Original Research Article

Impacts of Climate Change on the Water Sector in Mexico

ABSTRACT

Climate and the water cycle are intimately related; so, any change in temperatures and precipitation patterns estimated for different climate change scenarios will have an impact on the availability of water resources.
Aims: The objective of this study is to present a set of regional temperature and rainfall projections for Mexico under the IPCC's AR6 climate change scenarios, improving the projections of the Ocean-Atmospheric General Circulation Models and estimating the possible impacts of climate change on Mexico's water resources.
Methodology: A set of regional temperature and rainfall projections for Mexico under the IPCC's AR6 climate change scenarios during the present century were generated by the Climate change knowledge portal (CCKP) of the World Bank and together with the projections of soil moisture, Normalized Difference Vegetation Index (NVDI), Standardized Precipitation Evapotranspiration Indices (SPEI) and droughts will be evaluated. The vulnerability of Mexico's water resources.
Results: The regional models for Mexico show temperature increases ranging from 0.5 to 5 °C, while the % change in rainfall will range from -20.3% to 13.5% depending on the scenario and analysis period. Low soil moisture (mm), negative changes in NDVI and SPEI 12 show that the North, West and Bajío areas presented reductions in precipitation and increase in temperature that caused a severe deficit of soil moisture and water stress in plants considering these areas with scarce vegetation and presence of semi-permanent meteorological drought. Under these scenarios it is expected that practically the entire country will be subjected to moderate droughts (Central and South) to extremely strong (North) that will last and sharpen between now and the end of the century. These conditions have already been registered in the main hydrological basins of Mexico and if adaptation and mitigation measures are not adopted, the country's food security is put at risk . Also, in addition to the decrease in rainfall, it is estimated that they are more intense with the presence of extreme events, which will increase the vulnerability of some basins throughout the country, in the Central and Northern areas with extreme drought events, while in the Southeast with floods.
Conclusion: To reduce the effects of climate change on water resources in Mexico, it is necessary to design and prioritize adaptation actions and implement mitigation measures that avoid intensifying the effects of climate change in the most vulnerable hydrological regions of the country.

Keywords: Water resources, Climate change, scenarios.

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1. INTRODUCTION

One of the biggest concerns with climate change concerns its potential effects on water resources and thus on food security. In fact, climate, the hydrological cycle and food production are intimately related and it is difficult to define the boundaries between them; the climate depends on relevant variables of the hydrological cycle, such as relative humidity, precipitation, evaporation among others and the productivity of crops depends on the climate and water availability. The climate system and the hydrological cycle are closely linked to the oceans, as evidenced by the ENSO phenomenon (El Niño-Southern Oscillation) [1]. Of course, the dynamics of the oceans will also

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register important changes due to the effect of global warming, which will interact with the global climate system. Inland water bodies are large climate regulators creating micro-climates in a radius close to the body of water. Thus, the increase in temperature expected in climate change scenarios will have important repercussions on the hydrological, global, regional and local cycle, and therefore, on the availability of water resources in the most vulnerable areas of Mexico on which food production depends.

The Sixth Report of the Intergovernmental Panel on Climate Change (IPCC) has concluded that: "*A.1 It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere; A.2 The scale of recent changes across the climate system as a whole -and the present state of many aspects of the climate system- are unprecedented over many centuries to many thousands of years; A.3 Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5; A.4 Improved knowledge of climate processes, paleoclimate evidence and the response of the climate system to increasing radiative forcing gives a better estimate of equilibrium climate sensitivity of 3°C, with a narrower range compared to AR5"* [2].

The effects of global climate change are already being observed with greater or lesser intensity in different regions of the world. Figure 1 shows the anomalies of a) temperature and b) global rainfall; figure 2 shows the change in global sea level [2]. As can be seen, the increase in temperature is especially important from the seventies.

The World Meteorological Organization (WMO) in its analysis of the main reanalysis databases of international research centers, indicates that the global average temperature over the continents and oceans during the year 2020 has been one of the three warmest on record. This meant a positive anomaly of 1.2 °C, compared to the average temperature of the pre-industrial era, which comprises the period between the years 1880 and 1900, as shown in Figure 3. The average surface temperature over the past ten years has been the warmest. Therefore, the decade between 2011 and 2020 has been the warmest on a global scale on record.

According to the AR6, compared to 1850-1900, is very likely that the global surface temperature averaged during 2081-2100 will be higher than 1.0 to 1.8 °C in the very low GHG emissions scenario (SSP1-1.9), of 2. 1 to 3. 5 °C in the medium GHG scenario (SSP2-4.5) and 3.3 to 5. 7 °C in the scenario of very high GHG (SSP5-8.5). The scenarios that are considered most likely today are the so-called SSP2-4.5 intermediates [2].

Temperature rise forecasts for these scenarios are shown in Table 1 [2]. In the SSP2-4.5 scenario (commonly referred to as the "medium scenario"), the expected global average temperature at the end of the century will increase from 2.1 °C and can reach 3.5 °C.

In the second most likely scenario SSP3-7.0, considered one of the critical scenarios, the expected increase will be from 2.8 to 4.6 °C. As GHG emissions continue to grow, even at an increasingly higher rate than expected, pessimistic forecasts seem to be coming true.

Mexico has a great variety of biomes, the Northern and Central areas are very arid and semi-arid and occupy 56% of the territory, the mountains and coastal plains of the Pacific, Gulf of Mexico and Northeastern of Yucatan represent the subhumid area that represents 37% and the humid areas are located in the rest of the territory with 7%. Its location between two oceans and complex topography increases the country's exposure to extreme hydro-meteorological events such as tropical cyclones, frost, heat waves and floods.

The climate of Mexico presents regional differences resulting from its topography and geographical location. The average temperature of the country varies from 15 to 20°C in the central highlands; from 23 to 27°C in the coastal lowlands. Seasonal variations are minimal in the south, but range from less than 10 °C to 30 °C in summer in the northernmost parts of the country. Mexico's average annual temperature is 20.6 °C, with average monthly temperatures ranging from 15 °C (January) to 25 °C (June).

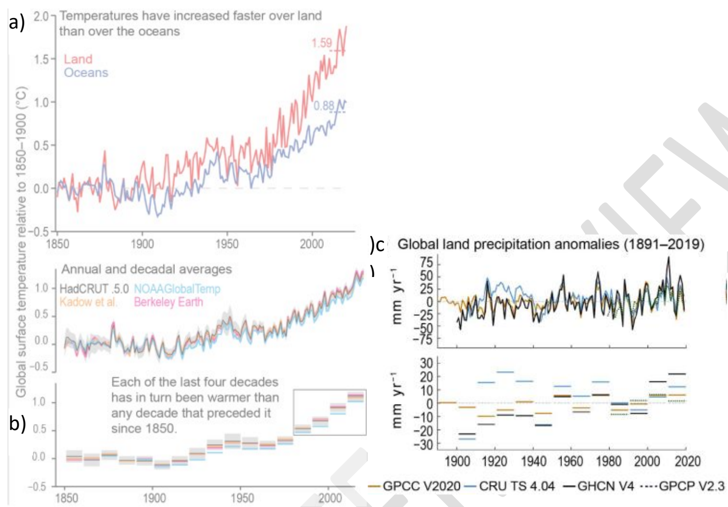


Figure 1. Earth's surface temperature history with key findings annotated within each panel. (a) Temperature from instrumental data for 1850–2020, including (upper panel) multi-product mean annual timeseries assessed for temperature over the oceans (blue line) and temperature over the land (red line) and indicating the warming to the most recent 10 years; and b) annually and decadally resolved averages for the GMST datasets. The grey shading shows the uncertainty associated with the HadCRUT5 estimate (Morice et al., 2021). c) Changes in observed precipitation. Annual time series and decadal means from 1891 to date relative to a 1981–2010 climatology [3].

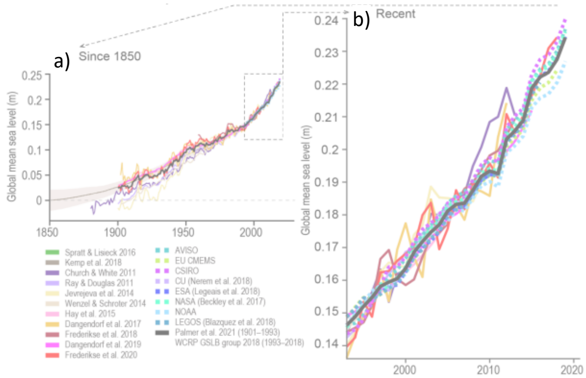


Figure 2.Changes in global mean sea level. a) Tide-gauge and, more latterly, altimeter based estimates since 1850. (b) The most recent period of record from tide-gauge and altimeter based records [3].

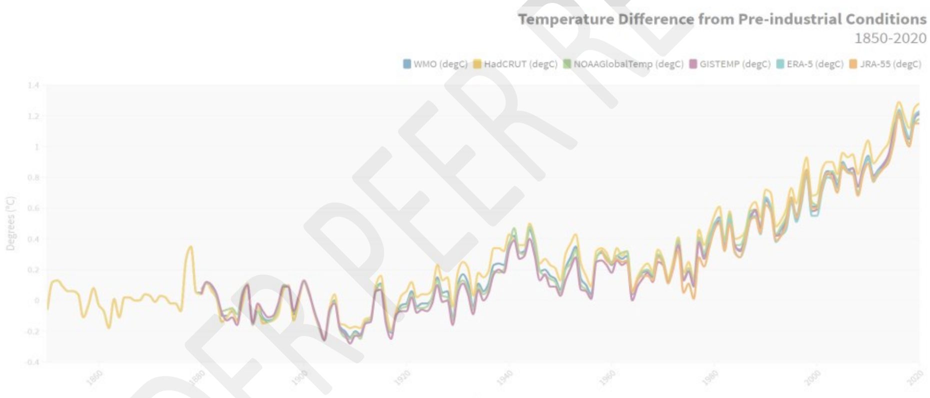


Figure 3. Average air temperature anomaly at two meters globally in 2020, from different research centers such as: ERA5 (COPERNICUS Climate Change Service of ECMWF, C3S); GISTEMPv4 (NASA); HadCRUT4 (Met Office Hadley Center); NOAA GlobalTemp (NOAA), JRA-55 (JMA) and WMO [4].

Table 1 Changes in global surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered. Temperature differences relative to the average global surface temperature of the period 1850–1900 are reported in °C. This includes the revised assessment of observed historical warming for the AR5 reference period 1986–2005, which in AR6 is higher by 0.08 [–0.01 to +0.12] °C than in AR5. Changes relative to the recent reference period 1995–2014 may be calculated approximately by subtracting 0.85°C, the best estimate of the observed warming from 1850–1900 to 1995–2014 [2].

	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
Scenario	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

The average annual rainfall is 725 mm, with constant rainfall throughout the year, but especially from June to October. In the far north, precipitation is less than 50 mm per month throughout the year, while the southern regions and central highlands experience a distinct wet season from June to October, with an average of 550 mm per month in the southernmost regions. From June to November, the Atlantic and Pacific coasts are vulnerable to hurricanes and Mexico's climate is heavily influenced by events such as the ENSO, which provides wet and cool weather in the winter, followed by warmer, drier conditions in the summer.

The historical data used for Mexico's climate projection is based on the Climate Research Unit (CRU) of the University of East Anglia. The data is presented with a resolution of 0.5ºx0.5º (50 km x 50 km).

In Mexico, the same pattern of temperature increase is observed, although with values higher than the world average, as shown in Figure 4 [4] the anomalies for the period 1950-2000 and Figure 5 temperatures for the period 1901-2020 [5]. It is noteworthy that the average temperature growth rate in the country over the past twenty years is 0.3 °C per decade, and 0.72 °C in the last decade. These values confirm Mexico's high vulnerability to climate change.

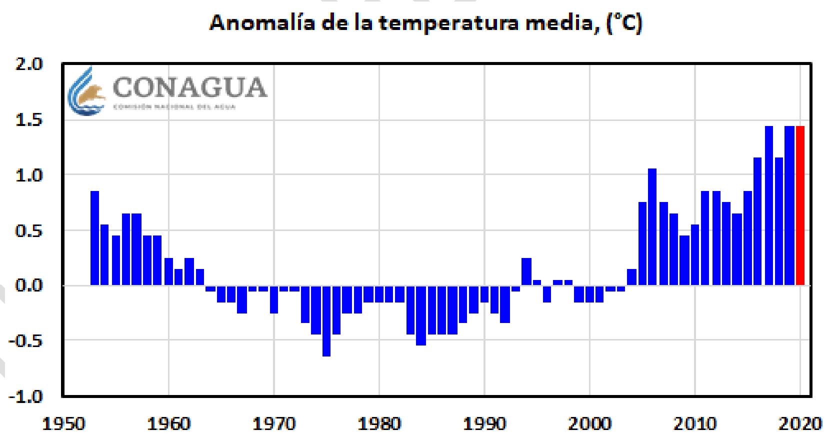


Figure 4. Anomaly of the average annual temperature in degrees Celsius (°C), the bar in red corresponds to the national anomaly estimated in 2020. Prepared based on estimates since 1953 of the National Weather Service [4].

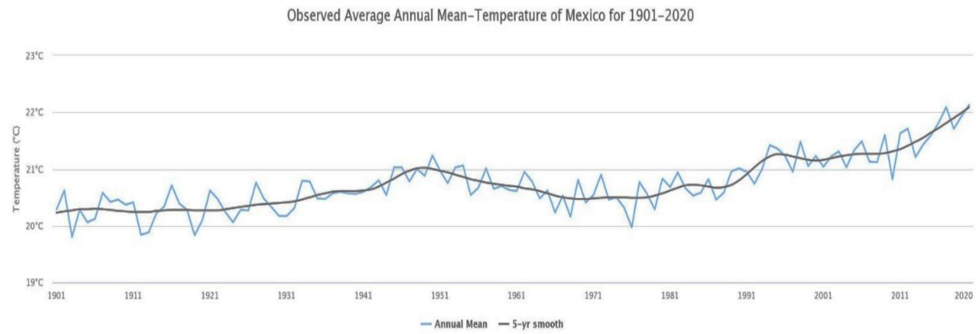


Figure 5. Average annual and five-year temperature in the period 1901-2020 [5].

As for rainfall based on historical records for the period 1941-2020, 1943 continues to be the driest year and 1958 the wettest year. The year 2020 is the second consecutive year with below-average rainfall and with it 5 years with deficit rainfall were completed in the decade from 2011 to 2020 (Figure 6). The average annual and five-year rainfall in the period 1901-2020 is presented in Figure 7.

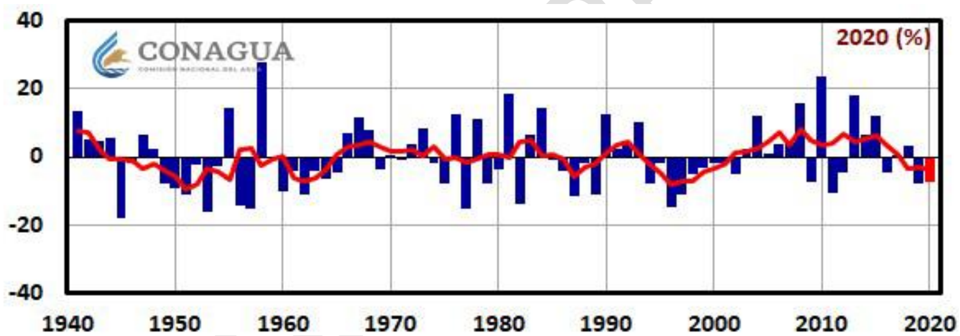


Figure 6. Precipitation anomalies at the annual national level (blue bars), five-year moving average (red line) [4].

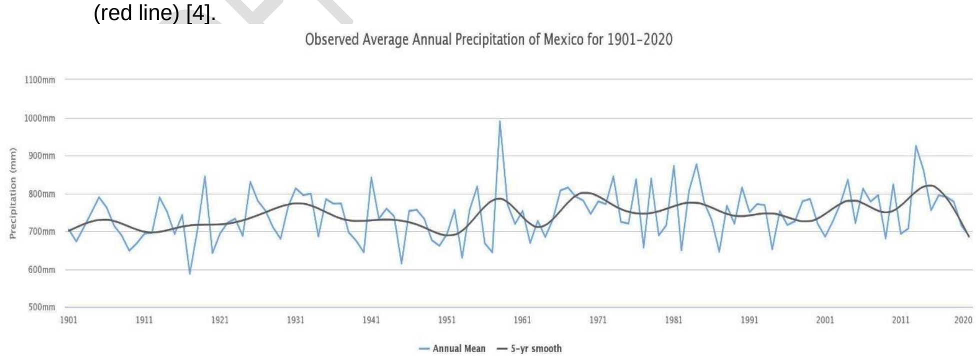


Figure 7. Average annual and five-year rainfall in the period 1901-2020 [5].

Regarding the variations in sea level, figure 8 shows measurements reported by INE-SEMARNAT-UNAM [6], which show sea level increases in some points of the coasts of Mexico. These differences are due to the fact that the increase in sea level caused by thermal expansion and thaw resulting from climate change, geological phenomena such as subsidence due to the collision of tectonic plates or continental elevation due to sediment discharge into the deltas of large rivers are added or subtracted depending on the region in question.

Future climate conditions will depend primarily on the amount of GHG emissions in the world, particularly carbon dioxide (CO_2). Thus, scientific predictions are elaborated in terms of scenarios, which will depend on the ability of our civilization to control its GHG emissions, as well as on the protection of biomes, which allows, for example, to maintain jungle and boscose regions, in which an important part of CO_2 can be captured. emitted into the atmosphere.

The objective of this study is to present a set of regional projections of temperature and rainfall under conditions of the IPCC AR6 climate change scenarios for Mexico, correcting some of the systematic errors observed in the Ocean-Atmospheral General Circulation (AOGCM) Modelos. Also establish the possible impacts of temperature and precipitation changes on Mexico's water resources.

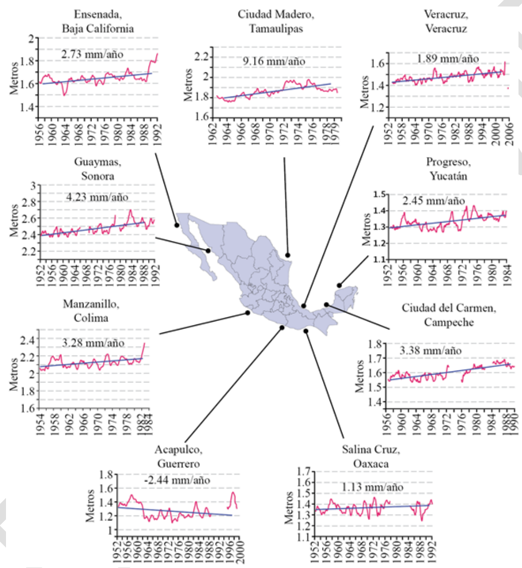


Figure 8. Variation of sea level in some places of the Mexican coasts [6].

2. METHODOLOGY

Climate change scenarios at the regional level provide the information needed to estimate the potential impacts of extreme weather on the environment and human activities [2]. Scenarios should not be tacitly considered as predictions or forecasts, but as consistent visualizations of possible future climates, responding to increased radiative forcing. This is very important since climate at the regional level can be affected by other variables that are not included in global models and climate projections such as the effects of land-use change, tropical cyclones, among others.

The Ocean-Atmosphere Global Circulation Models (AOGCM) do not have sufficient spatial resolution to represent some atmospheric processes of relevance to the regional climate of the tropical Americas (e.g., tropical cyclones) or land surface processes that determine the unique regional heterogeneity of Mexico's climate. Thus, biases in the simulations and the limited number of high spatial and temporal resolution experiments, either with nested models or statistical techniques, affected confidence regarding regional and local precipitation scenarios and, to a lesser extent, temperature scenarios. Therefore, the approach of obtaining regional scenarios focuses on reducing systematic errors in AOGCM to reach an adequate estimate of the expected ranges of change due to increased GHG concentrations.

Due to the coarse scale at which AOGMCs operate, the geographical locations of coasts or mountain ranges may be distorted, inducing systemic discrepancies in regional climate simulations. These discrepancies can spread in regional climate change scenarios if simple linear interpolation is used as a downscaling tool. Therefore, it is necessary to adjust the AOGGM so that their production can be interpolated at the regional level. CMIP6 [5] was developed by the World Bank to statistically reduce discrepancies in climate model production from seasonal and regional climate predictions to perform regional model validation. The spatial resolution fields of the thick climate model of temperature and precipitation (approximately 300 × 300 km) can be reduced to finer spatial scales of the order of 100 × 100 km, comparable to observed analyses of regional climate.

Downscaling techniques (global to regional) calibrate statistical transfer functions through historical relationships between modeled and observed fields so that systematic errors in model output are reduced. The identification of such errors is best achieved when not only grid points but also patterns and modes of variability are correlated [7]. The CMIP6 scenarios form the database of the IPCC Assessment Reports, so they were used to produce regional projections.

Integrations for climate change studies for the IPCC span from around 1900 to 2100, making it possible to construct transfer functions using the high spatial resolution of the temperature and precipitation fields observed for the period 1900-2020. In the present analysis, the stability and ability of the transfer function are evaluated using data from 1995-2014 as the reference period. As in any bias correction method, the quality of observational datasets limits the quality of bias correction. In addition, it is assumed that the bias behavior of the model does not change over time; therefore, in the downscaling approach, the relationships for downscaling are assumed to be stable in a changing climate, i.e. for the period 2001-2100. This may be an important assumption for any downscaling approach to climate change scenarios [8].

Various statistical approaches have been proposed to reduce the scale of the climate change scenarios of the AOGCM for Mexico to project the activity of medium, and even extreme events [9, 10]. However, most of these are based on only a few models and lack the benefit of a multi-model set perspective, such as that presented in the IPCC AR6. The AOGCM climate change scenarios used for the IPCC AR6 model projections of surface temperature and precipitation are available at the IPCC Data Distribution Centre. The multi-assembly model output fields for the radiative forcing scenarios of SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 have been reduced with CMIP6 scenarios. The CMIP6 reference scenarios for each AOGCM were used as a reference to construct the projected changes in the regional climate.

In the downscaling process, the monthly observed temperature and precipitation fields of the Climate Research Unit (CRU) of the University of East Anglia were used, with a spatial resolution of 50 × 50 km for the period 1901-2020 [11]. CMIP6 data capture Mexico's low-frequency variability and temporal temperature and precipitation trends.

For the present study, climate projection data are modeled data from the global climate model compilations of the Coupled Model Intercomparison Projects (CMIP), overseen by the World Climate Research Programme. The data presented are CMIP6, derived from the Sixth Phase of the CMIP form the database of the IPCC Assessment Reports. This climate predictability tool, used as a statistical method of downscaling, allows the preparation of regional climate change projections to estimate the spread between models as a measure of uncertainty in projected changes in temperature and precipitation. In this way, the changes in temperature and precipitation for the present century are obtained and together with vulnerability projections, the potential impacts on the water sector are estimated. The projection data is presented with a resolution of 1.0º x 1.0º (100 kmx100 km). In this way, a set of regional projections on climate change for the period 2020-2099 was prepared.

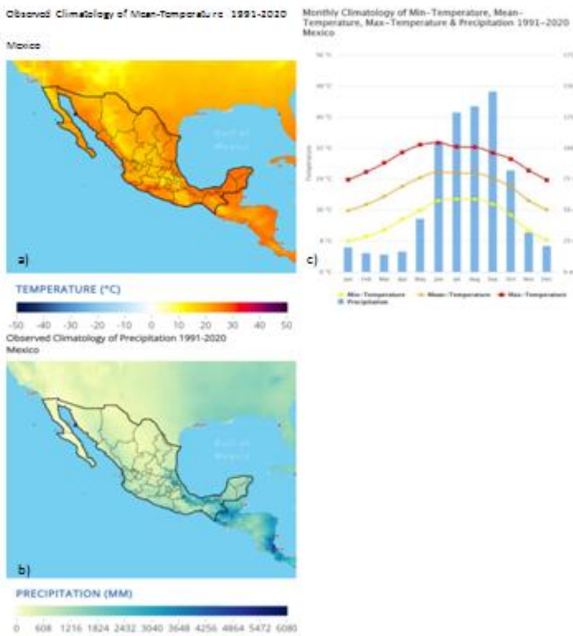
The ability to generate scenarios over a long period makes it possible to reproduce climate parameters, as well as the response of the regional climate to large-scale forcing, such as increased radiative forcing resulting from increased greenhouse gas concentrations. Thus, the estimated trend of temperature and precipitation on a regional scale for Mexico between 2020 and 2099 was obtained.

Complementary data were used for impact analyses. To this end, the Normalized Difference Vegetation Index (NDVI) was taken from the NASA data archive [12]. This index serves to assess the impact of anomalous climatic conditions on vegetation and is a measure of the amount and vigor of vegetation on the soil surface. NDVI spatial composite imaging is developed to more easily distinguish green vegetation from bare soils. The index has values ranging from −1.0 to 1.0, with negative values indicating clouds and water, positive values close to zero, indicating bare soil, and higher positive values ranging from sparse vegetation (0.1−0.5) to dense green vegetation (≥ 0.6). The impact of projected higher temperatures on plants can be estimated by considering the high correlation between temperature anomalies and plants in Mexico [13]. Because NDVI is an indicator of the amount and vigor of vegetation greenery, positive anomalies correspond to healthy vegetation conditions and negative NDVI anomalies to stressed vegetation. Standardized precipitation evapotranspiration indices (SPEI) were also used, which is an indicator of drought derived from precipitation, which calculates drought based on the standard deviation of accumulated precipitation from the long-term mean, including evapotranspiration. Positive values indicate a positive water balance (wet conditions) and negative values indicate a negative water balance (dry conditions). This indicator shows the frequency and intensity of droughts observed with a duration of 6 and 12 months (accumulation periods). Shorter accumulation periods (e.g., ≥6 months) may be used to indicate very sensitive impacts, such as low soil moisture. Longer accumulation periods (e.g. ≥12 months) can be used to indicate risks associated with prolonged hydrological drought, such as reduced reservoir recharge and water availability. This indicator excludes other factors that influence drought, such as geology and soils, flow, melting glaciers and evapotranspiration. Temperature increases generally increase moisture losses, therefore increasing the risk of drought. This indicator should be used carefully in typically arid regions and dry seasons. The reference period for calculating the SPEI indicator has been set at 1981-2010. Soil moisture (m^3/m^3) was also estimated to show the average water content of the topsoil (0 to 5 cm deep) and can be used as an indicator of the extent and duration of drought. There is a strong interrelationship between soil moisture, vegetation and climate in the short and long term. Soil moisture influences the type and condition of vegetation and in turn, evapotranspiration. Change in soil moisture can have considerable impacts on agricultural productivity, ecosystem health, and food security. Soil moisture data can be used to anticipate and manage drought-related risks and secondary hazards, support crop insurance models, and guide long-term agricultural resilience programming. Ideally, this indicator should be used in combination with other drought indicators. Finally, this information will be complemented by maps of drought.

3. RESULTS AND DISCUSSION

The historical data used to establish Mexico's baseline climatology were taken from the Climate Research Unit (CRU) of the University of East Anglia. Figure 9 presents the climatology for the period 1990-2020, the data present a resolution of 0.5º x 0.5º (50 km x 50 km) for a) the average annual temperature, b) accumulated annual precipitation and minimum, maximum, average and monthly precipitation temperatures during the period 1991-2020.

Figure 9. High spatial resolution climatology with CRU data (50 × 50 km) (base period 1991-2020) observed of a) average annual surface temperature (°C), (b) average annual precipitation (mm) and (c) minimum, maximum, average temperatures and monthly precipitation [5].



The tendency to change in temperature and precipitation are a measure of the sensitivity of climate to increased radiative forcing. The latter has increased in recent years, thus forcing a warmer climate [2]. The regional linear trend over Mexico for the period 1991-2020 is captured by CMIP6's regional set of climate change scenarios.

For projections of this century, the sources of uncertainty on a global scale are related to GHG emission scenarios. However, the differences in projections for the coming decades relate more to natural variability and how it adds up in different models [14], as well as internal instabilities or processes not well captured by the thick spatial resolution of AOGCM (tropical cyclones). Differences between climate change experiments have been used as a measure of uncertainty, concluding that the greater the dispersion between models, the greater the uncertainty in the projection.

More detailed spatial information increases uncertainty about the finer-scale dynamic processes that result in regional climate. The assessment of uncertainty at the regional and local scale is complicated by the lower relationship between signal and internal variability [14, 15]. Thus, regional climate scenarios show more consistency between projections of temperature changes than in precipitation projections. However, the interpretation of regional climate change scenarios requires a certain level of knowledge of the dynamics of the processes resulting from the climate characteristic of the region.

Regional climate change scenarios

Most studies agree that temperature will increase in the coming decades and that this will affect the hydrological cycle on a global and regional scale [2, 16, 17]. The impacts of permanent climate changes are expected to have a large number of socio-economic consequences, particularly in regions where several natural climate disasters have occurred in recent decades. The IPCC [2,16] has concluded that Mexico will be among the regions where the water deficit will be exacerbated due to expected increases in temperature and reduced rainfall. The regional climate change scenarios obtained through CMIP6 are able to show the contrasts in the projected climate changes between the regions of Mexico. The magnitude of the temperature increase is expected to vary, mainly because the dynamic mechanisms that control climate variability are related to processes in the Pacific and Atlantic oceans [18, 19].

Regional models for Mexico show that the average annual surface temperature can experience a variety of increases ranging from 0.5 to 5 °C depending on the scenario and period selected, while the percentages of change in rainfall from -20.3% to 13.5% depending on the scenario and period of analysis. It is estimated that it is unlikely to limit GHGs and radiative forcing to scenarios SSP1-1.9, SSP1-2.6, on the other hand it is expected that the actions that are re-implemented to mitigate GHG emissions will allow the scenarios not to be reached (SSP5-8.5), based on this it is estimated that the two most likely scenarios are the intermediate scenario SSP2-4.5 and the SSP3-7.0 high scenario, both of which will be described and discussed. For anomalies of temperature, precipitation and changes in the percentage of rainfall, the period 1995-2014 will be taken as a reference. Likewise, they will be the scenarios with which the impacts on water resources in Mexico will be evaluated.

Table 2. Anomalies of temperature, precipitation and change of % of precipitation for Mexico according to the different scenarios of the IPCC (2014) SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5 during the present century, obtained from regional models (data to [5]).

Temperature anomalies in °C				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	0.68±0.09	0.81±0.08	0.70±0.1	0.61±0.10
SSP1-2.6	0.82±0.06	1.19+±0.07	1.32±0.06	1.25±0.09
SSP2-4.5	0.83±0.06	1.46±0.06	1.96±0.09	2.35±0.12
SSP3-7.0	0.75±.04	1.59±0.06	2.49±.11	3.49±0.14
SSP5-8.5	0.94±0.04	1.93±0.05	3.14±.08	4.54±0.15
Precipitation anomalies in mm				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	1.57±5.41	2.58±5.83	2.27±5.98	1.58±5.28
SSP1-2.6	1.12±3.39	0.28±3.75	-0.65±3.38	0.08±3.75
SSP2-4.5	0.12±3.71	-0.93±4.45	-2.12±5.00	-3.40±6.31
SSP3-7.0	-0.97±2.13	-3.51±4.64	-5.92±8.35	-7.77±11.18
SSP5-8.5	-1.78±2.56	-3.32±5.82	-5.63±8.49	-9.38±14.07
Changes in % precipitation in mm				
	2020-2039	2040-2059	2060-2079	2080-2089
SSP1-1.9	-2.60±5.84	-1.64±5.57	-1.36±4.94	-2.90±3.84
SSP1-2.6	0.42±3.45	-0.21±3.62	-1.27±4.38	-0.35±4.54
SSP2-4.5	-0.98±4.48	-3.10±6.71	-5.1±6.49	-5.81±7.59
SSP3-7.0	-1.46±3.60	-4.94±6.15	-8.78±8.94	-10.59±12.66
SSP5-8.5	-1.65±4.76	-4.28±7.57	-7.63±11.18	-12.80±16.15

For the SP2-4.5 scenario, the average annual temperature anomalies (°C) for Mexico in the period 2020-2039 are estimated at 0.83±0.06 °C, while for 2040-2059 with a value of 1.46±0.06 °C, the period 2060-2069 of 1.96±0.09 °C and at the end of the century (2080-2099) will reach a value of 2.35±0.12 °C with respect to the reference period 1995-2014 (Table 2 and Figure 10). It should be remembered that the values are differentiated according to the region, state and municipality. In the SSP3-7.0 scenario the average annual temperature anomaly (°C) in the period 2020-2039 is estimated at 0.75±0.04 °C, the period 2040-2059 with a value of 1.59±0.06 °C, the period 2060-2069 of 2.49±0.11 °C and in 2080-2099 it will reach 3.49±0.14 °C (Table 2 and Figura 11).

Regional precipitation projections tend to produce negative and positive changes depending on the period analyzed and/or the region of the country. In some periods the most important changes are in the Norte zone, while in others in the Centro and Sur zone of Mexico. However, most of the changes are decreased rainfall in almost the entire country. For scenario SP2-4.5, the average annual precipitation anomalies (mm) in the period 2020-2039 are estimated at 0.12±3.71, the period 2040-2059 with a value of -0.93±4.45, the period 2060-2069 of -2.12±5.00 and at the end of the 2080-2099 century will reach -3.40±6.31 (Table 2 and Figure 12). In the SSP3-7.0 scenario, the average annual precipitation anomalies (mm) in the period 2020-2039 are estimated at -0.97±2.13, the period 2040-2059 with a value of -3.51±4.64, the period 2060-2069 of -5.92±8.35 and in 2080-2099 will reach -7.77±11.18 (Table 2 and Figura 13). Precipitation anomalies in mm are difficult to interpret so they were reported in % of precipitation change for a simpler interpretation. For the SP2-4.5 scenario, the changes in the % average annual precipitation in the period 2020-2039 is estimated at -0.98± 4.48 %, the period 2040-2059 with a value of -3.10±6.71%, the period 2060-2069 of -5.1± 6.49% and at the end of the century 2080-2099 will reach -5.81±7.59% (Table 2 and Figure 14). In the SSP3-7.0 scenario, the changes in the % average annual precipitation in the period 2020-2039 is estimated at -1.46±3.60%,2040-2059 with a value of -4.94±6.15%, between 2060-2069 of -8.78±8.94 and in 2080-2099 it will reach -10.59±12.66% (Table 2 and Figure 15).

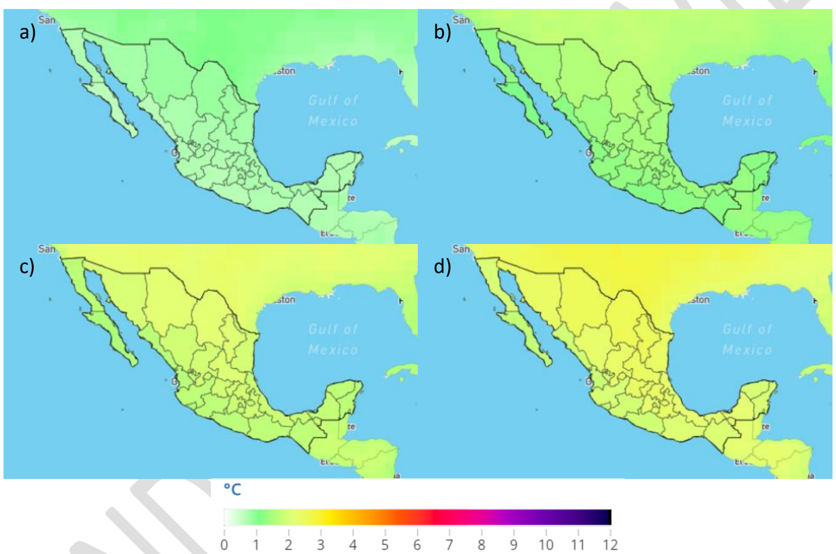


Figure 10. Projected Mean Temperature Anomaly (Annual) for Mexico under the SSP2-4.5 scenario a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 [5].

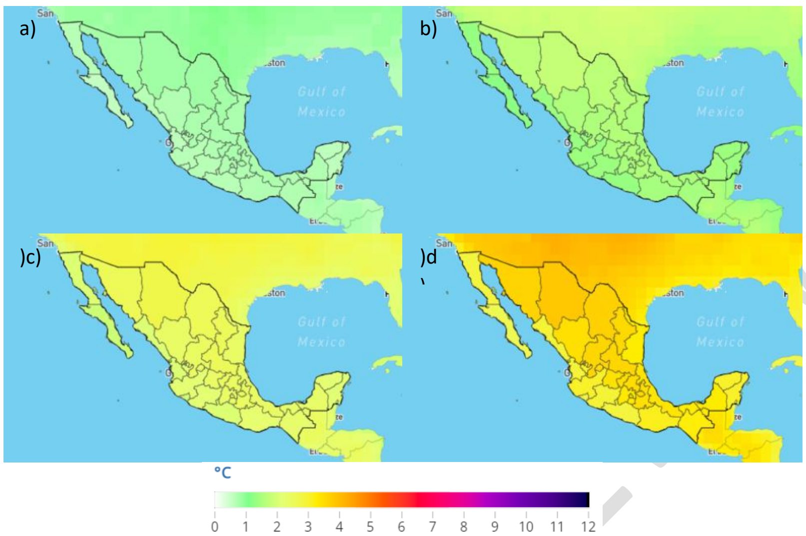


Figure 11. Projected Mean Temperature Anomaly (Annual) for Mexico under the SSP3-7.0 scenario a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 [5].

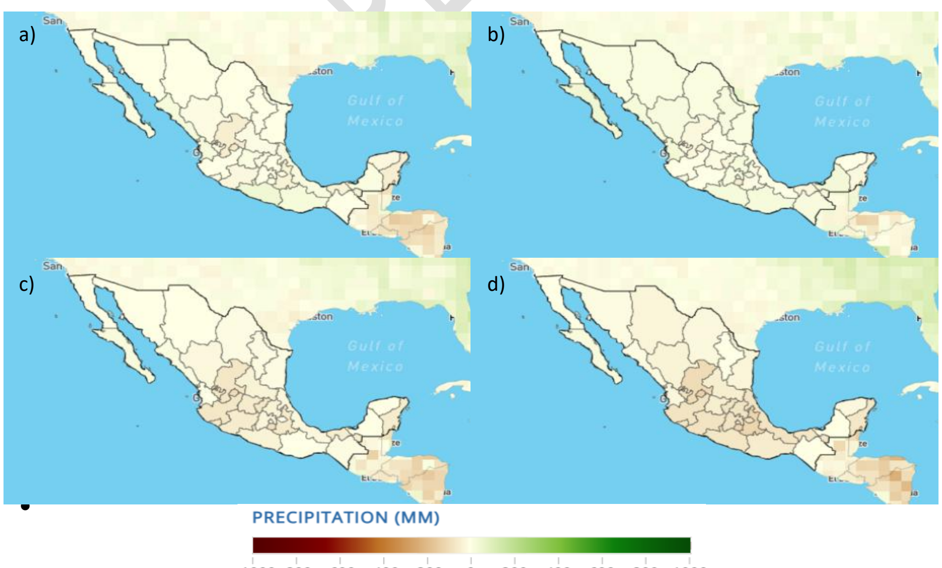


Figure 12. Projected Precipitation Anomaly (Annual) for Mexico under the SSP2-4.5 scenario a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 [5].

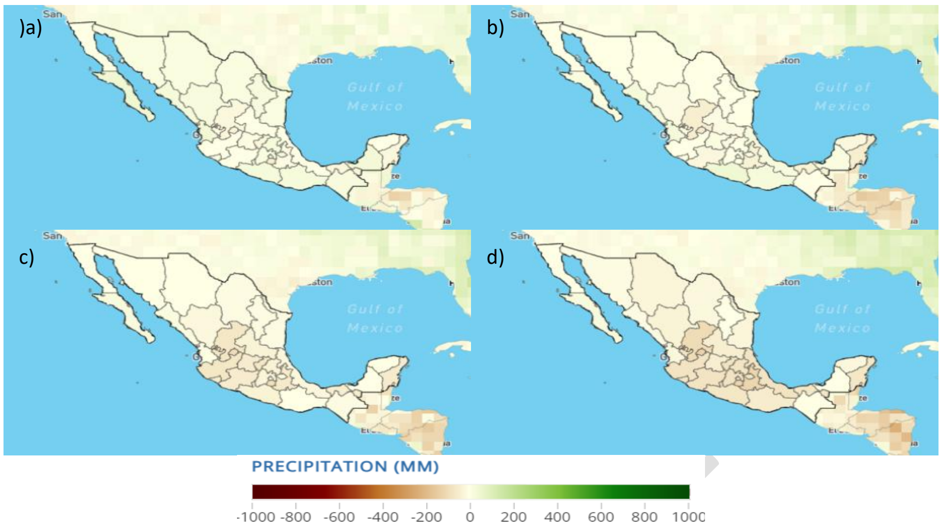


Figure 13. Projected Precipitation Anomaly (Annual) for Mexico under the SSP3-7.0 scenario a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 [5].

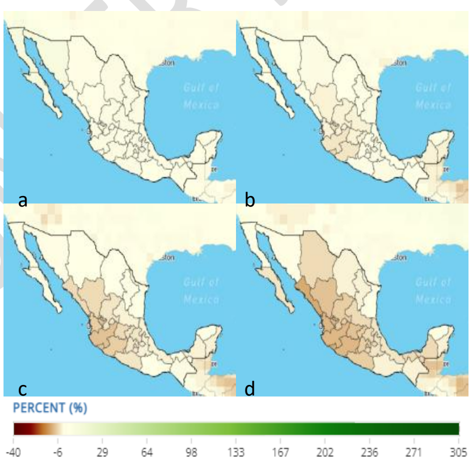


Figure 14. Projected Precipitation Percent Change Anomaly for Mexico under the SSP3-7.0 scenario a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 [5].

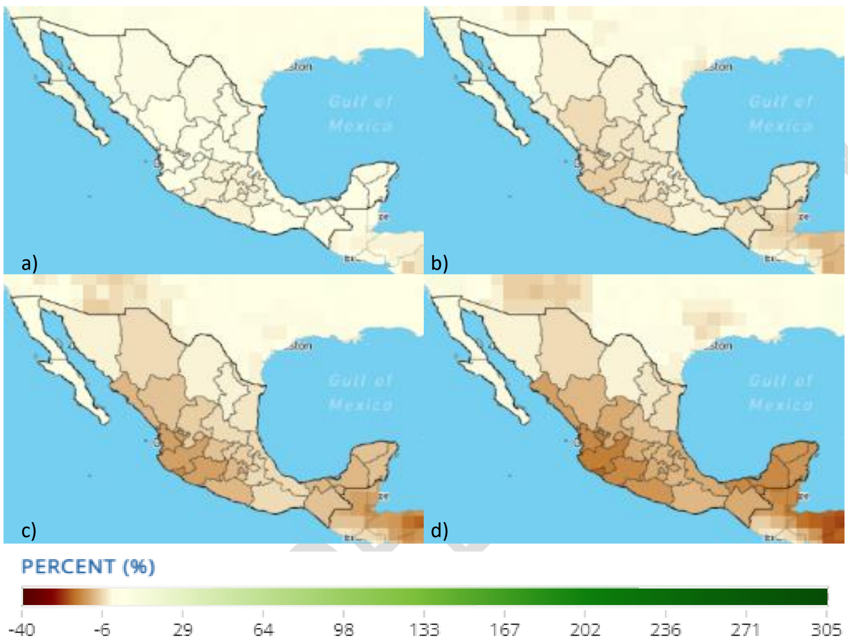


Figure 15. Projected Precipitation Percent Change Anomaly for Mexico under the SSP3-7.0 scenario a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 [5].

Mexico is located in one of the regions of the world where rainfall is most likely to decrease under climate change [16]. These reductions in rainfall combined with large increases in temperature imply a large increase in potential evapotranspiration and a substantial reduction in the availability of water and soil moisture, affecting Mexico's seasonal and irrigated agriculture and with them agricultural productivity that could put food security at risk. Thus, in general, the expected magnitude of negative changes in rainfall is expected by the end of the century to be between -5 and -10%. Natural climate variability produces larger changes in annual precipitation than those estimated by climate change. However, if a large negative anomaly in precipitation resulting from natural variability is combined with the negative trend in precipitation due to the effect of climate change, then the effect would be magnified.

The magnitude of the projected precipitation change is less than the dispersion between the models as can be seen in the large standard deviation values of the change in % precipitations. This makes precipitation scenarios for the present century more uncertain than those for temperature. An additional and important source of uncertainty is the fact that the availability of water in some regions depends on the passage of tropical cyclones as is the case of the Baja California peninsula.

The temporal evolution of the projections indicates that decreases in rainfall are more likely to be significant during the second half of the twenty-first century, showing a clear negative trend in any of the CIMP6 scenarios. If we add to this the observations of soil moisture (mm), 12-month Standard Precipitation Index SPEI 12 Log (ERAS LAND), the Normalized Difference Vegetation Index (NDVI) and drought events (Figure 16) gives us a more robust picture of how temperature and precipitation changes will affect Mexico's water resources. Thus, the soil moisture map (mm) allows us to show that the North, West and Bajío areas have the lowest values of soil moisture with values below 0.1, which will be intensified with higher temperatures that will cause greater evaporation and with less rainfall that will not allow the soil to recover its moisture; hence the importance of rainfall during the boreal winter months that although they are scarce, can be important to maintain certain levels of soil moisture and reduce water stress in vegetation during the spring [20]. The South, Gulf and Southeast areas, although they have a higher level of soil moisture (between 0.2 and 0.4 mm), will also be affected as a result of climate change (Figure 16 a). The SPEI is a standardized version of precipitation anomalies and has been used to characterize the severity of meteorological drought [19]. SPEI 12 makes it possible to evidence the effects of persistent precipitation anomalies and to estimate the potential trend towards more meteorological droughts. The SPI 12 map shows the prolonged droughts that occurred in the 1910s, 1930s, 1950s, 1970s and those of the late 1990s to date throughout the country, with more intensity in the North (Figura 16 b). The magnitude of SPEI 12 during the 20th century ranged from -1 to −2 when prolonged droughts occurred, which corresponds to the category of extremely dry conditions. The corresponding precipitation projections of the multimodel set at the regional scale for 2000−2099 do not have the magnitude of the observed natural variability. However, a more definite trend towards negative values of SPEI 12 is observed under the SSP3-7.0 scenario than under the SSP2-4.5 scenario, with average values of around -1. Conditions considered as semi-permanent moderate meteorological drought over Mexico.

NDVI (Figura 16 c) is closely related to temperature and soil moisture [13]. Thus, the negative changes of the NDVI over Mexico are related to reductions in rainfall and increased temperatures. The patterns projected for the second half of the 21st century correspond to a severe deficit of soil moisture and water stress in plants. NDVI values are considered sparse vegetation. The projected scenario could be analyzed with the conditions of previous droughts. For example, projected changes in soil moisture and NDVI in SSP scenarios resemble anomalies observed under conditions of intense ENSO events (1982-1983, 1986-1993, 1997-1998, 2014-2016). Most of the affected regions are semi-arid areas, where natural vegetation is a niche of very rich biodiversity. The very low frequency climate variability over Mexico with surface temperature anomalies close to 5 °C and water stress (decreased rainfall) has resulted in a greater number of forest fires, without considering the effect of climate change. If these conditions are added to the positive anomalies of temperature and the negative ones in the rainfall, it is possible that this exacerbated the increasing presence of fires in forests and jungles of Mexico, a situation that could last until the end of the century.

Regional climate change scenarios suggest that by the end of the 21st century, water availability in northern Mexico may be reduced by up to 30% due to global warming, result of possible reductions in rainfall and temperature increases. Historically, droughts have had serious consequences on primary activities such as agriculture, livestock, forestry and the environment. To examine the impact of climate change, conditions during a similar anomalous hot and dry period can be analyzed. Anomalous high temperatures in northern Mexico persisted during the summers of 1998-2002 (around +2 °C) with below-normal rainfall (-20 to -30%), leading to a prolonged drought. Such climatic anomalies resulted in a severe deficit of soil moisture and water stress in crops and vegetation that increased the potential for forest fires. The spring of 1998 turned out to be the season with the highest number of forest fires in Mexico in recent decades, not only due to hydrological stress in the vegetation, but also due to slash and burn practices in the agricultural sector [21]. Vulnerability in northern Mexico has not been reduced since then [22] and consequently, the risk of a major environmental disaster is still present [23] and the effects of climate change (increase in temperature and decreases in rainfall) will be greatly complicated.

The map of droughts (Figure 16 d) shows the current droughts, where practically the entire country has suffered from moderate droughts (Center and South of the country) to extremely strong (North of the country). Under the climate change scenarios SSP2-4.5 and SSP3-7.0 with conditions of strong increase in temperatures and decrease in rainfall, the panorama of droughts in Mexico will continue and worsen between now and the end of this century, with the social (food security and health), economic (well-being), political implications, (public expenditure), associated cultural.

Impacts of climate change on water resources

On a global scale, it is expected that the effects of climate change on water resources will be extensive, but of different signs from one region to another, according to latitude, high tide, biomes, orographic conditions, hydrography among others. In some regions of the planet, the first symptoms of affectation in water resources are already recorded.

According to the Sixth IPCC Report, the global surface temperature in the first two decades of the twenty-first century (2001-2020) was 0.99 [0. 84 to 1. 10] °C above 1850-1900. And from 1.09 [0.95 to 1.20] °C higher in 2011-2020 than 1850-1900, with greater increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C) [2]. In the case of the data analyzed in the present study, an increase in the surface temperature of Mexico of approximately 1.8 °C was evidenced for the year 2020 but with respect to 1900, remaining above the global values.

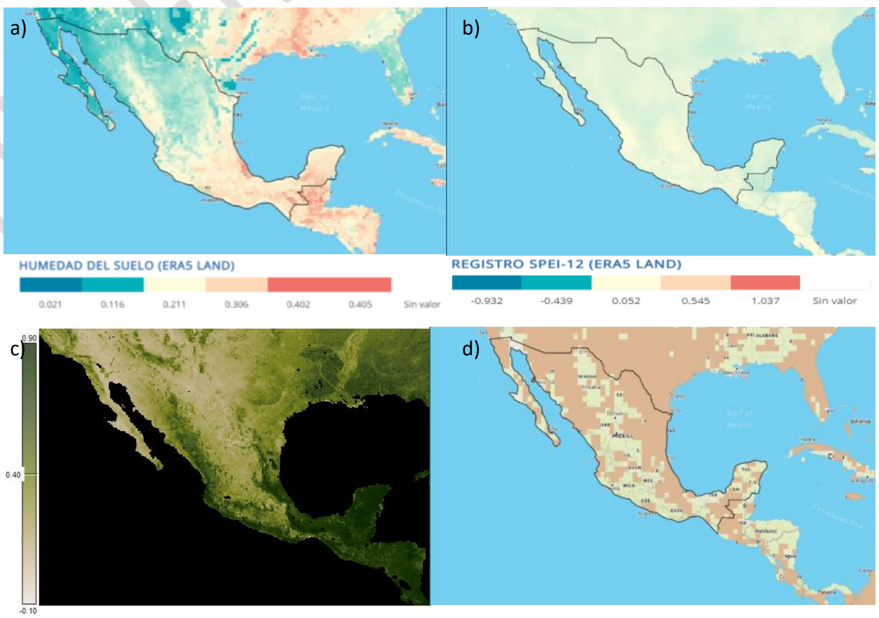


Figure 16. (a) Soil moisture (mm) and (b) SPEI 12 Log (ERAS LAND), c) normalized difference vegetation index (NDVI) changes and d) Droughts events in SSP2-4.5 scenario for the second half of the 21st century [5].

The report also estimates that it is virtually certain that warm extremes (including heat waves) have become more frequent and more intense in most land areas since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe. being human-induced climate change the main driver of these changes [2]. The regional models of CIMP6 for Mexico show a behavior similar to the global projection where in most of the Mexican territory heat waves are more frequent and intense, while extreme cold events have decreased in frequency and intensity. This has led to very hot summers and less harsh winters.

At the global level, global surface temperature will continue to rise until at least mid-century in all emission scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless there are deep reductions in CO_2 and other greenhouse gas emissions in the coming decades [2]. In the case of Mexico, the projected regional scenarios show that Mexico's surface temperature will continue to increase proportionally from the period 2020 to the period 2080-2099 in all GHG emission scenarios considered and exceeding the threshold of 2 °C increase.

Compared to 1850-1900, it is very likely that the global surface temperature averaged during 2081-2100 will be higher between 1.0 to 1.8 °C in the very low GHG scenario (SSP1-1.9), of 2. 1 to 3. 5 °C in the medium GHG scenario (SSP2-4.5) and 3. 3 °C to 5. 7 °C in the very high GHG scenario (SSP5-8.5) [2]. The projections show that Mexico will present with respect to the period of 1994-2014 the following increases: in the period 2081-2099 for the most likely intermediate scenarios SSP2-4.5, from 1.78 to 2.58 °C and for the high scenario SSP3-7.0 it will reach 2.75 to 3.84 °C. In the first case below the IPCC and in the second case above what is projected by the IPCC at the global level.

Based on the evaluation of multiple lines of evidence, global warming of 2 °C, relative to 1850-1900, would be exceeded during the twenty-first century in the high and very high GHG scenarios (SSP3-7.0 and SSP5-8.5, respectively). It is very likely that the increase of 2 °C in the medium GHG scenario (SSP2-4.5) will be exceeded. The threshold of 2 °C is very likely to be crossed in the mid-century period (2041-2060) in the high (SSP3-7.0) and very high (SSP5-8.5) GHG scenarios, and more likely to occur in the medium GHG scenario (SSP2-4.5) [2]. In the regional projections for Mexico, this threshold in the period 2040-2059 would be exceeded by all scenarios except for the SSP1-1.9 scenario, which is consistent with the global scenarios already proposed.

It is estimated that with the further increase in global temperature, changes in the limbs continue to become larger. For example, every 0.5°C additional of global warming will cause increases in the intensity and frequency of hot extremes: heat waves, heavy rainfall, as well as meteorological, agricultural and ecological droughts in some regions, with more regions showing increases than decreases. There will be an increasing occurrence of some extreme events never before seen in the observational record with additional global warming of 1.5 °C [2]. In Mexico, the projected regional scenarios will reach temperature levels higher than global ones (1.8°C) with the fact that it is very likely that both hot extremes (heat waves, intense rainfall, meteorological, agricultural and ecological droughts) will increase both in frequency and intensity. as never before observed).

Global assessments project that some mid-latitude and semi-arid regions will see the greatest increase in temperature on the hottest days, about 1.5 to 2 times the rate of global warming [2]. Mexico is within these regions so the regional projections coincide with the estimates with the global projections with temperature increase in hot days in the global ranges.

The IPCC report estimates that human influence has likely increased the likelihood of extreme compound events since the 1950s. This includes increases in the frequency of concurrent heat waves and droughts on a global scale, fires in some regions of all continents, and compound floods in some places [2] .Global phenomena that have already been projected by regional models for Mexico where it is estimated that in the present century the frequency of extreme events such as heat waves, recurrent droughts, forest fires and floods will increase.

As for rainfall, the IPCC report mentions that heavy rainfall events are very likely to intensify and become more frequent in most regions with additional global warming. On a global scale, extreme daily precipitation events are projected to intensify by around 7% for every 1°C of global warming. The proportion of intense tropical cyclones (category 4-5) and their most intense maximum wind speeds are projected to increase on a global scale with increasing global warming [2]. For Mexico this will only happen with increases in rainfall only in the first projection period (2020-2039) and in very low and low scenarios. In the rest of the scenarios the tendency will be to decrease the amount of precipitation. However, in all cases the intensity of the rains will increase.

Continued global warming is also expected to further intensify the global water cycle, including its variability, global monsoon rainfall, and the severity of wet and dry events [2]. In Mexico the initial period (2020-2039) will present increases in the amount of precipitation, but in the 3 subsequent periods (2040-2059, 2060-2079 and 2080-2099) there will be a decrease in wet events and a greater presence of dry ones.

There is strong evidence that the global water cycle will continue to intensify as global temperatures rise and rainfall and surface water flows are projected to become more variable in most regions of the world within seasons and from year to year. On land-based, the annual global average of precipitation is expected to increase by 0-5 % in the very low GHG scenario (SSP1-1.9), by 1.5-8% for the scenario (SSP2-4.5) and by 1 to 13% in the very high GHG scenario (SSP5-8.5) by 2081–2100 relative to 1995–2014. Rainfall is projected to increase at high latitudes, the Pacific equatorial zone, and parts of monsoon regions, but decrease in parts of the subtropics and limited areas in the tropics by SSP2-4.5, SSP3-7.0, and SSP5-8.5 [2]. The regional projections for Mexico meet the global forecasts for tropical areas with a decrease in rainfall in the scenarios SSP2-4.5 (-5.81±7.59%), SSP3-7.0 (-10.59±12.66) and SSP5-8.5 (-12.80±16.15) in the period 2080-2099.

Warmer weather is estimated to intensify very wet and very dry weather, weather events and seasons, with implications for floods or droughts, but the location and frequency of these events will depend on projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm paths. It is very likely that the variability of rainfall related to ENSOs is amplified by the second half of the century in the stages SSP2-4.5, SSP3-7.0 and SSP5-8.5 [2]. Regional projections of the decrease in soil moisture, the SPEI 12 index, NVDI and the great periods of droughts of recent decades confirm for Mexico the global estimates of intensification of very dry weather and prolonged droughts.

The monsoon season is projected to have a late start in North America [2]. Given the conditions presented in the regional projections, it is estimated that the North American monsoon will increasingly be delayed as the century progresses and together with the decrease in precipitation will cause great storage problems in the water bodies of the north of the country.

It is estimated that at 2°C of global warming and above, the level of confidence and magnitude of change in droughts and heavy and average rainfall increase compared to 1. 5 °C. Thus, an increase in meteorological, hydrological and agricultural droughts is projected in Central, North America and the Caribbean [2]. This has already manifested itself in Mexico during the first two decades of this century and is projected to continue to intensify between now and the end of the century.

Many regions are projected to experience an increased likelihood of compound events such as heat waves and more frequent concurrent droughts, even in crop-producing areas, becoming more frequent at 2°C and more so compared to global warming of 1.5°C [2]. Estimates for the end of the century in Mexico under the most likely scenarios will be above 2 °C which could mean effects on crops by compound events.

In general, in the middle latitudes and subtropical zones (location of Mexico), significant decreases in precipitation and runoff are expected, which will cause an increase in the conditions of scarcity and greater pressure on diversified water resources in the different regions.

In various regions of the world and in several of Mexico, there are already conditions of scarcity that are expected to increase, even without climate change, due to the effect of projected population growth, growing urban concentration, pollution of water bodies and overexploitation of water resources, in particular underground, coupled with a scarce culture of water resources. To this scenario must be added the effects of climate change, which in Mexico will be mostly a reduction in the natural availability of water as a result of the increase in temperature and decrease in rainfall, which together poses very great challenges for the management and sustainable use of water.

According to the IPCC [16], in many regions current water management practices will not be adequate or sufficient to meet the challenges associated with climate change. Likewise, meteorological and hydrological records will most likely no longer be able to be used under the consideration that the statistical values of the past will be representative of the future. Mexico is among those countries where the public management policies implemented so far will not be sufficient to face the impacts of climate change.

On the other hand, a warmer climate will mean more intense precipitation events, even in places where average annual precipitation will likely be lower. What is already happening and will continue to happen in southern and southeastern Mexico. Indeed, the average annual rainfall may even decrease, but more intense rains will be recorded, which will make it more difficult to control these flows through the current channels. These extreme events will be among the most difficult to forecast in future climate change scenarios, as they have an eminently local character. It is to be expected that the impacts of global warming on runoff will be detected first in the occurrence of these extreme events than in annual availability, which in itself has significant natural variations.

In the case of Mexico, this effect of climate change will increase vulnerability in basins in southern and southeastern Mexico such as the Grijalva-Usumacinta systems in Chiapas and Tabasco, Papaloapan in Veracruz to name a few examples that already register flooding problems [24]. The existence of heavier rainfall is compatible with the forecast of minor annual runoff. On the other hand, the increase in the occurrence of droughts in the north of the Mexican territory is evident, which is consistent with the predictions of decreased precipitation and runoff and is expected to occur more frequently and intensely. In the absence of major adaptation measures, the availability of water resources in quantity and quality and, as a consequence, the food security and health of the population of Mexico could be at great risk.

4. CONCLUSIONS

Based on the results, the main conclusions are that the regional models for Mexico show annual surface temperature increases ranging from 0.5 to 5 °C, while the % change in rainfall will range from -20.3% to 13.5% depending on the scenario and analysis period. For scenario SP2-4.5, mean annual temperature anomalies (°C) are estimated to be between 0.83±0.06 °C (2020-2039) and 2.35±0.12 °C (2080-2099), while in the SSP3-7.0 scenario variations are estimated from 0.75±0.04 °C (2020-2049) to 3.49± 0.14 °C (2080-2099).

Changes in the % average annual precipitation in the SP2-4.5 scenario are estimated to be between -0.98±4.48% (2020-2039) and -5.81±7.59% (2080-2099). In the SSP3-7.0 scenario they will vary between -1.46±3.60% (2020-2039) and -10.59±12.66% (2080-2099).

Soil moisture (mm) shows that the North, West and Bajío areas have values below 0.1 mm, while the South, Gulf and Southeast areas, although they have a higher level of soil moisture (between 0.2 and 0.4 mm), will also be affected by climate change. NDVI changes are negative and are related to the reduction in precipitation and temperature increase. The projected patterns correspond to a severe deficit of soil moisture and water stress in plants, in semi-arid regions, where vegetation is a niche of biodiversity. NDVI values are considered as sparse vegetation. The negative values of SPEI 12 under the SSP3-7.0 scenario are lower than the SSP2-4.5 scenario, with average values of around -1. Conditions considered as semi-permanent moderate meteorological drought over Mexico. The map of droughts shows that practically the whole country has suffered from moderate droughts (Centro and Sur of the country) to extremely strong (North of the country). Under the climate change scenarios SSP2-4.5 and SSP3-7.0 with increased temperatures and decreased rainfall, the panorama of droughts in Mexico will continue and worsen between now and the end of this century.

Climate change will substantially affect the world's available water resources. For Mexico, the expected effects of climate change will be a significant increase in temperatures (above 3 °C) and a decrease in precipitation (above 20%). As a consequence, surface runoff and aquifer recharge and therefore water availability will be reduced, which will be added to the water stress due to climate change (low soil moisture, decrease in NDVI and SPEI 12 and recurrent droughts) together with the population and economic growth expected in the XXI century. Another effect expected by climate change will be the decrease in agricultural and livestock productivity in food production, since, as the temperature rises, evapotranspiration also increases and with it the crops are subjected to greater thermal stress, drastically impacting their yield.

It is recommended, based on the results evidenced, to design and prioritize adaptation actions to the effects of climate change in the most vulnerable hydrological regions of Mexico, and with it the approach of public policies that allow future generations to have the minimum conditions of water sustainability in the country, where food security, health, social welfare, economic conditions and cultural activities that may be compromised are shielded.

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