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DOWNSCALED CLIMATE CHANGE IMPACTS ON AGRICULTURAL WATER RESOUCES IN PUERTO RICO

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ABSTRACT

The purpose of this study is to estimate reference evapotranspiration (ET_o), rainfall deficit (rainfall – ET_o) and relative crop yield reduction for a generic crop under climate change conditions for three locations in Puerto Rico: Adjuntas, Mayagüez, and Lajas. Reference evapotranspiration is estimated by the Penman-Monteith method. Rainfall and temperature data were statistically downscaled and evaluated using the DOE/NCAR PCM global circulation model projections for the B1 (low), A2 (mid-high) and A1fi (high) emission scenarios of the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios. Relative crop yield reductions were estimated from a function dependent water stress factor, which is a function of soil moisture content. Average soil moisture content for the three locations was determined by means of a simple water balance approach. Results from the analysis indicate that the rainy season will become wetter and the dry season will become drier. The 20-year mean 1990-2010 September rainfall excess (i.e., rainfall – $ET_o > 0$) increased for all scenarios and locations from 149.8 to 356.4 mm for 2080-2100. Similarly, the 20-year average February rainfall deficit (i.e., rainfall – $ET_o < 0$) decreased from a -26.1 mm for 1990-2010 to -72.1 mm

for the year 2080-2100. The results suggest that additional water could be saved during the wet months to offset increased irrigation requirements during the dry months.

Relative crop yield reduction did not change significantly under the B1 projected emissions scenario, but increased by approximately 20% during the summer months under the A1fi emissions scenario. Components of the annual water balance for the three climate change scenarios are rainfall, evapotranspiration (adjusted for soil moisture), surface runoff, aquifer recharge and change in soil moisture storage. Under the A1fi scenario, for all locations, annual evapotranspiration decreased owing to lower soil moisture, surface runoff decreased, and aquifer recharge increased. Aquifer recharge increased at all three locations because the majority of recharge occurs during the wet season and the wet season became wetter. This is good news from a groundwater production standpoint. Increasing aquifer recharge also suggests that groundwater levels may increase and this may help to minimize saltwater intrusion near the coasts as sea levels increase, provided that groundwater use is not over-subscribed.

INTRODUCTION

In recent years great emphasis has been given to the potential impact that human induced increases in atmospheric carbon dioxide (CO_2) will have on the global climate during the next 50 to 100 years (IPCC, 2001; IPCC 2007a). Significant changes are expected to occur in the air temperature, sea surface temperature, sea level rise, and the magnitude and frequency of extreme weather events. Potential impacts on water resources in rain-dominated catchments, such as those found in the Caribbean Region (IPCC, 2007b) include higher precipitation extremes, an increase in streamflow seasonal variability, with higher flows during the wet season and lower flows during the dry season, and an increase in extended dry period probabilities, and a greater risk of droughts and flood. Extended dry periods and the potential for greater evaporation will have a negative impact lake levels used for freshwater supply. Groundwater use will likely increase in the future due to increasing demand, and because groundwater may be needed to offset declining surface sources during the drier months. Extended dry periods will also reduce soil moisture and therefore increase water demand by irrigated agricultural.

This study addresses the global warming-temperature dependent changes in reference evapotranspiration (ET_o) and rainfall deficit (or rainfall excess) for the 21^{st} Century at three locations on the Island of Puerto Rico. In this study we specifically estimated future values of reference evapotranspiration and rainfall deficit. Numerous other studies have been conducted using general circulation models (GCMs) output for hydrologic model forcing. Bouraoui et al. (1997) coupled the hydrologic model ANSWERS (Beasley et al., 1980) with a GCM showing that although large-scale GCM output data could be one of the best available techniques to estimate the effects of increasing greenhouse gases on rainfall and evapotranspiration, their coarse spatial resolution was not compatible with watershed hydrologic models. Bouraoui et al. (1997) proposed a general methodology to disaggregate large-scale GCM output directly to hydrologic models and illustrated by predicting possible impacts of CO_2 doubling on water resources for an agricultural catchment close to Grenoble, France. The results showed that the doubling atmospheric CO_2 would likely reduce aquifer recharge causing a negative impact on groundwater resources in the study area. However, the authors warned the results were obtained from only one GCM and since many uncertainties still exist among different models, they must be used with caution. The disparate spatial scales between GCMs and hydrologic models requires that statistical or dynamic downscaling techniques be used (Charles et al., 1999).

Miller et al. (2003) analyzed the sensitivity of California streamflow timing and amount using two GCM projections and the U.S. National Weather Service – Rive Forecast Center's Sacramento-Snow model and found that regardless of the GCM projection, the hydrologic response will lead to decreased snowpack, early runoff, and increased flood likelihoods, with a shift in streamflow to earlier in the season. Maurer and Duffy (2005) evaluated the impact of climate change on stream flow in California based on downscaled data from ten GCMs. They observed significant detection of decreasing summer flows and increasing winter flows, despite the relatively large inter-model variability between the 10 GCMs. Brekke et al. (2004) evaluated water resources for the San Joaquin Valley in California using two GCMs (HadCM2 and PCM). They predicted impacts on reservoir inflow, storage, releases for deliveries, and streamflow. They concluded that the results were too broad to provide a guide for selection of mitigation projects. Most of the impact uncertainty was attributed to differences in projected precipitation type (rain, snow), amount, and timing by the two GCMs. Dettinger et al. (2004) applied a component resampling technique to derive streamflow probability distribution functions (PDFs) for climate change scenarios using six GCMs. The results indicated that although the total amount of total streamflow per water year in California did not change significantly, peak flows occurred earlier in time (between 15 to 25 days earlier), as was observed initially in 1987 (Roos 1987). The results were consistent with Stewart et al. (2005) who evaluated 302 western North American gauges for their trends in steamflow timing across western North America.

Regional or mesoscale models have also been used to evaluate potential future impacts on water resources. For example, Pan et al. (2002) coupled the National Center for Atmospheric

Research (NCAR)/Penn State University mesoscale model version 5 (MM5), the U.S. Department of Agriculture (USDA) Soil Water Assessment Tools (SWAT), and the California Environmental Resources Evaluation System (CERES) together to form a two-way coupled soil-plant-atmosphere agro-ecosystem model. The purpose of this coupled model approach was to predict seasonal crop-available water, thereby allowing evaluation of alternative cropping systems.

The water cycle of tropical islands in the Caribbean Region is determined by a unique set of external and local factors. Although the general characteristics of the hydrological cycle are well understood, little information is available on the sensitivity of flux rates and therefore, relative importance of the various components of the hydrologic cycle, especially under different global climate change scenarios and local land use practices in tropical regions. Furthermore, there is a lack of understanding relative to the linkage between mesoscale weather processes and the hydrologic cycle at the basin scale. Improving our understanding of these processes is crucial for managing risks in the future related to climate and land use change. This study presents a methodology that can be used to evaluate reference evapotranspiration and rainfall deficits and can potentially be applied at other locations throughout the world.

APPROACH

The objective of this study was to analyze future rainfall, rainfall deficit and relative crop yield reduction at three locations in western PR. Although the temperature and rainfall data were downscaled to specific locations (Adjuntas, Mayaguez and Lajas, PR), generic values were assumed for other parameters required in the analysis. For example, soil texture was assumed to be clay, as this is the dominant soil texture in all three areas. Average values of evapotranspiration crop coefficients and yield response factors were taken for all crops, and a single value of the monthly runoff coefficient was used based on values derived for the two principal watersheds in the study area.

Temperature and precipitation were statistically downscaled to to single sites matching historical distributions (1960 to 2000) using the method of Miller et al. (2006, 2007) at Adjuntas, Mayagüez and Lajas, Puerto Rico. The locations were selected because they represent a relatively wide range of conditions within the region (Figure 1, Table 1). Adjuntas is humid, receives a large amount of rainfall (1871 mm/yr), is at a relatively high elevation at 549 meters above sea level (MASL), the topography is mountainous and is located relatively far from the coast. Mayagüez is humid, receives a large amount of rainfall (1744 mm/yr), is located immediately adjacent to the Mayagüez Bay, the elevation is close to sea level, topography is relatively flat near the ocean but rises in elevation away from the ocean. Lajas is less humid than the other two locations, receives less rainfall (1143 mm/year), is located in a flat valley, and is located about half the distance to the ocean as Adjuntas (27 MASL). The Lajas Valley is well-known for its elaborate irrigation and drainage system. Irrigation water is derived from the Lago Loco reservoir located at the eastern end of the Valley (Molina-Rivera, 2005).

The GCM data were obtained from the Department of Energy (DOE)/National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM) (Washington et al. 2000). The emission scenarios considered are from the Intergovernmental Panel on Climate Change Special

Report on Emission Scenarios (IPCC SRES) B1 (low) A2 (mid-high) and A1fi (high). (Nakicenovic, et al., 2000)

Reference evapotranspiration (ET_o) was estimated using the Penman-Monteith (PM) method, which depends on the following input variables: net radiation, soil heat flux, air temperature, actual and saturated vapor pressure, and wind speed. The PM ET_o equation is presented below (Allen et al., 1989):

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

where Δ is slope of the vapor pressure curve, R_n is net radiation at the surface [Wm^{-2}], G is soil heat flux density [Wm^{-2}], γ is psychrometric constant, T is mean daily air temperature at 2-m height, u_2 is wind speed at 2-m height, e_s is the saturated vapor pressure and e_a is the actual vapor pressure [Kpa]. Equation 1 applies specifically to a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 $sec.m^{-1}$ and an albedo of 0.23. Vapor pressure was calculated using the following equation:

$$e(T) = 0.6108 \cdot \exp\left(\frac{17.27 \cdot T}{T + 237.3}\right) \quad (2)$$

where e(T) is vapor pressure [Kpa] evaluated at temperature T [K]. Saturated and actual vapor pressures were estimated using equation 2 with the mean monthly air temperature (T_{mean}) [C^o] and mean monthly dew point temperature (T_{dew}) [C^o], respectively. The Food and Agriculatural Organization (Allen et al., 1998) has reported that T_{dew} can be estimated based on the use of the monthly minimum air temperature (T_{min}) and this approach was used in this study. A correction factor was recommended by Allen et al. (1998, equation 6-6) based on local conditions: T_{dew} = T_{min} + $K_{o,}$ where K_o is a temperature correction factor.

Lajas, Mayaguez and Adjuntas are located in Climate Divisions 2, 4 and 6, respectively. The -2.5 ^oC correction factor for Division 2 (Lajas) is consistent with the recommendation by Allen et al. (1998) to "subtract 2-3 ^oC from T_{min}" for arid and semi-arid regions. Harmsen et al. (2002) derived values of K_o for the six NOAA Climate Divisions in Puerto Rico, which are listed in Table 2. In this study T_{dew} was estimated using the downscaled minimum air temperature plus the appropriate correction factor from Table 2.

The FAO recommends that wind speed be estimated from nearby weather stations, or as a preliminary first approximation, the worldwide average of 2 m/sec can be used. In this study we used the wind speed values presented by Harmsen et al. (2002), which were based on average station data within the Climatic Divisions established by the NOAA, and are presented in Table 3. The data in Table 3 were derived from wind speed sensors located at airports and university experiment stations. Average wind speeds were based on San Juan and Aguadilla for Div. 1; Ponce, Aguirre, Fortuna and Lajas, for Div. 2; Isabela and Rio Piedras for Div. 3; Mayagüez, Roosevelt Rd. and Yabucoa for Div. 4; Gurabo for Div. 5; and Corozal and Adjuntas for Div. 6.. The sensor heights were 10 m and 0.58 m above the ground for the airports and experiment stations, respectively. Measured wind speeds were adjusted to the wind speed at 2 m above the ground using the following equation (Allen et al., 2005): $u_2 = (4.87\ u_z) / [\ln (67.8\ z - 5.42)]$, where u_z is the wind speed at height z above the ground. Note also that the wind speeds in Table 3 are the average daytime wind speeds.

Solar radiation (R_s) was estimated using the Hargreaves' radiation formula (Allen et al., 1998):

$$R_s = k_{Rs} (T_{max} - T_{min})^{1/2} R_a \qquad (3)$$

where k_{Rs} is an adjustment factor equal to 0.16 for interior locations (Adjuntas) and 0.19 for coastal locations (Mayagüez and Lajas). The various formulas used to calculate R_a, R_{net} and G are presented in Allen et al. (2005).

The rainfall deficit was estimated by subtracting the monthly cumulative ET_o from the monthly cumulative rainfall. A positive value indicates water in excess of crop water requirements and a negative value indicates a deficit in terms of crop water requirements. It should be noted that we estimated the excess rainfall using the reference evapotranspiration and not the actual crop evapotranspiration.

Relative crop yield reduction was estimated from the expression presented by Allen et al. (1998):

$$YR = K_y \cdot (1 - K_s) \qquad (4)$$

where YR is relative crop yield reduction, K_y is a yield response factor, K_s is a water stress coefficient defined as the ratio of ET_{cadj} to ET_c where:

$$ET_{cadj} = K_s \, ET_c \qquad (5)$$

and

$$ET_c = K_c \, ET_{o,}, \qquad (6)$$

where ET_{cadj} is the adjusted crop evapotranspiration accounting for limited water availability, ET_c is the crop evapotranspiration under well watered conditions, and ET_o is crop reference evapotranspiration.

In this study a generic crop with K_c, and K_y values equal to 1 is considered. The assumption of a K_c equal to 1 is especially applicable for long season crops such as banana, pineapple, sugar cane, and citrus, in which the mid season lengths are 120-180 day, 600 days, 135-210 days, and 120 days, respectively. For these same crops, average mid season K_c values are 1.15, 0.5, 1.25 and 0.8 (average 0.94).

Here we assume the generic crop has a seasonal yield response factor K_y equal to 1. Allen et al. (1998) reported K_y values for 24 crops with an approximate average equal to 1. The crop stress coefficient, K_s, was determined as follows: for soil moisture values between the soil field capacity (θ_{FC}) and the threshold moisture content (θ_t), equal to the θ_{FC} minus the readily available water (RAW), K_s was equal to 1. Between the θ_t and the soil wilting point (θ_{WP}), K_s varied linearly between 1 (at θ_t) and 0 (at θ_{WP}). RAW is defined as p TAW, where p is the average fraction of the total available water (TAW) that can be depleted from the root zone before moisture stress occurs and ET is reduced. In this we used a value of p equal to 0.5, a recommended value for forage crops, grain crops and deep rooted row crops (Keller and Bliesner, 1990).

The volumetric soil moisture content is needed to estimate water stress coefficient Ks and the relative crop yield reduction (YR). In this analysis a generic vertical one meter clay soil profile was assumed (predominant soil texture in Puerto Rico) with the following characteristics (Schwab et al., 1996, Clay soil): soil porosity (φ) = 530 mm, field capacity (FC) = 440 mm and wilting point (WP) = 210 mm. The mean-monthly soil moisture content was derived from the following water balance:

$$S_{i+1} = R_i - ET_{cadj,i} - RO_i - Rech_i + S_i \ , \qquad (7)$$

where S_{i+1} is the depth of soil water at the beginning of month i+1 [mm], S_i is the depth of soil water in the profile at the beginning of month i [mm], R_i is rainfall during month i [mm], $ET_{cadj,i}$ is actual evapotranspiration during month i [mm], RO_i is surface runoff during month i [mm] and $Rech_i$ is percolation or aquifer recharge during month i [mm].

Surface runoff, RO, was determined based on the following simple monthly runoff equation: RO = C R, where R is monthly rainfall and C is monthly runoff coefficient = 0.3. The value of 0.3 was based on the fact that for the two main rivers in the study area, the Añasco River and the Guanajibo River, the estimated C values were 0.33 and 0.2, respectively (USGS, 2004). Aquifer recharge was estimated from the follow relations:

$$S_{i+1} = R_i - ET_{cadj,i} - RO_i + S_i \qquad (8a)$$

$$\text{If } S_{i+1} \leq FC \text{ then } Rech_i = 0 \qquad (8b)$$

$$\text{If } S_{i+1} > FC \text{ then } Rech_i = S_{i+1} - FC, \text{ and } S_{i+1} = FC \qquad (8c)$$

RESULTS

Figure 2 shows the average daily air temperatures for the three locations derived from historical records. The slopes of the trend lines were $9x10^{-5}$ $^oC/day$, $8x10^{-5}$ $^oC/day$ and $5x10^{-6}$ $^oCday^{-1}$, respectively, for Adjuntas, Mayagüez and Lajas. The slopes for the Adjuntas and Mayagüez data were statistically significant at the 95% confidence level. However, the slope for the Lajas data was not significant. From 1970 to 2000 the average temperature at Adjuntas increased by 0.99 ^oC. From 1961 to 2000 the average temperature for Mayagüez increased by

1.17 ^{o}C. These increases in temperature are significantly greater than the global average increase of 0.6 ± 0.2°C during the last century (Peterson et al., 2002).

Since the slope associated with the Lajas regression equation was not significant, an estimate of the increase in temperature based on the slope is not appropriate. It should be noted that the non-significant increase in air temperature for Lajas is anomalous when compared with the data presented by Ramirez-Beltran et al. (2007) which indicated an average trend in air temperature in Puerto Rico, based on data from 53 stations collected between 1950 and 2006, similar to those shown in Figure 2a and 2b, for Adjuntas and Mayagüez. Similar increasing air temperature trends have been observed in the Dominican Republic, Haiti, Jamaica and Cuba (Ramirez-Beltran et al., 2007). It is of interest to note that Harmsen et al. (2004) reported anomalously low pan evaporation values for the Lajas Experiment Station, which may have been due to the land cover changes during the period of record. This being the case, the historic air temperature data from Lajas should be viewed with caution.

Whatever caused the Lajas historical air temperature data (moved instrument, change of instruments and/or land use change) to respond differently than the other two sites, the temperature increase predicted by the statistical downscaling procedure preserved this increase in temperature for Lajas for the next 100 years, as shown in Figure 3 (Scenario A2). Figure 3 also shows predicted minimum and maximum air temperatures. Figures 4, 5 and 6 show the air temperature difference (T_{min} – T_{max}), vapor pressure deficit (VPD), and reference evapotranspiration (ET_o) for the A2 scenario for Lajas during the next 100 years. Increasing variance can be observed in the T_{max}-T_{min}, VPD and ET_o data, which is probably due to the increasing variance evident in the mean air temperature (Figure 3). Interestingly, the variance in the minimum temperature can be seen to decrease with time.

Figure 7 shows the downscaled rainfall at Lajas for climate change scenario A2. The regression equation indicates a negative slope which means that the average rainfall is slightly decreasing and is not statistically significant. However, if we look at the rainfall for individual months we see a different picture of the trend in rainfall. For the wettest and driest months, respectively, Figure 8 shows increasing rainfall during September (i.e., positive slope in the linear regression trend line) and a slight decrease in rainfall during February (i.e., negative slope in the linear regression trend line). Figure 9 shows the monthly average rainfall for each month of the year for the years 2000 and 2090 for the three climate change scenarios and the three locations. The predicted rainfall values are based on 20-year averages, for example, the average monthly rainfall for 2090 was based on the average of the monthly rainfalls from 2080 through 2100. Figure 9 indicates that the B1 scenario average monthly rainfall does not change significantly between 2000 and 2090, whereas the monthly average rainfall for the A1fi scenario dropped markedly during every month for the two periods, except during September. The results are consistent with other studies indicating the rainy season in the Caribbean will become wetter and the dry season will become drier (e.g., Pulwarty, 2006, IPCC, 2007).

Table 4A presents the rainfall deficit for the three locations and the three climate change scenarios for the months of February and September, for the years 2000, 2050 and 2090. Note that virtually all of the values for February are negative indicating a deficit in terms of crop water requirements and virtually all of the values for September are positive indicating an excess in terms of crop water requirements. Table 4B presents the difference in the rainfall deficit relative to the year 2000.

Table 4A shows increasing deficits in February at all locations for the A1fi and A2 scenarios. Although there was an increase in the deficit for the B1 scenario in February, the trend is not as clear. Interestingly the largest deficits occurred for the A2 scenario, not the A1fi scenario, which produced higher near-surface air temperatures. Increases in rainfall excess occurred in September at all locations for all scenarios. The average estimated rainfall excess (i.e., rainfall – ETo > 0) increased in September (the wettest month) to 356.4 mm for the year 2090 relative to an average rainfall excess of 149.8 mm for 2000. The average rainfall deficit (i.e., rainfall – ETo < 0) in February increased to -72.1 mm for the year 2090 relative to an average rainfall deficit of -26.1 mm for 2000. These results indicate that the driest month (February) may become drier and the wettest month (September) may become wetter.

Table 5 presents the annual average components of the hydrologic water balance for the three study areas for years 2000, 2050 and 2090 under climate change scenarios B1, A2 and A1fi. The components of the water balance in millimeters include: rainfall, reference evapotranspiration, adjusted crop evapotranspiration, surface runoff, aquifer recharge and soil moisture storage. Table 5 also lists the predicted annual rainfall deficit (or excess) and relative crop yield reduction for the three studies areas for years 2000, 2050 and 2090 under climate change scenarios B1, A2 and A1fi.

Figure 10 shows the average monthly variation in the relative crop yield reduction for Lajas for 2000 and 2090 for the three climate change scenarios. The relative yield reduction is an indication of the potential yield reduction that may occur based on a deficiency in soil water. Under current conditions, without irrigation, crops grown in Lajas will experience a significant yield reduction. This can be seen from the results for the current period in Figure 10C (Year 2000). Under the B1 scenario for Lajas (Figure 10A), relative yield reduction did not change significantly in the future. However, under the A1fi scenario (Figure 10C), the relative yield reduction increased significantly in the future during the May/June period (greater than 20%). The relative yield reduction decreased for all scenarios during September owing to higher soil moisture conditions.

Table 5 includes annual estimates of aquifer recharge and surface runoff. These two water balance components are important indicators of the change in water resources within the study area. Little research has been done on the impacts of climate change on aquifer recharge (IPCC, 2007b). However, for all of the scenarios used in this study relative aquifer recharge increased at all three locations between 2000 and 2090, because the majority of this recharge occurs during the wet season. This is good news from a groundwater production standpoint. Increasing aquifer recharge also suggests that groundwater levels may increase and this may help to minimize saltwater intrusion near the coasts as sea levels increase, provided that groundwater use is not over-subscribed. Surface runoff trends were not as clear. If we consider the A1fi and A2 scenarios, surface runoff decreased between 2000 and 2090. This is good from a surface water quality standpoint because less surface runoff means less soil erosion. However, this may indicate less water will be available for filling storage reservoirs. For the B1 scenario, surface runoff increased during the simulation period.

For the B1 scenario, soil moisture content did not change significantly in Lajas and Adjuntas, but decreased slightly in Mayaguez. For the A2 and A1Fi scenarios, soil moisture decreased at all three locations. For these same scenarios the relative crop yield reduction correspondingly increased.

LIMITATIONS IN RESULTS PRESENTED

The results presented in this paper should necessarily be viewed with caution since they are based in part on coarse resolution GCM data downscaled to single sites. As Pielke et al. (2006) rightly point out, future "agricultural impacts extend far beyond a global mean temperature and include other anthropogenic climate forcings." Some of these forcings include land-use change, atmospheric aerosols, and complex nonlinear feedbacks, not accounted for in present-day, and likely next-generation, GCMs. Statistical downscaling itself assumes that the predictor - predictand relationship remains constant in time with stationary dynamic conditions under future climate change (Mearns et al., 2003). Furthermore, this study was based on only one GCM and since many uncertainties still exist among different models, the results need to be used with caution (Bouraoui et al.,1997). Finally, several simplifying assumptions were made with respect to parameters used in the monthly water budget (equ. 7), which may also contribute to uncertainty in the results of this study.

CONCLUSIONS

The results from this study are consistent with other studies which indicate that the rainy season will become wetter and the dry season will become drier (e.g., Pulwarty, 2006). This has important implications on agricultural water management. With increasing rainfall deficits during the dry months, the agricultural sector's demand for water will increase, which may lead to conflicts in water use. Although the dry season will become drier and longer, the analysis revealed that aquifer recharge will increase by an appreciable amount over the next 100 years, which may help to offset some of the additional demand for water in the agricultural sector. The increased groundwater recharge may also help to reduce the problem of saltwater intrusion which is expected to increase with rising sea levels. The results indicate that the wettest month

(September) will become significantly wetter. The excess water can possibly be captured in newly constructed reservoirs to offset the higher irrigation requirements during the drier months.

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Tables

Table 1. Latitude, elevation, average rainfall, average temperature, NOAA Climate Division and distance to the coast for the three study locations.

Location	Latitude (decimal degree)	Elevation (m)	Annual Rainfall (mm)	T_{mean} (^oC)	T_{min} (^oC)	T_{max} (^oC)	NOAA Climate Division	Distance to Coast (km)
Adjuntas	18.18	549	1871	21.6	15.2	27.9	6	22
Mayaguez	18.33	20	1744	25.7	19.8	30.5	4	3
Lajas	18.00	27	1143	25.3	18.8	31.7	2	10

Table 2. Temperature correction Factor K_o used in Equation 2 for NOAA Climatic Divisions 2, 4 and 6 within Puerto Rico. (From Harmsen et al., 2002)

NOAA Climatic Division*	2	4 and 6
K_o (^oC)	-2.9	0

* See Figure 1 for Climate Divisions

Table 3. Average daily wind speeds 2 meters above the ground by month and NOAA Climatic Division* within Puerto Rico. (From Harmsen et al., 2002)

	Average Daily Wind Speeds (m/s)**											
NOAA Climatic Division*	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1	2.7	2.8	3.0	2.9	2.6	2.6	2.9	2.7	2.1	1.9	2.2	2.6
2	1.8	2.0	2.2	2.1	2.2	2.4	2.4	2.1	1.7	1.5	1.4	1.5
3	2.2	2.4	2.6	2.4	2.2	2.4	2.7	2.5	2.0	1.8	2.0	2.3
4	1.8	2.0	2.1	2.1	2.0	2.0	2.0	1.8	1.6	1.6	1.6	1.6
5	1.1	1.3	1.4	1.5	1.6	1.7	1.6	1.3	1.1	0.9	0.9	0.9
6	1.3	1.5	1.5	1.5	1.6	1.8	1.8	1.5	1.2	1.1	1.0	1.0

* See Figure 1 for NOAA Climate Divisions

** Averages are based on San Juan and Aguadilla for Div. 1; Ponce, Aguirre, Fortuna and Lajas, for Div. 2; Isabela and Rio Piedras for Div. 3; Mayagüez, Roosevelt Rd. and Yabucoa for Div. 4; Gurabo for Div. 5; and Corozal and Adjuntas for Div. 6.

Table 4. Estimated September rainfall defict (A) and change in rainfall deficit relative to 2000 (B) for Adjuntas, Mayaguez and Lajas, PR, for 2000, 2050 and 2090. Values represent 20 year averages. A negative value indicates a deficit and a positive value indicates an excess relative to crop water requirements.

A

		RAINFALL DEFICIT (mm)					
		February			September		
Scenario	**Year**	**Adjuntas**	**Mayaguez**	**Lajas**	**Adjuntas**	**Mayaguez**	**Lajas**
A1fi	2000	-6.3	-52.7	-80.3	169.1	100.5	-21.5
	2050	-25.6	-70.3	-105.2	250.4	178.0	9.7
	2090	-35.8	-84.5	-130.5	480.7	377.4	150.4
A2	2000	36.9	-22.2	-37.1	222.2	144.0	152.6
	2050	-28.6	-77.1	-82.9	339.3	241.4	237.8
	2090	-41.2	-94.9	-104.2	467.1	344.8	336.4
B1	2000	12.9	-38.2	-48.1	253.4	168.1	160.0
	2050	-22.7	-72.5	-82.0	305.1	206.5	198.8
	2090	-3.7	-72.1	-82.1	437.2	305.3	308.3

B

		Change in Rainfall Deficit Relative to 2000 (mm)					
		February			September		
Scenario	**Year**	**Adjuntas**	**Mayaguez**	**Lajas**	**Adjuntas**	**Mayaguez**	**Lajas**
A1fi	2000	0.0	0.0	0.0	0.0	0.0	0.0
	2050	-19.3	-17.6	-24.9	81.3	77.5	31.2
	2090	-29.6	-31.8	-50.2	311.5	276.9	171.9
A2	2000	0.0	0.0	0.0	0.0	0.0	0.0
	2050	-65.5	-54.9	-45.8	117.1	97.5	85.1
	2090	-78.1	-72.7	-67.1	244.9	200.9	183.7
B1	2000	0.0	0.0	0.0	0.0	0.0	0.0
	2050	-35.6	-34.3	-33.9	51.8	38.4	38.8
	2090	-16.6	-33.9	-34.0	183.8	137.2	148.3

Table 5. Annual components of the hydrologic water balance for the three studies areas for years 2000, 2050 and 2090 under climate change scenarios B1, A2 and A1fi. All units are in millimeters.

			R	ET_0	ET_{cadj}	RO	Rech	S	RFD	YR
Lajas	**B1**	**2000**	1280	1982	915	384	42	290	-702	52
		2050	1258	2010	857	377	90	283	-751	56
		2090	1372	2015	908	412	111	290	-643	53
	A2	**2000**	1324	1984	950	397	33	292	-660	50
		2050	1202	2028	858	361	63	282	--826	56
		2090	1155	2082	794	346	88	278	-927	60
	A1fI	**2000**	1275	2022	920	383	29	289	-746	53
		2050	1089	2124	812	327	35	276	-1035	61
		2090	1107	2186	756	332	108	271	-1079	65
Adjuntas	**B1**	**2000**	2036	1456	1155	611	280	354	579	20
		2050	2033	160	1096	610	336	345	573	23
		2090	2188	1460	1124	656	417	353	728	21
	A2	**2000**	2129	1454	1189	639	308	360	674	17
		2050	1935	1451	1029	581	345	339	484	27
		2090	1885	1441	968	566	378	332	445	31
	A1fI	**2000**	2033	1483	1165	610	270	354	551	21
		2050	1736	1511	990	521	250	328	226	33
		2090	1745	1478	855	523	393	317	267	40
Mayaguez	**B1**	**2000**	1916	1788	1215	575	165	328	128	33
		2050	1875	1855	1134	563	221	315	20	40
		2090	1989	1998	1199	597	250	312	-9	41
	A2	**2000**	1918	1772	1205	575	162	329	146	33
		2050	1829	1812	1092	549	235	319	17	40
		2090	1731	1855	1015	519	247	306	-124	46
	A1fI	**2000**	1918	1772	1205	575	162	329	146	33
		2050	1604	1736	992	481	170	311	-131	43
		2090	1544	1718	861	463	263	298	-175	50

R is rainfall; ET_o is reference evapotranspiration; ET_{cadj} is adjusted crop coefficient; RO is surface runoff; Rech is aquifer recharge; S is soil moisture storage, RFD is rainfall deficit and YR is relative yield reduction.

Figures

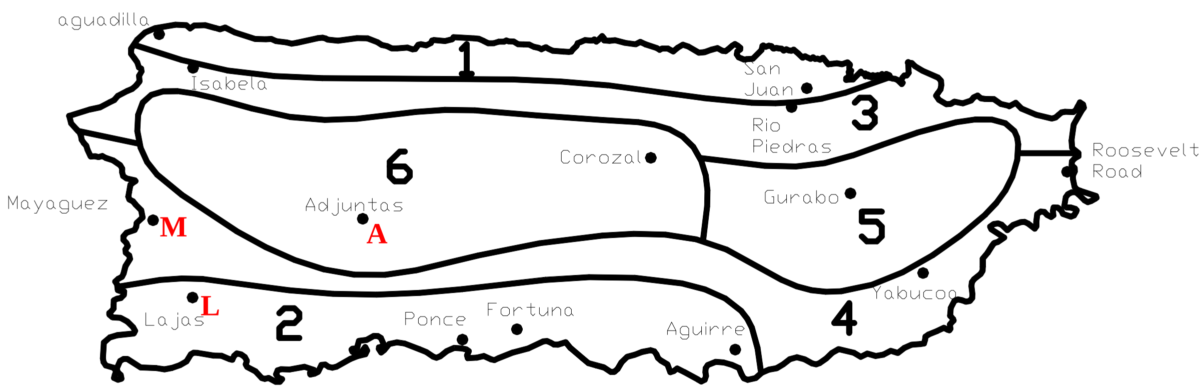
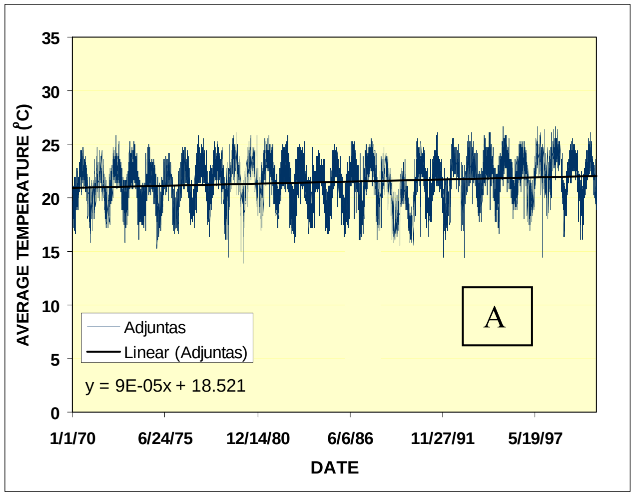
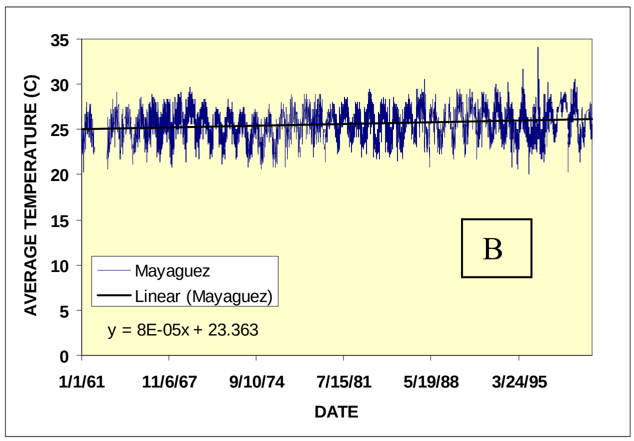


Figure 1. Map of Puerto Rico showing the locations of Adjuntas (A), Mayagüez (M) and Lajas (L) . Numbers indicate National Oceanic and Atmospheric Administration (NOAA) Climatic Divisions. 1, North Coastal; 2 South coastal; 3, Northern Slopes; 4, Southern Slopes; 5, Eastern Interior; and 6; Western Interior.





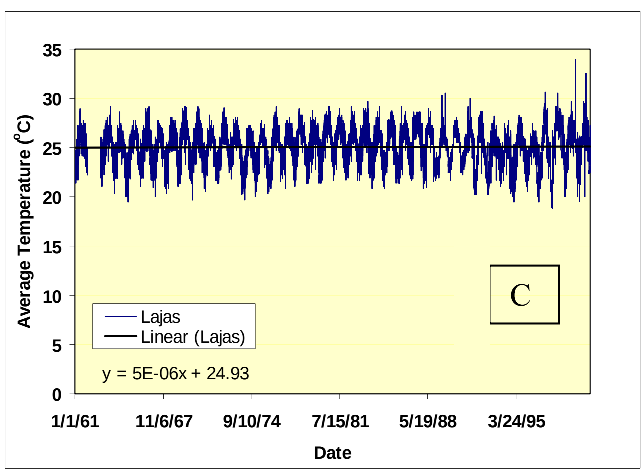


Figure 2. Historic mean air temperatures at Adjuntas (A), Mayaguez (B) and Lajas (C), PR. Linear trend lines and associated equations have been included.

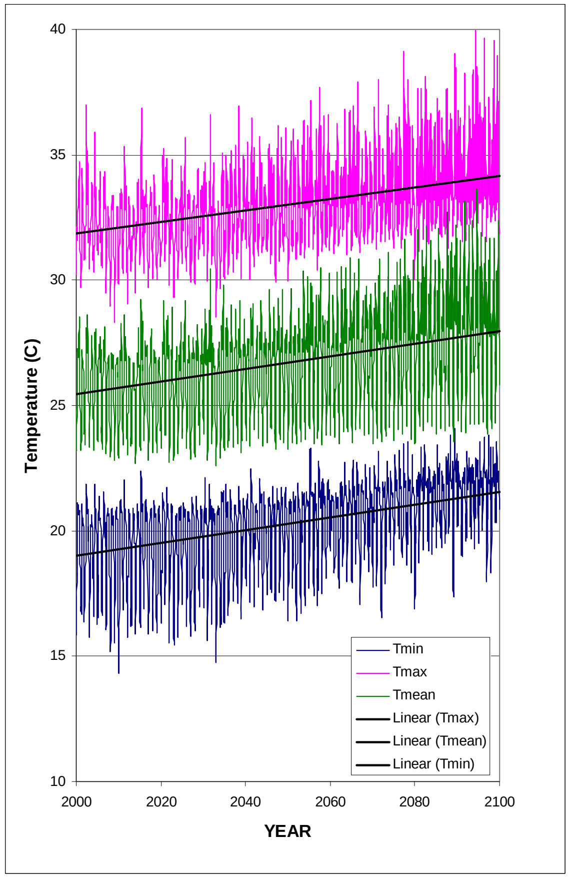


Figure 3. Minimum, mean and maximum air temperature for the A2 scenario at Lajas. Linear regression trend lines are shown.

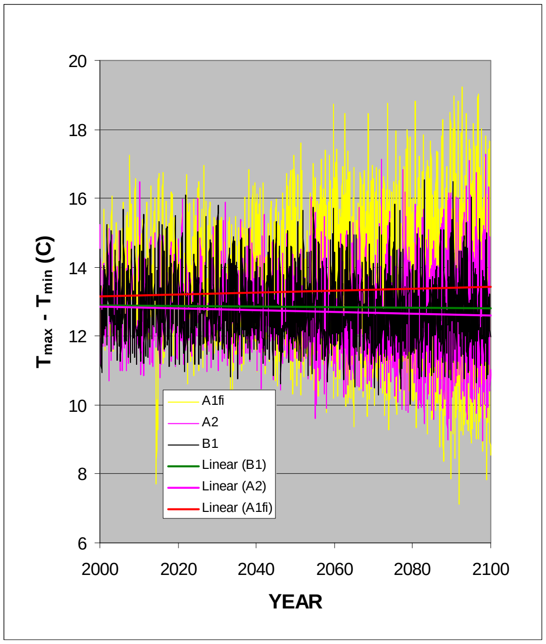


Figure 4. Tmax-Tmin for the A2 scenario at Lajas. Linear regression trend lines are shown.

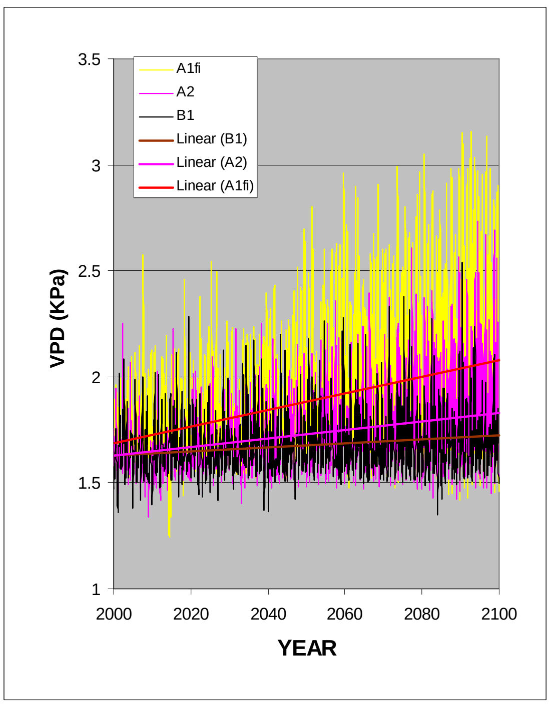


Figure 5. Vapor pressure deficit (VPD) for the A2 scenario at Lajas. Linear regression trend lines are shown.

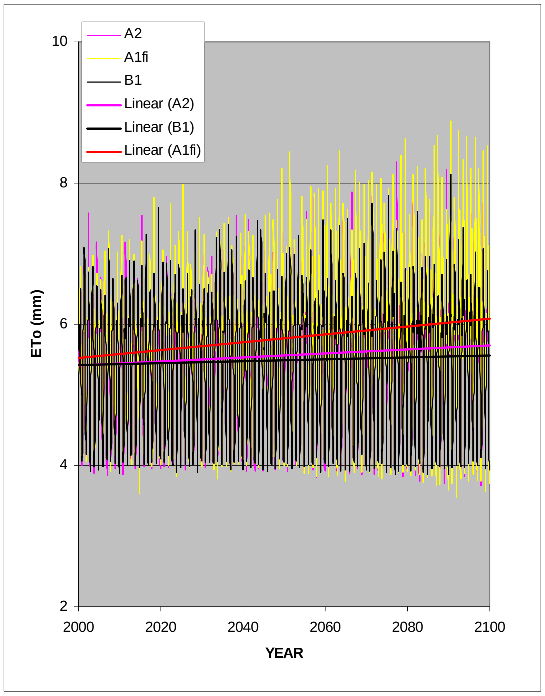


Figure 6. Reference evapotranspiration for the A2 scenario at Lajas. Linear regression trend lines are shown.

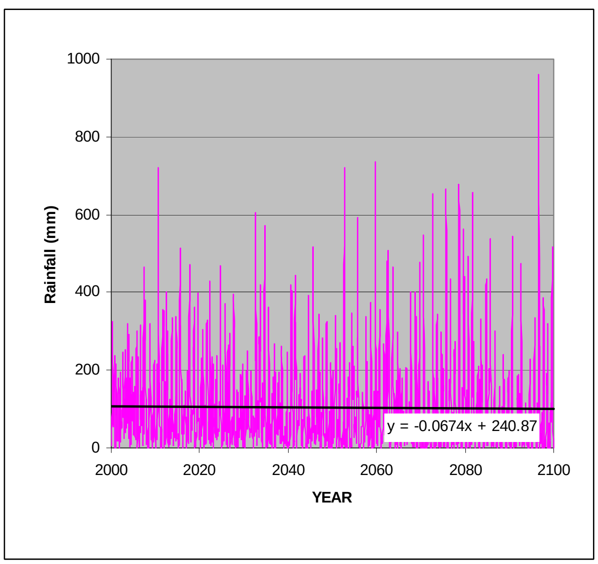


Figure 7. Average monthly rainfall at Lajas for climate change scenario A2.

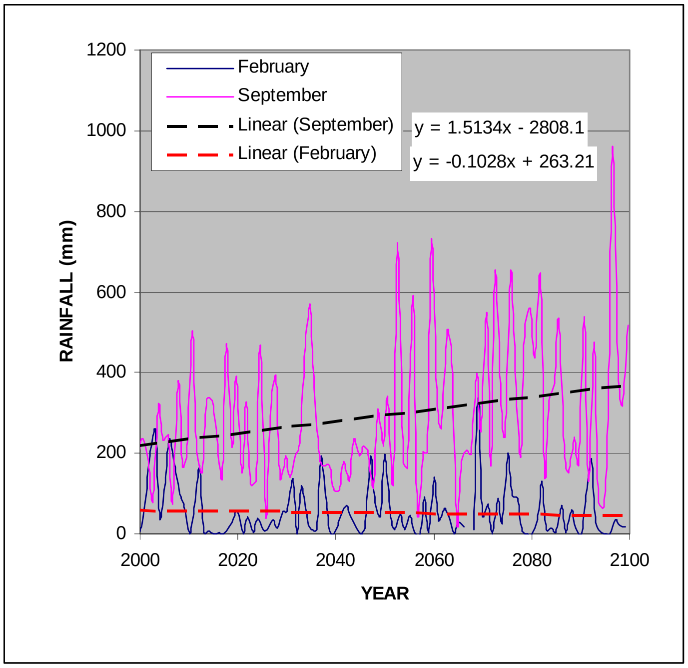


Figure 8. Estimated rainfall at Lajas for climate change scenario A2 for February and September.

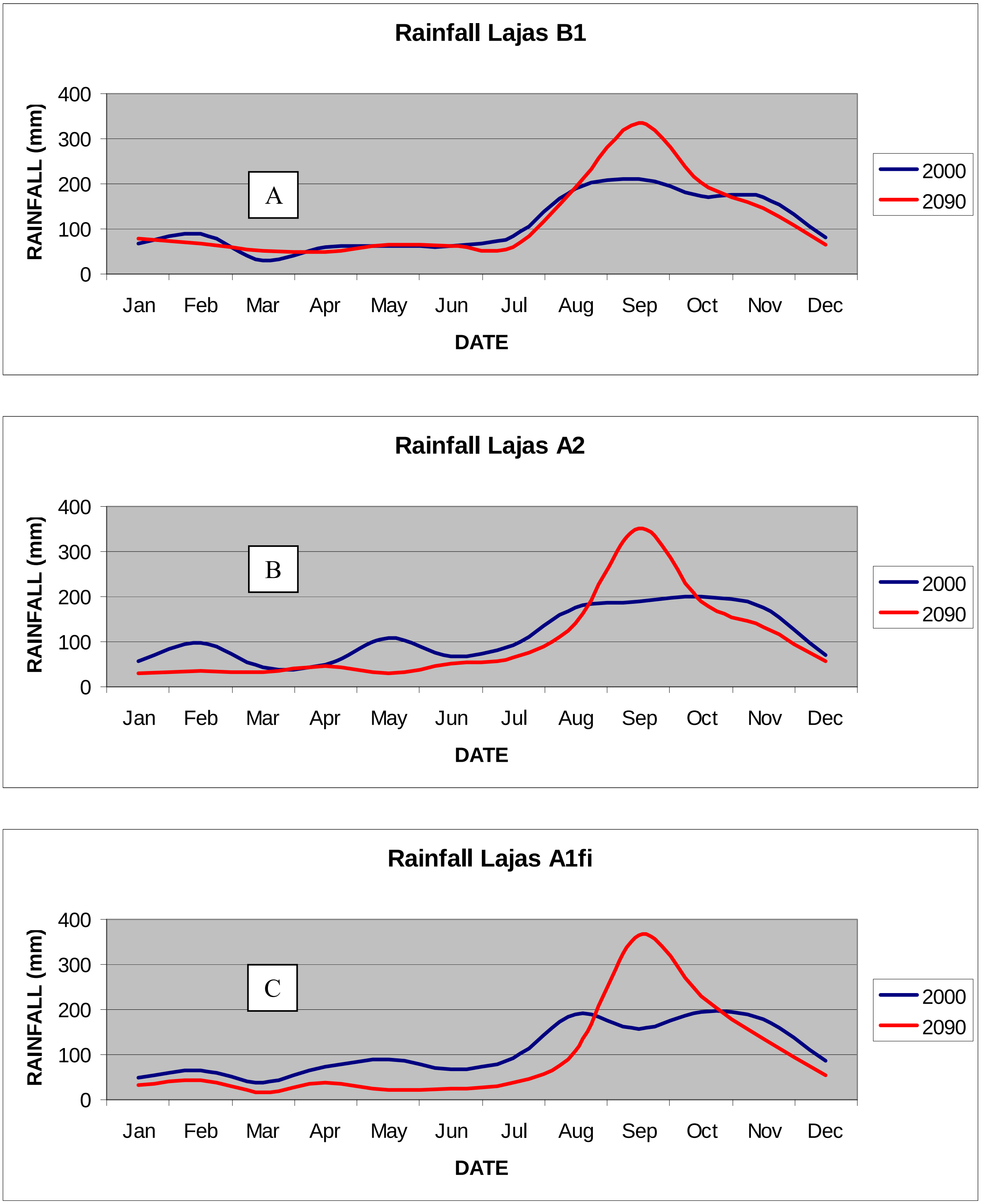
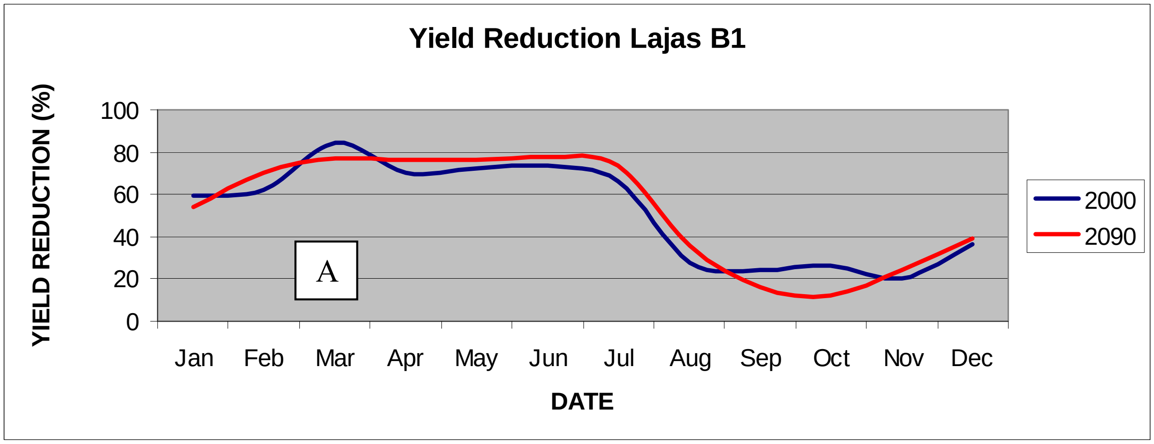
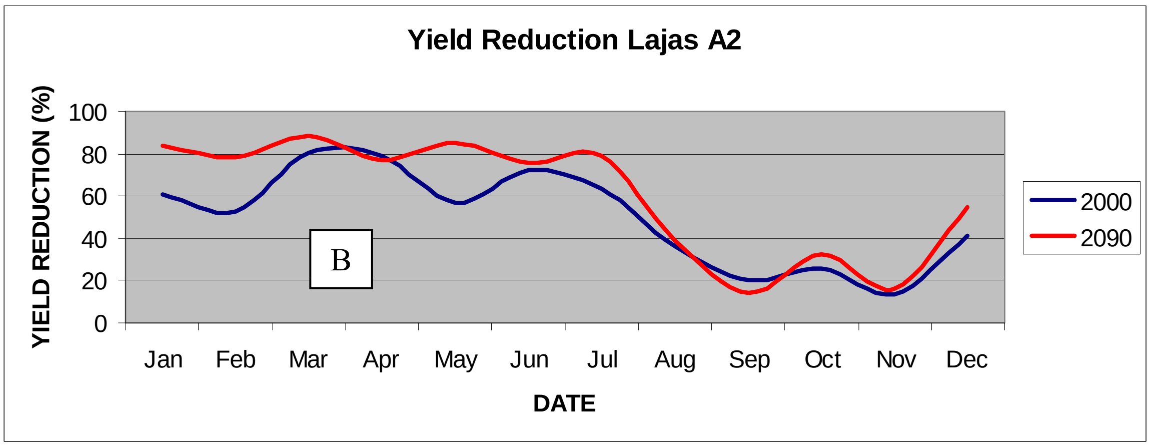


Figure 9. Rainfall for Lajas for scenario B1 (A), A2 (B) and A1fi (C) by month for 2000 and 2090 for Lajas, PR.





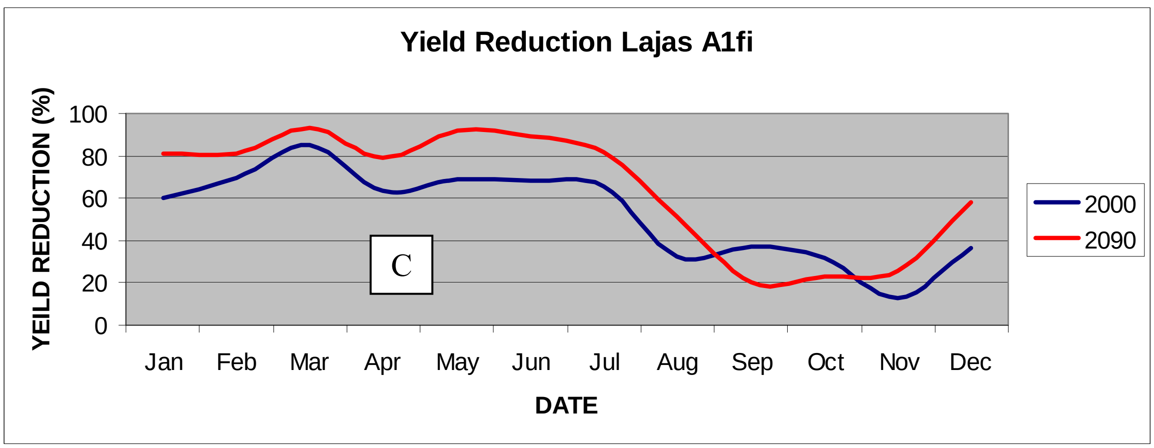


Figure 10. Relative crop yield reduction for Lajas for scenario B1 (A), A2 (B) and A1fi (C) by month for 2000 and 2090 for Lajas, PR.