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Research Paper

Climate change impacts on the accumulation of growing degree days for corn in central Mexico

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ABSTRACT

Temperature is the main driving factor for plant development and growth and determines, in an important way, crop yields and is projected to increase under various climate change scenarios, which is expected to affect the thermo-sensitive crop like corn. Therefore, an attempt has been made to identify the spatio-temporal behavior of temperature, through the accumulation of growing degree days (GDD) in the Atlacomulco Rural Development District (ARDD) of Mexico. The maximum and minimum temperatures for the historical period 1985-2017 and projected under the SSP2-4.5 and SSP5-8.5 climate scenarios for distant time horizon (2061-2080) were analysed. It was identified that the average GDD in the ARDD corresponds to 1,440 ºC, being the northern zone the one with the highest accumulation with up to 1800 ºC. SSP2-4.5 identifies an increase of 298 ºC with respect to historical values, while SSP5-8.5 indicates the greatest increase of up to 33% in the accumulation of GDD with an average value of 1,914 ºC. The warming that is projected in the distant horizon allows identifying warm characteristics in the ARDD, which could increase corn production in this temperate climate.

Keywords: Climate scenario, LARS-WG, Thermal weather, Corn production, GDD, CMIP6.

Temperature is an essential factor that controls the rate of plant development and crop yield, however; extreme temperatures can be a limiting factor that slows plant growth and can lead to injury or even death (Mishra *et al.,* 2023). Decreasing or increasing temperatures above specific thresholds during the growing season triggers heat and cold stress in various agricultural crops, which limit their growth and metabolism (Kim and Lee, 2023). As temperature increases during the present century due to climate change, changes may occur in crop production zones, because temperatures will no longer remain within the critical range, conditioning the establishment of a crop (Anandhi, 2016). The growing degree days (GDD) index is based on the integration of the temperature above the base temperature (Tbase) of a crop, which can represent the thermal supply of a site, and also represents the thermal constant required for a crop to achieve the change between two phenological stages, and is a function of temperature (McMaster and Wilhelm 1997). GDD is widely used to determine the duration of plant phenological stages, and allows to evaluate the length of the growing season for different

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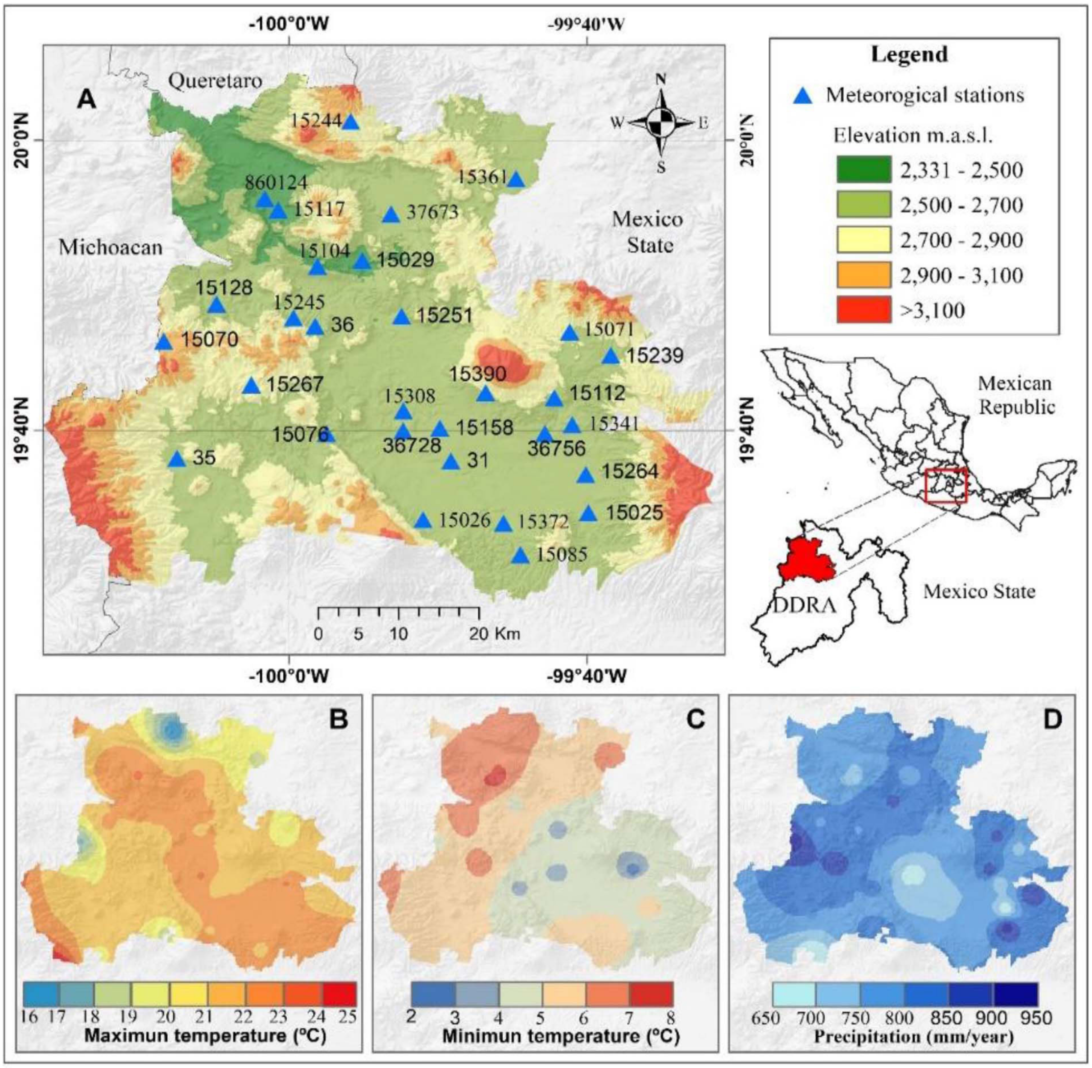

Fig. 1: (A) Geographic location of the Atlacomulco Rural Development District (ARDD), (B) maximum temperature, (C) minimum temperature and (D) precipitation.

locations, predict sowing dates, at the beginning of harvest and the length of crop cycles (Hussain *et al.,* 2023; Kumar *et al.,* 2023).

Maize is an important crop in Mexico and much of its production is concentrated in the high valleys, whose altitude is above 2200 masl. These zones are differentiated by their temperate climatic conditions; which determine a longer time in reaching the GDD necessary to comply with its phenological stages (Arista-Cortes *et al.,* 2018). Given the above premise, the objective of this research was to identify the spatio-temporal behavior of GDD accumulation, through historical and projected temperature series under a climate change scenario in the Atlacomulco Rural Development District (ARDD); a region that annually produces about 580 thousand tons of corn in an average area of 150 thousand hectares, and which corresponds to more than 40% of the total production of the State of Mexico (SIAP, 2024).

MATERIALS AND METHODS

Study area and data

The Atlacomulco Rural Development District (ARDD) is located in the northern region of the State of Mexico (Fig. 1), at an average altitude of 2600 meters above sea level, the dominant climate is temperate sub-humid with summer rains (CW), the average annual temperature is 13.4 °C, the minimum and maximum temperatures vary approximately between 5.1 °C and 21.7 °C respectively, the average annual precipitation is 780 mm (CONAGUA, 2023; Cruz-González *et al.,* 2023). Daily meteorological data of maximum and minimum temperatures, and precipitation for the period of 33 years (1985-2017) was obtained from 30 meteorological stations of the National Water Commission (CONAGUA, 2023) and the National

Table 1: Average minimum and maximum temperature changes for the months of the agricultural cycle, with the reference historical period (1985-2017)

Periods	Minimum temp. (°C)	Change (°C)	Maximum temp. (°C)	Change (°C)
Historical (1985-2017)	7.4	-	21.6	-
SSP2-4.5 (2061-2080)	9.0	1.6	23.6	2.0
SSP5-8.5 (2061-2080)	10.1	2.7	24.5	2.9

Institute of Forestry, Agricultural and Livestock Research (INIFAP, 2023) (Fig. 1).

Climate change scenarios data

Two climate change projections were generated using the statistical downscaling software LARS-WG 8.0 for the maximum and minimum temperature variables (Semenov and Stratonovitch, 2015). The CMIP6 MRI-ESM2-0 General Circulation Model (GCM) was used, which utilized the Shared Socioeconomic Paths SSP2-4.5 and SSP5-8.5, and was projected to a distant time horizon of 2061-2080. In this study, only the months corresponding to the corn agricultural cycle (May-October) were considered, in which the different phenological growth stages of the corn crop develop: germination and emergence VE (28 days), development stages V1-V12 (62 days), tasseling VT (33 days), as well as grain-filling and maturity R1-R6 (60 days) (Jasso-Miranda *et al.,* 2022).

Growing degree days computation

For the calculation of GDD, methodology described McMaster and Wilhelm (1997) in which upper threshold temperature (Tx) was used.

$$GDD = \left(\frac{T_{max+}T_{min}}{2}\right) - T_{base}$$

Where, Tmax is daily maximum temperature, Tmin is daily minimum temperature, and Tbase: base temperature.

This methodology proposes the following conditions for the calculation of the GDD.

Tmean: average temperature, $\left(\frac{T_{max+}T_{min}}{2}\right)$

- Tmean<Tbase, Tmean =Tbase, therefore, GDD= 0
- Tmean>Tx, then Tmax=Tbase
- Tbase<=Tmean<=Tx, then GDD=Tmean -Tbase

Tbase and Tx were set at 7 ºC and 27 ºC, respectively (Hernández y Carballo, 1984).

The GDD was calculated for both the historical period and the distant horizon (2061-2080) of climate change under SSP2-4.5 and SSP5-8.5.

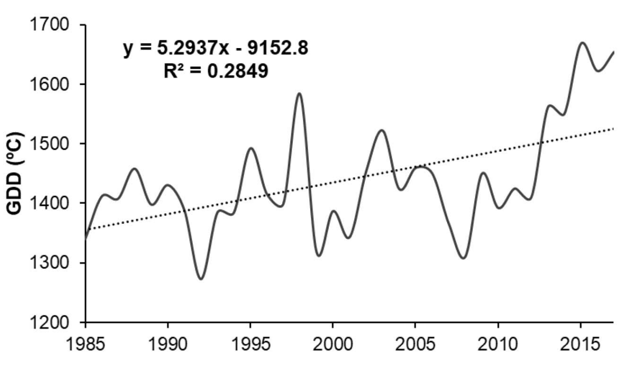

Fig. 2: Annual accumulation of GDD for the period 1985-2017 in the ARDD.

RESULTS AND DISCUSSION

Future climate projections

The MRI-ESM2-0 model of CMIP6 projected increases in maximum and minimum temperature in the ARDD, where it shows that the greater the shared socioeconomic pathway, the greater the potential increase in these variables towards the distant horizon (2061-2080). The mean annual minimum temperature is expected to increase by 1.6 °C in SSP2-4.5 and by 2.0 °C in SSP5-8.5, while maximum temperature increases of up to 2.7 ºC and 2.9 °C, respectively, could be expected for the SSP2-4.5 and SSP5-8.5 scenarios (Table 1). Temperatures towards the far horizon in the ARDD indicate a scenario with better agroclimatic aptitudes for corn production, since the mean annual temperature during the agricultural cycle (Table 1) would increase from 14.5 ºC to 16.3 ºC and 17.3 ºC with the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

The temperature increase identified in this study is consistent with the continued increase in warming observed for the end of the 21st century by the IPCC6, which indicates a global increase from 1.1 °C in SSP1-2.6 to 5.4 °C in the SSP5-8.5 scenario (IPCC, 2021). In this regard, Estrada *et al.,* (2023) identified that in the geographic area of the State of Mexico at the end of the 21st century, the average temperature is expected to increase by 2.5 ºC and 4.8 °C under the SSP2-4.5 and SSP5-8.5 trajectories, respectively. For their part, Ruiz-Corral *et al.,* (2016) in the same entity, identified that towards 2100, a moderate warming is expected with a shallow drying process, where the average temperature projects an increase of 1 to 2 °C.

Past and projected growing degree days (GDD)

During the corn agricultural cycle in the ARDD, the average value of GDD corresponds to 1,440 ºC. Fig. 2 indicates a slope (rate of change) in the regression equation corresponding to 5.2 ºC year-1, with an increase in GDD during the entire period analyzed of 175 ºC, which is identified as potentiated after the year 2012. The lowest value occurred during 1992 with 1,272 ºC while the highest GDD accumulation was in 2015 with 1,667 ºC. In this sense, Cruz-González *et al.,* (2023), identified in the ARDD during the period 1985-2017, an increasing trend in the maximum and minimum temperature variables, which increased by 1.0 ºC and 0.9 ºC respectively, indicating, an important climatic variability in that region for recent years.

Fig. 3A shows the zones with the lowest and highest GDD accumulation. The highest values are located in the northeast zone, which range from 1528 to 1838 ºC. The areas of lower GDD accumulation are focused in the higher parts of the ARDD, corresponding to the mountain areas, which tend to be colder (Fig. 3). With the SSP2-4.5 scenario (Fig. 3B), it is possible to identify an increase with respect to the historical period, since an average temperature of 15.5 °C is projected; and it is observed that the range of 1,636-1,795 GDD is the one that occupies the largest area. The

Table 2: GDD accumulation for each phenological stage; VE (germination and emergence), V1-V12 (development stages), VT (tasseling), R1-R6 (grain-filling and Maturity)

Periods	VE	V1-12	VT	R1-R6
Historical (1985-2017)	275	770	1,010	1,440
SSP2-4.5 (2061-2080)	327	920	1,210	1,740
SSP5-8.5 (2061-2080)	366	1,020	1,330	1,915

cumulative average for this scenario is 1,740 GDD, an increase of 298 GDD with respect to the historical period, which represents approximately 21%. With respect to SSP5-8.5, the northeast is identified as the area with the highest GDD accumulation, with values above 2,000 GDD (Fig. 3C). In this scenario, GDD tends to increase with respect to the base period, with ranges that go from 1,200 to 2,320 GDD, the annual average is 1915 ºC. An increase of 475 GDD was identified, which represents an increase of 33% with respect to historical values.

Phenological growth stage and GDD

Table 2 identifies the amount of GDD required to fulfill each phenological growth stage in the corn crop. During the historical period with an average temperature of 13.6 ºC and 180 accumulated days, the germination and emergence stages accumulated 275 ºC; for the development stages, 770 ºC are required; for the tasseling stage, 1,010 ºC are necessary and finally, in the grain-filling and maturity stage, 1,440 ºC are required. Under the SSP2-4.5 scenario with an average temperature of 15.5 ºC, these values increased by 19%, 40%, 19% and 23% respectively, while under the SSP5-8 scenario with an average temperature of 16.5 ºC, even greater increases were seen, with 34%, 63%, 30% and 36% respectively. In the two scenarios, the phenological growth stage with the highest GDD accumulation is the development stages (V1-V12) with mean values of 600 ºC for SSP2-4.5 and 655 ºC for SSP5-8.5.

In Mexico, various studies have been reported, indicating the GDD and base temperatures that are necessary to meet the different phenological stages growth of the maize crop; in this regard, Arista-Cortes *et al.,* (2018) determined the GDD necessary to reach the female tasseling stage, for different varieties of criollo maize in the states of Chiapas, Hidalgo, San Luis Potosí, Veracruz and Yucatán, which correspond to 1,362, 1,860, 1,713, 1,447 and 1,139 GDD respectively with different base temperatures. Marcial *et al.,* (2021) found in the Comarca Lagunera (northern region of Mexico) that corn emergence occurred with an accumulation of 300 GDD, development stages occurred between 300 and 900 GDD, ear formation was between 900 and 1,100 GDD, while grain filling was possible with an accumulation of 1,100 to 1,600 GDD, and finally physiological maturity occurred from 1,600 to 1,650 GDD.

CONCLUSION

Results revealed that the average temperature has increased in recent years, and consequently the GDD increased, which in turn increases the speed of occurrence of phenological changes in the corn crop. The SSP2-4.5 and SSP5-8.5 scenarios projected a warmer distant horizon, whose temperature increase will provide better climatic conditions for the growth and development of the corn crop. In the high valleys, as in the case of the ARDD, thermal conditions will favor intermediate-cycle varieties adapted to warm climates to ensure higher yields and grain quality.

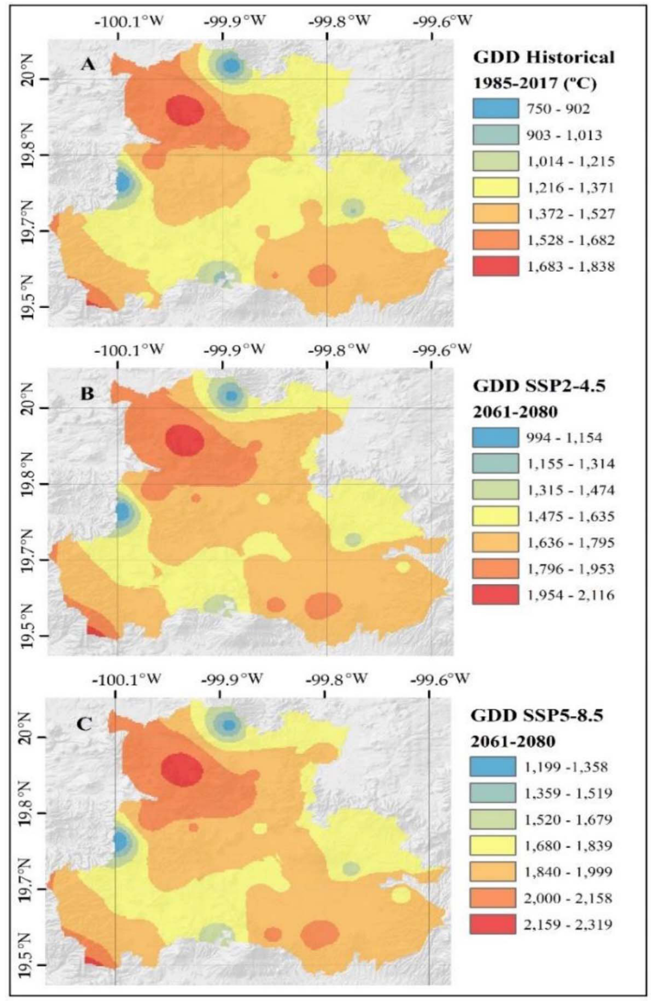

Fig. 3: Spatial distribution of GDDs in the ARDD; (A) Historical (B) SSP2-4.5 (C) SSP5-8.5.

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Author contribution: **A. Cruz-González:** Conceptualization, Writing-original draft, Writing-review editing, Methodology, Investigation and Formal analysis; **R. Arteaga-Ramírez:** Writing-review editing, Funding acquisition and Supervision; **I.**

Sánchez-Cohen: Conceptualization, Writing–review editing and Methodology. **J. Soria-Ruiz:** Critical review and Supervision; **A. I. Monterroso-Rivas:** Writing–review editing; **A. Quevedo-Nolasco:** Supervision and Validation.

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