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The Potential Impact of Climate Change on Agriculture in Puerto Rico

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Abstract: This paper discusses the implications of climate change on agriculture in general terms, with special emphasis on agricultural water resources. Specific potential impacts from climate change in Puerto Rico are also discussed. A detailed case study is presented in which crop water requirements are predicted during the next 100 years for three locations in western Puerto Rico: Adjuntas, Mayagüez and Lajas. Rainfall and temperature data were statistically downscaled from predictions obtained from the DOE/NCAR PCM global circulation model. The B1 (low), A2 (mid-high) and A1fi (high) emission scenarios of the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios were evaluated. The average estimated rainfall excess (i.e., rainfall – ETo > 0) for all scenarios and locations 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. The implications of these results suggest that additional water could be saved during the wet months, which would be needed to offset increased irrigation requirements during the dry months.

Keywords. Climate change, global warming, agriculture evapotranspiration, rainfall deficit.

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INTRODUCTION

In recent years great emphasis has been given to the potential impact that human induced increases in atmospheric carbon dioxide (CO2) will have on the global climate during the next 50 to 100 years (IPCC, 2001). Significant changes are expected to occur in, for example, the air temperature, sea surface temperature, sea level rise, and the magnitude and frequency of extreme weather events. This study addresses the potential impacts on agriculture and specifically on crop water use during the 21st Century at three locations on the Island of Puerto Rico.

Before discussing global climate change it is important to understand that there is a significant uncertainty associated with predictions related to climate change, whether the predictions are of air temperature, sea level rise, evaporation or rainfall. Many of the future predictions have been made with global circulation models (GCMs). These models are highly nonlinear, and some nonlinear processes have not yet been incorporated into current-day models Pielke et al. (2006) have warned that beyond some time period, our ability to provide reliable quantitative and detailed projections of climate must deteriorate to a level that no longer provides useful information to policymakers. What this statement implies is that we do not know what will happen in 50 or 100 years, although numerous GCMs predict a 1 to 2 ^{o}C rise in air temperature.

Global warming is caused by the increasing concentration of greenhouse gases in the atmosphere. When the earth's surface absorbs energy from the sun, it is converted to infrared radiation which is emitted towards the atmosphere. The larger the concentration of greenhouse gases in the atmosphere, the more infrared radiation becomes trapped. In the case of global warming there is more energy coming in from the sun than can leave via infrared radiation transfer to space. The net result is a rise in air temperature and sea surface temperature. Other radiative forcings exist which contribute to climate change including: solar irradiance, snow albedo, stratospheric aerosols, reflective tropospheric aerosols, an aerosol indirect effect, and land use (Pew Center on Global Climate Change, 2006).

It is difficult to separate global warming from the cycles that occur naturally in the weather. Therefore it is difficult to answer the question "How is global warming affecting agriculture?" Even though increasing air temperatures are evident in the historical data for Puerto Rico and the Caribbean (Ramirez-Beltran et al., 2007), the small change may not be producing measurable impacts on agriculture production. Plants and animals may respond directly to changes in air temperature, however, there are a host of other variables that are related to temperatures which affect crop growth and yield, for example evaporation, transpiration, and vapor pressure deficit. Even solar radiation has been shown to be related to the diurnal air temperature difference (Hargreaves, 1985; Allen et al., 1998). The difference between the daily minimum air temperature and the daily maximum air temperature ($T_{max} – T_{min}$) is smaller when clouds are present in the atmosphere and larger during clear conditions.

So what might be some of the consequences of climate change on agriculture in Puerto Rico and the Caribbean? With increasing temperatures, evapotranspiration (the combination of soil evaporation and plant transpiration) is expected to increase (although studies conducted by the author have shown that this is not always the case; Harmsen et al., 2007). Increasing evapotranspiration will tend to dry out soils and increase the need for irrigation. Rainfall is expected to increase in some areas but decrease in other areas. In those areas were rainfall remains the same or decreases, increased evapotranspiration will decrease aquifer recharge and cause the water table to drop. In those areas which rely on water from groundwater resources, supplies will become diminished. If soils are drier, it will require large rainfalls to produce runoff, which is necessary to fill storage reservoirs. Puerto Rico depends on reservoirs for water supply and for irrigation. Extreme weather events, such as hurricanes, are expected to increase and may provide the extra rainfall needed to produce runoff from drier soils, but may also increase soil erosion, which results in the filling of our reservoirs.

In those areas where subsistence farmers rely on rainfall for crop production, the difference between rainfall and evapotranspiration, which is called the rainfall deficit, may increase thereby causing crop stress and reduced yields. This crop stress would be superimposed on other stresses related to poor soil fertility, disease, and other less than ideal conditions. The reduced yield could be devastating for a family and in the worst case could lead to malnutrition or even starvation. Extreme weather events (floods, tornados, hurricanes, landslides caused by excessive rainfall, etc.) could wipe out crops leaving the subsistence farmer with no yield at all.

Planners need to be concerned about the potential for sea level rise and the displacement of poor farmers. Sea level rise has already begun to cause the loss of farm lands in coastal areas around the world. The unfortunate consequence is that valuable land is lost, food production on these lands ceases, and the farm families become food consumers instead the food producers. The United Nations Food and Agricultural Organization (FAO, 1998) has reported that a 1 meter rise in sea level will affect 6 million people in Egypt, with more then 10% of agricultural land lost, 13 million in Bangladesh with a decrease in rice production of 16%, and 72 million in China with tens of thousands of hectares of productive land lost.

Farmers may need to contend with changing rainfall patterns. In those areas which become drier, this will put more stress on aquifer systems, pitting agricultural water supply needs against those of other sectors of society. It is necessary to understand that global warming is not the only threat to developed country agriculture. The high agricultural productivity of these countries depends on high inputs of energy which are becoming more costly. The cost of fuel, fertilizers, and water may become prohibitive for farmers and may even drive them out of the business.

Agricultural yields are affected by numerous factors including soil fertility, environmental factors (e.g., solar radiation and humidity), agronomic factors (e.g., plant spacing, row orientation, tillage practices), diseases, etc. General relationships exist which describe the reduction in crop yield with decreasing water (e.g., Allen et al., 1998). When the soil profile becomes dry, the water remaining in the soil becomes increasingly difficult for the plants to extract, thereby resulting in water stress and reduced yields. At the University of Puerto Rico we are studying different varieties of common bean and its response to drought stress (e.g., Ramirez et al., 2006). We hope that the study will lead to bean varieties which are more drought tolerant. This is especially important in the case of the common bean, since so many developing countries consume beans as a staple crop. Increased drought tolerance could help to offset the negative effects of drier conditions in the future.

Crop yields can also be reduced by too much water. When excessive rainfall occurs or the water table rises near the ground surface the root zone can become saturated and effectively suffocate the plants. In some cases it may be necessary to switch whole agricultural management schemes, e.g., instead of growing upland rice we may have to grow more swamp rice, like in East Asia. Ideally, varieties of crops need to be bread to withstand both dry and wet conditions.

Increasing air temperature will have the effect of increasing soil temperature, which may increase the rate of chemical reactions in the soil, especially reactions that are mediated by microbes. This may cause an increase in the release of certain greenhouse gases from the soil (e.g., carbon dioxide, methane and nitrous oxide). There is also the potential loss of organic soils under a scenario in which a region becomes drier. Organic matter in these soils is subject to chemical reduction and volatilization when the soil becomes unsaturated, allowing oxygen to enter the pore spaces.

In the Caribbean it is uncertain whether rainfall will increase, decrease or remain the same. According to the NOAA’s Climate Diagnostic Center, the Caribbean region can expect fewer but more intense tropical storms. The overall annual rainfall may not change, just the timing of it. Long gentle rainfalls are preferable to short intense storms, since the soil has limited infiltration and water holding capacities. If the rainfall rate exceeds the infiltration capacity of the soil, the water will run off the field and be lost. If the soil water holding capacity is exceeded then water will percolate past the root zone and enter the groundwater system. In both cases chemicals used in agricultural production can be carried with the water thereby contaminating surface and groundwater systems. With fewer but more intense tropical storms we can expect more surface and groundwater contamination.

It seems likely that agriculture in every country will be affected by global warming, although not necessarily in a negative way. Areas which are currently dry that will receive more rainfall will benefit. Areas in which the growing season increases in length can take advantage of new opportunities for increased agricultural production.

It is important that policy makers become educated about the possible impacts of global warming. Some changes may occur rapidly but other changes may take several or more decades. This means that we have time to develop strategies and to plan for the cost of needed infrastructure. For example in the case of Puerto Rico, we are blessed with plentiful rainfall in the mountainous areas of the island. Additional reservoirs could be constructed around the island. Other projects could be initiated which enhance aquifer recharge, as opposed to allowing water to runoff to the ocean.

Some entities in the Caribbean region are already working on ways to mitigate the negative impacts of global warming on agriculture. For example, the Caribbean Agricultural and Research Development Institute (CARDI) is calling for an action plan to protect Caribbean food systems. The Caribbean Planning for Adaptation to Global Climate Change (CPACC) Project was initiated by the Organization of American States in partnership with the University of the West Indies. A Joint Institute for Caribbean Climate Studies has been started by an interdisciplinary group of researchers at the University of Puerto Rico. This group is studying everything from climate change detection to trends in extreme weather events, regional scale modeling of atmospheric processes, expected impacts on the hydrologic cycle, and ways to show climate change which has occurred in the recent and distant past.

Some studies have been conducted to evaluate climate change in Puerto Rico and the Caribbean. Ramirez-Beltran et al. (2007) evaluated historical land surface temperatures in Puerto Rico, Dominican Republic, Haiti, Jamaica and Cuba. The data presented indicated increasing trends in the land surface air temperatures in these islands between 1950 and 2006. Percent cloudiness for the Caribbean region was also presented between 1983 and 2006, which indicated a decreasing trend. No trend was evident in sea level rise in the Caribbean as compared to the marked increase in sea level rise globally during the years 1993 to 2006.

Using an isotopic proxy in the coral skeleton, Winter et al. (200) showed that the northeastern Caribbean is 2-3 ^{o}C warmer than during the period between 1700 and 1815. Gonzalez et al. (2005) and Velazquez-Lozada et al. (2006) investigated the so called Urban Heat Island (UHI) effect for San Juan, PR. They showed air temperature 2.5 to 3 ^{o}C higher within the urban area relative to the surrounding non-urban areas. Current work (Gonzalez, E. personal communication) is focusing on the possible negative influence of urbanization on the Luquillo Experimental Rainfall Forest near San Juan. While the UHI effect is due to changes in the land cover and not global warming, it may produce adverse effects include rising air temperatures within the forest and a cloud-base rise, which could lead to drier conditions. This has obvious implications for crops such as coffee, which are grown in mountainous areas of the island.

Historical pan evaporation data were evaluated by Harmsen et al. (2004) to determine if increasing or decreasing trends exist in data from seven University of Puerto Rico (UPR) Agricultural Experiment Stations. Significant decreasing pan evaporation was observed at Lajas and Río Piedras. Significant increasing pan evaporation was observed at Gurabo and Adjuntas. No significant trends were observed at Fortuna, Isabela and Corozal. The observed changes in pan evaporation could not be directly attributed to global climate changes. In the case of Lajas, for example, the significant decrease in pan evaporation over the forty year period may be attributable to land use changes within and near the experimental station. Roderick and Farquhar (2002) and Ohmura and Wild (2002) have reported that on average, pan evaporation rates have been decreasing globally.

As an example of climate change in Puerto Rico and its potential impacts on agriculture, a case study is presented in which rainfall deficits are estimated from downscaled GCM data for three locations in Puerto Rico. Historical mean daily air temperatures are also presented for the three locations.

APPROACH

Temperature and precipitation were statistically downscaled to match historical distributions (1960 to 2000) using the method of Miller et al. (2006a and 2006b) 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, is at a relatively high elevation, the topography is mountainous and is located relatively far from the coast. Mayagüez is humid, receives a large amount of rainfall, 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, is located in a flat valley, and is located about half the distance to the ocean as Adjuntas. 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).

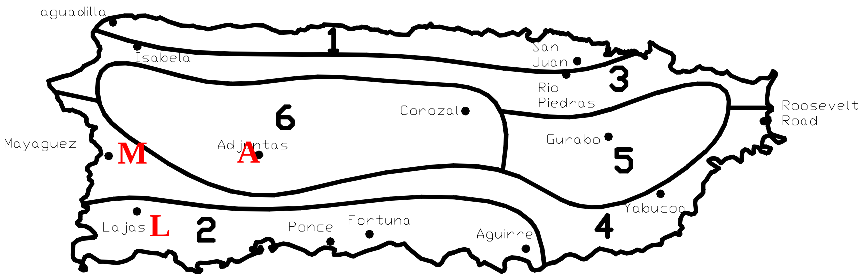

Figure 1. Map of Puerto Rico showing the locations of Adjuntas (A), Mayagüez (M) and Lajas (L) . Numbers indicate National Oceanic and Atmospheric Administration (NOAA) Climatic Divisions. 1, North Coastal; 2 South coastal; 3, Northern Slopes; 4, Southern Slopes; 5, Eastern Interior; and 6; Western Interior.

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)	Tmin (^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

The GCM data were obtained from the Department of Energy (DOE)/National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM). The emission scenarios considered are from the Intergovernmental Panel on Climate Change Special 2001 Report on Emission Scenarios (IPCC SRES) B1 (low) A2 (mid-high) and A1fi (high).

Reference evapotranspiration (ET_o) was estimated using the Penman-Monteith (PM) method (Allen et al., 2005), which depends on the following input parameters: net radiation, soil heat flux, air temperature, actual and saturated vapor pressure, and wind speed. Downscaled minimum, maximum and average air temperatures for the three locations were used in the analysis. Other parameters (net radiation, soil heat flux, dew point temperature and wind speed were estimated using the procedures developed for Puerto Rico by Harmsen et al. (2002). A detailed description of the procedure used in this research can be found in Harmsen et al. (2007).

The rainfall deficit was estimated by subtracting the monthly ET_o from the monthly 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.

RESULTS

Figure 2 shows the average daily air temperatures for the three locations during the period of record. The slopes of the trend lines were 9×10^{-5} ^{o}C/day, 8×10^{-5} ^{o}C/day and 5×10^{-6} ^{o}C/day, 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 ^{o}C. 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. It is of interest also, that Harmsen et al. (2004) reported anomalously low values of pan evaporation from the Lajas Experiment Station, and which may have been caused by land cover changes during the period of record. This being the case, the air temperature data from Lajas should be viewed with caution.

Whatever the caused the Lajas historical air temperature data to respond differently than the other two sites, the temperature increase predicted by the GCM did produce increasing temperature for Lajas during 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. The A1fi scenario produced the largest increases in the VPD and ET_o.

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 decreasing. 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).

Table 2 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. Rainfall deficits presented are 20-year averages; for example, a rainfall deficit value for 2090 is the average of values from 2080 to 2100. 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 3 presents the difference in the rainfall deficit relative to the year 2000.

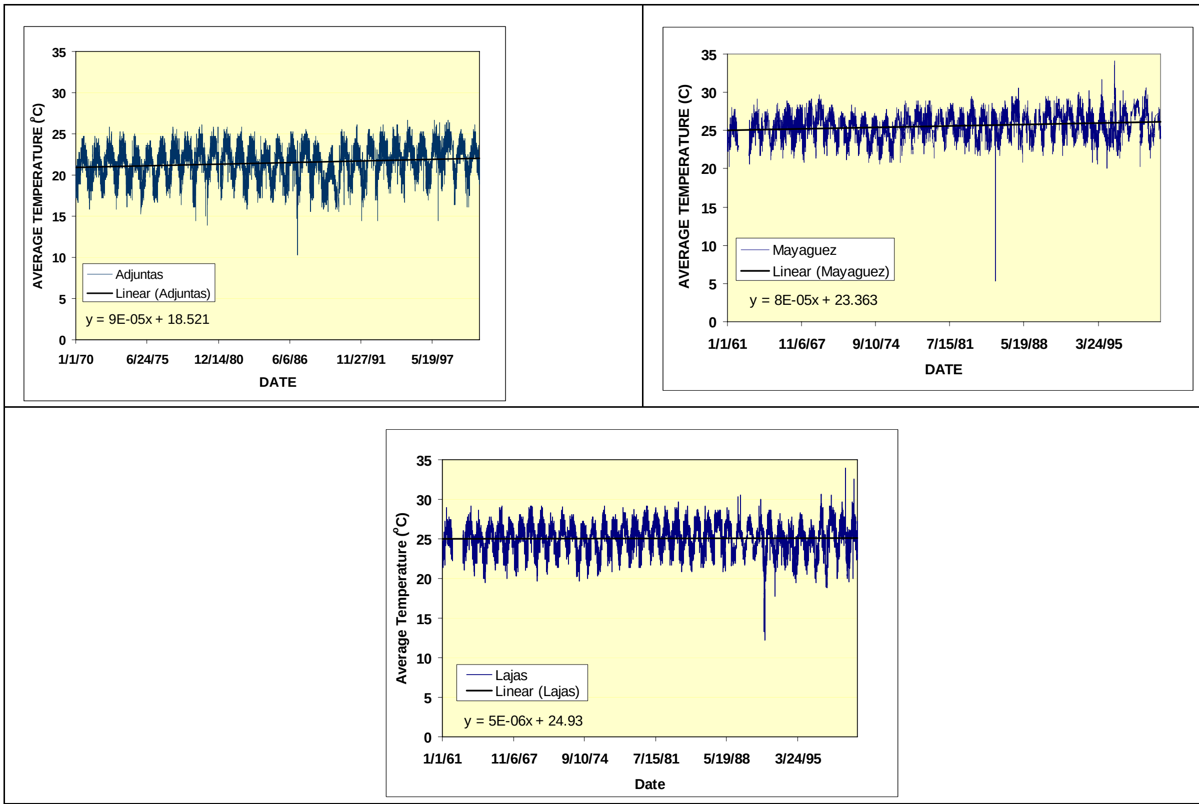

Figure 2. Historic mean air temperatures at Lajas, Adjuntas and Mayagüez, PR. Linear trend lines and associated equations have been included.

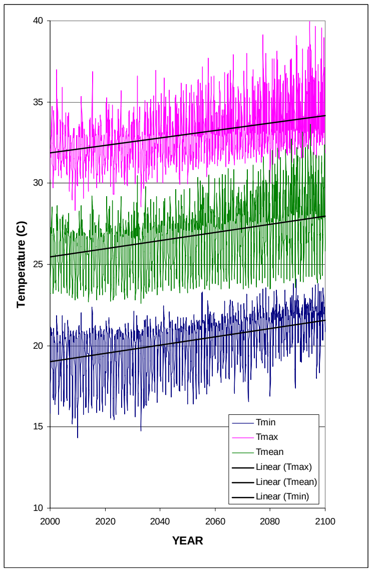

Figure 3. Minimum, mean and maximum air temperature for the A2 scenario at Lajas. Linear regression trend lines are shown.

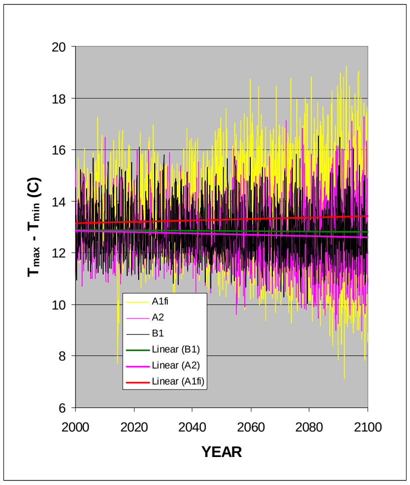

Figure 4. Tmax-Tmin for the A2 scenario at Lajas. Linear regression trend lines are shown.

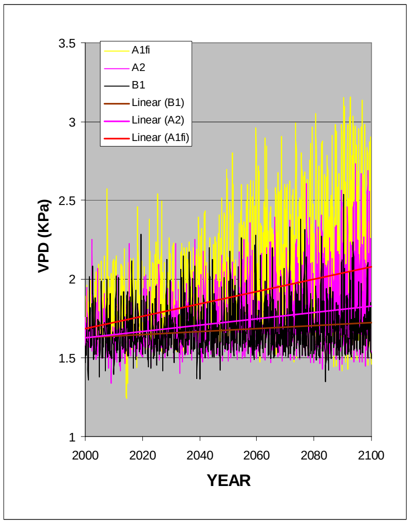

Figure 5. Vapor pressure deficit (VPD) for the A2 scenario at Lajas. Linear regression trend lines are shown.

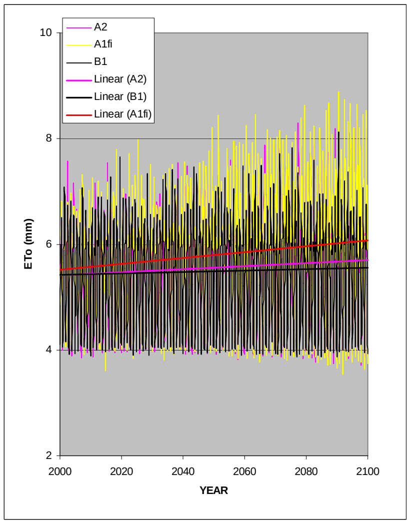

Figure 6. Reference evapotranspiration for the A2 scenario at Lajas. Linear regression trend lines are shown.

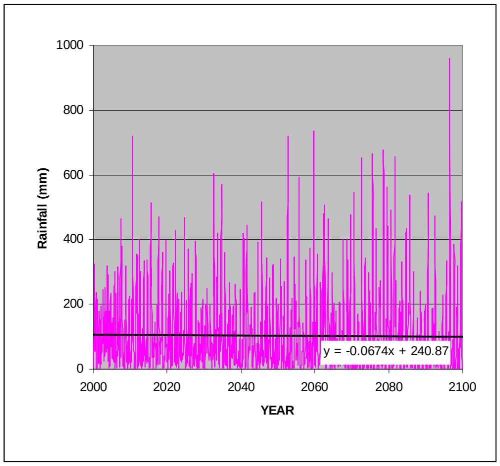

Figure 7. Average monthly rainfall at Lajas for climate change scenario A2.

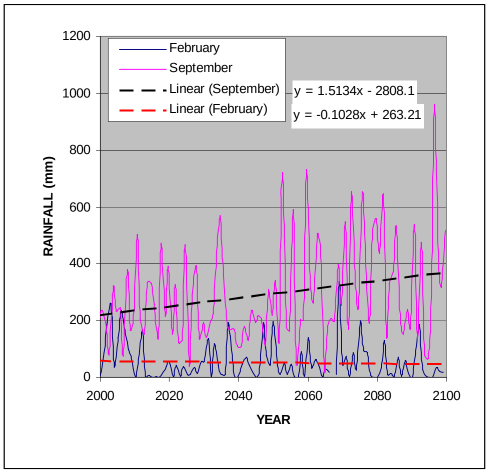

Figure 8. Estimated rainfall at Lajas for climate change scenario A2 for February and September.

Table 2. Estimated September rainfall defict (mm) 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.

		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

Table 3. Difference in rainfall deficit relative to the year 2000 for Adjuntas, Mayaguez and Lajas, PR. Values represent 20 year averages. A negative value indicates a deficit and a positive value indicates an excess relative to crop water requirements.

		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 2 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 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. The reader is referred to Harmsen et al. (2007) for a discussion on the limitations in the results presented.

Conclusion

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. The results also indicate that the wettest month (September) will become significantly wetter. The excess water can possibly be captured in reservoirs to offset the higher irrigation requirements during the drier months.

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