DOWNSCALED CLIMATE CHANGE IMPACTS ON REFERENCE EVAPOTRANSPIRATION AND RAINFALL DEFICITS IN PUERTO RICO

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ABSTRACT
The purpose of this study was to estimate reference evapotranspiration (ET_o) and rainfall excess (rainfall – ET_o) under climate change conditions for three locations in Puerto Rico: Adjuntas, Mayagüez and Lajas. Reference evapotranspiration was estimated by the Penman-Monteith method. 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.

Results from the analysis indicate that the rainy season will become wetter and the dry season will become drier. The average estimated rainfall excess (i.e., rainfall – $ET_o > 0$) 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.

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). 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 changes in reference evapotranspiration (ET_o) and rainfall deficit (or rainfall excess) that might be caused by global climate change during the 21st 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 which evaluated various hydrologic parameters using downscaled global circulation models (GCMs). Bouraoui et al. (1997) coupled the hydrologic model ANSWERS (Beasley et al., 1980) with a GCM. In their work, the authors emphasized 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. A general methodology to disaggregate outputs of large scale models to use them directly by hydrologic models was proposed 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. The authors warned that given that the results were obtained from only one particular GCM and since many uncertainties still exist among different models, they must be used with caution.

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 rainfall predicted 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) mesoscale model (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 the coupled model approach was to predict seasonal crop-available water, thereby allowing evaluation of alternative cropping systems.

There is a growing trend to discourage the use of downscaled GCM data to evaluate impacts from future climate (e.g., Pielke et al., 2006). The argument is that the current GCMs do not account for all of the anthropogenic forcings, are based on historical training periods applied to future conditions that are assumed stationary, and therefore do not provide skillful forecasts of future climate. We readily acknowledge these concerns, but consider the use of current downscaled GCM data as useful as a means of understanding how hydrologic processes may respond should such conditions occur in the future. This study presents a methodology that can be used to evaluate reference evapotranspiration and rainfall deficits at other locations throughout the world.

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).

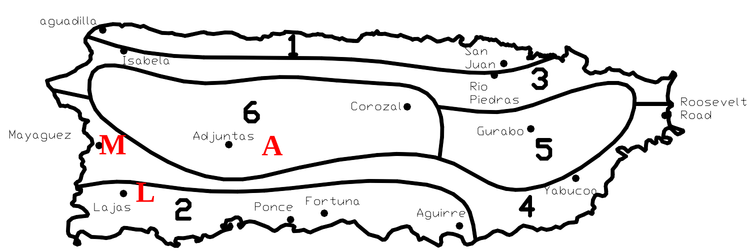

Figure 1. Map of Puerto Rico showing the locations of Adjuntas (A), Mayagüez (M) and Lajas (L) . Numbers indicate National Oceanic and Atmospheric Administration (NOAA) Climatic Divisions. 1, North Coastal; 2 South coastal; 3, Northern Slopes; 4, Southern Slopes; 5, Eastern Interior; and 6; Western Interior.

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 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, which depends on the following input parameters: 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):

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

where Δ is slope of the vapor pressure curve, R_n is net radiation, G is soil heat flux density, 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. 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 and an albedo of 0.23. Vapor pressure was calculated using the following equation:

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

where e(T) is vapor pressure evaluated at temperature T. Saturated and actual vapor pressures were estimated using equation 2 with the mean monthly air temperature (T_{mean}) and mean monthly dew point temperature (T_{dew}), respectively. The FAO (Allen et al., 1998) has reported that T_{dew} can be estimated based on the use of the monthly minimum air temperature (T_{min}). A correction factor, which is added to the minimum temperature 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. Harmsen et al. (2002) derived values of $K_o$for the six NOAA Climate Divisions in Puerto Rico, which are listed in Table 2.

Table 2. Temperature correction Factor K_o used in Equation 2 for NOAA Climatic Divisions 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

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. 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. 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.

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.

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 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

Figures 2, 3, 4 and 5 represent the minimum, mean and maximum air temperatures, T_{max}-T_{min}, the vapor pressure deficit (VPD) and the reference evapotranspiration 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. 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.

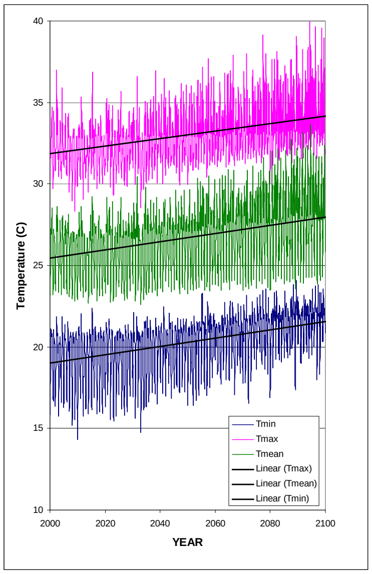

Figure 2. Minimum, mean and maximum air temperature for the A2 scenario at Lajas. Linear regression trend lines are are shown.

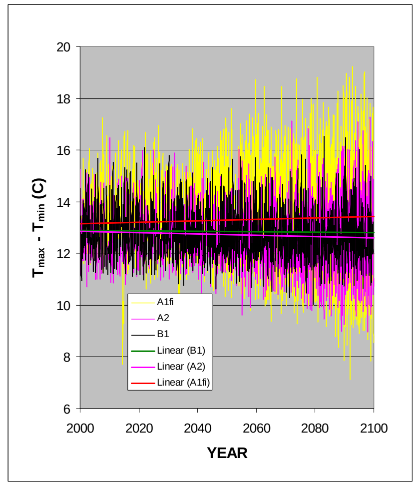

Figure 3. T_{max}-T_{min} for the A2 scenario at Lajas. Linear regression trend lines are shown.

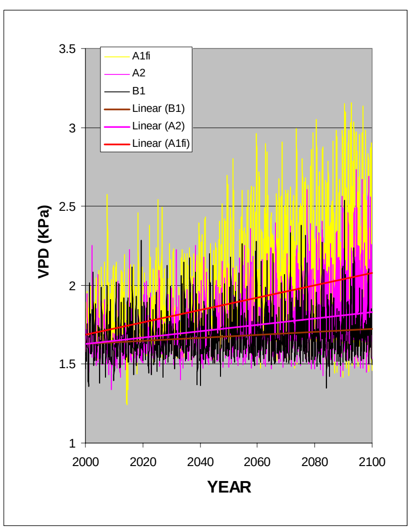

Figure 4. Vapor pressure deficit (VPD) for the A2 scenario at Lajas. Linear regression trend lines are shown.

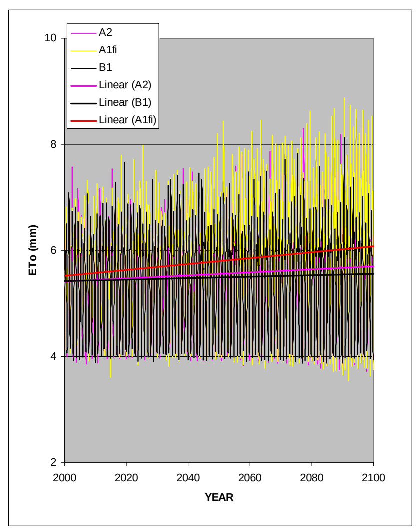

Figure 5. Reference evapotranspiration for the A2 scenario at Lajas. Linear regression trend lines are shown.

Figure 6 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 7 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).

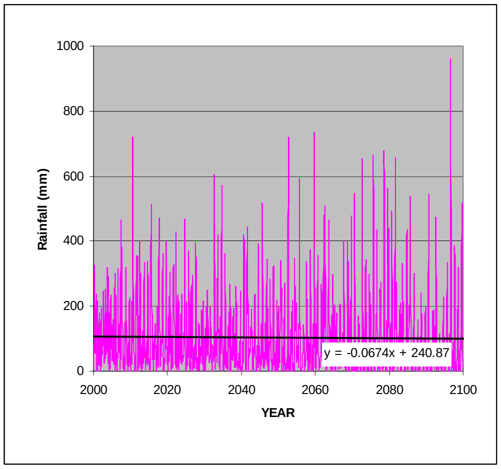

Figure 6. Average monthly rainfall at Lajas for climate change scenario A2.

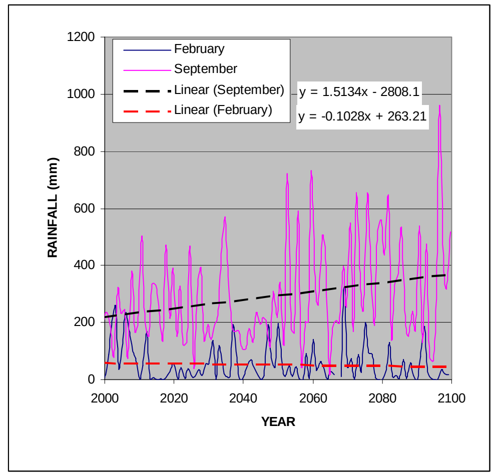

Figure 7. Estimated rainfall at Lajas for climate change scenario A2 for February and September.

Table 4 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 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 5 presents the difference in the rainfall deficit relative to the year 2000.

Table 4. 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 5. 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 5 shows increasing deficits in February at all locations for the A1fi and A2 scenarios. Although there was a 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 – $ET_o > 0$) 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.

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).

The Penman-Monteith equation has been thoroughly tested and has been shown to provide accurate estimates of ET_o, given accurate values of input data. In this study several input parameters were estimated including solar radiation, dew point temperature, wind speed, soil heat flux and net radiation, each of which represents a potential source of uncertainty.

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. 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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REFERENCES

Allen, R. G., I. A. Walter, R. Elliott, R. Howell, D. Itenfisu and M. Jensen, R. L. Snyder, 2005. The ASCE Standardized Reference Evapotranspiration Equation. Environmental and Water Resources Institute of the American Society of Civil Engineers. 57 pages.

Allen, R. G., L. S. Pereira, Dirk Raes and M. Smith, 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., L. F. Huggins, and E. J. Monke. 1980. ANSWERS: A model for watershed planning. Trans. ASAE 23(4): 938-944.

Brekke, L. D., N. L. Miller, K. E. Bashford, N. W. T. Quinn, and J. A. Dracup. 2004. Climate change impacts uncertainty for water resources in the San Joaquin River Basin, California. Journal of the American Water Resources Association. February, pp 149-164.

Bouraoui F., Vachaud G., Haverkamp, B., 1997. A distributed physical approach for surface subsurface water transport modeling in agricultural watersheds. J. Hydrol.

Dettinger, M.D., Cayan, D.R., 1995. Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. J. Clim. 8, 606–623.

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

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

Maurer, E. P. and P. B. Duffy, 2005. Uncertainty in projections of streamflow changes due to climate change in California. Geophysical Resarch Letters, vol. 32, LO3704. pp 1-5.

Mearns, L.O., F. Giorgi, P. Whetton, D. Pabon, M. Hulme, and M. Lal. 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, J. Jin, and K. Hayhoe, 2006a. Projected Extreme Heat and Energy Demand under Future Climate Scenarios. Proceedings of the Caribbean Climate Symposium, University of Puerto Rico – Mayagüez Campus, April 24 – 25.

Miller, N. L., K. Hayhoe, J. Jin, M. Auffhammer, 2006b. Climate, Extreme Heat, and Electricity Demand in California, JAMC (in review)

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

Pan, A., E. Takle, R. Horton, and M. Segal. 2002. Warm-Seasonal Soil Moisture Prediction Using A Coupled Regional Climate Model. 16th Conference on Hydrology, January 13-18. Orlando, Florida.

Pielke, R. A., Sr. J. O. Adegoke, T. N. Chase, C. H. Marshall, T. Matsui, D. Niyogi, 2006. A new paradigm for assessing the role of agriculture in climate system and in climate change. Agricultural and Forest Meteorology. In press.

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

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

Stewart, R. I., D. R. Cyan., and M. D. Dettinger. 2005. Changes towards earlier stream flow timing across Western North America. Journal of Climate, vol. 18, pp 1136-1155.