Original Research Article

Climate change and its economic impacts in mexico

ABSTRACT

Introduction: Climate change is one of the great challenges of the 21st century, due to its global causes and consequences and its heterogeneous and asymmetric regional impacts, with those who contribute the least to the phenomenon receiving the greatest negative impacts. Mexico has a minor contribution to climate change in terms of greenhouse gas emissions; however, it is highly vulnerable to its negative effects. Climate change is a long-term global phenomenon, with a high level of uncertainty. The economic analysis of climate change has a high level of risk, which makes it a process where risk must be managed. Despite these characteristics and limitations, it is a fundamental instrument for public policy and society since it identifies options and alternatives to build sustainable development strategies and protect natural resources and ecosystems for future generations beyond their economic value. However, it must be understood that projections are not one-off forecasts but only prospective scenarios.

Objective: The objective of this study is to evaluate the economic impacts of Climate Change for Mexico during this century, according to the different scenarios of the IPCC AR6.

Methodology: The methodology consists of presenting a set of regional projections of climate variables under the IPCC's AR6 climate change scenarios, and estimating the possible impacts of climate change on Mexico's economic sector.

Results: Regional models show temperature increases between 0.5 and 5 °C, while changes in precipitation will range between -20.3% and 13.5%. Low soil moisture, negative changes in vegetation (NDVI) and drought (SPEI12) will lead to soil moisture deficits, water stress, sparse vegetation and semi-permanent drought. The entire country is expected to be subjected to moderate (Central and Southern) to extremely severe (Northern) droughts that will worsen by the end of the century. Climate change will have effects on crop yields, livestock reproduction, production of meat and its derivatives throughout the country in a differentiated way, with increases in food prices. It will also cause a deficit of land suitable for agricultural activities; and water availability. Diseases associated with climate change will become more acute by the end of the century, with increases in health spending. It is estimated that the investment of the Gross Domestic Product (GDP) in the health sector would go from 6.25% to more than 18%, which could be unfeasible for the national economy. Based on the likely temperatures by the end of the century, it is estimated that the risk of extinction of species will range between 3 and 48% in terrestrial, oceanic and coastal ecosystems, the risk of biodiversity loss will go from moderate to very high. The total costs of climate change reach 2050, with a discount rate of 4%, values that range between 9 and 13% of GDP in the most likely scenarios for the end of the century and reach between 28 and 36% of GDP at a discount rate of 0.5%, while by 2100 with a discount rate of 4%. around 16.5% of GDP and reach maximums between 69 and 76% of GDP at a discount rate of 0.5%.

Conclusion: The results allow us to conclude that climate change has significant impacts on the Mexican economy and that the costs of inaction are higher. Thus, it is more efficient to act now than to leave the problem to future generations, beyond the ethical considerations that it implies.

Keywords: Climate Change, Impacts, Economy, Mexico

1. INTRODUCTION

Climate change (CC) is one of the great challenges of the 21st century, due to its global causes and consequences and its heterogeneous and asymmetrical regional impacts by country and socioeconomic groups, with those that contribute the least to the phenomenon receiving the greatest negative impacts. Mexico has a historically lower contribution to climate change in terms of greenhouse gas (GHG) emissions. However, it is highly vulnerable to the negative consequences of CC and will be affected by any international agreement.

The challenge of climate change is associated with the presence of unsustainable production and consumption patterns, dependent on fossil fuels with high carbon emissions. Consequently, it imposes limits and restrictions and forces a reorientation of the production and consumption paradigm. The challenge is to adapt to the new climatic conditions and implement mitigation strategies, recognizing common but differentiated responsibilities and heterogeneous capacities.

Recently, Mexico has shown economic growth that has improved economic and social conditions. However, it has also generated negative side effects, such as greater air pollution in urban areas and deterioration of natural assets (non-renewable resources, water, forests, among others). In addition, economies and societies are observed with high vulnerability to the impacts of extreme events and with a productive and consumption matrix with high levels of carbon emissions. These factors erode the foundations that sustain the current economic dynamism. Mexico must move towards sustainable development that preserves economic, social and natural assets. That goal should be within the framework of economic growth with greater equality and social inclusion and low carbon emissions.

The analysis of climate change is a complex process that requires combining scientific and economic models in a consistent way; generating climate scenarios by the end of the century with the possible consequences on the country's productive and service sectors; and to generate economic scenarios in a long-term horizon; with appropriate risk margins and recognize the existence of significant uncertainty in the results obtained, including effects without market value and that in some cases are irreversible, such as the loss of biodiversity.

The economic analysis of climate change is an extremely consequential issue because climate change is a long-term global phenomenon with a high level of uncertainty, which manifests itself in a very heterogeneous way by regions with significant asymmetric effects. The CC contains a high level of risk and, from the point of view of economic analysis, in a process where risk must be appropriately managed. The economic analysis of climate change, despite these characteristics and limitations, is, from the perspective of public policy and society, a fundamental instrument since it allows the identification of options and alternatives to build sustainable development strategies and protect natural resources and ecosystems for future generations beyond their economic value.

The consequences of climate change for Mexico are multidimensional and heterogeneous both in geographical spaces, between social groups, sectors and natural systems. CC is characterized by persistent and irreversible impacts, by amplifying and feeding back concurrent socio-environmental problems and inequities, by the presence of critical points that can modify the behavior of the climate system or systems influenced by it.

The economic assessment of the possible consequences of climate change is therefore a complex and uncertain task. It is very common that data to estimate relationships between climate and economy are scarce and allow the impacts to be approximated in a limited way to some region, sector, activity, or element of the system. Likewise, the use of different methodologies of economic analysis causes a large number of disparate estimates. However, to really appreciate the importance of this phenomenon, it is necessary to be able to obtain the most complete estimates of the effects on natural and human systems in the short, medium and long term.

1.1 Climate change: evidence and future scenarios at the global level

Evidence indicates that climate change manifests itself in increased atmospheric and oceanic temperatures, changes in precipitation patterns, decrease in ice and snow volumes, sea level rise, and changes in extreme weather patterns, with anthropogenic activities being the fundamental cause of climate change [1].

Each of the past four decades has been successively warmer than any previous decade since 1850. The global surface temperature of the first two decades of the twenty-first century (2001–2020) was 0.99 [0.84 to 1.10] °C higher than in the period 1850–1900. The global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than in 1850–1900, and the increases were greater over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C). The estimated increase in global surface temperature since the AR5 is mainly due to further warming from 2003–2012 (+0.19 [0.16 to 0.22] °C). The likely range of total global surface temperature increase caused by human activities from 1850–1900 to 2010–201911 ranges from 0.8 °C to 1.3 °C, with a best estimate of 1.07 °C (Figure 1) [2].

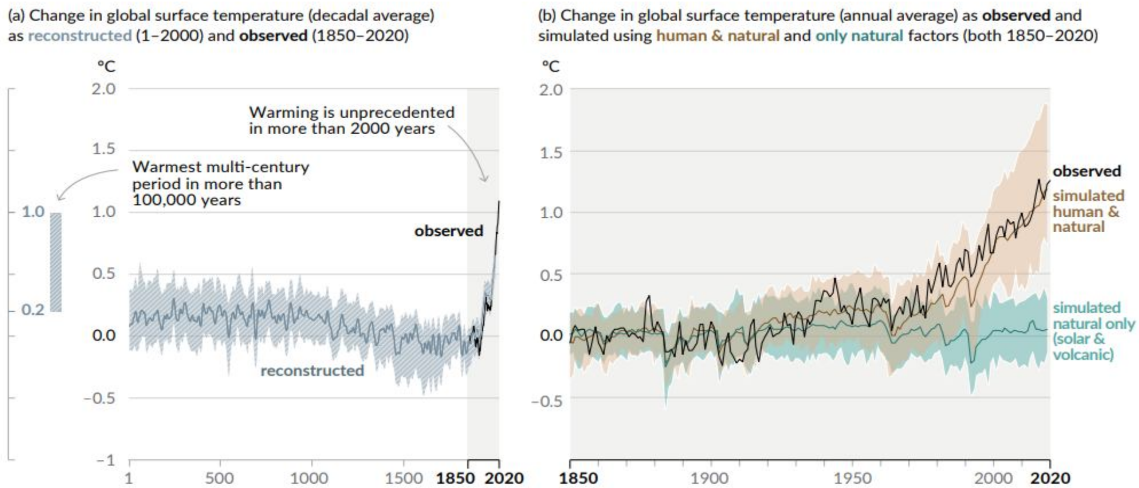

Figure 1 History of global temperature change and causes of recent warming [2]

Extreme weather events show that since 1950, the number of severe continental rainfall has increased in more regions than it has decreased. However, the global trend of droughts and cyclonic activity with the climate change has been differentiated between regions. The frequency and intensity of heavy rainfall has increased since 1950 on most continental surfaces, and human-induced climate change is likely to be the main driving force. Human-induced climate change has contributed to increased agricultural and ecological droughts in some regions due to increased evapotranspiration of the land. The global proportion of tropical cyclones of higher intensity (category 3 to 5) is likely to have increased over the past four decades, and it is very likely that the latitude at which tropical cyclones in the western North Pacific reach their maximum intensity has shifted northward; these changes cannot be explained by internal variability alone. Attribution studies of these phenomena and physical understanding indicate that anthropogenic climate change increases the intense rainfall associated with tropical cyclones. It is likely that human influence has increased the possibility of compound extreme events occurring since 1950. This includes an increased frequency of simultaneous heat waves and droughts on a global scale, weather conditions favorable for the occurrence of wildfires in some regions of all inhabited continents, and compound floods in some places [2].

Along with the increase in temperature, there is a decrease in the mass of the Greenland and Antarctic ice sheets, a retreat in glaciers and a significant reduction in Arctic ice. The rate of glacier loss is estimated to have been, on average, 226 [91 to 361] gigatons of ice per year (Gt/year) over the period 1971-2009. Meanwhile, ice loss from the Greenland mantle has increased from 34 [-6 to 74] Gt/year during the period 1992-2001 to 147 [72 to 221] Gt/year during the period 2001-2011. In addition, the average annual area of Arctic Sea ice has seen a reduction of between 0.45 and 0.51 million km^2 per decade over the period 1979-2012, with areas becoming smaller and smaller in the summer [2].

Global mean sea level rose 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1] mm per year between 1901 and 1971, and increased to 1.9 [0.8 to 2.9] mm per year between 1971 and 2006, and even more to 3.7 [3.2 to 4.2] mm per year between 2006 and 2018. It is very likely that human influence was the driving force behind these increases [2].

Meanwhile, emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) show unprecedented levels in the last 800,000 years. CO_2 concentrations increased from 280 parts per million (ppm) in the pre-industrial era to 410 ppm, as a result of the burning of fossil fuels and land use change. Methane concentrations increased from 700 parts per billion (ppb) to 1876 ppb, and nitrous oxide increased from 270 ppb to 332 ppb. In addition, about 56% of anthropogenic CO_2 has been absorbed by land and oceans, leading to acidification [2].

In 2019, atmospheric CO_2 concentrations were higher than at any time in at least the last 2 million years, and concentrations of CH_4 and N_2O were higher than at any time in the last 800,000 years. Since 1750, increases in CO_2 (47%), CH_4 (156%) and N_2O (23%) concentrations far exceed the multimillennial natural changes between glacial and interglacial periods (800,000 years) [2].

CO_2 concentrations in the atmosphere are the determining factor of global warming and their increase is caused by the burning of fossil fuels, cement production and changes in soil cover, in particular, deforestation. It is estimated that in 2013 global CO_2 emissions from fossil fuel burning and cement production reached 36.2 gigatons of CO_2 ($GtCO_2$), where 43% comes from the use of coal, 33% from oil, 18% from gas and the rest from cement production and gas combustion. Emissions from land-use change reached 3.2 $GtCO_2$. The growth of global CO_2 emissions from the burning of fossil fuels has been, on average, 2.6% per year during the period 1960-2013, with a greater increase between 1960 and 1970, at an annual rate of 4.7%. In contrast, emissions from land-use change have decreased at an annual average rate of 0.9% in the period 1960-2013.

1.2 Future climate scenarios at the global level

The most likely projections of temperature increase by 2100 are between 1.4 and 4.4 °C, with maximums of 5.7 °C (Table 1). Thus, with the exception of the SSP1-1.9 scenario, a temperature increases of more than 1.5 °C is projected by the end of the century, with a high probability of exceeding 2 °C. In this way, the SSP1-1.9 scenario is linked to the scenario where the temperature remains below 2 °C with respect to pre-industrial levels. On the other hand, the extreme scenario, SSP5-8.5, is associated with an increase equal to or greater than 4 °C. Likewise, the climate will continue to show interannual and decadal variability, and will be heterogeneous between regions (Figure 2a) [2].

On a daily and seasonal scale, the frequency of extreme hot temperatures is virtually certain to increase, while cold extremes will be less frequent on most continents. Thus, the ability of warmer air to contain more water vapor will generate a tendency to make regions dryer, drier; while humid regions will be wetter. Thus, by the end of the century, the intensity and frequency of extreme precipitation phenomena will increase in mid-latitudes and humid tropical areas (IPCC, 2021).

Table 1. Changes in global surface temperature over 20-year periods and in the five emission scenarios considered. Temperature differences relative to the global mean surface temperature for the period 1850-1900 are reported in °C. [2]

	Near term, 2021-2040		Mid-term, 2041-2060		Long term, 2081-2100	
Scenario	**Best estimate**	**Very likely range**	**Best estimate**	**Very likely range**	**Best estimate**	**Very likely range**
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

Many changes in the climate system are major in direct relation to increased global warming. These include increased frequency and intensity of extreme heat events, marine heatwaves, heavy rainfall and, in some regions, agricultural and ecological droughts; an increase in the proportion of intense tropical cyclones; and the reduction of Arctic Sea ice, snowpack and permafrost [2].

Arctic ice cover and glacier extent will continue to decline. By the end of the century, sea ice extent will have decreased year-round, and the Arctic Ocean, in the SSP5-8.5 scenario, is likely to be nearly ice-free by September by 2050. While in glaciers, projections suggest that by 2100, their volume globally will have decreased by 15% to 55% in the most optimistic scenario (SSP1-2.6), and by 35% to 85% in the most pessimistic scenario (SSP5-8.5) (Figure 2b) [2].

Climate models project sea level rise at a faster rate than in the period 1971-2010, due to ocean expansion due to greater warming, and the loss of mass from glaciers and ice sheets. Thus, an increase of 24 to 30 cm is expected by 2050, and from 40 to 63 cm by 2100 and greater CO_2 absorption by the oceans intensifying their acidification (Figure 2c,d) [2].

Projections for the 21st century estimate that the frequency of tropical cyclones in the world will change, and the maximum wind speed and rainfall intensity will increase on average. In regions with air pollution, the increase in local surface temperatures can trigger regional chemical feedbacks and local emissions that will generate increased levels of ozone and $PM_{2.5}$ particles, with negative consequences for health [2].

The trend of current emissions would cause the scenario of increased radiative forcing SSP5-8.5. Hence, as a result of the feedback from the climate system, even if emissions were significantly reduced, some level of warming could be expected during this century. A 2°C increase from pre-industrial levels by 2050 seems virtually inevitable.

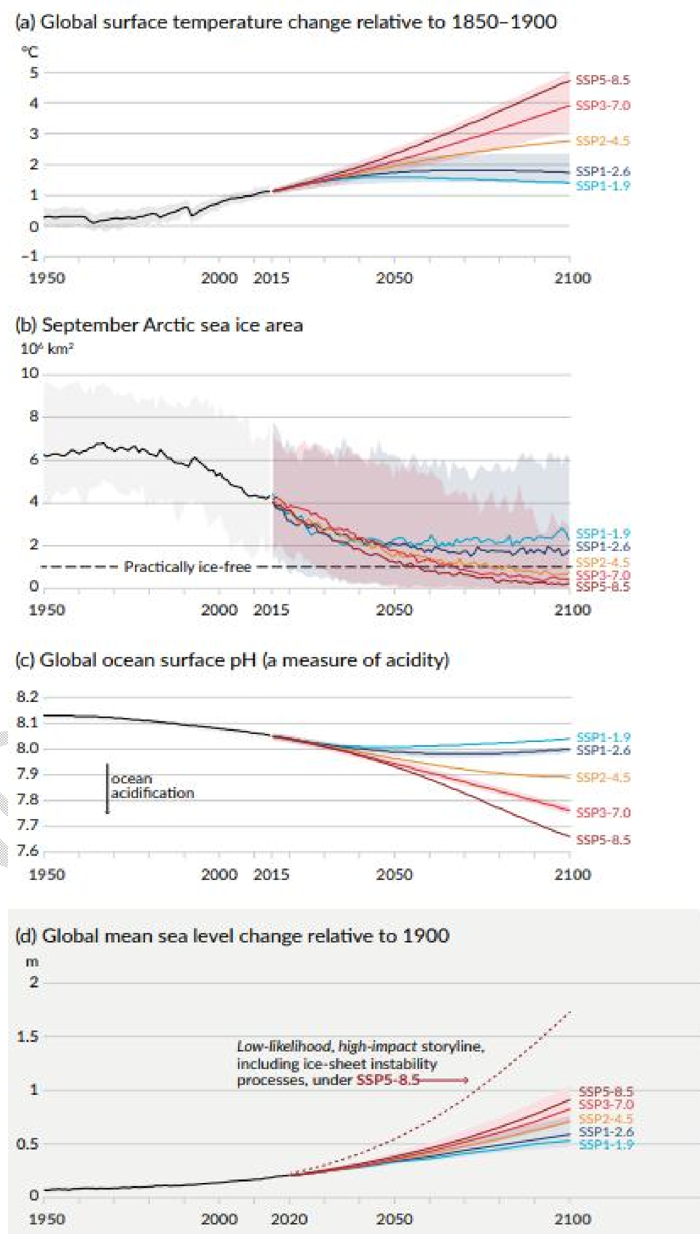

Figure 2 (a) Global surface temperature changes in °C, (b) September Arctic Sea ice area, (c) Global Ocean surface pH and (d) Global mean sea level change [2].

1.3 Climate change: evidence and future scenarios for Mexico.

Climate projections suggest a temperature increase of between 1.6 and 4°C in Mexico, the modification of extreme weather phenomena and the possibility of rising temperatures in some regions. Likewise, changes in precipitation of between -22% and 7% are projected by the end of the twenty-first century.

Mexico will also be affected by various climatic phenomena such as the intertropical convergence zone, the North American monsoon, El Niño/Southern Oscillation, the Atlantic Ocean oscillations and tropical cyclones [7]. These phenomena influence the subregional climate and, therefore, the modification of its patterns has an important impact on climate projections. El Niño will continue to be the dominant factor of interannual variability in the tropical Pacific and with the increase in humidity, the variability in precipitation associated with the phenomenon will intensify [7].

In order to stabilize GHG concentrations in the atmosphere in a manner consistent with an increase of no more than 2 °C over pre-industrial temperatures, the annual flux of GHG emissions would need to be progressively reduced from 45.4 gigatons of CO_2eq ($GtCO_2$eq) (about 7 tons per capita) per year to 20 $GtCO_2$eq in 2050 (2 tons per capita), and at 10 $GtCO_2$eq by the end of the century (1 ton per capita) [8-10]. Thus, the stabilization of the climate would imply moving from approximately 7 tons to 2 tons per capita in the next 40 years. However, if infrastructure continues to be developed in high CO_2 emissions, with a matrix of subsidies and relative prices and regulations in accordance with a high-carbon economy, it implies remaining in a growth that is difficult to reverse in the short and medium term and that implies non-compliance with the climate goals for 2050.

Estimates of the economic costs of climate change in the region related to a 2.5°C temperature increase (around 2050) ranges from 1.5% to 5% of GDP today. These estimates are conservative and limited to certain sectors and regions that have difficulty incorporating adaptation processes and the potential effects of extreme weather events [11].

2. MATERIAL AND METHODS

For the present study, data from the global climate model compilations of the World Climate Research Programmer's Coupled Model Intercomparison Projects (CMIP) were used. The data presented are CMIP6, derived from the Sixth Phase of the CMIP and form the IPCC Assessment Reports database. This climate prediction tool, used as a statistical method of downscaling, allows regional projections of climate change to be made. In this way, the changes in temperature and precipitation for the present century are obtained; and together with the vulnerability projections, the potential impacts are estimated. The projection data is presented at a resolution of 1.0º x 1.0º (100 km x 100 km). In this way, a set of regional projections on climate change for the period 2020-2099 were made for Mexico [12-17].

Complementary data were used for impact analyses, such as the Normalized Difference Vegetation Index (NDVI) based on NASA data; which made it possible to evaluate the impact of anomalous climatic conditions on vegetation, negative values indicate clouds and water, positive values close to zero, which indicate bare soil, and higher positive values range from sparse vegetation (0.1-0.5) to dense green vegetation (0.6 and more). Thus, positive anomalies correspond to healthy vegetation conditions and negative anomalies correspond to stressed vegetation. The standardized precipitation evapotranspiration index (SPEI12) was also used as an indicator of drought. Positive values indicate a positive water balance (wet conditions) and negative values indicate a negative water balance (dry conditions). This indicator was evaluated over 12-month periods, as an indicator of the risks associated with prolonged hydrological drought, such as reduced reservoir recharge and water availability. However, it excludes factors that influence drought, such as geology, soil type, flow, glacier melt, and evapotranspiration. Soil moisture (m^3/m^3), which is the average water content of the topsoil (0 to 5 cm deep), was also estimated and is 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 evapotranspiration. Change in soil moisture can have considerable impacts on crop productivity, livestock, ecosystem health, and food security. Soil moisture is used to anticipate and manage risks related to drought and wildfires, support crop insurance models, and guide long-term agricultural resilience programs. Finally, drought maps were used over the past two decades [12-17].

The historical data to establish the reference climatology in Mexico was taken from the Climate Research Unit (CRU) of the University of East Anglia. Figure 3 presents the climatology for the period 1990-2020, with a resolution of 0.5º x 0.5º (50 km x 50 km) for a) the average annual temperature, b) accumulated annual precipitation and c) minimum, maximum and average monthly temperatures and monthly rainfall in the period 1991-2020. The trend of change in temperature and precipitation is a measure of the sensitivity of the climate to increased radiative forcing. The latter has increased in recent years, leading to a warmer climate [2]. The linear trend over Mexico between 1991 and 2020 is captured by the regional set of climate change scenarios CMIP6. For projections for this century, the sources of uncertainty on a global scale relate to GHG emissions scenarios. The differences between climate change experiments have been used as a measure of uncertainty, concluding that the greater the dispersion between the models, the greater the uncertainty in the projection.

The construction, simulation and projection of economic scenarios linked to energy, regional and environmental scenarios is a complex task with a high degree of uncertainty and risk. To do this, it is necessary to identify the regular patterns existing among the most relevant economic variables. In general, the trajectory of the Gross Domestic Product (GDP) is the result of a complex matrix of factors and interrelationships, but where it is possible to identify that the GDP follows a cyclical behavior, usually autocorrelated, around an upward trend. The methodology for estimating economic impacts in Mexico was based on cost-benefit analysis (CBA) as a guide to evaluate the various public policy options. The CBA consists of identifying and monetarily estimating the costs and benefits of some public policy measure. This requires considering future monetary flows at present value, so it is necessary to use a specific discount rate. This process is complex due to the presence of imperfect competition, government intervention, absence of market prices, the existence of negative externalities or elements that are difficult to assess such as human life and biodiversity. This sometimes leads to the use of shadow prices or different forms of economic valuation [18]. Based on this, the total costs of climate change for the Mexican economy by 2050 and 2100 were estimated for the most likely IPCC scenarios (SSP1-2.6, SSP2-4.5 and SSP3-7.0) at different discount rates (0.4%, 2% and 4%).

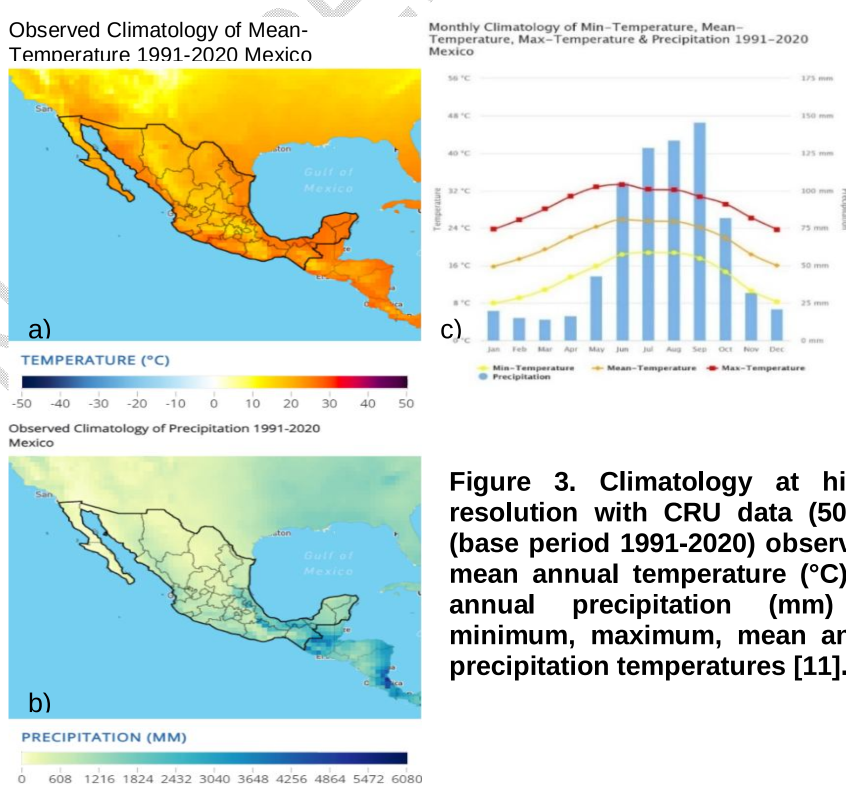

Figure 3. Climatology at high spatial resolution with CRU data (50 × 50 km) (base period 1991-2020) observed from a) mean annual temperature (°C), (b) mean annual precipitation (mm) and (c) minimum, maximum, mean and monthly precipitation temperatures [11].

3. RESULTS AND DISCUSSION

3.1 Regional climate change scenarios for Mexico

Most studies agree that temperature will increase in the coming decades and that it will affect the hydrological cycle on a global and regional scale [2, 19, 20]. The impacts of climate change are expected to have a large number of socio-economic consequences, particularly in regions where several climate disasters have occurred in recent decades. The IPCC [2, 19] has concluded that Mexico will be one of the regions where the water deficit will worsen due to the increase in temperature and the decrease in rainfall. The regional climate change scenarios obtained through CMIP6 show contrasts in projected climate changes between regions of Mexico. Temperature increases are expected to vary because the dynamic mechanisms that control climate variability are related to processes in the Pacific and Atlantic oceans [21-22].

Regional models for Mexico show that the annual mean surface temperature can experience increases ranging from 0.5 to 5 °C depending on the scenario and period, while percentages of change in precipitation range from -20.3 to 13.5% depending on the scenario and period. It is considered unlikely to limit GHGs and radiative forcing to the SSP1-1.9 and SSP1-2.6 scenarios, on the other hand, GHG emission mitigation actions are expected to allow not to reach the worst scenario (SSP5-8.5), so it is estimated that the most likely scenarios are SSP2-4.5 and SSP3-7.0. For the anomalies of temperature, precipitation and precipitation percentage, the period 1991-2020 was taken as a reference.

For the SSP2-4.5 scenario, the annual mean temperature anomalies for Mexico in the period 2020-2039 are estimated at 0.83±0.06 °C, for 2040-2059 1.46±0.06 °C, for the period 2060-2069 1.96±0.09 °C and in 2080-2099 they will reach a value of 2.35±0.12 °C with respect to the reference period 1991-2020 (Table 2). The values differ by region, state, and municipality. In the SSP3-7.0 scenario, the annual mean temperature anomaly in the period 2020-2039 is estimated at 0.75±0.04 °C, between 2040-2059 it will be 1.59±0.06 °C, and for 2060-2069 it will be 2.49±0.11 °C and in 2080-2099 it will reach 3.49±0.14 °C (Table 2 and Figure 4).

Regional precipitation projections (mm) tend to produce negative and positive changes depending on the period analyzed and/or region of the country. The most important changes will be in the northern, central and southern areas of Mexico. However, most of the changes are decreased rainfall in most parts of the country. For the SSP2-4.5 scenario, the average annual precipitation anomalies in 2020-2039 are 0.12±3.71, in 2040-2059 -0.93±4.45, in 2060-2069 -2.12±5.00 and in 2080-2099 -3.40±6.31. In the SSP3-7.0 scenario, the average annual precipitation anomalies for 2020-2039 are estimated at -0.97 ±2.13, in 2040-2059 -3.51±4.64, in 2060-2069 -5.92±8.35 and in 2080-2099 -7.77 ±11.18 (Table 2). The percentage change in precipitation for the SSP2-4.5 scenario in 2020-2039 is -0.98± 4.48%, in 2040-2059 -3.10±6.71%, in 2060-2069 -5.1±6.49% and in 2080-2099 -5.81±7.59%. In the SSP3-7.0 scenario, the percentage change in the average annual precipitation in 2020-2039 will be -1.46±3.60%, in 2040-2059 -4.94±6.15%, in 2060-2069 -8.78±8.94 and in 2080-2099 -10.59±12.66% (Table 2 and Figure 5).

Mexico is in one of the regions where rainfall is most likely to decrease under climate change [19]. The reduction in rainfall together with the increase in temperature implies an increase in potential evapotranspiration and a substantial reduction in the availability of water and soil moisture, affecting agriculture; agricultural productivity would put food security, livestock and other economic sectors at risk. Thus, by the end of the century, the magnitude of changes in rainfall would be between -5 and -10%.

The evolution of the projections indicates that it is more likely that the decreases in rainfall will be significant during the second half of the twenty-first century, showing a negative trend in any of the scenarios. If we add to this the soil moisture trend (mm), the 12-month Standard Precipitation Index (SPEI12), the Normalized Difference Vegetation Index (NDVI) and drought events (Figure 6), we get an overview of how changes in temperature and precipitation will affect Mexico's resources. The soil moisture map (mm) shows that the North, West and Bajío zones have the lowest soil moisture values (less than 0.1), which together with higher temperatures will cause more evaporation, less precipitation, and will not allow the soil to recover its moisture. The South, the Gulf and the Southeast, although they have higher soil moisture (between 0.2 and 0.4 mm), will also be affected as a result of CC (Figure 6a). The SPEI12 map shows prolonged drought, with greater intensity in the North (Figure 6b). The SPEI12 during the twentieth century ranged between -1 and -2 when prolonged droughts occurred, considered extremely dry conditions. There is a trend of more negative values of SPEI12 in the SSP3-7.0 scenario compared to SSP2-4.5, considered a moderate semi-permanent meteorological drought.

Table 2 Temperature, precipitation and % precipitation change anomalies for Mexico according to the regional models of the IPCC (2014) SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5 scenarios during the current century (Authors, data from [11]).

	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±0.04	1.59±0.06	2.49±0.11	3.49±0.14
SSP5-8.5	0.94±0.04	1.93±0.05	3.14±0.08	4.54±0.15
	Precipitation anomalies in mm			
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			
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

NDVI (Figure 6c) is closely related to soil temperature and moisture. Negative changes in NDVI are related to reduced precipitation and rising temperatures. The patterns projected for the second half of the twenty-first century correspond to a severe deficit of soil moisture and water stress in plants. NDVI are considered sparse vegetation and together with changes in soil moisture in SSP scenarios resemble intense conditions of ENSO events (1982-83,1986-93,1997-98,2014-16).

Most of the affected regions are semi-arid areas, where natural vegetation is a niche of very rich biodiversity. Very low frequency climate variability in Mexico, with surface temperature anomalies of 5 °C and water stress, has resulted in an increase in the number of forest fires, without considering climate change. If positive temperature and negative precipitation anomalies are added to these conditions, the growing presence of fires in forests and jungles in Mexico will worsen, a situation that will 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, possible reductions in rainfall and temperature increases. Historically, droughts have had serious consequences on primary activities such as agriculture, livestock, forestry and the environment. During the summers of 1998-2002, anomalously high temperatures persisted in northern Mexico (about +2 °C) with below-normal rainfall (-20 to -30%), leading to a prolonged drought. Such climatic anomalies resulted in severe soil moisture deficit and water stress on crops and vegetation, which increased the potential for wildfires. The spring of 1998 was the season with the highest number of forest fires in Mexico in recent decades, not only due to water stress on vegetation, but also due to agricultural logging and burning practices [23]. In northern Mexico, vulnerability has not been reduced [24] and the risk of a major environmental disaster remains [25] and will be complicated by the effects of climate change.

The drought map (Figure 6d) shows that practically the entire country suffers from moderate (central and southern) to extremely severe (northern) droughts. Under the SSP2-4.5 and SSP3-7.0 climate change scenarios with conditions of rising temperatures and decreased rainfall, the drought outlook in Mexico will be prolonged and worsen between now and the end of this century, with the associated social, economic, political, and cultural implications.

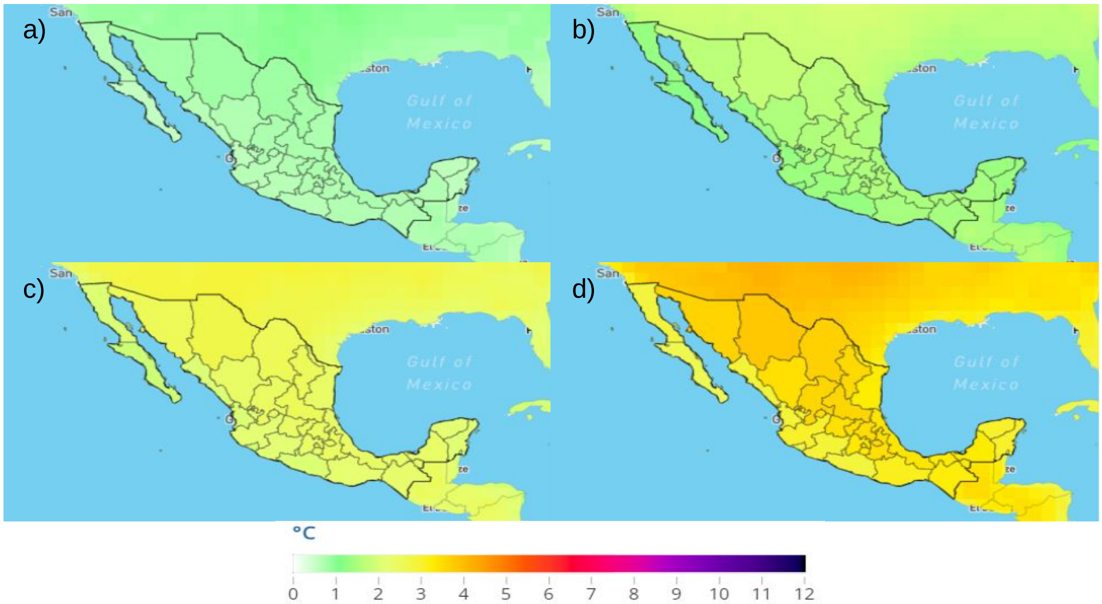

Figure 4 Average (Annual) Temperature Anomaly projected for Mexico under the SSP3-7.0 a) 2020-2039 scenario; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 [11].

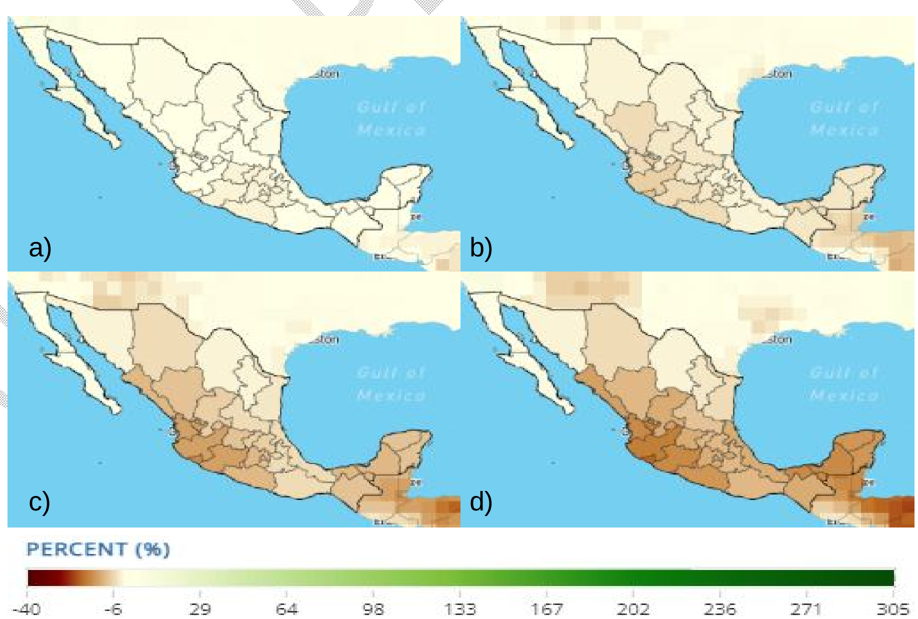

Figure 5 Projected Precipitation Percentage Change Anomaly for Mexico under the SSP3-7.0 scenario a) 2020-2039; (b) 2040-2059; (c) 2060-2079 and (d) 2080-2099 [11].

3.2 Impacts of climate change in Mexico

3.2.1 Water sector

The results show an increase in surface temperature of approximately 1.8 °C for the year 2020 compared to 1900, being above global values. CIMP6 regional models show that in most of Mexico, heat waves are more frequent and intense, while extreme cold events have decreased in frequency and intensity, causing very hot summers and less harsh winters. The projected regional scenarios for Mexico show that the surface temperature will continue to increase from 2020 to 2099 in all the GHG emission scenarios considered, exceeding the 2°C threshold. Projections for the period 2081-2099 show an increase of 1.78 to 2.58 °C for the SSP2-4.5 scenario and from 2.78 to 2.84 °C for the SSP3-7.0 scenario.

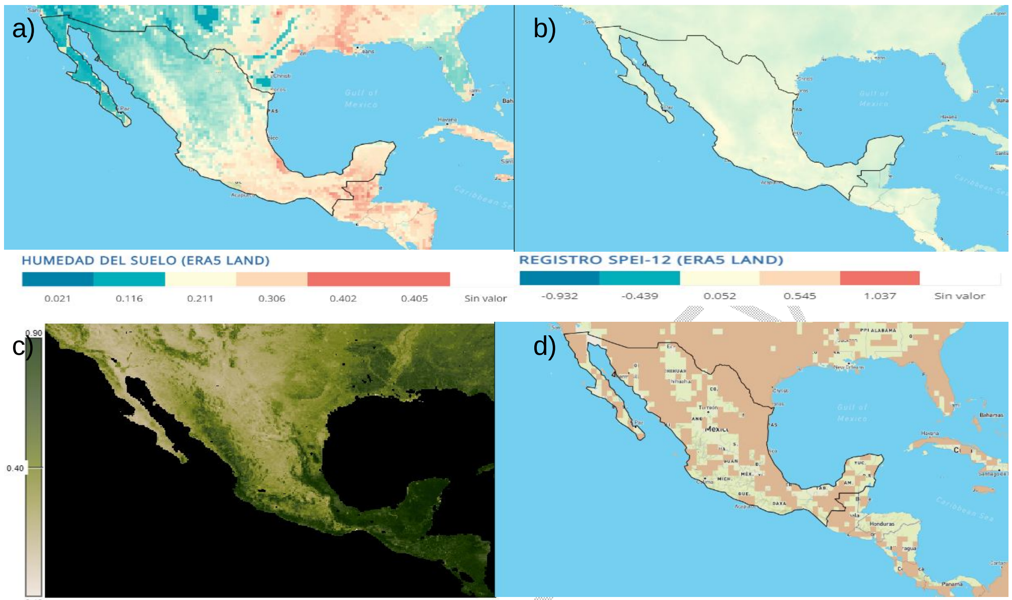

Figure 6 (a) Soil moisture (mm) and (b) SPEI 12 Log (ERAS LAND), c) changes in the Normalized Difference Vegetation Index (NDVI) and d) Drought events in the SSP2-4.5 scenario for the second half of the 21st century [11].

In the regional projections, the threshold of 2°C in the period 2040-2059 would be exceeded by all global scenarios except for SSP1-1.9. It is estimated that, with the further increase in global temperature, changes in extremes continue to become larger, with greater intensity and frequency of heat waves, heavy rainfall, meteorological, agricultural and ecological droughts in some regions, with more increases than decreases. In Mexico, the projected regional scenarios will reach temperatures higher than global temperatures (1.8°C), increasing the frequency and intensity of hot extremes (heat waves, intense rains, meteorological, agricultural and ecological droughts). Regional models estimate that the frequency of extreme events will increase in this century.

The IPCC report estimates that heavy rainfall will intensify by 7% for every °C of global warming. The proportion of intense tropical cyclones (category 4-5) and their maximum wind speeds are projected to increase with increasing global warming [2]. For Mexico, increases in rainfall are only estimated for the period 2020-2039 and in low scenarios. In the rest of the scenarios, the trend will be towards a decrease in rainfall; while the intensity of the rains will increase.

In Mexico, the period 2020-2039 will show an increase in precipitation, and from 2040 to 2099 there will be a decrease in wet events and an increase in dry events. The regional projections for Mexico coincide with the global forecasts of rainfall decrease in the SSP2-4.5 (-5.81±7.59%), SSP3-7.0 (-10.59±12.66%) and SSP5-8.5 (-12.80±16.15%) scenarios in the period 2080-2099. The decrease in soil moisture, the SPEI12 index, the NDVI and the great periods of drought in recent decades confirm for Mexico the global estimates of intensification of very dry climates and prolonged droughts.

Regional projections estimate that the North American monsoon will be increasingly delayed as the century progresses and, along with declining rainfall, will cause storage problems in the country's northern water bodies. With 2°C or more of global warming, the magnitude of change in droughts and heavy and medium rainfall is expected to increase. Thus, in Mexico there has been an increase in meteorological, hydrological and agricultural droughts so far this century and they are expected to intensify by the end of the century.

Likewise, many regions are projected to experience an increase in compound events such as more frequent concurrent heat waves and droughts, and in general, significant decreases in precipitation and runoff are expected for Mexico, which will cause an increase in scarcity conditions and greater pressure on diversified water resources in the regions and with serious consequences problems in the economic sectors.

In various regions of Mexico, water scarcity is expected to increase, even without climate change, due to the contamination of water bodies, population growth, growing urban concentration, and overexploitation of resources. Added to this scenario are the effects of climate change, which will be a reduction in the availability of water as a result of the increase in temperature and decrease in rainfall, which together pose great challenges for the management and sustainable use of resources in Mexico. Mexico's resource management practices and public resource management policies are neither adequate nor sufficient to meet the challenges of climate change.

On the other hand, a warmer climate will cause more intense rainfall, even in places where annual rainfall will be lower, which happens and will continue to happen in the south and southeast. In fact, the annual rainfall may decrease, but there will be heavier rainfall, which will make it difficult to control the flows. This effect of climate change will increase vulnerability in southern and southeastern Mexico, such as the Grijalva-Usumacinta systems in Chiapas and Tabasco, Papaloapan in Veracruz, which register flooding problems [26]. On the other hand, the increase in droughts in the north coincides with predictions of decreased rainfall and runoff, which are expected to occur with greater frequency and intensity.

3.2.2 Health Sector

The IPCC's sixth report [2] mentions that climate change has negatively affected the physical and mental health of people around the world and in the regions assessed. In all regions, extreme heat episodes have caused human mortality and morbidity. The incidence of climate-related food- and water-borne diseases has increased. The incidence of vector-borne diseases increased due to the expansion of the range and/or the increase in the reproduction of disease vectors. Animal and human diseases, including zoonoses, are emerging in new areas. The risks of waterborne and foodborne diseases have increased regionally due to climate-sensitive aquatic pathogens and toxic substances from freshwater cyanobacteria. Although diarrheal diseases have decreased worldwide, rising temperatures, increased rainfall, and flooding have increased diarrheal diseases, such as cholera and other gastrointestinal infections. Some mental health problems are also associated with rising temperatures, trauma from extreme weather events, and loss of livelihoods and culture. Increased exposure to wildfire smoke, atmospheric dust, and aeronautical allergens has been associated with climate-sensitive cardiovascular and respiratory distress. Health services have been disrupted by flooding [2].

The health sector in Mexico has fewer resources than other OECD countries. In 2020, Mexico spent 6.2% of GDP on health, equivalent to $1230 per capita per year (PPP), lower than the OECD average of 8.9%, equivalent to $4000 PPP. Out-of-pocket spending in Mexico represents 45% of the income of the health system and 4.0% of household spending. Both figures are among the highest in the OECD [27].

When categorizing deaths into three main groups, in 2019 the age-adjusted mortality rate for communicable diseases was 52.4 per 100,000 inhabitants (Habs.), while for noncommunicable diseases it was 468.7 per 100,000 Habs. On the other hand, the rate of external causes was 58.8 per 100,000 inhabitants, among which land transport accidents (12.9 per 100,000 inhabitants), homicides (25.3 per 100,000 inhabitants) and suicides (5.3 per 100,000 inhabitants) stand out. In 2000, the percentage distribution of causes was 70.2% for noncommunicable diseases, 17.9% for communicable diseases and 11.9% for external causes, while in 2019 they were 80.4%, 9.1% and 10.5%, respectively.

The increase in deaths has been steady between 1998 and 2019 (from 400,000 to 700,000 deaths), and increased dramatically in 2019 and 2020 (1150,000) due to the COVID-19 pandemic [27]. In the case of diseases caused by zoonoses, during 2020 a total of 1,510,795 cases of COVID-19 were registered in Mexico, which represented 11,928.8 per million inhabitants. In 2021, the identified cases amounted to 2,536,807, equivalent to 20,016.5 per million inhabitants. Deaths directly caused by COVID-19 in 2020 were 199,429 deaths of people diagnosed with COVID-19, i.e., 1156 per million Habs., while in 2021 238,070 were reported, representing 1846 deaths per million Habs. In the Americas, Mexico ranked 2nd in the number of deaths from COVID-19 in 2020, and by 2021 it ranked 17th, with a cumulative figure for both years of 3002 deaths per million inhabitants. According to the WHO, the total number of excess deaths in 2020 was 314,596 cases, or 244 per 100,000 inhabitants. For 2021, 311,327 deaths were estimated, which represents an excess of 239 per 100,000 inhabitants. In the case of vector-borne diseases, there are records of dengue, which had 36,742 cases in 2021 [28].

Among the main causes of death in Mexico in the last 20 years, the first places are occupied by diseases associated with climate change such as diabetes mellitus and malignant tumors, heart disease, cerebrovascular diseases, pneumonia-influenza, chronic lung diseases, bronchitis, asthma and emphysema, intestinal infectious diseases, gastric and duodenal ulcers, malnutrition, anemia, suicides, among others.

Currently, the population in Mexico is 128 million Mexicans (2020), and an estimated population growth of 25% (160 million Mexicans) by 2050 and 20% (153 million) by 2100. Under these scenarios, there would be a population of more than 50 million people over 60 years of age, with the respective increase in expenditures on the preservation of their health. Estimating that health spending would grow in the same proportion without reducing poverty, or increasing total and per capita GDP, it would be necessary to triple the 6.2% of GDP (2020) on health to more than 18% and increase spending from $1230 per capita per year (2020) to $3800 dollars in 2100, which would be unfeasible for the economy. Likewise, out-of-pocket spending in Mexico would constitute 65% of the income of the health system and more than 50% of household spending.

Regional models for Mexico show that temperature increases range from 0.5 to 5 °C, and percentage changes in rainfall range from -20.3 to 13.5% depending on the scenario and period of analysis. Low soil moisture (mm), negative changes in NDVI and SPEI 12 show that the entire country will present reductions in precipitation and temperature increase, flooding of land due to rising sea levels, disappearance of agricultural land and biodiversity, a large number of extreme events such as heat waves, intense rains, meteorological droughts, etc. A decrease in the number of wet events, a greater presence of dry periods, intensification of moderate to prolonged drought, storage problems in reservoirs and the transition from meteorological droughts to hydrological and agricultural droughts, a greater number of forest fires, a decrease in food productivity, malnutrition and greater vulnerability to the appearance and exacerbation of diseases typical of Mexicans (chronic-degenerative, obesity, diabetes mellitus, among others) and greater vulnerability to diseases caused by climate change such as heat stress, heat islands, respiratory, vector-borne and water-contaminated diseases, water and food scarcity; mental illness, among others.

In Mexico, the aforementioned health disorders are already present and have increased in the last 20 years, such is the case of mortality and morbidity due to an increase in diseases caused by contaminated food, vectors (dengue, zika and chikungunya); waterborne diseases (cholera, red tide); mental illnesses (anxiety and depression); respiratory, cardiovascular and allergic diseases derived from fires and air pollution, and interruption and/or disappearance of health services due to extreme flooding in southeastern Mexico. Likewise, migratory phenomena, where communities abandon their places of origin and migrate to large cities in search of opportunities, compromising their health and lives in the face of extreme weather events, malnutrition, anemia, food insecurity; malnutrition, stress, anxiety and depression due to extreme events or violent conflicts. Indigenous communities in Mexico suffer from high vulnerability that causes damage to their health. The health of the population is compromised by food insecurity, malnutrition and diseases derived from and associated with climate change and these are expected to increase significantly with the increase in temperature, the decrease in rainfall and the recurrent presence of extreme weather events.

In the case of Mexico, the most important risks are found on the coasts of the Gulf of Mexico and the Caribbean Sea, where the greatest sea level rises are expected, cold regions will be favored initially, but perhaps by the end of the century they will begin to have health problems. Problems that are already occurring in communities in northern Mexico (due to drought) and in the southeast (due to floods), as well as problems of violence due to the availability of resources, incidence of physical and mental illnesses; and deaths due to violence and suicides. In Mexico, due to poverty, there are problems of malnutrition, which will be aggravated by these factors, which will lead to serious health problems, with the corresponding expenses.

3.2.3 Agricultural Sector

Throughout this century, the effects of climate change and its impact on the agricultural sector will reduce economic growth, affect food security, and complicate efforts to reduce poverty [29]. In economic terms, it is very likely that the agricultural and livestock sectors will be the most affected by the negative effects of climate change [30-31]. According to the INECC, agriculture in Mexico can be affected by the presence of pests, insects and extreme weather events due to climate change. Rising temperatures have been shown to affect the growth of some crops and livestock development, especially if water consumption and the proliferation of pests and diseases increase [32].

Estimating that the demand for agriculture in Mexico would grow at the pace of the population (25%) without reducing poverty or increasing total and per capita GDP, 26 million hectares (ha) of crops would be needed instead of the 21 million planted in 2020. However, only 24.6 million hectares of land suitable for cultivation are available, with a deficit of 1.5 million hectares without considering climate change. Based on the 10 main crops in Mexico and their climatic requirements, estimates of possible changes in each of them were made. In the case of corn (grain and forage), it is estimated that productivity could fall between 20 and 30% for the SSP2-4.5 and SSP3-7.0 scenarios; for the different varieties of beans, productivity decreases are estimated between 30 and 50%, the productivity of sorghum will decrease from 5 to 10%, sugarcane will be reduced between 20 and 30%, the productivity of coffee will decrease from 10 to 40%, and that of wheat from 10 to 20%. In the case of barley, their production will decrease from 5 to 15%, oats between 10 and 30%, in the case of pastures, productivity will decrease from 25 to 35% depending on edaphic, climatic and climate change modification variables. Averaging all the decreases in crop productivity, these would be -22%, which would represent a deficit due to low productivity of 4.84 million ha, which if we add the deficit due to lack of arable land of 1.5 million ha, would give a total deficit of 6.4 million ha of crops, which would represent a significant decrease in food production.

As for livestock production, estimating that the demand for livestock in Mexico would grow in the same proportion as the population (25%) without reducing poverty, or increases in total and per capita GDP, 137.25 million hectares would be needed dedicated to livestock (70.5% of the national territory), which is unfeasible. Taking the main livestock species in Mexico and their optimal and critical temperatures, estimates of the effects on the agricultural sector in Mexico were developed. For cattle, the conditions will not be conducive to their reproduction, development and maturity, with a reduction in milk and meat production. Pigs would reduce their reproduction and production of meat and its derivatives. The reproduction of sheep and goats; and its production of meat and its derivatives would decrease. As for birds, their reproduction will be affected, with the consequent reduction in the number of units, egg production and poultry meat. On the other hand, livestock activities will demand on average between 11-15% more water for their development, going from the current 1.33-3.21 million m^3/day to consume 1.53-3.69 million m^3/day, which is unlikely to be available due to the decrease in water resources as a result of climate change. The impacts of climate change on agricultural activities will be intensified by the presence of extreme weather events such as frosts, droughts, hurricanes, and extreme rainfall [32].

3.2.4 Biodiversity sector

Mexico is a "megadiverse" country, and is part of the select group of nations with the greatest diversity of animals and plants, with almost 70% of the world's species [33], it is home to more than 200,000 species of plants and animals, many of which are unique to Mexico. However, it also faces challenges in trying to preserve its environment in the face of climate change. One of the most pressing problems is habitat loss due to deforestation and land use change. Forests and jungles are being cleared at an alarming rate, mainly due to the expansion of agriculture, cattle ranching and urbanization. This not only affects the species that live there, but also contributes to climate change by releasing CO_2 into the atmosphere.

Mexico faces a major impact of climate change on its marine ecosystems. Rising sea levels, temperature and ocean acidification are putting pressure on the country's coastal communities and the diversity of marine life. For Mexico, where increases of more than 2°C are projected by the end of the century in the SSP2-4.5 and SSP3-7.0 scenarios, species threats and extinctions are unlikely to be minimized. Regional differences exist, and risks are greatest when species are close to their upper thermal limits and to the persistence of multiple non-climatic factors and where vulnerability is high. These risks are unavoidable in the short term, regardless of the emissions scenario.

In Mexico, there are non-climatic factors that increase the vulnerability of biodiversity, which will be difficult to stop and eliminate; and that, along with the impacts of climate change, the number of threatened and endangered species will increase, with no certainty as many going extinct. At the probable temperatures by the end of the century (0.5 to 5 °C), it is estimated that the risk of extinction will range between 3 and 48% in terrestrial ecosystems, while in oceanic and coastal ecosystems the risk of biodiversity loss will go from moderate to very high; and for endemic species, the risk of extinction is very high with the possibility of increasing more than ten times. The projections of the regional models estimate the dangers of crop failure and death of tree species above the global models; the floods will put species at risk in the southern and southeastern areas of the country. Mexico presents a risk of an increase in forest fires due to climatic and non-climatic factors with a risk of threat and danger of extinction of plants, animals, fungals and chromists.

The inevitable rise in sea level will bring impacts that will result in losses of coastal ecosystems and ecosystem services, salinization of groundwater, flooding, and damage to coastal infrastructure that will become risks to livelihoods, health, well-being, settlements, food and water security, and cultural values in the short and long term [2]. Events that have been happening for decades in the jungles of the southeast, in the forested and mountainous areas throughout the country and in the coastal areas of the Gulf of Mexico and the Pacific Ocean.

In Mexico, poor adaptation and mitigation strategies, instead of contributing to the reduction of climate change, have contributed to increasing the risk of threats to biodiversity. Every tenth of a percentage point of temperature increase and reduction in precipitation will increase biodiversity loss. According to the Red List of Threatened and Endangered Species of the International Union for Conservation of Nature and Natural Resources [34], Mexico is one of the countries with the highest risk of biodiversity loss and has 2437 threatened species (plants are the largest group, followed by fish, amphibians, other invertebrates, reptiles, mammals, birds and mollusks).

A decrease in agricultural and livestock productivity would represent a significant decrease in food production; which would put at risk plant and animal species that are not currently part of the food system, which would increase the risk of threat and extinction of these species. In Mexico, climate change puts increasing pressure on biodiversity, the increase in the frequency, intensity and severity of droughts, floods and heat waves, the continuous rise in sea levels, will increase the risks of species loss in moderate to highly vulnerable regions with temperature increases between 1.5-2°C of global warming. With global warming of more than 2°C in the medium term, the risks to biodiversity will be more severe. CC will weaken soil health and pollination, increase disease and pest pressure, and reduce marine animal biomass. At global warming of 3°C or more in the long term, areas exposed to climate-related hazards will expand, increasing the disparity in risks to biodiversity.

3.2.5 Economic impacts of climate change in México

The economic analysis of the costs of climate impact by sector is very limited, most analyses make an assessment of the total costs. In this study, an effort was made to present the costs by sector and the total costs of climate change, all as a percentage of national GDP at different discount rates. Thus, the results of the evaluation of the costs by sector and the total costs of climate change in Mexico are shown in Table 3. Doing an analysis by sector we have to:

There are few studies of the economic impact on the ***water sector*** in Mexico, there are only qualitative estimates of the impact of climate change on water resources in a context of growing demand for water, both for economic activities and for the population, which will intensify pressures on these resources. Water consumption will increase, although proportionally less than GDP growth. The use of economic instruments is important for controlling consumption, but it also has its limitations and must include other social considerations. Rising temperatures and changes in precipitation patterns will also affect the trajectory of water consumption. In particular, rising temperatures will result in increased demand for water, intensifying pressures on water [35].

The results show that for the ***water sector***, costs will range between 3.77 and 13.2% of GDP by 2050, while by 2100 they will be between 7 and 29% of GDP depending on the GHG scenario and the discount rate. These results differ from those presented by Galindo and Caballero where the costs of the water sector by 2050 represent between 2 and 8% of GDP, while by 2100 they report values between 4.5 and 19% of GDP [18].

For the ***agricultural sector***, CEPAL (2015) estimated that potential losses in agricultural activities are between 25 and 35% of GDP, based on Ricardian models [36]. On the other hand, Galindo and Caballero (2016) reported that the costs of the agricultural sector by 2050 represent between 1 and 2.5% of GDP, while by 2100 they report values between 2 and 10% of GDP using Cost-Benefit Analysis (CBA) [18]. These reported data coincide with those obtained in the present study, which reports between 1.6 and 4.3% of GDP by 2050 and between 1.5 and 10% by 2100. Climate change will induce modifications in agricultural production patterns and will have a greater impact on subsistence crops. It will also cause increases in food prices, with their effects on nutrition, on public finances due to food subsidies and on the greater consumption of water in agricultural activities as a mechanism for adapting to new climatic conditions. Climate change affects the rate of economic growth, particularly agricultural activities, which are sensitive to climatic conditions.

The reported evidence on impacts in the **livestock sector** is scarce, and only the results from the study by Galindo and Caballero were available, showing that costs in this sector range between 0.5 and 1.2% of GDP for 2050, while for 2100 they report values between 0.8 and 4.8% of GDP [18]. These reported data are lower than those obtained in the present study, which reports values between 1.2 and 3.2% of GDP for the year 2050 and between 1.1 and 6.7% for 2100.

As for the ***health sector***, there are no reports of the costs due to the impacts of climate change. The data shown in this study show that it is one of the sectors that has the greatest impact on the economy, since the estimated costs for 2050 range between 4 and 11.3% of the national GDP, while for 2100 they are estimated between 7 and 15%.

The data reported in the ***land use sector*** are those of Galindo and Caballero where the costs of the agricultural sector for 2050 represent between 0.07 and 0.37% of GDP, while for 2100 they report values between -0.02 and -0.28% of GDP [18]. These data differ significantly from those reported in this study: between 0.44 and 2.3% of GDP by 2050 and between 0.05 and 0.74% by 2100.

The ***biodiversity sector*** is one of the costs that are not regularly monetized and that is very difficult to assess. However, it was found reported by Galindo and Caballero that the costs of 2050 represent between 0.01 and 0.03% of GDP, while by 2100 they report values between 0.04 and 0.52% of GDP [18]. The data reported are lower than those presented in this study, which reports between 0.5 and 1% of GDP by 2050 and between 0.06 and 0.71% by 2100.

Finally, the ***tourism sector*** has not been evaluated and analyzed individually either. Only Galindo and Caballero have reported costs between 0.0 and 0.01% of GDP by 2050, while by 2100 they report values between 0.02 and 0.16% of GDP [18]. Those obtained in this study of 1.18% of GDP by 2050 and between 0.19 and 1.12% by 2100 are much higher than those of Galindo and Caballero.

The results show that the evidence reported in the literature in a sectoral manner is that of Galindo and Caballero, who although they used the same methodology used in the present study

(CBA), the results differ in most sectors because in their study they used the GHG scenarios (B1, A1B and A2) of the IPCC AR4 [1], while in this study the SSP1-2.6, SSP2-4.5 and SSP3-7.0 trajectory scenarios of the IPCC AR6 were used [2].

The comparative analysis of the total economic costs of climate change in Mexico is broader than that by sector, since there are several studies that have estimated the total costs, with different methodologies, scenarios, models and initialization data. Thus, the results are very varied and dissimilar from each other.

For Estrada and Botzen, under a scenario of very high GHG emissions (SSP5-85), the costs accumulated during this century would be comparable to losing between 85% and up to 5 times Mexico's current GDP [37].

Compliance with the Nationally Determined Contributions (NDCs) would represent a reduction of around 20% of economic losses for Mexico with respect to the inaction scenario. The benefits of the NDC scenario would be between 28% and 71% of current GDP and residual costs would amount to between 68% and up to four times current GDP.

The failure of key actors to comply with international mitigation agreements would impose costs on other countries. In the event that the United States and China decide not to participate in the NDCs, this would impose a cost to Mexico in the range of 5% to 28% of current GDP and 4% to 36% of current GDP respectively. The present value of the costs accumulated during this century for Mexico would be between 45% and 241% of the current national GDP.

Table 3. Costs by sector and totals of climate change for the Mexican economy in 2050 and 2100 as percentages of Gross Domestic Product (% GDP) [2].

2050

	Discount rate of 0.5%			2% discount rate			4% discount rate		
Sector	**SSP1-2.6**	**SSP2-4.5**	**SSP3-7.0**	**SSP1-2.6**	**SSP2-4.5**	**SSP3-7.0**	**SSP1-2.6**	**SSP2-4.5**	**SSP3-7.0**
Water	12.57	12.94	13.02	6.66	6.85	6.90	3.64	3.75	3.77
Agricultural	3.58	4.07	4.24	2.33	3.52	2.73	1.36	1.54	1.58
Cattleman	1.53	2.33	3.18	0.98	1.52	2.05	0.57	0.89	1.18
Bless you	9.96	10.61	11.38	7.12	7.36	7.82	3.56	3.82	3.98
Land Use	0.31	1.30	2.28	0.15	0.63	1.12	0.06	0.25	0.44
Biodiversity	0.03	0.57	0.96	0.01	0.34	0.48	0.01	0.23	0.48
Tourism	0.01	0.64	1.18	0.01	0.64	1.18	0.01	0.64	1.18
Total	**28.00**	**32.46**	**36.23**	**17.26**	**20.87**	**22.28**	**9.21**	**11.12**	**12.61**

2100

	Discount rate of 0.5%			2% discount rate			4% discount rate		
Sector	**SSP1-2.6**	**SSP2-4.5**	**SSP3-7.0**	**SSP1-2.6**	**SSP2-4.5**	**SSP3-7.0**	**SSP1-2.6**	**SSP2-4.5**	**SSP3-7.0**
Water	28.21	28.83	28.93	14.08	14.39	14.44	6.73	6.88	6.91
Agricultural	8.25	8.90	9.39	3.65	3.86	3.94	1.48	1.52	1.48
Cattleman	5.44	6.16	6.73	2.43	2.71	2.87	1.00	1.10	1.12
Bless you	27.53	27.58	28.51	14.49	13.79	13.58	7.25	6.90	6.79
Land Use	-0.75	-0.09	0.74	-0.22	-0.03	0.20	-0.04	-0.01	0.05
Biodiversity	0.24	0.36	0.71	0.08	0.12	0.24	0.03	0.03	0.06
Tourism	0.14	0.82	1.12	0.06	0.34	0.44	0.03	0.13	0.19
Total	**69.06**	**72.56**	**76.15**	**34.58**	**35.19**	**35.70**	**16.48**	**16.55**	**16.59**

According to estimates, the economic costs of climate change by 2050 are between 1.5% and 5% of regional GDP. The impacts are not linear and occur heterogeneously in different regions and periods.

For Stern, the costs of inaction imply losing between 5 and 13% of GDP, while mitigation costs reach only 1% of GDP, although with a range of variation of between -2 and 5% of GDP [38]. The total costs of climate change, according to Galindo and Caballero (2016), reach values between 3.2 and 10.5% of GDP by 2050 and reach between 6 and 30% of GDP by 2100 [18]. These costs do not include additional impacts such as livestock activities and extreme events, nor costs associated with biodiversity and human lives.

The results obtained in this study of the total costs of climate change reach 2050, with a discount rate of 4%, have values that range between 9 and 13% of GDP in the most likely scenarios for the end of the century and reach between 28 and 36% of GDP at a discount rate of 0.5%. By 2100 with a discount rate of 4%, a value of around 16.5% of GDP would be reached and would reach maximums of between 69 and 76% of GDP with a rate of 0.5%. It should be noted that these costs also do not include estimated additional impacts such as extreme events, nor the costs associated with the loss of human lives, due to the absence of a market. Of course, these costs must be taken with caution, since they assume that there are no processes or costs of adjustment and adaptation.

As can be seen, there is a great variation between the results of the literature and those reported here, due to the different methodologies, scenarios, models and initialization data, so it is necessary to try to establish a systematized protocol to evaluate the economic impacts of climate change in Mexico.

Based on the above, it is understood that the current inertia of GHG emissions suggests that climate change is inevitable, at least during the 21st century. Thus, it is essential to implement adaptation processes in order to reduce the expected damage. However, it should not be forgotten that adaptation processes have limits, face various barriers, can be inefficient and have residual damage that can sometimes be irreversible. It is worrying that inefficient adaptation processes imply additional costs. It has been suggested that mitigation targets should be in place to control GHG emissions and limit the increase in average temperature to a range not exceeding 2°C. This change requires modifying the energy matrix and the available infrastructure, which are prone to high CO_2 emissions and involve long periods of time. Thus, in order to meet the emissions targets, it will be necessary to modify the development style and move to sustainable development in which mitigation processes result from modifications of the energy matrix, the generation of new infrastructure and more environmentally friendly sectors.

It has been reported that the costs of remediating climate change impacts are higher compared to GHG mitigation costs, making a strong argument to support a global agreement to reduce GHG emissions. Stern estimated that the costs of inaction imply losing between 5 and 13% of GDP, while mitigation costs reach only 1% of GDP, with a range of variation of -2 and 5% of GDP [38].

In Mexico, it is estimated that the costs of mitigation, with reductions of 50% of emissions by 2100 compared to 2002 and a discount rate of 4%, are between 0.7 and 2.2% of GDP. In this sense, the costs of inaction are higher than the costs of mitigation for the Mexican economy. Thus, the results allow us to identify that climate change has significant impacts on the Mexican economy and that the costs of inaction are higher than participation in an equitable international agreement, which recognizes the common but differentiated responsibilities of countries. From the economic point of view, it is therefore more efficient to act than to leave the problem for future generations, beyond the ethical considerations that this entails. There are economic arguments that suggest the importance of supporting mitigation processes, but that point out that the conditions under which the abatement process is applied must be considered.

4. CONCLUSION

Regional models show that by the end of the century temperature increases will be between 0.5 and 5 °C, while changes in precipitation will range between -20.3% and 13.5%. Low soil moisture, negative changes in vegetation (NDVI) and drought (SPEI 12) will lead to soil moisture deficits, water stress, sparse vegetation and semi-permanent meteorological drought. The entire country is likely to be subject to moderate to extremely severe droughts that will worsen by the end of the century. Climate change will have effects on water availability, crop yields, land deficits, livestock reproduction, meat production and meat products throughout the country, with increases in food prices. Likewise, health effects, with worsening of diseases associated with climate change, with increases in health spending; increasing from 6.25% to more than 18% of GDP, which could be unviable for the national economy. Based on likely temperatures, the risk of

species extinction will range from 3 to 48% in terrestrial, oceanic and coastal ecosystems and the risk of biodiversity loss will go from moderate to very high. The sectoral economic costs will be more important in the water, health, agriculture and livestock sectors. The total costs of climate change reach 2050, with a discount rate of 4%, values that range between 9 and 13% of GDP in the most likely scenarios and reach between 28 and 36% of GDP at a discount rate of 0.5%, while by 2100 with a discount rate of 4% around 16.5% of GDP and reach maximums of 69 -76% of GDP with a discount rate of 0.5%.
The results allow us to conclude that climate change has significant impacts on the Mexican economy and that the costs of inaction are higher. The costs of remediating climate change impacts are higher compared to the costs of GHG mitigation. Thus, it is more efficient to act now than to leave the problem to future generations, beyond the ethical considerations that this implies.

5. RECOMMENDATIONS AND FUTURE SCOPE OF STUDY

The analysis of climate change is a complex process that requires combining scientific and economic models in a consistent way; generating climate scenarios by the end of the century with the possible consequences on the country's productive and service sectors; and to generate economic scenarios in a long-term horizon; with appropriate risk margins and recognize the existence of significant uncertainty in the results obtained, including effects without market value and that in some cases are irreversible. However, it must be understood that projections are not one-off forecasts but only prospective scenarios. Finally, it must be remembered that the projections of climate and economic models are not static, since they can change suddenly and modify the projections, which further increases the uncertainty of the scenarios and consequences in the future, which must be taken into consideration in adaptation and mitigation measures, both personal and those of public policies.

A large number of public policy proposals have already been developed to minimize the risks of climate change. Proposals such as that of the American economist William D. Nordhaus, who was the first economist to develop a quantitative model that reproduces the interaction between economic development and climate change on a global scale. For Nordhaus, the solution to curb climate change is to put a deterrent price on carbon, since the current price is too low and does not encourage people to look for alternatives such as renewable energies. Nicholas Stern, former chief economist of the World Bank, had previously stated that "greenhouse gas emissions are the biggest market failure the world has ever seen." To summarize, the main conclusion of the Stern Review is the need to make an investment equivalent to 2% of global GDP to mitigate the effects of climate change, instead of investing more than 30% of global GDP in reducing the ravages of climate change. However, after the analysis carried out in this study, we consider that in addition to implementing these two public policies suggested by these renowned economists, a whole series of short-, medium- and long-term cross-cutting public policies are needed to minimize the risks of climate change: Therefore, we consider that the policies suggested by the World Commission on the Economy and Climate in a 2018 report, where it mentions that the adoption of ambitious climate measures could generate economic benefits of 26 trillion dollars until 2030, as well as 65 million new low-carbon jobs. According to this report, to build a more resilient and beneficial growth model, we must accelerate structural transformation in five key economic sectors:

- Clean energy systems: The decarbonization of energy systems combined with decentralized, digitally enabled electrification technologies can provide access to energy services to the 1 billion people who currently lack energy.
- Smarter urban developments: More compact, connected, and coordinated cities would save us $17 trillion by 2050 and stimulate economic growth by improving access to jobs and housing.
- Sustainable land use: Shifting to more sustainable forms of agriculture combined with forest protection could generate economic benefits of close to $2 trillion per year.
- Smart water management: Water-scarce areas could see their GDP fall by as much as 6% by 2050. This can be avoided by using water more efficiently through technological improvements and investment in public infrastructure.

- Industrial circular economy: Today, 95% of the value of plastic packaging material is lost after the first use. Policies that encourage a more circular and efficient use of materials could improve global economic activity and reduce waste and pollution.

The World Commission on the Economy and Climate urges public and private sector leaders to take urgent action over the next three years: putting a price on carbon, mandating disclosure of climate-related financial risks, accelerating sustainable infrastructure investment, maximizing the power of the private sector by boosting innovation, and advancing value chain transparency, and adopt a people-centred approach to ensure equitable growth.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

REFERENCES

[1] IPCC "Summary for Policymakers", Climate Change (2013). The physical science basis. Contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T.F. Stocker et. Al. (eds.), Cambridge, Cambridge University Press.

[2] IPCC Summary for Policymakers. In: Climate Change (2021). The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, and Zhou B. (eds.)].

[3] PNUMA (Programa de las Naciones Unidas para el Medio Ambiente) (2013), The Emissions Gap Report 2013, Nairobi. (2010), Perspectivas del Medio Ambiente: América Latina y el Caribe: GEO LAC 3, Ciudad de Panamá.

[4] Vergara, Walter et al. (2013), The Climate and Development Challenge for Latin America and the Caribbean: Options for Climate-Resilient, Low-Carbon Development, Banco Interamericano de Desarrollo (BID), April.

[5] Hepburn, Cameron y Nicholas Stern (2008), "A new global deal on climate change", Oxford Review of Economic Policy, vol. 24, Nº 2.

[6] Stern, Nicholas (2013), "The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models", Journal of Economic Literature, vol. 51, Nº 3, September.

[7] Voituriez, B. and Jacques, G (2000) El Niño. Fact and Fiction. Paris: UNESCO, 2000, 142 pp.

[8] Morice CP, Kennedy JJ, Rayner NA, Hogan E, and Killick REEA. An updated assessment of near-surface temperature change from 1850: the HadCRUT5 data set, J. Geophys. Res.-Atmos. 2021;126, e2019JD032361, https://doi.org/10.1029/2019JD032361

[9] Gulev SK, Thorne PW, Ahn J,. Dentener FJ, Domingues C.M, Gerland S, Gong D, Kaufman DS, Nnamchi HC, Quaas J, Rivera JA, Sathyendranath S, Smith SL, Trewin B, von Shuckmann K, Vose RS. Changing State of the Climate System. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

[10] CONAGUA (2022). El Reporte del Clima en México. Informe Anual 2020 Coordinación General del Servicio Meteorológico Nacional de la Comisión Nacional del Agua. 2021; PP. 98. www.conagua.gob.mx. https://smn.conagua.gob.mx/es/.

[11] World Bank Group (2021). Climate change knowledge portal (CCKP). 2021. climateknowledgeportal. worldbank.org

[12] Ramírez-Sánchez HU, Fajardo-Montiel AL., García-Guadalupe ME. (2021). Changes in the temperature of the Guadalajara Metropolitan Zone, Mexico under climate change scenarios. Brazilian Journal of Animal and Environmental Research.

[13] Ramírez-Sánchez HU, Fajardo-Montiel AL, García Guadalupe ME. (2021) Climatology and vulnerability to climate change in the "Altos de Jalisco" region, Mexico. Ann Environ Sci Toxicol 5(1): 001-011. DOI: https://dx.doi.org/10.17352/aest.000029
[14] Ramírez-Sánchez HU, Fajardo-Montiel AL, Ortiz-Bañuelos AD and De la Torre-Villaseñor (2022). Impacts of Climate Change on the Water Sector in Mexico. Asian Journal of Environment & Ecology, 17(2), 37–57. https://doi.org/10.9734/ajee/2022/v17i230289
[15] Ramírez-Sánchez HU, Fajardo-Montiel AL, Ortiz-Bañuelos AD and De la Torre-Villaseñor O (2022). The Agricultural Sector and Climate Change in Mexico. Journal of Agriculture and Ecology Research International. 23(3), 19–44. https://doi.org/10.9734/jaeri/2022/v23i330222
[16] Ramírez-Sánchez HU, Fajardo-Montiel AL, Ortiz-Bañuelos. AD, Castellanos-Tadeo CA and De la Torre-Villaseñor O. (2023). Climate Change and Its Impact on Human Health in Mexico. International Journal of Environment and Climate Change. 13(6), 219–243. https://doi. org /10.9734/ijecc/2023/ v13i61819
[17] Ramírez-Sánchez HU, Fajardo-Montiel Al, García-Guadalupe ME, Ulloa-Godínez HH. (2023). Climate Change and Its Impacts on Biodiversity in Mexico. Asian Journal of Environment & Ecology, 20(4), 29–54. https://doi.org/10.9734/ajee/2023/v20i4446
[18] Galindo, L. M., & Caballero, K. (2016). La economía del Cambio Climático en México: algunas reflexiones *Gaceta de Economía, 21(41).*
[19] IPCC (2007). Climate change 2007: The physical science basis. Contribution of Working Group I to the 4th assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
[20] Alcamo J, Flörke M, Märker M (2007) Future long-term changes in global water resources driven by socioeconomic and climatic changes. Hydrol Sci J 52:247–275.
[21] Magaña V, Vázquez JL, Pérez JL, Pérez JV. (2003). Impact of El Niño on precipitation in Mexico. Geofis Int. 42: 313−330.
[22] Méndez M, Magaña V. (2010), Regional aspects of prolonged meteorological droughts over Mexico. J Clim. 23: 1175−1188.
[23] Magaña V. (1999). Los impactos de 'El Niño' en México. Centro de Ciencias de la Atmósfera UNAM, Dirección General de Protección Civil, Secretaría de Gobernación. 1999
[24] Liverman DM. (2001). Vulnerability to drought and climate change in Mexico. In: Kasperson JX, Kasperson R (eds) Global environmental risk. UNU and Earthscan, New York, NY, p 201−216.
[25] Wilder M, Scott CA, Pineda N, Varady RG, Garfin GM, McEvoy J. (2010). Adapting across boundaries: climate change, social learning, and resilience in the United States−Mexico border region. Ann Assoc am Geogr, 100: 917−920
[26] Martínez-Austria P and Patiño-Gómez C. (2012). Efectos del cambio climático en la disponibilidad de agua en México. Tecnología y Ciencias del Agua, 2012; III: 1, Enero-marzo p. 5-20.
[27] OECD. Health spending (indicator). doi: 10.1787/8643de7e-en (Accessed on 25 March 2023).
[28] PAHO (2023), Social and Environmental Determinants of Health, Mexico, Pan American Health Organization. 2022.https://hia.paho.org/es/paises-2022/perfil-mexico.
[29] Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bihir TE, and White LL (eds.) (2014), IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press/ Cambridge, United Kingdom / New York.
[30] Fischer G, Shah M, Tubiello FN, and Van Velhuizen H. (2005). Socio-economic and Climate Change Impacts on Agriculture: An Integrated Assessment, 1990-2080, Philosophical Transactions of the Royal Society B: Biological Sciences, Vol. 360, no. 1 463, pp. 2067-2083
[31] Mendelsohn, R. (2009). The Impact of Climate Change on Agriculture in Developing Countries, Journal of Natural Resources Policy Research, Vol. 1, núm. 1, pp. 5-19.
[32] CEDRSSA (2019). El cambio climático y el sector agropecuario en México. Centro de Estudios de Desarrollo Rural Sostenible y Soberanía Alimentaria. LXIV Legislatura de la Cámara de Diputados. Gobierno de la República. Abril 2019. Pp. 11
[23] CONABIO (2023). México es un país megadiverso. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad 2023. https://www.biodiversidad.gob.mx/pais/quees

[34] IUCN (2023). The IUCN Red List of Threatened Species. Version 2022-2. https://www.iucnredlist.org
[35] Sebri, Maamar (2014), A meta-analysis of residential water demand studies, Environment, Development and Sustainability, vol. 16, Nº 3, June.
[36] CEPAL (2015) Comisión Económica para América Latina y el Caribe. La economía del cambio climático en América Latina y el Caribe: Paradojas y desafíos del desarrollo sostenible.
[37] Estrada, F. & Botzen, W. J. W. (2021). Economic impacts and risks of climate change under failure and success of the Paris Agreement. Ann. N. Y. Acad. Sci. 1504, 95–115.
[38] Stern, Nicholas (2007), The Economics of Climate Change: The Stern Review, Cambridge University Press, January.