Aaron Hogan
Professor - Nick Brokaw
Ecosystemas Tropicales
May 2013

Defining the Dry Season in an Everwet Tropical Forest: El Verde Field Station, Puerto Rico

Higher levels of precipitation typify tropical climates. In the Caribbean, climatic patterns are the product of the intricate interplay of many natural phenomena. This study seeks to understand observed trends in precipitation patterns for an aseasonal tropical wet forest located in the Luquillo Mountains of Puerto Rico in relation to both greater regional climate perspectives as well as local-scale changes in forest structure and dynamics. Data from a 37 year representative sample was analyzed to help answer the question of how do we know when an everwet tropical forest dries out. Deciles were obtained to quantify the wettest and driest ten percent of precipitation events in order to determine when to sample soil moisture in the 16- Ha Luquillo Forest Dynamics Plot. Analyses of the data confirmed previously understood patterns of rainfall in terms of seasonality across months, with peaks in rainfall occurring in April/ May and November/ December. Annual fluctuations in the data corresponded to observed historical records, with the least amount of rain occurring during the drought year of 1994, and the maximum recorded during the strong La Niña event of 2010. The El Niño Southern Oscillation plays a major role in drought years in the LEF, while there is a significant inverse relationship to rainfall amounts and the North Atlantic Oscillation (NAO).

1. Introduction

The Caribbean region has a unique and complex climate that proves to be affected by many meteorological phenomena. It is comprised of two archipelagos of islands that are situated on the Caribbean plate surrounding the Carribbean Sea. The northeastern archipelago are the older and larger Greater Antilles, such as Jamaica, Hispaniola, Cuba and Puerto Rico, while many other smaller and more geologically recent islands form the Lesser Antilles . Although there is some debate into the paleo-biogeography of the region, it is possible that there existed a land bridge during the late Triassic to middle Jurassic periods (Nacional, Natural & Armas, 2006).

During the late Jurassic period, the Caribbean basin began to form as a small pathway between the eastern edge of the Pacific and Cocos plates, as the Caribbean plate began its subduction into the North American plate (Iturralde-vinent, 1999). This subduction zone between the Caribbean and North American is one of the oldest in the world and forms the second deepest trench in marine environments globally. The Puerto Rican Trench is 800 kilometers long and has a maximum depth of 8,648 m.

Puerto Rico is a moderately sized island located immediately south of the trench and the fault zone between the Caribbean and North American plates. It measures approximately 110 miles east to west by 30 miles north to south.

The topography of Puerto Rico is steep and fissured, with most of the geological substrates being derived from either volcanic and clay soils around the mountainous regions and karstic limestone near coastal regions. There are two main mountain ranges. The central mountain range runs east to west across the island and reaches its highest point at 1,330 meters above sea level (masl). The Luquillo mountain range expands from the central mountain range to the northeast corner of the island, and is home to largest portion of conserved forest on the island.

The Luquillo Experimental Forest (LEF) is one of the most studied tropical montane wet forests in the Caribbean. It is located in the northeastern part of Puerto Rico on the leeward side of the Luquillo Mountains. In the northeastern part of the LEF exists the 16-Ha Luquillo Forest Dynamics Plot, part of the National Science Foundation's Long Term Ecological Research (NSF LTER) and Center for Tropical Forest Science (CTFS) Networks. The rich research history of this forest has provided a holistic framework of understanding into the processes behind the dynamics of tropical wet forests.

The LEF covers 11,231 hectares and reaches a maximum elevation of 1079 masl. It has a warm and wet climate and includes a variety of tropical habitats and forest types and streams, and a high diversity of plants and animals. The animal species richness of the forest is less than that found in similar-sized continental tropical forests, and can be explained by Wilson and MacArthur's Island Biogeography Theory (Brokaw et al., 2012). A key feature of these ecosystems is disturbance. Hurricanes, landslides, and human disturbance have shaped the forest, and research into disturbance regimes and their mechanisms has stimulated a new appreciation of large scale disturbances in tropical forested ecosystems and the key role of plants and animals in shaping the response to these events. Hurricanes occurring one and 10 years after the forest dynamics plot was established in 1988 provided landscape-scale natural experiments which are still yielding important findings into forest recover dynamics (Thompson et al., 2002).

The background research in the earth and plant sciences at the LFDP provides a comprehensive framework for understanding the ecosystem as a whole. The biota has been well studied. Food webs and energy flows between trophic levels have been established and understood (Waide and Reagan, 1996). Plant community assemblages are known and unique research into the successional recovery patterns of the forest in relation to the disturbance regime is documented, going back to Hurricane Hugo in 1989. The recent thinking paradigm surrounding the study of disturbances at the LEF is that of a "tapestry" approach. Multidimensional in nature, the tapestry is an ideological metaphor that captures important aspects of the spatiotemporally dynamic ecosystems of the Luquillo Mountains. It incorporates historical factors, such as land-use, abiotic and biotic conditions over time to provide a picture into abundances and distributions of species in the LEF (Brokaw et al., 2012).

The land-use of the area has been shown to play a major factor in determining both species composition and overall structure of the resulting mature tropical forest (Thompson et al., 2002). There are two distinct land uses that dominate the LFDP and this greatly affects the community assemblages. The northern part of the plot was more heavily impacted by human settlements and activity prior to the purchase of the forest by the USDA Forest Service in the early twentieth century. The southerly portion was only selectively logged, and consequently was more intact. The northern part of the plot is primarily dominated by *Caseria arborea*, while the in the southern portion there exists the distinct and native, *Sloaena bertariana* and *Dacryodes excelsa* dominated forest (Thompson et al., 2002).

In the most recent research efforts into the forest dynamics of the LEF, the aim has been to link seedling survival and recruitment to the phenology of the forest. There is extensive data on the survival rates of the different species, however it is necessary to how understand extraneous biotic and abiotic factors, such as competition and soil moisture play a role in the recruitment- fecundity dynamic (Brokaw et al., 2012). Soil moisture is easy to measure with modern technology, but there still exists the dilemma of know when and how frequent to sample. Random sampling will generate a good overview of the range of possible soil moisture conditions. However, in this case we are primarily concerned with understanding the extreme wet and dry events. The practical application of this analysis is to determine when soil moisture sampling is needed to help gain data on the wet and dry precipitation events in the LEF.

The scope of this investigation is two-fold, aimed at: 1) is to understand how precipitation patters can be understood as they relate to larger scale climate models and 2) how the precipitation patterns can be related to possible changes in the forest dynamics of the LEF. The scope was formulated with the aim of generating an applicable synthesis of information from the general question: When does it get dry in the LEF and how do we know it's dry in the LEF.

2. Methods

Meteorological sensors are located at the top of a 20 m tower, the NADP Tower, behind the main buildings of El Verde Field Station, 350 masl. No large trees are present near the tower. Sensors are connected 10X data logger, with a storage module, and downloaded every two weeks using a wireless radio connection from the laboratory to the tower. The station was initiated in 1999.

In a separate physical location, rainfall and maximum and minimum air temperatures are measured manually on a daily basis. The manual data for rainfall goes back to 1975, and entails more than 13,800 records. In undertaking this analysis, the two data sets were compared to find that there are no significant differences between them over the last 13 years. Therefore the manual data was used for all analyses, providing a more robust window for the time series dating from 1975 through 2012.

The analysis for this study was done in R using the HydroTSM package. This is a method of time-series analysis and is standard procedure when dealing precipitation data. By calculating the deciles for time series, we wanted to quantify the ten percent of wettest and driest events that the LEF has experienced over 37 years on record. Deciles were calculated, and applied back to the data to correlate them with historical observations over the same time span. The frequency of rainfall events corresponding to the decile values was obtained and plotted in relation to time (shown in Fig 6.2).

3. Results

The time series for the data is shown in Figure 3.1. The average annual precipitation for El Verde Field Station proved to be 3807 mm. per year, making it one of the wettest of the CTFS sties. It should be noted that the temperature at El Verde Field Station ranges from 20 to 25 degrees Celsius, with an annual average of 22.9 degrees Celsius. Corresponding to these measures of precipitation and temperature, the official Holdridge classification for the LEF is an “everwet aseasonal tropical wet forest” (Waide and Reagan, 1996).

Seasonal variation in the data was observed, with the months of April, May, November and December having increased average amounts of rainfall (Figure 3.2). There is significant variation between the annual amounts of rainfall, as well, with the drought year of 1994 having the lowest value with 1404.52 mm. and 2010 having the maximum value of 5560.98 mm.

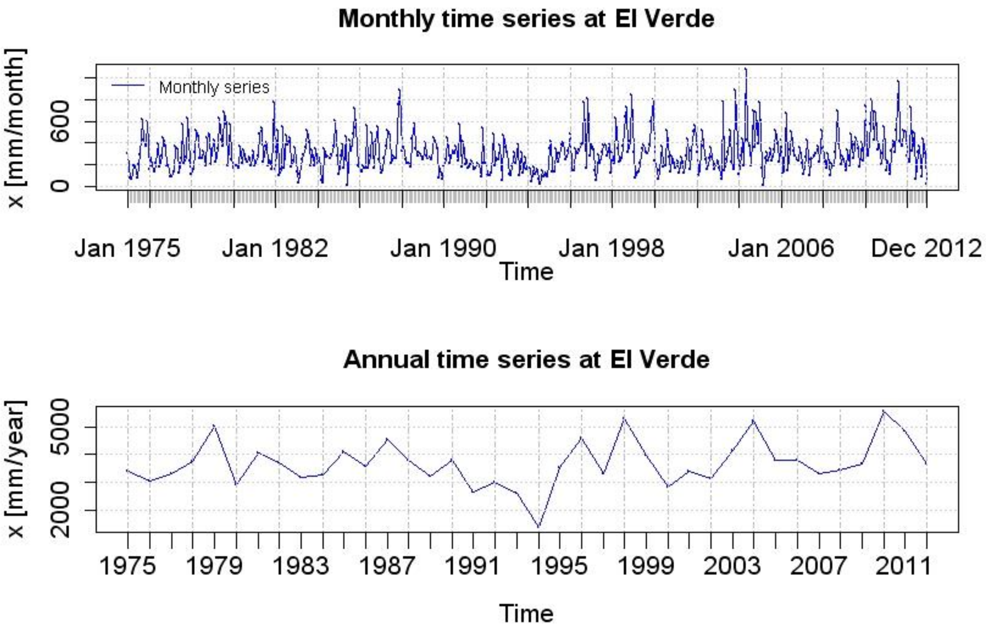

Fig 3.1 - The pattern of rainfall at El Verde Field Station
by month and year from January 1975 – December 2012.

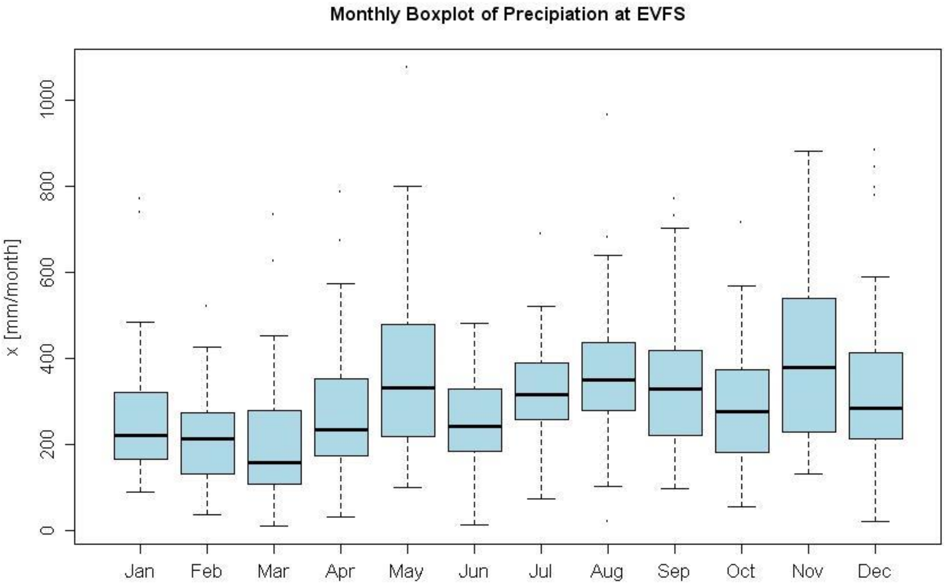

Fig 3.2 - The mean monthly pattern of rainfall at El Verde Field Station for the 37 years on record.

Table 3.1 shows the raw values for the deciles. Wet weeks were defined as the wettest ten percent of averaged weekly rainfall events. Similarly, dry weeks were defined as the driest ten percent of averaged weekly rainfall events. Bi-weeks, Tri-weeks and Quad-weeks correspond to the same calculations over 14, 21, and 28 day intervals, respectively.

	Wet	Dry
Weeks	> 150.62 mm.	< 8.3 mm.
Bi-weeks	> 277.6 mm.	< 33.9 mm.
Tri-weeks	> 385.07 mm.	< 67.04 mm.
Quad- weeks	> 485.86 mm.	< 107.69 mm.

Table 3.1 – Decile calculations for wet and dry weeks, bi-weeks, tri-weeks and quad- weeks at El Verde Field Station, PR

Since the quantification of the deciles, we have experienced 3 times at the Luquillo Forest Dynamics Plot. The month of March, 2013 was quite dry. El Verde Field Station only recorded 166.12 mm. of rainfall in month of March. During this span, the rainfall totals were low enough to meet the dry week, bi-weekly and tri-weekly criteria. Soil moisture sampling was conducted during the first three weeks of March.

4. Discussion

Rainfall is highly variable across the island and is influenced greatly by elevation. Interestingly, if one considers the elevation of the mountains of Puerto Rico in addition to the astounding depth of the Puerto Rican Trench, the peaks of the Luquillo Mountains measure taller than Mount Everest. This speaks to the realized size of the Luquillo Mountains as a geographic barrier to meteorological fronts coming in off of the Atlantic Ocean. Precipitation coming to Puerto Rico is orographic in nature, meaning it is the product of cloud uplifting caused by the Luquillo Mountains. Warm, moisture-rich air from the Atlantic Ocean is carried by the Trade Winds over Puerto Rico, where it is forced to cool and expand, dropping rain in the process. (Jury, Malmgren & Winter, 2007).

This creates an orographic rain shadow effect that leads to great differences in rainfall as one moves from east to west over Puerto Rico. Being as the Luquillo Mountains are the first major land mass that the Trade Winds encounter, it is not surprising that they are the wettest places on the island, averaging over 3,500 mm. of rain annuall. It is not uncommon for the Luquillo Mountains to have annual rainfall totals greater than 5,000 mm. However, the central mountain range is still higher in elevation explaining why areas such as Toro Negro, the place in Puerto Rico with the highest elevation, can rainfall events in terms of single event totals. Despite this, the rainfall pattern of the Luquillo Mountains is more constant, and can be attributed to a higher frequency of higher speed storm exposures. In other words, smaller faster-moving storm fronts drop the majority of the precipitation on the Luquillo Mountains, while slower-moving larger storms tend to contribute to the majority of precipitation in the Central Mountains. This explains why there is less seasonality in the Luquillo Mountains, corresponding to the added rainfall of more-frequent, smaller-scale precipitation events in the LEF (Garcia-martino, Arner, Catena & Ivco, 1996).

Precipitation patterns across the island and throughout the Caribbean region can be explained by global-scale meteorological phenomenon. It is important to stress the role that the Inter-Continental Convergence Zone (ITCZ) plays in tropical areas globally. Hadley Cells are the precipitation drivers as the convective air currents carry evaporating moisture away from equatorial regions of the Atlantic Ocean. Simultaneously, the Trade Winds are moving this precipitation west toward the Caribbean. Furthermore, the ITCZ shifts as the year progresses, due to the inclination of the earth’s axis. During July the ITCZ is in the more northerly position, with the low-pressure area of convergence located more over the Caribbean. The low-pressure convergence zone shifts south as the year progresses, and becomes located more over South America in January (Jury, Malmgren & Winter, 2007).

The seasonal variation of eastern Puerto Rico is marked by low precipitation amounts through the winter and early spring (January- April) followed by increasing rainfall amounts from May onward with a maximum peak in October (Jury, Malmgren & Winter, 2007). These peaks in rainfall correspond to when the ITCZ is located more over the Greater Antilles and Puerto Rico. Annual variations in the data match historically observed accounts, and can be liked to the global climate drivers El Nino and La Niña.

The El Niño Southern Oscillation (ENSO) is a well-studied global climate pattern that is characterized by warmer than usual ocean surface temperatures off the western coast of South America. When El Niño is in effect, warmer than average oceanic temperatures are accompanied by higher air to surface pressures in the Western Pacific. In effect, the global high and low-pressure areas are shifted which causes erratic climate behaviors in many places of the world, including the Caribbean (Malmgren, Winter & Chen, 1998). For example, the extreme 1990-1994 extended El Niño event corresponded to 20 dry weeks in 1994, one of the driest years on record at El Verde Field Station.

ENSO increases the amount of ocean tidal flow off the southerly coasts of Puerto Rico, Cuba, Hispaniola and acts as subtropical jet pulling equatorial moisture across the Caribbean. Despite increasing the chances of hurricanes and tropical storms, this helps to draw convective outflows northward from the ITCZ, resulting in an overall warming effect of the Caribbean. This can serve to decrease rainfall during hurricane season but increases rainfall over the remainder of the year. Jury et al. (2002) found that this leads to an overall increase of rainfall in the Caribbean, especially the eastern Greater Antilles due to ENSO. Despite this, there is no clear directional relationship between ENSO and increased or decreased rainfall for the Caribbean. Conclusive evidence from the data at El Verde Field Station and across the greater Antilles show that during strong El Niño events, unpredictable changes in propitiation patterns and climate regime result.

The corollary to ENSO is the North Atlantic Oscillation (NAO). The NAO is said to be in effect when the high-pressure zone that is located over the Icelandic Islands grows and intensifies. The temperature in Puerto Rico is generally warmer during El Niño years and cooler during positive NAO events. The prevailing Westerly winds going to Europe have decreased velocity during a positive NAO. This reduces the air turnover rates of Hadley cells at the ITCZ, but leads to an increase in tropical Trade Wind speeds and reduced rainfall for many areas of the Caribbean. Jury, Malmgren and Winter (1998) found that the NAO is negatively associated with Caribbean rainfall when the preceding winter season is considered with respect to seasonal rainfall for Eastern Puerto Rico and the surrounding islands. However, the monthly-scale analysis suggested an unstable and generally positive simultaneous association with rainfall of the Lesser Antilles in the south-eastern Caribbean.

Other studies have wanted to explore the relationships between rainfall, run-off and elevation in the Luquillo Mountains. Significant relationships were found between elevation and a mean annual rainfall, with areas at higher elevations receiving higher levels of rainfall. Elevation was inversely related to the average number of days per year without rainfall and annual stream run-off levels were positively related to the mean elevation of corresponding watershed areas (Garcia-martino, Arner, Catena & Ivco, 1996).

There is need for further study into the chemistry of rainfall and how it relates to nutrient cycling dynamics in the LEF. This would allow the connection of the freshwater sciences to the Atmospheric climate models, and help considerably in understanding the role of the LEF in this context.

5. Works Cited

Brokaw, Nicholas, et al., eds. *A Caribbean forest tapestry: the multidimensional nature of disturbance and response*. OUP USA, 2012.

Garcia-martino, A. R., Arner, G. L. S. W., Catena, F. R. N. S., & Ivco, D. A. L. C. (1996). Rainfall, Runoff and Elevation Relationships in the Luquillo Mountains of Puerto Rico, *32*(4).

Heartsil-Scalley, Tamara, Carlos R. Estrada Ruiz, and Samuel Moya. "Patrones de lluvia, Translocación y flujo de nutrientes en las cuencas." Acta Científica 20.1-3 (2006): 67-88.

Heartsill-Scalley, Tamara, et al. "Disturbance and long-term patterns of rainfall and throughfall nutrient fluxes in a subtropical wet forest in Puerto Rico."Journal of Hydrology 333.2 (2007): 472-485.

Heartsill-Scalley, Tamara, et al. "Long-term dynamics of organic matter and elements exported as coarse particulates from two Caribbean montane watersheds."Journal of Tropical Ecology 28.2 (2012): 127-139.

Iturralde-vinent, M. A. (1999). Paleogeography of The Caribbean Region: Implications for Cenozoic Biogeography, (238).

Jury, Mark, Björn A. Malmgren, and Amos Winter. "Subregional precipitation climate of the Caribbean and relationships with ENSO and NAO." Journal of Geophysical Research: Atmospheres (1984–2012) 112.D16 (2007).

Malmgren, Björn A., Amos Winter, and Deliang Chen. "El Niño-southern oscillation and North Atlantic oscillation control of climate in Puerto Rico."Journal of Climate 11.10 (1998): 2713-2717.

Nacional, M., Natural, D. H., & Armas, P. De. (2006). Meso-Cenozoic Caribbean Paleogeography: Implications for the Historical Biogeography of the Region, *48*, 791–827.

Thompson, Jill, et al. "Land use history, environment, and tree composition in a tropical forest." *Ecological Applications* 12.5 (2002): 1344-1363.

Waide, R. B., and W. B. Reagan. "The food web of a tropical rainforest."*University of Chicago* (1996).

6: Appendix:

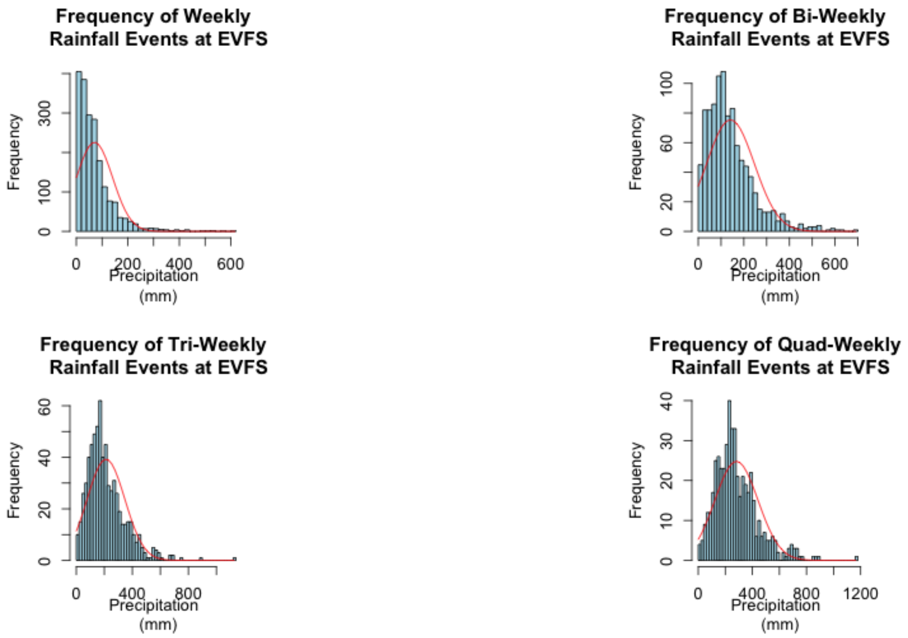

Fig 6.1 – Rainfall Distributions for Weekly, Bi-weekly, Tri-weekly, and Quad-weekly rainfall events at El Verde Field Station, PR.

-

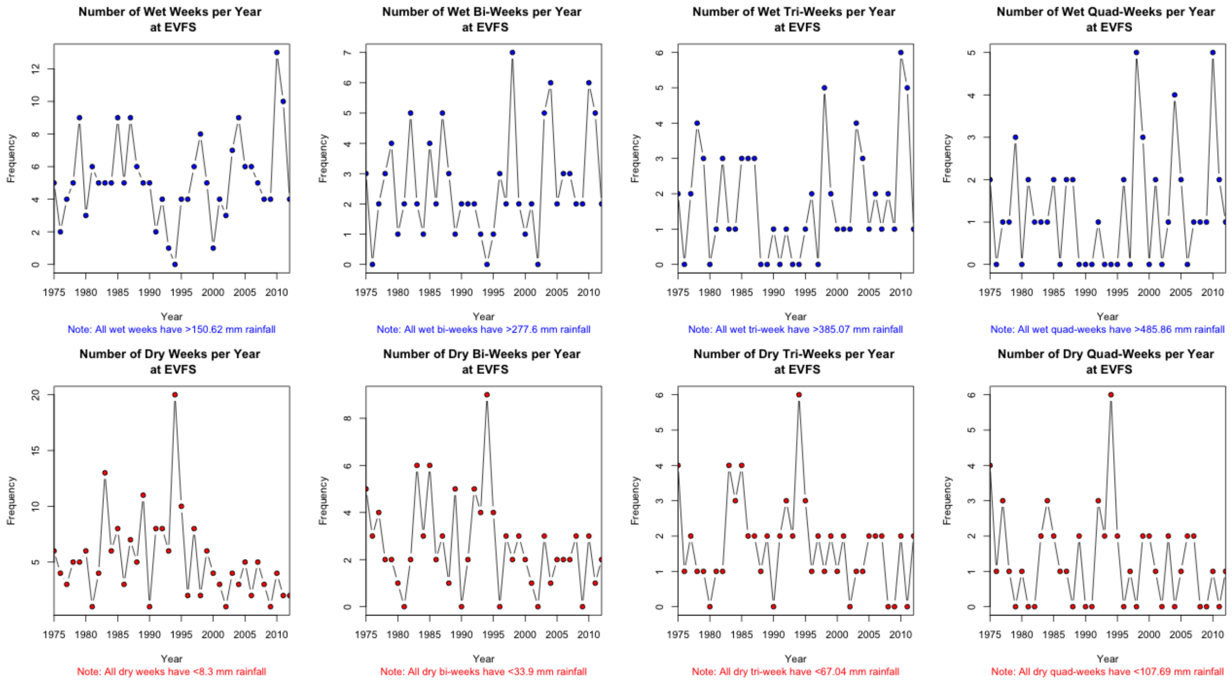

Fig 6.2 – Frequency of Dry and Wet Weekly, Bi-weekly, Tri-weekly, and Quad-weekly rainfall events by year at El Verde Field Station, PR.

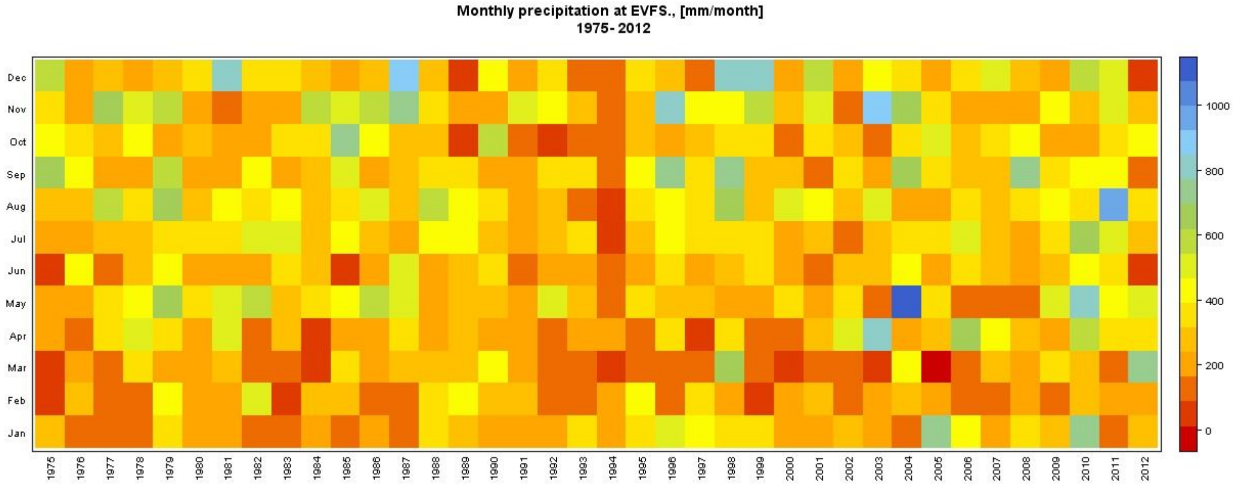

Fig 6.3 – Matrix plot of precipitation at El Verde Field Station relating monthly totals to corresponding year