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STATE AND PERSPECTIVES

OF CLIMATE CHANGE IN MEXICO:

A STARTING POINT

State and Perspectives of Climate Change in Mexico a Starting Point

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Contenido

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Prologue

In today's world, global change impacts different areas: climate, pollution, loss of biodiversity, energy transition, and food sustainability to name but the most critical. Gathering accurate information for in-depth analysis is paramount to the design and implement viable public policies.

With this publication, the National Autonomous University of Mexico (UNAM: *Universidad Nacional Autónoma de México*) reaffirms its commitment to education and to the generation and dissemination of scientific knowledge to address the most pressing global and national problems of our times. At a time when the environmental crisis in all its manifestations is intensifying and its effects are becoming increasingly evident, this publication marks the beginning of a series of periodic assessments of the status and perspectives of climate change in our country. It is our goal to use an integral, multidisciplinary approach involving close collaboration with academic institutions and agencies to provide society and decision-makers with the best information and currently available tools to take on this challenge.

Contributions to *State and Perspectives of Climate Change in Mexico: Starting Point* were made by fifty-eight researchers and experts from UNAM institutes, ten universities, and research centers in Mexico and other countries. This joint effort, coordinated by the Climate Change Research Program (PINCC: *Programa de Investigación en Cambio Climático*) and the Institute of Atmospheric Sciences and Climate Change (ICAYCC: *Instituto de Ciencias de la Atmósfera y Cambio Climático*), considers climate change, along with the intricacy and diversity of its manifestations, as significant challenge to society and the environment in Mexico. In particular, it addresses the current and future implications of the phenomenon for aspects that are central to the country's development, such as agriculture, biodiversity, water, health, energy, and the economy. The analyses presented underscore the urgent need for strategies and policies designed to adapt, mitigate, and transform our climatic and social realities. Achieving these objectives necessarily involves appreciating and supporting the development of scientific and humanistic knowledge, education, and culture.

We are confident that this initial document will serve to encourage a broader participation of the country's scientific community to promote continoued and, sustained research, on climate chage in México, and dissemination of results. UNAM is committed to sustaining this effort over the long term by promoting the formation and consolidation of human resources, projects, and research groups on climate change in Mexico, thereby contributing to an informed more actively involved in decisions for the common good that affect us collectively.

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Introduction

Climate change is a problem arising from the interaction of complex human and natural systems which has many causes and effects. The profound uncertainty surrounding some processes associated with this global phenomenon, how to evaluate the risks involved and the measures to be taken in response, as well as the possibility of global climate catastrophes, compromise the wellbeing of present and future generations. Moreover, in addition to being a multidimensional phenomenon that encompasses scientific, technological, socioeconomic, political, ethical, and cultural aspects, it is a dynamic, non-linear problem in constant evolution. It is, thus, indispensable to continously generate to continously generate evolution. It is, thus, indispensable to continously generate knowledge concerning its causes and consequences. To provide updated information based on the best available science to society, government, and other decision makers.

Climate change represents enormous challenges—and potential areas of opportunity—for our country. To address them, long-term integral and multi/transdisciplinary research on all of its aspects must be carried out and increasingly fomented. Adaptation and risk reduction require timely, solid knowledge and information on the causes and consequences of climate change, as well as the systems that generate them and are impacted by them, their exposure, vulnerability, and ability to transform and adapt.

Studies conducted over the last three decades by the National Autonomous University of Mexico (UNAM) and other institutions have revealed that Mexico is particularly vulnerable to climate change impacts. In a scenario involving high greenhouse gas emissions, significant negative effects on agricultural production, human health, biodiversity, cities, and energy in addition to significant increases in the frequency and magnitude of extreme events and consequential damages. For example, the economic losses accumulated during this century are estimated to be equivalent to several times today's gross domestic product. Moreover, these impacts will have long-lasting and differentiated effects among the country's diverse social sectors and regions, increasing inequality and making it difficult to achieve poverty reduction targets and sustainable development goals.

Nevertheless limited efforts have been made to summarize and communicate the State of climate change and its effects on the country and to provide an overview of the possible evolutions of the climate system and its influence on natural and human systems during this century. Those most worthy of mention are the six *National Communications to the United Nations Framework Convention on Climate Change* submitted between 1997 and 2018, and three biennial Update Reports initially coordinated by the National Institute of Ecology (INE, initials in Spanish), which was constituted in 1992, and later by the National Institute of Ecology and Climate Change (INECC, initials in Spanish), constituted in 2012. Elsewhere, in the academic sector, the Mexican Climate Change Report was published by the UNAM's Climate Change Research Program (PINCC) in 2015. While the structures and goals of the aforesaid documents are different, both are, in principle, reference sources of information for making decisions related to climate change and society in general.

To generate updated, timely information on climate change in Mexico, UNAM, through the PINCC and the Institute of Atmospheric Sciences and Climate Change (ICAYCC), decided to undertake the task of carrying out regular assessments of the state and perspectives of climate change in Mexico. This publication marks the start of the production of these regular assessment reports in addition to other special thematic reports related to emerging issues of where greater depth or more frequent updates are required; it does not represent a full assessment report, but a brief account of some of the most relevant aspects for decision-makers. Therefore, this is not intended to be an exhaustive study, but rather reference materials to give readers a quick overview of certain aspects of climate change in Mexico that have been observed or are projected, as well as some of the consequences and actions that might be taken to deal with them.

It also provides an assessment of research needed in several areas and a glimpse of the research agenda. The work involved nine focus groups and contributions were received from fifty-eight researchers and experts from institutes whitin UNAM institutes and another ten universities and research centers throughout the country. As work on this document was in progress, simultaneous studies began on a variety of topics that will make it possible to present a more complete assessment report in the near future with greater participation of the broder national academic community involved in this important topic. We consider the role of UNAM and other national academic institutions of paramount importance to the generation, publication, and dissemination of scientific knowledge on climate change to contribute to decision-making based on the best available knowledge and the development of an informed and participatory society. Achieving this goal requires a long-term effort to build a consensus among multidisciplinary and multi-institutional groups on various aspects of climate change that are not subject to the vagaries of political will and that have sufficient funding to operate and move forward. An effort coordinated by UNAM, with broad participation of Mexican, will have the capacity to call for national and international support to make these conditions possible.

Background

Mexico's National Communications, coordinated by the federal government, have been submitted intermittently every three to seven years. Thus, thematic continuity has not been maintained; nor has support been obtained for the upkeep of specialized working groups that stimulate advances in research on topics of national relevance. Moreover, the most recent National Communication was published in 2018, and there is no official deadline for the next one. In this context, it is worth noting that it has been over seven years since the UNAM's PINCC published a *Mexican Climate Change Report*, which was the first initiative from academia to present an overall national climate change assessment focused on, and produced in, the country. For the first time, this document presented a diagnosis of what was known about Mexico's climate and its observed changes; as well as compiling available studies on adaptation, it compiled work done on the phenomenon's effects and impacts; moreover, it analyzed the country's contributions to global greenhouse gas emissions and proposals to mitigate them. This was a groundbreaking report as it compiled the knowledge in three volumes: the scientific basis of climate change (Vol. I); impact, vulnerability, and adaptation to climate change (Vol. II); and greenhouse gas emissions and mitigation efforts (Vol. III). Two hundred and forty academics took part in drawing up the report.

Three special reports and the Sixth Assessment Report (AR6) have been published during the Sixth Assessment Cycle of the Intergovernmental Panel on Climate Change (IPCC), which began in 2016. Among other results, these reports have unequivocally highlighted the role of human activities in global warming and previously observed associated impacts which are predicted to increase considerably in the coming decades. These studies show that regions in low latitudes, with lower levels of socioeconomic development and greater social inequalities, are and will be considerably more affected by climate change than other regions. Even though national experts contributed to the production of the IPCC reports, which are a very important source of information for decision-makers, academia, and society in general, said reports are not designed to meet national or sub-national information needs, nor to present the knowledge of climate change in sufficient detail. Information generated locally by countries is not always properly reflected in international reports. However, national, and sub-national efforts to generate knowledge are key to a better understanding of this phenomenon, its implications, challenges, and areas of opportunity and are decisive to the formulation of public policies in this area.

It is in this context that the UNAM's PINCC and ICAYCC coordinated the creation of this document concerning the status and perspectives of climate change in Mexico. To this end, academics from different UNAM institutes and programs and other universities and institutions in Mexico and abroad were invited to participate. This publication marks the start of regular assessments as both general and specific reports. This initial document presents an assessment of the effects of climate change on the regional climate, extreme events, and adjacent oceans with emphasis on their impacts on agriculture, biodiversity, water, health, energy, and the economy.

This document summarizes some of the studies conducted to date and incorporates new research in cases in which it was possible to address some key information gaps. The studies are grouped into four areas: aspects of climate change and variability; impacts on different natural and human systems; greenhouse gas (GHG) emissions; and mitigation strategies. This document is an executive summary based on the results of extensive reports that can be accessed by using the corresponding links in each section. All of these documents should be considered works in progress that will culminate in a national assessment report to be published in late 2024 or early 2025 with the broad participation of academics and national experts.

For the first time, this publication includes a selection of digital resources and specialized software (created by the PINCC in collaboration with the ICAYCC) along with access to the DataPINCC data portal, which makes it possible to view, consult, and process geo-referenced climate change databases. The use of these resources and their possible applications will be made known through webinars so that users can take full advantage of them.

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Climate Change in Mexico: Observations and Projections

Changes Observed in the Climate

The climate is a complex system that is determined by its internal natural variability, which may take effect over the immediate short-term or over hundreds of years, and by external natural and anthropogenic forces and their interactions. The analysis of climate change focuses on identifying, characterizing, and understanding long-term changes in trends and variability by measuring central tendency and the variability of different climate variables. This section shows some of the main changes in Mexico's climate and demonstrates that it is already considerably different than the climate recorded at the beginning of the twentieth century. For more detailed, complete information, consult the reports specified at the end of this chapter.

Temperature

Average air temperature in Mexico has risen by around 1.69°C (1.59°C to 1.81°C) as compared to the start of the twentieth century.

Considering 1900-1930, as referent period, the increase in average air temperature in Mexico for 2022 is in the range of 1.59°C to 1.81°C, depending on the database used (HadCRUT5, GISSTEMP, NOAA-GlobalTemp_v5). Uncertainty about the magnitude of this increase is largely due to the data retrieval, quality control, and processing methods used by the generating institutions (see **Figure 1a**).

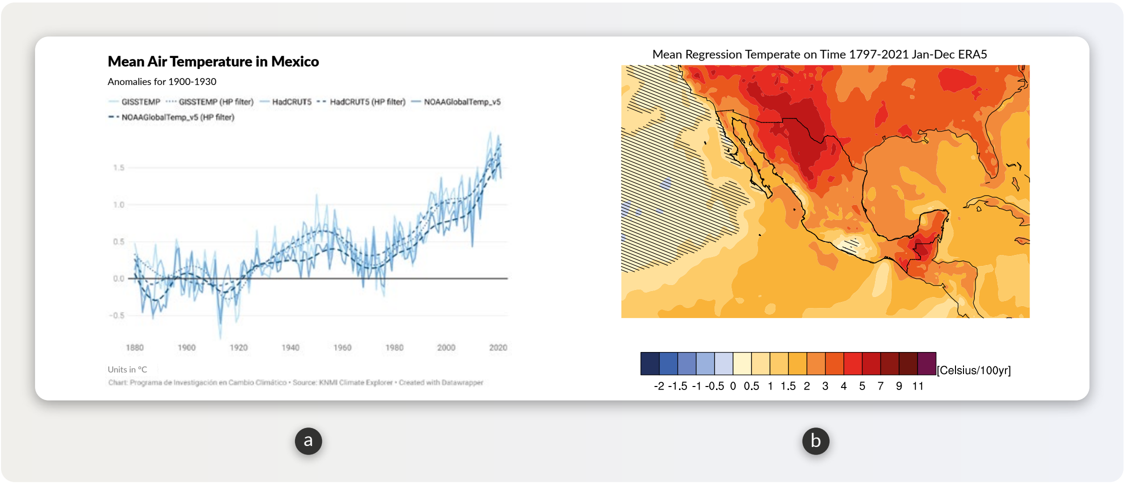
The increase and growth rates of the mean air temperature in Mexico are higher than the global average.

While mean air temperature in Mexico since the beginning of the twentieth century rose by 1.69°C (1.59°C to 1.81°C), the increase in average global temperature was 1.23°C during the same period. The growth rate of the mean annual temperature in Mexico is considerably higher than the average global rate. The global temperature has risen at a rate of 1.90°C (1.78°C to 1.97°C) per century while in Mexico the growth rate is 2.88°C (2.77°C to 3.03°C) per century. Over the next few decades, warming is expected to continue to be faster in Mexico than the global average.

The warming observed in Mexico is due to an increase in the atmospheric concentration of greenhouse gases (GHG), which are anthropogenic emissions that have been produced since the industrial revolution.

The general mean air temperature trend in Mexico is determined by anthropogenic GHG forcing while other climate drivers and variability processes have a modulating effect. Without the cooling effect of other forcing agents, the rise in annual average air temperature in Mexico would have been about 70% higher than recorded. The contribution of solar forcing to observed warming represents about 6% of that produced by anthropogenic GHGs[1].

Figure 1. Timeline and spatial trends of mean air temperature in Mexico.



Panel a) Show the mean annual temperature change (°C) in Mexico from 1880 to 2021 compared to 1900-1930. Panel b) shows the trends (°C/100yr) in mean annual temperature change for 1979-2021.

Source: Estrada, F. et al. 2023

Mean annual temperature increases are not even: greater increases are in the northern and southeastern México.

Warming rates show large variations in terms of spatial patterns and the magnitude of the changes; in general, warming rates of 2°C to 4°C per century were recorded across a large part of the country from 1975 to 2021. The different databases (HadCRUT5, GISSTEMP, CRUTS4.05) agree that observed warming rates were higher in northern Mexico. Figure 1b, based in ERAS data from 1979 to 2021, indicates warming rate per century higher than 6°C in the north and close to 5°C in the southeast.

Temperature increases vary throughout the year: they are higher in fall and spring, and lower in winter and summer.

Spring (March-April-May) and fall (Sept-Oct-Nov) are the seasons with the highest increase in mean air temperature: 1.77°C (1.61°C to 2.03°C) and 1.77°C (1.66°C to 1.85°C), respectively, for 1900-1930. Winter (Dec-Jan-Feb) is the season with the lowest rise in mean temperature with 1.51°C (1.37°C to 1.77°C), while the increase in summer (Jun-Jul-Aug) was 1.53°C (1.51°C to 1.56°C).

Precipitation

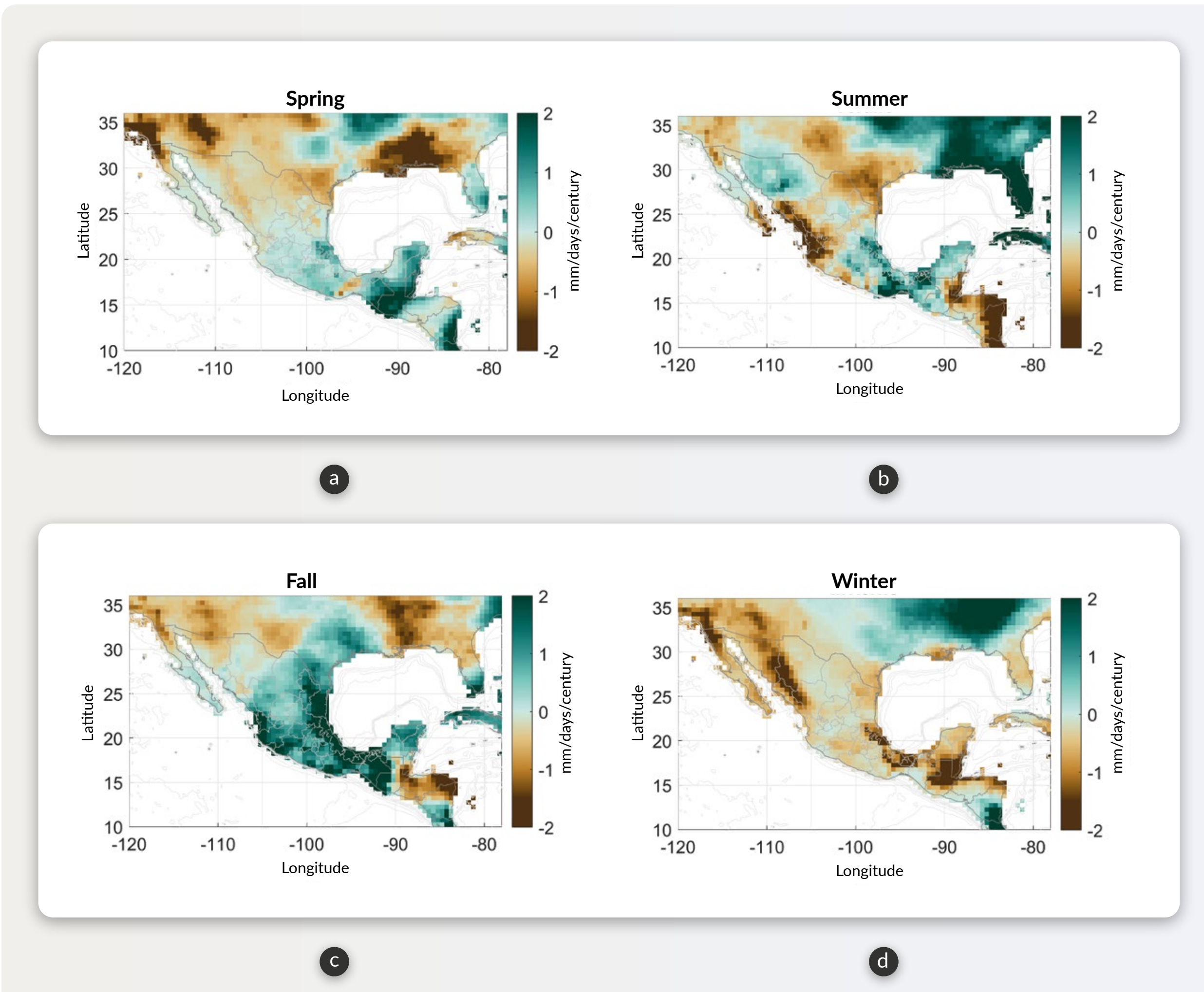
The average annual precipitation in Mexico has increased by 3.1 (2.4-3.8) mm/month per century since the start of the twentieth century. Climate change has modified the seasonal distribution of precipitation with significant increases in summer and fall.

The databases analyzed (GPCC, CRUTS 4.05) agree that precipitation shows a constant positive trend from 1901 to 2021. However, there is significant uncertainty regarding the magnitude of the trend: 2.4 mm/month per century (GPCC) as opposed to 3.8 mm/month per century (CRUTS 4.05). Significant positive trends were reported for both summer and fall by both databases, but the magnitudes of change vary significantly. According to GPCC, fall and summer precipitation increased at rates of 6.5 and 5.1 mm/month per century, respectively. In contrast, CRUTS 4.05 specifies the corresponding rates of increase as 7.7 mm/month per century in fall and 8.8 mm/month per century in summer.

Changes in precipitation are far from being even across the country. In general terms, precipitation has decreased in northern regions of the country and increased in central and southern regions. Seasonal changes in precipitation are also uneven.

From 1975 to 2021, annual precipitation showed a negative trend of -0.2 to -1 mm/day per century in the northeast and increases of between 0.5 and 2 mm/day per century in most of the central and southern regions of the country. In winter, negative trends in precipitation were observed throughout the country, particularly in the northwest and southeast, with values of up to -2 mm/day per century. During spring, a pattern of reduction was noted in the northwest along with increases in most of the central and southern regions of the country in agreement with annual precipitation. Summer trends showed large reductions in the north and center, reaching -0.5 to -2 mm/day per century with the largest decreases in Jalisco, Nayarit, Sinaloa, Tamaulipas, and Nuevo León. In contrast, in the southeast and center of the country, increases of between 0.5 and more than 2 mm/day per century were observed, with the largest ones in Oaxaca and Chiapas. With the exception of the northwest, trends are positive for almost the entire country during fall (between 0.5 and 2 mm/day per century), reaching maxima of above 2 mm/day per century in Tabasco, Veracruz, Chiapas, and Jalisco, as shown in **Figure 2**.

Figure 2. Seasonal precipitation trends in Mexico for 1975-2021.



Panels a), b), c), and d) show precipitation trends for spring, summer, fall and winter, respectively. Units are expressed in mm/day per century.

Source: Estrada F. et al, 2023

Evolution of Extreme Events During the Period Observed

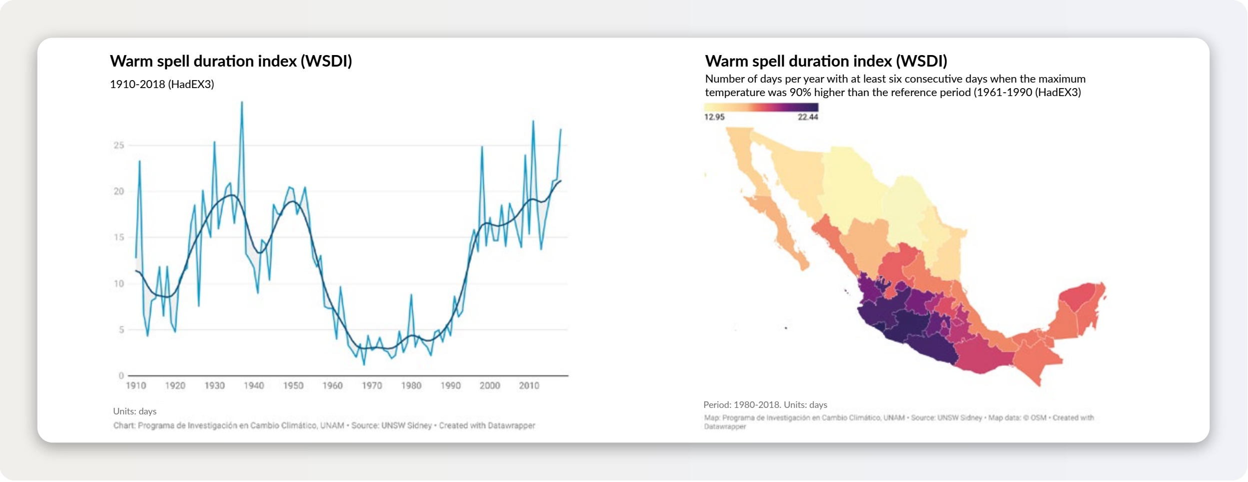
Extreme events both temperature and precipitation over the period (1975-2021) have risen in number, including longer dry periods and higher precipitation amount. Extreme temperature events have increased evenly across the whole country although several indices reveal the influence of low-frequency oscillations that modulate the underlying trends. This section presents a short summary of the extreme events studied and readers are invited to consult the more complete reports mentioned at the end of this chapter.

Extreme Temperature Events

From 1990 to 2020, warm spells lasted longer and reached the highest magnitude on record, wich were observed between 1930 and 1960.

The states of Colima, Michoacán, Guerrero, and Jalisco in central and western regions of the country, experienced the longest warm spells[1] (about 22 days per year), while the shortest spells (between 12 and 15 days per year) occurred in the north. Trends observed during 1980-2018 showed increases of about 10 additional days per decade in the central-western region of the country while increases of approximately 5 additional days per decade were reported in the north. In the rest of the country, increases are in the vicinity of 7-8 additional days per decade. The increase in the duration of warm spells recorded as of the mid 1980s comes after a period of almost thirty years (1960-1990) with the shortest spells recorded for this variable as shown in **Figure 3**.

Figure 3. Evolution of the warm spell duration index (WSDI) during the period observed.



The panel on the left presents the WSDI timeline showing mean warm spell evolution in Mexico. The panel on the right showsthe spatial distribution of WSDI trends (1980-2018).

Source: Estrada F. et al, 2023

The percentage of days with maximum temperature above the 90th percentile (OJO: superíndice th) (TX90p) has almost doubled since 1970 considering (1961-1990) as the reference period.

The percentage of days when the maximum temperature ia above the 90th percentile considering 90 the reference period (1961-1990) has risen considerably since the early 1980s, when the average

1. This index is defined as the number of days per year with at least six consecutive days when the maximum temperature was greater than 90%

porcentade of days with temperatures greater than the 90th percentile was 9%. In recent years, this value has doubled (17%). Increases greater than 4% per decade are observed in Michoacán and Jalisco while increases are of 3 to 4% in the center and northwest and 2 to 3% in the northeast are of.

The percentage of days with minimum temperature above the 90th percentile (TNX90p) for the reference period (1961-1990) has increased since the 1970s and has accelerated since the 2010s.

In recent years, the TN90p reached its historical high with approximately 20% of the days having minimum temperatures surpassing this threshold. Trends in this variable indicate that the number of dayswith minimum temperature above the 90th percentile period has increased more rapidly in states already possessing the highest percentages of days with temperatures above this threshold. Growth trends in the vicinity of 3% per decade were recorded in the Yucatan Peninsula and the southeast while in the center of the country growth was measured at 2.5% per decade. In summary, the combination of changes occurring at opposite ends of the temperature sacle in TX90p and TN90p, has led to more frequent days with record maximum and higher minimum temperatures, thereby negatively impacting human comfort, health, and labor productivity, especially in the Pacific states.

Extreme Precipitation Events and Droughts

Seasonal rainfall distribution has become more extreme with longer droughts and increasingly extreme precipitation events.

Since the early 2000s, the number of consecutive dry days[2] has increased from an average of approximately 70 days per year to about 80. The trends observed in this variable are much greater in the northwest, with increases of 6 and up to 8 additional days per decade in Baja California, Sonora, Sinaloa, and Chihuahua.

Very rainy days[3] have increased from about 21% to 26% in recent years: an increase of almost 25%. From 1980 to 2018, regions impacted by tropical cyclones and the North American monsoon, were those in wich extreme events contributed a large fraction to the annual precipitation (24-26%). In the rest of the country, the contribution of extreme rainfall events to annual precipitation is close to 23%; during this period, the contribution of very rainy days increased by as much as 2-4% per decade in most of the country.

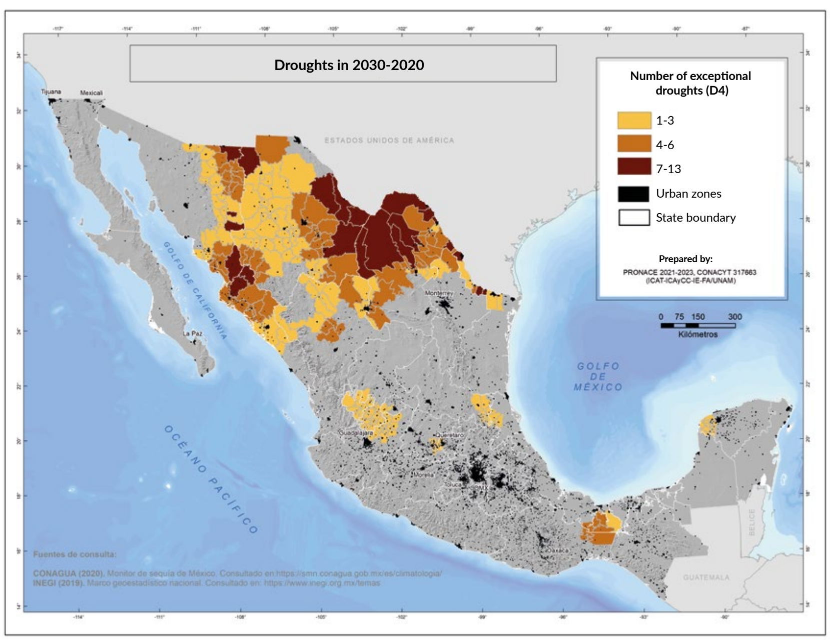
2. This index accounts for the number of consecutive days with precipitation of less than 1 mm.
3. Very rainy days are defined as those with precipitation above the 95th percentile of rainy days calculated for the reference period (1961-1990).

Extremely rainy days[4] proportionately exhibiteven larger changes from 6% to 9% of the total precipitation during 1980-2018: corresponding to: a 50% increase. The states with the largest increase in these events are Baja California Sur (3.34%), Yucatán (1.59%), and Colima (1.54%).

Droughts have become more frequent and severe.

According to the Drought Monitor issued by the National Metereological Service, central and northern Mexico have been impacted by frequent, exceptional droughts (D4) as shown in **Figure 4**. Exceptional droughts are characterized by exceptional widespread crop or pasture losses; exceptional fire risk; total water shortage in reservoirs, streams, and wells; and the likelihood of emergency situations water shortages.

Figure 4. Exceptional droughts in 2003-2020.



Source: Ortíz and Haro, G.A., et al 2023; CONAGUA (2020) Drought monitor in Mexico. Consulted on https//smn.conagua.gob.mx/es/climatología/

INEGI (2019). National geostatistical framework. Consulted on https//inegi.org.mx/temas

4. Extremely rainy days are defined as those with precipitation above the 99th percentile of the rainy days calculated for the reference period (1961-1990).

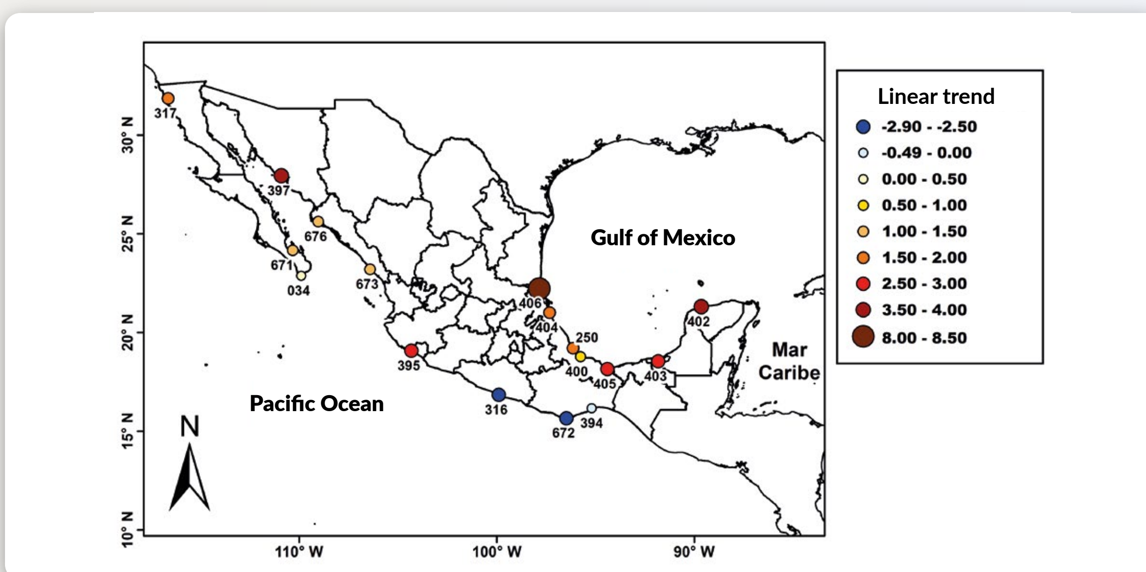
Mean Sea Level along Mexican Coasts

Mean sea level varies markedlythroughout the year and region to region ally. Highest sea levels along the Mexican Pacific coast occur mainly in September and in October along the Gulf of México coast; annual cycles have an average amplitude 0.23m and 0.26m, respectively. The lowest value on Mexican Pacific coasts occurs in February and April and on Gulf of Mexico coasts during the months of January, March, May, or June.

There are differentiated observed increases in mean sea level in the Gulf of Mexico and the Mexican Pacific since the second half of the twentieth century.

The average rate of increase is higher along the Gulf of Mexico (2.4 mm yr^{1}) than along the Mexican Pacific (1.1 mm yr^{1}). The trend observed in the Gulf of Mexico is considerably higher than that reported globally (1.8 mm yr^{1}) during a similar period (Gulf of Mexico: 1946 to 2006, global estimate: 1946 to 2002). Certain regions in the southern Mexican Pacific, particularly on the coasts of Oaxaca and Guerrero, experienced deacreases in mean sea level at an average rate of 1.5 and 2.8 mm yr^{1}, respectively, as shown in **Figure 5**. This may be due to vertical movements of Earth's crust occurring in the vicinity, or to earthquakes, slow earthquakes and/or subsidence.

Figure 5. Spatial distribution of long-term sea-level trends at 17 coastal locations in Mexico.



Source: López-Espinoza E.D., et al 2023 and the National Tidal Data Service, UNAM.

Rising local sea-level trends are spatially heterogeneous and some of the largest changes are found in regions with a high degree of marginalization.

The highest rate of mean sea level rise is observed in the southern and northwestern Gulf of Mexico. In addition, four of the seven sites analyzed show a higher rate than reported at a global scale (Coatzacoalcos in Veracruz with 2.8 [1.7 to 3.9] mm yr^{1}, Cd. Del Carmen in Campeche with 3.0 [1.6 to 4.4] mm yr1, Progreso in Yucatán with 3.7 [2.4 to 5.0] mm yr^{1}, and Cd. Madero, Tamaulipas with 8.3 [2.4 to 14.2] mm yr^{1}). Particularly, the rate of increase observed in the southern Gulf of Mexico occurs at locations near cities with a high marginalization index. In the Mexican Pacific, the highest rates of sea level rise are observed in the central region and in the Gulf of California, peaking in Manzanillo (in Colima) and Guaymas (in Sonora) at 2.8 [0.6 to 5] mm yr^{1} and 3.7 [1.8 to 5.6] mm yr^{1}, respectively.

Climate Projections for the Twenty-first Century

This section presents some state-by-state climate change scenarios for the country derived from phases 5 and 6 of the Coupled Model Intercomparison Project (CMIP), the CLIMRISK model and the AIRCC-Clim emulator developed by the Climate Change Research Program, the Institute of Atmospheric Sciences and Climate Change, (both at UNAM) and the VU Amsterdam[2,3]. The results presented here are based on ensamble simulations data and are useful for illustrating possible changes that may occur; they should neither be taken as a estimates of model uncertainty nor thought of as a forecast. Readers are invited to access the DataPINCC data portal (https://datapincc.unam.mx/datapincc/) for a wider collection of climate change scenarios.

Up to of the second half of this century, changes in the country's (and the world's) climate are almost entirely determined by emissions, and policy ddecisions made in the previous decades and also by the persistence in memory of the climate system itself.

The changes projected for 2030-2040 are mostly unavoidable through conventional mitigation policies and call for the expansion and strengthening of adaptation strategies with the involvement and joint collaboration of government, society, and academia to co-design said strategies.

The climate changes that will take place in Mexico during the second half of this century, and in the more distant future, depend on the socioeconomic path that global society as a whole decides to take.

In a scenario involving extremely high GHG emissions (SSP585), the average annual air temperature in Mexico could increase by about 6ºC by the end of this century (as compared to 1986-2005). In a scenario of GHG emissions similar to current trends without significant international mitigation (SSP370), such an increase could exceed 5°C by 2100. On the other hand, in a scenario involving strict compliance with the Nationally Determined Contribution (NDC; similar to SSP245) commitments adopted by participating countries, the increase in average annual temperature in Mexico could be kept as low as 3°C as compared to 1986-2005. Finally, if the goals expressed in the Paris Agreement were achieved (SSP126), the average temperature in Mexico could stabilize at around 2°C by the end of this century.

Despite significant uncertainty concerning precipitation forecasts, scenarios with high GHG emissions imply significant reductions in average annual precipitation in the country. In contrast, scenarios involving intermediate and low emissions imply changes in the country's average precipitation level similar to those observed in the reference period.

According to the average of all the ensemble simulations from the CMIP6 Intercomparison Project, high GHG emission scenarios (SSP585 and SSP370) would imply a reduction of about 15% (8%) by the end (mid) of the century. Intermediate emissions scenarios like SSP245 project much smaller changes in average annual precipitation for the country (5% or less) during this century and a scenario compatible with the Paris Agreement (SSP126) could imply a slight increase in precipitation.

Simulations of state-of-the-art climate models suggest that the country could face drier and much warmer conditions this century. Projected seasonal changes vary greatly and are very uneven spatially; these differences tend to be accentuated in scenarios of high GHG emissions and long-term forecasts.

In a very high GHG emissions scenario (SSP585), the increase in statewide annual average temperature could range from 1.8°C to 2.5°C from 2050 to the end of the century. The highest rises would occur in the north of the country in states like Coahuila, Chihuahua, and Sonora with up to 2.5°C (2050) and 5.4°C (2090), while Yucatán and Quintana Roo would have the lowest increases (about 1.80°C in 2050 and 3.9°C in 2090). In the SSP585 scenario, by the end of the century the annual temperature rise in 27 states could exceed 4.5°C and, in the case of seven northern states, the rise could be greater than 5°C. All of the above increases are calculated with respect to the average temperature in each state during the reference period 1986-2005.

A generalized decrease in precipitation is projected in all other scenarios involving higher GHG emissions (SSP245, SSP370, SSP585, but not SSP126), especially for the second half of this century. The largest decreases in precipitation are expected in the Yucatan peninsula with values that may exceed -20% in the period 2081- 2100. In general, seasonal reductions are projected for all

seasons with the exception of fall. In for SSP585 scenario for 2050 horizon,the largest increases (>10%) occur in the central region of the country. These increases vary significantly for the states under different GHG emission scenarios; the responses to different levels of forcing are nonlinear, may be positive or negative, and vary in magnitude across the different SSPs, particularly in the short term. In spring, the largest reductions in precipitation (>30% by 2090) occur in the central and northern areas of the Pacific coasts (Colima, Jalisco, Nayarit, Sonora, and Michoacán) and the smallest reductions occur in the Yucatán peninsula and the southeast. In contrast, the largest reductions in summer precipitation occur in the Yucatan Peninsula and most of southeastern Mexico while the smallest reductions occur in the north. In places like Yucatan, Campeche, and Quintana Roo, precipitation reduction would be in the vicinity of 50% in the SSP585 scenario. Reductions in winter precipitation would be greater in the central Pacific coastal zone (Colima, Jalisco, Michoacán, and Nayarit) with magnitudes of at least 20% in the short term and 40% in the long term.

Note that th”se r’sults are purely indicative as there are important differences between the projections produced by different climate models, particularly in terms of precipitation andat small geographical scales (see **Figures 6** and **7**).

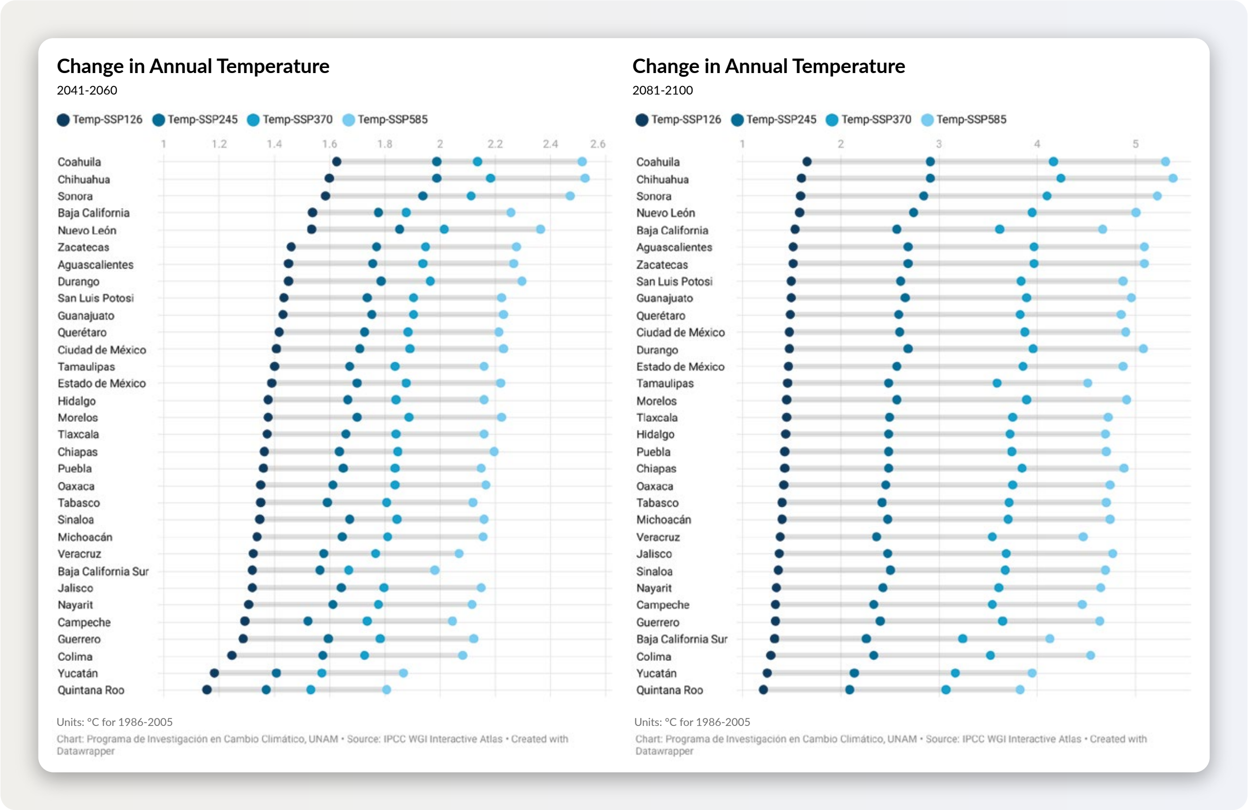
In contrast, in a GHG emissions scenario aligned with the Paris Agreement (SSP126), the rise in temperature could be as low as 2°C for the entire century and for all states in the country. This scenario would also limit annual precipitation variations.

Even GHG scenarios involving intermediate international mitigation efforts, such as strict compliance with current NDCs (similar to SSP245), could restrict increases in statewide annual average temperature to less than 3°C this century.

Over the short term, temperature increases in fall and winter are slightly lower than in summer and spring. The lowest temperature increases occur in the winter period where projections do not exceed 5°C (1.6°C) in the SSP858 scenario (SSP126). The general pattern of statewide warming is very similar in all seasons and emission scenarios. In general, northern states show the highest levels of rising temperature (Coahuila, Chihuahua, Sonora, Durango), although in summer Chiapas and Tabasco are among the top 5 states The states exhibiting the least warming in all seasons of the year are typically those in the Yucatan and the Baja California peninsulas (except in winter).

The average of all the ensemble simulations in the CMIP6 suggests that precipitation could rise in most of the country in low-emission scenarios at least until the middle of the century. In particular, in scenario SSP126, 23 of the 32 states would have slight increases in precipitation through 2050.

Figure 6. Changes in mean annual temperature for 2050 and 2090.



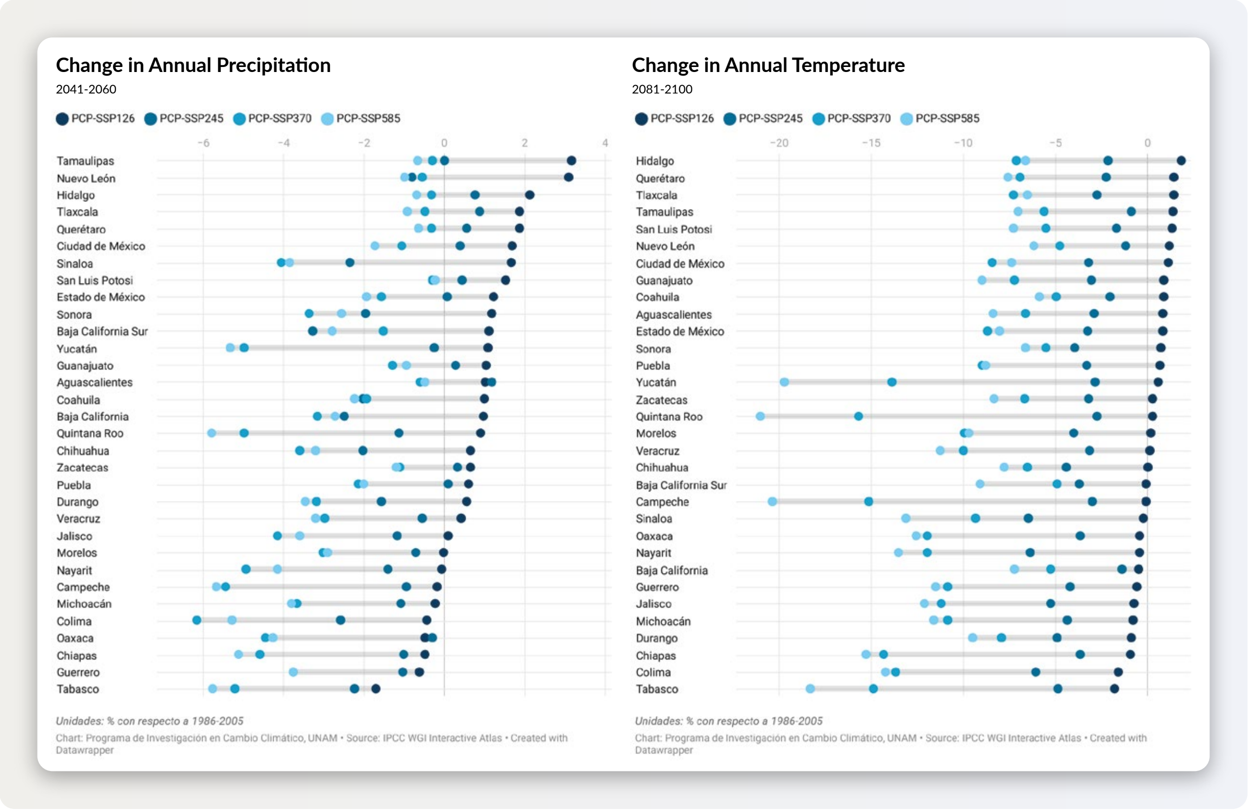
The charts present the median ensemble simulations in the CMIP6 and four emissions scenarios (SSP126, SSP245, SSP370, SSP5885) for each state. The panels show changes in mean air temperature (°C) for 2041-2060 (left) and 2081-2100 (right). All changes are shown with respect to the reference period 1986-2005.

Source: Estrada, F., et al 2023.

Precipitation patterns are expected to become more extreme this century, particularly in scenarios involving higher GHG emissions.

Precipitation patterns in most states would change significantly with longer dry periods and increases in precipitation on the wettest day of the year. Ensemble average simulations from the CMIP5 models indicates that virtually every state in the country would have a larger number of consecutive dry days (CDD) in any of the GHG emission scenarios analyzed as compared to 1970-2000. In particular under the RCP8.5 GHG scenario consecutive dry days could increase by more than 10 and 21 days per year by 2050 and 2090, respectively, in states such as Baja California Sur and Colima. States such as Durango, Guerrero, Jalisco, Michoacán, Nayarit, Sinaloa, and Sonora could experience more than 7 additional consecutive dry days per year by 2050 and more than two additional weeks by the end of the century. For most states and GHG emissions scenarios, a reduction in the number of days with extreme precipitation (R10mm) and an increase in the precipitation on the wettest day of the year (Rx1day) are projected, suggesting a lower number of extreme precipitation events per year, but higher in intensity. In general, simulations indicate that Mexico will have to deal with a hotter, drier climate with higher frequency and intensity of extreme temperature events and higher intensity of extreme precipitation events.

Figure 7. Changes in annual precipitation by 2050 and 2090.



The panels show the changes in annual precipitation (%) projected for 2041-2060 (left) and 2081-2100 (right). All changes are shown with respect to the reference period 1986-2005.

Source: Estrada, F., et al 2023.

Extreme temperature events are projected to increase in intensity during this century even in the most ambitious international GHG mitigation scenarios and particularly in high-emission scenarios.

During this century and under all GHG emissions scenarios, the maximum temperature of the hottest day of the year (TXx) is expected to over the entire country with respect to the 1970-2000 reference period. In emissions scenario RCP2.6, the statewide average rise in TXx would be 1.8°C, and one fifth of the states would experience increases greater than 2.0°C (e.g., Chihuahua, Guanajuato, San Luis Potosi, San Luis Potosi). By the end of the century, the statewide average increase would remain at about 1.7ºC. In contrast, there would be a statewide TXx rise of at least 2.0ºC by 2050, with 7 states surpassing 3ºC. By 2100, the average statewide TXx rise would be 5.3ºC with 7 states having increases close to or above 6ºC.

The most optimistic international GHG mitigation scenarios in which Paris Agreement goals are met provide a first estimate of the minimum temporal and geographical requirements needed for different human and natural systems.

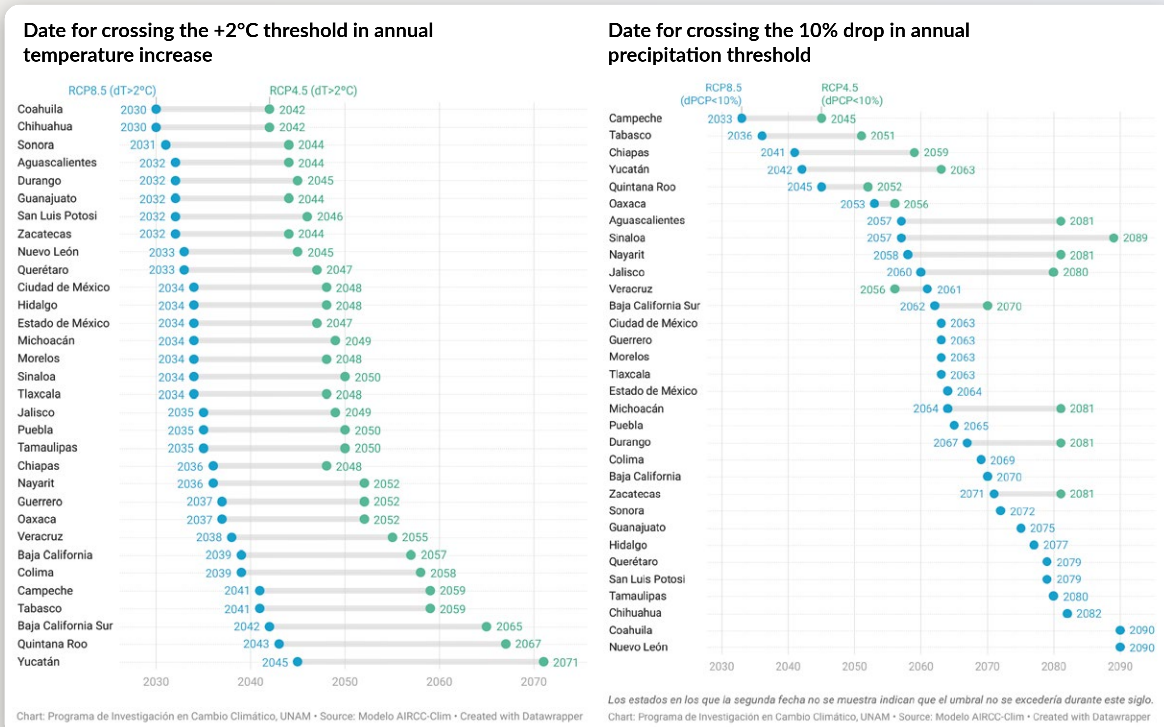
Particular mitigation efforts cannot avoid residual risks and impacts requiring adaptation and risk reduction strategies. Climate change projections based on progressively ambitious mitigation efforts can help formulate minimum adaptation and risk reduction requirements for different time horizons, geographical adaptation and for different human and natural systems.

Even less ambitious international mitigation efforts may reduce some of the risks of climate change to the country and provide time for adaptation.

The projected dates for crossing risk thresholds may be delayed, thereby allowing more time for the implementation of adaptation measures. This is the case of the Nationally Determined Contributions (NDCs) currently negotiated with most countries. Although current NDCs are insufficient to limit global temperature increase to below 2°C by the end of the century, they would make it possible to reduce/delay risk threshold crossing date.

For instance, going from a very high GHG emissions and inaction scenario (RCP8.5) to an emission scenario consistent with e current NDC (RCP4.5) would result in an average delay of 15 (12 to 26) years in the time that individual states would take to observe increases of more than 2°C with respect to the reference period 1986-2005. Moreover, this international mitigation effort would delay the reduction threshold crossing date by at least 10% (about 15-20 years) in many states and in certain cases it would even prevent crossing the threshold during this century (see **Figure 8**).

Figure 8. Risk threshold crossing dates in two emission scenarios.



The panel on the left shows the estimated dates for surpassing mean annual air temperature by 2°C in a very high emission scenario (RCP585) and a scenario strictly aligned with current NDCs (RCP245).

The panel on the right shows the estimated dates for surpassing annual drops in precipitation by more than 10% in a very high emission scenario (RCP585) and a scenario strictly aligned with current NDCs (RCP245).

Source: Estrada, F., et al 2023.

The information presented in this section was taken from the following reports:

Estrada, F., Calderón-Bustamante, O., Raga G., Altamirano del Carmen, M.A., Torres, V., Zavala-Hidalgo, J., 2023. Análisis del cambio climático observado y proyectado para México. In: *Estado y perspectivas del cambio climático en México. Un punto de partida*. Reporte técnico, Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-analisis-observado-y-proyectado.pdf

López-Espinoza E.D., Gómez-Ramos O., Zarza Alvarado M.A., Zavala-Hidalgo J., Osorio-Tai M.E., 2023. El cambio en el nivel medio del mar en las costas mexicanas. In: *Estado y perspectivas del cambio climático en México. Un punto de partida*. Reporte técnico. Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-nivel-medio-del-mar-en-lascostas-mexicanas.pdf

Ortiz Haro, G.A., Gress Carrasco, F., Mazari Hiriart, M., 2023. Recursos hídricos y cambio climático: una visión desde México. In: *Estado y perspectivas del cambio climático en México. Un punto de partida*. Reporte técnico, Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-impactos-recursos-hidricos.pdf

Use the following QR code to access further information concerning the database, methodology, and additional results:

Impacts on Human and Natural Systems in Mexico: Diagnosis and Projections

The consequences of climate change are profound and multidimensional and extremely heterogeneous in terms of spatial distribution and within and between social groups, sectors, and natural systems.

The impacts of climate change are characterized by their uncertainty, by their exacerbating of certain concurrent socio-environmental problems and inequities, by their being persistent and even irreversible, in addition to the existence of critical points that may dramatically modify the behavior of the climate system itself or the systems it affects. This section summarizes the state of research in different sectors and the main effects associated with climate change that have already been observed, as well as those projected for the rest of the century.

Agriculture

The following is an overview of research on agriculture and climate change in Mexico, highlighting the principal topics and existing outcomes. The main challenges, opportunities, and gaps information are identified with the aim of directing future scientific research and of sharing results with decision makers. Several significant impacts of climate change on the Mexican agricultural sector have already been observed and projected. However, few crops have been analyzed and a geographic bias focuses only on certain areas of the country.

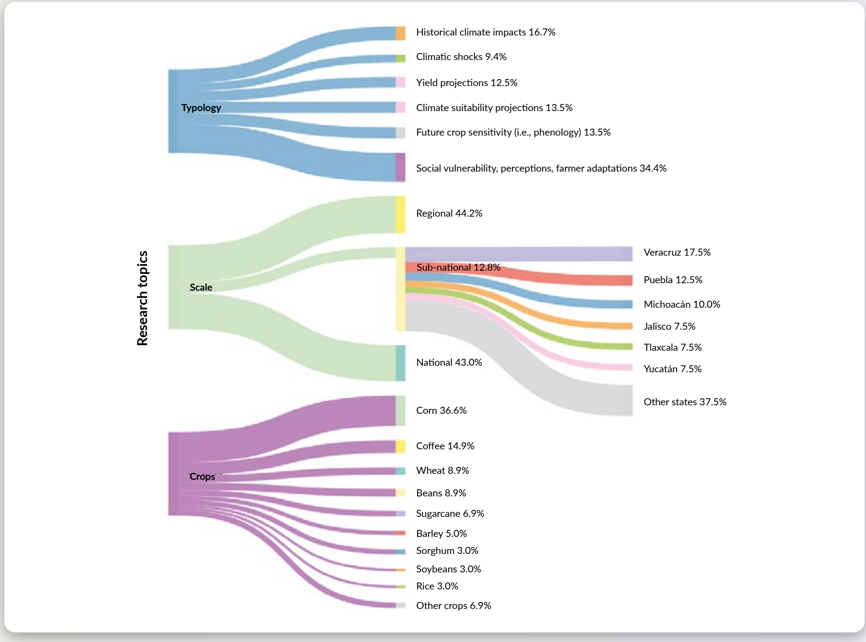
Research on agriculture and climate change in Mexico focuses on a limited diversity of crops and is geographically biased towards certain areas of the country.

A systematic review of scientific literature found ninety-six articles published between 1990 and 2022 on the topic of agriculture and climate change in Mexico. Most of these are regional and nationwide studies on corn, followed by studies on coffee, beans, and wheat. On a subnational level, the most commonly analyzed states are Veracruz, Puebla, Jalisco, and Tlaxcala (see **Figure 9**). 16.7% of the publications analyze the relationship between climatic variables, such as the duration of dry and rainy seasons, maximum and minimum temperatures, evapotranspiration, aridity or days of growth and flowering. The crops most frequently studied were corn and coffee (36.7%) followed by rye and apples (12.5%). This type of study was done primarily by state; those most looked at were Sonora, Veracruz, Sinaloa, Jalisco, and Chihuahua. The main results show how climatic variability negatively impacts crops and underscore the need to modify seeding patterns in response to changes in start-date in and of the length of rainy seasons[4-6].

A high percentage of climate change and agriculture studies in Mexico concentrate on estimating future impacts on crops that are nationbal interest A much smaller number of studies focus on historical impacts and climate impacts.

Most of the literature on agriculture and climate change in Mexico focuses on estimating future impacts (39.8%). In contrast, 16.7% of the publications concentrate on the analysis of the relationship between phenological aspects of crops and climatic variables, such as the duration of the dry or rainy seasons, maximum and minimum temperatures, or evapotranspiration. The crops most commonly appearing in this type of analysis are corn and coffee (36.7% each) followed by rye and apples (12.5%). An even smaller proportion of the literature deals with aspects like droughts, floods, frosts, or extreme events that occurred in the past. These include studies analyzing the influence of the *El Niño-Southern Oscillation* on corn and beans[7] and the effects of drought on sugarcane production[8].

Figure 9. Typology of the literature review, geographic level of study and most common crops appearing in studies of climate change and its impacts on agriculture in the country.



Percentages refer to thenumber of studies devoted to each topic.

Source: Mendoza-Ponce A., 2023

A variety of significant climate change impacts on the Mexican agricultural sector have already been observed and are projected to become more pronounced over the course of the century.

Available studies in general project a reduction in agricultural production towards the end of the century due to variations in average and minimum/maximum values of climatic variables. Climate change is expected to lead to possible expansion or intensification of agriculture with negative effects on ecosystems and water and soil resources in addition to an increase in agri-food dependence and greater exposure to variability in international price.

In a very high emissions scenario, climate change could severely reduce the country's agricultural yields, particularly those of rainfed production.

There are few studies that analyze the impacts of climate change on different crops and management practices. A recent study forecasts a sharp drop in corn, wheat, sorghum, rice, and soybean yields[9]. By the end of the century, nationwide yield reductions in soybean and rice could be greater than 50%, while those in corn and sorghum yields could exceed 40%, and wheat yields 20%. There is a great deal of uncertainty in the projections for surgarcane made by different biophysical models and depend on the assumptions made about CO_2 fertilization. However, one of the most widely used biophysical models suggests reductions of up to 11% by the end of the century. These six crops represent 65% of the cultivated area in Mexico and have the highest consumption. This scenario implies yield reductions of between 5% and 20% for these crops, over the next two decades and up to 80% by the end of the century for some crops and in some states states.

Observed and potential impacts of climate change on corn are negative. Yields are projected to drop by up to 80% in some areas of the country along with a decrease of between 3.0% and 18.0% in climatic suitability.

The first reported studies about corn and climate change in Mexico suggested that, given a 2.0°C increase and a 20% reduction in precipitation, the area suitable for growing corn would be reduced by 18.0%[10]. However, later projections[11] using physical climate models suggested reductions of only 3.0% to 4.3%. More recent studies based on the RCP8.5 climate change scenario projected national rainfed corn yield reductions of 10%[12], regional drops of as high as 80%, 81.6%, 84%, and statewide drops of up to 80%[9,13-15]. The states most suited to rainfed corn production (Jalisco, Mexico, Nayarit, Morelos, Michoacán, Guerrero, and Colima) could lose between 30% and 40% of their yields by the end of the century. Currently, twenty-three states have rainfed corn production yields above one ton per hectare, but only eleven of them will still be producing at least one ton per hectare by the end of the century. Other estimates based on absolute yields suggest drops of between 0.25 to 0.5 t/ha[16]. Water availability and the duration of the dry season are important factors, especially for rainfed corn, mainly in the northeast and south of the country[13,15]. These zones are also reported to have the greatest reductions (up to 5.5%) in climatic suitability for this crop[17].

Observed and potential impacts of climate change on coffee are negative. Current records show yield reductions of 42.5% and 23.4% from 2010 to 2020 for irrigated and rainfed coffee, respectively.

Studies on coffee production and climate change in Mexico date back to 2006[18], when a 34% drop in production was projected for Veracruz by 2020 due to climate change. The observed reduction has actually been greater, with a drop of 36.7%19 from 2010 to 2020. This reduction attributed to several factors. First, a reduction in the harvested area of both crops such as; a 48.6% decrease in irrigated area. And secondly, there was also a yield reduction of 42.5% in rainfed and 23.4% in irrigated crops[19] between 2010 and 2020. The climatic and socio-environmental causes of these changes need to be analyzed.

By mid-century, yields of rainfed wheat and irrigated wheat could be reduced by up to 23.3% and 20.0%, respectively. These impacts could be mitigated through the cultivation of new varieties more resistant to extreme weather conditions.

The analysis of wheat in Mexico is relevant because, even though the country imports most of its wheat (~65%), new varieties and technologies developed by the International Maize and Wheat Improvement Center[20] (CIMMYT) have been introduced into the country. These developments mean that Mexico has higher yields than the global average[21]. There are studies that suggest that, under climate change scenario RCP8.5, 2050 yields would fall by ~15% for rainfed wheat and ~7.5% for irrigated wheat[15,22]. Other projections suggest that, by the end of the century, the figures could drop as low as 23.3% and 20.0% for rainfed and irrigated crops, respectively[9].

Variations in temperature and precipitation negatively impact bean production in Mexico; however, there are varieties that have shown better adaptation to dry and hot climates.

Beans could suffer yield reductions of 10% to 40% due to higher temperatures and reduced precipitation[15]. However, it has been shown that species of the genus *Phaseolus* such as *P. filiformis*, *P. purpusii*, and *P. maculatus* have adapted better to drier climates[23].

The information presented in this section was taken from the following report:

Mendoza-Ponce A., Ortiz Haro G.A., Murray-Tortarolo G.N., Salazar Frausto, J.L., 2023. Agricultura y cambio climático en México. In: *Estado y perspectivas del cambio climático en México. Un punto de partida*. Reporte técnico, Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-impactos-agricultura.pdf

Use the following QR code to access further information concerning the database, methodology, and additional results:

Biodiversity

There is ample evidence of the global impacts of contemporary climate change on biodiversity[24-27]. Moreover, evidence of disturbances to biological and ecological processes at different scales of organization from genetic to ecosystem levels[25] has been found. Climate change will exacerbate the effect of other anthropogenic factors that already threaten species and ecosystems, such as habitat loss, invasive species, pollution, pathogen outbreaks, among others[28,29]. However, most of the evidence of the impacts is concentrated on species and ecosystems in temperate regions of countries in the Global North[24,25,25,30,31], and there is very little information on the impacts on tropical and subtropical species and ecosystems. Mexico is recognized for its high diversity of species and endemism due to its llocationed in a biogeographic transition zone between Nearctic and Neotropical regions. This heterogeneity makes it particularly vulnerable to climate change and priority must be given to understanding how climate change affects and could affect biodiversity and how the combination of ecological traits and evolutionary history could help to understand how species respond to changes in climatic regimes. Current available information concerning the impacts of contemporary climate change on biodiversity is rather poor and disperse[32]. This section presents some of the main results on ecosystems for which specific studies have been done.

Impacts Observed in Mexican Ecosystems

There have been drastic reductions in hard coral cover in the Mexican Caribbean since the 1970s due to the effects of climate change and natural climate variability events.

In the coastal and marine systems of the Mexican Caribbean, the amount of hard coral has decreased drastically since the 1970s: from 50% of the reef floor to the current 10%. Coral bleaching events were reported during El Niño in 1997-1998[33]. These events resulted in a loss of more than 90% of the coral surface area along the coasts of Oaxaca and Jalisco. However, coral reefs along the Mexican Pacific coast have recovered from these mortality events, showing a high degree of resilience, and are now considered to be thermally stable[34]. This resilience is expected to drop off with more frequent oceanic heat waves and shorter periods without thermal stress. No mass mortality events were identified following a bleaching event in Mexico and the Caribbean Sea[35], and no severe coral cover variations have been identified in the Mexican Pacific and other regions of the planet[36]. However, it is expected that the Mexican Caribbean will experience important increases in thermal stress and heat waves[37,38].

Little is known about the effects of climate change on mangroves, dunes, and seagrasses despite their importance in mitigating impacts of extreme events and the implementation of ecosystem-based adaptation strategies.

These ecosystems are very important for regulation and protection from the impacts of extreme events such as tropical cyclones[39-41]. Research on the effects of climate change on them is a priority, as is undertaking restoration and conservation actions in the context of Ecosystem-based Adaptation strategies[42].

There is limited evidence concerning the impacts of climate change on terrestrial species. However, local extinctions and a variety of negative effects associated with this phenomenon have been documented.

There is evidence of local extinctions of at least 12% of the populations of forty-eight species of lizards of the genus *Sceloporus* due to increases in maximum and minimum temperatures[43] as shown in Figure 10, in addition , there are declining populations of forest species such as oaks and conifers[44]. There is evidence of changes in the species composition of birds in some regions of the country in the twentieth century[45]. In particular, desert areas (e.g., Chihuahua, Sonora, northern Baja California) and the Usumacinta River basin are reported as areas with the highest extinction rates and species turnover[45].

Altitudinal migrations of different vegetation types have been documented in the context of observed climate change.

Recently, remote sensors have been used to assess whether tree line altitudinal limits in mountainous regions of Mexico changed between 1985 and 2018. Altitudinal migrations of at least 500m were documented in forests and grasslands surrounding fifteen volcanoes in central Mexico over a period of three decades[46].

Projected Future Impacts on Biodiversity

Several studies based on correlative and ecological niche models show potential reductions in species distribution areas throughout the country.

Some regions may be more susceptible to gains and losses in the distribution of endemic species. Local extinctions and reductions of up to 50% of the current distribution areas are projected for several taxonomic groups, mainly terrestrial vertebrates[47-53].

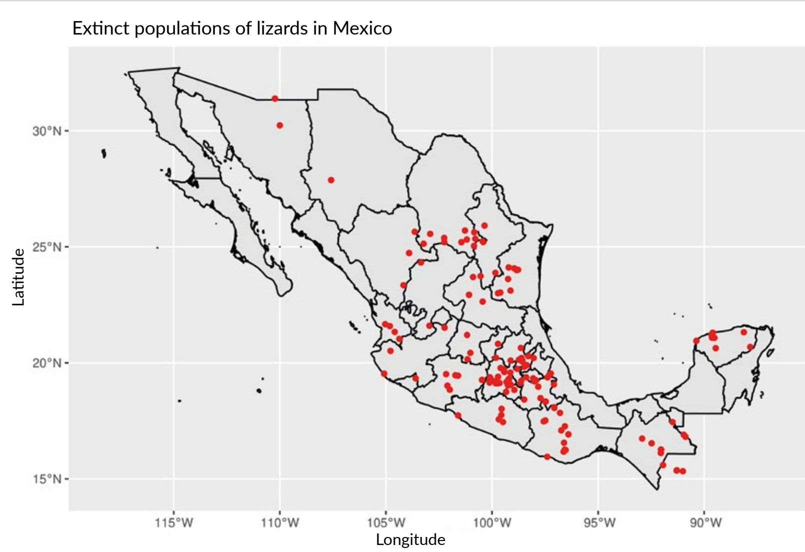
Climate change impacts vary between taxonomic groups are geographically heterogeneous, and exacerbate existing socio-environmental pressures.

For the cases of birds and amphibians, threatened and ecologically -restricted species will suffer more negative impacts under future climate change scenarios[50,54]. The largest amphibian species losses are projected in the southern Gulf of Mexico and the Yucatan Peninsula[48]. Similarly, certain studies project drastic reductions of more than 60% of pine species habitats in Mexico[55].

A major limitation of ecological niche models and future projections is that they have failed to incorporate the uncertainty associated with climate models and GHG emission scenarios appropriately.

Available studies have neither incorporated the uncertainty associated with climate models and emissions scenarios appropriately nor between ecological models[56-60]. Most of these studies have only used a small set of climate models and emissions scenarios. This limitation may hinder the incorporation of such results in decision making and in the generation of public policies aimed at protecting biodiversity from the impacts of climate change.

Figure 10. Locations where the extinction of local lizard species populations of the genus *Sceloporus* have been reported and are attributable to increases in temperature over the last century.



Source: Grupo de Investigación e Incidencia en la Biología de Cambio Climático (Research and Incidencia in the Biology of Climate Change Group: InBioCC, 2023).

The information presented in this section was taken from the following report:

Grupo de Investigación e Incidencia en la Biología del Cambio Climático (InBioCC): Aguirre-Liguori, Jonas A.; Álvarez-Filip, Lorenzo; Búrquez-Montijo, Alberto; Correa-Metrio, Alex; Domínguez, Omar7; Escobedo-Galván, Armando H.; Garrido-Garduño, Tania; Gómez-Ruiz, Pilar Angélica; Jiménez-García, Daniel; Lara-Resendiz, Rafael; Luna-Aranguré, Carlos; Martínez-Meyer, Enrique; Mendoza-González, Gabriela; Nava-Bolaños, Angela; Ochoa-Ochoa, Leticia M.; Prieto-Torres, David A.; Ramírez-Barahona, Santiago; Sáenz-Romero, Cuauhtémoc; Velasco, Julián A. 2023. Estado del cambio climático en México: Biodiversidad. In: Estado y perspectivas del cambio climático en México. Un punto de partida. Reporte técnico, Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-impactos-biodiversidad.pdf

Use the following QR code to access further information concerning the database, methodology, and additional results:

Water Resources

Climate change, coupled with the growing demand for water resources caused by population growth, environmental degradation, and unprecedented demand for natural resources, are major challenges for the water sector in Mexico. An insufficient supply of high-quality water, in addition to poor wastewater management, are socio-environmental problems of great relevance today that are aggravated by climate changes[61,62]. These changes are characterized by not being uniform in space or time and by high levels of uncertainty, all of which exacerbate the complexity of water planning and management. The World Economic Forum (WEF) predicts that water crises, the spread of infectious diseases, the inability to adapt to climate change, and the loss of biodiversity over the next decade will comprise the most significant social impacts with interconnected long-term effects worldwide[63].

Research on water resources and climate change in Mexico is disperse, concentrated in specific regions, and comprises a high proportion of gray literature that is not very up to date.

Sixty-two documents from the literature published between 1980 and 2022 were systematically compiled and analyzed. Of these, 79% are scientific articles and 21% are classified as gray literature. The largest number of studies are concentrated in the northwest (23%) and central regions of the country with more than half of the studies conducted at basin or hydrological regional scale. In general, these studies focus on large agricultural and urban territories, particularly on the risks associated with changes in water availability in urban areas and the overexploitation of aquifers due to intensive irrigation in arid zones. Approximately a quarter of the studies are concerned with climate change projections and their potential effects on water availability, water balance, runoff, infiltration, and recharge. Another quarter focus on integrated watershed management, risk management, and the perspectives for water resources evolution in the context of climate change. About 11% of the literature addresses water resource vulnerability, hydrological risks, vulnerability, and the security of water and water supply sources.

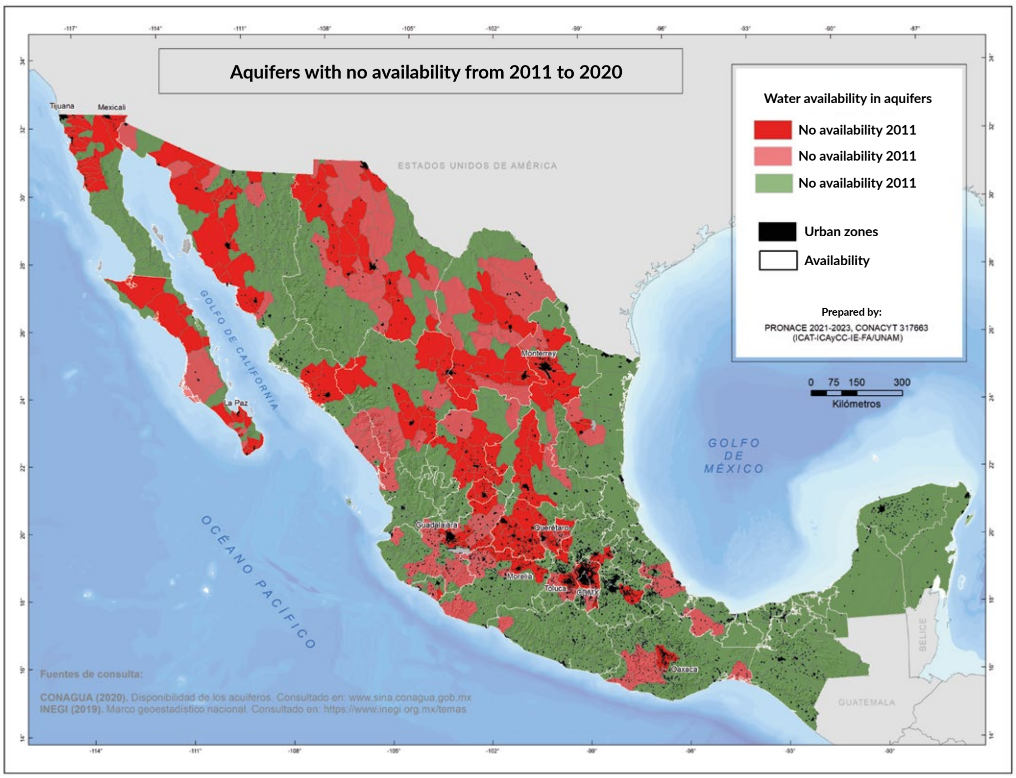
Natural water availability has dropped off due to changes in precipitation and droughts caused by climate change. Significant impacts are expected on various components of the hydrological cycle in the country.

In Mexico, 451.585 billion m3 of water are used annually, of which 61% is obtained from surface water systems and 39% from groundwater. Concessionaries are largest for agriculture (59%), public supply (27.5%), and self-supplied industry (13.5%)[64,65]. A sudden increase in the depletion of groundwater systems and a reduction in their availability has been reported with growth from 178 unavailable aquifers in 2011 to 275 in 2020; this has implications for water availability in urban areas such as Monterrey, Tijuana, Guadalajara, and Mexico City, among others (see **Figure 11**). About 42% of the aquifers are reported as having compromised availability and 58% of the groundwater is extracted from 101 overexploited aquifers[66,67]. According to climate change projections (see the first section of this report), water scarcity is expected to affect the north and center of the country, while the south and southeast could be affected by excess water. In large urban areas such as Mexico City, there is already significant vulnerability to water scarcity, flooding, and water-borne diseases[68-70].

Water demand has grown in recent years and will continue to increase under different climate change scenarios, variations in land use, and population growth.

Mexico's population has nearly quintupled since the mid-twentieth century and is projected to reach 138 million by 2030. There are currently 35 cities in the country with more than 500,000 inhabitants, putting enormous demand pressure on water supply services. This poses great challenges in the context of climate change because more than 75% of the urban population was located in areas of low water availability and high water stress at the beginning of this century[71-73]. 75% of the urban population was located in areas of low water availability and high water stress[71-73].

Figure 11. Aquifers with no availability from 2011 to 2020.



Source: Ortiz Haro, G.A., et al 2023; CONAGUA (2020). Disponibilidad de los acuíferos en https//sina.conoagua.gob.mx; INEGI (2019). Marco geoestadístico nacional en https://ingi.org.mx/temas

Climate change is expected to have serious effects on various components of the hydrological cycle in different regions of the country.

Observed droughts have become more frequent and severe. These effects of climate change will become more critical and will impact different segments of society. Negative impacts on the country's water systems are expectedunder scenarios of medium and high GHG emissions. Variations in the spatial and seasonal patterns of precipitation are projected with longer dry periods and increases in annual precipitation caused by extreme events[69,72]. Total precipitation in certain regions (mainly in the north and center) could undergo significant decreases in water availability, average annual runoff, infiltration volumes, and aquifer recharge[74]. According to projections, the impacts become more critical due to increases in temperature and evapotranspiration. The Mexico City metropolitan area could be affected by a drop in annual precipitation of 5% by 2020 in the Cutzamala System[69,70].

Negative impacts on river flow are expected in the north of the country with a runoff reduction of up to 60% in the long term[74].

Climate change is expected to have a significant negative impact on water availability and, consequently, on agricultural production, thereby posing a high risk to national food security.

Agricultural production is 25% irrigated and 75% rainfed with the former contributing 40% of the value of total national production[75]. Nationwide, drought has already brought about significant crises in corn and bean production, in which several drought events between 1940 and 1987 affected the whole territory, particularly states in the north[76].

Water quality in most of the surface aquatic ecosystems is poor and the rise in temperature and drecrease in precipitation will exacerbate this problem.

Currently, more than 90% of Mexico's population inhabit hydrological regions with pollution problems. Contamination of water bodies by wastewater discharges brings about a drop in system availability. Very little research has been done on how climate change impacts water quality; however, water source affectation could be intensified by higher temperatures and their effect on the physiochemical and microbiological characteristics of water[73,77,78].

In response to temperature increase, there has been a rise in algae and sargassum due to eutrophication of the country's bodies of water and seas.

The presence of potentially toxic algae (i.e., cyanobacteria) in freshwater systems along with an increase in eutrophication (nutrient enrichment) will result in reduced availability of water supply sources as well as the alteration of natural and artificial systems (i.e., dams). Higher temperatures and evapotranspiration, combined with lower rainfall, lead to eutrophication with deleterious effects on aquatic ecosystem biodiversity. The upsurge of the pelagic macroalga *Sargassum* spp. in coastal areas has affected the northern coast of the Mexican Caribbean since 2011. These are regional and local events that respond to various factors such as nutrient enrichment, rising temperatures, and weather pattern variations, in addition to causes as yet unknown. The impact of tons of sargassum has implications for ecosystem functioning and biodiversity, as well as socioeconomic impacts on fisheries, tourism activities, and local social disruption that may cause health issues.

Infrastructure problems, resource mismanagement or inefficient resource management, and lack of infrastructure make the challenges of climate change more critical.

Much of the water distribution infrastructure is in poor condition and has not been modernized. Deficiencies persist in the operation and maintenance of water distribution systems and sanitation infrastructure. It is estimated that as little as 20% of wastewater is treated, which has environmental effects in terms of greenhouse gas emissions[79]. Vulnerability of the infrastructure is high due to its poor condition, which results in lower capacity and exposure to damage by third parties; climate change will exacerbate this vulnerability. Lower precipitation will bring about a decrease in the availability of water from surface sources, in addition to affecting the recharge of the aquifers that feed distribution systems. High imperviousness in large cities aggravates the hydrological effects as there is increased runoff followed by a reduction in water recharge. Rising temperatures and the increasing frequency and intensity of heat wave events will increase the demand for water, which could lead to regional, national, and international, social conflicts[80].

The information presented in this section was taken from the following report:

Ortiz Haro, G.A., Gress Carrasco, F., Mazari Hiriart, M., 2023. Recursos hídricos y cambio climático: una visión desde México. In: *Estado y perspectivas del cambio climático en México. Un punto de partida*. Reporte técnico, Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-impactos-recursos-hidricos.pdf

Use the following QR code to access further information concerning the database, methodology, and additional results:

Human Health

Anthropogenic climate change is recognized as a threat to human health. Impacts may be direct, mainly in response to changes in the frequency of extreme weather events[81] (e.g., heat waves, droughts) or they may be indirect, mediated by the effect on natural systems that alters the life cycle dynamics of a particular pathogen[82]. There are also diseases of zoonotic origin, which are naturally transmissible between vertebrate/invertebrate animals and humans. These diseases involve a wide range of pathogens, including viruses, bacteria, fungi, protozoa, and helminths[83-85]. About 70% of infectious diseases affecting humans worldwide originated from pathogens in wild or domestic animals (zoonotic pathogens)[86,87]. Climate change can modify the dynamics of zoonotic diseases in different ways, thereby altering the pathogen's development cycle and bringing about changes in the population and phenological distribution of vectors and hosts.

Despite the relevance of the topic, studies on climate change and health in Mexico are scarce and produced by a small number of institutions. There are large information gaps.

A review of the literature on health and climate change and variability published between 2000 and 2022 produced a total of 192 research articles. The National Institute of Public Health (INSP), the National Autonomous University of Mexico (UNAM), and the National Polytechnic Institute (IPN) are responsible for more than 50% of these papers, while the participation of other academic institutions and federal and state health agencies is limited. With regard to the direct effects of climate and weather conditions, the literature in Mexico has focused on lower respiratory events, cardiovascular disease, kidney disease, suicide, food systems, all-cause mortality, and death by scorpion bites.. An exhaustive literature review of nine viral, parasitic, and bacterial diseases of importance in the country associated with climate change identified major information gaps (see **Figure 12**). Most research on zoonotic diseases and climate change has been conducted on the observed impacts of dengue and how they are related to temperature and precipitation. Except in the case of dengue and the El Niño-Southern Oscillation, there are no studies on the effects of extreme events and climate variability on these diseases. Most climate change and zoonotic disease studies have been conducted at the state level and, largely on the mosquito as a vector of dengue fever. The disease research imbalance generates information gaps on many topics that should be prioritized for risk assessments of the emergence and reemergence of the different zoonoses. In general, there are few studies on the future impacts of climate change in the sector.

Changes in infection prevalence may be associated with changes in temperature and/or precipitation. Most of this evidence in Mexico focuses on vector-borne zoonotic diseases (VBDs).

Climate variability is closely related to the incidence of dengue, mainly due to increases in temperature and precipitation[88,89], with the highest incidences observed during the rainy season (June-October)[89,90]. Similarly, Chagas disease has a clear seasonality with the highest incidences of cases occurring in spring and summer[91]. A positive relationship between the highest incidences of leptospirosis (a bacterial disease) and the rainy season in Yucatan has been reported[92]. The close relationship between the seasons and the incidence of clinical cases is indicative of the potential for temporal change that may occur due to variations in temperature and precipitation brought about by climate change.

Dengue. In Mexico, it has been documented that climate variability is closely related to the incidence of dengue, mainly due to increases in temperature, humidity and precipitation[88,89,93-99]. The highest incidences of dengue are observed during the rainy season (June-October)[89,90] and have been associated with the El Niño-Southern Oscillation phenomenon[88,89,100]. Furthermore, an inverse relationship has been established with altitude[101-107]. Ecological niche models suggest that conditions conducive to vector development are related to the minimum temperature of the coldest month, precipitation of the rainiest month, and precipitation seasonality[106].

Malaria. A negative association has been observed between the presence of *Anopheles albimanus* (which transmits malaria) and altitude[108]. Furthermore, the intensity of malaria transmission in Oaxaca has been associated with tropical climate areas with summer rains and low evaporation[109].

Chagas disease. The area of distribution of *Triatoma recurva*, a Chagas disease vector, is determined by temperature and precipitation conditions during the year as well as geographical factors such as altitude[110-113]. However, several species of triatomines (vectors of the Chagas disease pathogen) are now being recorded in temperate zones and at higher altitudes, and individuals positive for the pathogen (*Trypanosoma cruzi*) have been recorded. This is related to landscape alterations and rising temperature in the presence of these species[114]. The disease shows a higher incidence of cases in spring and summer[91]. It has been observed that geo-climatic determinants influence its dispersion[115-120] and a positive association has been established between rainfall and temperature with the infestation of the vector that transmits this disease[121]. Furthermore, it has been observed that the spatial and seasonal patterns of triatomines and the distribution of the different species are influenced by climate and have a seasonal pattern[116]; it has even been observed that temperature increases affect the relationship between the vector and the virus[122].

Zika. Studies have reported that temperatures during the warmest quarter of the year contribute to the risk of Zika transmission[123]. However, it has been reported that higher temperatures decrease the vectorial capacity of mosquitoes[124].

Lyme disease. Regions at high altitudes with low temperatures have a greater potential for Lyme disease transmission[125]. Moreover, maximum temperatures and precipitation largely determine the distribution of *Ixodes scapularis*: the tick that transmits the disease[126].

Leishmaniasis. This disease has been associated with temperature and precipitation[127], which suggests the ecological niche could be altered by climate change[128]. It has also been reported that temperature and precipitation seasonality are key predictors of cutaneous leishmaniasis distribution, whereas temperature and mean annual temperature are the predictors of visceral leishmaniasis[129].

Leptospirosis. The incident of this bacterial disease has a positive relationship with the rainy season in Yucatan[92]. The close relationship between seasons and the incidence of clinical cases is indicative of the potential for temporal changes that may occur due to climate change.

Figure 12. Research topic frequency in the literature reviewed on climate, meteorological variables, extreme events, climate change, and causal agents of zoonotic diseases in Mexico.

	Variables				Extreme Events						Scale				Topic				Origin	
	Temperature	Precipitation	Humidity	Niño/Niña	Heat events	Cold events	Droughts	Floods	Hurricanes	Fires	Global	National	State	Municipal	Observed impacts	Future impacts	Mitigation	Adaptation	National research	International research
Viral Diseases	26	25	9	6	0	0	0	0	0	0	8	4	8	3	21	3	5	0	16	10
Denge-pathogen	19	17	4	6	0	0	0	0	0	0	5	3	8	3	17	2	5	0	10	7
Zika-pathogen	3	3	0	0	0	0	0	0	0	0	2	0	1	0	2	1	1	0	0	3
Chikungunya-pathogen	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	1
Nile virus-pathogen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mosquitoes-vectors	10	10	4	0	0	0	0	0	0	0	1	3	3	3	4	2	2	0	8	2
Hantivirus-pathogen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rodents-vectors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parasitic Diseases	4	3	0	0	0	0	0	0	0	0	1	2	0	1	1	2	2	0	3	1
Chagas-pathogen	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	0
Leishmaniasis-pathogen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chagas-vectors	2	2	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	2	0
Leishmaniasis-vectors	2	2	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	0	2	0
Bacterial Diseases	2	2	0	0	0	0	0	0	0	0	1	1	0	0	0	2	0	0	1	1
Lyme-pathogen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lyme-vectors	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1
Leptospirosis	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0
Leptospirosis-vectors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The totals are not cumulative since the categories are not mutually exclusive (i.e., an article may include data on more than one topic).

Source: González-Salazar, C., et al, 2023

The pathogenic agents involved in infectious intestinal diseases are viruses, parasites, and bacteria, the best known of which are Salmonella, Shigella, Escherichia, Vibrio, Campylobacter, and Yersinia, which have been associated with high temperatures and extreme precipitation.

The highest prevalence of *Salmonella spp*. occurs in areas with temperatures between 35ºC and 37°C in northwestern Mexico and rainfall greater than 1,000 mm. Territories classified as arid and xeric, with short periods of humidity, limit its prevalence and geographic distribution by presenting a low percentage of organic matter[130].

Climate change has the potential to reduce or expand the distribution of vectors, hosts, and pathogens, thereby transforming previously uninhabitable regions into favorable habitats.

The presence of the primary dengue-transmitting mosquito (*Ae. Aegypti*) has been documented at altitudes higher than its usual limits (<1,200 masl) in Xalapa, Veracruz[131], and Mexico City[132]. However, these studies did not evaluate the presence of pathogens nor the possible role of favorable climate or landscape variations.

Climate change can generate changes in vector and host populations, thereby increasing their abundance, favoring shorter life cycles and/or seasonal changes in their reproductive cycles.

A positive relationship has been found between *Ae. aegypti* abundance patterns and higher rainfall in Baja California Sur and Morelos[101,133]. The larger number of homes infested by *Triatoma dimidiata* (the *T. cruzi* vector) is positively associated with higher temperatures and more abundant precipitation[121].

Climate change favors pathogen load variations caused by changes in reproduction rates, replication, or development in vectors.

Laboratory studies have documented that high temperatures accelerate the development of *Trypanosoma cruzi* in vectors[134-136]. However, these kinds of studies were conducted in South America and there are no field observations that assess this effect and its impact on the prevalence of pathogens in vector populations or the emergence of clinical cases.

Prospective studies on variations of vector distribution suggest an increase in areas with favorable climatic conditions and, consequently, a greater risk of contact with new human populations.

Distribution projections have been done in Mexico for the *Aedes* mosquito, which is a vector of the dengue, zika and chikungunya viruses[137,138], bedbugs (*Triatoma sp.*: a *T. cruzi* vector)[114,115], ticks (*Ixodes sp.*: a *Borrelia sp.* vector)[126], and sandflies (*Lutzomyias sp.*: a Leishmania sp. vector)[127,128].

Chronic diseases of the lower respiratory tract are one of the leading causes of death in Mexico and have been associated with changes in temperature as well as with exposure to ozone (O3), a short-lived climate pollutant (SLCP).

Several studies reveal a significant association between temperature and humidity conditions and these respiratory diseases. Temperatures above 33.2°C are correlated with increases in acute respiratory infections in children under the age of five[139]. Furthermore, a 1°C increase in temperature reduces COVID-19 transmission by 13% and mortality by 7.5%, while a 1g/m3 increase in absolute humidity is associated with a decrease of 11.41% in mortality caused by this virus[140]. In Mexico City, the number of confirmed daily infections is related to temperature and air inflow[141]. A positive association between O_3 exposure and cases of COVID-19 infections and deaths[142] has also been documented. An increase in O_3 levels is associated with a 10% increase in respiratory symptoms in asthmatic children[143] and with respiratory deaths of children of low socioeconomic status in Mexico City[144].

Heart disease is the leading cause of death nationwide and has been associated with both decreasing and rising temperatures.

The increased risk of death from cardiovascular causes in metropolitan zones in Mexico is 7.1% for cold temperatures [0.01, 14.7] and 7.1% for warm [0.6, 14.0], respectively[145]. Moreover, there is consistent evidence of a positive association between short-term exposure to O_3 with an increase in emergency department visits due to cardiovascular causes[146].

Recently, a rise in temperature has been considered a risk factor for kidney disease due to periods of dehydration and the metabolism of certain hormones essential for water balance.

This condition has been associated with repeated episodes of exposure to high temperatures. A kidney disease study in Mesoamerica reveals that it spreads when average annual maximum temperatures rise above 30°C and among men who work in sugarcane fields on the Pacific coast[147].

Seasonal fluctuations in suicide patterns have been observed that could be related to changes in social activities and exposure to variables such as temperature, humidity, and sunlight.

Although there is a significant gap in research on mental health and exposure to climate change in Mexico, an association between temperature and risks associated with mental health, such as suicide rates, has been reported[148]. In Mexico, seasonality may increase suicide risk[149] with a relative risk of 1.24 [1.16,1.32]. Furthermore, days with no rain and temperatures between 30°C and 40°C are associated with incidence of suicide among men[150].

The incidence of scorpion bites shows a strong seasonal pattern that correlates with climatic variables.

Fewer scorpion bites have been documented[151] at temperatures below 16°C. For every 1°C increase in temperature, cases of scorpion stings increase by 9.8% in the hotter parts of the state of Morelos[152].

Exposure to sub-optimal temperatures has been associated with an increase in all-cause as well as cause-specific death.

Minimum mortality temperature (MMT) has been used as an indicator of sub-optimal temperatures. A multi-country study including Mexico suggests that the MMR varies between 14.2°C and 31.1°C and provides evidence of long-term adaptation to the local climate[149]. Analyses conducted on metropolitan areas in Mexico have documented a non-linear relationship (inverted U or J) between short-term temperature exposure and mortality, with an all-cause mortality risk of 10.2% and 6.3% for hot and cold temperatures, respectively[145]. Studies involving climate change scenarios are rare. However, one such study suggests an increase in heat-related mortality between 3.0% (-3.0 to 9.3) in Central America to 12.7% (-4.7 to 28.1) in Southeast Asia in the RCP8.5153 scenario[153].

A relationship has been established between precipitation and temperature and the consumption of processed foods.

In Mexico, it has been reported that, mainly in tropical regions, an annual reduction of 0.5 mm in precipitation and an annual increase of 0.1°C are associated with lower consumption of unprocessed foods and higher consumption of ultra-processed foods[154].

The information presented in this section was taken from the following report:

Hurtado-Díaz, M., Rangel-Moreno, K., Riojas-Rodríguez, H., 2023. Estado del arte de la investigación en salud y cambio climático en México. In: *Estado y perspectivas del cambio climático en México. Un punto de partida*. Reporte técnico, Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-salud-humana.pdf

González-Salazar, C., García Peña, G., Zarza Villanueva, H., Aguirre-Peña A., Fernández-Castel, K.P.J., Saldaña Rangel, I.E., Becker, I., Stephens, C.R., 2023. Salud: Enfermedades zoonóticas. In: *Estado y perspectivas del cambio climático en México. Un punto de partida*. Reporte técnico, Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-salud-zoonosis.pdf

Use the following QR code to access further information concerning the database, methodology, and additional results:

Socioeconomic Impacts

Climate change generates persistent and even irreversible impacts; it amplifies and adds to a variety of concurrent socio-environmental problems and inequities and may dramatically modify the behavior of the climate system itself or of systems influenced by it. The consequences of climate change for our country are profound and multidimensional with effects that are extremely uneven spatially and within and between social groups, sectors, and natural systems[18,53,155-157]. Moreover, there are synergies and interactions between these risks and other existing socio-environmental problems that can exacerbate their consequences and restrict adaptations, thereby making them difficult to manage. Consequently, the phenomenon could significantly compromise the country's socioeconomic development and the achievement of its sustainable development goals[3,158-162].

This section addresses the physical impacts of the phenomenon, emphasizing those classified as chronic or gradual and not the acute impacts resulting from, for example, climatic or hydrometeorological extremes. It does not address the transition risks associated with amendments to energy or regulatory policies, nor the investment costs of achieving a world with lower climate-polluting emissions.

Aggregate economic climate change impacts in Mexico in "business-as-usual" and policy scenarios.

In a business-as-usual scenario, the economic costs of climate change for Mexico would be enormous.

|

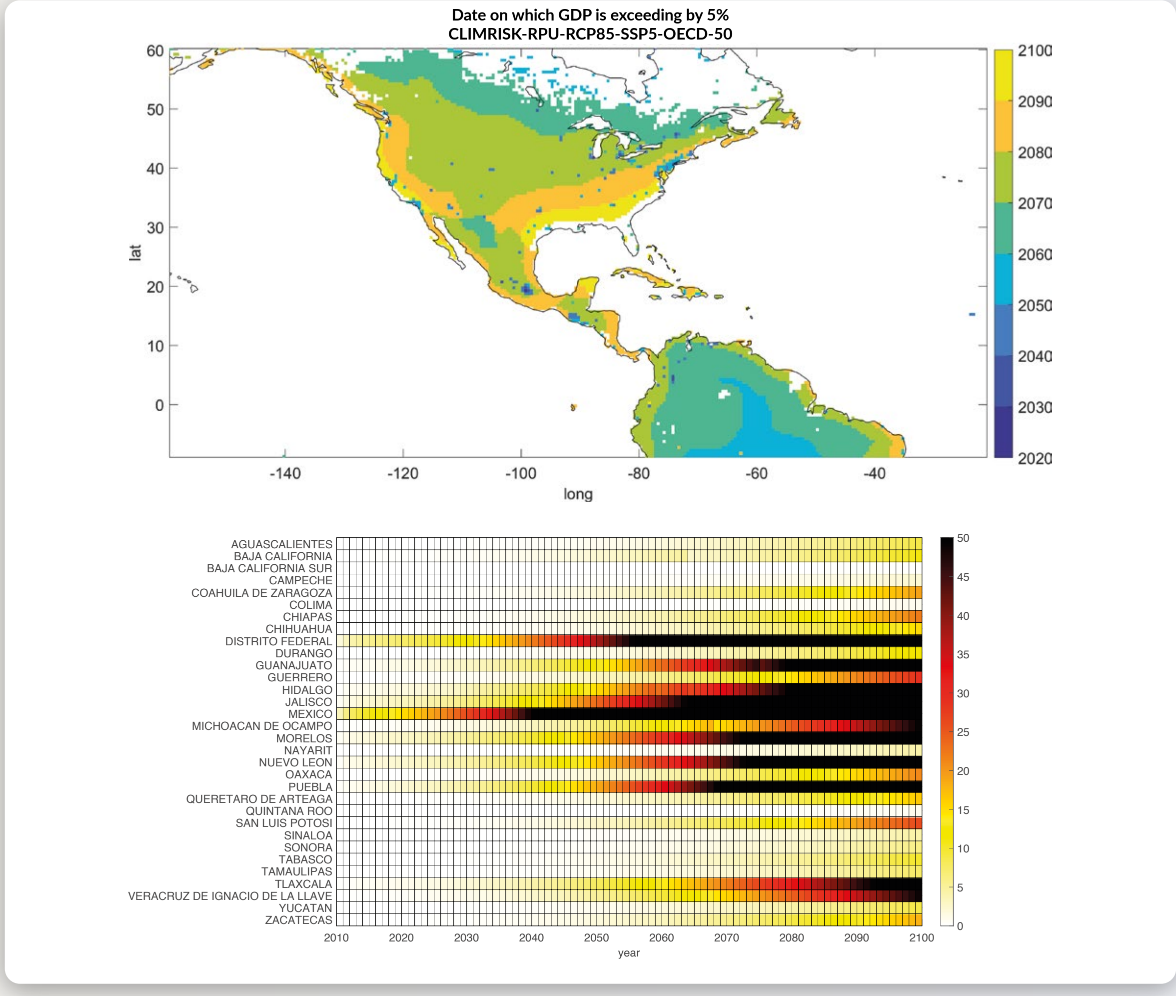
In a very high GHG emissions scenario (SSP585), the cumulative costs during this century would be comparable to losing between 85% and up to five times Mexico's current GDP[3]. Estimates include local warming of cities due to urbanization and the persistence of climate change impacts. In this business-as-usual scenario, most of Mexico would have annual losses equal to or greater than 5% of local GDP during this century as a consequence of climate change. In large urban centers, this threshold could be crossed between 2030 and 2040.

The distribution of the economic impacts of climate change will be increasingly unequal between and within the country's different regions and states.

The impacts of climate change are the result of the interaction of multiple factors such as exposure, threat, and sensitivity, each of which has very different spatial distributions. Thus, the costs of climate change are not evenly distributed geographically, nor among different social groups, sectors, or activities.

The five states with the highest aggregate economic losses accumulated during the century are the State of Mexico, Mexico City, Jalisco, Puebla, and Morelos (see **Figure 13**). Some states could record annual losses in excess of twenty billion USD by 2050 (State of Mexico, Mexico City, Jalisco, Nuevo León, Puebla, Morelos). In a scenario of high GHG emissions and economic growth (SSP585), the average current statewide value of the impacts of climate change during this century would be close to three times urban the current GDP although some states would receive considerably greater impacts.

Figure 13. Economic impacts of climate change in Mexico.



Top panel: Estimated date by which climate change impacts would exceed 5% of GDP at each grid point. Bottom panel: Annual economic losses per state due to climate change for 2010-2100 (billions of dollars).

Source: Estrada, F., Calderón-Bustamante, O., 2023.

Large cities could be particularly affected by climate change due to a confluence of environmental problems and high exposure. A business-as-usual scenario in the near future implies large economic losses and high levels of risk for the country's large urban centers.

Globally, cities are characterized by disproportionate exposure (80% of the world's GDP and more than 50% of the world's population) and by the confluence of other socio-environmental problems; one those most likely to exacerbate the negative effects of global climate change on large cities is local climate change caused by the heat urban island phenomenon[161]. In the case of Mexico, the costs of the joint effects of global and local climate change are close to double those that only contemplate the effects of global climate change. These areas will experience large economic losses in the near future or even in the present. In the metropolitan areas of Mexico City, Guadalajara, and Monterrey, the losses caused by climate change could exceed $1 billion USD per year in the 2020s. Areas surrounding these large urban centers could surpass this loss threshold during the 2030s and 2040s. This result underscores the need to combine international mitigation strategies with local adaptation measures[161].

Many of the impacts projected for the next decade cannot be prevented by mitigation efforts alone. The implementation of adaptation and risk reduction strategies are effective policy instruments to counter these impacts.

Climate, social, and economic system inertia means that the climate changes projected changes for the near future are largely inevitable. International mitigation efforts alone will not succeed in reducing some of the risks and impacts of climate change no matter how significant those efforts may be. However, these impacts can be reduced through the implementation of adaptation and risk reduction strategies.

Nationally Determined Contributions (NDCs) are only a first step to combat climate change. However, compliance with them would represent a significant risk reduction for Mexico.

Compliance with NDCs would signify a reduction of about 20% of Mexico's economic losses with respect to the business-as-usual scenario. The benefits of compliance with the NDC scenario would be between 28% and 71% of current GDP. However, residual costs would be between 68% and four times current GDP. For much of Mexico, this scenario would push back the date on which the risk threshold would be crossed by two to three decades with respect to climate change-driven GDP losses of more than 5% and annual temperature increases of at least 4%.

Failure of key stakeholders to comply with the NDCs would have significant costs for the country and would make international GHG mitigation efforts less effective.

Failure of key players to comply with international mitigation agreements would imply costs for all countries. If the United States decided not to participate in the NDCs, this decision would cost Mexico in the range of 5% to 28% of current GDP. Non-compliance by China would cost Mexico in the range of 4% to 36% of current GDP.

A profound GHG emission mitigation scenario that meets Paris Agreement targets would represent important benefits for Mexico in terms of prevented losses and risk reduction.

A scenario that limits the increase in global temperature to below 2°C above its pre-industrial value would cut the economic costs of climate change for Mexico in half and stave off surpassing many of the country's critical climate thresholds. However, residual costs are considerable in even this profound mitigation scenario (between 45% and 241% of current national GDP), which underscores the need to complement mitigation policies with adaptation strategies.

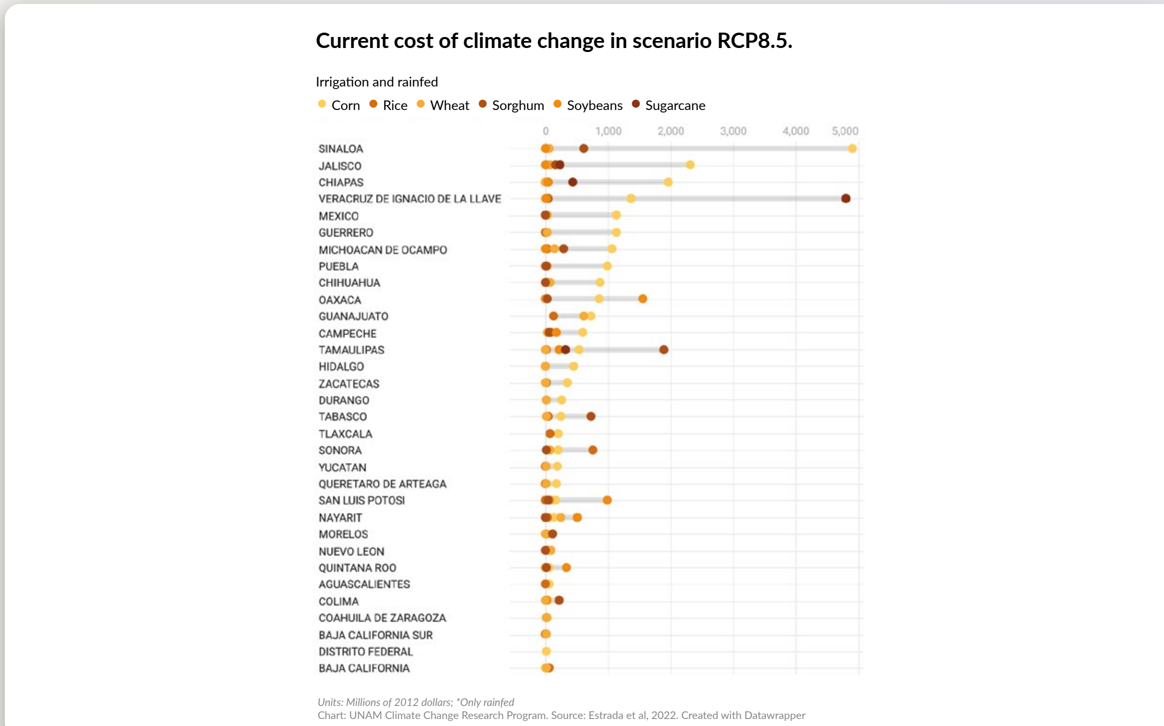
Estimates of climate change impacts and risks in specific sectors.

The impacts of climate change are variable and can entail costs or benefits, in addition to risk increases or reductions, for a particular sector. In general, for the sectors analyzed, climate change implies large economic costs for most states. Even under the most ambitious policy scenarios, residual impacts could be very high.

In a business-as-usual scenario, climate change may drastically reduce Mexico's agricultural production capacity and, consequently, impose considerable socioeconomic costs on present and future generations.

For crops such as corn, sugarcane, sorghum, wheat, rice, and soybeans, a business-as-usual scenario implies yield reductions of between 5% and 20% in the next two decades and up to 80% by the end of the century for certain crops and states. The states most suited to rainfed corn production today could lose between 30% and 40% of their yields by the end of the century. The current nationwide cost of climate change in this century for corn, sugarcane, sorghum, wheat, rice, and soybeans is as high as $38 billion dollars (see **Figure 14**), which is nearly twice the total national agricultural product in 2012. 69% of these losses came from rainfed crops, while reductions in corn yields accounted for 70% of total economic losses, approximately half of which can be attributed to Veracruz, Sinaloa, Tamaulipas, and Jalisco. 16% of the total economic losses occur in states such as Chiapas, Oaxaca, and Guerrero, which typically possess high levels of marginalization, poverty, and subsistence agriculture. Climate change will significantly increase the risks that subsistence farmers already face.

Figure 14. The current cost of climate change in scenario RCP8.5.



The current cost of climate change affecting corn, rice, wheat, sorghum, soybeans, and sugarcane, including rainfed and irrigation except for sugarcane (for which only irrigation is reported). Figures in millions of dollars.

Source: Estrada, F., Calderón-Bustamante, O., 2023.

A scenario aligned with Paris Agreement goals would significantly limit losses in most crops. In the case of corn production (rainfed and irrigated), nationwide economic losses would be reduced by 57%, while the reductions in the case of wheat and rice would be 23% and 41%, respectively.

River flood risks in Mexico are already high and are projected to increase significantly due to climate change and increased socioeconomic exposure.

Currently, the total cost of river flooding in Mexico is approximately $7 billion dollars per year and the average state is expected to incur annual damages caused by river flooding to the tune of $200 million dollars. Tamaulipas, Veracruz, and San Luis Potosi are the states with highest risk levels with expected annual damages of between $400 million and $800 million dollars. In scenario RCP8.5, nationwide annual damages projected for 2080 could reach $112 billion dollars due to alterations of socioeconomic conditions and climate change (see **Figure 15**). Compared to current climatic conditions, the states suffering the highest variations in river flood risk are located in the center of the country.

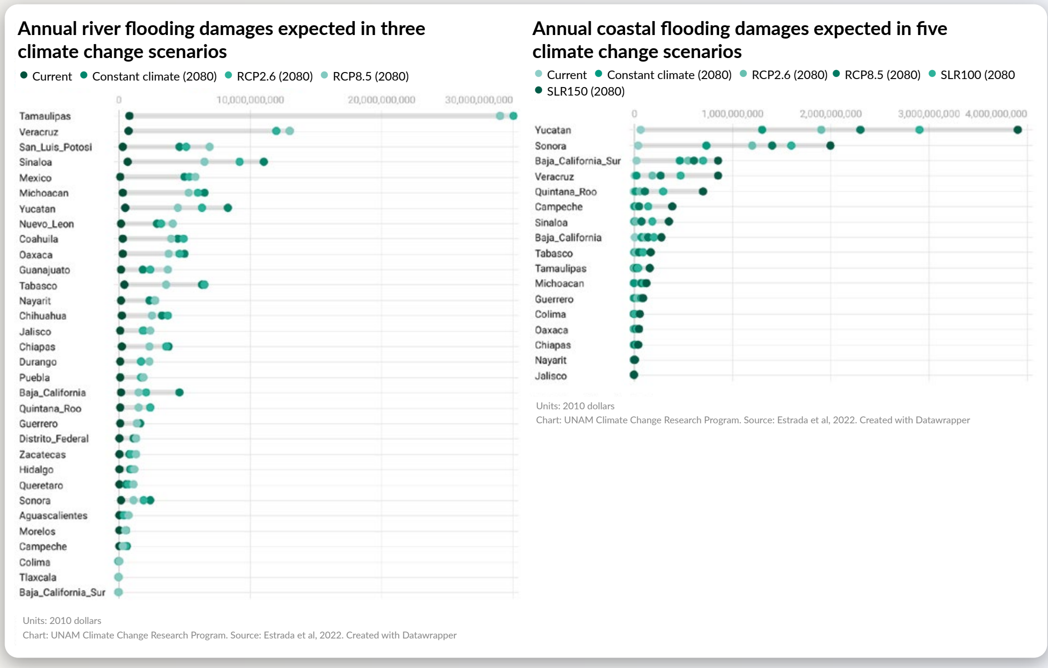
The risk of coastal flooding in Mexico will increase considerably this century due to the expected increase in exposure and the rise in sea level brought about by climate change.

Currently, projected annual damages from coastal flooding are close to $130 million per year. Due to changes in socioeconomic conditions alone, this figure is expected to rise to $2 billion per year by 2080. The combined effect of socioeconomic development in coastal regions and the projected rise in sea level would lead to expected damages of up to $10 billion per year.

Rises in sea level rise will increase the risk of flooding in all coastal states nationwide. However, certain states will experience far greater impacts.

Yucatan is the state at the greatest risk of coastal flooding in the country with current projected annual damages of $67 million which, under a climate change scenario, could increase to $4 billion. Other states that would face significant increases in coastal flooding risk are Campeche, Sonora, and Baja California Sur as shown in **Figure 15**.

Figure 15. Annual river and coastal flooding damages expected per state and in different climate change scenarios.



Annual river and coastal flooding damages expected per state and under different climate change scenarios. Current: climate conditions in 2010; Constant climate: 2010 climate scenario with socioeconomic changes until 2080; RCP2.6: scenario with socioeconomic and climate changes aligned with emissions scenario RCP2.6 until 2080; RCP8.5: scenario with socioeconomic and climate changes aligned with the RCP8.5 emissions scenario until 2080; SLR100: scenario with socioeconomic changes and sea level rise of 1 meter; SLR150: scenario with socioeconomic changes and sea level rise of 1.5 meters. Figures in 2010 dollars.

Source: Estrada, F., Calderón-Bustamante, O., 2023.

The information presented in this section was taken from the following reports:

Estrada, F., Calderón-Bustamante, O., 2023. Impactos económicos del cambio climático en México. In: *Estado y perspectivas del cambio climático en México. Un punto de partida*. Reporte técnico, Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-impactos-economicos.pdf

Use the following QR code to access further information concerning the database, methodology, and additional results:

Emissions and Mitigation Policies in Mexico

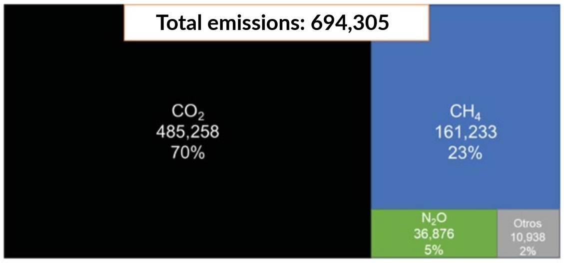
Mexico accounted for 1.10% of global carbon dioxide emissions in 2021, 1.19% of accumulated global emissions, and has lower per capita emissions than the global average[5]. This notwithstanding, it makes an important contribution to international mitigation measures and is the thirteenth largest GHG emitter in the world. This section analyzes Greenhouse Gas and Compound (GYCEI, initials in Spanish) emission and sink inventories in Mexico, which were generated by different studies and platforms and compares them to the official data of the National Inventory of Greenhouse Gases and Compounds (INEGYCEI, initials in Spanish). The imbalance in the literature on this topic is revealed as most scientific articles have focused solely on CO_2 emissions. The National Policy on Climate Change's main advances and achievements in mitigation after Mexico's most recent national communication are also analyzed[163].

Emissions Inventory

According to INEGYCEI data, total GYCEI emissions amounted to an average of 694,305.6 Gg CO2e per year[1].

Terrestrial ecosystems accounted for 23% of these emissions. 70% of the remaining total emissions are CO_2, followed by CH_4 and N_2O in third place (see **Figure 16**). There are discrepancies between the values reported by INEGYCEI, specialized literature, and those derived from independent global measurement products, in addition to critical gaps in information. Discerning the nature of the discrepancies and bridging the information gap are essential for future scientific research and decision-making on GHG mitigation policies.

Figure 16. Average annual balance of GYCEI emissions in Mexico from 2000 to 2019. All units are presented in Gg CO2e per year[1].

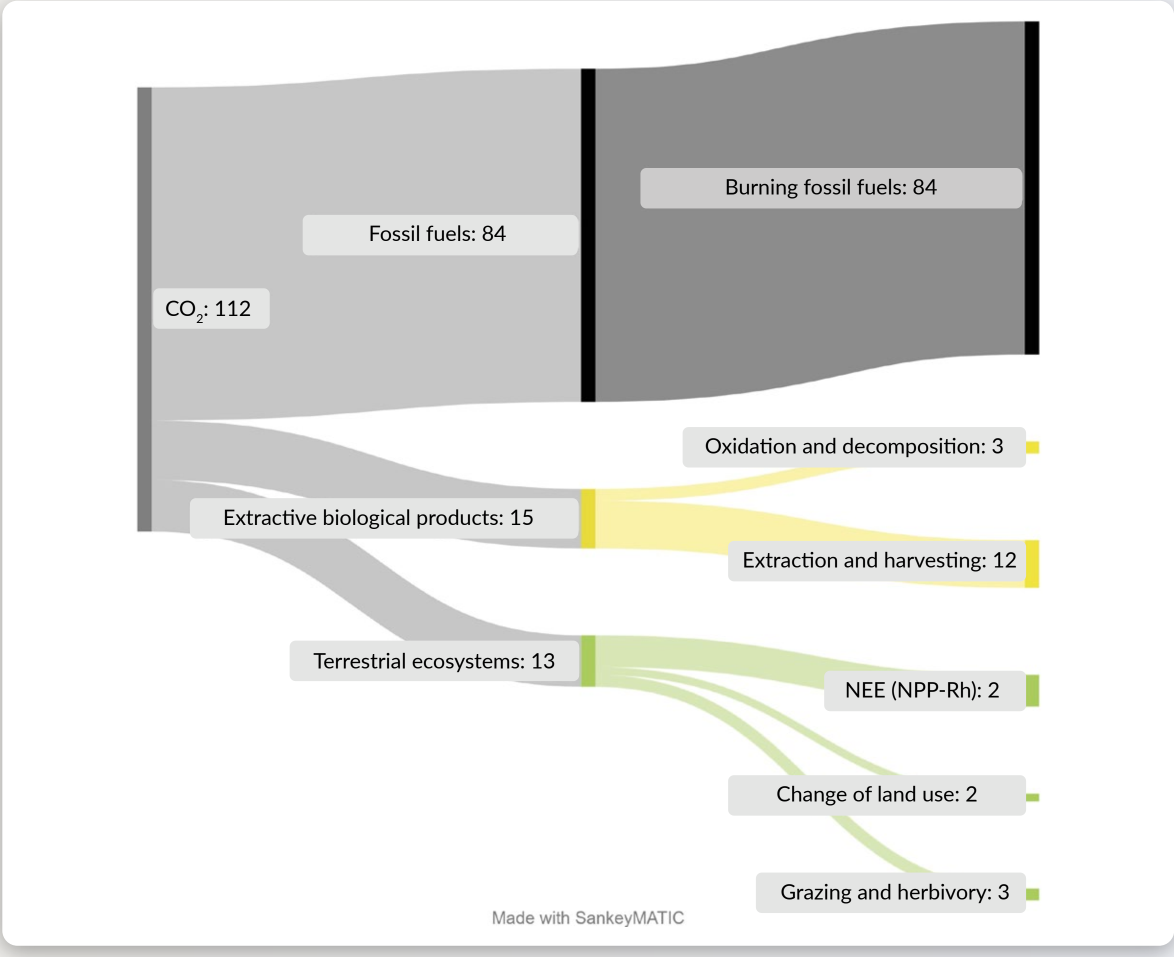


Source: Murray Tortarolo, G.N., et al 2023. Created using data from INEGYCEI 1990-2019, SEMARNAT, INECC, 2022.

The most important source of CO_2 emissions into the atmosphere is the burning of fossil fuels.

CO_2 emissions from the burning of fossil fuels is the most studied and reportedflux in the literature and there is broad agreement between estimates from different sources. This makes the reported average annual value of 460 Tg CO_2e per year[1] for the last two decades very reliable (see **Figure 17**).

Figure 17. Articles containing data reported for national and regional CO_2 flows.



The figures specified are the number of articles that report each flow.

Source: Murray Tortarolo, G.N., et al 2023.

The second most important flux is the carbon sink in the Agriculture, Forestry and Other Land Uses (AFOLU) sector. However, the discrepancies between estimates of this flux are of one order of magnitude.

INEGYCEI estimates that Mexico's ecosystems have captured an average of -165 Tg CO2e per year[1] over the last two decades (36% of carbon dioxide emissions from the burning of fossil fuels). In contrast, global product data estimate that Mexico has functioned as a small carbon sink over the past two decades with a value of only -35 Tg CO_2e per year[1], and that in certain years it becomes a carbon source. Identifying the origin of these discrepancies to have reliable estimates may well be the most important research priority among all the GYCEI's information gaps in Mexico for proper management of national public GHG mitigation policies.

The most important CH_4 flux into the atmosphere (and the most studied) comes from the AFOLU sector, here, estimates from different sources are generally the same. The second most important flux is the burning of fossil fuels.

Eighty-two percent of CH_4 emissions come from the AFOLU sector (131-145 Tg CO_2e per year[1]), particularly from livestock (70 Tg CO_2e per year[1], followed by waste decomposition (38-50 Tg CO_2e per year-1) and agricultural emissions (including rice fields, manure extraction and management; 17-21 Tg CO_2e per year[1]). The fossil fuel combustion flux accounts for 18% of total emissions (28 Tg CO_2e per year[1]) averaged over the last two decades. A critical lack of information on CH_4 concerns emissions from wetlands, biomass burning in stoves, and CH_4 absorption by soil.

The most important N_2O flux is from the AFOLU sector and estimates from different sources coincide. However, there are no studies reported in s the cientific literature.

Most N_2O emissions are concentrated in the AFOLU sector. Inorganic fertilizer oxidation and the subsequent emission of this gas account for almost all emissions. Estimates from the national inventory's most recent report and from global products coincide on 30 Tg CO_2e per year[1], although this flux has not been reported in scientific publications.

N_2O emissions from fuel combustion are a minor component of the flux, but estimates differ.

The largest discrepancies in the estimates of this compound's flux are in fossil fuel emissions: global products estimate double the inventory values associated with fossil fuels.

Although black carbon (BC) flows are smaller than the other GYCEI, their importance is highlighted in large cities because of their impact on human health.

Average BC emissions in Mexico are 76.88 Gg: fossil fuel burning is most important flux (90%), followed by the AFOLU sector (8%) and waste (2%). Information onBC comes from studies on air quality in urban areas (50%), the use of firewood as energy (19%), and transportation (13%). Forty-four percent of the studies correspond to the metropolitan areas of Mexico City, Guadalajara, and Monterrey, while 19% report estimates for the country as a whole.

The information presented in this section was taken from the following reports:

Murray Tortarolo, G.N., Perea K., Mendoza, A., Jaramillo, V.J., Murguía-Flores, F., Martínez-Arroyo, M.A., García García, M.A., Vargas, R., 2023. Flujos de gases y compuestos de efecto invernadero en México en décadas recientes (2000-2019). In: *Estado y perspectivas del cambio climático en México. Un punto de partida*. Reporte técnico, Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-emisiones-flujos-gycei.pdf

Use the following QR code to access further information concerning the database, methodology, and additional results:

National Climate Change Policy on Mitigation and Adaptation

Given the complex and multidimensional nature of climate change, strategies to address it must be based on knowledge and establish institutional structures that promote cross-cutting, dynamic, flexible mechanisms for the construction, implementation, and monitoring of public policies that respond to a dynamic process. Government climate change policies are not merely management tools, but also demand interplay between knowledge of the different aspects of climate change, the actions needed to address it in different sectors of society, the formulation of regulations governing its implementation, in addition to follow-up and assessment of results and the application of corrective or complementary measures when the conditions of the phenomenon have changed or when there is better applicable knowledge.

The construction of public policies based on knowledge requires methodologies built through multidisciplinary work as well as governmental institutions specialized in the subject.

Mexico has a General Law on Climate Change (LGCC, initials in Spanish) that establishes a cross-cutting institutional framework for the issue at the federal level and has created a National Climate Change System (*Sistema Nacional de Cambio Climático*) with the nationwide participation of states, municipalities, and the Legislative Branch of government. This system includes a fit-for-purpose technical-scientific body (the National Institute of Ecology and Climate Change: INECC, initials in Spanish) which, in addition to integrating, generating, and disseminating knowledge on climate change in Mexico nationally and globally, conducts specific oversight and technical assessment of public policies on climate change through an Evaluation Coordination (EC) with the participation of experts from the academic and social sectors.

Since 2018, there have been two amendments to the General Law on Climate Change (LGCC, initials in Spanish) concerning mitigation issues. These amendments formalize the commitments acquired under the Paris Agreement (PA) and strengthen the establishment of a Mexican Emissions Trading System (ETS). However, other legal-administrative measures (such as the dissolution of the public trust allocated to the Climate Change Fund) do not provide a clear idea of the mechanisms for capturing and channeling financial resources to support climate change mitigation and adaptation actions.

The evaluation of public policies on climate change reflects the dynamic relationship between scientific knowledge and public administration.

INECC's Evaluation Coordination Unit conducted two strategic assessments of national policy and one of subnational policies. The first addressed the Special 2014-2018 Climate Change Program[164] (PECC, initials in Spanish) and the second the 2013-2017 cross-cutting annex of the Federal Expenditure Budget on Climate Change (AT-CC)[165]. The PECC and the AT-CC are the most important instruments that provide federal funding for national climate change policies. However, the assessment was not on economic resources but rather the technical criteria for their design: significant inconsistencies were detected between the criteria for allocating resources for mitigation and adaptation through the AT-CC and the goals and activities set forth in National Climate Change Policy. Nor was there alignment with the PECC. Moreover, the Evaluation Coordination evaluated sub-national mitigation measures and integrated the attributions of the three levels of government in selected topics (electric power generation, land transportation, and urban solid waste management)[164]. These evaluations generated fundamental materials for research projects that would help find solutions to some technical, economic, and socio-environmental problems, among others.

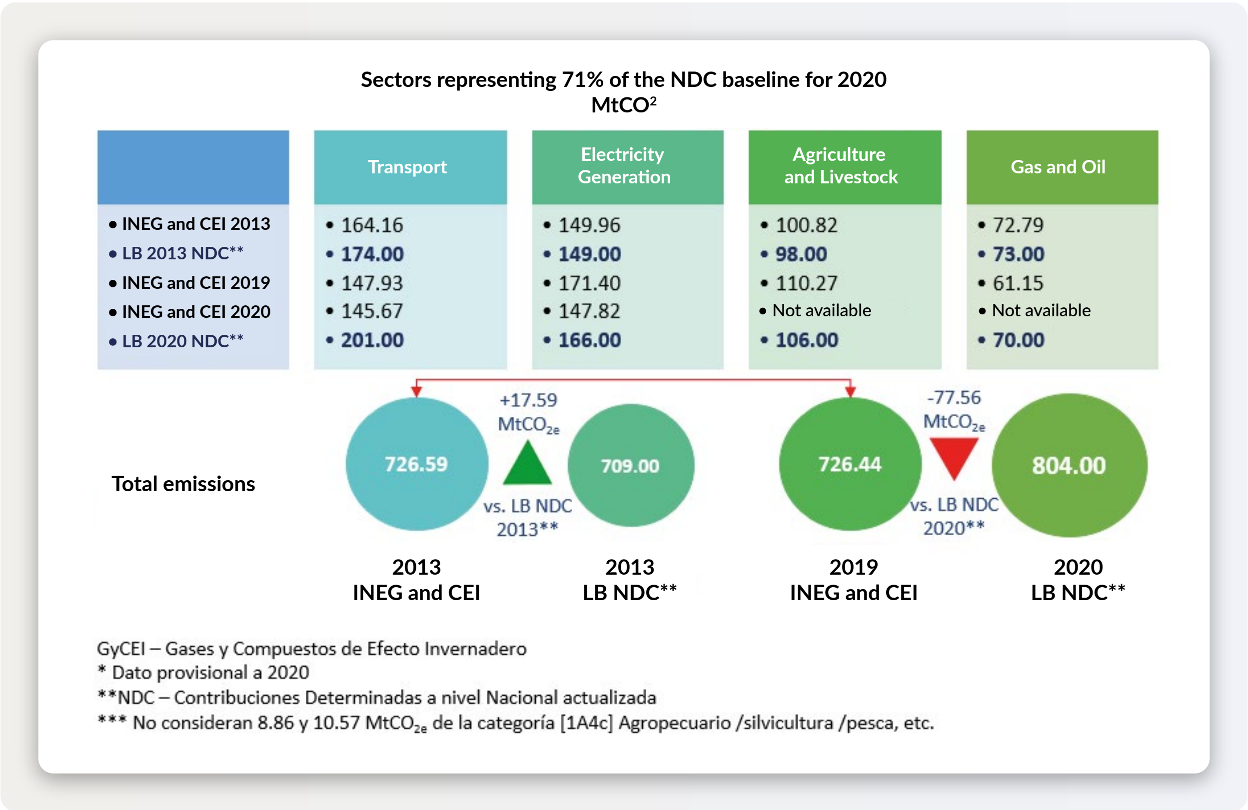
Identifying limitations, correcting, and monitoring policy implementation in a systematic fashion can be as important as the scientific formulation of the measures themselves.

The EC also developed National Climate Change Policy evaluation indicators to identify elements measuring policy progress on this matter[166]. Here it is worth highlighting the participation of the EC's social advisors from academia or the private sector alongside scientific and technical personnel from the governmental sector. However, greater transparency and access to information is needed to foster larger participation of social scientists in these tasks.

Academic evaluation of Mexico's compliance with its Nationally Determined Contribution is not systematized and displays information transparency discrepancies.

While official information presents data suggesting that Mexico is on the right path to complying with its NDC, more in-dept sector-by-sector analysis may suggest more ambitious goals. For instance, as shown in Figure 18, although electricity generation decreased by around two $MtCO_2e$ in 2020 as compared to 2013, this value is higher than the prospective emissions of approximately the 63 $MtCO_2e$ and 47 $MtCO_2e$ specified by SENER in its Annual Report on GHG Mitigation Potential in the Electricity Sector[167] for 2020 and 2030, respectively.

Figure 18. Evolution of GYCEI emissions in 2013-2020 and NDC baseline updated in 2013 and 2020.



Source: Islas Samperio, J.M. Carrasco González, F., 2023.

On the other hand, at least ten studies published between 2008 and 2020 suggested that under certain technical, economic, and financial conditions it is possible to double Mexico's unconditional NDC to achieve an annual mitigation of between 424 $MtCO_2e$ and 490 $MtCO_2e$ by 2030.

The information presented in this section was taken from the following reports:

Islas Samperio, J.M, Carrasco González, F., 2023. Estado del arte de la Política nacional de cambio climático en materia de mitigación. In: *Estado y perspectivas del cambio climático en México. Un punto de partida*. Reporte técnico, Programa de Investigación en Cambio Climático, UNAM.

https://cambioclimatico.unam.mx/wp-content/uploads/2023/10/cambio-climatico-en-mexico-mitigacion.pdf

Use the following QR code to access further information concerning the database, methodology, and additional results:

Digital Tools and Resources

AIRCC-Clim V2: Regional probabilistic climate change scenario generator

AIRCC-Clim is a tool for generating probabilistic climate change scenarios and risk measures[2]. This tool's most important features are:

- Integrated model: AIRCC-Clim is a stand-alone, user-friendly software designed for a variety of applications, such as impact, vulnerability, and adaptation evaluations, and integrated evaluation modeling.
- Graphical interface: It possesses a graphical interface that allows rapid evaluation of global and regional climate impacts in international mitigation policies through user-defined experiments.
- Scenario generation: The tool allows the generation of probabilistic regional climate change scenarios, which helps gain an understanding of possible climate change in different geographical areas.
- Risk measures: AIRCC-Clim also provides risk measures that help quantify and evaluate the challenges associated with projected climate change.

AIRCC-Clim is a versatile tool that allows users to explore and understand the effects of climate change in different regions by generating probabilistic scenarios and evaluating risk measures. Its graphical interface and its ability to evaluate international mitigation policies make it a valuable tool for impact studies and adaptation planning.

AIRCCA: A model for estimating impacts on crop growing due to climate change

AIRCCA is a biophysical crop model emulator designed for rapid and global evaluation of agricultural production risks at specific geographical locations[168]. Its main features are:

- It is a tool for the evaluation of climate change impacts and risks in agriculture. It allows for a rapid and comprehensive evaluation of the effects of climate change on corn, wheat, and rice yields.
- Probabilistic impact scenario generation: AIRCCA produces probabilistic impact scenarios in specific geographical locations and user-defined risk metrics for four Intergovernmental Panel on Climate Change (IPCC) emissions scenarios.
- Spatial resolution and crops contemplated: The tool generates impact scenarios and risk measures for three major global crops (rainfed corn, wheat, and rice) at a spatial resolution of 0.5 × 0.5 degrees.

AIRCCA offers an accessible and efficient way to conduct rapid evaluations of climate change impacts and risks on agriculture globally and in specific geographic locations. The tool integrates crop emulators, probabilistic climate scenario generation, and impact and risk estimation modules, thereby enabling users to explore different metrics and compare various scenarios.

AIRCC-BioDiv: A model for the estimation of impacts on species richness

The AIRCC-BioDiv model is a tool designed to explore global risks to biodiversity under future climate change scenarios. Its main features are:

- Future projections of species diversity loss: AIRCC-BioDiv allows the generation of future projections of species richness loss for four groups of terrestrial vertebrates (amphibians, reptiles, mammals, and birds).
- A variety of climate models and emission scenarios: The software makes it possible to use a wide range of climate models available in CMIP5 and both IPCC emissions scenarios as well as user-defined ad hoc emissions scenarios.
- Probabilistic risk metrics: Users can use a variety of probabilistic risk metrics, including estimating probabilities of surpassing certain species loss thresholds per cell; identifying dates when those thresholds are crossed; and estimating multivariate risk hotspots, i.e., sites where biodiversity losses converge for all four taxonomic groups. These metrics can be calculated on an annual frequency or for user-defined time intervals.
- Visualization of significant climate risks: The tool enables users to visualize the regions where the most significant climate risks to terrestrial vertebrate richness are projected.

The AIRCC-BioDiv model provides a platform for exploring and evaluating the potential risks of climate change on global biodiversity. By generating projections and using different risk metrics, users can identify critical areas and moments for the loss of species in specific taxonomic groups and produce information of interest for in biodiversity conservation and management decision making.

DataPINCC: Climate change research data and resource portal

DataPINCC is a comprehensive platform that exists to provide access to climate change research relevant databases and an online system to query, view, and analyze geo-referenced data on climate and socio-economic scenarios. The portal seeks to concentrate and standardize databases, promote research on climate change, facilitate access to existing information and stimulate the exchange of information among various national and international agencies and institutions in the field. Its main features are:

› Access to databases and analysis tools: This tool provides access to relevant climate change databases thereby facilitating multidisciplinary research. It also offers an online system to query, view, and analyze geo-referenced data including climate scenarios, impacts, vulnerability, adaptation, risk measures, and other aspects of natural and human systems.
› Standardization and Data Exchange: It seeks the standardization of database formats and encourages data exchange between national and international institutions and agencies, promoting intra- and inter-institutional collaboration and a multidisciplinary approach.

The DataPINCC portal is a comprehensive platform that seeks to facilitate climate change research by providing access to useful data and tools for the scientific and educational community interested in understanding and furthering the study of climate change.

EpI-SPECIES University spatial eco-epidemiology platform

EpI-SPECIES is an interactive tool for the analysis of the epidemiological niche of infectious diseases and for the creation of predictive models to analyze their spatial-temporal dynamics in Mexico. The platform uses Bayesian algorithms to characterize the bioclimatic, ecological, and sociodemographic profile of vectors, hosts, or humans that have tested positive for a pathogen. Thus, it generates ecological and geographical models for the presence of infectious diseases. Moreover, the platform makes it possible to generate models of infectious disease incidence in environmental change scenarios. The Atlas of Infectious Diseases is a public consultation system for viewing spatiotemporal information on infectious diseases in Mexico and is a spatial eco-epidemiology tool for users in academia and government.

UNIATMOS: Regionalized climate change scenario CORDEX, AR6, IPCC atlas and repository for Mexico, Central America, Cuba, Jamaica, and southern United States of America.

The Atlas provides specialized and general users with visual materials and interactive monthly databases on the internet of regionalized climate change scenarios involving maximum and minimum temperatures and precipitation for Mexico, Central American countries, Cuba, Jamaica, and southern United States of America that serve as input for studies of impacts, vulnerability, and adaptation to climate change based on the Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC).

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