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Climate Change Effects on Evapotranspiration in Mexico

Martín Mundo-Molina

Investigation Centre, Faculty of Engineer, Autonomous University of Chiapas, Tuxtla Gutiérrez, Mexico
Email: ic_ingenieros@yahoo.com.mx, cidestachi@yahoo.com.mx

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Abstract

In Mexico's case, the scarcity of water in the north of the country is worrying, even more from the agricultural point of view because according to the results of general circulation models, a major impact due to global warming is expected in this region, and it will have important repercussions on the rural sector in the north of Mexico. According to [1] the results of the sensitivity analysis made in this study indicate that the most vulnerable zone is the north of Mexico, wherein the increase of evapotraspiration (ET) is greater in comparison to the rest of the country; up to 8% annual average for a +3˚C growth in mean annual temperature. Due to some limitations in this preliminary investigation (e.g., global temperature data was used without regionalizing it), it was decided to make more detailed studies to estimate the climate change effects on ET on a regional scale, using the downscaling method to adjust temperature data. In this study a new methodology to estimate the ET before climate change scenarios is introduced, which includes the selection of the Hargreaves-Samani method (HS), calibrated and compared against the Penman-Monteith ASCE method in various irrigation districts in the northern part of the country, obtaining ET estimations with a 93% precision. This procedure was applied to nine states in north Mexico: Baja California, Baja California Sur, Chihuahua, Sinaloa, Sonora, Tamaulipas, Nuevo León, Coahuila y Durango. The principal results are enunciated as follows: the ET variations between the contemporary scenario and the 2030 scenario are quite significant, according to the data of 160 meteorological stations; for temperature variations between 0.1˚C to 0.45˚C the corresponding ET fluctuation goes from 2% in the current scenario to 7% in the 2030 scenario. These obtained percentages are greater than the ones expected to happen for the precision of the method. It is important to note that a 7% rise of ET (related to a regional temperature increase of approximately one degree) would represent in practice having more millions of m3 of water in dams to satisfy the water demand of crops.

Keywords

Climatic Change, Reference Evapotranspiration, Irrigation Agriculture

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1. Introduction

The observation networks of the World Meteorological Organization (WMO) have registered a raise in worldwide mean temperature from 3˚C to 6˚C during the last hundred years because of increment of greenhouse gases in the atmosphere during the last 2000 years.

According to stored data and physical evidence, the increase of greenhouse gases has originated Earth's overheating. In 1998, the United Nations Environment Programme (UNEP) and WMO created the Intergovernmental Panel on Climate Change (IPCC). The objective of this group is to analyze thoroughly and objectively scientific, technical and socioeconomic information to understand the risks and impact of climatic change, as well as the possible adaptation and reduction methods of it. The IPCC consists mainly of three work groups and a special team (which makes inventories about greenhouse gases) and has published up until now four scientific reports on climate aspects, mitigation and vulnerability (the last two reports focus on climate change impact in natural and socioeconomic systems). IPCC work team I (scientific group) published in Paris, on February 2007, the fourth evaluation report about global warming. It includes the results of the studies made on the last six years, and future perspectives about their possible effects.

In Mexico's case, the scarcity of water in the north of the country is worrying, even more from the agricultural point of view. According to the results of general circulation models, a major impact due to global warming is expected in this region, and it will have important repercussions on the rural sector in the north of Mexico. This area has been subject to dry seasons for long periods of time and this situation will increase the problems of water availability for crop irrigation. The major agricultural districts are at the north of the country and they consume 80 of every 100 liters of water used in Mexico, from which 50% of water resource is wasted. Therefore, considering the potential risk and vulnerability of the area, it is important to estimate the effects of climatic change in evapotranspiration (ET) in the principal irrigation districts of the country to calculate the possible growth on water demand, for it would mean to make use of a greater water volume from the dams in a region where this resource is limited.

However, it is not easy to quantify climate change effects on agriculture for several scientific reasons; the most important of them are three: first, the estimation of the quantitative effects of global warming over future climate involves the use of numeric models on global scale that do not contain all variables influencing the phenomenon (e.g. ocean's CO_2 absorption). It also uses inconsistent data; for example the rate of greenhouse gases emission depends on the anthropogenic effect, especially in the consumption and emission of fossil fuels, choice of technology, economy evolution and demographic growth of each country. In second place the results of global models that estimate future climate (increase or decrease of temperature or precipitation) generate data that cannot be directly applied to specific regions, so it's necessary to regionalize it in a process that, if not executed, directly affects the accuracy of the calculations. In third place, empiric (temperature and radiation models) and semi-empiric (Penman-Monteith models) evapotranspiration models were not designed to estimate ETo under climatic change conditions. In its current state, this set of equations is limited to model climate change and its effects on ETo, and can be used to perform sensitivity analysis at most.

Due to the complexity of global warming effects on temperature estimations, IPCC established different scenarios of climate change that take on account expected variability of conditions instead of a single calculation of greenhouse gas emission, and its relationship with the raise of global temperature. Each exponential shows answers based on different actions to mitigate climate change impact; for example: The higher tendency (upper exponential) is constructed under a vision of total failure in the efforts to diminish the effects of global climate change. The two center exponentials are associated with the hypothesis of the proper function of carbon market, *i.e.*, the state and private actions are effective to diminish the greenhouse gas emission which allows a moderately lesser impact of climate change. Finally, the lower exponential of the graph assumes that all involved countries sign the Kyoto Protocol to mitigate climate change impact.

2. Background

Based in these scenarios, efforts have been made in order to estimate climatic change effect on irrigated agriculture and dryland farming in Mexico. In dryland farming case, sensibility studies were elaborated with two specific models, the CERES-MAIZE and GFDL-R30 models. The CERES-MAIZE model simulated the performance of different corn crop productions on non-irrigated areas, with varied weather, seed and soil conditions. On the other hand, the GFDL-R30 model created theoretical agro climatic maps (*i.e.*), maps of potential suitable regions for certain crop production. Both models were applied in the following municipalities: Atlacomulco (state of Mexico), Izúcar and Ixcamilpa (Puebla), Tuxpan and Coatepec (Veracruz) and Magdalena and La Huerta (Jalisco) (**Figure 1**). These models were used considering arbitrary temperature (+2˚C and +4˚C) and pre-cipitation (±10% and ±20%) increases, and even combinations of both. The CERES-MAIZE model simulation results indicate a reduction in corn crop performance in all studied regions (except Atlacomulco), which means a negative climate change effect. Moreover the GFDL-R30 model results show that the simulated regions and their agro climatic areas are unfit for crop production under potential climatic change scenarios. For irrigated agriculture, the first studies elaborated in Mexico about climate change effects in evapotranspiration of crops was made in the Mexican Institute of Water Technology (IMTA in its Spanish acronym), about a decade ago. This preliminary study consisted in the application of a FAO radiation model to estimate the effects of climate change on ET annually in Mexico. **Figure 2** shows the obtained results with the radiation model, which consist of a set of ET isolines on a national scale, calculated under a climate change scenario with actual temperature conditions. **Figure 3** depicts the ET annual estimates under a 3˚C increase of global temperature scenario [1].

The results of the sensitivity analysis made in this study indicate that the most vulnerable zone is the north of

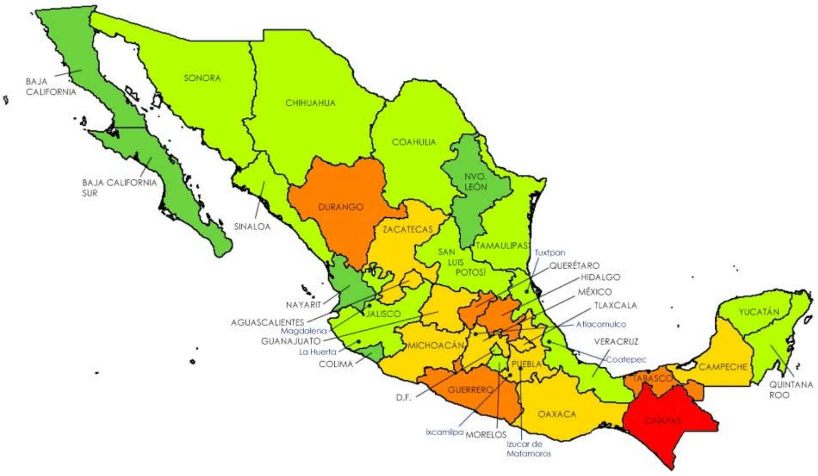

Figure 1. Location where were applied the The CERES-MAIZE models: Atlacomulco (state of Mexico), Izúcar and Ixcamilpa (Puebla), Tuxpan and Coatepec (Veracruz) and Magdalena and La Huerta (Jalisco).

Figure 2. ET isolines under current temperature conditions [1].

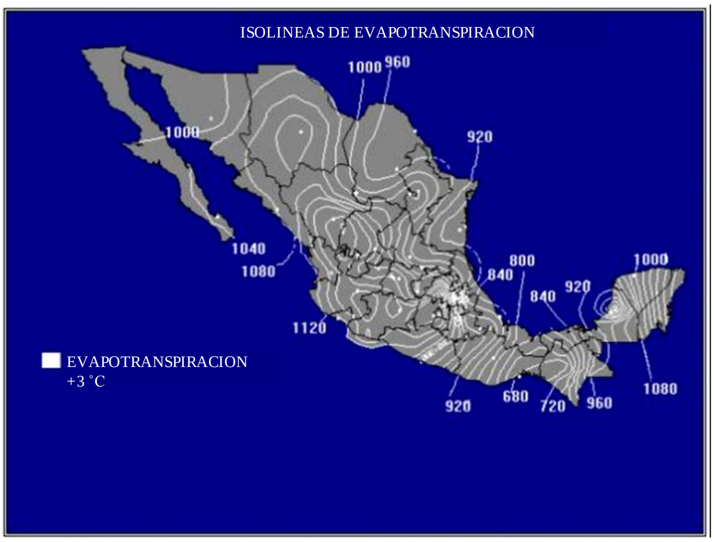

Figure 3. ET isolines with a 3˚C increase on temperature [1].

Mexico, wherein the increase of ET is greater in comparison to the rest of the country; up to 8% annual average for a +3˚C growth in mean annual temperature. Although the results of this study are indicative, they allow an idea of the increment of water for crop irrigation. Even without considering a climate change scenario, an important rise in irrigation water demand is expected by 2025 in México, as explained in **Table 1** (this increase is estimated by 16.5% between 1995 and 2025).

3. ET Estimations Made with Hargreaves-Samani Method and Regional Data

The indicative preliminary study on climate change effects in ET that used the radiation method mentioned above has several additional limitations to the ones indicated in the introduction. These are the most important: a) The IPCC scenarios were used without data on regional temperature; the process of deriving information from large scale models (global models) to regional scale models was not done; b) The same temperature increments were used for different seasons (not regionalized); c) Equal temperature increments were used for all months of the year.

A research was conducted to correct these limitations. It was made under a cooperative agreement between IMTA and the Autonomous University of Chiapas (UNACH in its Spanish acronym). The following methodology was used:

a) *A method for calculating ET on the northern region of Mexico was selected.* This method was to meet certain requirements, including: the usage of few variables to estimate ET, for the lack of meteorological data prevented the use of the Penman-Monteith (PM) equation; accuracy in the ET estimate results, or close to parallel the precision of the PM equation and to serve as reference for different researchers as a precise method for ET assessment.

b) *The site to calibrate the method was selected.* Irrigation district 041 in Valle del Yaqui, state of Sonora was chosen, due to Sonora being one of the most important states in the northern region of the country and having a network of automated meteorological stations for the calibration of the selected method.

c) *The method was calibrated to estimate ET.* The daily and monthly results were compared against the estimated results obtained from the witness method (Penman-Monteith ASCE).

d) *The northern states of Mexico which include major irrigation districts were selected.* Nine states from the north were designated, as well as 160 meteorological stations that hold records with more than 30 years worth of data.

e) *Climate change scenarios were selected.* Once the method for evapotranspiration estimation was calibrated, two types of scenarios were picked, the A1B and the A2. The results obtained with the A1B scenario are presented in this work.

f) *Data of average anomalies in temperature obtained from IPCC models on A1B scenarios was used.* The

Table 1. Water consumption for irrigation in Mexico, real and predicted [2].

Population ad water data	Historical data						Predictec
	1950	1960	1970	1980	1990	1995	2010	2025
Population (M)	27.49	36.71	50.4	67.05	84.5	93.97	118	136.72
Irrigation area (M ha)	1.6	3	3.58	4.98	5.6	6.2	6.8	7.1

results processed from 16 climate models that participated in IPCC for the fourth evaluation report were analyzed by the hydro-meteorology IMTA team using the downscaling technique. The data was later used in the research.

g) The ET data in the "zero scenario" (current conditions), and the average temperature anomalies calculated for year 2030 *were compared*. The ET was evaluated with the current scenario anomalies (present temperature conditions) and the estimated stipulation for year 2030; after that, a comparison was made between both sets.

Therefore, for a precise ET calculus under climate change scenarios (sensibility analysis) it would be convenient to use the Penman-Monteith ASCE equation for all the northern part of the country, as the one stated below [3]:

$$\lambda Et_o = \left(\frac{\Delta}{\Delta+\gamma^*}\right)(Rn-G) + \left(\frac{\gamma}{\Delta+\gamma^*}\right)\frac{k_1(0.622)\rho\lambda}{P_a}\frac{1}{r_a}\left(e_z^o - e_z\right) \tag{1}$$

where:

ET_o = Evapotranspiration of referenced crop (mmd^{-1})
Rn = Net solar radiation on the surface of the crop ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)
G = Sensitive heat flux from soil ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)
Δ = Vapor pressure curve inclination (kPa)
γ = Psychometric constant ($\text{kPa}^\circ\text{C}^{-1}$)
γ^* = Modified psychometric constant ($\text{kPa}^\circ\text{C}^{-1}$)
ρ = Density of the fluid at a constant pressure ($\text{kg}\cdot\text{m}^{-3}$)
λ = Latent vaporization heat ($\text{MJ}^{-1}\cdot{}^\circ\text{C}^{-1}$)
P_a = Atmospheric pressure (kPa)
e_z^o = Saturated vapor pressure of air at z height (kPa)
e_z = Vapor pressure of air at z height (kPa)
r_c = superficial resistance to vapor transfer (sm^{-1}), or simply surface resistance.
r_a = Aerodynamic resistance to sensible heat and vapor transfer (sm^{-1}), or aerodynamic resistance.

However this equation needs variables and data that are not available in all studied places. For this reason an analysis was made on over a dozen of empiric methods that would allow calculating with precision the ET. Thus the Hargreaves-Samani (HS) method was selected to estimates these variables. The HS method originates from [4] and [5] though various adjustments were made to the initial equation introduced on 1975. This HS equation estimates the evapotranspiration of a harvest using grass as reference. The HS equation is [3]:

$$ET_o = 0.0023 R_a (TD)^{1/2} (t_m + 17.8) \tag{2}$$

where:

TD = Difference between maximum and minimum temperature (˚C)
R_a = Extraterrestrial radiation (mmd^{-1}), (R_a Variable is obtained from tables or with a equation)
Rs = Solar radiation (mmd^{-1})

This method is recommended by several investigators, [3] [6]-[9] for its precision. It can even, if required, be used to estimate ET for periods of five days and on daily scale [10] and [11]. It is a simple method that only needs extraterrestrial radiation and minimum and maximum temperature data to calculate ET. For its calibration the daily and monthly information collected from 10 stations in irrigation district 041, Valle del Yaqui (**Figure 4**) was used, Stations have daily measurements of radiation, relative humidity, wind speed, temperature and precipitation; some with over ten years of data.

In **Figure 5** and **Figure 6** are shown the results of the comparison between the HS and the Penman-Monteith ASCE methods for the CIANO station, located in block 910, lot 3, in the following coordinates of Yaqui Valley: 27˚22'14 North latitudes, 109˚55'4 West longitudes.

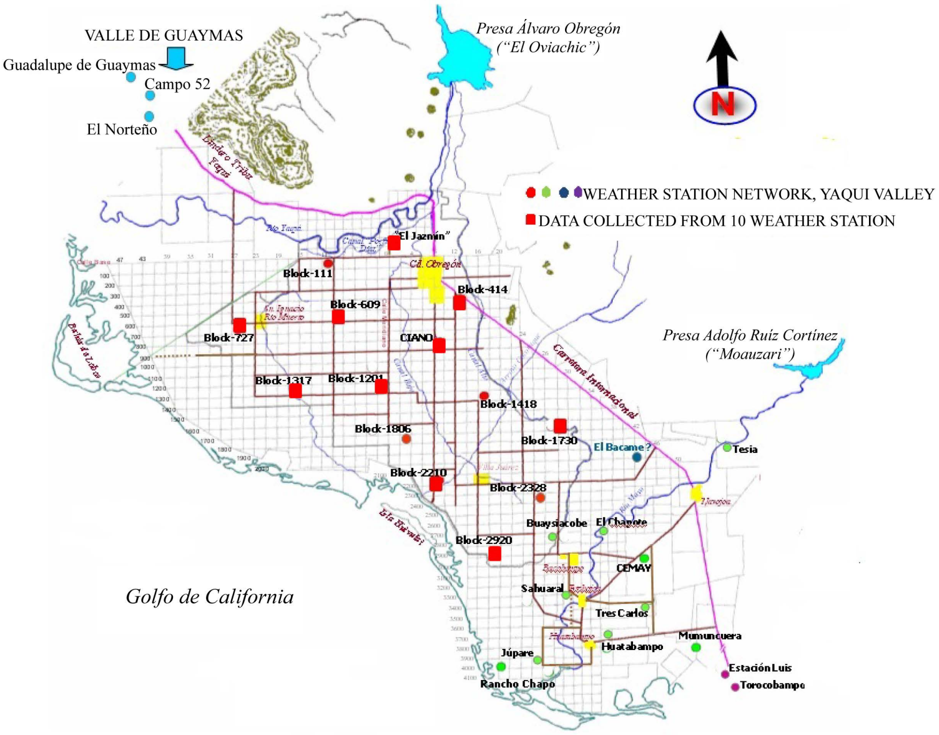

Figure 4. The small circles and small rectangle represents the weather stations network, Yaqui Valley Sonora Mexico.

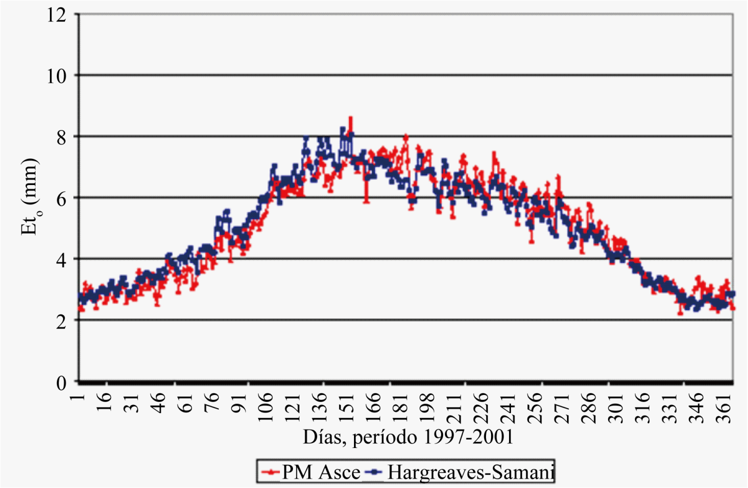

Figure 5. Penman-Monteith (PM) ASCE vs. Hargreaves-Samani comparison on a daily scale.

In both cases the linear regression coefficient is higher than 0.92, with a standard deviation from the model of 1.63 mm, a quadratic error of 0.44 in the first case and 0.6 in the second case, as well as 0.93 model efficiency for the daily scale and 0.97 for the monthly scale. Once the precision of the method was proven, the selection of the IPCC climate change scenarios proceeded. The results presented in this work were obtained under the A1B scenario considerations. The A1 family is characterized by a rapid economic growth, a global population that will reach its peak in 2025 and a society that adopts and uses efficient technologies. This family divides into two: A1F1 (intense use of petroleum fuels) and A1B (balanced use of different energy sources); the latter is considered as the most likely scenario to occur, according to the scientific community.

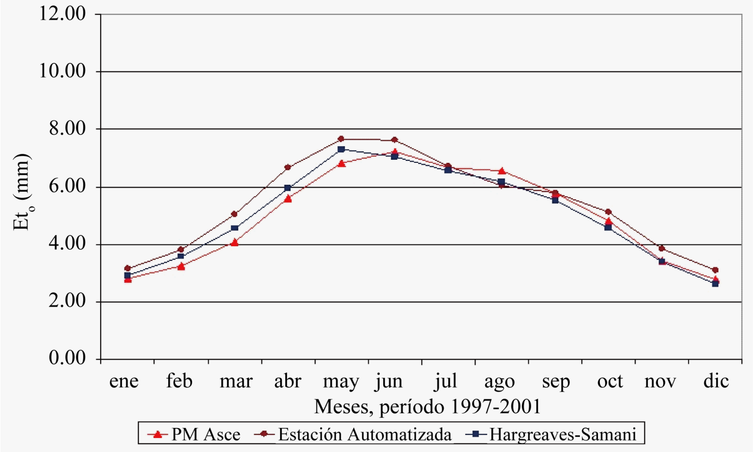

Figure 6. Penman-Monteith (PM) ASCE vs. Hargreaves-Samani comparison on a monthly scale.

When the scenario was selected, an analysis of the obtained information on the global IPCC models followed. Large scale climate models are not able to adequately simulate climate variations at regional level (regional climate behavior is a stochastic process, conditioned by global climate), therefore it is necessary to use downscaling techniques to complete the process. Downscaling techniques allow the derivation of information from global models to regional ones through the statistic inference of the relationship between both scales. Consequently, investigators from the sub-coordination of hydrometeorology of IMTA[2] studied the results of 16 climate models addressed in the Fourth Evaluation Report (2007), from where the monthly average anomalies registered during the 1960-1989 period for the A1B scenario were obtained from the models using statistic downscaling techniques. With the estimated temperature anomalies for year 2030 (in A1B scenarios), simulations were performed to calculate ET in the principal irrigation districts of the following states: Baja California, Baja California Sur, Chihuahua, Sinaloa, Sonora, Tamaulipas, Nuevo León, Coahuila y Durango (**Figure 7**). **Figure 8** shows, in ˚C, the difference between the actual and the 2030 scenarios for more than 160 stations in this states (the variability observed in **Figure 8** is due to regionalization of temperature through downscaling techniques).

The result of the sensitivity analysis with the HS method is shown in **Figure 9**, where the differences in percentage of ET between the actual and the 2030 scenarios can be observed.

Figure 10 shows the ET isolines for July in the current scenario while **Figure 11** illustrates ET isolines for the 2030 scenario.

When both figures are compared, an increment by 7% in the ET is clear between the actual scenario and the 2030 scenario, as well as a major density of isolines in 2030 that indicates greater temperature gradients.

4. Conclusions

Global climate change is a theme that has gained relevance in the last decade, and one that is studied from different perspectives: socioeconomic, technical and scientific. There is worldwide concern about the potential repercussions of climate change on natural resources; in Mexico's case, the climate change effects are worrisome, especially in the agriculture sector in the north of the country for it is a wide region with scarce water resources. One of the first studies in Mexico about these potentials risks was made about a decade ago in the Mexican Institute of Water Technology. This preliminary study consisted in the application of the FAO radiation model to estimate the climate change effects on evapotranspiration, and the results obtained were a set of ET isolines under diverse scenarios that indicated the most vulnerable zone in the country, the northern region of Mexico. In this region the annual increment of ET is 8% greater than the rest of the country for a raise of 3˚C in mean temperature. Due to some limitations in this preliminary investigation (e.g., global temperature data was used without regionalizing it), it was decided to make more detailed studies to estimate the climate change effects on ET on a regional scale, using the downscaling method to adjust temperature data. In this study a new methodology to estimate the ET before climate change scenarios is introduced, which includes the selection of the Hargreaves-Samani method (HS), calibrated and compared against the Penman-Monteith ASCE method in various irrigation districts in the

Figure 7. Principal irrigationdistricts in thenorth of Mexico: Baja California, Baja California Sur, Chihuahua, Sinaloa, Sonora, Tamaulipas, Nuevo León, Coahuila y Durango.

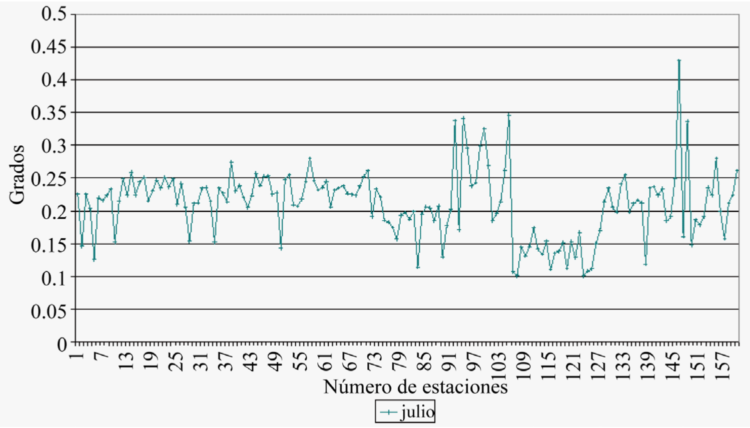

Figure 8. ET Difference between the current and the 2030 scenarios for the month of July (in ˚C).

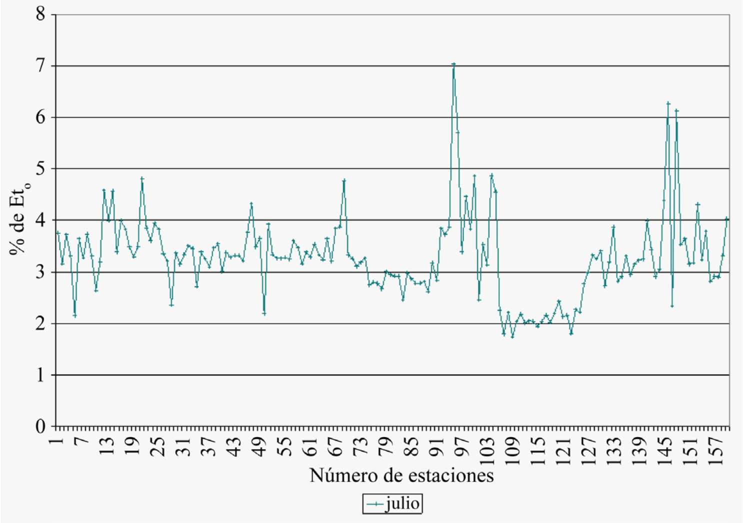

Figure 9. Percentage difference of ET for the month of July between the current and 2030 scenarios.

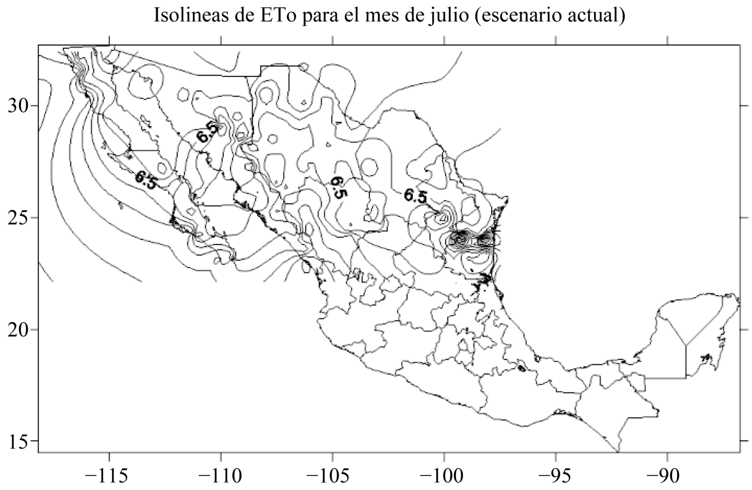

Figure 10. ET isolines in July for the current scenario.

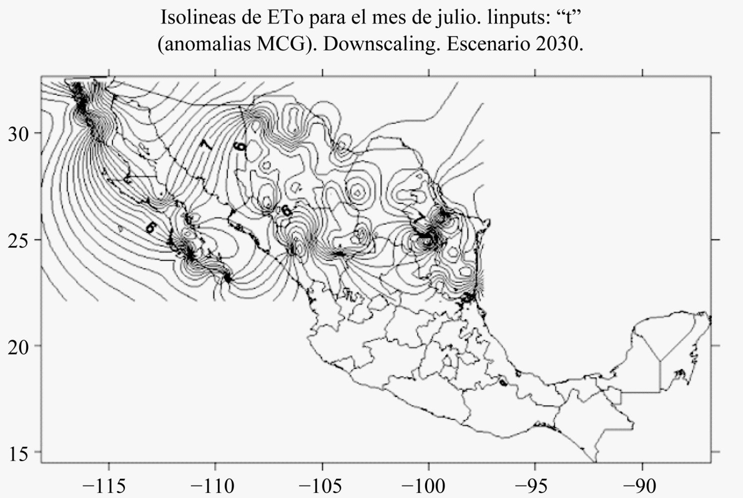

Figure 11. ET isolines in July for the 2030 scenario.

northern part of the country, obtaining ET estimations with a 93% precision. This procedure was applied to nine states in north Mexico: Baja California, Baja California Sur, Chihuahua, Sinaloa, Sonora, Tamaulipas, Nuevo León, Coahuila y Durango. The principal results are enunciated as follows: the ET variations between the contemporary scenario and the 2030 scenario are quite significant, according to the data of 160 meteorological stations; for temperature variations between 0.1˚C to 0.45˚C the corresponding ET fluctuation goes from 2% in the current scenario to 7% in the 2030 scenario. These obtained percentages are greater than the ones expected to happen for the precision of the method.

It is important to note that a 7% rise of ET (related to a regional temperature increase of approximately one degree) would represent in practice having more millions of m^3 of water in dams to satisfy the water demand of crops. With the intention to proportionate an idea of this additional water volume, data from the irrigation water volumes used in Sonora in 2004 was taken. That year, a surface of 631 200 hectares was irrigated with a total of 6315 Mm^3 of water for agricultural purposes only (superficial and underground water).

Considering that the average efficiency in water consumption for irrigation is 48%, 3283 Mm^3 of water were lost, and only 3031.20 Mm^3 were employed. The 7% of the used water volume is 211.58 Mm^3, which is almost a third of the Adolfo Ruiz Cortinez dam capacity. Therefore 211.58 Mm^3 would be the additional water demand for a 0.5˚C temperature increase in Sonora. It is prudent to point out that these results are only indicative because of the limitations the evapotranspiration methods have to do ET estimations under climate change scenarios and the complexity of the theme, however, it is also important to highlight that the results allow to form an idea of the potential effect of mean temperature increase in irrigation zones. Because of the importance of the topic and the need to calculate more accurately the effects of climatic variability in irrigation and seasonal areas, the investigation must continue as well as the developing of new calculation methods that include not only the climate change effect, the needs and availability of water for crops but also the consequence of these changes on crop performance. It's important to develop and adapt methodologies that allow the estimating of crop functionality by using biological simulations, also ones that consider the potential effect of carbon dioxide and water availability. It is also important to obtain the anomaly values of "t" in a lower scale (downscaling), e.g. on a watershed scale or an irrigation district scale to obtain more accurate ET estimations under climate change scenarios.

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