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REMEXCA

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Article

Effects of climate change on reference evapotranspiration and their impact on corn production

Alejandro Cruz-González[1]
Ramón Arteaga-Ramírez[1]
Ignacio Sánchez-Cohen[2,§]
Héctor Flores-Magdaleno[3]
Jesús Soria-Ruiz[4]
Alejandro Ismael Monterroso-Rivas[5]

1 Posgrado en Ingeniería Agrícola y Uso Integral del Agua-Universidad Autónoma Chapingo. Carretera México-Texcoco km 38.5, Chapingo, Estado de México. CP. 56230. Tel. 712 2474131. (alex-cg20@hotmail.com; rarteagar@taurus.chapingo.mx).

2 Centro Nacional de Investigación Disciplinaria en Relación Agua-Suelo-Planta-Atmósfera-INIFAP. Margen derecha canal Sacramento km 6.5, Zona industrial Gómez Palacio, Durango. CP. 35140. Tel. 871 1590105.

3 Colegio de Postgraduados-Campus Montecillo. Carretera México-Texcoco km 36.5, Montecillo, Texcoco, Estado de México. CP. 56264. (mhector@colpos.mx).

4 Laboratorio de Geomática-Sitio Experimental Metepec-INIFAP. Carretera Toluca-Zitácuaro, Zinacantepec, Estado de México. CP. 52176. (soria.jesus@inifap.gob.mx).

5 Departamento de Suelos-Universidad Autónoma Chapingo. Carretera México-Texcoco km 36.5, Chapingo, Estado de México. CP. 56230. Tel. 595 9521633. (aimrivas@correo.chapingo.mx).

Autor para correspondencia: sanchez.ignacio@inifap.gob.mx.

Abstract

The effect of climate change on reference evapotranspiration (ET_0) in the Atlacomulco Rural Development District was evaluated; it is considered one of the most important variables in the management of water resources and the programming of agricultural irrigation. The climate change scenarios were projected using the general circulation model, HadGEM2-ES, with two representative concentration trajectories, 4.5 and 8.5, for two time horizons, 2021-2040 and 2041-2060, using the LARS-WG software; subsequently, the ET_0 was determined with the Ref-ET program to finally model the effective precipitation, the crop evapotranspiration, and the irrigation requirement for corn crops with the CROPWAT software of FAO. The results show that, during the base period 1985-2020, ET_0 ranges from 3.93 to 4.17 mm day^{-1}; RCP 4.5 projects an increase of up to 2.6 and 4.1%, whereas RCP 8.5 an increase of 4.2 and 7.4%, respectively, for both horizons; this increase is reflected on the effective precipitation, crop evapotranspiration, and irrigation requirement towards the four scenarios; the most vulnerable areas are the southeast and northwest. Through the variables analyzed, it was possible to identify that the effective precipitation is not sufficient to meet the evapotranspiration demands of the corn crop, so it is necessary to cover the irrigation requirement with some water input. The data obtained can be used to generate adaptation and mitigation strategies to improve the efficiency of water use in the Atlacomulco Rural Development District and propose agricultural management alternatives

Keywords:

crop evapotranspiration, CROPWAT, effective precipitation, irrigation requirement, LARS-WG.

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Introduction

Current anthropogenic greenhouse gas emissions accelerate the conditions that contribute to climate change at the global level (IPCC, 2019). Increased air temperature, irregular distribution of precipitation, presence of extreme storms, increased evapotranspiration, and fluctuation between dry periods are some visible effects of the climate change phenomenon that contribute to the changing water balance, which can significantly affect the water cycle and ecohydrological patterns (Zeng et al., 2021).

In agronomy, the terms reference evapotranspiration (ET_0) and crop evapotranspiration (ET_C) are used; the former represents the evapotranspiration of a hypothetical reference crop (grass) in active growth, adequately irrigated, and characterized by defined values of height, surface resistance and albedo, which is, therefore, associated with meteorological evaporative demand, whereas ET_C refers to the actual water needs of the crops and operational monitoring of soil and plant water balance; in the FAO-56 approach, crop evapotranspiration is estimated by combining a reference evapotranspiration (ET_0) and crop coefficients (Kc) that express both plant transpiration and soil evaporation (Allen et al., 1998; Xiang et al., 2020).

According to the study by Monterroso-Rivas et al. (2021), they identified that the projected changes for meteorological variables associated with climate change affect the behavior of ET_0, modifying crop water requirements and pronouncing a long-term drought period; therefore, a better understanding and evaluation of the spatial-temporal trends of this variable is of great importance for crop management and water resource planning in the agricultural sector at scale regional and global.

It is likely that ET_0 and, consequently, ET_C as well as the irrigation requirement (IR) of a crop are perceived to be severely affected by climate change given their close relationship with air temperature and precipitation; as a result of this variability, ET_0 presents increases or decreases, depending on the global region; therefore, it is essential to understand the change in trend of this variable to improve crop growth and irrigation water management, the variation of ET_0 is a critical step to understand how climate change affects hydrological processes (Fan et al., 2016).

In this research, the objective was to model and analyze ET_0 and, consequently, its related variables: ET_C, EP and IR, for corn crops in the DDRA under climate change scenarios using the following programs: Long Ashton Research Station Weather Generator (LARS-WG), Reference Evapotranspiration-Standardized Calculations (Ref-ET), and Crop Water and Irrigation Requirements Program of FAO (CROPWAT). In 2020 alone, this district contributed approximately 35.3% of the harvested area with 122 088 ha and 41.4% of the production with 516 438 t of corn in the State of Mexico, being the most important agricultural area in terms of corn productivity at the state level (SIAP, 2021).

Materials and methods

Study area

The DDRA is located in the physiographic province of the Trans-Mexican Volcanic Belt, which is part of the upper basin of the Lerma River, and it is located between parallels 19° 25’ and 20° 5’ north latitude and between 99° 30’ and 100° 17’ west longitude (INAFED, 2018). The DDRA is made up of 10 municipalities: Acambay, Atlacomulco, El Oro, Ixtlahuaca, Jocotitlán, Jiquipilco, Morelos, San Felipe del Progreso, San José del Rincón, and Temascalcingo (Figure 1), belonging to the northern region of the State of Mexico (SIAP, 2021).

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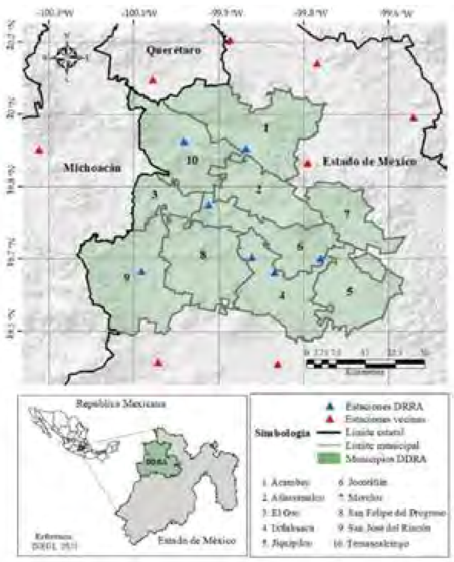
Figure 1. Spatial location of the DRRA and the meteorological stations.



In the DDRA, there is a predominance of subhumid temperate climate with rainfall in summer (CW), the average annual temperature is 13.4 °C, an average minimum temperature of 5.1 °C and a maximum of 21.7 °C, with the highest temperatures occurring in April and May, whereas the lowest temperatures occur in December and January, the average annual rainfall is 780 mm year^{-1}, with 75% of the annual total occurring between June and September (Cruz-González et al., 2023).

Climate data

The meteorological variables of precipitation, maximum and minimum temperature, as well as solar radiation were obtained from 15 stations of the ESSENGER meteorological data system of the National Institute of Forestry, Agricultural, and Livestock Research (INIFAP), for its acronym in Spanish (Rodríguez-Moreno, 2021), with a continuous daily record of 36 years from 1985 to 2020. These stations are located in the areas of agricultural use and productive potential in the DDRA (Figure 1).

LARS-WG

LARS-WG 6.0 is a stochastic climate generator that can be used to create climate change scenarios; this program incorporates GCM projections of the CMIP5 set (Semenov and Stratonovitch, 2015). The calibration was performed according to the procedure recommended by Semenov and Barrow (2002).

The observed meteorological data from the INIFAP stations (1985-2020) were used to generate two representative concentration trajectories: RCP 4.5 (moderate emissions) and RCP 8.5 (high emissions), for two time horizons: 2021-2040 and 2041-2060, selecting the HadGEM2-ES (Hadley Center Global Environment Model) GCM, which has a high effective climate sensitivity to the increase in CO_2 in addition to the fact that this model has been used in climate change scenarios for Mexico (INECC, 2022). These climate change scenarios were then used as input data in Ref-ET and CROPWAT.

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Ref-ET

The software used was Ref-ET version 4.1, which provides standardized ET_0 calculations for fifteen of the most common methods and equations currently used in the United States of America and Europe. The calculations are based on the weather data measurements that the user enters. For this research, the Hargreaves-Samani method was used given the conditions of the availability of historical meteorological data and data projected to climate change, carrying out the methodological process recommended by Allen (2016).

CROPWAT

Cropwat 8.0 is a computer program to support decision making in the agricultural sector and was developed by Smith (1992). It depends on a series of equations to estimate: ET_0, ET_C, EP, and IR and PR, using as input data: crop, soil, and climate data, which support the calculation of water requirements for different cropping patterns under irrigated and rainfed conditions (Clarke et al., 2001). To accurately estimate the requirements of corn crops in the DDRA, the parameters describing the ET_C, EP, and IR were calculated from the methodologies proposed by Smith (1992); Allen et al. (1998).

Climate data

The daily climate variables of ET_0 and total precipitation (TP), both those of the historical period and those projected with climate change scenarios, were added to monthly values to be used as input data in the Cropwat model.

Crop data

The crop parameters were determined from the dates of sowing, development, and harvest of some landrace and hybrid corn varieties for high valleys reported in the DDRA by Tadeo-Robledo et al. (2015), in which the following was determined: a cycle of 230 days with a sowing date of April 25 and a harvest date of December 10, the length of the initial stage was 35 days (K_C= 0.3), development stage 55 days (K_C= 1.2), mid- season 90 days (K_C= 1.2), and end of season 50 days (K_C= 0.35); the K_Cs used in this study were those recommended by Smith (1992); Allen et al. (1998).

Crop evapotranspiration (ET_C

The ET_C of the corn crop was calculated from equation 1: ET C = K C × ET 0 1). Where: ET_C= crop evapotranspiration in mm dia^{-1}; K_C= crop coefficient, dimensionless; ET_0= reference crop evapotranspiration in mm day^{-1}.

Effective precipitation (EP)

The USDA Soil Conservation Service method was used to calculate the annual EP using the following criteria: when total precipitation (TP) is > 250 mm year^{-1}, EP is obtained by equation EP= 125+ 0.1 × TP 2). Where: EP= effective precipitation (mm year^{-1}); TP= total precipitation (mm year^{-1}).

Irrigation requirement

From the ET_C calculated for the corn crop and the EP values, the IR was calculated using equation IR= ET c - EP 3). Where: IR= irrigation requirement (mm year^{-1}); ET_C= crop evapotranspiration (mm year^{-1}); EP= effective precipitation (mm year^{-1}). The spatial distribution of the ET_0, EP, IR, and ET_C variables was performed with the inverse distance weighting (IDW) method with ArcGIS 10.8 software.

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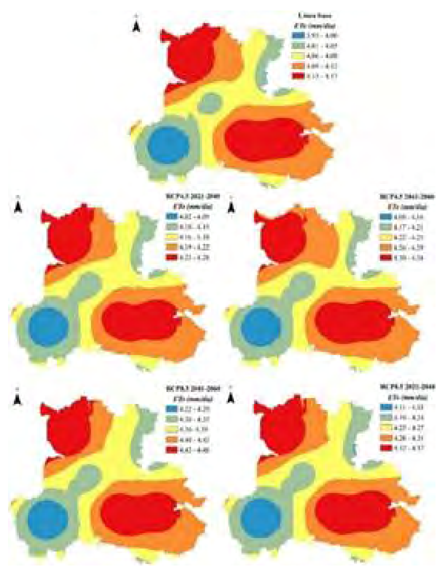
Results and discussion

Potential changes in ET_0

The result presented in Figure 2 indicates that the ET_0 values in the baseline are lower than the four scenarios projected in the future, the intensity pattern is located in the southeast and northwest areas of the DDRA, the opposite areas are those with the lowest ET_0 values. The trend of ET_0 in the first period RCP 4.5 2020-2041 is similar to the base time scale. However, there is a considerable difference compared to RCP 4.5 2041-2060 and RCP 8.5 2021-2040, the largest projected increase is towards RCP 8.5 horizon 2041-2060. Zeng et al. (2021) identified that the increases in ET_0 are projected on a smaller scale towards RCP 4.5 and on a larger scale towards RCP 8.5, due to the greater climate radiative forcing driven by the increase in greenhouse gases in this scenario.

Figure 2. Daily spatial distribution of the average daily ET_0 in the DDRA.



On a monthly scale, ET_0 presents a similar behavior in all the stations analyzed; the highest values occurred in March, April, May and June, reaching 5 to 6 mm day^{-1}, whereas the lowest ET_0 occurs in November, December and January, with values close to 3 mm day^{-1}. In Mexico, Monterroso-Rivas and Gómez-Díaz (2021) identified a general increase in ET_0 as a result of climate change, they project an increase in air temperature and a decrease in relative humidity, this increase in ET_0 could limit productivity in some regions of the country.

This situation has a significant impact on crop plant growth and yield, and climate change has a potential influence on crop water demands (Fan et al., 2016). Ben-Hamouda et al. (2021), in the Italian region of Emilia-Romagna, projected with climate change scenarios of the GCMs; RCA4, RACMO22E, and Copernicus CDS, the annual average ET_0 variable, in the region there are 735 mm yr^{-1} in the reference period 1981-2005 and it is expected to reach values ranging from 764 mm yr^{-1} for RCP 4.5 to 772 mm yr^{-1} for RCP8.5 towards the 2021-2050 horizon.

Crop evapotranspiration

The baseline presents an accumulated of 828-883 mm year^{-1} during the agricultural cycle (April 25 to December 10), with a greater incidence towards the northeast and southeast of the district, where the areas with the highest ET_C are well focused, while for the four scenarios, the future trend is towards an increase, which is perceived with a greater pronouncement in RCP 8.5 2041-2060, reaching 884-943 mm year^{-1}. The scenario with the least change is RCP 4.5 2021-2040, which shows values that range from 842 to 926 mm year-1 for the largest DDRA area (Figure 3). The ET_C projects an increase of 1.9% in the RCP 4.5, 21-40 scenario to reach 6.4%. towards RCP 8.5, 41-60.

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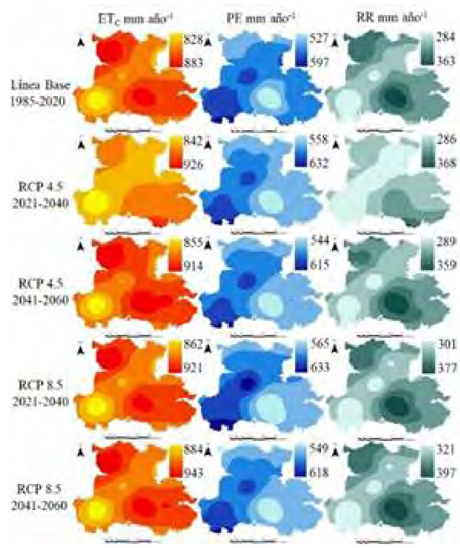
Figure 3. Spatial distribution of ET_C, EP and IR in the DDRA.



Compared to this study, Şen (2023) documented a more severe increase in corn ET_C for the Adana Province, Turkey, in which he determined an average of 615.5 mm year^{-1} for the period between 1971 and 2000, and reported that under the RCP 4.5 scenario, ET_C increased by 9.2% for 2025-2054 and 11.7% for 2069-2098, and in RCP 8.5, ET_C values showed a substantial increase of 20% for 2069-2098, compared to the historical period. On the other hand, Gabr (2023) reported, in a study for Egypt, that the ET_C for corn will increase by 5.1% and 5.9% according to RCP 4.5 2023-2080 and 2081-2100, respectively, whereas for RCP 8.5 2023-2080 and 2081-2100, it will increase by 7.7% and 9.7%, respectively, compared to the historical ET_C calculated for the 1990-2022 period, which corresponds to 1 060 mm year^{-1}. These studies made it possible to measure the increases in ET_C at a global level due to climate change.

Effective precipitation

Figure 3 shows the results of the EP; in the baseline during the agricultural cycle, there is a minimum EP of 527 and a maximum of 597 mm year^{-1}, heterogeneously distributed in the DDRA, the lowest values are found in the southern part, whereas the lowest are located in the southeast zone.

For climate change projections, a very similar behavior is maintained in the spatial distribution of EP, identifying increases in all scenarios compared to the baseline; in RCP 4.5 horizons 2021-2040 and 2041-2060, increases of 558-633 and 544-615 mm year^{-1} were identified while for RCP 8.5 towards the horizons 2021-2040 and 2041-2060, EP reaches 565-633 and 549-618 mm year^{-1}, respectively. It is observed that the largest increases occur in both horizons of the RCP 4.5 scenario. For the EP, an increase in RCP 4.5 of 5.1% and 6.3%, respectively, is identified in both horizons and a smaller increase is projected towards RCP 8.5, with 2.7% and 3.3%.

The results of Ruiz et al. (2011) reported that, for the High Valleys in Mexico (2 200 to 2 600 masl), such as the DDRA, a decrease in precipitation will be projected due to climate change; -4.1% (2011-2020), -3.3% (2031-2040) and -0.4% (2051-2060) with the lowest emissions scenario. Despite these changes, it is mentioned that precipitation would still be sufficient to cover the demand for water in the corn crop, this study disagrees with these scenarios; however, uncertainty was greater in their precipitation trends, probably due to the projected scale and the type of GCM used. Worldwide, cases have been documented in which EP increases compared to the base period, such as in Roba et al. (2021), where the base period (1984-2013) registers an EP of 813 mm year^{-1} under the forcing of the RCP 4.5 scenario, whereas for the 2014-2043 and 2044-2073 periods, an EP of 844 mm year^{-1} and 828 mm year-1 is estimated, respectively.

Revista Mexicana de Ciencias Agrícolas

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Watering requirement

Of the four climate change trajectories in this study, three show an increase in irrigation requirements compared to the baseline, except for RCP 4.5 2041-2060, as observed in Figure 3, in which a range of 284-363 mm year^{-1} was identified, with the lowest irrigation requirements being identified in the central area of the district, whereas the highest IRs are found in the southeast zone; this condition prevails for all four scenarios.

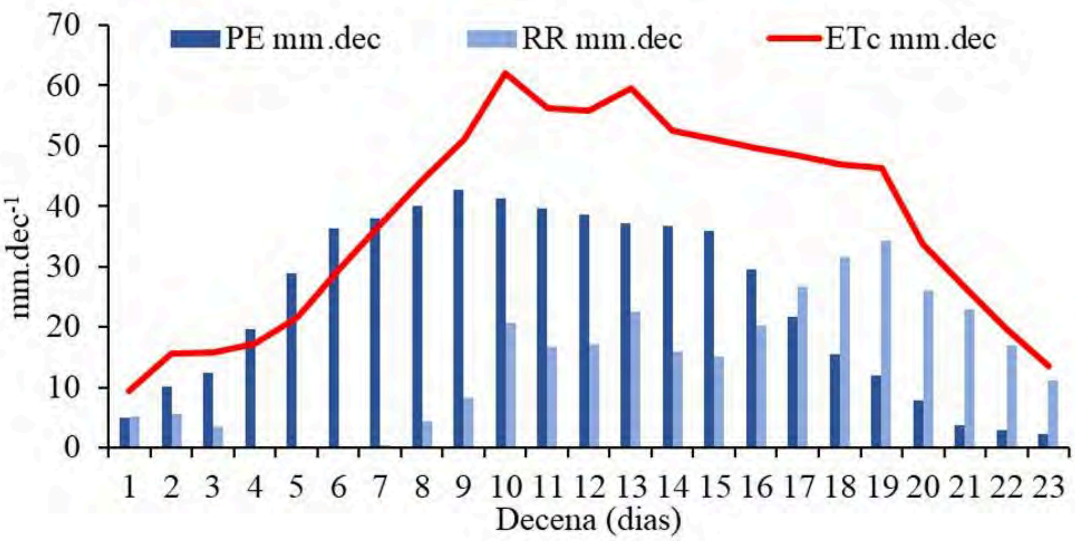
For the projection in RCP 8.5 horizon 2041-2060, a range of 321-397 mm year^{-1} is projected, this being the scenario with the greatest increase in irrigation demand, while the smallest increase in IR was for RCP 4.5 horizon 2041-2060, it is expected to reach 289-359 mm year^{-1}. #en (2023) reported the IR for the 1971-2000 period, which was 459.2 mm year^{-1}, while for RCP 4.5 2025-2054, the calculated IR was 546.5 mm year^{-1}; in contrast, for the 2069-2098 period, it was 558.8 mm year^{-1} and in the RCP 8.5 scenario, the IR values for the 2025-2054 and 2069-2098 periods were determined at 558.4 mm year^{-1} and 618.9 mm year^{-1}, respectively.

Relationship between effective precipitation, irrigation requirement, and crop evapotranspiration

The result shown by Cropwat allows us to identify the temporal behavior and the close relationship of ET_C, EP, and IR in relation to the water requirements of the corn crop in the agricultural cycle. Figure 4 shows the average of the stations analyzed in the DDRA, the result is shown for each ten-day period. When analyzing the baseline, it is observed that the ET_C increases over time, reaching the maximum values during the middle stage, and decreases according to the late stage, reaching up to 60 mm dec^{-1} in ten-day periods 10 and 13.

Figure 4

Average ratio of EP, IR and ET_C for corn in the DDRA, on a ten-day timescale. A: baseline (1985-2020).



It was possible to identify that the EP reached its maximum level in ten-day period 9, which corresponds to the beginning of the middle stage, and began to decrease until the end of the cycle; it is also observed that from ten-day period 7, the EP stops covering the needs of ET_C until ten-day period 23 when the agricultural cycle ends; it is during this period that there was an increase in the amount of IR for all ten-day periods. The RCP 4.5 and 8.5 climate change projections for both time horizons show a very similar condition to the baseline for each variable.

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Conclusions

Using climate projections from the HadGem-2 GCM, this study indicated an increase of ET_0 compared to the baseline (1985-2020), which was on a scale of 3.9 to 4.2 mm day^{-1}; the scenario with the lowest impact is RCP 4.5 with a range of 4 to 4.3 mm day^{-1}, whereas the scenario with the highest increase is for RCP 8.5 with a range of 4.1 to 4.5 mm day^{-1}. As a result of the increases in ET_0, significant increases are expected on the related variables: ET_C and IR.

The ET_C for corn in the DDRA was not fully satisfied by the EP; therefore, it is necessary to provide an amount of water through an irrigation system in order to cover the water deficit of the plant. However, the need for IR in the agricultural cycle is notable during the critical stages of flowering, silking, and grain filling, which coincide with the greatest water deficit, which potentially impacts crop yield. The methodology proposed in this research made it possible to identify potential future changes on ET_0 and related variables, with which it is possible to carry out management, mitigation, and adaptation strategies in the face of the impacts of climate change in the agricultural sector.

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