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Impact of climate change on irrigation water requirement, mitigation, and adaptation strategies: A case study in Egypt

Mohamed Elsayed Gabr[1]

[1] *Civil Engineering Department, Higher Institute for Engineering and Technology, New Damietta, Ministry of Higher Education, Cairo, Egypt. email: mohamed.gabr@ndeti.edu.eg*
ID:0000-0003-2448-610X

Correspondence: [Mohamed Elsayed Gabr]; [٤٢٥٢٣]; Tel [+201094500344]; Email: mohamed.gabr@ndeti.edu.eg

ABSTRACT

Irrigation is critical for food security; yet, climate change impacts the water required for long-term irrigation. The current study examines how climate change impacts future irrigation needs in Egypt's Greater Cairo Territory (Cairo, Giza, and Qalyubia) using the medium emission RCP 4.5 and high emission RCP 8.5 scenarios for the future years 2040, 2060, 2080, and 2100. Crop, soil, and climate data for the current scenario 2023 were acquired from Giza station. Crop, soil, and climate data for the current scenario 2023 were acquired from Giza station. The FAO-CROPWAT 8.0 model was used to calculate evapotranspiration (ETo) and irrigation crop requirements (CWR) for the principal crop's maize, cotton, rice, sugar beet, tomato, wheat, dry bean, berseem clover, and potatoes. The results show that ETo values for RCP 4.5 for the years 2040, 2060, 2080, and 2100 indicate an increase of 2.9, 4.07, 5.35, and 6.43% respectively above the current scenario 2023, whereas, RCP 8.5 for same years indicate a rise of 3.64, 5.59, 8.5, and 11.4% respectively. The study area is semi-arid, and rainfall during the winter season contributes only a small amount of irrigation water as the effective rainfall in the study area is zero. RCP 4.5 shows a reduction in CWR by 5.5, 6.6, 8.1, and 8.9% for years 2040, 2060, 2080, and 2100 respectively, compared to the current scenario (2023). While for the high emission scenario RCP 8.5 for the same years, the decrease in CWR was 6.0, 8.3, 11.0, and 13.0%, respectively. Crop water requirements variations can be used to make appropriate suggestions for future irrigation planning and reservoir operation modeling in Egypt's regions. This study looks into mitigation and adaptation strategies for the effects of climate change on crop production in Egypt.

Keywords: *Water resource management; Reference evapotranspiration; Crop Evapotranspiration; Climate change; mitigation measures; Egypt.*

1. Introduction

Both natural and human activities alter the composition of the global atmosphere, leading to higher concentrations of greenhouse gases (GHGs) (Xin et al. 2023; Fader et al. 2016). GHG emissions have caused warming of the air and oceans, as well as depletion of the ozone layer, contributing to climate change (Malhi et al. 2021; El-Tahan 2018). Changes in average climatic components like temperature and precipitation can cause climate changes. Climate change has caused challenges in managing water resources for agriculture, influencing productivity, water supplies, and nutritional quality (Mohebbi et al. 2024; Zhu et al. 2023). The limited availability of freshwater supplies and rising demand provide further concerns (Soares et al.2023). Climate change indirectly impacts crop requirements from irrigation (CWR) by increasing evapotranspiration and thus crop water consumption (Gabr 2023; Shahid 2011; Allani et al. 2020). Sabzevari and Eslamia 2023, examined and provided the theory, principles, and methods for estimating reference evapotranspiration. To evaluate climate change, meteorological data should first undergo significance trend testing. One of these tests is the nonparametric Mann-Kendal test, which is commonly used in the literature. Nonparametric tests use the rank of the data rather than the true value, and no normal distribution is required for the data. Using the Mann-Kendal test, Fouad et al. (2022), found that maximum and minimum annual and seasonal temperatures in Egypt increased between 1901 and 2016. They confirmed an increasing trend in temperatures in Egypt, the yearly temperature increased by 0.87°C during this period, indicating a positive trend. The summer season saw the biggest warming trend of 1.35 °C, followed by the winter season with a 0.46 ℃ increase. Farmers will need to adapt to climate change by practicing climate-smart agriculture (Awo et al. 2022, Alotaibi et al. 2023; El-Rawy et al 2023), which involves better soil management to retain water, carbon, and nutrients. Farmers must adjust to both climate change and the rising global population. To ensure food security, it's crucial to produce more food in a sustainable way (Gabr 2021). The Intergovernmental Panel on Climate Change (PCC) assessment reports have spanned multiple generations and emissions scenarios (IPCC 2014; Pedersen et al. 2021). Some examples are the "1990 IPCC First Scientific Assessment" (SA90), the "1992 IPCC Scenarios" (IS92) (Leggett et al. 1992), and the 2000 "Special Report on Emissions Scenarios" (SRES) (Leggett et al. 1992) SRES considers four potential scenarios: A1, A2, B1, and B2. Scenarios A and B emphasize economics and the environment, while scenarios 1 and 2 emphasize globalization and regionalization (Nakicenovic 2004). The IPCC has lately produced scenarios like "Representative Concentration Pathways" (RCPs) (Sun and Shi 2020) and "Shared Socioeconomic Pathways" (Van et al. 2011; O'Neill 2014). RCPs (Table 1) are a collection of greenhouse gas concentration and emission trajectories that support research on climate change consequences and potential policy responses (Riahi et al. 2017). The increase in radiation is represented in W/m^2. The first scenario, RCP2.6, is a rigorous mitigation scenario with a peak radiative forcing of roughly 3 W/m^2. RCP4.5 and RCP6.0 are intermediate scenarios that represent a medium forcing level, where society limits the increase of GHG emissions (with radiative forcing peaks of roughly 4.5 and 6 W m-2). RCP8.5 predicts a growing radiative forcing of 8.5 W/m^2 until the end of the 21st century. RCP8.5 is a "baseline" scenario that does not set particular climate mitigation targets (Shrestha et al. 2016). RCP4.5 and RCP8.5 are extensively used scenarios for studying climate change implications (Riahi et al. 2011).

Table 1. Future climate change projections (IPCC, 2014)

		2016-2065		2081–2100	
Temperature increase compared to the 1986–2005 period (ºC)	Scenario	Mean	Probable variation	Mean	Probable variation
	RCP 2.6	1	0.4 – 1.6	1	0.3-1.7
	RCP 4.5	1.4	0.9 – 2.0	1.8	1.1-2.6
	RCP 6.0	1.3	0.8 – 1.8	2.2	1.4-3.1
	RCP 8.5	2	1.4 – 2.6	3.7	2.6-4.8

Climate change poses a significant danger to global food security, hindering the agricultural sector's ability to produce enough food for a growing population while remaining environmentally sustainable (Maitah et al. 2019; Roushdi 2024). Agriculture is heavily impacted by climate change, highlighting the need for further efforts to suggest adaption solutions. GHG-induced air temperature increases have a significant impact on soil salinity development, crop cycle, phenology, productivity, and water requirements (Funes et al. 2021). Implementing sustainable methods to improve crop yield and quality (Zhao et al. 2022; Haj-Amor 2020) and strengthen cropping systems (Hussain and Bangash 2017) is critical in this complex context. Schilling et al. (2021), investigated and compared the vulnerability of Egypt, Libya, Algeria, Tunisia, and Morocco to climate change, focusing on the socioeconomic effects. According to the findings, all countries are at risk of experiencing significant temperature increases and droughts as a result of climate change. According to Zittis et al. (2021), summer heat extremes in the Medal East and North Africa regions (MENA) are expected to increase significantly due to global climate predictions. Unprecedented super- and ultra-extreme heat waves are expected in the second half of this century if current trends continue. Extremely high temperatures (up to 56°C or higher) and lengthy duration (several weeks) may pose a risk to human life. By the end of the century, about half of the MENA population (600 million) may experience annual super- and ultra-extreme heatwaves. According to Ritchie and Roser (2020), climate change is one of the world's most important concerns. Human-caused greenhouse gas emissions have contributed to a 1°C rise in global temperatures since pre-industrial times. These gases include CO2, methane, and others. Global CO2 emissions exceed 36 billion tons per year and continue to rise above 400 ppm concentrations in the atmosphere. These are the greatest levels in around 800,000 years. China is now the world's top CO2 emitter, accounting for around 25% of total emissions. This is followed by the United States (15%), the European Union-28 (10%), India (7%), and Russia (5%). In Egypt, research has primarily focused on the influence of climate change on crop productivity or water consumption. However, investigations on the impact of climate change on total water needs are also necessary. This study aims to provide decision makers with data on irrigation water requirements for major crops under climate change conditions. The goal is to identify areas that can be grown under future conditions and develop plans to use the lost area if necessary. The current study examines how climate change affects Egypt's water resources, with a focus on agriculture. The study attempts to identify water-saving strategies for agricultural crops through adaptation techniques. The present study uses the medium emission RCP 4.5 and high emission RCP 8.5 scenarios to assess how climate change may affect future irrigation needs in Egypt's Greater Cairo Territory (Cairo, Giza, and Qalyubia). The FAO CROPWAT 8.0 model FAO 2024, was used to compute evapotranspiration (ETo) and irrigation crop requirement (CWR) for major crops such as maize, cotton, rice, sugar beet, tomato, wheat, dry bean, berseem clover, and potatoes. Crop water need variations can be used to make appropriate suggestions for future irrigation planning and reservoir operation modeling in Egypt's regions. To achieve the study objectives, (1) the current studies that projected the adverse effects of rising temperatures on crop irrigation water requirements and crop harvest are revised, (2) the Intergovernmental Panel on Climate Change (IPCC 2014) Fifth Assessment Report (AR5) attended as the source for the climatic projections for medium emission RCP 4.5 and high emission RCP 8.5, which were used to estimate the patterns of temperature and rainfall in Giza climate station, (3) ETo and CWR for Greater Cairo Territory key crops are estimated using FAO-CROPWAT 8 model, based on the predicted climatic parameters were used as an input into the CROPWAT model for future irrigation demand estimation for seven scenarios: (1) current climate conditions 1990–2023; (2) temperature and rainfall change for periods 2024–2040, 2041-2060, and 2061-2100 for RCP 4.5 medium emission; (3) temperature and rainfall change for periods 2024–2040, 2041-2060, and 2061-2100 for RCP 8.5 high emission.

2. Material and methods

2.1. Study area

Egypt is located between longitudes 22o to 32o and latitudes 24o to 37o. It has a total size of around one million km^2. It is located in the north-east of Africa, bordering the Mediterranean Sea on the north and the Red Sea on the east. Egypt shares territorial borders with Palestine, Sudan, and Libya as shown in Figure 1. Egypt has a total population of 106.6 million people Central Agency for Public Mobilization and Statistics (CAPMAS 2024). Egypt has two different types of climates. On the northern coast, there is a Mediterranean climate, while there is a desert climate in inland for Upper Egypt. Egypt has low precipitation, high ETo rates, and a dry or semi-arid climate throughout the year [8]. The physiographic area of Egypt includes the Nile Valley and Delta, Eastern Desert, North West Coast, Western Desert, and the Sinai Peninsula. Egypt has several soil types, including alluvial soils in the Delta and Valley, desert soils in the Western and Eastern Deserts, calcareous soils along the Egyptian coast, and soils in the Sinai Peninsula (Gabr et al. 2022; Gabr et al. 2023). This study will look at agricultural land and related irrigation water resources in Egypt's Greater Cairo Territory (Cairo, Giza, and Qalyubia). The current climate data (maximum temperature, minimum temperature, and Rainfall) were collected for the Greater Cairo Territory from the Giza climate station (Figure 2).

2.2. Crop and soil data

Soil and crop data were collected to determine the crop water requirements for nine major crops grown in the Greater Cairo Territory (maize, cotton, rice, sugar beet, tomato, wheat, dry bean, berseem clover, and potatoes). Data on crops and soil in the various regions were gathered using a combination of field observations, interviews with farmers and stakeholders, and the Ministry of Agricultural and Land Reclamation (MALR 2024) guidebook for agricultural operations in Egypt. The crop pattern in the research area includes data on first and final planting and harvesting dates, first and last irrigation application depths, irrigation application frequencies and intervals, plant growth stage duration, and rooting depth. Table 2 presents the soil and crop data in the study area, where heavy clay soils predominate.

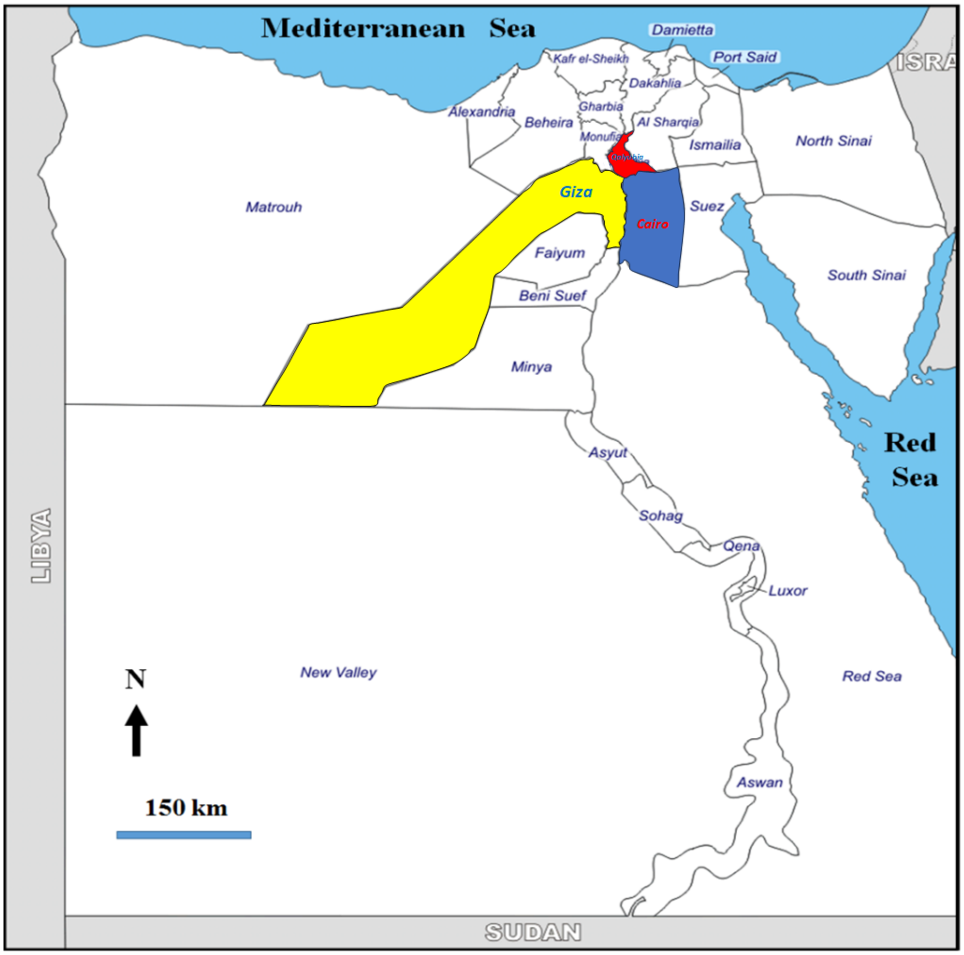
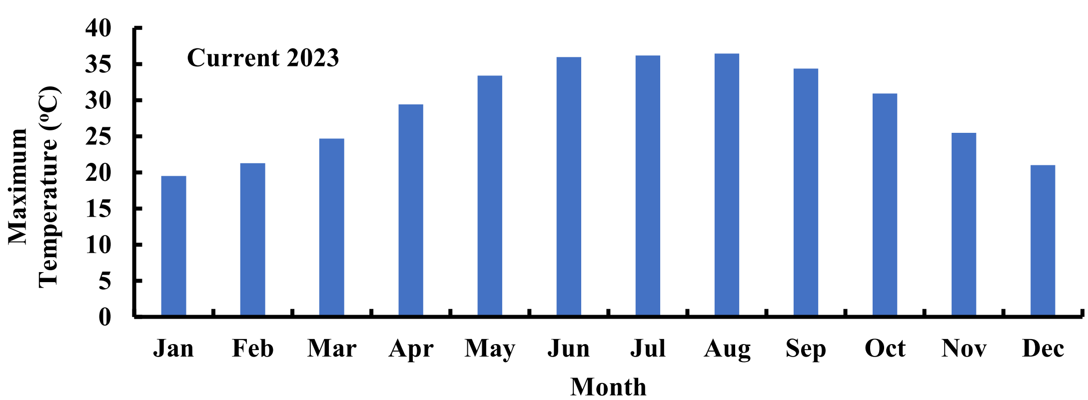


Figure 1 Study area, Greater Cairo Territory (Giza, Cairo, and Qalyubia).



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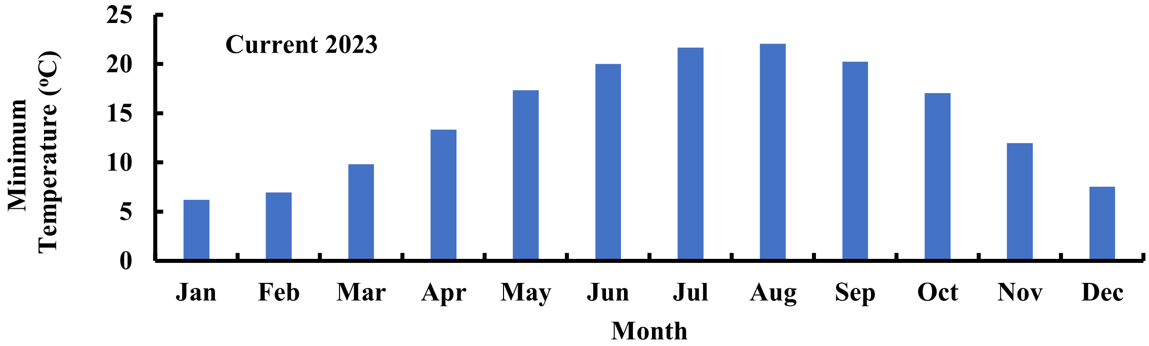

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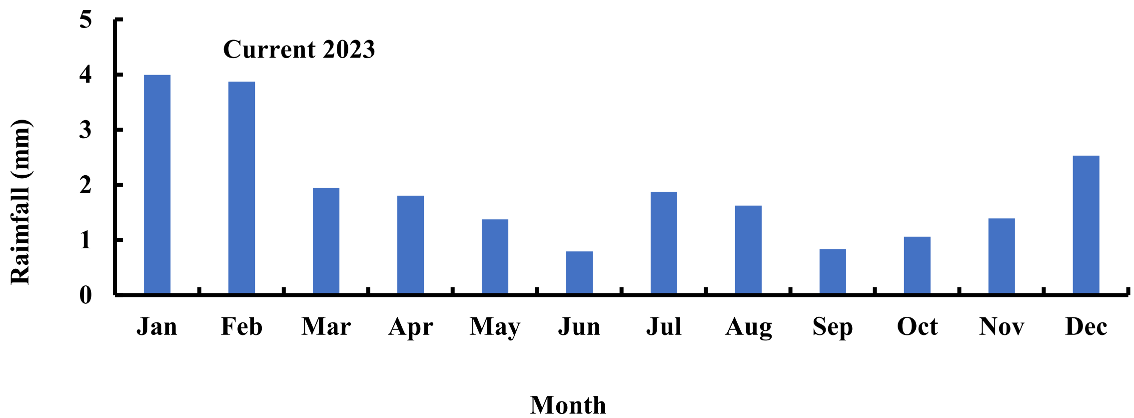

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Figure 2 Current climate data for Giza station, A: maximum temperature, B: minimum temperature, and C: Rainfall.

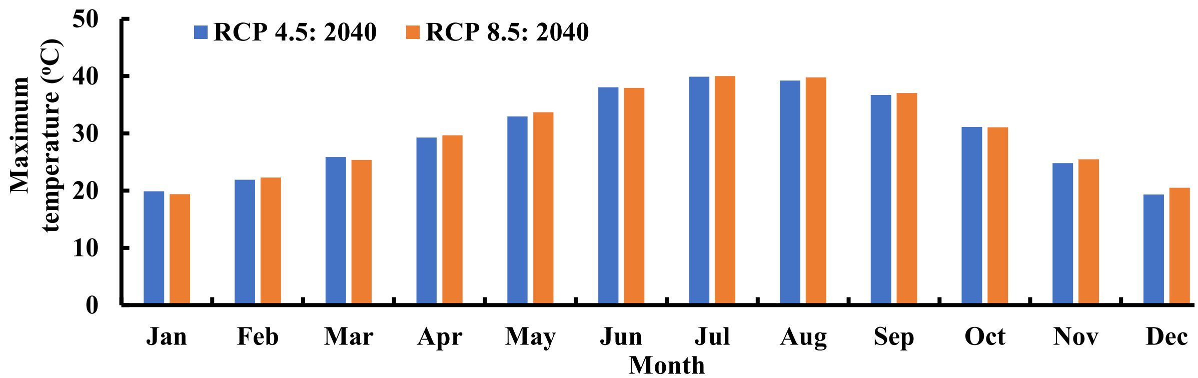
Table 2 Main cultivated crops data in the Greater Cairo Territory.

Season	Crop	Planting date	Harvesting Date	Greater Cairo Territory Cultivated Area (Fad.)
Summer	Maize	20 Apr.	22 Aug.	20374
	Cotton	1-May	11 Nov.	34
	Rice	15-May	11 Sep.	9159
	Sugar Beet	1 Aug.	7 Jan.	3674
	Tomato	6 Jun.	28 Oct.	26493
Winter	Wheat	1 Nov.	10 Mar.	91931
	Dry Bean	1 Oct.	18 Jan.	121
	Berseem Clover	15 Oct.	45439	19579
	Potatoes	1 Sep.	8 Oct.	28289

Fad., Faddan (one Fed. = 4200 m^2)

2.3. Climate data

Climate change research falls into two categories: (i) projecting future trends and (ii) analyzing past data to identify patterns. Currently, GCMs are the most dependable instruments for developing climate scenarios. They propose climatic scenarios that provide an overview of potential future climate conditions. General circulation models (GCMs) primarily account for future greenhouse gas emissions. This research utilized the HadGEM2-ES GCM model developed by the National Space Research Institute in the United Kingdom. Downscaling technologies build local-scale climatic scenarios from large-scale GCM results. The LARS-WG downscaling model was employed in this study. The database contains HadGEM2-ES outputs for RCP 4.5 and RCP8.5, based on the desired station's longitude and latitude. This study employed the Intergovernmental Panel on Climate Change (IPCC) and the Fifth Assessment Report, the climatic projections for RCPs 4.5 and 8.5 to simulate precipitation, minimum and maximum temperatures, and their probability of occurrence for the years 2040, 2060, 2080, and 2100. Figure 3 shows the maximum temperature for Giza station for RCP 4.5 and RCP 8.5 for the future 2040, 2060, 2080, and 2100. In addition, Figure 4 shows the minimum temperature for the Giza station, RCP 4.5, and RCP 8.5 for the future 2040, 2060, 2080, and 2100. Finally, Figure 5 shows the climate data for rainfall for Giza station, RCP 4.5, and for the future 2040, 2060, 2080, and 2100.



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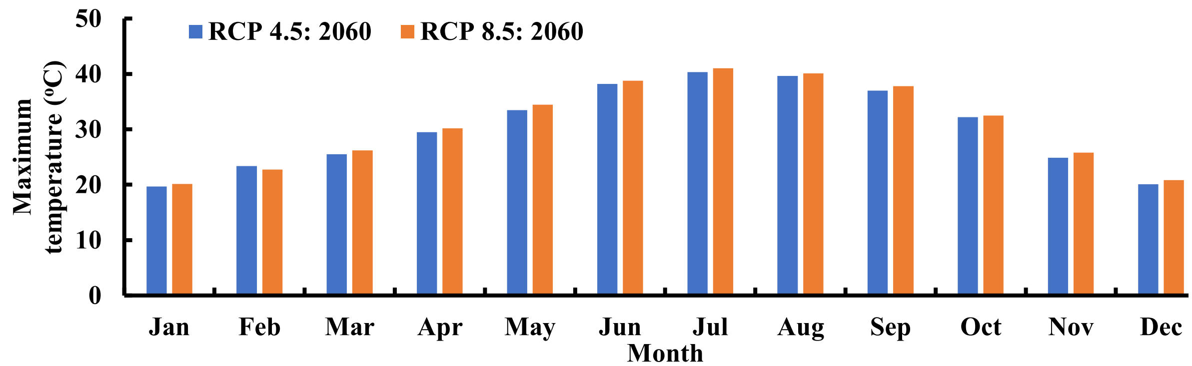

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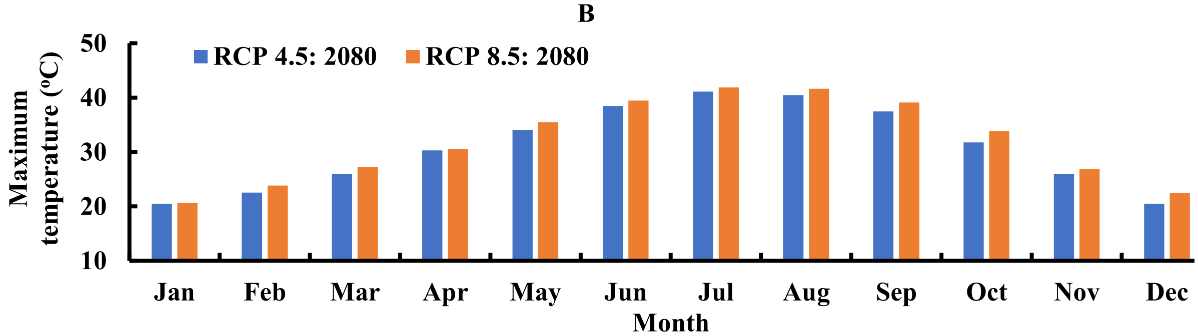

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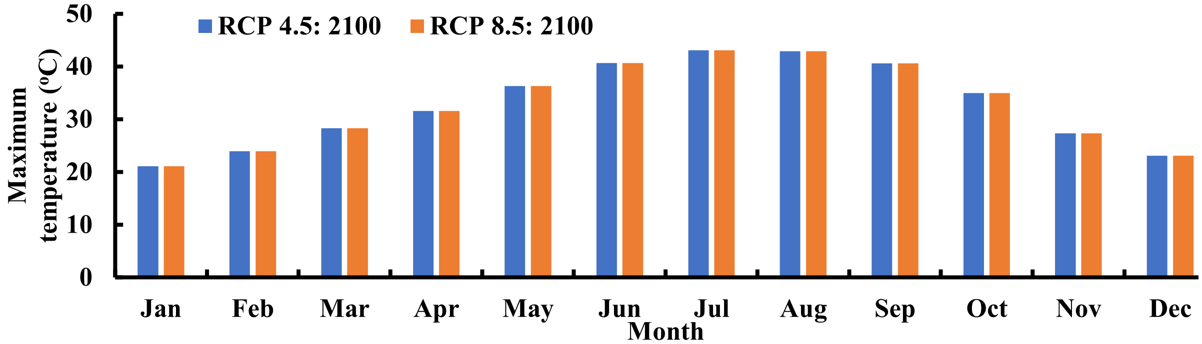

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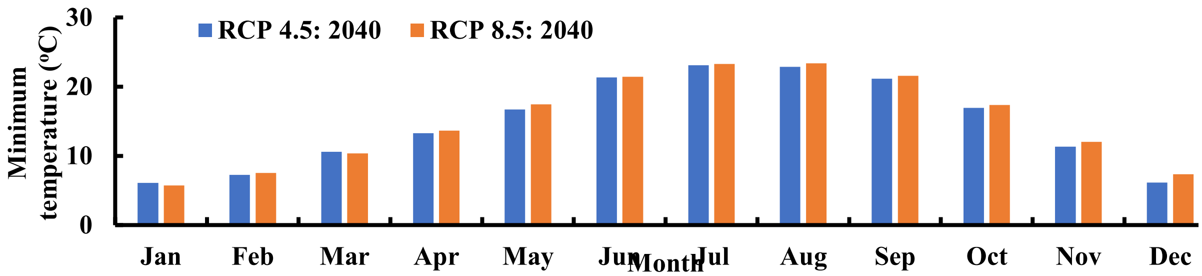
Figure 3 Maximum temperature for Giza station, RCP 4.5 and RCP 8.5, A: 2040, B: 2060, C: 2080, and D:2100.



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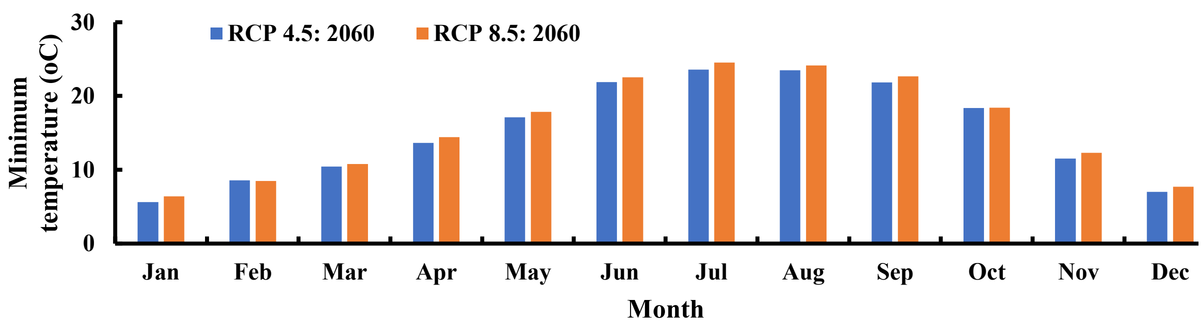

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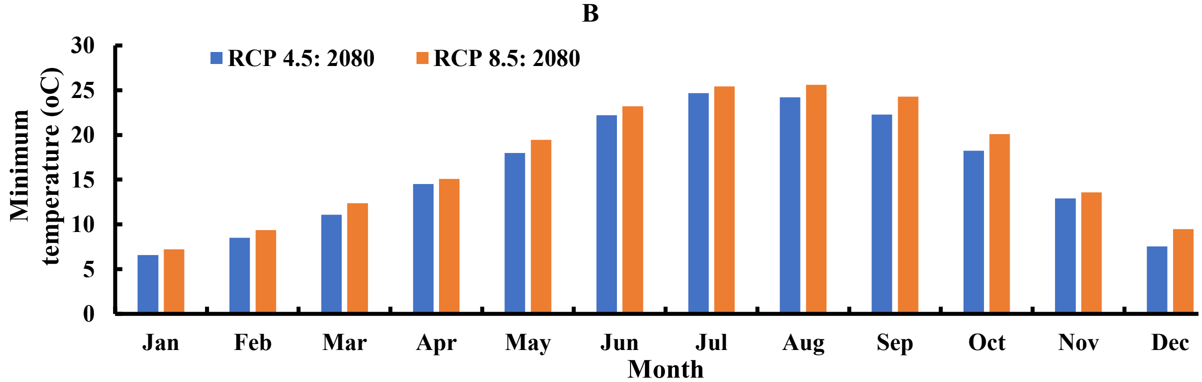

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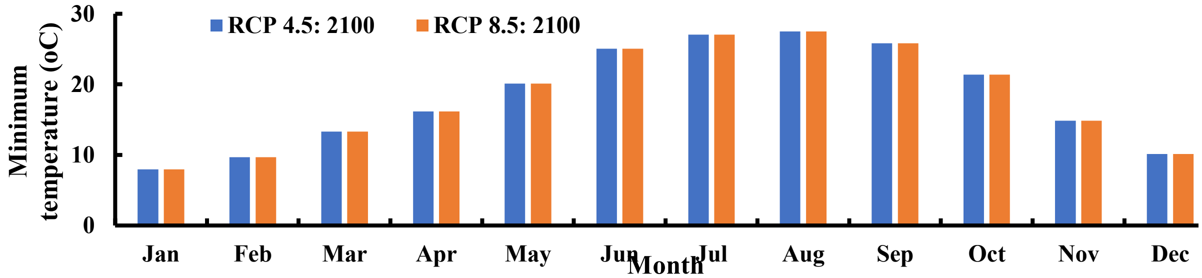

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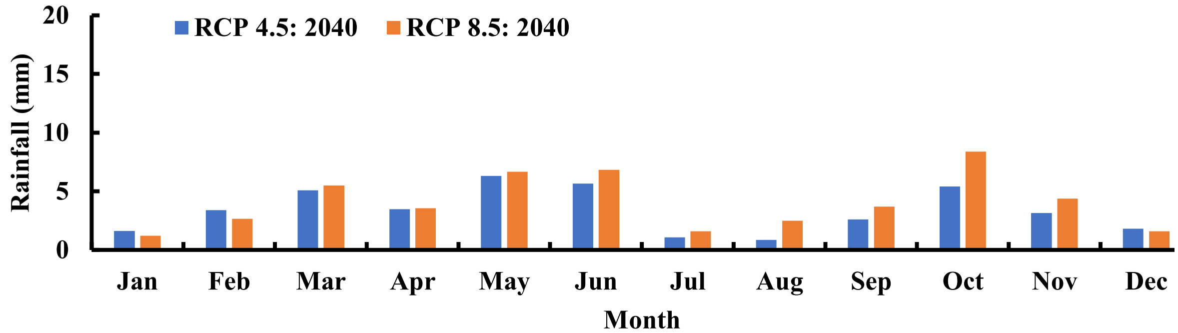
Figure 4 Minimum temperature for Giza station, RCP 4.5 and RCP 8.5, A: 2040, B: 2060, C: 2080, and D:2100.



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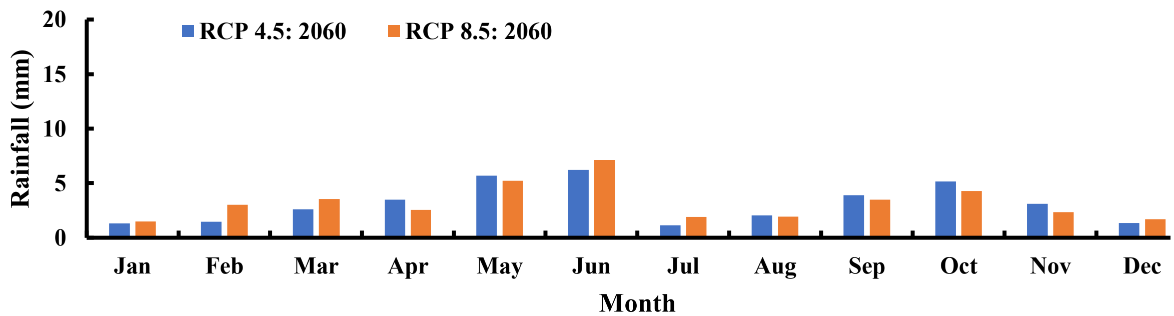

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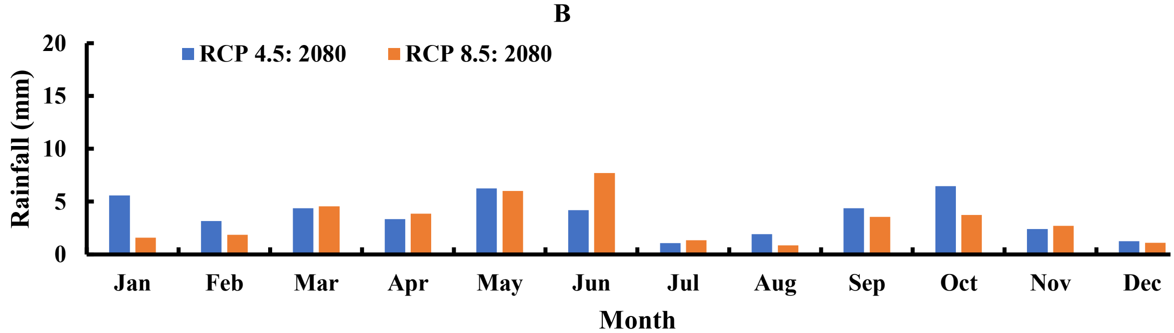

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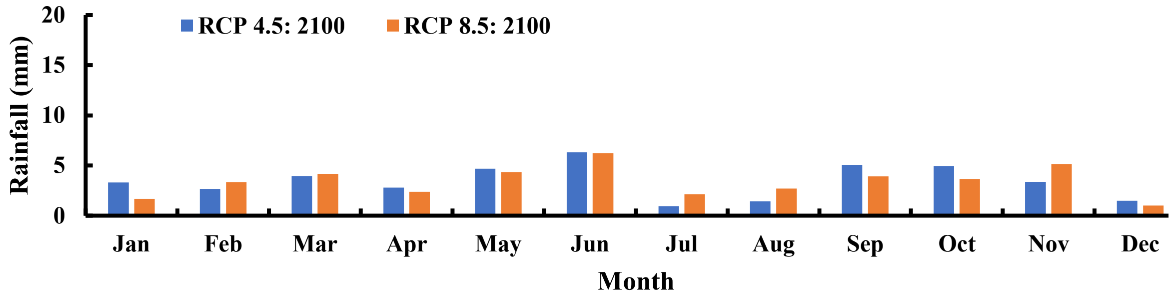

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Figure 5 Rainfall data for Giza station, RCP 4.5 and RCP 8.5, A: 2040, B: 2060, C: 2080, and D:2100.

Crop water and irrigation water requirements (CWR)

CROPWAT 8.0 is a decision-support computer application developed by the FAO that combines rainfall, soil, crop, and climatic data to determine ETo, crop water requirements (CWR), net irrigation water requirement, and irrigation schedule (FAO 2024). Reference evapotranspiration (ETo): The modified Penman-Monteith method suggested by (Allen et al. 1998) was used to compute reference evapotranspiration (ETo). The FAO Penman-Monteith method to estimate ETo is given below:

$$ETo = \frac{0.408\Delta .4\,(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where, ETo = Reference evapotranspiration [mm/day], R_n = net radiation at the crop surface [MJ/ m2/day], T = air temperature at 2 m height [°C], e_a = actual vapor pressure [kPa], e_s= saturation vapor pressure [kPa], $e_s - e_a$ = saturation vapour pressure deficit [kPa], G = soil heat flux density [MJ/ m^2/day], γ = psychrometric constant [kPa/°C], U_2 = wind speed at 2 m height [m/s], and Δ = slope vapor pressure curve [kPa/°C].
Crop evapotranspiration: The relationship between crop evapotranspiration (ETc) and reference evapotranspiration (ETc) can be expressed by the following equation (Allen et al. 1998) was used in this study in order to estimate the crop evapotranspiration:

$$\text{ETc} = \text{ETo} \times \text{Kc} \quad (2)$$

Where, ETc = crop evapotranspiration, ETo = reference evapotranspiration, Kc = crop coefficient. The crop coefficient (Kc) for different orchard crops varied in different month based on phonological stages of plant and percentage of the growth shaded by the tree canopy. In the present study the phonological stage wise values of crop coefficient for perennial fruit crops were taken as given by (Allen et al. 1998) (Table 3).

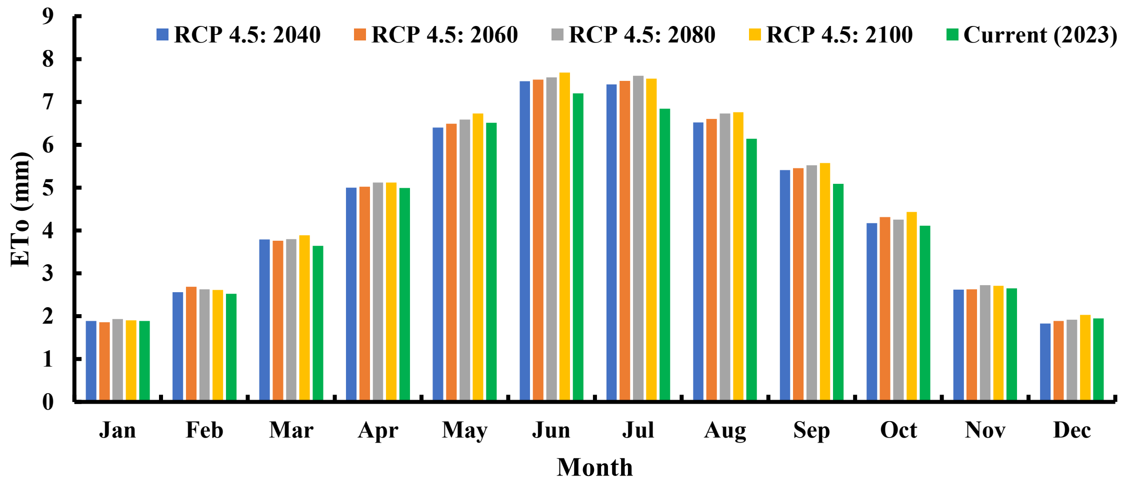
Table 3 Crop coefficient (Kc) for the studied crops

Parameters	Crop								
	Maize	Cotton	Rice	Sugar beet	Tomato	Wheat	Dry bean	Berseem clover	Potatoes
Kc	0.8	0.8	0.8	0.9	0.9	0.7	0.76	0.7	0.9
Total growing days	125	195	150	160	145	130	110	225	130

Results

3.1 Impact of climate change on ETo

Figure 6 shows the ETo variations for the RCP 4.5 and RCP 8.5 for years 2040, 2060, 2080, and 2100. The significant impact of climate change on reference evapotranspiration and rainfall patterns during the current stage 2023 monthly ETo values ranged from 1.89 mm in January to 7.2 mm in June with an annual average of 4.46 mm. On the other hand, for RCP 4.5 for the year 2040 ETo values ranged from 1.83-7.48 mm with an average of 4.64 mm, indicating a 2.9% increase above the base year (2023). In addition, ETo values for RCP 4.5 for years 2060, 2080, and 2100 show an increase of 4.07, 5.35, and 6.43% respectively above the base year (2023). While, for RCP 8.5 for the year 2040 ETo values ranged from 1.91-7.48 mm with an average of 4.62 mm, indicating a 3.64% increase above the base year (2023). In addition, ETo values for RCP 8.5 for years 2060, 2080, and 2100 show an increase of 5.59, 8.5, and 11.4% respectively above the base year (2023).



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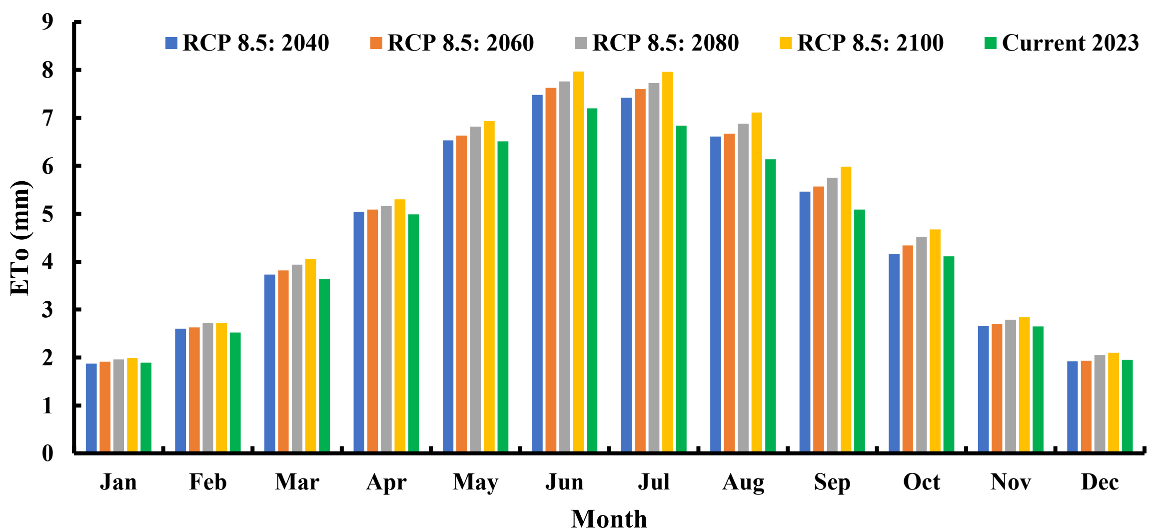

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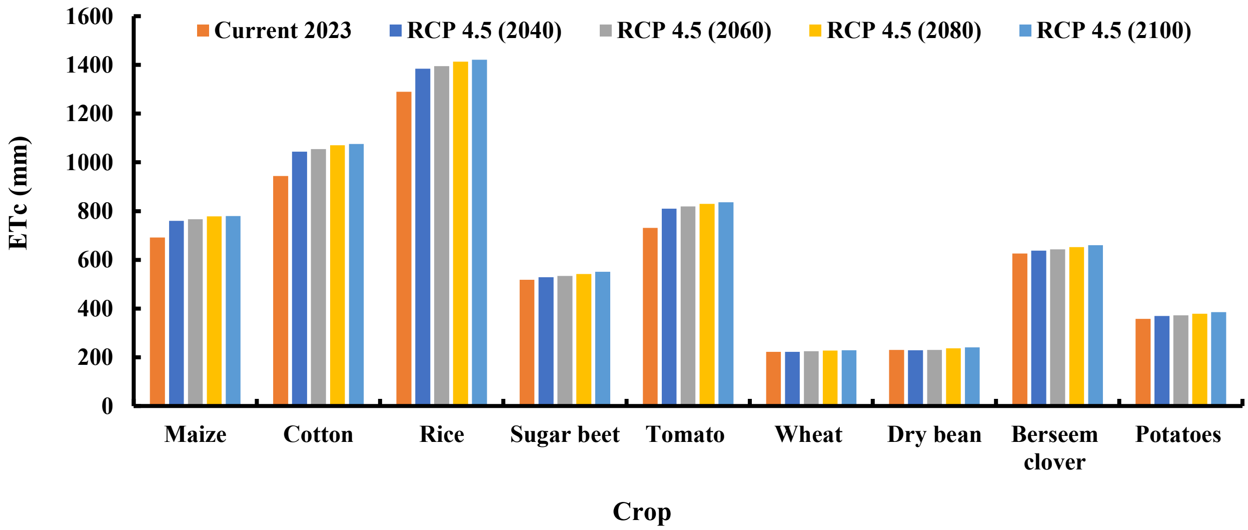
Figure 6 ETo variations, A: RCP 4.5 and B: RCP 8.5 for the future years 2040, 2060, 2080, and 2100.

3.2 Impact of climate change on ETc

Figure 7 shows the impact of climate change on ETc for the studied crops that determined by the FAO-CROPWAT 8 output model. Therefore, ETc values for the current year 2023 for summer crops recorded the highest ETc of 763.6, 1050.2, 1384.5, 534.2, and 814.8 mm for maize, cotton, rice, sugar beet, and tomato respectively during the cultivation season. While, winter season crops recorded current ETc of 224.1, 233.3, 638.2, and 368.9 mm for wheat, dry bean, berseem clover, and potatoes respectively during the cultivation season. On the other hand, for RCP 4.5 for the year 2040 ETc values show an increase of 9.9, 10.7, 7.3, 2.1, and 10.8% for summer season crops maize, cotton, rice, sugar beet, and tomato respectively.



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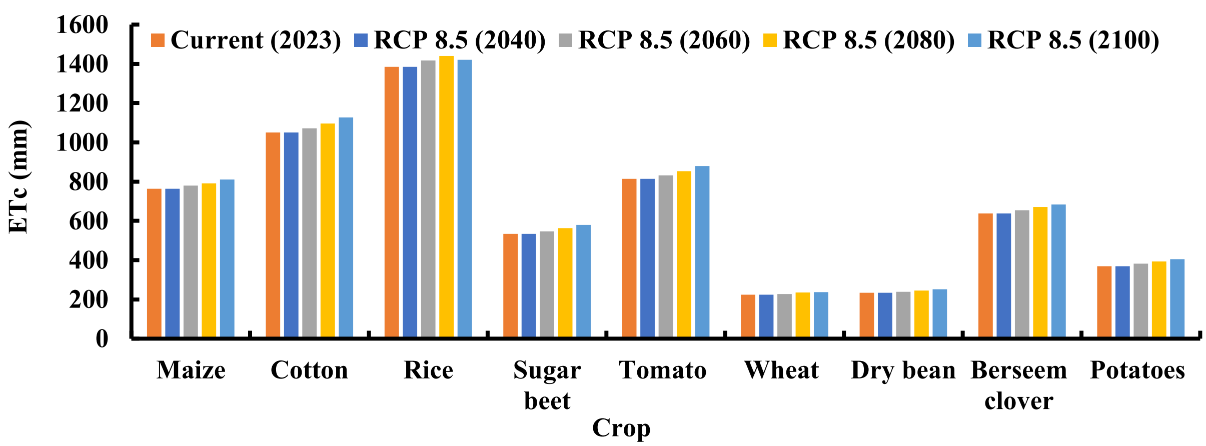

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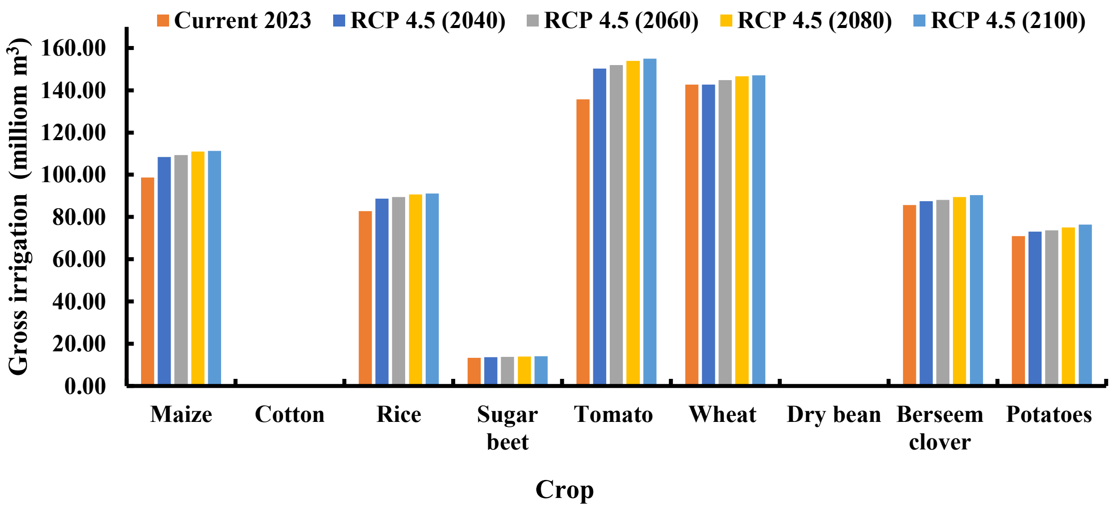
Figure 7 Crop water requirement variations, A: RCP 4.5 and B: RCP 8.5 for the future years 2040, 2060, 2080, and 2100.

While, for winter crops ETc RCP 4.5-2040 increased by 0.9, 1.0, 2.1, and 3.0% for wheat, dry bean, berseem clover, and potatoes respectively above the base year (2023). In addition, RCP 4.5 for years 2060, 2080, and 2100 show more increase in ETc values. RCP 4.5 for the year 2100 ETc values are increased by 12.7, 14.0, 10.1, 6.4, and 14.2% for summer season crops maize, cotton, rice, sugar beet, and tomato respectively. While, for winter crops ETc for RCP 4.5-2100 increased by 3.1, 4.4, 5.5, and 7.7% for wheat, dry bean, berseem clover, and potatoes respectively above the base year (2023) as shown in Figure 7A. Whereas, for RCP 8.5- 2040 scenario, ETc values show an increase of 10.4, 11.3, 7.3, 3.2, and 11.4% for summer season crops maize, cotton, rice, sugar beet, tomato respectively above the base year (2023). While, for winter crops ETc RCP 4.5-2040 increased by 1.1, 1.3, 2.1, and 3.0% for wheat, dry bean, berseem clover, and potatoes respectively above the base year (2023). Also, RCP 8.5 for years 2060, 2080, and 2100 show more increase in ETc values. RCP 4.5 for the year 2100 ETc values are increased by 17.2, 19.5, 10.1, 11.9, and 20.2% for summer season crops maize, cotton, rice, sugar beet, and tomato respectively. While, for winter crops ETc for RCP 4.5-2100 increased by 7.2, 8.9, 9.2, and 13.0% for wheat, dry bean, berseem clover, and potatoes respectively above the base year (2023) as shown in Figure 7B.

3.3 Impact of climate change on gross irrigation

Figure 8 shows the gross irrigation variations for the RCP 4.5 and RCP 8.5 for years 2040, 2060, 2080, and 2100 determined by the FAO-CROPWAT 8 output model. Rainfall contribution to irrigation is neglected as the winter is the rainfall season and summer is the dry season. The current maximum monthly rainfall intensity recorded in Giza station is 3.99 mm in January, the minimum rainfall is 0.79 mm recorded in June, and the annual rainfall is 23.08 mm.



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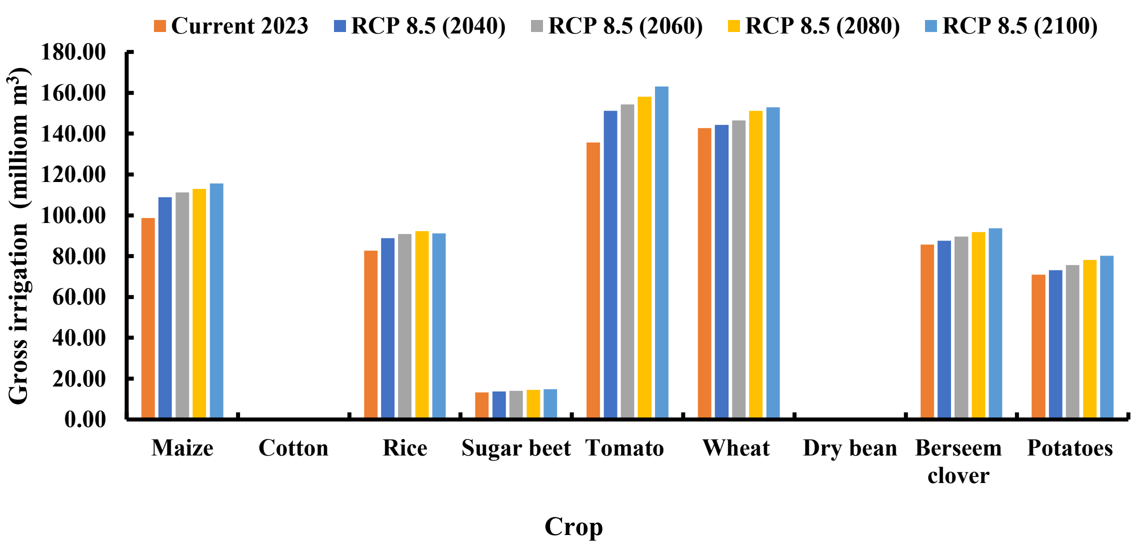


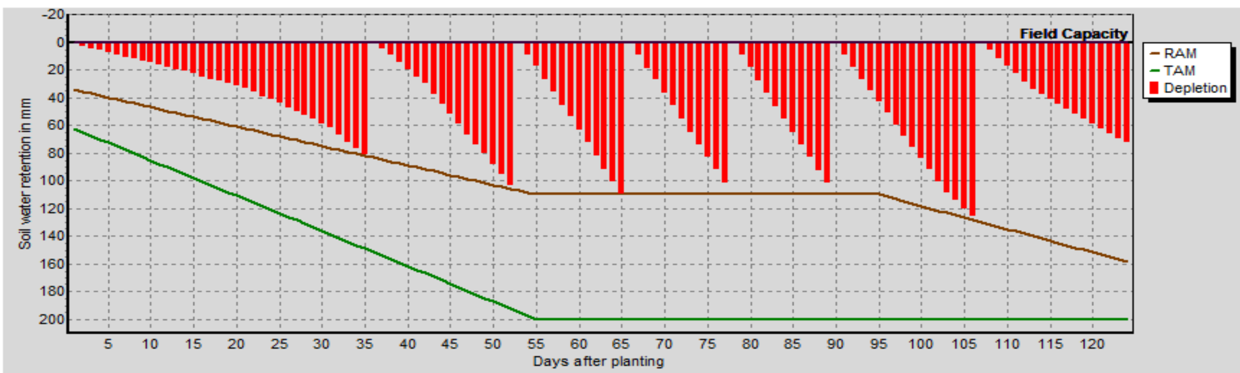
B

Figure 8 Gross irrigation variations, A: RCP 4.5 and B: RCP 8.5 for the future years 2040, 2060, 2080, and 2100.

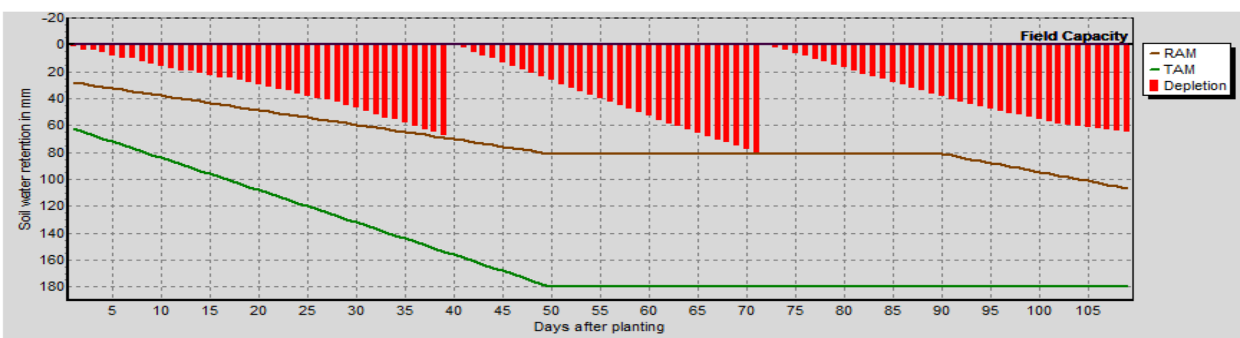
Therefore, the crop water requirement (CWR) is equal to ETc, the irrigation system is surface irrigation with an efficiency of 60%. The annual gross irrigation water volume for the current 2023 is 630.05 million m^3. The annual gross irrigation water volume for the RCP 4.5were 664.76, 671.59, 681.01, and 685.82 million m^3 for the future years 2040, 2060, 2080, and 2100 respectively. Indicating an increase of 5.5, 6.6, 8.1, and 8.9% above the current annual gross irrigation water for the future years 2040, 2060, 2080, and 2100 respectively. On the other hand, the annual gross irrigation water volume for the RCP 8.5 were 667.69, 682.55, 699.32, and 711.9 million m^3 for the future years 2040, 2060, 2080, and 2100 respectively. Indicating an increase of 6, 8.3, 11, and 13% above the current annual gross irrigation water for the future years 2040, 2060, 2080, and 2100 respectively.

3.4 Irrigation schedule

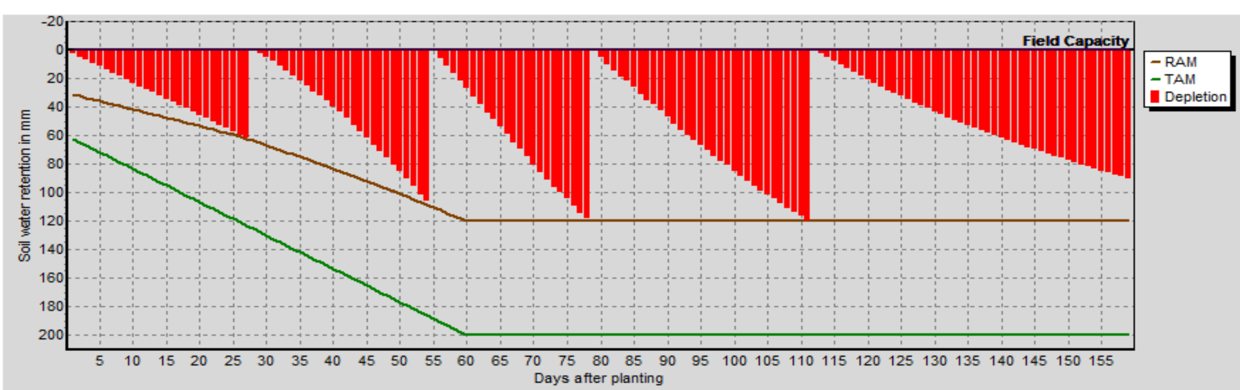
The irrigation schedules for cultivated crops maize, cotton, rice, sugar beet, tomato, wheat, dry bean, berseem clover, and potatoes were calculated by the FAO-CROPWAT 8 model. Figure 9 shows some irrigation schedules for maize, dry beans, sugar beet, and tomato. Therefore, maize, dry beans, sugar beet, and tomato needed 6, 2, 4, and 13 irrigation events respectively. These results suggest that there are potential savings even in very limited conditions when using science-based irrigation scheduling consistently and seasonally.



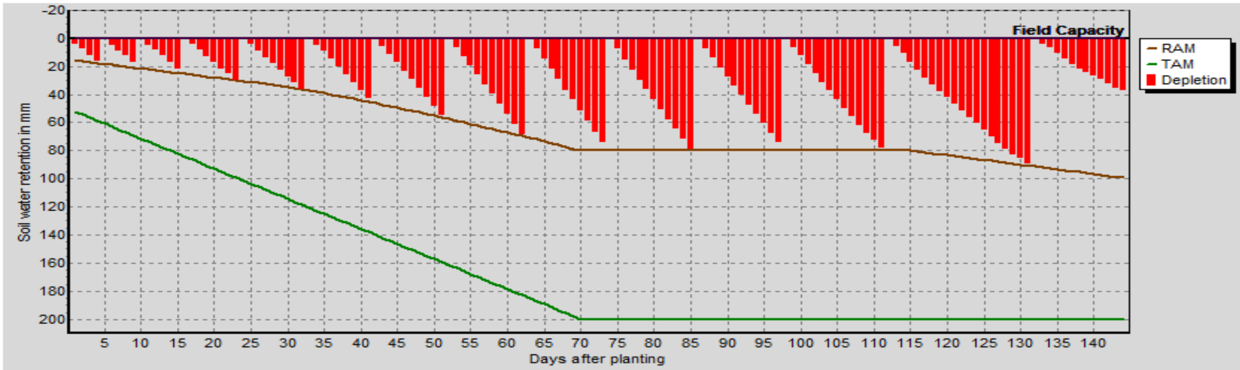
A



B



C



D

Figure 9 Irrigation schedule for A: Maize B: Dry bean, C: Sugar beet, and D: Tomato

Discussion

The Middle East region is one of the most vulnerable to climate change, with consequences such as increased aridity, heat waves, and sea-level rise. If greenhouse gas emissions are not reduced, the area could become uninhabitable by 2100 (Lorenzo and Alvarez 2020; Fusco 2022; Gabr 2023; Alvarez 2024). Even if warming is confined to 1.5°C, life in the Middle East and North Africa will become increasingly tough. The Middle East is already more sensitive to climate change than most other places due to limited water supplies and long, hot summers (Duran-Encalada et al. 2017). The latest investigation agreed with Gabr 2023 findings. He investigates how climate change may affect future irrigation requirements in Egypt's Upper Region under the medium greenhouse emission RCP 4.5 and high emission RCP 8.5 scenarios. The findings show that under RCP 4.5 for the periods 2023-2080 and 2081-2100, the total net irrigation water requirements for all evaluated crops increased by 5.1 and 5.9%, respectively, compared to the current climate in 2022. Under the RCP 8.5 greenhouse emission scenario, the total net irrigation water requirements for all crops increased by 7.7 and 9.7% for the periods 2023-2080 and 2081-2100, respectively, compared to the current total net irrigation water requirements.

In addition, the results of the present study agreed with El-Rawy et al. 2023, who found that climate change is predicted to negatively affect water irrigation management in Saudi Arabia's dry region. In the 2100s, the Shared Socioeconomic Pathways (SSP)2-4.5 and SSP5-8.5 scenarios indicated annual average ETo increases of 0.35 mm/day (6%) and 0.7 mm/d (12.0%), respectively. They investigated the net irrigation water requirement and growth of irrigation water requirement for primary crops in the Al Quassim region using the current, SSP2-4.5, and SSP5-8.5 scenarios. SSP5-8.5 predicts growth of irrigation water requirement increase of 2.7, 6.5, 8.5, and 12.4% in the 2040s, 2060s, 2080s, and 2100s compared to the current growth of irrigation water requirement level. Zittis et al. 2021, also employed the Regional Climate Model ALADIN-Climate to look at predicted changes in temperature, precipitation, and associated severe events in the Middle East and North Africa (MENA). According to the study's findings, warming rates over land range between 0.2 and 0.5 °C every decade, depending on the scenario. The projected heat waves are expected to be longer and more powerful. Drought is predicted to persist in the region's northern half.

4.1 Mitigation and adaptation strategies to the impact of climate change on crop production in Egypt

Climate change will have a significant impact on crop and water productivity. Weather parameters primarily control the rate of evapotranspiration from vegetative surfaces. Changes in weather parameters will impact crop water requirements and productivity, particularly in arid and semiarid areas with limited water resources (IPCC 2019; Grigorieva et al. 2023). Therefore, it is appropriate to emphasize various mitigation and adaptation techniques to assist Egyptians in dealing with the impact of climate change on crop output. These mitigation and adaptation strategies include either basic traditional/indigenous planting methods or emerging advanced technical methods and practices.

Micro-irrigation technique

Implementing pressurized irrigation methods like drip and sprinklers can improve water efficiency to fulfill crop water demand and adapt to climate change. Drip irrigation delivers water straight to plants' roots, allowing for precise watering to meet crop needs. Additionally, it provides for the use of water-soluble chemicals such as fertilizers and insecticides alongside irrigation water. The system uses low-rate, pressurized water to maintain optimal soil moisture levels for plant growth. The system has an application efficiency of approximately 90%, compared to 25-30% for surface irrigation (Ogisi and Begho 2023). Sprinkler irrigation systems are widely recognized for their excellent water efficiency, increased crop output, improved produce quality, and cost savings on irrigation and labor. Sprinkler irrigation mimics rainfall-style watering. Sprinklers have a higher overall efficiency of 65%, compared to 25-30% for surface methods of irrigation. The technique benefits close-growing crops by providing a sufficient water supply. This conserves irrigation water and ensures uniform application over the field (Teklu et al. 2023).

Supportive system for decision making

Supportive systems for decision-making such as remote sensing, satellites, GPS, GIS, e-mail, modeling, mobile devices, and high data transfer rates are creating unprecedented potential and competitiveness in information technology. Efficient decision support systems are crucial for optimizing water, irrigation, inputs, marketing, production, demand, supply, imports, exports, and tailoring requests. This will require collaboration across disciplines, commodities, sectors, and institutions. Satellite sensor deployment, image/spectral analysis, and modeling of spatial and temporal distribution can create economic benefits for marketing, crops, commodities, systems, and capital. It is possible to achieve high order usage efficiency while having minimal environmental impact. Enormous potential to generate marketing, agriculture, commodity, and systems (Janga et al. 2023; Barons et al. 2024).

Canal commands

Canal commands have led to waterlogging and secondary salinization of soil, reducing agricultural production. Water congestion, floods, and shallow water tables may create chances for new technologies. The goal is to maximize the use of water for aquaculture, livestock, agricultural production, horticulture, residential, industrial, and environmental services. Integrated planning and networking can increase water productivity by 5–7 times. Diversification opportunities include cultivating fish in dug-out refuges in paddy fields, rearing fish in ponds on 65% of the land, and growing vegetables and horticulture on raised embankments (35% of the area) (Gabr et al. 2024).

Rainwater harvesting for groundwater recharge

If water cannot be held above ground, it must be stored underground using artificial groundwater recharge (Gabr et al. 2022b). Given that 98% of the earth's freshwater resources are stored underground, there is plenty of room for additional storage. Artificial recharge involves applying water to the land surface, allowing it to percolate into the soil and eventually reach groundwater (Gabr et al. 2022a; Gabr et al. 2023). Permeable soils, particularly sands and gravels, and unconfined aquifers with freely moving groundwater tables are necessary for these systems. During flooding, infiltration rates in these soils can range between 0.5 and 3 m/d. Flooding can cause dispersed particles to build on the surface, creating a fouling layer that slows infiltration. The infiltration system requires regular repair.

Farmers' perceptions

Farmers' perceptions of the impact of climate change and soil degradation are a must. The farmers thought that soil and its qualities have altered as a result of soil erosion, desertification, dessert encroachment, leaching, and other related issues, resulting in poor soil quality, crop performance, and crop yield in the research area (Arsene et al. 2023).

Agricultural diversification

Agricultural diversification including poultry, ducker, fisheries, and apiculture, combined with diversified crop production or value-added products in rainfed rice ecosystems, has been shown to effectively mitigate drought and alleviate poverty by providing high-income, regular employment, and balanced and quality food with less water (Grigorieva 2020; Hayrol ey al. 2024). Agricultural diversification includes many farm companies and crops, offering farmers a 'basket of complementary options' to mitigate weather risks in single-commodity agriculture.

Conclusions

The FAO-CROPWAT 8 model was used to predict the irrigation requirements of nine key crops grown in Egypt's Greater Cairo Territory (Cairo, Giza, and Qalyubia) under eight climate scenarios. The crops were maize, cotton, rice, sugar beet, tomato, wheat, dry bean, berseem clover, and potatoes. The simulation outputs were expressed in terms of reference evapotranspiration (ETo), crop evapotranspiration (ETc), crop water requirements (CWR), and gross irrigation water requirements (GIWR). The results demonstrate that ETo values for RCP 4.5 for the years 2040, 2060, 2080, and 2100 indicate an increase of 2.9, 4.07, 5.35, and 6.43% above the current scenario 2023, but

RCP 8.5 for the same years predict a rise of 3.64, 5.59, 8.5, and 11.4%, respectively. The research area is semi-arid, and rainfall during the winter season delivers just a little amount of irrigation water because the study area receives no effective rainfall. RCP 4.5 increases the CWR by 5.5, 6.6, 8.1, and 8.9% in 2040, 2060, 2080, and 2100, respectively, as compared to the current scenario (2023). For the same years under the high emission scenario RCP 8.5, the CWR increases by 6.0, 8.3, 11.0, and 13.0%, respectively. Crop water demand variations can be used to generate appropriate recommendations for future irrigation planning and reservoir operation modeling throughout Egypt's regions.

The study suggested the following adaptation options for the effects of climate change on crop production in Egypt: (i) changes in planting and harvesting seasons to cultivate crops by the current climate conditions, (ii) mixed cropping, multiple cropping, cover crop planting, and crop rotation, (iii) use smart irrigation systems, (iv) use resistant, improved varieties and crops that mature early, (v) irrigation methods and watershed management, (vi) afforestation and tree planting, (vii) proper soil management procedures, (viii) increased weeding frequency, (ix) indigenous land management approaches (which include microclimate management and ethno engineering), (x) enhancing research and development for innovative technologies, (xi) establishing functional metrological centers in remote areas to promote accurate and timely weather forecasting, (xii) education and training for farmers and stakeholders, and (xiii) strengthening the creation and implementation of rules and regulations.

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