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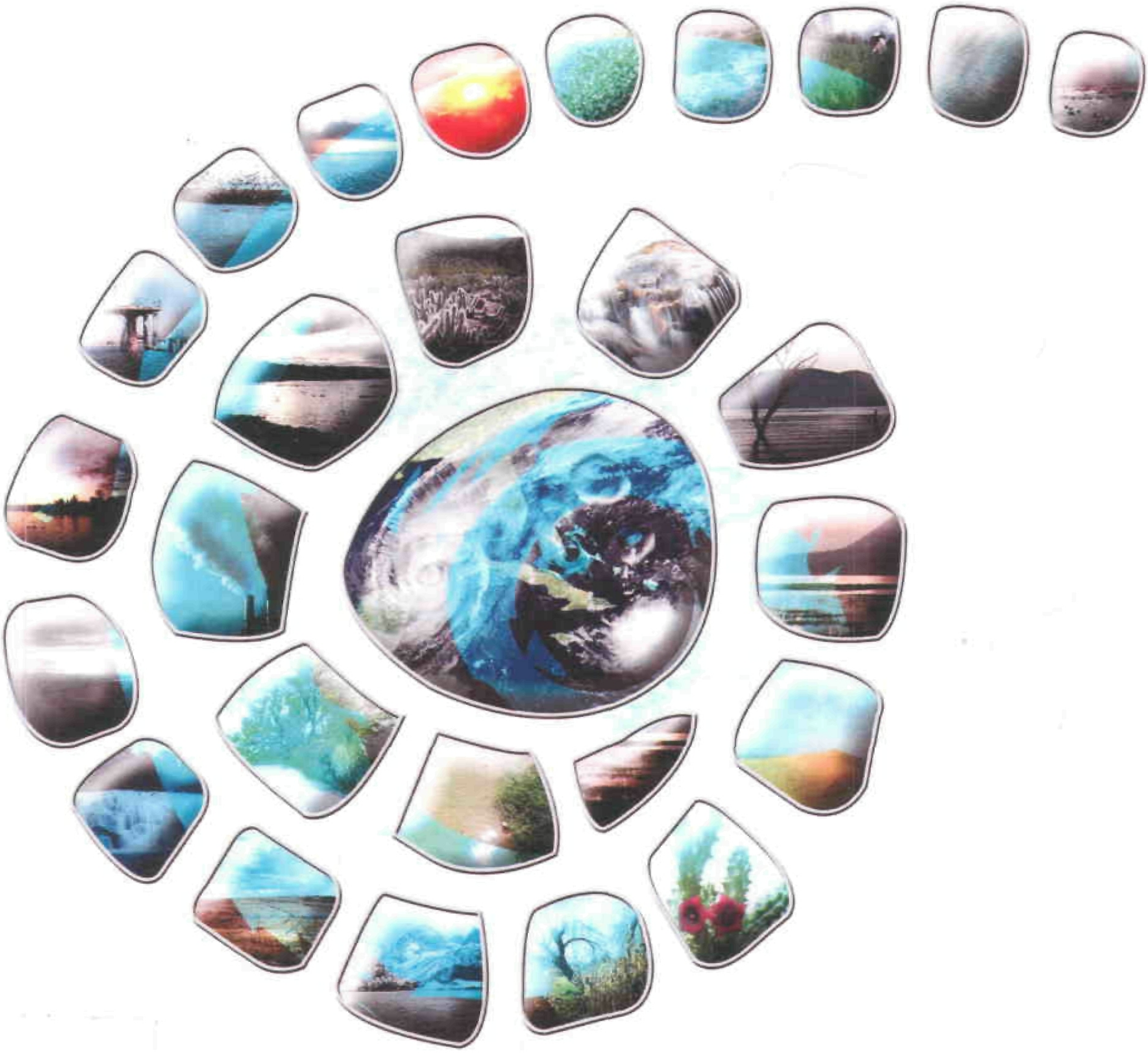
Effects of climate change on Mexico's water resources



Polioptro F. Martínez Austria

EFFECTS OF CLIMATE CHANGE ON MEXICO'S WATER RESOURCES

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SEMARNAT

PLANNING DIVISION

MEXICAN INSTITUTE
OF WATER TECHNOLOGY

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Preface

Based on evidence recognized by the international scientific community, climate change is already an unquestionable reality whose first effects are beginning to be measured. Available climate projections and models help anticipate potential far-reaching consequences for development processes. Climatic transformations will impact the environment, especially biodiversity and water resources; will put several productive processes at risk; and will represent a threat for public health, among other consequences. Climate change is emerging as the environmental problem of greatest significance in the 21st century, and as one of the most important global challenges faced by humanity as a whole.

The origin of this phenomenon is anthropogenic, derived from human activities that use the atmosphere as a dumping site of greenhouse gases (GHGs), mainly byproducts of the burning of fossil fuels and the destruction of plant cover. It is most pressing to increase mitigation efforts in order to reduce GHG emissions and develop adaptation capacities against their predictable adverse impacts, some of which are already inevitable.

In response to this challenge, Mexico signed the United Nations Framework Convention on Climate Change in 1992 and the Kyoto Protocol in 1997, ratifying both multilateral instruments in 1993 and 2000, respectively. Our country has performed three National

Inventories of GHG emissions according to the guidelines and methodologies of the Intergovernmental Panel on Climate Change (IPCC) and presented three National Communications; the last one issued in November 2006. More recently, in May 2007, the President of Mexico, Felipe Calderón, presented the National Strategy for Climate Change.

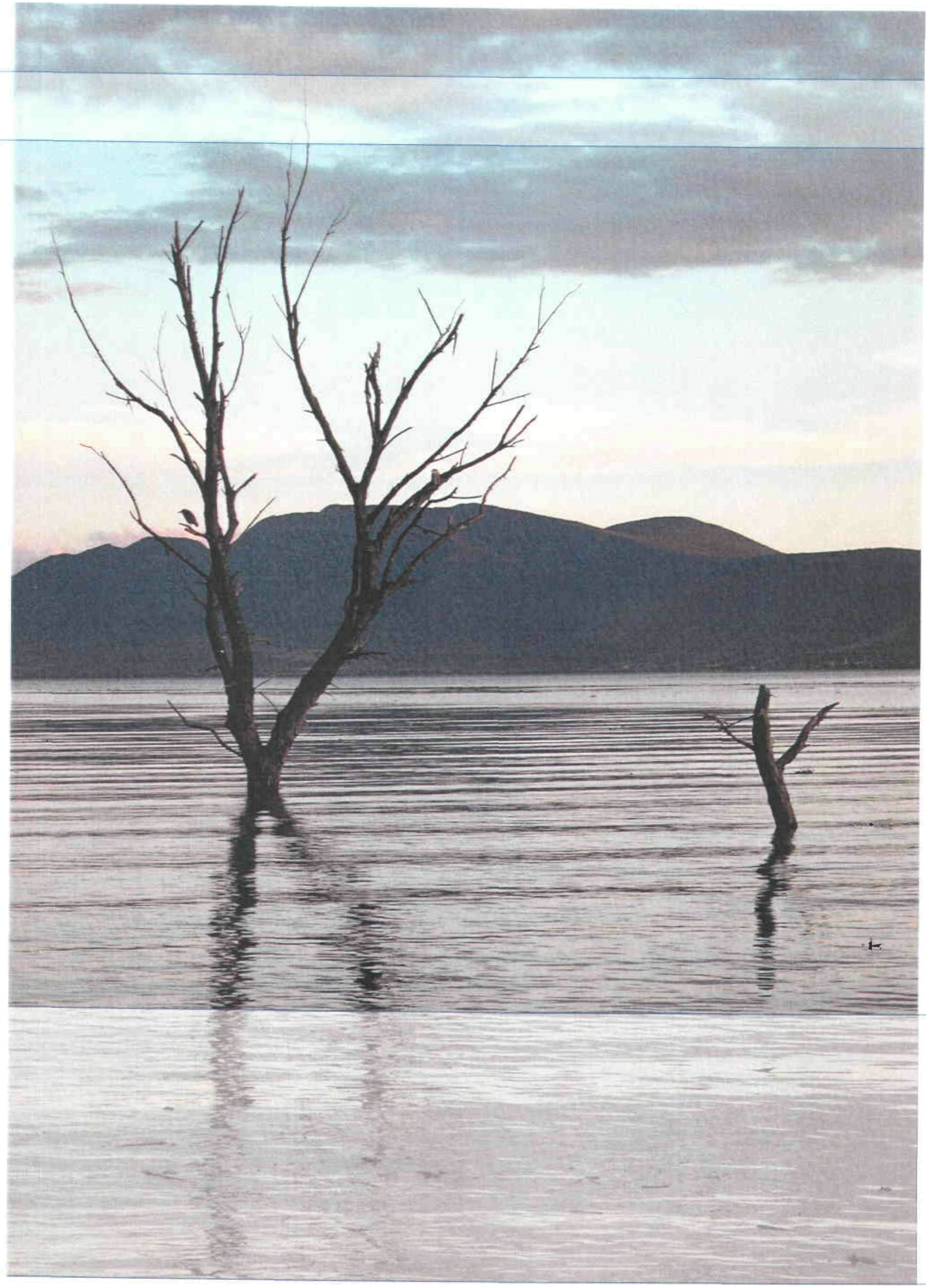
Due to its geographical location and its socioeconomic conditions, Mexico is highly vulnerable to climate change. Effects on the water cycle, in particular, determine the need to revise current water resources management models. Despite the importance of the problem, there is no text to be found in Mexico that summarizes the current knowledge on the implications of climate change, the vulnerability conditions, and the needs for adaptation in water resources use and management.

With this book, Dr. Polioptro Martínez, Director General of the Mexican Institute of Water Technology, contributes to filling this void. Based on solid technical information, he presents in a simple and clear way the reality of the climate conditions that prevail in the planet, and particularly in Mexico; the way they relate to valuable water resources, and how climate change will impact our environment, according to the different climate change scenarios developed by the IPCC. The book's orientation is eminently practical, by providing the necessary information for revising public policies and facilitating the decision-making process for medium-term planning. It enables us to see climate change from the perspective of river basins and the specificity of each one of them.

The author also stresses the need to conduct more detailed studies in areas that are particularly vulnerable to climate change. The valuable ideas presented here should motivate regional studies to help reduce the uncertainty of forecasts, locate the effects, and define adaptation measures and prioritize their application. Dr. Martínez's work aims towards the development of a specific strategy for the water resources in our country that will be included in the Climate Chance Special Program currently in the making.

While the challenge is of global proportions, we need to face it as an organized society and as individual citizens. No technological answer, no mater how advanced, will be sufficient if we are not capable of quickly transforming our production and consumption pattens, our territory occupation patterns, and our individual and collective conducts regarding natural resources, and particularly water.

Dr. Fernando Tudela



Background

During the First World Water Forum, held in Morocco in March 1997, professor Godwin O. P. Obasi, Secretary General of the World Meteorological Organization (WMO) chose "Climate Change and Water Management" as the topic for his keynote address (Obasi, 1997). The choice of this topic, made in such a special juncture as that of the first worldwide meeting to discuss water issues, was indeed not unintended. It obeyed an irrefutable reality: climate change is the main long-range threat looming over worldwide water resources and, thus, over the entire human race.

Today, more than a decade later, professor Obasi's remarks have been confirmed by new empiric evidences and a better understanding of global atmospheric dynamics, attained chiefly thanks to the efforts of the Intergovernmental Panel on Climate Change (IPCC). Back then, WMO's Secretary General, quoting from the conclusions of the Second Report of the Intergovernmental Panel, stated that "...the balance of evidence suggests a discernible human influence on global climate" (IPCC, 1995). In 2001, the Third Report for Policymakers (IPCC, 2001) established that during the 20th Century, global temperature increased by 0.6 ± 0.2 °C, which is greater than the increase in the last ten thousand years, and that there will be an even greater global warming in the 1990-2100 period of 1.4-5.8 °C. Another report from IPCC's Working Group I (2001a) noted that it is "widely recognized that human-influenced emissions of greenhouse gases have the potential to alter the climate system". Lastly, IPCC's 2007 Report for Policymakers clearly establishes that "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" (IPCC, 2007).

Global warming, by retaining a greater amount of energy in the atmospheric system, will intensify the hydrological cycle. One of the main effects will be the modification of rainfall-runoff patterns. Consequently, there will be changes in water availability and in the frequency and intensity of extreme hydrometeorological events.

Mexico is specially vulnerable to the global warming that will cause significant changes to its hydrological cycle, since it is subject to recurrent droughts in some regions, or to strong stational precipitations caused by hurricanes and tropical storms in others. Furthermore, two thirds of its territory are characterized as arid or semiarid, and thus, according to most global circulation models, it is foreseeable that such an area will experiment a marked decrease in rainfall and runoff.

If we add to the equation the fact that in many of the main watersheds and aquifers in Mexico water resources are reaching or have reached overexploitation levels, the importance of analyzing the possible effects

Intergovernmental Panel on Climate Change
(IPCC)

The IPCC is an intergovernmental group of experts on climate change created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). It is open to all members of the United Nations and the World Meteorological Organization.

Its role is to assess on a comprehensive, objective, open and transparent basis the latest scientific, technical and socio-economic information produced worldwide relevant to the understanding of the risk of human-induced climate change, its projected impacts and options for adaptation and mitigation. The IPCC does not conduct any research nor does it monitor climate related data or parameters; rather, it bases its assessment mainly on published peer-reviewed scientific and technical literature.

One of the main activities of the panel is to make a periodic assessment of the knowledge on climate change. The IPCC also produces special reports and technical documents on topics that require scientific and independent information and consulting, and supports the United Nations Framework Convention on Climate Change (FCCC) by working on methodologies related to national greenhouse gas inventories.

of global warming on water management could be better understood.

Moreover, hydraulic structure and system design criteria are based on the assumption that the recorded climatic information is a reliable guide for the future; that climatic and hydrological variables depend on processes that do not change over time. [1]. However, there are now weighty reasons to estimate that the climate will change during the useful life of many of the great hydraulic structures, and future design criteria will have to adapt to foreseeable changes in climatic and hydrometeorological conditions in relation to the duration of the project (Linz H., *et al.*., 1990). It is even possible that the current hydrological designs of existing structures need to be revised.

Since 1994, when the Country Study was conducted, Mexico has been developing

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In statistical terms, which are stationary and ergodic processes.

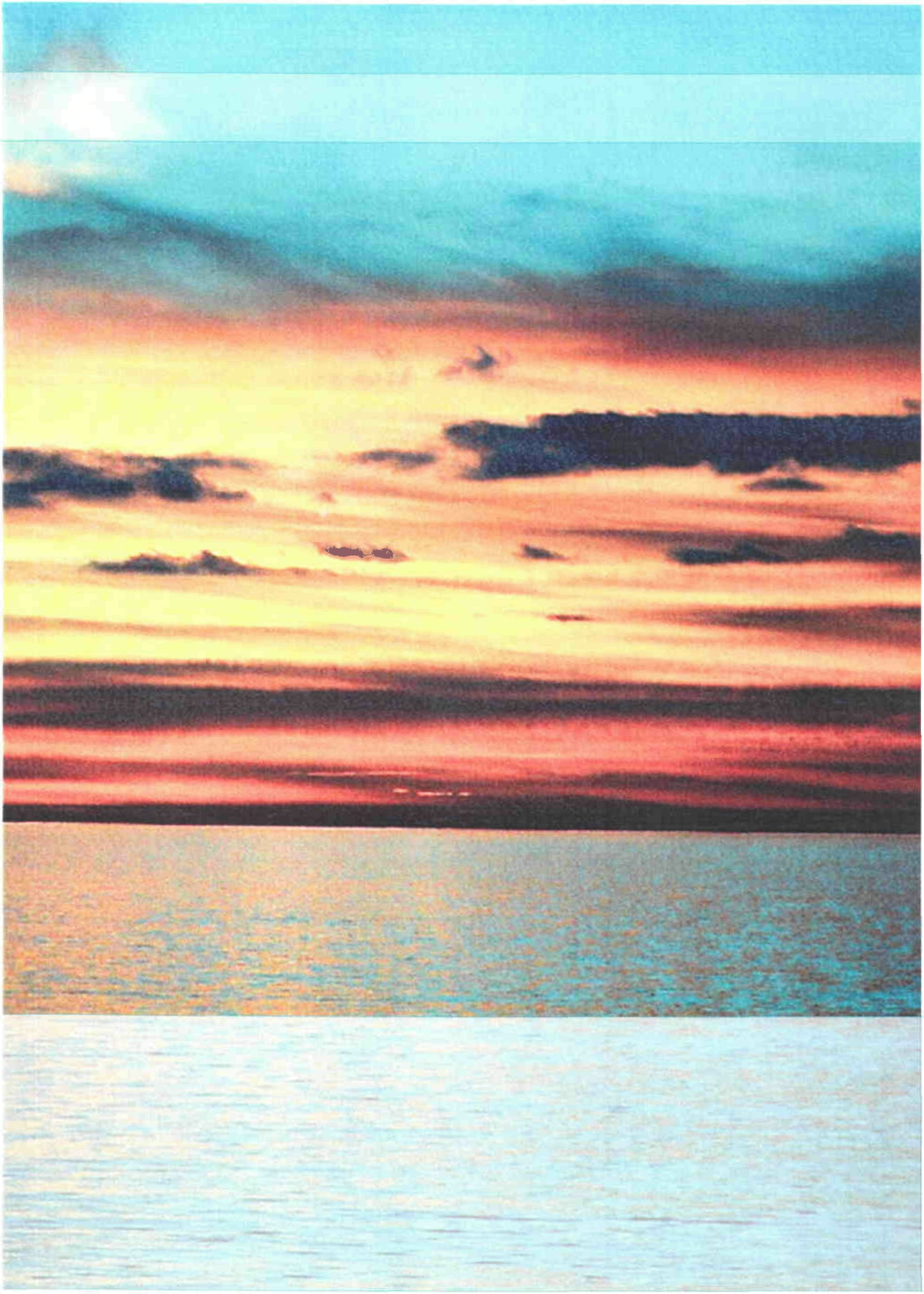
a continuous effort of analyzing climate change and its effects in its territory. This Country Study comprised three main aspects: greenhouse gas inventory, climate change scenarios, and vulnerability studies in seven different areas, including agriculture and water resources.

In addition, Mexico has presented three extensive National Communications to the United Nations Framework Convention on Climate Change. The first one was published in 1997, the second one in July 2001, and the third one in late 2006 (SEMARNAP, 1997; SEMARNAT, 2001; SEMARNAT, 2006). The first communication reported the results of the Country Study regarding vulnerability and mitigation.

The second document focused on the advances on the greenhouse gas inventory and on mitigation actions in the forest and energy sectors. It did not include mitigation actions on water resources. The third communication was an update on the greenhouse gas inventory and focused on global warming mitigation actions. The contents of the National Climate Action Program are also worth mentioning (SEMARNAP, 1999).

The recently published National Climate Action Strategy is a document that places Mexico at the forefront of countries that are facing the challenges of global warming. This document, coordinated by SEMARNAT but the result of the joint work of seven ministries of state, summarizes the mitigation and adaptation strategies proposed by each sector. These strategies will in turn become part of a national climate action program.

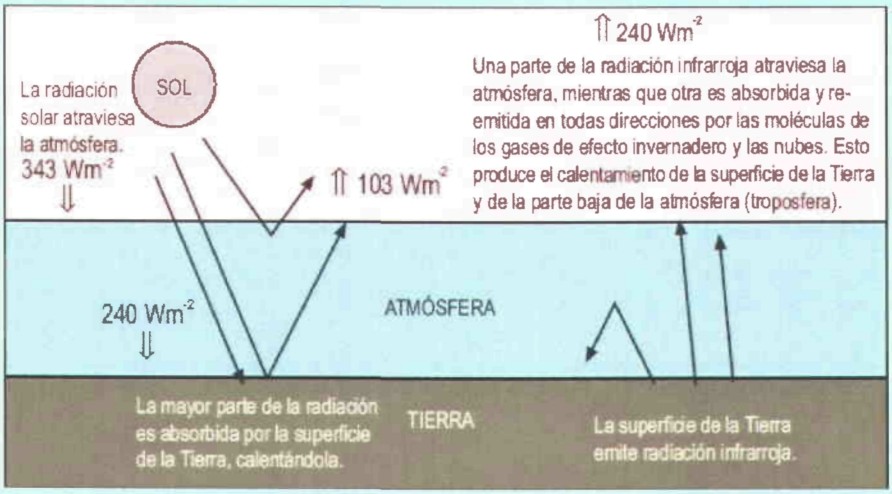
In spite of the importance of the efforts made in Mexico for the study of climate change, no book summarizes the current knowledge on the effects on and the vulnerability and adaptation of water resources and their management. This document has the purpose of helping to fill that void and to provide necessary information for policy- and decision-makers for medium-range planning.



Global Warming

The greenhouse effect, capable of producing global warming, is caused by the presence in the atmosphere of gases that retain long-wave radiation emitted by the Earth while dissipating the heat received from the Sun. Indeed, as shown in figure 1, a part of the total radiation that reaches the Earth from the Sun (~343 W/m^2) is immediately reflected back to outer space (~103 W/m^2), another part is absorbed by the Earth (~240 W/m^2), which heats up and emits back some of that energy in the form of infrared frequency radiation. However, before reaching outer space, a portion of this radiation is captured by some gases in the atmosphere, whose lower layers (the troposphere) heat up by this process, thus increasing the temperature of the planet.

Figure 1. Schematic representation of global warming (Semarnap, 1997).



The gases that retain heat in the atmosphere, known as greenhouse gases, include carbon monoxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). These gases, except for CFCs, occur naturally in the atmosphere and are responsible, to a good extent, for creating life-supporting conditions in our planet. Nevertheless, even small variations in their amount can increase atmospheric temperature significantly, with the consequences this implies.

From among the greenhouse gases, CO_2 is the most abundant one and the main cause of global warming from anthropogenic origin, i.e. produced by modern human activities that release it to the atmosphere through the burning of fossil fuel. In the pre-industrial era, CO_2 concentration was 280 ppm; in 2005, it reached 379 ppm (IPCC, 2007b), and is unfortunately rising continuously to our days.

Table 1 reproduces pre-industrial concentrations, those for 1998, and concentration increase rates of the main greenhouse gases calculated with information from the 1990-1999 period.

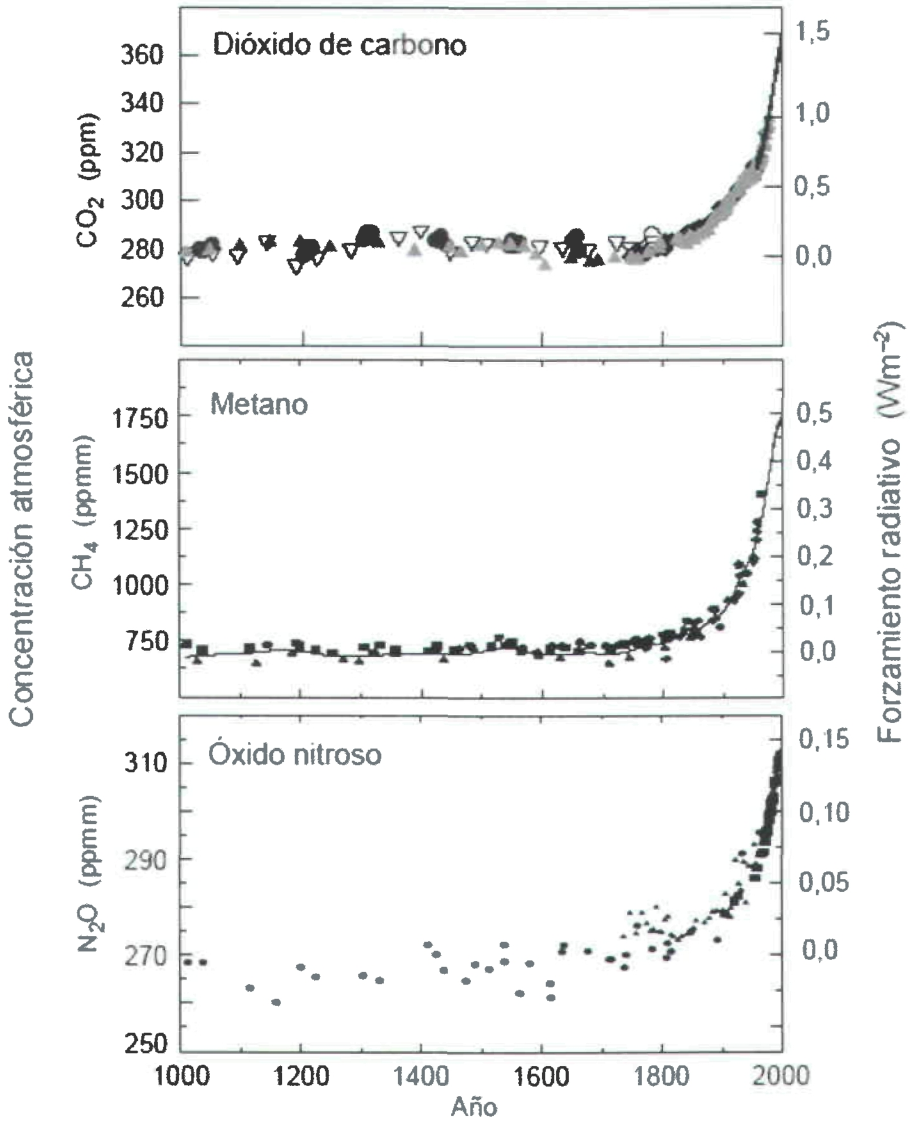
Figure 2 shows the variation, during the last one thousand years, of three of the main greenhouse gases. The oldest data, before direct measurements were availa-

Table 1. Main greenhouse gases, concentrations and increase rates (IPCC, 2001a).

	CO_2 Carbon dioxide	CH_4 Methane	N_2O Nitrous oxide	CFC-11 Chlorofluorocarbon-11	HCF-23 Hydrofluorocarbon-23	CF_4 Perfluorocarbon
Preindustrial concentration	280 ppm	700 ppb	270 ppb	zero	zero	40 ppt
Concentration in 1998	365 ppm	745 ppb	314 ppb	268 ppt	14 ppt	80 ppt
Annual increase rate	1.5 ppm	7.0 ppb	0.8 ppb	- 1.4 ppt	0.55 ppt	1 ppt
Atmospheric lifetime	5 - 200	12	114	45	260	> 50.000

ble, are inferred from observations in ice cores extracted in Antarctica or snow from Greenland. These values are complemented with others measured directly during the last few decades. The left axis shows the value of the radiative forcing (in *watts* per square meter) that these gases are estimated to produce. It is important to notice that their increase coincides with the beginning of the industrial era, and that during the 20th century their increase was virtually exponential.

Figure 2. Atmospheric increase of the main greenhouse gases in the last one thousand years (IPCC, 2001b).



As a clear correlation with these changes in greenhouse gases in the atmosphere, a significant increase in mean temperature has been recorded, as shown in figure 3. If records of the last one thousand years are reconstructed, the result would be that shown in figure 4, where an increase in temperature is observed from the beginning of the industrial era, which becomes notorious, almost exponential, in the last decades of the 20th century.

Figure 3. Mean atmospheric temperature variation from 1860 to 2006, compared to the average in the 1961-1990 period (University of East Anglia, U.K.).

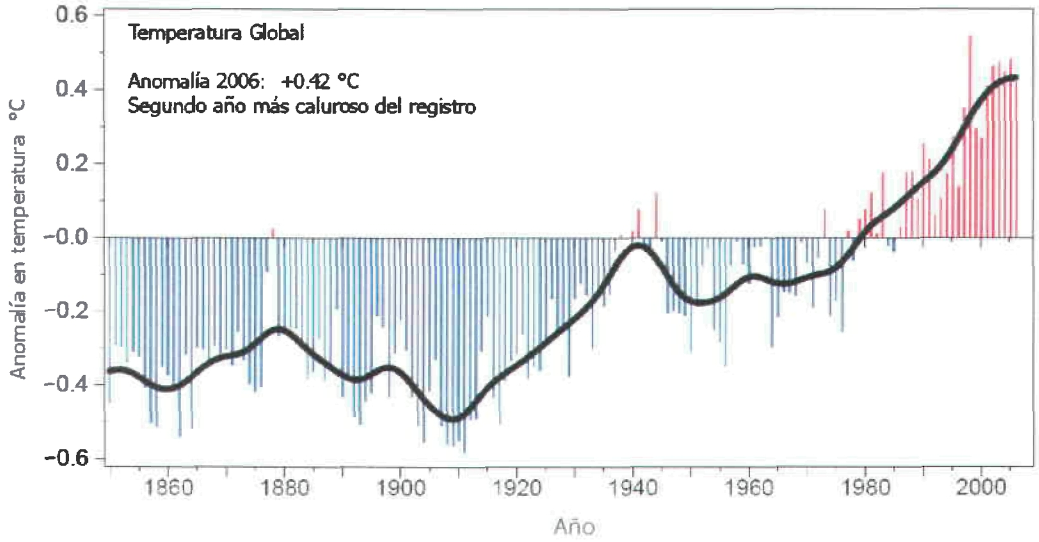
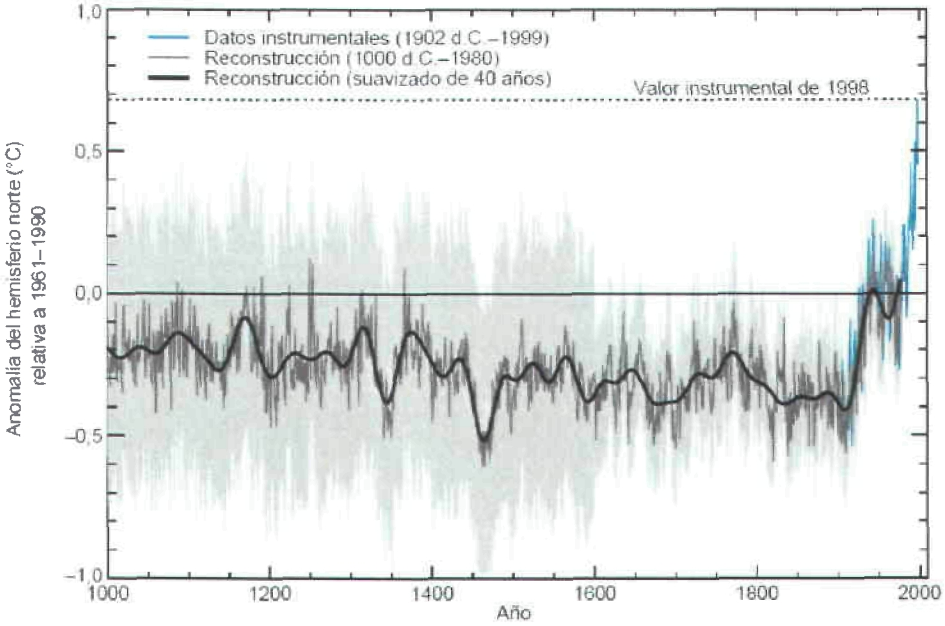
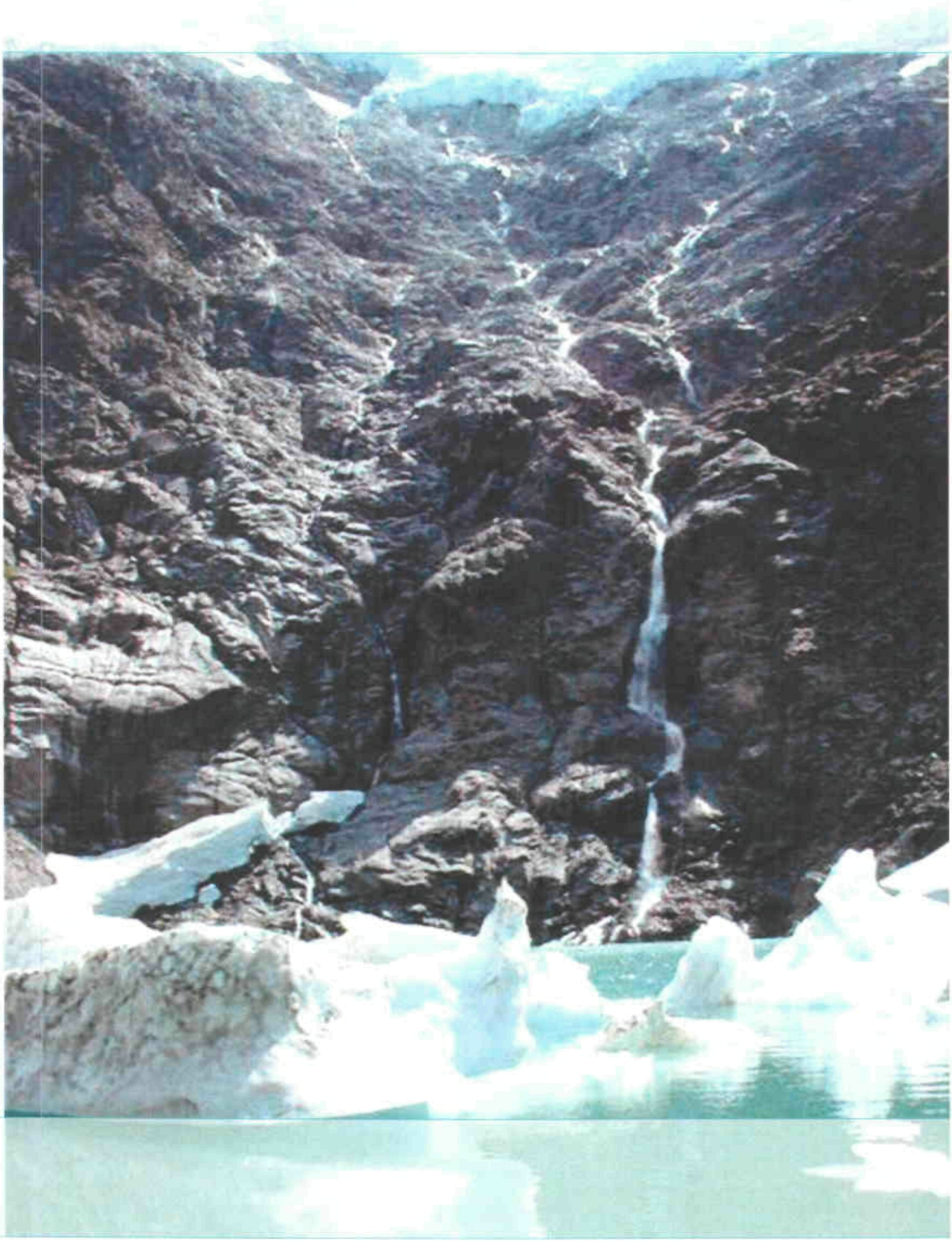


Figure 4. Temperature anomaly during the last one thousand years, compared with the average in the 1961-1990 period.





When climate change studies began to be conducted, there was a heated controversy regarding the origin of the modified temperature levels: Was it natural or anthropogenic? Today this discussion has been settled, and while it is granted that there is a natural component, it is albeit too small to justify the changes observed in the Earth's temperature within the studied period. Atmospheric warming is produced by human activities.

Human activities increase greenhouse gas concentrations

Carbon dioxide CO_2 is the indispensable bond that links the Sun and the Earth by means of the biochemical exchange that enables luminous energy to be "incorporated" into living systems. With the help of solar energy and with the intervention of molecules such as chlorophyll and water, it participates in the construction of food by means of photosynthesis in green plants (autotrophs).

The energy contained in food can be used within the cell of the same plant or of any other organism (heterotroph) through oxidation processes that allow these compounds to be "burned" by the process of respiration and so, CO_2 goes back to the atmosphere.

Photosynthesis and respiration are the metabolic processes that have been used by the Earth for thousands of years to make $CO_{2\,\text{circulate}}$ ($CO_{2\,\text{cycle}}$). It is estimated that, under natural conditions, it takes CO_2 around three hundred years to complete this cycle.

A good part of the carbon cycle takes place in water, where large amounts of photosynthetic aquatic organisms fixate it in organic molecules, while others release it through breathing. Carbon dioxide, once released, goes on to form compounds such as carbonates. Some scientists estimate that half of the circulating CO_2 is absorbed in the oceans. A large amount of these carbonates are found in the bottom of the sea "dragged down" by the organisms that die and fall into the deep.

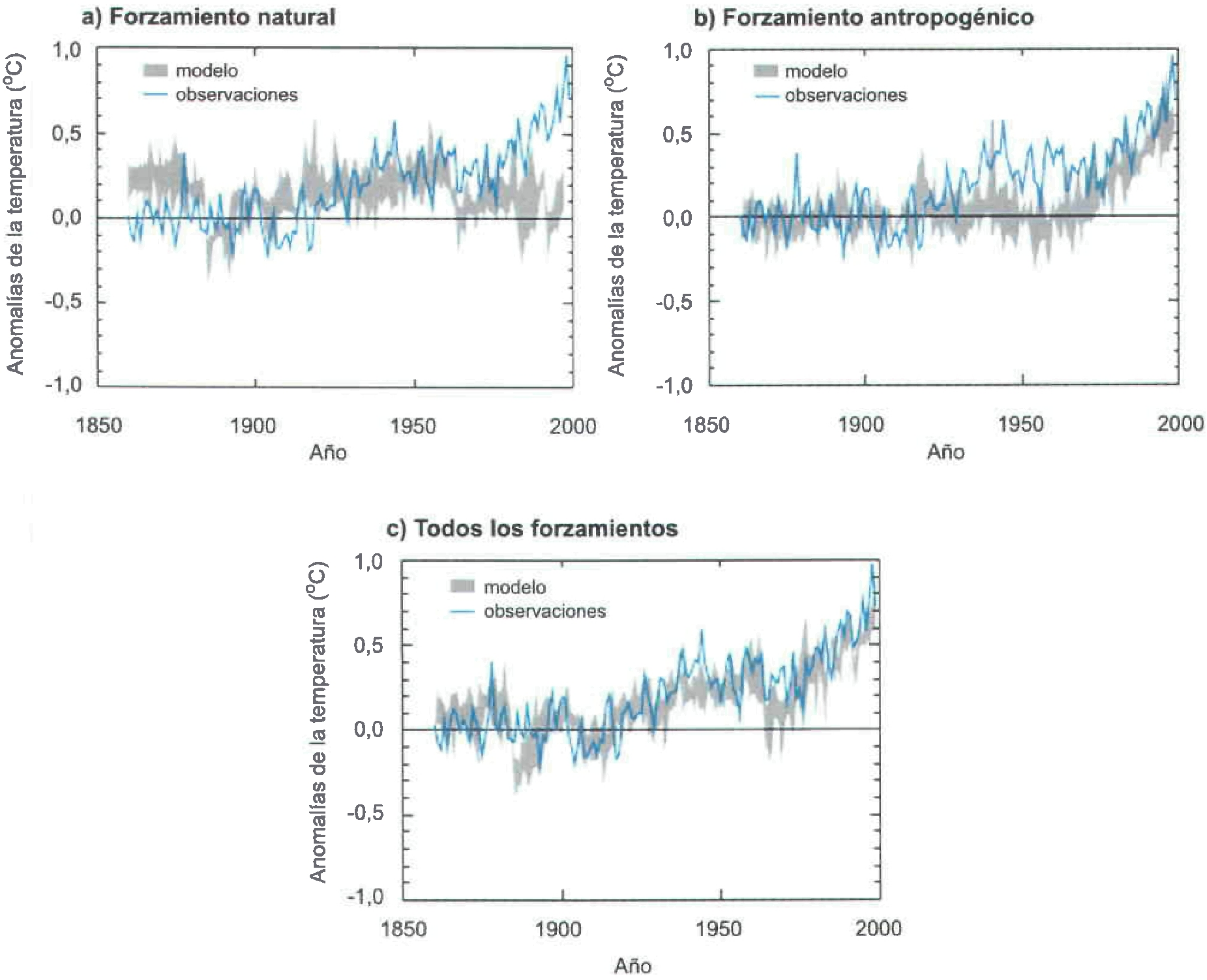
A series of carbonate <=> bicarbonate reactions occur constantly in the water. Calcareous sediments contain many of those compounds, and thus carbon remains deposited at the bottom of the sea, since these compounds dissolve very slowly.

The natural carbon cycle, as we know, has been altered considerably due to environmental pollution and the velocity and intensity with which plants can use it in photosynthesis. Therefore this gas cannot be prevented from accumulating in the atmosphere.

The burning of fossil fuels, which had remained deposited for thousands of years in the depths and that now are used as gas, oil, and gasoline, has put large amounts of carbon into circulation (in the atmosphere).

Figure 5 shows a comparison developed by the IPCC of the variations predicted according to the global circulation models when caused by: natural processes (a), anthropogenic effects (b), and the combination of both effects (c). It can be observed that natural variation models do not explain the temperature changes seen, which occurs when summing up the effect of the increase of greenhouse gases produced by human activities.

Figure 5. Simulation of climate change according to its causes (IPCC, 2001 b).



Climate change scenarios

If global temperature changes recorded since the pre-industrial era are produced mainly by the increase in greenhouse gasses, it is evident that in the near future, towards the end of this century, global climate will depend on the capacity of societies to limit or reduce the consumption of fossil fuels and, in general, to control the emissions of greenhouse gases, as well as to create conditions for these gases to be absorbed through natural processes, mainly those related to vegetable activity.

Since it is not practicable to determine with precision what the modification of greenhouse gas volumes will be like in the future, due to the fact that it depends on social and economic variables impossible to determine accurately, it is customary to build scenarios that take into account probable future conditions. From this perspective, each scenario is a scientifically obtained view of a plausible tomorrow, based on known models and the most probable combinations of greenhouse gas emissions in the future.

In 1996, the IPCC started to develop new emissions scenarios to update those made in 1992, known as the IS92 Scenarios.

Four scenario families were built, each of them based on a description --or so-called storyline--of the conditions that will possibly prevail in the future. These new scenarios are known in generic terms as SRES Scenarios.

The A1 scenario family describes a world characterized by rapid economic growth, a world population that reaches its peak halfway through this century and begins to decline from then on, and adopts more efficient technologies. This scenario family is subdivided according to the technologies used: Fossil fuel intensive (A1FI), alternative energy (A1T), and balanced use of different sources of energy (A1B).). This latter scenario is one of the most commonly used in simulations, since it is considered among the most likely.

The A2 scenario family refers to a coming world characterized by a continuous population increase, albeit with a much smaller economic growth than for A1 scenarios. A2 scenarios are pessimistic in that they predict a steady increase of greenhouse gas emissions, particularly of carbon dioxide.

The B1 scenario family describes a future in which the population, as in A1 scenarios, reaches its peak by the mid 21st century, with an accelerated economic growth, but oriented to services and information technologies, with a decreased use of raw materials and with a sustainable use of resources, but still failing to take specific measures regarding the climate.

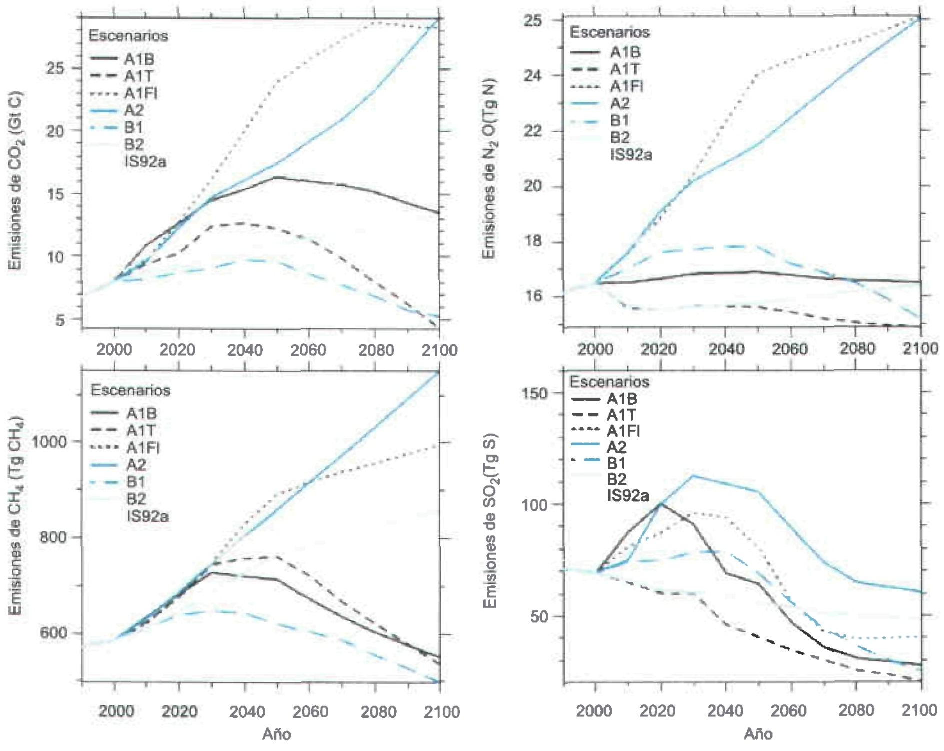
Lastly, the B2 scenario family depicts a future in which precautions were taken at the local and regional level to protect the environment and with a lower population growth than for A1 and B1 scenarios. This seems to be a very optimistic scenario, based on the observation of current tendencies so far.

None of these scenarios foresee full compliance with commitments established at the United Nations Framework Convention on Climate Change and in the Kyoto Protocol.

IPCCs 2001 reports did not take into consideration all scenario combinations, since these were not approved until 2000, so calculations and simulations were made for a reference scenario of each of the groups, A1B, A2, B1, and B2. Subsequently, in order to include possible favorable changes in technology, simulations with other two variations of the A1 family were made, identifying them as A1F I and A1T. In IPCC's 2007 report, as shall be seen further below, scenarios A1B and A2 were specially analyzed.

Figure 6 shows the foreseeable greenhouse gas emissions according to these climate change scenarios.

Figure 6. Future emissions of greenhouse gases, according to IPCC's SRES Scenarios. Scenario IS92a is also included for comparison purposes (IPCC 2001b).

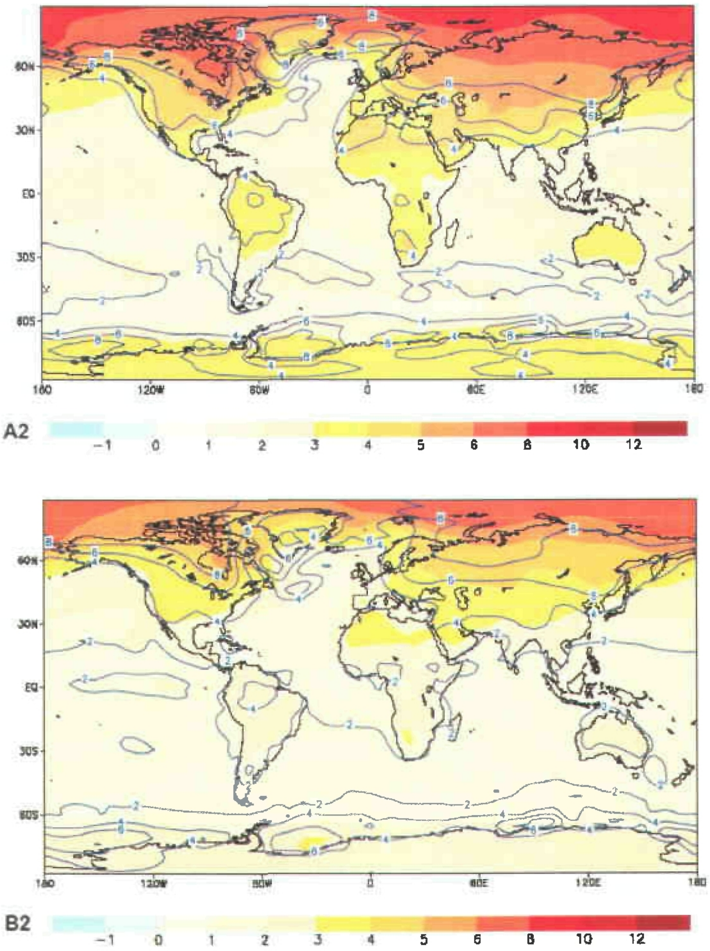


As can be seen, possible greenhouse gas emission variations are quite ample, going from situations where they will decrease below current values, such as in scenarios A1T and A1F I, to others where they will continue to increase significantly, as in scenario A2. Experts think that the probable mean temperature variation of the planet by the year 2100 will be between 1.5 and 4.5 °C, corresponding to a 100% increase in atmospheric CO_2 concentration. . The difference between both temperature extremes is due to the uncertainty in the simulation models, whose main cause is the effect that water vapor increase in the atmosphere will have as a result of global warming, and which in turn exacerbates it to anextent that is difficult to calculate.

According to IPCC's 2007 report, global temperature will increase, in scenario A1B, between 1.7 and 4.4 °C towards the end of the 21st century and between 2.0 and 5.4 °C in scenario A2 (IPCC 2007b).

Of course, the change in temperature will not be uniform; it will affect more severely those regions in higher latitudes, causing some places to experience heat well beyond the expected average. Figure 7 shows the temperature results obtained from the simulation with a general circulation model for scenarios A2 and B2.

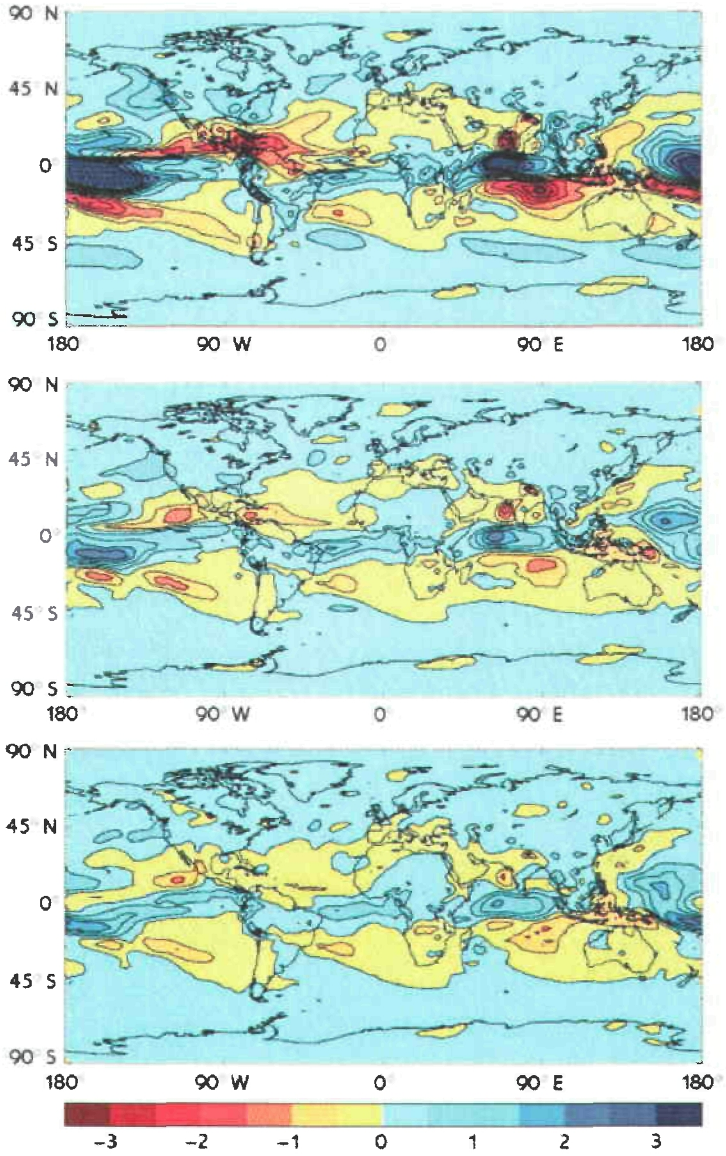
Figure 7. Changes in temperature foreseen according to scenarios A2 and B2. Temperature averages from 1970 to 1990 are compared to those estimated for 2070-2100, calculated with a general circulation model (IPCC, 2001b).



It is worth noting that in both cases, the temperatures foreseen for Mexico are higher than those recorded, in average, for the rest of the world. In the case of scenario B2, temperatures in Mexico would increase between 2 and 4 °C, and in the case of scenario A2, between 4 and 6 °C. These values would certainly have crucial effects on the hydrological behavior of most watersheds and on the different water uses.

With the results of temperature models, possible changes in precipitation can be calculated. In general terms, an increase in precipitation and in water vapor content in the atmosphere is foreseeable in high latitudes, while the opposite would be true for middle latitudes. In other words, at the regional level there will be increases in some areas and decreases in others. Therefore, it is necessary to conduct more detailed studies at

Figure 8. Changes towards 2080 in precipitation (in mm/day) for no mitigation scenarios (top) and with CO_2stabilization at 750 ppm (middle) and 550 ppm (bottom) (Met. Office, 1999).



Kyoto Protocol and United Nations Framework Convention on Climate Change

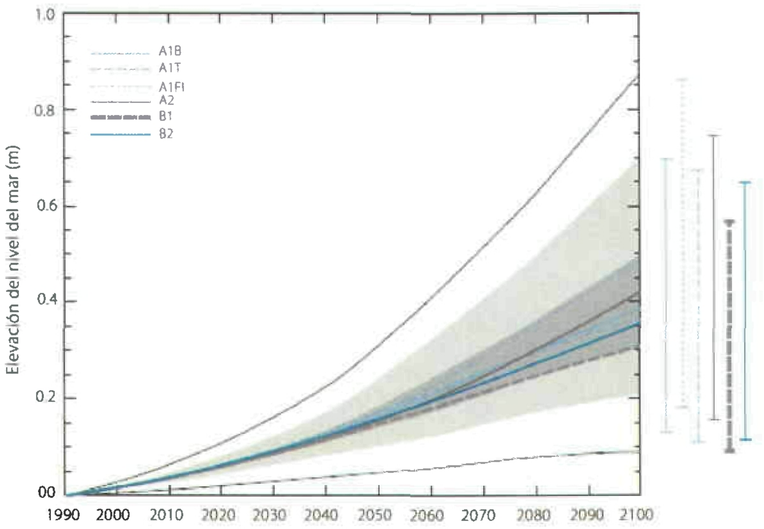
The 1997 Kyoto Protocol has the same objectives, principles, and institutions as the Framework Convention, but the latter is significantly strengthened by the former, since all parties—countries—commit themselves to achieving individual and legally binding objectives to limit or reduce their greenhouse gas emissions. Only those parties in the Convention that are also parties in the Protocol (i.e. those that ratify, accept, and adhere to it) will be bound to the commitments thereby established. The individual objectives for the parties are listed in the Kyoto Protocol. All in all they add up to at least a 5% greenhouse gas reduction compared to 1990 levels in the 2008-2012 commitment period.

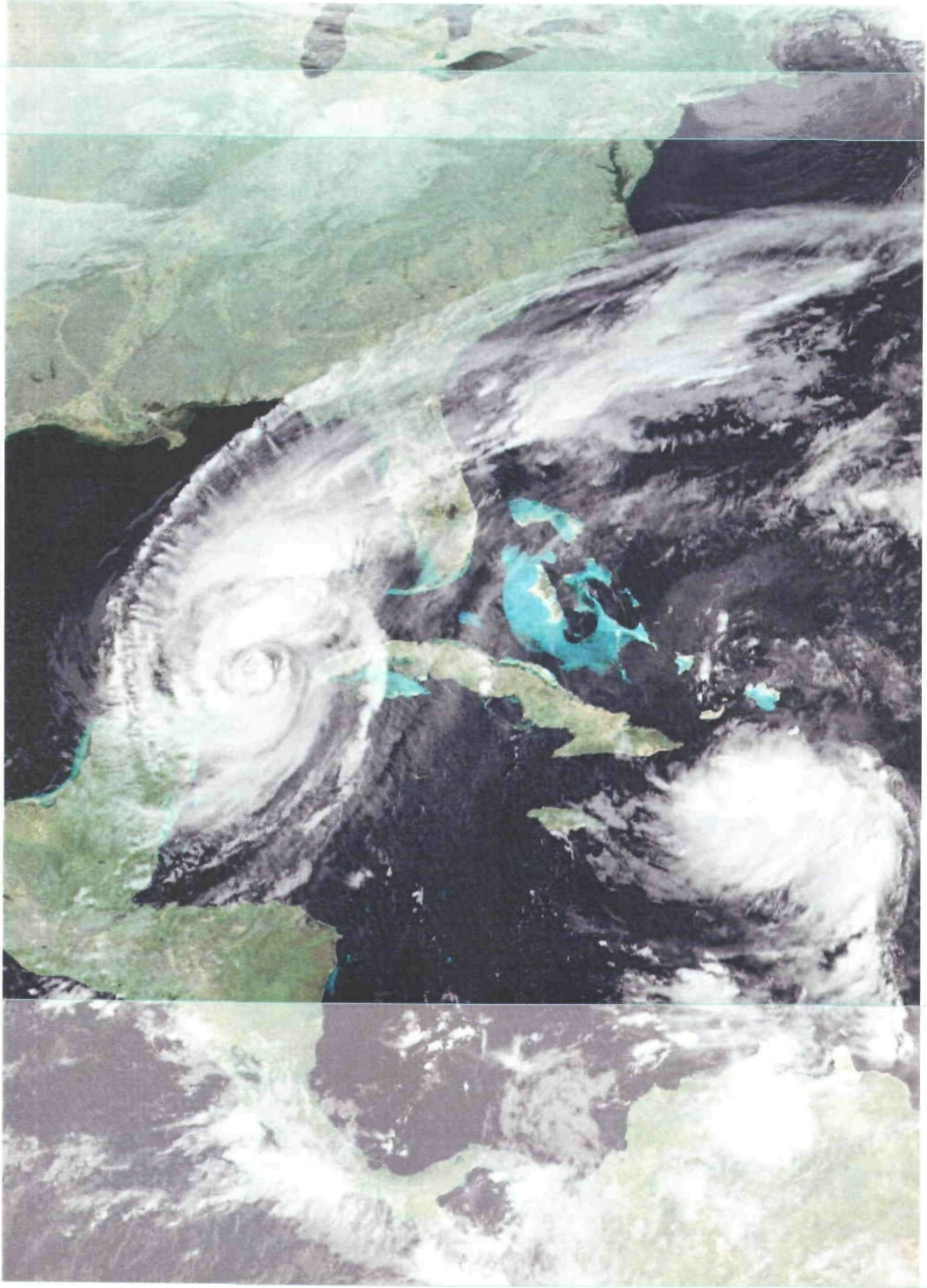
the regional scale. As shown in figure 8, (Met Office, 1999) expected changes are of a different magnitude, depending on the CO_2 stabilization levels reached in the future. This figure is also useful for demonstrating the difficulty of predicting the effects of global warming on precipitation in Mexico, since depending on CO_2 stabilization levels precipitation can decrease more in several regions within the country.

In the no-mitigation scenario, precipitation decreases of up to 3 mm/day would occur in some regions, while in CO_2 balance scenarios--unfortunately more unlikely--these decreases would be less significant. Since covering this topic is one of the main purposes of this book, it will be discussed to greater detail further below.

Another foreseeable effect of climate change affecting water resources and aquatic ecosystems in coastal areas will be sea level rise. According to IPCC's estimates--shown in figure 9--the level of the ocean will increase between 0.4 and 0.8 m over 1990's values, mainly due to thermal expansion.

Figure 9. Foreseen mean sea level rise between 1990 and 2100, according to IPCC estimations (2001b).





Effects of climate change on water resources

Since the inception of research on climate change, it was observed that the modification of the mean temperature of the planet would have serious impacts on the hydrological cycle, in as much as several of its main components, such as precipitation and evaporation, depend on it. These two variables, in turn, have effects on runoff, soil moisture content, and aquifer recharge.

Moreover, climate change will affect water demand, specially that of ecosystems and agriculture, which is currently the main water user in the world. Changes will also be observed in the water quality of rivers and, with greater intensity, of lakes, wetlands, and coastal ecosystems.

Since water is the source of life, it is to be expected that changes in the hydrological cycle will produce in turn significant modifications in ecosystems and health, the effects on which are beyond the scope of this book and are mentioned casually when they are directly associated with one of the expected impacts on water resources.

It should be mentioned at this point that the magnitude of these changes at the regional scale is still under debate due to the lack of data and properly calibrated models.

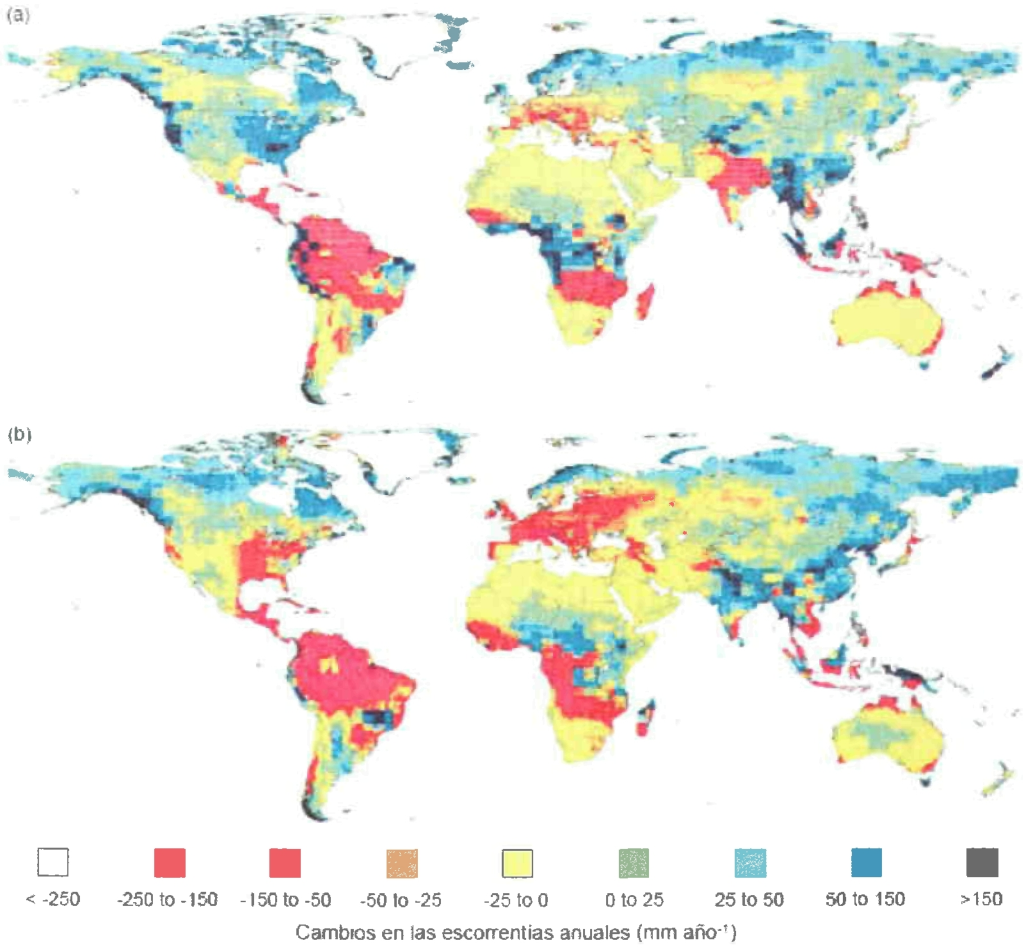
It is also necessary to note, before going into details, that water resources are already subject to enormous pressure due to population growth; to a social and economic development with increasing demands, specially in the industrial and service sectors; and to changes in land use and catchment areas caused mainly by deforestation and erosion. Coupled to these effects is the institutional incapacity in vast areas of the planet to attain a reasonable water resources governance. Due to all this, the probable effects of climate change will be yet another factor that will hinder--

in many cases permanently--the sustainable use of water.

The first effect of global warming in a hydrological variable has already been mentioned: the estimated changes in precipitation shown in figure 8. These results are obtained from general circulation models that lack the necessary resolution for obtaining conclusions in specific watersheds, but that do allow to estimate general tendencies in a qualitative way. Thus, although tendencies vary in different regions of the world, one could say that, in general, an increase in precipitations is expected in high altitudes within the northern hemisphere and decreased precipitations in middle latitudes and tropical and subtropical zones. It should be stressed once again that there is a great difference in the values expected between a scenario with no mitigation measures and those in which the increase of greenhouse gases is restricted.

As a consequence of variations in precipitation, together with changes in temperature, soil moisture, and evaporation, significant modifications in runoff are expected. Figure 10 shows the alterations in runoff foreseen for the year 2050, in contrast to those observed in the 1961-1990 period, estimated in a scenario of an annual CO_2

Figure 10. Effects of climate change in runoff, in mm/year. Changes projected to the year 2050, compared to mean values recorded between 1961 and 1990 (IPCC, 2001c).



increase of 1%, which is lower than the current increase rate. Although the connection is not strictly linear, changes in runoff are expected to be similar to those foreseen for precipitation. Increases in runoff are then expected to occur in high altitudes and in the region of the Indian subcontinent and Indochina. In North America, general decreases of a lesser magnitude are predicted in the central continental region, and of more relevance in the Mississippi watershed, in southern Mexico, and in Central America.

Also worth noting is the drastically reduced runoff expected in the northern region of the South American subcontinent, as well as in practically all of Europe.

These reductions will of course be of greater or lesser relevance depending on the condition of each of the watersheds, some of which already show clear signs of scarcity. The capacity of countries and institutions for facing these reductions through adaptation actions will be very important, for instance by controlling water supply and demand.

Figure 10 reproduces Arnell's calculations (1999), quoted by the IPCC, obtained by using a macro-scale hydrological model with a spatial resolution of 0.5 x 0.5°, which does not reproduce adequately the complex physiography of watersheds. In this regard, the IPCC has recommended since its second report that watershed-scale modeling efforts be made in order to reduce the uncertainty introduced by calculations based on the scale used by global circulation models. No such studies have been performed yet in Mexico.

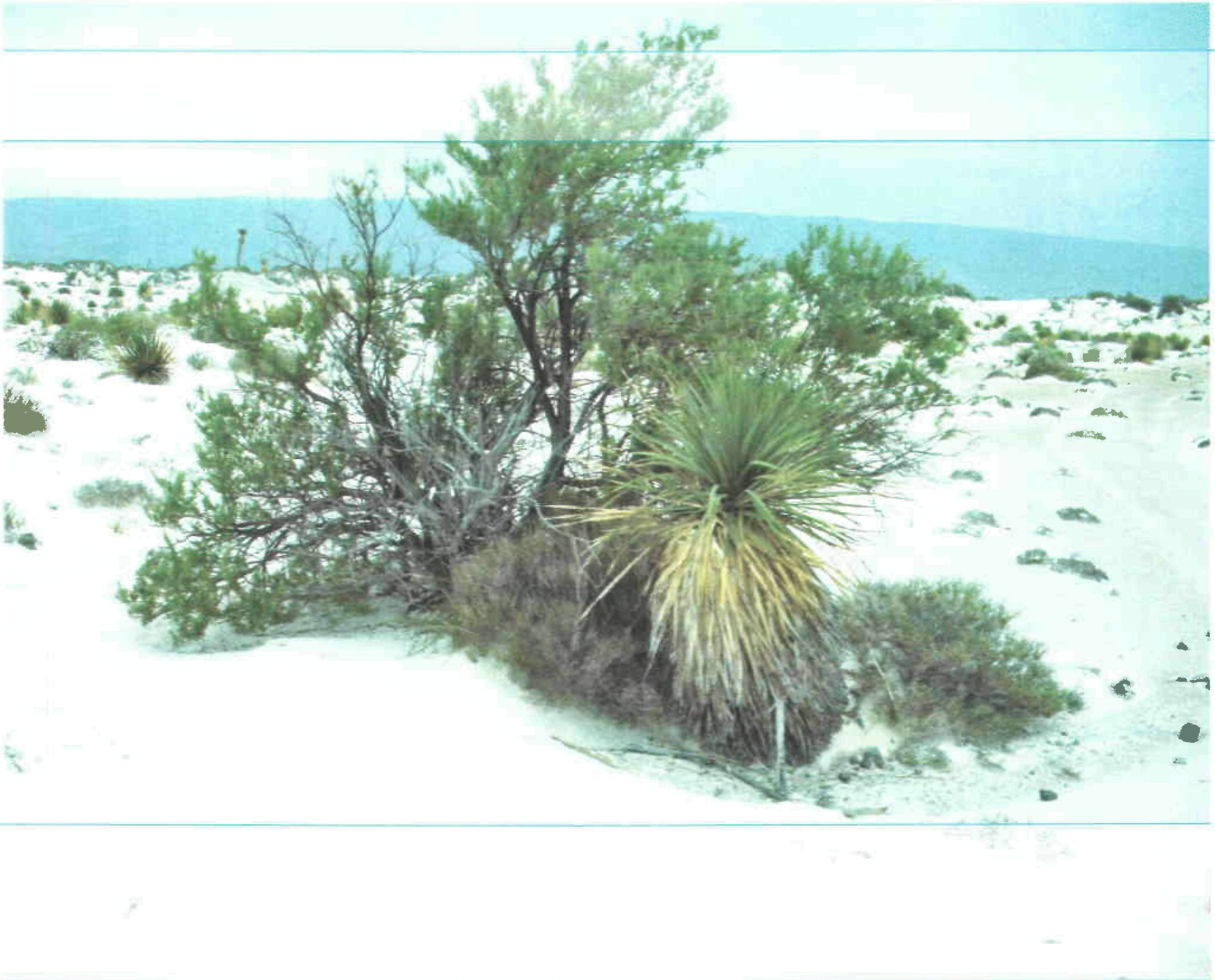
Due to the inherent difficulties of rainfall-runoff process modeling and to the cost of calibration of these models, very few studies have been conducted in specific watersheds. Chapter 4 of the Impacts and Adaptation Report of the Intergovernmental Panel on Climate Change (IPCC, 2001: pages 203-204), presents a summary table of the impact studies performed in the watersheds of some of the most important rivers of the world. It should be noted that there are virtually no documents of this type for Latin America.

Another variable of the hydrological cycle that will be affected by climate change is evaporation, which includes the one produced in the soil, that which originates in lakes, or that which is produced by vegetation. It is accepted that evaporation depends, among other factors, on temperature; therefore, if the latter increases, so will the former. Nevertheless, the magnitude of these changes will depend also on other variables, such as the plant cover, the wind, the albedo, and air moisture content; except in arid zones, where these conditions barely affect evaporation.

Soil moisture content will also be significantly influenced by climate change. In general, it will diminish with an increased ambient temperature, but the precise magnitude of this phenomenon depends on other variables, mainly the type of soil and plant cover. A decreased moisture content is particularly important in arid or semiarid regions, since the lesser the soil moisture, the lesser the capacity of the watershed to convert rainfall into runoff. In other words, less effective rainfall volume and less amount of water available in streams and aquifers. Finally, aquifer recharge, on which the water supply of almost all cities in Mexico depends, will change following much the same pattern of precipitation, though in greater or lesser magnitude according to its type (more or less torrential); of soil moisture; and on plant cover.

Evidently, changes in precipitation will not be perceivable only in mean annual volumes, but also in seasonal patterns: there will be variations in torrential runoffs or floods, as well as in the frequency and intensity of droughts. Available models foresee more storms and torrential rains in some regions, droughts in others, and, in general, a greater climate variability (*US National Assessment*, 2003).

While it is possible that floods and inundations will increase in frequency in some regions of the world, the effects per watershed cannot be determined yet in quantitative terms. Nevertheless, nature itself seems to agree with the models that predict increased storms and floods. Suffice it to quote the number of high-intensity hurricanes that hit the North Atlantic in 2004, or moreover, to mention the first occurrence in history of a hurricane in the South Atlantic, which stroke the coasts of Brazil in march of that same year. [1]. Scientists of the US National Oceanic and Atmospheric Administration (NOAA) have found evidence of the ongoing intensification of the hydrological cycle, which will foreseeably continue with global warming. However, these conclusions cannot be considered to be definite as yet, since the number of records analyzed so far is still small (Easterling *et al*, 2000).



Hydrological droughts are expected to increase in regions where mean precipitation is likely to decrease. Simulation results indicate that there will be changes in the frequency, intensity, and duration of extreme phenomena. Models project, for example, an increase of hot days, heat waves, and heavy precipitations, as well as a decrease of cold days and frosts. According to IPCC's Report for Policymakers (2001c), "many of these projected changes would lead to increased risks of floods and droughts in many regions, and predominantly adverse impacts on ecological systems, socio-economic sectors, and human health".

Figure 11 is a reproduction of IPCC's summary table, where the main effects of extreme events are shown. It can be seen that among the very likely events, understood as those with a 90 to 99% probability of occurrence, in the case of global warming, are intense precipitations. Among likely events, i.e. those with a 66 to 90% chance of occurring, increased summer drying in midlatitudes (where Mexico is located) is projected, with the risk of more frequent and intense droughts. Moreover, the destructive power of tropical cyclones would increase, though not their number.

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1 Until now, the occurrence of a hurricane in the southern hemisphere was deemed virtually impossible.

Figure 11. Effects of the global change in extreme events and their probability (IPCC, 2001d).

Projected Changes during the 21st Century in Climate Phenomena	**Representative Examples of Projected Impacts[b] (all high confidence of occurrence in some areas)[a])**
Simple extreme events	
Higher maximum temperatures; more hot days and heat waves over nearly all land areas (very likely)[a])	• Increased incidence of death and serious illness in older age groups and urban poor. • Increased heat stress in livestock and wildlife. • Shift in tourist destinations. • Increased risk of damage to a number of crops. • Increased electric cooling demand and reduced energy supply reliability.
Higher (increasing) minimum temperatures; fewer cold days, frost days and cold waves[d]over nearly all land areas (*very likely*) [a])	• Decreased cold-related human morbidity and mortality. • Decreased risk of damage to a number of crops, and increased risk to others. • Extended range and activity of some pest and disease vectors. • Reduced heating energy demand.
More intense precipitation events ((*very likely*[a], *over many areas*))	• Increased flood, landslide, avalanche, and mudslide damage. • Increased soil erosion. • Increased flood runoff could increase recharge of some floodplain aquifers. • Increased pressure on government and private flood insurance systems and disaster relief.
Complex extreme events	
Increased summer drying over most midlatitude continental interiors and associated risk of drought (*likely*)[a])	• Decreased crop yields. • Increased damage to building foundations caused by ground shrinkage. • Decreased water resource quantity and quality. • Increased risk of forest fire.
Increase in tropical cyclone peak wind intensities in case of tropical cyclones, and in mean and peak precipitation intensities (*likely* [a]*over some areas*))[e]	• Increased risks to human life, risk of infectious disease epidemics and many other risks. • Increased coastal erosion and damage to coastal buildings and infrastructure. • Increased damage to coastal ecosystems such as coral reefs and mangroves.
Intensified droughts and floods associated with El Niño events in many different regions (*likely* [a]) (see also under droughts and intense precipitation events)	• Decreased agricultural and rangeland productivity in drought- and flood-prone regions. • Decreased hydro-power potential in drought-prone regions.
Increased Asian summer monsoon precipitation variability (*likely* [a])	• Increase in flood and drought magnitude and damages in temperate and tropical Asia.
Increased intensity of mid-latitude storms (little agreement between current models) [d]	• Increased risks to human life and health. • Increased property and infrastructure losses. • Increased damage to coastal ecosystems

a The term *likely* refers to a judgmental estimate of confidence used in the WGI TAR: very likely (90% chance); likely (66-90% chance). Unless otherwise stated, information on climatic phenomena is taken from the WGI TAR Summary for Policymakers.

b These impacts can be lessened by applying appropriate response measures.

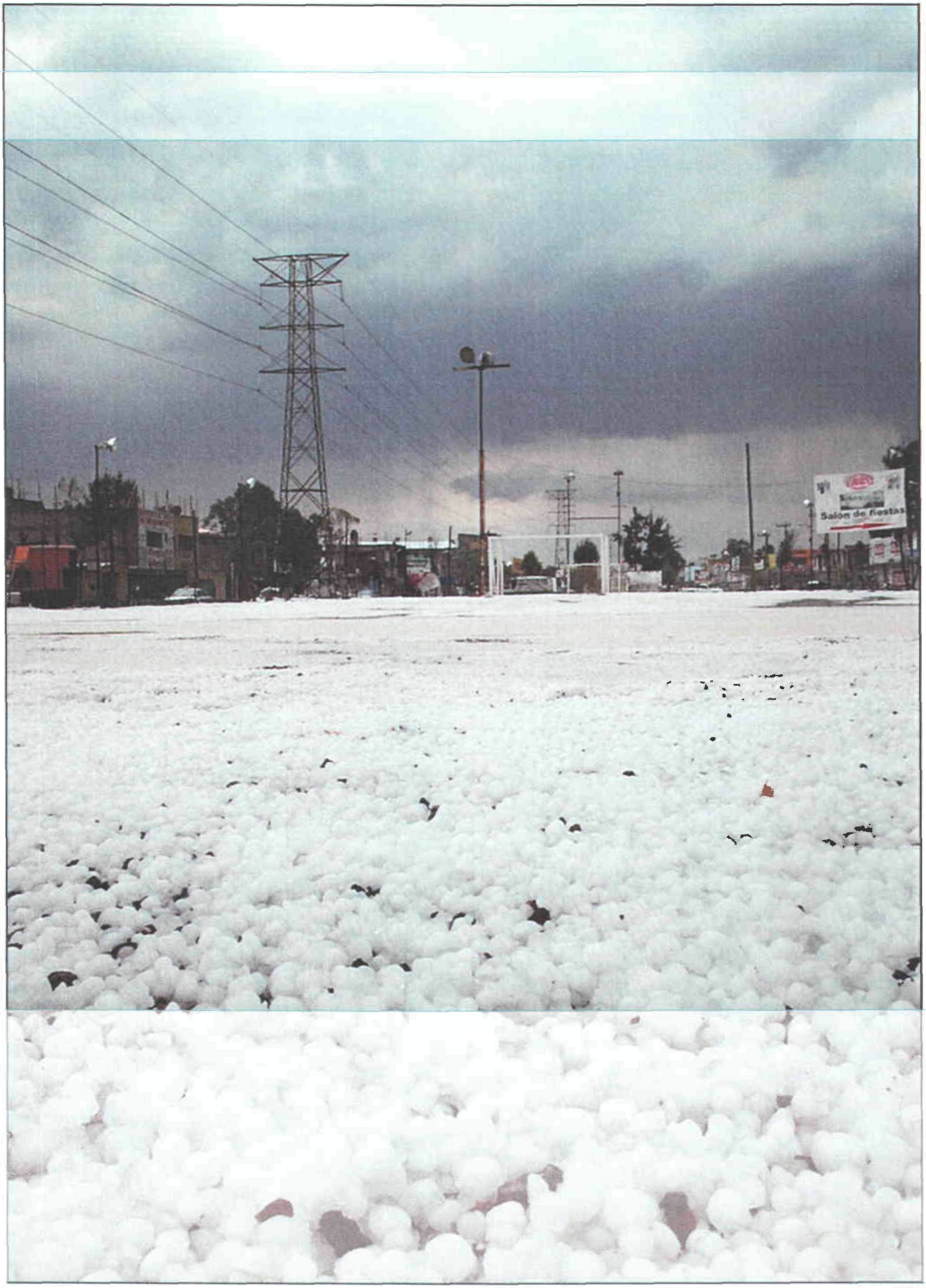
c Based on information from chapters of this report; high *confidence* refers to 67-95% chances, as described in note 6 of the WGI TAR Summary for Policymakers.

d Information from WGI TAR Technical Summary (Section F.5).

e Changes in regional distribution of tropical cyclones are possible but have not been established.

In addition to the effects on water availability, important impacts on its quality are also projected. Firstly, those caused by decreased runoffs and secondly, those caused by increased temperature, which reduces the oxygen retention capacity of water bodies. A smaller amount of oxygen dissolved in water bodies translates into a greater eutrophication, which is already a problem, due to the excess of nutrients poured into most lakes and rivers of the planet as a result of human activities. Water quality would also diminish due to a greater consumption of oxygen by plants induced by a higher ambient temperature.

One of the main and most visible effects of global warming, already observed in different regions, will be a reduced snowpack in several parts of the planet, specially in the glaciers. At first glance, this would not affect Mexico; however, several of the transboundary flows that reach our country from American watersheds come from this source of runoff. In particular, the Colorado River, from which the economy of the state of Baja California depends, originates in the Rocky Mountains in the United States, whose snowpacks have been decreasing in the last few decades.

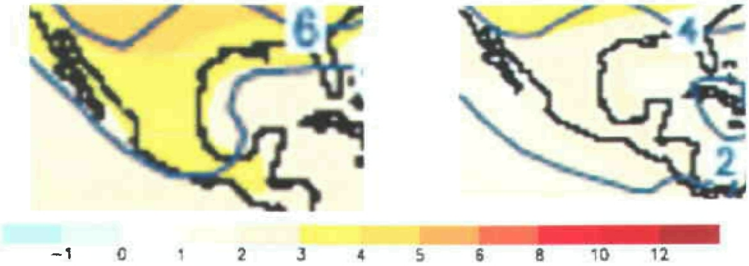

Salón de fiestas

Effects on Mexico's water resources

A first approach to analyzing the effects of global warming on Mexico's water resources is to observe the results of the Global Change Models (GCMs), particularly those published by the Intergovernmental Panel on Climate Change.

According to these results, significant temperature rises are projected to occur in Mexico during the present century. Thus, in scenario A2 (high), increases between 4 and 6 °C are projected, while in scenario B2 (medium) increases between 2 and 4 °C are expected. This is shown in figure 12, obtained with an amplification of the results of figure 7, to show the limited resolution of global scale models for simulating regional effects. In both scenarios, these temperature rises are high enough to cause

Figure 12. Temperature changes in Mexico, in °C. Amplification of the results of figure 7, foreseen according to scenarios A2 (left) and B2 (right). Temperature averages from 1970 to 1990 are compared to those estimated for 2070-2100, calculated with a general circulation model (IPCC, 2001b).



severe effects on runoff and on the water consumption of crops and ecosystems. If, in addition, we see that the greatest alterations will occur in the northern region, where irrigation agriculture is practiced exclusively, we can anticipate the seriousness of the effects of global warming in Mexico. As mentioned previously, a shortcoming of these models is the low resolution of results, which precludes a more detailed regional analysis. Higher resolution results will be presented further below.

Scenarios A2 and B2 have been built taking into account certain economic, demographic and technological trends that can be considered more ore less likely. Another approach for building future scenarios is to foresee that there will be some extent of mitigation in the emission of greenhouse gases, without taking into consideration the social conditions that will bring it about. This way, a stabilization level in CO_2 concentration is established, and the expected changes in climatic variables are calculated by using global circulation models in different time horizons.

Figure 12a shows the most recent estimates for North America published by the IPCC. As can be seen, with higher resolution, mean temperatures for scenario A1B in Mexico would increase between 3.5 and 4 °C in the northern region by the late 21st century. The extreme values recorded in the summer would be greater.

According to results of the Met Office (Met Office, 1999), reproduced in figure 13, in the case of a non-mitigation scenario, the expected temperature rise in Mexico would be between 5 and 6 °C. In the case of adopting some mitigation measures that would stabilize atmospheric CO_2 to 750 ppm (approximately twofold the value recorded in 1990), in the year 2080 the temperature in Mexico would rise by 4 °C, which is consistent with recent IPCC's predictions. Finally, if the content of atmospheric CO_2 were to stabilize in 550 ppm, which seems to be overoptimistic, the temperature in Mexico would rise between 2 and 3 °C in the northern region and between 1 and 2 °C in the south central region.

Figure 12a. Estimated temperature increases in the United States of America for the 2080-2099 period, compared to the 1980-1999 period. Annual average (left), winter (center) and summer (right) (IPCC 2007a).

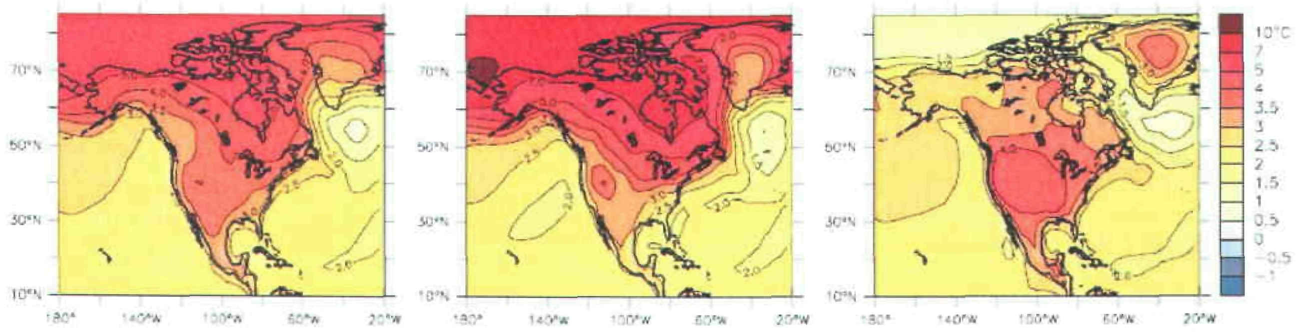
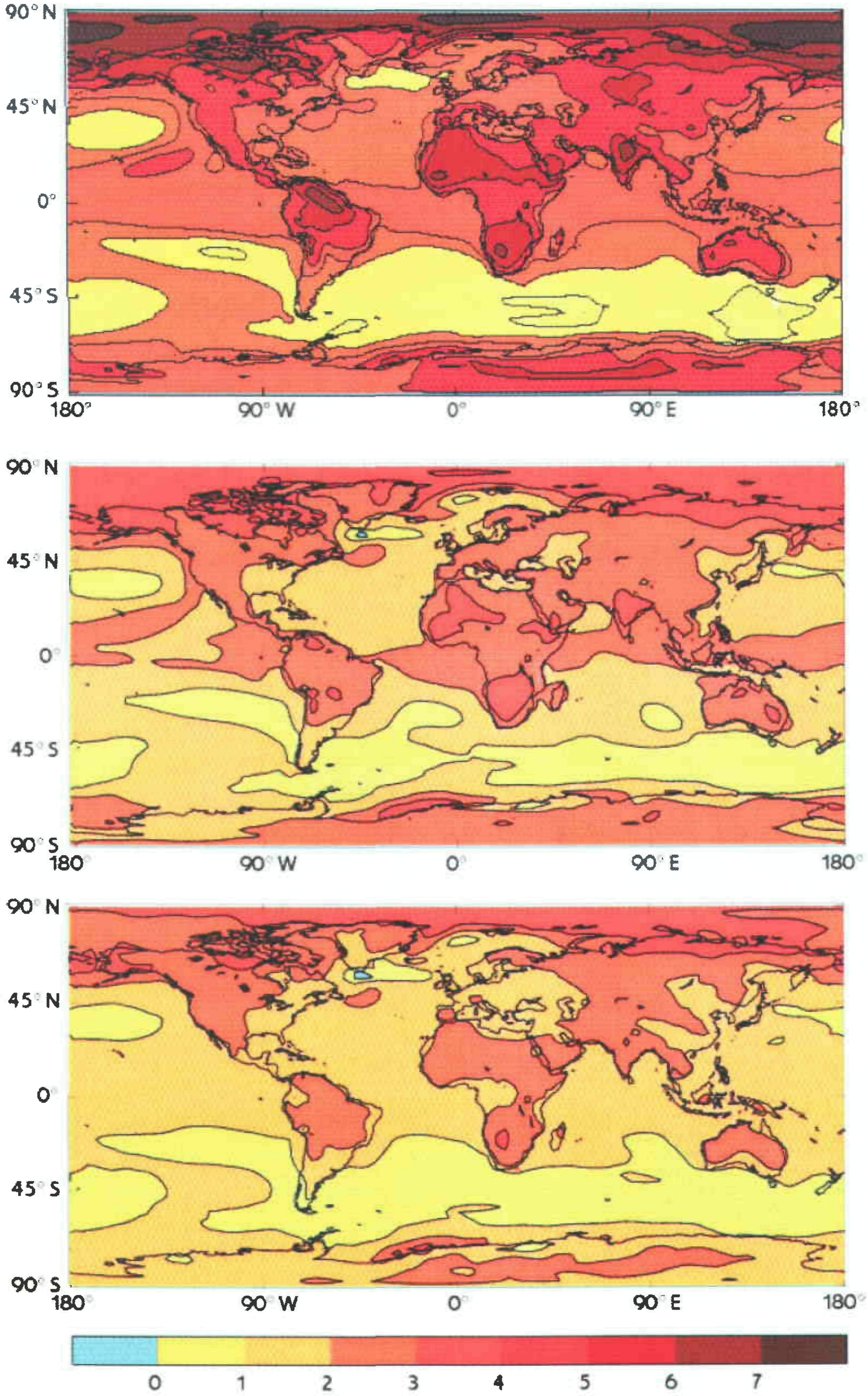


Figure 13. Foreseen temperature increases, in °C, towards the year 2080, as a result of no mitigation scenarios (top), with CO_2 stabilization to 750 ppm (middle) and to 550 ppm (bottom), (Met Office, 1999).



The Met Office projects, as shown in figure 8, that whatever the scenario, a more or less severe precipitation reduction is to be expected in Mexico. According to the non-mitigation diagnosis, then, precipitation can decrease by up to 3 mm/day in the south, while the most favorable vision, with a stabilization of atmospheric CO_2 to 550 ppm predicts a practically uniform decrease in precipitation of about one millimeter per day.

Figure 13a reproduces the most recent IPCC estimates for North America in a A1B scenario. It can be observed that precipitation in Mexico will decrease by 10 and 15% in the North and Northwest, respectively, where the main and largest irrigation districts of our country are located.

A decreased precipitation will surely have very different effects in the Southeast, where natural availability is higher than in the North, a region markedly characterized as dry and with no availability.

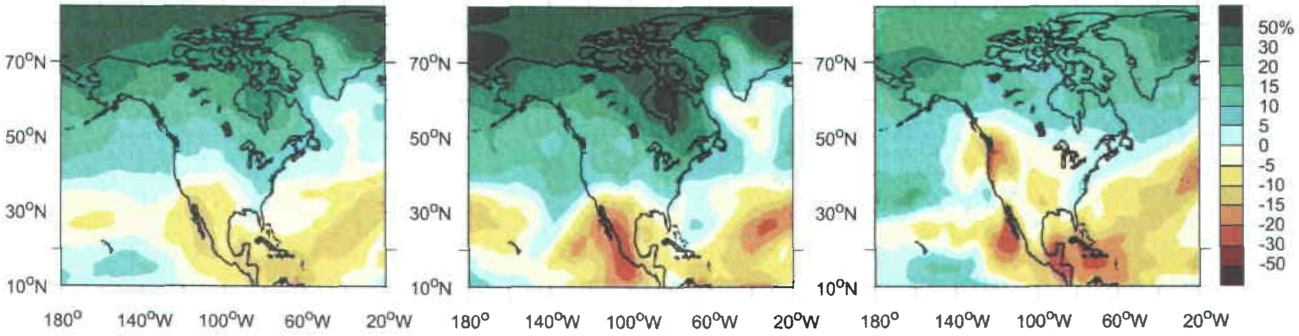
There is an evident need for more accurate results than those obtained from typical simulations with general circulation models. It is not only a problem of calculation mesh size, but also of incorporating meso-scale situations, i.e. local atmospheric phenomena.

At CONAGUA's request, Morales *et al* (2001) carried out a regional, more detailed study on precipitation and temperature changes in Mexico. With this purpose, they scaled up the results of a global circulation model.

Morales *et al* (2001) ran several experiments with GCMs and selected the German Climate Center Research, European Center/Hamburg Model #4, known as ECHAM4, as the most appropriate, since it showed the lowest standard deviation from all the models tested with historical data.

Once the GCM has been selected, the scaling up process is performed, which in broad terms consists in finding a linear multivariate regression between the parameter to be modeled and the large-scale variables from the ECHAM4 model from which it depends. Two regression equations were established in this study: one for temperature and one for precipitation. This procedure requires establishing the main

Figure 13^{a}. Estimated precipitation changes in the United States of America for the 2080-2099 period compared to the 1980-1999 period. Annual average (left), winter (middle), and summer (right) (IPCC 2007a).



variables that govern the phenomenon. In this case, only the large-scale surface temperature variable from the ECHAM4 model corresponding to the simulation of the years 1961-1990 was used, which reduces the accuracy or the results.

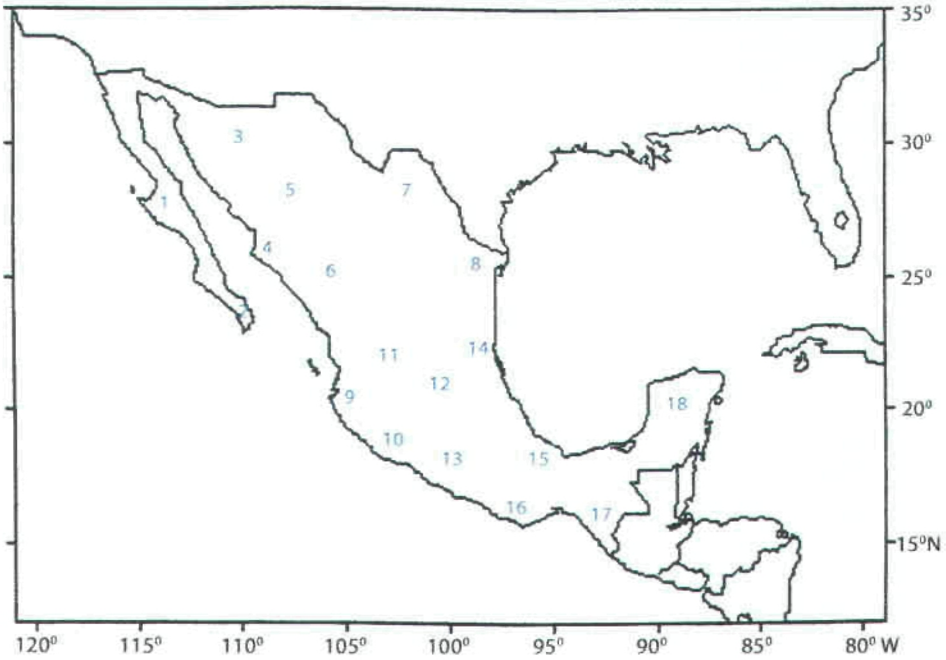
In their calculations, Morales *et al* (2001) used the 18 climate regions (shown in figure 14) proposed by Douglas (1966). Figures 15 to 18 show the results of the scaling up of the ECHAM4 model developed by these authors.

The temperature increases projected for the summer (figure 16) are qualitatively consistent with previously shown GCM calculations. Nevertheless, they are even greater, reaching values between 4 and 6 °C in the northwestern region and in the Chiapas-Tabasco zone and between 2 and 4 °C in the central region of Mexico, in the north of Sonora, and in the south of the Yucatán peninsula. In the coasts of this region and in those of the Northwest, the temperature changes are lower. Evidently, if the increases foreseen for the arid regions of the North were to take place, maximum daily temperatures during the summer would reach very high levels, causing severe effects on water resources and human health.

Calculated winter temperature increases (figure 15) are more evenly distributed and are in general much lower than summer values. The case of the Baja California Peninsula is of note, where lower winter temperatures are projected.

The results of the Morales *et al* (2001) scaled-up model for precipitation, as would be expected due to the difference in resolution and the methodology used, are not completely consistent with other GCM models previously presented . These models predict generalized precipitation decreases.

Figure 14. Climate regions proposed by Douglas.



Thus, as shown in figures 17 and 18, precipitation increases are projected for virtually all the Mexican territory in summer and winter: ranging from 80 to 100% in the northwestern north-central part and from 60 to 80% in the Baja California Peninsula. These are modifications on very low absolute precipitation values, since the rainy season in Mexico occurs mainly during the summer.

There would be an increase in summer precipitation of 20-40% in the central and northeastern regions, as well as in Chiapas, Tabasco, and Yucatán, with a slight decrease of about 10% in the central-eastern region, which seems to coincide with the Huasteca. Precipitation decreases of 20% are foreseen in the northeastern region, and up to 40% in the northwestern coast and in the Baja California peninsula.

An alternative approach to scaling up with linear regression is that used with GCM simulation but with a much smaller mesh size. With this method, Hulme and Sheard performed a modeling--quite useful for the purposes of this book--of a sub-region that was called Mesoamerica (Hulme, M. and Sheard, N.,1999). It is worth clarifying here that the study zone, which in this case covered all of the Mexican territory, Central America and the Caribbean, does not correspond to the Mezoamerica where the most important pre-Hispanic civilizations flourished, which covered the central and southeastern region of Mexico and the northern region of Central America. The results of this study have been published by the Climatic Research Unit (CRU) of the University of East Anglia Norwich in the United Kingdom.

Hulme and Sheard (1999) present the results of the average of simulations with ten GCM models using a more refined mesh; therefore, their data are more reliable in

Figure 15. Winter temperature changes (in °C), 2070-2099 (Morales *et al* , 2001).

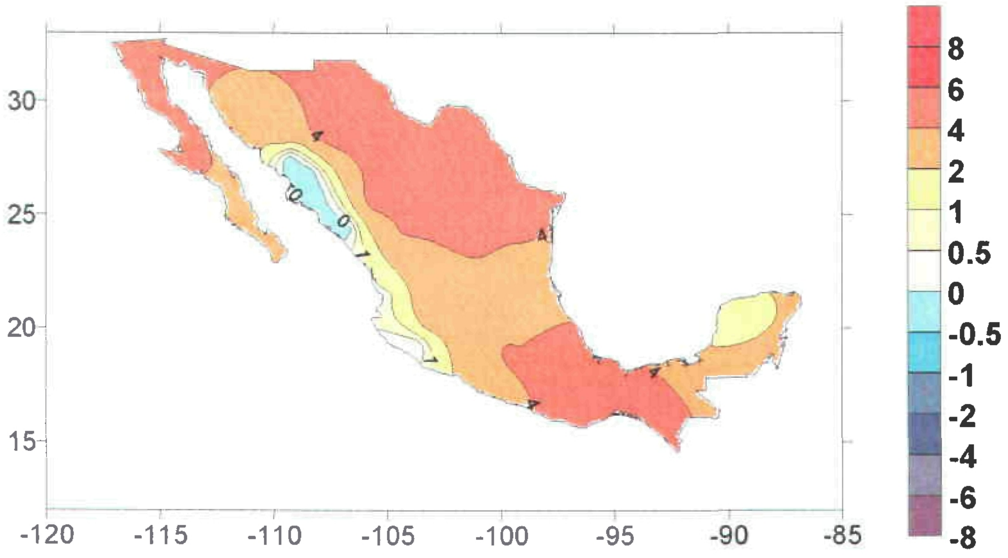
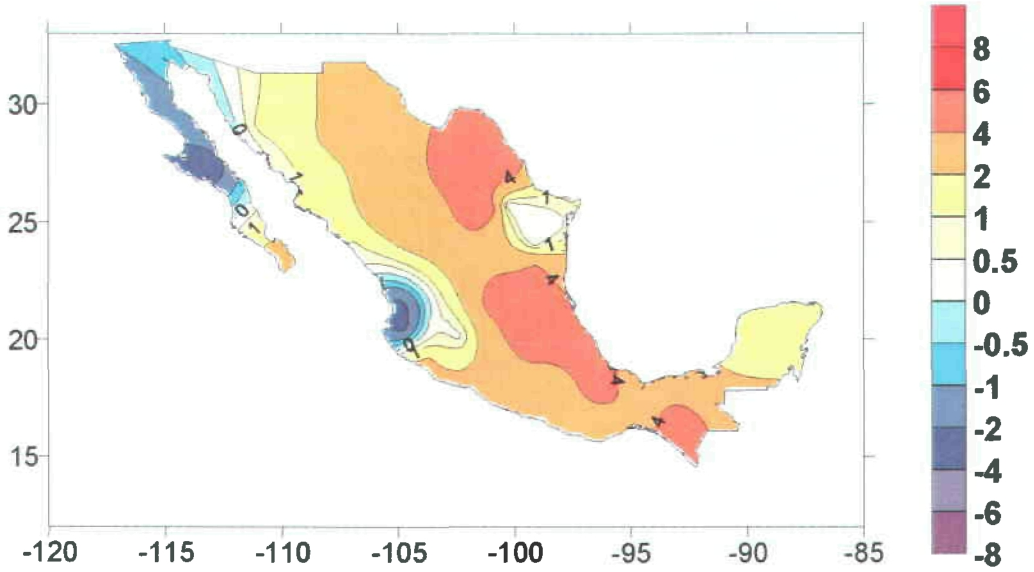


Figure 16. Summer temperature changes (in °C), 2070, 2099 (Morales *et al*, 2001.



the sense of producing one of the best assessments possible with currently available tools. This regional study presents, foremost, the anomalies observed in the temperature (1901-1998) and the precipitation (1901-1996) with respect to mean temperature and precipitation values: 22.1 °C and 1,215 mm annually, respectively.

Figure 17. Percent precipitation change in the winter, 2070-2099
(Morales *et al*, 2001).

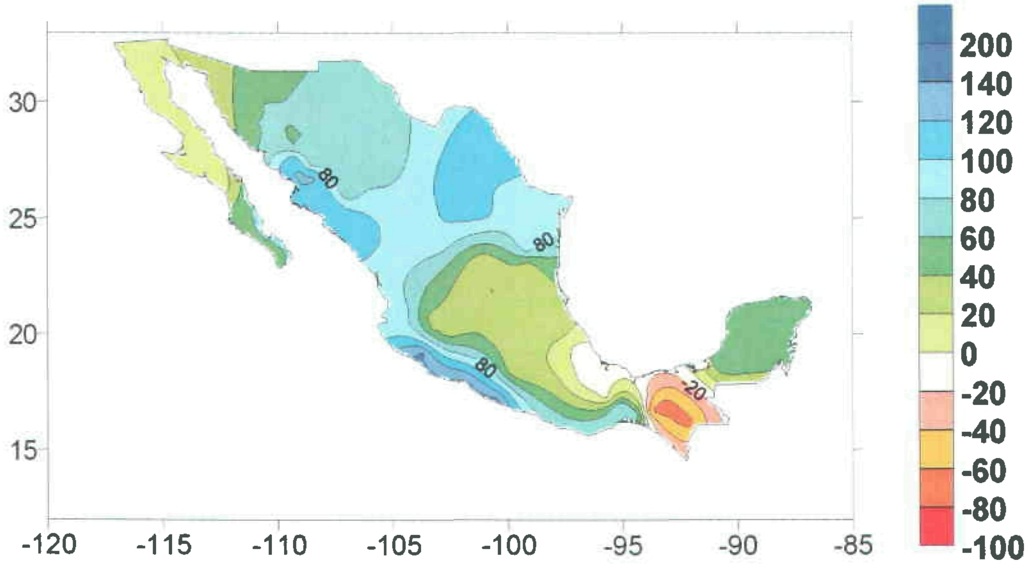


Figure 18. Percent precipitation change in the summer, 2070-2099 (Morales *et al*, 2001).

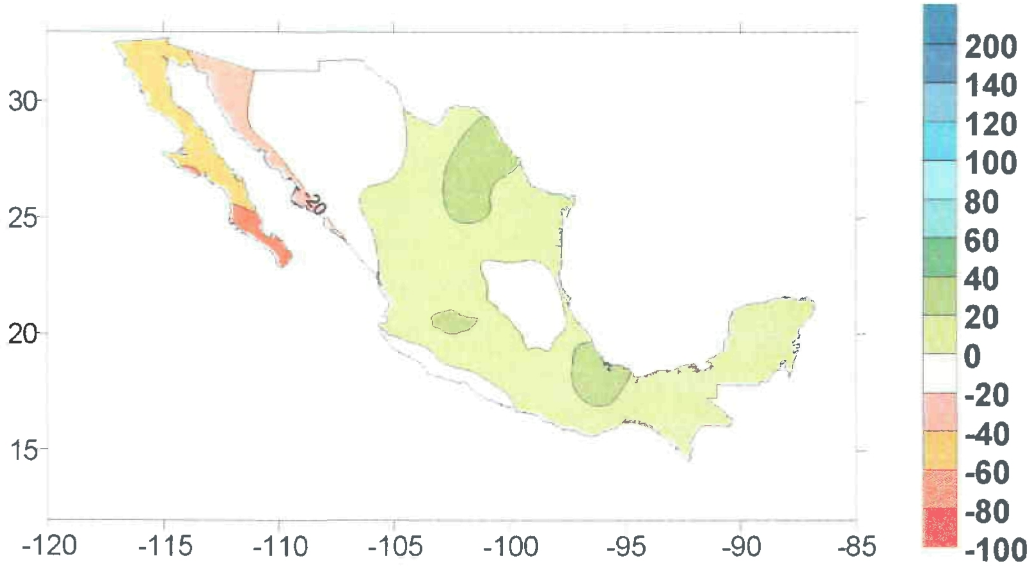


Figure 19. Anomaly observed with respect to mean annual temperature (22.1 °C, top) and mean annual precipitation average (bottom) in Mesoamerica, (Hulme, M. and Sheard, N., 1999),

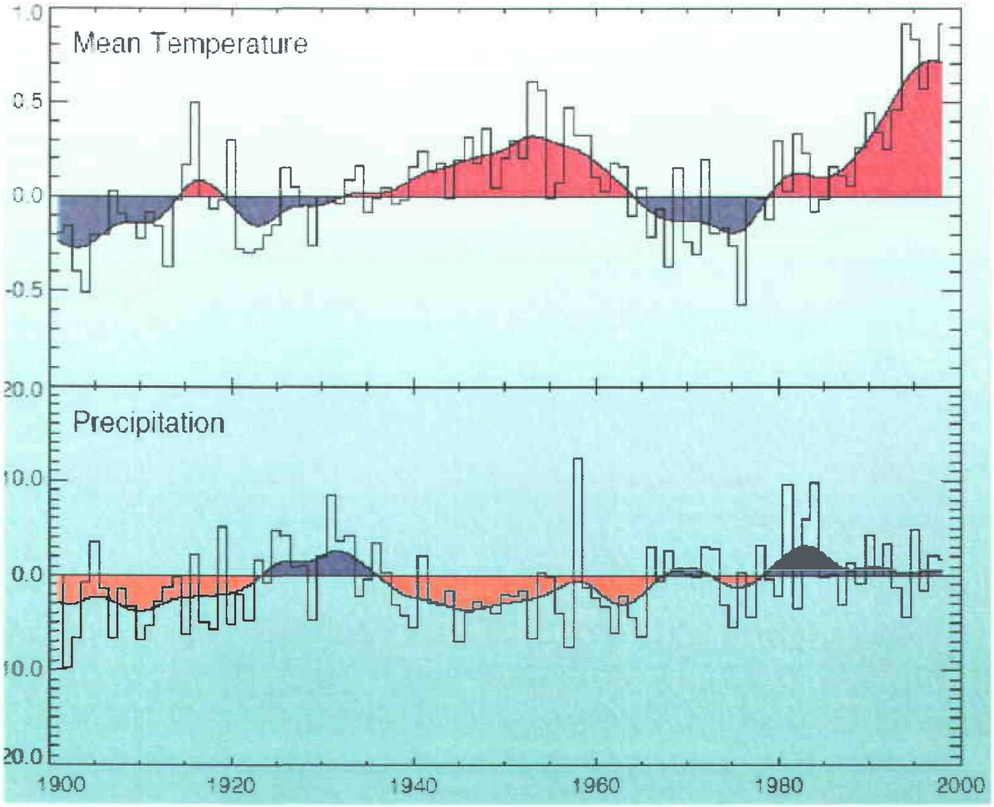


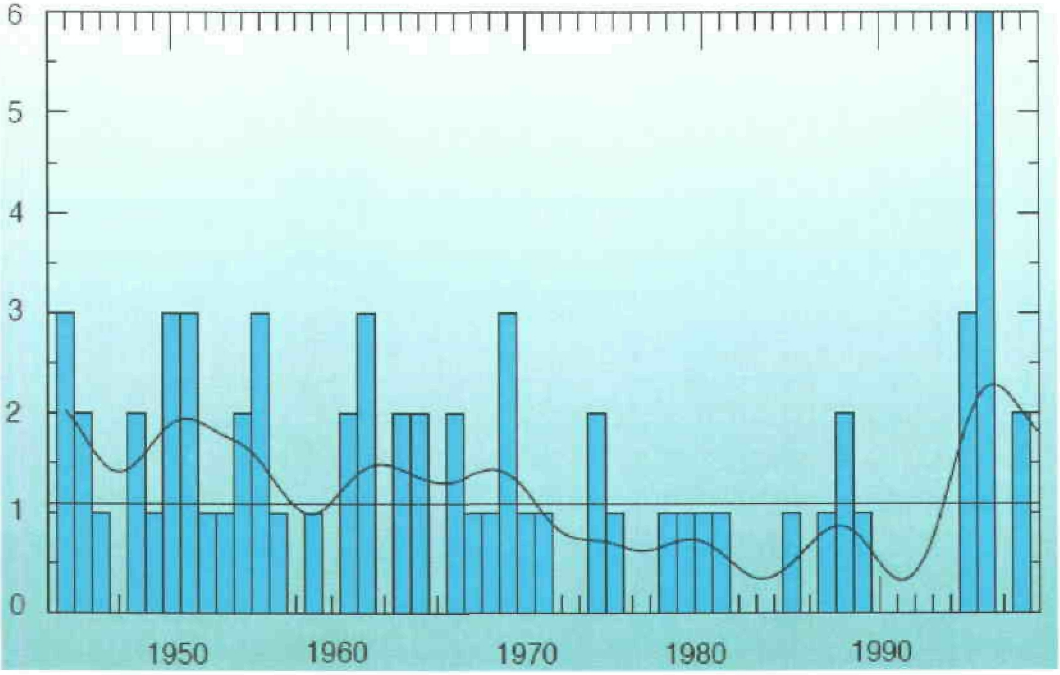
Figure 19 shows the variations in temperature and precipitation observed according to the mean values of the region, 22.1 °C and 1,215 mm, respectively, in a period of time covering the 20th century. It can be observed that the temperature has already risen almost 1 °C compared to that of 1901, which is greater than the world average of 0.6 °C for the same period. Precipitation, in contrast, has only increased slightly, specially in the summer, the main rainy season in the region.

Of special note, as can be seen in figure 20, is the increase in the number of hurricanes recorded in the zone every season, which was an average of 1.1 in the early 20th century, and which has increased significantly during the last few years, with the well-known disastrous consequences in Central America and the Caribbean.

In order to analyze the effects of global warming on Mesoamerica, Hulme and Sheard made projections of the climate for the year 2100 using ten general circulation models in seven climate laboratories located in six countries.

These simulations used four climate scenarios, which are consistent with those proposed in the IPCC Special Report on Emission Scenarios (SRES) (2001). The scenarios belonging to families A and B were chosen: B1, B2, A1, and A2. A summary of their characteristics can be consulted in table 2. As can be seen in these scenarios, it is be-

Figure 20. Annual hurricane frequency in the Caribbean Sea, 1944-1998 (Hulme, M. and Sheard, N., 1999).



lieved that atmospheric CO_2 concentration for the year 2080, taking the B1 scenario into consideration, will increase its valued of 370 ppm to a concentration close to 550 ppm, and for the year 2100, taking into account the A2 scenario, will increase to over 830 ppm. The concentrations of other greenhouse gases would also increase.

The effect of increased greenhouse gas concentrations on global climate change depends to a large extent on the sensitivity of the Earth's climate to these increased concentrations. Three different values were chosen for climatic sensitivity: low (1.5 °C), medium (2.5 °C), and high (4.5 °C). By combining the three climatic sensitivities with the four SRES scenarios, the variations in the global climate change curves were calculated (Figure 3.5) that very likely comprise approximately 90% of the possible fluctuations of future climates. These vary from B1-low (the scenario with less emissions combined with that of the lowest sensitivity) to A2-high (the scenario with higher emissions combined with the

Table 2. Summary of changes in the global environment by the 2020s, 2050s and 2080s for the four scenarios. Changes are calculated with respect to the 1961-90 average (Hulme and Sheard, 1999).

1980*	1990*		2020			2050			2080		
Temp. °C	Temp. °C		CO_2 ppm	Temp. °C	Sea level (cm)	CO_2 ppm	Temp. °C	Sea level (cm)	CO_2 ppm	Temp. °C	Sea level (cm)
0.13	0.28	B1-low	421	0.6	7	479	0.9	13	532	1.2	19
0.13	0.28	B2-mid	429	0.9	20	492	1.5	36	561	2.0	53
0.13	0.28	A1-mid	448	1.0	21	555	1.8	39	646	2.3	58
0.13	0.28	A2-high	440	1.4	38	559	2.6	68	721	3.9	104

highest sensitivity). The results of the simulations described are reproduced in figures 21, 24, and 25.

As can be seen in figure 21, average variation of the mean temperature expected in the whole region would increase between 1.3 and 4 °C, which is consistent with IPCC and other studies. The results of Hulme and Sheard agree with the rest of the models analyzed in this document.

On the other hand, maximum temperatures are already quite high in the North (a place referred to by historians more accurately as "Aridoamerica"); as can be seen in figure 22, maximum temperatures for the summer are currently higher than 35 °C. Running the GFDL model for the year 2080, using the calculation facilities of the IPCC Data Distribution Center produces the graph shown in figure 23, which predicts mean temperature increases for the summer between 2 and 4 °C in the northern zone of the region, which would represent mean summer temperatures close to 40 °C, with very negative effects on the region's productive activities, specially on agriculture.

Back to Hume and Sheard's detail simulation (1999), the results for mean temperature in Mesoamerica, according to the different scenarios used, are shown in figure 24. As can be observed, warming is more

Figure 21.- Calculated changes (1960-2100) in global and Mesoamerican temperature for the year 2100, according to the four scenarios (Hulme, M. and Sheard, N., 1999). Color codes: A2-high, A1 mid, B2 mid and B1-low).

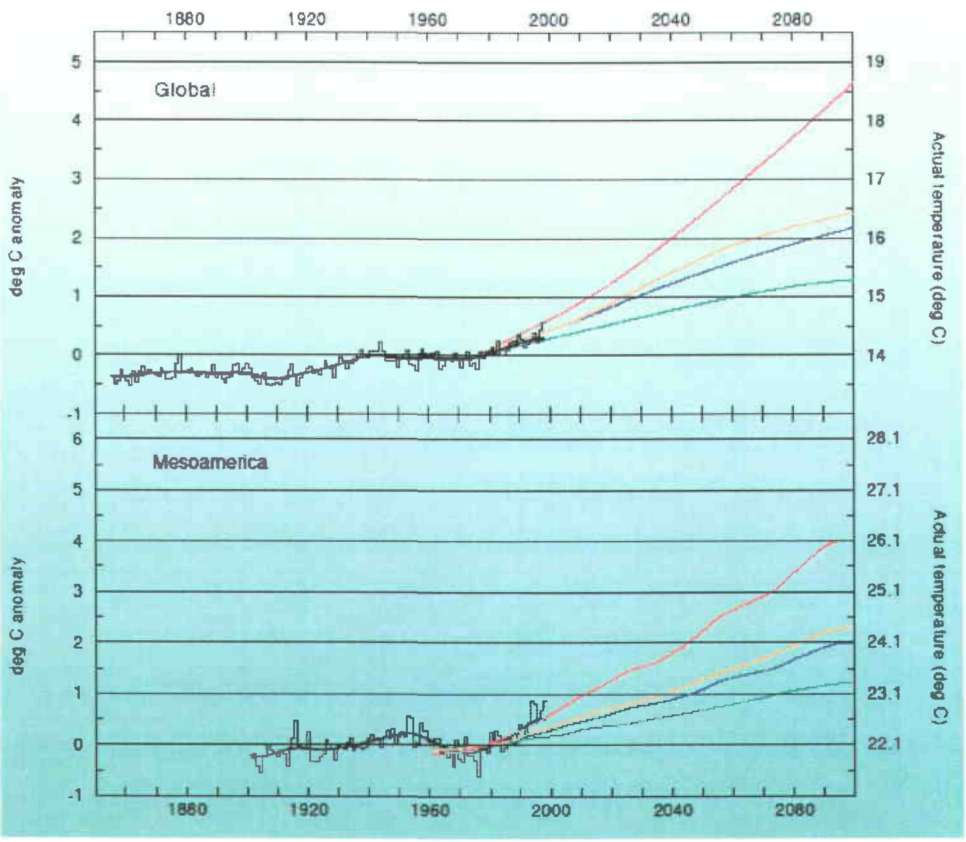
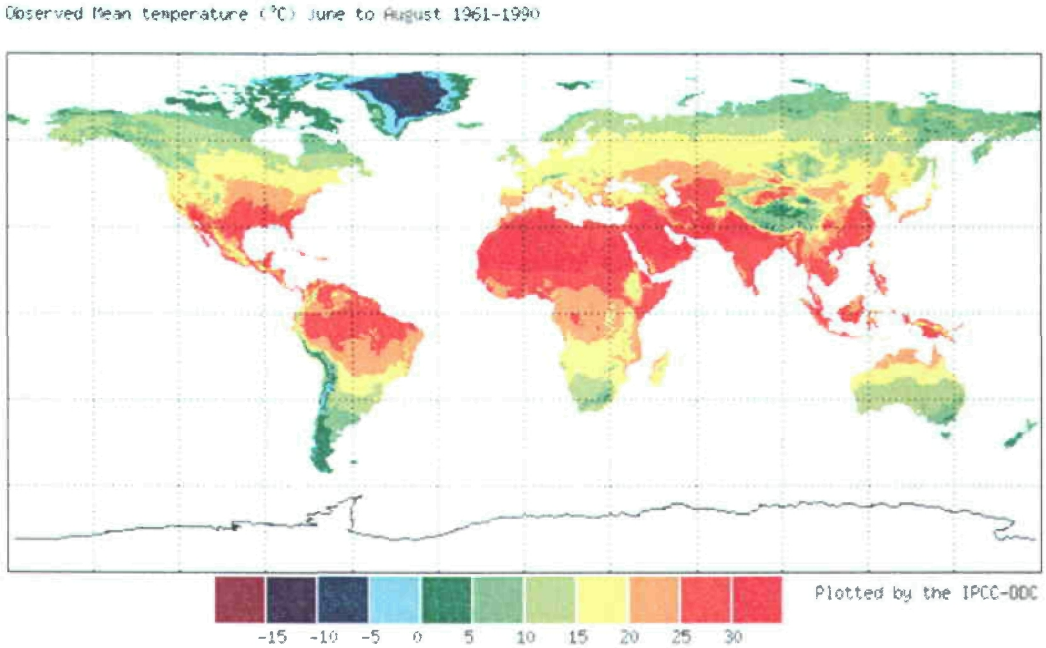
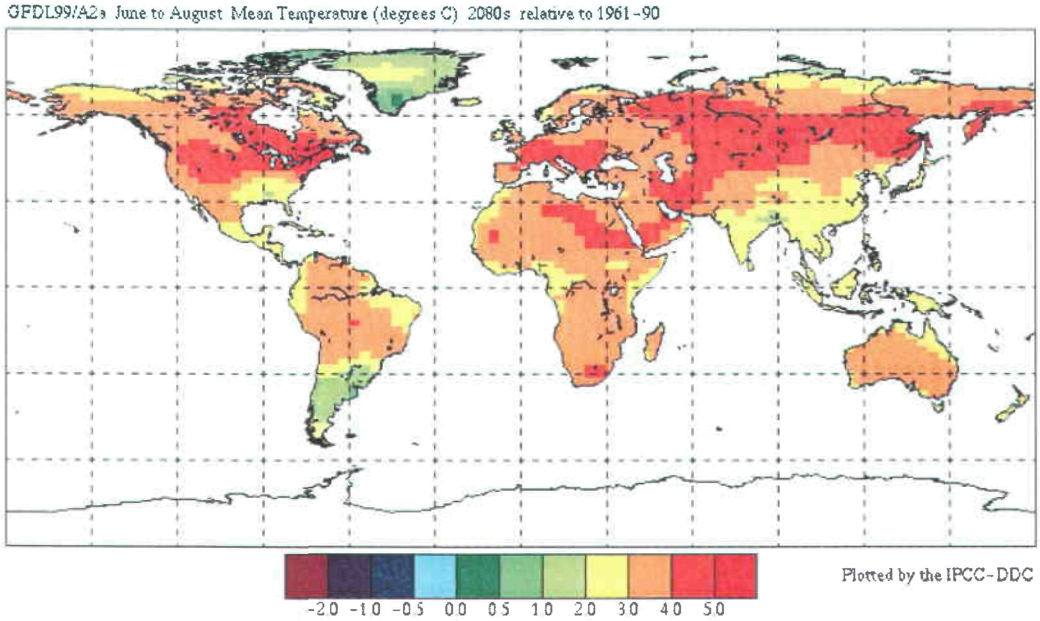


Figure 22. Observed mean temperature in the summertime, June-August (developed with data and graphic facilities of IPCC's Data Distribution Center).



Observed Mean temperature (°C) June to August 1961-1990

Figure 23. Temperature increase projected for summertime, June-August, to the year 2080 (calculated with a GFDL model and for scenario A2a, using the calculation tools and graphic facilities of IPCC's Data Distribution Center).

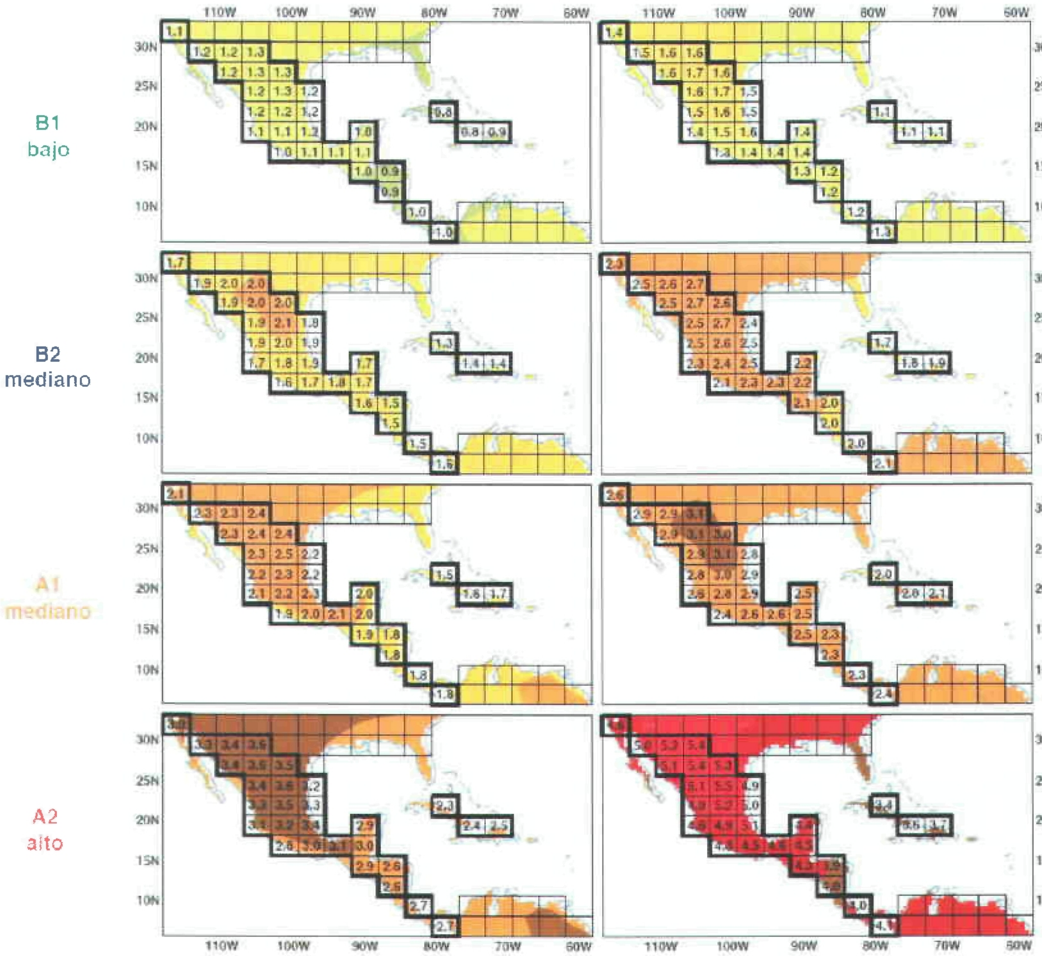


GFDL99/A2a June to August Mean Temperature (degrees C) 2080s relative to 1961-90 intense in the regions of higher latitude and lower in the islands of the Caribbean and in Central American countries.

For the year 2080, most of Mexico would register, according to scenario A2-high, an annual average temperature 5 °C higher than the current value, while in the Caribbean islands of Cuba and Jamaica, the increase would be only of 3.5 °C. This scenario is the extreme of the possibilities. For scenario A1 (medium), temperature increase in Mexico will fluctuate between 2 °C in the Southeast, to 2.4 and 2.5 °C in the center-north and northeast in 2050, reaching up to 3 °C in 2080. It is worth noting that these increases are higher to those initially foreseen in the first IPCC calculations (1995), but lower to the most recent ones performed by the Panel.

The calculated changes in precipitation, reproduced in figure 25, predict a decrease in all the region, which would be more marked in the south of Mexico and in Guatemala. Taking into consideration only the results of scenario A1 (medium), for the year 2050, precipitation decreases of 7 to 12% are projected in our country in the

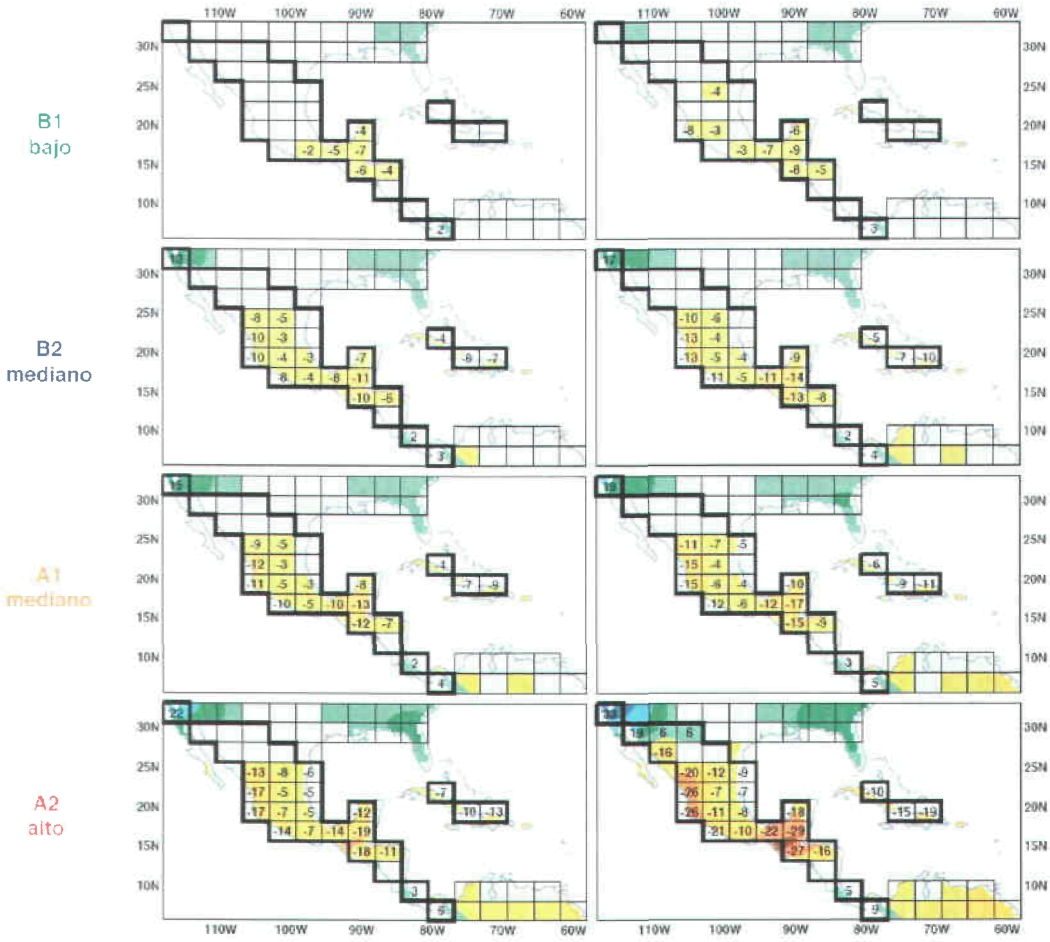
Figure 24. Changes in mean temperature (in °C in Mesoamerica for the 2050s (left) and the 2080s (right), from the average 1961-90 average temperature (Hulme, M. and Sheard, N., 1999).



south of the Grijalva and Usumacinta river watersheds, of 3% in the slope of the Gulf of Mexico, and up to 11% in the central-western coast; without changes in the northern watersheds. For the year 2080, in this same scenario, reduced precipitation would be expected in the south of the Usumacinta and Grijalva river watersheds of 12-17%. This decrease in the region of the country where the heaviest rains fall, would have effects specially on the national hydroelectric energy generation capacity, since most of it is produced in these watersheds. Less abundant precipitations would occur in the central-western part of Mexico, of about 11-15%, which would cause problems in the ecological systems of the region and in the availability of water for agricultural purposes. In the northern region no changes in precipitation are predicted. Nevertheless, even in this situation there would be less runoff, due to increased evapotranspiration and less soil moisture, which together would reduce the amount of water available in surface flows and aquifer recharges.

It is important to note that the north of Mexico is located in what can be called a transition zone: between the latitudes that expect a decrease in precipitation, such as Central and South America, and those where precipitation increases are projec-

Figure 25. Per cent change in mean annual precipitation in Mesoamerica in 2050 (left) and in 2080 (right) compared with average precipitation from 1961-1990 (Hulme, M. and Sheard, N., 1999).



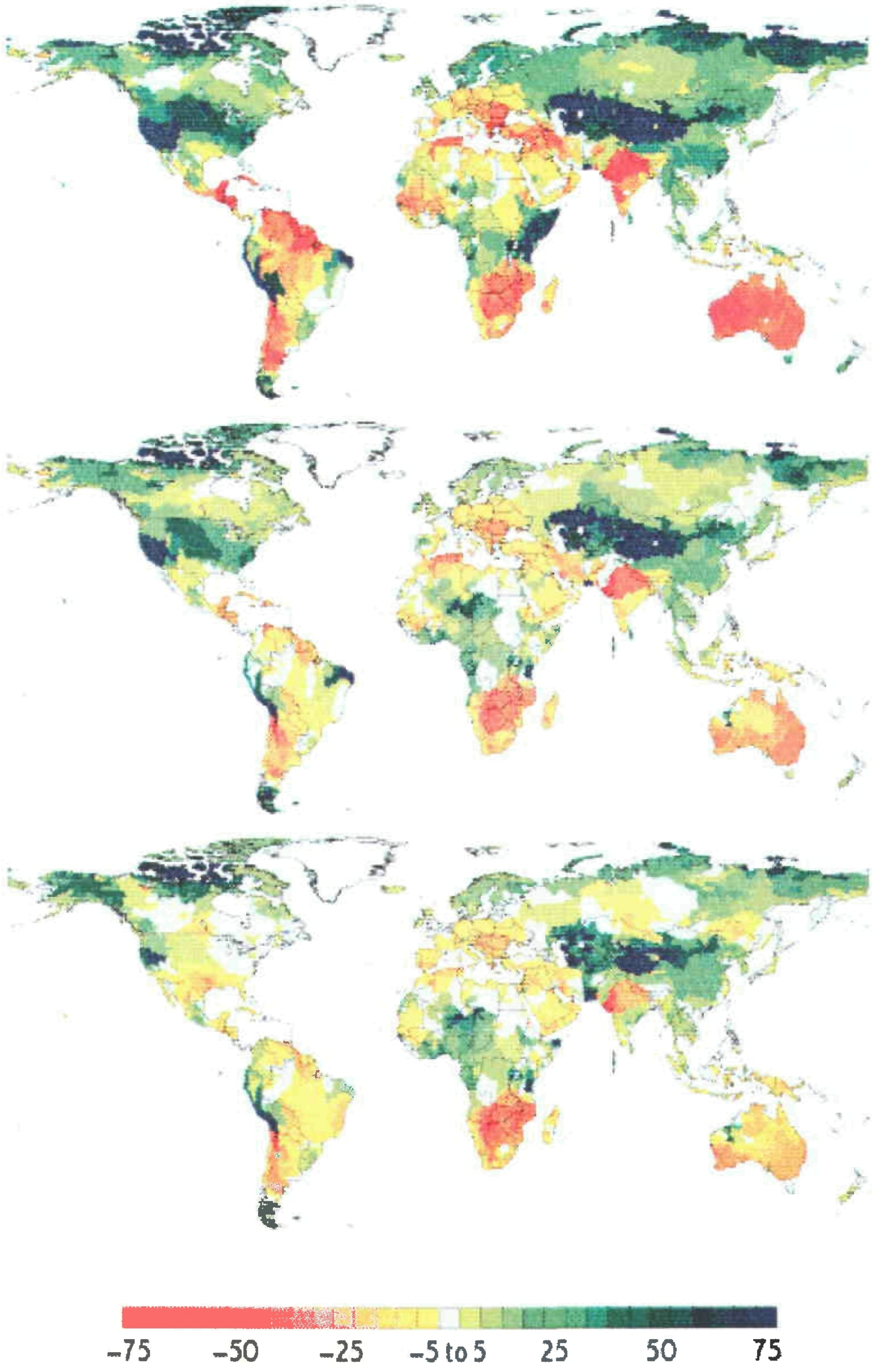
ted, such as North America. This characteristic makes it harder to prognosticate the changes calculated for this zone.

As for the effects of runoff in Mexican watersheds, caused by changes in precipitation, there are no detailed studies available. However, the rainfall-runoff relation is known to be highly nonlinear; which means that changes in precipitation are magnified in runoff. For example, in some arid watersheds, a 10% decrease in precipitation can cause decreases of up to 30% in runoff. Taking into account that these surface flows are the ones put to productive uses, the effects in arid and semiarid zones can be extensive and serious.

Figure 26 reproduces the calculations of the Met Office (Met Office 1999) for the changes in runoff projected for the year 2080, for three atmospheric CO_2 stabilization scenarios. It can be seen that in most of Mexico runoff decreases between 5 and 25% would be expected, with the exception of some watersheds in the central-western region, where increases of about 10% are projected. Of course, a 20% decrease does not have effects of the same intensity in southern watersheds, except in energy generation, than in the arid watersheds of the north of Mexico, where there are already water scarcity conditions. These changes will impose restrictions to several water users, specially agriculture.

Nevertheless, due to the fact that modeling the rainfall-runoff relation depends on geomorphological, topographical, edaphological, plant cover, and other watershed-specific characteristics, the results given above should be considered as indicative; that is, they give only the direction and order of magnitude of foreseen runoff changes . Even so, they are a strong indication of the seriousness of the changes in surface flows expected in those watersheds.

Figure 26. Per cent changes in runoff projected for 2080, considering no mitigation scenarios (top), with stabilization at 750 ppm of CO_2 (middle) and at 550 ppm of CO_2 (bottom) (Met Office, 1999).



Transborder watersheds in the north of Mexico deserve special attention, since water from the Bravo/Grande and Colorado rivers is assigned according to international instruments signed with the United States of America (USA). Mexico receives water from the Colorado River according to the International Water Distribution Agreement between Mexico and the USA, signed in 1944; and from the Bravo/Grande River in the Juárez Valley according to the Convention on the Equitable Distribution of the Waters of the Rio Grande, signed in 1906. The changes in water availability in these watersheds in American territory may jeopardize the delivery of such water volumes to Mexico, since both international instruments provide for a reduced deliveries in case of drought.

According to studies performed in the United States (Jacobs *et al*, 2000) there has been an increase in average precipitation in that country, and under most climate change scenarios this tendency will prevail. Nevertheless, in watersheds dominated by surface flows due to snowmelt, changes in seasonality are projected. It seems that in some western watersheds, such as the Sacramento River watershed, these are already occurring ((Jacobs *et al*, 2000, page 413).

Moreover, increased evapotranspiration is also foreseen, so that the water availability balance could be negative in some watersheds in the United States. Frederick and Gleick (1999) made a regional analysis of the effects that changes in precipitation and temperature could have on runoff in the main hydrological regions of the United States. Results for the Colorado River watershed are shown in table 3. Decreases in runoff, even with no changes in precipitation, are quite pronounced and would have serious effects on water availability, since all of the water of the Colorado River watershed is already being used.

No quantitative evaluations have been made of changes in aquifer recharge, which could impact groundwater availability. However, a reduced availability is expected in shallow aquifers in arid zones, following the decreasing tendency in precipitation, where aquifers replenish from seasonal rains (Arnell & Liu, 2001). The effects on water availability will depend on the current water balance of aquifers: if this balance is now positive, there could be

Table 3. Impact on average annual runoff (percentage) in some transborder watersheds in the United States of America (Developed with data from Frederick & Gleick, 1999).

Precipitation change (%)	Watershed	Temperature	
		+2 °C	**+4 °C**
-20	Upper Colorado	-	-41
-10	Entries to the Glen Canyon dam	-23	-31
	Upper Colorado	-35	-
	Lower Colorado	-56	-
0	Entries to the Glen Canyon dam	-12	-21

negligible effects, but if water extractions and replenishments are similar or if the former are excessive, then, their sustainable use will be further compromised.

Moreover, as with runoff, the relation between precipitation and groundwater recharge is highly nonlinear, i.e. a decrease in precipitation may cause a much greater decrease in the recharge. Arnell and Liu (2001) quote the case of an aquifer in central Tanzania, where a 15% decrease in precipitation would cause a 40-50% decrease in water recharge, even without considering temperature rises.

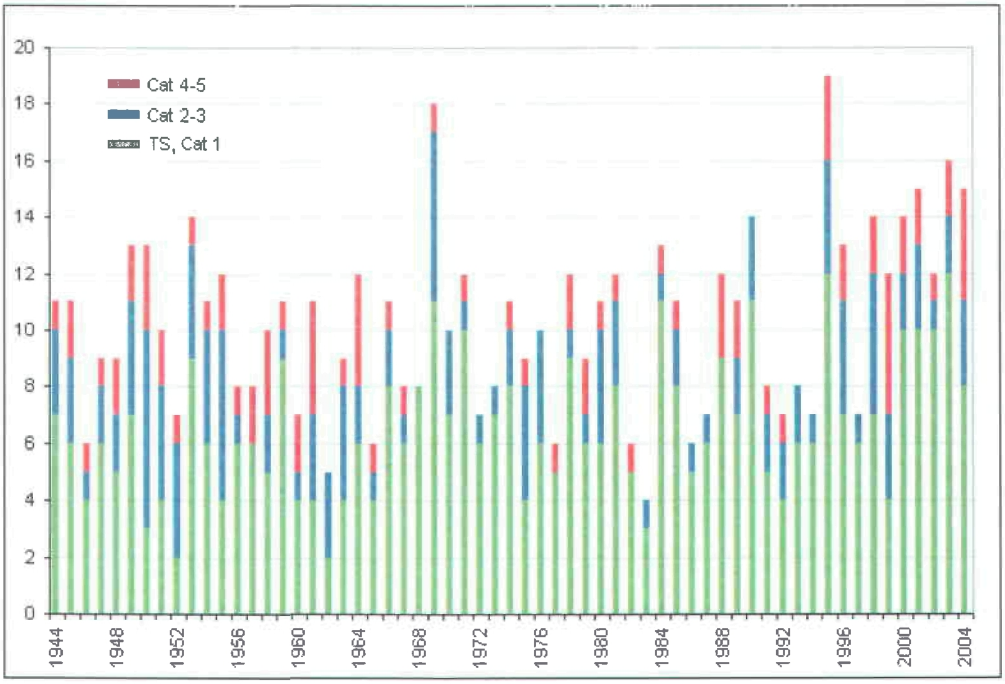
Another change in the water regime that can occur under global warming scenarios is the frequency of extreme events: droughts or floods. The periodicity of floods and inundations in our country will depend mainly on the number of tropical storms and hurricanes, inasmuch as decreased mean annual precipitations are projected for the south of Mexico.

Until now, no statistically significant change in the number of hurricanes can be detected, since it is quite variable, as can be seen in figure 27, which shows the frequency between 1944 and 2004 in the North Atlantic and the Caribbean.

However, the discussion regarding the change in hurricane frequency and intensity, within the global warming scenario, seems to converge in the conclusion that the intensity of these extreme phenomena will increase, while their frequency will not be altered.

In recent investigations, Knuston and collaborators (Knuston & Tuleya, 2004; Knuston *et al*2001) found that, regardless of the cir-

Figure 27.- Annual number of hurricanes in the Caribbean in the 1944-2004 period (taken from http://www.euronet.nl/users/e_wesker/atlhur.html).



culation model used, as the CO_2 increases, so will the intensity of hurricanes.

Knuston and Tuleya (2004) made more than 1,300 five-day simulations of a high-resolution hurricane prediction system with which large-scale conditions of nine climate models were obtained assuming a 1% atmospheric CO_2 increase for the next eighty years. Average aggregate results indicate that in that scenario, the intensity of hurricanes will increase as the central pressure in a hurricane's eye decreases by 14%, maximum wind velocity increases by 6%, and precipitation increases by 18% in a 100-km radius from the center of the meteorological phenomenon. Since no changes are expected in the frequency of these phenomena, these conclusions mean that there will be a greater number of category 5 hurricanes.

Since the beginning of research, it was found that climate change would increase the frequency and severity of droughts, with greater effects in arid zones. Figure 28 reproduces the map of drought severity included in the First Communication from Mexico to the United Nations Framework Convention on Climate Change (Semarnap, 1997). According to the recent modeling of Morales *et al* (2001), in the northern region of Mexico there will be a decrease in precipitation of up to 30% towards the end of the 21st century, the effects of which will begin to be felt since the first quarter of this century.

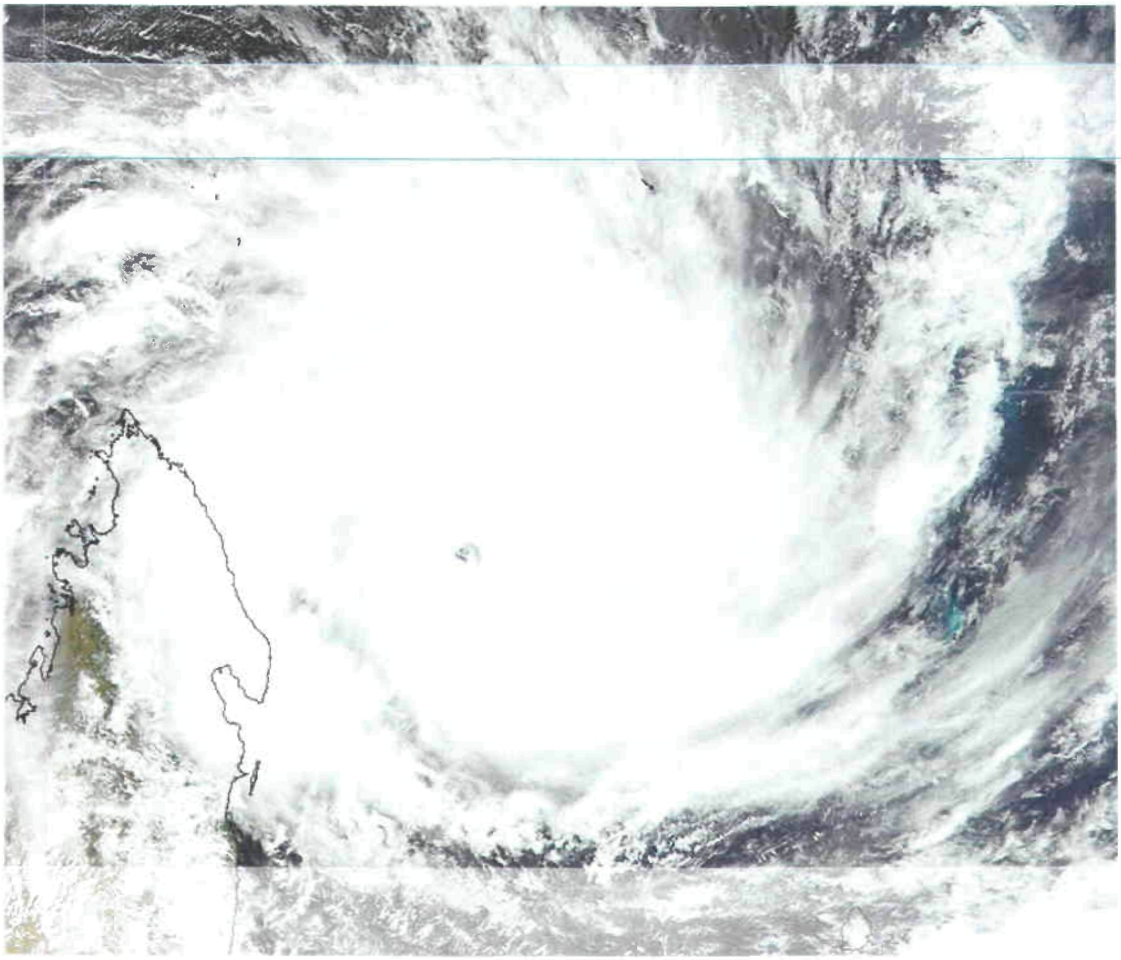
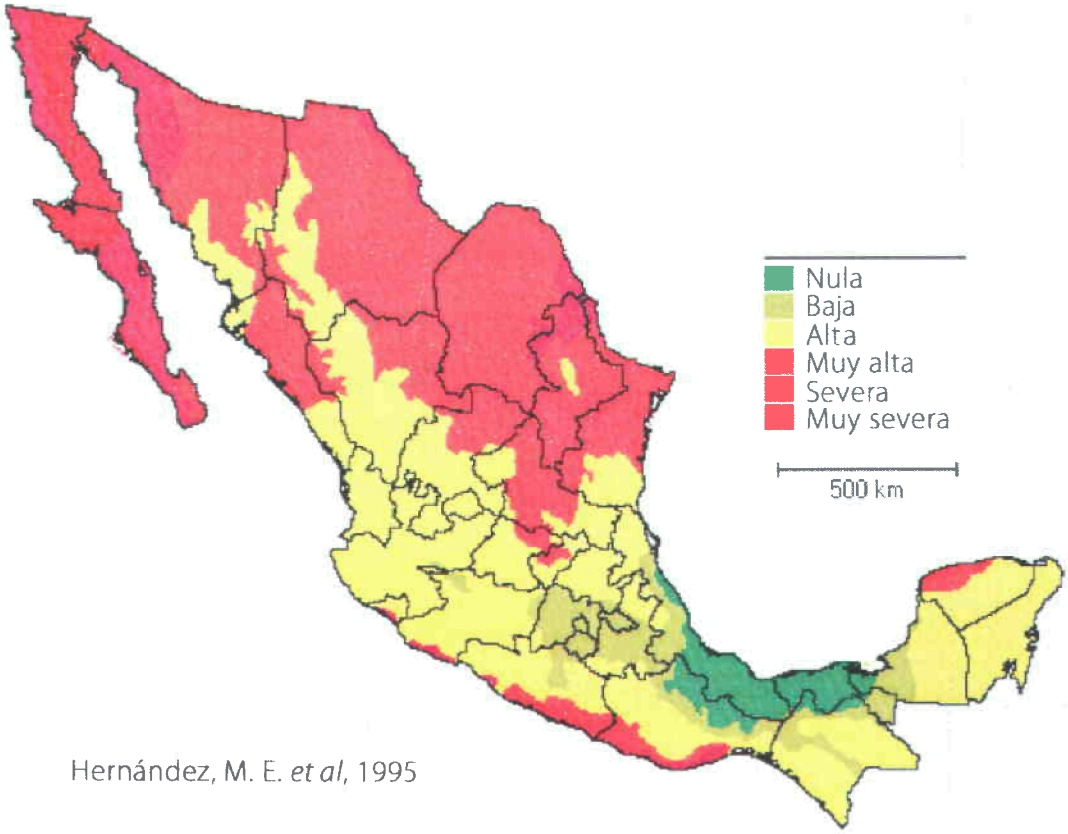


Table 4 summarizes the results of the precipitation scenarios calculated by Morales *et al* (2001) for winter and summer. Towards the end of the 21st century, severe decreases in precipitation are expected in the northern region, most severe in the west, with -40% in Baja California, and less severe towards the east, with -10% in Chihuahua. In the north-atlantic region, starting from Coahuila, precipitation increases would be observed. It is a fact--which for now can only be pointed out as a coincidence--that such is the qualitative precipitation pattern observed during recent years, with extraordinary rains in Nuevo León and Tamaulipas, and dams reaching their maximum capacity or even overflowing, while droughts persist in Chihuahua,in the central region of the Bravo River watershed.

These results are qualitatively consistent with those from other models. This is not the case of Morales *et al*'s forecast (2001) for the south of the country, where precipitation increases are predicted, while most other models also foresee significant decreases in this variable.

Figure 28. Drought severity map (Semarnap, 1997).



Hernández, M. E. *et al*, 1995

Table 4. Per cent variation of precipitation in the 18 Douglas regions (Fig. 14), calculated with the ECHAM4 model and scaling techniques (Morales *et al*, 2001).

Region	**States**	**Precipitation scenario (%)**					
		Winter			Summer		
		2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099
1	BCN and BCS	-50	-20	+10	+30	-20	-40
2	BCS	+50	+50	+60	+20	-20	-60
3	Sonora	+50	+40	+50	-10	-10	-20
4	Sonora and Sinaloa	+20	+50	+80	-10	-10	-20
5	Chihuahua	+20	+40	+60	+20	-10	-10
6	Durango and Zacatecas	+20	+50	+80	-20	-10	+20
7	Coahuila and Nuevo León	-20	+40	+90	-40	-10	+40
8	Nuevo León and Tamaulipas	-20	+40	+80	-10	+20	+20
9	Nayarit and Jalisco	-20	+20	+80	-10	-10	+20
10	Col., Gro. and Mich.	+20	+40	+80	+20	+10	+10
11	Jal., Gto. and Mich.	+20	+40	+60	+20	+20	+30
12	SLP, DF, Hgo. Gto. and Mex.	+40	+40	+40	-20	+10	-10
13	Mor., Pue. and Gro.	-20	+20	+50	-10	+10	+10
14	SLP, Tamps., Hgo., and Ver.	-20	+20	+40	+20	+20	0
15	Oaxaca and Veracruz	-20	-20	-20	-20	+20	+30
16	Oaxaca	+20	+40	+60	0	+20	+30
17	Chiapas	+20	-20	-40	+20	+20	+20
18	Campeche and Yucatán	+20	+40	+60	+20	+20	+20

Changes in water demand

As temperature increases, changes are expected to occur in the natural availability and demand of water, mainly that allocated for agricultural use, currently consuming more than 76.8% (CONAGUA, 2006), by the way, an use that is specially sensitive to temperature. Therefore, the studies on the above-mentioned changes have focused mainly on water use for food production.

Martínez-Austria and Mundo Molina (1995) analyzed the effects of climate change on water demand in one of the most important irrigation districts of the north of Mexico, located in the valley of Yaqui, Sonora. In order to make these calculations, they developed a modified radiation model that enables to simulate changes in temperature and soil moisture.

With the modified radiation model, a change in the water needs of corn crops in the Yaqui valley was observed. From these results it follows that there would be increases in potential evapotranspiration, ET_o and in actual evapotranspiration ET_r, of up to 14%, for the critical scenarios of medium temperature increases studied, consistent with prognoses of general circulation models, which means greater water requirements in a zone where water is already scarce. This increase in corn ET_o and ET_r in the critical scenarios exposed here increases in turn, in a proportional way, the water volumes necessary for maintaining crops with an adequate water balance and preventing a production decrease. As to soil moisture conditions, there will be a deficit of up to 15% in critical scenarios. Table 5 shows the corresponding results.

Table 5. Change in crop water needs for critical global warming scenarios (Martínez-Austria and Mundo Molina, 1995).

Scenario	Month	Sown Surface (Ha)	Required volume (m³)	Change in water needs (%)
zero	Full cycle	220 000	2158 700 000	0
+3oC	"	"	2425 800 000	12,40
+4oC	"	"	2446 224 000	13.31

Irrigation District 041, Río Yaqui, has three major dams: Álvaro Obregón, Plutarco Elías Calles, and La Angostura, with a storage capacity of 2,989 Hm^3, 2,925 Hm^3 and 864 Hm^3, respectively, for a total of 6,778 Hm^3. This means that in the critical scenario an additional capacity, equivalent to 31% of the La Angostura dam, will be required. If one considers that this region will experiment a decrease in natural availability, the final water balance in the agricultural zone, due to climate change, will be negative. In order to face this possible situation, costly adaptation measures will be required.

Martínez-Austria *et al* (1998) determined the potential evapotranspiration curves in Mexico for the current situation and for various climate change scenarios. The procedure consisted basically in calculating the values of evapotranspiration of crops in the current situation, and in the average conditions proposed for different scenarios given by the IPCC. The meteorological information used consisted of the historical series available in the meteorological observatories of Mexico, located mainly in the capital cities of the different states and other important cities.

The method used for the calculation of evapotranspiration, proposed by Mundo and Martínez-Austria (1994), consists in a modification of the one by the United Nations Food and Agriculture Organization (1976), which is the most widely used in the world. The calculation known as "reference crop" was included. This means that the results are applicable to any crop by multiplying them by the crop coefficient particular to every vegetable variety.

Figures 29 to 32 show mean annual evapotranspiration forecasts for scenario zero and for scenarios with temperature increases of 1, 2, and 3 °C, which today seem rather conservative. It can be observed that most sites show increased water needs, which will negatively affect the water balance, especially so when precipitations decrease.

This study indicates that in Mexico, the effects of climate change will be felt more markedly in the northern region, where crop water requirements will increase in greater proportion than in the rest of the country. The difference between current potential evapotranspiration demands and the extreme scenario of a 3 °C increase, averages eight percent.

Figure 29. Potential evapotranspiration Scenario zero. (Martínez-Austria *et al*, 1998).

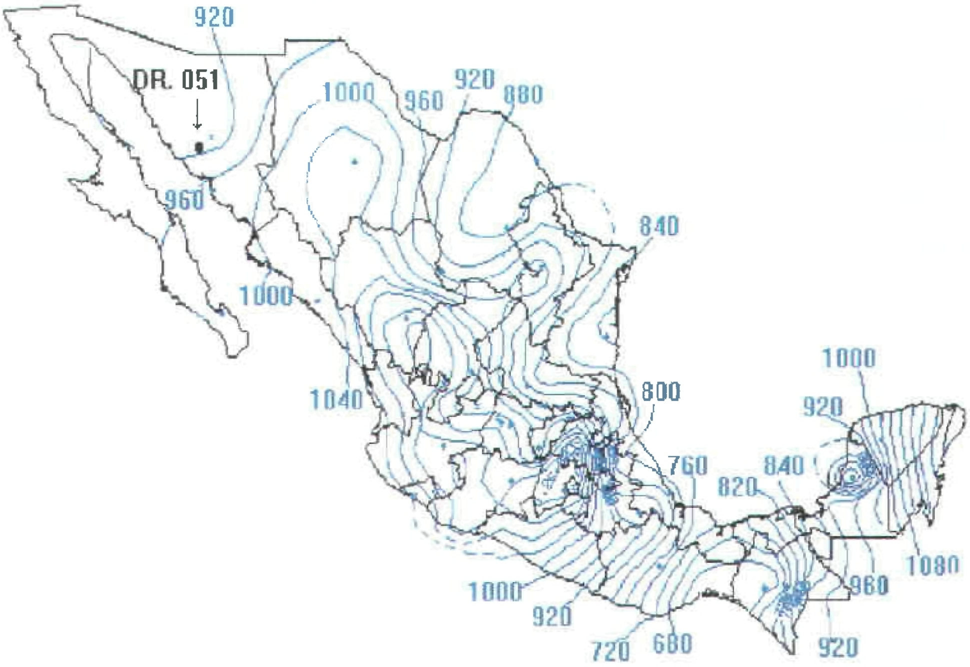


Figure 30. Potential evapotranspiration Scenario with a 1 °C-increase. (Martínez-Austria *et al*, 1998).

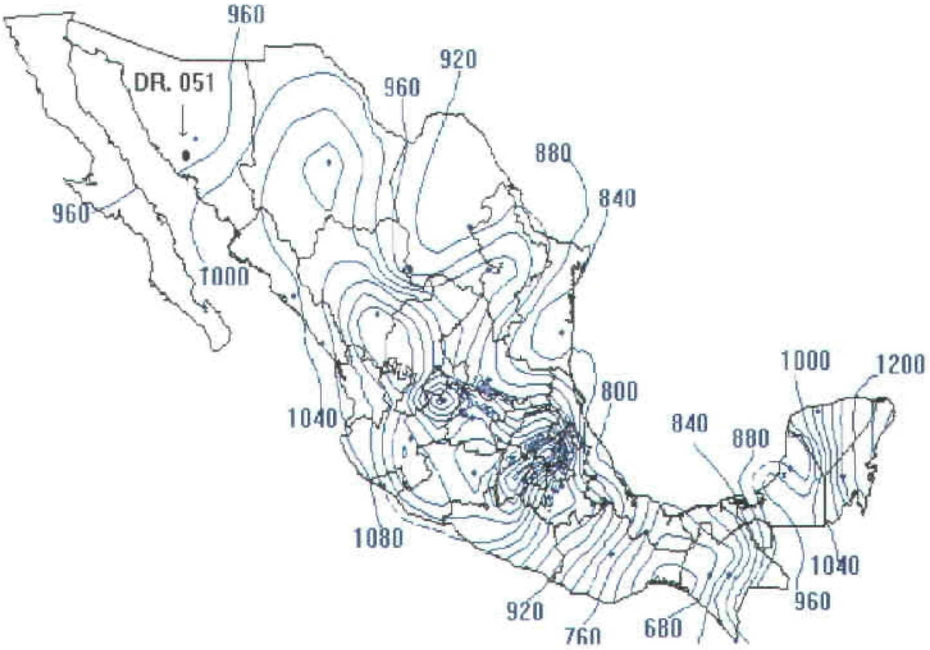


Figure 31. Potential evapotranspiration Scenario with a 2 °C-increase.
(Martínez-Austria *et al*, 1998).

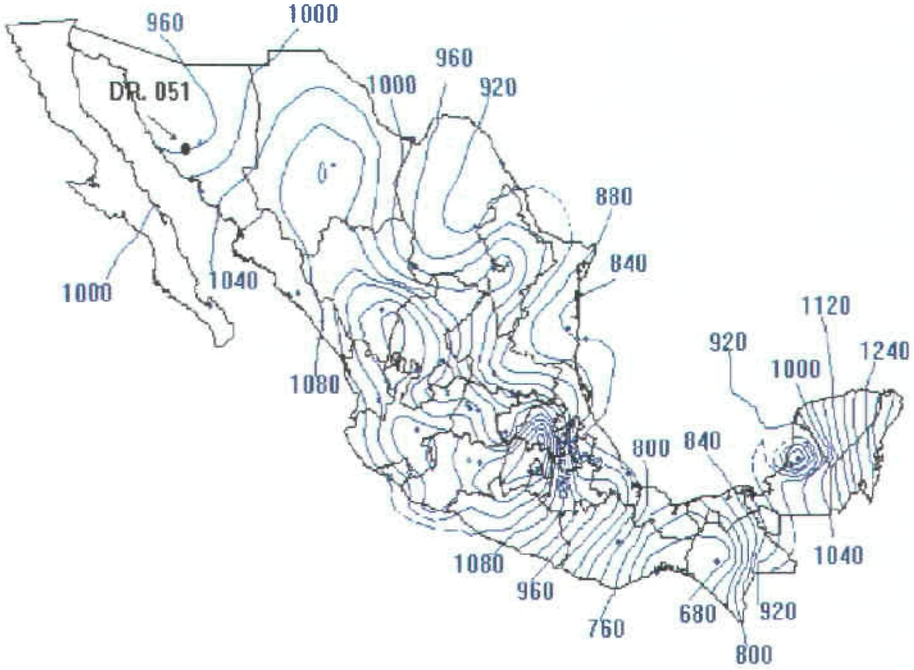
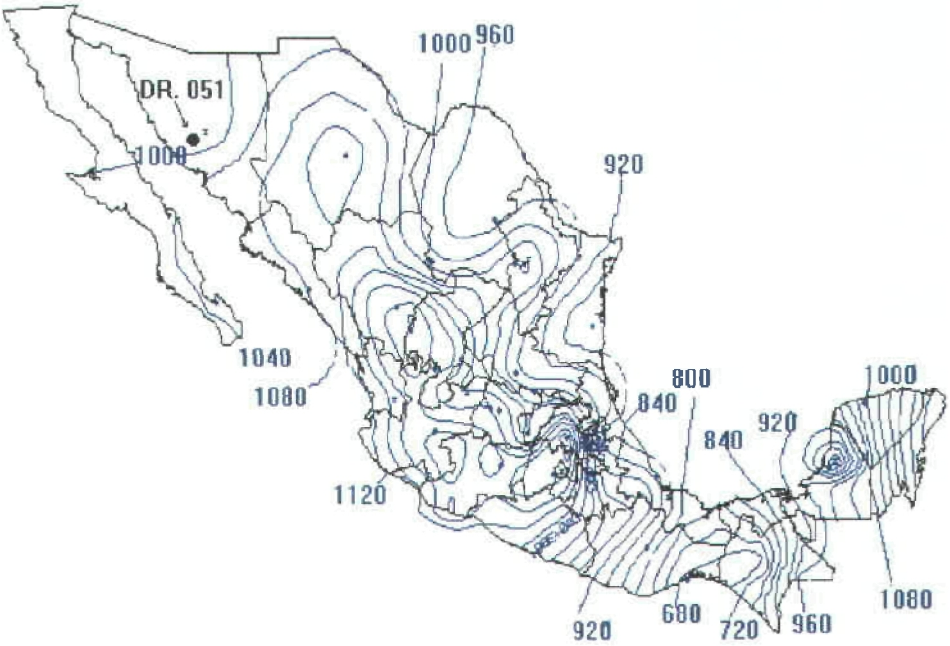


Figure 32. Potential evapotranspiration Scenario with a 3 °C-increase.
(Martínez-Austria *et al*, 1998).



Water management and climate change

In Mexico, water management already faces enormous challenges (CONAGUA, 2006). It is a country with a wide range of climates: while the north has dry to very dry environments, subject to recurrent droughts, in the south these are humid, with frequent tropical storms and floods (figure 33). A mean precipitation of around 771 mm annually is, like many averages, a misleading figure. This can be seen in figure 34, since, while in the southern, coastal, and central regions values are as high as 2,000 mm annually, in the northwest and northeast precipitation amounts to a mere 250 mm and 500 mm a year, respectively. In a contrast that is well known, most of the population, with the consequential economic development, lives in the regions where less water is available, as shown in figure 35.

The United Nations considers that water availability is low if values are between 2,001 and 5,000 m^3/inhab/year , very low if between 1,001 and 2,000 m^3/inhab/year, and extremely low if it is below 1,000 m^3/inhab/year.In Mexico, water availability has been decreasing due to economic

Figure 33. Mexico climates (CONAGUA, 2000)

Figure 34. Mean annual precipitation (CONAGUA, 2006).

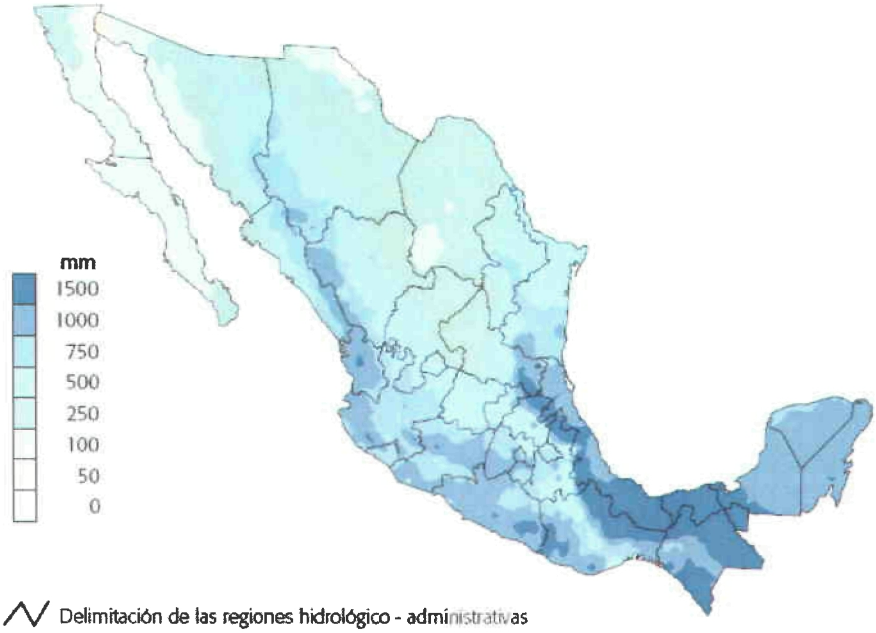
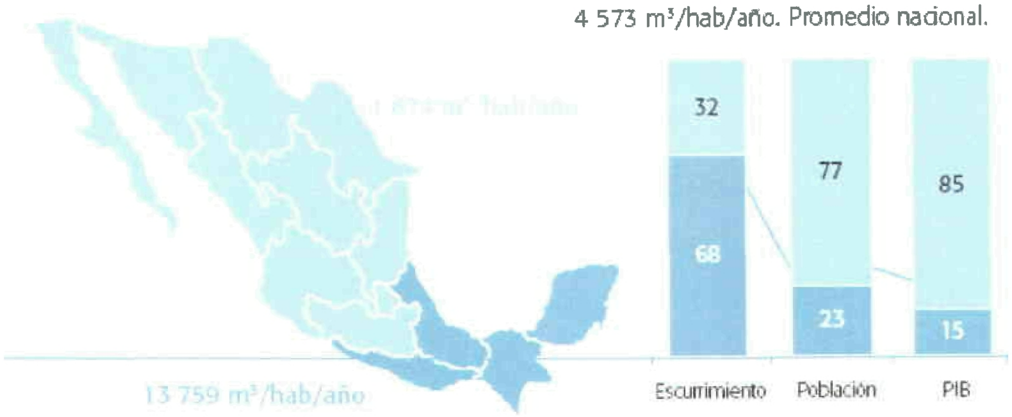


Figure 35. Contrast between development and water availability (CONAGUA, 2006)

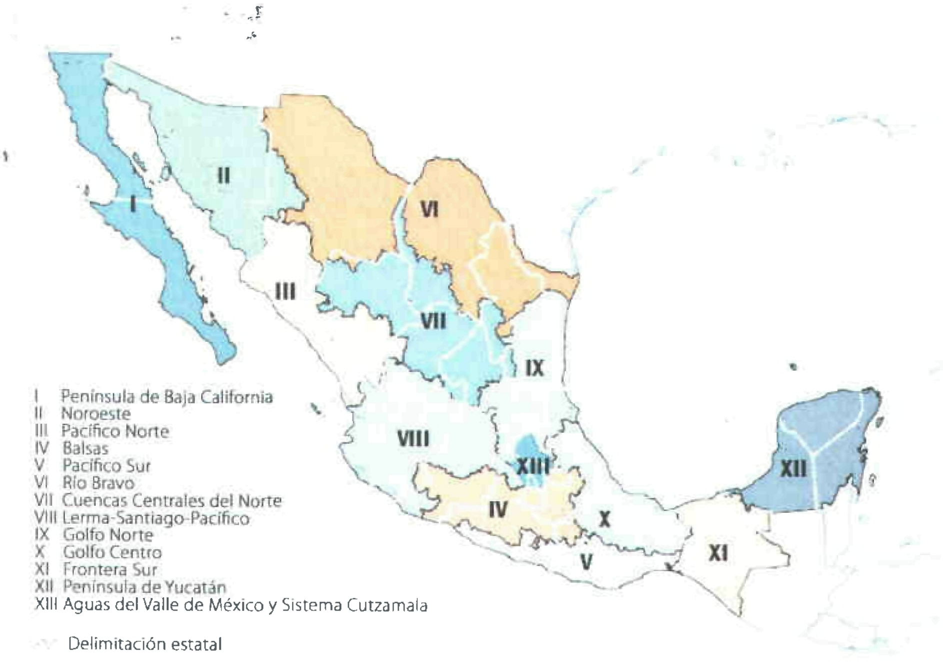


development and, mainly, to demographic growth. Thus, water availability per capita went from 11,500 m^3/inhab/year in 1955 to 2,500 m^3/inhab/year in the year 2000. With current growth rates, for the year 2025 water availability is expected to decrease to 3,500 m^3/inhab/year, which will generate greater scarcity in arid and semiarid zones.

In order to manage water resources, CONAGUA has divided the country in 13 hydrologic-administrative regions

Even with no climate change, water resources management in Mexico will get complicated in the next few years as a result of demographic growth and economic development, which typically increase per capita consumption. Table 6 shows annual water availability per inhabitant in each hydrologic region for the years 2003 and 2025, which is the planning horizon used by CONAGUA. As can be seen, demographic growth alone will

Figure 36. Hydrological-Administrative Regions (CONAGUA, 2006).

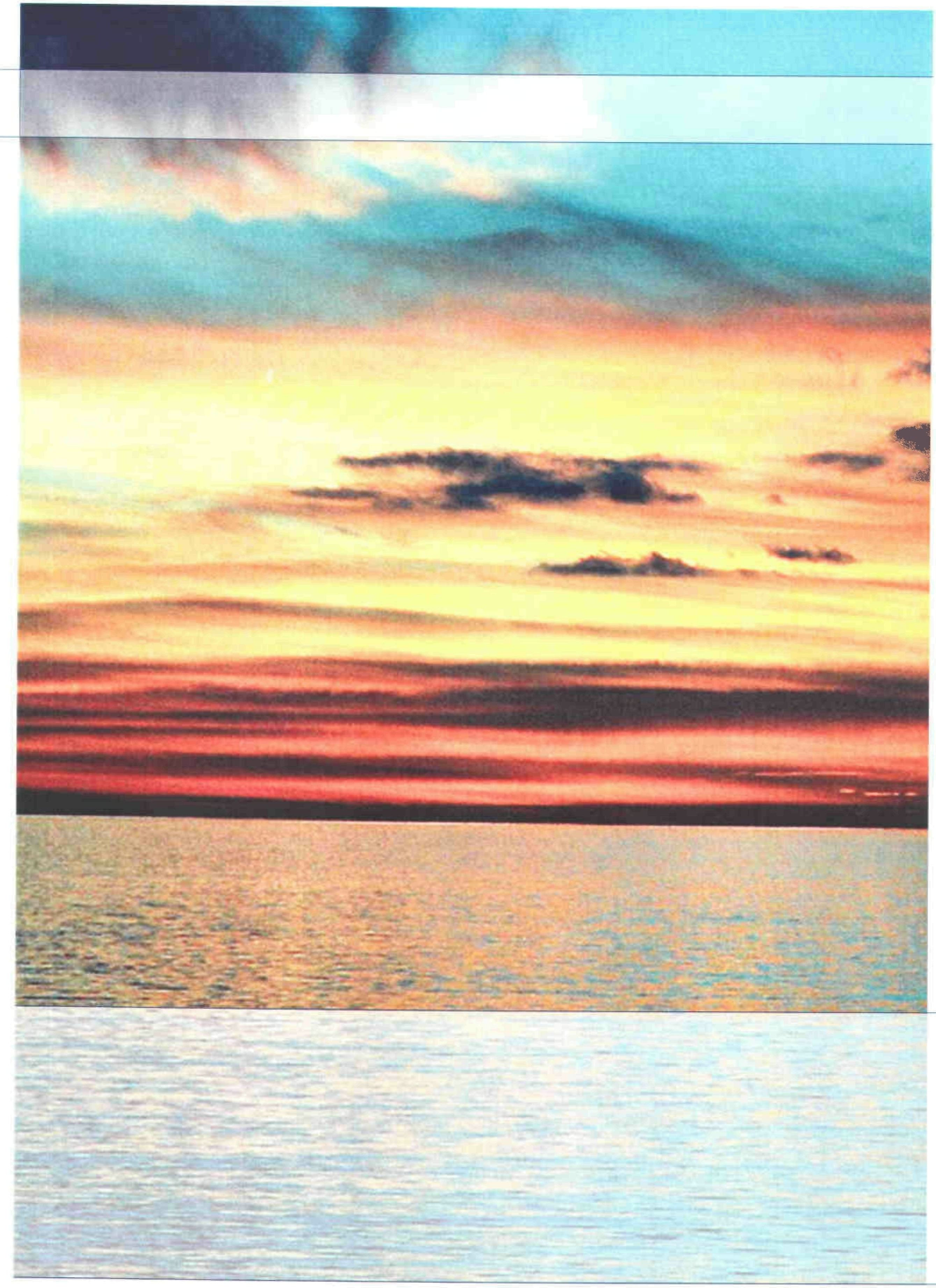


Hydrological-Administrative Region		Total mean natural availability (Hm^3)	Mean per capita availability, 2003 (m^3/inhabitant	Classification	Mean per capita availability, 2025 (m^3/inhabitant	Classification
I	BAJA CALIFORNIA PENINSULA	4,423.00	1,336	Very low	833	Extremely low
II	NORTHEAST	8,214.00	3,236	Low	2,491	Low
III	NORTH PACIFIC	24,741.00	6,035	Medium	5,496	Medium
IV	BALSAS	28,909.00	2,713	Low	2,402	Low
V	SOUTH PACIFIC	33,177.00	7,963	Medium	7,529	Medium
VI	RIO BRAVO/ GRANDE	13,718.00	1,324	Very low	974	Extremely low
VII	NORTH CENTRAL WATERSHEDS	6,836.00	1,729	Very low	1,605	Very low
VIII	LERMA-SANTIAGO-PACIFIC	39,680.00	1,962	Very low	1,699	Very low
IX	NORTHERN GULF	23,347.00	4,685	Low	4,200	Low
X	CENTRAL GULF	102,546.00	10,604	High	9,853	Medium
XI	SOUTHERN BORDER	157,999.00	24,674	Very high	19,758	High
XII	YUCATÁN PENINSULA	29,063.00	8,178	Medium	5,671	Medium
XIII	WATERS OF THE VALLEY OF MEXICO AND THE CUTZAMALA SYSTEM	3,803.00	182	Extremely low	156	Extremely low

cause a decrease of such a magnitude in water availability, that the Baja California and Rio Bravo/Rio Grande regions will go from the very low to the extremely low classification, which means water availability will be as low as 1,000 cubic meters per inhabitant per year.

This scenario should be complemented with the effects of climate change; however, there are no regional studies with the necessary resolution to produce a good estimate. Qualitatively speaking, suffice it to consider that in the northern region, taking into account a CO$_2$ stabilization level of 550 ppm, a 15% runoff decrease would be expected for the year 2080 (Met Office, 1999).

The change is so big in a zone that will experience severe scarcity, that it should be included in long-term planning exercises. It is necessary that water resources managers, and especially those responsible for public policies within the sector, take into account climate change scenarios; otherwise, they could establish strategies that will fall short for adapting water systems to a situation foreseen based on the studies performed.



Final considerations

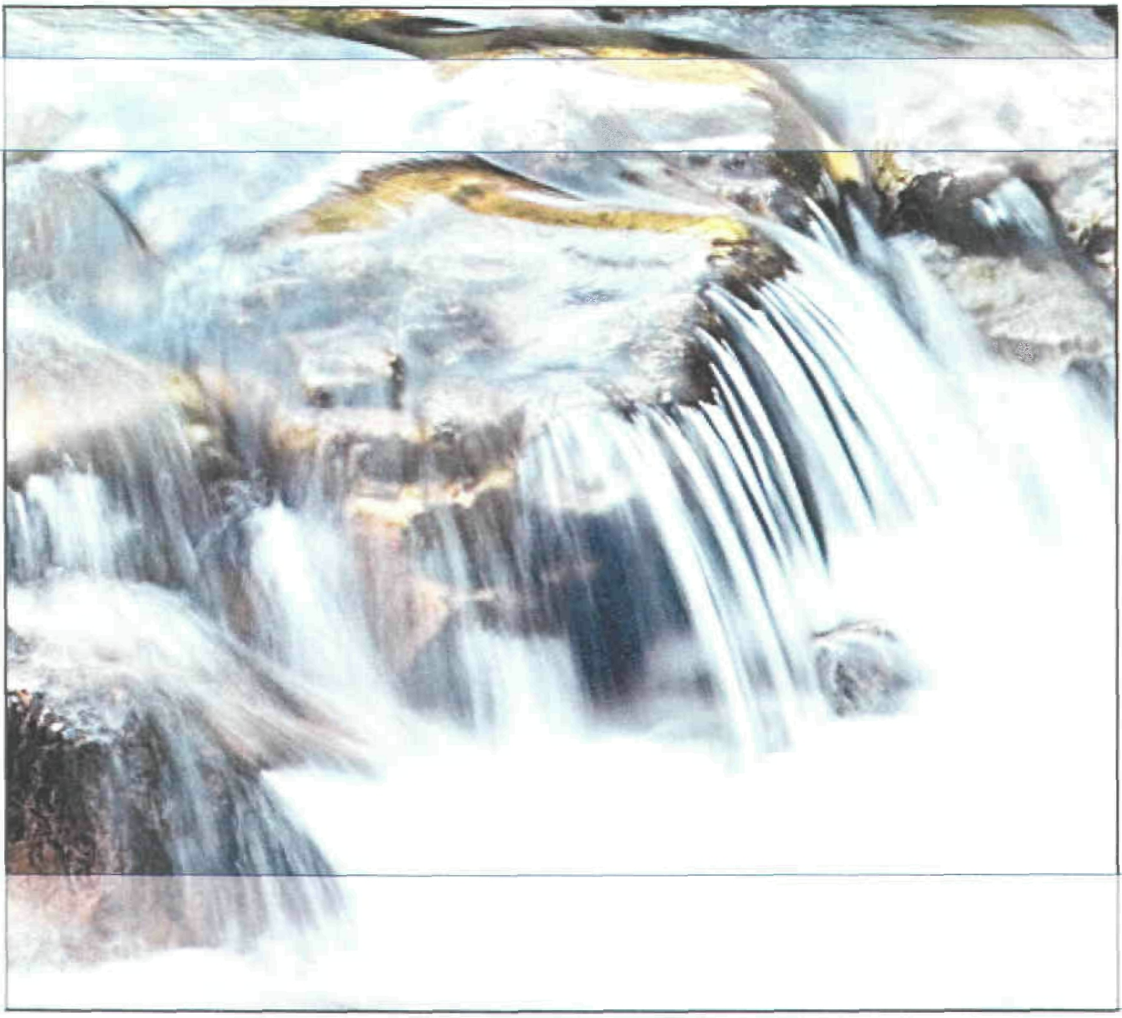
Climate change is an on-going process that will have significant consequences on water availability in Mexico. Different estimates agree in that there will be temperature increases, towards the end of the next century, of 3 to 4 degrees Celsius.

The conditions described will cause changes in precipitation, mainly in the northern part of the country, where less frequent rains and increasingly recurrent and intense droughts are projected, together with a decrease in runoff, which in some cases will be close to 20% in the late 21st century. As water requirements increase, especially in agriculture, so will water demand, which, compounded with a lower natural availability, creates a scenario of increasing scarcity. As mean precipitation decreases in the Southeast, lower volumes for energy generation are also foreseen.

Moreover, tropical storms are projected to increase in intensity, though not in frequency. More category-four and -five hurricanes will be observed, with more intense precipitations.

Sea level rise in the coasts of Mexico will render some regions vulnerable to floods, since the discharge capacity of streams diminishes. Greater risks are predictable, especially at the mouth of the Grijalva River in Tabasco, and of the Coatzacoalcos and Pánuco rivers in Veracruz.

Changes in ocean rise, surf intensity and patterns, and littoral currents could cause significant alterations in erosion-sedimentation processes in coastal zones, which would have considerable environmental effects in mangrove swamps and littoral lagoons.



Sea level rise will also have relevant effects in the salinization of coastal aquifers.

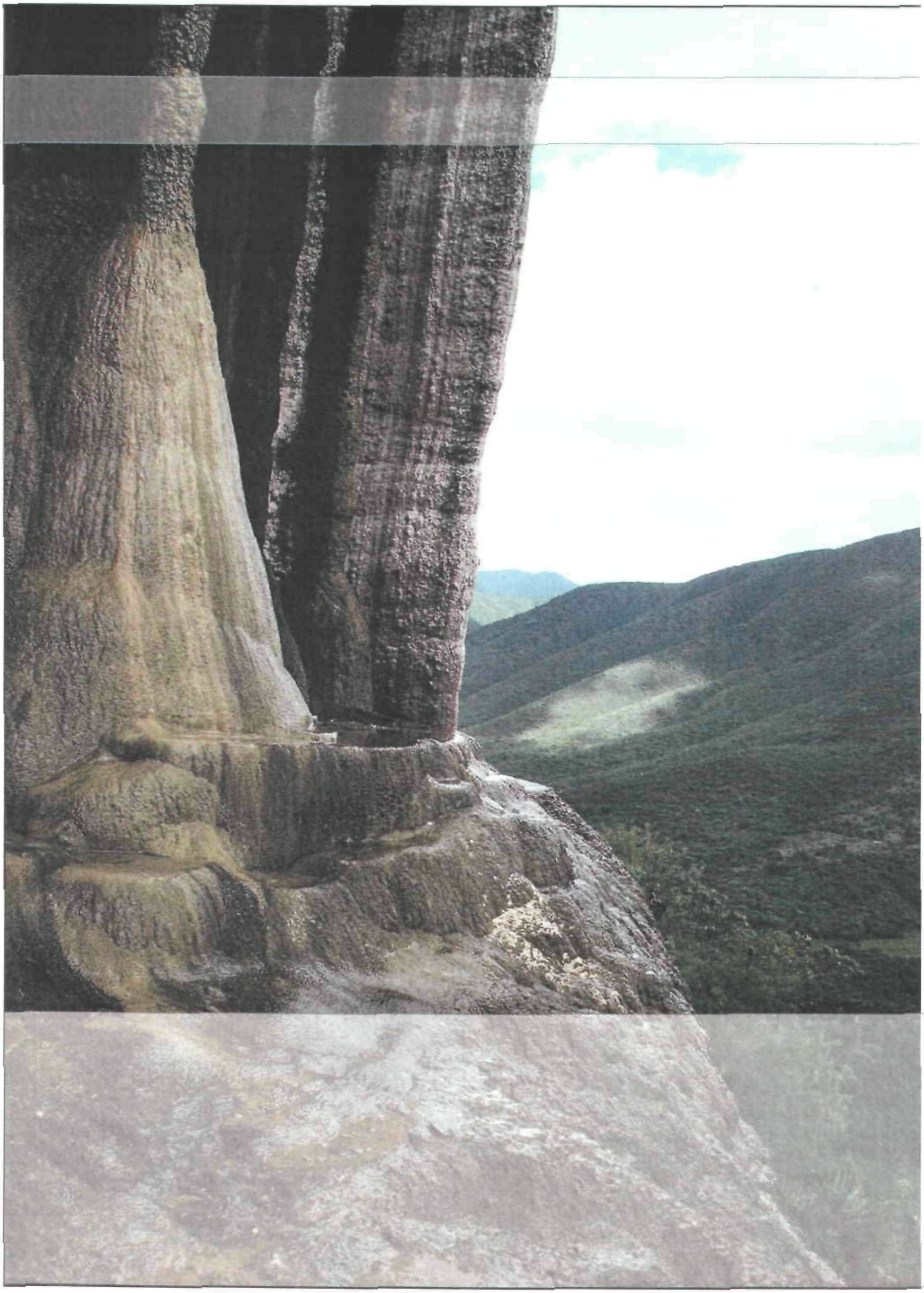
In arid regions, a greater frequency of more intense droughts is foreseen. Special attention should be given to the watersheds of rivers in the northern region, especially of the Bravo/Grande River.

In order to improve these results, detailed studies on the zones this study has shown to be more vulnerable are required. Table 7 shows a qualitative description of the main effects of climate change in the different hydrologic-administrative regions of Mexico, which can serve as an orientation for the more necessary vulnerability and adaptation studies for each zone. Water management in the future, already complicated by demographic and economic growth in areas with a natural scarcity, will have even greater challenges as a consequence of climate change. It is pressing that regional studies be performed in order to eliminate uncertainty as much as possible from prognoses, to localize the effects, to define adaptation measures, and to prioritize their implementation in the regions that prove to be more vulnerable. A specific water strategy will me necessary in the National Climate Action Plan.

Finally, the effect of climate change on water quality, particularly in lakes and other surface water bodies, has not been studied. It is a known fact that they will be negatively affected, but to what extent remains unknown.

Table 7. Qualitative vulnerability of the Hydrological-Administrative Regions of Mexico.

Hydrological-Administrative Region	EFFECTS OF CLIMATE CHANGE						
	Demand changes	Availability changes	Shortage	Hurricanes and storms	Droughts	Sea level changes	Observations
I Baja California Peninsula	Major	Less availability	Very vulnerable	Mostly slightly vulnerable	Vulnerable	Slightly vulnerable	The watershed depends on runoffs from the US, which will become reduced
II Northeast	Major Main user: agriculture	Less availability	Very vulnerable	Slightly vulnerable	Vulnerable	Effects on saline intrusion in coastline aquifers	One of the most vulnerable regions in Mexico
III North Pacific	Major Main user: agriculture	Uncertain	Vulnerable due to higher demand	Vulnerable	Uncertain	Effects on saline intrusion in coastline aquifers	More studies and modeling required for this region
IV Balsas	Major	Probable reduction	Vulnerable	High vulnerability in the coastal zone of Guerrero and Michoacán	Vulnerable	Mainly in the mouth of the Balsas River	Severe effects in rainfed agriculture in Tlaxcala and highlands
V South Pacific	Major	Uncertain. *Some models* predict increased precipitation	Slightly vulnerable, except in high mountainous zones	Very vulnerable, especially in the coastal zone	*Slightly* vulnerable	*Slightly* vulnerable	It is one of the most vulnerable regions as far as severe storms are concerned
VI Rio Bravo/ Grande	High, due to demographic effects and temperature rise	Significant runoff and aquifer recharge reductions are projected	Very vulnerable	Slightly vulnerable	Very vulnerable	Not vulnerable	One of the most important watersheds in Mexico and one of the most vulnerable to droughts and shortages
VII North Central Watersheds	High, due to temperature increases	Significant runoff and aquifer recharge reductions are projected	Very vulnerable	Not applicable	Very vulnerable	Not vulnerable	One of the watersheds in Mexico most vulnerable to droughts and shortages.
VIII Lerma-Santiago-Pacific	Medium	Uncertain, the models predict little change	Very vulnerable, due to overexploitation	Slightly vulnerable	Vulnerable, with high natural variability.	Slightly vulnerable	Detailed studies required for this region, due to its current high vulnerability and uncertain scenarios
IX Northern Gulf	High, due to temperature increases	Likely to increase, according to most models	Slightly vulnerable	Vulnerable	Slightly vulnerable	Very vulnerable at the mouth of several rivers	Probable need of reviewing the design of hydraulic structures, dams, and flood control
X Central Gulf	High, due to temperature increases	Likely to increase, according to most models	Slightly vulnerable	Vulnerable	Slightly vulnerable	Very vulnerable at the mouth of several rivers	Probable need of reviewing *the design of hydraulic* structures, dams, and flood control. Special care in flood prevention in mountainous zones
XI Southern Border	Major, due to temperature changes	Slight, due to high availability in the region	Slightly vulnerable	Highly vulnerable, especially in the coast of Chiapas	Slightly vulnerable, but storage structures will be needed	Very vulnerable, *especially in* flood fields of the Grijalva and Campotón rivers	Probable need of reviewing *the design of hydraulic* structures, dams, and flood control. Special care in flood prevention in mountainous zones
XII Yucatán Peninsula	Major, due to temperature changes	Vulnerable, since there are no storage structures	Vulnerable, if no catchment and storage adaptation measures are taken	Very vulnerable in the coastal zone	Seasonal Vulnerable	Vulnerable, due to saline intrusion in aquifers	Due to its peculiar geology, detailed studies are required
XIII Valley of Mexico	Not significant	Not significant. Already a region in deficit	Very vulnerable	Vulnerable, but hardly associated with climate change	Slightly vulnerable	Not applicable	Already a region in deficit. Costly adaptation measures required



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