,A - 0.0011\,T - 2.84\times10^{-5}\,V - 0.0010\,P \\ & - 1.74\times10^{-5}\,AT + 9.70\times10^{-9}\,AV - 1.41\times10^{-5}\,AP \\ & - 1.01\times10^{-7}\,TV + 2.48\times10^{-6}\,TP - 5.94\times10^{-7}\,VP\end{aligned} \tag{9}$$

Table 20. Downscaling with Precipitation. Calculated Values and T-Statistics of the Regression Coefficients.

Coefficient	Value	Squared Error	t-statistic Value	P Value (%)
a_{0000}	-0.1695	1.3395	1.0252	0.30531
a_{1000}	0.0053	14.698	9.338	1.22×10^{-20}
a_{0100}	-0.0011	45.548	-0.83293	0.40491
a_{0010}	-2.84×10^{-5}	0.000142	-4.5968	4.35×10^{-6}
a_{0001}	-0.0010	0.03909	2.7672	0.005665
a_{1100}	-1.74×10^{-5}	499.48	-9.2555	2.63×10^{-20}
a_{1010}	9.70×10^{-9}	3.60E-05	4.3932	1.13×10^{-5}
a_{1001}	-1.41×10^{-5}	0.010979	14.904	1.25×10^{-49}
a_{0110}	-1.01×10^{-7}	0.004823	4.4645	8.13×10^{-6}
a_{0101}	2.48×10^{-6}	1.3345	-2.6503	0.008057
a_{0011}	-5.96×10^{-7}	1.01E-07	-11.3	2.08×10^{-29}

Since the p-values of the regression coefficients are below the significant level, the null hypothesis of the t-statistic test is rejected, and all regression coefficients are considered as significant. The p-value of the F-statistic test is less than 0.0001 and the R-squared is 0.155, but the correlation is 0.0468. This is expected since the purpose of adding rainfall as a variable was to increase the SM in the areas where the precipitation event was occurring. These results should assess the limitation observed in the validation of the AMSR2 25km SM with the SCAN-NRCS. By observing the results of this equation in Figure 49, it is clear that the model is overestimating in the area where the storm event was happening. To assess this new issue, the precipitation parameter was weighted.

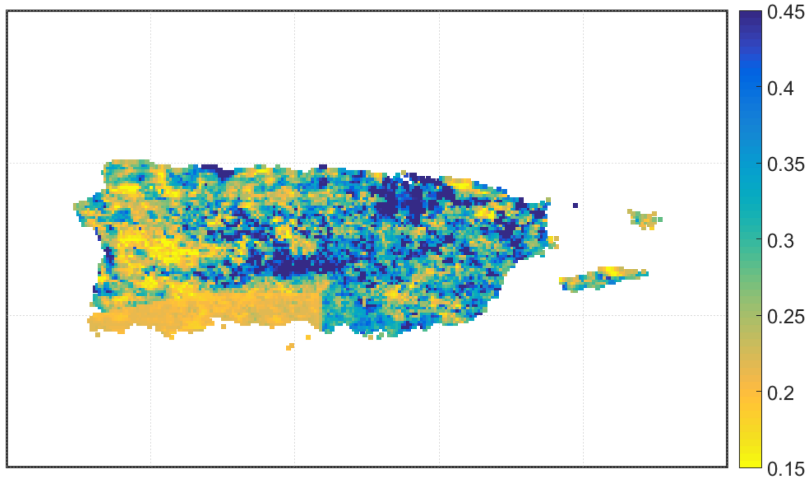


Figure 49. Downscaling AMSR2 with Precipitation for September 5, 2016.

The new equation yields the regression coefficients shown in Table 21. All weighted regression coefficients are significant since the p-values for the t-statistic test are less than the significant level for each parameter. By weighting precipitation, the combination of NDVI and LST became completely insignificant (a_{1100} = 0). The model provides good fit since the p-value for the F-statistic test is also less than the significant level and the R-squared is 0.146, but the correlation is 0.1742.

Table 21. Downscaling with Weighted Precipitation. Calculated Values and T-Statistics of the Regression Coefficients.

Coefficient	Value	Squared Error	t-statistic Value	P Value (%)
a_{0000}	10.334	0.93006	11.111	1.70×10^{-28}
a_{1000}	1.2354	0.27001	4.5755	4.81×10^{-6}
a_{0100}	-342.57	31.635	-10.829	3.72×10^{-27}
a_{0010}	-0.001	0.000137	-7.2948	3.25×10^{-13}
a_{0001}	0.001883	0.000785	2.3986	0.01648
a_{1100}	0	0	-	-
a_{1010}	0.000187	3.60E-05	5.2031	2.00×10^{-7}
a_{1001}	0.00248	0.000203	12.207	5.37×10^{-34}
a_{0110}	0.033386	0.004672	7.1457	9.66×10^{-13}
a_{0101}	-0.05938	0.026789	-2.2167	0.026668
a_{0011}	-2.47E-08	2.02E-09	-12.187	6.80×10^{-34}

This low correlation is expected and by observing Figure 50 it can be noticed that the new issue has been assessed, the SM over Puerto Rico is increased from the AMSR2 and is not showing excess moisture like the last iteration of the model. This new data will be validated with the SCAN-NRCS stations and compared with the other models and the coarse resolution validation to learn if these results are enhancing the SM retrieval over Puerto Rico.

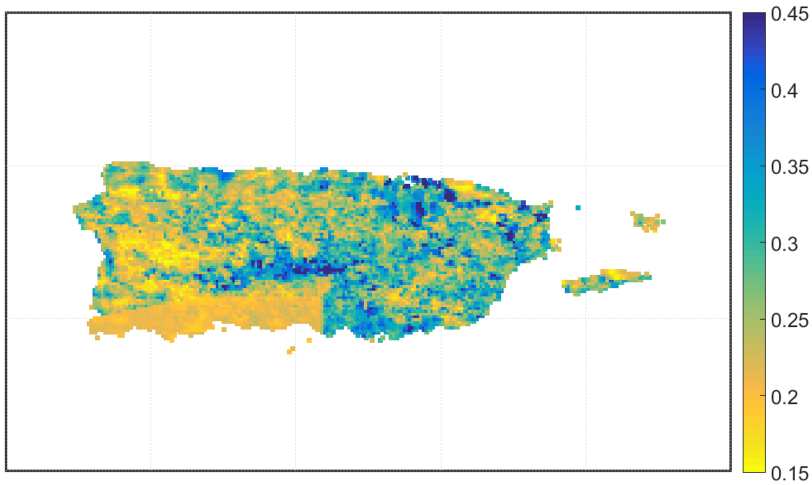


Figure 50. Downscaling AMSR2 with Weighted Precipitation for September 5, 2016.

4.3 Validation of Downscaled SM Product

Table 23 provide the basic statics for the downscaling validation. These tables include the maximum, minimum, average, mode, variance, and standard deviation for all SM data from 2012-2016 on each SCAN-NRCS station and the compared downscaled SM values. For most SCAN-NRCS stations it can be observed that the AMSR2 maximum SM is very similar, while in the minimum, the downscaled values still tend to underestimate, but at a slightly smaller magnitude than the AMSR2 25km values did. The average and mode are mostly below the medium SM value, reinforcing the fact that the downscaling model is underestimating SM in Puerto Rico.

To expand the spatial coverage of the downscaled product to the entire region of Puerto Rico, a daily average SM from the 25km pixels was calculated and assumed in all regions not covered by the AMSR2. Since the downscaled SM covers the entire island at a 1km resolution, spatial coverage in no longer an error source. Though, this assumption led to an increase in instances where the bias is ±0.15, and to a slight decrease in the correlations. The increase in instances inside the bias range is an enhancement. On the other hand, the decrease in the correlations is a negative effect from the assumption of an average daily SM value.

Table 22. Frequency of biased, and correlation coefficient for the validation of the downscaled SM in each SCAN-NRCS station.

Station	Adjuntas	Cabo Rojo	Corozal	Guánica	Isabela	Juana Díaz	Maricao	Mayagüez
Percent inside ±0.15 error range	33%	50%	30%	45%	41%	70%	84%	1%
R^2	0.6206	0.2399	0.7231	0.4648	0.6369	0.3752	0.5327	0.6705

Table 23. Overall basic statistics for the validation of the downscaled SM in each SCAN-NRCS station.

Adjuntas	NRCS SM	AMSR2 SM
Maximum	0.574	0.537
Minimum	0.119	0.042
Average	0.238	0.193
Mode	0.217	0.042
Variance	0.0061	0.0086
Std. Deviation	0.0782	0.0929

Cabo Rojo	NRCS	AMSR2
Maximum	0.333	0.326
Minimum	0.107	0.023
Average	0.165	0.137
Mode	0.128	0.023
Variance	0.0020	0.0041
Std. Deviation	0.0450	0.0644

Corozal	NRCS	AMSR2
Maximum	0.536	0.540
Minimum	0.118	0.033
Average	0.243	0.201
Mode	0.179	0.033
Variance	0.0082	0.0102
Std. Deviation	0.0905	0.1008

Guánica	NRCS	AMSR2
Maximum	0.376	0.484
Minimum	0.004	0.023
Average	0.072	0.126
Mode	0.022	0.023
Variance	0.0034	0.0031
Std. Deviation	0.0583	0.0554

Isabela	NRCS	AMSR2
Maximum	0.478	0.540
Minimum	0.118	0.028
Average	0.257	0.204
Mode	0.213	0.028
Variance	0.0064	0.0084
Std. Deviation	0.0799	0.0915

Juana Díaz	NRCS	AMSR2
Maximum	0.445	0.430
Minimum	0.112	0.023
Average	0.189	0.156
Mode	0.163	0.023
Variance	0.0028	0.0056
Std. Deviation	0.0531	0.0745

Maricao	NRCS	AMSR2
Maximum	0.396	0.515
Minimum	0.084	0.022
Average	0.178	0.137
Mode	0.194	0.022
Variance	0.0032	0.0062
Std. Deviation	0.0568	0.0786

Mayagüez	NRCS	AMSR2
Maximum	0.578	0.522
Minimum	0.454	0.334
Average	0.536	0.435
Mode	0.568	0.334
Variance	0.0019	0.0026
Std. Deviation	0.0435	0.0511

5. Conclusion

This research work was the first attempt to validate and downscale satellite SM (Passive Microwave) estimates for Puerto Rico and the Caribbean region. The validation of the AMSR2 SM product at a 25km resolution with the SCAN-NRCS stations revealed that the AMSR2 spatial coverage of 25km may not provide a good estimate of SM in Puerto Rico. AMSR2 consistently underestimate SM, however, there are multiple uncertainties associate with the validation, (i.e. low density of ground data).

The overall results of the validation show that only about 35% of the AMSR2 SM estimates behaves like the SCAN-NRCS SM measurements with a linear correlation of 0.54. The low correlation between the coarse resolution estimate and the ground-based measurements is suspected to be due to the low density of ground data and changes in vegetation density, land use, topography, precipitation, and soil properties in Puerto Rico.

The downscaling method provided a good fit with the AMSR2 raw data, with a correlation of 0.61 and an overall RMSE of 0.0050. The resulting downscaled SM from the linear equation (regression model ??) that relates Albedo, LST, and NDVI from MODIS with the SM from AMSR2 showed a tendency to increase SM where a precipitation event occurred. This enhancement increased the percentage of AMSR2 estimates that behaves similarly to the ground-based measurements to 44%, but slightly decreased the correlation to 0.53. To expand the coverage of the AMSR2, a daily average SM value was assumed for the area that was left out of the 25km grids. However, this assumption led to a decrease in correlation, but it can be modified in future research. The addition of a precipitation in the downscaling methodology is an alternative to correct the underestimation of the AMSR2 SM product.

6. Future Research

Future research is needed to refine the downscaled SM product. The raw product will be downscaled to a 5 and 10km resolution to study the variability at different spatial resolutions. The downscaling equation will be optimized by performing a sensitivity analysis on all the regression coefficients. Additional parameters such as topography and soil properties will be added to the downscaling equation to study new correlations with hopes of improving the downscaled product. These parameters will be evaluated using a step wise regression to determine their significance in the estimation of SM based on the raw AMSR2 SM product. An online database will be developed to provide daily soil moisture product at a 1km resolution for Puerto Rico.

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