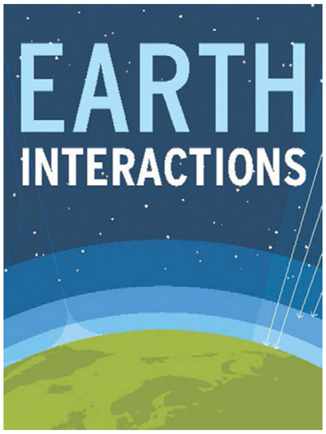

Sensitivity of Crop Water Need to 2071–95 Projected Temperature and Precipitation Changes in Jamaica

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ABSTRACT: This study uses empirical models to examine the potential impact of climate change, based on a range of 100-yr phase 5 of the Coupled Model Intercomparison Project (CMIP5) projections, on crop water need in Jamaica. As expected, crop water need increases with rising temperature and decreasing precipitation, especially in May–July. Comparing the temperature

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and precipitation impacts on crop water need indicates that the 25th percentile of CMIP5 temperature change (moderate warming) yields a larger crop water deficit than the 75th percentile of CMIP5 precipitation change (wet winter and dry summer), but the 25th percentile of CMIP5 precipitation change (substantial drying) dominates the 75th percentile of CMIP5 temperature change (extreme warming). Over the annual cycle, the warming contributes to larger crop water deficits from November to April, while the drying has a greater influence from May to October. All experiments decrease crop suitability, with the largest impact from March to August.

KEYWORDS: Jamaica; Climate change; Water budget; Agroclimatic suitability

1. Introduction

As society begins to adapt to, plan for, and mitigate the impacts of climate change, it is clear that human activities linked closely to ecosystems or natural resources will be severely impacted (Solomon et al. 2007). Of particular concern for many developing regions is the impact of climate change upon food security, especially for those countries reliant on rain-fed agriculture (Godfray et al. 2010). Many areas can expect to see a combination of increasing temperatures (and subsequent increase in evapotranspiration) and decreasing rainfall, leading to increased stress on food productivity and sustainability.

The Caribbean is particularly vulnerable to such climate stress. Under most global warming scenarios, the region's climate is expected to become warmer and drier over time, with potentially harmful impacts on agricultural productivity (Nurse and Sem 2001; Mimura et al. 2007). Much of the region's farming is carried out by small farmers lacking access to irrigation, and changes in growing conditions may therefore have negative consequences for rural communities, as well as for the food security and economic development of Caribbean nations (McElroy and de Albuquerque 1990; Kendall and Petracco 2009).

Although scholars are beginning to assess the extent and possible trajectories of climate change in the Caribbean, attempts to examine its impacts on farming are less common. In what follows, we draw upon a recent Coupled Model Intercomparison Project to forecast future agricultural suitability in Jamaica given a range of anticipated changes to both temperature and rainfall. Our aim is to determine the separate and combined effects of projected temperature and precipitation change on the water budget and crop suitability for a small island developing state (SIDS) with a large economically active population in agriculture, comprising a significant percentage of value added to the gross domestic product (GDP; FAO 2014). Following a brief review of the literature on Caribbean climate change, we discuss below our methodology in greater detail in section 3. We describe how monthly meteorological data, global climate model projections, and simple water balance and agroclimatic suitability models are used to make benchmark predictions of future climatic stressors. Results, given in section 4, quantify an increase in crop water stress and decrease in agroclimatic suitability in Jamaica and point to similar climate–agriculture vulnerabilities for other SIDS in the Caribbean. Finally, some concluding thoughts are presented in section 5.

2. Climate change in the Caribbean region

Climatic variability and trends have already been documented for the Caribbean, and such studies generally support predictions of a warmer, drier Caribbean climate in the future (Nurse and Sem 2001). Peterson et al. (Peterson et al. 2002), for example, report a statistically significant warming trend over the Caribbean since the late 1950s. Long-term changes in rainfall are less obvious. Peterson et al. (Peterson et al. 2002) report a slight decline in daily precipitation intensity but a significant decrease in the number of consecutive dry days in the latter half of the twentieth century. Other studies suggest drying trends in recent decades, which may be related to a phase change in the Atlantic multidecadal oscillation (Enfield et al. 2001). Taylor et al. (Taylor et al. 2002), for example, showed a marked negative trend in early (May–July) and late (August–October) season Caribbean rainfall beginning in the 1960s, and Perez and Jury (Perez and Jury 2013) show insignificant trends over Hispaniola since the 1900s but drying after 1978. In a study employing satellite data, Gamble et al. (Gamble et al. 2010) show a decrease in the standardized precipitation index over Jamaica, indicating more drought months between 1991 and 2008, as compared to 1979–91.

Validation studies of global climate models in the Caribbean (e.g., Biasutti et al. 2012) suggest that temperatures are fairly well simulated, although there is a dry bias, with underestimates of precipitation around 30% (J. D. Campbell et al. 2011). The Intergovernmental Panel on Climate Change (IPCC) multimodel dataset forced with A1B greenhouse gas concentrations show an increase in temperature at the end of the twenty-first century of 1.4°–3.2°C with a median of 2.0°C (Christensen et al. 2007). More recent phase 5 of the Coupled Model Intercomparison Project (CMIP5) projections with the representative concentration pathway 4.5 (RCP4.5) scenario yield a somewhat lower range (0.7°–2.4°C) and median (1.4°C) (Stocker et al. 2014). In terms of precipitation, most models project a drying of the Caribbean, with changes ranging from -29 to $+14\%$. This drying is enhanced in the summer months, especially in the Greater Antilles. Angeles et al. (Angeles et al. 2007), on the other hand, also using a general circulation model, indicate an increase in rain production during the Caribbean wet season.

CMIP5 models are able to reproduce large-scale drivers of precipitation in the Caribbean better than their CMIP3 predecessors (Ryu and Hayhoe 2014) and most importantly show improvement characterizing the midsummer dry spell. Figure 1 shows the 26-model-mean annual cycle of temperature and precipitation for the island of Jamaica. The time period is 1980–2004. CMIP5 is somewhat warmer and substantially drier than what is observed over Jamaica according to the Climatic Research Unit (CRU) dataset for the same 25-yr climatology. Annually, the model-mean precipitation is only 37% of the CRU mean. Furthermore, model biases and projections have similar magnitudes (Ashfaq et al. 2011). These uncertainties underscore the need for a suite of climate change vulnerability scenarios to inform stakeholders in the Caribbean.

Taken together, predictions of increased temperatures and decreased rainfall have significant implications for Caribbean agriculture. Smallholders, in particular, may be entirely dependent upon the amount and timing of annual rainfall. Indeed, the IPCC Fourth Assessment Report notes that lack of water availability is an increasing threat to food security for Caribbean countries (Mimura et al. 2007). In

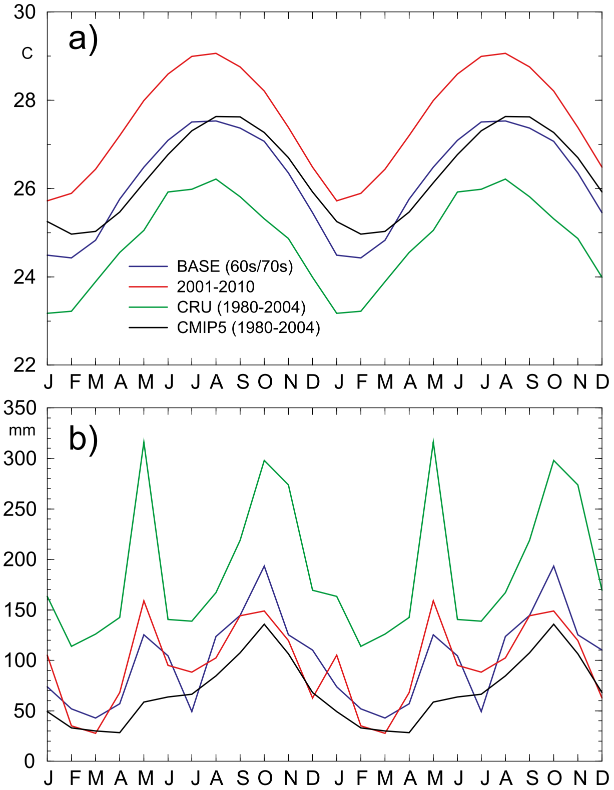


Figure 1. The 24-month annual cycle of (a) temperature and (b) precipitation for Jamaica. The 1960s and 1970s climatology (BASE) is in blue, the 2000–10 climatology is in red, the CRU 1980–2004 climatology is in green, and the CMIP5 model-mean 1980–2004 climatology is in black. (Units: (a) °C and (b) mm month^{-1}.)

Jamaica, where much of the rural population depends on agriculture for their livelihood, one study found that 65% of farmers said that droughts are longer and more frequent than in the past (D. Campbell et al. 2011). Watts (Watts 1995) characterizes drought as a ubiquitous hazard across the Caribbean, one that should receive as much attention as the better understood tropical storm hazard, and the impact of which is expected to increase in a future warmer climate (Mimura et al. 2007). Jamaica has some of the largest agricultural land areas among Caribbean small island states, but less than 10% of the land is irrigated (Trotman et al. 2009). This lack of irrigation infrastructure, along with difficulties procuring water during drought (e.g., nonresponsive government agencies or price gouging), exacerbates the challenges created by drying conditions (D. Campbell et al. 2011).

3. Data and methods

Given the threat that climate change poses to farming in the Caribbean, our aim in what follows is to provide an initial assessment of how water stress and agricultural suitability may be altered as climate change unfolds in Jamaica. To do so, we utilize the Thornthwaite water balance model to calculate both annual water deficit and monthly crop suitability under baseline and future climate change scenarios using the long-term Montego Bay meteorological station. A large proportion of domestic farming in Jamaica takes place in southern St. Elizabeth Parish near the coast. Montego Bay, on the north side of the island, has one of the longest records of monthly precipitation and temperature in Jamaica and adequately emulates the climate conditions experienced in southern St. Elizabeth. In fact, Batjes (Batjes 1994) places these locations in similar intermediate moisture availability agroecological zones.

The first step in our analysis was to assemble the baseline climatology. Ten complete years of monthly-mean temperature and total precipitation from the 1960s and 1970s (1964–68; 1970; 1972; 1974; and 1976–77) were selected from the Global Historical Climatology Network (Vose et al. 1992). Ten years are necessary to compile a pseudoclimatology and to fulfill requirements for the agroclimatic suitability model (CROPRISK) described later. The precipitation and temperature time series will be referred to as BASE_P and BASE_T, respectively. To assess the potential impact of future temperature and rainfall change, we next developed future climatologies based off of the same Montego Bay station. Precipitation and temperature data were extracted from the National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environmental Prediction (NCEP)/Climate Prediction Center (Ropelewski et al. 1985) for the 10-yr period of 2001–10.

BASE_T has a similar mean temperature as CMIP5 (1980–2004); however, Montego Bay is warmer by over 1°C in the 2001–10 time period (Figure 1a). Interestingly, the annual cycle of CMIP5 temperature lags all the observational products. CMIP5 correlations between CRU, BASE_T, and the 2000s increase from 0.91 to 0.98, 0.96 to 0.97, and 0.91 to 0.99, respectively, with a 1-month lag. The annual mean of BASE_P and the 2000s climatology are similar (Figure 1b) but exhibit variability at the monthly scale. BASE_P has a more pronounced midsummer dry spell (MSD) in July and a wetter October, while during the 2000s precipitation was more abundant in May. The Montego Bay station is drier than the CRU estimated precipitation for the island as a whole, and approaches the CMIP5 mean (Figure 1b). CMIP5 precipitation shows a similar annual cycle to BASE_P, and the correlation between these two time series is largest (0.89).

CMIP5 temperature and precipitation projections for Jamaica were downloaded from the U.S. Geological Survey (USGS; Alder et al. 2013). Models included in this analysis are found in Table 1. Since the models have varying grid spacing, the native resolution was first extracted by the country boundary and then regridded to a common $0.1° \times 0.1°$ grid without interpolation. Finally, an area-weighted country average was performed using a GIS shapefile. The climate change experiment used for this study was RCP8.5 ending at the 2071–95 time period. Figure 2 shows box plots of the monthly changes in temperature and precipitation over the 26 models. Temperature changes are all positive and mostly above 2°C (Figure 2a). The median is highest in September and lowest in May. Precipitation change (in %; Figure 2b) is more variable among models, where both positive and negative trends can be found in every month. However, 75% or more of the models project drying in the months March through September. The 25th and 75th percentiles of CMIP5 temperature and precipitation change for Jamaica are given in Table 2.

Table 1. Acronyms, expanded names, and origins of CMIP5 models used in this study.

BCC_CSM1.1	Beijing Climate Center Climate System Model, version 1.1	Beijing Climate Center (BCC), China Meteorological Administration, China
BCC_CSM1.1(m)	Beijing Climate Center Climate System Model, version 1.1 (moderate resolution)	BCC, China Meteorological Administration, China
BNU-ESM	Beijing Normal University–Earth System Model	Global Change and Earth System Science (GCESS), Beijing Normal University (BNU), Beijing, China
CanESM2	Second Generation Canadian Earth System Model	Canadian Centre for Climate Modeling and Analysis (CCCma), Victoria, British Columbia, Canada
CCSM4	Community Climate System Model, version 4	National Center for Atmospheric Research (NCAR), Boulder, Colorado
CESM1 (BGC)	Community Earth System Model, version 1 (Biogeochemistry)	National Science Foundation (NSF) Department of Energy (DOE) NCAR, Boulder, Colorado
CESM1 (CAM5)	Community Earth System Model, version 1 (Community Atmosphere Model, version 5)	NSF DOE NCAR, Boulder, Colorado
CESM1 (WACCM)	Community Earth System Model, version 1 (Whole Atmosphere Community Climate Model)	NSF DOE NCAR, Boulder, Colorado
FGOALS-g2	Flexible Global Ocean–Atmosphere–Land System Model, gridpoint version 2	Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences, Beijing, China
FGOALS-s2	Flexible Global Ocean–Atmosphere–Land System Model, second spectral version	IAP, Chinese Academy of Sciences, Beijing, China
GFDL CM3	Geophysical Fluid Dynamics Laboratory Climate Model, version 3	NOAA/GFDL, 201 Forrestal Rd., Princeton, NJ 08540
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics (GOLD) component	NOAA/GFDL, 201 Forrestal Rd., Princeton, NJ 08540
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model with Modular Ocean Model, version 4 (MOM4) component	NOAA/GFDL, 201 Forrestal Rd., Princeton, NJ 08540
GISS-E2-H	Goddard Institute for Space Studies Model E2, coupled with Hybrid Coordinate Ocean Model (HYCOM)	National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS), New York, New York
GISS-E2-R	Goddard Institute for Space Studies Model E2, coupled with the Russell ocean model	NASA GISS, New York, New York
HadGEM2-AO	Hadley Centre Global Environment Model, version 2—Atmosphere and Ocean	National Institute of Meteorological Research (NIMR), Seoul, South Korea
HadGEM2-CC	Hadley Centre Global Environment Model, version 2—Carbon Cycle	Met Office Hadley Centre, Fitzroy Road, Exeter, Devon, EX1 3PB, United Kingdom

Table 1. (*Continued*)

HadGEM2-ES	Hadley Centre Global Environment Model, version 2—Earth System	Met Office Hadley Centre, Fitzroy Road, Exeter, Devon, EX1 3PB, United Kingdom
INM-CM4.0	Institute of Numerical Mathematics Coupled Model, version 4.0	Institute for Numerical Mathematics (INM), Moscow, Russia
IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution	L'Institut Pierre Simon Laplace (IPSL), Paris, France
IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace Coupled Model, version 5A, mid resolution	IPSL, Paris, France
IPSL-CM5B-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5B, low resolution	IPSL, Paris, France
MPI-ESM-LR	Max Planck Institute Earth System Model, low resolution	Max Planck Institute for Meteorology
MPI-ESM-MR	Max Planck Institute Earth System Model, medium resolution	Max Planck Institute for Meteorology
NorESM1-M	Norwegian Earth System Model, version 1 (intermediate resolution)	Norwegian Climate Centre
NorESM1-ME	Norwegian Earth System Model, version 1 (intermediate resolution) with carbon cycling (and biogeochemistry)	Norwegian Climate Centre

To understand how this spectrum of projected change in climate may impact farming at the local scale, using Montego Bay as an example, first trends were removed by adjusting the monthly means of 2000–10 temperature and precipitation to exactly match the monthly means of BASE_T and BASE_P (Figure 1). Although there is little trend in precipitation between these two time periods (less than 4% annually; see Figure 1b), there is a substantial upward trend in temperature (+1.3°C; see Figure 1a). These adjusted datasets are referred to as ADJ00_T and ADJ00_P. Next the monthly means of ADJ00_T and ADJ00_P were modified in order to create differences with the BASE_T and BASE_P climatologies that exactly match a sample of Jamaican-averaged CMIP5 projections of temperature and precipitation. The coarse resolution of CMIP5 models does not allow us to exactly match the location of the Montego Bay station. Thus, the variability of the 2001–10 period remains as observed in all cases, but the new means represent the 2071–95 conditions as modeled by CMIP5. The six imposed trends are as follows: the 25th percentile of temperature change (MOD_T), the 75th percentile of temperature change (EXT_T), the 75th percentile of precipitation change (MOD_P), and the 25th percentile of precipitation change (EXT_P); they are given in Table 2. The 25th percentile of precipitation change represents the extreme case, as the models are weighted toward drier conditions in Jamaica at the end of the century.

Sensitivity studies of water availability were performed using the USGS version 1.1.0 Thornthwaite water balance model (McCabe and Markstrom 2007). The model analyzes components of the hydrologic cycle with monthly temperature and precipitation data according to Thornthwaite (Thornthwaite 1948). Input parameters for the model were selected based on typical soil types (Ultisols and Oxisols)

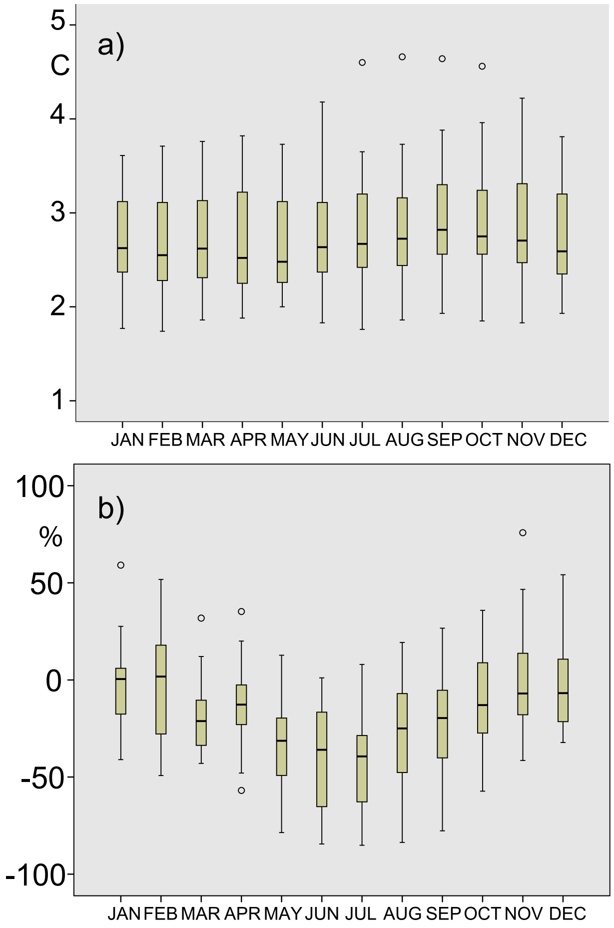


Figure 2. Box plot representing monthly RCP8.5 trends from 1980–2004 to 2071–95 of the 26 CMIP5 models. Outliers are open circles. (Units: (a) Temperature change (°C) and (b) precipitation change (%).)

in the Caribbean and the hydrology literature. Runoff generation is specified as 50% of the surplus water generated when soil-moisture storage exceeds its capacity (Wolock and McCabe 1999). Soil-moisture storage capacity is set at 150 mm (McCabe and Wolock 1999), and the fraction of precipitation that becomes direct runoff from infiltration excess overflow is defined as the common value of 0.05 (Wolock and McCabe 1999). Finally, the latitude parameter is adjusted to 18°N. While several variables are output from the model, we only retain potential evapotranspiration (PET) and actual evapotranspiration (AET) for further analysis.

Water deficit is defined as PET minus AET. Stephenson (Stephenson 1998) postulated that this metric, which can be viewed in terms of energy conservation, has greater biological significance than soil water deficit and that PET − AET is directly related to drought stress in agricultural fields. Deficit from maximum crop yield (DY) is defined as 1 minus the ratio of the actual yield to the maximum yield. Batjes (Batjes 1987) ran a crop risk model for Jamaica (CROPRISK) and showed that DY can be estimated from PET and AET in the following formula:

$$\mathrm{DY} = \mathrm{ky}\,(\mathrm{ETC} - \mathrm{AET})/\mathrm{ETC},$$

where ETC = (kc)(PET) and kc is the crop coefficient for the specific growing stage and type of crop under prevailing climatic conditions and typically ranges between 0.35 and 1.15. The yield response factor (ky) reflects the effect of water stress on a crop, with stress increasing for ky values greater than unity. Batjes (Batjes 1987) presents a table of ky values and mean marketable yield for annual crops commonly grown in Jamaica. The average ky value weighted by mean yield is 1.03, indicating that Jamaican crops tend to be slightly sensitive to water availability. In this study we set ky = 1.05, which is close to the mean and represents the value for tomato. We chose to use this particular crop because it is commonly grown in Jamaica (and throughout the Caribbean) by small holding farmers for sale in domestic markets for local consumers and tourism facilities (Sealey 1992). Tomato's kc value begins at 0.45 at planting, increases to 0.75 during the development stage, reaches a maximum of 1.15 at midseason, and then falls to 0.8 at late season. Here we choose a value of 1.0, which is representative of harvest time but avoids negative DYs, which is possible with smaller kc values.

After determining crop water need, agroclimatic suitability classes were then defined based on Batjes (Batjes 1987) and are dependent upon the number of years out of 10 that 80% and 60% of the crop's maximum yield can be obtained. Highly suitable (HiS) is defined when the 80% condition is met in at least 6 out of 10 years and the 60% condition is met in at least 8 out of 10 years. For the moderately suitable (MoS) class the number of years drops to at least 4 and 6, respectively, and for the marginally suitable (MaS) class the numbers are at least 2 and 4, respectively. Finally, the not suitable category is defined when 80% of the crop's maximum yield is obtained in less than 2 out of 10 years and when 60% of the maximum is obtained in less than 4 out of 10 years.

Crop water need and agroclimatic suitability classes were determined over the annual cycle for six different climate change experiments. First, the base climatology (BASE_T and BASE_P) was input into the models. Next, six future scenarios were explored: modifying ADJ00_T and ADJ00_P to match the moderate climate change scenarios <MOD_T; MOD_P>, modifying them to match the extreme scenarios <EXT_T; EXT_P>, and changing temperature and precipitation separately: <ADJ00_T; MOD_P>, <ADJ00_T; EXT_P>, <MOD_T; ADJ00_P>, and <EXT_T; ADJ00_P> (see Table 2). These latter scenarios are intended to determine the relative importance of temperature and precipitation on future crop water need and agricultural productivity.

4. Results

4.1. Climatologies

Figure 3 shows the time series of BASE_T, MOD_T, and EXT_T temperatures and BASE_P, MOD_P, and EXT_P precipitation for the 10-yr time span. MOD and EXT are constructed from the same dataset and simply represent different scenarios of the future based on CMIP5 models. The time series were each tested for trends, but no significant trends were identified over the decade of data. Changes in temperature among the three datasets are obvious: precipitation changes are less

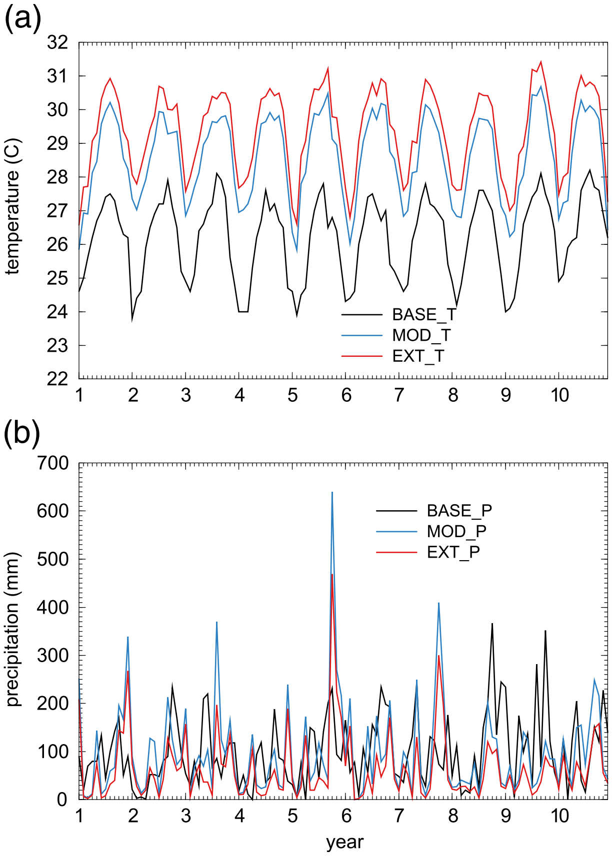


Figure 3. Time series of temperature and precipitation in Montego Bay, Jamaica, for the 10-yr period in the 1960s and 1970s (BASE; black line) and experiments where moderate (blue) and extreme (red) CMIP5 trends are superimposed on the mean-adjusted 2001–10 data. (a) Temperature (°C), where EXT_T represents the 75th percentile of CMIP5 models and MOD_T represents the 25th percentile of CMIP5 models, and (b) precipitation (mm), where EXT_T represents the 25th percentile of CMIP5 models and MOD_T represents the 75th percentile of CMIP5 models.

so. MOD_P does not show a substantial difference with BASE_P as some months are adjusted upward and others are adjusted downward (Table 2). EXT_P does show drier conditions compared to BASE_P, even though individual months in this future time series may receive more rain as compared to the baseline time series. In fact, EXT_P is punctuated by several months of heavy rainfall. This is consistent with climate change science, which suggests an increase in extreme events in conjunction with an overall drying for the Caribbean.

4.2. Crop water stress

The USGS Thornthwaite model was executed 8 times as described in section 3. Crop water need (PET − AET) was computed for the six future scenarios

<MOD_T; MOD_P>, <EXT_T; EXT_P>, <ADJ00_T; MOD_P>, <ADJ00_T; EXT_P>, <MOD_T; ADJ00_P>, and <EXT_T; ADJ00_P> and the baseline climatology <BASE_T; BASE_P>. Monthly averages were calculated and summed to yield an annual crop water stress value, reported in ascending order in Table 3. As expected, the combined extreme temperature and precipitation scenario delivers the largest change in crop water stress as compared to the baseline climatology, a threefold increase in PET − AET. However, considering the extreme scenarios separately shows that precipitation change has a larger effect than temperature change. While temperature increases, regardless of CMIP5 model, precipitation change is more variable. The moderate precipitation change scenario includes months of both increasing and decreasing precipitation (Table 2), while the extreme precipitation scenario amounts to substantial drying in all months. It should be noted that the 75th percentile of CMIP5 precipitation change still has a net effect of increasing crop water stress.

The timing of temperature and precipitation change during the course of the annual cycle is critical for crop suitability. Figure 4 shows the annual cycle of crop water stress for the baseline climatology and the six future experiments (ordered as in Table 3). For the baseline climatology, the largest crop water stress occurs in July. This is the time of the MSD, when precipitation is reduced but temperatures are highest (Figure 1). In general, the experiments that only adjust temperature have their largest impact from January to April, and the <ADJ00_T; EXT_P> experiment achieves a large crop water deficit from May to September. Interestingly, during the peak of the summer season in July, the <MOD_T; MOD_P> experiment has a substantial impact on crop water stress. An examination of values at these percentiles (Table 2) reveals that warming increases from April to July at the same time the precipitation change becomes increasingly negative.

4.3. Agroclimatic suitability

Next the agroclimatic suitability model was run for the baseline climatology <BASE_T; BASE_P> and the same six experiments, <MOD_T; MOD_P>, <EXT_T; EXT_P>, <ADJ00_T; MOD_P>, <ADJ00_T; EXT_P>, <MOD_T; ADJ00_P>, and <EXT_T; ADJ00_P>. Figure 5 shows the suitability classes for each month. Montego Bay's baseline climatology results in one month that is not suitable for agriculture: July. The climate change experiments indicate a consistent decrease in suitability under future climate change scenarios. The <MOD_T; ADJ00_P> and <ADJ00_T; MOD_P> experiments both show an expansion of the MSD-related not suitable category into August. The only difference between these two experiments occurs from January to March, when the temperature change causes a decline in crop suitability compared to the precipitation change. This is consistent with the difference in crop water deficit discussed in the previous section (Figure 4). The <MOD_T; MOD_P> experiment shows evidence of a collapse of crop suitability for half of the year from March to August. Recall that the most substantial decrease in precipitation during this experiment is from May to July. Increasing temperatures at the 75th percentile of CMIP5 but keeping precipitation at normal levels gives a similar picture of crop suitability as <MOD_T; MOD_P>, but conditions improve

Table 2. CMIP5 monthly projections of change in Caribbean temperature (°C) and precipitation (% change) for the RCP8.5 scenario with average change calculated between 2071–95 and 1980–2004. The 25th and 75th percentiles of the 26 models in CMIP5 are given to represent the range of possibilities.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CMIP5 25th T (°C) MOD_T	+2.38	+2.29	+2.31	+2.26	+2.27	+2.38	+2.42	+2.44	+2.56	+2.56	+2.48	+2.36
CMIP5 75th T (°C) EXT_T	+3.10	+3.06	+3.13	+3.21	+3.12	+3.11	+3.17	+3.15	+3.29	+3.23	+3.29	+3.20
CMIP5 75th P (%) MOD_P	+5.2	+17.6	−11.7	−3.1	−20.1	−17.1	−29.2	−7.3	−7.2	+6.4	+13.2	+10.1
CMIP5 25th P (%) EXT_P	−17.1	−27.3	−33.4	−22.6	−47.7	−64.8	−60.7	−46.7	−40.1	−26.7	−17.1	−21.0

Table 3. Experiment name and annual crop water stress value.

Expt		Annual crop water stress value (PET − AET; mm)
1) BASE_T	BASE_P	269.71
2) ADJ00_T	MOD_P	356.12
3) MOD_T	ADJ00_P	480.52
4) MOD_T	MOD_P	524.86
5) EXT_T	ADJ00_P	543.13
6) ADJ00_T	EXT_P	623.43
7) EXT_T	EXT_P	883.9

greatly in June. Finally, the experiments that depict the 25th percentile of CMIP5 precipitation change, extreme drying, indicate that farming will be not suitable in Jamaica from March to August. The <EXT_T; EXT_P> experiment shows further declines in crop suitability with not even one month being deemed highly suitable.

5. Discussion

This study investigated the impact of climate change on crop water stress and agroclimatic suitability for Jamaica using a simple empirical approach. Projections of climatological monthly temperature and precipitation at the end of the twenty-first century (assuming the RCP8.5 economic trend) were taken from phase 5 of the Coupled Model Intercomparison Project (CMIP5). To determine a

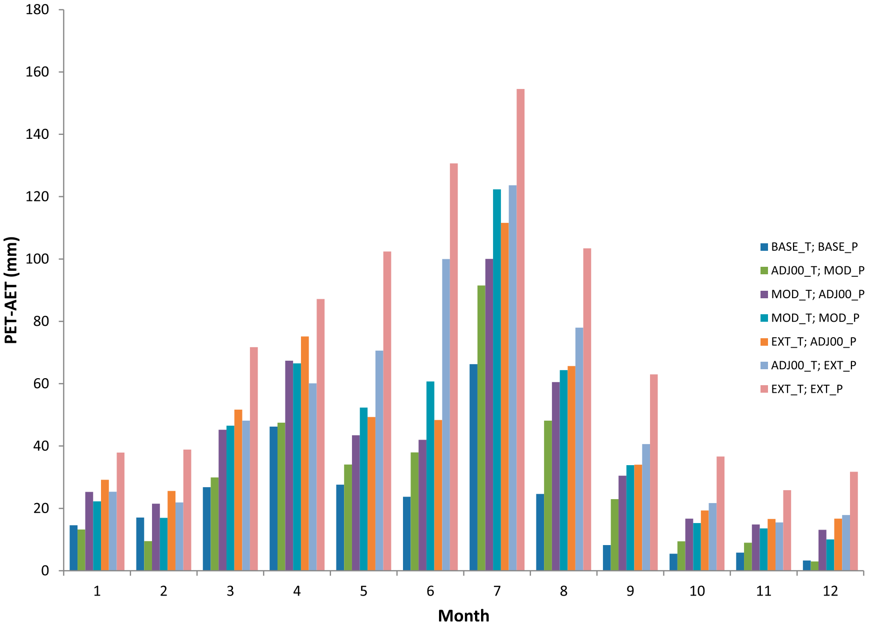
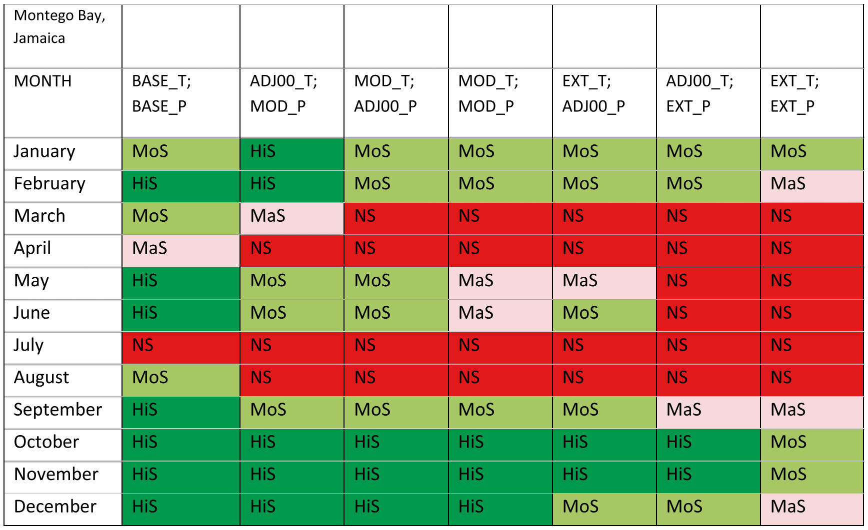


Figure 4. Annual crop water need (PET − AET) for Jamaica. Blue bars are for the baseline observations and the remaining bars represent the six imposed trends. (Units: mm.)



Montego Bay, Jamaica							
MONTH	BASE_T; BASE_P	ADJ00_T; MOD_P	MOD_T; ADJ00_P	MOD_T; MOD_P	EXT_T; ADJ00_P	ADJ00_T; EXT_P	EXT_T; EXT_P
January	MoS	HiS	MoS	MoS	MoS	MoS	MoS
February	HiS	HiS	MoS	MoS	MoS	MoS	MaS
March	MoS	MaS	NS	NS	NS	NS	NS
April	MaS	NS	NS	NS	NS	NS	NS
May	HiS	MoS	MoS	MaS	MaS	NS	NS
June	HiS	MoS	MoS	MaS	MoS	NS	NS
July	NS	NS	NS	NS	NS	NS	NS
August	MoS	NS	NS	NS	NS	NS	NS
September	HiS	MoS	MoS	MoS	MoS	MaS	MaS
October	HiS	HiS	HiS	HiS	HiS	HiS	MoS
November	HiS	HiS	HiS	HiS	HiS	HiS	MoS
December	HiS	HiS	HiS	HiS	MoS	MoS	MaS

Figure 5. Crop suitability classes (see text for definition) for Montego Bay, Jamaica. Suitability is given for the baseline climatology and six future scenarios: <MOD_T; MOD_P>, <EXT_T; EXT_P>, <ADJ00_T; MOD_P>, <ADJ00_T; EXT_P>, <MOD_T; ADJ00_P>, and <EXT_T; ADJ00_P>. Here, highly suitable is in green shading, moderately suitable is in light green shading, marginally suitable is in pink shading, and not suitable is in red shading.

range of future climates and test for the sensitivities between precipitation and temperature change, the 25th and 75th percentiles were chosen. Observed Montego Bay temperature and precipitation from 2001 to 2010 were adjusted by these CMIP5 trends to yield 10-yr future climatologies of crop water stress and crop suitability.

As expected, crop water stress increases with the projected changes to temperature and precipitation. Given the uncertainty of climate models and the emphasis on precipitation change in producing agricultural vulnerability, we chose to separate the effects of precipitation and temperature change. A conservative estimate of temperature change (25th percentile) has a larger impact on annual crop water deficit than a conservative estimate of precipitation change (75th percentile). This is due to the fact that a temperature increase greater than 2°C is a likely scenario for most CMIP5 models, yet many models show both increases and decreases in monthly precipitation.

Interestingly, temperature has a slightly larger impact on crop water stress and crop suitability in the spring season. This is primarily driven by warming in the winter, the time when precipitation is expected to increase by the end of the twenty-first century according to about half of the CMIP5 models. On the other hand, the precipitation adjustment has a larger impact in the summer to fall season. July stands out as having large increases in crop water deficit for all experiments. One dynamical cause of this change in midsummer precipitation is likely associated with the Caribbean low-level jet, which has its relative maximum in July. A regional climate change model suggests that the jet will strengthen between Jamaica, Hispaniola, and Puerto Rico and the north coast of South America (Taylor et al. 2013), likely caused by an anthropogenic induced ridging of the North Atlantic subtropical high toward the southwest (Li et al. 2011). The increase in wind speed would also accelerate evapotranspiration and exacerbate water stress at these locations. With regards to crop suitability, even the conservative climate change scenario, with a range of month temperature change between +2.26° and +2.56°C and a range of monthly precipitation change between −29.2% and +17.6%, indicates that farming in Jamaica will be a tenuous proposition from March to August.

In summary, we have shown how changes to precipitation and temperature can lead to farming vulnerability in Jamaica. One of the key findings is that temperature change is as important as precipitation change, especially for the percentiles of CMIP5 output that produce the more conservative trends. Furthermore, there is more confidence in the temperature projections from CMIP5 as compared to the precipitation projections. Little to no change in precipitation but a +2.26° to +2.56°C change in temperature still amounts to an almost doubling of crop water deficit and substantial loss of agricultural productivity.

These results can potentially be applied to other small island developing states in the Caribbean, as the climate change scenarios are similar throughout the Greater Antilles. However, soil profiles, crop choices, and irrigation at a given location are also critically important. In regard to Caribbean soils, it is rare to find expansive, deep soil deposits on Caribbean islands, and their shallow soils have much regolith present in the column (Sealey 1992). Since the crop water models used in this study assume a uniform deep soil profile, they may actually underestimate the potential for drying that farmers will face in the future.

Assuming that predicted changes to temperature and rainfall come to pass, traditional smallholder farmers will need to adapt to new realities, where common crops such as tomato may be suitably grown only during a month or two in the winter season. Some adaptation strategies used in Jamaica include favoring drought-tolerant crops (e.g., scallion, beetroot, sweet potato, and cassava), mulching, or using drip irrigation (D. Campbell et al. 2011). All of these practices will require governments to realize the extent of the problem and offer necessary assistance. To this point, there has been limited policy response on the part of Caribbean agriculture managers to observed trends and future projections of climate (Trotman et al. 2009), even as climate hazards increasingly threaten vulnerable populations. Despite the many development challenges faced by Caribbean states, the potential loss of domestic crop production and subsequent food insecurity arising from climate change is an issue that should be placed firmly on the agenda.

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