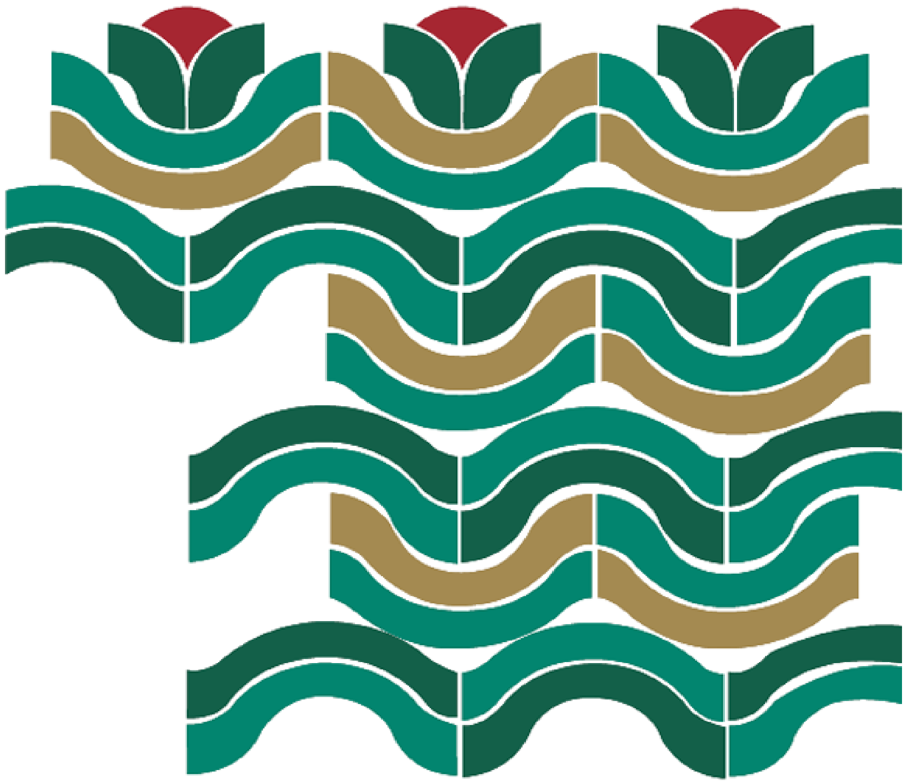
Volume 96, issue 7, July 2009

ISSN 0378-3774
96 (7) 1061–1180 (2009)

ELSEVIER

Agricultural Water Management

an International Journal



Agricultural Water Management 96 (2009) 1085–1095

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Seasonal climate change impacts on evapotranspiration, precipitation deficit and crop yield in Puerto Rico

Eric W. Harmsen [a,*], Norman L. Miller [b], Nicole J. Schlegel [c], J.E. Gonzalez [d]

[a] Dept. of Agricultural and Biosystems Engineering, Univ. of Puerto Rico – Mayagüez Campus, Mayagüez, PR 00681, United States
[b] Climate Science Department, Earth Sciences Division, Berkeley National Laboratory, United States
[c] Earth and Planetary Science Department, University of California, Berkeley, United States
[d] Department of Mechanical Engineering, City College of New York, United States

ARTICLE INFO

Article history:
Received 15 May 2008
Accepted 4 February 2009
Available online 24 March 2009

Keywords:
Climate change
Evapotranspiration
Precipitation
Precipitation deficit
Crop yield
Downscaling
GCM

ABSTRACT

The purpose of this study was to estimate precipitation (*P*), reference evapotranspiration (ET_o), precipitation deficit ($PD = P - ET_o$) and relative crop yield reduction (YR) for a generic crop under climate change conditions for three locations in Puerto Rico: Adjuntas, Mayagüez, and Lajas. Reference evapotranspiration was estimated by the Penman–Monteith method. Precipitation 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 reduction was estimated from a 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 average September precipitation excess (i.e., $PD > 0$) increased for all scenarios and locations from 121 to 321 mm between 2000 and 2090. Conversely, the 20-year average February precipitation deficit (i.e., $PD < 0$) changed from −27 to −77 mm between 2000 and 2090. The results suggest that additional water could be saved during the wet months to offset increased irrigation requirements during the dry months. The 20-year average relative crop yield reduction for all scenarios decreased on average from 12% to 6% between 2000 and 2090 during September, but increased on average from 51% to 64% during February. Information related to the components of the hydrologic water budget (i.e., actual evapotranspiration, surface runoff, aquifer recharge and soil moisture storage) is also presented. This study provides important information that may be useful for future water resource planning in Puerto Rico.

1. 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 50–100 years (IPCC, 2001, 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, increase in streamflow seasonal variability, with higher flows during the wet season and lower flows during the dry season; 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 on lake levels used for freshwater supply. Groundwater use will likely be increased 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 precipitation deficit (or precipitation excess) for the 21st Century at three locations on the Island of Puerto Rico. In this study we specifically estimated future values of reference evapotranspiration and precipitation deficit, based on data from a general circulation model (GCM). This study is the first of its kind in Puerto Rico and provides potentially important information for water resource planners.

* Corresponding author.
E-mail addresses: EHarmsen@uprm.com (E.W. Harmsen), NLMiller@lbl.gov (N.L. Miller), Schlegel@EPS.Berkeley.edu (N.J. Schlegel), gonzalez@me.ccny.cuny.edu (J.E. Gonzalez).

0378-3774/$ – see front matter
doi:10.1016/j.agwat.2009.02.006

Numerous other studies have been conducted using general circulation model (GCM) 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 precipitation 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's 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 streamflow in California based on downscaled data from 10 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, the mean 30-year (1961–1990) climatological peak streamflow shifted 15–25 days earlier under the climate projection scenario, 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 precipitation deficit (as defined by De Pauw, 2002), and can potentially be applied at other locations throughout the world. Other components of the hydrologic water balance and relative crop yield reduction are also evaluated.

2. Approach

The objective of this study was to analyze future precipitation, reference evapotranspiration, precipitation deficit and relative crop yield reduction at three locations in western PR. Although the temperature and precipitation 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. This assumption affects the values of the soil field capacity and wilting point. Average values of evapotranspiration crop coefficients and yield response factors were used for the generic crop, and average monthly runoff coefficients were used based on values derived from the two principal watersheds in the study area (Añasco and Guanajibo Watersheds).

Near-surface air temperature and precipitation were statistically downscaled to the three sites matching historical distributions (1960–2000) using the method of Miller et al. (2006, 2008). Historical near surface air temperatures were obtained at 2-m height above the ground surface. The site locations were selected because they represent a relatively wide range of conditions within the region (Fig. 1, Table 1). Adjuntas is humid, receives a large amount of precipitation, 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 precipitation, is located immediately adjacent to the Mayagüez Bay, the elevation

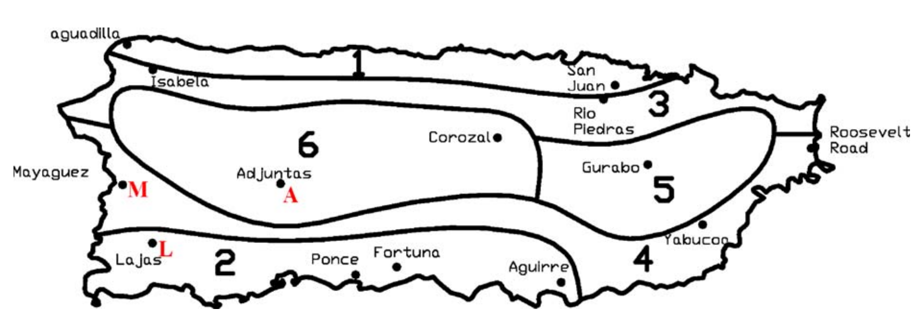


Fig. 1. Map of Puerto Rico showing the locations of Adjuntas (A), Mayagüez (M) and Lajas (L). Numbers indicate National Oceanic and Atmospheric Administration (NOAA) Climatic Divisions: 1, North Coastal; 2, South coastal; 3, Northern Slopes; 4, Southern Slopes; 5, Eastern Interior; and 6, Western Interior.

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

Location	Latitude (decimal degree)	Elevation (m)	Annual precipitation (mm)	T_{mean} (°C)	T_{min} (°C)	T_{max} (°C)	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	27	1143	25.3	18.8	31.7	2	10

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 precipitation, is located in a flat valley, and is about half the distance to the ocean as Adjuntas. The Lajas Valley, designated by the Commonwealth of Puerto Rico as an Agricultural Reserve, 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 Lajas 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) (Nakićenović et al., 2000).

Reference evapotranspiration (ET_o) was estimated using the Penman–Monteith (PM) method (Allen et al., 1998):

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

where ET_o is reference evapotranspiration [mm day^{-1}], Δ is slope of the vapor pressure curve, R_n is net radiation at the surface [W m^{-2}], G is soil heat flux density [W m^{-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]. Eq. (1) applies specifically to a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s 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 [°C]. Saturated and actual vapor pressures were estimated using Eq. (2) with the mean monthly air temperature (T_{mean}) [°C] and mean monthly dew point temperature (T_{dew}) [°C], respectively.

In this study T_{dew} was assumed to be equal to T_{min} for the Adjuntas and Mayaguez sites, a valid assumption for reference conditions or regions characterized as humid and subhumid (Allen, 1996). For non-reference sites or arid and semiarid climates, the T_{dew} can be estimated from the following relation (Allen et al., 1998): $T_{dew} = T_{min} + K_o$, where K_o is a temperature correction factor ($K_o < 0$). Lajas is located in the National Oceanic and Atmospheric Administration's (NOAA) Climate Division 2 for PR (Fig. 1), which is classified as semiarid. Harmsen et al. (2002) determined a value of $K_o = -2.9$ °C for this climate division, which was used in this study for the Lajas site (Table 2).

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

NOAA Climatic Division[a]	2	4 and 6
K_o (°C)	−2.9	0

[a] See Fig. 1 for Climate Divisions. Climate Divisions 1, 3, and 5, where not relevant to this study.

The FAO recommends that wind speed be estimated from nearby weather stations, or as a preliminary first approximation, the worldwide average of 2 m/s 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 (Fig. 1), 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 and 0.58 m above the ground for the airports and experiment stations, respectively. The experiment station wind speed sensors were the standard agricultural cup-type anemometer which measures the daily distance in miles. Information about the airport wind speed sensors was not available. Harmsen et al. (2002) obtained the wind speed data from the International Station Meteorological Climate Summary (National Climate Data Center, 1992). Measured wind speeds were adjusted to the wind speed at 2 m above the ground using the following equation (Allen et al., 2005): $u_2 = (4.87u_z)/[\ln(67.8z - 5.42)]$, where u_z is the wind speed at height z above the ground.

Solar radiation (R_s) was estimated using the Hargreaves' radiation formula (Hargreaves and Samani, 1985):

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

where k_{R_s} is an adjustment factor equal to 0.16 for interior locations (Adjuntas) and 0.19 for coastal locations (Mayagüez and

Table 3
Average daily wind speeds 2 m above the ground by month and NOAA Climatic Division[a] within Puerto Rico (from Harmsen et al., 2002).

NOAA Climatic Division[a]	Average daily wind speeds (m/s)[b]											
	January	February	March	April	May	June	July	August	September	October	November	December
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

[a] See Fig. 1 for NOAA Climate Divisions.
[b] 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.

Lajas); T_{max} and T_{min} are the mean monthly maximum and minimum air temperature [°C], respectively; and R_a is the extraterrestrial radiation [W m^{-2}]. The various formulas used to calculate R_a (Eq. (2)), R_n and G (Eq. (1)) are presented by Allen et al. (2005).

The precipitation deficit (PD) was estimated by subtracting the monthly cumulative ET_o from the monthly cumulative precipitation (P). This approach has been used previously by De Pauw (2002) in an agroecological study of the Arabian Peninsula. 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 PD 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):

$$YR = K_y \cdot (1 - K_s) \tag{4}$$

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:

$$ET_{cadj} = K_s ET_c \tag{5}$$

and

$$ET_c = K_c ET_o \tag{6}$$

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

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 days, 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 average value of 1.04. Considering the evapotranspiration crop coefficient values for just these 24 crops, the average K_c rounds to 1.1. However, crops are within the "mid" growth stage only a portion of the time, and during other periods the K_c would be lower; therefore a lower value of 1.0 is justified.

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 study 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 K_s and 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:

$$S_{i+1} = P_i - ET_{cadj,i} - RO_i - Rech_i + S_i \tag{7}$$

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], P_i is precipitation 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 was determined based on the following simple monthly runoff equation: RO = CP, where P is monthly precipitation and C is monthly runoff coefficient. The monthly values of C were derived from the ratio of runoff (streamflow) and precipitation data from the two principal watersheds in the study area (Añasco and the Guanajibo watersheds). The twelve monthly C values (January through December) were 0.40, 0.29, 0.30, 0.31, 0.51, 0.38, 0.30, 0.29 0.52, 0.52, 0.60, and 0.64, respectively. Historical average stream-

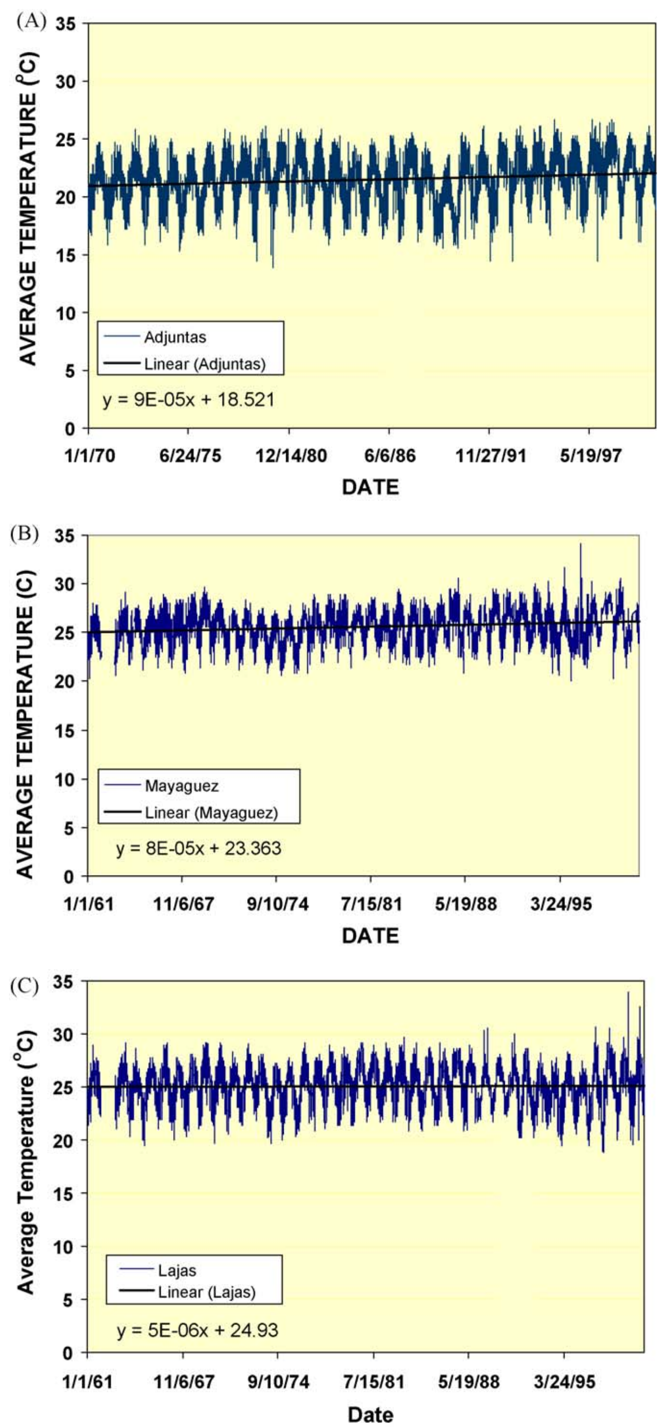


Fig. 2. Historic daily mean air temperatures at Adjuntas (A), Mayaguez (B) and Lajas (C), PR. Linear trend lines and associated equations have been included.

flow was obtained from the USGS for Water Year 2002 (USGS, 2004). Average monthly watershed precipitation was derived from interpolated rain gauge data obtained from the USGS, covering the period between 1990 and 2000.

Aquifer recharge was estimated from the follow relations:

$$S_{i+1} = P_i - ET_{cadj,i} - RO_i + S_i \tag{8a}$$

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

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

3. Results and discussion

Fig. 2 shows the average daily air temperatures for the three locations derived from historical records. The slopes of the trend lines were 9×10^{-5} °C/day, 8×10^{-5} °C/day and 5×10^{-6} °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 °C. From 1961 to 2000 the average temperature for Mayagüez increased by 1.17 °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), who 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 Fig. 2A and B, for Adjuntas and Mayagüez, respectively. Similar increasing air temperature trends have been observed in the Dominican Republic, Haiti, Jamaica and Cuba (Ramirez-Beltran et al., 2007).

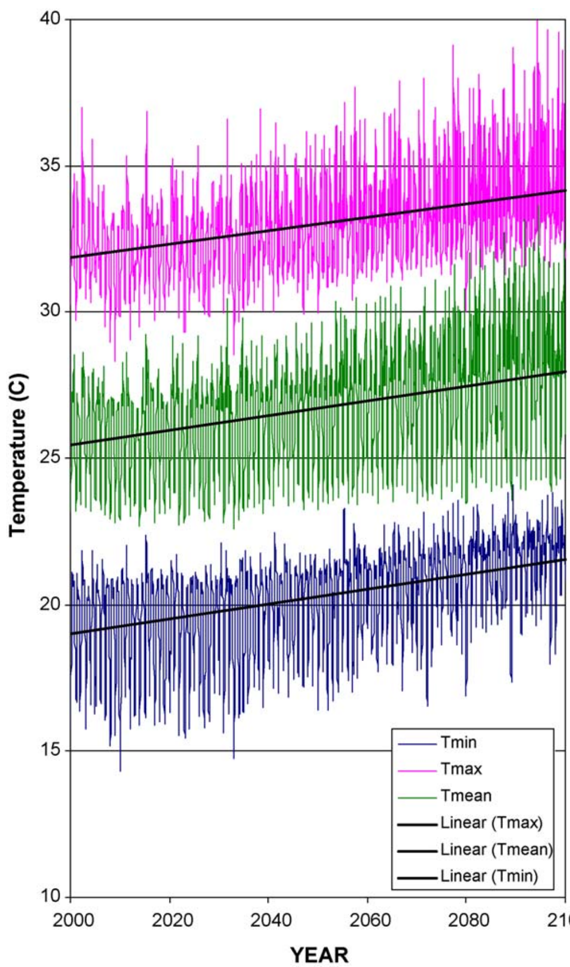


Fig. 3. Monthly minimum, mean and maximum air temperature for the A2 scenario at Lajas. Linear regression trend lines are shown.

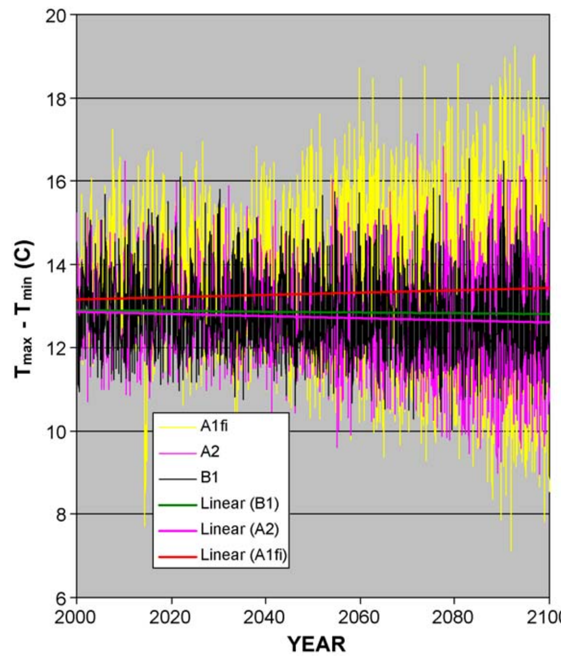


Fig. 4. Mean monthly $T_{max} - T_{min}$ for the A2 scenario at Lajas. Linear regression trend lines are shown.

Whatever caused the Lajas historical air temperature data to respond differently than the other two sites (possibly moved instrument, change of instruments, station proximity to paved road, and/or land use change), the temperature increase predicted by the statistical downscaling procedure preserved the increase in temperature for Lajas for the next 100 years, as shown in Fig. 3 (Scenario A2). Fig. 3 also shows predicted minimum and maximum air temperatures. Figs. 4–6 show the air temperature difference ($T_{max} - T_{min}$), 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 (Fig. 3). Interestingly, the variance in the minimum temperature can be seen to decrease with time.

For the wettest (September) and driest (February) months, respectively, Fig. 7 shows increasing precipitation during September (i.e., positive slope in the linear regression trend line) and a slight decrease in precipitation during February (i.e., negative slope). Fig. 8 shows the predicted monthly average precipitation for each month of the year for the years 2000 and 2090 for the three climate change scenarios for the Lajas location. The predicted precipitation values are based on 20-year averages, for example, the average monthly precipitation for 2000 was based on the average of the monthly precipitation from 1990 through 2010. Note that the 2000 precipitation results vary slightly between scenarios. This is due to the influence of the climate change scenario during the period between 2000 and 2010. Slight variations in the 2000 results for other predicted variables between scenarios will also be observed. Fig. 8 indicates that the B1 scenario average monthly precipitation does not change

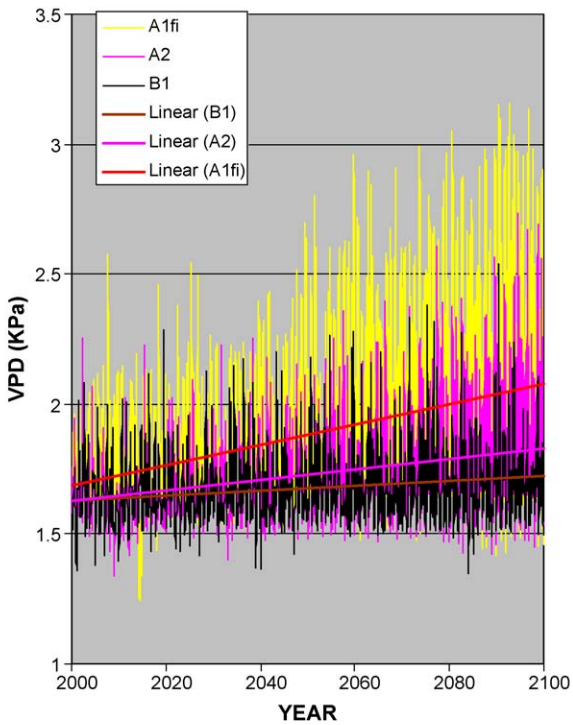


Fig. 5. Mean monthly vapor pressure deficit (VPD) for the A2 scenario at Lajas. Linear regression trend lines are shown.

significantly between 2000 and 2090 for the months of November through July. However, for the A1fi scenario, the 2090 monthly precipitation dropped markedly (−50 mm on average) during these months, relative to 2000. In all scenarios the 2090 rainfall increased significantly during September (150 mm on average),

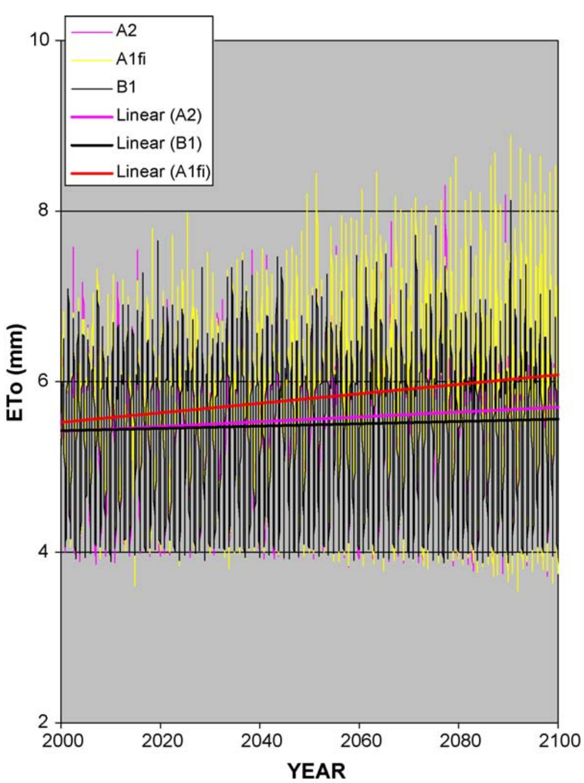


Fig. 6. Mean monthly reference evapotranspiration for the A2 scenario at Lajas. Linear regression trend lines are shown.

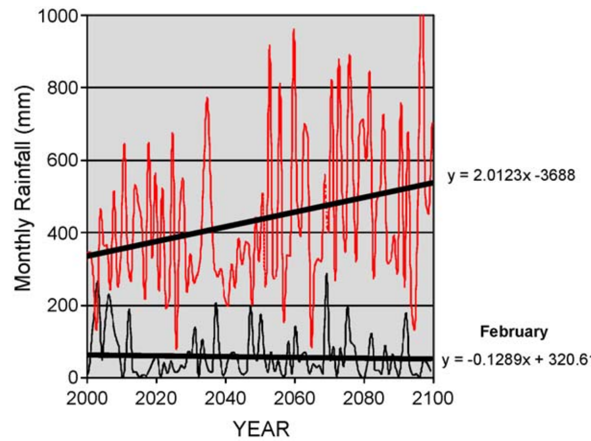


Fig. 7. Estimated precipitation at Lajas for climate change scenario A2 for February and September.

relative to 2000. 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, 2007a,b; Scatena, 1998).

Table 4A presents PD 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 all of the values for February are negative indicating a deficit in terms of crop water requirements and all but one value for September are positive indicating an excess in terms of crop water requirements. Table 4B presents the difference in the PD 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 deficit occurred for the A2 scenario (−130.8 mm), not the A1fi scenario, which was expected since the A1fi scenario produces higher air temperatures. However the deficit associated with the A1fi scenario for Adjuntas for 2090 was essentially identical (−130.5 mm). The higher (or equal) value of PD for the A2 scenario relative to the A1fi scenario was likely caused by the fact that the A2 scenario produced slightly lower rainfall (35.89 mm) as compared to the rainfall (42.52 mm) produced under the A1fi scenerio.

Increases in precipitation excess (i.e., $PD = P - ET_o > 0$) occurred in September at all locations for all scenarios. The average estimated precipitation excess increased in September (the wettest month) to 321 mm for the year 2090 relative to an average precipitation excess of 121 mm for 2000. The average PD (i.e., $P - ET_o < 0$) in February increased to −77 mm for the year 2090 relative to an average PD of −27 mm for 2000. Fig. 9 presents the graphical distribution of PD for each month of the year for 2000 and 2090 for the Lajas location. Of particular note is that for the B1 scenario, in which the PD did not change significantly, except during the period around September when the 2090 precipitation *excess* exceeded the 2000 precipitation *excess* by greater than 100 mm. On the other hand, for the A1fi scenario, the PD increased during all months between November and August. For June, the PD exceeded 200 mm for 2090, as compared to an estimated 140 mm PD for 2000. The magnitude of the predicted deficit under the A1fi scenario has serious potential implications on irrigation water management in the future.

Tables 5a and 5b, respectively, present the February and September 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 predicted components of the hydrologic water balance are based on 20-year averages. From Table 5a (February), the following observa-

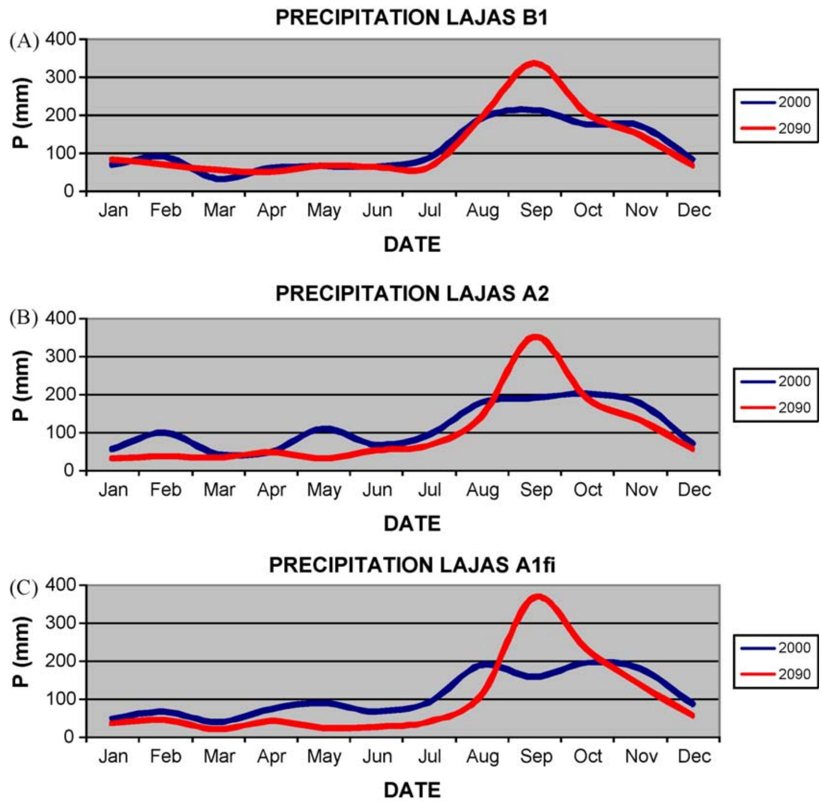


Fig. 8. Precipitation (*P*) for Lajas for scenario B1 (A), A2 (B) and A1fi (C) by month for 2000 and 2090 for Lajas, PR.

Table 4

Estimated September precipitation deficit (A) and change in precipitation 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 precipitation deficit and a positive value indicates a precipitation excess relative to crop water requirements.

Scenario	Year	Precipitation deficit (mm)					
		February			September		
		Adjuntas	Mayaguez	Lajas	Adjuntas	Mayaguez	Lajas
A							
A1fi	2000	−6.2	−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	−42.3	222.2	144.0	17.6
	2050	−28.6	−77.2	−103.0	339.3	241.4	84.0
	2090	−41.2	−113.9	−130.8	467.1	344.8	162.7
B1	2000	14.4	−38.2	−51.5	249.0	168.1	40.6
	2050	−18.9	−72.5	−92.1	301.9	206.5	74.4
	2090	−3.7	−72.1	−80.1	437.2	305.3	159.0
Scenario	Year	Change in precipitation deficit relative to 2000 (mm)					
		February			September		
		Adjuntas	Mayaguez	Lajas	Adjuntas	Mayaguez	Lajas
B							
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	−55.0	−60.7	117.1	97.5	66.4
	2090	−78.1	−91.7	−88.5	244.9	200.9	145.1
B1	2000	0.0	0.0	0.0	0.0	0.0	0.0
	2050	−33.2	−34.3	−40.6	52.8	38.4	33.9
	2090	−18.1	−33.9	−28.5	188.1	137.2	118.4

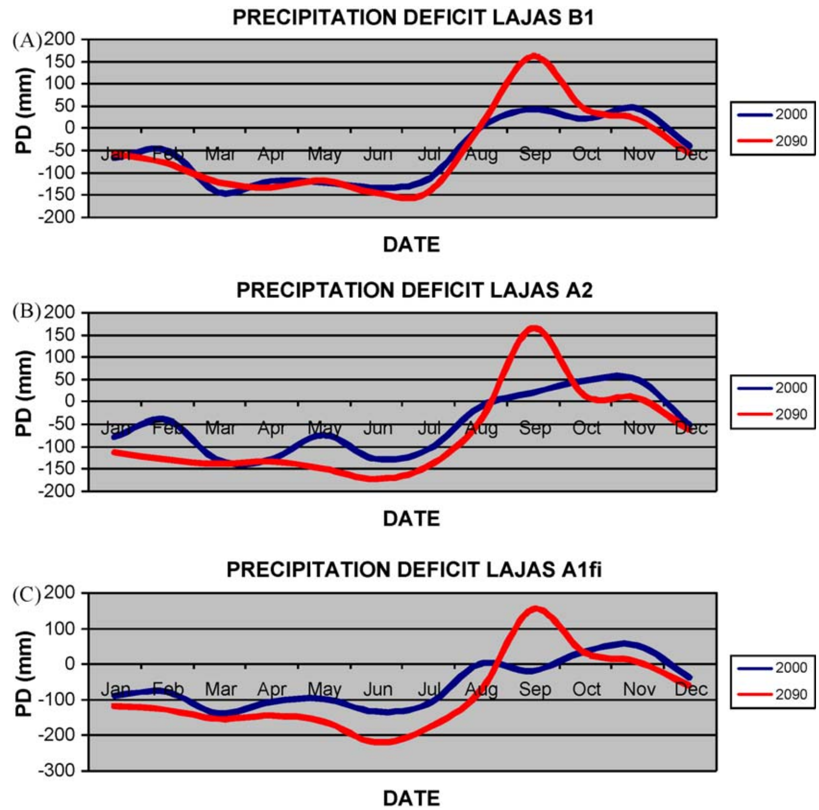


Fig. 9. Precipitation deficit (PD) for Lajas for scenario B1 (A), A2 (B) and A1fi (C) by month for 2000 and 2090 for Lajas, PR. A negative value indicates a deficit and a positive value indicates an excess precipitation with respect to crop water requirements.

tions can be made: in general, ET_{cadj}, surface runoff and soil moisture content decreased with time. An exception to this is scenario B1 for Adjuntas, in which the ET_{cadj} more or less remained the same. Aquifer recharge in February generally decreased, and in all cases dropped to zero by 2090, except for scenario B1 at Adjuntas. It is noted that the current condition (2000) aquifer recharge in most cases is negligible. From Table 5b (September), the following observations can be made: precipitation, surface

Table 5a
February 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.

Site	Scenario	Year	P (mm)	ET_o (mm)	ET_{cadj} (mm)	RO (mm)	Rech (mm)	MC (%)	YR (%)
Adjuntas	A1FI	2000	97	103	67	28	8	32	35
		2050	76	102	54	22	0	30	46
		2090	60	96	45	17	0	28	53
	A2	2000	139	102	75	40	14	34	26
		2050	72	100	53	21	2	29	47
		2090	56	97	52	17	0	29	46
	B1	2000	116	102	69	33	23	32	32
		2050	83	102	67	28	0	31	34
		2090	98	101	72	27	6	33	28
Lajas	A1FI	2000	66	146	43	19	0	26	69
		2050	54	159	38	16	0	25	76
		2090	43	173	33	12	0	24	81
	A2	2000	98	140	65	27	0	28	53
		2050	48	151	37	14	0	25	75
		2090	36	167	35	10	0	25	79
	B1	2000	88	140	51	25	8	28	62
		2050	54	146	42	15	0	25	70
		2090	68	148	42	19	0	26	70
Mayaguez	A1FI	2000	72	124	49	20	0	27	60
		2050	57	127	42	16	0	26	67
		2090	45	129	31	13	0	25	76
	A2	2000	72	124	49	30	0	27	60
		2050	53	130	39	15	0	26	70
		2090	41	136	33	12	0	25	76
	B1	2000	87	126	50	25	5	28	59
		2050	60	133	44	17	0	26	67
		2090	72	144	47	21	0	26	67

P is precipitation; ET_o is reference evapotranspiration; ET_{cadj} is the actual evapotranspiration adjusted for soil moisture availability; RO is surface runoff; Rech is aquifer recharge; SM is soil moisture; and YR is relative crop yield reduction.

Table 5b
September 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.

Site	Scenario	Year	*P* (mm)	ET_o (mm)	ET_{cadj} (mm)	RO (mm)	Rech (mm)	MC (%)	YR (%)
Adjuntas	A1FI	2000	297	128	125	153	56	41	3
		2050	376	125	119	194	88	41	5
		2090	599	118	118	309	224	43	0
	A2	2000	348	126	125	180	75	42	1
		2050	462	123	123	239	142	43	0
		2090	583	116	116	309	219	44	0
	B1	2000	374	125	125	188	94	42	0
		2050	426	124	121	211	136	41	2
		2090	560	123	123	270	219	43	0
Lajas	A1FI	2000	157	178	110	81	8	31	37
		2050	210	200	130	108	8	32	35
		2090	366	216	171	189	74	36	20
	A2	2000	189	171	136	105	6	34	20
		2050	262	178	146	119	35	35	18
		2090	351	188	161	182	59	38	14
	B1	2000	211	171	128	109	15	34	25
		2050	250	175	131	129	33	35	25
		2090	335	176	145	173	74	37	17
Mayaguez	A1FI	2000	254	154	143	131	32	39	7
		2050	323	145	133	167	65	40	9
		2090	523	146	145	270	171	42	1
	A2	2000	254	154	143	155	32	39	7
		2050	401	159	157	207	94	42	2
		2090	509	164	164	263	163	42	0
	B1	2000	323	155	145	167	61	40	6
		2050	370	163	147	191	94	40	9
		2090	488	183	177	252	153	40	3

P is precipitation; ET_o is reference evapotranspiration; ET_{cadj} is the actual evapotranspiration adjusted for soil moisture availability; RO is surface runoff; Rech is aquifer recharge; SM is soil moisture; and YR is relative crop yield reduction.

runoff and aquifer recharge increased with time. Table 5b indicates that surface runoff is predicted to increase during September for all scenarios and locations. This is a positive result with respect to irrigation water supply; however, surface water may suffer due to increased soil erosion and may lead to accelerated filling of reservoirs by sedimentation. There was no clear trend with ET_{cadj}; Adjuntas ET_{cadj} decreased, while Lajas and Mayaguez increased. Soil moisture content in general increased, except for the B1 scenario for Mayaguez, in which the moisture content remained constant at 40%. In February the ET_{cadj} was markedly lower than the ET_o (Table 5a), whereas for September the ET_{cadj} was similar in magnitude to ET_o.

Little research has been done on the impacts of climate change on aquifer recharge (IPCC, 2007b). However, for the three scenarios considered in this study, aquifer recharge increased at all locations by 108 mm (overall average) between 2000 and 2090 in September, the season when the majority of the island's aquifer recharge occurs. The February overall average aquifer recharge decreased by only by 5 mm. Since the drier months do not contribute significantly to aquifer recharge, a large increase during the wet season will likely produce a net increase in the annual aquifer recharge. 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 rise, provided that groundwater use is not over-subscribed. Saltwater intrusion has already been observed at coastal locations in Puerto Rico (e.g., Rodríguez-Martínez et al., 2005).

The relative crop yield reduction (YR) increased in February (Table 5a), and decreased or remained essentially unchanged in September (Table 5b). A note is in order relative to the interpretation of YR. Typically, YR is used to estimate the seasonal crop yield reduction. In this study, we are applying the index on a monthly basis. Crop seasons in Puerto Rico for typical agricultural crops are 3–4 months in duration, or longer. Therefore, an estimated YR value for a single month should not be taken as a seasonal relative crop yield reduction. Rather, the monthly YR should only be viewed as a contributor toward the overall seasonal yield reduction.

Fig. 10 shows the average monthly variation in the relative crop yield reduction for Lajas for 2000 and 2090 for the three climate change scenarios. 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 (Year 2000) period in Fig. 10 (A, B, C). Under the B1 scenario for Lajas (Fig. 10A), the relative crop yield reduction did not change significantly in the future. However, under the A1fi scenario (Fig. 10C), the relative crop yield reduction increased significantly in the future during the May/June period (greater than 20%). The relative crop yield reduction decreased for all scenarios during September owing to higher soil moisture conditions.

4. 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. (2007) 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).

Several simplifying assumptions were made with respect to parameters used in the analysis, which may also contribute to

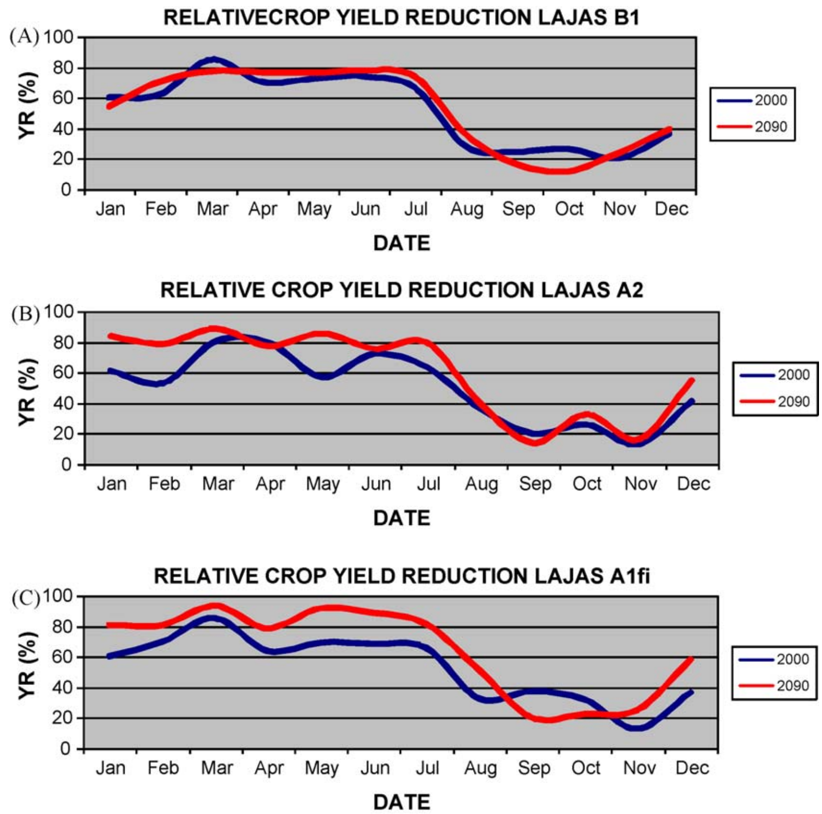


Fig. 10. Relative crop yield reduction (YR) for Lajas for scenario B1 (A), A2 (B) and A1fi (C) by month for 2000 and 2090 for Lajas, PR.

uncertainty in the results of this study. However, it is quite possible that the uncertainties in the assumptions made relative to the parameters are less than the uncertainties associated with the future climate predictions, and therefore, a more precise parameterization may be unwarranted.

5. Conclusions

The purpose of this study was to estimate reference evapotranspiration, precipitation deficit and relative crop yield reduction for a generic crop under climate change conditions for three locations in western Puerto Rico: Adjuntas, Mayagüez, and Lajas. Precipitation and temperature data from the DOE/NCAR PCM global circulation model was statistically downscaled to the three study locations. The 100-year (2000–2100) climate change/hydrologic analysis focused on the driest and wettest months of the year (i.e., February and September, respectively). 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. This has important implications on agricultural water management. With increasing precipitation deficits during the dry months, the agricultural sector's demand for water will increase, which may lead to conflicts in water use.

The analysis revealed that lower soil moisture and increases in the relative crop yield reduction were associated with increasing precipitation deficits during the dry season. Relative crop yield reduction decreased during September, and was associated with increasing precipitation excess. Runoff and aquifer recharge can be expected to increase in the future during the wet season. The additional surface runoff can possibly be captured in newly constructed reservoirs to offset the higher irrigation requirements during the drier months, however, increased surface runoff may be associated with increased soil erosion and degradation of reservoirs. Increased aquifer recharge during the wet season will help offset potential increased demand for water and may increase groundwater water levels in coastal areas, which will help to counter the growing threat of saltwater intrusion in Puerto Rico's coastal aquifers.

Acknowledgements

We would like to thank the NASA-EPSCoR, NASA-IDEAS, NSF-CASA, USDA-TSTAR (100) and USDA HATCH (H402) projects for their financial support. We would also like to thank Katharine Hayhoe for providing us with the simulated PCM scenario output data that was used in this analysis.

References

Allen, R.G., 1996. Assessing integrity of weather data for reference evapotranspiration estimation. ASCE J. Irr. Drainage Eng. 122 (March/April (2)), 97–106.
Allen, R.G., Walter, I.A., Elliott, R., Howell, R., Itenfisu, D., Jensen, M., Snyder, R.L., 2005. The ASCE Standardized Reference Evapotranspiration Equation. Environmental and Water Resources Institute of the American Society of Civil Engineers, 57 pp.
Allen, R.G., Pereira, L.S., Dirk Raes, Smith, M., 1998. Crop Evapotranspiration Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome.
Beasley, D.B., Huggins, L.F., Monke, E.J., 1980. ANSWERS: a model for watershed planning. Trans. ASAE 23 (4), 938–944.
Bouraoui, F., Vachaud, G., Haverkamp, B., 1997. A distributed physical approach for surface subsurface water transport modeling in agricultural watersheds. J. Hydrol.
Brekke, L.D., Miller, N.L., Bashford, K.E., Quinn, N.W.T., Dracup, J.A., 2004. Climate change impacts uncertainty for water resources in the San Joaquin River Basin, California. J. Am. Water Resour. Assoc. (February), 149–164.
Charles, S.P., Bates, B.C., Whetton, P.H., Hughes, J.P., 1999. Validation of downscaling models for changed climate conditions: case study of southwestern Australia. Clim. Res. 12, 1–14.
De Pauw, E., 2002. An Agroecological Exploration of the Arabian Peninsula. ICARDA, Aleppo, Syria, 77 pp.
Dettinger, M.D., Cayan, D.C., Meyer, M.K., Jeton, A.E., 2004. Simulated hydrologic responses to climatic change variations and change in the Merced, Carson, and American River Basin, California 1900–2099. Clim. Change 62, 283–317.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. J. Appl. Eng. Agric. 1 (2), 96–99.

Harmsen, E.W., Goyal, M.R., Torres Justiniano, S., 2002. Estimating evapotranspiration in Puerto Rico. J. Agric. Univ. P.R. 86 (1–2), 35–54.

IPCC, 2001. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Climate Change 2001: 'The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change'Cambridge University Press, 881 pp.

IPCC, 2007a. Climate Change 2007: The Physical Science Basis – Summary for Policy Makers. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Released February, 2007, 21 pp.

IPCC, 2007b. Fourth Assessment Report, Working Group II Report, Impacts, Adaptation and Vulnerability, Chapter 3 Freshwater resources and their management, pp. 174–210.

Keller, J., Bliesner, R., 1990. Sprinkler and Trickle Irrigation. Van Nostrand Reinhold Publisher.

Maurer, E.P., Duffy, P.B., 2005. Uncertainty in projections of streamflow changes due to climate change in California. Geophys. Res. Lett. 32, 1–5 LO3704.

Mearns, L.O., Giorgi, F., Whetton, P., Pabon, D., Hulme, M., Lal, M., 2003. Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments. The Intergovernmental Panel on Climate Change Data Distribution Center. Final Version, 10/30/03.

Miller, N.L., Bashford, K.E., Strem, E., 2003. Potential impacts of climate change on California hydrology. J. Am. Water Resour. Assoc. 771–784.

Miller, N.L., Jin, J., Hayhoe, K., 2006. Projected extreme heat and energy demand under future climate scenarios. In: Proceedings of the Caribbean Climate Symposium, University of Puerto Rico – Mayagüez Campus, April, pp. 24–25.

Miller, N.L., Hayhoe, K., Jin, J., Auffhammer, M., 2008. Climate, extreme heat, and electricity demand in California. J. Appl. Meteor. Climatol. 47, 1834–1844.

Molina-Rivera, W., 2005. USGS, Estimated Water Use in Puerto Rico, 2000. USGS. Open-File Report 2005-1201.

Nakićenović, N., Davidson, O., Davis, G., Grübler, A., Kram, T., La Rovere, E.L., Metz, B., Morita, T., Pepper, W., Pitcher, H., Sankovski, A., Shukla, P., Swart, R., Watson, R., Dadi, Z., 2000. Intergovernmental Panel on Climate Change Special Report on Emission Scenarios. Cambridge University Press. National Climate Data Center, 1992. International Station Meteorological Climate Summary (ISMCS), Version 2.

National Climate Data Center, 1992. International Station Meteorological Climate Summary (ISMCS), Version 2.

Pan, A., Takle, E., Horton, R., Segal, M., 2002. Warm-seasonal soil moisture prediction using a coupled regional climate model. In: Proceedings of the 16th Conference on Hydrology, Orlando, Florida, January 13–18.

Peterson, T.C., Taylor, M.A., Demeritte, R., Duncombe, D.L., Burton, S., Thompson, F., Porter, A., Mejia, M., Elba, V., Semexant Fils Rony, Klein Tank, A., Albert, M., Robert, W., Antonio, J., Willis, M., Lisa, A., Gleason, B., 2002. Recent changes in climate extremes in the caribbean region. Journal of Geophysical Research 107 (D21), 16-1–16-9.

Pielke Sr., R.A., Adegoke, J.O., Chase, T.N., Marshall, C.H., Matsui, T., Niyogi, D., 2007. A new paradigm for assessing the role of agriculture in climate system and in climate change. Agric. Forest Meteorol. 142 (2–4), 234–254.

Pulwarty, R.S., 2006. Climate Change in the Caribbean: Water, Agriculture, Forestry Mainstreaming Adaptation to Climate Change (MACC). Issue Paper (DRAFT). University of Colorado and NOAA/Climate Diagnostics Center Boulder CO 80305. http://www.oas.org/macc/Present/CCH20AgFor.ppt.

Ramirez-Beltran, N.D., Julia, O., Gonzalez, J.E. S, 2007. Detection of global and Caribbean climate changes. In: 19th Conference on Climate Variability and Change at the 87th American Meteorological Society Annual Meeting, San Antonio TX, January 14–19.

Rodríguez-Martínez, J., Santiago-Rivera, L., Rodríguez, J.M., Gómez-Gómez, F., 2005. Surface-Water, Water-Quality, and Ground-Water Assessment of the Municipio of Ponce, Puerto Rico, 2002–2004. Scientific Investigations Report 2005-5243. U.S. Department of the Interior, U.S. Geological Survey, p. 96.

Roos, M., 1987. Possible change in California snowmelt patterns. In: Proc., Fourth Pacific Climate Workshop, Pacific Grove, CA, pp. 22–31.

Scatena, F.N., 1998. An assessment of climate change in the Luquillo Mountains of Puerto Rico. In: Proceedings of the Third International Symposium on Water Resources, Fifth Caribbean Island Water Resources Congress, San Juan, PR, July. American Water Resources Association, pp. 193–198.

Schwab, G.O., Fangmeier, D.D., Elliot, W.J., 1996. Soil and Water Management Systems, 4th edition. John Wiley and Sons Publisher.

Stewart, R.I., Cyan, D.R., Dettinger, M.D., 2005. Changes towards earlier streamflow timing across Western North America. J. Clim. 18, 1136–1155.

USGS, 2004. Water Resource Data, Puerto Rico and the US Virgin Islands, Water Year 2004. Water Data Report PR-0401, 578 pp.

Washington, W.M., Weatherly, J.W., Meehl, G.A., Semtner, A.J., Bettge, T.W., Craig, A.P., Strand, W.G., Arblaster, J., Wayland, V.B., James, R., Zhang, Y., 2000. Parallel climate model (PCM) control and 1% per year CO_2 simulations with a 2/3 degree ocean model and 27 km dynamical sea ice model. Clim. Dyn. 16, 755–774.