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REPORT

Socio-economic vulnerability to climate change in the central mountainous region of eastern Mexico

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Abstract Climate change effects are expected to be more severe for some segments of society than others. In Mexico, climate variability associated with climate change has important socio-economic and environmental impacts. From the central mountainous region of eastern Veracruz, Mexico, we analyzed data of total annual precipitation and mean annual temperature from 26 meteorological stations (1922–2008) and from General Circulation Models. We developed climate change scenarios based on the observed trends with projections to 2025, 2050, 2075, and 2100, finding considerable local climate changes with reductions in precipitation of over 700 mm and increases in temperature of ~9°C for the year 2100. Deforested areas located at windward were considered more vulnerable, representing potential risk for natural environments, local communities, and the main crops cultivated (sugarcane, coffee, and corn). Socio-economic vulnerability is exacerbated in areas where temperature increases and precipitation decreases.

Keywords Climate change · Social vulnerability · Economic vulnerability · Temperature and precipitation trends · Region of the Great Mountains · Mexico

INTRODUCTION

Climate change is increasingly accepted as a major issue facing human societies (Houghton et al. 2001), and it is recognized as a serious challenge affecting our planet, its people, the environment, and the economy (Lindner et al. 2010). Climate change effects are predicted to increase intensity and frequency of extreme weather events, alter precipitation patterns affecting incidence and severity of droughts, and increase temperature (Seneviratne et al. 2012; Dai 2011; Min et al. 2011; Zwiers et al. 2011; Coumou and Rahmstorf 2012; IPCC 2014). Temperature has increased at unprecedented rates in the last 100 years (Houghton et al. 2001), and the last three decades have been successively warmer at the Earth's surface than any preceding decade since 1850 (IPCC 2014). Along with the predicted changes in temperature, precipitation, and extreme weather events, changes in food and agricultural production and prices, water availability and access, and nutrition and health status are also expected to occur in future years increasing vulnerability (IPCC 2014).

Vulnerability to climate change is defined as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change (IPCC 2014). Vulnerability can be understood as the propensity of human and ecological systems to suffer harm and their ability to respond to stresses imposed as a result of climate change effects (Adger et al. 2007). The United Nations (2004) identified four internal vulnerability factors as relevant for disaster reduction: environmental, physical, economic, and social. Social vulnerability is defined as the susceptibility of a given population to be harmed from exposure to a hazard, directly affecting its ability to prepare for, respond to, and recover (Hewitt 1997). As a socially constructed phenomenon, vulnerability is influenced by institutional and economic dynamics. A system's vulnerability to climate change can be determined by its exposure, physical setting, ability, and opportunity to adapt to change (Granados 2012). Although some responses are intrinsically vulnerable to certain hazards, others acquire vulnerability over time due to historical events. Social vulnerability and equity in the context of climate change are important because climate change will impact the world's

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regions differently (Beaumont et al. 2011), and some populations may have less capacity to prepare for, respond to, and recover from climate-related hazards. Such populations may be disproportionately affected by natural hazards and climate change (Lynn et al. 2011).

Climate change effects will be more severe for some segments of society due to geographic location, degree of association with climate-sensitive environments, and unique cultural, economic, and political characteristics of human populations (Lynn et al. 2011). The most adverse impacts are predicted to occur in the developing world because of geographic isolation, reliance on climate-sensitive sectors, low incomes, and weak adaptive capacity (Cline 2007; IPCC 2014). Socio-economic systems typically are more vulnerable in developing countries where economic and institutional circumstances are less favorable, and vulnerability increases in places with higher sensitivity to climate change (Watson et al. 1996). Socio-economic factors that determine the adaptive capacity to climate change include technology and infrastructure, information, knowledge and skills, institutions, equity, social capital, and economic development (IPCC 2014).

Concerning the economic development, a region's vulnerability depends to a great extent on its wealth, where poverty limits the adaptive capabilities (Watson et al. 1998). Although related, vulnerability and poverty are different concepts; however, poor people are usually among the most vulnerable (Moser 1998). Poverty is an important aspect of vulnerability because it is directly associated to resource access. Poverty affects vulnerability through individuals' expectations of impacts of hazards and their ability to invest and alleviate risks; it also affects coping and recovery from extreme events and reduces resilience to impacts (Adger 1999).

Isolated from social reality vulnerability studies are incomplete. This paper outlines a framework for analyzing the socio-economic vulnerability to the impacts of global warming induced by climate change in the Region of the Great Mountains, Veracruz, Mexico. Because we expect that climate change effects will affect population differentially, our aim is to analyze how climate is changing in the region and make regional climate change scenarios to provide useful information for local/regional managing and planning in terms of climate change adaptation.

MATERIALS AND METHODS

Study area

The Region of the Great Mountains is located in the south-central part of Veracruz (19°54′08″N, 96°57′19″W) (Fig. 1) with a surface of 6350.85 km^2. The region is part of the Neovolcanic Ridge and the Sierra Madre Oriental. Abrupt topography is the main characteristic going from sea level up to 5500 m above sea level (asl) in a distance of 100 km. Vegetation types go from tropical cloud forest to semi-arid and arid communities (Gómez-Pompa 1978).

Population and finance

We gathered information related to population and finance from the Regional Planning Studies (ERP for its acronym in Spanish, 2011), the National Council of Population (CONAPO for its acronym in Spanish, 2011), and the Veracruz State Government (accessed July 15, 2014). Fifty-seven municipalities conform the region (Fig. 1). Twenty-two are completely rural, and only two are metropolitan areas: Orizaba and Córdoba. 98.6 % of the urban settlements have <5000 inhabitants. In the year 2000, the population was 1 237 461; 10.5 % were included in the range of 5–9 years old. 539 090 individuals lived in rural conditions and 698 371 lived in urban concentrations. 57.1 % are beneficiaries to health services, 64.4 % of households have cement/firm floor, and 13.3 % do not have floor; 14.2 % of households do not have piped water service, 18.9 % have no drainage, and also 3 % of households do not have electricity. As for access to transportation, the region has 1938.3 km road network comprised (ERP 2011).

According to the Laws of Revenue for the State Municipalities for the Fiscal year of 2011, the municipalities of the region have 234.05 million USD from their own income, equity, and federal contributions to meet the population demands, with a public spending/municipalities of 278.55 millions USD, where Córdoba and Orizaba had the major incomes and spending (ERP 2011).

Land use: Vegetation and agricultural activities

The region is known for its land-use guidance to primary sector activities with more than 67.9 % of its territory intended to pasture and agricultural activities. According to the National Institute of Statistics and Geography (INEGI 2013), 62.42 % of the territory (3779.32 km^2) comprised agricultural activities, whereas 36.37 % (2202.57 km^2) presents different vegetation types, and only 1.18 % (71.89 km^2) of the territory has urban cover (Table 1; Fig. 1). The region has a wide variety of crops, highlighting sugarcane, coffee, corn, chayote, potatoes, lemon, beans, gladiola, and hevea rubber (ERP 2011).

Socio-economic indicators: The Human Development Index (HDI) and the marginalization level

We considered as socio-economic indicators the HDI and the marginalization level (CONAPO 2001). The

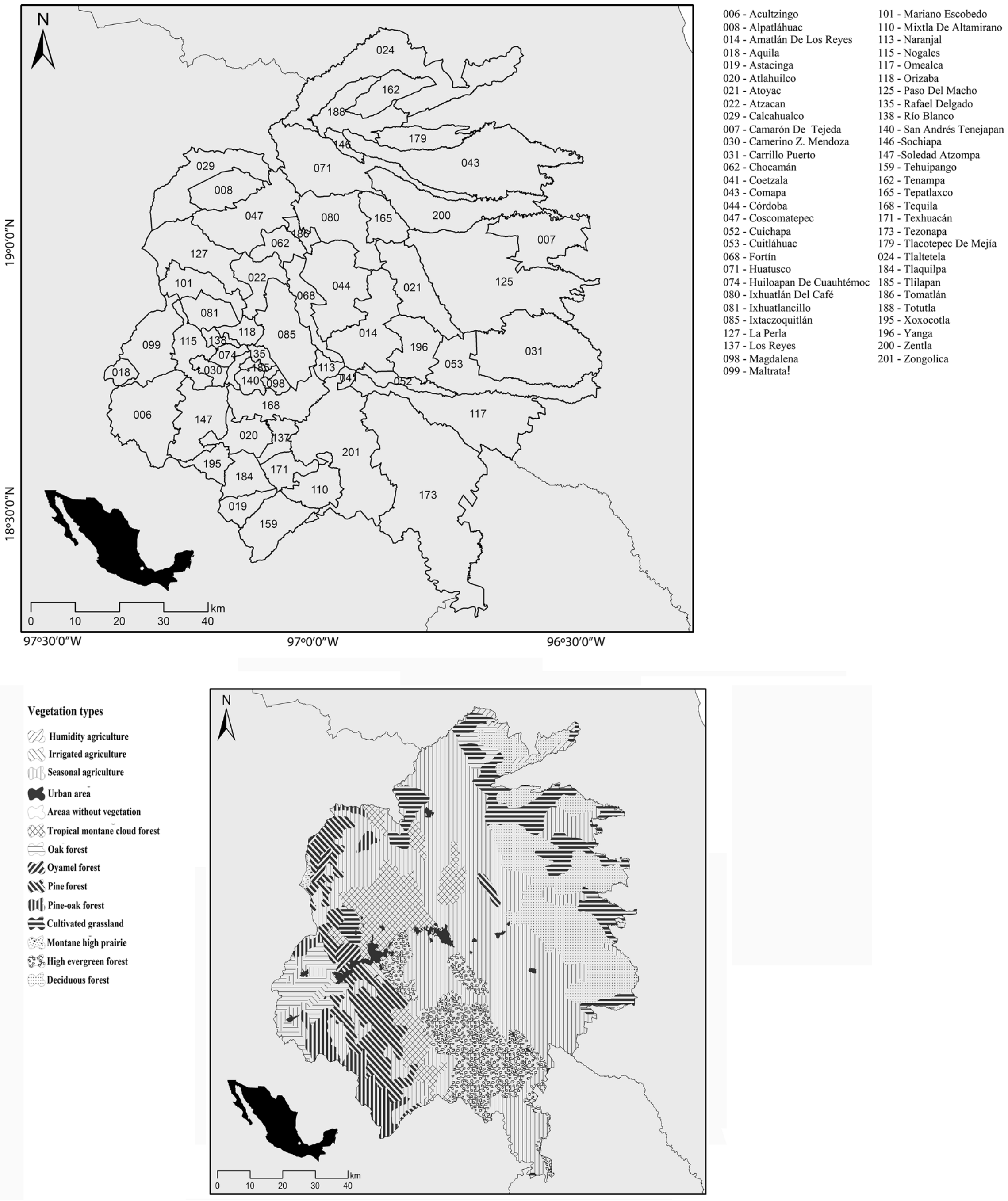

Fig. 1 Location, vegetation types, and municipalities of the Region of the Great Mountains, Veracruz

marginalization level is a measure of intensity of deficit and deprivation, and lack of population related to education, housing, and monetary income, categorized it into five levels: very high, high, medium, low, and very low (CONAPO 2001). CONAPO (2001) considers four structural dimensions of marginalization: housing, education, employment income, and population distribution.

In contrast, the HDI is a comparative index created to emphasize that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone (CONAPO 2001). Three dimensions compose the index: health, education, and income, and is a summary measure of average achievement in key dimensions of human development considering a

Table 1 Vegetation types and covered area in the Region of the Great Mountains, Veracruz

Vegetation type	Area (km^2)
Area without vegetation	1.09
Cultivated grassland: Secondary vegetation of deciduous forest	6.80
Montane high prairie	11.45
Irrigated agriculture	28.34
Seasonal agriculture: Secondary vegetation of deciduous forest	31.33
Cultivated grassland: Seasonal agriculture	32.19
Humidity agriculture	36.27
Deciduous forest	42.91
Oyamel forest	48.30
Urban area	71.89
Secondary vegetation of deciduous forest: Cultivated grassland	151.72
Secondary vegetation of deciduous forest: Induced grassland	213.54
Oak forest	220.47
Pine–oak forest	231.68
Seasonal agriculture: Cultivated grassland	234.36
Secondary vegetation of deciduous forest: Seasonal agriculture	427.16
Pine forest	472.97
Cultivated grassland	481.08
Seasonal agriculture: Secondary vegetation of semi-evergreen seasonal forest	515.75
Tropical montane cloud forest	530.79
High evergreen forest	644.00
Seasonal agriculture	1620.78

long and healthy life, being knowledgeable and have a decent standard of living (CONAPO 2001).

Climatological data

General Circulation Models (GCMs)

Historic data from GCMs were obtained in the period 1960–2000 from the Climatic Research Unit (CRU) data base version TS3.1 and from the weighted Reliability Ensemble method (REA) (Giorgi and Mearns 2001). For future climate change projections (periods 2015–2039 and 2075–2099), we took data from the Coupled Model Intercomparison Project Phase 5 (CMIP5). We downloaded data for three Representative Concentration Pathways (RCP): 4.5, 6.0, and 8.5 (http://escenarios.inecc.gob.mx/index2.html, accessed May 23, 2015).

Precipitation and temperature trends

We took data from all active meteorological stations from the region. Because of the low number of stations with adequate data (only eight: Coscomatepec, El Coyol, Ixhuatlán del Café, Huatusco, Naranjal, Tenampa, Totutla, and Villa Tejeda), we also selected fifteen meteorological stations from the north region and three from the south region in the state of Puebla (San Bernardino Lagunas, Telpatlán, and Alcomunga) (Fig. 2), in order to elucidate how climate is changing (two case studies are shown in Fig. 3). We analyzed all data available related to total annual precipitation and average annual temperature from 1922 to 2008. The analysis was carried out with data from the Mexican National Weather Service (accessed 17 July 2014).

Using the observed data, we projected the precipitation and temperature trends to develop climate change scenarios for the years 2025, 2050, 2075, and 2100 using *Surfer* 9.11 software with the Kriging interpolation method. Kriging is a geostatistical gridding method, which attempts to express trends suggested within the source data; it is a very flexible method whereby the default parameters may be accepted to produce an accurate grid of the source data (Cressie 1990, 1991). We considered all stations to evaluate climatic conditions and create climate change scenarios. Nevertheless, this study should be considered more an exploratory assessment of the possible changes in temperature and precipitation, rather than future predictions.

Socio-economic vulnerability

We start from the premise that there is a strong relationship among social, agricultural, and climatic factors, as well as

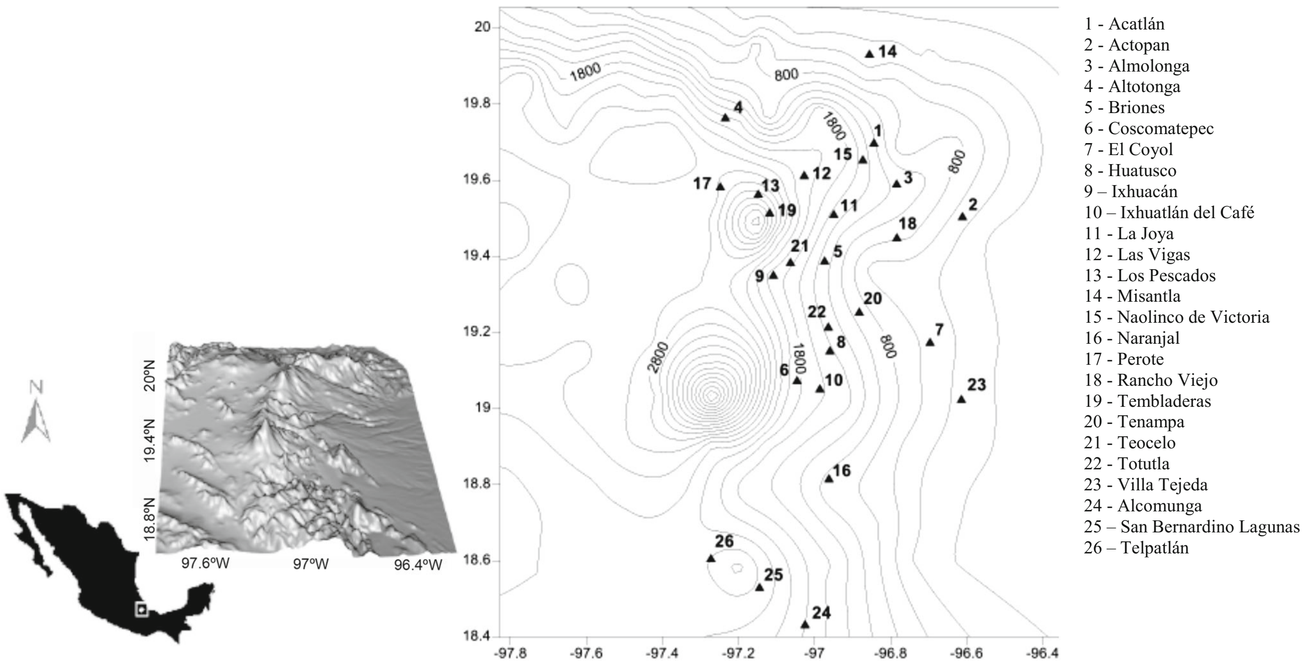

Fig. 2 Location of the 26 meteorological stations in the Region of the Great Mountains, Veracruz, and contour line distribution (range 200 m) for the region

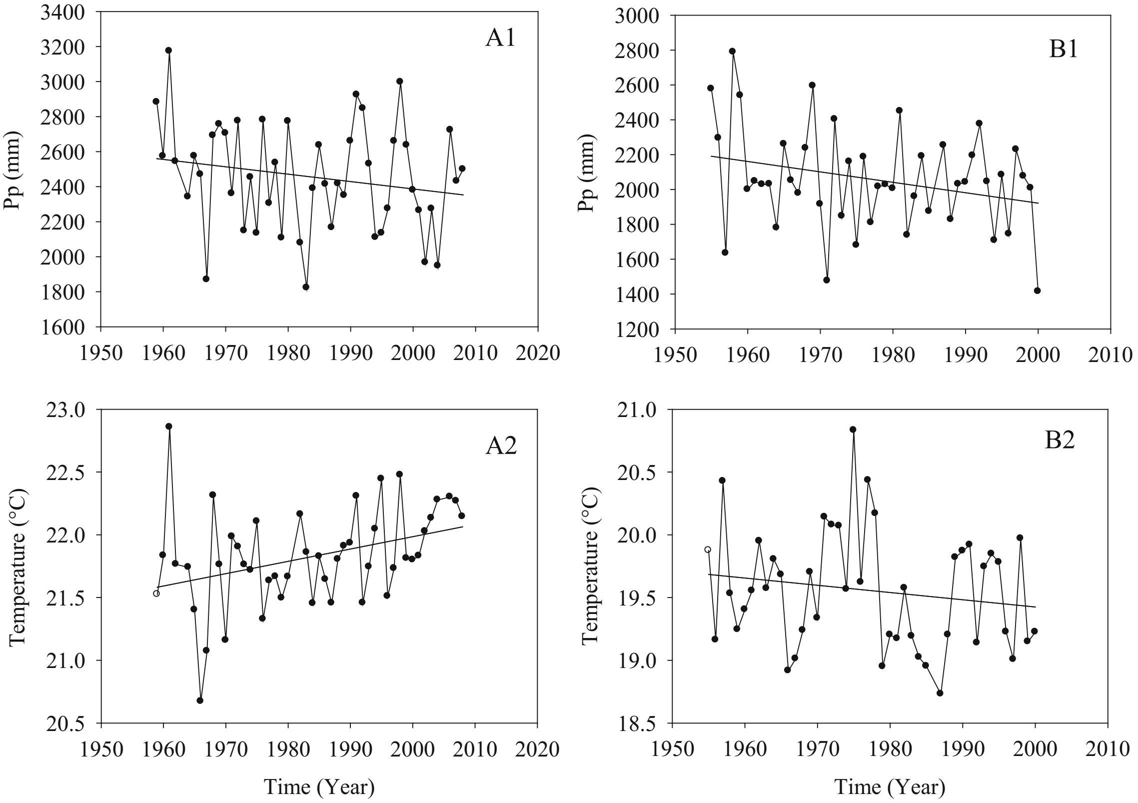

Fig. 3 Precipitation (**A1**, **B1**) and temperature (**A2**, **B2**) trends for the meteorological station of El Naranjal (**A1**, **A2**) and Huatusco (**B1**, **B2**) from the Region of the Great Mountains, Veracruz

the availability of productive capital (Patz et al. 2005). That is, changes in precipitation and temperature patterns and changes in the agricultural production affect food supply, especially basic grains. We linked the social situation in the region, reflected in the HDI and the marginalization level, with the agricultural production in each municipality, and how the effects of climate change would affect their crops. Thus, a municipality is considered more vulnerable when the HDI is lesser, its marginalization level is higher, it is more dependent on agricultural activities, and also its crops are more susceptible to local and regional climate changes.

Statistical analysis

We analyzed data with *XLSTAT* statistical package to determine whether trends increase or decrease. We performed the Mann–Kendall test (Nasrallah et al. 1990) to analyze whether temperature and precipitation trends were significant. The purpose of the Mann–Kendall test is to statistically assess if there is a monotonic upward or downward trend of the variable of interest over time (Mann 1945; Kendall 1975). Statistical significance was considered at 95 % for all cases.

RESULTS

Socio-economic differences were noted when we analyzed human development and marginalization. For marginalization, 17 municipalities had “Very high” level, 14 “High” and only two “Very low.” Municipalities with “Very high” level of marginalization have high population densities and are considered as rural areas. Their populations suffer absence/lack of access to education, inadequate housings, and insufficient monetary perception and income. As for the HDI, one municipality had “Low” level, most municipalities have “Medium,” and 7 had “High,” Only these 7 municipalities can be considered to have a long and healthy life, being knowledgeable, and have a ‘good’ standard of living (Supplementary material Table S1).

Contrasting municipalities: Marginalization and human development

To emphasize differences of marginalization and human development, and the socio-economic contrast, we compared two municipalities: the biggest and most populated and the smallest and less populated (Table 2). Córdoba is the largest municipality with 196 541 inhabitants and an extension of 135.6 km^2 used for agricultural activities. Main crops are sugarcane (445 152 Mt with an estimated value of 14 679 122.62 USD), coffee (6996 Mt with an estimated value of 2 212 918.75 USD), and corn (2557 Mt with an estimated value of 716 921.15 USD). In contrast, Aquila has 1797 inhabitants and is completely rural. More than half of its territory is destined for agricultural activities, where population depends on corn production (1040 Mt with an estimated value of 363 916.97 USD) (Veracruz State Government, accessed 15 July 2014). Differences found between Aquila and Córdoba (Table 2) made us consider Aquila to be more vulnerable against the possible climate change effects. We considered more vulnerable those areas that are small and poor, with most of its economically active population dedicated to the primary sector.

Climatological data

General Circulation Models (GCMs)

The CMIPP5 showed an historic increase in the temperature for the period 1960–2000, where the REA had a clear temperature increase of 0.5°C; whereas the CRU had a greater variability over time but temperature increased only by 0.02°C. Regarding precipitation, the CRU presented a higher change projection (mm per day), with an increase of 0.46 mm/d at the end of period; whereas the REA had a more constant and lower change projection with a decrease of 0.072 mm/d. For future projections, in both periods 2015–2039 and 2075–2099, the three RCP had increases in temperature: (i) RCP4.5: 1.54°C, (ii) RCP6.0: 2.17°C, and (iii) RCP8.5: 3.82°C. For precipitation, the three RCP had decreases: (i) RCP4.5: −0.23 mm/d; (ii) RCP6.0: −0.11 mm/d, and (iii) RCP8.5: −0.23 mm/d.

Precipitation and temperature trends

15 meteorological stations had no statistically significant trends (Table 3). However, no statistically significant trend should not be misinterpreted as ‘no trend’; it can equally mean that the calculation has been performed over a time frame too short to detect any real trend in statistical terms. In contrast to the GCM, we found positive and negative trends related to average annual temperature and total annual precipitation. 15 stations had decreases and 11 had increases of precipitation, whereas 16 stations had increases and 10 had decreases of temperature (Table 3). As it can be seen in Fig. 4, temperature/precipitation distribution is not uniform in the region, finding particular local trends.

Agriculture in the region

We found that sugarcane is the major crop with 58.6 % of total production value, followed by coffee and corn

Table 2 General characteristics, poverty and marginalization indicators, Human Development Index, and housing characteristics for two contrasting municipalities in the Region of the Great Mountains, Veracruz (Data from 2010; Veracruz State Government, retrieved July 15, 2014)

General characteristics	Municipality	
	Córdoba	Aquila
Inhabitants	196 541	1797
Extension (km^2)	159.9	20.6
Agricultural activities (km^2)	135.6	11.9
Urban areas (km^2)	15.8	–
Economically active population	85 004	700
Primary sector (%)	3.4	74.6
Secondary sector (%)	18.9	5.5
Tertiary sector (%)	73.1	19.7
Economic participation rate (%)	55.2	54.5
Gross production	1 298 481 003.97 USD	22 062.76 USD
Fixed assets	439 941 279.95 USD	46 181.55 USD
Poverty indicators		
Population living in food poverty (%)	17.6	54.1
Population in capacity poverty (%)	26.4	64.1
Population living in patrimony poverty (%)	52.5	83.9
	Reference	
Marginalization indicators		
Marginalization level	Low	Very high
Marginalization Index	−1.1793	1.5558
Place in the state context	200	15
Place in the national context	2153	169
Illiterate population (15 years or more) (%)	6.2	39.1
Population without complete primary education (15 years or more) (%)	21.3	66.0
Occupants in dwellings without drainage or exclusive toilet (%)	1.0	25.5
Occupants in dwellings without electricity (%)	0.8	6.2
Occupants in houses without running water (%)	12.4	36.6
Homes with some level of overcrowding (%)	40.4	69.5
Occupants in houses with dirt floors (%)	8.2	46.9
Population in towns with <5000 inhabitants (%)	17.5	100
Employed population with income up to 2 minimum wages (%)	51.5	80.3
Human Development Index		
Level of human development	High	Medium
Human Development Index	0.8370	0.6306
Education Index	0.8529	0.5974
Health Index	0.9105	0.6592
Index entry	0.7477	0.6356
Housing characteristics	%	
With availability of piped water	91.8	72.0
With availability of drainage	97.1	55.2
With availability of electricity	99.1	95.0

(19.8 and 10.2, respectively). Concerning harvested area, cherry coffee is the most representative crop, with an area of 816.29 km^2, followed by sugarcane and corn with 791.27 and 577.03 km^2, respectively. 43 municipalities cultivate corn, 26 coffee, and 17 sugarcane (ERP 2011).

Table 3 Precipitation and temperature trends from 26 meteorological stations in the Region of the Great Mountains, Veracruz. Trends' statistical significance was tested using the Kendall's tau at an alpha level of 0.05. [*Significant tendencies ($P < 0.05$)]

Meteorological station		Latitude	Longitude	Elevation (m asl)	Data (years)	Precipitation projection	Temperature projection
1 Acatlán	30338	19.6958	−96.8439	1751	1980–2008	$P_p = -2.4765(\text{year}) + 6415.5$	$T = -0.0011(\text{year}) + 17.3$
2 Actopan[a]	30003	19.5028	−96.6111	250	1954–2008	$P_p = -3.1451(\text{year}) + 7110.1$	$T = 0.0143(\text{year}) - 3.4852$
3 Almolonga	30007	19.5883	−96.7842	730	1971–2008	$P_p = 1.1793(\text{year}) - 1310$	$T = 0.0197(\text{year}) - 16.821$
4 Altotonga	30008	19.7625	−97.2347	1867	1960–2008	$P_p = 3.0385(\text{year}) - 4578$	$T = 0.0071(\text{year}) + 0.2055$
5 Briones	30452	19.5083	−96.9494	1349	1985–2008	$P_p = 4.781(\text{year}) - 7842$	$T = -0.0273(\text{year}) + 72.23$
6 Coscomatepec	30032	19.0717	−97.0461	1530	1954–2007	$P_p = 7.157(\text{year}) + 1951.8$	$T = -0.0674(\text{year}) + 20.238$
7 El Coyol[a]	30047	19.1722	−96.6964	545	1980–2008	$P_p = -8.6085(\text{year}) + 18255$	$T = 0.0358(\text{year}) - 48.352$
8 Huatusco	30066	19.15	−96.9597	1284	1955–2008	$P_p = -5.9775(\text{year}) + 13877$	$T = -0.0058(\text{year}) + 30.982$
9 Ixhuacán[a]	30336	19.3486	−97.1083	1802	1980–2007	$P_p = -8.9545(\text{year}) + 20689$	$T = 0.0444(\text{year}) - 73.24$
10 Ixhuatlán del Café[a]	30072	19.05	−96.9861	1350	1981–2008	$P_p = -1.9043(\text{year}) + 1926.4$	$T = 0.0415(\text{year}) + 19.704$
11 La Joya	30455	19.6108	−97.0272	2175	1991–2008	$P_p = -2.2086(\text{year}) + 6294.3$	$T = -0.1039(\text{year}) + 220.58$
12 Los Pescados	30097	19.5614	−97.1481	2395	1980–2008	$P_p = 1.0373(\text{year}) - 1210.5$	$T = 0.069(\text{year}) - 127.38$
13 Las Vigas[a]	30211	19.382	−97.0635	2400	1922–2008	$P_p = -3.7464(\text{year}) + 1336.1$	$T = 0.0132(\text{year}) + 11.114$
14 Misanla	30108	19.9292	−96.8556	310	1926–2008	$P_p = -2.3604(\text{year}) + 6675.9$	$T = -0.0172(\text{year}) + 56.38$
15 Naolinco de Victoria[a]	30114	19.6519	−96.8731	1542	1956–2008	$P_p = -2.5545(\text{year}) + 6770$	$T = 0.0271(\text{year}) - 36.547$
16 Naranjal[a]	30115	18.8139	−96.9622	697	1959–2008	$P_p = -4.2314(\text{year}) + 10849$	$T = 0.0098(\text{year}) + 2.3563$
17 Perote	30128	19.5808	−97.2478	2392	1967–2007	$P_p = 3.3255(\text{year}) - 6129.9$	$T = -0.0209(\text{year}) + 54.197$
18 Rancho Viejo	30140	19.4469	−96.7836	914	1969–2008	$P_p = -3.7932(\text{year}) + 8694$	$T = -0.0178(\text{year}) + 56.08$
19 Tembladeras	30175	19.5122	−97.1181	3102	1966–2008	$P_p = 3.0546(\text{year}) - 4407.6$	$T = 0.0162(\text{year}) - 22.781$
20 Tenampa	30177	19.2517	−96.8825	1015	1980–2004	$P_p = -8.6901(\text{year}) + 18994$	$T = -0.1673(\text{year}) + 353.2$
21 Teocelo[a]	30179	19.3861	−96.9736	1188	1946–2008	$P_p = -3.139(\text{year}) + 8299.7$	$T = 0.0351(\text{year}) - 49.33$
22 Totutla	30187	19.2125	−96.9639	1446	1960–2008	$P_p = 8.1987(\text{year}) + 1784.1$	$T = 0.0232(\text{year}) + 18.01$
23 Villa Tejeda	30364	19.0222	−96.6139	348	1983–2008	$P_p = 4.3279(\text{year}) + 989.21$	$T = -0.0081(\text{year}) + 24.237$
24 Alcomunga	21009	18.4306	−97.025	2485	1956–2009	$P_p = 15.664(\text{year}) + 2163.1$	$T = 0.136(\text{year}) + 11.536$
25 San Bernardino Lagunas[a]	21053	18.6039	−97.2725	1693	1955–2009	$P_p = -1.5411(\text{year}) + 741.39$	$T = 0.0617(\text{year}) + 12.817$
26 Telpatlán	21084	18.5281	−97.1447	2212	1955–2009	$P_p = 1.4843(\text{year}) + 1231.8$	$T = 0.0023(\text{year}) + 13.694$

	Meteorological station	Temperature				Precipitation			
		Mean	SD	Kendall's Tau	P value	Mean	Deviation	Kendall's Tau	P value
1	Acatlán	15.21	0.29	0.01	0.974	1467.03	305.63	0.03	0.873
2	Actopan	24.89	0.46	0.27	0.005*	873.81	198.04	−0.11	0.244
3	Almolonga	22.45	0.40	0.36	0.003*	1042.83	236.01	0.02	0.866
4	Altotonga	14.24	0.80	0.12	0.281	1445.87	322.25	0.08	0.442
5	Briones	17.72	0.39	−0.23	0.159	1707.60	224.96	0.12	0.456
6	Coscomatepec	18.42	1.27	0.22	0.045*	2145.06	396.38	−0.11	0.401
7	El Coyol	23.07	0.48	0.50	<0.001*	1089.85	178.50	−0.23	0.105
8	Huatusco	19.55	0.47	−0.07	0.540	2045.67	281.19	−0.10	0.349
9	Ixhuacán	15.40	0.78	0.28	0.265	2819.27	421.44	−0.07	0.757
10	Ixhuatlán del Café	20.24	0.78	0.49	0.034*	1901.68	249.96	−0.11	0.021*
11	La Joya	12.75	0.69	−0.62	0.001*	1876.81	205.36	−0.10	0.598
12	Los Pescados	10.13	0.80	0.45	0.001*	854.47	234.63	0.07	0.632
13	Las Vigas	11.66	0.59	−0.33	0.016*	1182.55	298.48	−0.20	0.023*
14	Misantla	22.68	0.94	−0.24	0.013*	2041.80	443.64	−0.10	0.297
15	Naolinco de Victoria	17.14	0.97	0.28	0.006*	1708.07	251.98	−0.06	0.559
16	Naranjal	21.83	0.39	0.27	0.008*	2447.10	303.68	−0.10	0.327
17	Perote	12.61	0.49	−0.34	0.003*	478.09	119.24	0.18	0.120

Table 3 continued

	Meteorological station	Temperature				Precipitation			
		Mean	SD	Kendall's Tau	*P* value	Mean	Deviation	Kendall's Tau	*P* value
18	Rancho Viejo	20.67	0.70	−0.19	0.095	1146.39	232.03	−0.12	0.289
19	Tembladeras	9.50	0.51	0.26	0.017*	1668.26	265.69	0.09	0.428
20	Tenampa	19.80	1.55	−0.51	0.001*	1685.36	328.90	−0.27	0.098
21	Teocelo	19.89	0.89	0.46	<0.001*	2103.79	293.25	−0.12	0.217
22	Totutla	18.53	3.55	0.61	0.674	280.50	280.50	−0.22	0.232
23	Villa Tejeda	24.01	3.84	0.33	0.750	1098.79	194.67	0.99	0.083
24	Alcomunga, Puebla	12.11	1.58	0.11	0.433	2393.21	760.70	0.13	0.061
25	San Bernardino Lagunas, Puebla	13.68	0.70	0.402	0.092	719.81	141.14	−0.30	0.342
26	Telpatlán, Puebla	13.73	0.88	0.271	0.125	1254.05	365.43	0.19	0.202

[a] Potential areas where the increment in temperature and the decrement in precipitation increase the vulnerability to fire and crop productivity

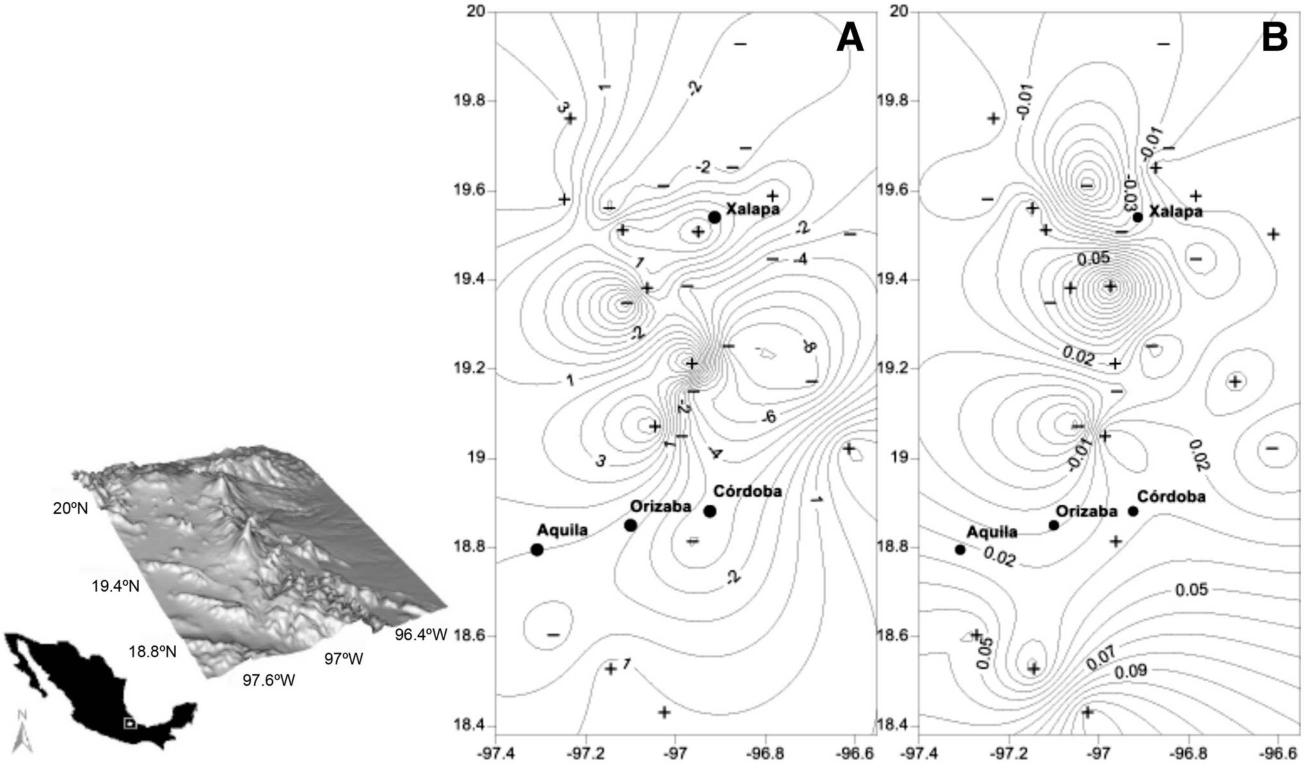

Fig. 4 Increment (+) and decrement (−) of precipitation (**A** mm year^{-1}) and temperature (**B** °C year^{-1}) in the 26 meteorological stations from the Region of the Great Mountains, Veracruz

Because of the importance of these crops, local farmers and producers must know the optimal conditions and when their crops are at risk. High-quality coffee requires more than 3000 mm, and with <1000 mm plant growth is limited; also, a very prolonged drought period conducts to defoliation and death. Optimum temperature goes from 17 to 23°C; also it is recommended relative humidity <85 % (Barva 2011). Vulnerability is high for coffee, especially where temperature increases and precipitation decreases; thus, the recommendation is that the mountainous central region where precipitation increases and the temperature decreases should be devoted to coffee.

As for corn, from planting to maturity it requires 500–800 mm, depending on variety and climate, but its average water requirement per cycle (1 year) is 650 mm. 6–8 mm/day is necessary during early stages of development. Optimum germination temperature ranges between 18 and 21°C, germination below 13°C is reduced significantly, and below 10°C no germination occurs. Photosynthesis and development is maximum between 30 and 33°C. Practically, no cultivation occurs where average temperature is lower than 19°C or when average temperature during night at summer falls below 13°C. The combination of temperatures above 38°C plus water stress during early formation and development prevents grain formation; whereas temperatures below 15.6°C delayed significantly flowering and maturity (Ruiz et al. 1999). For corn, vulnerability increases with temperature changes. Fortunately, corn is tolerant to low precipitation. In regions where precipitation decreases and irradiance increases, corn can be benefited. However, corn has high economical importance (75 % of the municipalities cultivate corn). Also, the region's culture is based on a corn-nutrition feeding; therefore, consequences in a production decrement would enhance vulnerability.

Concerning sugarcane, its growth is directly related to temperature. Optimum temperature for germination ranges between 32 and 38°C. Germination drops below 25°C, is optimal between 30 and 34°C, reducing around 35°C, and stops above 38°C. Temperatures above 38°C reduce photosynthesis rate and respiration increases. For ripening are preferred relatively low temperatures (12–14°C), and exerted a strong influence on reducing the vegetative growth rate and enrichment. As for precipitation, a total rainfall between 1100 and 1500 mm is suitable, providing adequate and abundant light during growth, followed by a dry period for ripening (Subirós-Ruiz 1995). For sugarcane, temperature changes may limit growth. However, a decrease in precipitation and clouds' reduction may increase irradiance favoring this crop. Crops more tolerant to low precipitation must be promoted in areas where precipitation decreases.

Socio-economic vulnerability

Not all municipalities will be affected similarly by climate changes. For some municipalities, such as Coscomatepec, Tepatlaxco, Totutla, and Zentla, climate changes will be beneficial. However, for Atoyac, Atzacan, Huatusco, Ixhuacán del Café, Naranjal, Sochiapa, Tenampa, and Tepatlaxco, increment in temperature and decrement in precipitation will enhance vulnerability. Coffee is the main crop in all these municipalities, except Atzacan, and they are located in regions where precipitation decreases; here <1000 mm of precipitation will have severe socio-economic consequences, especially in the drier region of Tenampa. Additionally, an increase of 2–3°C in Naranjal and Ixhuacán del Café will also affect coffee productivity. If climate changes are such that coffee production decreases by 50 %, these municipalities will have large revenue losses, where Tenampa and Tepatlaxco will be the most affected because of their greater dependence on this crop. For Atzacan, where the main crop is sugarcane, climate change could benefit the crop, as long as the rain is not less than 1000 mm and temperature is not lower than 25°C. For these municipalities, vulnerability is linked to the high marginalization level and their agricultural activities (Table 4).

DISCUSSION

Municipalities whose main activity is agriculture cannot generate enough income to stay out of the agricultural production falls, but they can mitigate the consequences of climate change through adaptation in at least two possibilities: (i) changing from agriculture to more profitable sectors and better employment or (ii) migrate to more productive regions (Assunçao and Chein Feres 2009). However, for some municipalities none of these possibilities are viable options, and in any case changes in local climate will affect volume and price of the harvested crops. In some of these areas, the rapid and total conversion to mono-cultural plantation cash crops might be widespread option. When the price of coffee drops so that the plantation is no longer an economically viable proposition, it cannot quickly revert to the biologically diverse forest that preceded it (McNeely 1995). Here, changing to sugarcane is not recommended because this land-use change could increase climate variability. One more favorable option to maintain biodiversity and crop production could be the incorporation of croplands to the payment of environmental services. The National Forestry Commission (CONAFOR) supports four types of forest environmental services and promotes the development of mechanisms for local, municipal, and state payments. The average support given (USD/ha/5 years) for conservation of biodiversity is 177.92, for agroforestry crops under shade is 162.77, for hydrological services is 162.15, and the elaboration of projects related to carbon sequestration is also paid (SEMARNAT-SHCP 2009). Maintaining biological diversity is essential for productive agriculture, and ecologically sustainable agriculture is in turn essential for maintaining biological diversity (Pimentel et al. 1992). In places where the new conditions are not favorable for coffee and the payment of environmental services is not suitable, some suggestions could be to change to other crops that maintain forest cover and diversity, diversify the

Table 4 Most vulnerable municipalities from the Region of the Great Mountains, Veracruz; their climatological risk regarding changes in temperature (T_A) and precipitation (P_p); the economically active population engaged in tertiary sector (PAE); their main crops including the harvested area, volume (Vol), and value (thousand of USD), and the marginalization level (ML) (Data from 2010; Veracruz State Government, retrieved 15 July, 2014). *NA* data no available

Municipality	Risk		PAE (%)	ML	Main crops	Harvested area (ha)	Volume (Mg)	Value
	T_A	P_p						
Atoyac	+	–	35.9	Medium	Coffee	3138.0	6150.5	1892.45
					Sugarcane	1530.0	108 451	3170.11
					Corn	345.0	552	148.62
Atzacan	+	–	40.9	High	Sugarcane	3000.0	255 000	6669.23
					Coffee	862.0	3017	1137.18
					Corn	594.0	1308	436.62
Huatusco	–	–	54.8	Medium	Coffee	7901.0	15 802	5469.92
					Corn	1050.0	1890	508.85
					Sugarcane	1050.0	52 500	1494.23
Ixhuacán del Café	+	–	24.9	High	Coffee	6392.0	9588	3318.92
					Corn	790.0	1580	425.38
					Bean	173.8	52.1	60.16
Naranjal	+	–	48.8	High	Coffee	920.0	2622	806.77
					Corn	140.0	207	55.73
					Sugarcane	51.0	4445	142.58
Sochiapa	+	–	18.6	High	Coffee	995.0	1990	688.84
					Sugarcane	363.0	18 150	516.58
					Corn	25.0	50	13.46
Tenampa	+	–	27.2	High	Coffee	2711.0	6777.5	2346.06
					Corn	220.0	440	118.46
					Mango	NA	NA	NA
Tepatlaxco	+	–	11.4	Very high	Coffee	2814.0	7316.4	2251.2
					Corn	561.0	897.6	241.66
					Sugarcane	31.0	2185	63.89

agricultural areas implementing more crops, or change the cropping pattern in warm regions shifting toward patterns used in hotter regions (Butt et al. 2006). These suggestions might help mitigate the impacts of climate change.

Nevertheless, the severity of theses impacts will depend on the regional situation and specific climatic changes (Schröter et al. 2005). While all people are dependent upon the function of natural ecosystems, connection between natural world and their livelihood is more direct for some groups, in particular those dependent upon a particular natural resource, such as agriculture or subsistence farmers (Cooley et al. 2012). Cropping patterns in agricultural producing areas are primarily determined by regional climatic conditions. Farmers would respond to climate change *inter alia* by altering the crop mixture they grow, which would reduce some climate-change-related losses (Butt et al. 2005). For the region, more than 60 % of the territory comprised agricultural activities, highlighting the importance of this activity. All municipalities have agricultural activities and more than half of them depend almost entirely on agriculture where 51 % of the municipalities rely on two or three crops. For a region with such an agricultural importance, adaptation to climate change becomes a matter of relevance.

The central insight into the adaptation process is that vulnerability is socially differentiated (Adger 1999). Vulnerability is not the same for different populations living under different environmental conditions or faced with complex interactions of social norms, political institutions, and resource endowments, technologies, and inequalities (Adger 1996). The region has severe problems related to marginalization aggravating vulnerability, especially in small municipalities that rely mostly on mono-agriculture. Climate change impacts fall disproportionately on people that have contributed the least to cause the climate change problem and have the least resources to cope with it (Mendelsohn et al. 2006). For these people, food security is an issue of major concern, because climate change will affect crop yields and agriculture (Parry and Carter 1998; Met Office et al. 2011).

The agricultural systems are vulnerable to climate variability, both naturally forced and due to human activities. Food crops' productivity is inherently sensitive to climate variability due to changes in precipitation. Lack of water affects crop's growth and productivity (Kramer 1980), and drought limits crop yields and species' distribution (Jones and Corlett 1992). Adaptation to climate change to ensure adequate food security must take into account the diversity of the vulnerable populations and their capacity to respond to global climate change (Handmer et al. 1999). Therefore, adaptation should be an important component of any policy response to climate change in this sector (Reilly and Schimmelpfennig 1999), and farmers and producers need to have physical, agricultural, economic, and social resources to moderate, or adapt to, the impacts of climate variability (Challinor et al. 2007). Farmers and producers also need to know how their crops will be affected and how they can benefit from some changes. For example, promoting coffee production in proper climatic regions might have economic benefits both locally and nationally. Currently, Veracruz's coffee production represents approximately 27.4 % of the national product (ranking second at national level), with a coffee area of 1520 km^2, equivalent to 13.92 % of the total of vegetation in the state (Olguín et al. 2011). Besides, encouraging coffee production can also promote the natural vegetation preservation. Coffee plantations are developed under the same environmental conditions of the cloud forest; therefore, coexistence and recombination (replacement) of species make them complementary (García-Franco et al. 2008). The system "coffee plantation-montane cloud forest" maintains a large and vast forest cover and provides environmental services (Olguín et al. 2011).

Regardless of the crop type, cultivation in the region must aim to ensure a more efficient water use (yield of product/water consumed), because the benefits that any crop could provide will be affected when the limiting factor is water (Galmés et al. 2011). Finding 15 stations with decrements in precipitation highlights the vulnerability in the region. Precipitation increases in the east at windward or in the coastal region but at low altitudes (<800 m asl). Previously, Barradas et al. (2011) hypothesized that changes in precipitation and fog frequency are mainly caused by deforestation, where lack of vegetation cover causes a forced ascent of moist air coming from the Gulf of Mexico. Here, we hypothesized that stations located at higher elevation and leeward had precipitation increases because vegetation might retain moisture before it is transported to higher elevations. Concerning temperature, the 16 stations that had increases are located in the regions where deforestation has increased (Barradas et al. 2011), and the stations that presented a temperature decrement are located above 1000 m asl. At El Coyol, a temperature increase and a decrease in rainfall can be attributed to the lack of vegetation at leeward by the introduction of livestock and farming (Barradas et al. 2011). In Los Pescados, where temperature and precipitation increased, we believe that the agricultural activity might have caused an increment in temperature by increasing soil surface temperature, but being located at higher altitude (2395 m asl) and at windward precipitation increases because moisture is deposited due to the orography effect. For Rancho Viejo and Acatlán, temperature and precipitation decreased; here, precipitation probably decreased by lack of moisture at leeward due to deforestation, and temperature might diminish because of the cold winds coming from north (Barradas et al. 2011).

Climate in this region is affected by deforestation and local and site-specific conditions where the mountainous and rugged terrain and the winds affect the humidity entrance of the Gulf of Mexico (Barradas et al. 2011). Yet, these climate conditions may respond to other factors such as changes in land use, human settlements, and global and regional climate change. Previous studies from the region found increases in temperature (Esperón-Rodríguez and Barradas 2014a) and decreases in precipitation implying potential reductions of as much as 50 % by the year 2023 (Barradas et al. 2010). Also, an increase in consecutive dry days was predicted (Esperón-Rodríguez and Barradas 2014b).

In this work, we found that the GCMs predicted an increase in temperature and a decrease in precipitation, although their estimations were considerably lower compared to the local trends. Also, the high GCM resolution did not allow identifying more detailed changes in the mountainous massif of the region, particularly with the temperature where GCMs only predict increases. With the analysis of local trends, we found considerable climatic changes estimating possible reductions in precipitation of over 700 mm and increases in temperature of ~9°C for the year 2100 (Fig. 5, Supplementary material Table S2). Despite these values that should be considered with caveats because they are only estimates derived from the projections of the observed trends and regardless of the method considered (GCMs or trends), climate changes will impact the region. Crops will have to adapt to future conditions, and in this region vulnerability is enhanced because more than half of its population relies entirely on agriculture. Additionally, projected climatic changes can have detrimental impacts on biodiversity (Karmalkar et al. 2011). Local climatic changes will affect natural ecosystems and crop production, and thus the local economy of a region already marginalized.

To face the climatic changes occurring in the region, natural ecosystems and crops might have three general responses: (i) adaptation. If species are capable of rapid evolutionary change or have a wide range of physiological tolerances, adjustment to changing conditions and

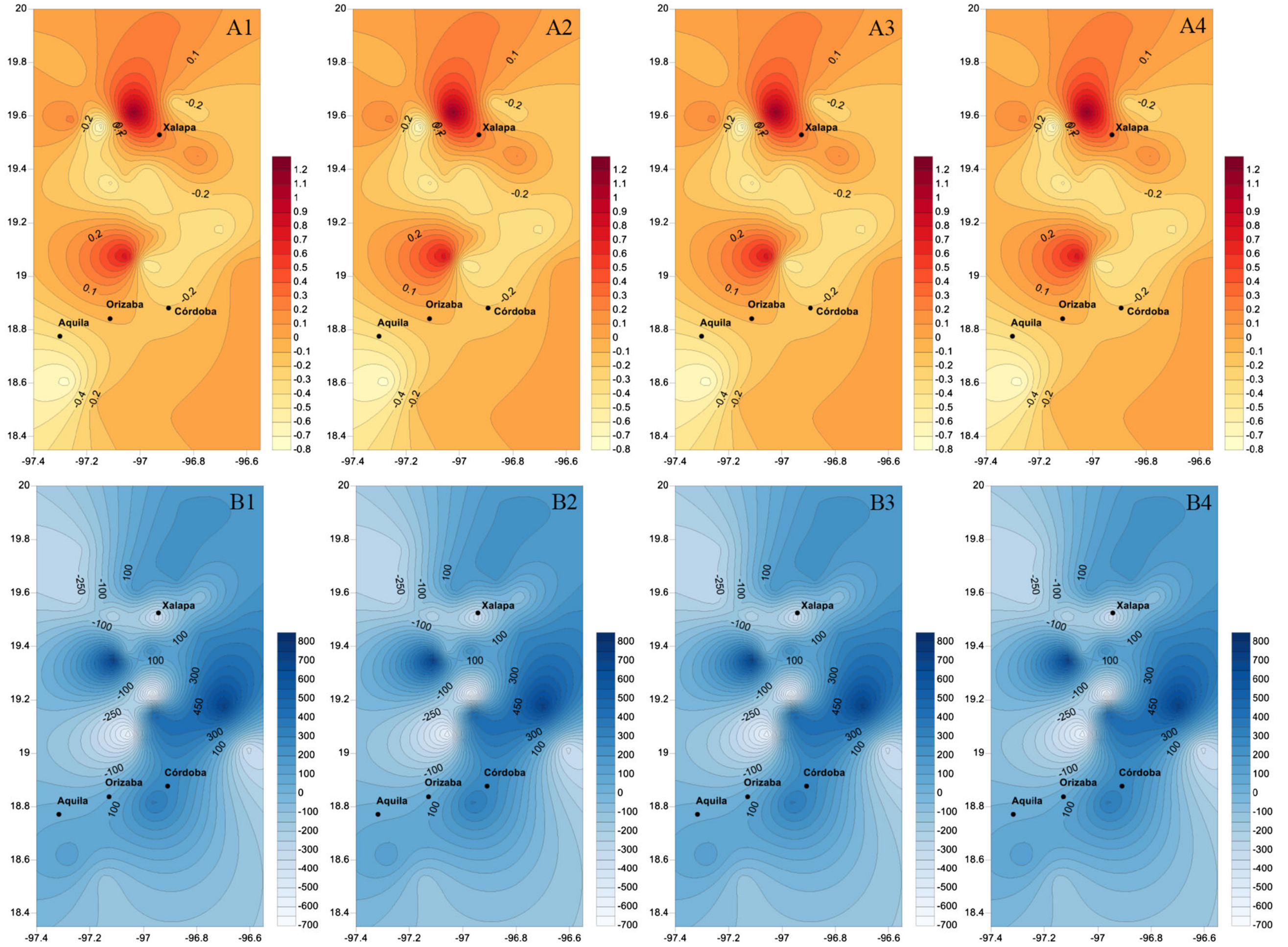

Fig. 5 Climate change scenarios in temperature (°C; color scale) for the years 2025 (**A1**), 2050 (**A2**), 2075 (**A3**), and 2010 (**A4**) and precipitation (mm; color scale) for the years 2025 (**B1**), 2050 (**B2**), 2075 (**B3**), and 2010 (**B4**) based on the temperature trends of 26 meteorological stations in the Region of the Great Mountains, Veracruz

landscapes may be possible (Holt 1990; Melillo et al. 1995); (ii) movement. If species are sufficiently mobile, they may track the geographic position of their ecological niches (Holt 1990; Melillo et al. 1995), considering space availability for new colonization, and (iii) failing adaptation and movement, extirpation is the likely result (Holt 1990; Melillo et al. 1995) for natural ecosystems and crops.

CONCLUSIONS

Future vulnerability studies must be assessed to analyze how climate change will affect the natural ecosystems, and whether the communities' coping strategies will have the capacity to deal with these scenarios. The Region of the Great Mountains is socio-economically vulnerable to climate change. Poverty, rural populations, and dependency on agriculture to support the economy enhance vulnerability. Changes in precipitation and temperature and future climate change scenarios highlight the importance to implement measures to protect the most vulnerable population, promoting crops that adapt better to the predicted climate conditions. Local, regional, and state climate analyses must be emphasized to climate impacts and mitigation strategies where communities must develop and implement adaptation plans. Local governments and regional planning agencies should conduct detailed studies to understand better the potential impacts of climate change. Also, local planning processes need to involve the most vulnerable communities when developing appropriate mitigation and adaptation strategies.

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