**NASA DEVELOP National Program**



Ames Research Center

*Fall 2015*

Puerto Rico Health and Air Quality

A Geospatial Assessment of Environmental Variability in Puerto Rico and its relation to Confirmed Dengue Cases

 **Technical Report**

Rough Draft – October 8, 2015

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# 1. Abstract

The dengue virus is the fastest-growing vector-borne disease in the world and has been declared endemic in the Caribbean and Puerto Rico. This deleterious illness is transmitted by tropical mosquitoes and can lead to hemorrhagic fever, shock, and death in severe cases, posing a major threat to the health of Caribbean communities. A high occurrence of the primary vector of the dengue virus *(Aedes aegypti*) has been detected in the city of San Juan, contributing to several dengue outbreaks, including instances in 2010, 2012, and 2013. This study examined the climatic and environmental conditions contributing to dengue cases from 2009-2013 using monthly NASA Terra/ Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) 1km resolution evapotranspiration (ET), land surface temperature (LST) products, along with 0.5° Climate Hazards Group InfraRed Precipitation (CHIRP) total rainfall (TP) data. These data were incorporated into a maximum entropy species distribution model to spatially delineate potential dengue risk, and output the statistical contribution of variables based on reported cases in Puerto Rico. Additionally, the statistical significance variables were seasonally compared to Confirmed Dengue Fever Cases (CDFC) from 2009-2013. Lastly, MODIS 4km sea surface temperature (SST) products were correlated to CDFC to better understand the relation between oceanic conditions and mosquito transmission behavior. Results indicate a moderate significance of LST and TP (p = ?) and low to moderate significance of ET (p =?) regarding confirmed dengue cases in Puerto Rico. Lower lying developed areas also contributed significantly to CDFC.

**Keywords**

Remote Sensing, Puerto Rico, Dengue, Maximum Entropy, MODIS

**2. Introduction**

***Background***

Dengue fever (DF) is a debilitating and potentially fatal mosquito-borne illness that is endemic in tropical regions. The Centers for Disease Control and Prevention (CDC) estimate that over 400 million people are infected globally each year by any one of four different serotypes, or variations, of the dengue virus [CDC, 2014]. Onset occurs within 3-7 days of the mosquito bite with symptoms that include fever, chills, rash, vomiting, and eye, muscle, and joint pain. The disease can further progress into dengue hemorrhagic fever (DHF) or dengue shock syndrome (DSS) in children, elderly individuals, and immunocompromised adults [Sharp et al., 2013]. Clinical signs at these advanced disease stages include severe bleeding, hypovolemic shock, disseminated intravascular coagulation (DIC), and death [CDC, 2014; Sharp et al., 2013].

Globally, the virus is spread by several species of mosquito within the genus, *Aedes*, with the primary vector being *Aedes aegypti* [Cox et al., 2007]. *A. aegypti* is a domestic mosquito that lives and breeds near or within human- occupied structures. This species lays its eggs in a variety of rain filled water containers such as rain barrels, abandoned tires, plastic jugs, or pot holes on roads that are in close proximity to humans [Harrington et al., 2005]. A secondary vector of the dengue virus is *Aedes albopictus*, a rural mosquito that inhabits tall vegetation and tree holes or other containers that fill with water during the rainy season [Cox et al., 2007].

Dengue fever is endemic to the island of Puerto Rico, with anywhere from 3,000 to 9,000 cases occurring in non-epidemic years [CDC, 2014]. However, dengue fever epidemics on the island have been increasing in frequency and severity in recent years. The largest epidemic on record in Puerto Rico occurred in 2010, with over 26,700 suspected and 12,500 laboratory confirmed cases of the disease [Sharp et al., 2013]. In this year, this outbreak was unique because the majority of cases were caused by serotypes 1 & 4, as opposed to 2 & 3, which had been circulating on the island from 2000-2009 [Barrera, Personal Communication, 2015]. The previous record outbreak occurred in 1998 and was similar to the 2010 outbreak, as both were caused by serotypes 1 & 4 and both occurred the year after major El Niño events [Barrera et al., 2011]. Also contributing to the 2010 outbreak were highly negative North Atlantic Oscillation index values that resulted in increased sea surface temperatures, and therefore increased rainfall in the region [Barrera et al., 2011]. Additionally, there have been two outbreaks since 2010. These occurred in 2012 and 2013, and both were primarily caused by serotypes 1 & 4 [Barrera, Personal Communication, 2015].

The primary vector known to contribute to dengue fever epidemics in Puerto Rico is *A. aegypti*. This species exists in all regions of the island where humans are present with the highest numbers occurring in densely populated areas [Harrington et al., 2005]. Thus, the majority of these mosquitoes exist in developed urban regions, such as San Juan and Bayamon [Barrera et al., 2011]. Although other dengue vectors, such as *A. albopictus*,also exist on the island, the CDC Dengue Branch has never confirmed that any of these species are infected with the dengue virus in Puerto Rico. Therefore, these species have not been incriminated as dengue vectors on the island [Barrera, Personal Communication, 2015].

There are multiple contributing environmental conditions that have been implicated in the spread of the dengue virus. These include increases in total rainfall, sea surface temperature, ambient temperature [Johansson et. al., 2009, Mendez-Larzaro et. al., 2014, Patz et. al., 1998], and relative humidity [Barrera et al., 2011], which all lead to favorable conditions for mosquito breeding. Additionally, overall SST has been correlated to dengue cases in Puerto Rico, Mexico, and New Caledonia [Mendez-Larzaro et. al., 2014, Ramos et. al., 2008, Diaz et. al., 2007]. In Puerto Rico, cool surface waters are correlated to drier periods, while warmer surface waters are correlated to wet periods from 1982-2010 with an R-squared of 0.50 [NEED TO CITE].

Several studies have examined dengue incidences using remote sensing techniques and geospatial analyses [Eisen & Lozano-Fuentes, 2009, Little et. al., 2011, Cox et. al., 2007]. These studies have identified density of urban and vegetation structures as important habitat features for *A. aegypti.* Therefore, this study utilized remotely-sensed products that represented these contributing environmental conditions, and found their relations to dengue seasonality on the island of Puerto Rico. To do this, this project analyzed the number of confirmed dengue cases from a continuous environmental geospatial modeling perspective.

***Project Objectives***

The primary objective of the first phase of this project was to create a Vulnerability Index Method (VIM) for dengue vector habitat based upon NASA Earth Observation (EO) environmental variables, as well as Confirmed Dengue Fever Cases (CDFC) within the island of Puerto Rico, using TerrSet Habitat Suitability Modeler. The VIM is a step-by-step method for modeling the suitability of dengue across Puerto Rico based upon the presence of dengue cases in conjunction with land cover and contributing environmental conditions. The results provided a geospatial overview of CDFC risk.

The secondary objective of this project included the statistical correlation of contributing environmental to dengue outbreaks on the island of Puerto Rico.

***Study Area***

Analyses were performed using within the political boundaries of the Commonwealth of Puerto Rico. The island is an unincorporated United States territory located in the Caribbean Ocean with general coordinates of 18°15'N latitude and 66°30'W longitude (Figure 1). Puerto Rico is a small, densely-populated island with a total area of 9,104 km2 and a population of over 3.5 million. The climate is tropical with annual average temperatures between 21°C and 27°C, and a rainy season from April to November. Climate varies along the length of the island, with the drier regions occurring in the south.

Land-based analyses were performed on the entire island, while correlations of SST to confirmed dengue cases extended past the study area to 256 km offshore (See 3.1 Data). Due to the habitat preferences of *A. aegypti*, developed regions at lower elevations were given a higher weight than undeveloped higher elevation regions. However, developed areas in higher elevation regions were also included in the model. This is because the highest peak on the island is Cerro de Punta (1,338 m), which is well within the altitude range for *A. aegypti*. Studies conducted in Mexico showed common *A. aegypti* presence in altitudes up to 1,700 m above mean sea level, and occasional presence in altitudes from 1,700 m to 2,130 m [Lozano-Fuentes et al., 2014; 2012].

***Study Period***

The project examined the months from January 2009 through December 2013. This date range coincides with the most recent dengue outbreak years (2010, 2012, and 2013) according to CDFC in-situ data (See 3.1 Data).

***National Application(s) Addressed***

This project addressed the Health and Air Quality Application area within NASA’s Applied Science Program. By using NASA Earth Observing (EO) data, as well as modeled data products, this project focused on human welfare through the creation of a vulnerability method that will be used by Puerto Rico public-health administrations to predict and combat outbreaks of dengue.

***Project Partners***

Currently, the various entities involved in this project use quantitative research on vector-borne diseases and outbreaks such as dengue to inform public policy on vector control measures that can be taken to prevent the spread of such illnesses.

The Puerto Rico Department of Health provides citizen services and public announcements, and conducts health assessments pertaining to dengue awareness on the island. The agency reports on recent statistics and information regarding mosquito vector habitats, and publishes scientific literature related to various illnesses in Puerto Rico.

The Dengue Branch of the CDC employs public health practices such as education on household spread of dengue, surveillance systems of dengue-infected hospitals, and diagnostic testing. They also conduct molecular research and field investigations regarding dengue contraction and control. Additionally, the agency is dedicated solely to dengue research, and is located in San Juan, Puerto Rico.

**3. Methodology**

**3.1** **Data**

All data collected were obtained or downloaded in monthly time steps from January 2009 to December 2013. The data can be divided into two categories: point data and spatial environmental data.

***2000-2015 Confirmed Dengue Fever Cases (CDFC)***

44,338 daily CDFC from January 2000 to August 2015 were obtained from the CDC. The CDC Dengue Branch tracks and monitors reported dengue cases and confirms these cases through laboratory tests. A vast majority of the data contain addresses, country name, zip code, and latitude/longitude coordinates. Cases without latitude/longitude coordinates and data that did not occur in the study time period were excluded. This study used a total of 29,575 CDFC points within Puerto Rico.

***2009-2013 Terra/ Aqua Moderate Resolution Imaging Spectroradiometer (MODIS)***

Three sets of *MODIS* data were downloaded to include Sea Surface Temperature (**SST**), Evapotranspiration (**ET**), and Land Surface Temperature (**LST**).

**SST** measurements (2007-2013) were obtained from NASA Earth Data Ocean Color Website [NASA Ocean Biology, 2015]. Level 3 Aqua MODIS products of SST are at 4km resolution, outputs are in degree Celsius, and products are derived using methods and algorithms produced by Brown & Minnett, 1999.

Level 4 MODIS **ET** data at 1km spatial resolution were downloaded for tile h11v07 from the Numerical Terradynamic Simulation Group’s (NSTG) website for the MODIS 16 Global Terrestrial Evapotranspiration Data Set through the University of Montana [MOD 16, 2007]. The dataset used MODIS products for albedo, land cover, fraction of absorbed photosynthetically active radiation (FPAR), and leaf area index (LAI), in combination with daily meteorological datasets from NASA’s Global Modeling and Assimilation Office (MERRA GMAO) and data from the Visible Infrared Imaging Radiometer Suite (VIIRS) Sensor [Mu et al, 2013]. The inputs were run through an algorithm based upon the Penman-Monteith equation, created to compute global ET measurements [Mu et al., 2013].

MODIS level 3 data product, MOD11A2 Version 5 8-day **LST** and Emissivity, were used to calculate monthly LST data; the data were downloaded for the h11v07 tile using Reverb, through the Land Process Distributed Active Archive Center (LP DAAC) website [LP DAAC, 2000].

***Climate Hazard Group InfraRed Precipitation with Stations (CHIRPS)***

Total Precipitation(**TP**)data from the Climate Hazard Group InfraRed Precipitation with Stations (CHIRPS) archive were downloaded from University of California, Santa Barbara’s Climate Hazards Group website for each month of interest [CHG, 2015]. CHIRPs is a precipitation product composed of a combination of satellite sources and in-situ station data, and it serves as a drought and environmental monitoring product. The inputs to CHIRPS include precipitation climatology from the Climate Hazard Group’s Precipitation Climatology model, infrared satellite observations from NOAA, Tropical Rainfall Measuring Mission (TRMM) data from NASA, NOAA Climate Forecast System rainfall data, and in-situ precipitation measurements [Funk et al., 2014].

***2001 National Land Cover Database (NLCD)***

2001 NLCD from 2001 for Puerto Rico was used as a landcover map, and has a spatial resolution of 30m. The map was a product of the Multi-Resolution Land Characteristics Consortium (MRLC) and was derived from Landsat 5 and 7 imagery. Puerto Rico NLCD data were downloaded from the MRLC website [MRLC, 2001]. Developed areas play a significant role in the breeding and presence of mosquito species, including *A. aegypti* [NEED TO CITE]. *A. aegypti* tend to breed and develop in rain-filled water containers such as rain barrels, abandoned tires, plastic jugs, or pot holes in roads [Harrington et al., 2005]. Thus, regions classified as developed areas by the NLCD are included as static variables contributing to dengue cases.

***USGS Elevation***

USGS Etopo1 Global Relief Model with a resolution of 1 arc min. was used for elevation data. The map was sourced from NOAA’s National Centers for Environmental Information [NEED TO CITE].  Elevation contributes a significant role to mosquito species type and habitat [NEED TO CITE]. Although elevation is not considered a weighted variable, geospatial results and model outputs that incorporate elevation data (See 3.2 Data Processing) will help link the role of elevation to occurrences of CDFC.

**3.2 Data Processing**

All monthly 2009-2013 CDFC, MODIS SST, LST, ET, and CHIRPS TP data were reprojected to NAD 1983 State Plane Puerto Rico Virgin Islands Lambert Conformal Conic projected coordinate system.

Here would be a great place to have a figure (flowchart) that connects all the steps below.

***CDFC***

Point shapefiles were created using known latitude/longitude coordinates for all confirmed cases. Separate point files were also created in monthly time steps for the study period.

***Model Builder***

Separate models were created in ArcGIS 10.3 Model Builder for the processing of **LST**, **ET**, **TP**, and **SST** data. All four models used the iterate rasters mechanism in order to repeat the use of specified tools; this expedited the task of processing five years of monthly data [Amante & Eakins, 2009] for each variable.

The **LST** processing model used ArcMap Tools to extract the LST subdataset and convert from HDF to TIFF, reproject to the NAD 1983 coordinate system, resample to the cell size of a designated processed LST image, and clip to the island of Puerto Rico. After being clipped to the study region, the MODIS LST 8-day data was combined and averaged for each month using the Raster Calculator tool.

The **ET** processing model was processed like that of LST, except in three aspects: the subdataset selected was ET, the Raster Calculator tool was not included, and the Math Tool was added to correct the data to units of mm/month by multiplying by 0.1.

The **TP** model included reprojecting, resampling, and clipping. The overall purpose of each model was to project the data to a single spatial reference, NAD 1983, resample it to a constant cell size (determined by a single processed MODIS LST image) to achieve precise overlapping of pixels, and clip it to our study area.

**SST** data were converted from NetCDF to TIFF, re-projected, and clipped to a radius of 256 Km off the coasts of the island.

**3.3 Analysis**

Three data analysis approaches were conducted to geospatially predict CDFC and statically analyze known environmental variables significant in dengue cases.

***Maximum Entropy Species Distribution***

Maximum Entropy modeling was conducted for every month from January 2009 to December 2013 for the entire country of Puerto Rico using TerrSet 1.0. TerrSet is an integrated geospatial software system for monitoring and modeling the earth system for sustainable development [Clark University, 2015]. The software incorporates IDRISI GIS Analysis, image processing tools, and several modeling approaches for geospatial processing and analysis. This study used the Habitat Suitability / Distribution Module within the Habitat and Biodiversity Modeler (HBM), which models habitat suitability based on maximum entropy, to produce geographic suitability of CDFC in all of Puerto Rico. HBM also outputs the statistical R2 (-1 to 1) significance for each variable contributing to CDFC for each monthly model run.

**Trend Analysis Method**

Monthly R2 output values were combined to create trends of significance for ET, LST, and TP. These trends were compared to trends based on number of CDFC from January 2009 to December 2013. These visual comparisons reinforce the significance for the assessed variables over a longer and continuous timeframe rather than single significance represented for each month.

**Time Series Frequency Analysis and Sea Surface Temperature**

SST values for all pixels within the 256 km radius off the coast of the island were averaged to represent a given value per month and year. These monthly averages were correlated to monthly CDFCs using a Time Series Frequency Analysis.

SST values were standardized by subtracting the mean SST value and dividing by the standard deviation using JMP 10 [SAS Institute Inc., 2015].

Once values were standardized, the correlation coefficients were calculated. Correlation coefficients measure the strength of association between two variables over time [Helsel and Hirsch, 1993]. The following equation was used:

Equation 2:   $r=\frac{\left[\frac{1}{N-1}\right]\sum\_{i=1}^{N}\left(x\_{i}-\overbar{x}\right)\left(y\_{i}- \overbar{y}\right) }{\left\{\left[\frac{1}{N-1}\right]\sum\_{i=1}^{N}(x\_{i}-\overbar{x})^{2}\right\}^{\frac{1}{2}} \left\{\left[\frac{1}{N-1}\right]\sum\_{i=1}^{N}(y\_{i }-\overbar{y})^{2}\right\}^{\frac{1}{2}}}$

where r represents the correlation coefficient, N is the number of data points, x is series one, and y is series two [Box and Jenkins, 1976]. By comparing and correlating these data, we strengthened the association between SST and CDFC data.

# IV. Results & Discussion

# V. Conclusions

# VI. Acknowledgments

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

This material is based upon work supported by NASA through contract NNL11AA00B and cooperative agreement NNX14AB60A.

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# IV. Appendices

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